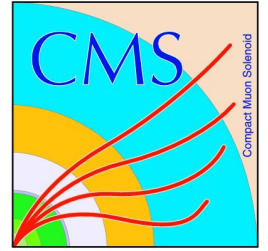


IMPERIAL



Exploring the Dark Sector at the CMS experiment

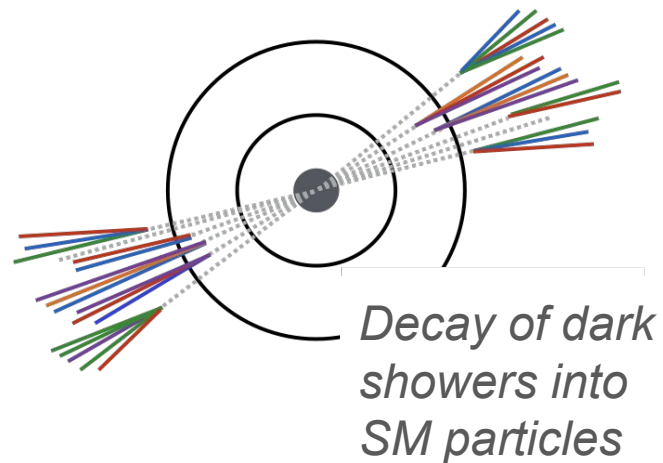
Kai Hong Law

Imperial College London

Imperial HEP seminar, 5 June 2026

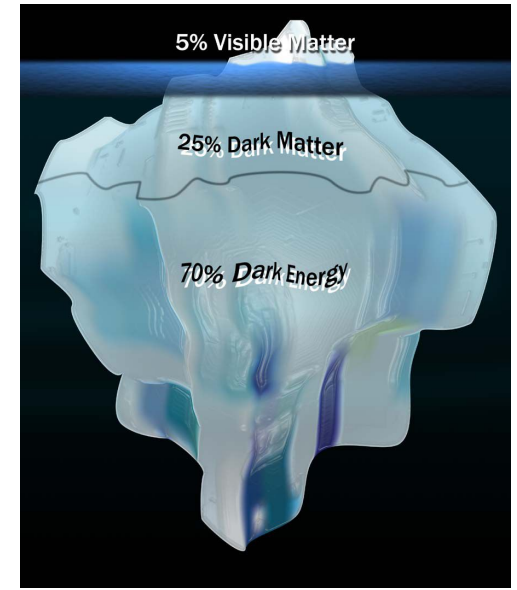
Talk outline

- Introduction to dark sector and hidden valley models
- Dedicated data streams in CMS
- Analyses and results
 - Search for dark showers with Run 2 Parking
 - Displaced dimuon search with early Run 3 Scouting
 - Search for lepton-enriched semi-visible jets with full Run 2
 - Search for soft unclustered energy patterns with Run 2 Scouting
- Summary



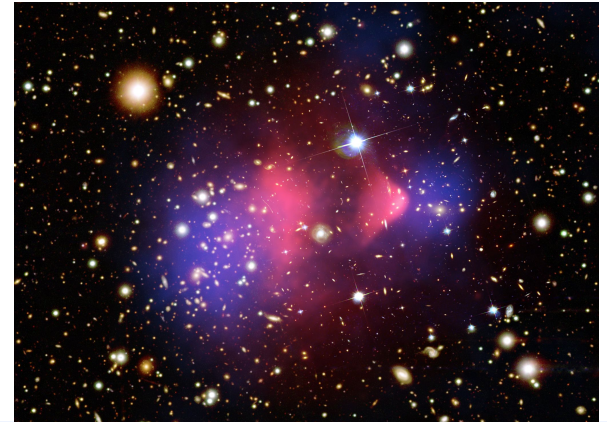
Introduction

- The Standard Model of particle physics has made many successful predictions, but it is not the full picture
- Missing pieces: dark matter, dark energy, gravity, matter-antimatter asymmetry, ...



Standard Model of Elementary Particles

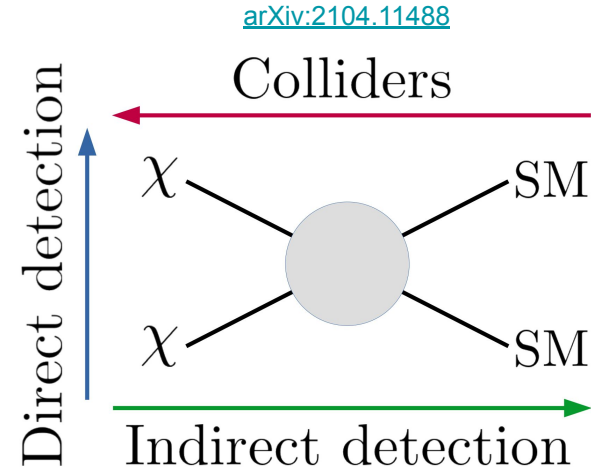
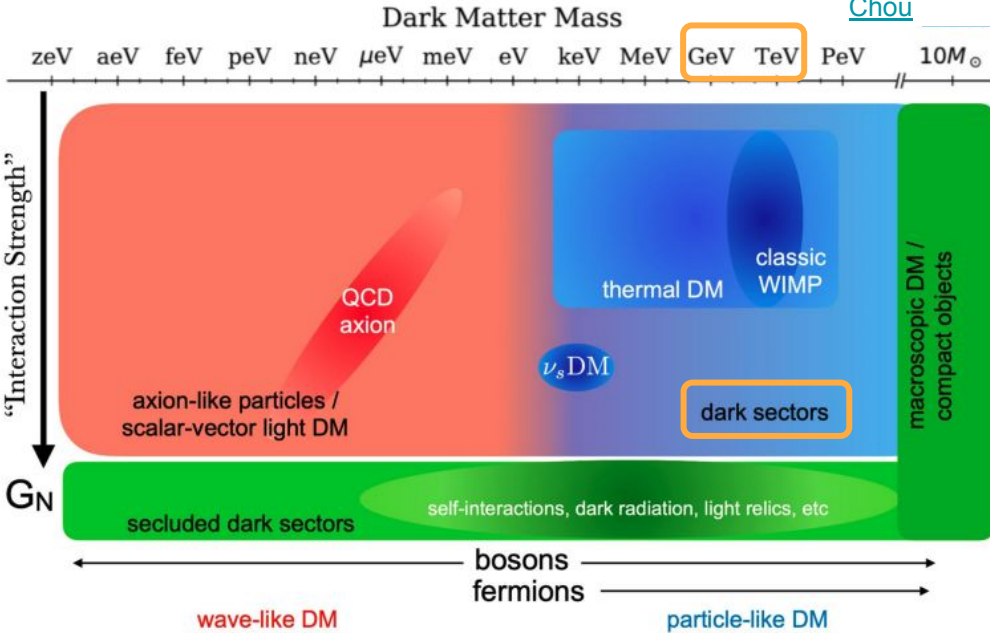
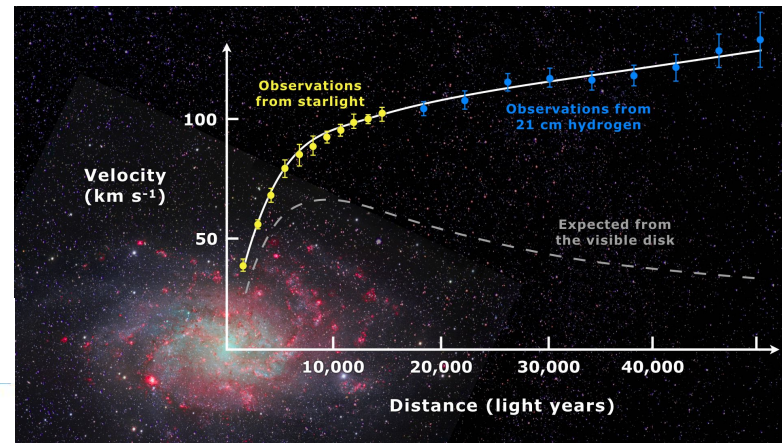
		three generations of matter (fermions)			Interactions / force carriers (bosons)	
		I	II	III		
QUARKS	mass	=2.16 MeV/c ²	=1.273 GeV/c ²	=172.57 GeV/c ²	0	=125.2 GeV/c ²
	charge	2/3	2/3	2/3	0	0
	spin	1/2	1/2	1/2	1	0
		u up	c charm	t top	g gluon	H higgs
		d down	s strange	b bottom	γ photon	
		e electron	μ muon	τ tau	Z Z boson	
		ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					SCALAR BOSONS	
					GAUGE BOSONS VECTOR BOSONS	



Introduction

- Strong astrophysical evidence for the existence of dark matter: galaxy rotation curves, gravitational lensing, cosmic microwave background, ...
- Dark matter can potentially be produced in LHC with mass in the GeV-TeV range

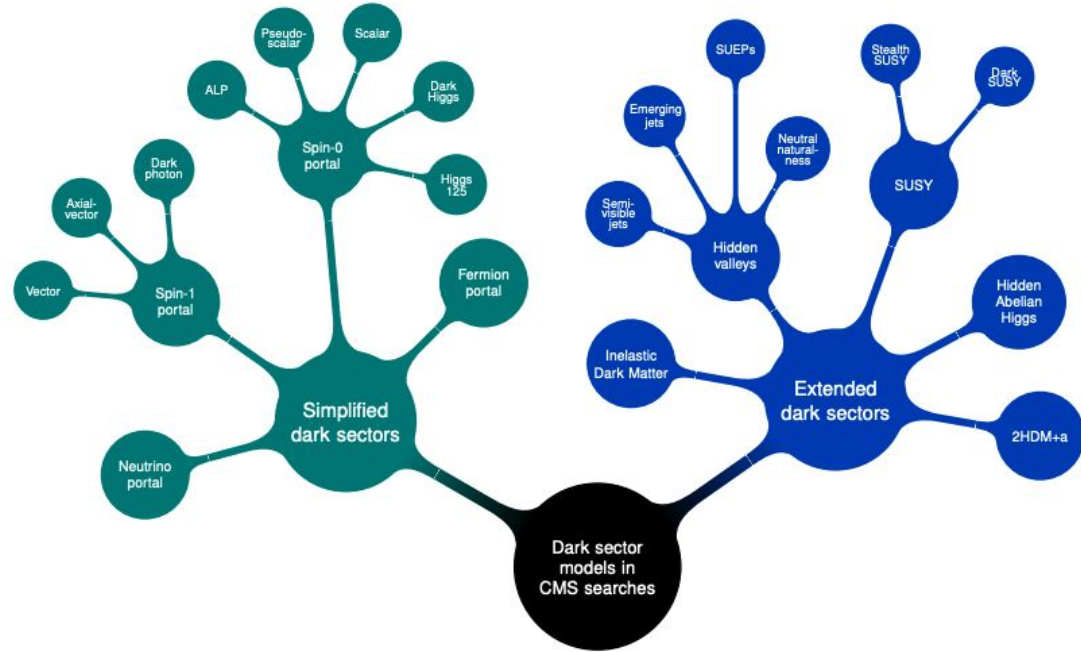
[CF strategy, SSS, A. Chou](#)



[arXiv:2104.11488](#)

Dark sector searches at CMS

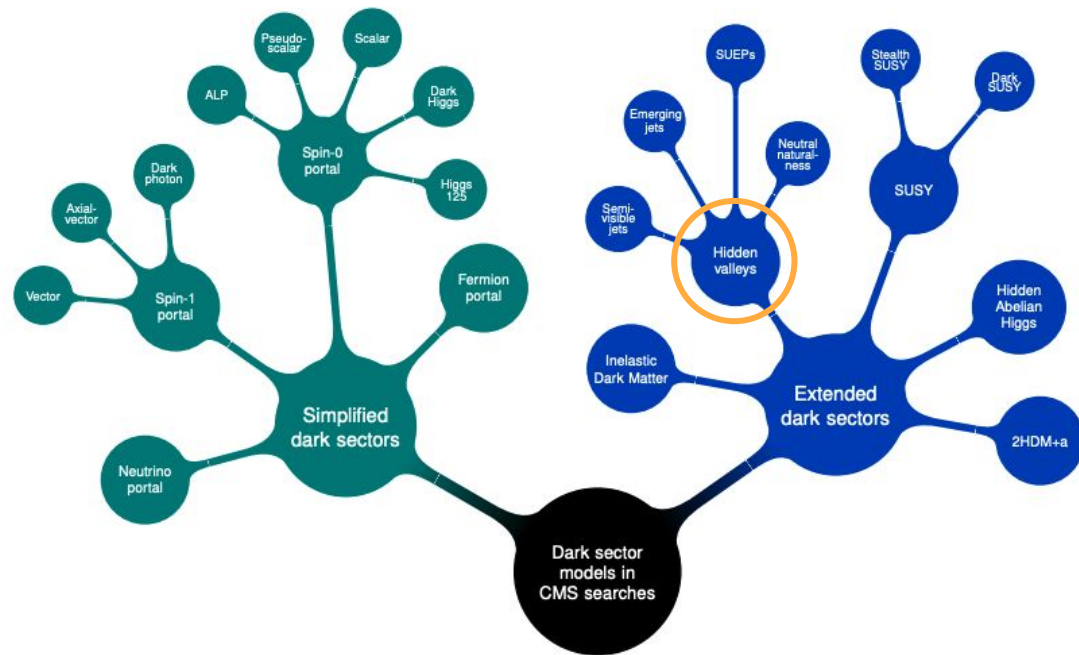
- **Dark sector:** a collection of yet-unobserved quantum fields and their corresponding new particles, primarily to explain the source of dark matter
- Searches guided by simplified benchmark models:
DM candidate + single mediator particle (connect the SM to the dark sector)



Phys. Rept. **1115**, (2025) 448

Dark sector searches at CMS

- Extended dark sector: models with complex dynamics in the dark sector, typically incorporating more than one DM particle species
- A wide variety of possible signatures
- Will focus on **Hidden valley models** in this talk

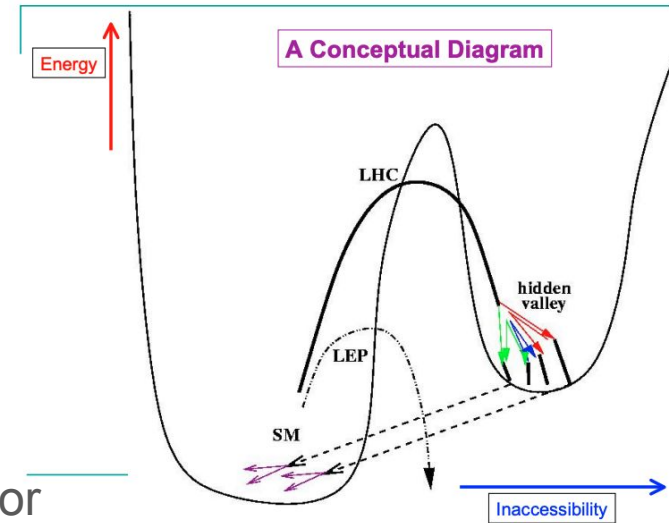
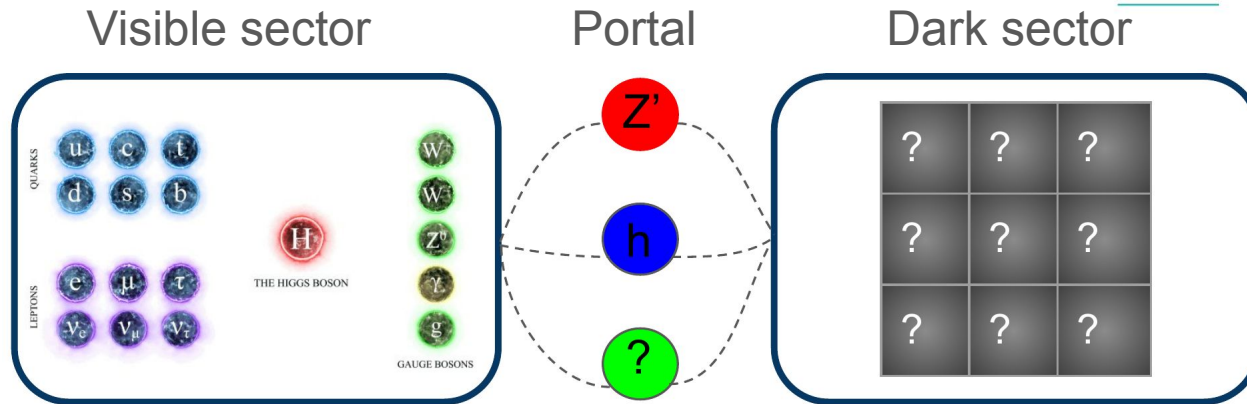


