IMPERIAL

# Exploring new physics in the Dark Sector at CMS

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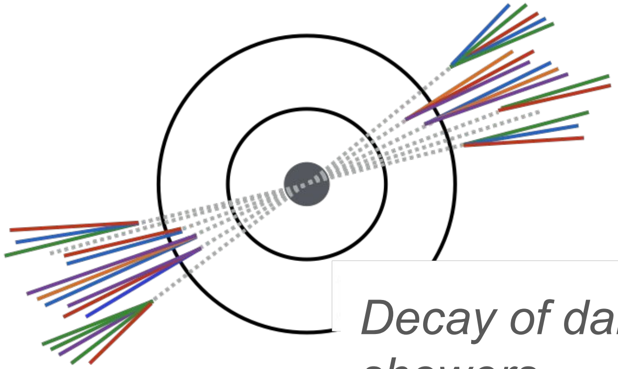
On behalf of the CMS collaboration

Lepton-Photon 2025
26th August

# Talk outline

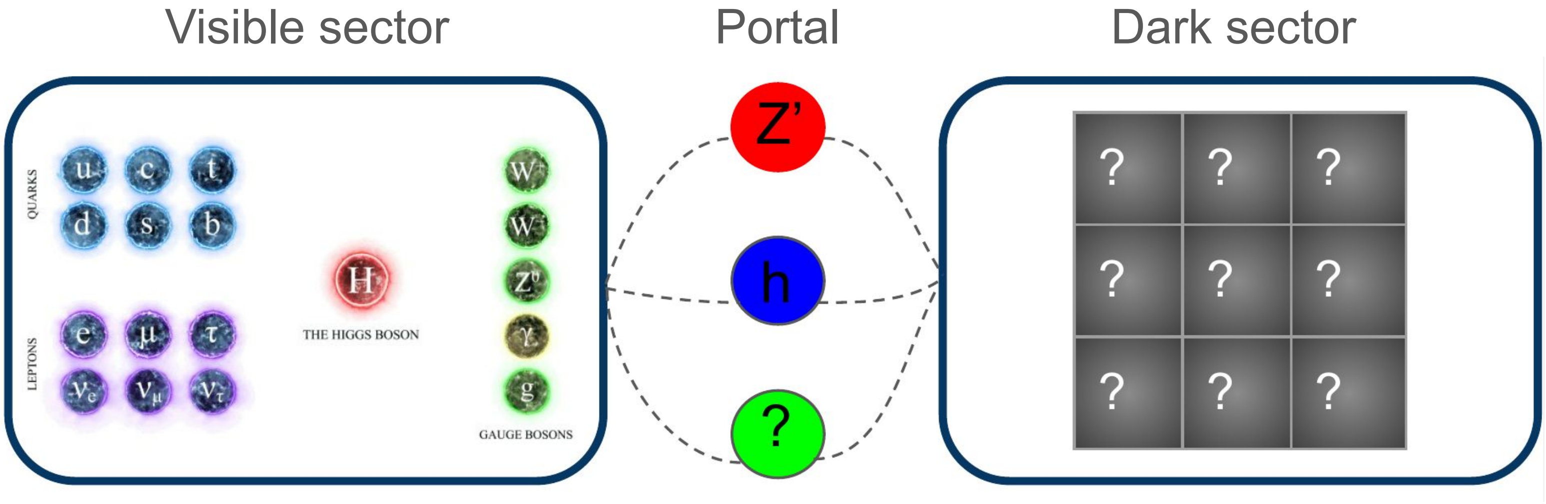
- Hidden Valley models
- Dedicated data streams in CMS
- Analyses and results
  - Run 2 Parking analysis: ***EXO-24-008***
  - Run 3 Scouting analysis: ***EXO-24-016***
  - Run 2 Search for lepton-enriched semi-visible jets: ***EXO-24-029***
- Summary



*Decay of dark showers*

# The dark sector

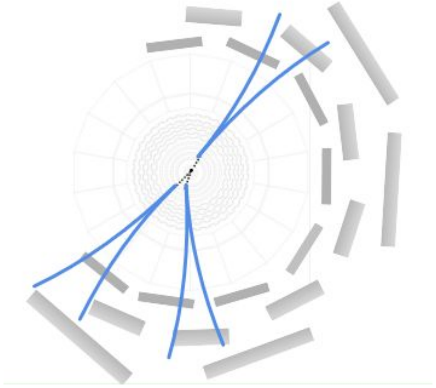
- **Hidden Valley models** extend the SM gauge group by a new non-Abelian gauge group, which describes a new dark sector
- Contain dark matter candidates that are uncharged under the SM gauge group
- Mediator particles connect the dark sector to the SM



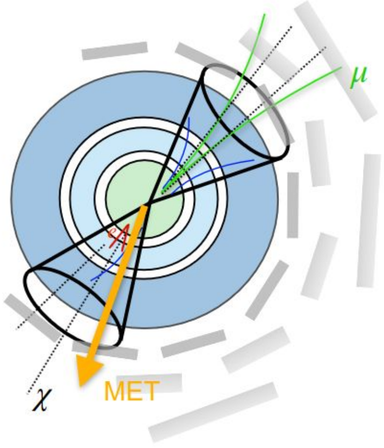
# Searches for dark showers in CMS

- 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)
    - NEW CMS-PAS-EXO-24-008

    ⇒ *Also see Jacopo Pazzini's talk and Jingyu Luo's talk!*
  - A general displaced muon search (Run 3)
    - NEW CMS-PAS-EXO-24-016
  - The first collider search for lepton-enriched semi-visible jets (Run 2)
    - NEW CMS-PAS-EXO-24-029 to be released soon!



*Displaced vertices*



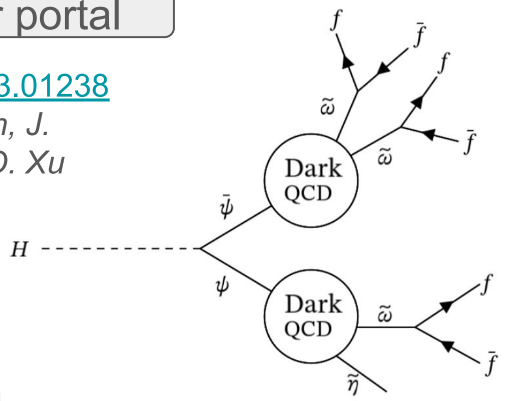

*Semi-visible jets*

# Hidden valley benchmark models

- First search for the production of dark showers from the SM Higgs
- Dark partons Ψ hadronise through dark QCD into dark mesons
- Extended benchmark models (Scenario A, B1) feature a light dark photon A' and two dark flavours
- Decay topologies can give **non-pointing** signature

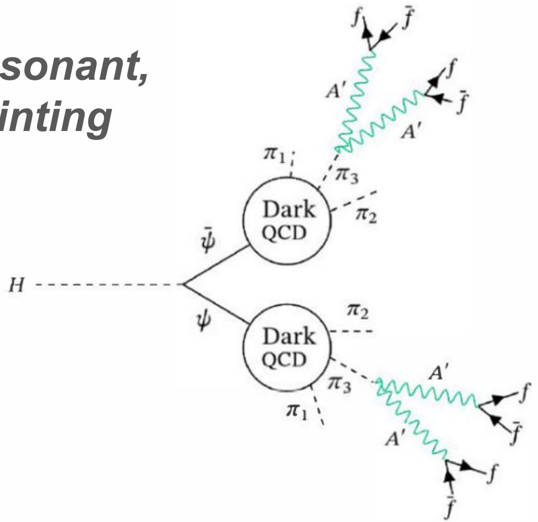
Vector portal

arXiv:2103.01238
*S. Knapen, J. Shelton, D. Xu*




Scenario A

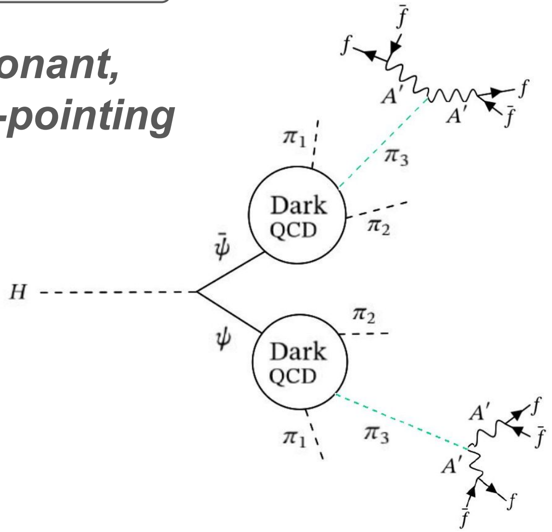
***Resonant, pointing***




arXiv:2303.04167
*S. Born, R. Karur, S. Knapen, J. Shelton*

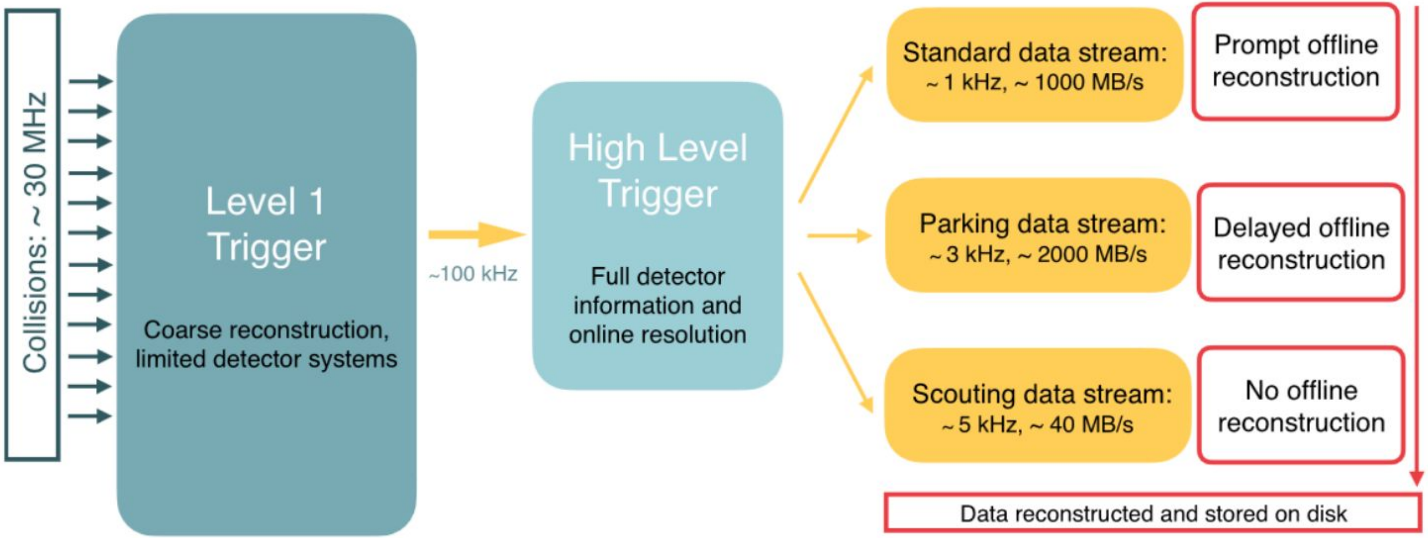
Scenario B1

***Resonant, non-pointing***



# 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




See Jacopo Pazzini's talk!

