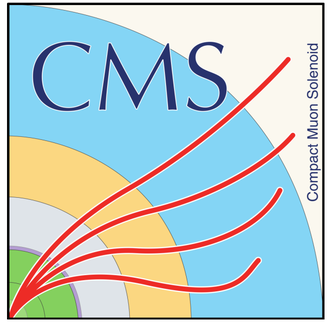


BROWN

Investigating the Physics of the Dark Sector with CMS

Jingyu Luo

Brown University

On behalf of the CMS collaboration

CERN LPCC EP-LHC seminar, July 9th, 2024

The standard model of particle physics

❖ **The standard model is amazingly successful**

The seminal paper by Weinberg 57 years ago

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

$$L \equiv [\tfrac{1}{2}(1+\gamma_5)]\begin{pmatrix}\nu\\ e\end{pmatrix} \qquad (1)$$

and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under T and Y gauge transformations is

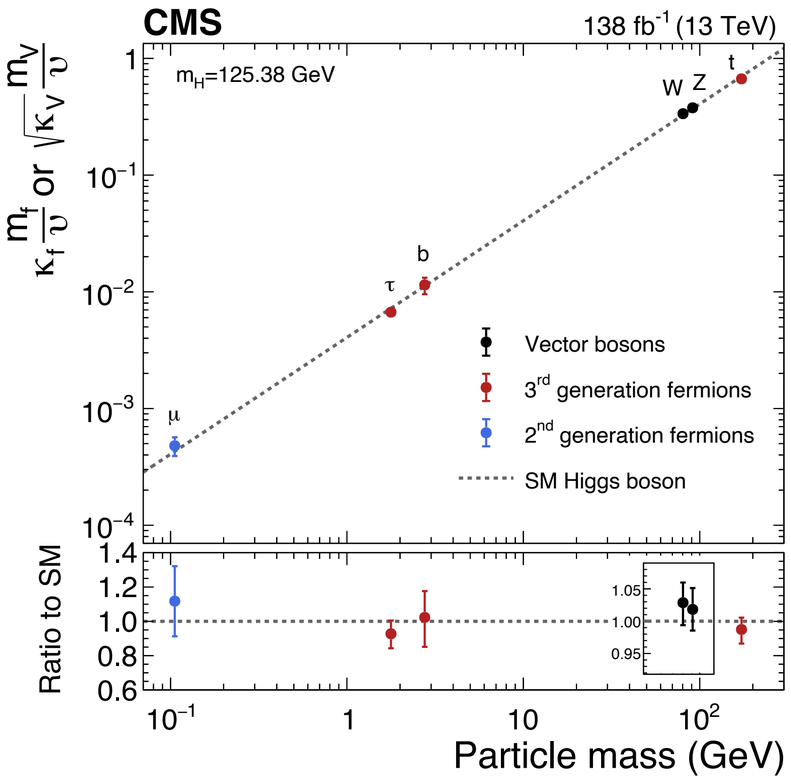
$$\mathfrak{L} = -\tfrac{1}{4}(\partial_\mu \vec{A}_\nu - \partial_\nu \vec{A}_\mu + g\vec{A}_\mu \times \vec{A}_\nu)^2 - \tfrac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar{R}\gamma^\mu(\partial_\mu - ig'B_\mu)R - L\gamma^\mu(\partial_\mu - ig\vec{t}\cdot\vec{A}_\mu - i\tfrac{1}{2}g'B_\mu)L$$

Higgs interactions

$$|\partial_\mu\varphi - ig\vec{A}_\mu\cdot\vec{t}\,\varphi + i\tfrac{1}{2}g'B_\mu\varphi|^2 - G_e(\bar{L}\varphi R + \bar{R}\varphi^\dagger L) + M_1{}^2\varphi^\dagger\varphi + h(\varphi^\dagger\varphi)^2. \qquad (4)$$

Gauge interactions | Yukawa couplings | Higgs potential

The discovery of the Higgs boson marks the most recent triumph



Nature 607 (2022) 60

However, there are still many profound mysteries, necessitating the quests beyond the SM.

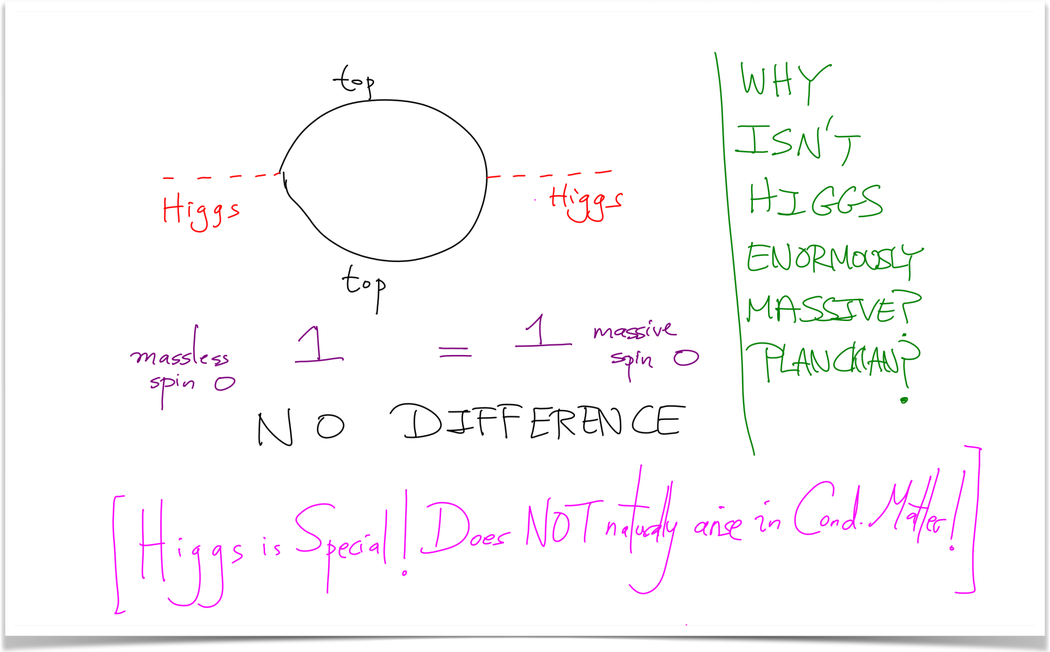
The Higgs boson — a new territory

❖The Higgs boson itself is in fact "new" physics

- The first (possibly) elementary scalar we have ever discovered in nature

> "*There is today a wide spread view that … scalar field theories with ϕ^4 interactions, are not mathematically consistent.*"
> — **Steven Weinberg,** *The Quantum Theory of Fields, vol. 2*

  - The Hierarchy Problem — m_H v.s. Λ_{Planck}
  - No Higgs boson in condensed matter systems



(**Nima Arkani-Hamed**, Higgs turns 10 celebration@CERN)

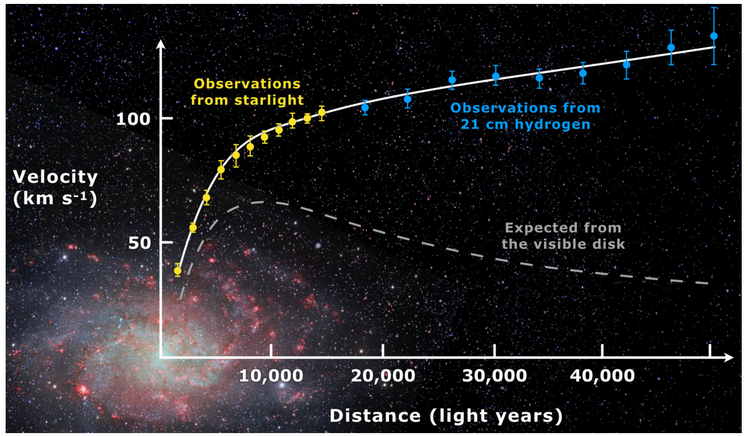
Exhaustively examining the Higgs boson is extremely important

A unique window into new "dark" sectors. [Brain Patt & Frank Wilczek, 2006]

Astrophysical and cosmological evidences of dark matter

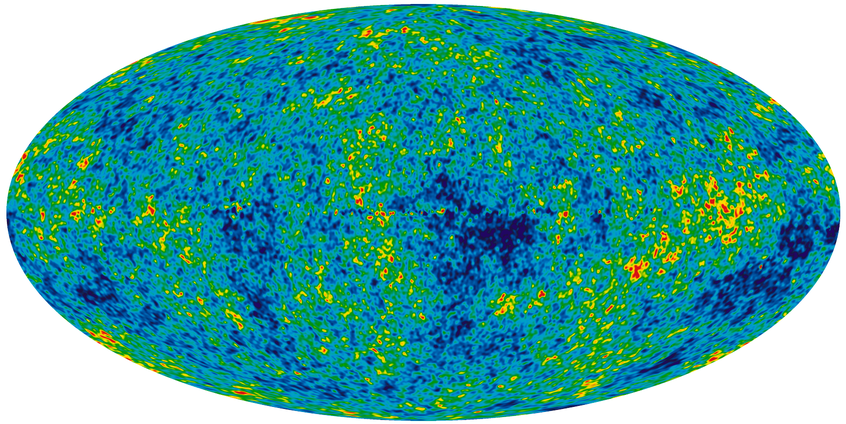
❖Evidences of dark matter are overwhelming

Galaxy rotation curves



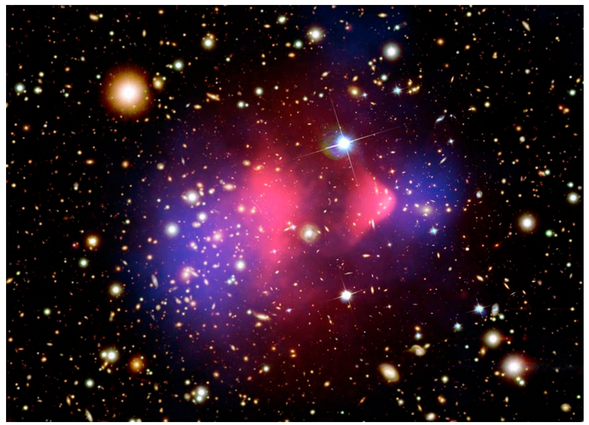
Galaxy Messier 33 — 21cm line

Cosmic microwave background (CMB)



Planck space observatory

Bullet cluster

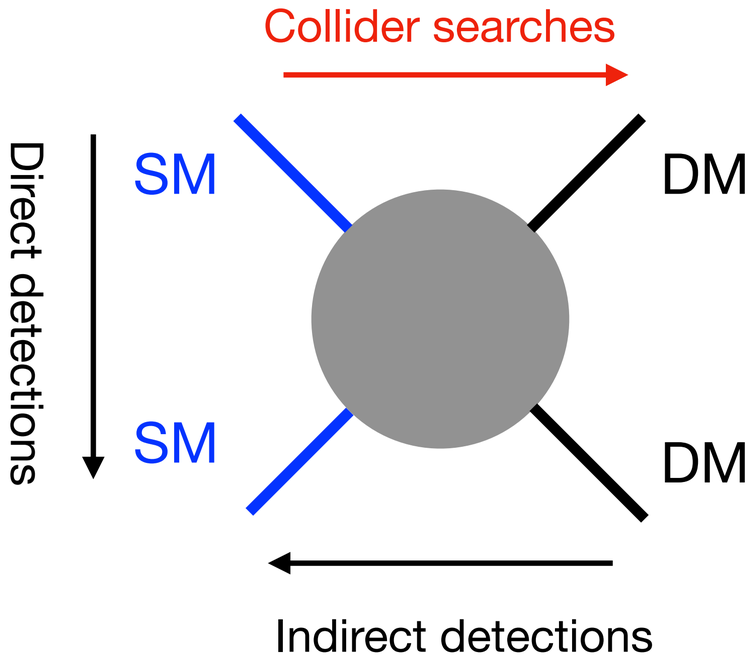


Chandra/Magellan/Hubble telescopes

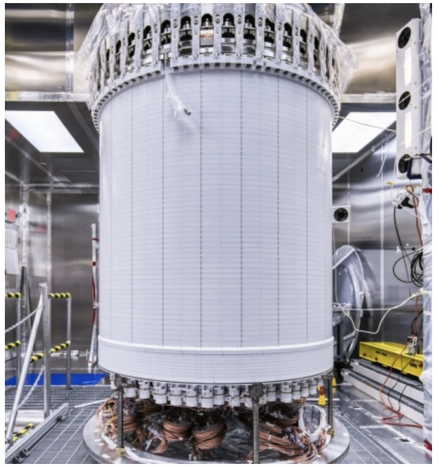
- Dark matter is 5x more abundant than ordinary matter (according to e.g. CMB fit);
- Standard model doesn't provide dark matter candidates;
- The particle nature of the dark matter remains a mystery.

Searches for dark matter/sectors

❖**Extensive searches have been performed with different experimental techniques**



EFT



LZ experiment

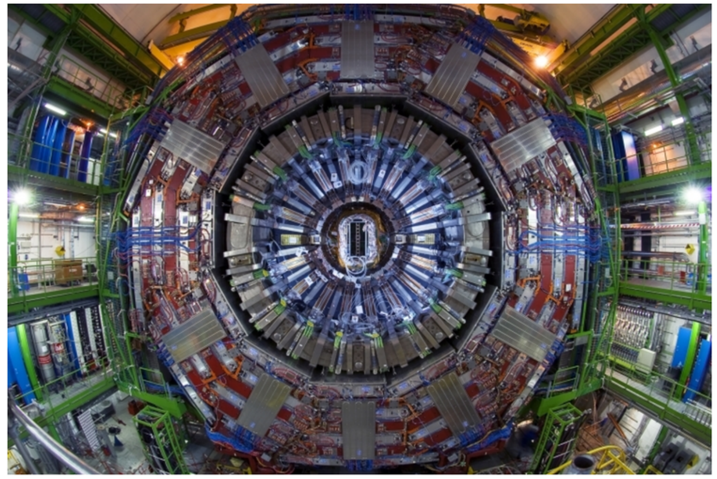
Direct detections

- *DM-nucleon scatterings;*
- *Axion conversions.*

AMS experiment

Indirect detections

- *DM annihilations*



CMS experiment

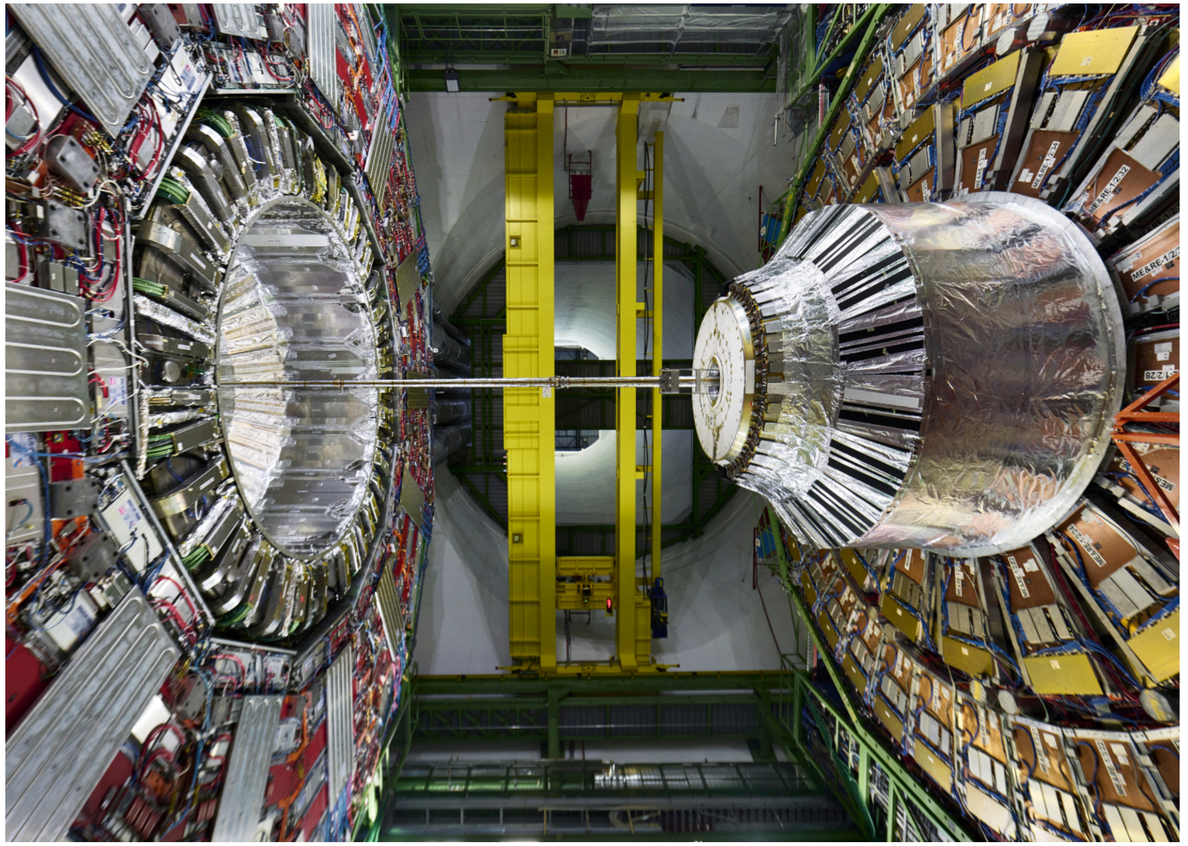
Collider Searches

- *Invisible/visible final states;*
- *Unconventional signatures.*

Dark matter/sector searches at CMS

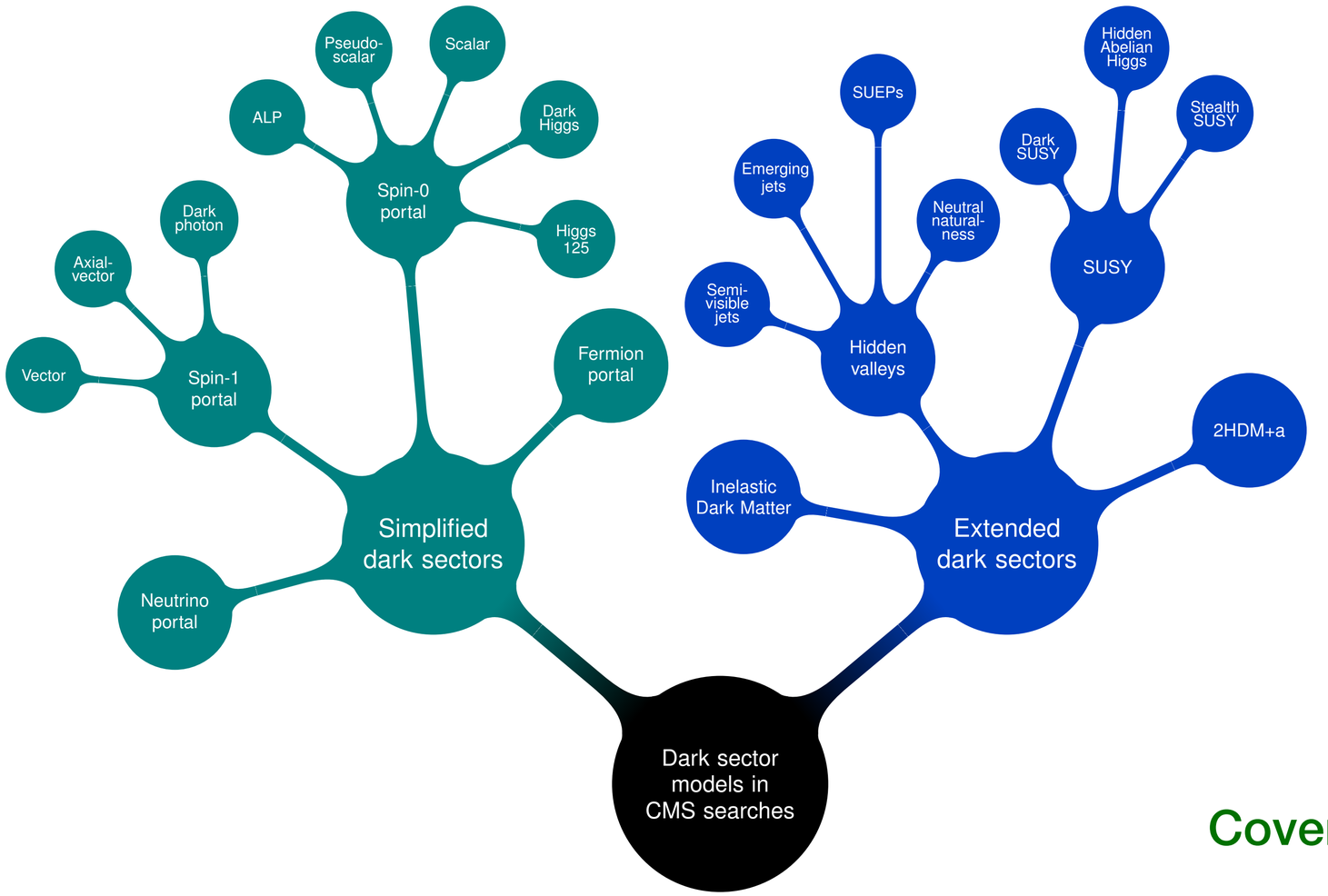
❖CMS is a powerful experiment in exploring dark sectors

- Excellent detector performances
- Highly flexible data-taking system
  - Dedicated trigger algorithms;
  - Data scouting — trigger-level objects for high-rate “real-time” analyses;
  - Data parking — delayed reconstruction for lower trigger thresholds.
- Innovative reconstruction and analysis techniques
  - Displaced tracking, timing, etc.
  - Advanced machine-learning algorithms.



