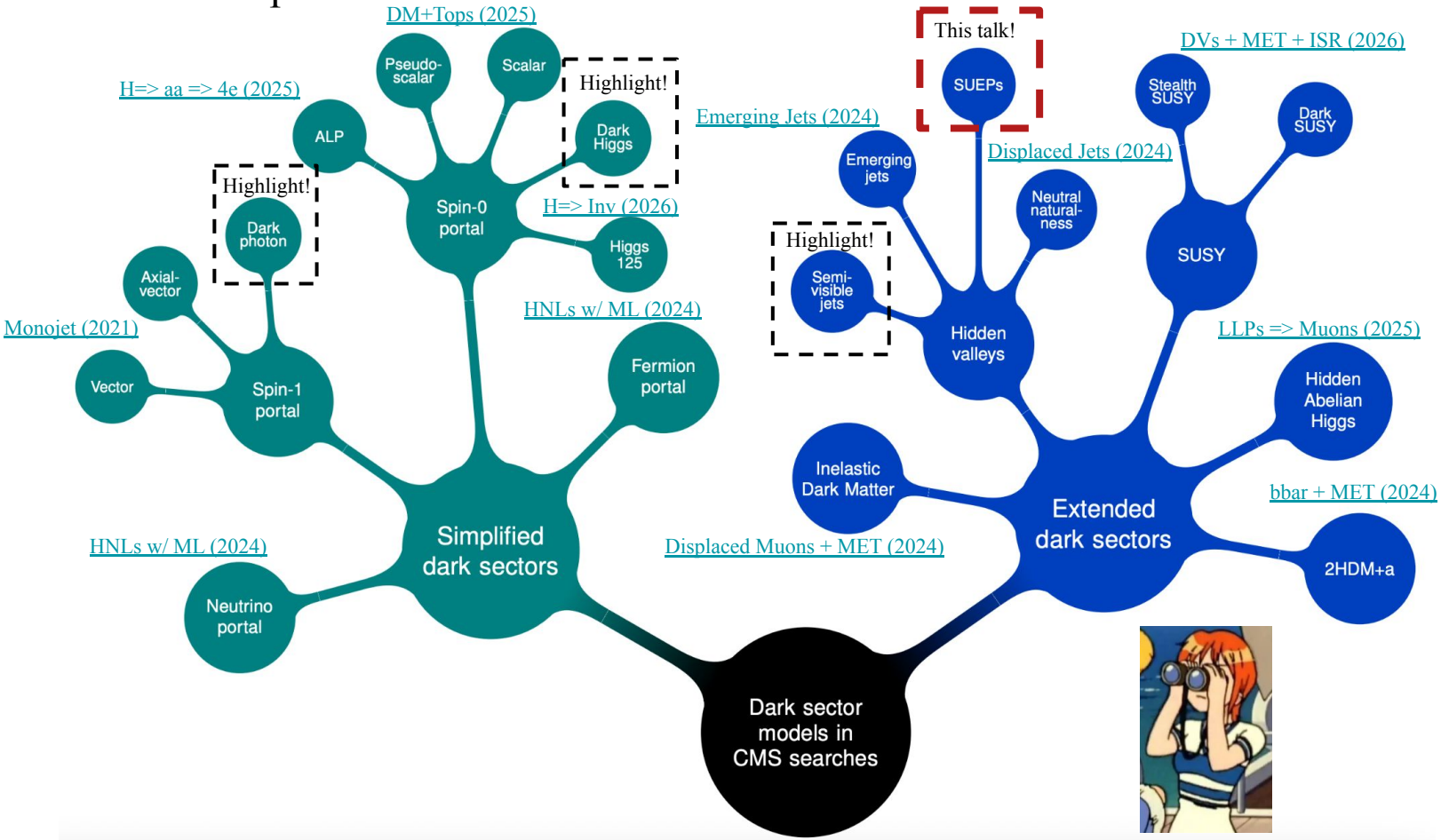
Searches for Dark Sector Signatures with CMS

Gianfranco de Castro (Cornell) *on behalf of the CMS Collaboration*

PHENO Symposium - 5/12/26

Dark Sector Landscape in CMS

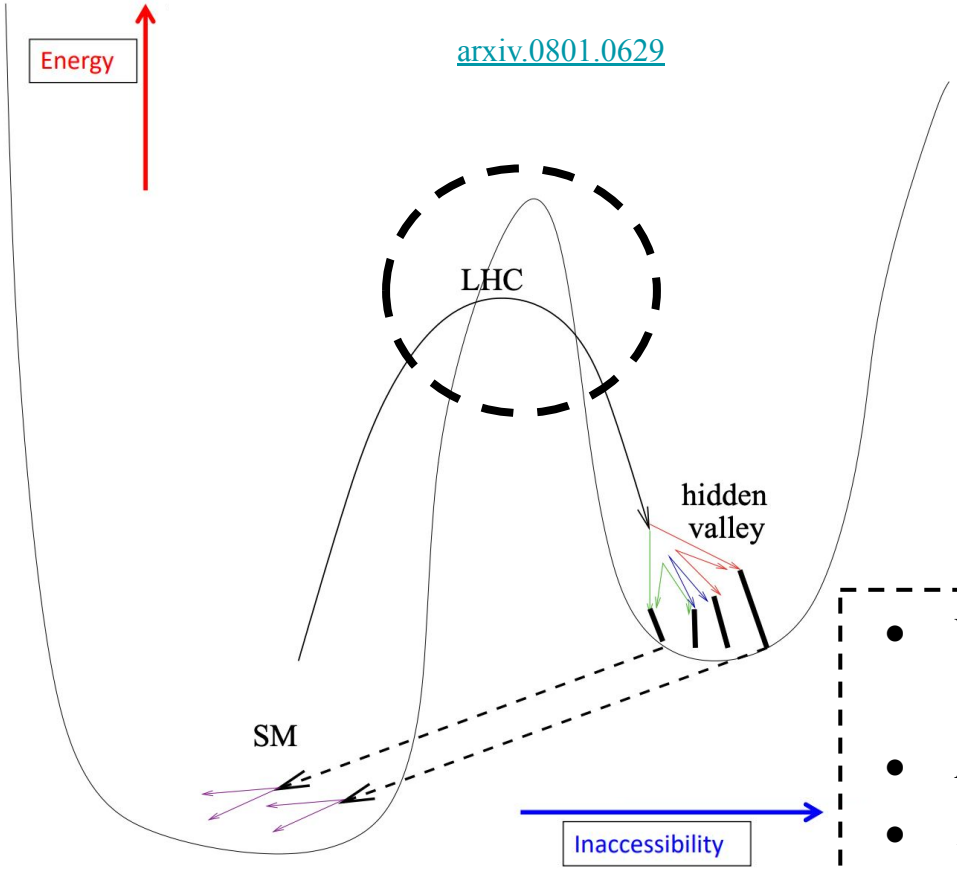
arxiv.2405.13778



Soft Unclustered Energy Patterns (SUEPs)

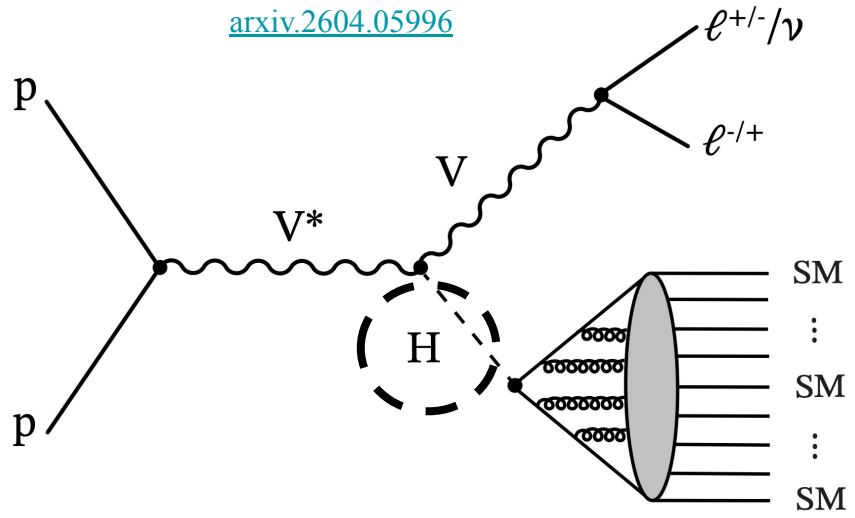
Gluon Fusion (ggF) - arxiv.2403.05311 (2024)
ggF Scouting - CMS PAS EXO-23-001 (2026) **NEW!**
Associated Production (VH) - arxiv.2604.05996 (2026) **NEW!**

SUEPs: Entering the Hidden Valley



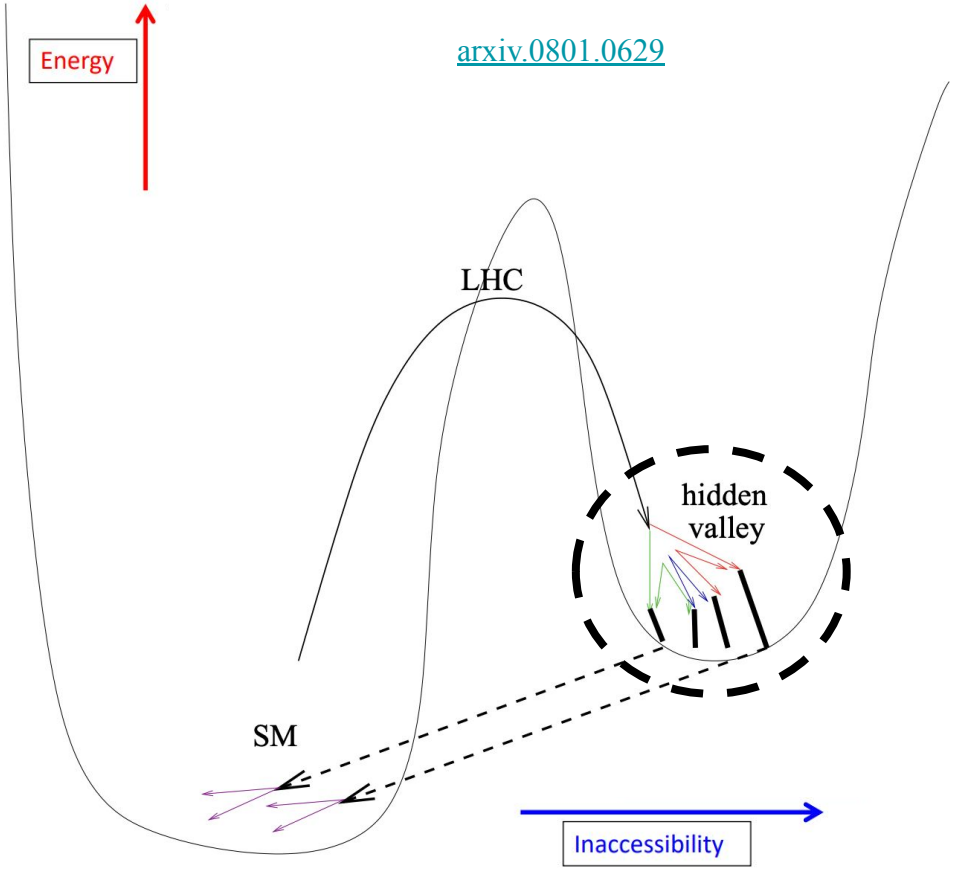
arxiv.0801.0629

arxiv.2604.05996



- We need a scalar mediator…
  - Let's choose something "Higgs-like"!
- Access to Higgs production modes: ggH, VBF, VH, ttH
- ***Trigger on the event's leptonic/hadronic activity***

