Recent Results on Dark Sectors in CMS

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Introduction

Dark Sectors at CMS:

This talk focuses largely on 2 classes of models:

1) **Hidden Valley (Dark QCD)**

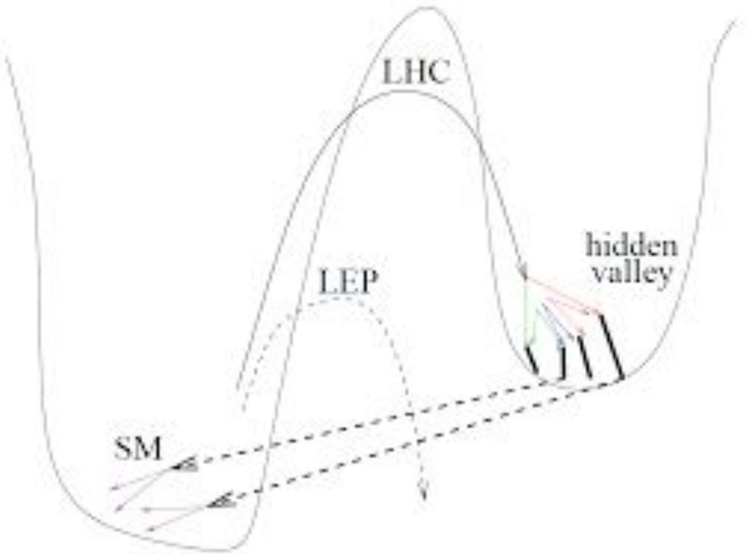
Portal particle which connects SM to a higher scale BSM sector
BSM Sector can have it's own internal structure (often coined "Dark QCD")
Is seen by decays back into SM particles (can be displaced)

2) **Dark Matter in final states with unbalanced p_T and standard objects**

Closer to traditional dark matter searches with look for missing momentum
Here we can have various dark matter production mechanisms

1. 2 Higgs Doublet Models (2HDM)
2. Dark Higgs

Searches look for missing momentum p_T^{miss} and traditional objects



First dedicated searches for:

1. Neutral long-lived particles in the Muon system (2402.01898)
2. Emerging Jets (2403.01556)
3. Soft Unclustered Energy Patterns (SUEPs) (2403.05311)
4. Dark Matter in DarkHiggs (WW+MET) (2310.12229)
5. Dark Matter produced in association with bottom quarks (2894114)

Dark Showers

Decays in Muon System:

1) Covers decays far away from IP (meters)
2) Excellent background suppression from shielding material
3) Muon system acts as a sampling calorimeter
4) Large cluster of hits (>100 hits)

Emerging Jets:

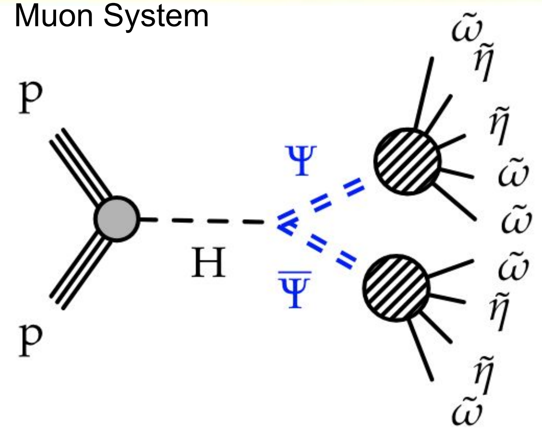
1) Less than ~500 mm
2) Fully data driven estimate of background
3) Both Model-agnostic and GNN tagger for EMJ
4) Small background in sensitive GNN bins

SUEPs:

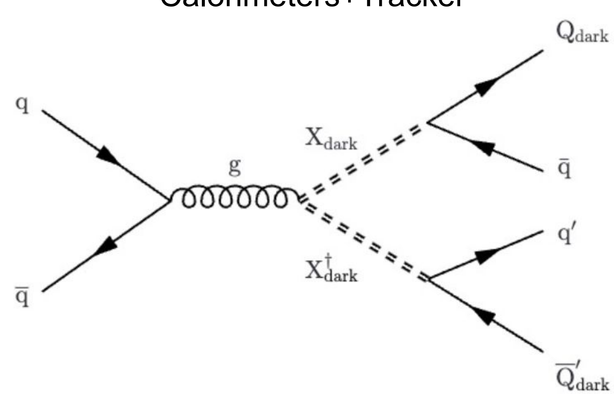
1) Fully prompt decay to SM
2) Novel Data driven estimate of large QCD Background
3) Recluster tracks with wide jets
4) Unique signature due to the sphericity and large number of tracks (>100)

Long-Lived **Prompt**

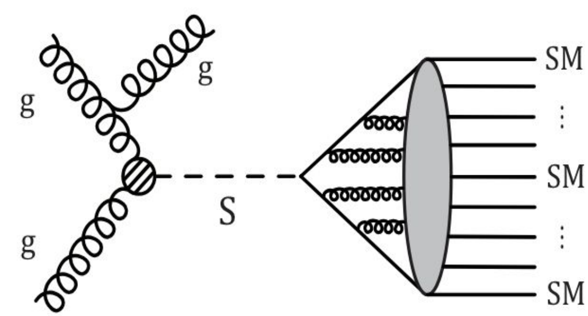
Muon System



Calorimeters+Tracker



Tracker



Decays in the Muon System

Event selection:

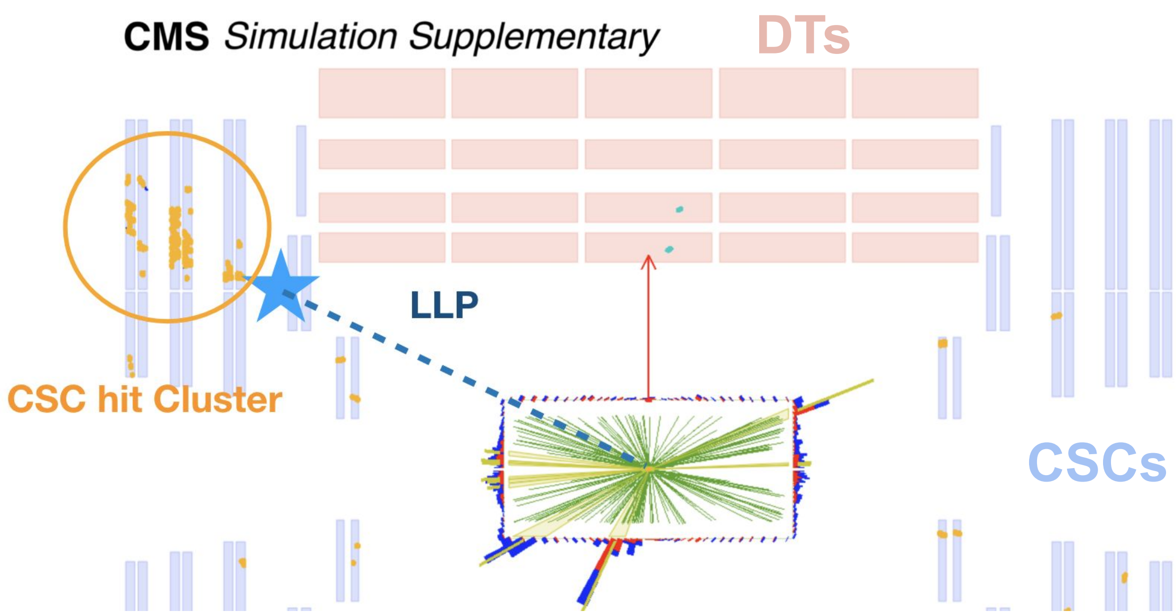
Trigger on MET (~1% efficiency). MET (≥ 200 GeV)

DBSCAN cluster of hits (>50 hits) in the muon system with no jets or tracks (Cluster efficiency (>80%))

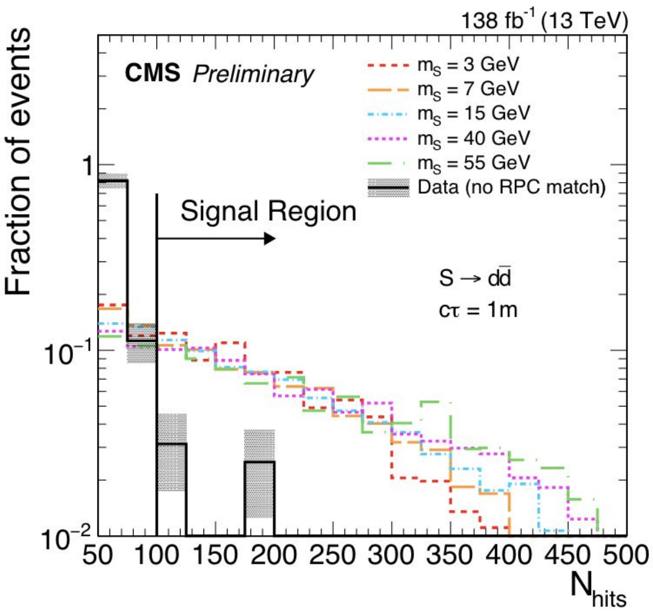
Split events into 3 mutually exclusive categories.

