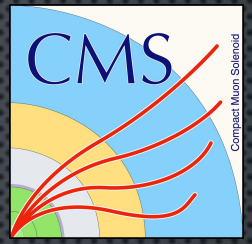


Searches for Dark QCD Signatures with CMS

July 31st, 2025

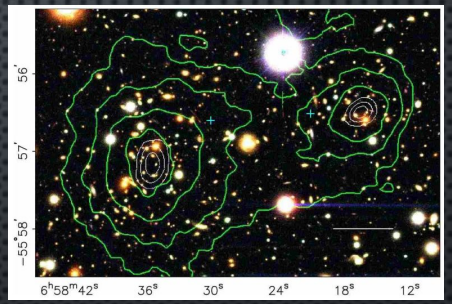
Emily Smith, on behalf of the CMS Collaboration
BOOST @ Brown

Fermilab

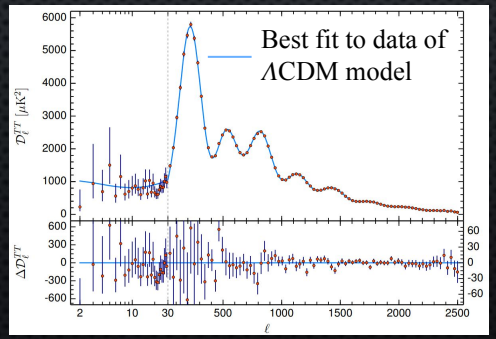
Dark Matter Exists - NASA Says So!

- NASA & Planck: Dark Matter exists and is different from regular matter, but no details
- WIMP signatures have been the focus of collider, direct detection, and annihilation
- Maybe time to look at more complex signatures?

"A direct empirical proof of the existence of dark matter" - NASA (Bullet Cluster Collision)



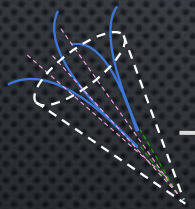
CMB Temperature Power Spectrum



"remarkable consistency with the 6-parameter ΛCDM cosmology… any signatures of new physics in the CMB must be small" - Planck Collaboration

Outline

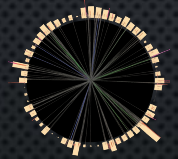
Strongly Coupled Dark Sectors



CMS Dark QCD Results

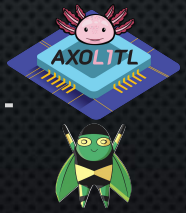
Semivisible Jets

Emerging Jets



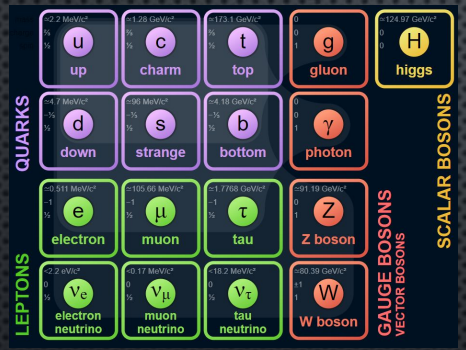
Soft Unclustered Energy Patterns

Tools and Techniques



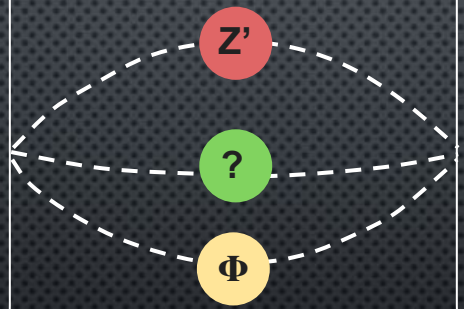
Strongly Coupled Dark Sectors

Visible Sector



$SU_c(3) \times SU_L(2) \times U_Y(1)$

Portal



Dark Sector

Inspired by M. Lisanti

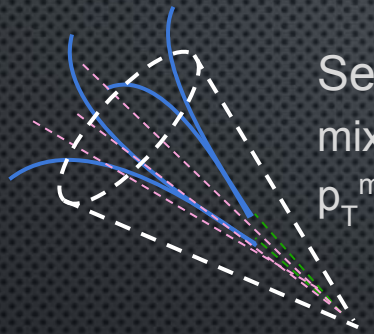
Potentially multiple types of particles interacting via new, dark forces

New “Dark QCD” force with it’s own dark hadrons, gluons, and quarks which hadronize and shower

Stable dark hadrons → Dark Matter candidates!
Unstable dark hadrons → decay back to SM

Echoes of a Hidden Valley at Hadron Colliders

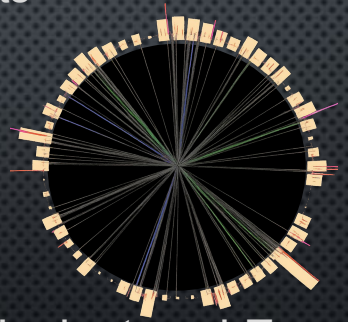
Dark QCD Phenomenology



Semivisible jets (SVJs)

mixture of stable and unstable dark hadrons

p_T^{miss} aligned with jets



Soft Unclustered Energy Patterns (SUEPs)

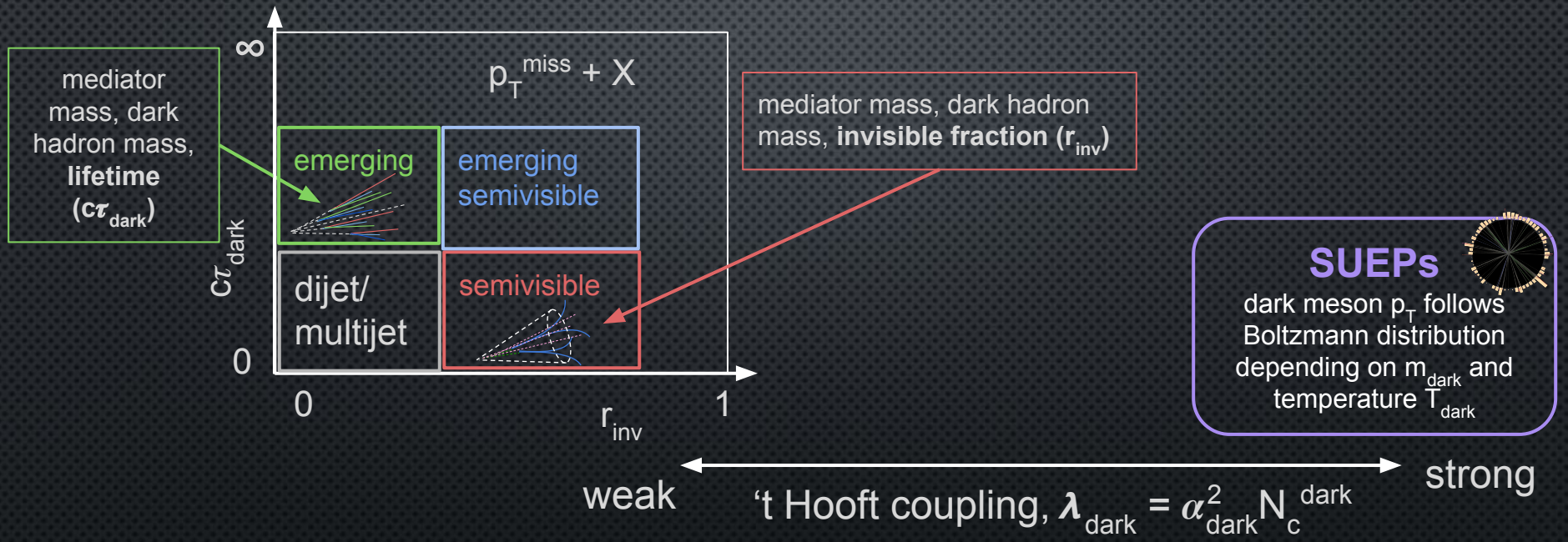
expand to confining theories with large ‘t Hooft coupling beyond QCD-like regime with spherical distribution of low-p_T tracks