SUEPs: Inside the Hidden Valley



arxiv.0801.0629

SUEPs

Isotropic distribution

$$\lambda = g_D N_c^D >> 1$$

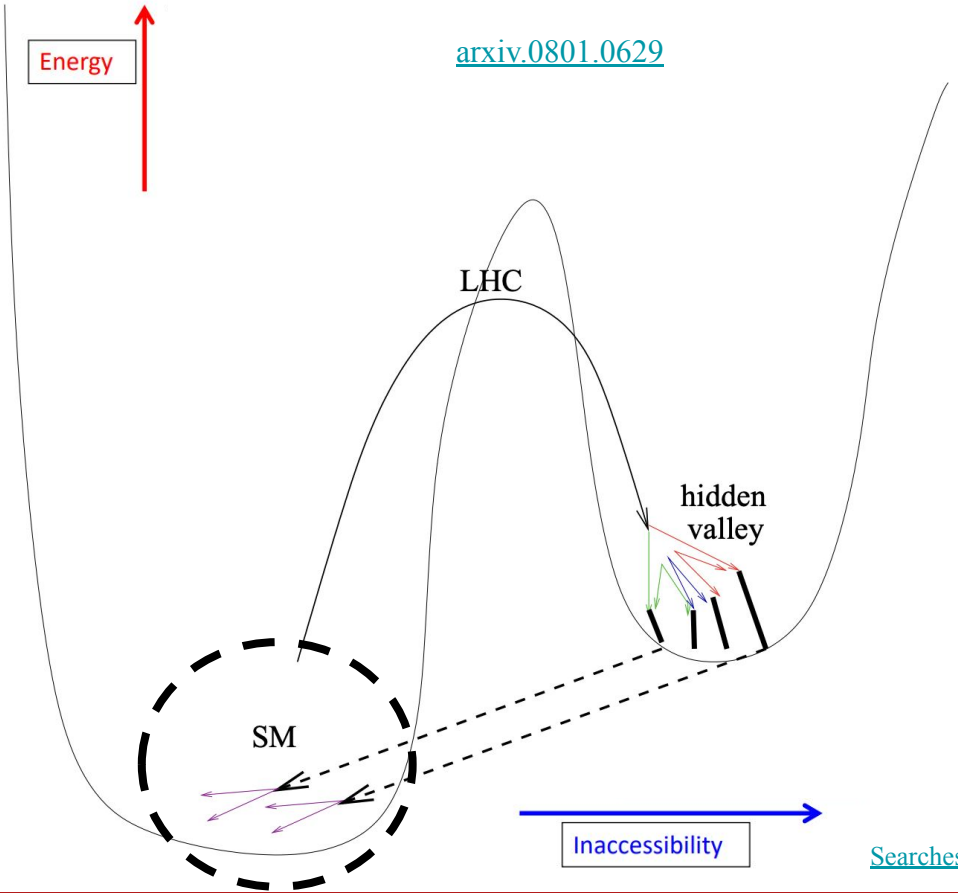
High Multiplicity

$$\langle n \rangle \approx \frac{m_s}{m_D}$$

Soft particles

$$\frac{dN}{d^3\mathbf{p}} \sim \exp[-\frac{\sqrt{\mathbf{p}^2 + m_D^2}}{T_D}]$$

SUEPs: Back to the SM



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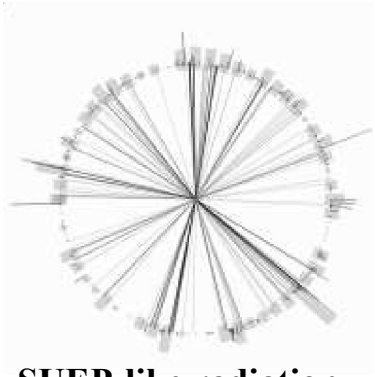
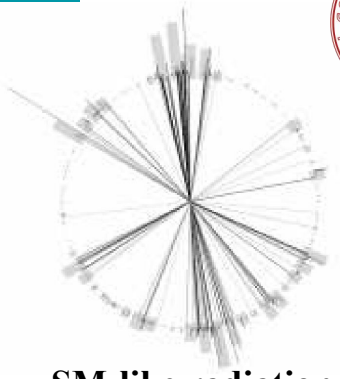
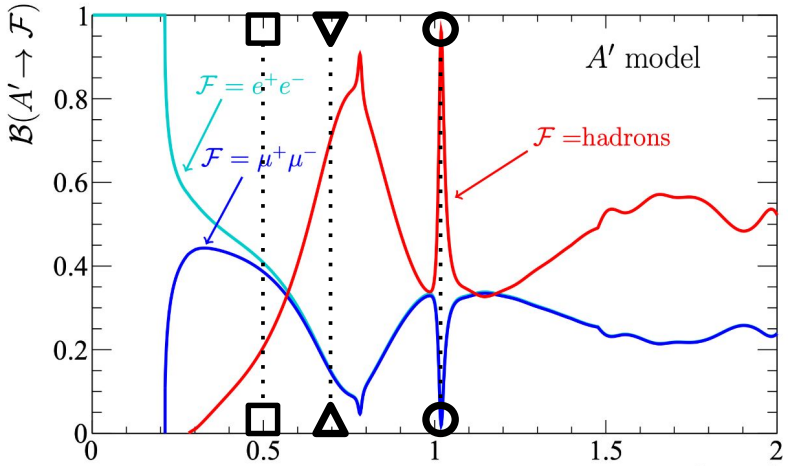


SUEP-like radiation



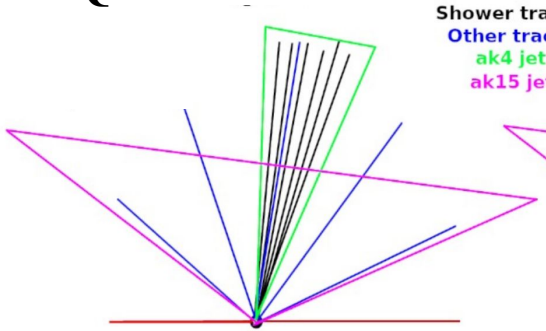
SM-like radiation



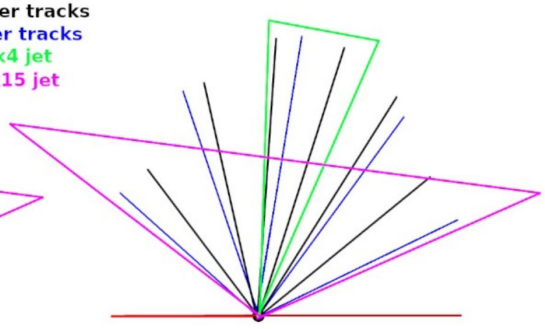
Searches for dark photons at accelerators, arxiv.2104.10280, Fig. 2

Reconstructing the SUEP + Background Estimation

QCD Radiation



SUEP



SUEP reconstruction (novel approach)
Use a wide radius (Ak15) jet!

Captures the expected ~isotropic and high track multiplicity topology.

Background estimation (developed in CMS)
Use the extended ABCD method!

Take advantage of the SUEP jet kinematics (track multiplicity, sphericity) to discriminate against background.

$$D = \frac{BC}{A}\ ;\ \mathcal{O}(\Delta^2)$$

$$N_{\mathrm{I}}^{i} = \frac{(N_{\mathrm{F}}^{i})^2}{N_{\mathrm{C}}^{i}} \frac{N_{\mathrm{H}}^2 N_{\mathrm{D}}^2 N_{\mathrm{B}}^2}{N_{\mathrm{G}} N_{\mathrm{A}} N_{\mathrm{E}}^4}\ ;\ \mathcal{O}(\Delta^4)$$

B	D
A	C

Nominal 4-region ABCD method

Mitigate higher order correlations between discriminating variables!

C	F	I
B	E	H
A	D	G

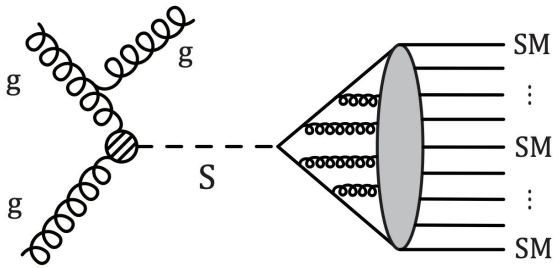
Extended 9-region ABCD method

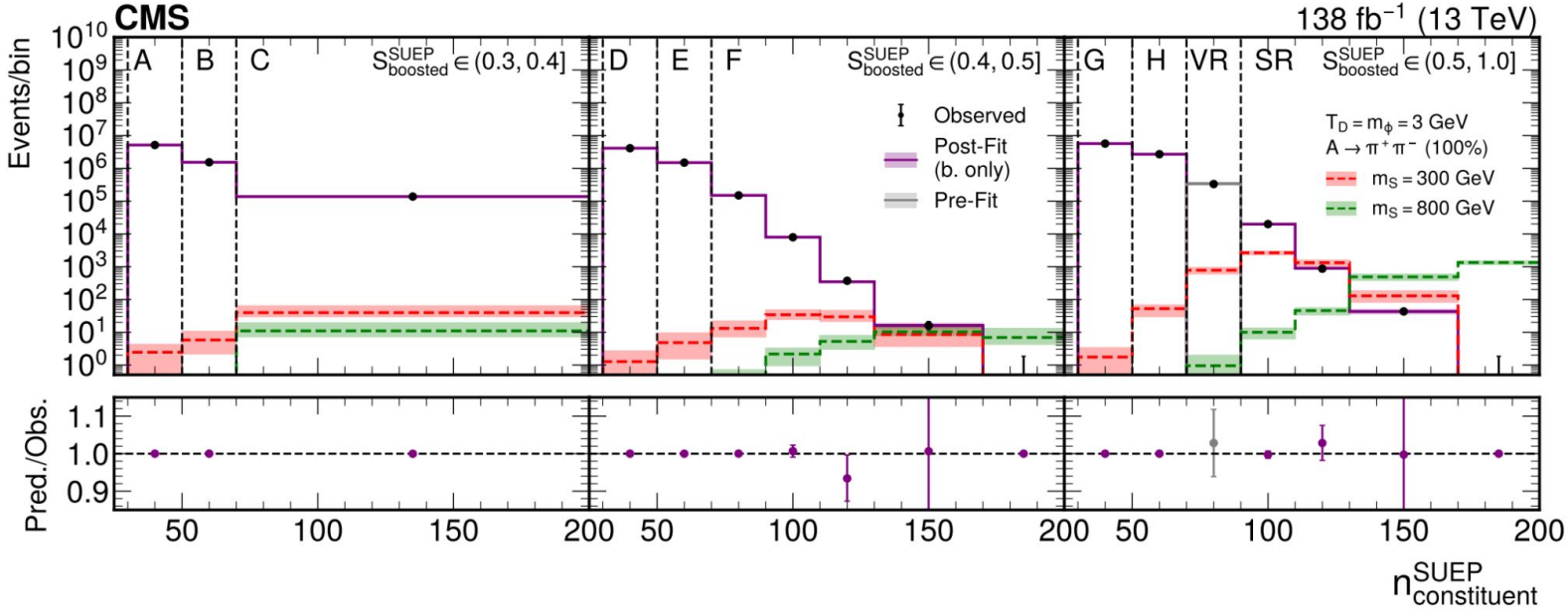
arxiv.1906.10831

Offline Gluon Fusion (Fit)

arxiv.2403.05311

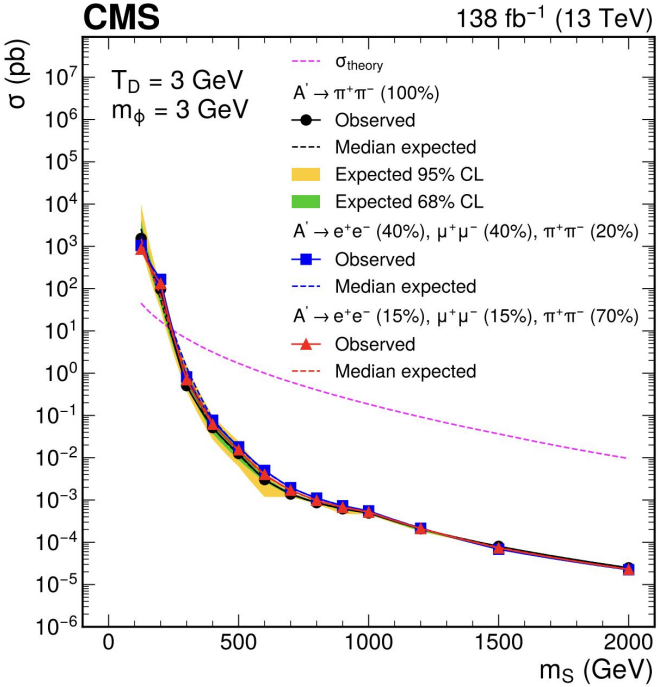
Trigger: Total hadronic activity in the event (HT)
Especially high due to the recoiling ISR jet
Bkg. Estimation: Extended ABCD
Number of SUEP (Ak15) Constituents
Boosted sphericity of the SUEP