Dark matter/sector searches at CMS

❖Map of CMS searches for dark sectors



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-106
2024/05/24

CMS-EXO-23-005

Dark sector searches with the CMS experiment

The CMS Collaboration*

arXiv: 2405.13778, submitted to Physics Reports

- Huge community efforts within CMS
  - ~**20** editors
  - ~**40** analyses
  - ~**500** authors
  - **145** pages
  - **10** updated summary plots
  - **27** new reinterpretations

Covered mass range from ~GeV to multiple TeV

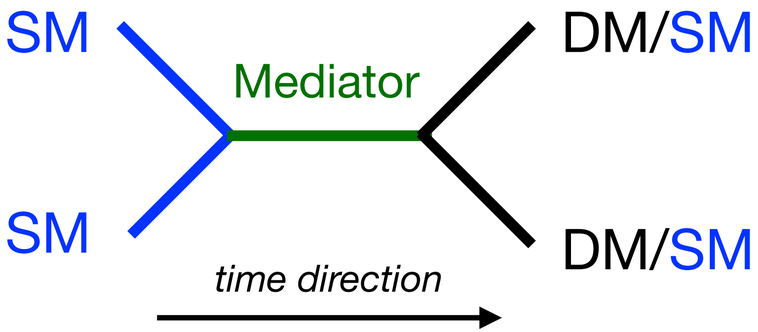
Covered analyses

Invisible	Visible	Long-lived
Mono-X	**Low-mass resonances**	**Displaced leptons**
Monojet (EXO-20-004)	Boosted dijet (EXO-18-012)	Displaced ee, emu, mumu (EXO-18-003)
Mono-Z (EXO-19-003)	Dijet + photon (EXO-17-027)	Displaced dimuons (EXO-21-006, EXO-23-014)
Monotop (EXO-16-051)	Boosted bbbar (EXO-17-024)	H to aa to 4mu (HIG-18-003)
Monophoton (EXO-16-053)	Dimuon including scouting (EXO-19-018)	Displaced dimuon scouting (EXO-20-014)
Mono-H (EXO-18-011)	Dimuon scouting (EXO-21-005)	**Hadronic LLP decays**
Dark Higgs (WW) + MET (EXO-21-012)	**High-mass resonances**	Displaced jets (EXO-19-021)
H to invisible	Dijet + ISR (EXO-19-004)	Displaced vertices (EXO-19-013)
VBF (HIG-20-003)	Dijet (EXO-19-012)	Emerging jets (EXO-18-001, EXO-22-015)
ttH/VH (HIG-21-007)	Dilepton (EXO-19-019)	Stopped particles (EXO-16-004)
Dark photons: ZH (EXO-20-005), VBF (EXO-19-007)	**Other signatures**	Muon detector showers (EXO-20-015, EXO-21-008)
Hidden Valley	Fractionally charged part. (EXO-19-006)	**LLP + p_T^{miss}**
Semivisible jets (EXO-19-020)	SUEPs, offline (EXO-23-002)	Inelastic DM (EXO-20-010)
	Stealth/RPV stops (SUS-19-004)	Delayed jets (EXO-19-001)
	ALPs in PbPb (FSQ-16-012)	Trackless and OOT jets (EXO-21-014)
	CEP w/ TOTEM (EXO-19-009)	Displaced vertices + MET (EXO-22-020)

Dark sector benchmarks

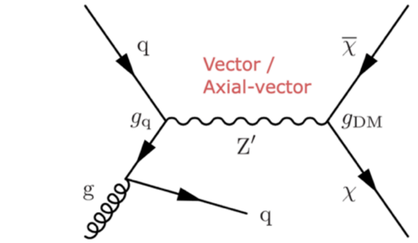
❖Simplified dark sectors

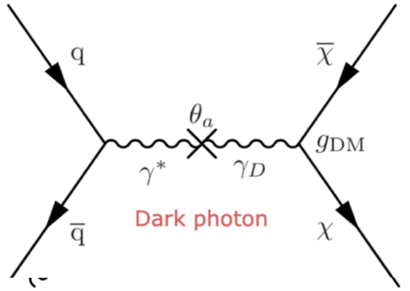
- One DM candidate + one mediator (portal)
- Additional states in the dark sector are assumed to be decoupled



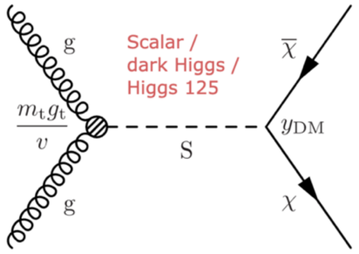
Categorized according to the mediator/portal

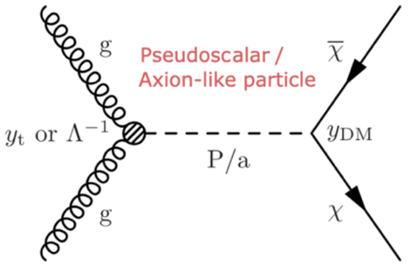
Spin-1 portal



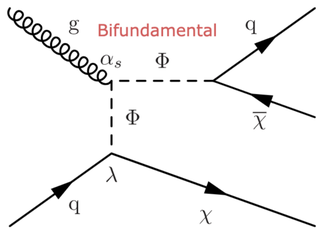


Spin-0 portal





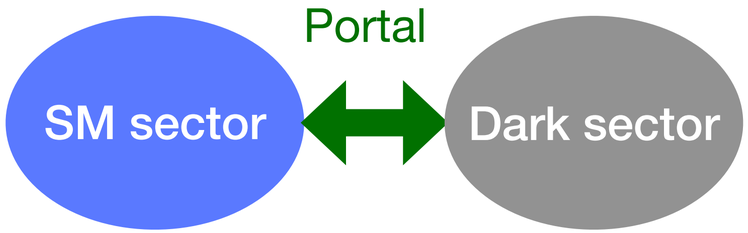
Fermion portal



- **Typical signatures:**
  - **Invisible final states:** DM productions
  - **Fully visible final states:** mediator resonances

Dark sector benchmarks

❖Extended dark sectors



General definition of a dark/hidden sector:

- *A family of particles/states that are SM singlets;*
- *Communicate with the SM sector through possible portal(s).*

- **Rich structures:**
  - Multiple particles/states including the DM candidate;
  - Can have its own symmetries and dynamics.

- **Important physics implications**
  - Dark matter, hierarchy problem, matter-antimatter asymmetry, neutrino mass, cosmological tensions, etc.

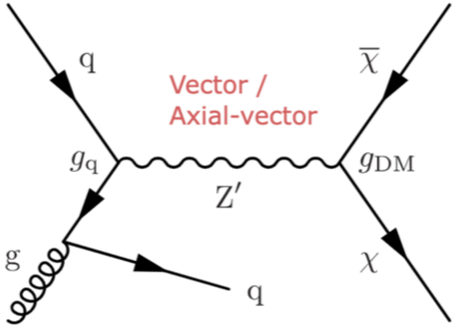
- **Rich phenomenology:**
  - Long-lived particles are a generic feature;
  - Other striking signatures.

"The idea of looking for hidden (dark) sectors is so natural, and so well-motivated, and so interesting, that you should just start with that."

— Nima Arkani-Hamed, IAS

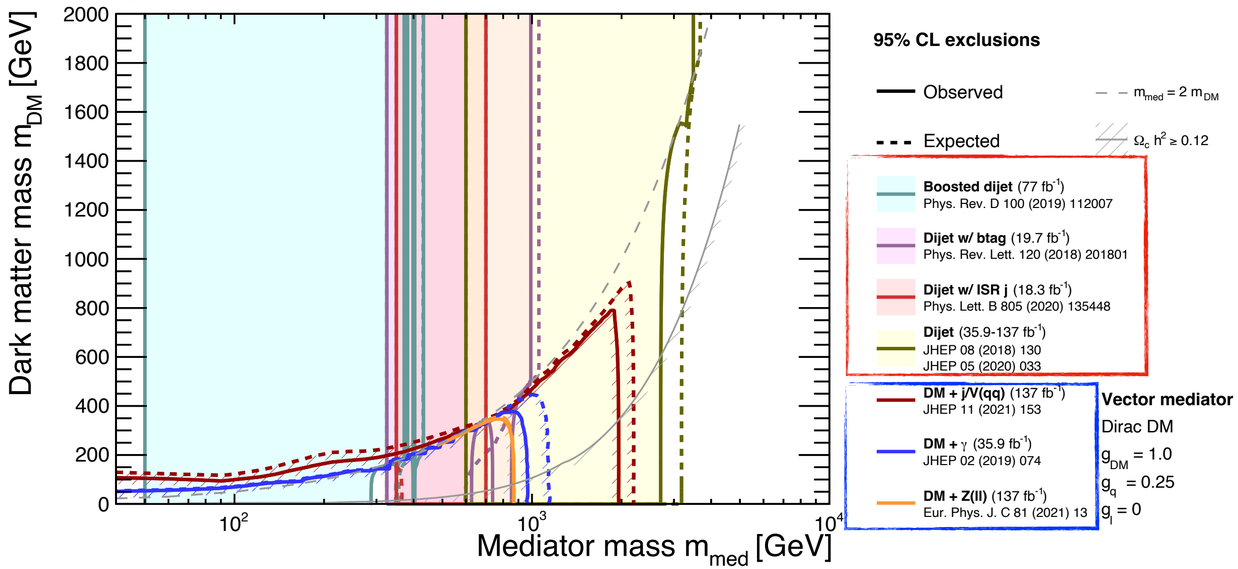
Spin-1 portal simplified dark sector

❖Vector/axial-vector couplings

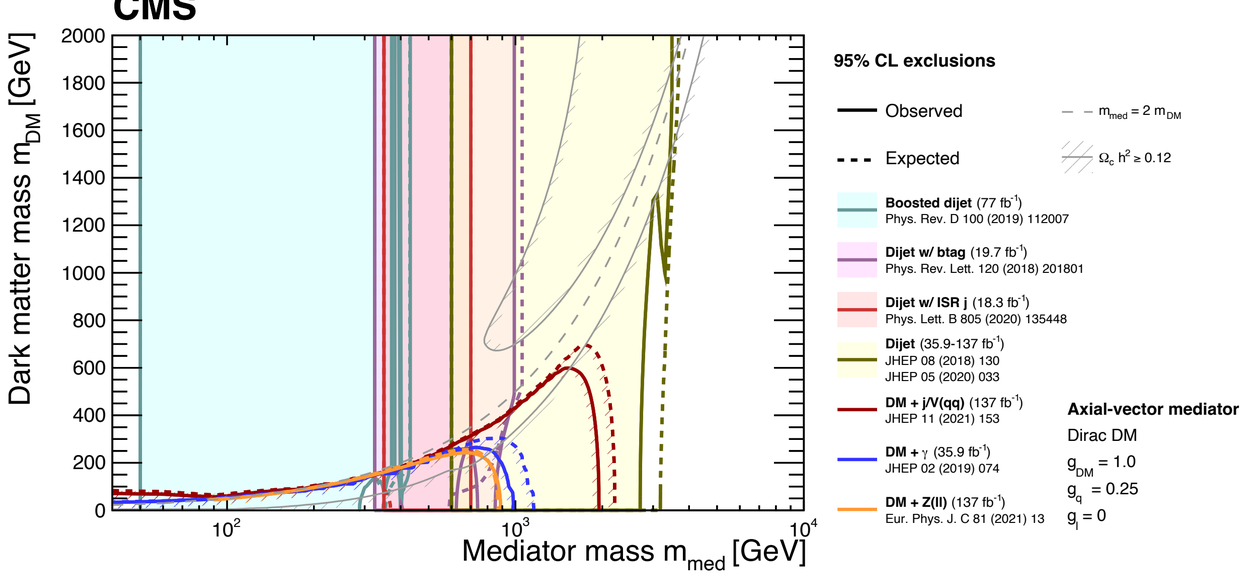


- Invisible final states: p_T^{miss}+X signatures (coupling to DM)
- Visible final states: mediator resonances (coupling to SM)

Vector mediator

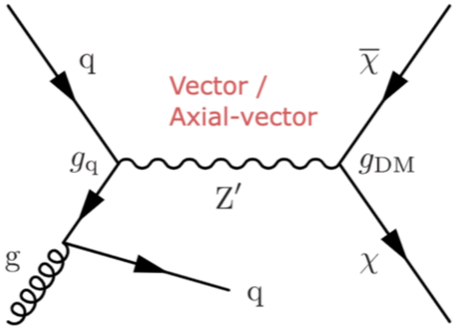


Axial-vector mediator



Spin-1 portal simplified dark sector

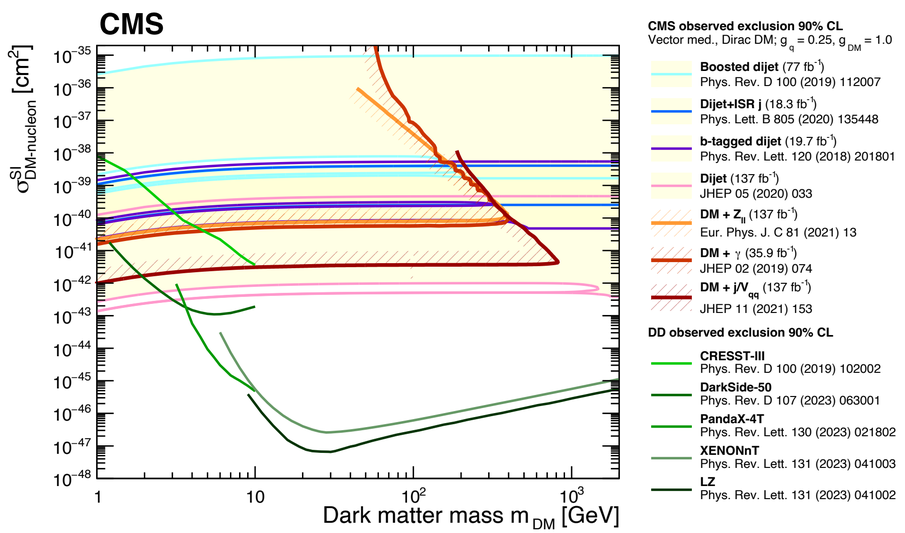
❖Vector/axial-vector couplings



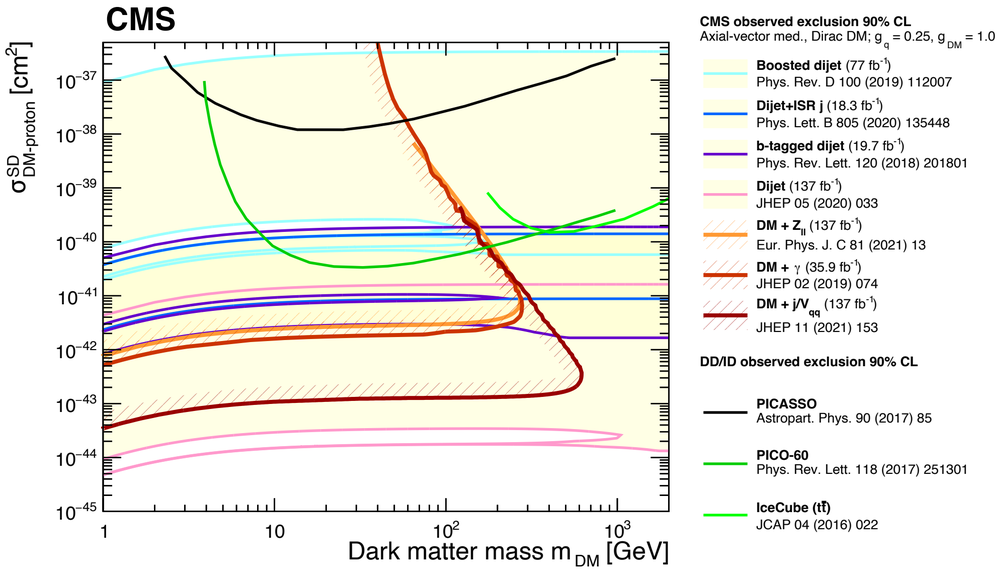
- Translated to spin-independent and spin-dependent DM-nucleon scattering cross sections
- Comparisons with direct/indirect-detection experiments

Better sensitivities for low masses or spin-dependent scenario.

Spin independent

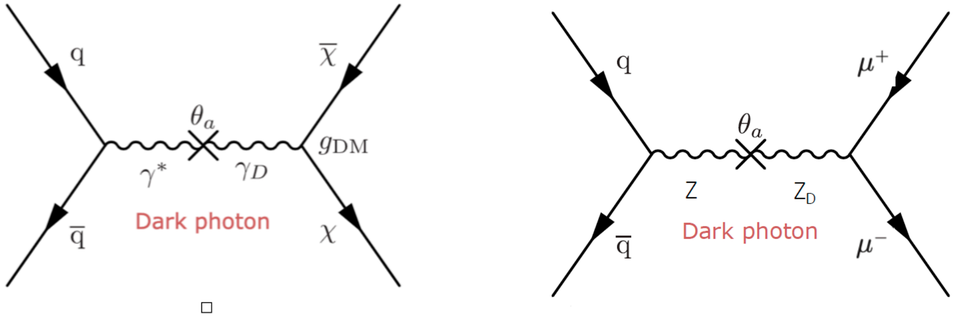


Spin dependent

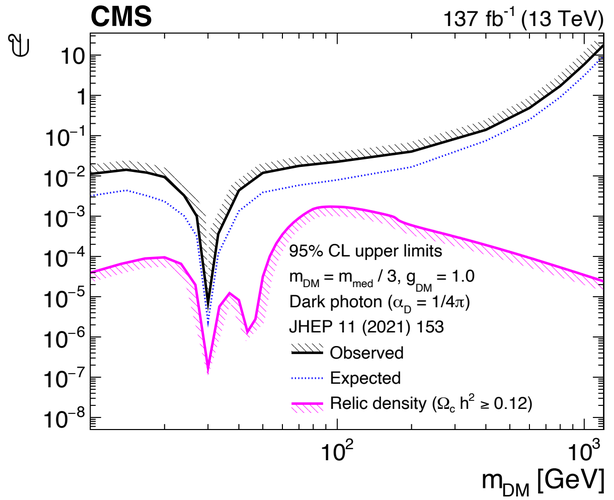


Spin-1 portal simplified dark sector

❖Dark photon couplings



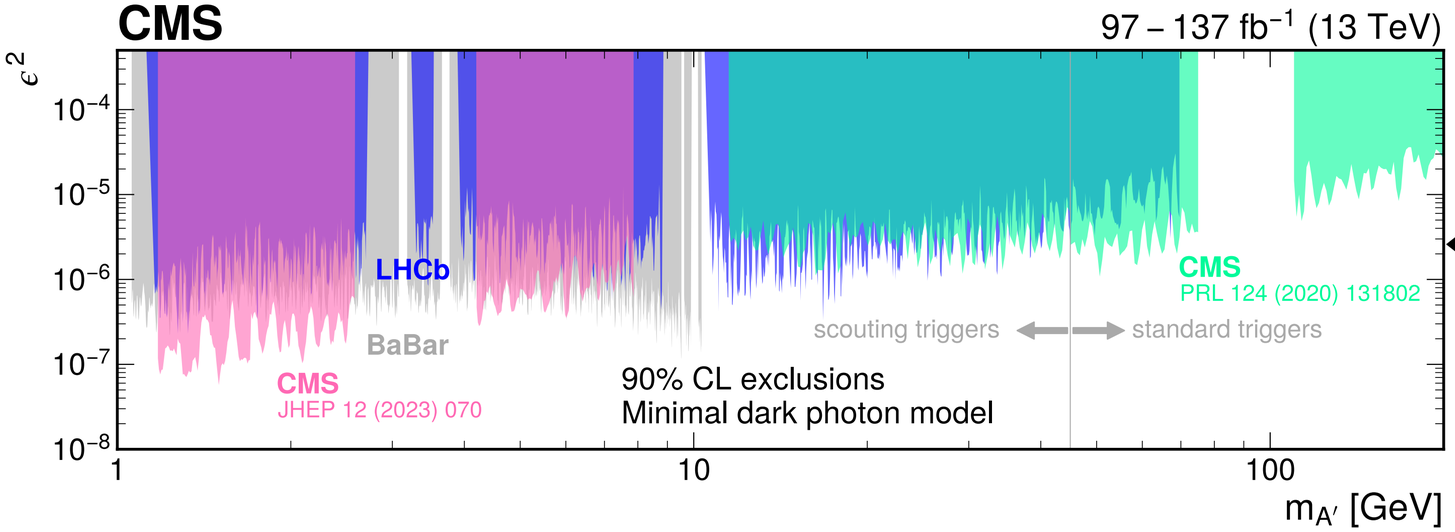
Mono-jet (invisible final states)



New interpretation!