Phys. Rept. 1115. (2025) 448

Hidden valley models

M. J. Strassler, K. M. Zurek,
Phys. Lett. B **651** 374 (2007)

- Extend the SM gauge group by a non-Abelian gauge group, which describes a dark sector
- Contain **dark matter candidates** that are uncharged under the SM gauge group
- **Mediator particles** connect the dark sector to the SM



The CMS experiment

*Tracker: vertex resolution of $\sim 10 \mu\text{m}$
in the transverse plane*

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel ($100 \times 150 \mu\text{m}^2$) $\sim 1.9 \text{ m}^2$ $\sim 124\text{M}$ channels
Microstrips (80 – $180 \mu\text{m}$) $\sim 200 \text{ m}^2$ $\sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying $\sim 18,000 \text{ A}$

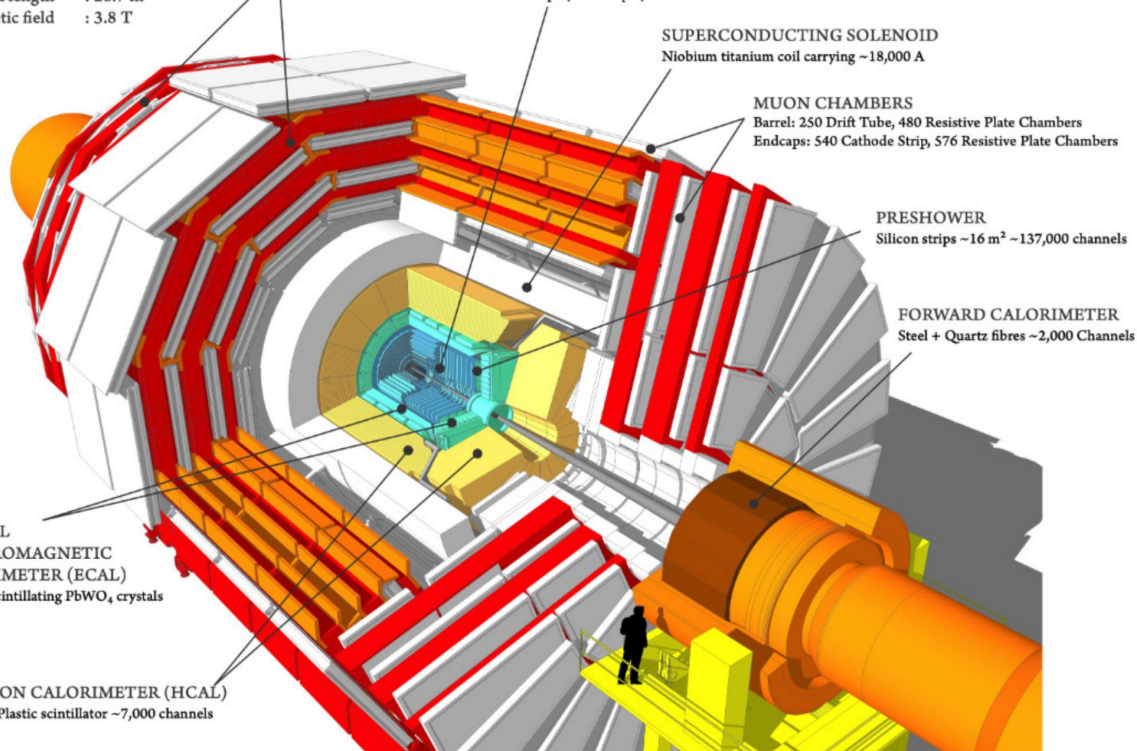
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
Silicon strips $\sim 16 \text{ m}^2$ $\sim 137,000$ channels

FORWARD CALORIMETER
Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

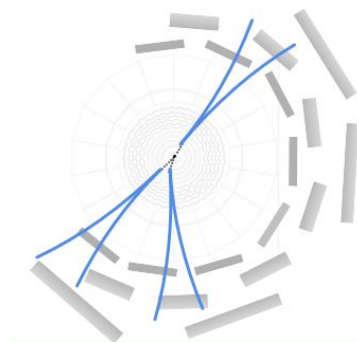
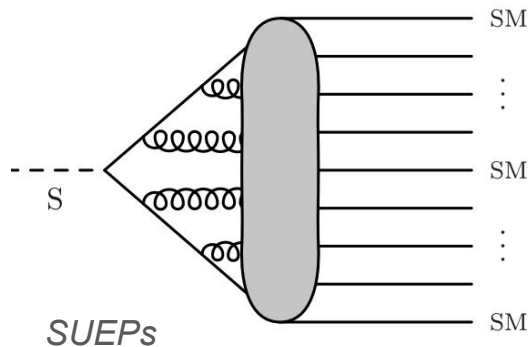
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels



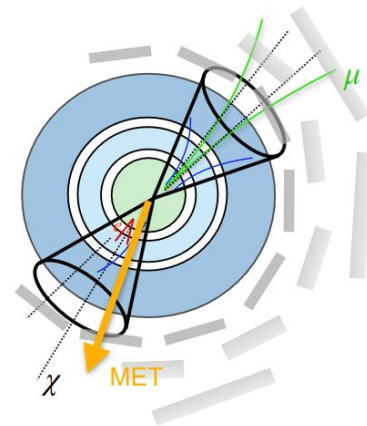
*Events are selected
by a two-tier trigger
system (not shown in
the figure)*

Searches for dark showers in CMS

- Hidden Valley models can produce dark hadrons with high multiplicity, known as **dark showers**
- This talk will include:
 - The **first dedicated search** in the LHC for dark showers decaying into **displaced muons** (Run 2)
 - [JHEP 03 \(2026\) 189](#) (EXO-24-008)
 - A **general displaced muon search** (Early Run 3)
 - [CMS-PAS-EXO-24-016](#)
 - The first collider search for **lepton-enriched semi-visible jets** (Run 2)
 - [CMS-PAS-EXO-24-029](#)
 - Search for **soft unclustered energy patterns (SUEPs)** (Run 2)
 - [CMS-PAS-EXO-23-001](#)



Displaced vertices



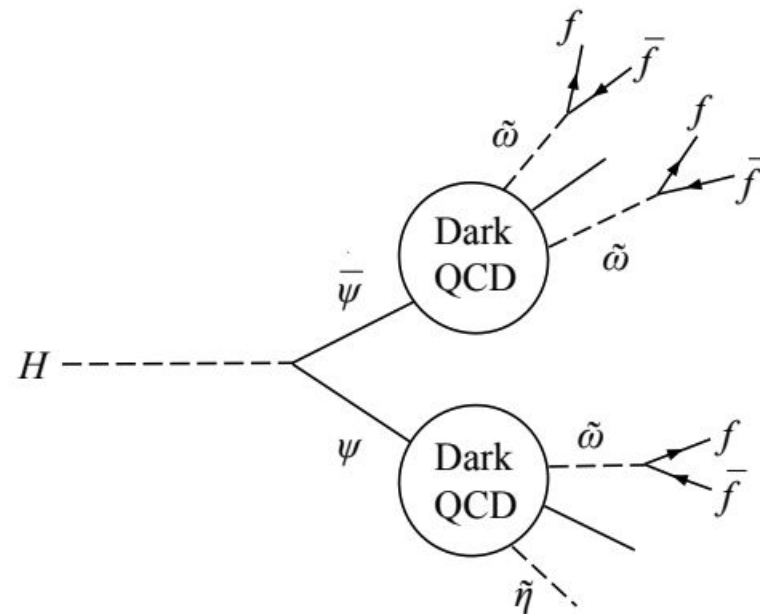
Semi-visible jets

Hidden valley benchmark model

S. Knapen, J. Shelton, D. Xu

[arXiv:2103.01238](https://arxiv.org/abs/2103.01238)

- Search for the production of dark showers from the SM Higgs
- First consider the **vector portal** model, which contains one dark flavour
- Ψ denotes the dark parton
- Simplified scenario: only one of the dark mesons ($\tilde{\eta}$ or $\tilde{\omega}$) has a detector-relevant lifetime
- $\tilde{\omega}$ (dark vector meson) is the visibly-decaying particle
- $\tilde{\eta}$ (dark scalar meson) is assumed to escape the detector as missing energy
- Use a branching ratio of $B(H \rightarrow \psi\psi) = 0.01$ when plotting the signal distributions

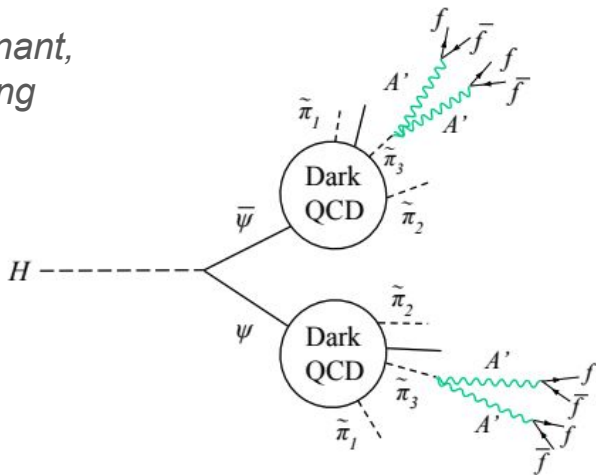


Vector portal

Extended hidden valley benchmark models

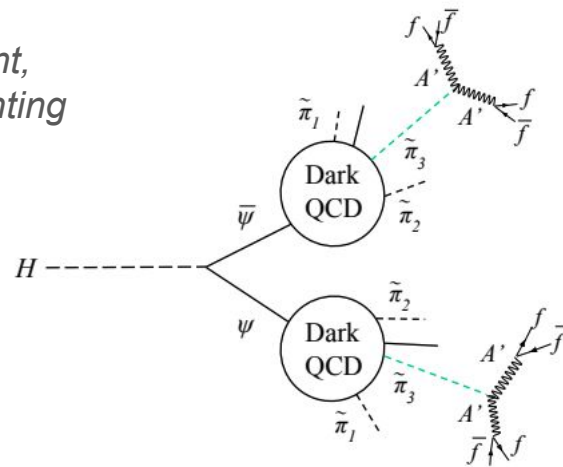
- Extended benchmark models feature a light dark photon A' with dark flavour-violating couplings
- Contain two dark flavours instead of one \implies wider spectrum of dark hadrons
 - pseudoscalar η and dark pions π_1, π_2, π_3
 - η decays promptly into π_i in **scenario A** and **scenario B1**
- Decay topologies can give **non-pointing** signals

*Resonant,
pointing*



Scenario A

*Resonant,
non-pointing*



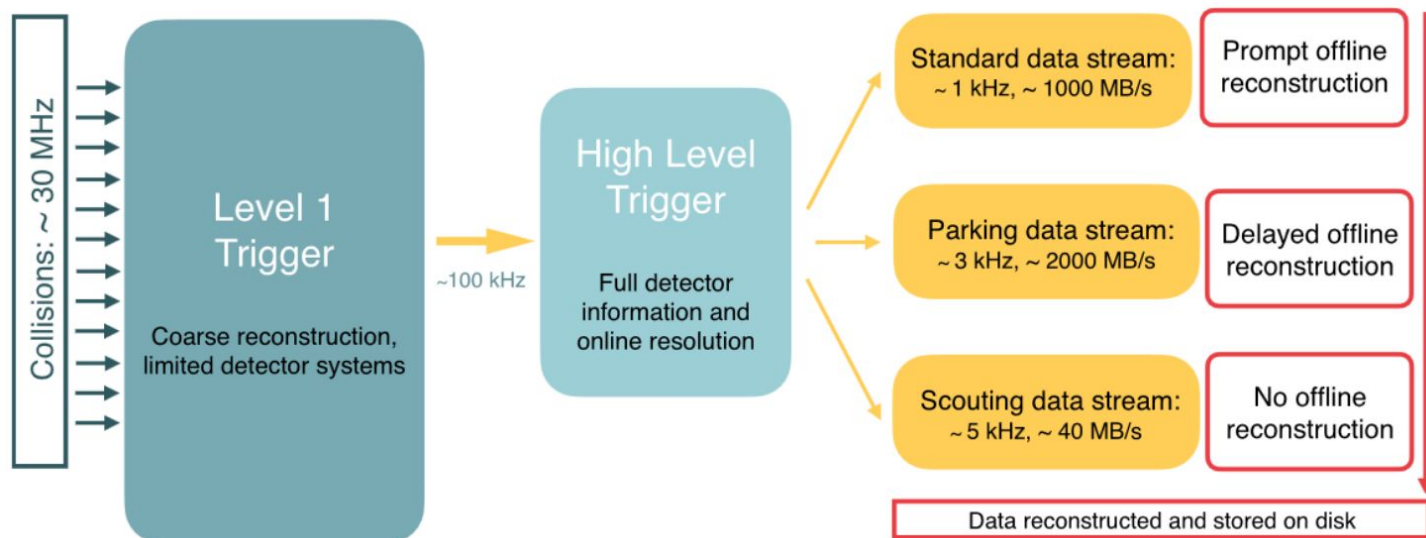
Scenario B1

[arXiv:2303.04167](https://arxiv.org/abs/2303.04167)

S. Born, R. Karur, S. Knapen, J. Shelton

Dedicated data streams in CMS

- Searches for displaced, low-mass signatures are challenging!
- Limited by standard trigger strategies
- Two dedicated data-streams to lower trigger thresholds and increase physics acceptance:
 - **Parking:** [Delayed offline reconstruction](#)
 - **Scouting:** [Reduced event content](#), reconstruction from High Level Trigger only



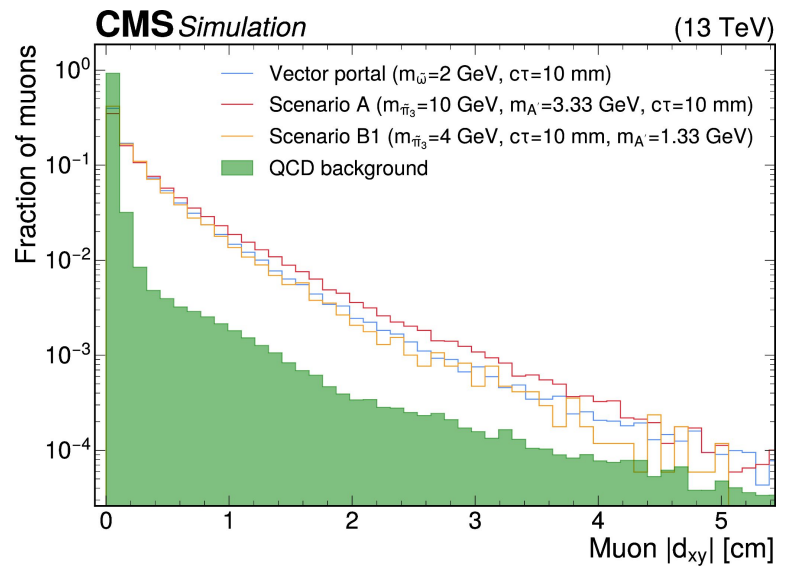
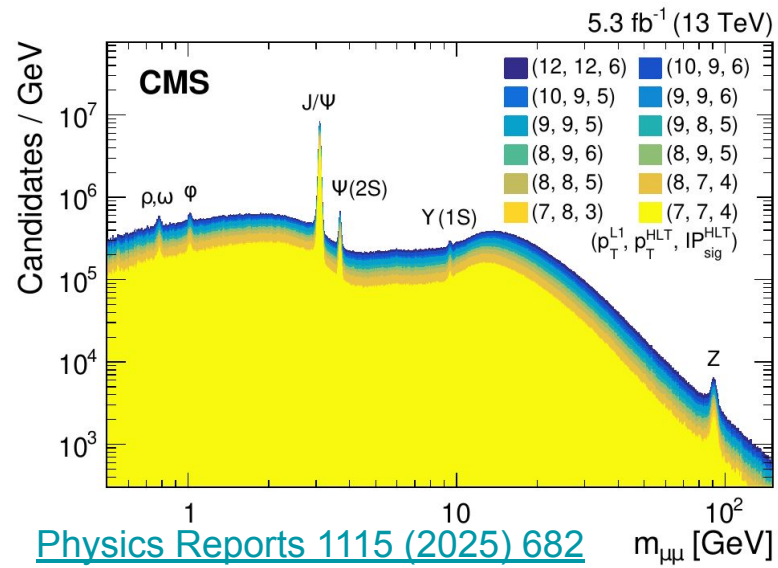
[Physics Reports 1115 \(2025\) 682](#)