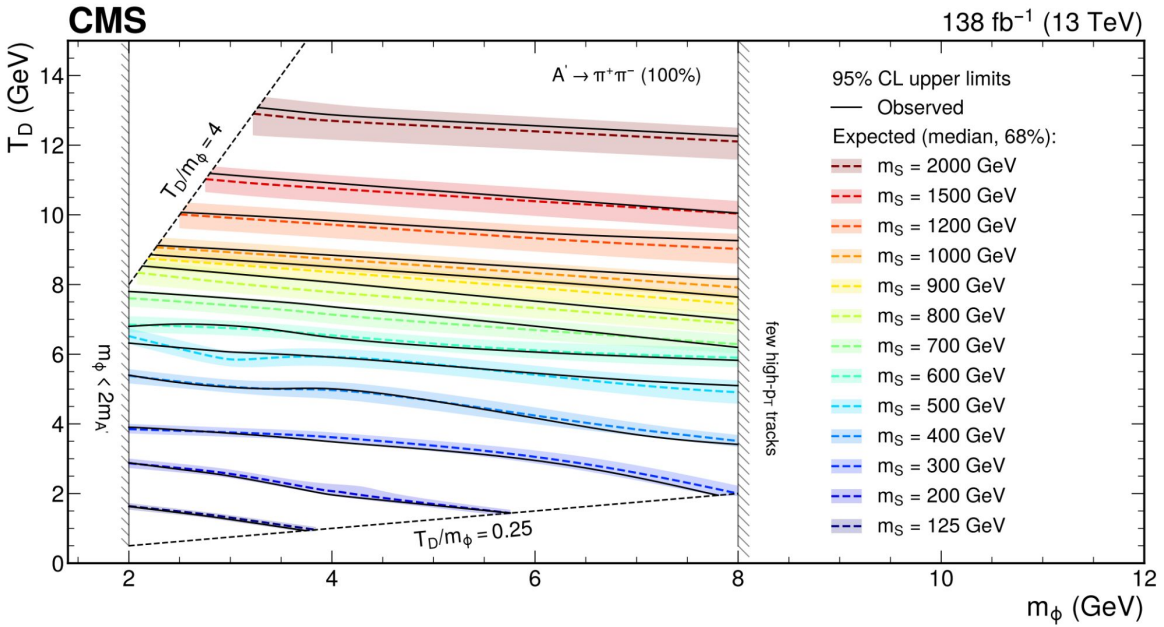




Offline Gluon Fusion (Limits)

arxiv.2403.05311





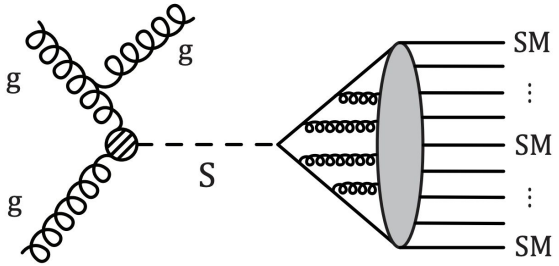
Results are independent of the A' decay mode

Demonstrates strength of the analysis at large mS

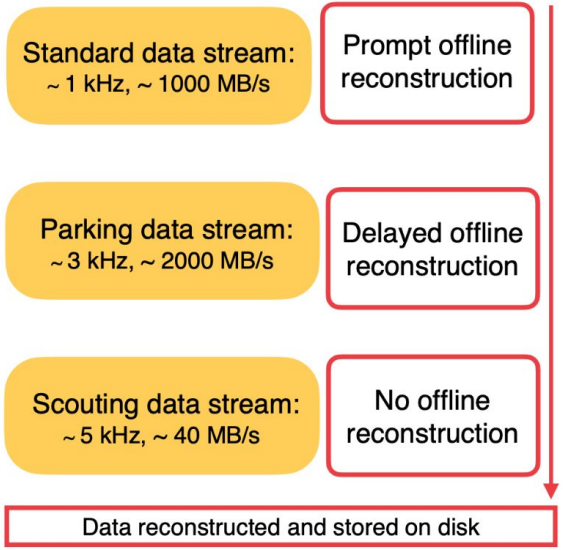
Scouting Gluon Fusion

CMS EXO-23-001 PAS

Trigger: Total hadronic activity in the event (HT)
Probe lower HT thresholds using ***scouting***
Bkg. Estimation: Extended ABCD
Same variables as offline!

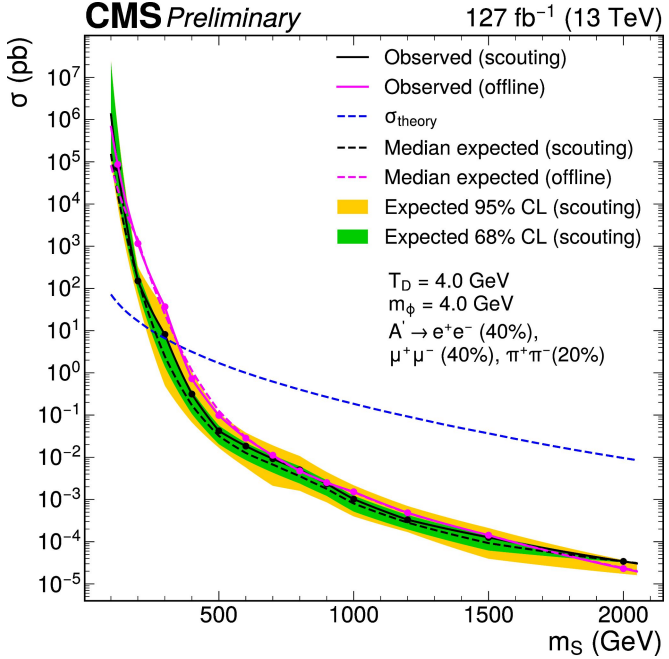


No excess!



Scouting reminder
+ Extremely low thresholds
- At the cost of resolution

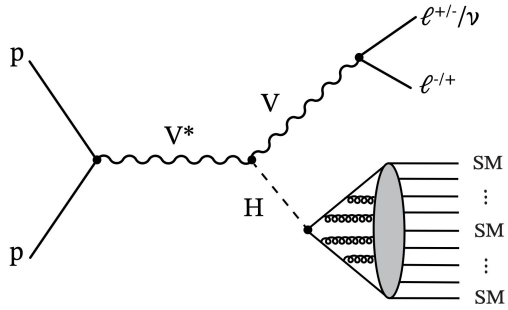
Stronger exclusion than the offline ggF search at low mS!



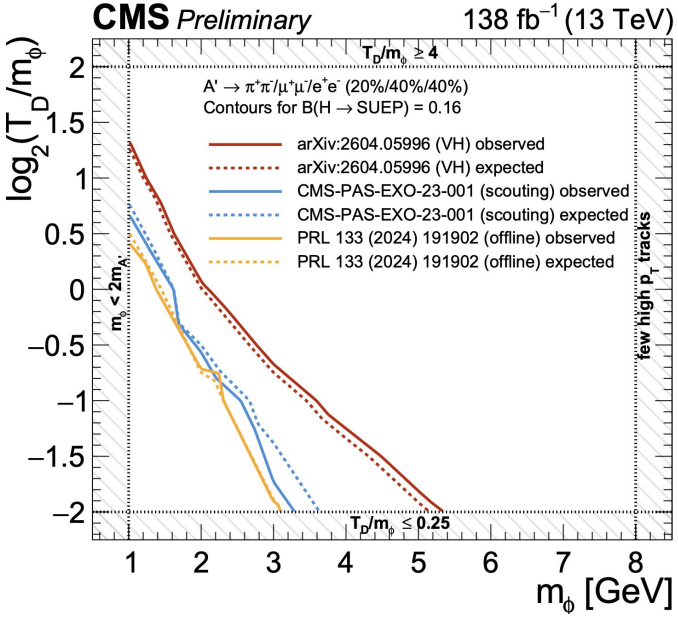
Associated Production (*VH*)

arxiv.2604.05996

Trigger: Lepton from the decay of the boson
Strongest exclusion for mS = 125 GeV
Bkg. Estimation: Extended ABCD
Number of SUEP Constituents (Both)
Boosted sphericity of the SUEP (WH)
pT of the event's leading Ak4 jet (ZH)



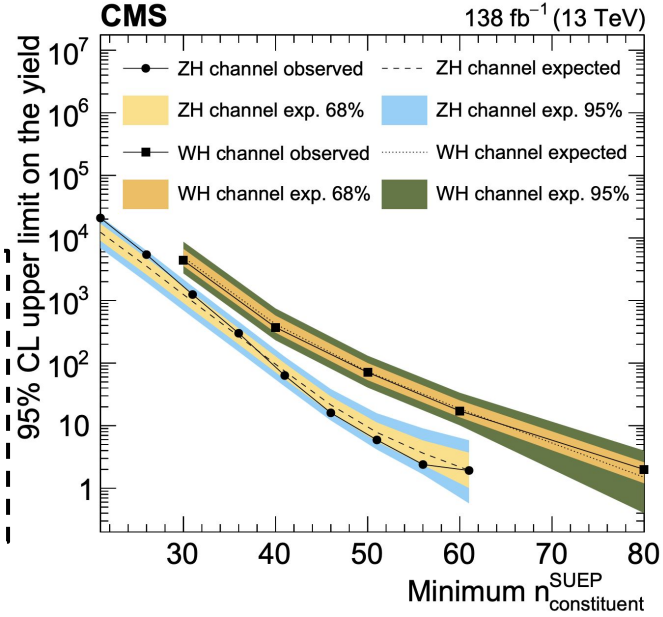
No excess!



Strongest exclusion for mS = 125 GeV

Model agnostic limits on SR yields! Part of released reinterpretation materials!