[JHEP 11 (2021) 153]

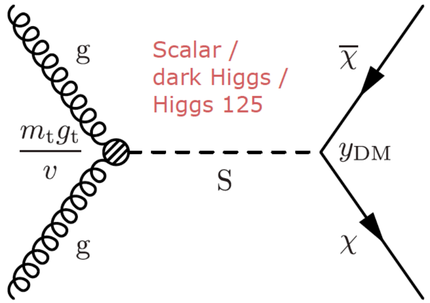
Dimuon searches (visible final states)



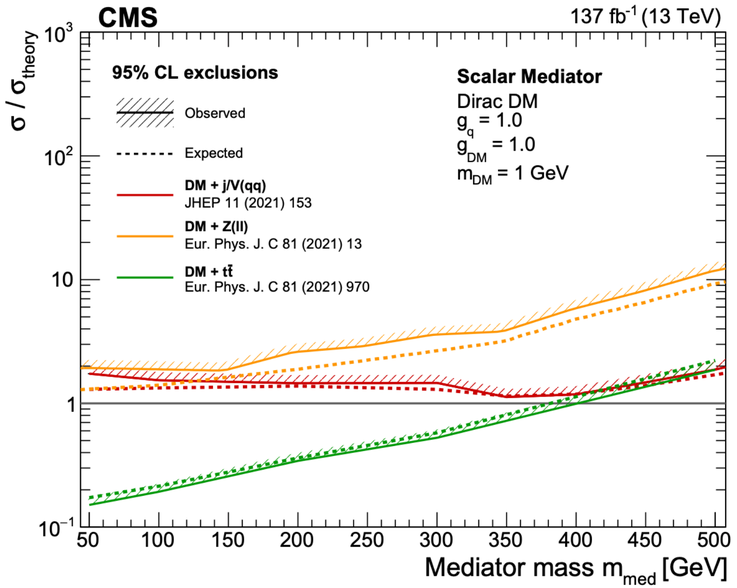
Different data-taking strategies are complementary:

- Data scouting allows sensitivities to the low-mass region

Spin-0 portal simplified dark sector



Scalar mediator

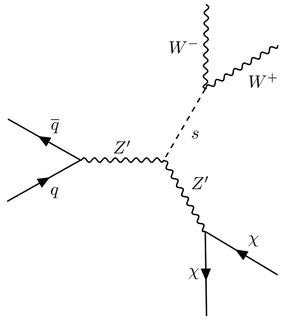


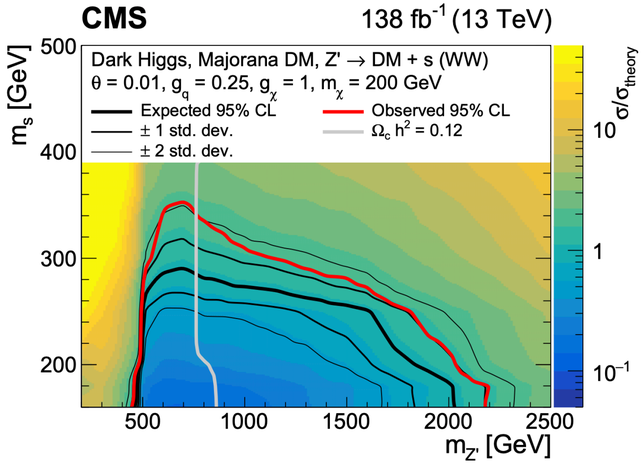
Sensitivities driven by $t\bar{t}+p_T^{miss}$
(Yukawa-like couplings)

Dark Higgs

Scalar mediator mixed with the Higgs boson

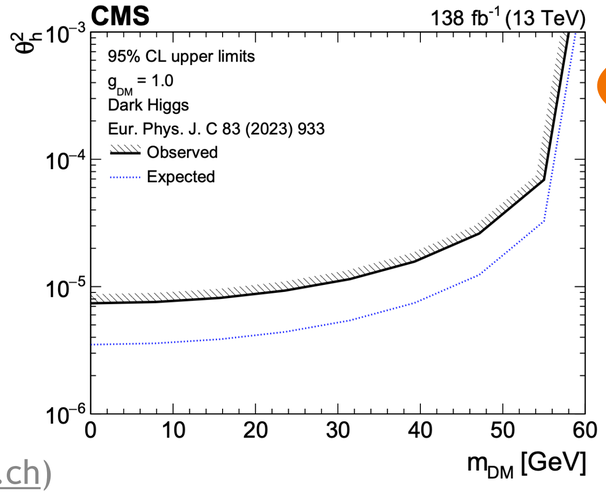
$s \rightarrow WW\ (+Z' \rightarrow DM)$





[JHEP 03 (2024) 134]

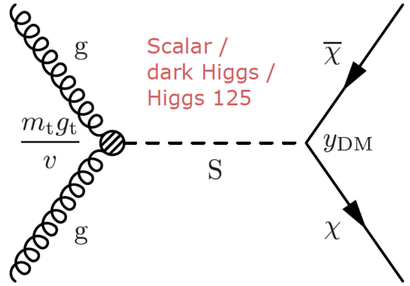
$H \rightarrow inv$



New interpretation!

[EPJC 83 (2023) 933]

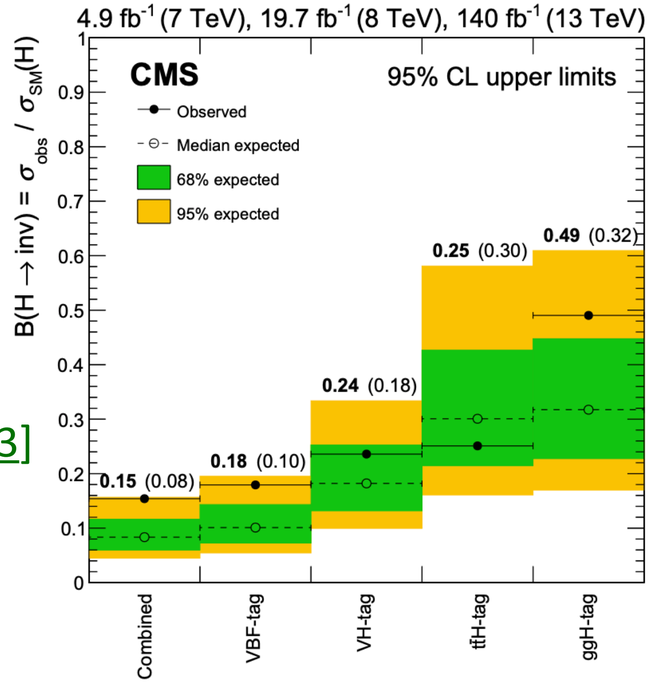
Spin-0 portal simplified dark sector



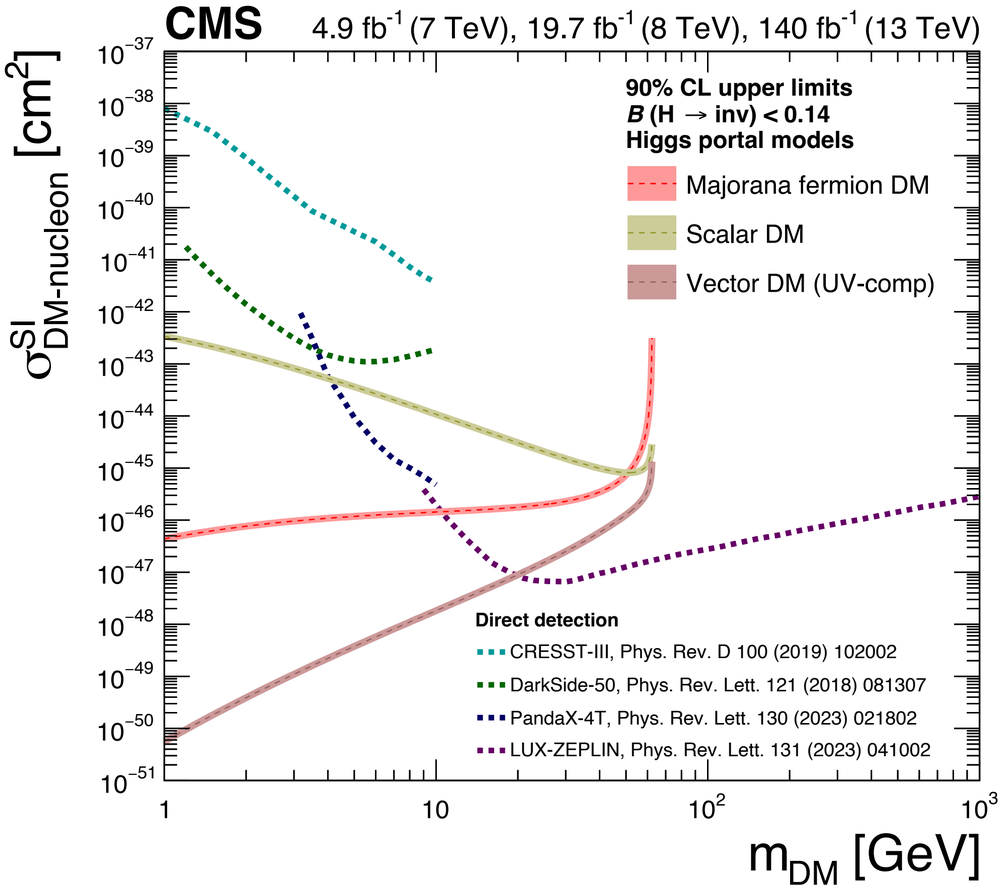
Higgs portal

$H \rightarrow inv$

[EPJC 83 (2023) 933]



Comparison with direct detections

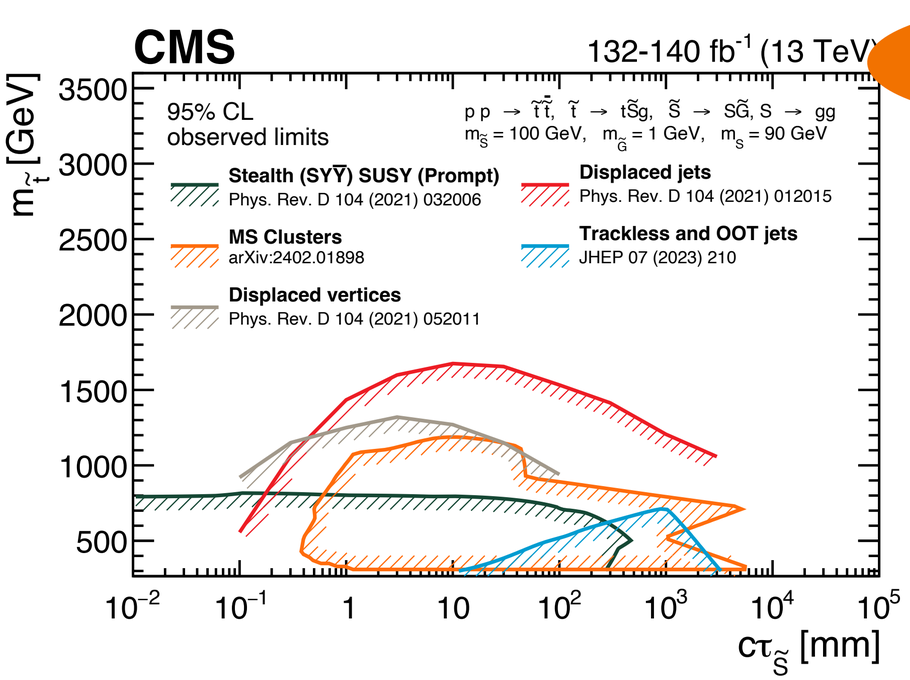


Extended dark sectors

Stealth SUSY

Highly supersymmetric dark/hidden sector

- Compressed spectrum;
- Highly suppressed p_T^{miss}, usually has LLPs

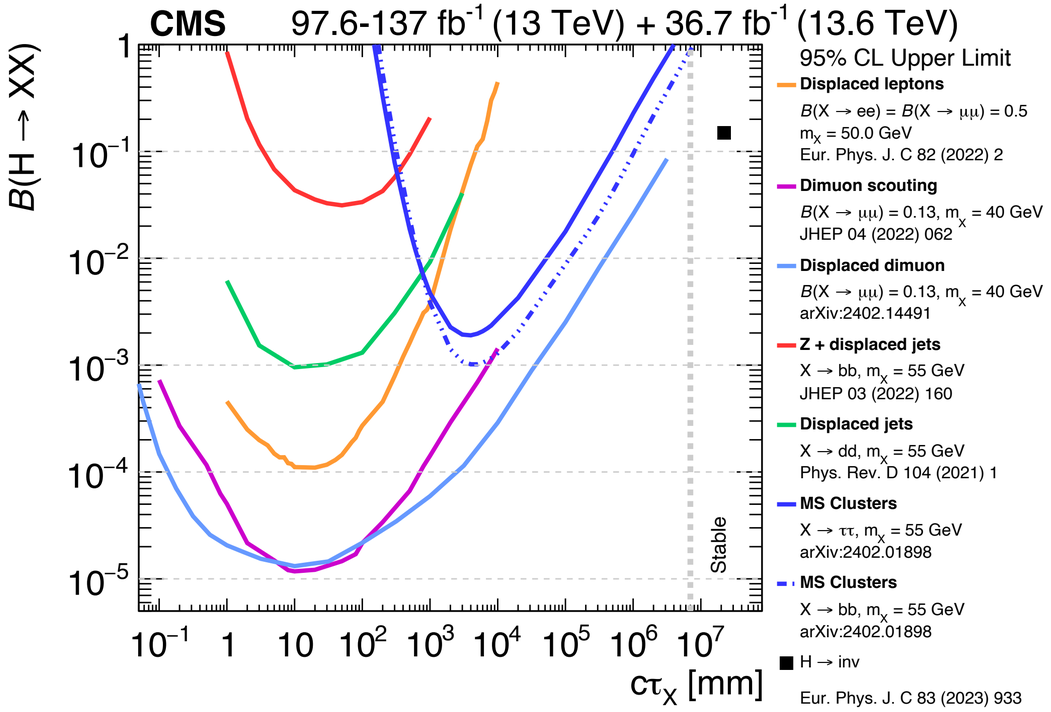


New interpretations!

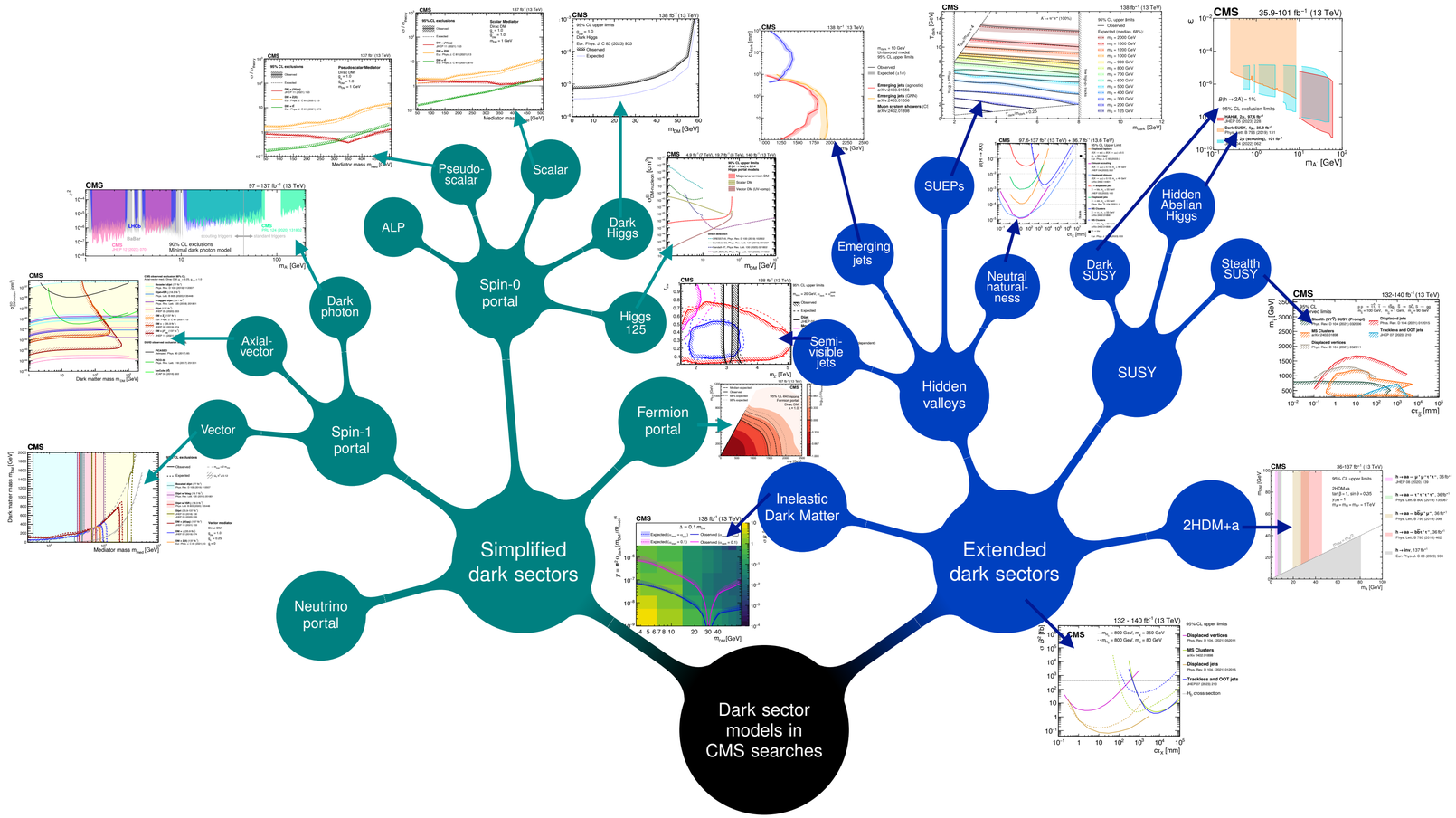
Higgs→LLPs

Higgs decays to LLPs in the dark sector

- Hadronic decays and leptonic decays
- Wide coverages for different lifetimes



Coverage of the dark sector searches at CMS



Many more results/ interpretations for 2HDM+a, semi-visible jets, emerging jets, SUEPs, Z'→LLPs, inelastic dark matter, …

<u>arXiv: 2405.13778</u>

submitted to Physics Reports

New and ongoing searches for dark sectors

❖**In addition to a harvest of the existing results, we are also actively exploring new frontiers of dark sectors**

- New signatures;
- New experimental techniques;
- New data — Run-3 dark sector search results available!