Emerging jets (EMJs)

dark hadrons decay after some lifetime

multiple displaced vertices in each jet

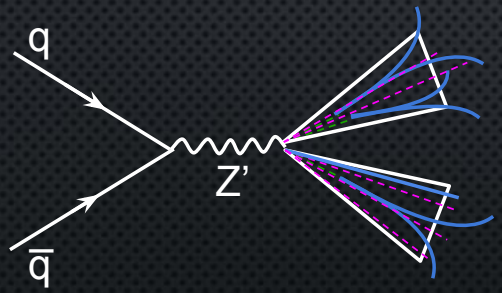
Effective Parameter Space



CMS Dark QCD Results

Semivisible Jets

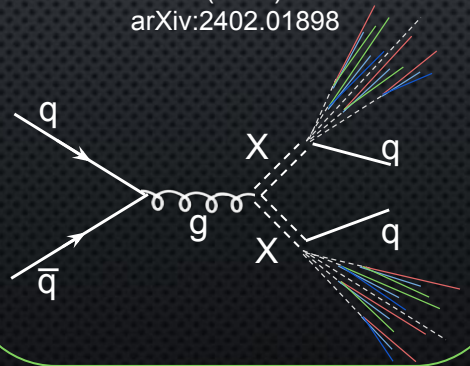
JHEP 06 (2022) 156
arXiv: 2112.11125



Emerging Jets

Track-based
JHEP 07 (2024) 142
arXiv:2403.01556

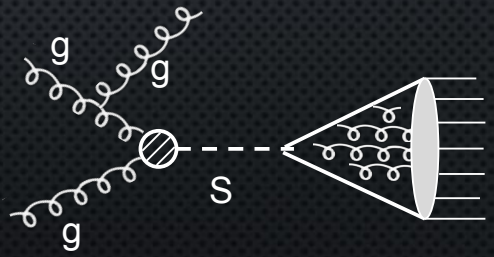
Muon Shower
PRD 110 (2024) 032007
arXiv:2402.01898



SUEPs

PRL 133 (2024) 191902
arXiv:2403.05311

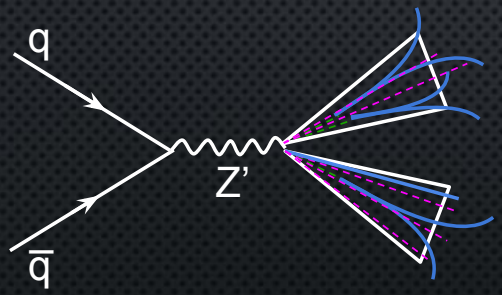
CMS PAS EXO-23-003.
CMS PAS EXO-24-030

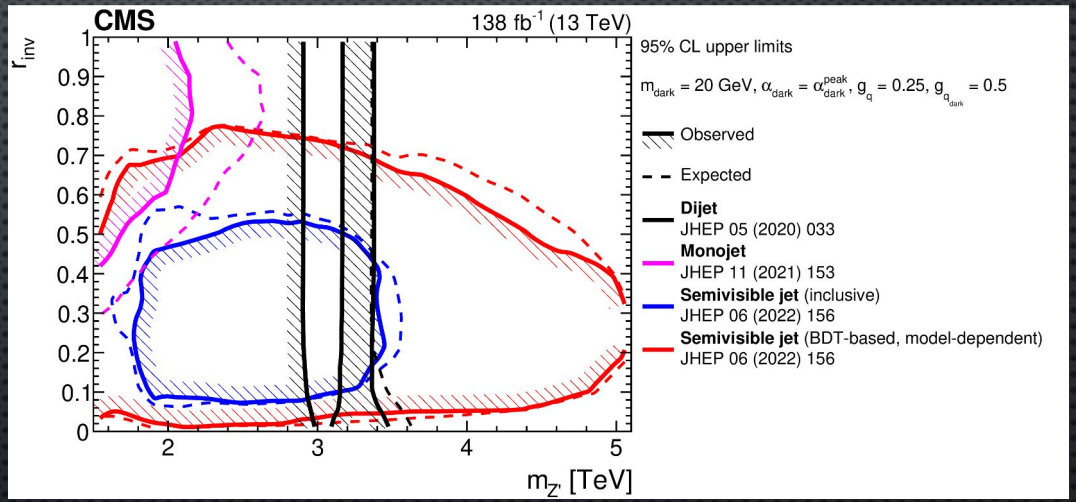


CMS Dark QCD Results - Semivisible Jets

Semivisible Jets

JHEP 06 (2022) 156
arXiv: 2112.11125



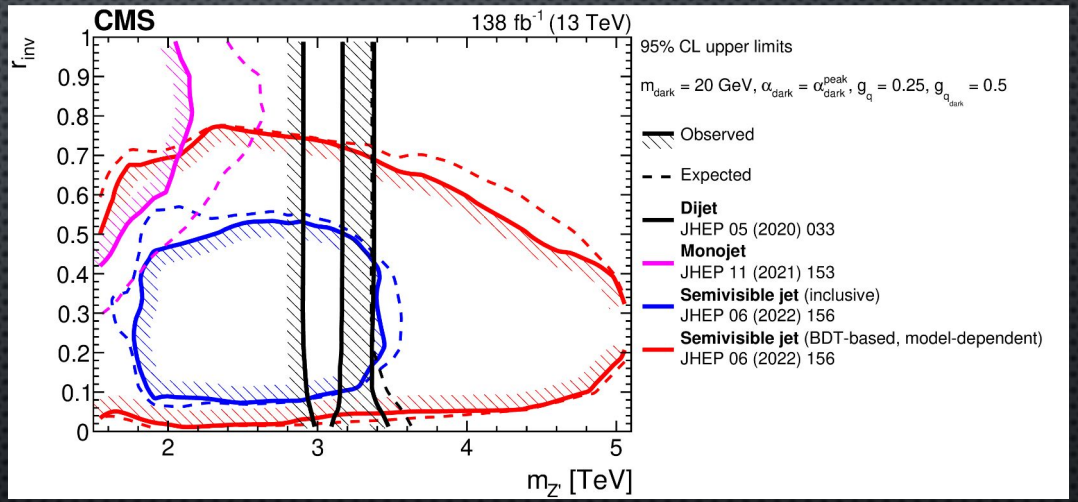


Dedicated SVJ search + reinterpretations of monojet DM and dijet resonance searches with SVJ model provide nice complementarity!