- ZH
- WH
- VH



Recent CMS Dark Sector Results

SVJs (τ-enriched) - CMS PAS EXO-26-005 (2026) **NEW!**
Dark Higgs + $b\bar{b}$ - arXiv:2604.20999 (2026) **NEW!**
Dark Photon Bremsstrahlung - CMS PAS EXO-23-008 (2026) **NEW!**

τ-enriched SVJs

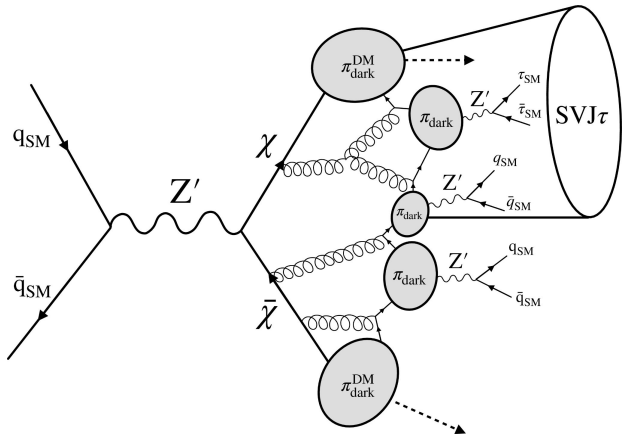
CMS PAS EXO-26-005

Signature: Two broad (Ak8) jets + MET, τ-enriched events

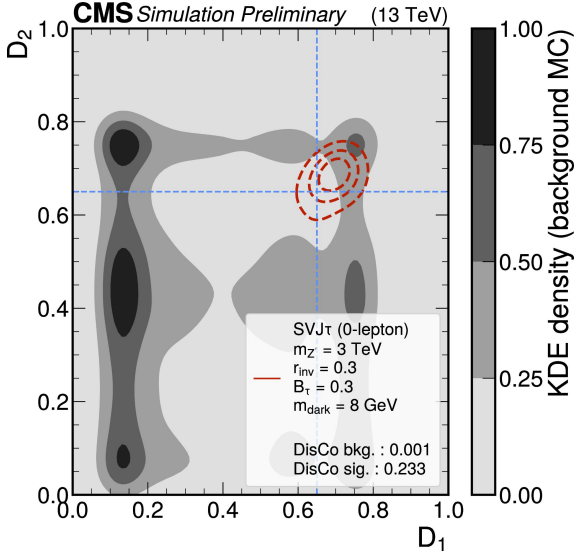
Trigger: Leading jet momentum or HT

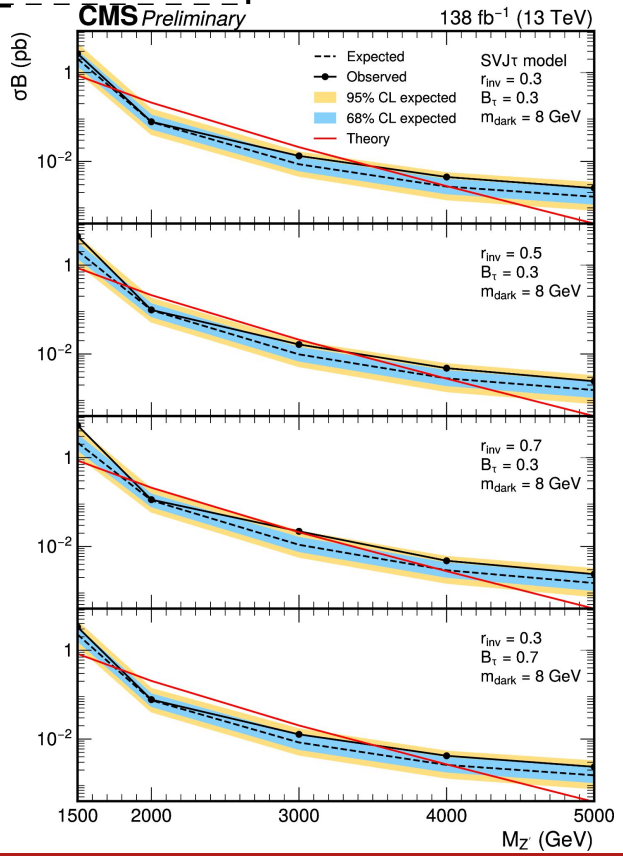
Bkg. Estimation: Apply the ABCD method with variables from MD-ABCDisCoTEC using kinematics and LundNet GNN scores.

No excess!



ABCD-DisCoTec Plane





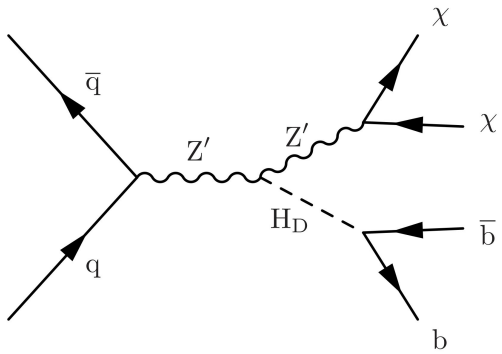
Dark Higgs + $b\bar{b}$

arxiv.2604.20999

Signature: MET + $b\bar{b}$ reconstructed with Ak15 jet

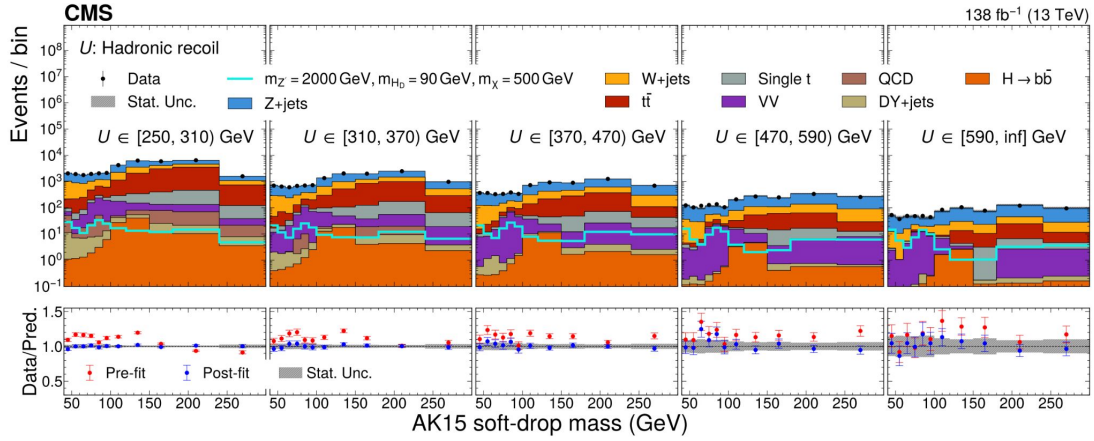
Trigger: MET + missing-HT

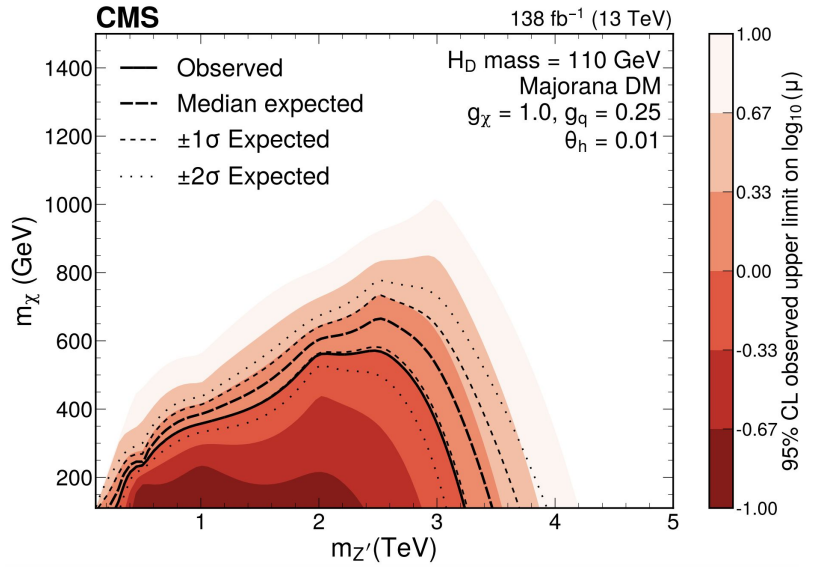
Bkg. Estimation: 2D simultaneous fit in the hadronic recoil (U) and Ak15 soft-drop mass using a signal region and lepton/ttbar-enriched control regions.



No excess!

Pre- and post-fit distribution in the 2D plane of the signal region





Dark Photon Bremsstrahlung

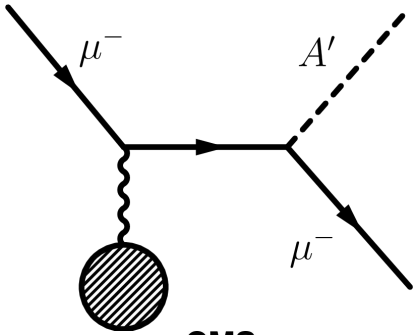
CMS PAS EXO-23-008

Signature: Treat CMS calorimeter endcap as a fixed target - Z=>μμ acts as a muon beam - probe for muon dark brem off calo nuclei

Trigger: A single isolated muon

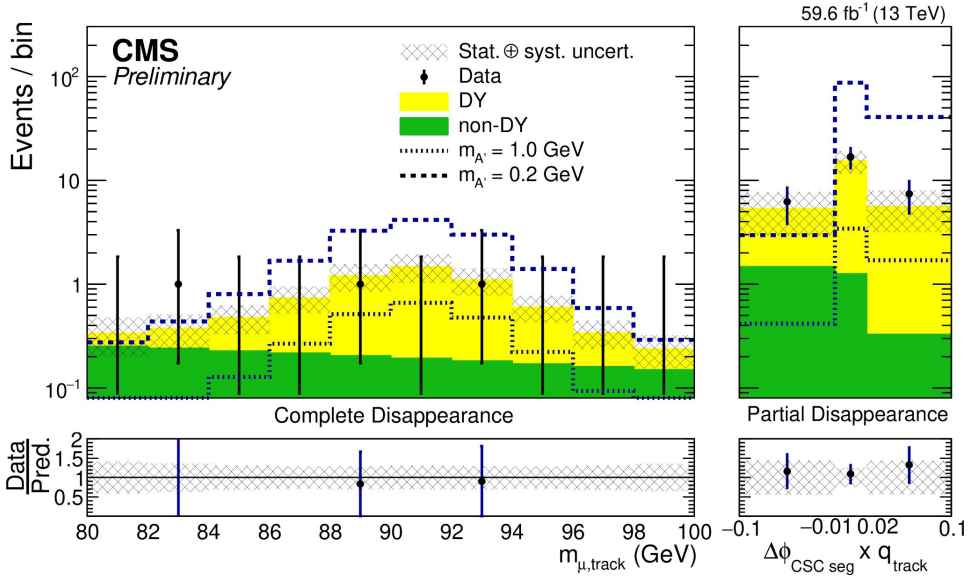
Fit Variables: *Completely missing*: Fit to the Z mass

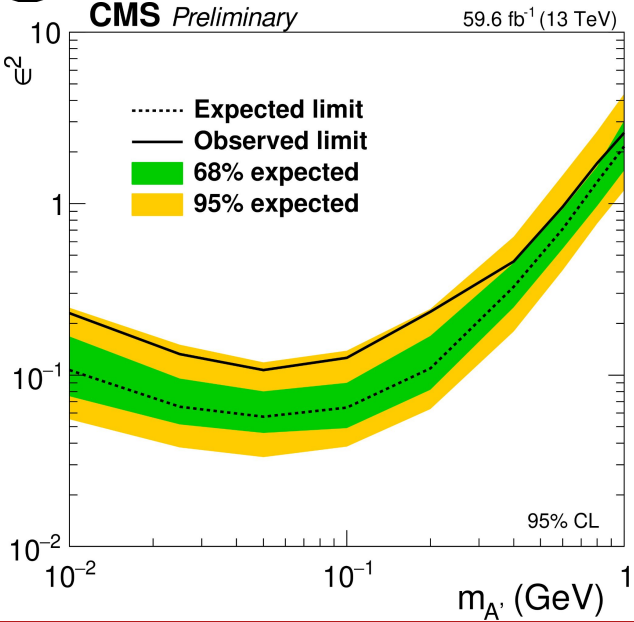
Partially missing: Fit to Δϕ x q



No excess!