*Numbers are representative for 2018

Run 2 Parking analysis

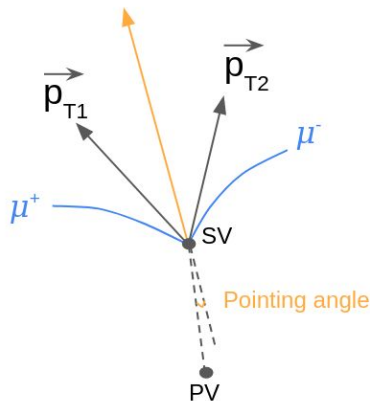
- The Run 2 “B-Parking” strategy:
 - originally motivated by the study of B flavour anomalies
 - **Displaced single muon triggers:**
 p_T thresholds range from 7 to 12 GeV,
 IP_{sig}^{HLT} thresholds range from 3 to 6

- Use of event-level BDT in the analysis to perform background rejection:
 - Variables from muons, muon secondary vertices (SVs), general SVs
 - Able to achieve **10^4 background rejection with > 30% signal efficiency!**

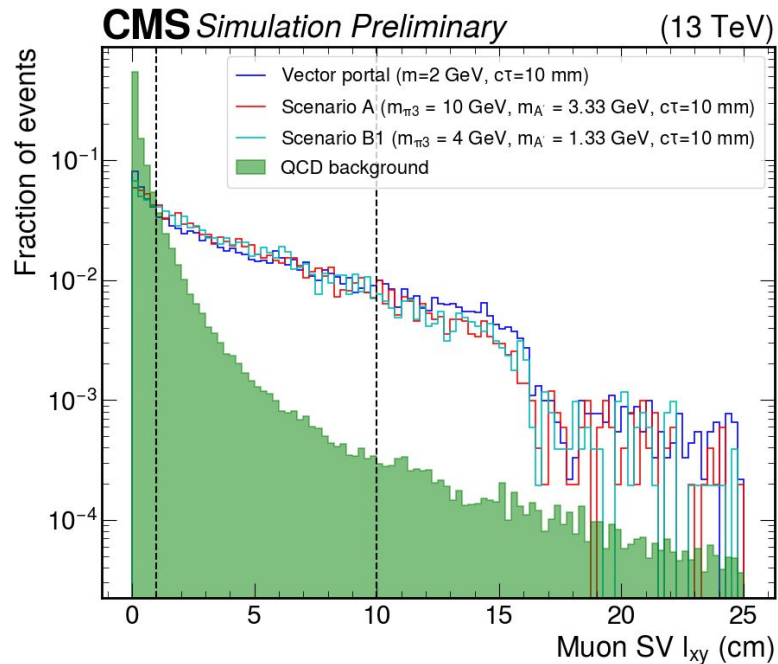


Event categorisation

- Check the muon SV multiplicity:
 - if there are at least two muon SVs with mass within 3% of each other:
 - **multi vertex** category
 - Otherwise:
 - **single vertex** category
- Categorise in **transverse displacement**:
 - $l_{xy} < 1$ cm,
 - $1 \text{ cm} < l_{xy} < 10$ cm,
 - $l_{xy} > 10$ cm
- Categorise in **pointing angle**:
 - pointing angle < 0.2 ,
 - pointing angle > 0.2

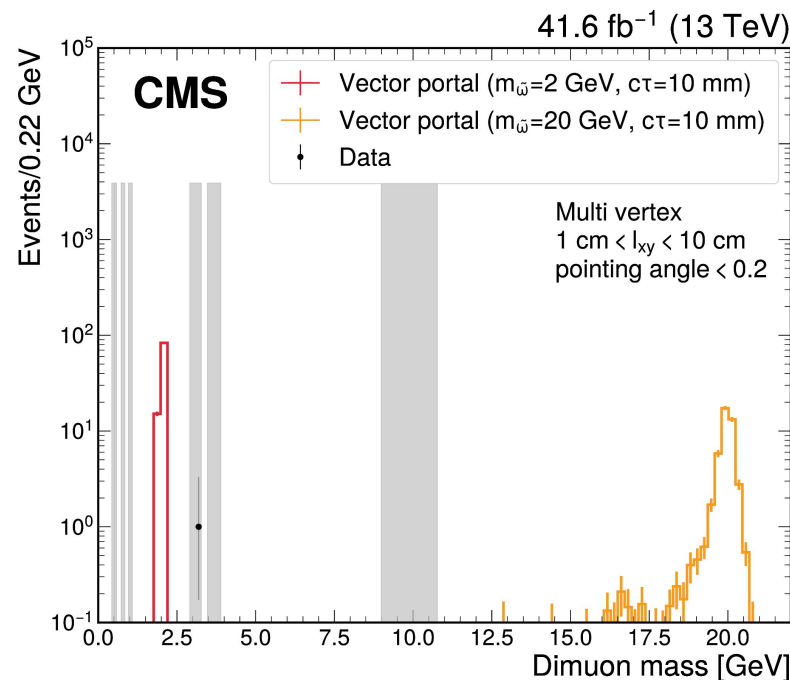
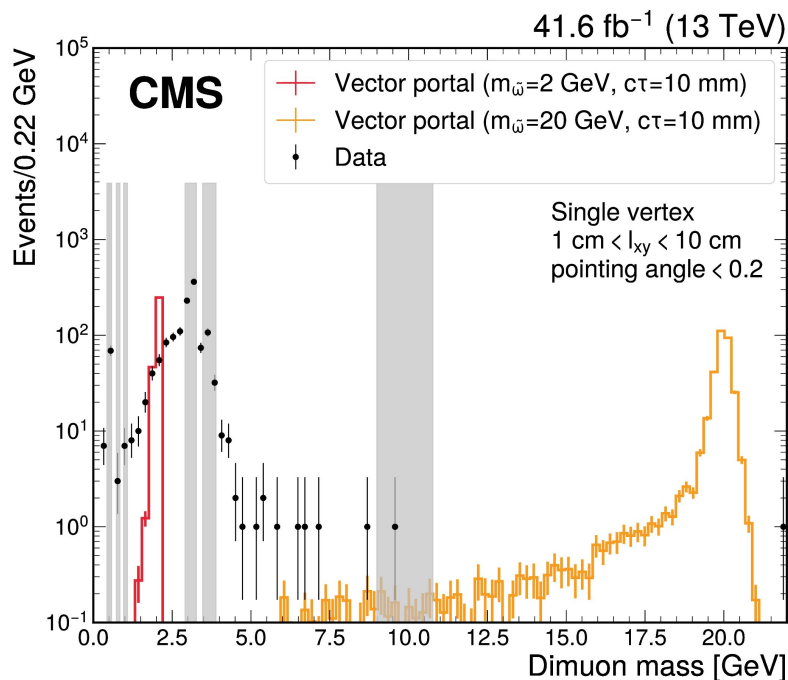


➔ 12 categories in total



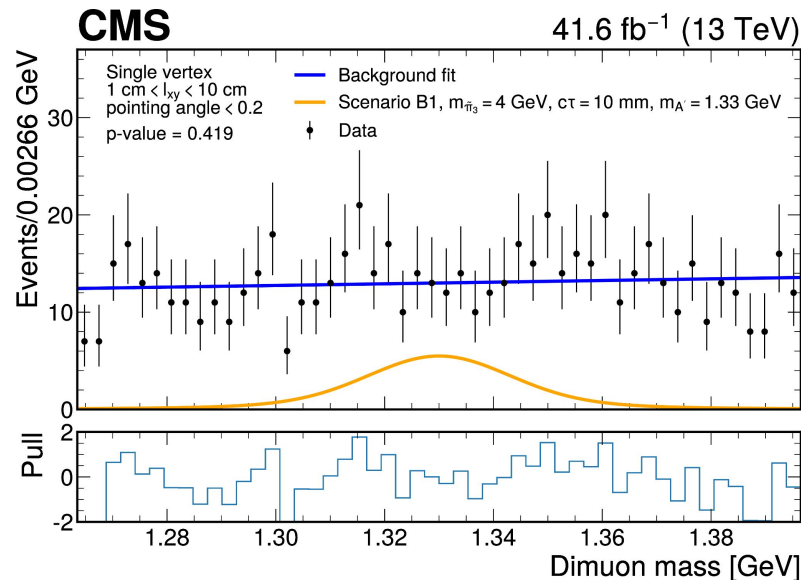
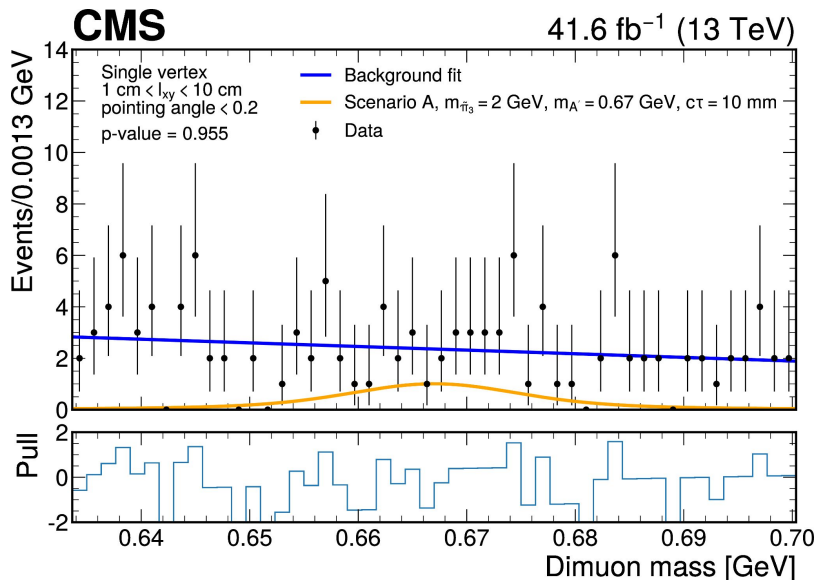
Dimuon mass distributions in example categories

- Much smaller background in the **multi vertex category (right)** compared to the **single vertex category (left)**
- Grey bands indicate mass regions of SM resonances, which are masked in the analysis
- Perform **parametric fit** with a sliding mass window to extract signal



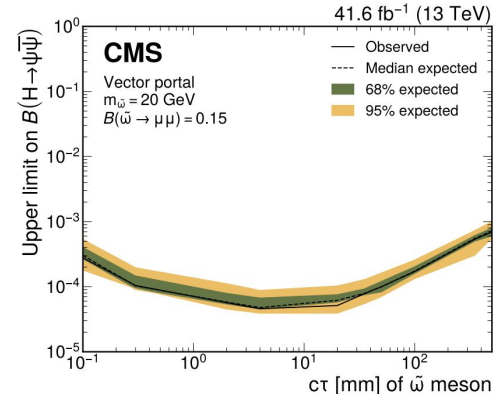
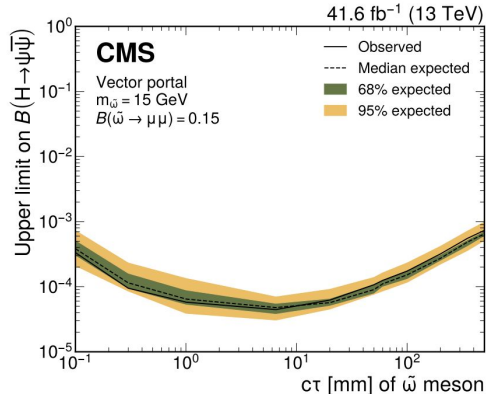
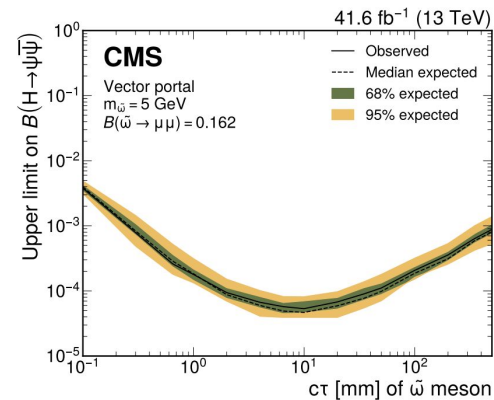
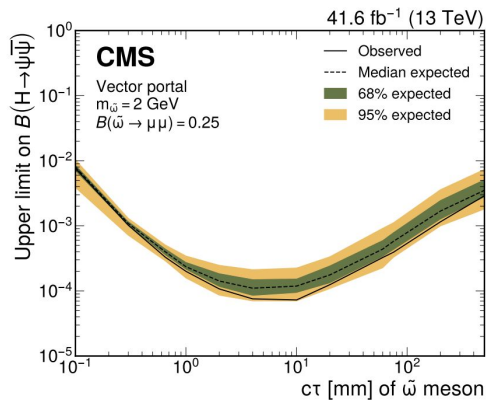
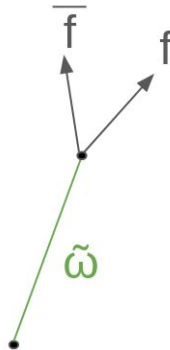
Fitting strategy

- Use the Voigtian function to model signal
- Fit with a sliding mass window of $5 \times \text{HWHM}$ (HWHM taken to be 1% of the signal mass) in each category
- Use an envelope of functions for the background fit - polynomial (first order), exponential and power law functions. Background estimated by fitting to data sidebands.
- Discrete profiling systematic
- GOF and bias tests have been performed



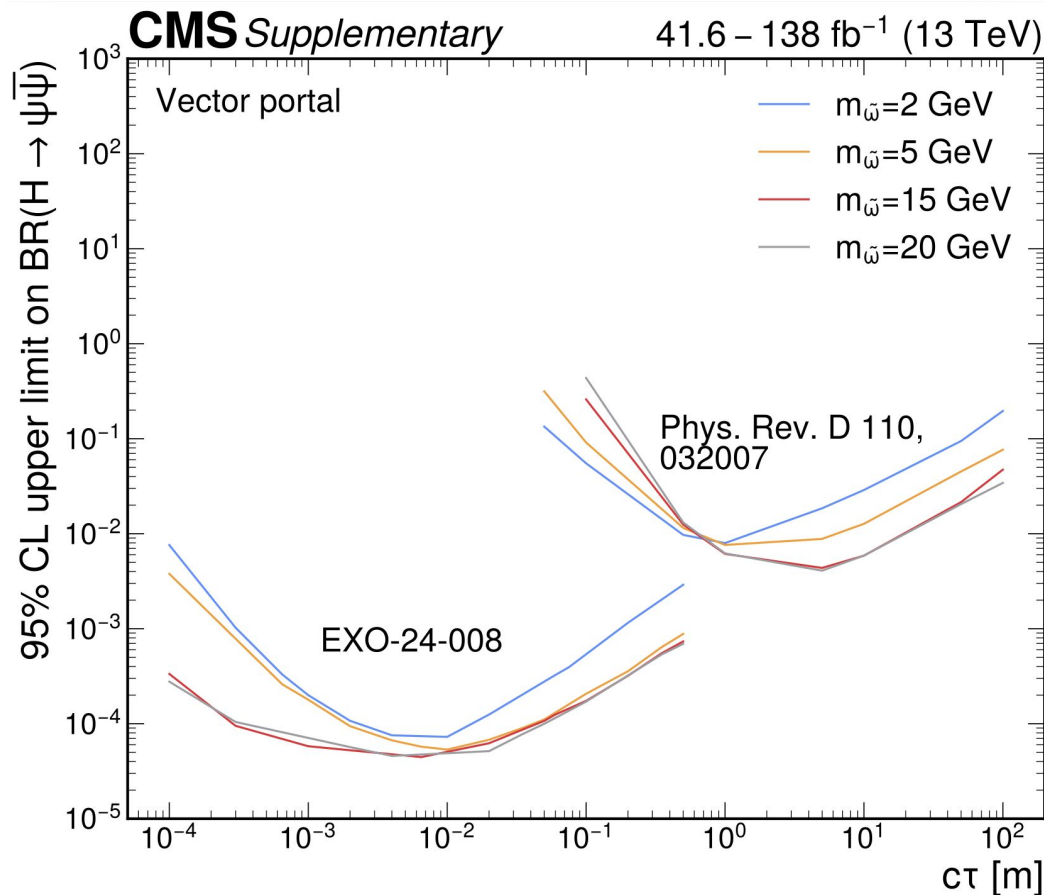
Limits - Vector portal

- 95% confidence level limits are obtained by performing parametric fit with a sliding mass window
- Computed limits on $B(H \rightarrow \psi\psi)$ as a function of the LLP ($\tilde{\omega}$ for the vector portal) mean proper decay length
- Able to impose limits on $B(H \rightarrow \psi\psi)$ at 10^{-3} to $\sim 5 \times 10^{-5}$ over much of the phase space



