CMS Experimental Results on Dark Showers

Long Wang (UMD)

on behalf of the CMS experiment

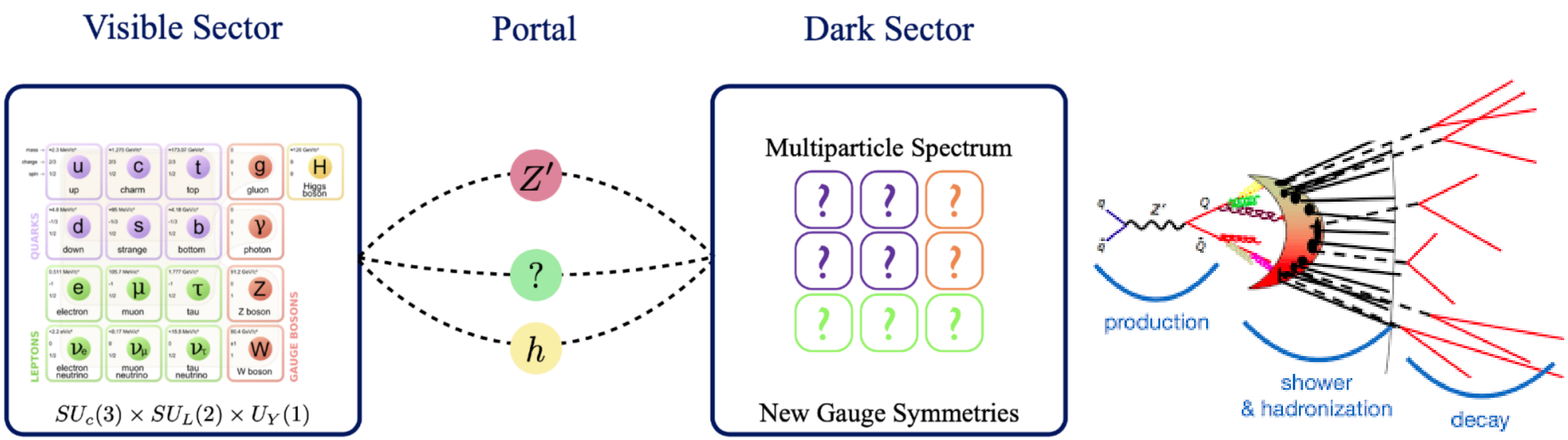
May 17, 2024

@Roadmap of Dark Matter models for Run3

Outline

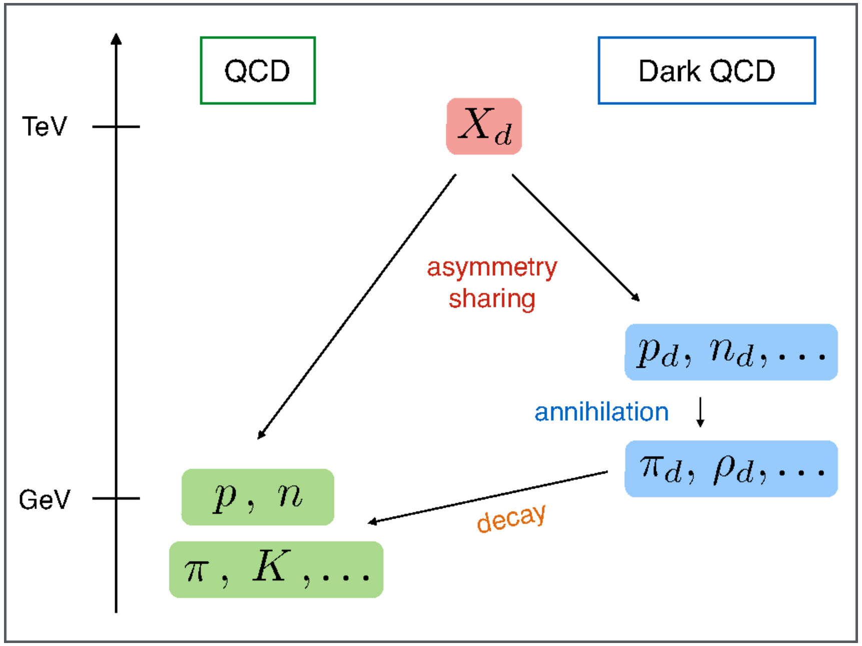
- Introduction
- Semi-visible Jets (SVJ)
- Emerging Jets (EJ)
- Soft unclustered energy patterns (SUEP)
- Summary

Dark QCD/Dark Shower



- Motivations:
  - So far, WIMP DM searches have excluded large phase spaces at the LHC;
  - Dark QCD models can easily explain the coincidence between energy density of DM and baryons;
- If producible at the colliders, mediator particles connects Dark Sector and SM;
  - bifundamental scalar mediator X, vector mediator Z', ect.
- Dark quarks undergo showering under $SU(N_D)$, where the stable dark hadrons contribute to DM candidates, unstable ones can decay back into SM, leaving exotic signatures on detector.

Dark QCD/Dark Shower



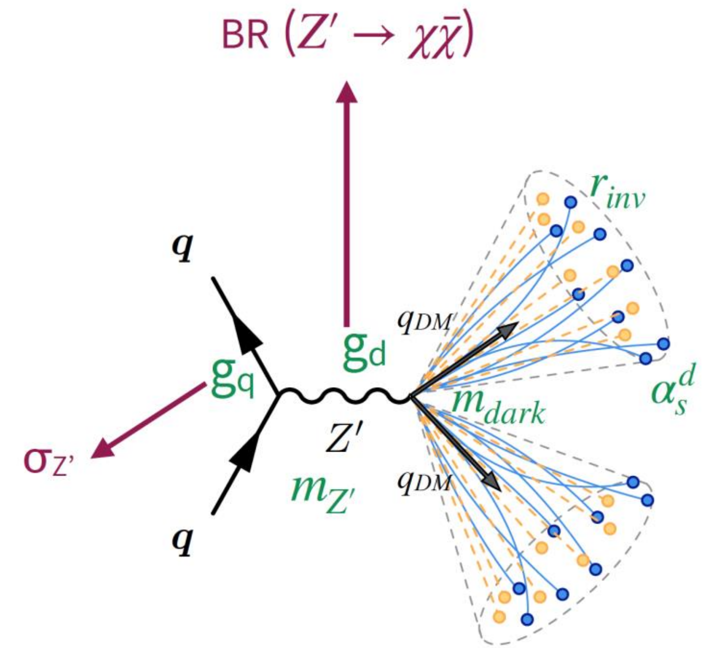
- Search scenarios on the CMS experiments can be generally categorized based on $SU(N_D)$ structure：
  1. $m_{qD} \lesssim \Lambda_D \ll \sqrt{s}$, shower enabled:
     a. small 't Hooft coupling λ, like the SM QCD, showers with emerging/semivisible jets；
     b. large λ, non-QCD like, soft unclustered energy patterns;
  2. $\Lambda_D \sim \sqrt{s}$: higher confinement leads to heavier bound states, resonance-like searches for dark bound states;
  3. $\Lambda_D \ll m_{qD} \lesssim \sqrt{s}$: heavy quirks;