1. double clusters,
2. single Cathode Strip Chambers (CSC) cluster
3. single Drift Tube (DT) cluster

Use data-driven ABCD method ($\Delta\varphi(p_T^{miss}$,cluster),N_{hits}) for background estimation: N_{hits} as main discriminator



N_{hits} as main discriminator



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Decays in the Muon System

No excess above SM background observed

We interpret the search result in 9 different decay modes with

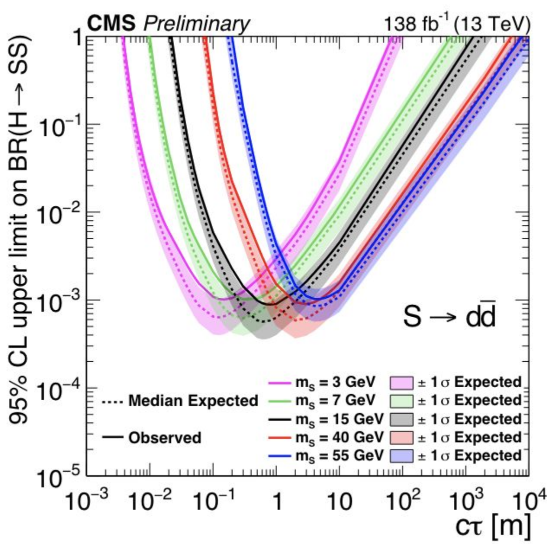
- hadronic shower (bb,dd,K^+K^-,K^0K^0,$\pi^+\pi^-$)
- EM shower ($\pi^0\pi^0$,γγ,e^+e^-)
- or both ($\tau^+\tau^-$)

Achieve first sensitivity to sub-GeV mass LLPs at BR(H →ss) = 10^{-3} level

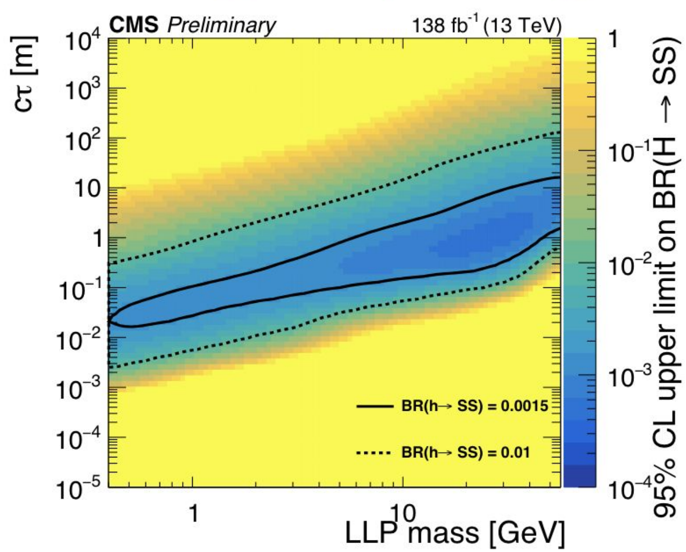
Achieve first sensitivity to dark shower model produced from Higgs decay at BR(H →ss) = 10^{-3} level

Observed Limits

Twin higgs model (dd decay)

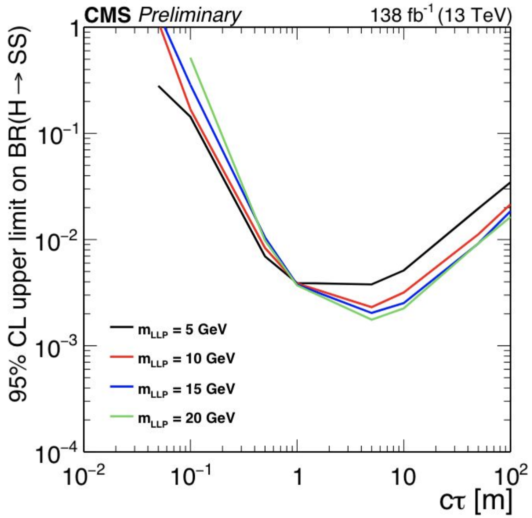


Twin higgs model (mixed decay)



Dark shower model (gluon portal)

$(x_{i\omega}, x_{i\Lambda}) = (2.5,1)$



2402.01898

Emerging Jets

Jet-tagging:

1) Model-agnostic EMJ tagging:

Unflavored: leverage track displacement within jet

Flavor-aligned: leverage track multiplicity within jet

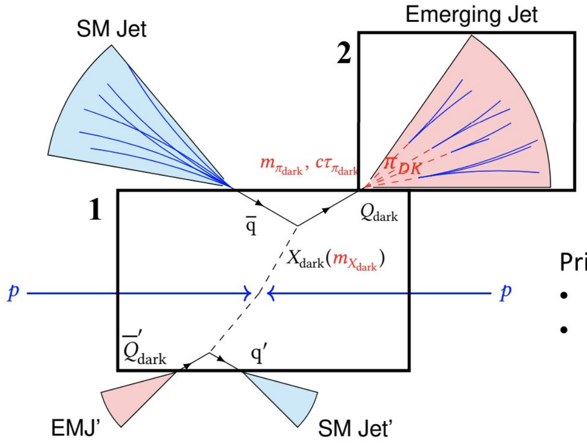
2) GNN EMJ tagging:

2 ParticleNet models trained separately on unflavored and flavor-aligned scenarios

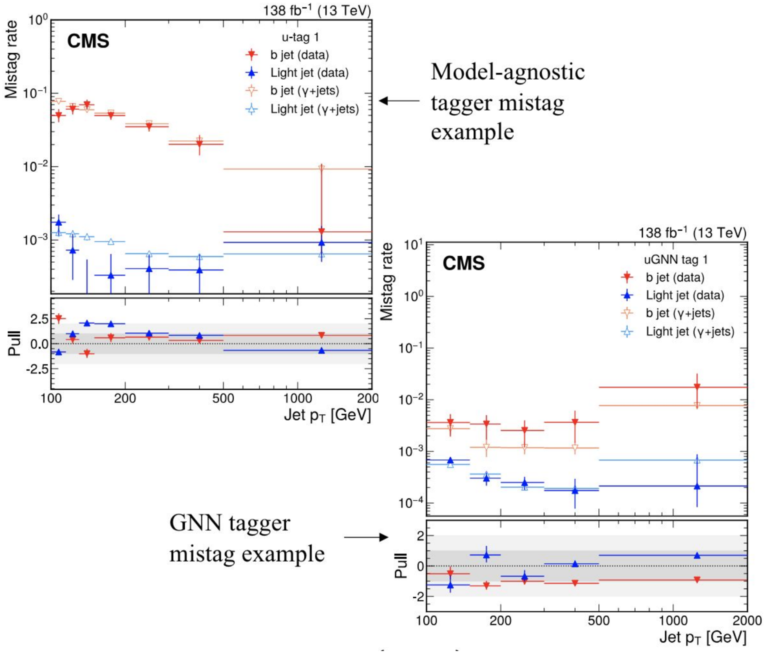
Data Driven Background Estimation:

Estimate # of bkg. events pass into SR using CR events and mistag rates from signal-free region

B-jet discriminator to calculate mistag on bs separately and b-jet fraction



Primary signature:
- High H_T
- 4 high p_T jets (2 EMJ, 2 SM jets)



Model-agnostic tagger mistag example

GNN tagger mistag example

2403.01556

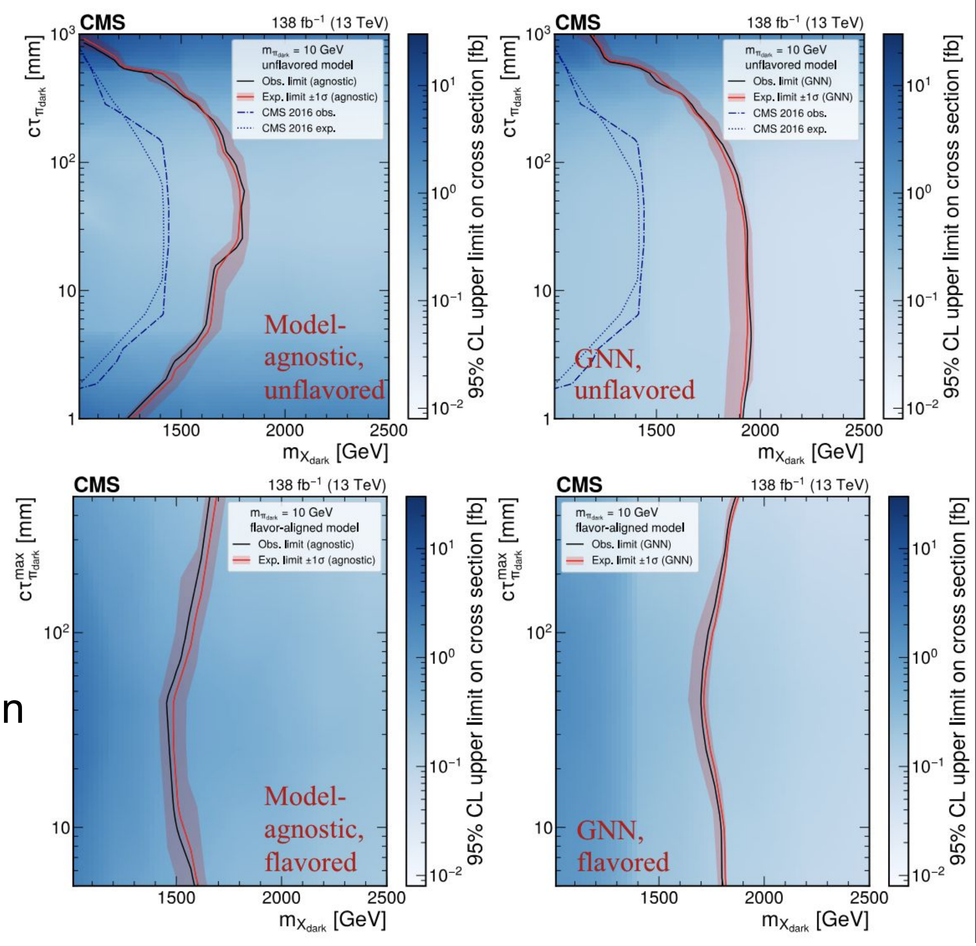
Emerging Jets

No excess observed

Limits set on 2 scenarios for both Model-agnostic and GNN.