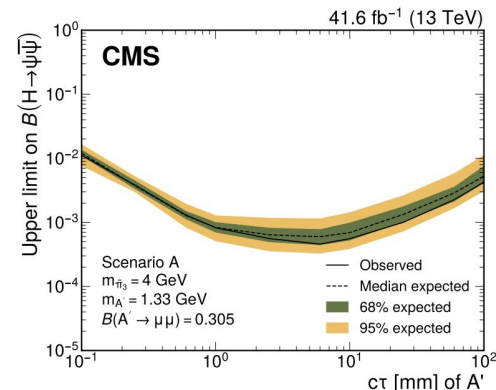
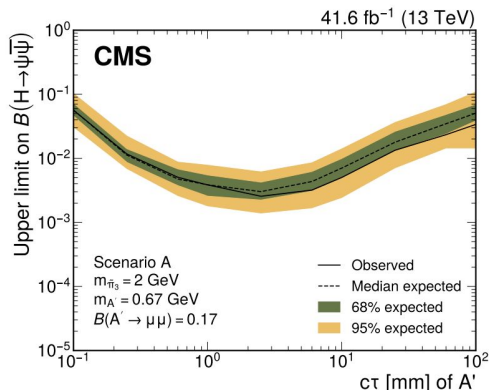
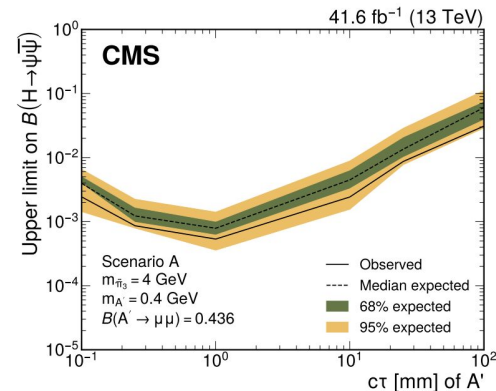
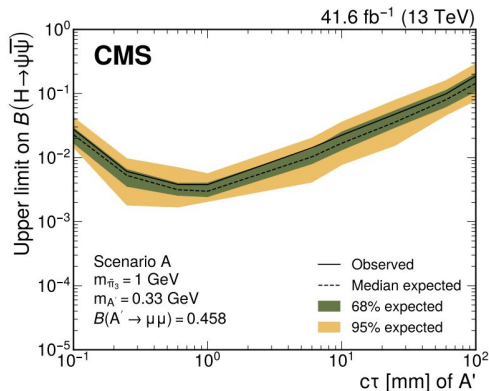
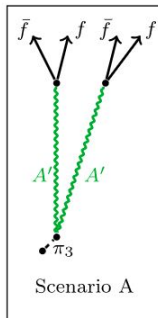
Limits - Vector portal

- Limits for the vector portal are complementary to those from the search with muon detector showers in CMS
- Make use of the tracker in this analysis which probes lower proper decay lengths
- Probe **new phase space** for **proper decay length less than 0.1 m** for all masses (as low as 2 GeV)
- Achieve an improvement in the limits of **up to 2 orders of magnitude**



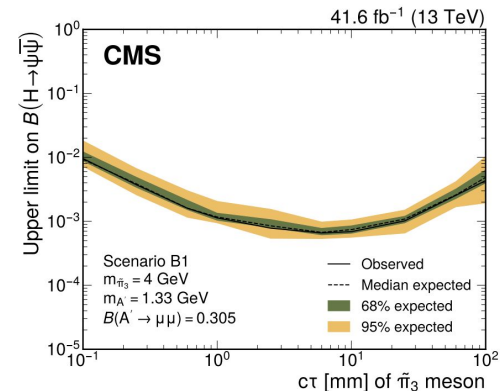
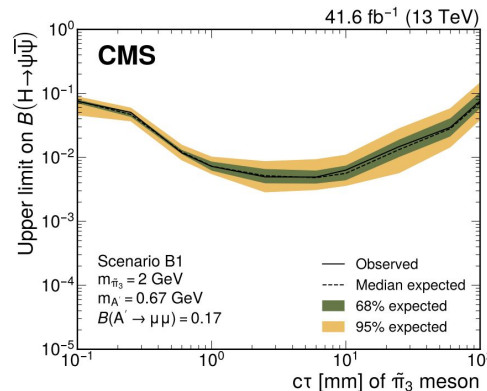
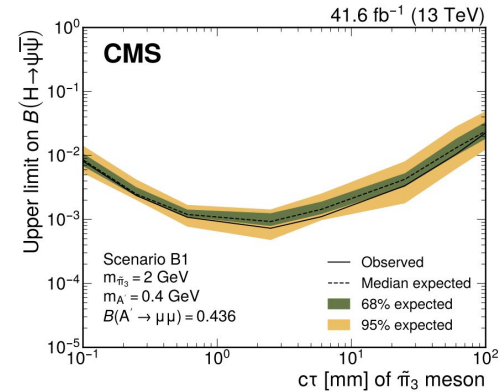
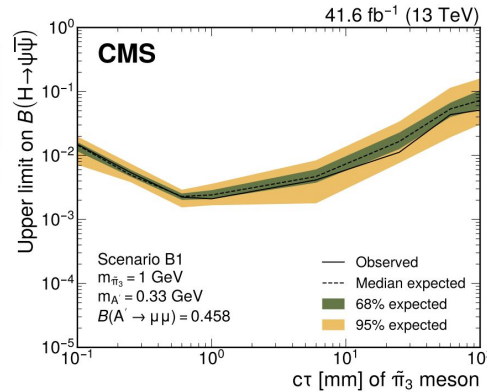
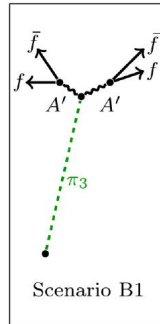
Limits - Scenario A

- Computed limits on $B(H \rightarrow \psi\bar{\psi})$ as a function of the LLP (A' for the scenario A) mean proper decay length
- Able to impose limits on $B(H \rightarrow \psi\bar{\psi})$ at 10^{-2} to $\sim 6 \times 10^{-4}$ over much of the phase space
- Low mass model points! (below 2 GeV)



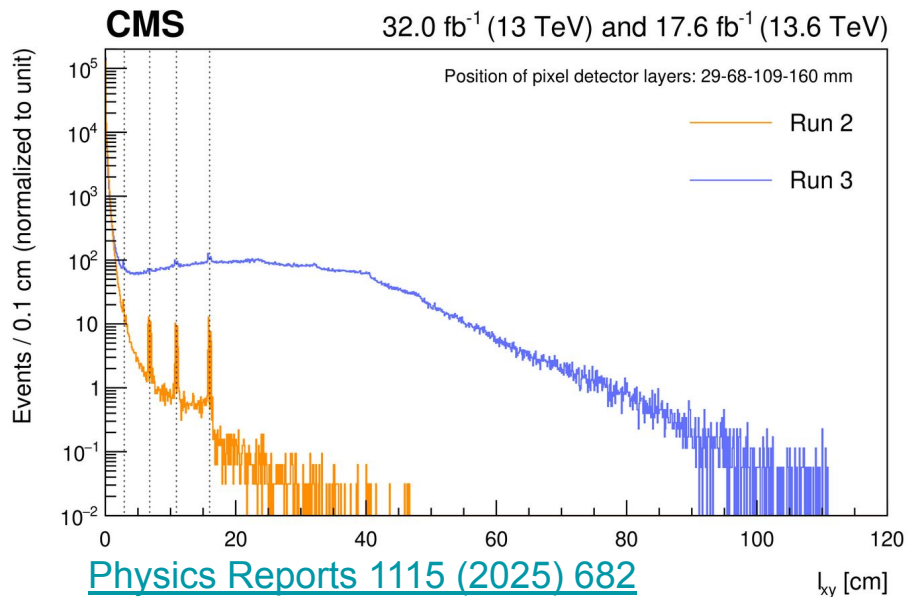
Limits - Scenario B1

- Computed limits on $B(H \rightarrow \psi\psi)$ as a function of the LLP (π_3 for the scenario B1) mean proper decay length
- Able to impose limits on $B(H \rightarrow \psi\psi)$ at 10^{-2} to $\sim 7 \times 10^{-4}$ over much of the phase space
- Low mass model points! (below 2 GeV)
- Good sensitivity achieved for both pointing and non-pointing scenarios!



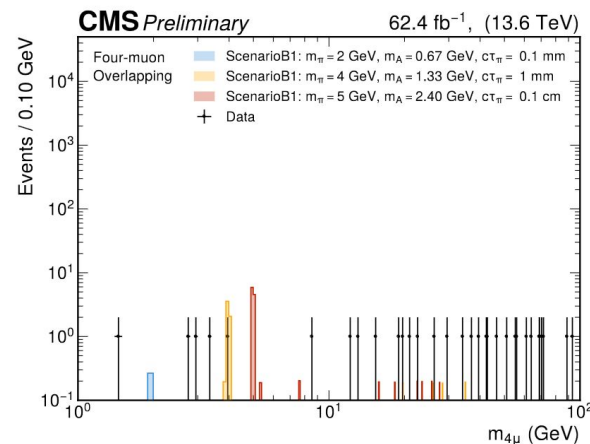
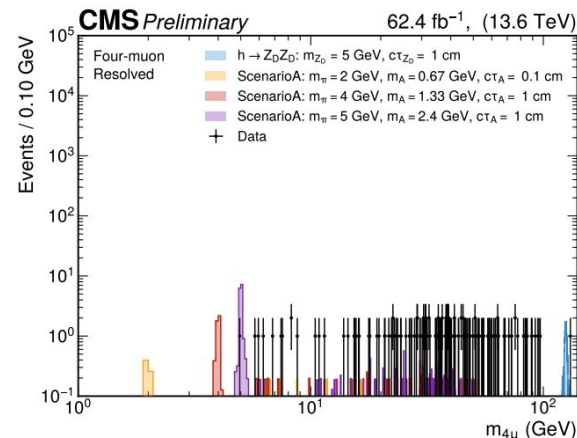
Run 3 Scouting analysis

- A [general displaced muon search](#) using 2022-2023 Scouting data
- Improvements in Run 3 Scouting:
 - Additional muon information e.g. track hit pattern
 - PF (pixel-only) candidates e.g. for isolation
 - $l_{xy} > 11$ cm becomes available for low p_T muon streams



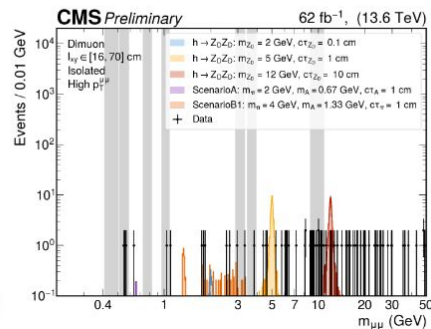
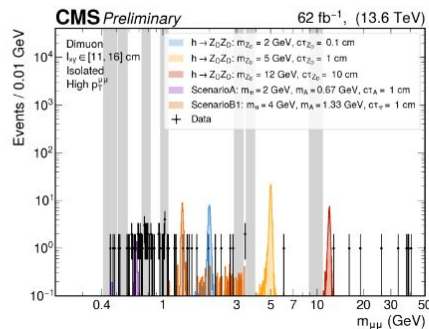
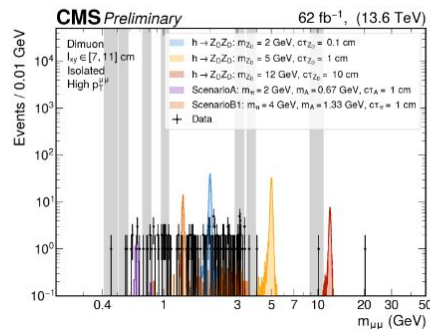
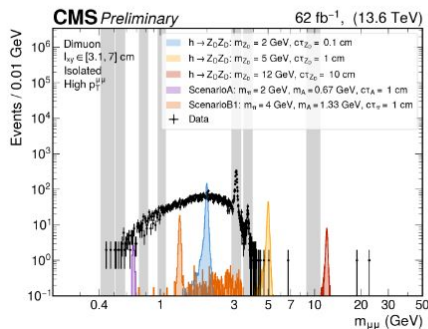
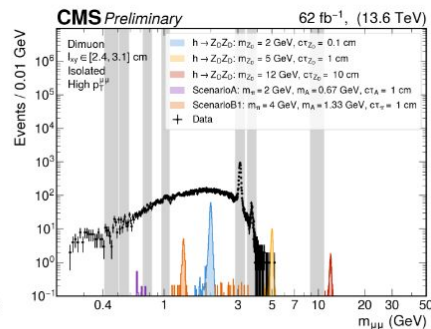
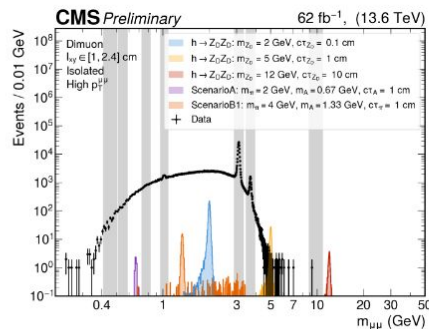
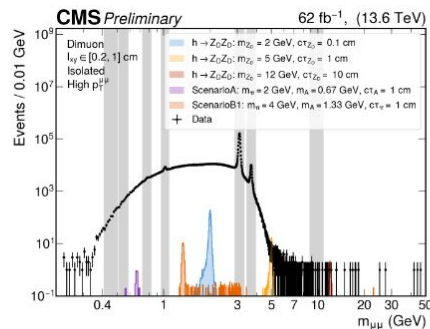
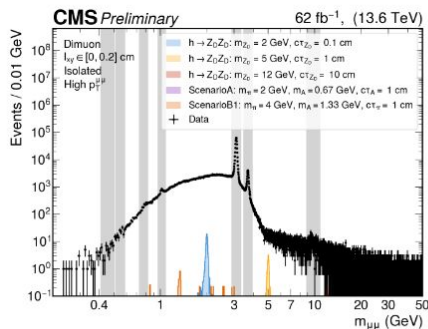
Run 3 Scouting analysis

- Scouting di-muon triggers with $p_T^\mu > 3$ GeV
- Event categorisation:
 - **Dimuon events:**
 - Split in $p_T^{\mu\mu}$, isolation, pointing angle
 - Further binned in eight l_{xy} bins
 - **Four-muon events:**
 - Multivertex category (two resolved SVs)
 - Overlapping vertex category
- Signal extraction by sliding windows over the mass spectra for the different hypotheses



Run 3 Scouting analysis - dimuon mass

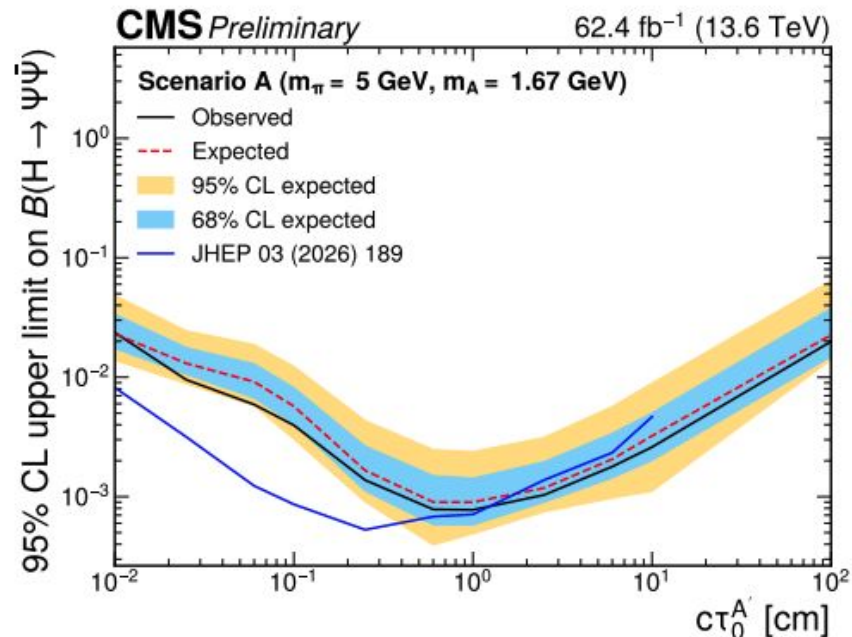
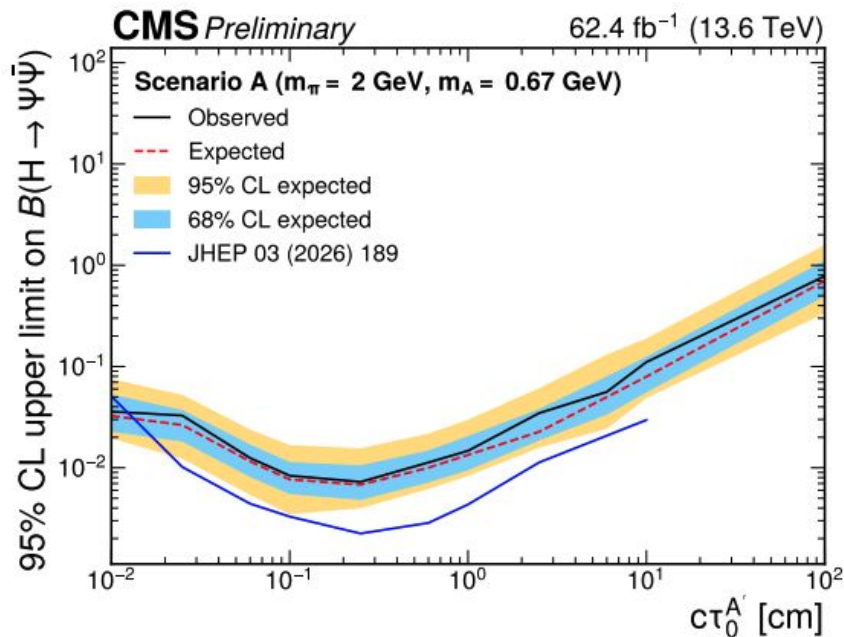
- Dimuon mass distributions in pointing, isolated, high p_T dimuon categories



