Higgs and the Dark Sector Searches at ATLAS and CMS

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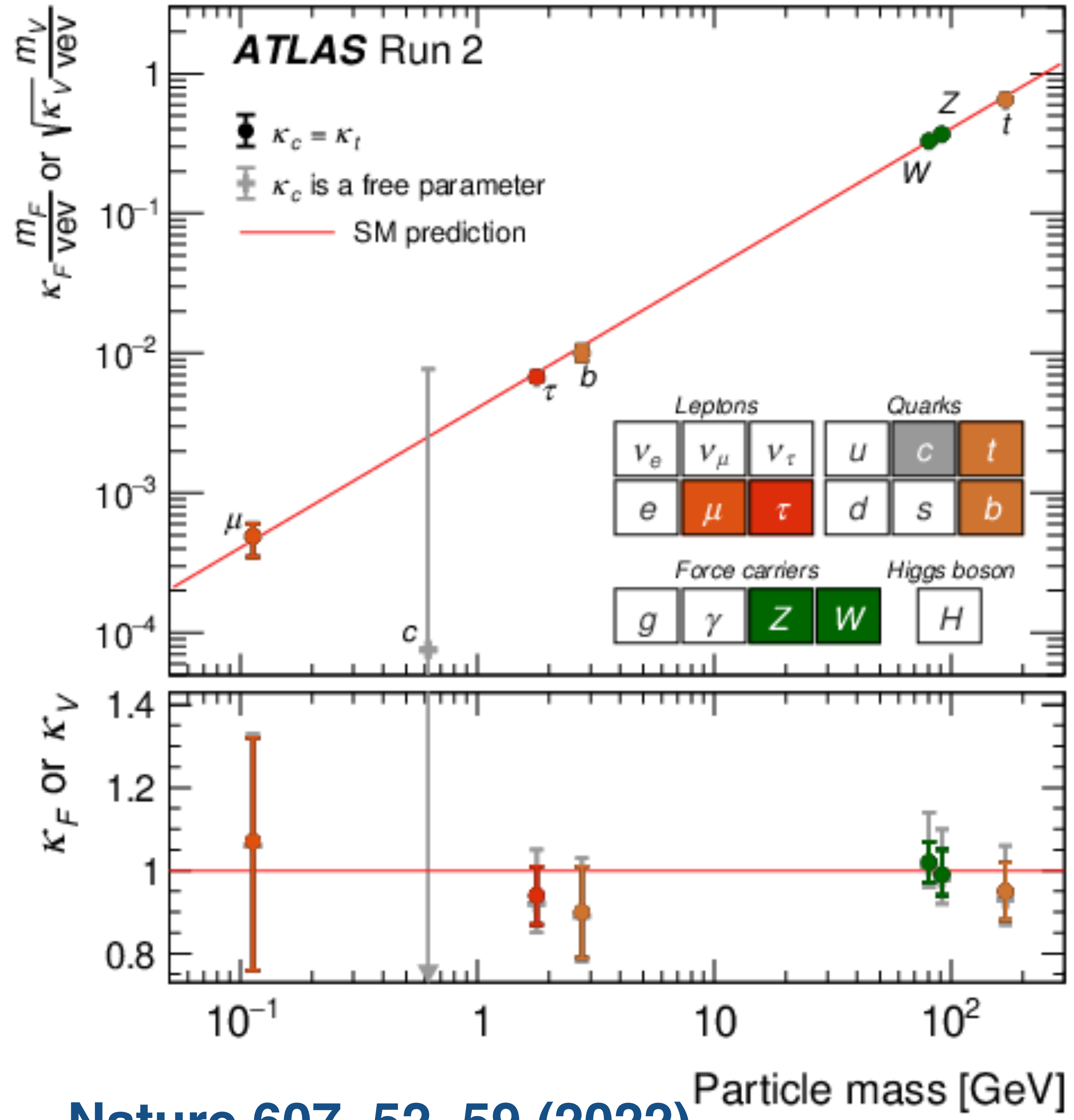
on behalf of ATLAS and CMS collaborations