Phys. Rept. 1115 (2025) 448 / arXiv:2405.13778

CMS Dark QCD Results - Semivisible Jets

- Monojet: trigger on ISR jet and look for high excess p_T^{miss}
- Dijet: m_{jj} resonance search
- Dedicated SVJ:
  - Leptophobic Z' mediator
  - Model-dependent BDT trained to tag SVJ using substructure variables (m_{SD}, τ_{12}, τ_{23}, etc)
  - Inclusive search improvement over dijets depends on r_{inv} and couplings



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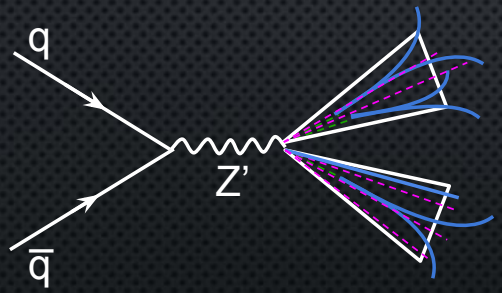

Emerging Jets

Track-based
JHEP 07 (2024) 142
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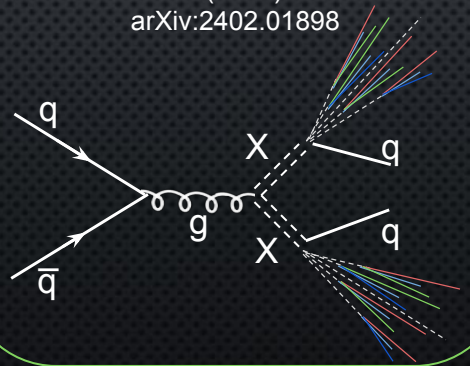
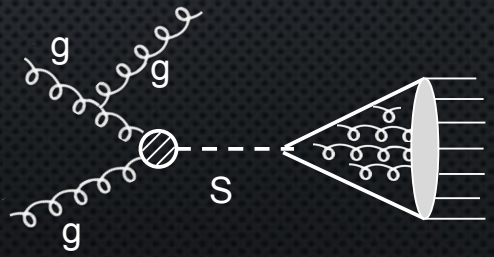
Muon Shower
PRD 110 (2024) 032007
arXiv:2402.01898



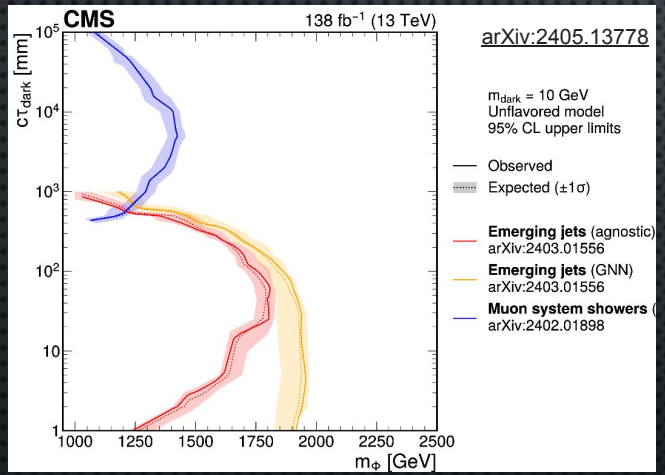
SUEPs

PRL 133 (2024) 191902
arXiv:2403.05311

CMS PAS EXO-23-003.
CMS PAS EXO-24-030



CMS Dark QCD Results - Emerging Jets



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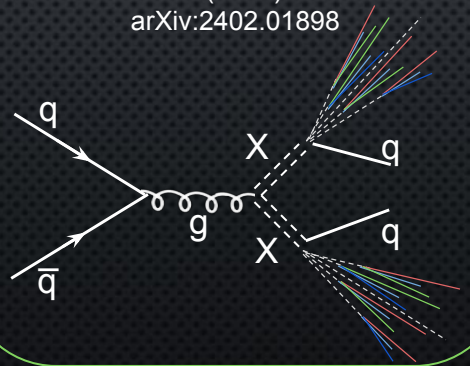
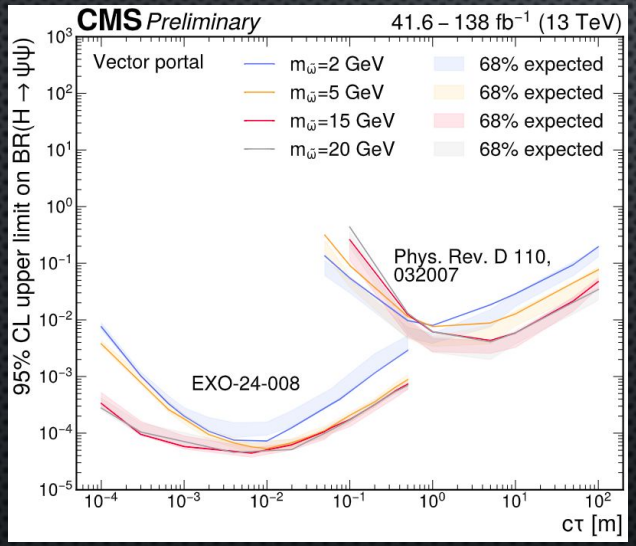


- Scalar mediator X → q q_{dark}
- EMJ selected based on track impact parameters (model-agnostic) or via GNN tagger
- Other long-lived particle searches not sensitive to EMJ
  - Prompt tracks, displaced vertex reconstruction, or delayed timing
- Muon shower sensitive at high lifetimes

CMS Dark QCD Results - Higgs → Emerging Jets

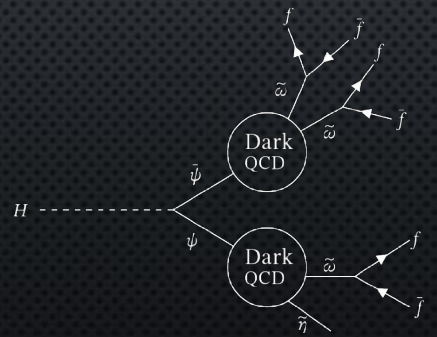


Emerging Jets

Higgs → EMJ

PRD 110 (2024) 032007
arXiv:2402.01898

CMS PAS EXO-24-008

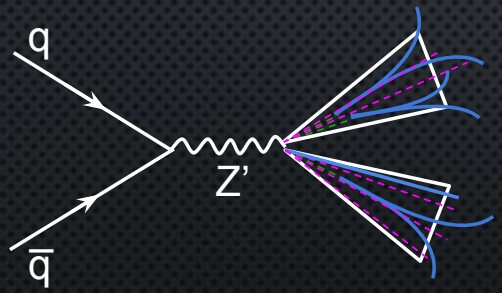


- H → LLPs, strongest limits on branching fraction set
- Complements muon shower search
- Newest results use B meson “parking” data from 2018
- Absorbers in front of muon detectors act as shields and reduce background significantly enough to require only on LLP decay