New results for simplified dark sectors

Search for dark matter associated with top final states

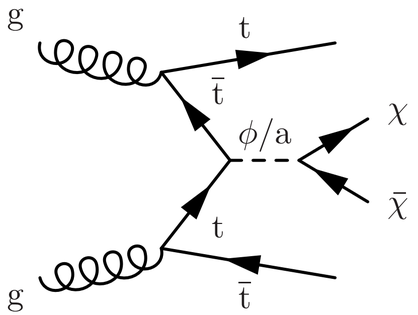
❖Spin-0 portal simplified dark sector

Scalar portal $$g_q \frac{S}{\sqrt{2}} \sum_q y_q q\bar{q} + y_\chi S\bar{\chi}\chi$$

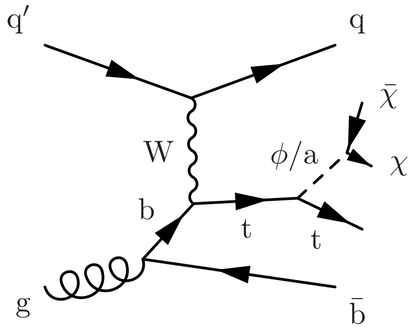
Pseudo-scalar portal $$g_q \frac{a}{\sqrt{2}} \sum_q y_q q\gamma^5\bar{q} + y_\chi a\bar{\chi}\gamma^5\chi$$

- Yukawa-like couplings to SM quarks (minimum flavor violation)
  - To avoid flavor physics constraints
  - Couplings to top quarks are favored

Motivates top quark(s) + p_T^{miss} signatures

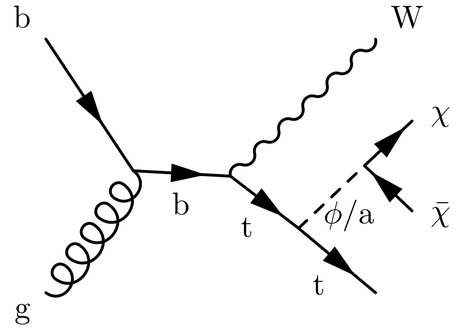


$t\bar{t}$ + DM



t + DM

(*t*-channel)

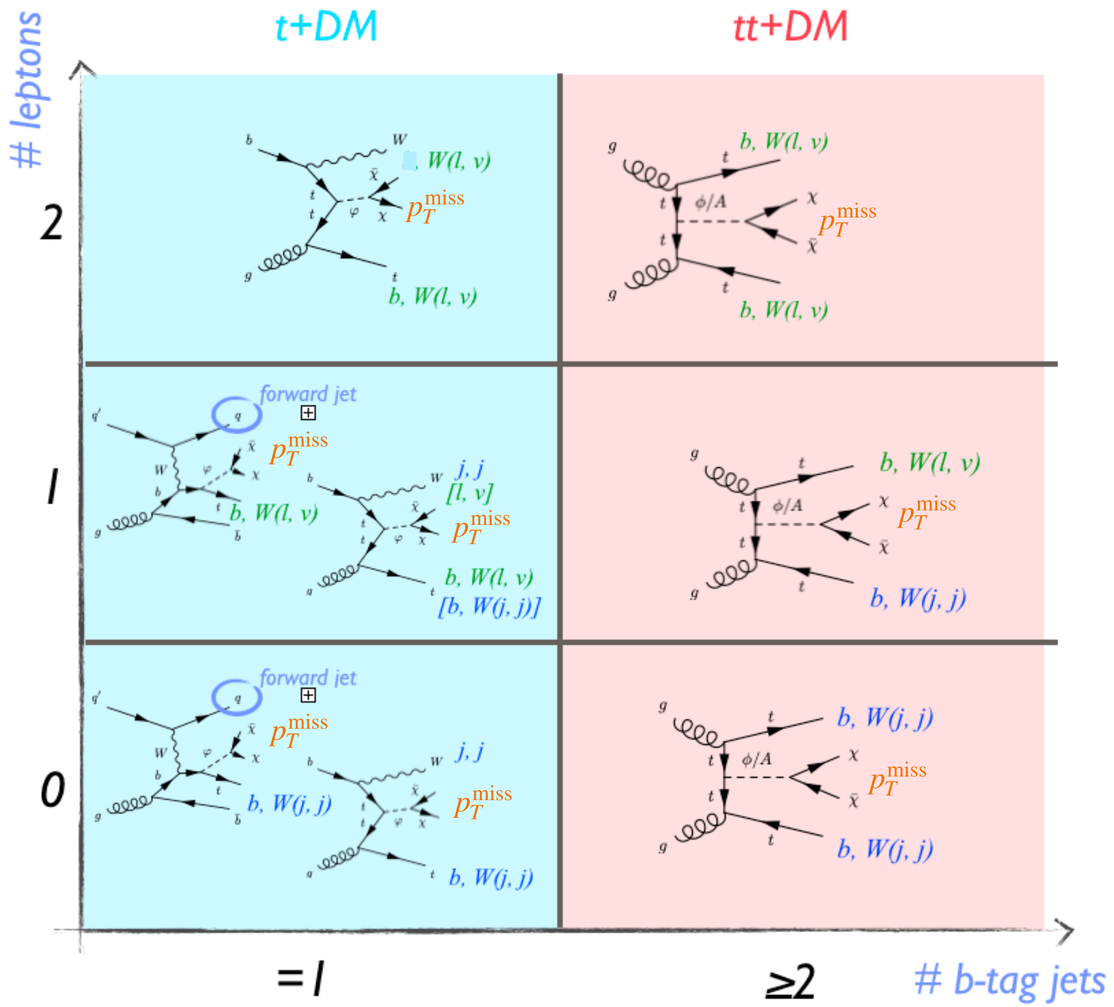


t + DM

(tW-channel)

Search for dark matter associated with top final states

- New full Run-2 results [CMS-PAS-EXO-22-014]



- Considering all three channels
  - all hadronic (AH),
  - semileptonic (SL)
  - dileptonic (DL)
- tt+DM and t+DM probed at the same time
- Events are categorized according to the number of leptons and the number b jets

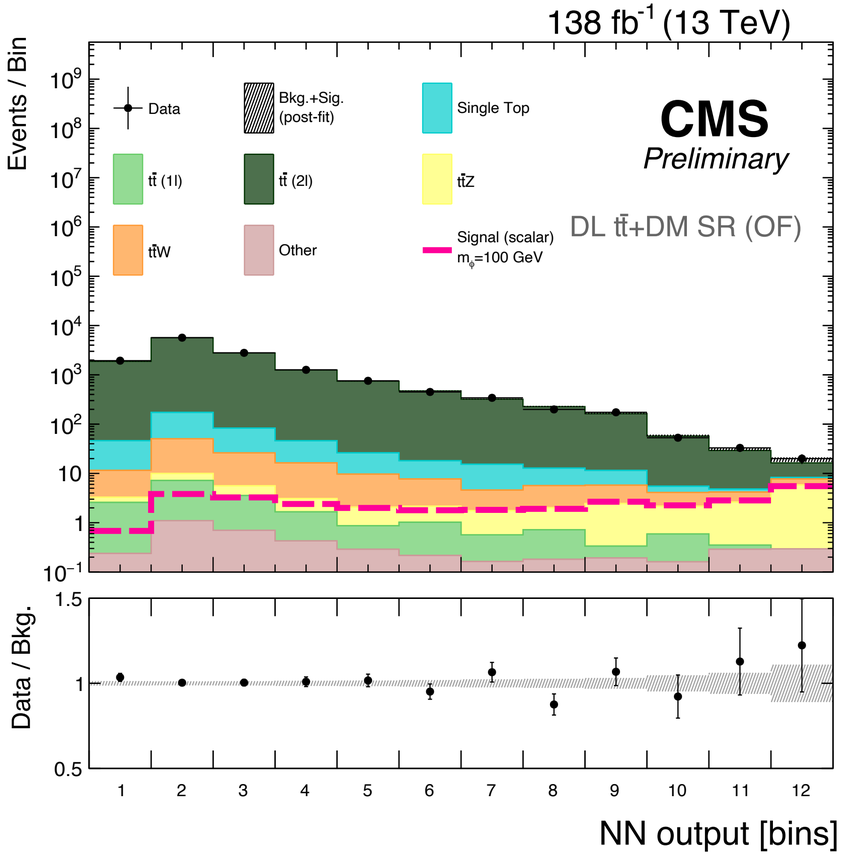
Search for dark matter associated with top final states

- Signal extraction
  - DL channel
    - **Main discriminator:** neural network (NN) using multiple kinematic variables
  - AH and SL channels
    - **Main discriminator:** p_T^{miss}

Simultaneous fit in SRs and CRs to the main discriminator to extract signals

Example post-fit distribution

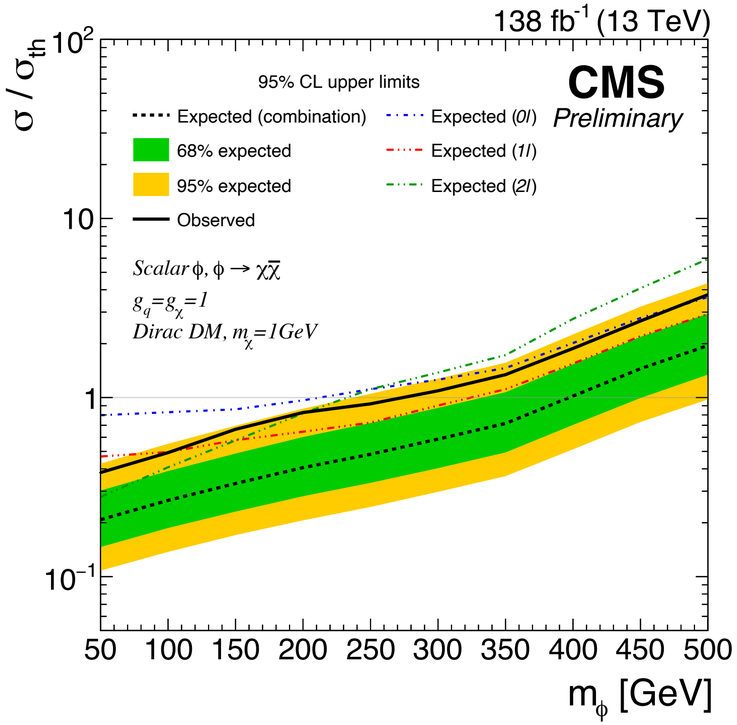
(DL $\geq 2b$ SR)

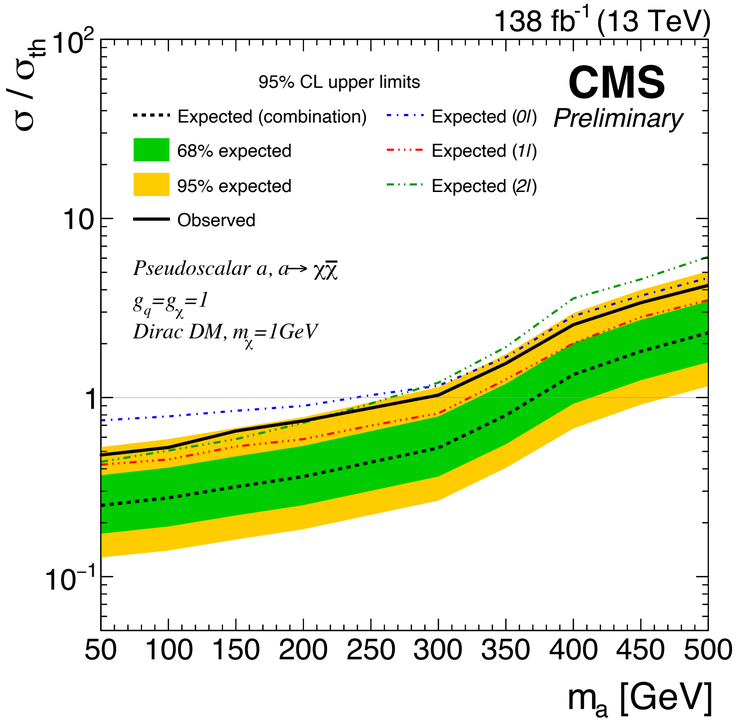


Search for dark matter associated with top final states

- Results
  - Limits set on DM production cross sections relative to theory predictions

    Scalar and pseudoscalar mediator masses excluded below 280 (400) GeV and 290 (380) GeV

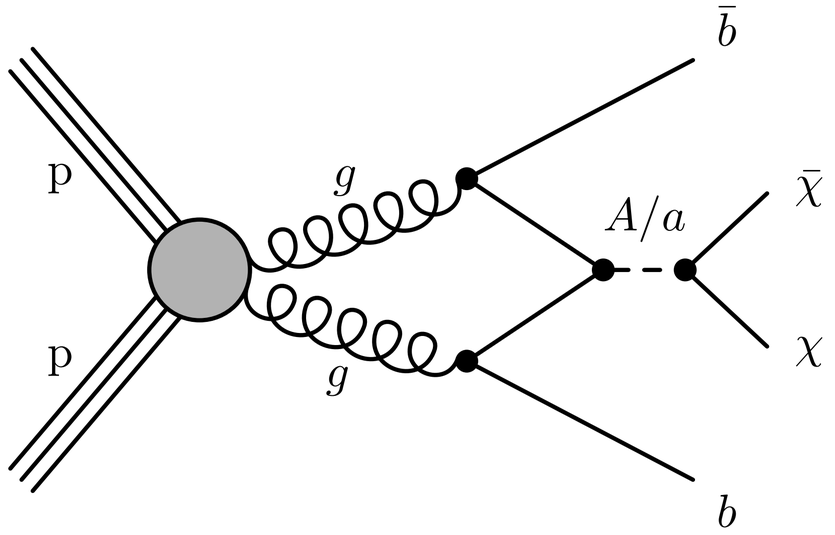




Search for dark matter associated with b quarks

❖2HDM+a DM benchmark

- Two Higgs Doublet Model (2HDM) + psuedoscalar a (mixed with A) + DM χ;
- If large $\tan\beta$ in 2HDM → enhanced $A - b$ couplings ;
- Motivates p_T^{miss}+ b quarks signature



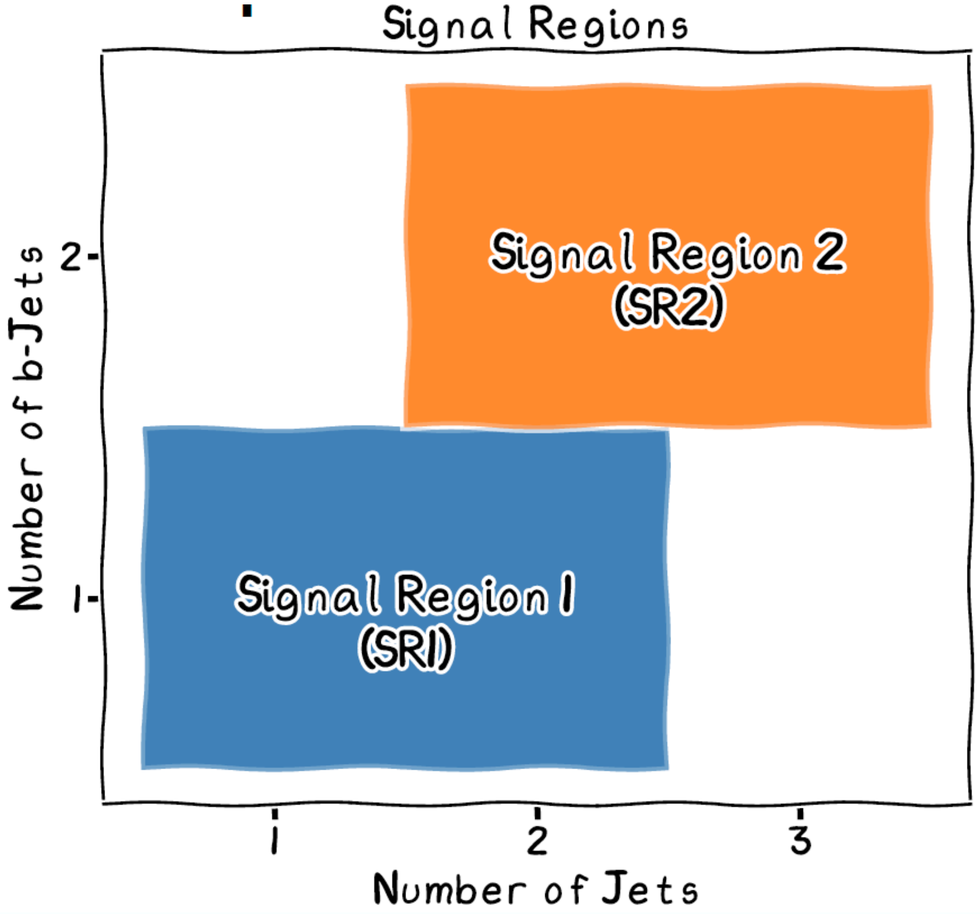
New full Run-2 results — CMS-PAS-SUS-23-008

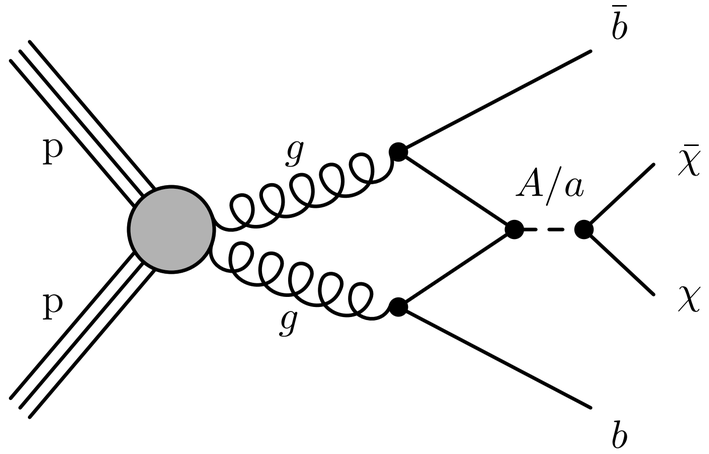
Search for dark matter production associated with a pair of b quarks

$$\mathscr{L} = 138\ \text{fb}^{-1}$$

Search for dark matter associated with b quarks

- Search for p_T^{miss}+ b quarks signature





- 1b or 2b signal regions;
- Large p_T^{miss};
- Additional letpons are vetoed;
- Large separation between p_T^{miss} and jets;
- Explore the η separation between the 2 b jets;

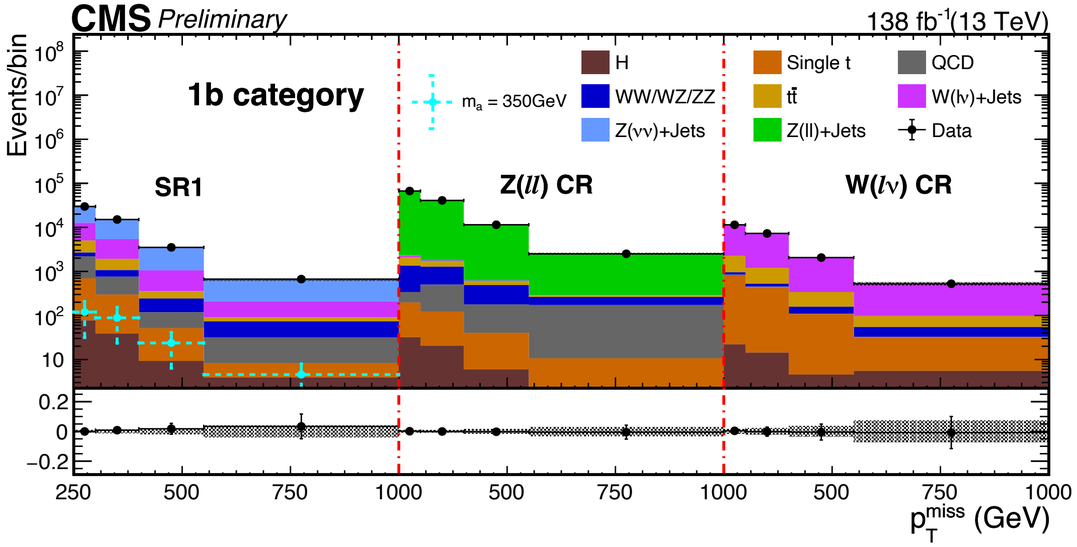
Search for dark matter associated with b quarks

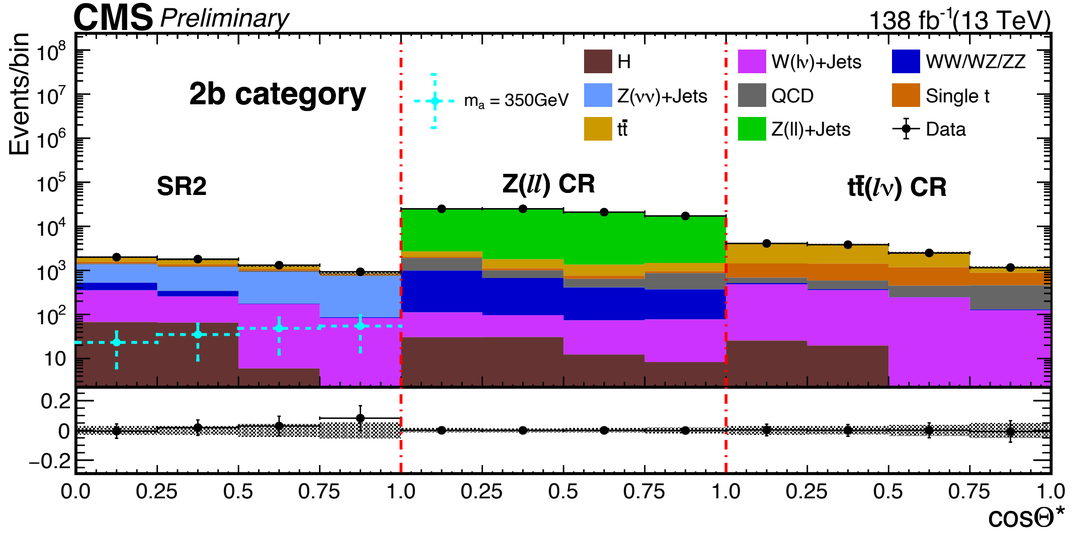
- Signal extraction

Simultaneous fit of the signal region and control regions (leptonic)

p_T^{miss} ($\vec{p}_T^{\text{miss}} + \sum \vec{p}_T^{\ell}$) for the 1b category

$\left| \tanh\left(\frac{\Delta\eta(\text{jet}_1, \text{jet}_2)}{2} \right) \right|$ for the 2b category