Unflavored down model:
Dark quarks couple to down quarks ONLY
All π_{dark} in event have same cτ

Flavored-aligned down model:
Dark quarks couple to down-type quarks ONLY (d, s, b)
π_{dark} lifetime differ based on dark pion composition



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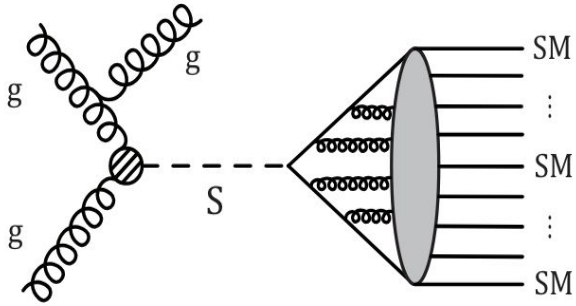
SUEPs

Soft unclustered energy pattern (SUEP):

prompt, high multiplicity, isotropic, low p_T tracks final state



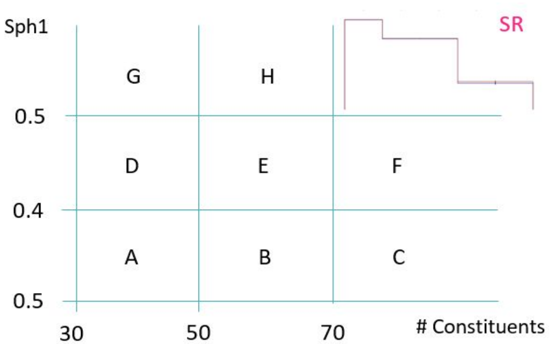
Analysis Strategy:

1) HT > 1200 GeV (SUEP recoil off ISR), Lepton Veto
2) Tracks cluster in wide "Jets" with ΔR=1.5, pT>150 GeV
3) SUEP Candidate as highest number of constituents
4) Boost into the SUEP candidate frame to calculate Sphericity

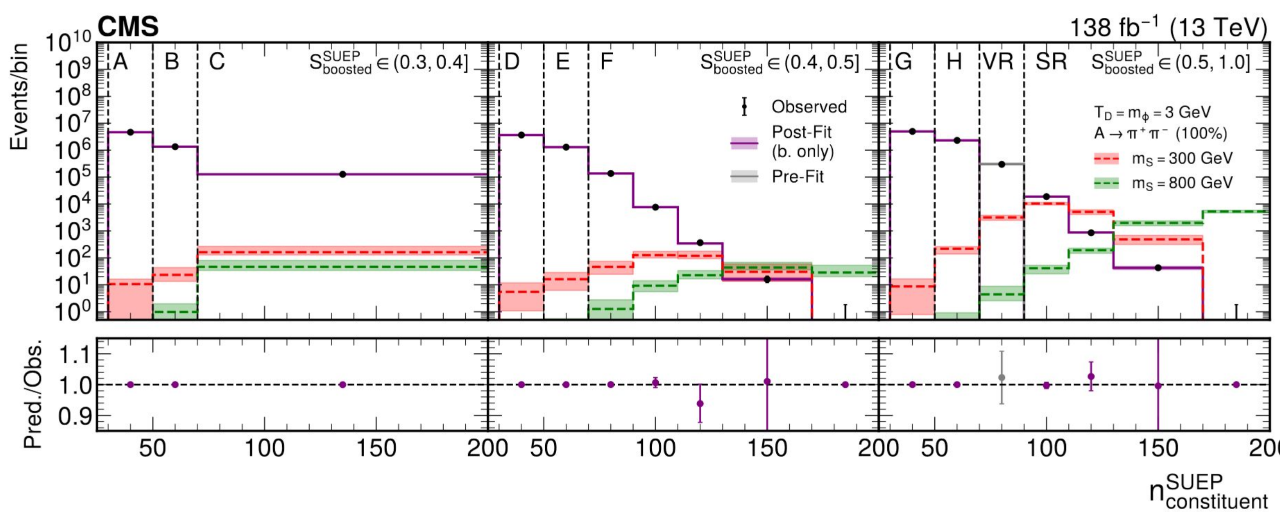
Large QCD background:

2403.05311

1) *Fully data driven*: Extended ABCD (9 regions)
2) # constituents and Sphericity of SUEP Candidate
3) Shape corrected with data driven systematics
4) Good agreement in Validation and Signal Regions



$$SR^{Bin\,i} \approx F^{Bin\,i}\frac{H^2 F\, D^2 B^2}{G\, C\, A\, E^4} + O(\Delta^4)$$



SUEPs

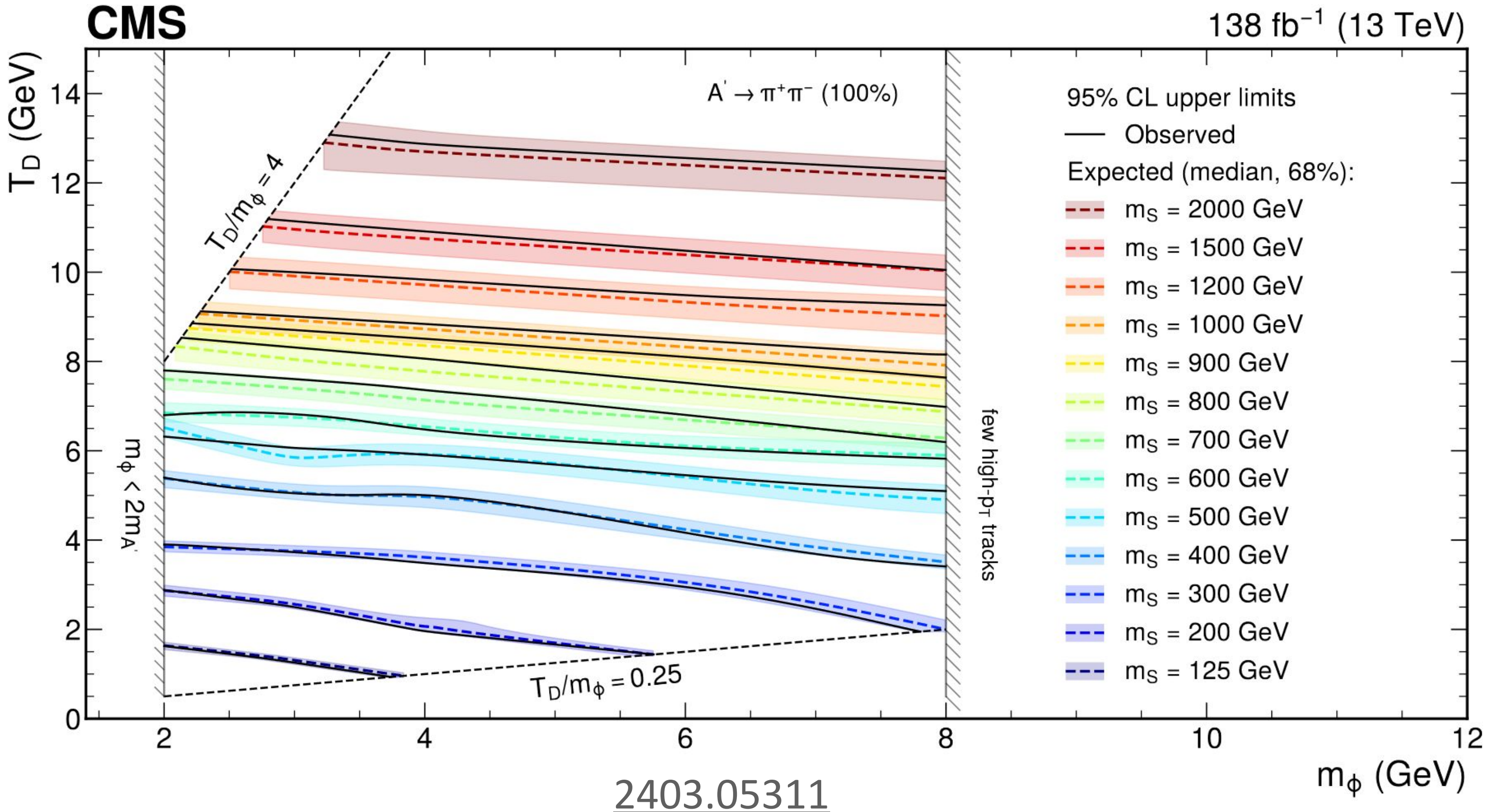
No excess observed in data:

- 4-dimensional parameter space T, mS ,$m\phi$,mA
- Discriminating variable we fit on is the # constituents, scales like $N\sim mS/m\phi \sim mS/T$

Limits on the cross-section are made and exclusion limits set for each scalar mass

More SUEP-like scenarios (bottom left) are covered

Sensitive across the mass range



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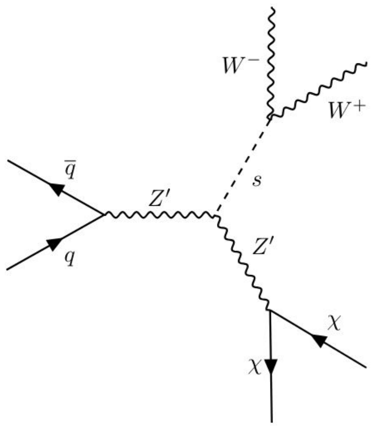
Higgs Sector

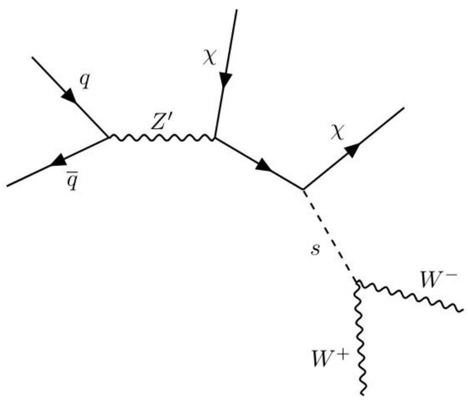
Dark Higgs:
2 mediators (Z', s)
χ as Dark Matter Candidate
here: s → WW → 2l2ν/lνqq

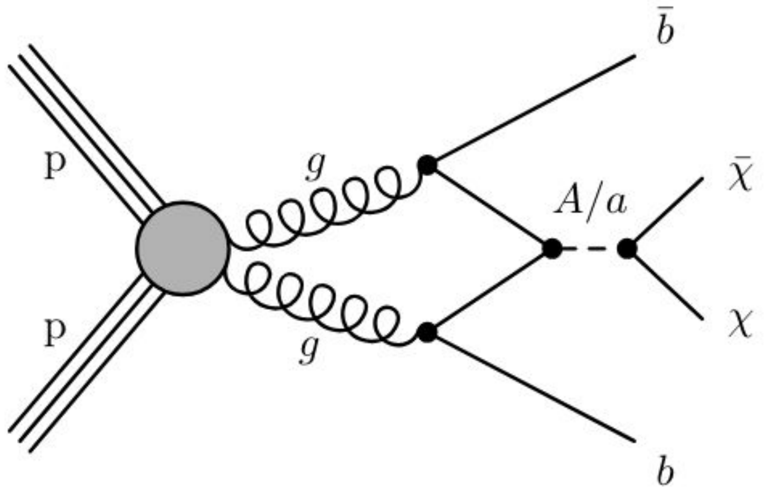
Strategy:
Look for large MET
Reconstruct s through W decays
Data-driven estimate for fakes