CMS Dark QCD Results

Semivisible Jets

JHEP 06 (2022) 156
arXiv: 2112.11125



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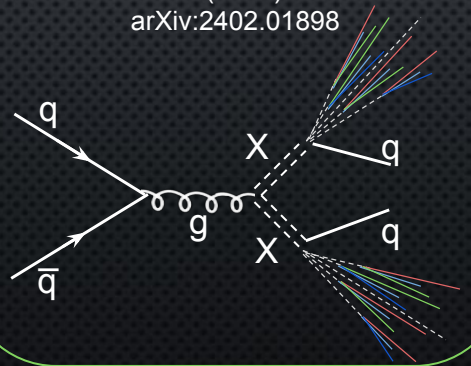

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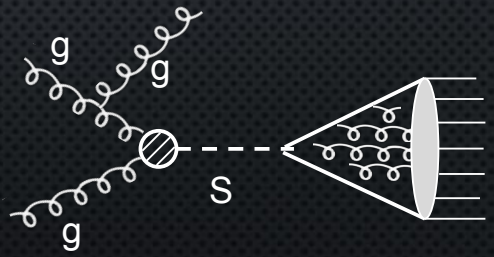
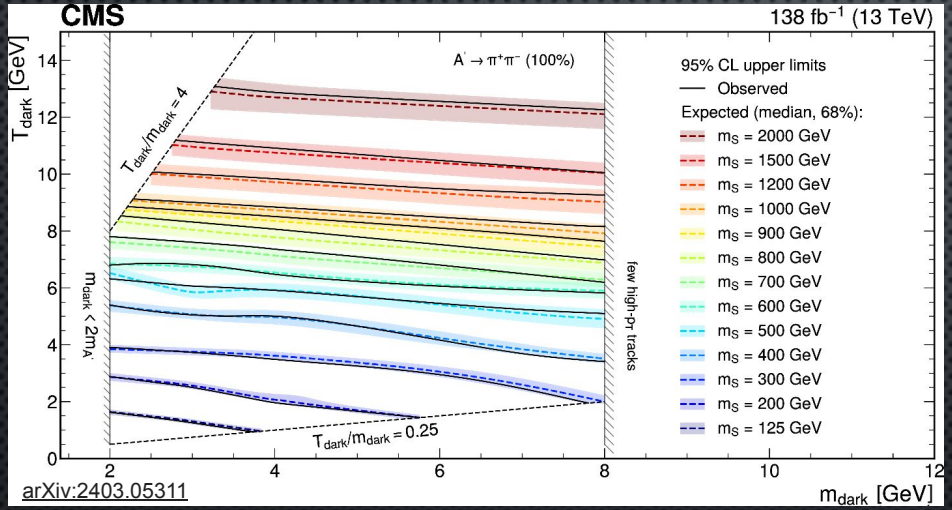


CMS Dark QCD Results - Soft Unclustered Energy Patterns

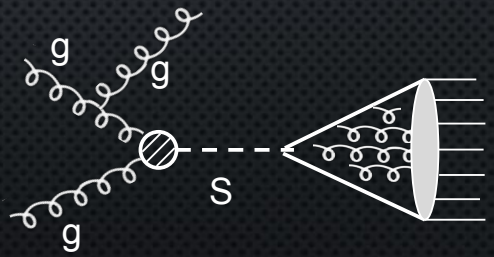


- $S \rightarrow q_{dark}q_{dark} \rightarrow$ dark shower to isotropic mesons (T_{dark}) $\rightarrow$ A'A' (dark photons), mixes with γ and decays to SM particles
  - results not particularly dependent on A' decay mode
- Multiplicity and sphericity of tracks used to select SUEP events

SUEPs

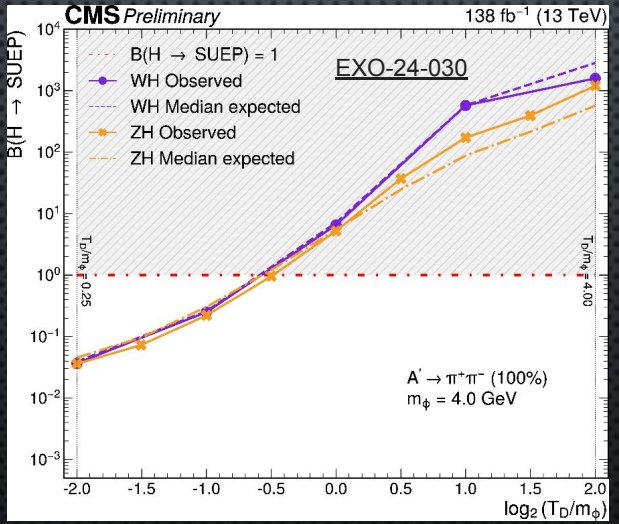
PRL 133 (2024) 191902
arXiv:2403.05311

CMS PAS EXO-23-003.
CMS PAS EXO-24-030



CMS Dark QCD Results - Higgs → SUEPs

- Higgs → $q_{dark}\,\bar{q}_{dark}$
  - More efficient triggering (leptons)
  - Reduces multijet background
- Strong limits on models with $T_D < m_\varphi$ → high-multiplicity low-momentum track final states



SUEPs

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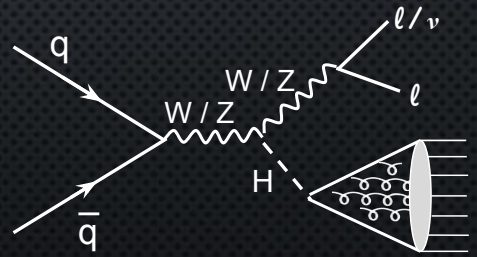
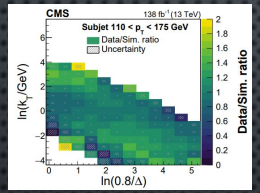


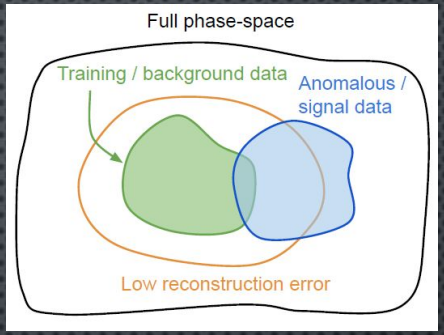
Techniques & Tools

- Dark QCD jets have unique substructure!
  - … if we can exploit it

Prong-based Lund Jet Plane calibration
arXiv:2507.07775



WNAE (Wasserstein Normalized Autoencoder)
CMS-PAS-MLG-24-002



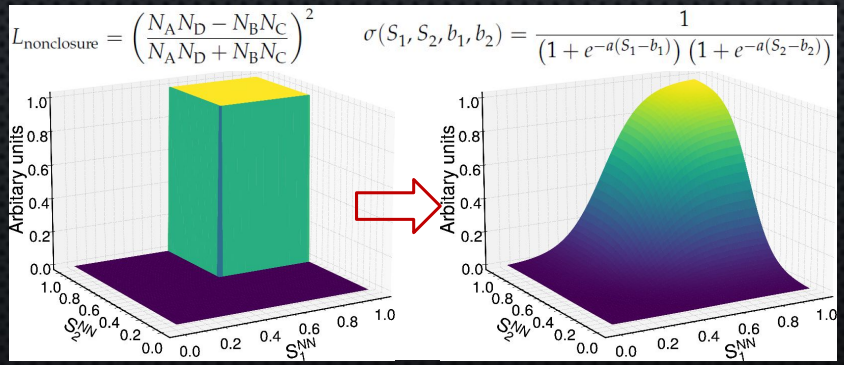
Learns probability distribution of input data