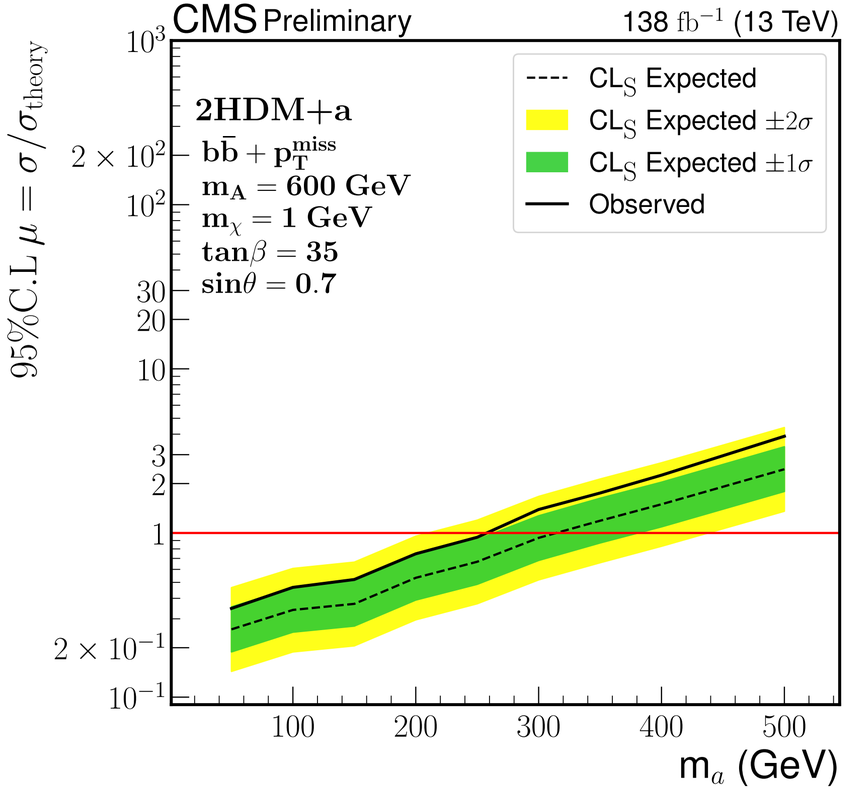


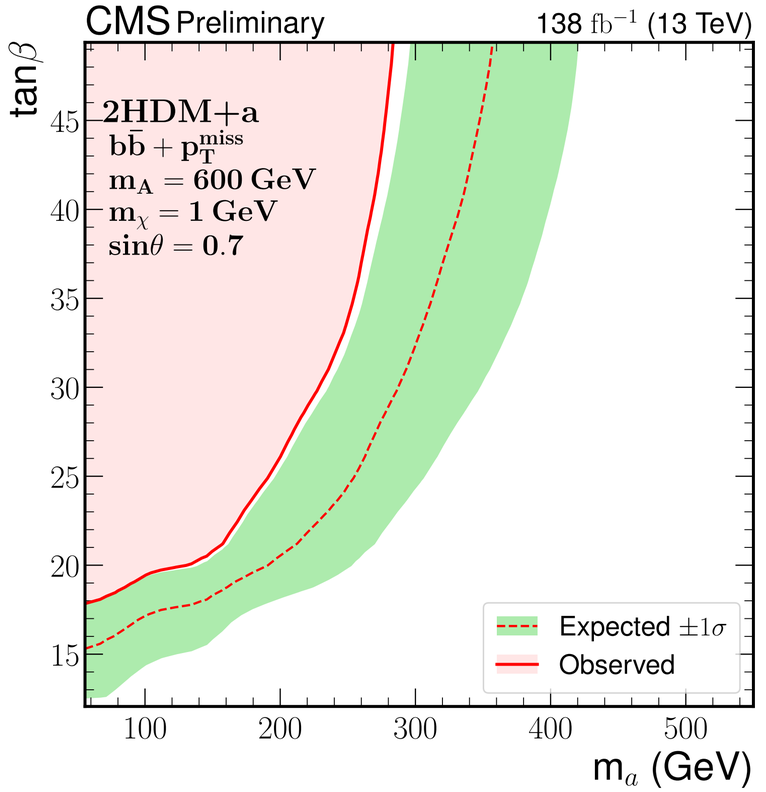


Search for dark matter associated with b quarks

- Results

Limits set on dark matter production cross sections and the phase spaces of 2HDM+a

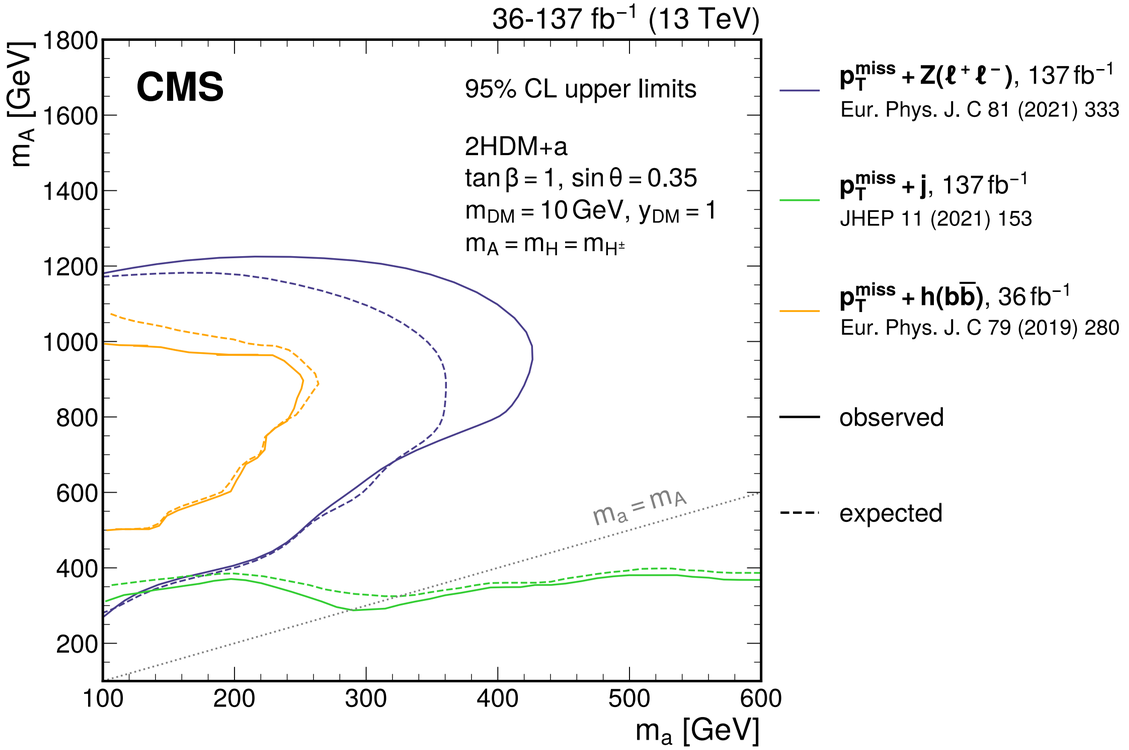


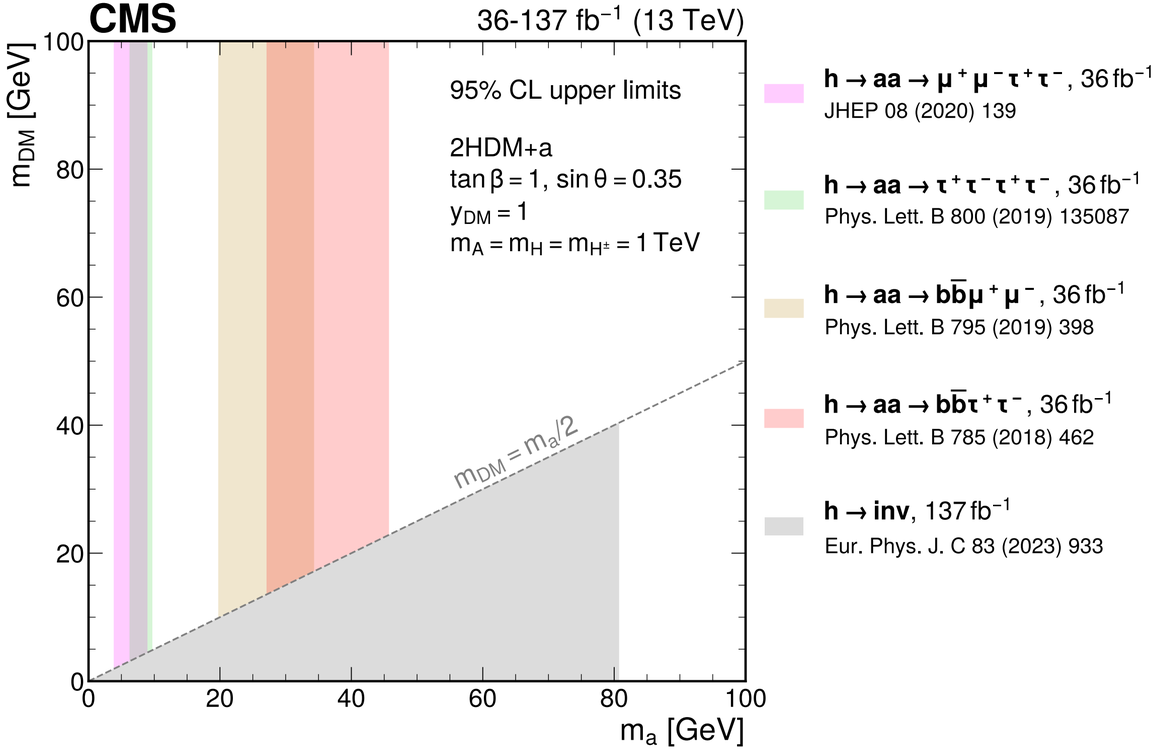


Search for dark matter associated with b quarks

Complementary with other existing searches for the 2HDM+a DM benchmark

Summary plots from the dark-sector review paper arXiv: 2405.13778





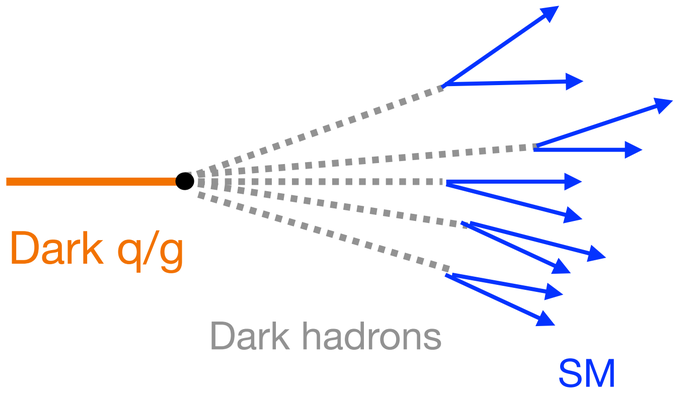
New results for extended dark sectors

Search for emerging jets

❖Emerging jets

- A confined gauge group (i.e. QCD-like) in the dark sector
- Parton shower and hadronization within the dark sector;
- Dark hadrons are produced and can form a dark jet.
- Dark hadrons can be long-lived and decay back to SM particles

Multiple displaced vertices within a jet



Belongs to a larger category of dark shower signatures:

- Emerging jets;
- Semi-visible jets;
- SUEP
- mixings of above;

•All of them are actively explored by CMS

(Stable dark hadrons can be DM candidates)

Search for emerging jets

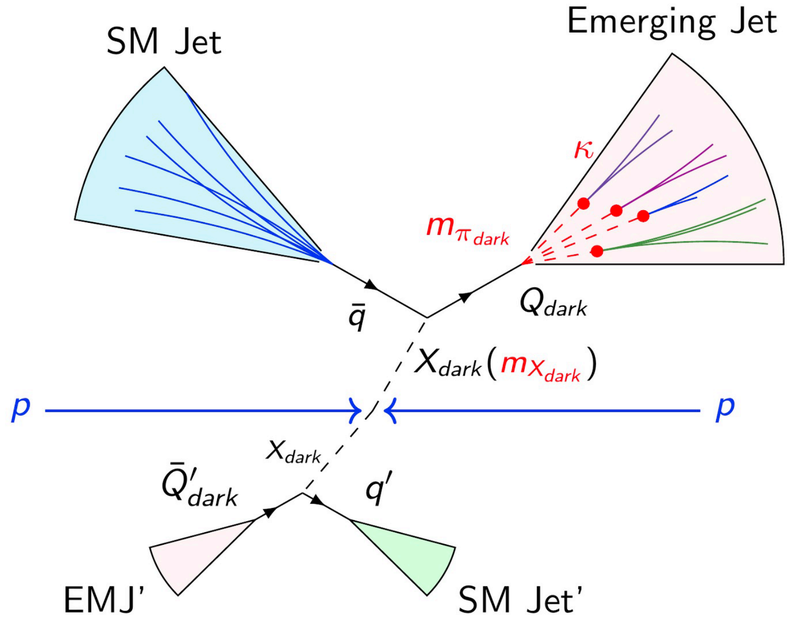
- Full Run-2 emerging-jets (EMJs) search at CMS arXiv: 2403.01556, submitted to JHEP

The chosen benchmark

A heavy mediator couples to the dark QCD and the SM QCD

$$\mathcal{L}_\kappa = \kappa_{ij}\overline{Q}_{d_i} q_j X_d + \text{h.c.}$$

Dark quark — SM quark — Mediator



Two scenarios considered:

- **Unflavored**: only couples to down quark — $\pi_{dark} \to dd$
- **Flavor-aligned:** universal couplings to d/s/b quarks:
  - Mix of dark pions with different lifetimes;
  - Decays to b quarks favored when above the threshold.

$m_X \sim$ TeV

- High H_T — for trigger;
- 4 high p_T jets — 2 SM jets, 2 EMJs;

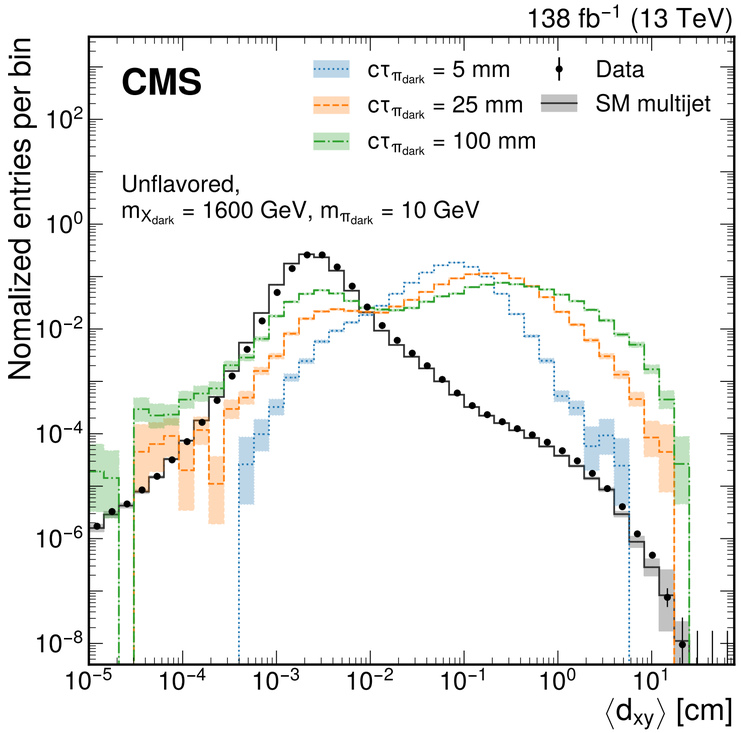
Search for emerging jets

- Emerging jets (EMJs) tagging — model-agnostic method

Cut-based tagging to mitigate model dependences

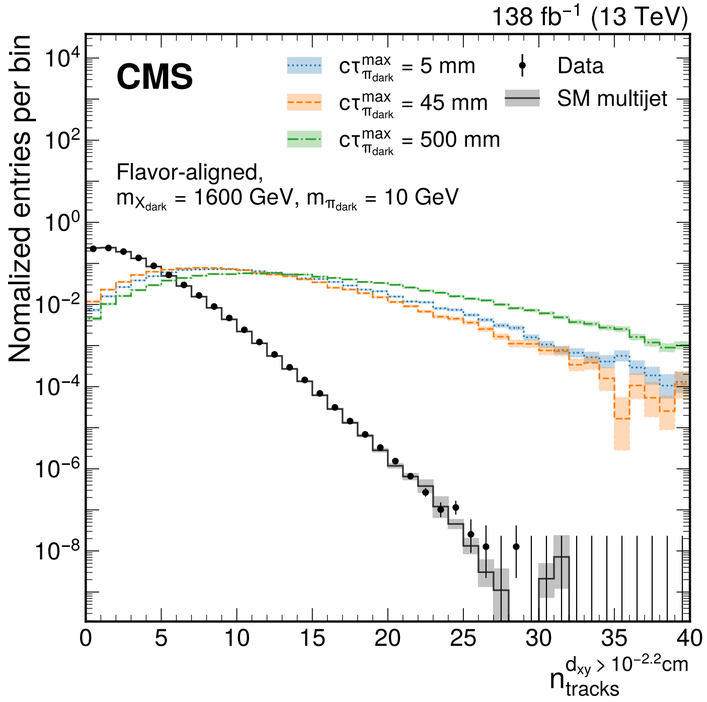
Unflavored EMJ tagging

- Median track 2D impact parameter (d_{xy}) of the jet;
- prompt track p_T fraction



Flavor-aligned EMJ tagging

- Number of tracks passing a given d_{xy} threshold
- p_T-weighted ΔR;
- "N-subjettiness"

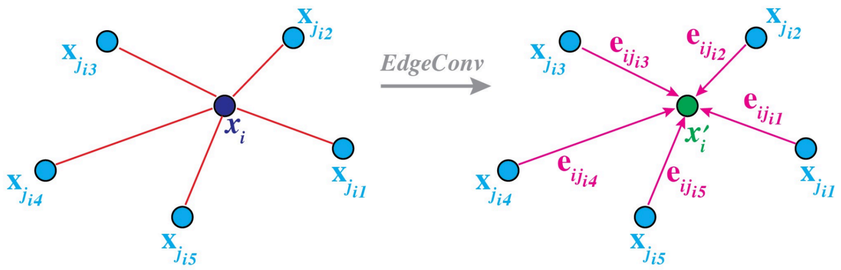


Search for emerging jets

- **Emerging jets (EMJs) tagging — graph neural network**

Machine learning algorithm to improve the sensitivity to a specific model

- **Based on ParticleNet architecture**



  - Particles (tracks) are viewed as a point cloud;
  - Graphs for particle-to-particle relations;
  - Graphs are updated dynamically.