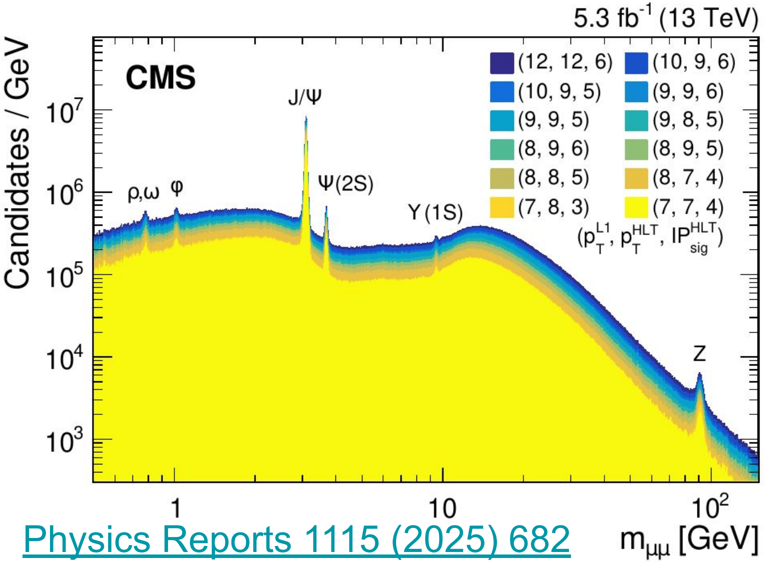
Physics Reports 1115 (2025) 682

*Numbers are representative for 2018

# Run 2 Parking analysis

**EXO-24-008**

- 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, $IP_{sig}$ thresholds range from 3 to 6

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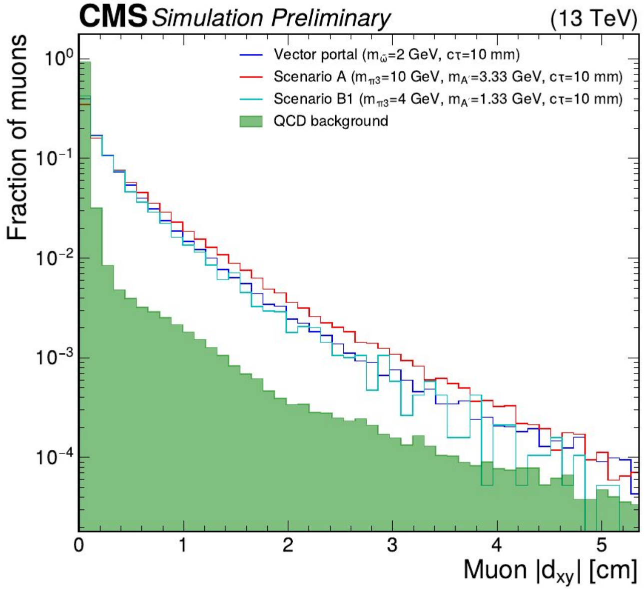
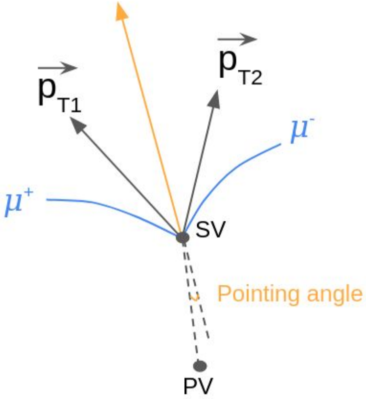
- Use of event-level BDT in the analysis to perform background rejection:
  - Variables from muons, muon secondary vertices (SVs), general SVs
  - Able to achieve $10^4$ background rejection with > 30% signal efficiency!

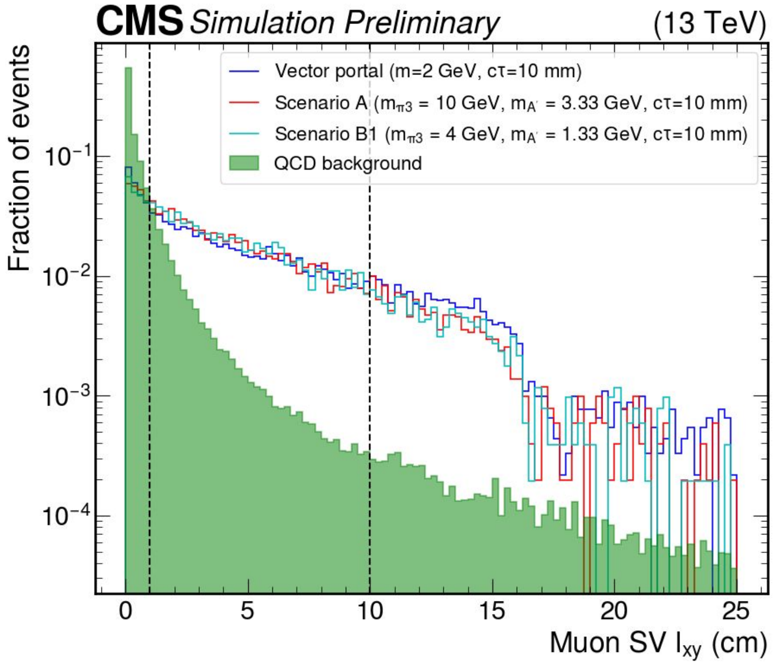


# Event categorisation



- 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 cm < $l_{xy}$ < 10 cm,
  - $l_{xy}$ > 10 cm
- Categorise in **pointing angle**:
  - pointing angle < 0.2,
  - pointing angle > 0.2



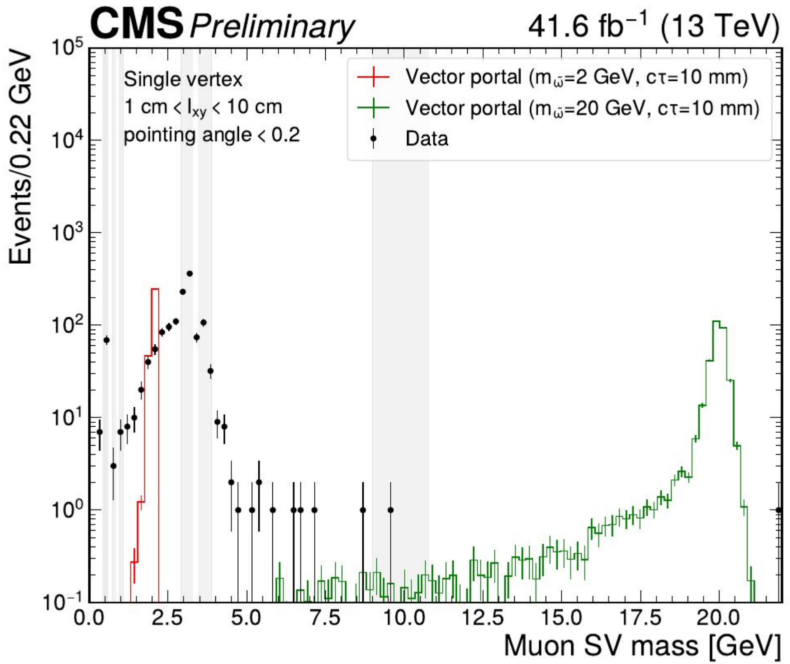



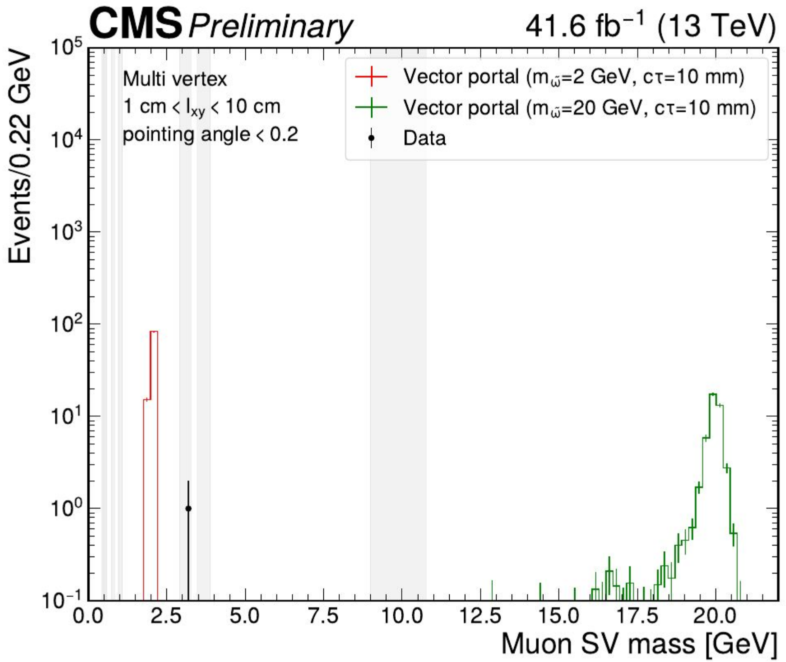

⇨ 12 categories in total

# Dimuon mass distributions in example categories

EXO-24-008

- 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

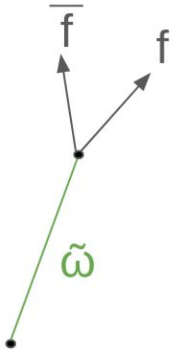


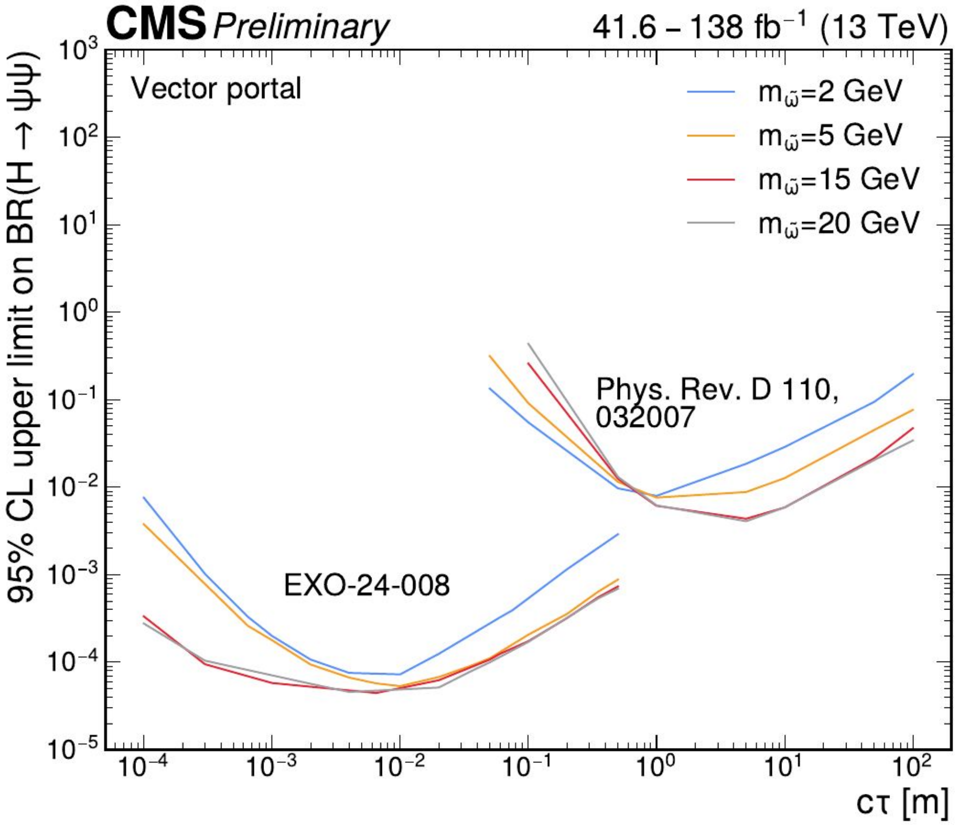



# Limits - Vector portal

EXO-24-008

- No significant excess is observed over the SM expectation
- Computed 95% confidence level (CL) upper limits on B(H➔ψψ) as a function of the mean proper decay length cτ of the long-lived particle (LLP), $\tilde{\omega}$
- Limits are complementary to those from a previous search with muon detector showers in CMS
- Probe **new phase space** for cτ 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** in the range of cτ between 0.1 and 0.5 m