- Current CMS searches presented public results for scenarios 1.a and 1.b.
  - Semi-visible Jets (SVJ)
  - Emerging Jets (EJ)
  - Soft unclustered energy patterns (SUEP)

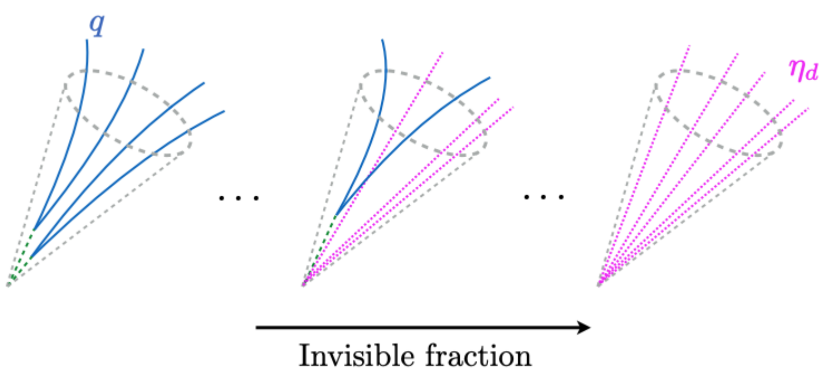
SVJ-search models

JHEP 06 (2022) 156

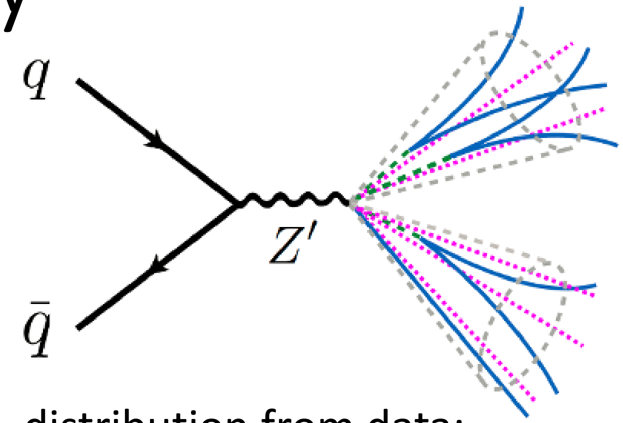
- s-channel dark quark pair produced via leptophobic vector Z' mediator from broken U(1) symmetry;
- $SU(N_D)$ with $N_f^{dark} = 2$, $N_D = 2$;
- Dark quarks shower and hadronize, unstable dark hadrons decay back to SM promptly, stable ones characterized by invisible fraction r_{inv};



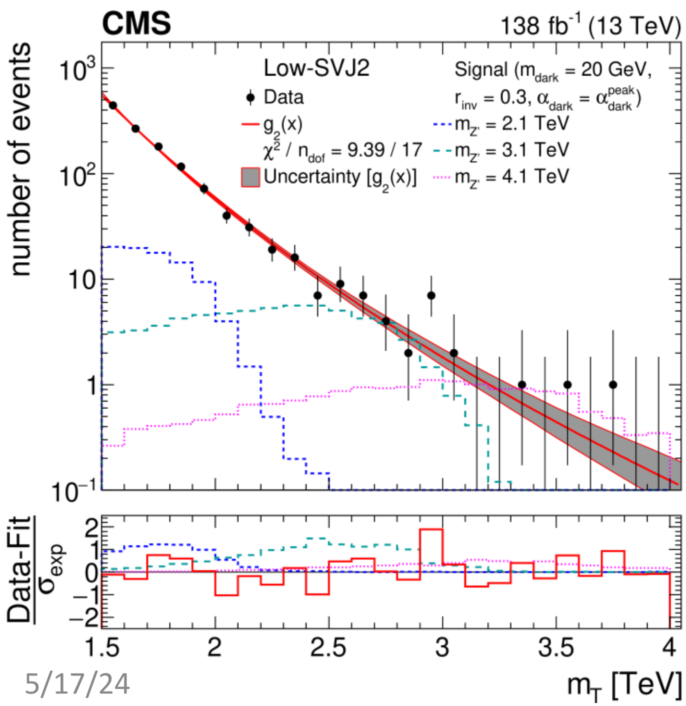
- Model parameters have:
  - $m_{Z'}$: mediator mass;
  - m_{dark}: dark hadron mass;
  - r_{inv}: stable hadrons fraction;
  - α_{dark}: running coupling of dark QCD.



SVJ-search methodology



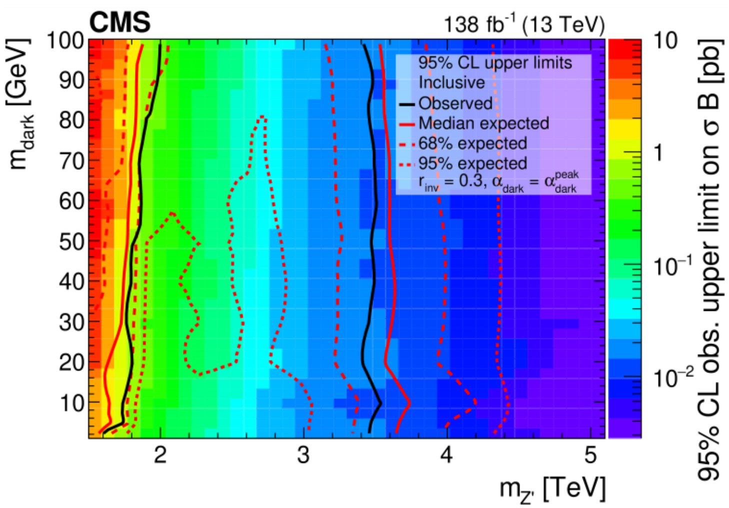
- Signal signatures on detector:
  - Two high-p_T and wide jets that contain mix of visible and invisible particles;
  - MET aligned with jets due to invisible contents in jets;
- **Bump hunt** of Z′ resonant in m_T(JJ, MET);
- Background estimated with analytic fit to observed m_T distribution from data;