Fit variables for data, signal, and background in the two search regions

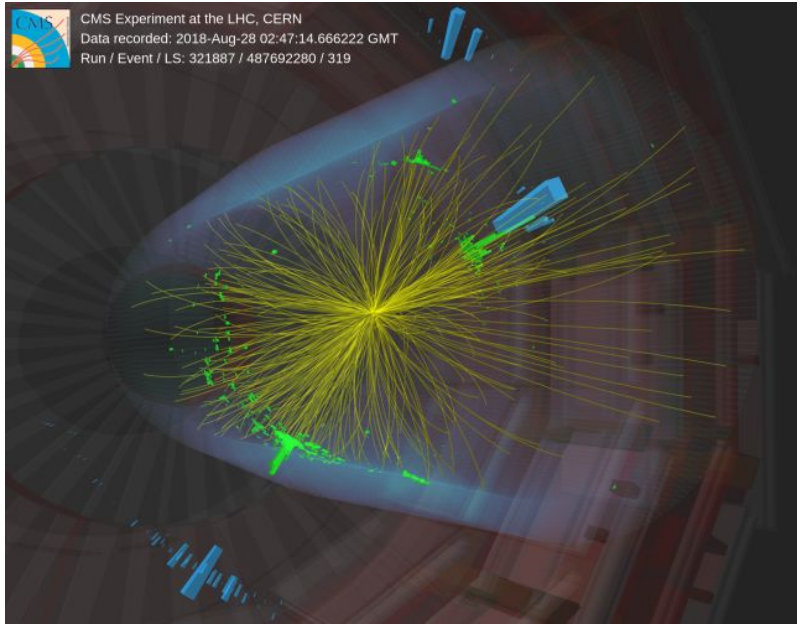




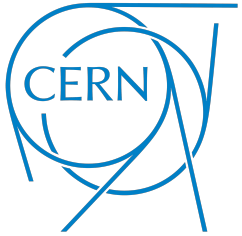
Dark Sectors @ CMS - Summary

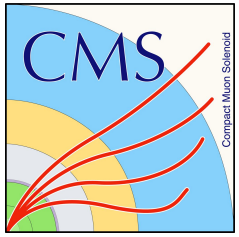
Each analysis pushes a different CMS capability :)

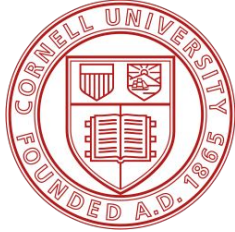
- ***SUEPs:*** Ak15 discriminants + extended ABCD to expose a tricky, PU-like signature
- ***SVJs:*** LundNet GNN tagger + ML-based background estimation using MD-ABCDisCoTEC
- ***Dark Higgs:*** Mass-decorrelated jet tagging + 7-CR likelihood fit to pin down background contributions
- ***Dark Photons:*** Cleverly treat the endcap calorimeters as a fixed-target experiment to search for dark muon brem



A Dark World Ruled by a Strong Force


CERN

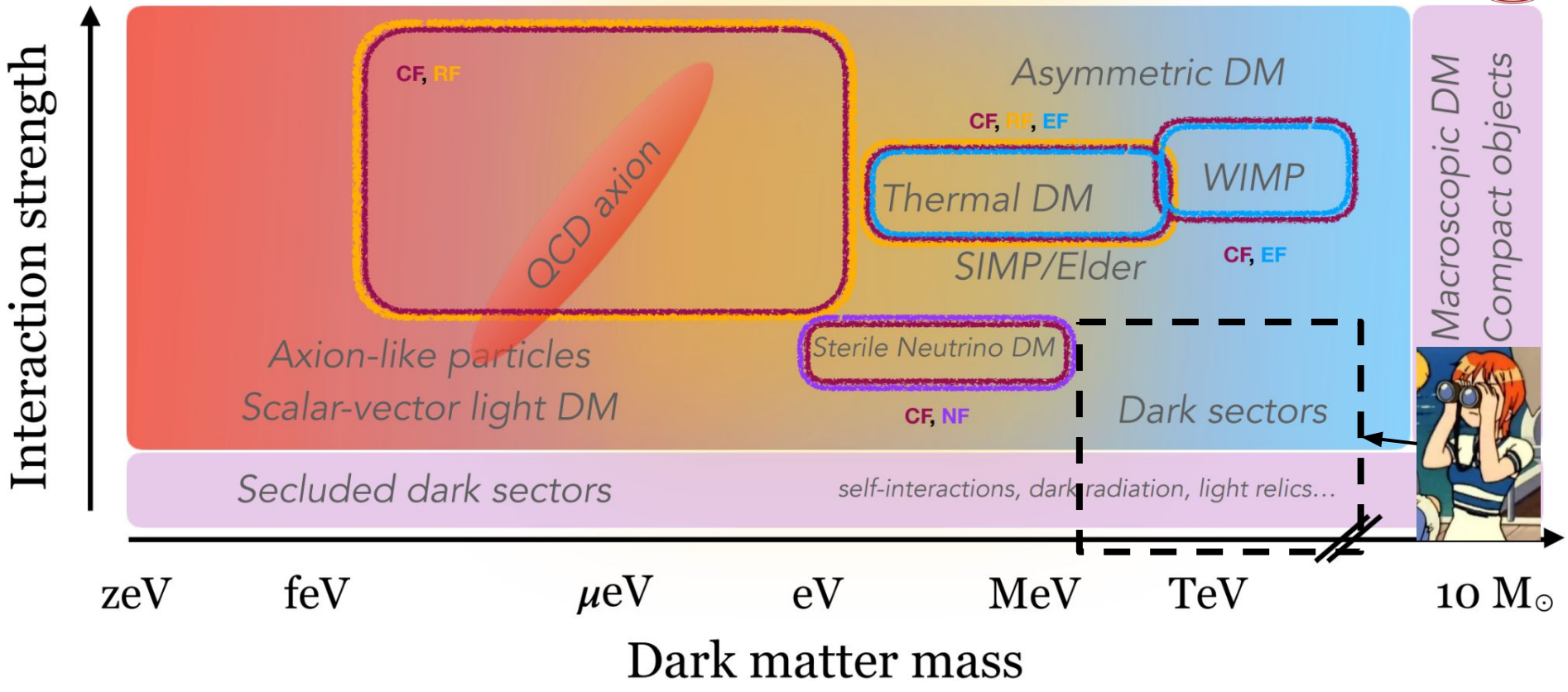

CMS
Compact Muon Solenoid


CORNELL UNIVERSITY
FOUNDED A.D. 1865

Backup!

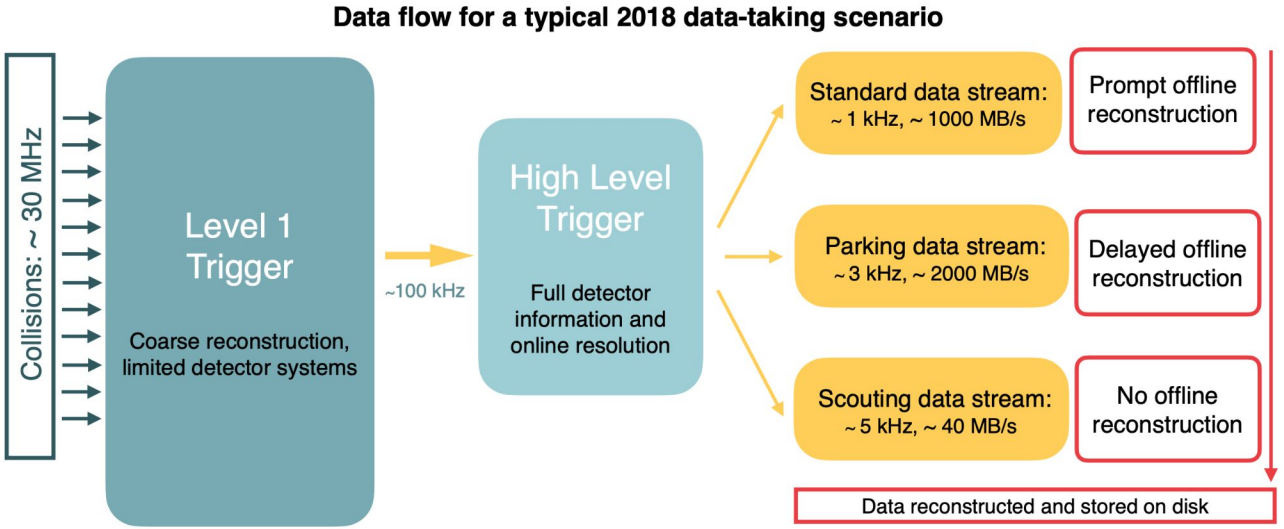
Dark Matter Searches

Snowmass 2021 DM Complementarity Report, arXiv:2210.01770, Fig. 1



CMS Trigger Innovations

Enriching the physics program… arxiv.2403.16134, Fig. 1



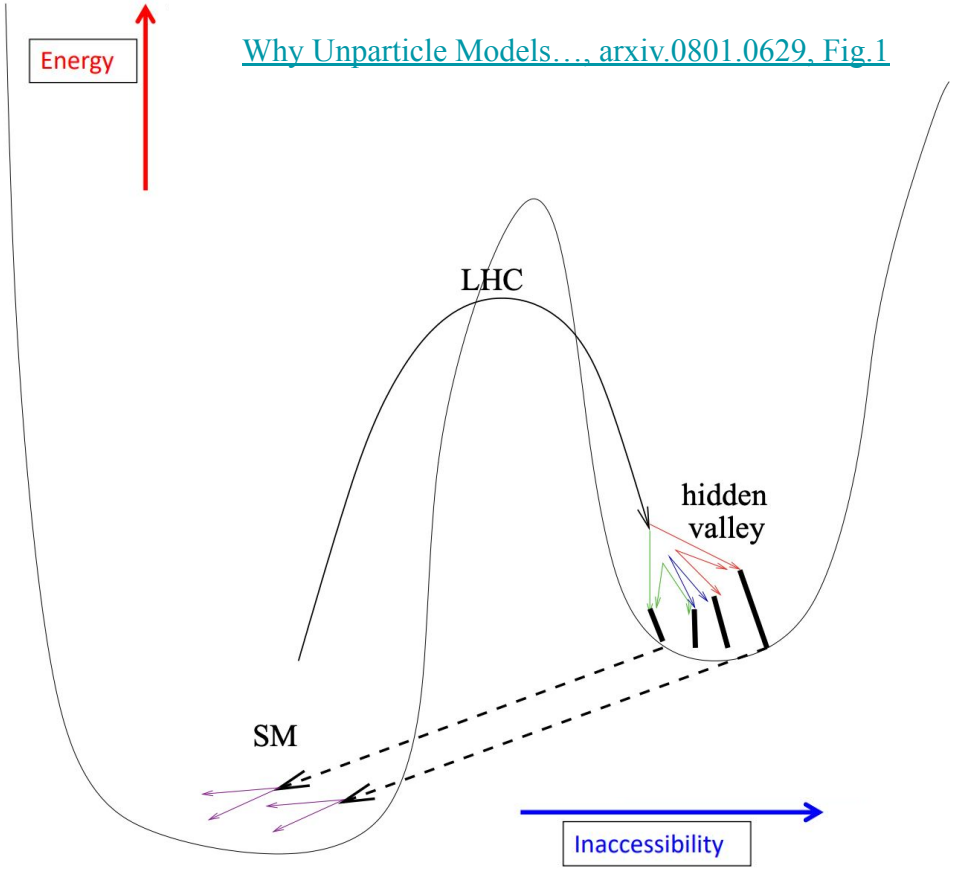
The "*industry standard*"

+ More data, softer objects
- Highly targeted

+ Extremely low thresholds
- At the cost of resolution

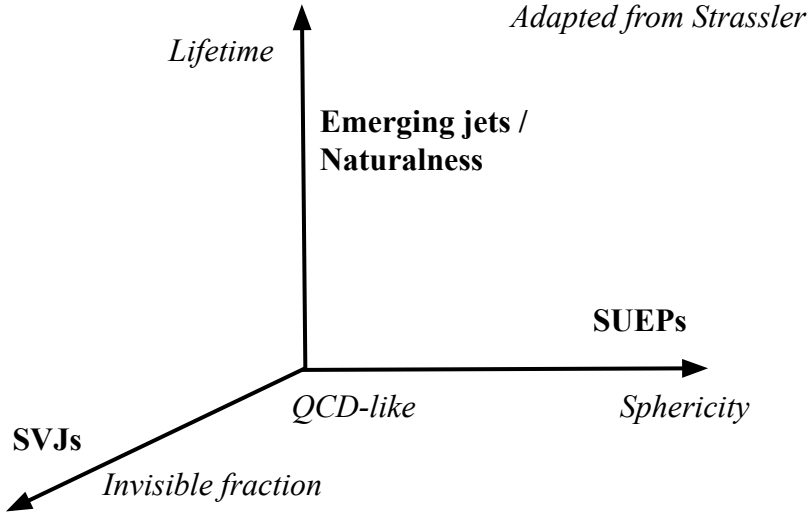
- The image above covers Run 2 (2015-18) innovations!
- Run 3 (2022-26) extends this with more novel triggers…