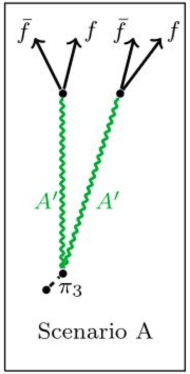


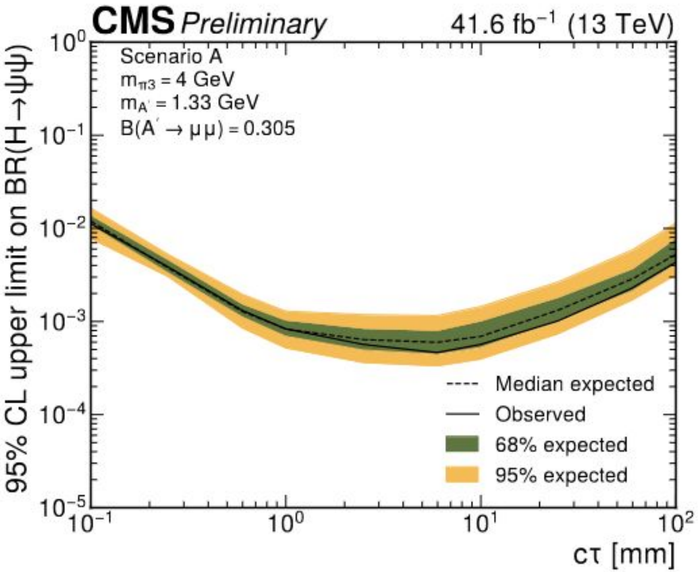
# Limits - extended benchmark models

**EXO-24-008**

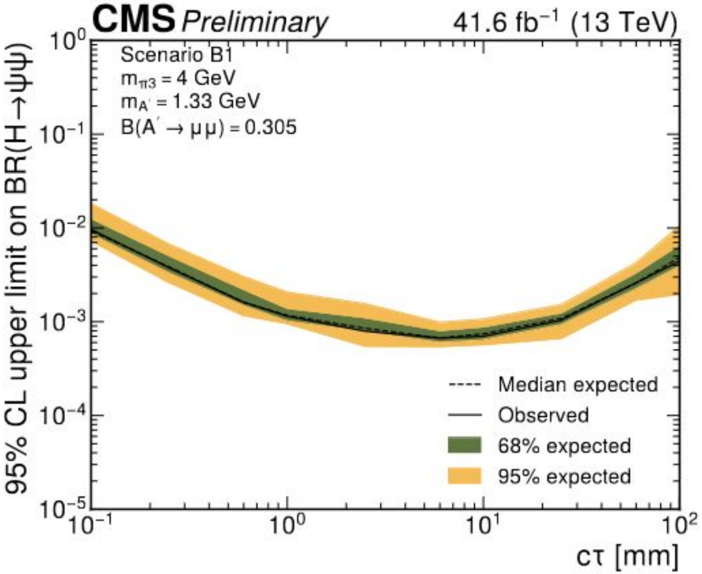
- Computed limits on B(H➔ψψ) as a function of the mean proper decay length of the LLP
- Able to impose limits at **$10^{-2}$ to ~$6\times10^{-4}$** over much of the phase space
- Low mass model points! (**below 2 GeV**)
- Good sensitivity achieved for both pointing and non-pointing scenarios!

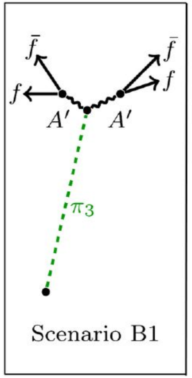



***resonant, pointing scenario***




***resonant, non-pointing scenario***

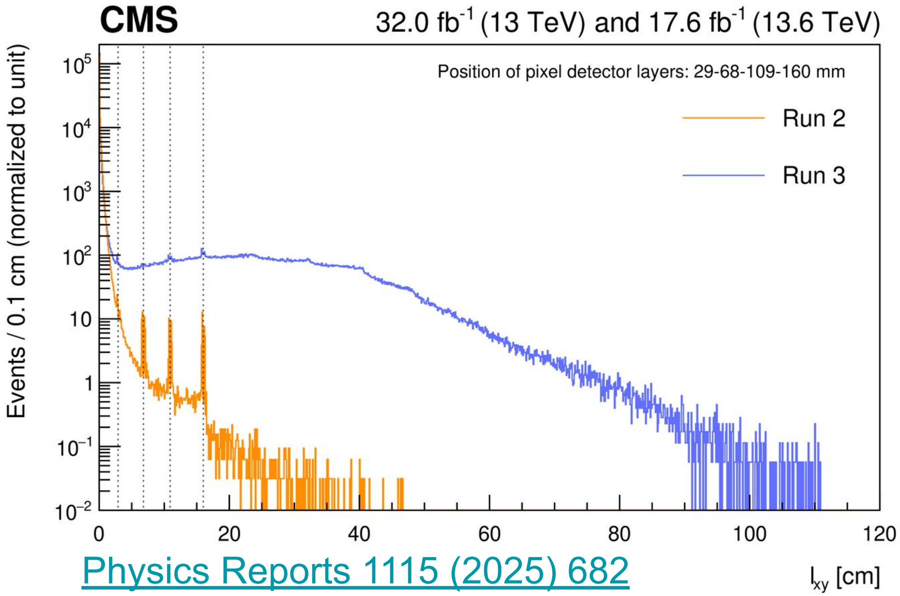


# Run 3 Scouting analysis

EXO-24-016

- 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

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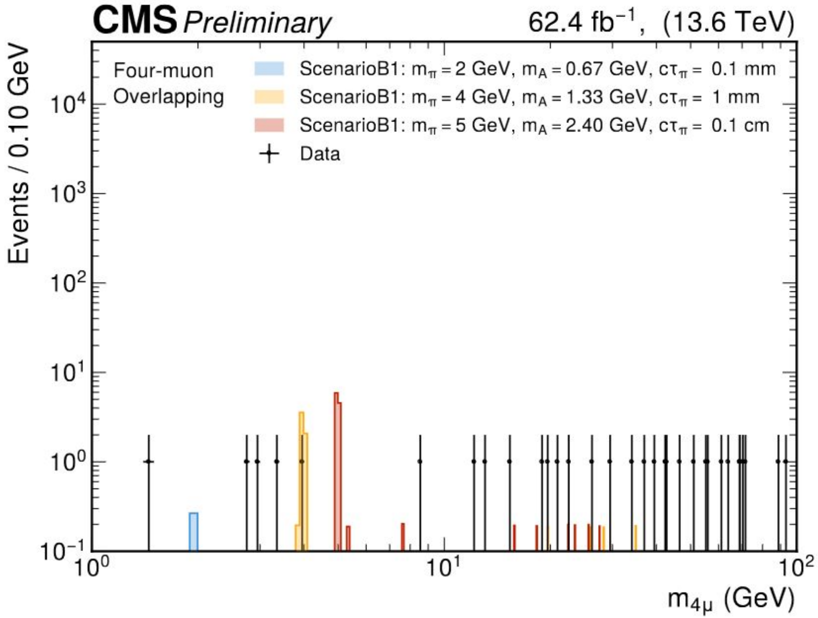
# Run 3 Scouting analysis