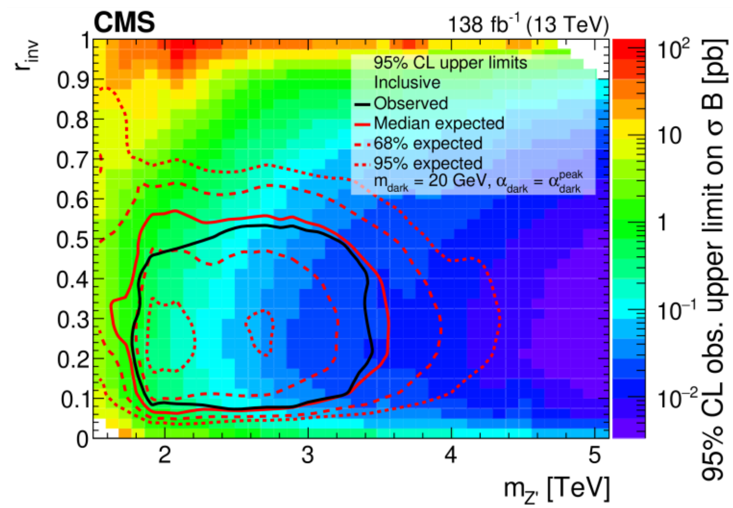


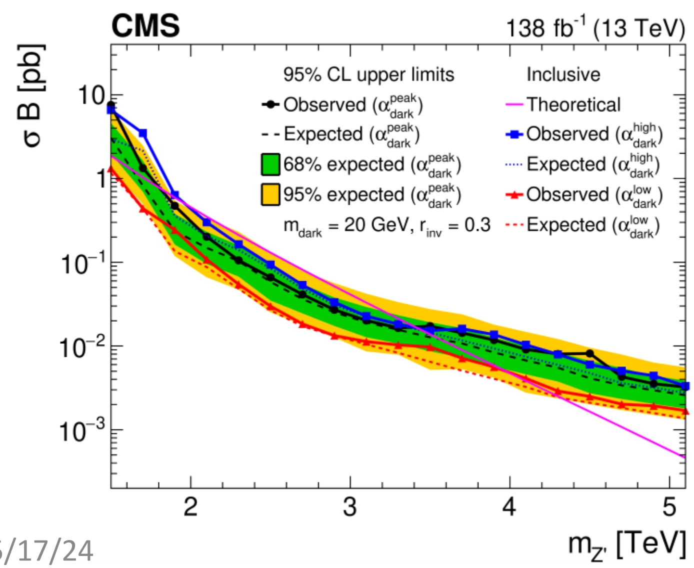
Dual strategy:

- **Inclusive search:**
  - Use only event-level kinematic variables;
  - Provides reinterpretability for other models with similar signature;
- **BDT-based search:**
  - Employ machine learning for optimized SVJ tagger;
  - maximizes sensitivity for the chosen signal models;

SVJ-search results, inclusive



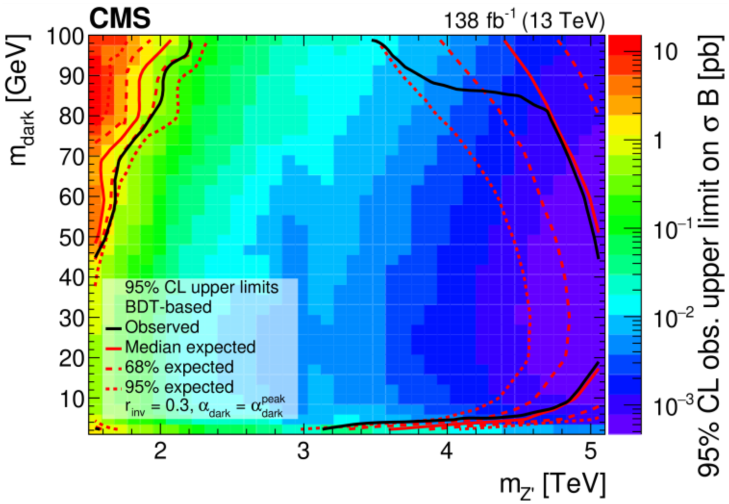


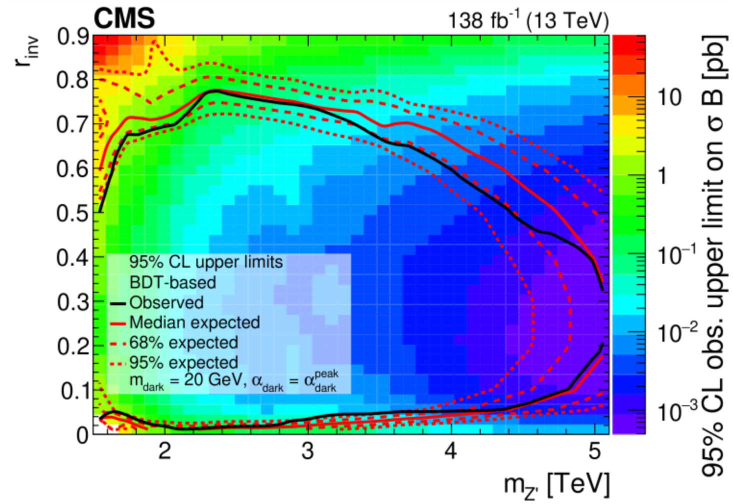


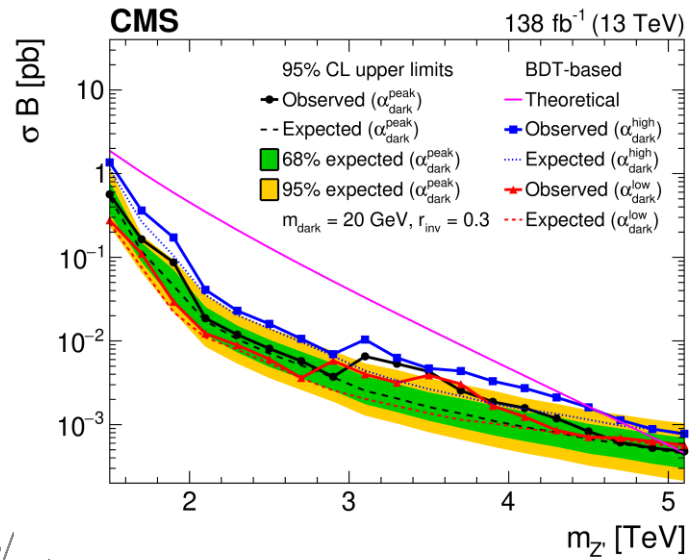
Observed (expected) exclusions:

- $1.5 < m_{Z'} < 4.0$ TeV ($1.5 < m_{Z'} < 4.3$ TeV)
- Depending on mZ':
  - $0.07 < r_{inv} < 0.53$ ($0.06 < r_{inv} < 0.57$)
- Lower bound on $m_{Z'}$ due to search using two resolved jets, boosted SVJ search probing lower $m_{Z'}$ close to publication.

SVJ-search results, BDT-based





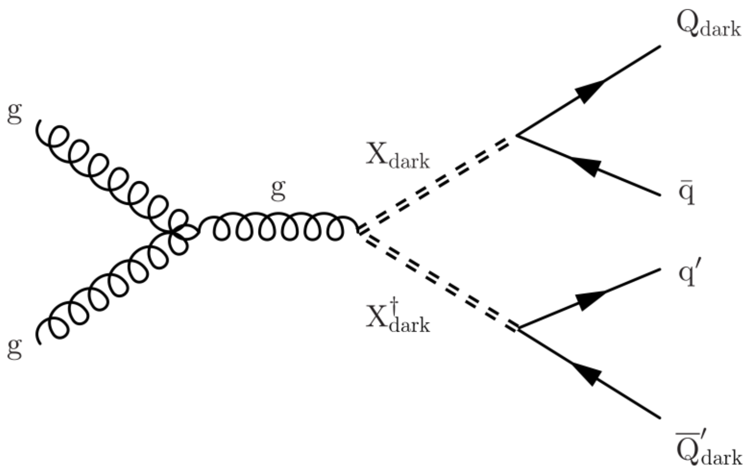


Observed (expected) exclusions:

- $1.5 < m_{Z'} < 5.01$ TeV ($1.5 < m_{Z'} < 5.1$ TeV)
- Depending on mZ':
  - $0.01 < r_{inv} < 0.77$ ($0.01 < r_{inv} < 0.78$)
- Wider exclusion comparing to inclusive approach.