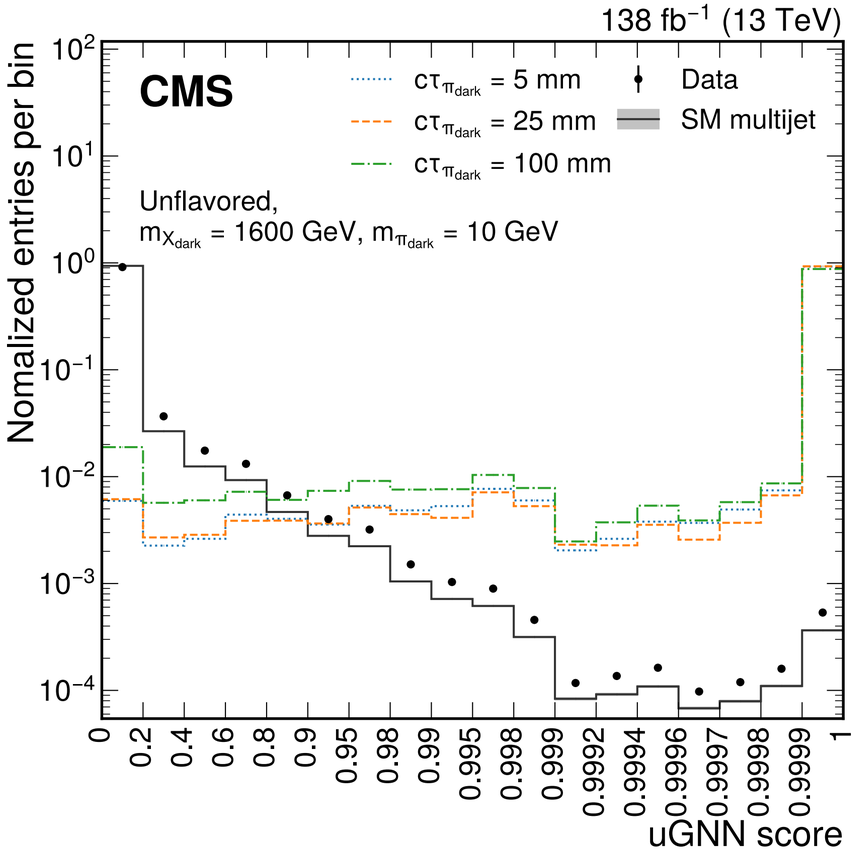
(The same ML architecture used for the official CMS b-tagging algorithm)

- **Dedicated ParticleNet taggers trained for EMJs**
  - Per-track inputs:
    - $\Delta\phi$, $\Delta\eta$, $\Delta R(\text{track}, \text{jet})$;
    - Track p_T and p_T ratio w.r.t. the jet;
    - Track impact parameters.
  - **Separate taggers trained for unflavored and flavor-aligned scenarios**

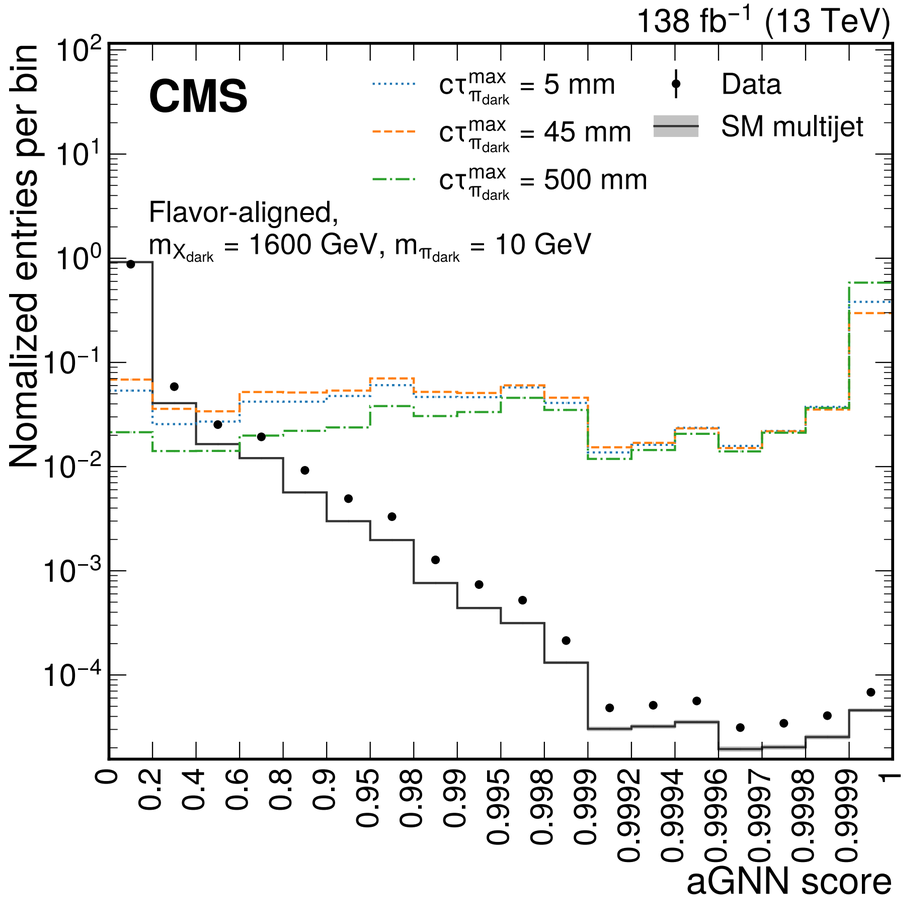
Search for emerging jets

- GNN taggers

▸Unflavored scenario



▸Flavor-aligned scenario



Search for emerging jets

- Event selection and background predictions

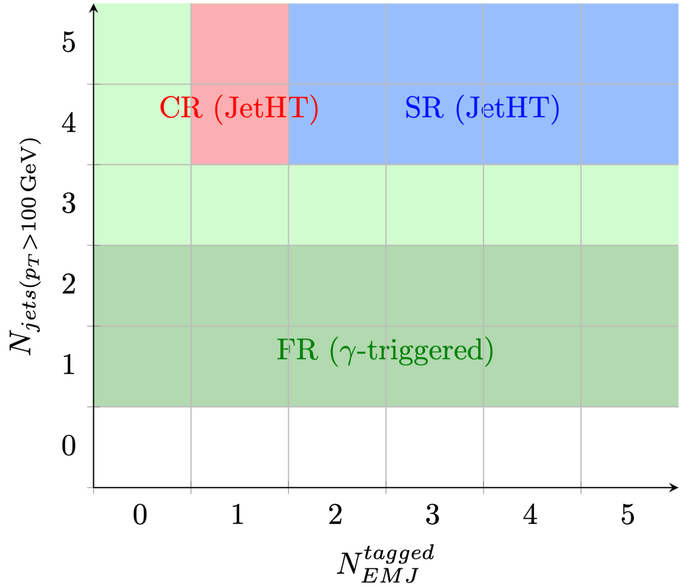
Look for events with ≥ 2 tagged EMJs

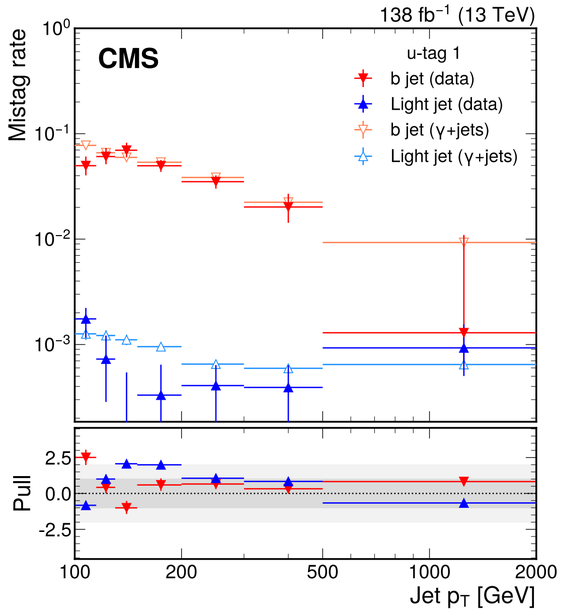
- Data driven background estimation

≥2-EMJ event yields estimated from 1-EMJ control region using mistagging rates:

- Mistagging rates measured in photon-triggered signal-free region (SR);
- Flavor dependence is extracted from b-enriched/ depleted regions;

Validated using data in orthogonal regions



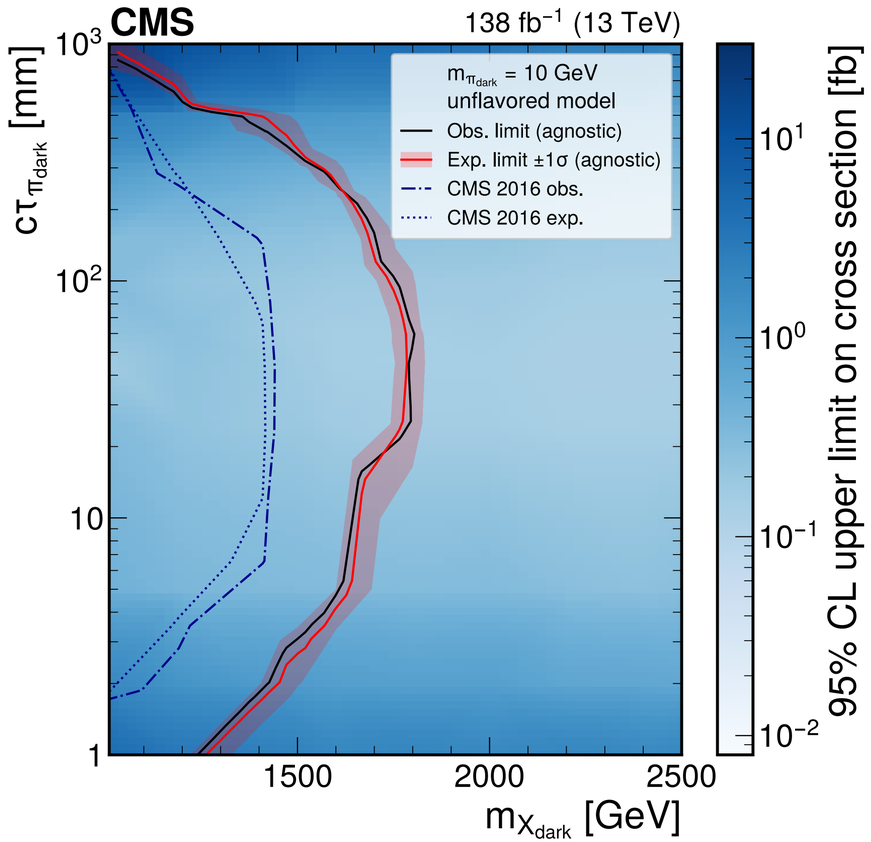


Search for emerging jets

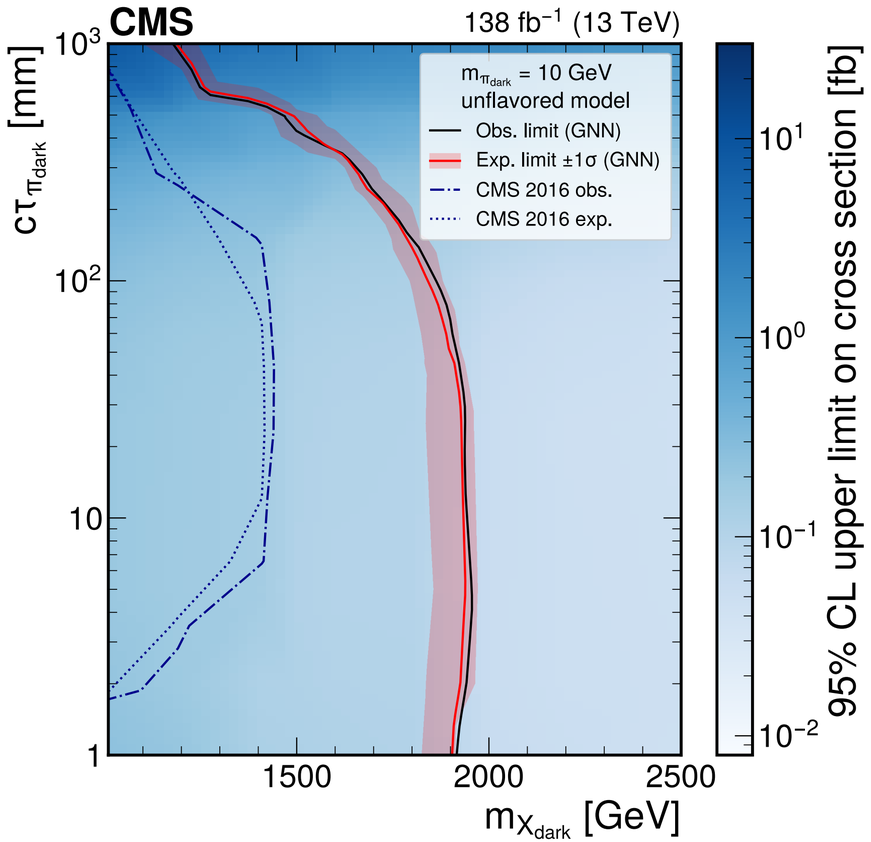
- Results

  Observations are consistent with background predictions — setting limits for different signal points

Unflavored — model agnostic tagging



Unflavored — GNN tagging



- Significant expansion of the coverage over previous 2016-only results;
- **GNN tagging**

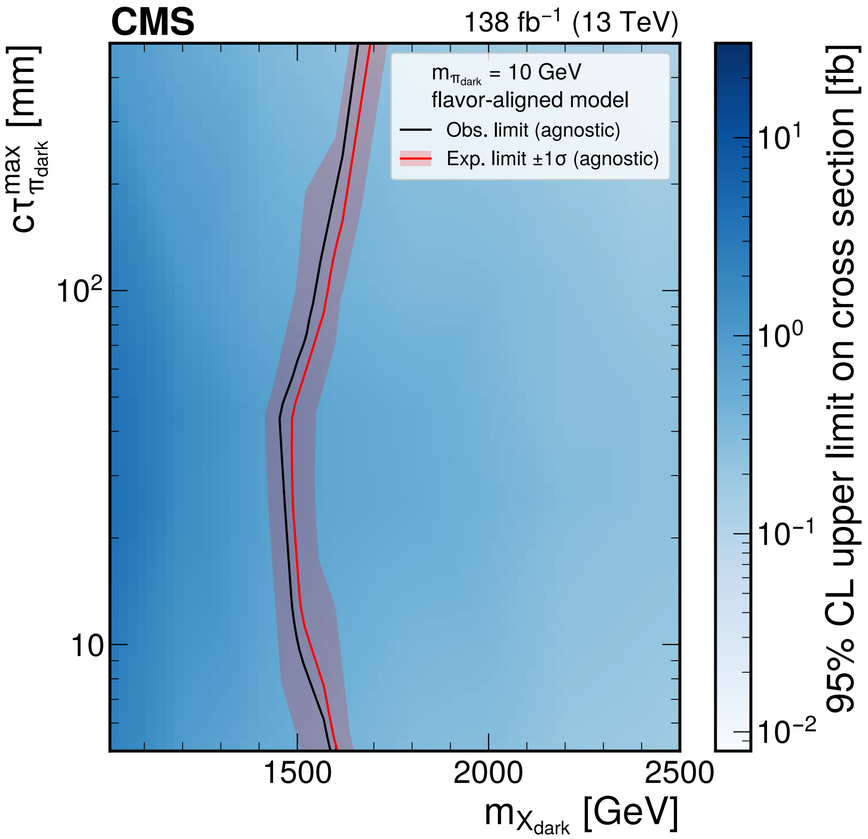
  Better sensitivities especially for shorter lifetimes;
- **Model-agnostic tagging**

  More immune to the dark-sector assumptions.

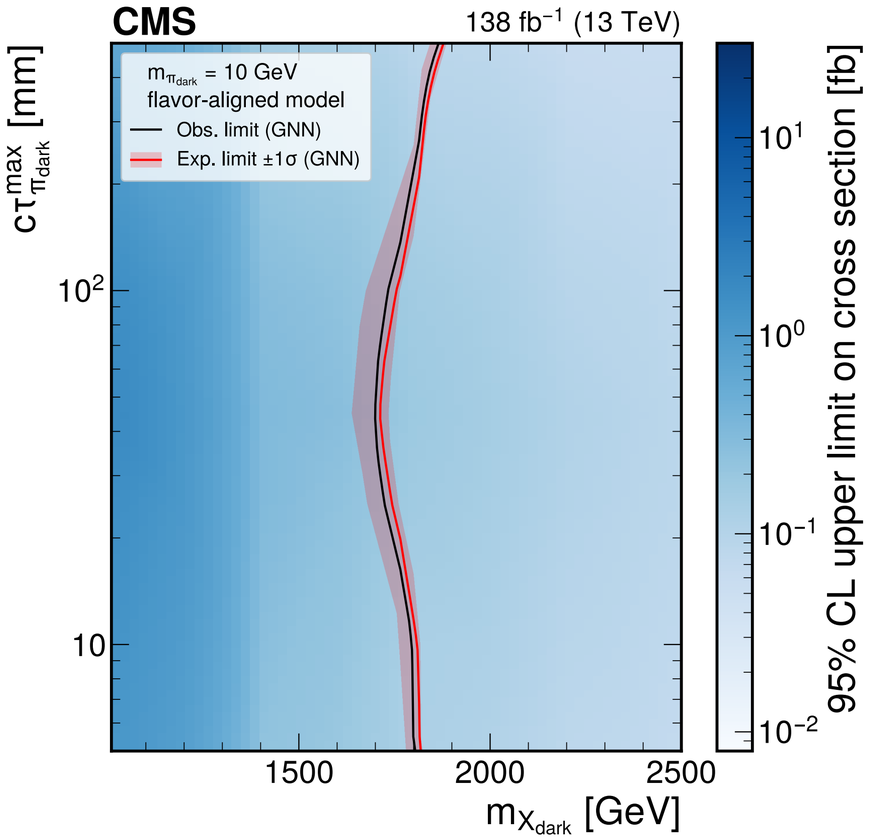
Search for emerging jets

- Results

Flavor-aligned — model agnostic tagging



Flavor-aligned — GNN tagging



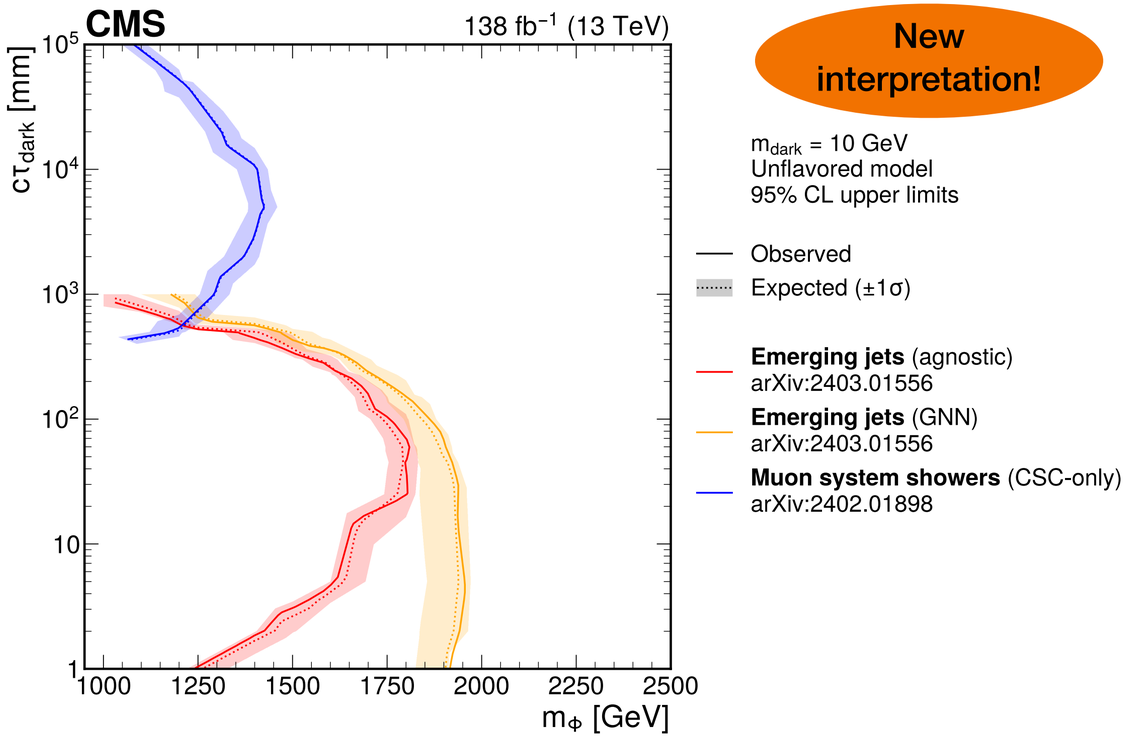
- Probed for the first time
- Sensitivities don't change much with $c\tau^{\mathrm{max}}_{\pi_{\mathrm{dark}}}$;
  - driven by short-lived dark pions that predominately decay to b-quarks

Search for emerging jets

Complementary with other existing searches

Summary plots from the dark-sector review paper arXiv: 2405.13778

▸Unflavored scenario



New interpretation!

m_{dark} = 10 GeV
Unflavored model
95% CL upper limits

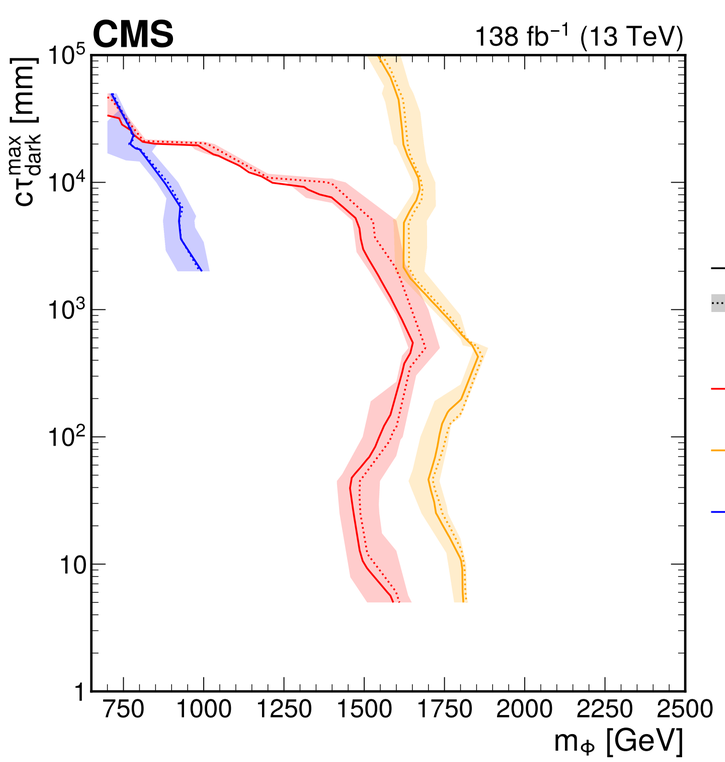
Observed
Expected (±1σ)

Emerging jets (agnostic)
arXiv:2403.01556

Emerging jets (GNN)
arXiv:2403.01556

Muon system showers (CSC-only)
arXiv:2402.01898

▸Flavor-aligned scenario



New interpretation!