EXO-24-016

- 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

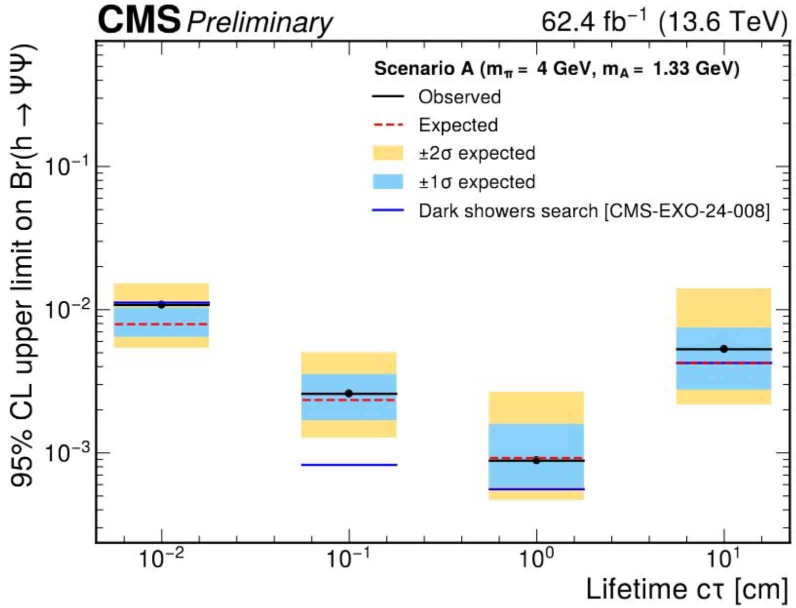


# Run 3 Scouting analysis

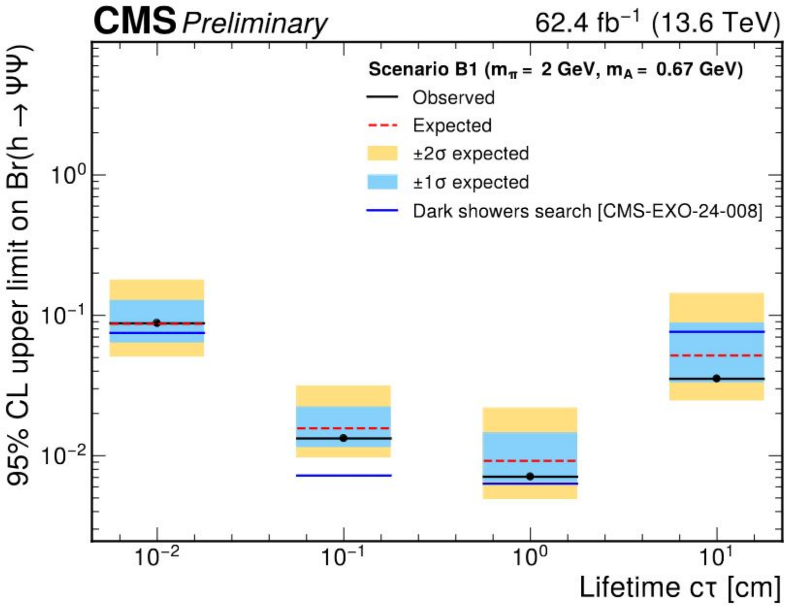
**_EXO-24-016_**

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

***resonant, pointing scenario***



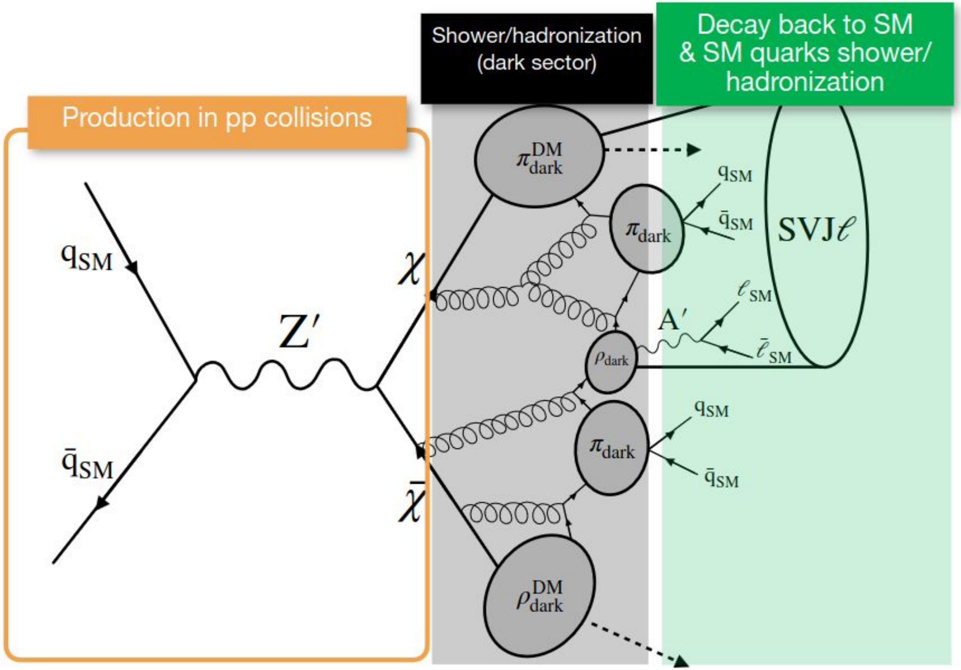

***resonant, non-pointing scenario***

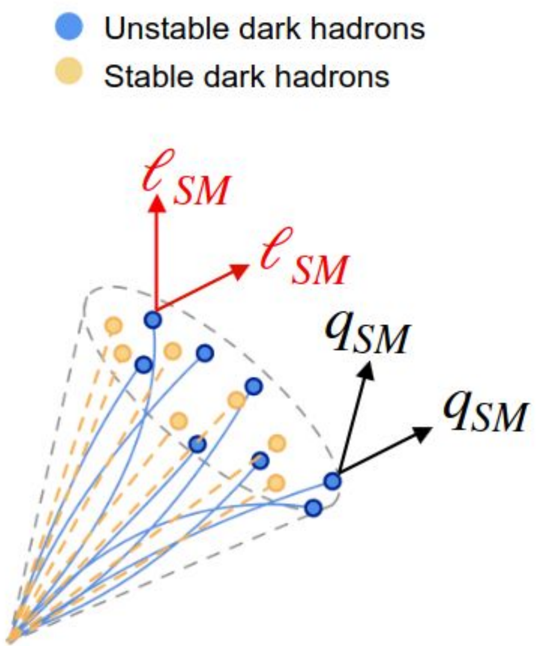


# Search for lepton-enriched semi-visible jets

EXO-24-029

- 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



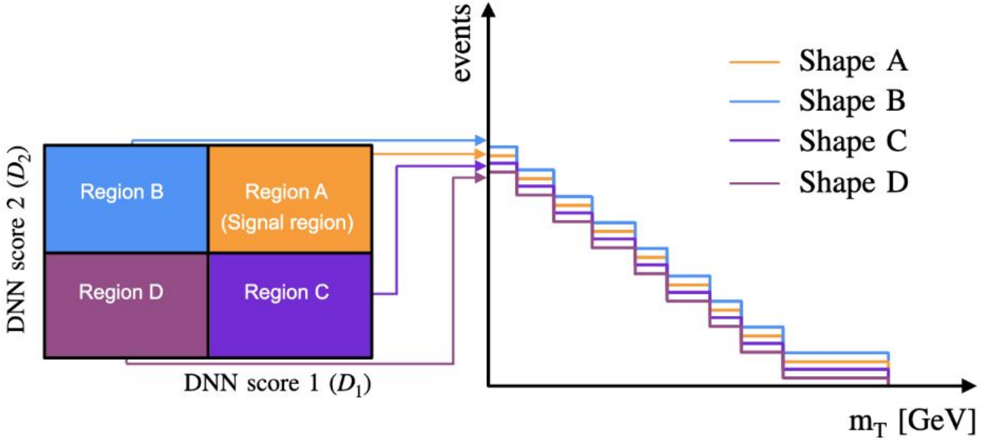



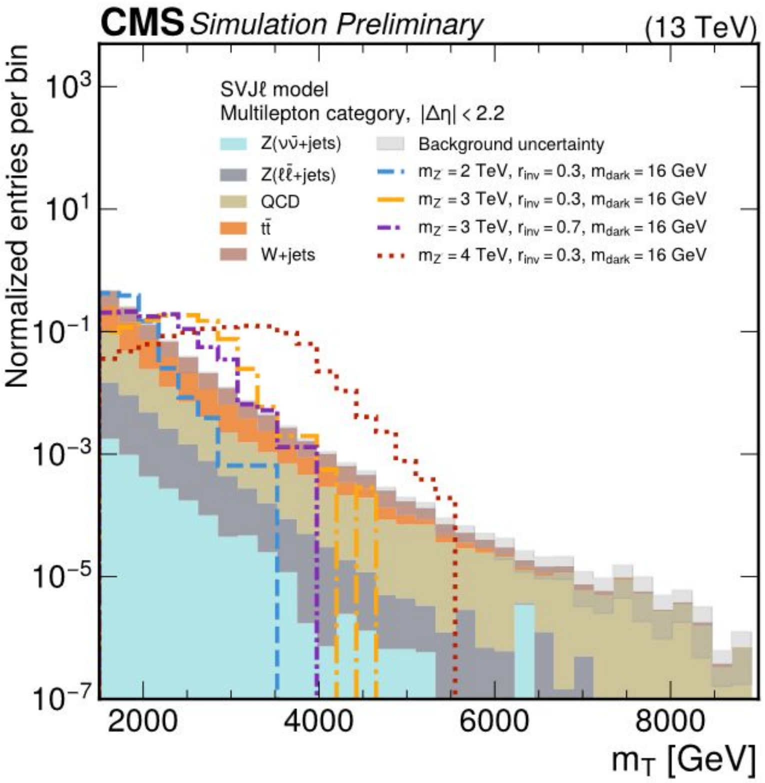

arXiv:2206.03909 *C. Cazzaniga, A. de Cosa*

# Search for lepton-enriched semi-visible jets

**EXO-24-029**

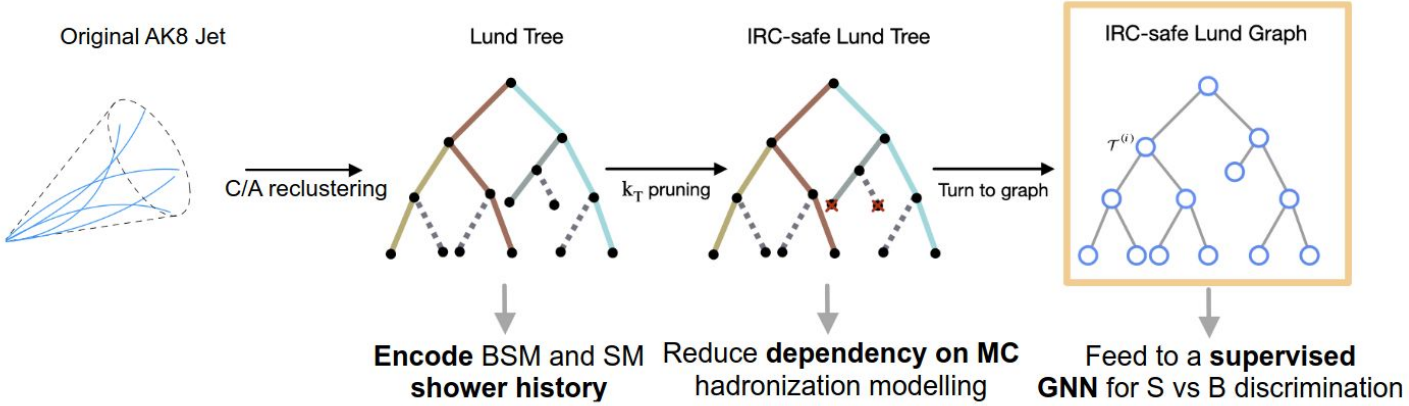
- Perform binned fit in dijet transverse mass
- Employ a graph neural network jet tagger (LundNet) to discriminate between signal and background jets
- Train two independent deep neural networks to engineer two discriminators for an ABCD method



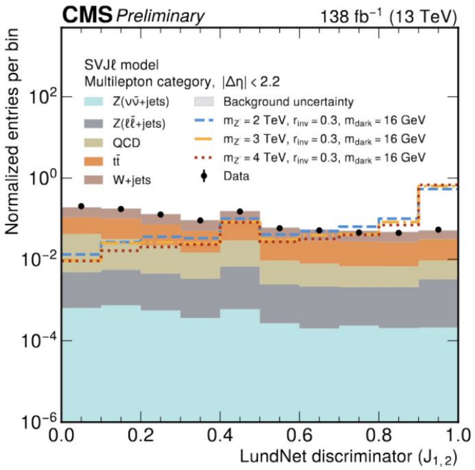



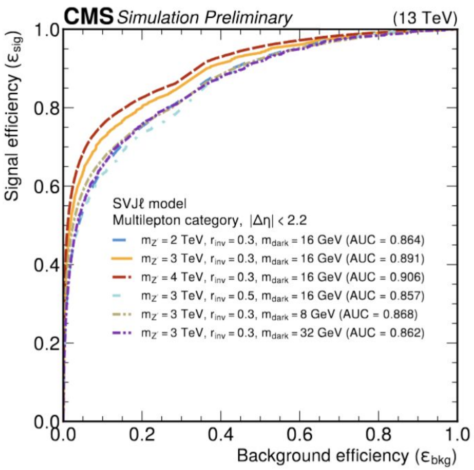
# LundNet semi-visible jet tagger

**EXO-24-029**




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

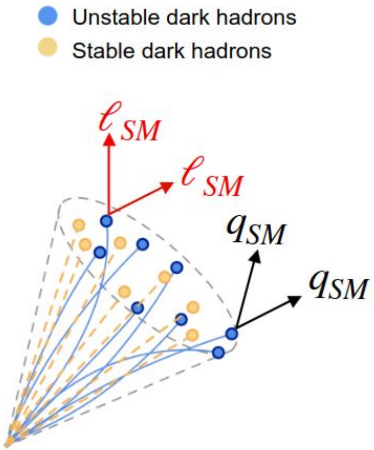


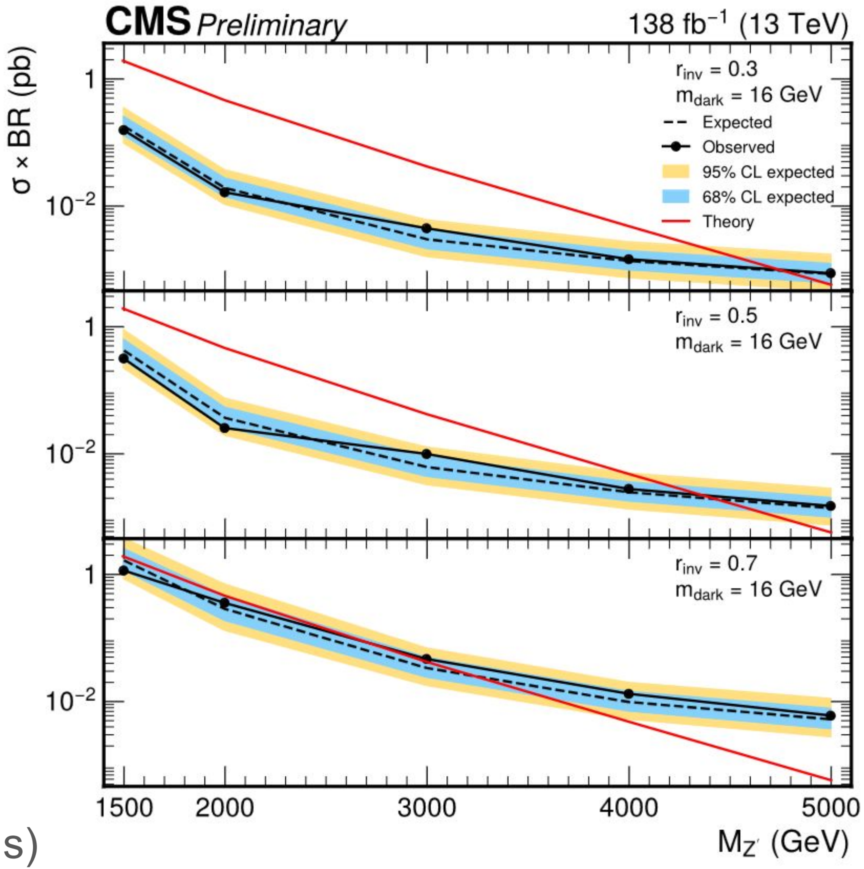



# Search for lepton-enriched semi-visible jets

EXO-24-029

- 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 $r_{inv}$=0.3
- Sensitivity decreases with increasing $r_{inv}$ (WIMP-like regime)




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

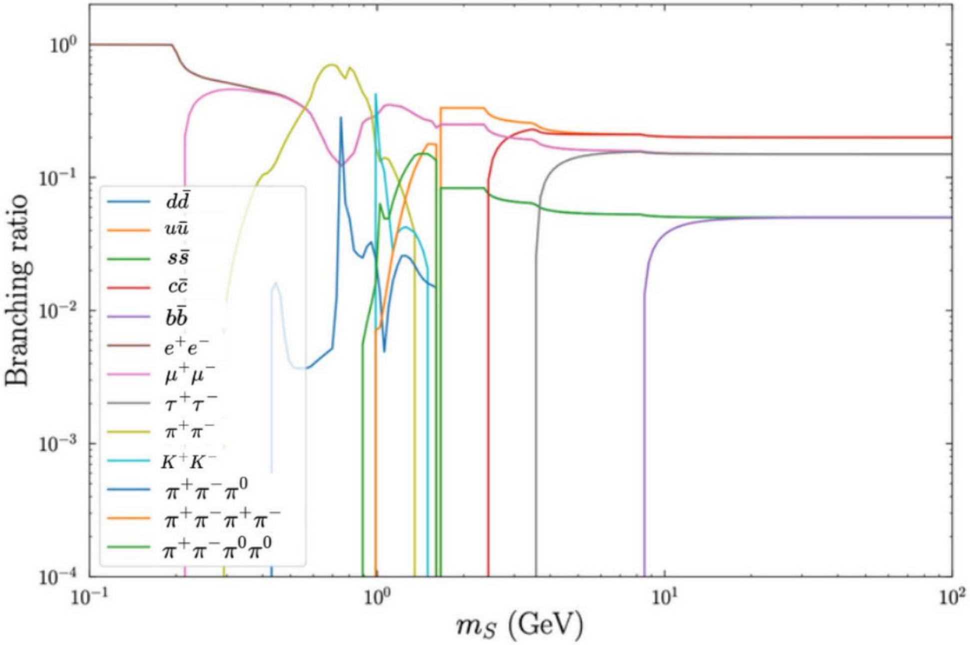
# Summary

- Hidden Valley models can produce challenging signatures
- Dedicated data streams in CMS provide opportunities to explore new phase space
- Presented results for the new Parking (Run 2) and Scouting (Run 3) analyses
  - Stringent limits are imposed on three dark shower benchmark models
  - Complementarity between the two data streams is achieved
- Also presented results for the first collider search for lepton-enriched semi-visible jet signature
- More searches to come!