Minimizes Wasserstein distance between this and Boltzmann distribution of the reconstruction error of the autoencoder

Anomaly Detection Triggers

ABCDisCoTEC: ABCD Distance Correlation Training Enhanced with Closure
CMS-PAS-MLG-23-003

$$L_{\text{nonclosure}} = \left(\frac{N_A N_D - N_B N_C}{N_A N_D + N_B N_C}\right)^2 \qquad \sigma(S_1, S_2, b_1, b_2) = \frac{1}{\left(1 + e^{-a(S_1 - b_1)}\right)\left(1 + e^{-a(S_2 - b_2)}\right)}$$



ML version of ABCD method

Continuous relaxation of “nonclosure” calculation ensures desired performance

Distance correlation and nonclosure terms included as constraints in loss function using modified differential method of multipliers

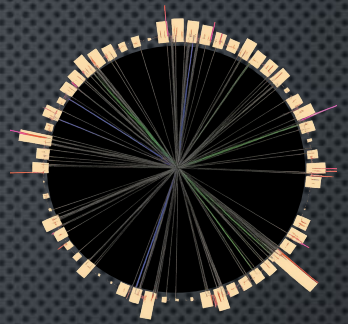
Conclusions

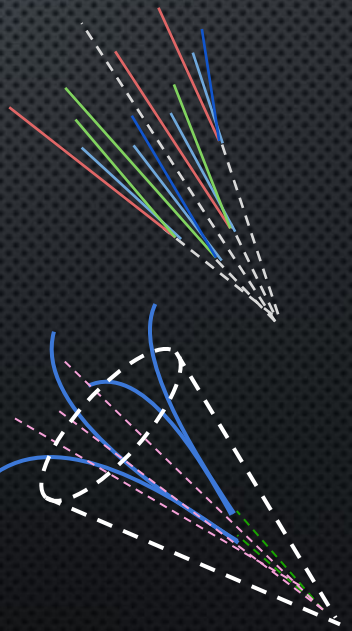
Good exploration of strongly coupled dark sectors in CMS program!

Model space is large and much still to be explored

Substructure & ML techniques are an important component of these analyses!

Stay tuned!