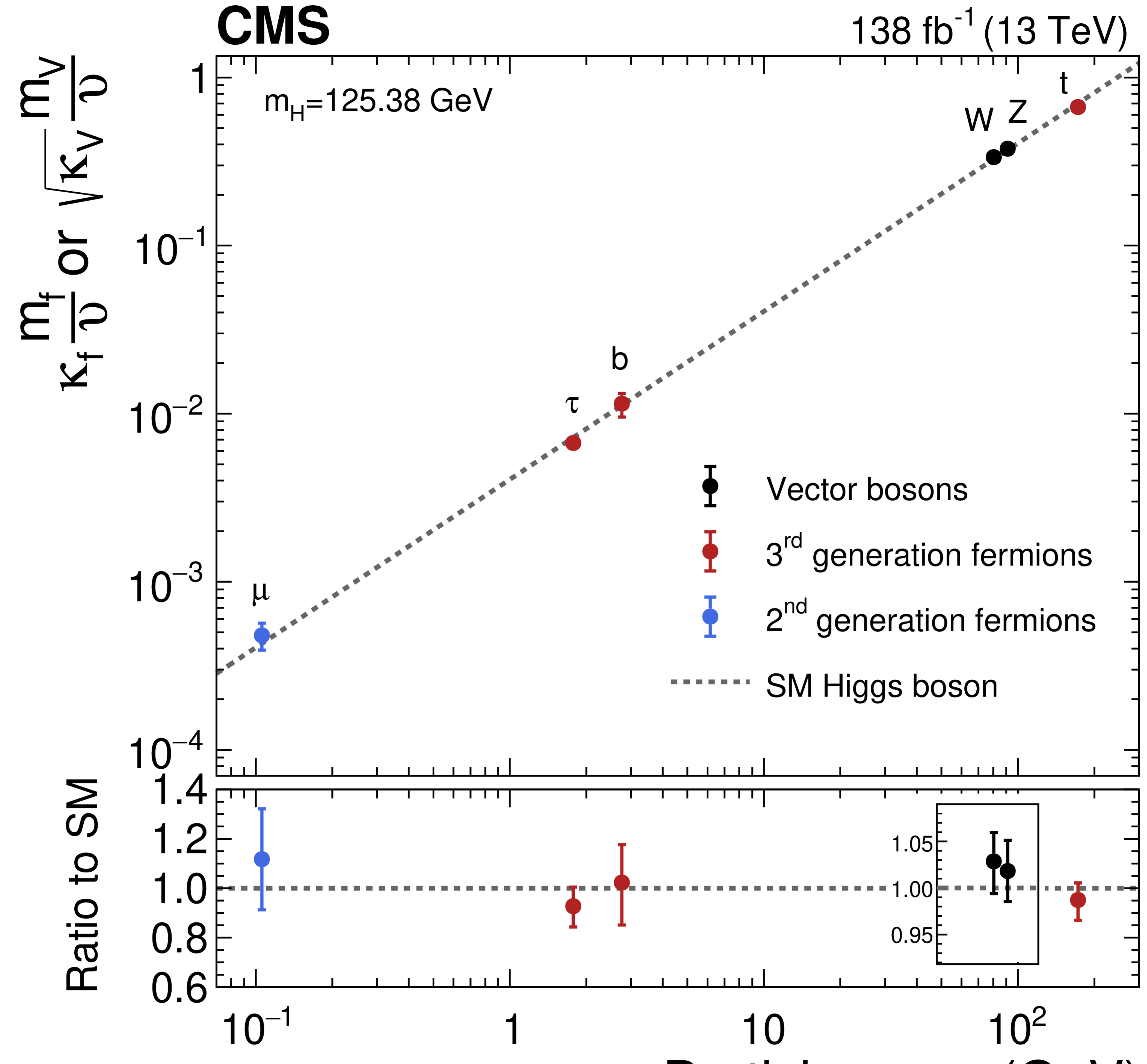
22 October 2024
Extended Scalar Sectors From All Angles, CERN