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Expected (±1σ)

Emerging jets (agnostic)
arXiv:2403.01556

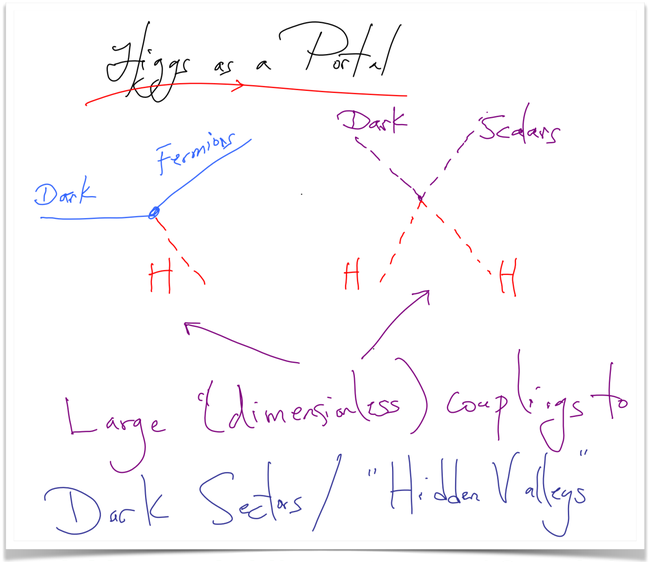
Emerging jets (GNN)
arXiv:2403.01556

Muon system showers (CSC-only)
arXiv:2402.01898

Higgs-portal dark sectors

❖The Higgs boson is a perfect candidate for the portal into dark sectors

- Has already been discovered experimentally;
- Unique status in the SM sector [Brain Patt & Frank Wilczek, 2006]

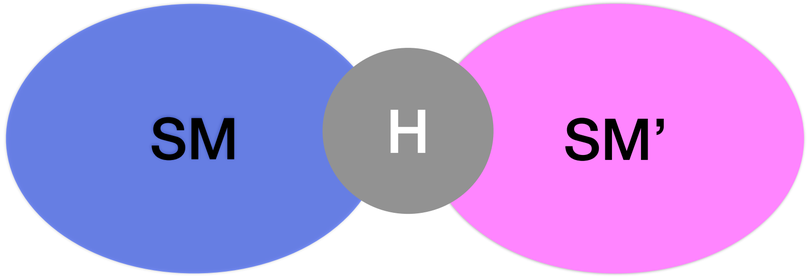


(Nima Arkani-Hamed, Higgs turns 10 celebration@CERN)

"*Neutral naturalness is expected to be one of the dominant paradigms driving experiment and theory over the next decade.*"

— **2021 Snowmass Theory Frontier Report**

A well-motivated example: Neutral naturalness

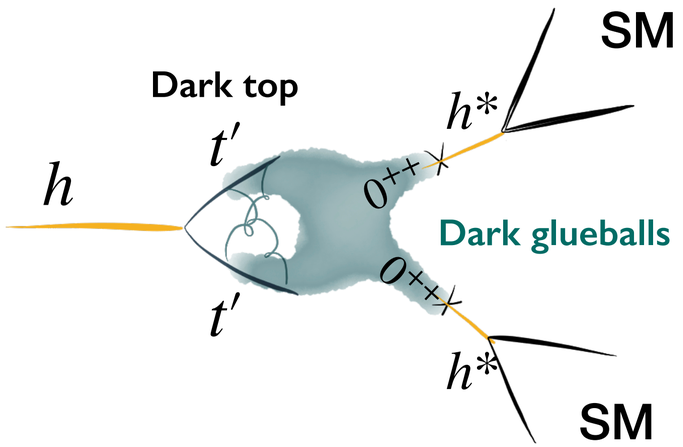


- **Hierarchy problem** — a global symmetry between the DS and the SM;
- **Dark matter** candidates;
- The origin of the **neutrino mass**;
- **Baryogensis**;

Higgs to LLPs in the dark sector

- A smoking-gun signature: Higgs → LLPs → displaced jets

Exotic Higgs decays



PC: Nathaniel Craig

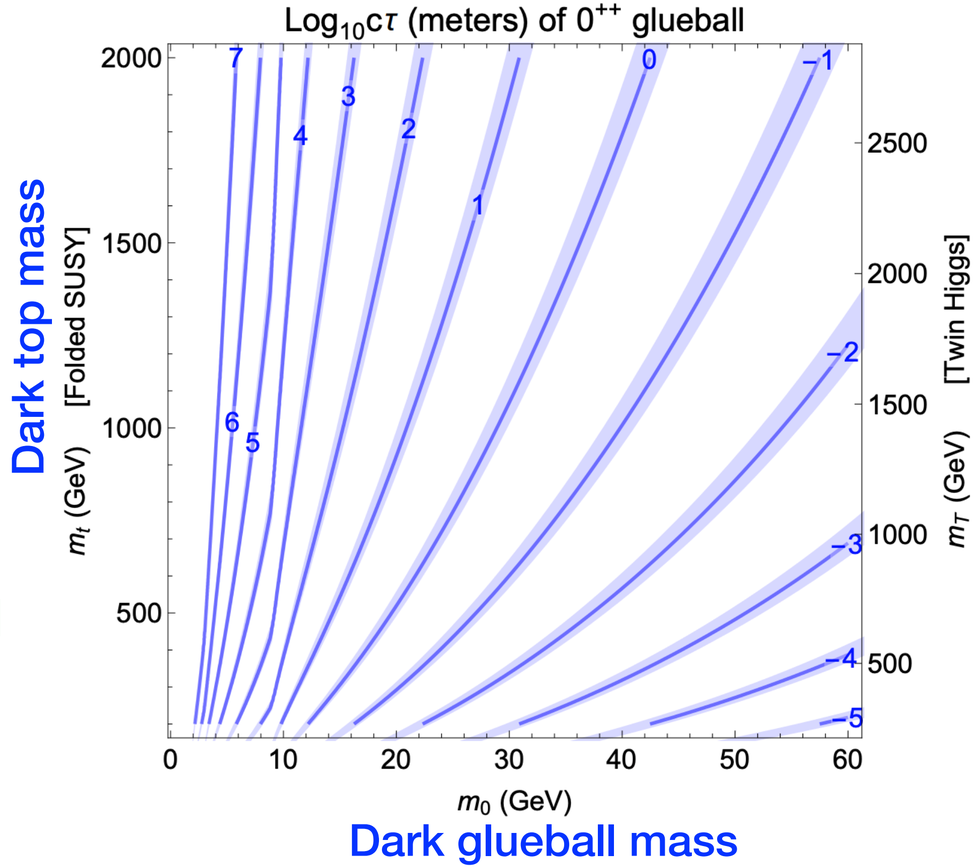
[Craig, Katz, Strassler, Sundrum, 2015]

[Curtin, Vehaaren, 2015]

[Csaki, Kuflik, Lombardo, Slone, 2015]

…

CERN LHC Higgs Yellow Report



- Naturally induces lifetimes that are relevant to LHC experiments;
- $\mathrm{LLP} \to \mathrm{bb}$ decay is preferred because of the Higgs portal interaction;
- LLP masses are preferred to be between 10 and 60 GeV;
- The branching ratio can easily be made very small.

$$BR \approx 10^{-3} \times \left(\frac{m_{t'}}{400\ \mathrm{GeV}} \right)^{-4}$$

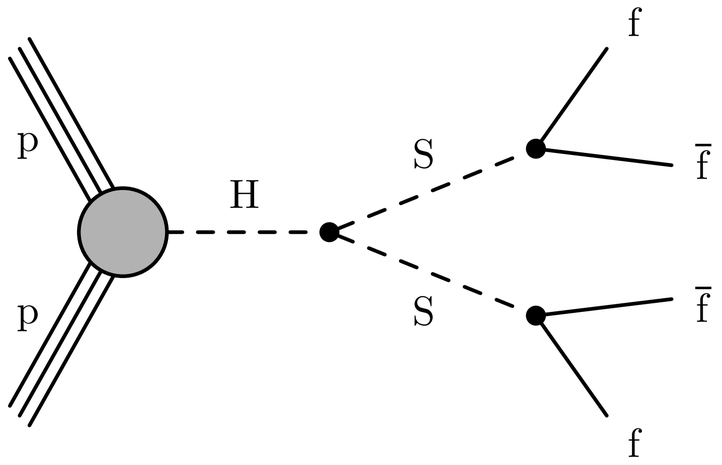
Run-3 H→LLPs search

- Tracker-based searches for H→LLPs with hadronic final states are extremely challenging

Especially for ggF production

- Soft objects (jets, tracks, vertices);
- Overwhelming QCD background:

Requires a background rejection of $\sim 10^{10}$



- **We have an early Run-3 result public recently!** [CMS-PAS-EXO-23-013]

Utilizing 13.6 TeV data collected in 2022

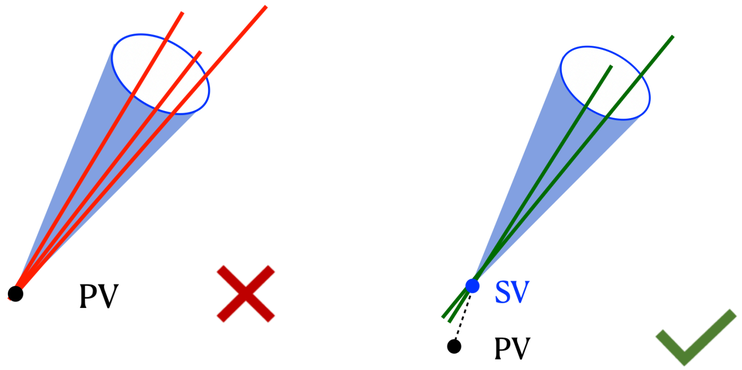
$\mathscr{L}$: 34.7 fb^{-1}

New techniques in trigger, reconstruction, and machine learning;

Significantly pushed the boundaries of what we can do at CMS.

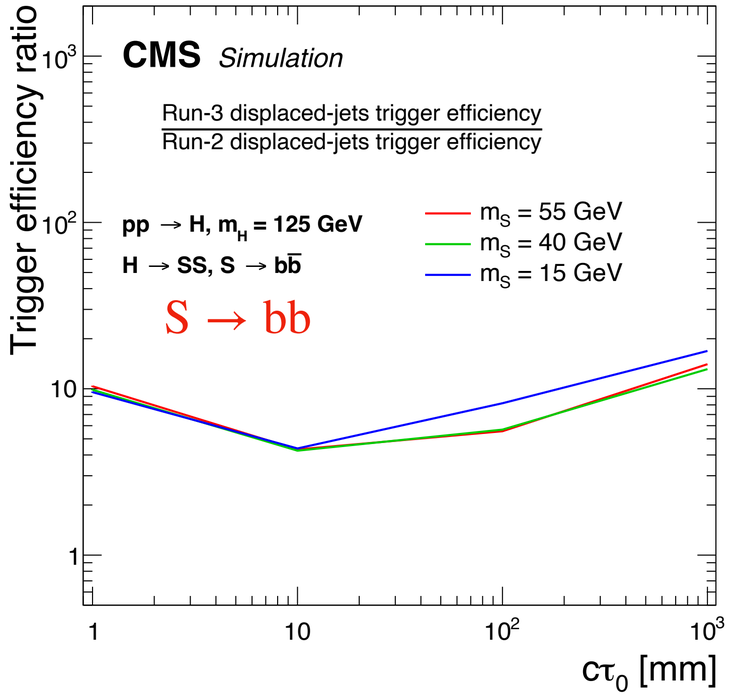
New displaced-jets triggers

- New displaced-jets triggers in Run 3
  - New tracking-based online displaced-jets tagging;
  - a factor of ~5-10 gain in efficiencies for $H \rightarrow LLPs$ compared to Run 2.



Efficiency gains w.r.t. Run 2

[CMS-DP-2023-043]

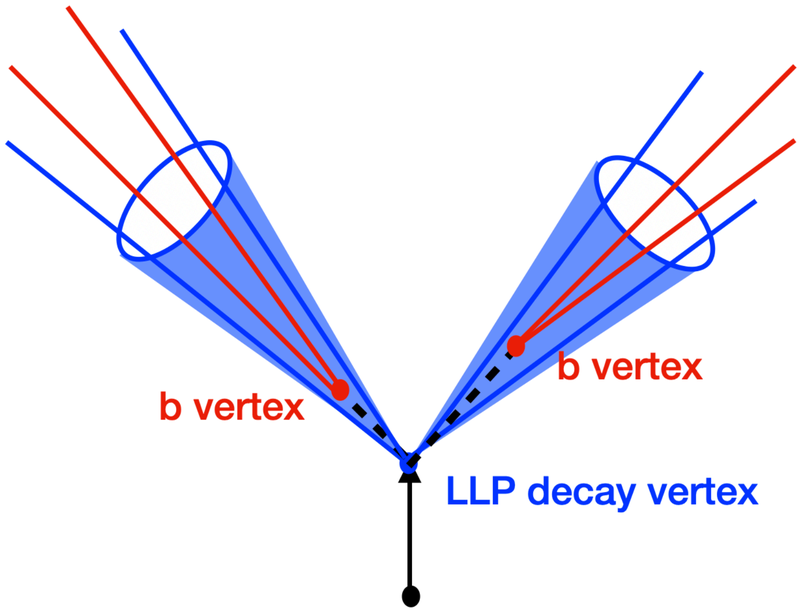


Further improved in 2023 and beyond thanks to the data parking dedicated to LLPs

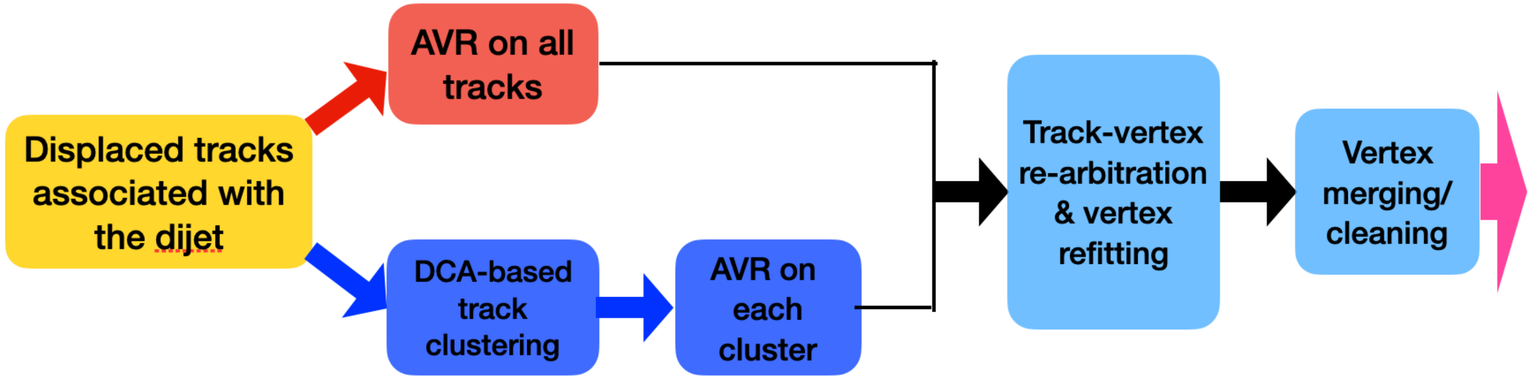
(CMS scouting and parking review paper — arXiv:2403.16134)

New displaced vertex reconstruction

- New displaced-vertex reconstruction in Run 3
  - To tackle complex LLP decay systems like $S \rightarrow bb$ (important for Higgs portal);



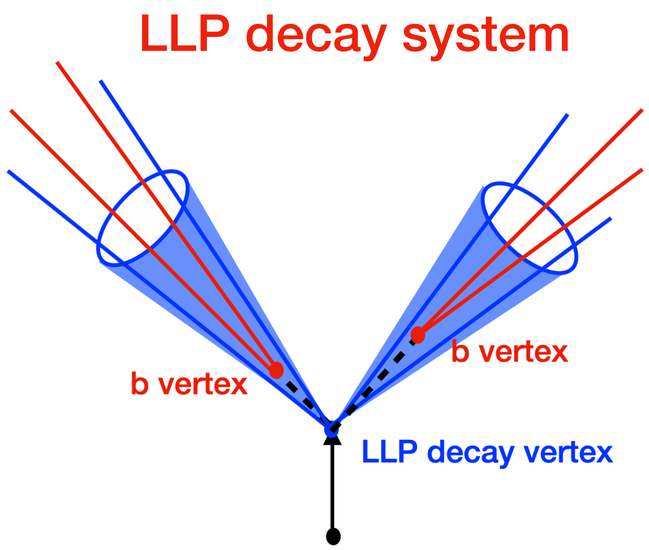
Starting with the displaced tracks associated with **two jets**

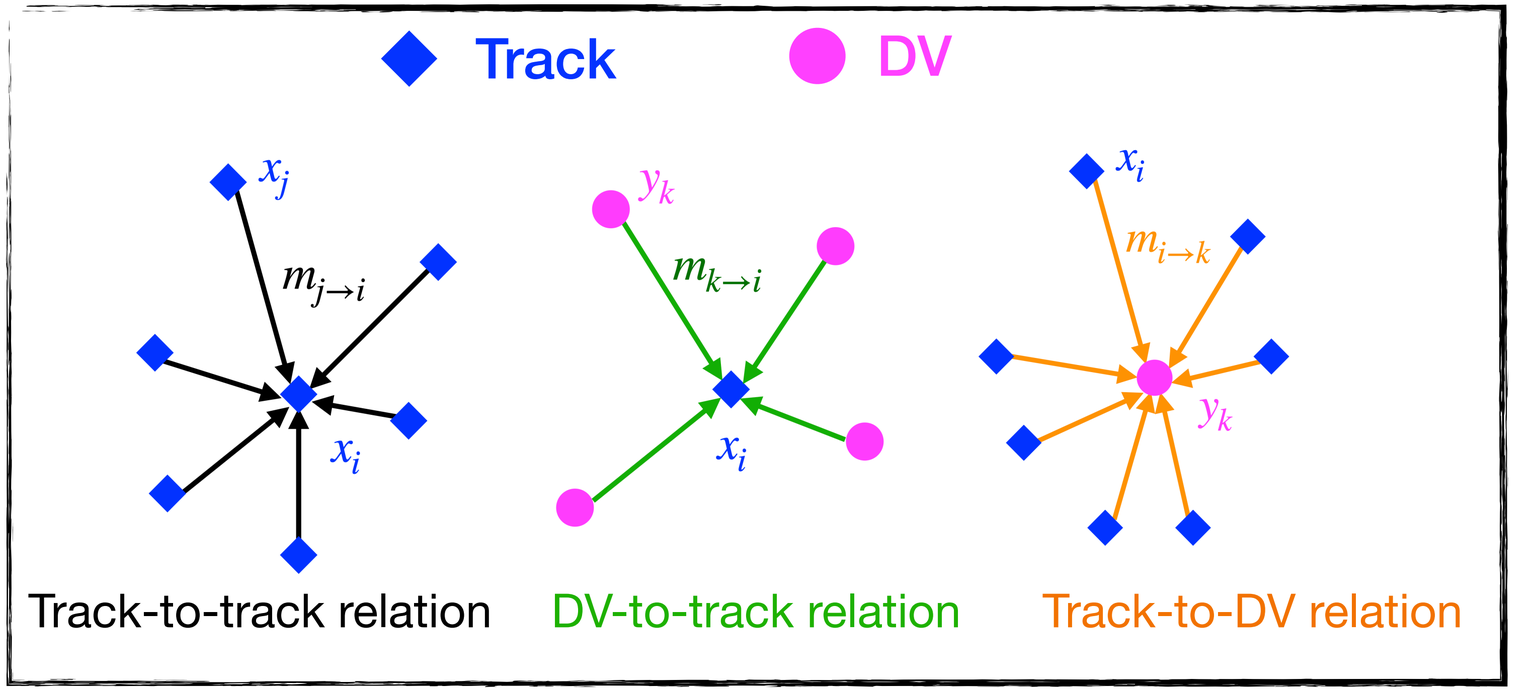


Compared to old algorithms, the main difference is the reconstruction of the additional DVs within the dijet — crucial for heavy-flavor decays

New GNN-based LLP tagging

- New GNN-based LLP taggers in Run 3
  - The design of the ML architecture is driven by and tailored for physics considerations.