2 Higgs Doublet Model (2HDM):
Higgs Doublet ($H, H^{\pm}, A$)
Additional pseudoscalar a
A/a → χχ
χ as Dark Matter Candidate

Strategy:
Look for large MET
Events with b-tagged jets
Lepton Vetoes



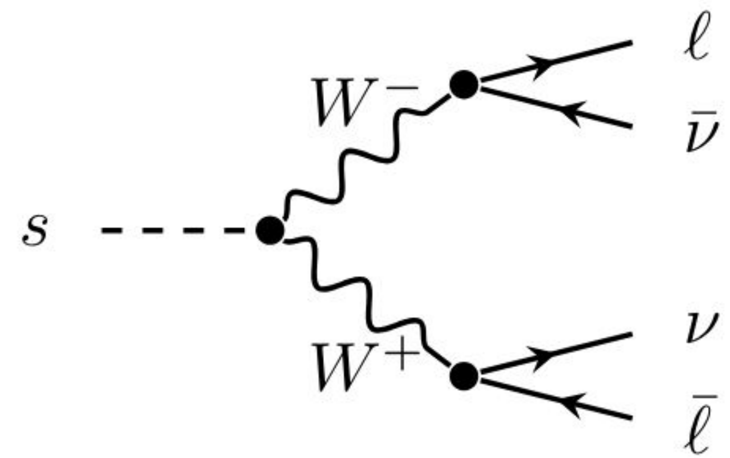




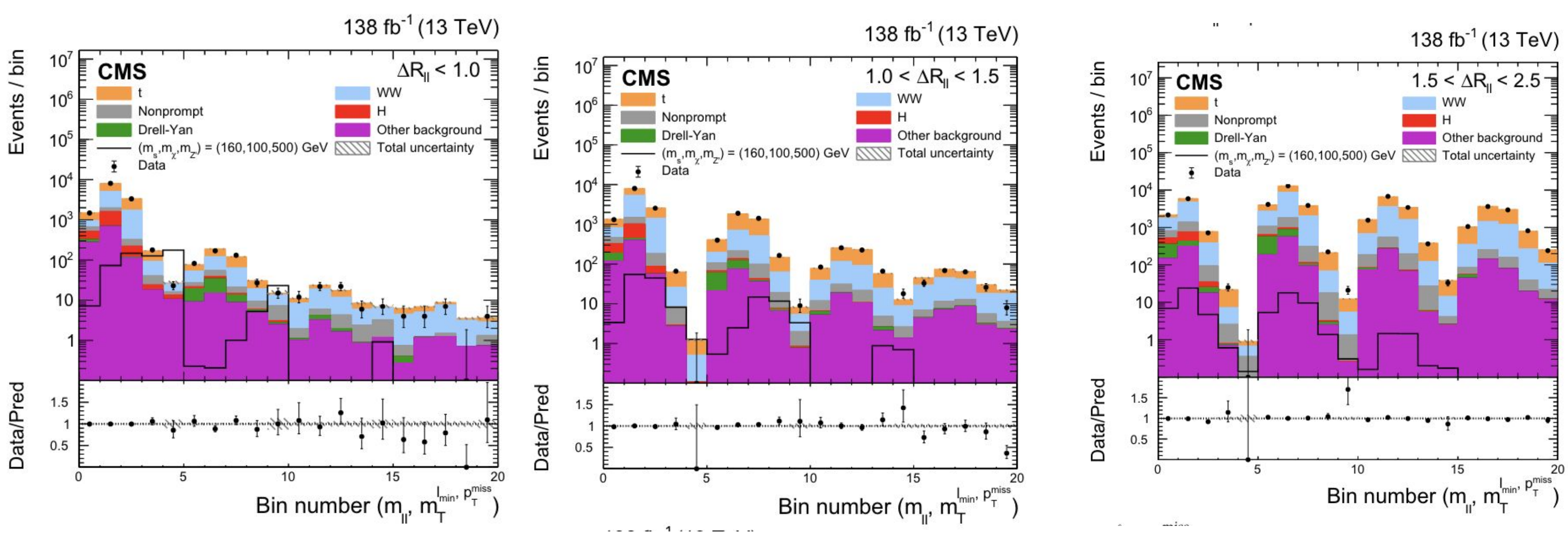
DarkHiggs

DarkHiggs:
2l2v: 3 SR unrolled 2D plots
Distributions split by ΔR [0,1.0,1.5,2.5]
Binned in mll and mT

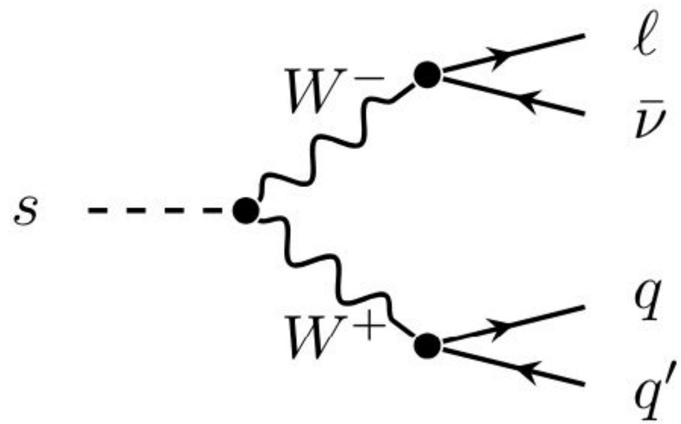
Top, NonPrompt, DY and WW:
Data driven NonPrompt
Rest estimated via MC through CRs.



2310.12229



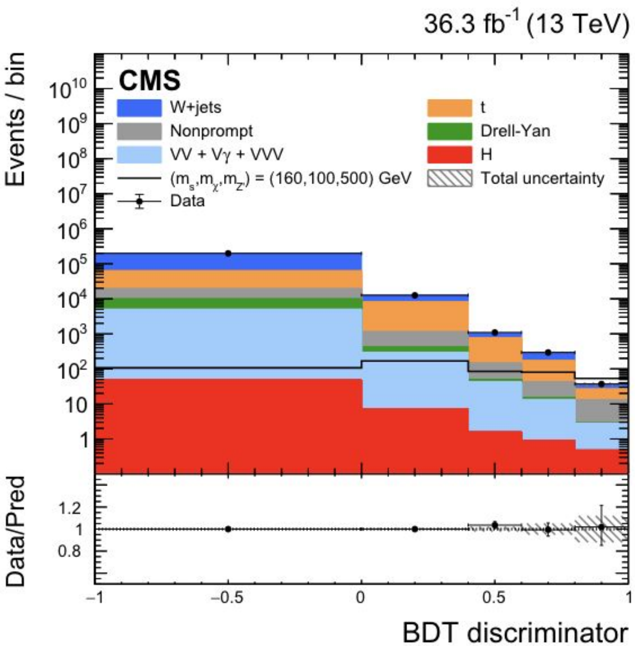
DarkHiggs:
lv2q: BDT discriminator
2016 split from 2017/2018
13 optimized kinematic inputs
(mostly sensitive to MET vs visible particles boost)

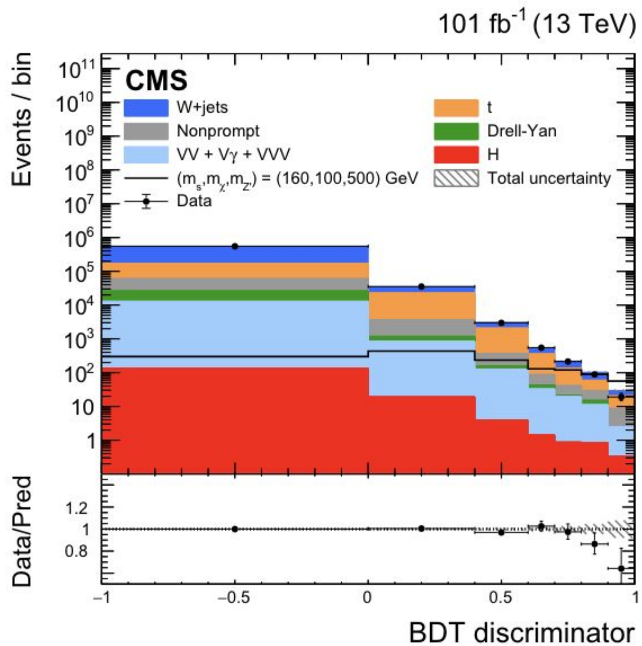


Top, W+Jets, and NonPrompt:
Data driven NonPrompt
Rest estimated via MC through CRs.