Run 3 Scouting analysis

- Set 95% CL upper limits on the **Scenario A and Scenario B1** benchmark models
- **Complementary sensitivity to the Parking analysis** is seen

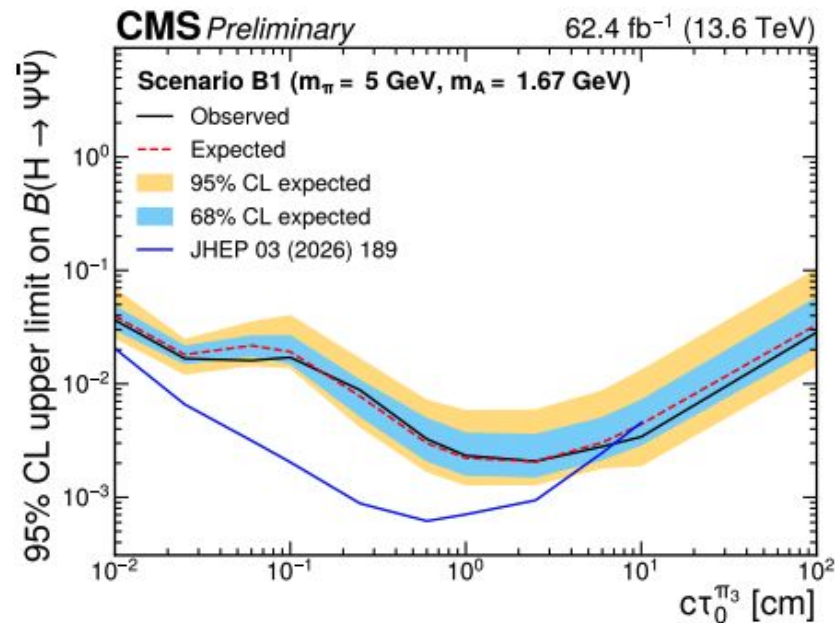
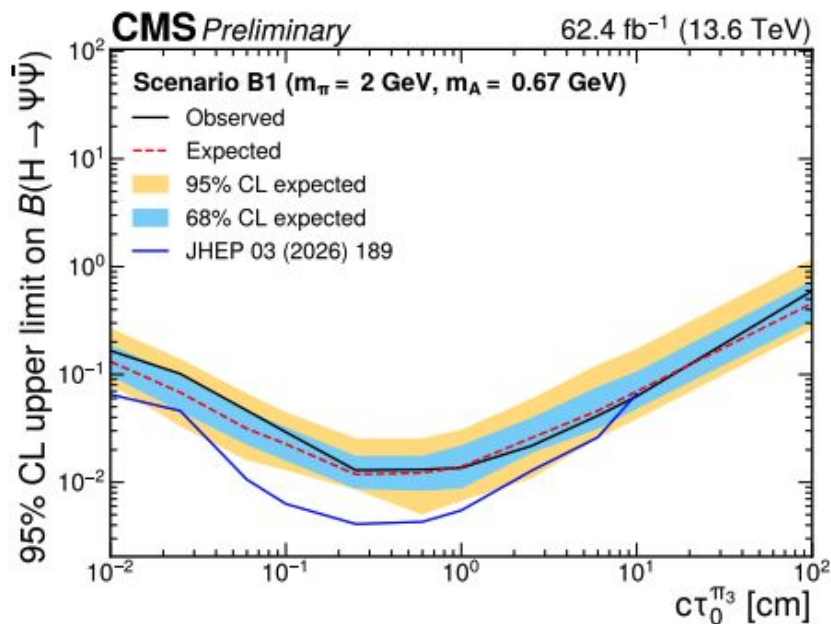
resonant, pointing scenario



Run 3 Scouting analysis

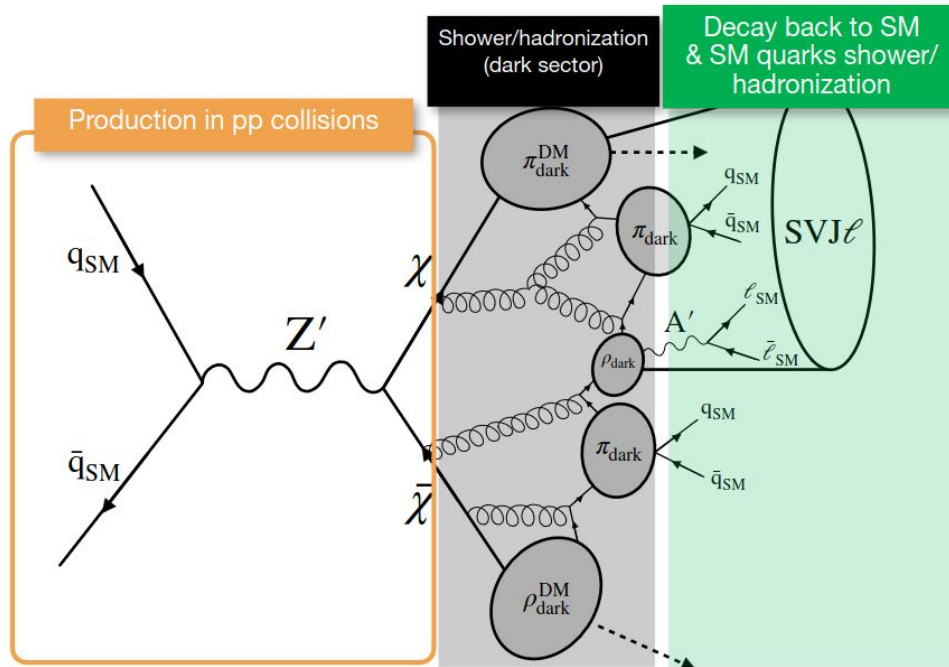
- Set 95% CL upper limits on some benchmark models in [Scenario A and Scenario B1](#)
- Complementary sensitivity to the Parking analysis is seen

resonant, non-pointing scenario



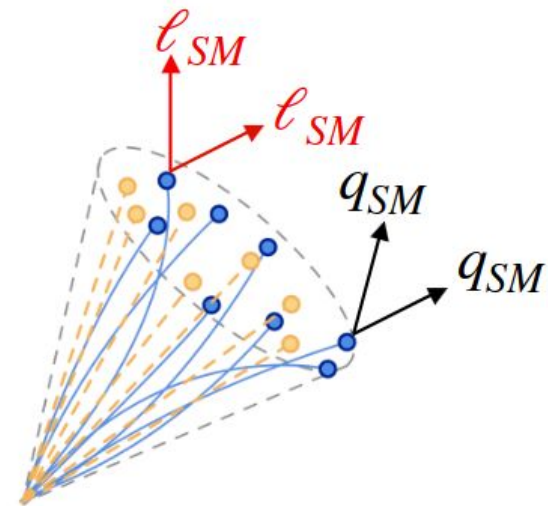
Search for lepton-enriched semi-visible jets

- Dark showers can produce **semi-visible jets** (MET aligned with jets) that contain opposite-charge **lepton pairs** produced by unstable dark hadrons
- **First collider search** for this signature



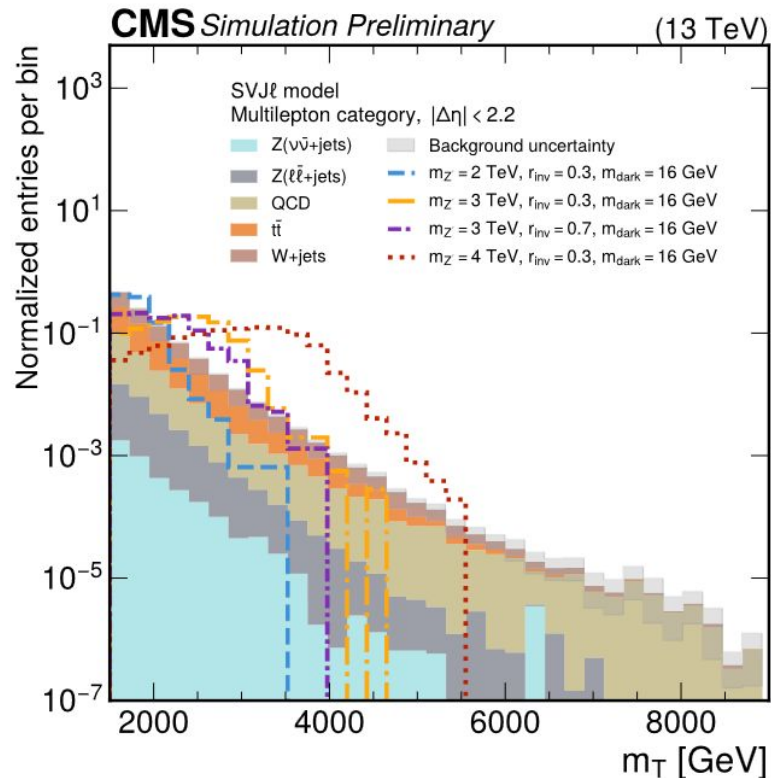
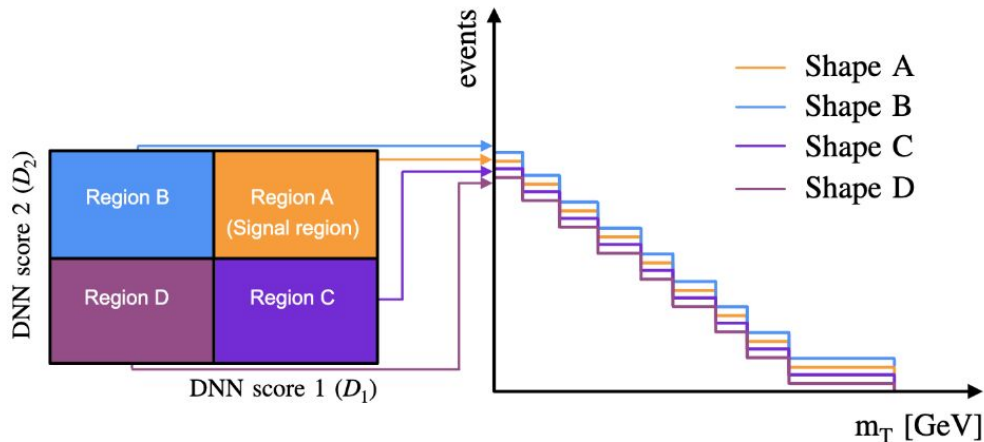
[arXiv:2206.03909](https://arxiv.org/abs/2206.03909) C. Cazzaniga, A. de Cosa

- Unstable dark hadrons (blue dot)
- Stable dark hadrons (yellow dot)

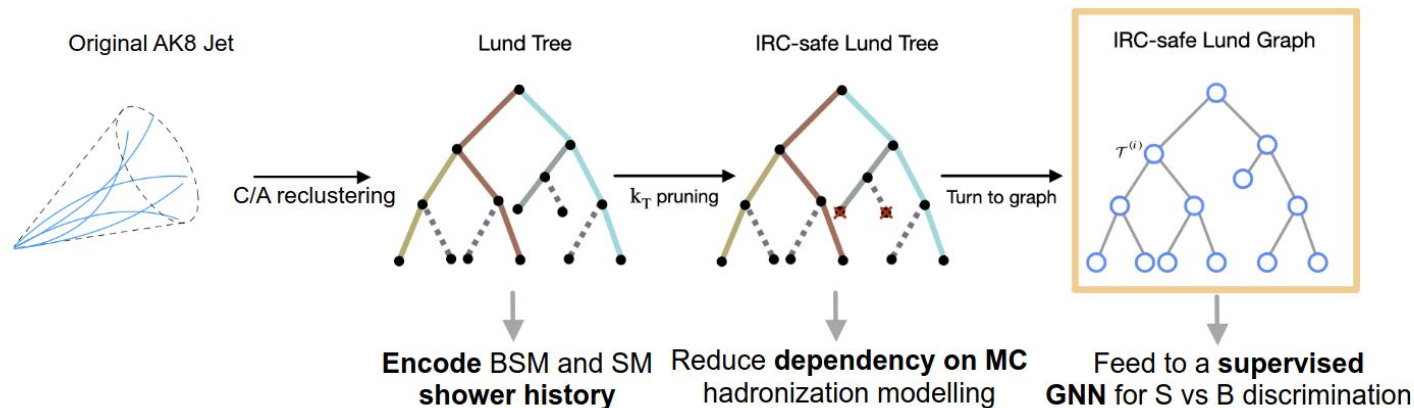


Search for lepton-enriched semi-visible jets

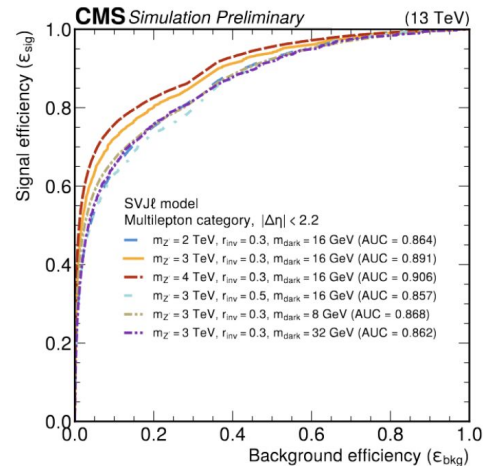
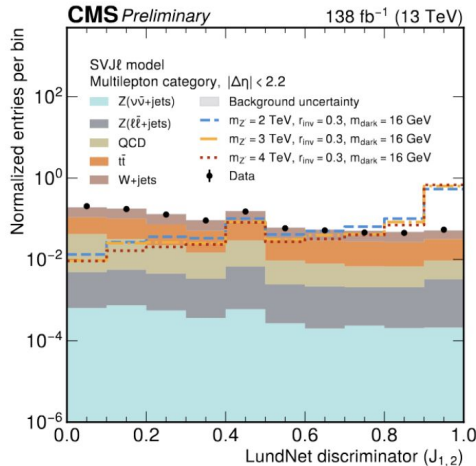
- Perform binned fit in **dijet transverse mass**
- Employ **a graph neural network jet tagger** (LundNet) to discriminate between signal and background jets
- Train **two independent deep neural networks** to engineer two discriminators for an **ABCD method** ([CMS-MLG-23-003](#))