# Backup slides

# Branching ratios

- BR for decay to $\mu\mu$ ~10-30% 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



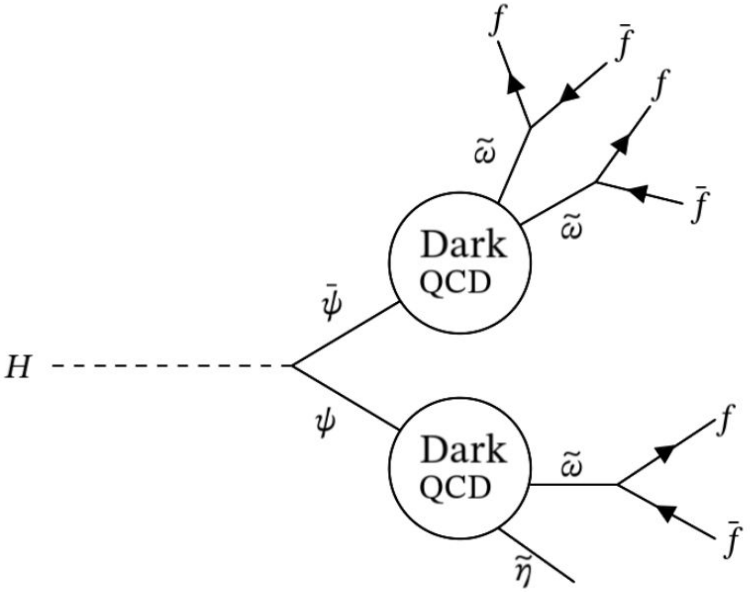

https://gitlab.com/simonknapen/dark_showers_tool

# Hidden valley benchmark model

*S. Knapen, J. Shelton, D. Xu*

arXiv: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
- ω̃ (dark spin-1 meson) is the visibly-decaying particle
- η̃ (dark spin-0 meson) is assumed to escape the detector as missing energy

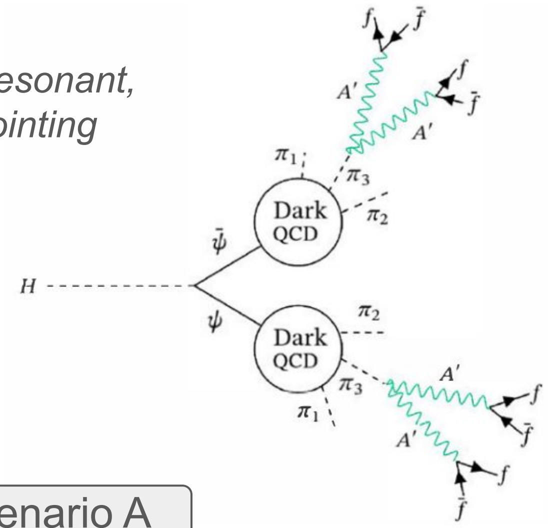



Vector portal

# Extended hidden valley benchmark models

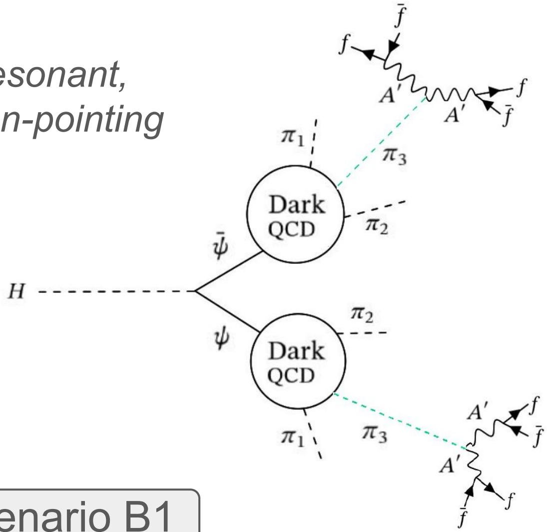
- Extended benchmark models feature a light dark photon A' with dark flavour-violating couplings
- Contain two dark flavours instead of one ⟹ wider spectrum of dark hadrons
  - pseudoscalar η and dark pions $\pi_1$, $\pi_2$, $\pi_3$
  - η decays promptly into $\pi_i$ in **scenario A** and **scenario B1**
- Decay topologies can give **non-pointing** signature

*Resonant, pointing*




Scenario A

*Resonant, non-pointing*




Scenario B1

arXiv:2303.04167 *S. Born, R. Karur, S. Knapen, J. Shelton*

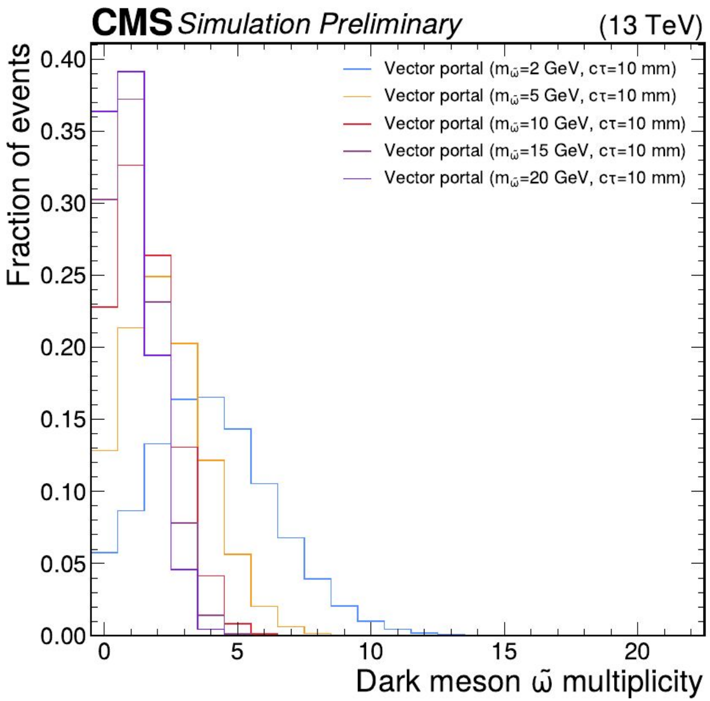
# Model parameters

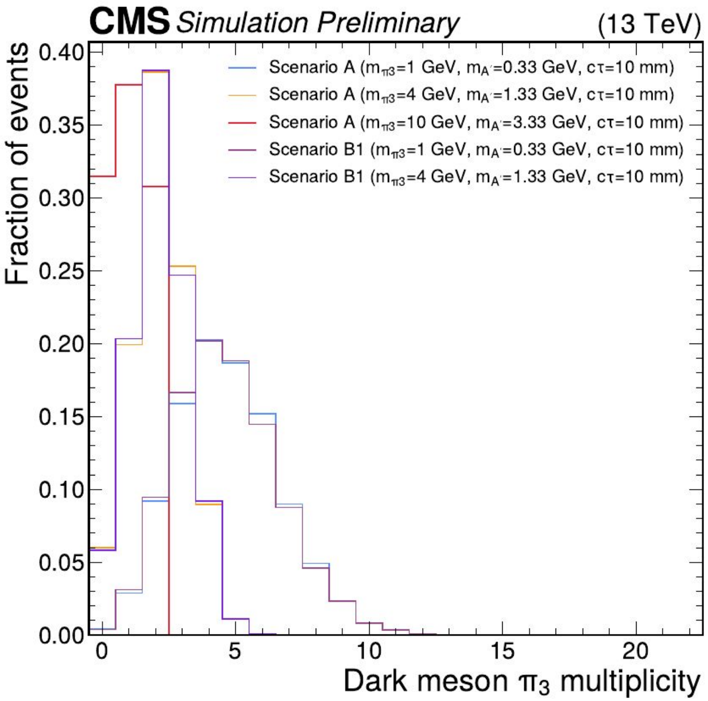
- Different mass and lifetime model points are considered in the analysis

| Signal model | Model parameters |
| --- | --- |
| Vector portal | $m_{\tilde{\omega}}$: mass of the dark vector meson<br>$c\tau$: mean proper lifetime of the dark vector meson |
| Scenario A/B1 | $m_{\pi 3}$: mass of the dark pion $\pi_3$<br>$m_{A'}$: mass of the dark photon<br>$c\tau$: mean proper lifetime of the dark photon (scenario A) or the dark pion $\pi_3$ (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