2310.12229

2016





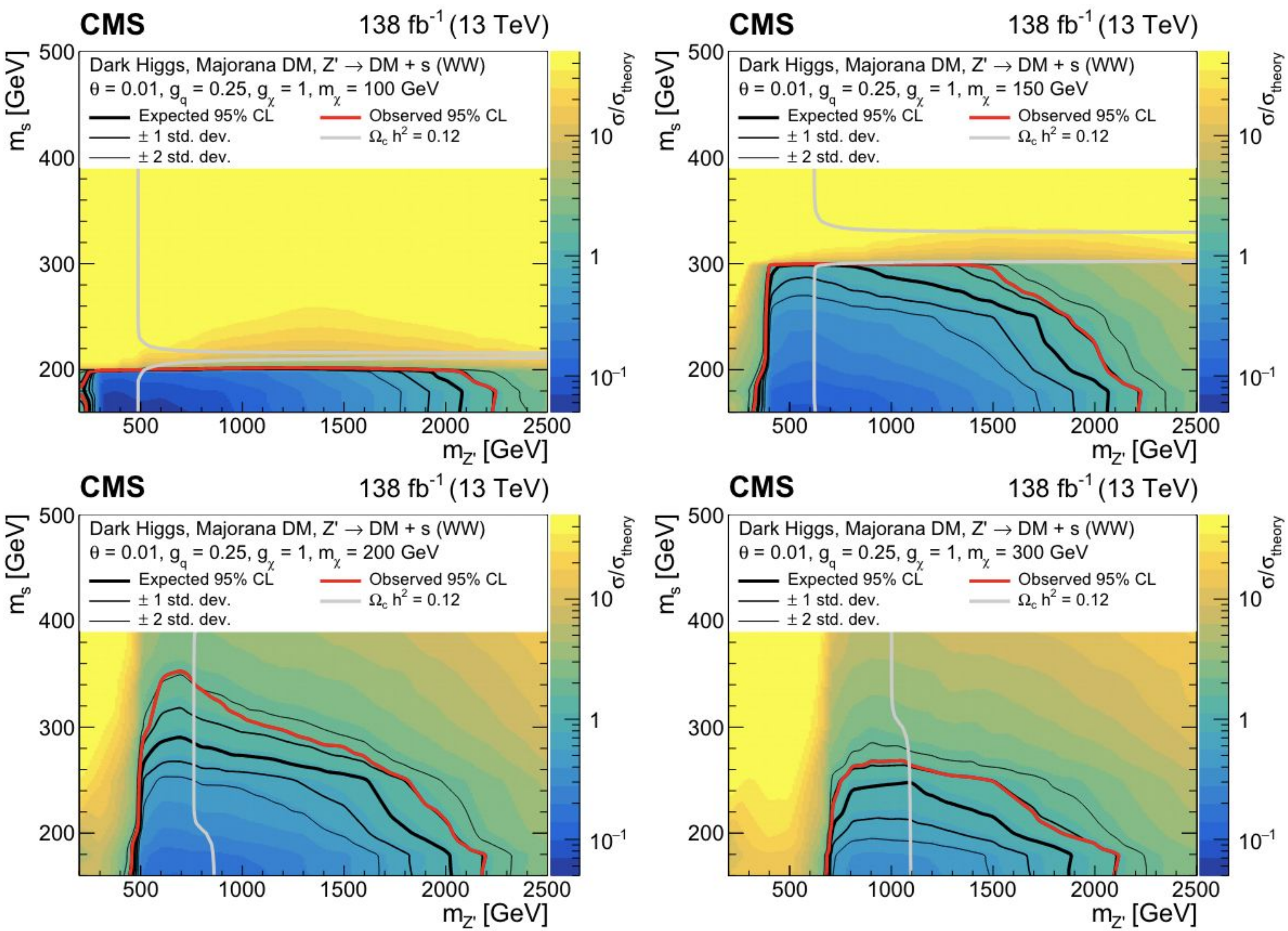
17/18

Different binning from S/Sqrt(S+B)

Small local deficit: 1.8σ in final bin

Limits set $m_{Z'}$ and m_s for various masses of χ

Sensitivity for m_s drops off for $m_s > 2m_\chi$



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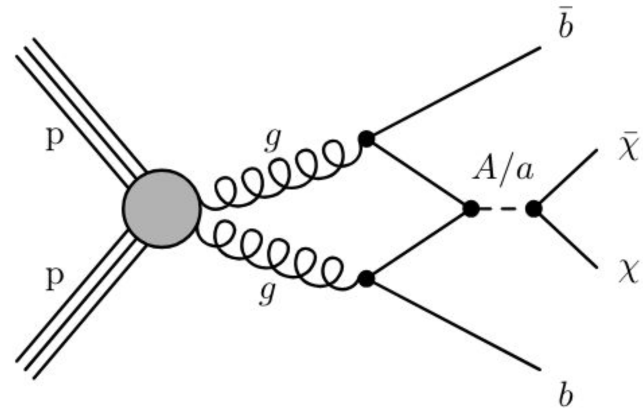


2894114

2HDM analysis:

1) MET > 250 GeV
2) Single Lepton veto (inverted for CRs)
3) b-tagging with loose ID

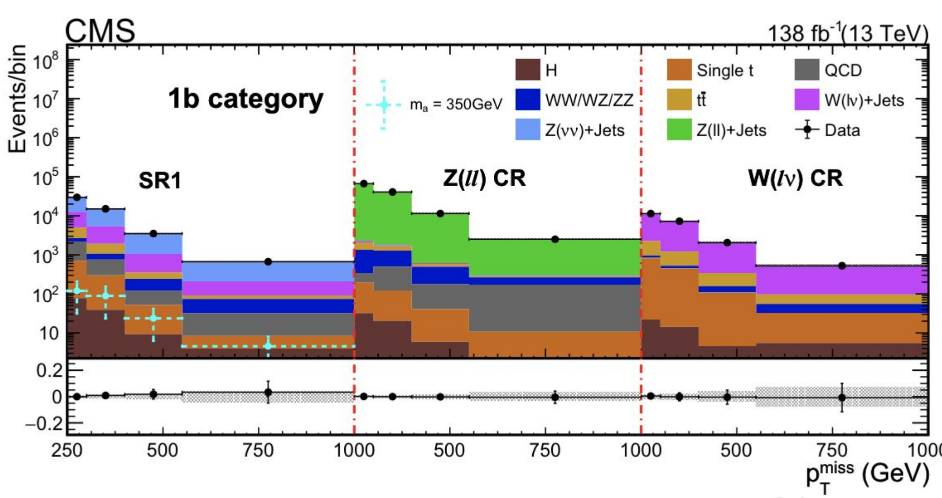
Combine Muon/Electron channels.
simultaneous binned profile likelihood fit on:

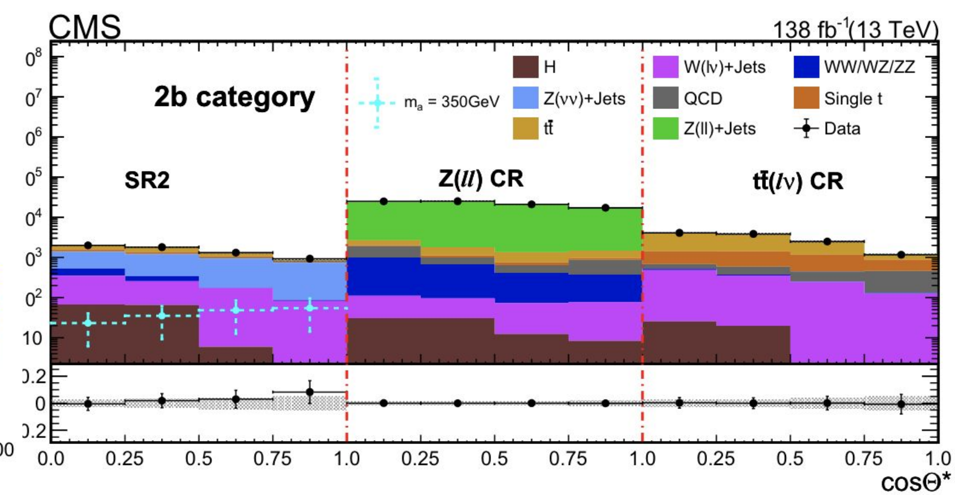
1b (p_T^{miss}):

SR1: At least 2 jets
Z(ll) CR: OSSF leptons, $70 < M_{ll} < 110$, Recoil > 250 GeV
W(lν) CR: Single lepton, $p_T^{miss} > 100$, $M_T < 160$, Recoil > 250 GeV

2b (cosθ*):

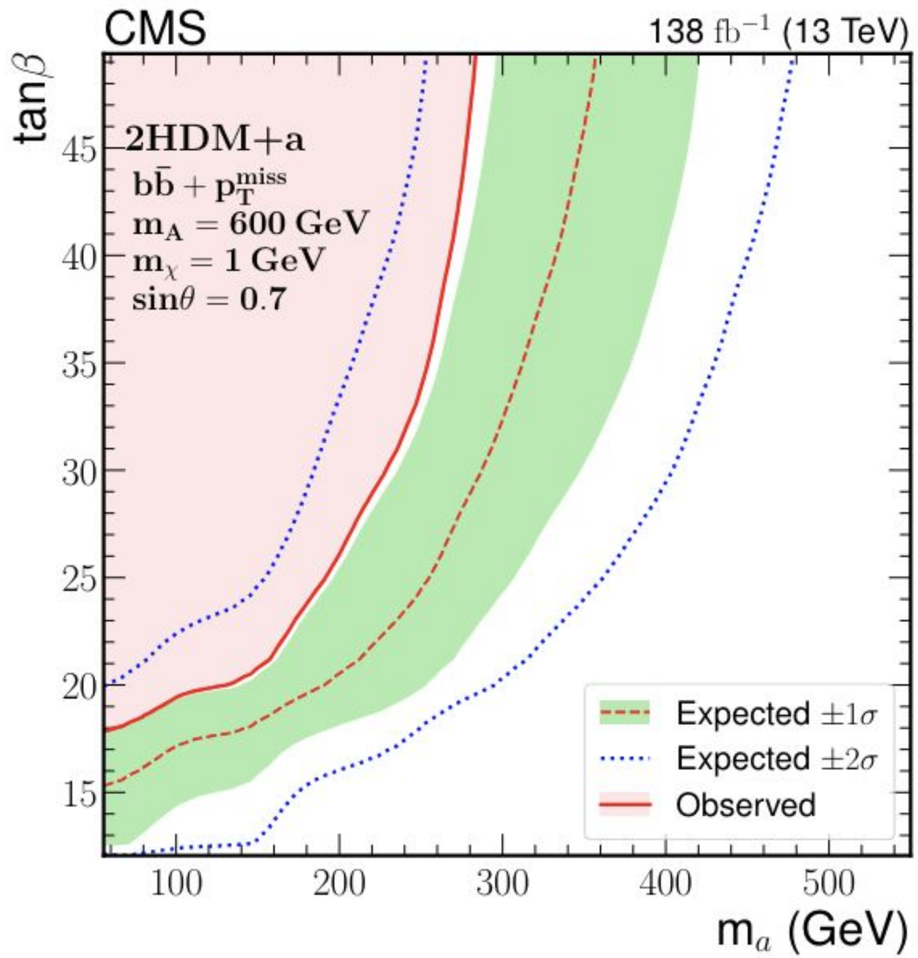
SR2: At least 2 jets
Z(ll) CR: OSSF leptons, $70 < M_{ll} < 110$, Recoil > 250 GeV
tt(lν) CR: Single lepton, $M_T < 160$, Recoil > 250 GeV