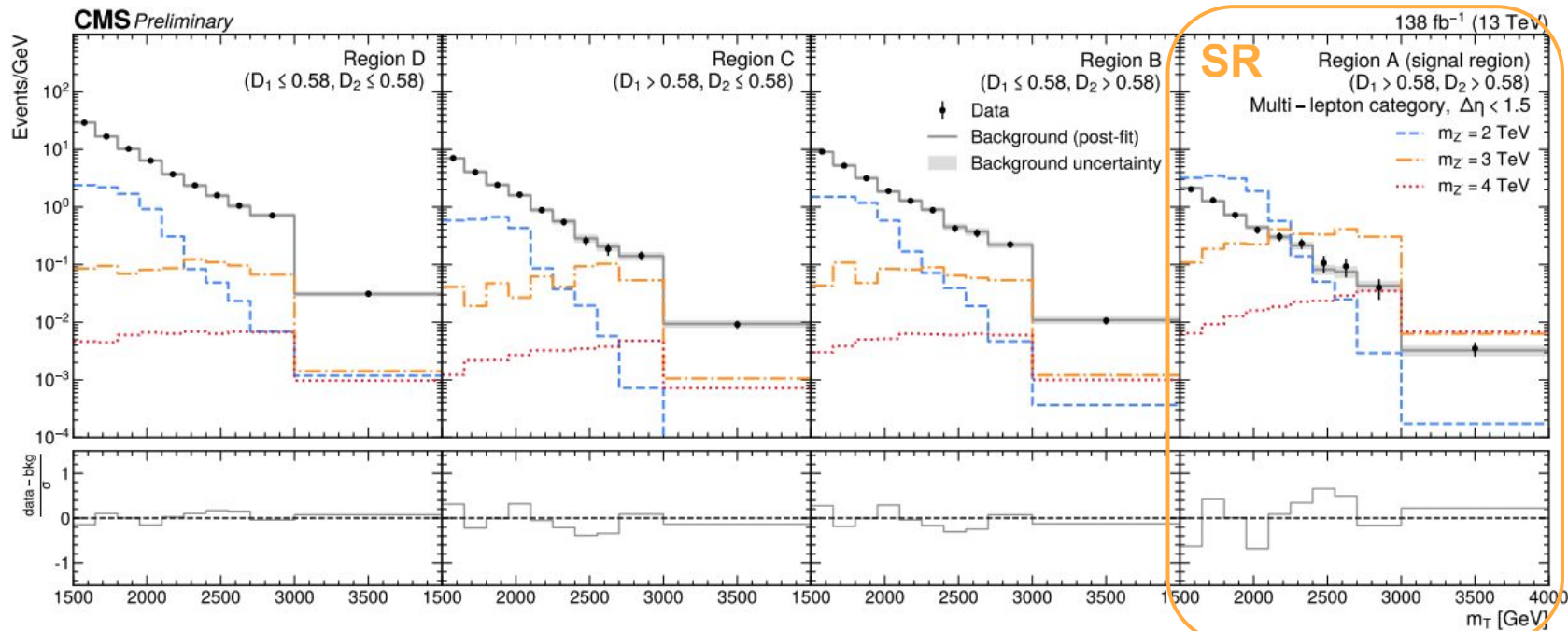


LundNet semi-visible jet tagger



- Good tagging performance for different signal model parameters
- Good modelling of GNN score

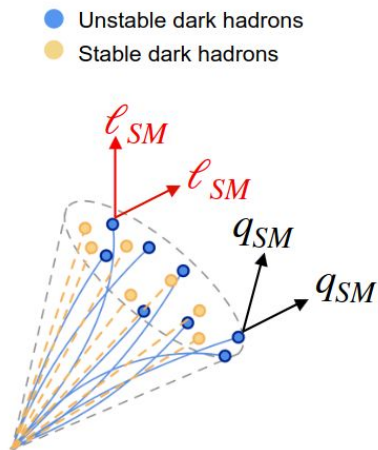


Search for SVJ ℓ - Fit

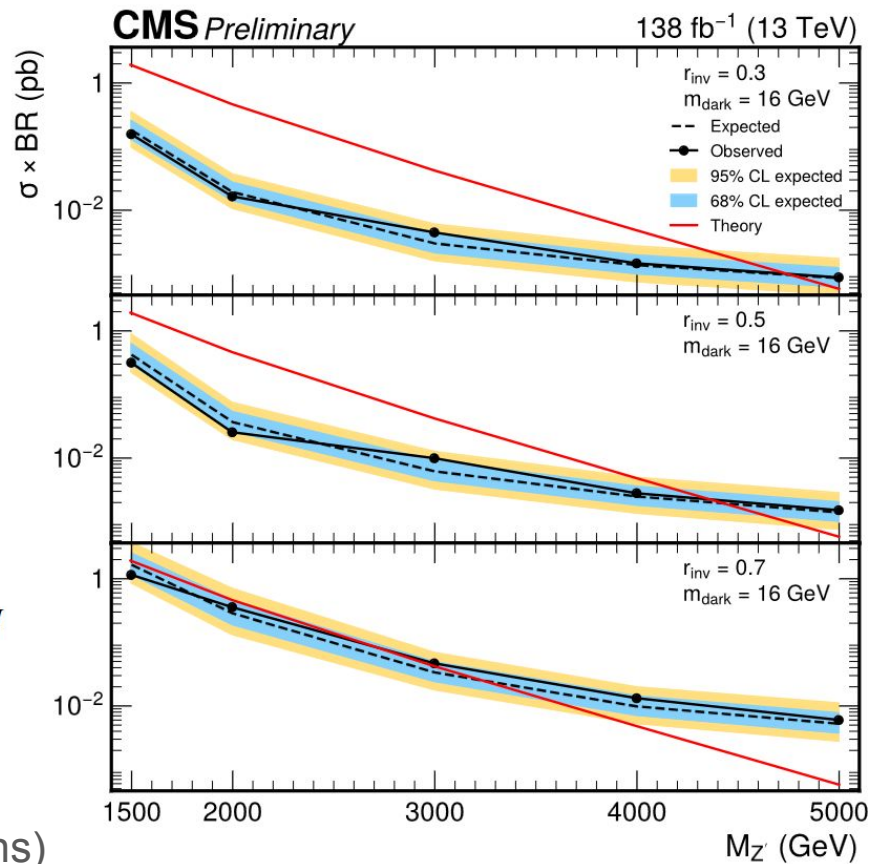
- The ABCD method is validated using a signal-depleted region ($1.5 < \Delta\eta < 2.2$)
- Yield systematic extracted from the validation region, shape systematic extracted from MC at $\Delta\eta < 1.5$

Search for lepton-enriched semi-visible jets

- No significant excess of events is observed above the expected background
- First mass exclusion limits** on lepton-enriched semi-visible jet signatures **up to 4.7 TeV** for $r_{\text{inv}} = 0.3$
- Sensitivity decreases with increasing r_{inv} (WIMP-like regime)

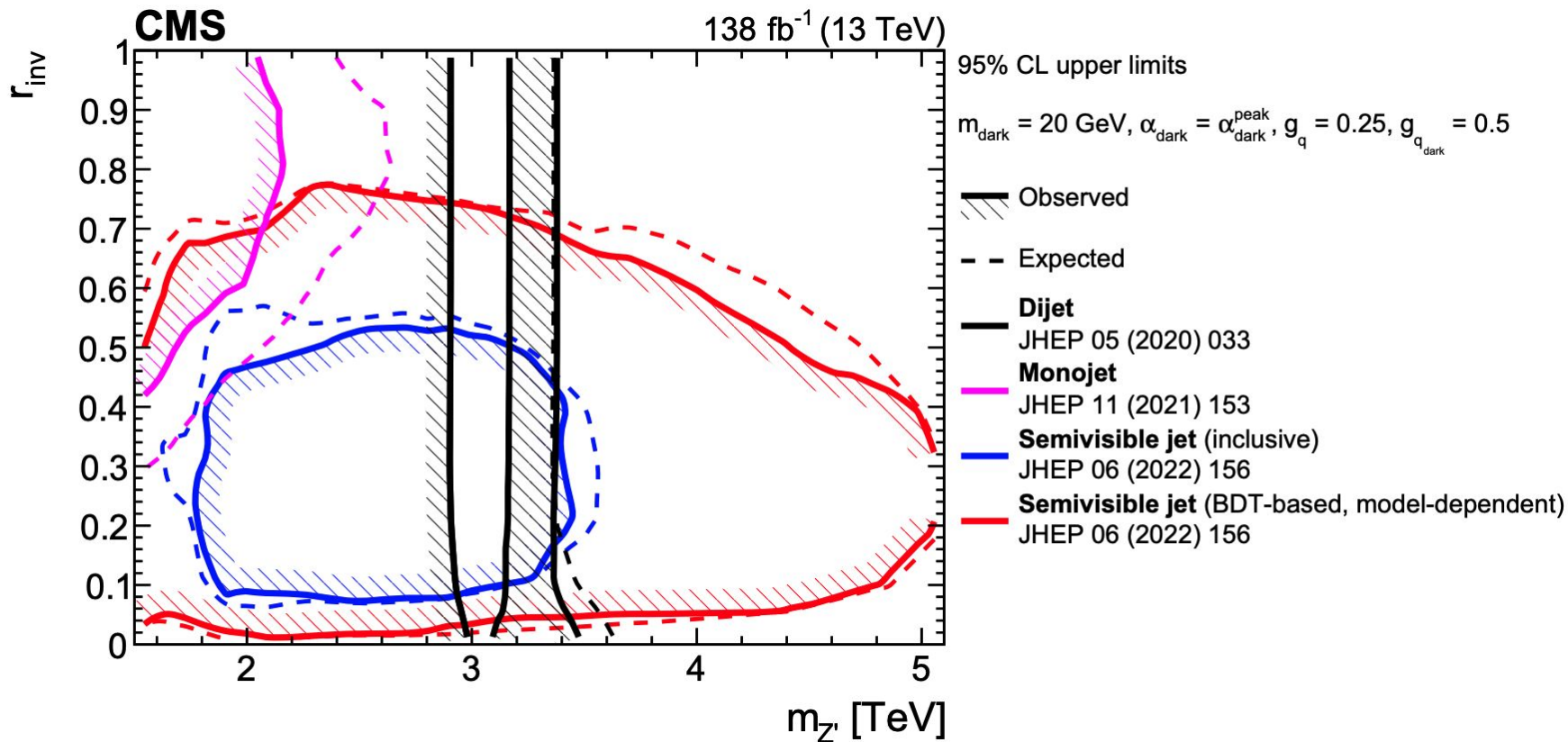


$$r_{\text{inv}} = N(\text{stable dark hadrons})/N(\text{dark hadrons})$$



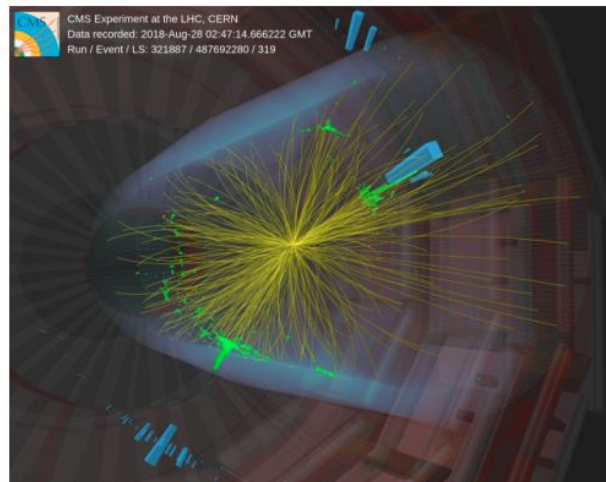
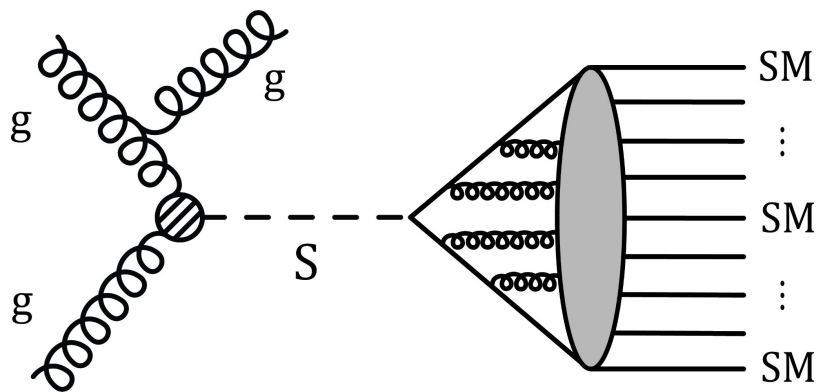
Semi-visible jet exclusion limits

- Observed and expected 95% CL excluded regions of the $m_{Z'}$ - r_{inv} plane from different searches



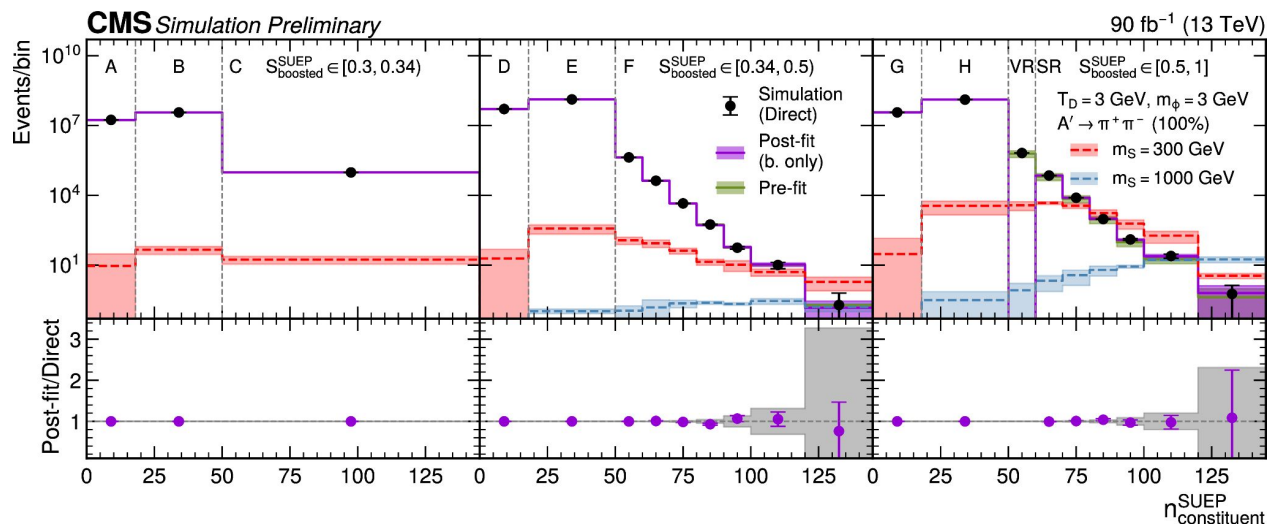
Search for Soft-Unclustered Energy Patterns (SUEPs)

- SUEPs: high-multiplicity, near isotropic spray of low p_T particles - no jet structure
- Produced from **strongly-coupled hidden sectors** with very large 't Hooft coupling \implies dark shower fragments into many low-energy dark mesons ϕ
- The distribution of the dark meson momenta is described by a relativistic Boltzmann distribution that depends on the **dark meson mass m_ϕ** and a **temperature parameter T_D**
- Dark hadrons decay back into SM via dark photons A' , forming dozens to hundreds of soft tracks/clusters in the final state



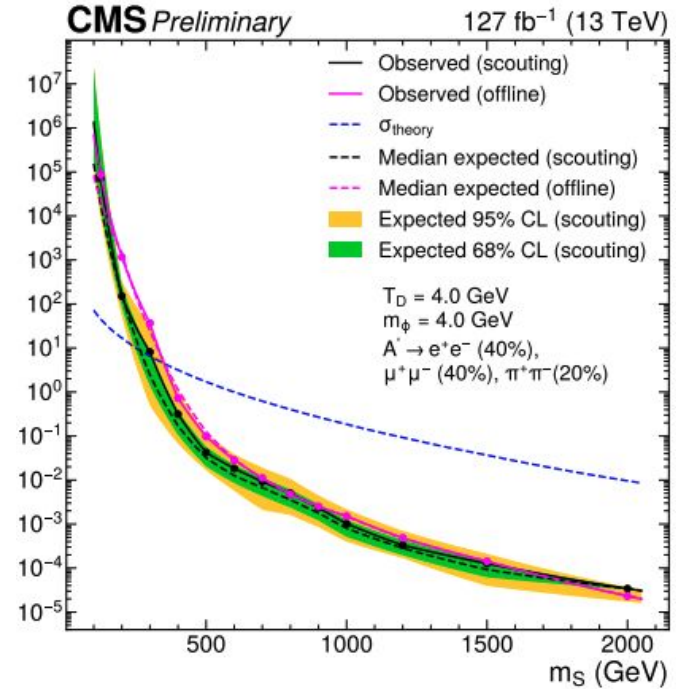
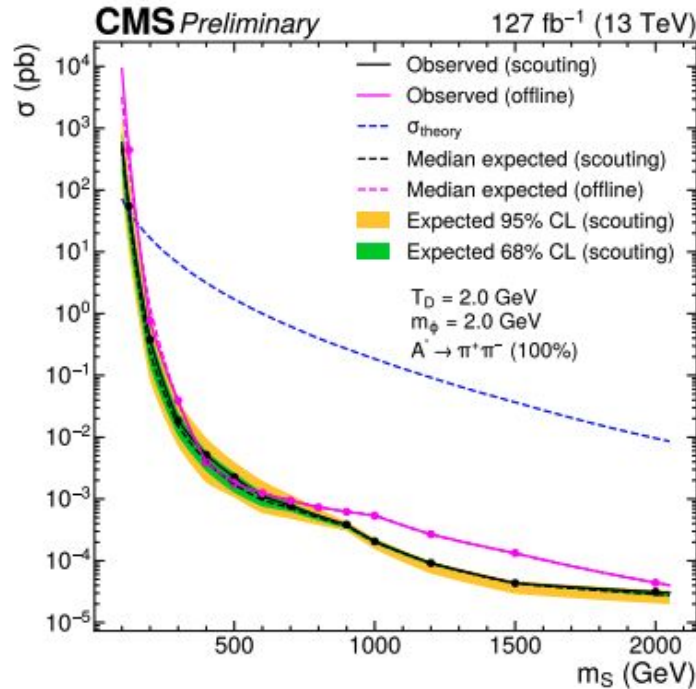
Search for Soft-Unclustered Energy Patterns (SUEPs)