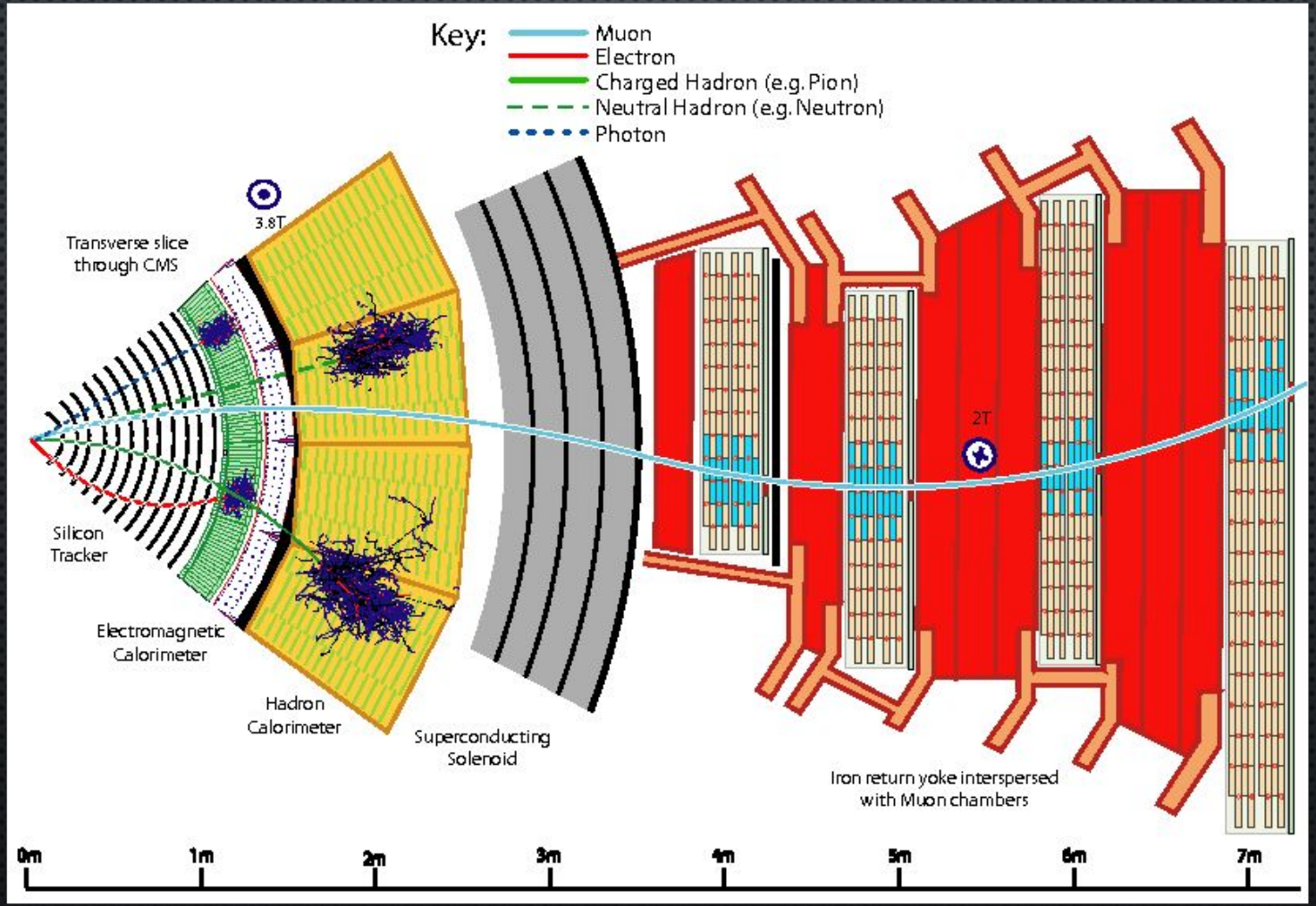




Backup

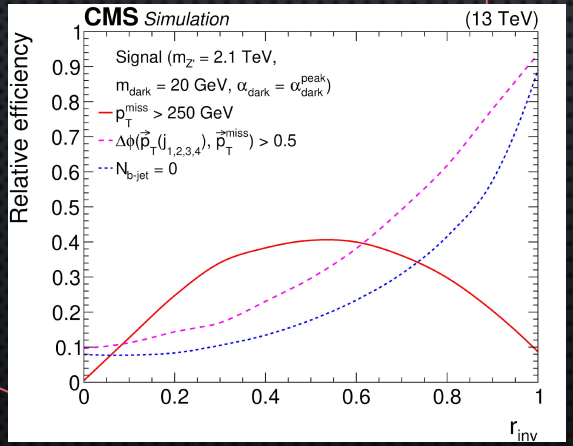
Dark QCD Models

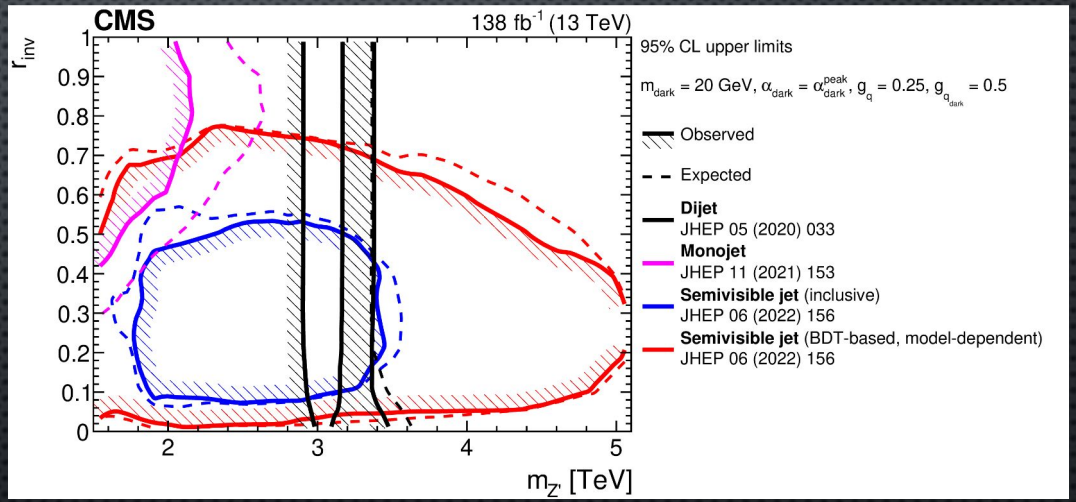
- Dark QCD Mediators
  - Z′: from broken U(1), vector, leptophobic, couplings g_q, g_χ
  - Φ: bifundamental, scalar, charged under both dark QCD and SM QCD, Yukawa couplings
  - S: scalar, Yukawa couplings to dark quarks and to SM quarks (potentially Higgs)
- Model parameter space large and complex!
  - Dark QCD itself: scale, number of colors
  - Mediators: masses, couplings
  - Dark quarks: masses, flavors
  - Dark hadrons: masses, spins, composition, etc
  - All the normal unknowns of SM QCD: hadronization, fragmentation, etc
- Novel collider phenomenology
  - missed by traditional searches looking for large p_T^{miss}
  - DM abundance arises from asymmetry mechanism → no annihilation
  - DM interactions with ordinary matter highly suppressed → no direct detection
- To perform actual searches, focus on simplified models that reproduce novel phenomenology with effective parameters


Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
3.8T
Transverse slice through CMS
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m

CMS Dark QCD Results - Semivisible Jets

- Monojet: trigger on ISR jet and look for high excess p_T^{miss}
  - Most sensitive at high r_{inv} ~0.8
  - Interrelated cuts on p_T^{miss}, $\Delta\varphi$, and $N_{b\text{-jet}}$





Dedicated SVJ search + reinterpretations of monojet DM and dijet resonance searches with SVJ model provide nice complementarity!

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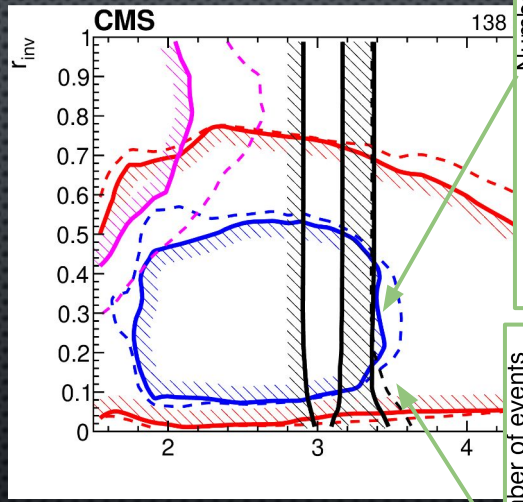
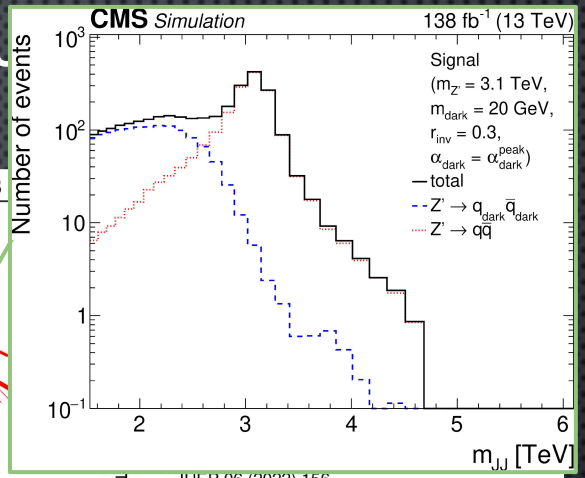
CMS Dark QCD Results - Semivisible J

- Monojet: trigger on ISR jet and look for high excess p_T^{miss}
- Dijet: m_{jj} resonance search
  - Overlap with SVJ
  - For $r_{inv} < 0.1$, similar m_{jj} region to dedicated SVJ results in enhanced resonance and better limits





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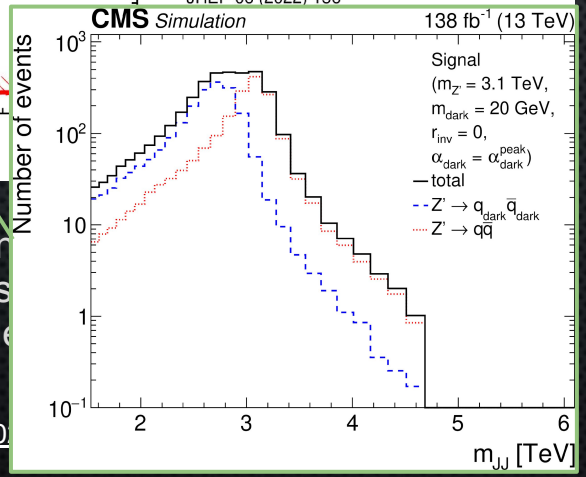