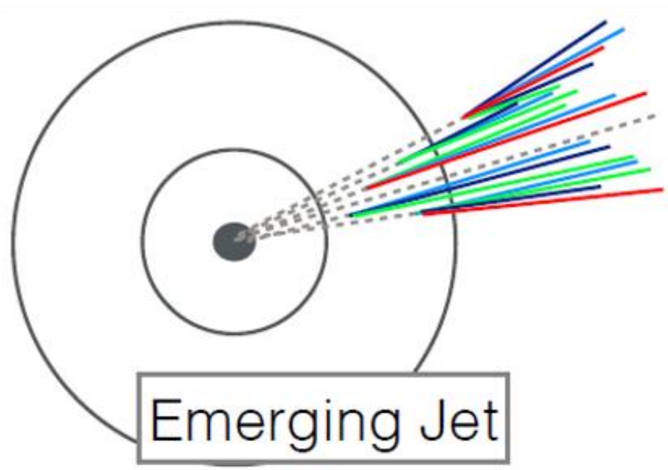
EJ-search models

JHEP 02 (2019) 179
arXiv:2403.01556 submitted to JHEP

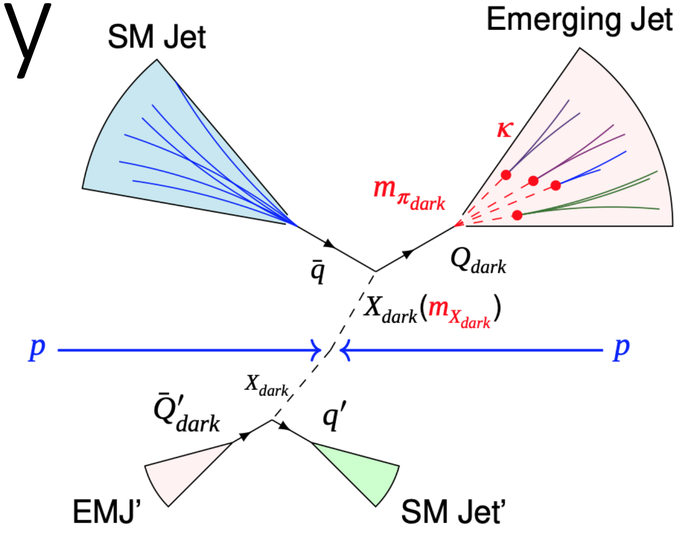


- Pair-produced bifundamental scalar mediator X_{dark} connects to SM quark and dark quark;
- $SU(N_D)$ with N_D=3, N_f=3;
- Two different signal model scenarios:
  - **Unflavored model**, where 3 generations of dark quarks are fully degenerate and couples unitarily to the SM d quark;
  - **Flavor-aligned model**, where 3 generations of dark quarks are flavor non-degenerate and couples differently to the SM down type quark;

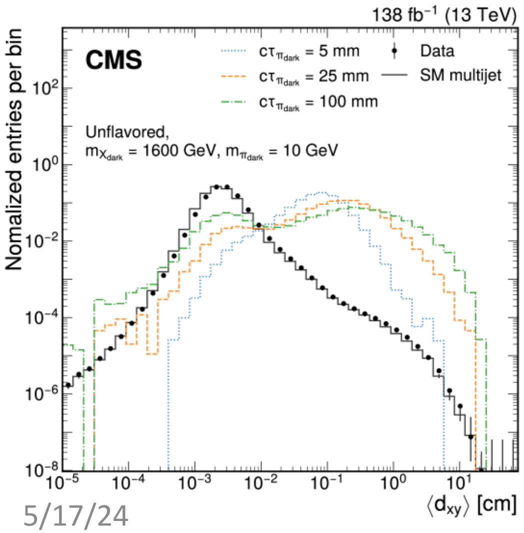
- Setting typical dark QCD configurations analogous to SM QCD, e.g. dark pion decay constant ~ dark pion mass, confinement scale ~ dark quark mass, free **model parameters** are left with $\mathbf{X_{dark}}$ **mass**, and **dark pions' mass and lifetime**.

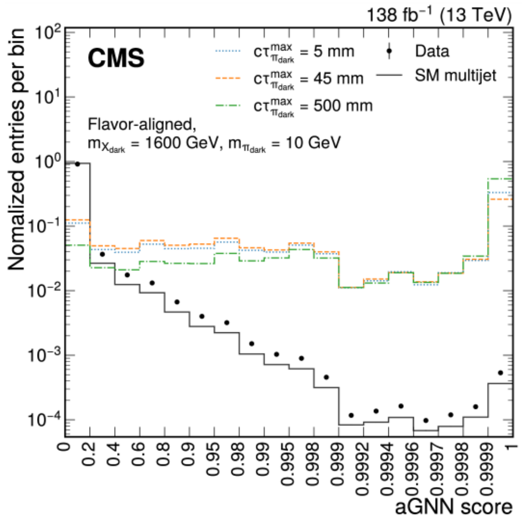


EJ-search methodology



- Signal signatures on detector:
  - Semi-long-lived dark mesons decay back to SM particles, forming **SM showers emerging from vertices** finite distances away from collision points;
  - Tree level two SM jets + 2 emerging jets;
- Cut & Count analysis
- Background estimated using control samples in data based on jet misidentification probabilities.