- Utilised Run 2 Scouting data: reduced trigger thresholds (1 TeV \rightarrow 410 GeV on H_T), increased acceptance
- SUEP recoils against initial state radiation (ISR)
- Recover isotropy by boosting tracks into SUEP candidate rest frame
- Compute the boosted sphericity of the SUEP candidate - close to 0: two-prong structure; close to 1: spherically symmetric
- Background estimation with extended ABCD method using **sphericity** and **number of constituents** as the two variables



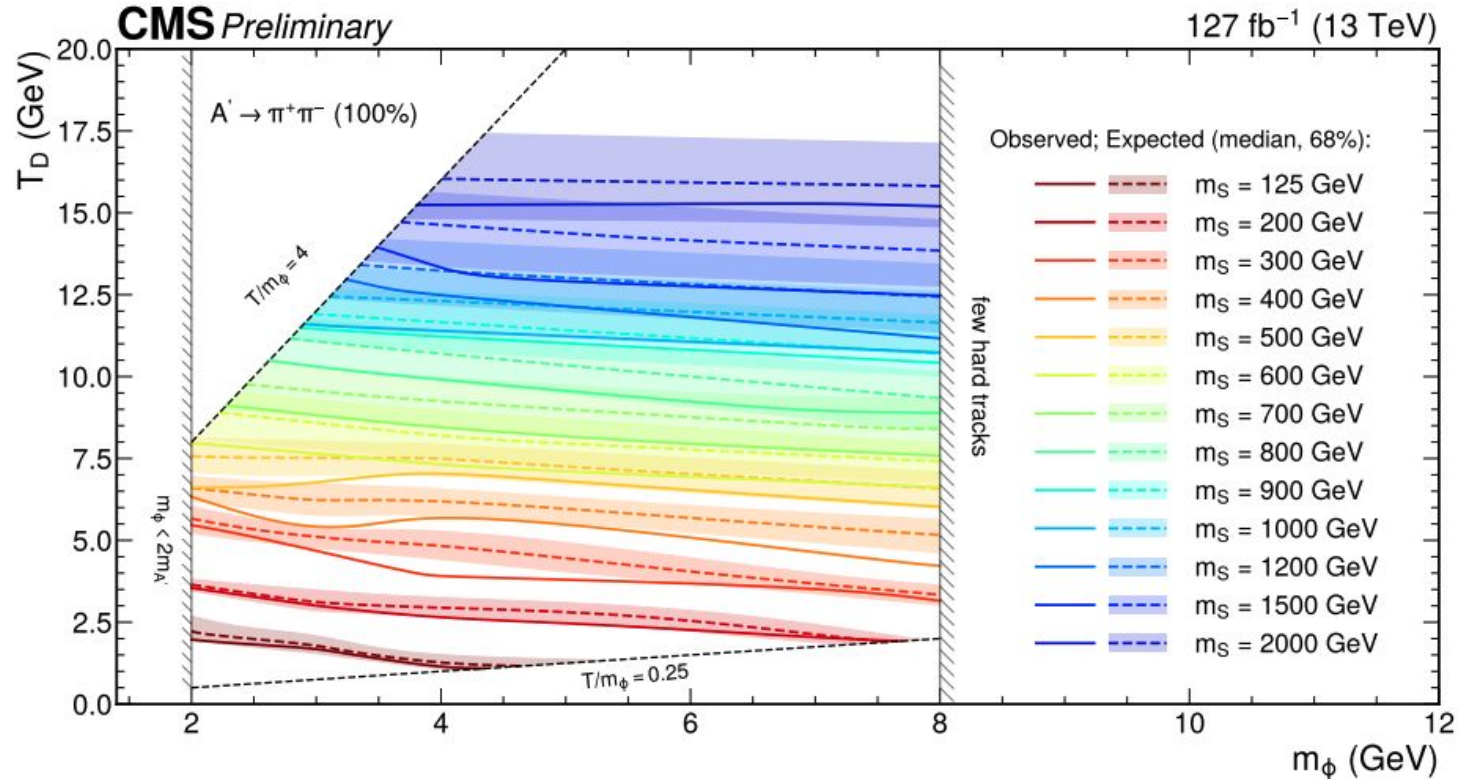
Search for Soft-Unclustered Energy Patterns (SUEPs)

- Targets mediator masses > 125 GeV
- Probes cross section to as low as ~ 0.05 -1 fb
- The most stringent limits to date are imposed on a large range of SUEP models



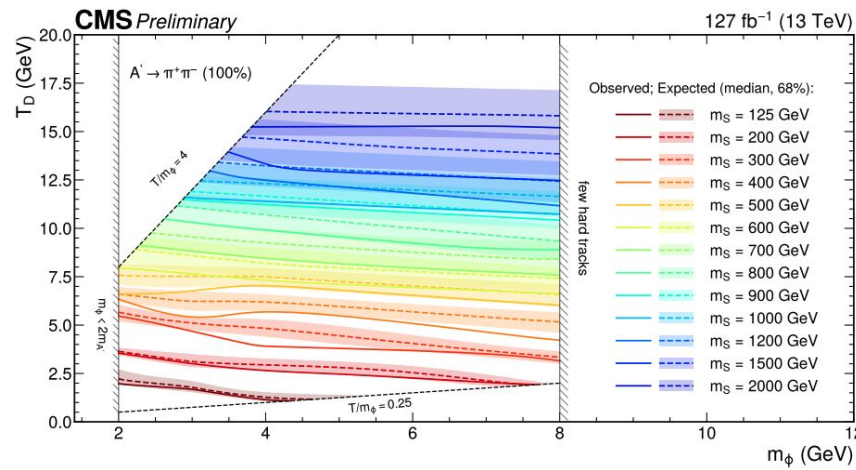
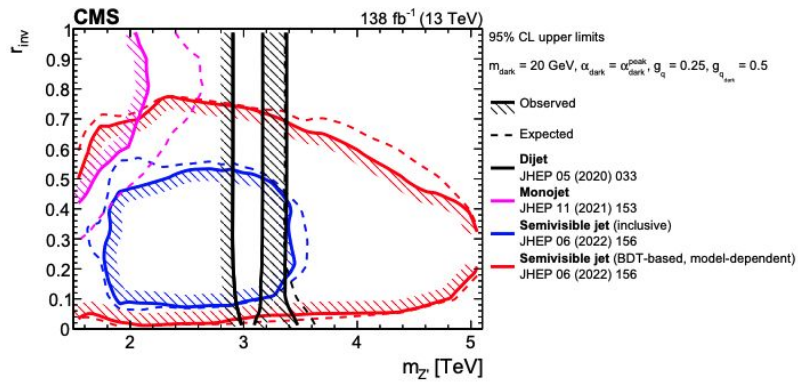
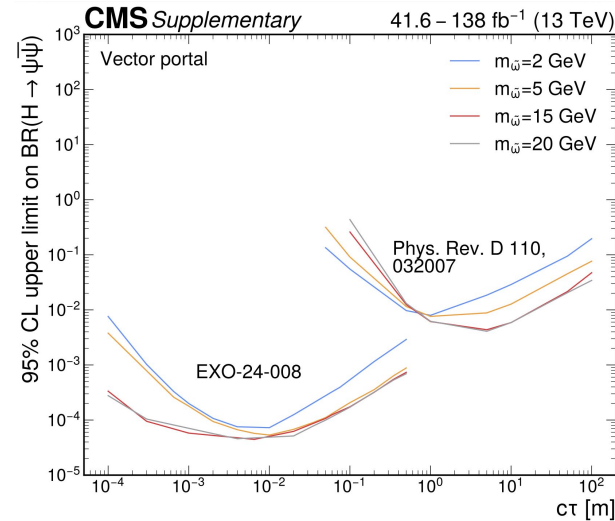
Search for Soft-Unclustered Energy Patterns (SUEPs)

- Exclusion limits as a function of T_D and m_ϕ for models with $m_{A'} = 1$ GeV (fully hadronic decays) and different m_S values:



Summary

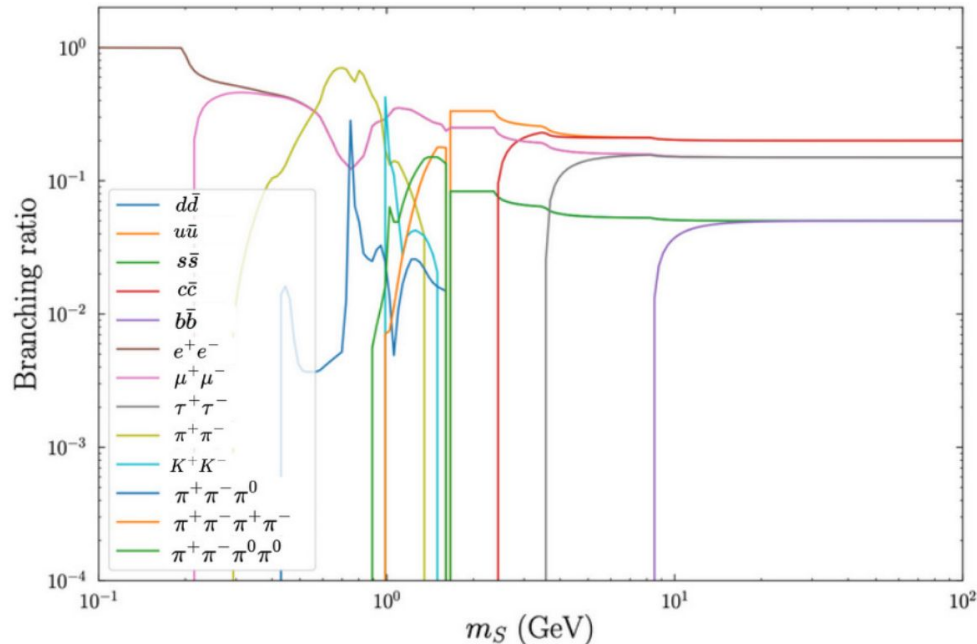
- **Hidden Valley models** can produce challenging signatures
- **Dedicated data streams in CMS** provide opportunities to explore new phase space
- Presented new results from CMS which impose the most stringent limits to date on different dark shower models in a **wide range of parameter space**
- More searches to come - stay tuned!



Backup slides

Branching ratios

- BR for decay to $\mu\mu$ $\sim 10\text{-}30\%$ in the vector portal depending on the mass
- $\mu\mu$ has a high BR across the full range of mass
- Use dimuon invariant mass to search for signal



https://gitlab.com/simonknapen/dark_showers_tool

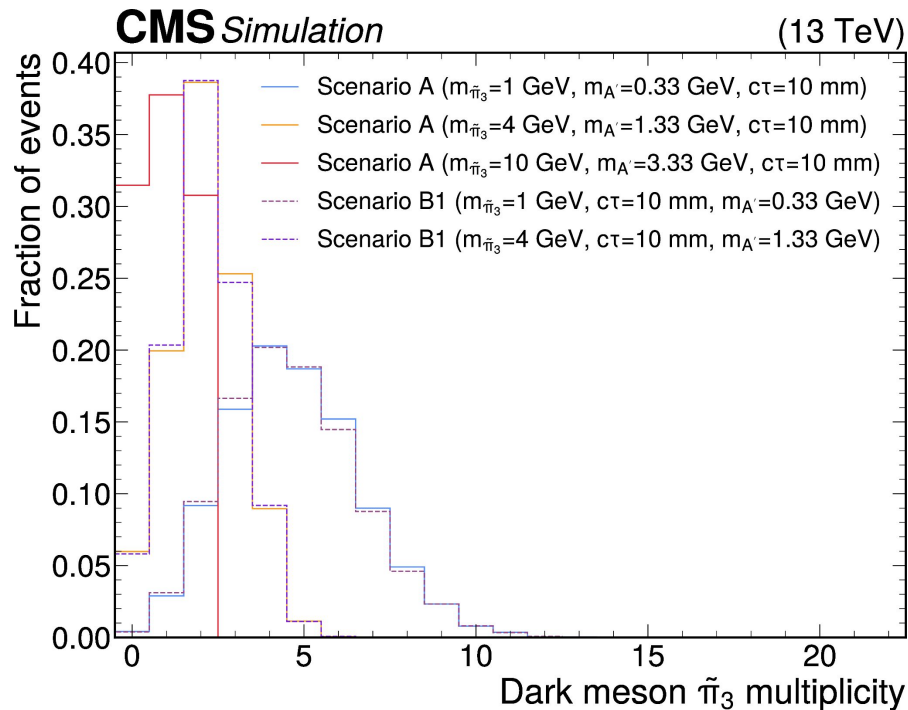
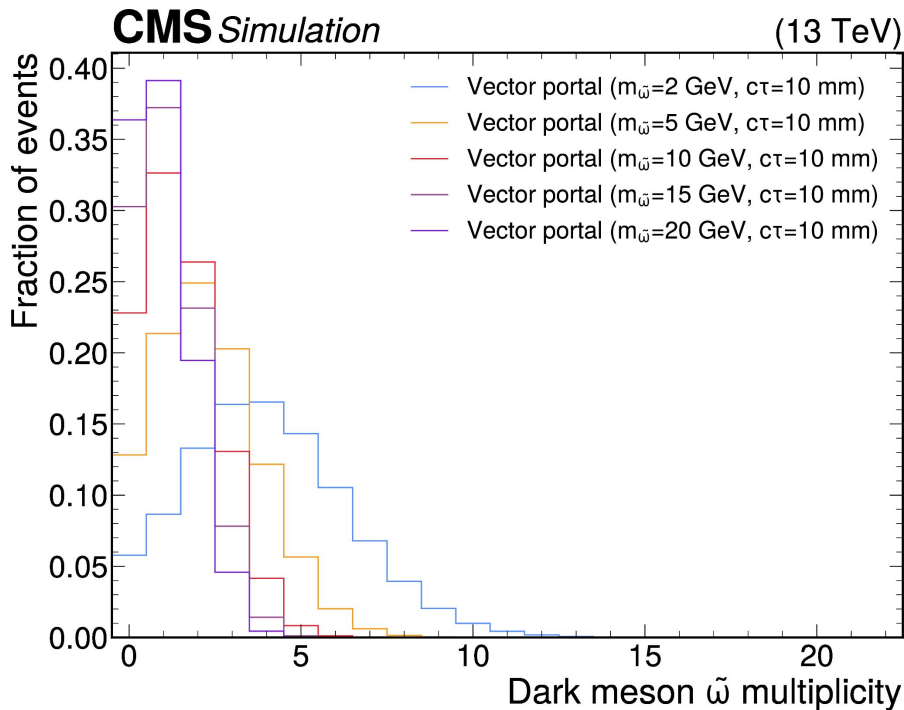
Model parameters

- Different mass and lifetime model points are considered in the analysis

Signal model	Model parameters
Vector portal	$m_{\tilde{\omega}}$: mass of the dark vector meson $c\tau$: mean proper lifetime of the dark vector meson
Scenario A/B1	m_{π_3} : mass of the dark pion π_3 $m_{A'}$: mass of the dark photon $c\tau$: mean proper lifetime of the dark photon (scenario A) or the dark pion π_3 (scenario B1)