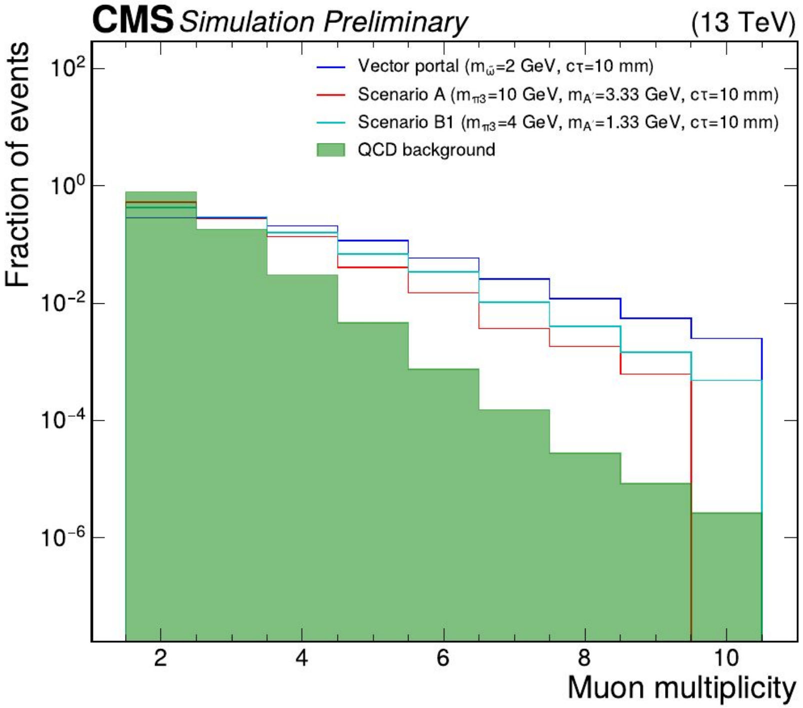


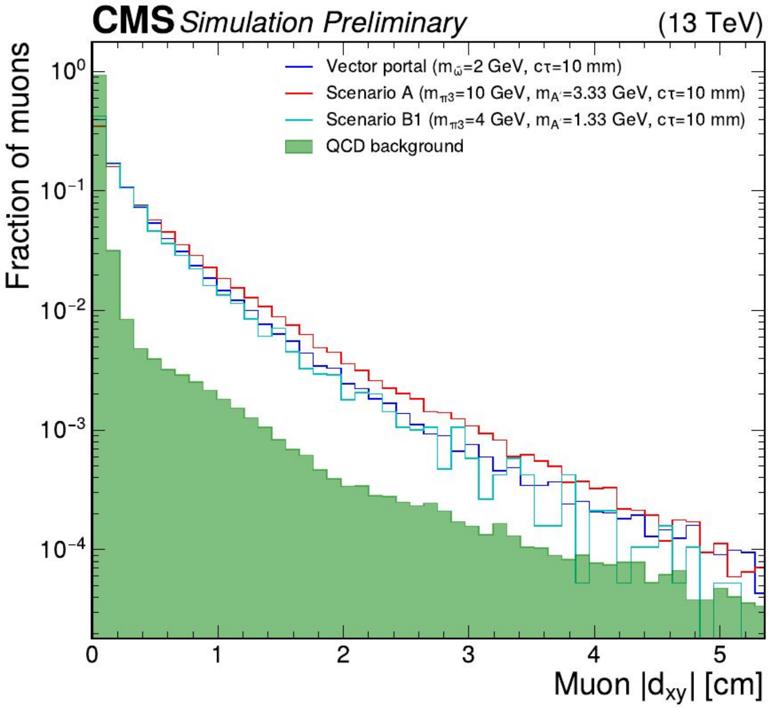



# Signal and background features

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



# Event-level BDT

**EXO-24-008**

## 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

# BDT input variables

EXO-24-008

Muons (16 variables): $\eta$, $\phi$, $p_T$, $p_T$ 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): $p_T$, $\eta$, $\phi$, $x$-position, $y$-position, $z$-position, $d_{xy}$, $d_{xy}$ significance, 3D decay length, 3D decay length significance, pointing angle, $\chi^2$, number of degrees of freedom.

Muon secondary vertices (15 variables): $\chi^2$, 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.

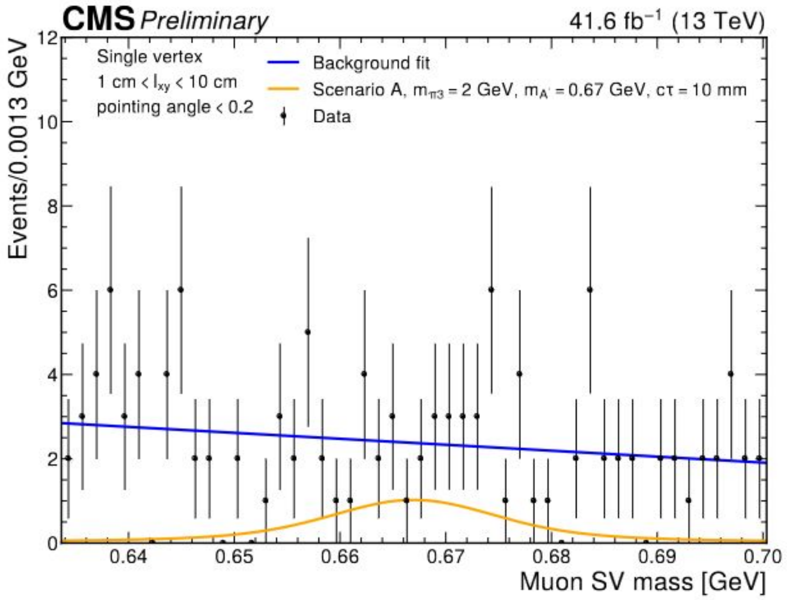
Other variables (3 variables): number of muons, number of secondary vertices and number of muon secondary vertices in the event.

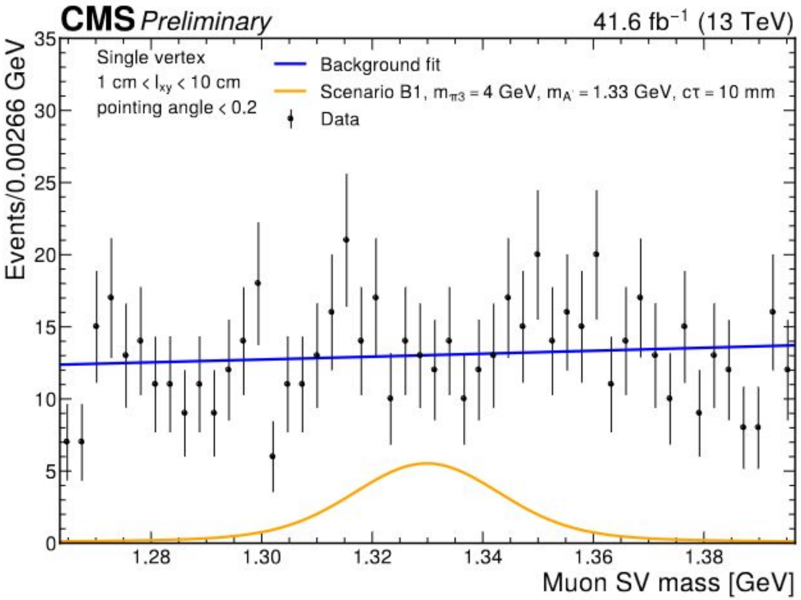
Maximum number of muons used: 8; maximum number of secondary vertices used: 8; maximum number of muon secondary vertices used: 8.

# Fitting strategy

EXO-24-008

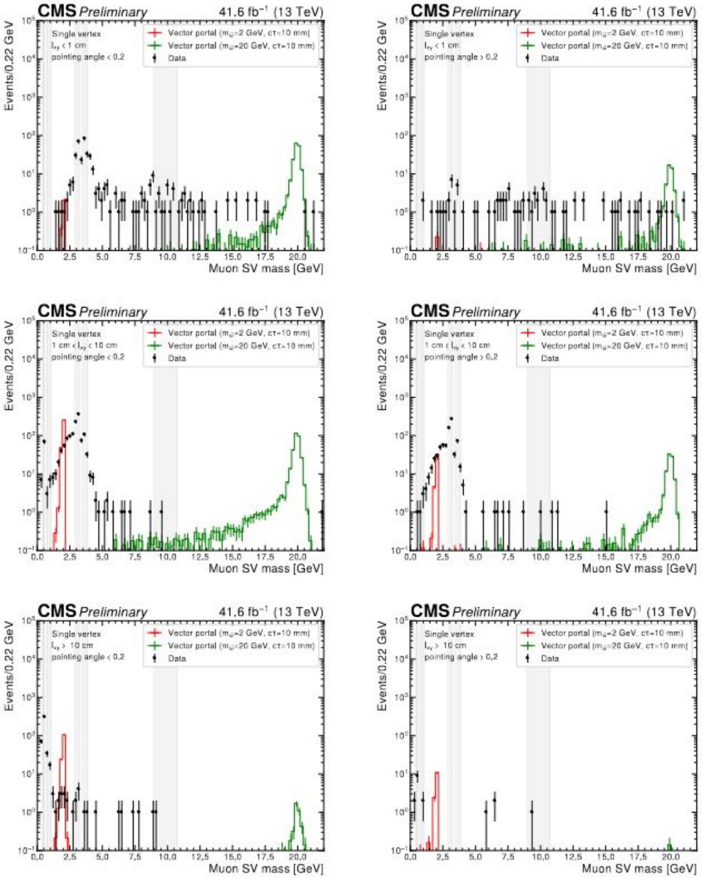
- Use the Voigtian function to model the signal
- Fit with a sliding mass window of 5×HWHM (HWHM found to be 1% of the signal mass) in each category
- Use an envelope of functions for the background fit
  - polynomial (first order), exponential and power law functions.
- Discrete profiling systematic



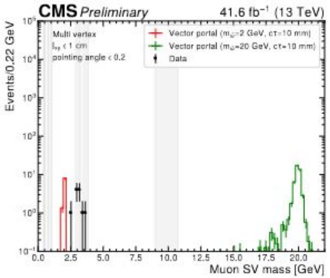
# Dimuon mass distributions in single vertex categories - vector portal

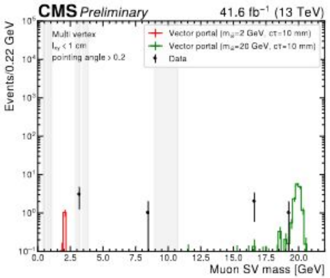
**EXO-24-008**

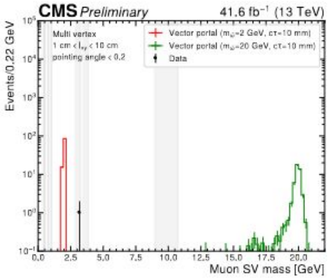


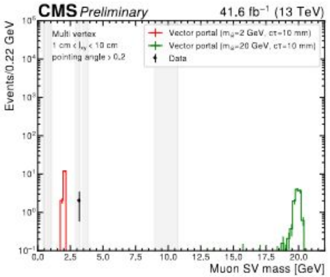
# Dimuon mass distributions in multi vertex categories - vector portal