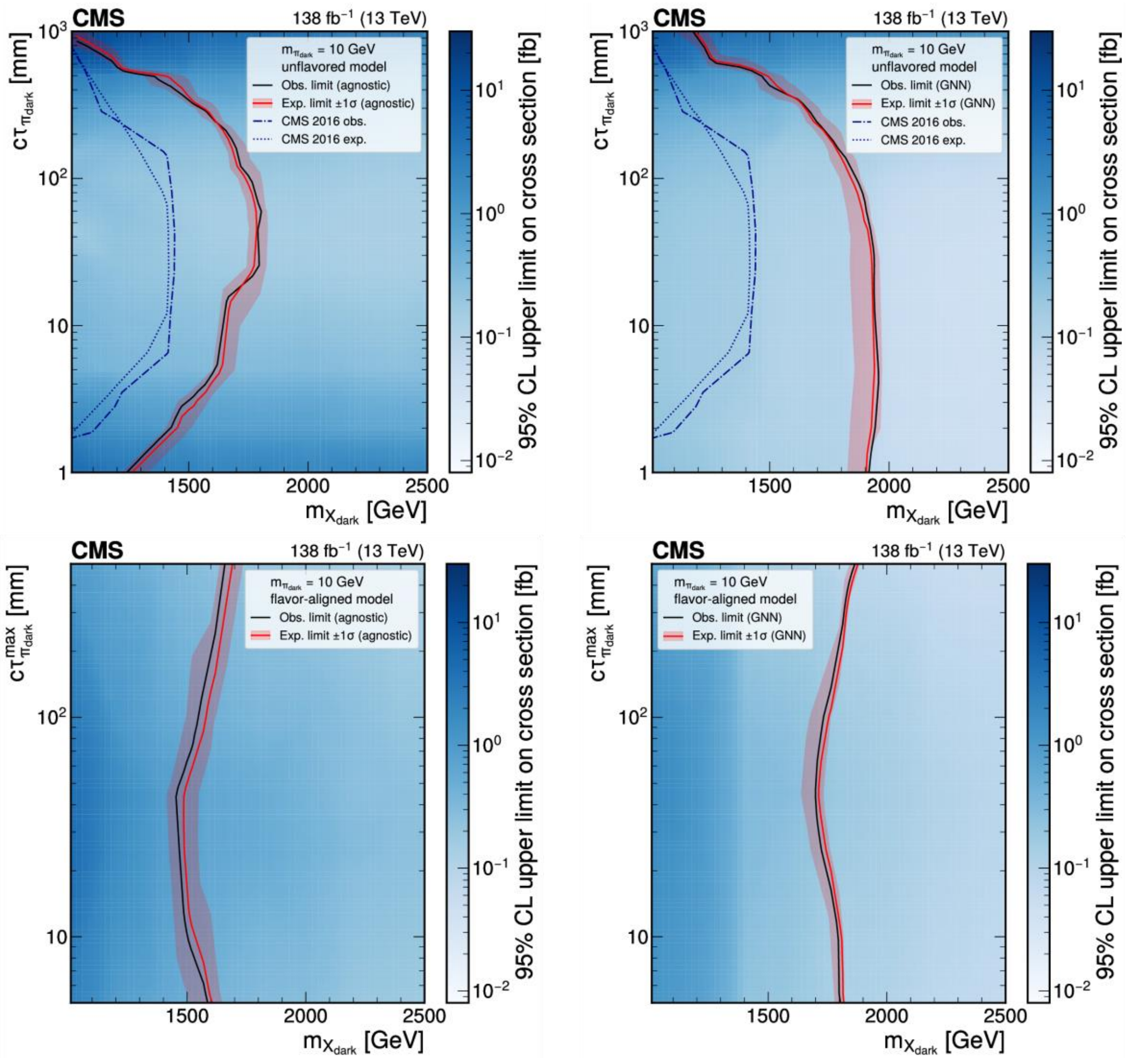




Two approaches:

- **Model-agnostic approach** for reinterpretability;
- **ML-based approach** to maximize sensitivity for the chosen models under search.

EJ-search results for $m_{\pi D}$=10 GeV

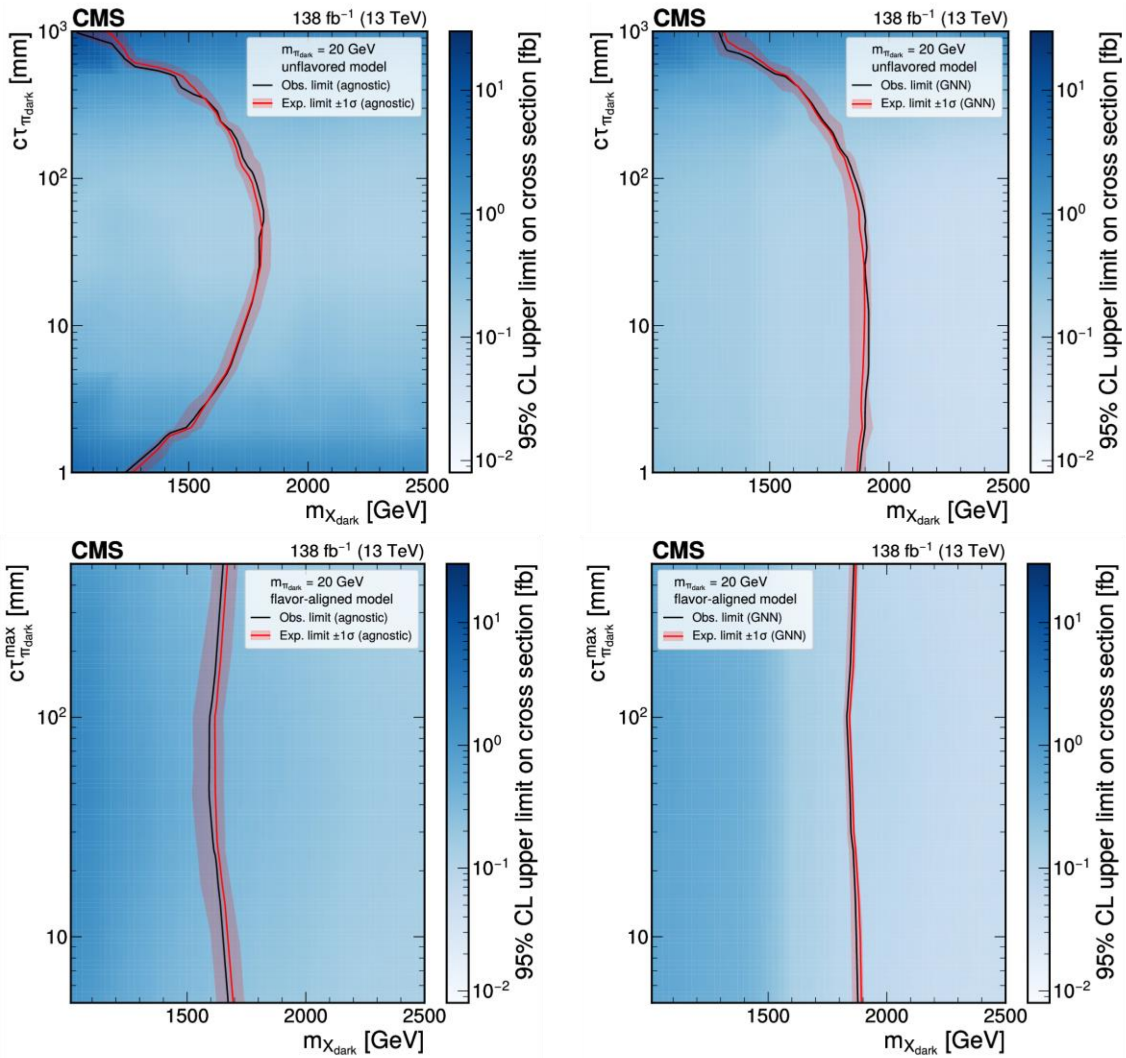


- Top: unflavored;
- Bottom: flavor-aligned;
- Left: model-agnostic;
- Right: ML-based;

- **Left side** of the contours are **excluded** by the search;
- **Large improvement** in the unflavored search **comparing to previous** publication;
- **Better sensitivity** in low dark pion lifetime regions **with ML-based search**;

- Search also provides tabulated observed event yields in the paper.