Generated dark meson multiplicity

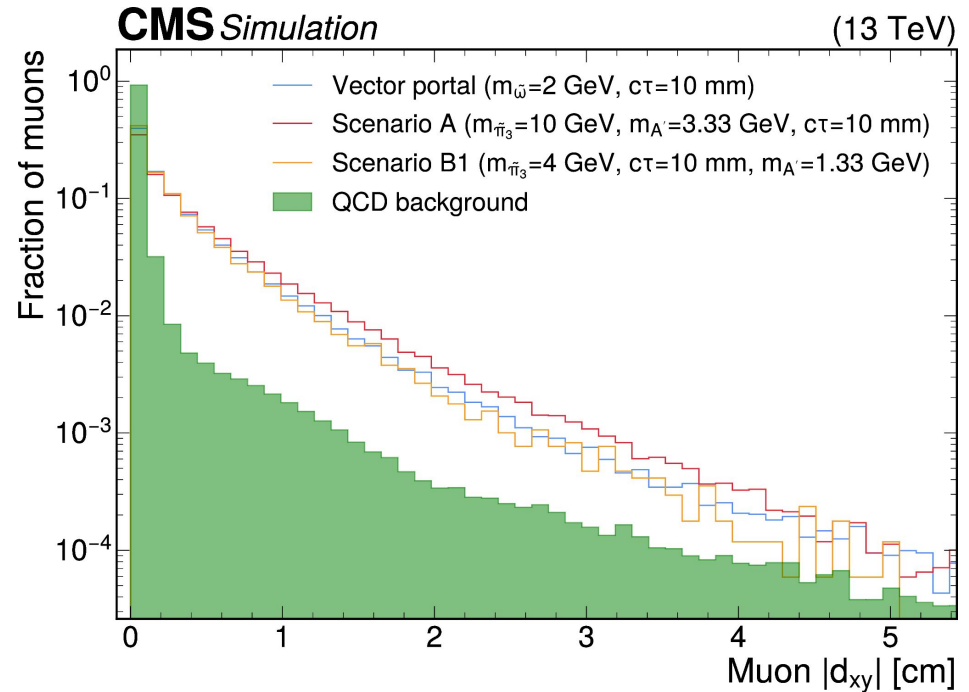
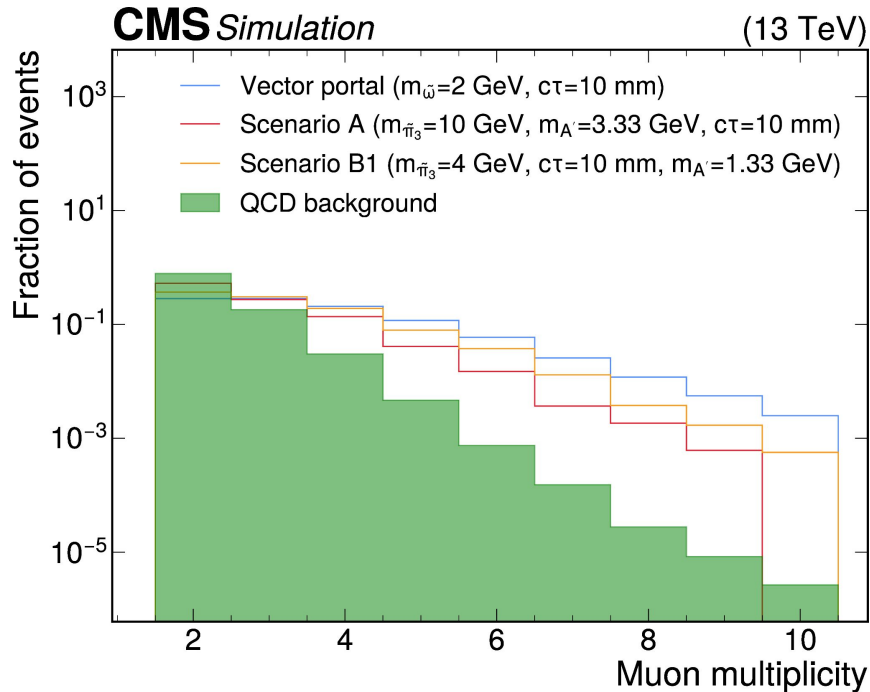
- The high muon multiplicity comes from the high multiplicity of dark mesons
- The dark meson multiplicity increases with decreasing mass of the dark meson



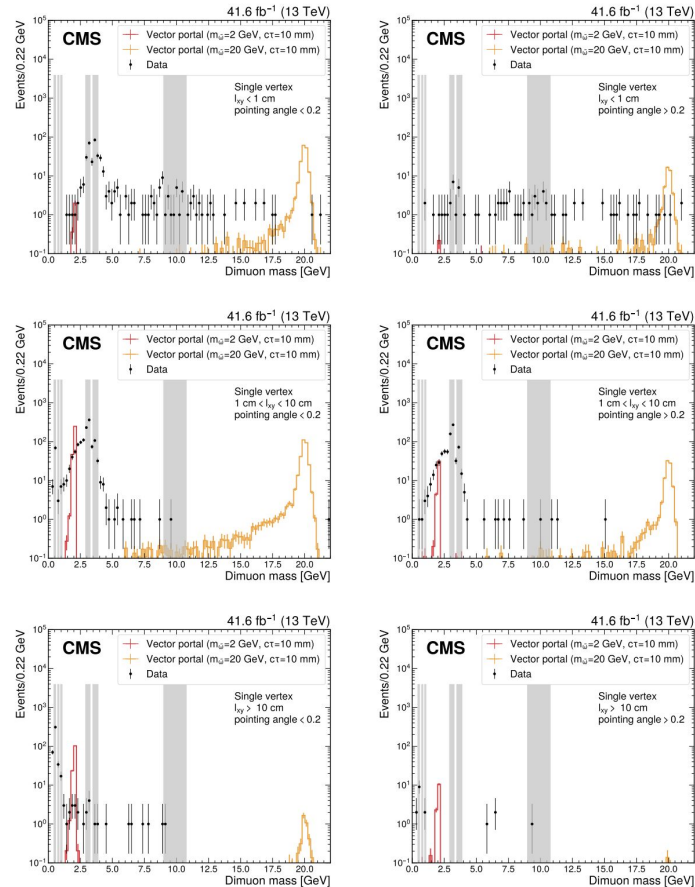
Signal and background features

EXO-24-008

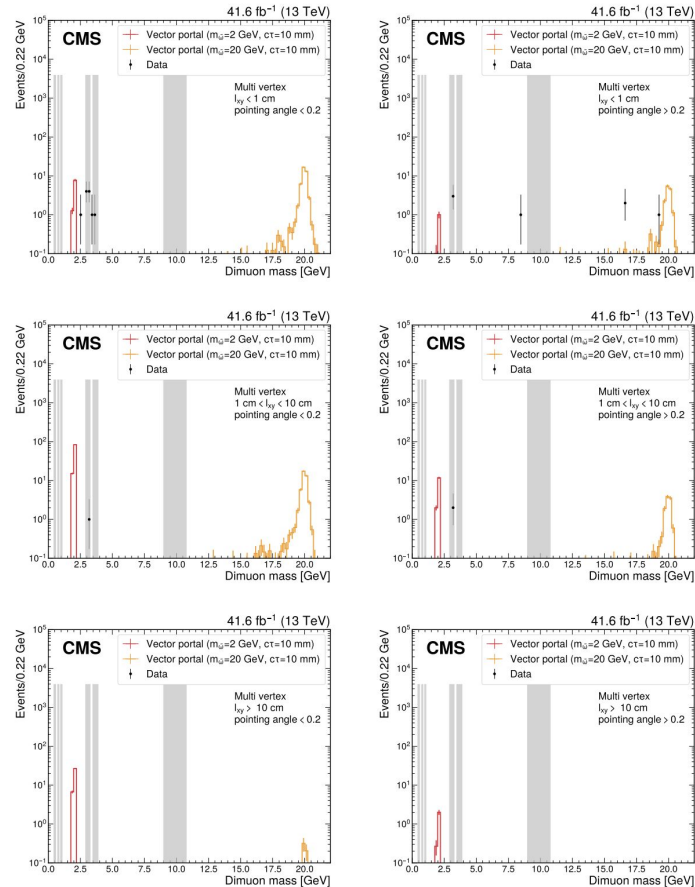
- A higher number of muons in the signal compared to the QCD background
- Muon variables provide excellent discrimination between signal and background



Dimuon mass distributions in single vertex categories - vector portal



Dimuon mass distributions in multi vertex categories - vector portal



Summary of systematic uncertainties

EXO-24-008

- Signal uncertainties:
 - Summarised in the table on the right
 - Measure the systematic uncertainties from the BDT and displaced muon identification using the J/Ψ mass region
 - Used the trigger scale factors derived by EXO-22-019 for the B-parking triggers
- Background uncertainties:
 - Discrete profiling systematic uncertainty accounts for the uncertainty in the choice of fitting function

	Signal systematic uncertainty
BDT	10%
Displaced muon ID	~1-17%
Trigger	~1-2%
Pileup	~5%
Theory uncertainty in ggF Higgs production	3.9%
Strong coupling constant	2.6%
PDF	1.9%
Luminosity	2.5%

Multivariate input:

- Muon: 16 variables
- SV: 13 variables
- Muon SV: 15 variables
- Global variables (number of muons, number of SVs, number of muon SVs)
- Maximum of [8, 8, 8] leading ordered muon, SV, muon SV considered

➡ On average ~100 input variables

Input samples:

- Use signal MC and QCD MC samples for the training
- Train/test/validation split of 60:30:10
- Signal and background are carefully weighted to give equal contribution to the training by using (event-by-event) weighted binary cross entropy loss
- All signal model mass and lifetime point samples have been reweighted to give equal contribution to the total signal class

Muons (16 variables): η , ϕ , p_T , p_T uncertainty, d_{xy} , d_{xy} error, d_z , d_z error, IP , IP significance, charge, tight ID, soft MVA, PF relative isolation (total), mini PF relative isolation (total), index of the associated jet.

Secondary vertices (13 variables): p_T , η , ϕ , x -position, y -position, z -position, d_{xy} , d_{xy} significance, 3D decay length, 3D decay length significance, pointing angle, χ^2 , number of degrees of freedom.

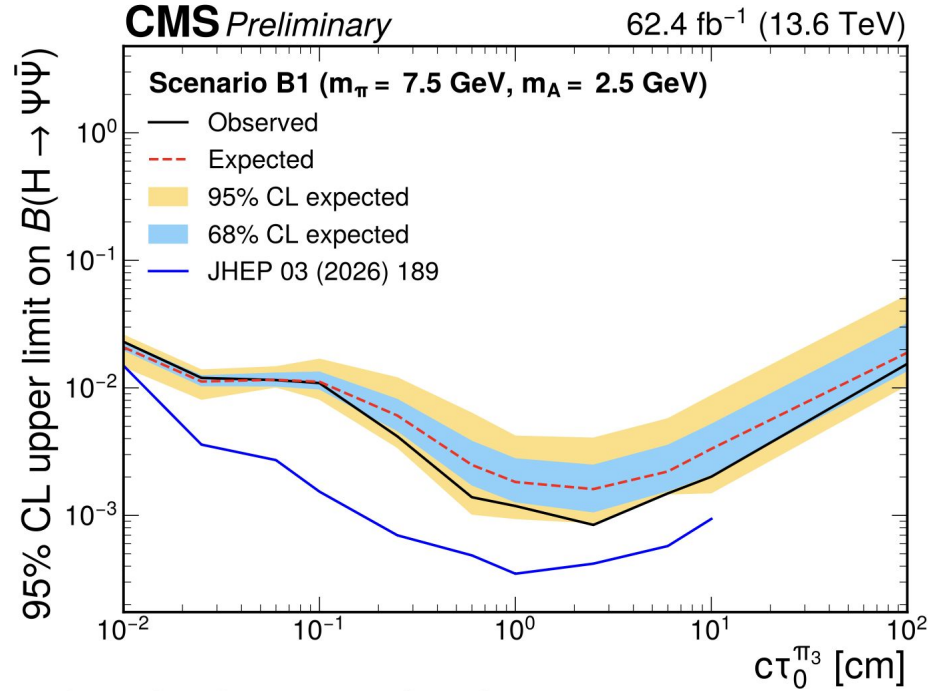
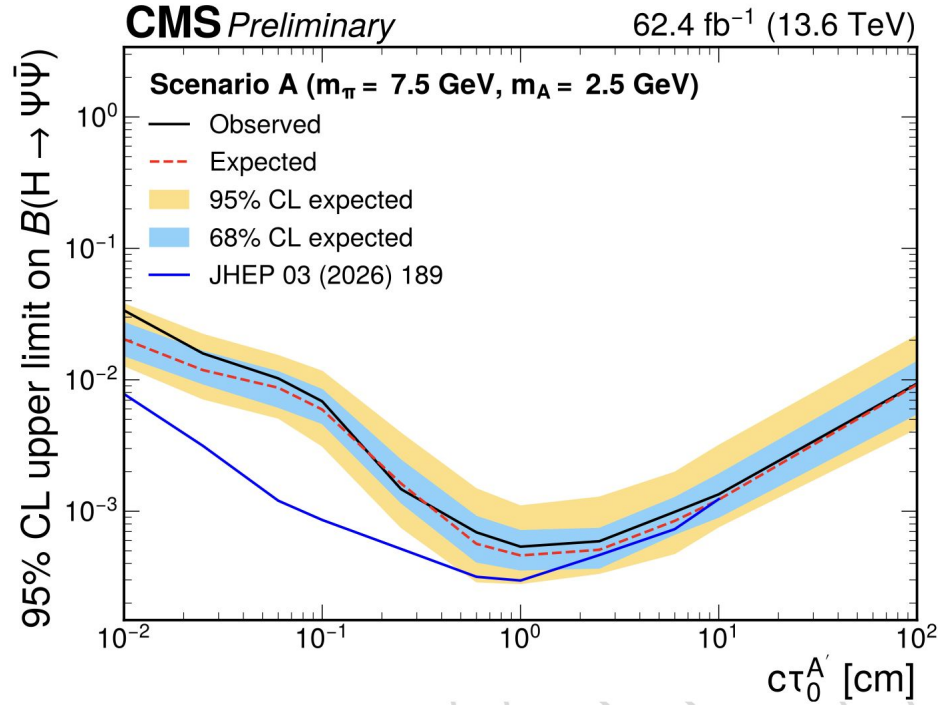
Muon secondary vertices (15 variables): χ^2 , pointing angle, 3D decay length, 3D decay length significance, d_{xy} , d_{xy} significance, $p_T(\mu_1)$, $\eta(\mu_1)$, $\phi(\mu_1)$, $p_T(\mu_2)$, $\eta(\mu_2)$, $\phi(\mu_2)$, vertex x -position, vertex y -position, vertex z -position.

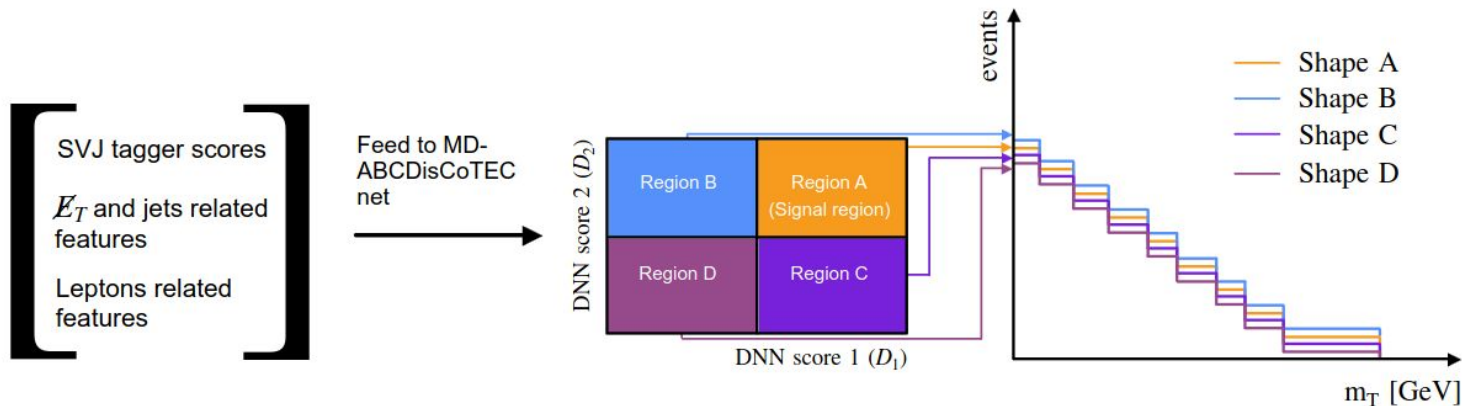
Other variables (3 variables): number of muons, number of secondary vertices and number of muon secondary vertices in the event.

Maximum number of muons used: 8; maximum number of secondary vertices used: 8; maximum number of muon secondary vertices used: 8.

Run 3 Scouting analysis - dark shower limits

EXO-24-016





Train simultaneously **two independent Deep Neural networks** to engineer **two optimal discriminators** that can be employed for an ABCD method in bins of m_T :

- Decorrelate DNNs against each other and against m_T
- Enforce ABCD closure in training

➔ Building on the method implemented in [CMS-MLG-23-003](#)