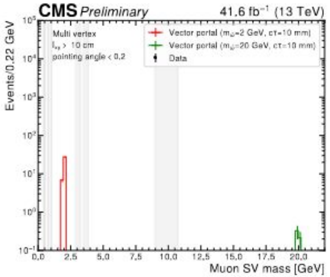
EXO-24-008

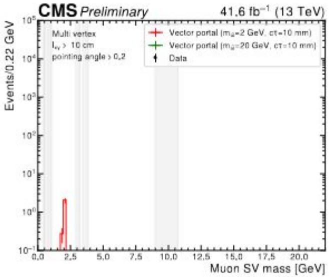


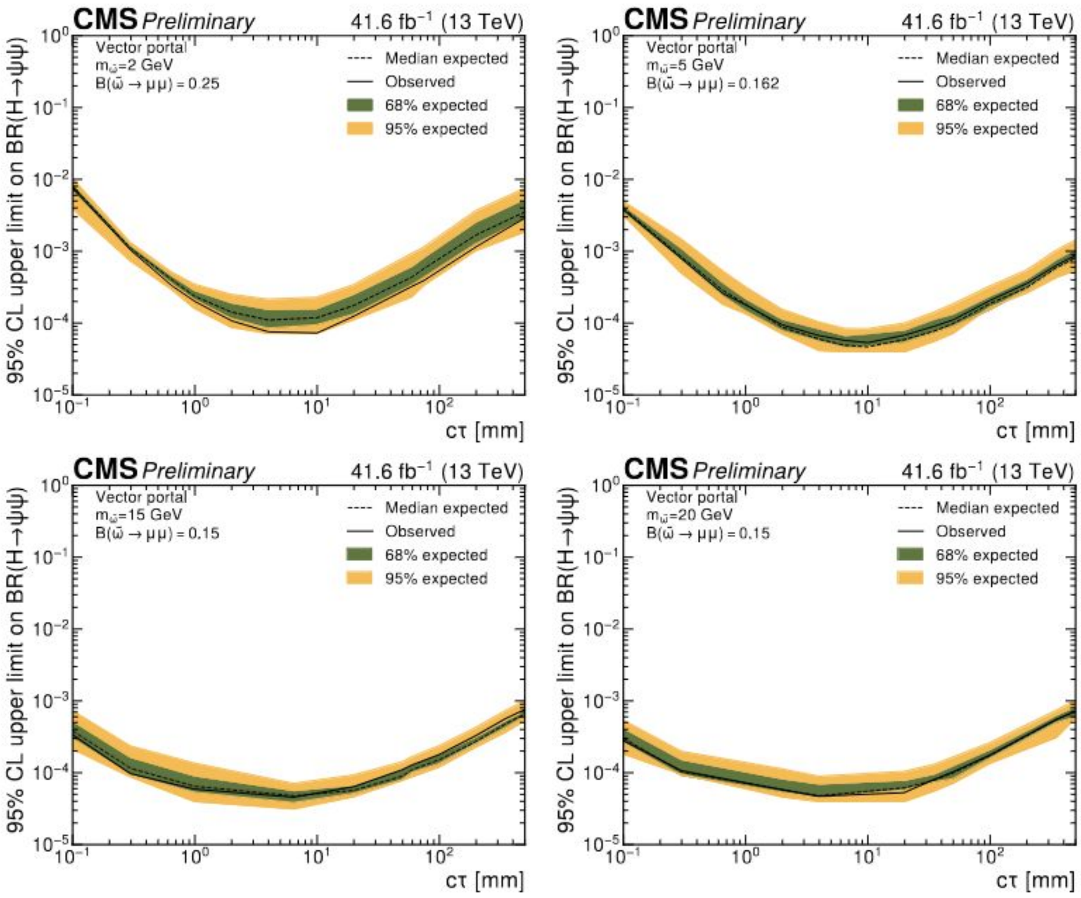



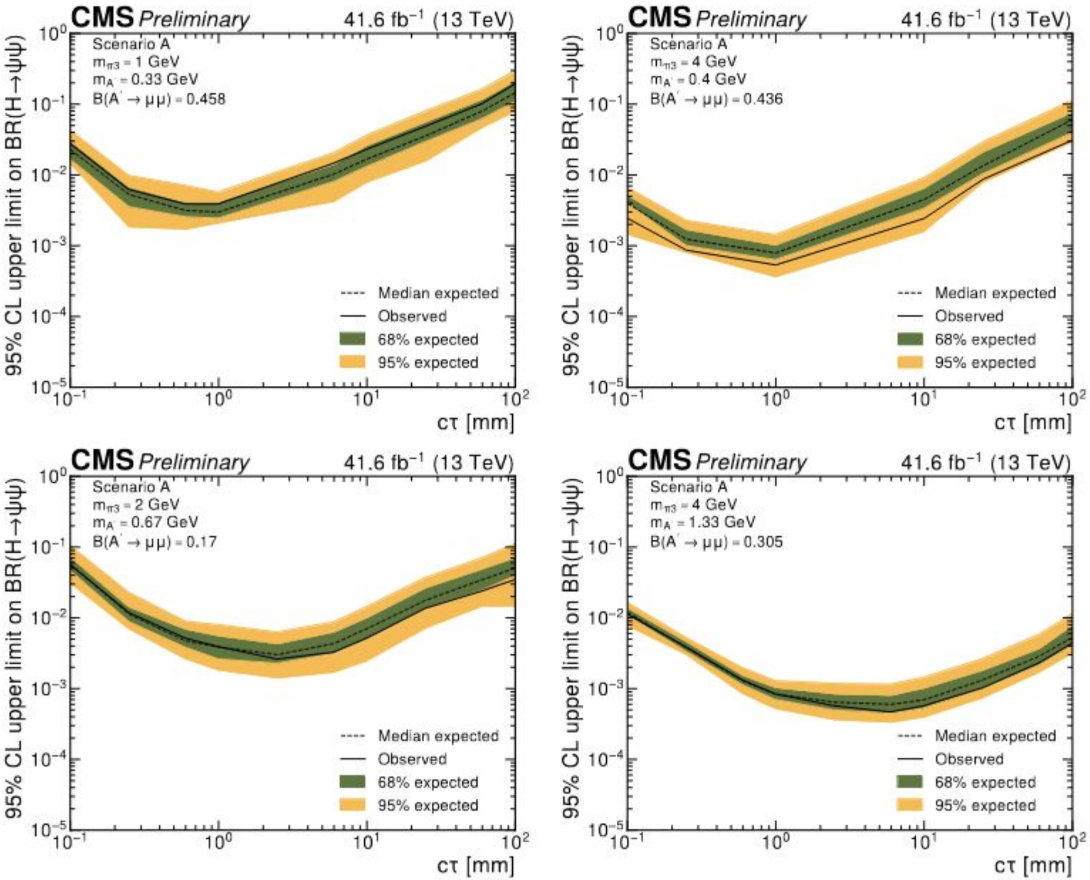
# Limits - Vector portal

EXO-24-008



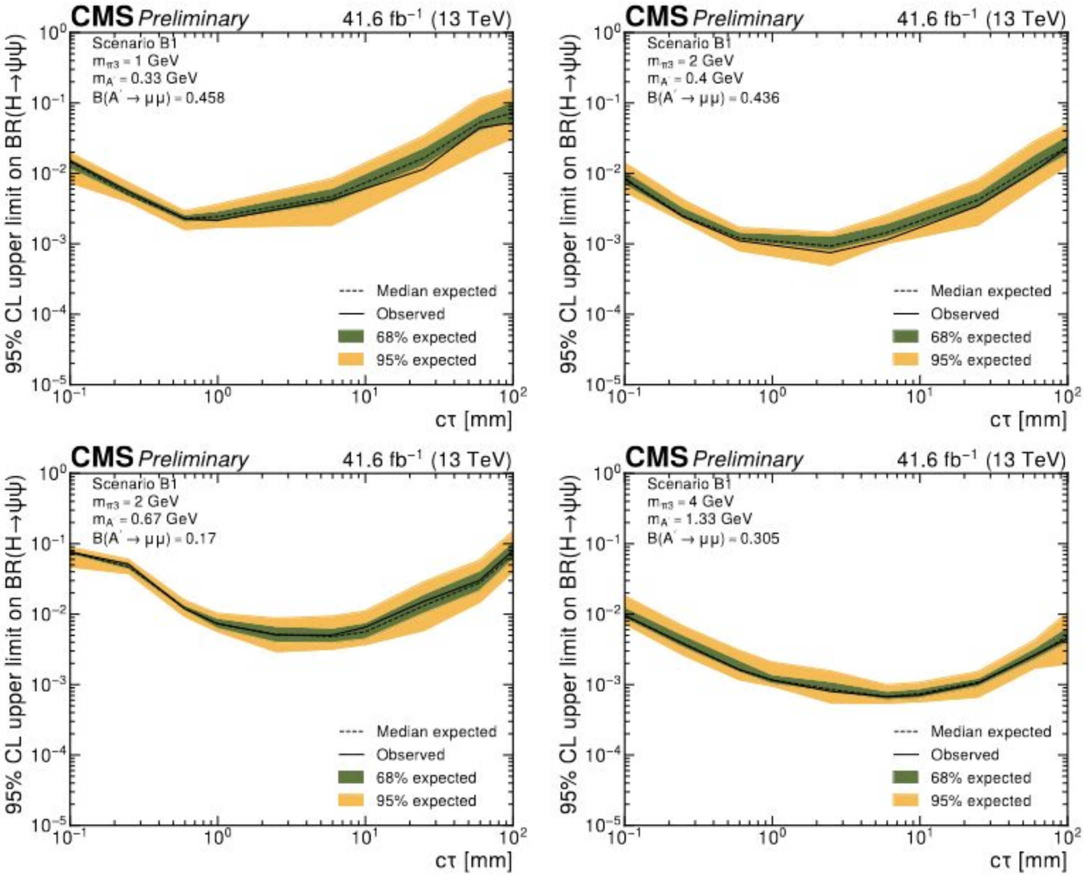
# Limits - Scenario A

EXO-24-008



# Limits - Scenario B1

EXO-24-008



# Summary of systematic uncertainties

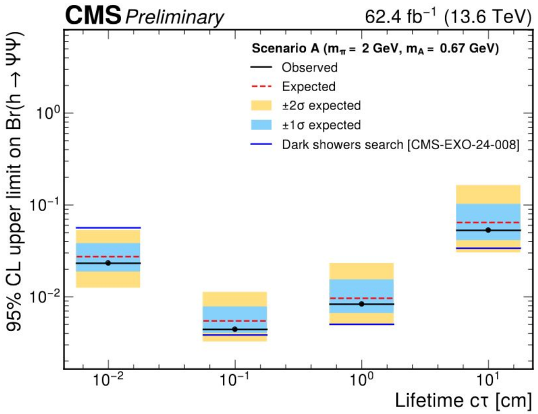
EXO-24-008

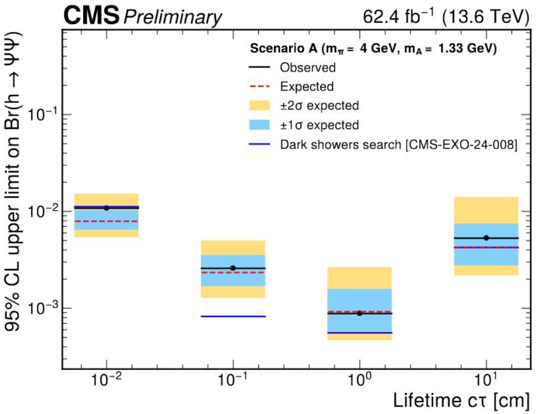
- Signal uncertainties:
  - Summarised in the table on the right
  - Measure the systematic uncertainties from the BDT and displaced muon identification using the J/Psi mass region
  - Used the trigger scale factors derived by EXO-22-019 for the B-parking triggers
- Background uncertainties:
  - Discrete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

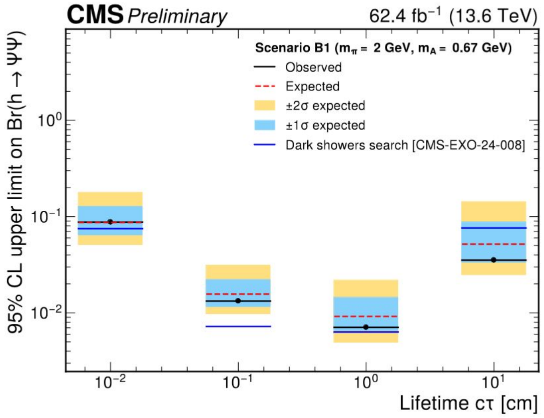
| | Signal systematic uncertainty |
|---|---|
| BDT | 10% |
| Displaced muon ID | ~1-17% |
| Trigger | ~1-2% |
| Pileup | ~5% |
| Theory uncertainty in ggF Higgs production | 3.9% |
| Strong coupling constant | 2.6% |
| PDF | 1.9% |
| Luminosity | 2.5% |

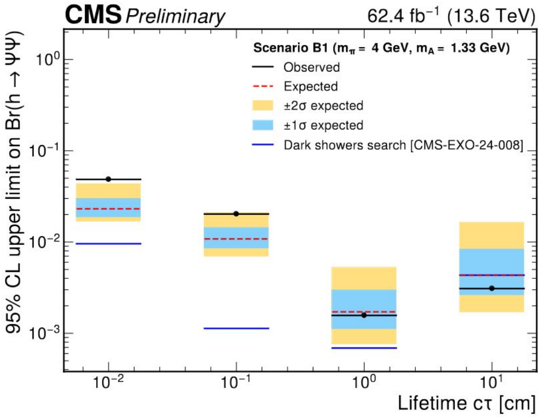
# Run 3 Scouting analysis - dark shower limits