EJ-search results for $m_{\pi D}$=20 GeV

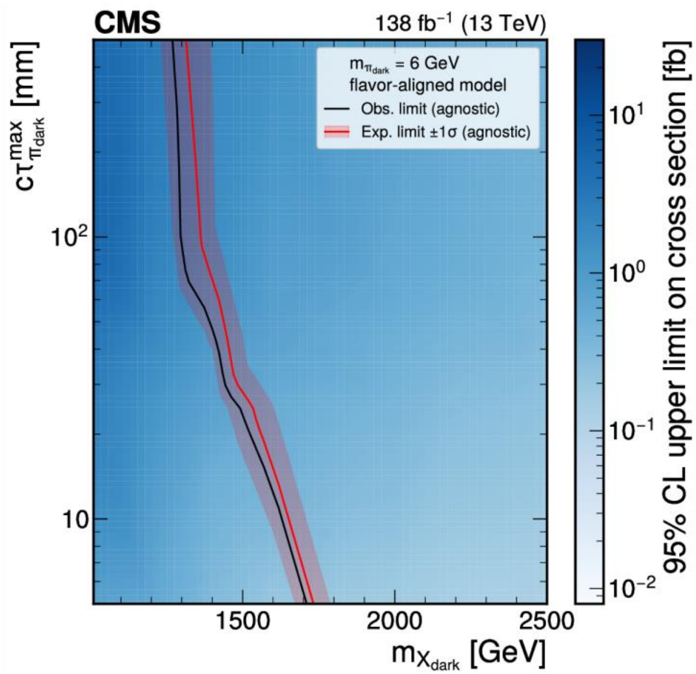


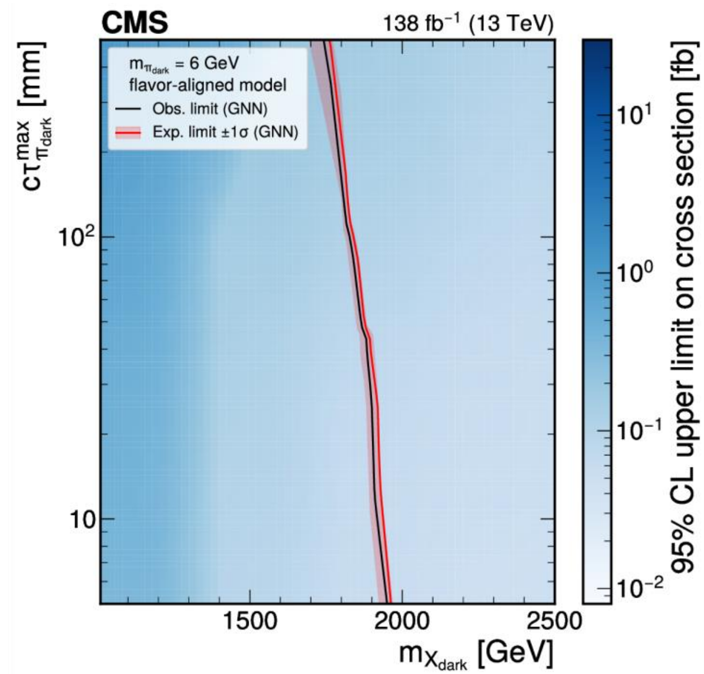
- Top: unflavored;
- Bottom: flavor-aligned;
- Left: model-agnostic;
- Right: ML-based;

- **Left side** of the contours are **excluded** by the search;
- **Large improvement** in the unflavored search **comparing to previous** publication;
- **Better sensitivity** in low dark pion lifetime regions **with ML-based search**;

- Search also provides tabulated observed event yields in the paper.

EJ-search results for m_{π_D}=6 GeV

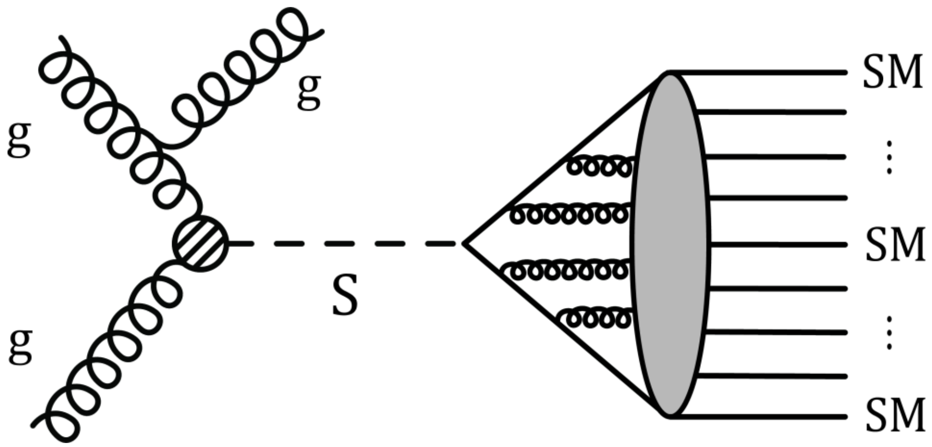


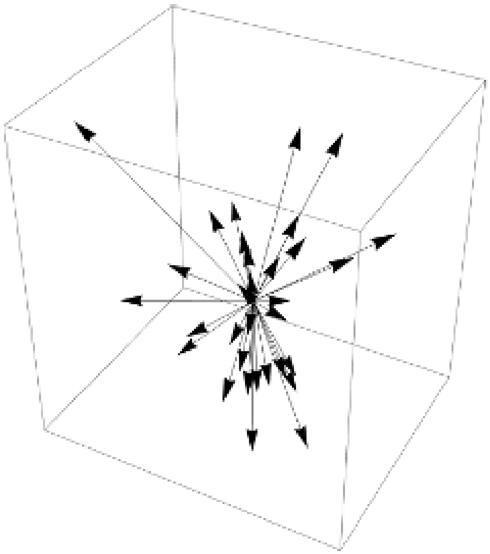


- Left: model-agnostic search; Right: ML-based search;

- Only **relevant for flavor-aligned model** scenario as the decay of dark pions starts to behave differently **due to kinematics accessibility**;
- Wider exclusion in ML-based approach comparing to model-agnostic approach.

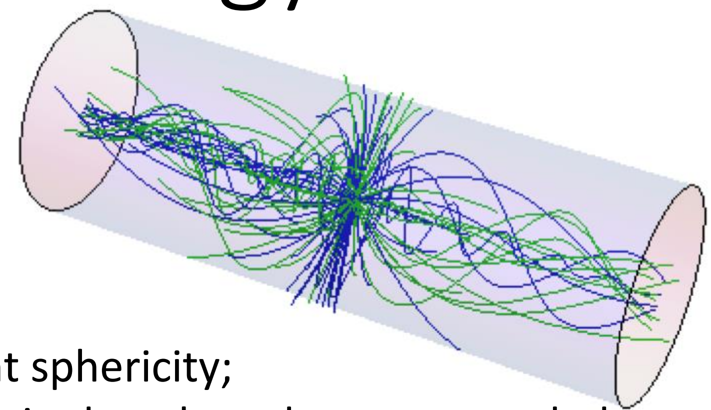
SUEP-search models [arXiv:2403.05311 submitted to PRL]





- **Production mode**: Heavy scalar mediator S produced via gluon fusion and decays to a dark quark-antiquark pair;
- Quasi-conformal dark QCD sector with large ‘t Hooft coupling λ >> 1 above Λ_D;
- Dark quarks form an **isotropic spray** of dark pseudoscalar mesons ϕ;
- **Dark mesons decay** to pairs of **dark photons A’**, that kinetically **mixes with** the SM hypercharge gauge field and decays promptly to **SM particles**;
- Model parameters of choices are: $\boldsymbol{m_S, m_\phi, m_{A'}}$ **and T** as temperature in LO Boltzmannian thermal model that governs the dark mesons decay.