Hidden Valley Models

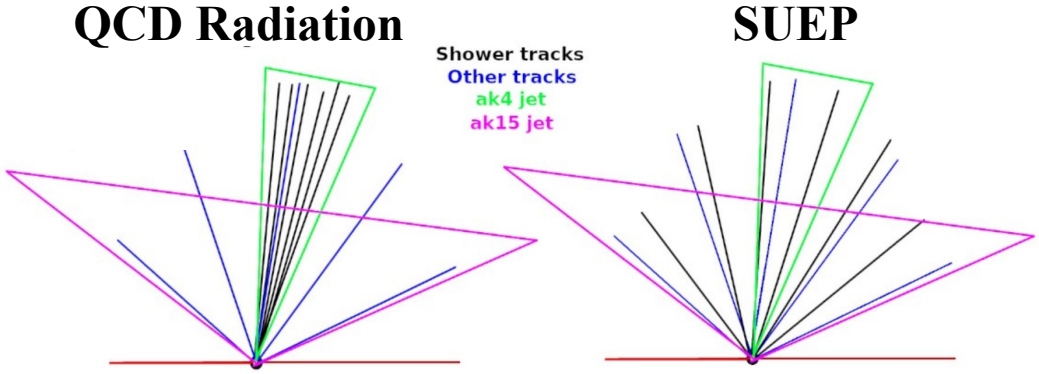


Why Unparticle Models…, arxiv.0801.0629, Fig.1

- Decoupled from SM at low energy => “hidden”
- Portal/mediator bridges the SM and HV at high energies
- Access to rich phenomenology within the HV
  - Potential DM candidates!



SUEP Discriminating Observables



Reconstruct the SUEP using a wide radius (Ak15) jet!

Captures the expected ~isotropic topology.

1. SUEP (Ak15) Track Multiplicity

$$\langle n \rangle \approx \frac{m_s}{m_D}$$

2. SUEP (Ak15) Sphericity Tensor

$$S^{(r)ab} = \frac{\sum_i |\mathbf{p}_i|^{r-2} p_i^a p_i^b}{\sum_i |\mathbf{p}_i|^r}$$

Eigenvalues of sphericity tensor => S $\in$ [0, 1]

$$S^{SUEP}_{boosted} \equiv \frac{3}{2}(\lambda_2 + \lambda_3)$$

3. Jet Behavior

	QCD Radiation	SUEP
Ak4	High pT	Low pT
Ak15	Low NTracks	High NTracks

Sphericity

To quantify isotropy, we boost the Ak15 constituents' momenta to the candidate rest frame and compute the sphericity tensor:

$$S^{(r)ab} = \frac{\sum_i |\mathbf{p}_i|^{r-2} p_i^a p_i^b}{\sum_i |\mathbf{p}_i|^r} \tag{3.3}$$

where $a, b \in \{1, 2, 3\}$ label the spatial components in the SUEP rest frame. The free parameter r controls how strongly high-p_T constituents are weighted in the tensor. We choose $r = 1$, which yields a definition that is (to first order) infrared and collinear safe, i.e. adding an arbitrarily soft particle changes $S^{(1)}$ negligibly, and a strictly collinear splitting of a particle into two daughters leaves the tensor essentially unchanged because their contributions add up to that of the original direction.

Let $\lambda_1 \geq \lambda_2 \geq \lambda_3$ denote the eigenvalues of $S^{(1)}$. We define the boosted-frame sphericity of the SUEP candidate as:

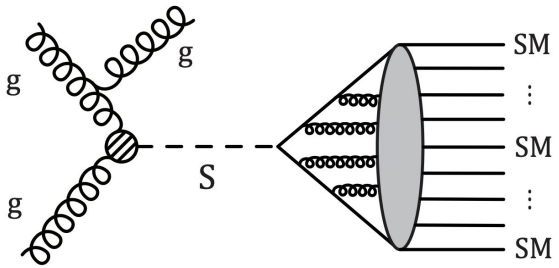
$$S^{SUEP}_{boosted} \equiv \frac{3}{2}(\lambda_2 + \lambda_3) \tag{3.4}$$

Results: Scouting Gluon Fusion (Fit)

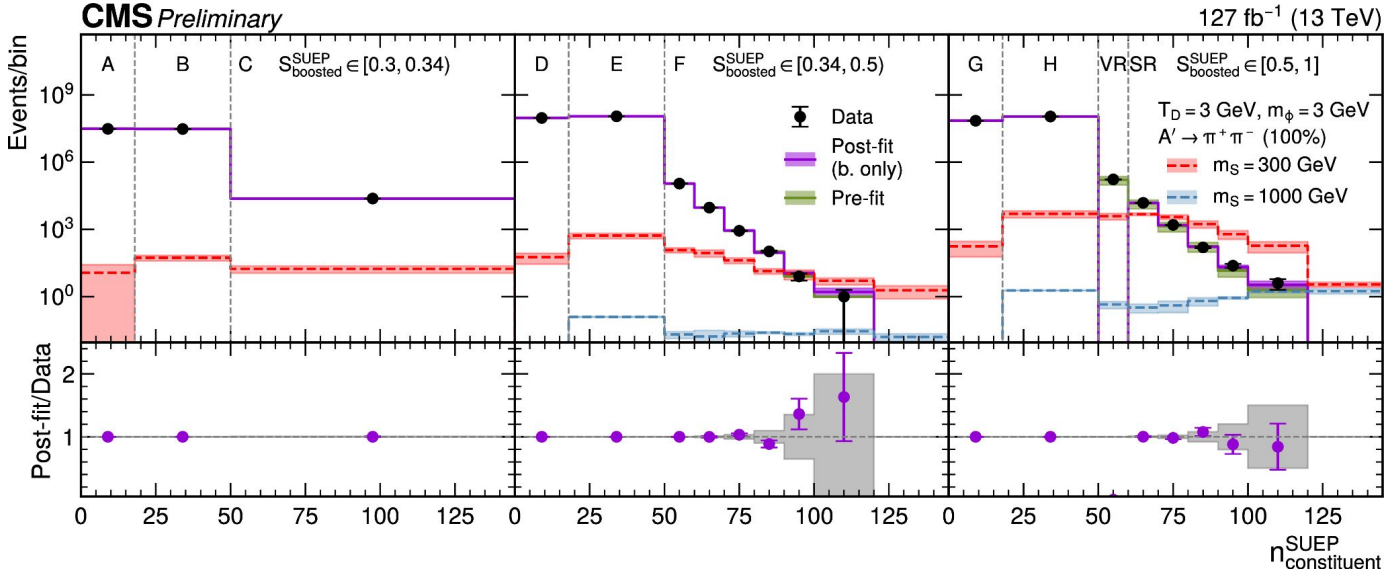
CMS EXO-23-001 PAS, Figs. 1, 2 and 3b

Trigger: Total hadronic activity in the event (HT)
Probe lower HT thresholds using ***Scouting***

Bkg. Estimation:
Number of SUEP (Ak15) Constituents
Boosted sphericity of the SUEP (Ak15)



No excess!

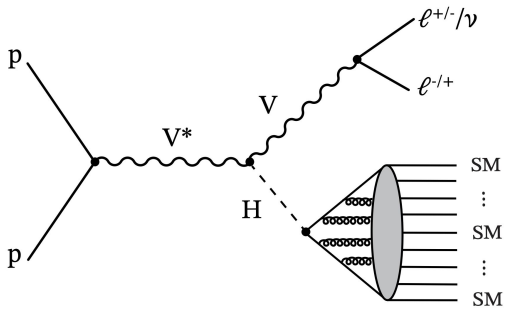


Results: Associated Production (*WH* Fit)

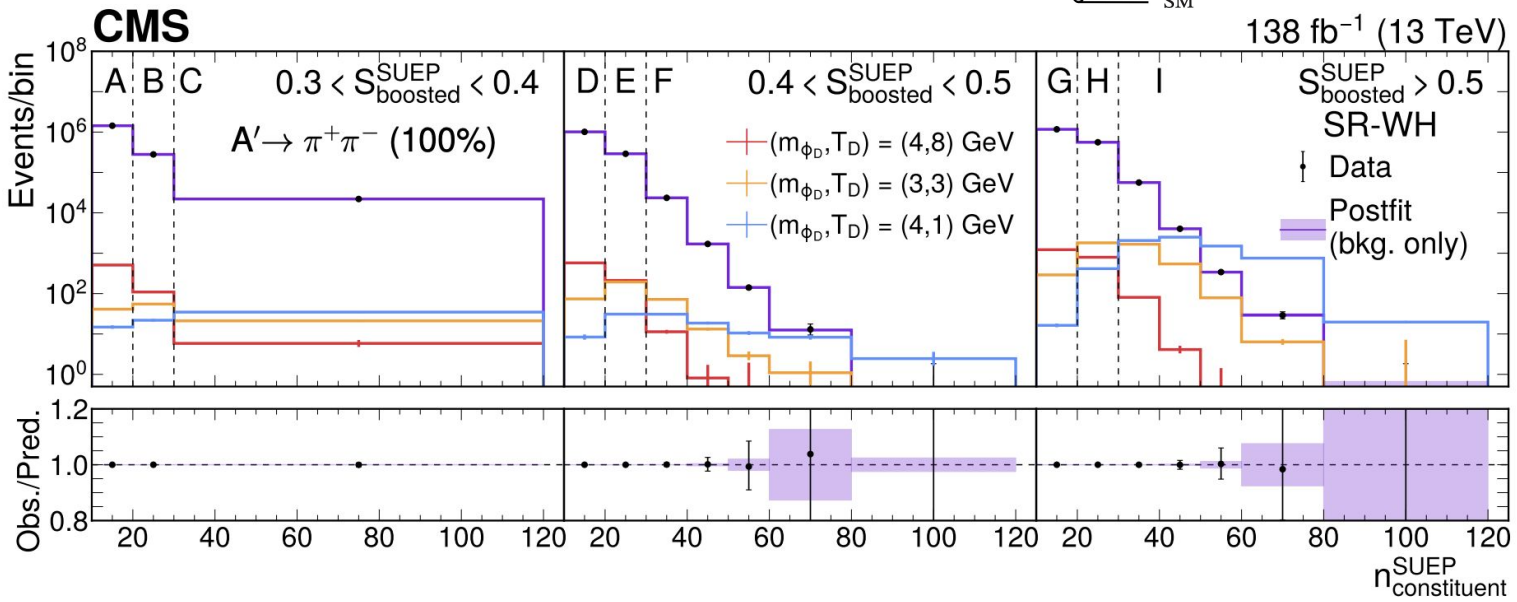
Search for SUEPs…, arxiv.2604.05996, Figs. 1 and 3

Trigger: Lepton from the decay of the boson
Strongest exclusion for mS = 125 GeV

Bkg. Estimation:
Number of SUEP (Ak15) Constituents
Boosted sphericity of the SUEP (Ak15)



No excess!