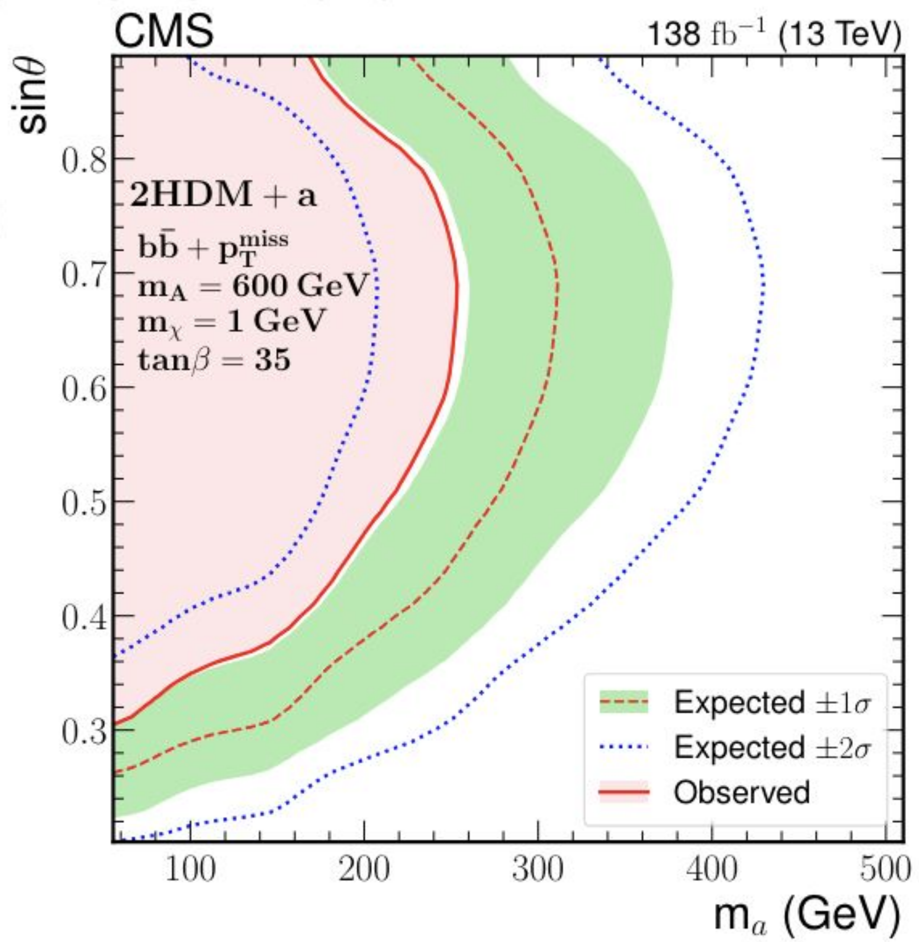




Dark Matter with bottoms

No excess observed. Limits set on
ma and the ratio of the vevs of the two Higgs doublets, tan β
ma and the mixing angle between the pseudoscalars (θ)





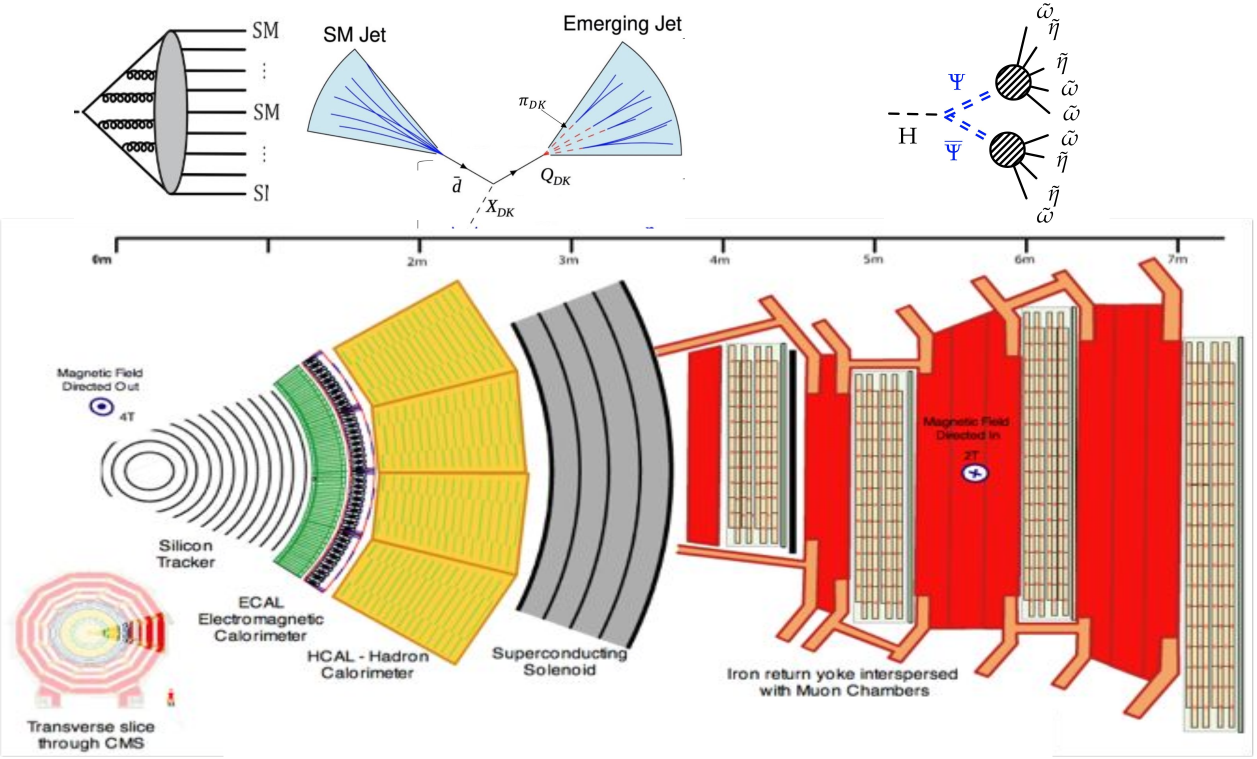
2894114

CMS continues to probe dark sector models with traditional objects:

1) Dark Higgs → MET and Ws
2) 2HDM → MET with b-tagged jets

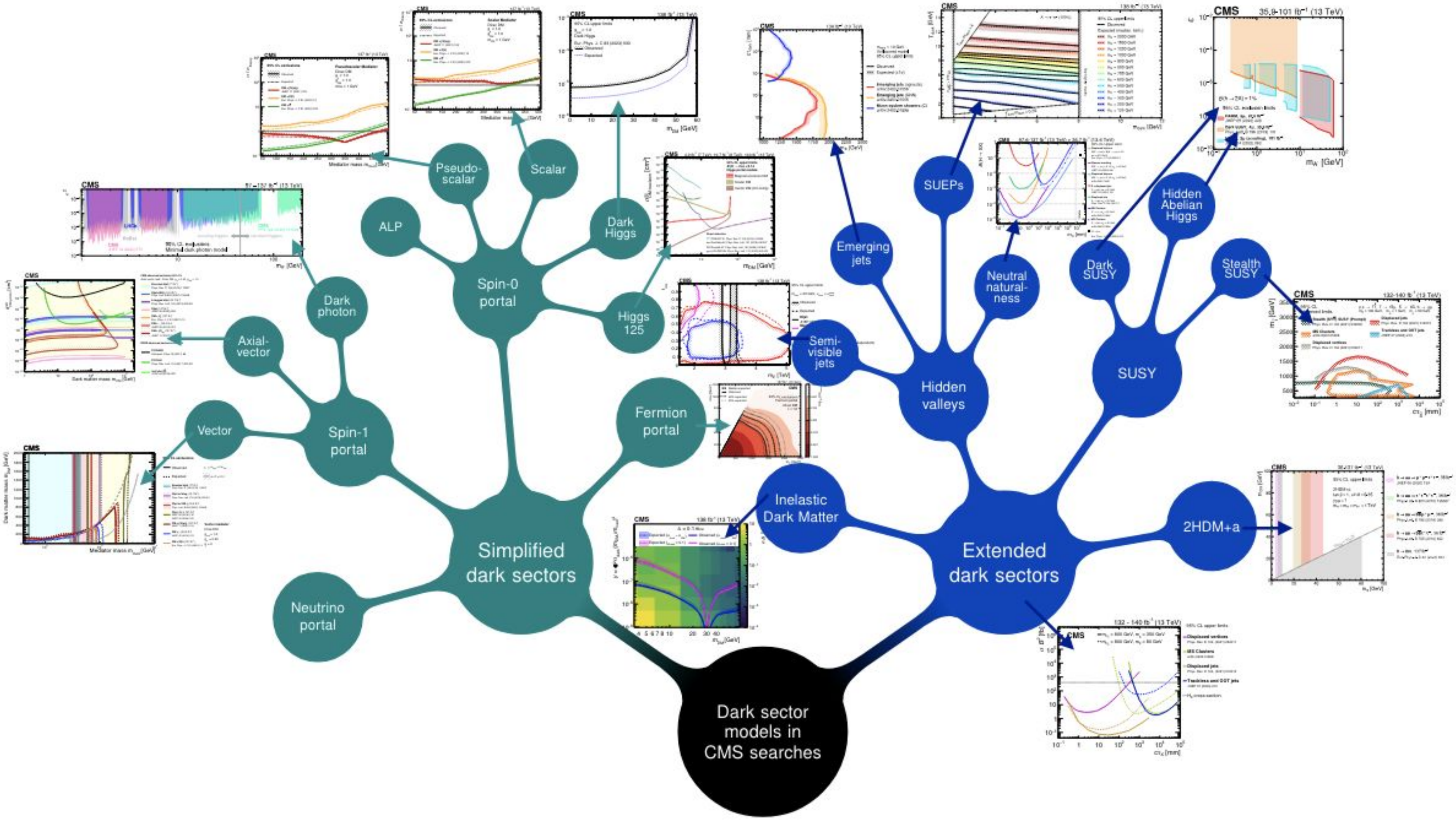
CMS has also grown a program looking for nontraditional objects (lifetimes):

3) SUEPs → Wide jets with large number of soft particles (prompt)
4) Emerging Jets → Jets with track displacement (cτ~100s mm)
5) Showers in the muon system → No associated tracks/muons (cτ~meters)