The Higgs and the Dark Sectors

- The Higgs discovery at the LHC is one the most important developments of the past years in particle physics.
  - **First elementary scalar particle**, offers unique windows to new physics searches
- Studying Higgs boson and its properties is extremely important



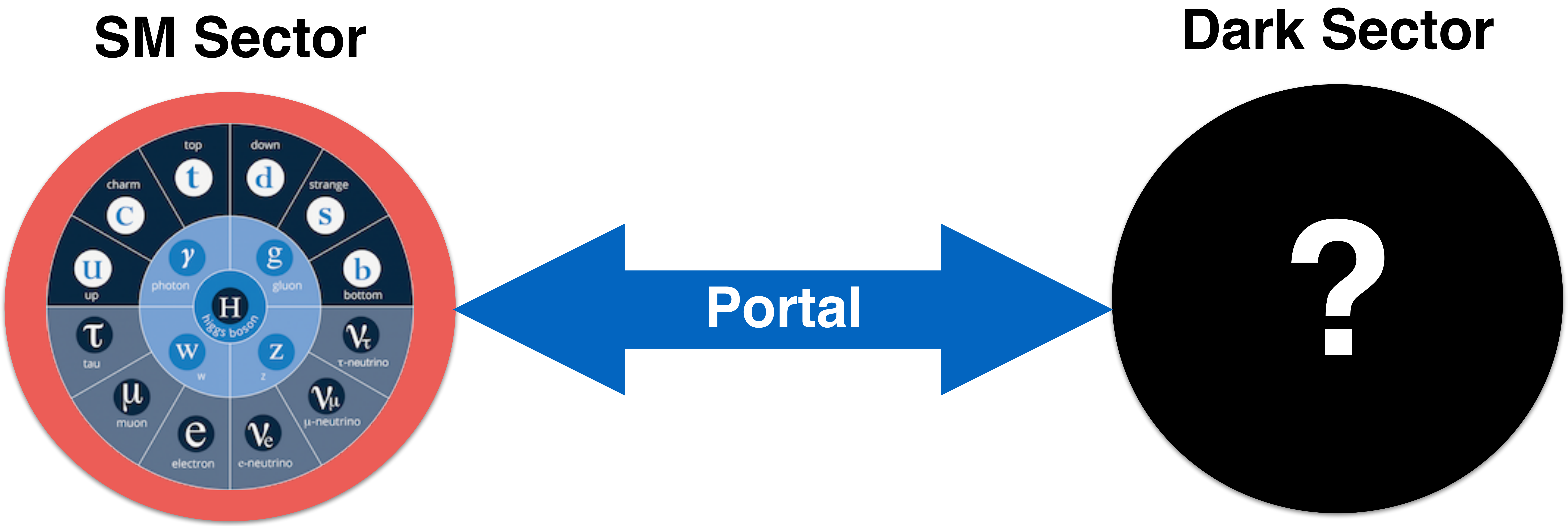
Nature 607, 52–59 (2022)



Nature 607, 60-68 (2022)