Results: Associated Production (*ZH* Fit)

Search for SUEPs…, arxiv.2604.05996, Figs. 1 and 3

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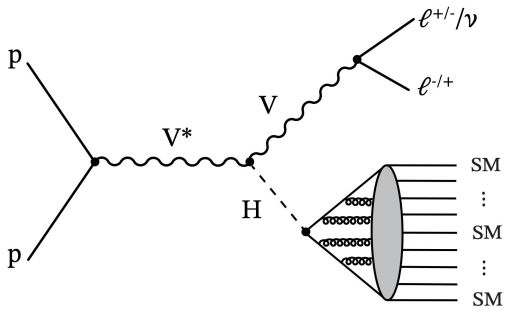
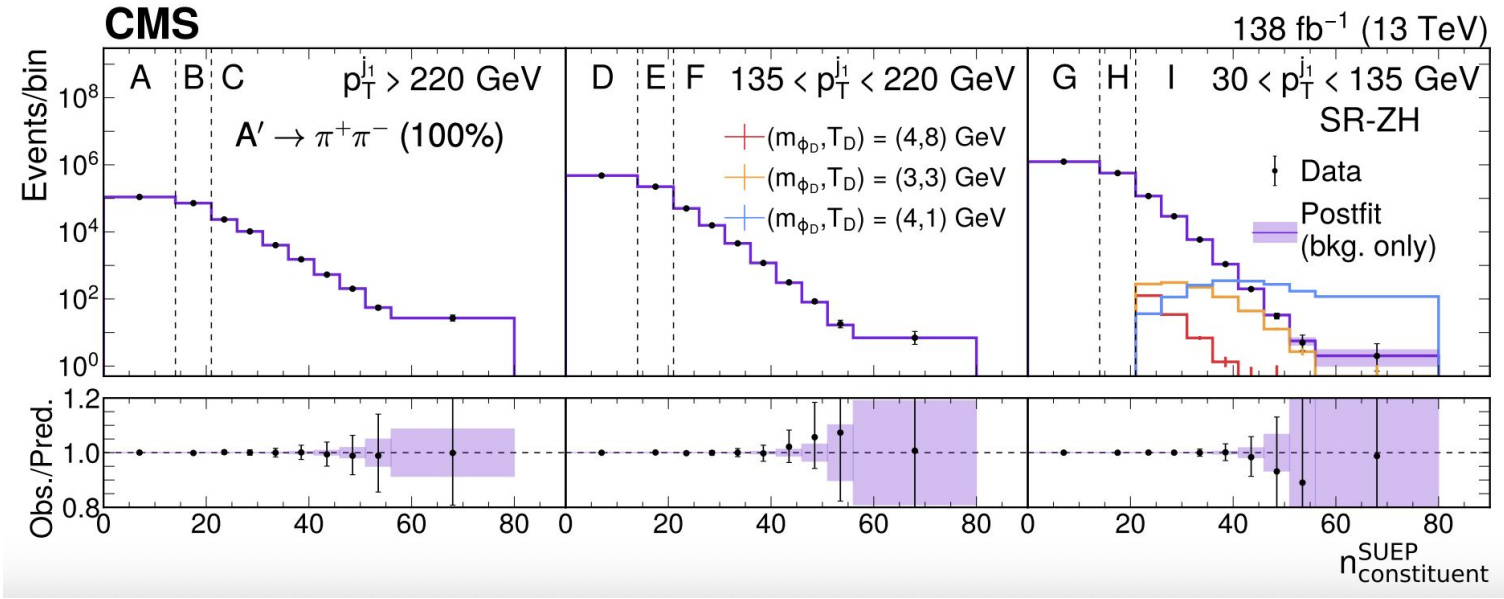
Bkg. Estimation:
Number of SUEP (Ak15) Constituents
pT of the event's leading Ak4 jet



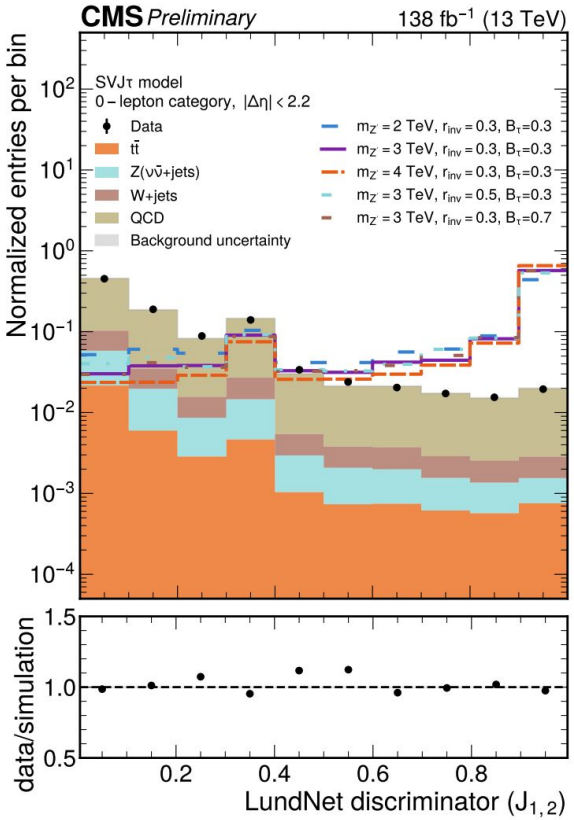
No excess!



τ-enriched SVJs

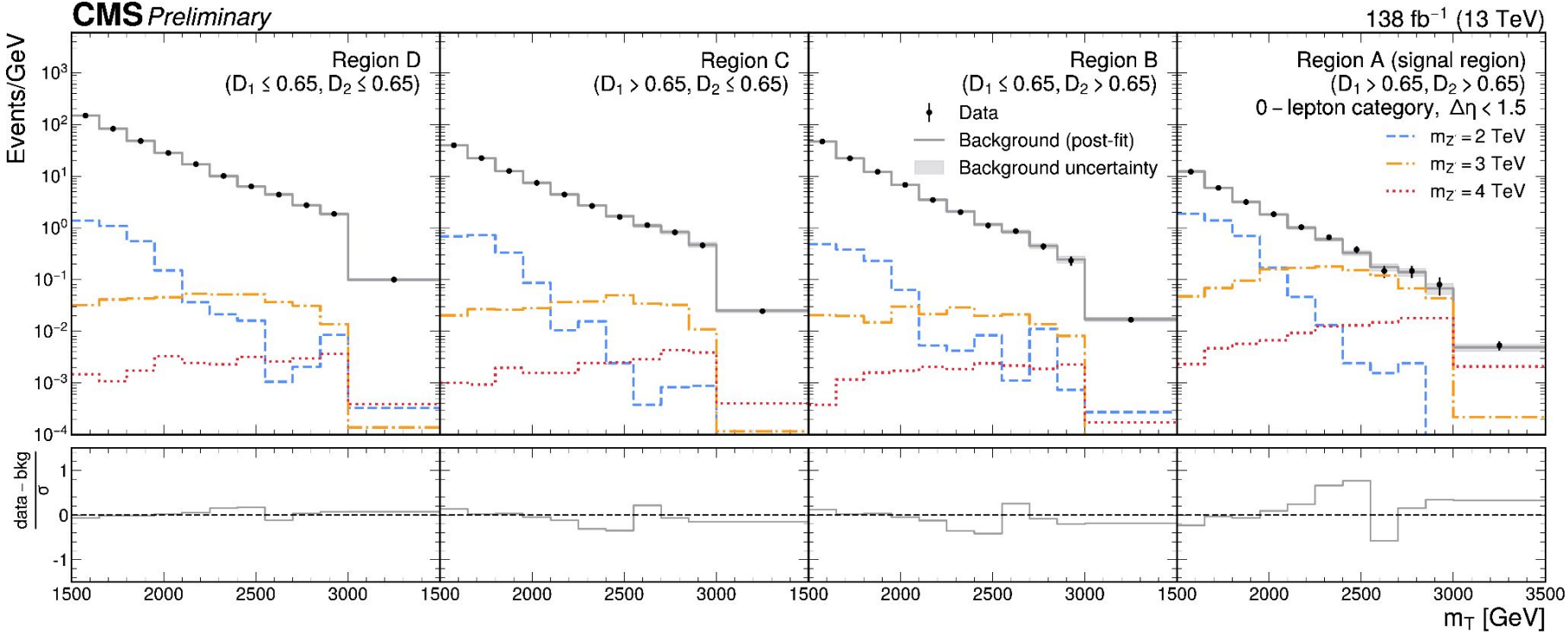
Search for s-channel production of τ-enriched… CMS PAS EXO-26-005, Fig. 3a

LundNet Data/MC Agreement



τ-enriched SVJs

Search for s-channel production of τ-enriched… CMS PAS EXO-26-005, Fig. 6



τ-enriched SVJs

Search for s-channel production of τ-enriched… CMS PAS EXO-26-005, Tables 1 and 2

Inclusive selection

$p_T(j_{1,2}) > 200\,\text{GeV}, \eta(j_{1,2}) < 2.4$

$R_T > 0.15$

$\Delta\eta < 1.5$

$m_T > 1.5\,\text{TeV}$

p_T^{miss} filters

$\Delta R(j_{1,2}, c_{\text{nonfunctional}}) > 0.1$

veto $f_\gamma(j_1) > 0.7$ & $p_T(j_1) > 1.0\,\text{TeV}$

veto $-3.05 < \eta_j < -1.35$ & $-1.62 < \phi_j < -0.82$ *

$\Delta\phi_{\text{min}} < 0.8$

Categorization

0-lepton region: $N_e + N_\mu = 0$

multilepton region: $N_e + N_\mu \geq 1$

Uncertainty	Yield effect [%]	
	0-lepton	multilepton
Integrated luminosity	1.6	1.6
Trigger efficiency	2	2
Jet energy corrections	0.1–18	0–16
Jet energy resolution	0–14	0–15
SVJ energy scale	0–12	0–17
Muon scale factors	—	1.5–5
Electron scale factors	—	1.2–3
Unclustered energy	0–20	0–17
Pileup reweighting	0–7	0–4
PDF	0–1	0–1
Parton shower FSR	0–4	0–7
Parton shower ISR	0–4	0–3
Renormalization and factorization scales	0–1	0–1

Dark Higgs + $b\bar{b}$

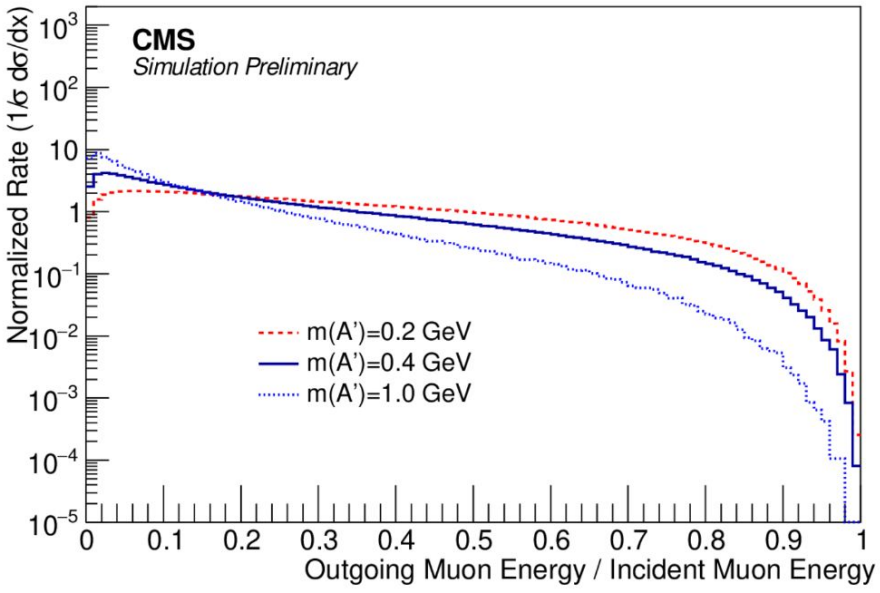
Search for dark matter produced in association with a dark Higgs…, arxiv.2604.20999, Tables 2 and 3