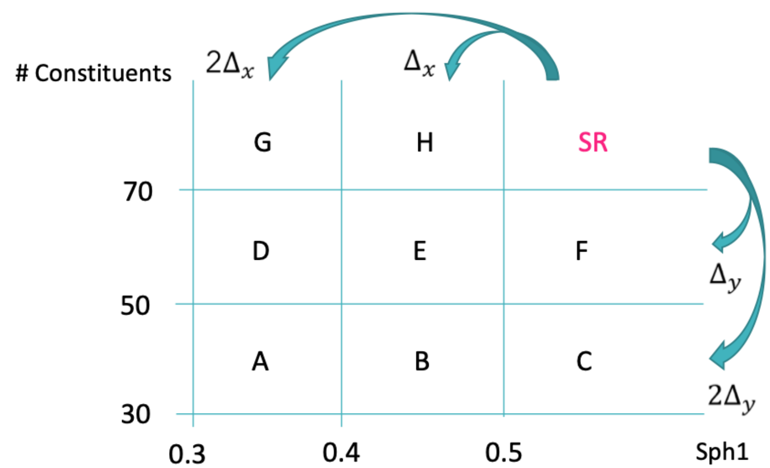
SUEP-search methodology



- Signal signatures on detector:
  - Large multiplicities of **isotropic, low p_T tracks** final state;
  - Spherically-symmetric event shape;
- Cut & Count with track multiplicity and event sphericity;
- Background estimated using control samples in data, based on an extended ABCD method;

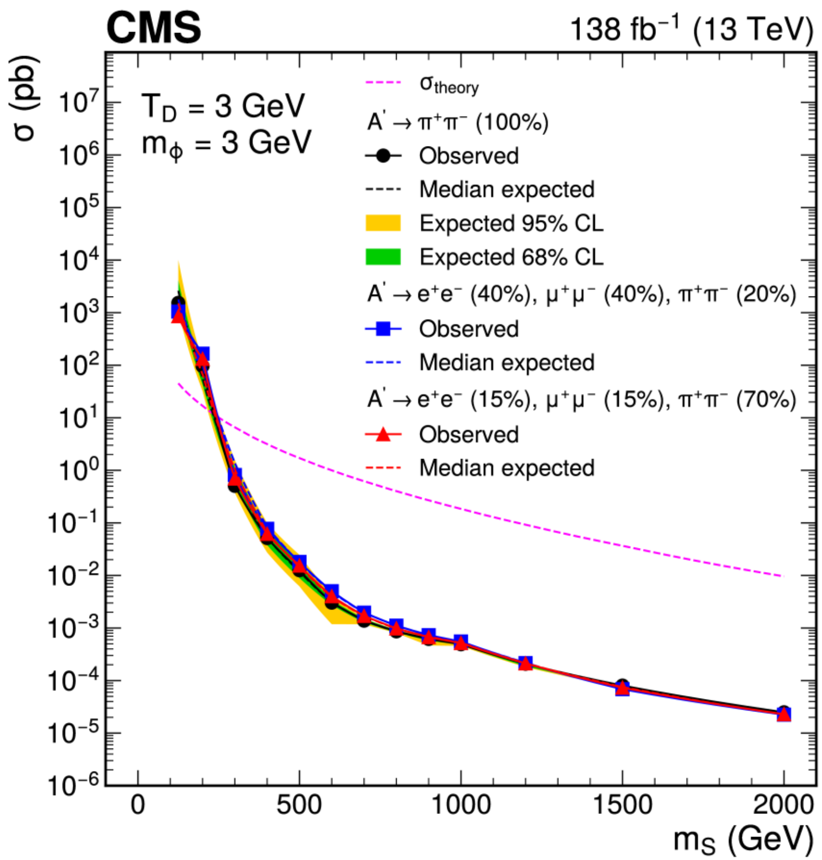
$$SR_{exp} = \frac{\frac{G\,C}{A}\left(\frac{\mathrm{H\,F}}{E}\right)^4}{\left(\frac{G\,F}{D}\right)^2\left(\frac{H\,C}{D}\right)^2} + O(\Delta^4)$$

$$SR_{exp} = (\mathrm{F\ histogram}) * \underbrace{\frac{\frac{G\,C}{A}\left(\frac{\mathrm{H}}{E}\right)^4 F^3}{\left(\frac{G\,F}{D}\right)^2\left(\frac{H\,C}{D}\right)^2}}_{\text{Scaling factor}} + O(\Delta^4)$$



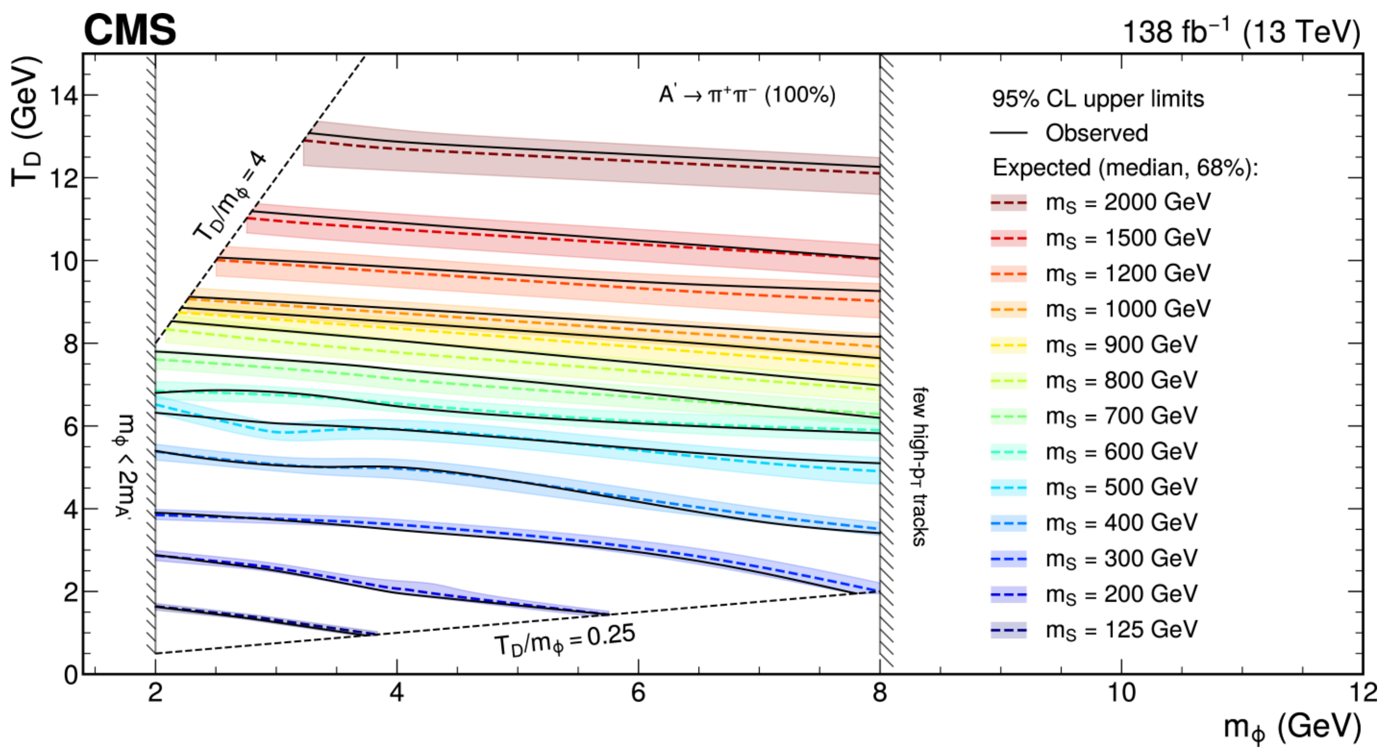
Example expanded ABCD method using SUEP candidate sphericity and constituents.