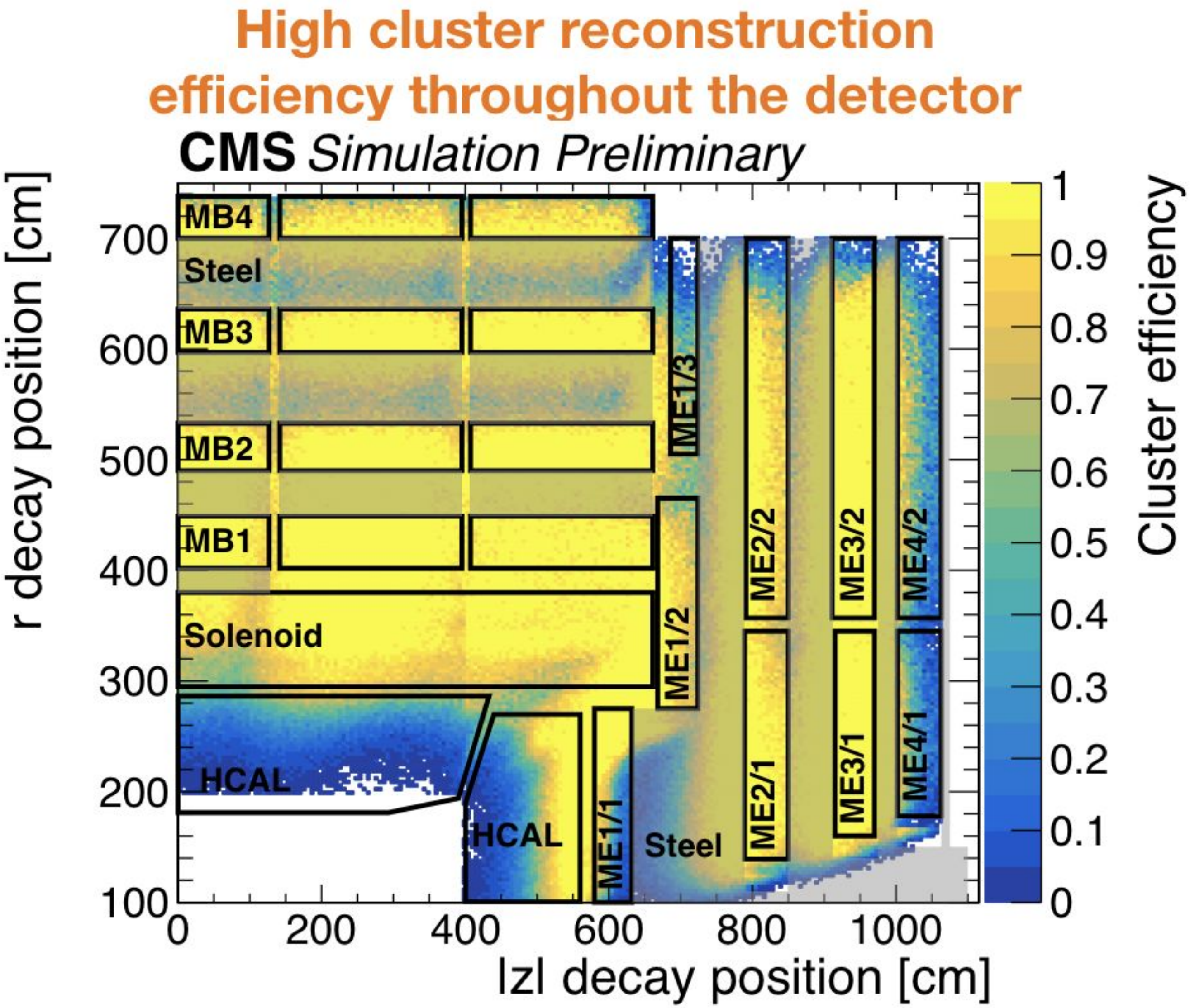
Backup

Dark Sector

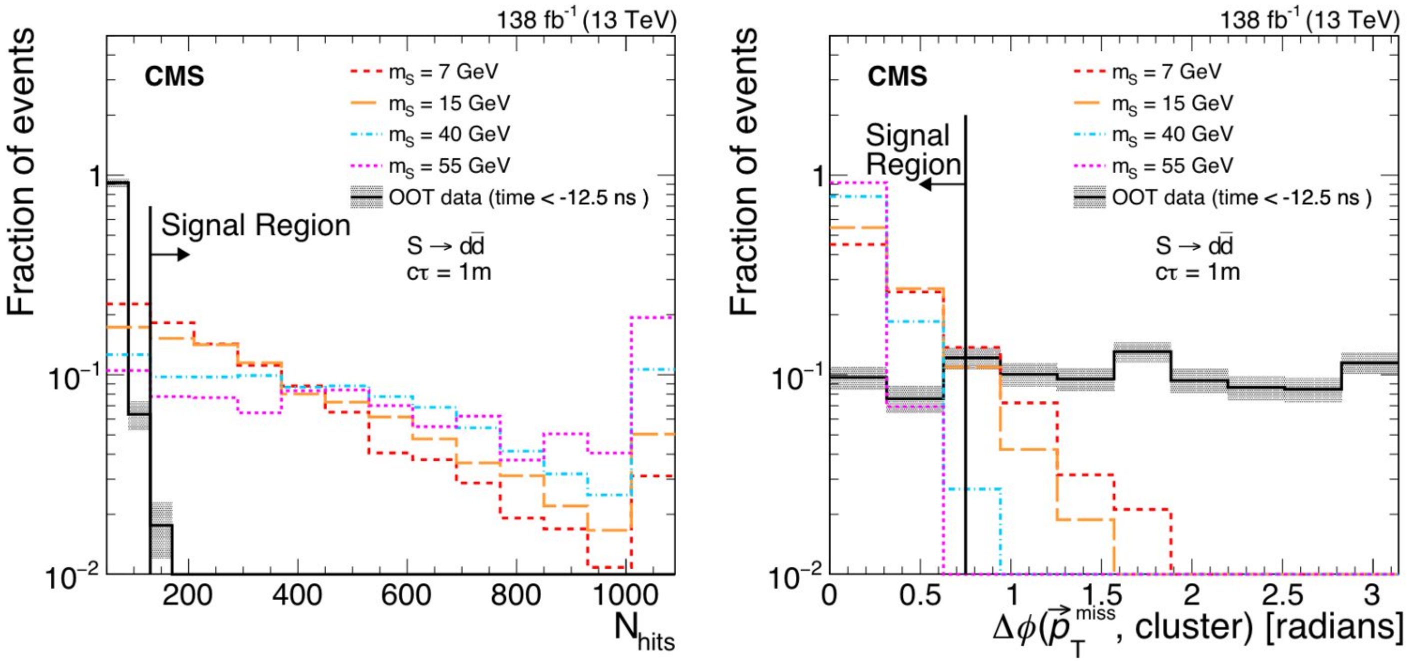


Dark sector models in CMS searches
Simplified dark sectors
Extended dark sectors
Neutrino portal
Spin-1 portal
Spin-0 portal
Fermion portal
Vector
Axial-vector
Dark photon
ALP
Pseudo-scalar
Scalar
Dark Higgs
Higgs 125
Inelastic Dark Matter
Semi-visible jets
Hidden valleys
Emerging jets
SUEPs
Neutral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

Muon Cluster Efficiency



Muon Cluster



Paper

N_{hits} > 130

- Main discriminator against background

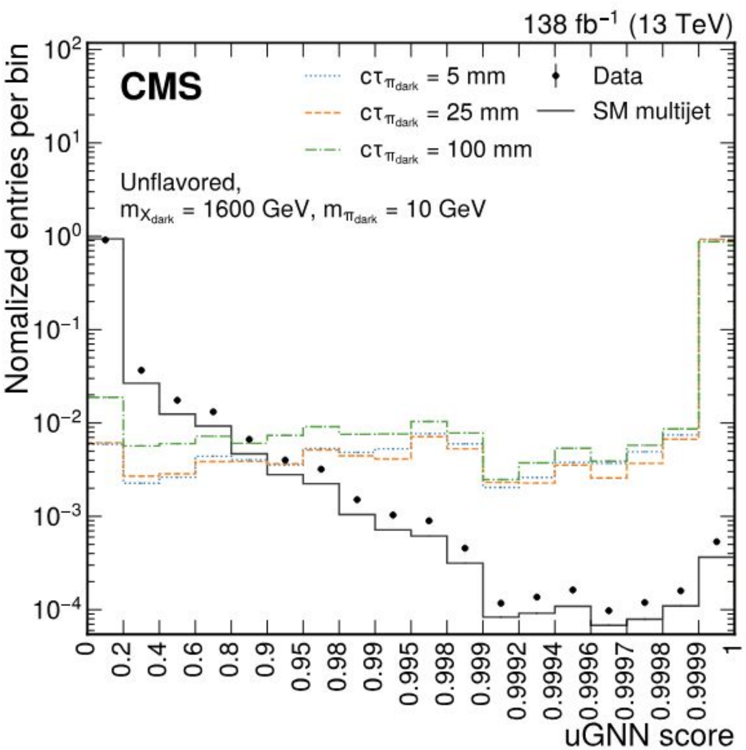
$\Delta\phi(\vec{p}_T^{miss}, \text{cluster}) < 0.75$

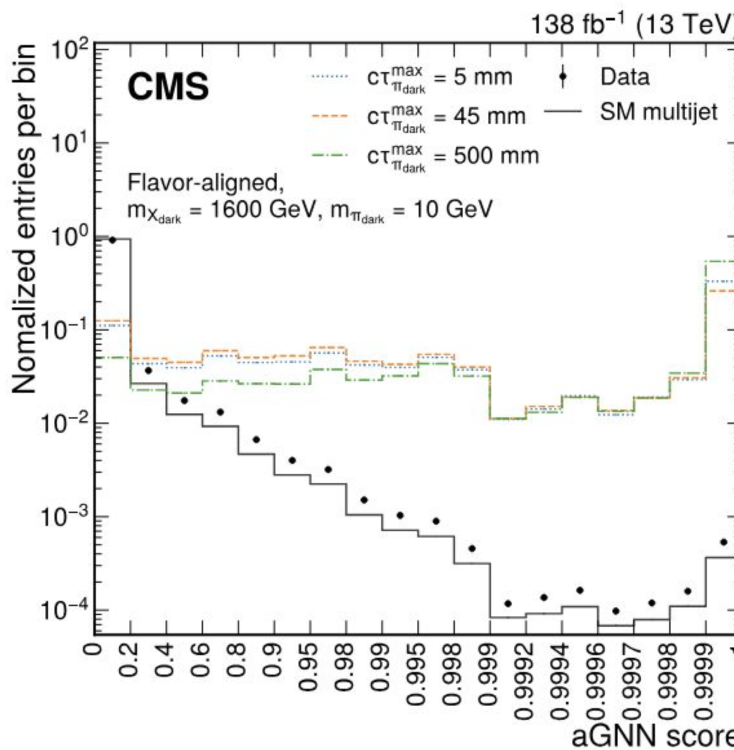
- Provides additional discrimination, and provides a variable that's independent of N_{hits} for the ABCD method
- For signal, MET and cluster are aligned because the LLP p_T is responsible for the MET