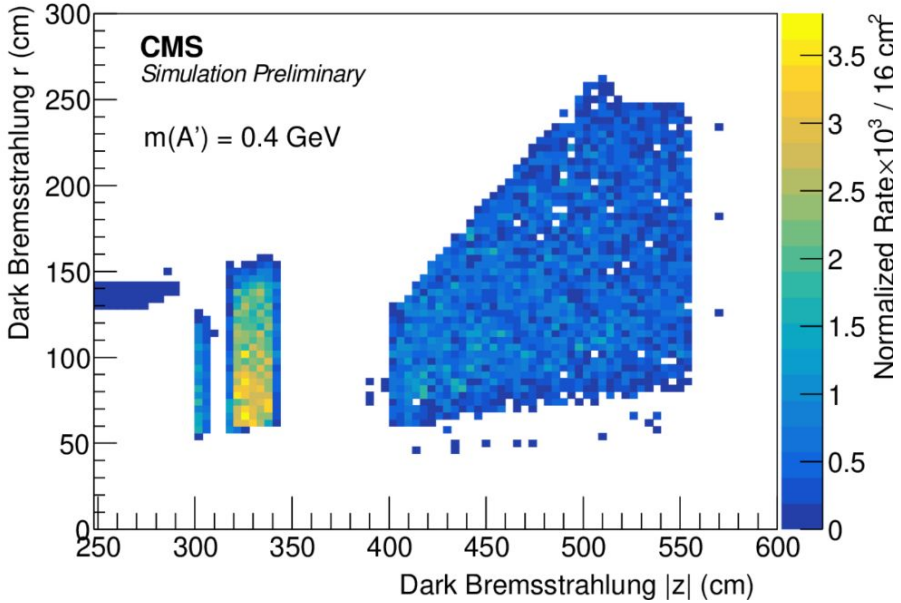
Source	Uncertainty
Integrated luminosity	0.6–2%
Pileup	1%
L1 prefiring	1%
p_T^{miss} trigger efficiency	1–2%
Single-electron trigger efficiency	1%
Muon isolation efficiency	1%
Muon identification efficiency	1%
Electron reconstruction efficiency	1%
Electron identification efficiency	2–3%
Tau veto	3%
Hadronic recoil U	5%
Jet energy corrections	4%
DEEPJET efficiency	Shape
DEEPAK15 efficiency	Shape
VV cross section	20%
H→$b\bar{b}$ cross section	20%
DY+jets cross section	20%
Single t cross section	10%
$t\bar{t}$ cross section	10%
QCD-p_T^{miss} normalization	100%
QCD-electron normalization	100%
QCD-muon normalization	100%
Higher-order corrections	Shape
Bin-by-bin event counts	Shape

Selection	SR	ZCR	WMPCR	WEPCR	WMFCR	WEFCR	TTMCR	TTECR
p_T^{miss} + H_T^{miss} trigger	✓	✓	✓	×	✓	×	✓	×
Single-electron trigger	×	×	×	✓	×	✓	×	✓
$U > 250\,\text{GeV}$	✓	✓	✓	✓	✓	✓	✓	✓
$\lvert p_T^{miss}(\text{PF}) - p_T^{miss}(\text{calo})\rvert / U < 0.5$	✓	✓	✓	✓	✓	✓	✓	✓
AK15 $p_T > 160\,\text{GeV}$	✓	✓	✓	✓	✓	✓	✓	✓
AK15 $m_{SD} \in [40, 300]\,\text{GeV}$	✓	✓	✓	✓	✓	✓	✓	✓
min $\Delta\phi(\vec{U}, \text{AK4s}) > 0.5$	✓	✓	✓	✓	✓	✓	✓	✓
min $\Delta\phi(\vec{U}, \text{AK15s}) > 1.5$	✓	✓	✓	✓	✓	✓	✓	✓
$p_T^{miss} > 100\,\text{GeV}$	×	×	×	✓	×	✓	×	✓
# of muons	0	0	1	0	1	0	1	0
# of electrons	0	0	0	1	0	1	0	1
# of photons	0	0	0	0	0	0	0	0
# of taus	0	0	0	0	0	0	0	0
# of extra b-tagged AK4 jets	0	0	0	0	0	0	≥1	≥1
DEEPAK15 requirement	pass	fail	pass	pass	fail	fail	pass	pass

Dark Photon Bremsstrahlung

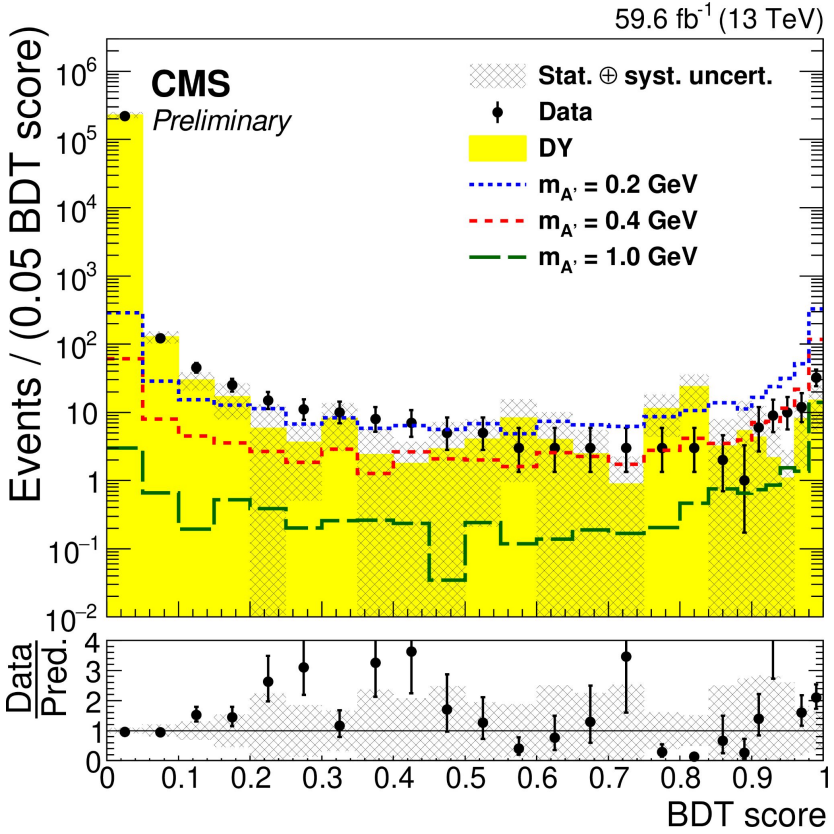
Search for dark photon bremsstrahlung …, CMS PAS EXO-23-008, Fig. 2





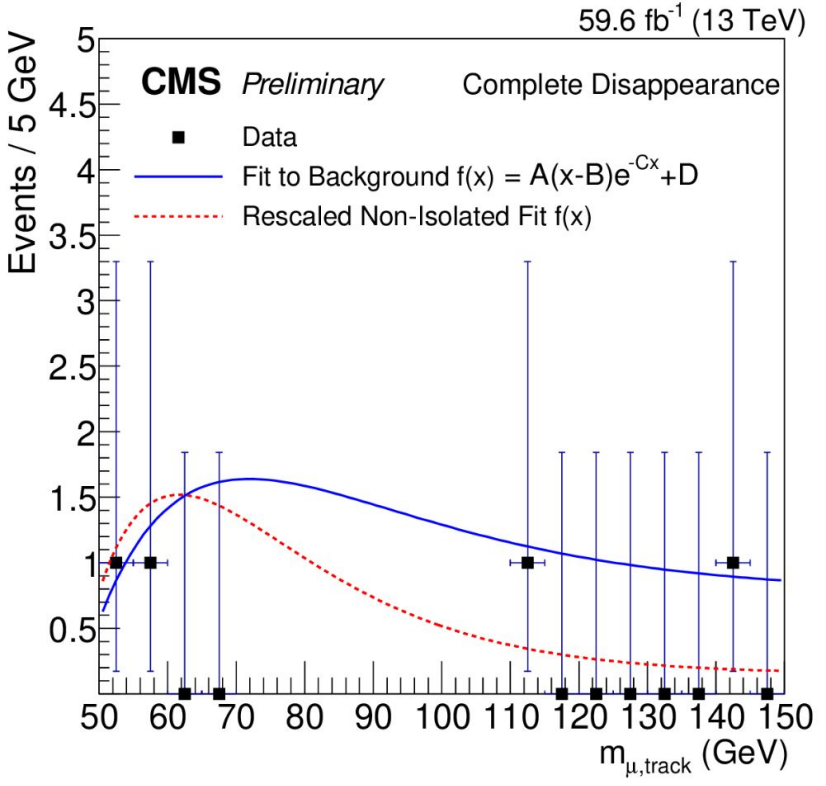
Dark Photon Bremsstrahlung

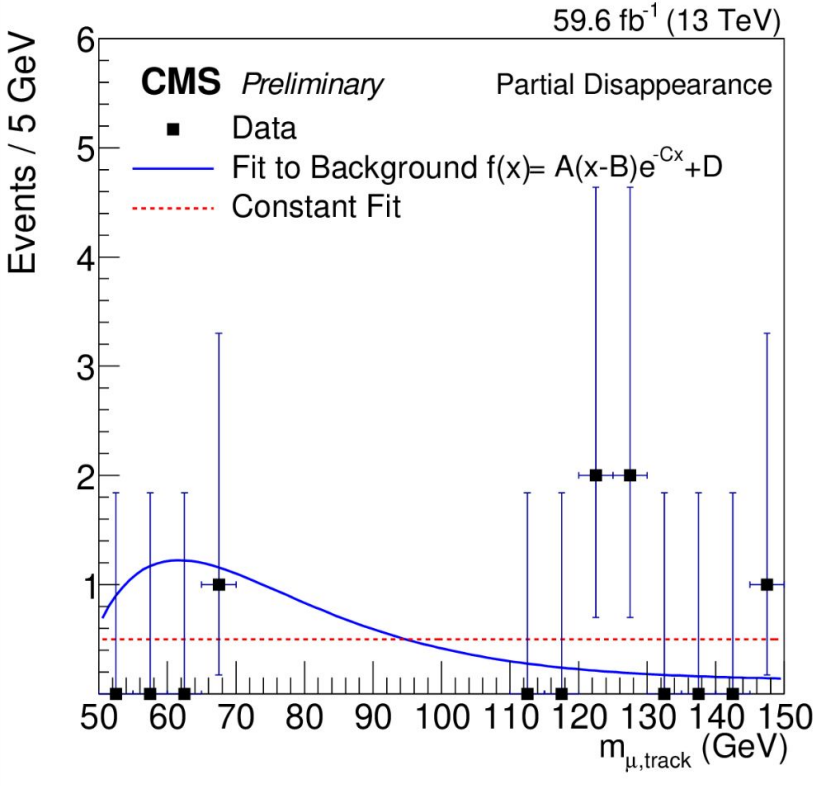
Search for dark photon bremsstrahlung …, CMS PAS EXO-23-008, Fig. 3



Dark Photon Bremsstrahlung

Search for dark photon bremsstrahlung …, CMS PAS EXO-23-008, Fig. 4





Dark Photon Bremsstrahlung

Search for dark photon bremsstrahlung …, CMS PAS EXO-23-008, Table 1

Source	Process	comp. bkgd. (%)	comp. signal (%)	part. bkgd. (%)	part. signal (%)	comp/part corr
Muon identification	DY/Signal	—	1.0	0.8	1.0	Sig
Muon isolation	DY/Signal	—	2.1	1.6	2.1	Sig
Pileup modeling	DY/Signal	—	5.0	6.0	3.3	Sig
Trigger	DY/Signal	—	1.0	0.8	1.0	Sig
Z p_T corr.	DY/Signal	—	0.5	19	0.6	Sig
BDT modeling	DY/Signal	—	—	17	17	–
Luminosity	DY/Signal	—	5.2	4.7	5.2	Sig
HCAL isolation	DY/Signal	—	8.3	—	—	–
DY missing hit rate	DY/Signal	35	—	—	—	–
Rescaled fit	non-DY	54	—	—	—	–
Fit function	non-DY	0.6	—	4.1	—	–
Signal contamination	non-DY	3.9	—	3.9	—	–
Theoretical	Signal	—	2.2	—	0.1	Sig
Tag/probe invariant mass peak	Signal	—	4.3	—	—	–
Energy in last HCAL depth	Signal	—	0.4	—	—	–
Statistical uncertainties	DY/Signal	4.9	11	22	2.8	
	non-DY	—	—	53	—	
Total	DY	35	—	24	—	
	non-DY	54	—	53	—	
	Signal	—	14	—	18	