Dedicated SVJ search + rein
dijet resonance searches
comple

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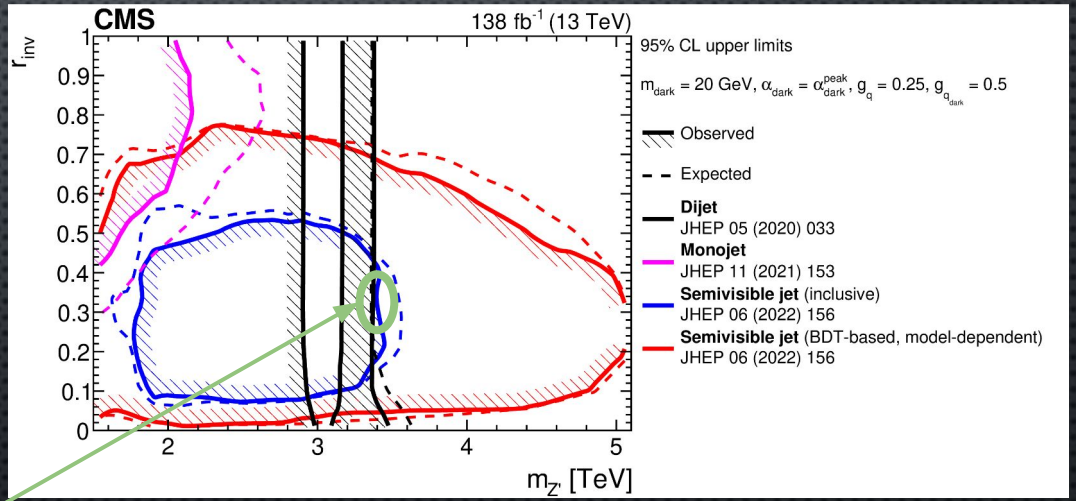
CMS Dark QCD Results - Semivisible Jets

- Monojet: trigger on ISR jet and look for high excess p_T^{miss}
- Dijet: m_{jj} resonance search
- Dedicated SVJ:
  - Model-dependent BDT trained to tag SVJ using substructure variables (m_{SD}, τ_{12}, τ_{23}, etc)
  - Inclusive search improvement over dijets depends on r_{inv} and **couplings**



Dedicated SVJ search + reinterpretations of monojet DM and dijet resonance searches with SVJ model

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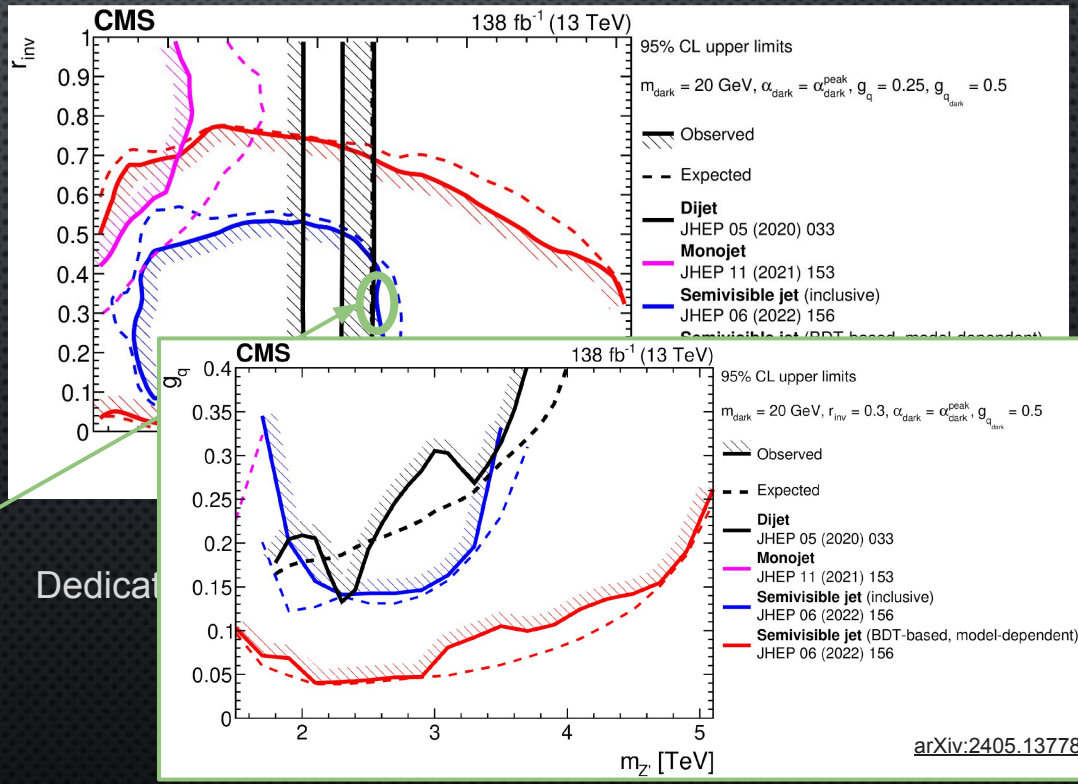


Semivisible Jets - Signal Model

- Leptophobic Z' model:
  - Mediator mass: $m_{Z'}$ = 1.5–5.1 GeV
  - Mass scale: m_{dark} = 1-100 GeV
  - Coupling strength of dark QCD force: α_{dark}^{peak} = 0.313 ± 50%
  - Fraction of invisible dark hadrons r_{inv} = 0-1
  - m_X = 0.5 - 50 GeV
  - $N_f^{dark} = N_c^{dark} = 2$

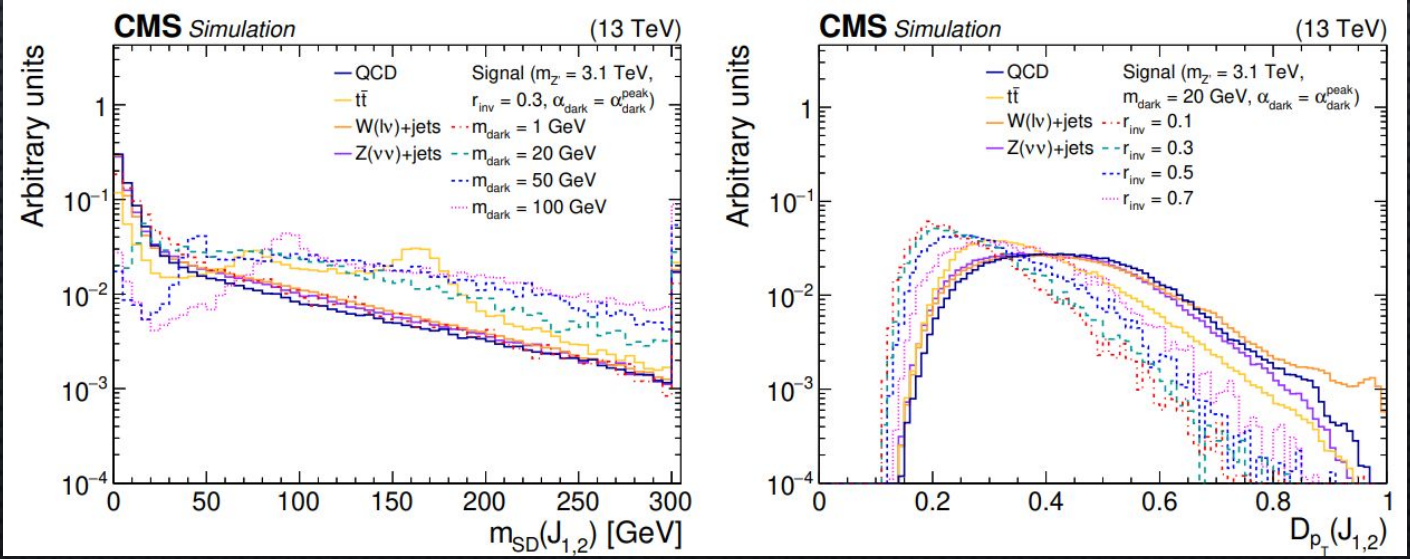
Scan	$m_{Z'}$ [TeV]	m_{dark} [GeV]	r_{inv}	α_{dark}
1	1.5–5.1	1–100	0.3	α_{dark}^{peak}
2	1.5–5.1	20	0–1	α_{dark}^{peak}
3	1.5–5.1	20	0.3	α_{dark}^{low}–α_{dark}^{high}