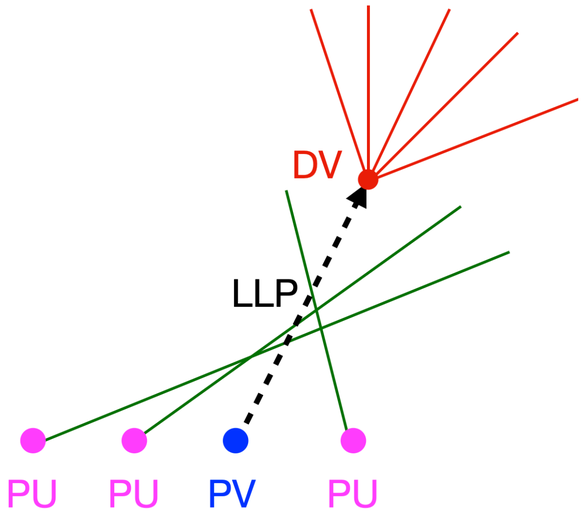


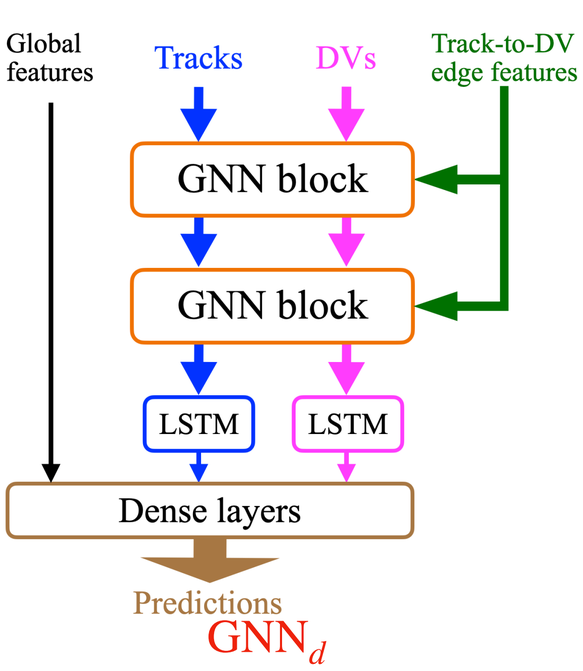


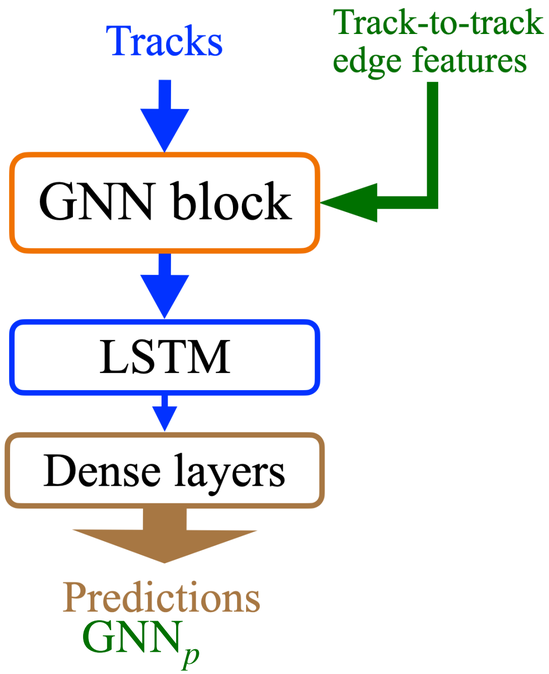
Message-passing formalism

New GNN-based LLP tagging

- New GNN-based LLP taggers in Run 3
  - Two GNN taggers using the tracks and DVs associated with a given dijet:
    - GNN_d: taking displaced tracks and DVs as inputs;
    - GNN_p: taking prompt tracks ($\mathrm{IP}_{2D} < 0.3$ mm) as inputs.





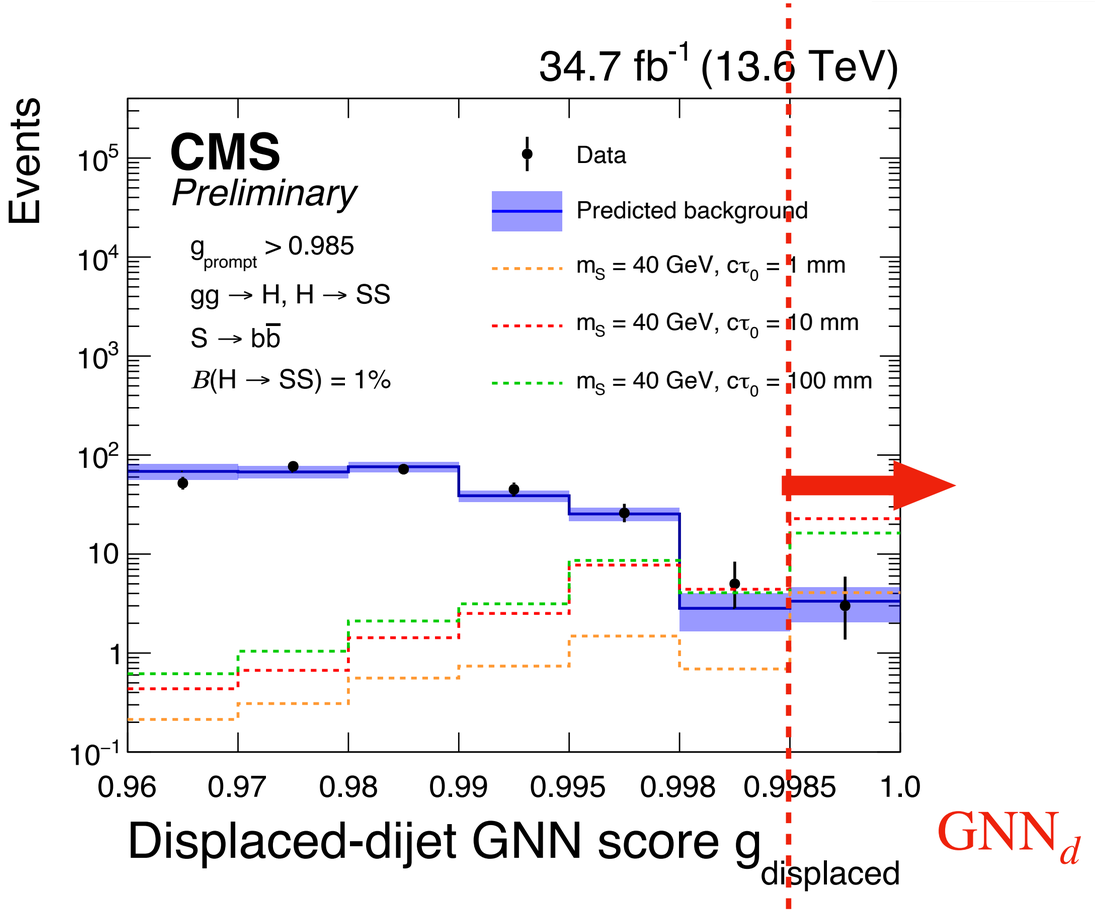


Small correlations for the two taggers in background

- data-driven ABCD method for the background estimation

Event selection and background estimation

- **High-level event selection is very simple**
  - Examine all possible dijet candidates with jets satisfying $p_{\mathrm{T}} > 40\mathrm{GeV},\ |\eta| < 2.0$;
  - Compute $\mathrm{GNN_d}$ and $\mathrm{GNN_p}$ for each dijet
  - Select the dijet having the largest $\mathrm{GNN_p}$ score in a given event;
  - Simple cuts on $\mathrm{GNN_d}$ and $\mathrm{GNN_p}$ to extract signals



Predicted background yield: 3.34 ± 1.28 **(stat. only)**

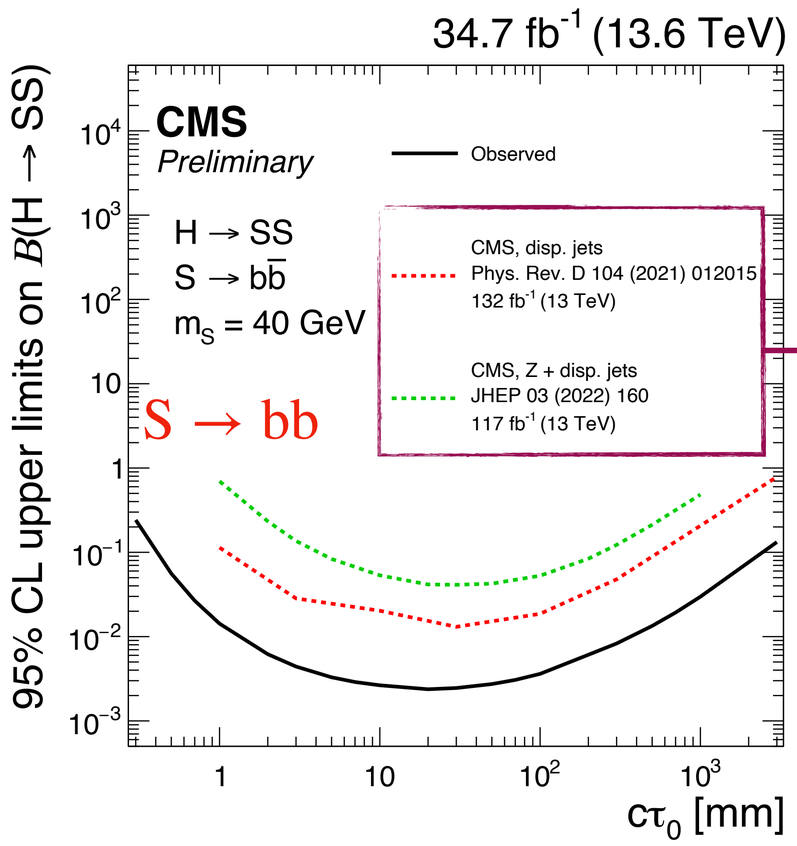
Observation: 3

The search remains to be highly model independent

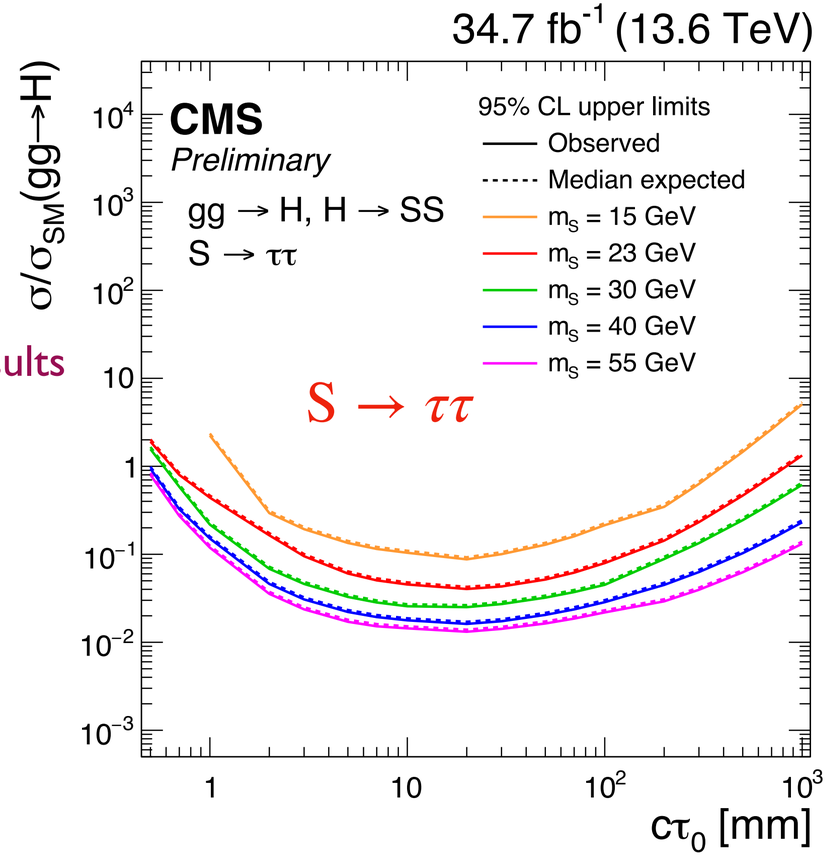
Early Run-3 Results

- Limits are set on the branching fraction for the Higgs boson to decay to LLPs

Orders-of-magnitude better than any other existing results



full Run-2 results

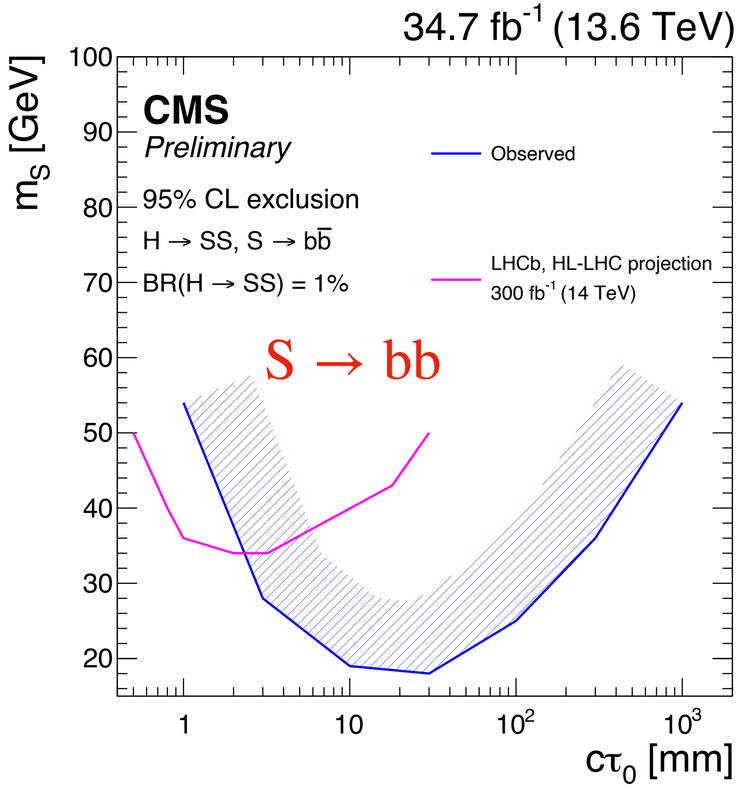


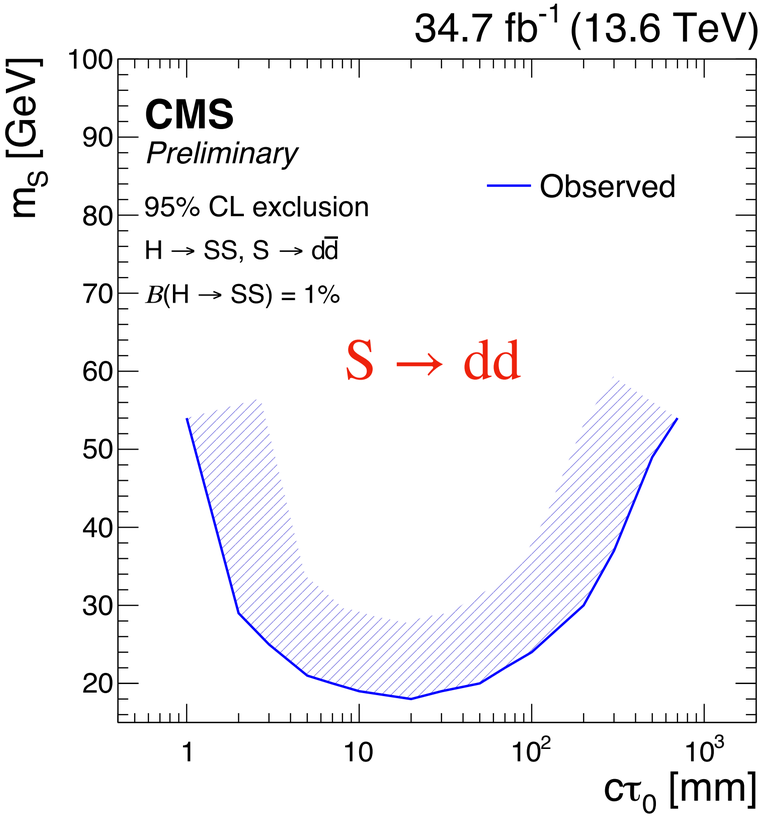
With only 1/4 of the luminosity compared to Run 2, achieved a factor of 10 improvement!

First-ever displaced hadronic tau sensitivities with decay lengths smaller than ≈ 1 m

Results

- BR=1% exclusion on LLP masses as a function of lifetime





$S \to bb$ and $S \to dd$ limits are now similar

(not the case in the Run-2 search)

Thanks to the new DV reconstruction

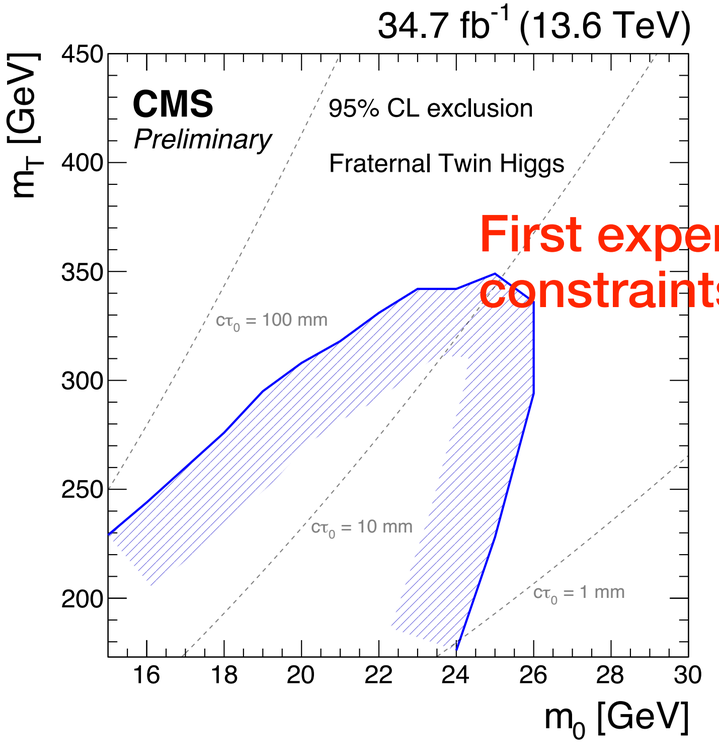
A full HL-LHC projection of LHCb is shown for comparison [arXiv:2105.12668]

Interpretations for the neutral naturalness scenario

- Interpretations for the neutral naturalness (NN) scenario

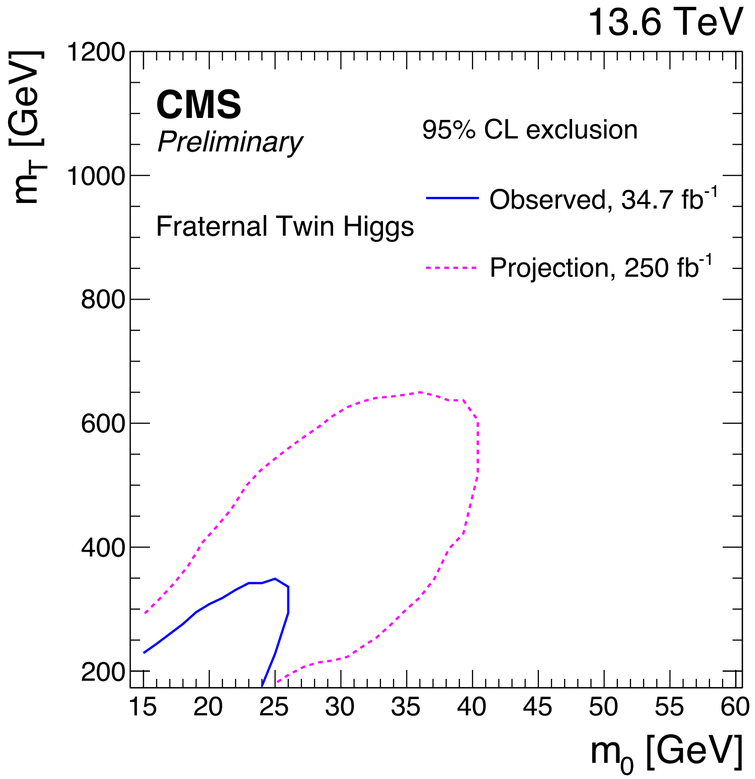
Fraternal Twin Higgs (main benchmark of NN)

[Craig, Katz, Strassler, Sundrum, 2015]



First experimental constraints

Projection with full Run-3 data

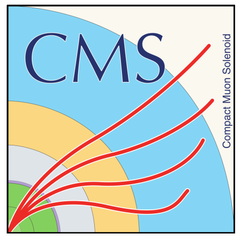


Significant expansions of the coverages are expected by the end of Run 3;

More new low-level techniques under development;

Can reach or even surpass some future collider projections by the end of Run 3

Higgs to LLPs in the dark sector



> "*Searches for exotic Higgs boson decays remain highly motivated… these new particles could be our only direct window into physics beyond the Standard Model. … Long lifetimes are a generic feature of BSM particles in these cascades, yielding hard to detect but extremely low background signatures. The rate of such decays can be very small, so large samples of Higgs bosons are needed* "
>
> **— 2023 P5 Report**

Expected to be a primary physics target over the next decades — HL-LHC and future colliders

CMS will continue to be highly competitive in searching for the signatures arising from Higgs-portal dark sectors

Outlooks of dark-sector searches

- We have a rich set of results for dark-sector searches
- We are just at the new beginning of an exciting journey of exploring dark sectors:
  - Much larger dataset to be analyzed by the end of Run 3;
  - More low-level developments — will further significantly push the boundaries of our capability in probing challenging dark-sector signatures;
  - many more challenging signatures to be explored:
    - HNLs, ALP, soft displaced objects from DM scenarios, high-quality axion, dark shower, etc.
- Exciting opportunities offered by the HL-LHC upgrades