SUEP-search results



- No significant excess of events over the SM prediction;
- **1-D upper limits** on production cross section from toy frequentist approach ;
- Best sensitivity for low-medium T, m_ϕ, and medium-high m_S, as all increase the number of constituents, and push the signal in the last bins of SR;
- Similar sensitivity to **different A' decay** modes as shown in the **colored** observed lines.

SUEP-search results



- Exclusion limits for various scalar masses in the plane of m_ϕ vs T for $A' \to \pi^+\pi^-$ with B=100%, regions below the observed limits are excluded;
- Available for SUEP-like cases with $m_S/T \sim m_S/m_\phi \sim 100$ where the final state has sufficient track multiplicity to populate the last bins of the SR.

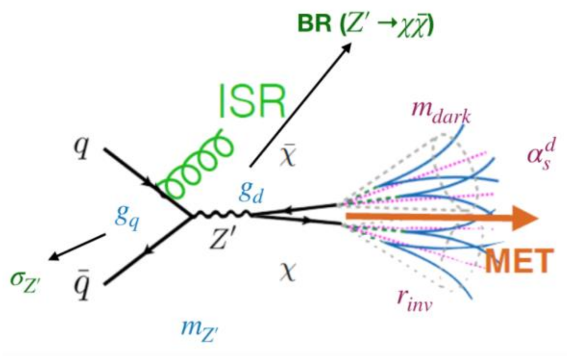
Summary

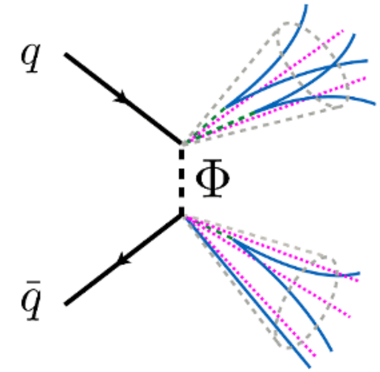
CMS has presented searches for $SU(N_D)$ gauge structured Dark Sectors focusing on scenarios $m_{qD} \lesssim \Lambda_D \ll \sqrt{s}$.

- Small 't Hooft coupling cases:
  - SVJ: Dark hadrons stable or decay promptly, vector mediator excluded within range of 1.5-5 TeV ;
  - EJ: Dark hadrons have short lifetimes, scalar mediator excluded up to 1.9 TeV;

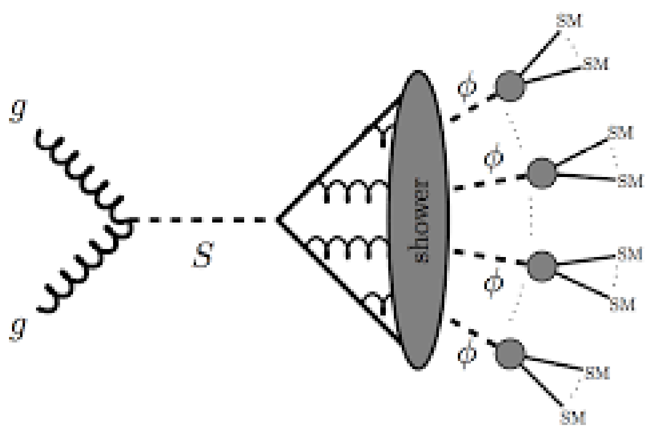
- Large 't Hooft coupling cases:
  - SUEP: Dark hadrons decay promptly without collimated jets signatures, first search at the LHC.

Backups - Undergoing DS searches

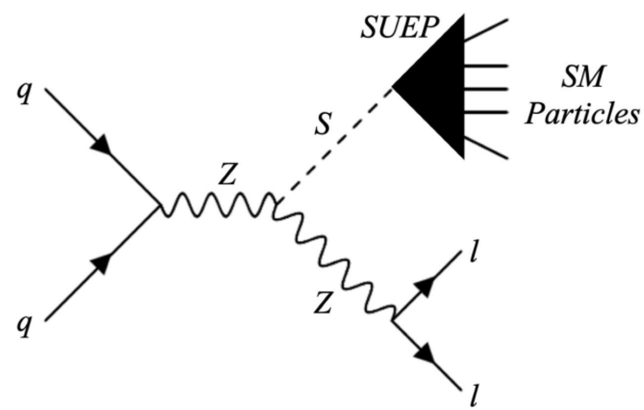




Boosted SVJ; t-channel SVJ; SVJ with leptons.



SUEP with scouting data



Associated SUEP production

Backups - EJ tabulated result

Selection set	Estimation ± stat. ± syst.	Observed yield
u-set 1	$56\ ^{+9}_{-5} \pm 20$	67
u-set 2	$20.0\ ^{+4.3}_{-2.5} \pm 7.0$	21
u-set 3	$22.9\ ^{+7.3}_{-2.1} \pm 4.9$	24
u-set 4	$7.9\ ^{+2.0}_{-1.6} \pm 2.2$	10
u-set 5	$11.3\ ^{+2.7}_{-1.9} \pm 2.0$	13
a-set 1	$8.8\ ^{+2.4}_{-1.0} \pm 2.0$	16
a-set 2	$1.67\ ^{+0.49}_{-0.23} \pm 0.38$	3
a-set 3	$1.97\ ^{+0.47}_{-0.22} \pm 0.37$	2
a-set 4	$2.30\ ^{+0.81}_{-0.30} \pm 0.39$	3
a-set 5	$10.2\ ^{+2.3}_{-1.1} \pm 3.4$	16
uGNN set 1	$15.6\ ^{+5.4}_{-1.9} \pm 3.8$	18
uGNN set 2	$0.73\ ^{+0.44}_{-0.16} \pm 0.27$	0
uGNN set 3	$7.6\ ^{+3.5}_{-1.3} \pm 2.3$	9
aGNN set 1	$45\ ^{+18}_{-8} \pm 16$	59
aGNN set 2	$0.30\ ^{+0.23}_{-0.07} \pm 0.18$	1
aGNN set 3	$3.8\ ^{+2.2}_{-0.7} \pm 2.0$	5