EXO-24-016



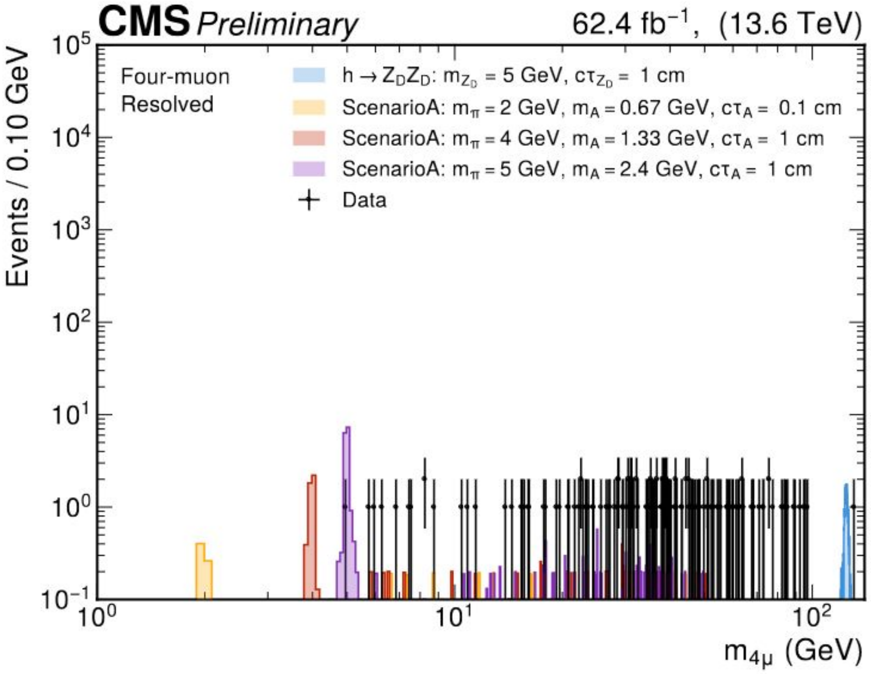



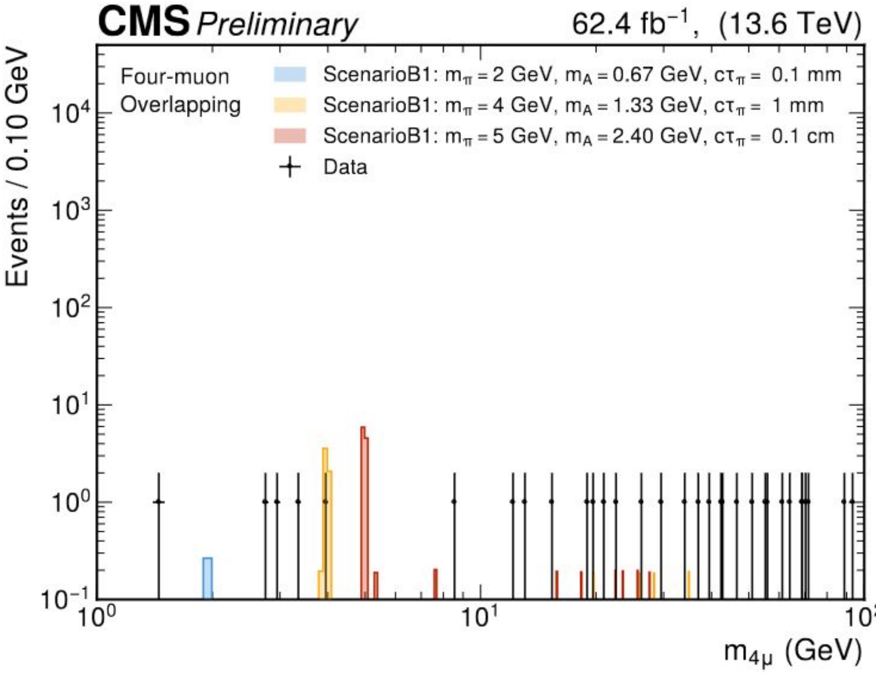
# Run 3 Scouting analysis - four muon mass

EXO-24-016

Resolved

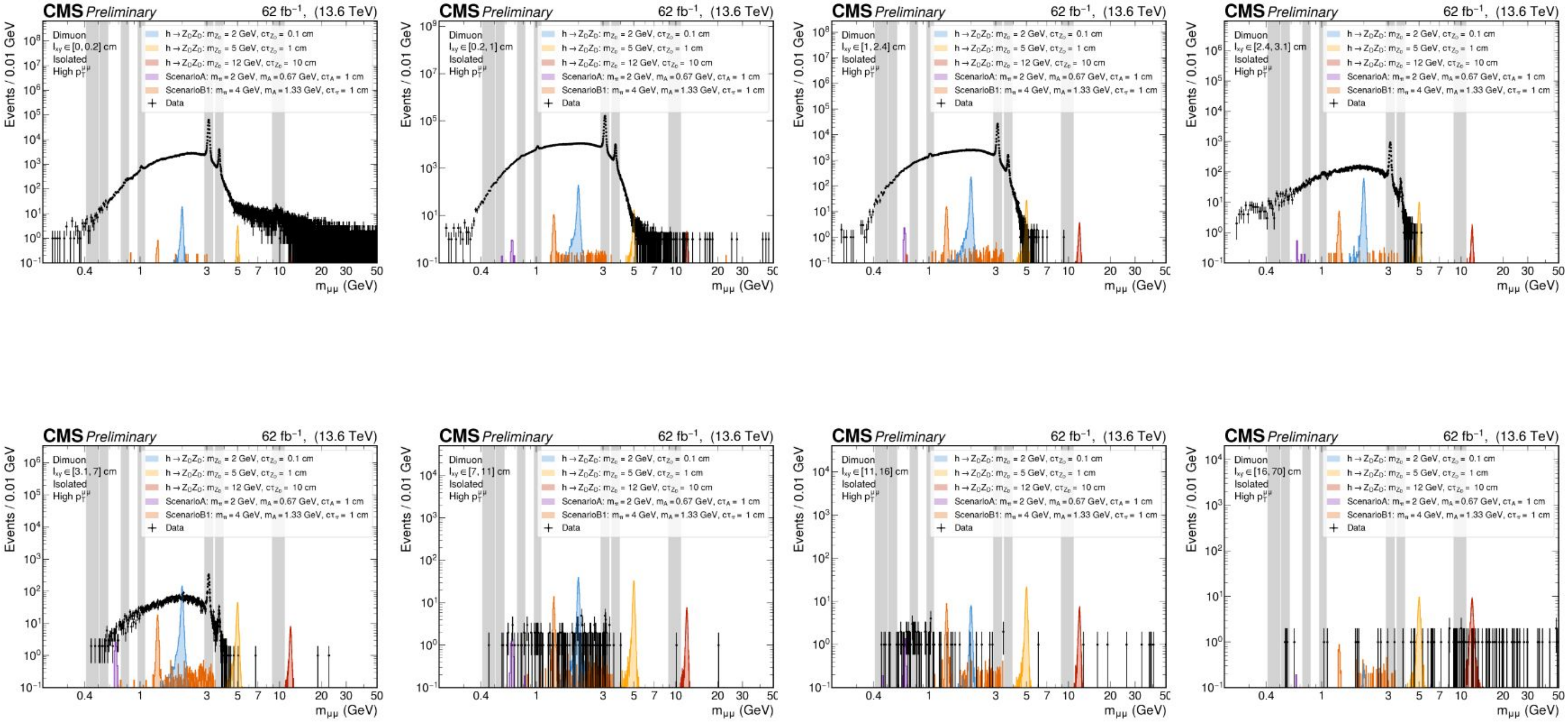



Overlapping



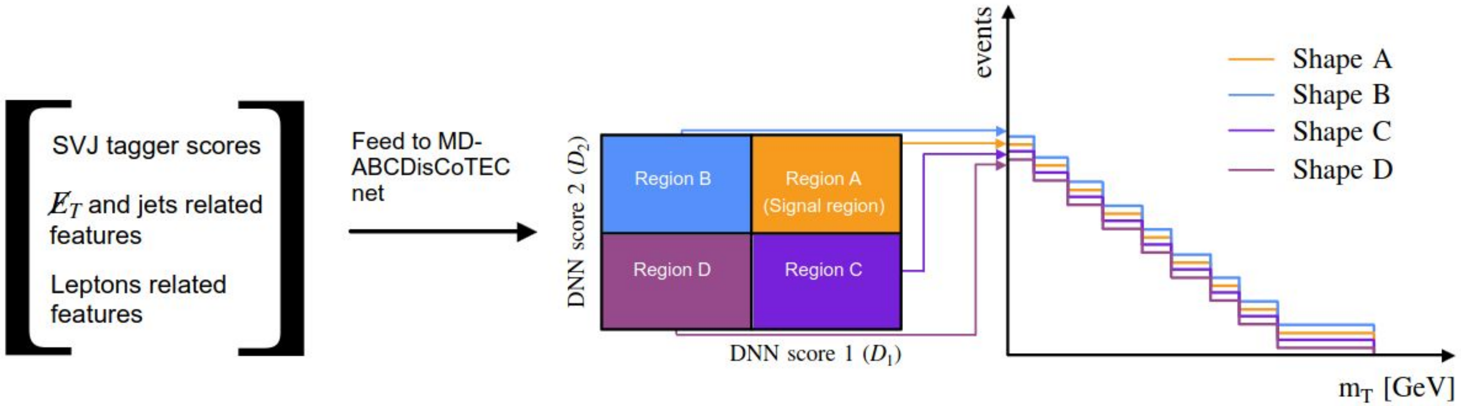
# Run 3 Scouting analysis - dimuon mass

**EXO-24-016**



# Search for SVJℓ - The MD-ABCDisCoTEC Method

**EXO-24-029**



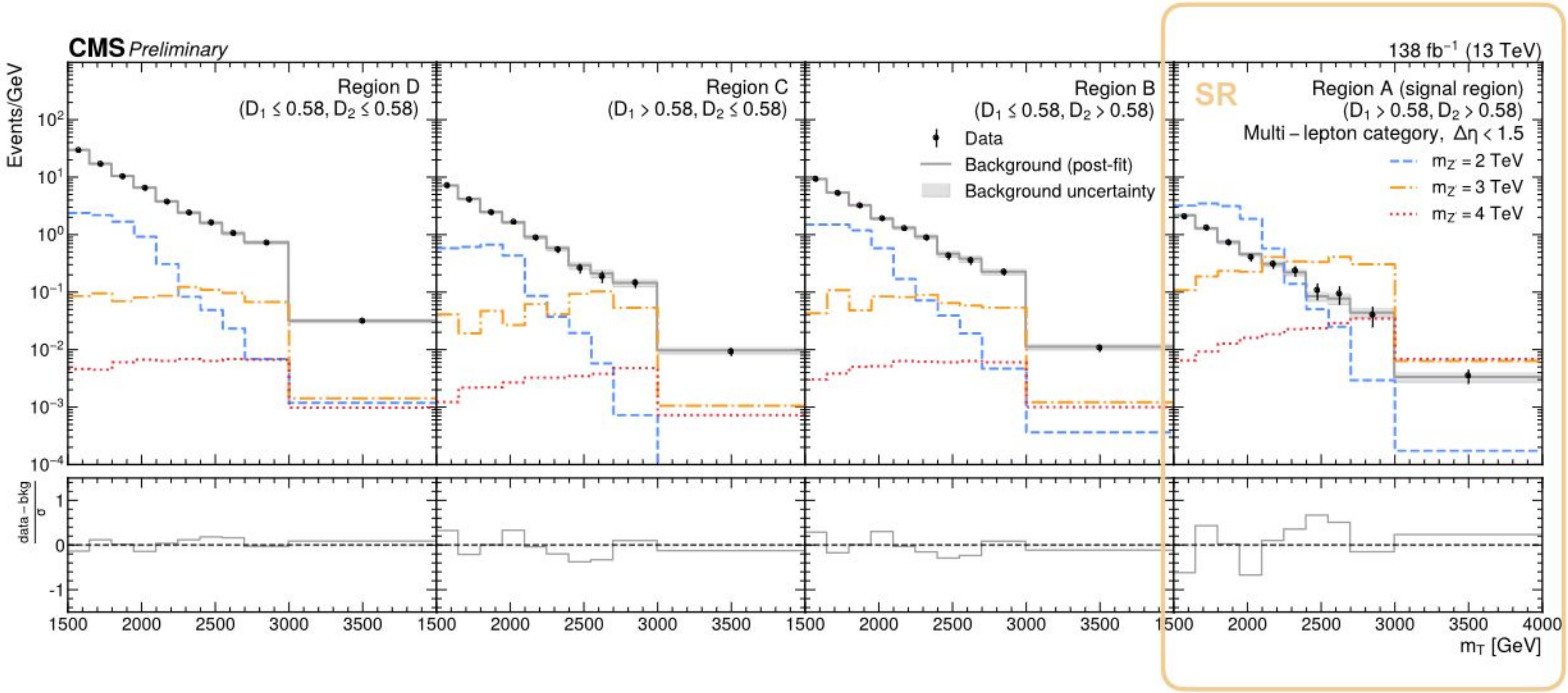

Train simultaneously **two independent Deep Neural networks** to engineer **two optimal discriminators** that can be employed for an ABCD method in bins of $m_T$:

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

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

# Search for SVJℓ - Fit

**EXO-24-029**




➡ Validation (VR) of the method using data in signal depleted region $(1.5 < \Delta\eta < 2.2)$

➡ Yield systematic on ABCD prediction from VR, shape systematic extracted from MC at $\Delta\eta < 1.5$