EMJ

- $\Delta R(\text{track}, \text{jet})$, as particles in EJs tend to have a wider angular separation than in the SM jets because of the heaviness of the dark mesons.
- $\ln(p_{\mathrm{T}}^{\text{track}}/1\,\text{GeV})$, $\ln(p_{\mathrm{T}}^{\text{track}}/\sum_i p_{\mathrm{T}}^{i})$, as the combination of the dark shower and the decay of the mesons back to the SM sector causes the p_{T} of tracks to be smaller on average for EJs than for SM jets.
- $T(d_{xy})$, $T(d_z)$. The transformation function $T(x)$ is applied to the track displacement variables, to reduce the range of values input to the GNN while preserving the variables' sign and continuity. It is defined as:

$$T(x) = \text{sign}(x) \ln \left(\left| \frac{x}{1\,\text{cm}} \right| + 1 \right).$$





Mistag rate scale factor (SF)

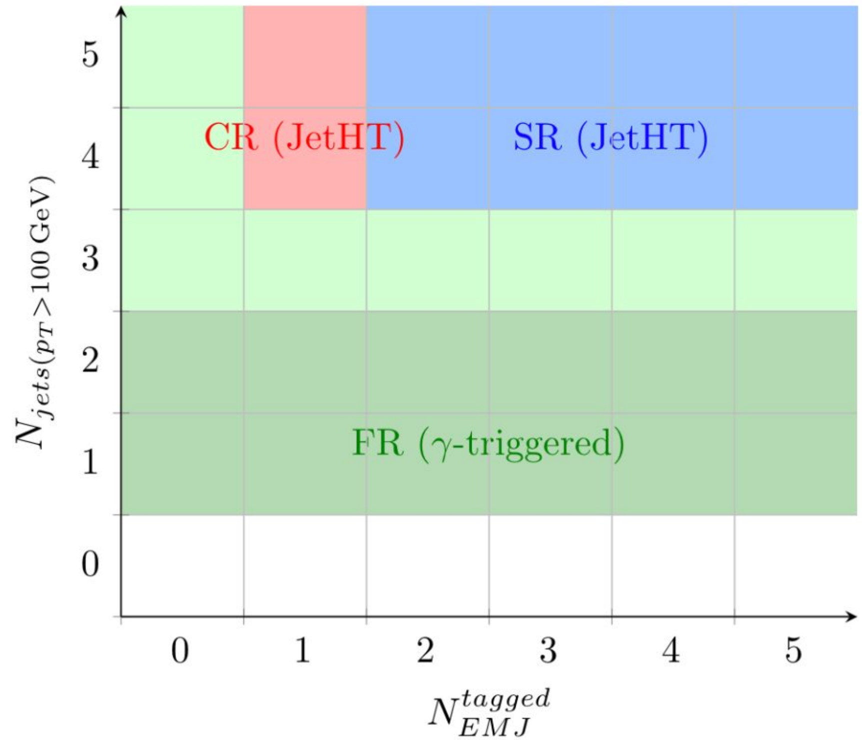
CR = JetHT trigger, $N_{EMJ}^{tagged} = 1$
SR = JetHT trigger, $N_{EMJ}^{tagged} \geq 2$
FR = γ-triggered

Use events in CR with mistag rates (ϵ) from FR to estimate # SM events in SR:

$$N_{SR} = \sum_{evt \in CR, j \in jets} SF_{N_{EMJ} \geq 2}(\epsilon_j)$$

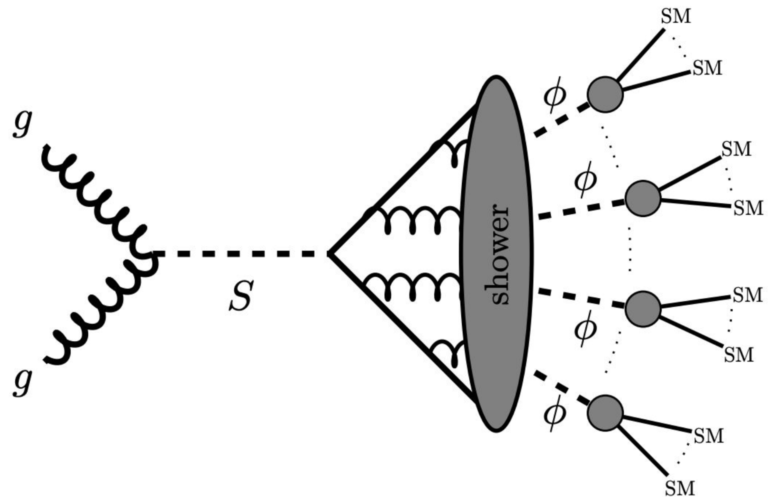
$$N_{SR} \sim \sum_{evt \in CR} \frac{1}{2} \sum_{j \notin tagged} \epsilon(f_j, p_{T,j})$$

SR
CR
FR



Soft Unclustered Energy Pattern (SUEP)

Soft Unclustered Energy Pattern (SUEP):

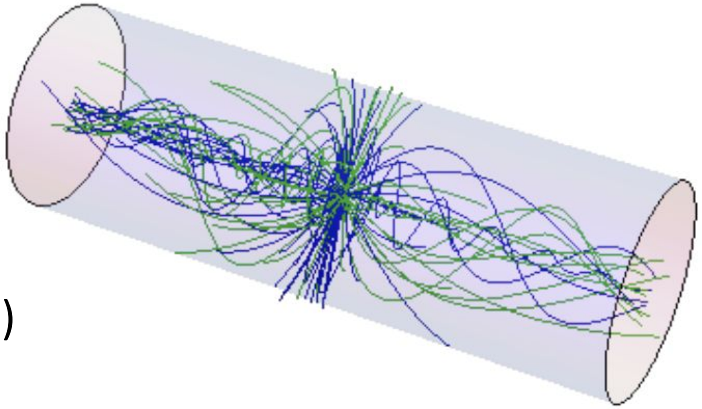


SUEP Model:

1. Rich phenomenology from Hidden Valley models
2. dark QCD scenario with a Heavy Spin-0 state (S)
3. Strongly coupled (large 'tHooft coupling)
4. light pseudoscalar meson(φ)
   - **promptly** decays back into SM particles

SUEP Signature:

With large 'tHooft coupling, dark QCD is no longer predominantly soft and co-linear, but leads to large angle, high p_T radiation



1. High multiplicity of low p_T tracks
2. Spherically-symmetric, soft spray of particles at

the bottom of the hidden valley spectrum. ("soft bomb")

3. case for a "Higgs-bomb" with m_S=125 GeV

https://arxiv.org/abs/1612.00850

Temperature

Parameter variations:

m_φ and T should be varied in addition to mS

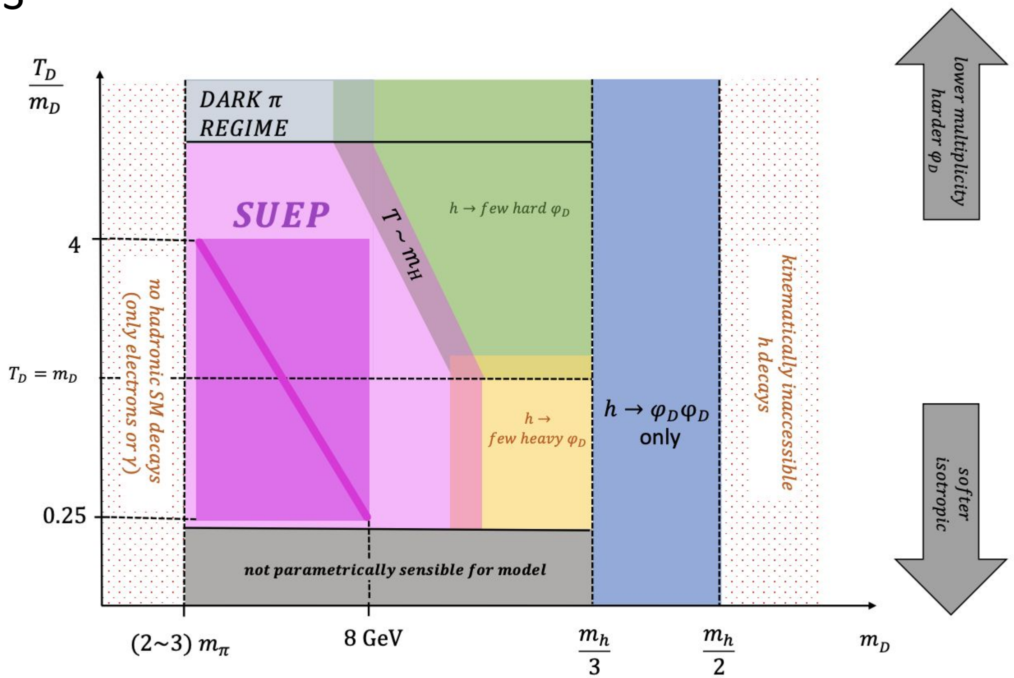
- Be careful to stay in a SUEP regime
- Restrict T/m_φ to [¼-4]
- Thermal approximation breaks (Green)
- Higgs decay to a few resonances (Orange and Green)

Plan to vary m_φ and T/m_φ:

Low m_φ constrained by m_A

m_φ : [1 ($2m_A$), 2, 3, 4]

T/m_φ :[0.25, 0.5, 1, 2, 4]



https://arxiv.org/pdf/2107.12379

2HDM

Z+Jets and W+Jets (tt) have the largest contribution in the 1b (2b) SR
Linking SR and CR through rataParam will all the systematics taken as nuisance parameters
One rateParam for each bin and for each region
A simultaneous binned profile likelihood fit is performed in Signal and Control Region