Semivisible Jets - Backgrounds

- QCD Multijet: jet mismeasurement gives p_T^{miss} aligned with jets
- tt: wide, high p_T jets, neutrino from W decay gives p_T^{miss}
- Semileptonic W: less likely than ttbar to mimic signal, but higher cross section
- Z to invisible: real p_T^{miss} but less likely to align with jet

SVJ Tagging with BDT

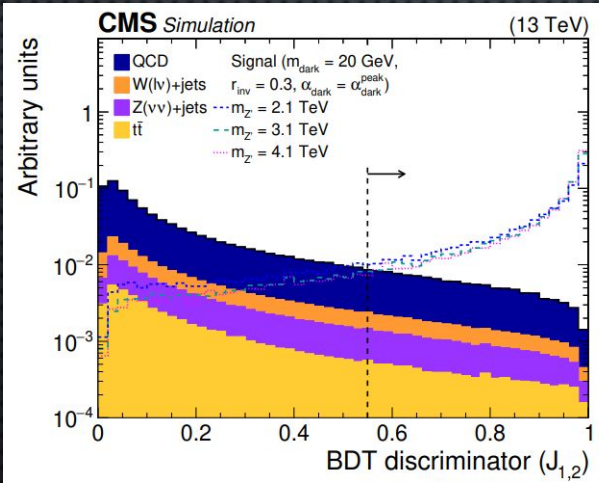
- Normalized distribution of input variables for SVJ tagging BDT
- Most important inputs are m_{SD}, D_{pT}, $\Delta\phi$, τ_{12}, τ_{23}

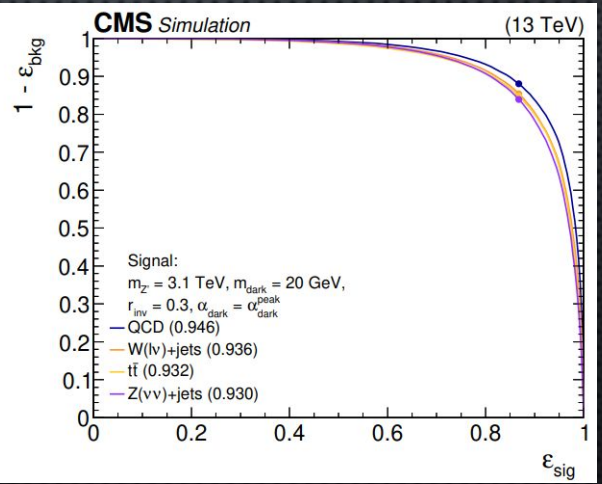


SVJ Tagging with BDT

- WP of 0.55
- Strong rejection of jets from all background processes

Background	Acc.	AUC	$1/\varepsilon_{bkg}$ ($\varepsilon_{sig} = 0.3$)
QCD	0.883	0.946	636.8
$t\bar{t}$	0.883	0.932	290.0
W+jets	0.883	0.936	477.1
Z+jets	0.883	0.930	455.4





Emerging Jets Models

Unflavored Model

- Scalar mediator mass: $m_{X'}$ = 1-2.5 TeV
- Mass scale: $m_{\pi dark}$ = 10,20 GeV
- N_f^{dark} = 7
- N_c^{dark} = 3
- Lifetime: 1-1000 mm
- Yukawa Coupling $\kappa_{\alpha i}$ only coupling to down quark is non-negligible in unflavored model

Model parameter	List of values
$m_{X_{dark}}$ [GeV]	1000, 1200, 1400, 1500, 1600, 1800, 2000, 2200, 2400, 2500
$m_{\pi_{dark}}$ [GeV]	10, 20
$c\tau_{\pi_{dark}}$ [mm]	1, 2, 5, 25, 45, 60, 100, 150, 225, 300, 500, 1000

Flavor-Aligned Model

- Mass scale: $m_{\pi dark}$ = 6,10,20 GeV
- N_f^{dark} = 3, couple to SM d,s,b via diagonal matrix of $\kappa_{\alpha i}$

$m_{X_{dark}}$ [GeV]	$m_{\pi_{dark}}$ [GeV]	κ_0 value				
1000	6	0.92	0.61	0.53	0.43	0.29
	10	0.62	0.42	0.36	0.30	0.20
	20	0.37	0.25	0.21	0.18	0.12
1200	6	1.10	0.73	0.63	0.52	0.35
	10	0.75	0.50	0.43	0.35	0.24
	20	0.45	0.30	0.26	0.21	0.14
1400	6	1.28	0.86	0.74	0.61	0.41
	10	0.87	0.58	0.50	0.41	0.28
	20	0.52	0.35	0.30	0.25	0.16
1600	6	1.47	0.98	0.85	0.69	0.46
	10	1.00	0.67	0.58	0.47	0.32
	20	0.59	0.40	0.34	0.28	0.19
1800	6	1.65	1.10	0.95	0.78	0.52
	10	1.12	0.75	0.65	0.53	0.36
	20	0.67	0.45	0.39	0.32	0.21
2000	6	1.83	1.23	1.06	0.87	0.58
	10	1.25	0.84	0.72	0.59	0.40
	20	0.74	0.50	0.43	0.35	0.23
2200	6	2.02	1.35	1.16	0.95	0.64
	10	1.37	0.92	0.79	0.65	0.43
	20	0.82	0.55	0.47	0.39	0.26
2400	6	2.20	1.47	1.27	1.04	0.70
	10	1.50	1.00	0.87	0.71	0.47
	20	0.89	0.60	0.51	0.42	0.28
2500	6	2.29	1.53	1.32	1.08	0.72
	10	1.56	1.04	0.90	0.74	0.49
	20	0.93	0.62	0.54	0.44	0.29

How do SUEPs SUEP?

Dark partons → dark mesons (mass scale << mediator mass scale)

Showering process has efficient branching over larger energy range than SM QCD and all information about momenta of initial partons is lost

Results in high multiplicity of light bound states emitted in spherical distribution in COM frame of shower