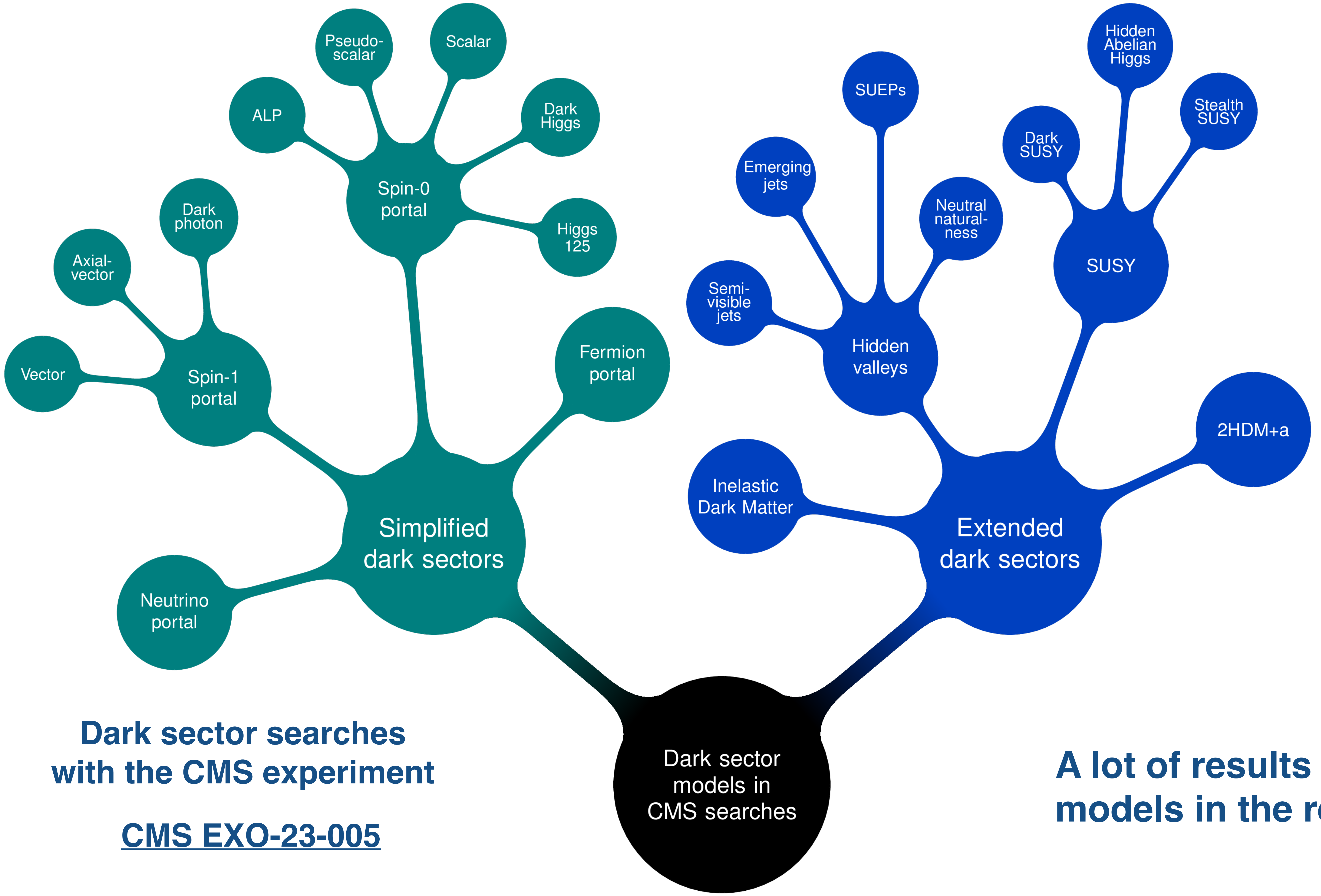
Dark Sectors

- Overwhelming evidence for Dark Matter from astrophysics & cosmology
  - No evidence from particle physics: **Particle nature is still a mystery!**
- DM can be a particle from a larger "dark sector" of SM singlets
  - With a "portal" between SM & DS via mediators



Dark Sectors

- A huge list of models with dark sectors within reach of the LHC experiments
  - Can be split into **simplified** and **extended** dark sector models



- **Simplified models:**
  - Minimal set of parameters
  - One DM + one mediator
- **Extended DS:**
  - A family of SM singlets that communicate with the SM thorough possible portals
  - Rich structures in DS, rich phenomenology for experiments

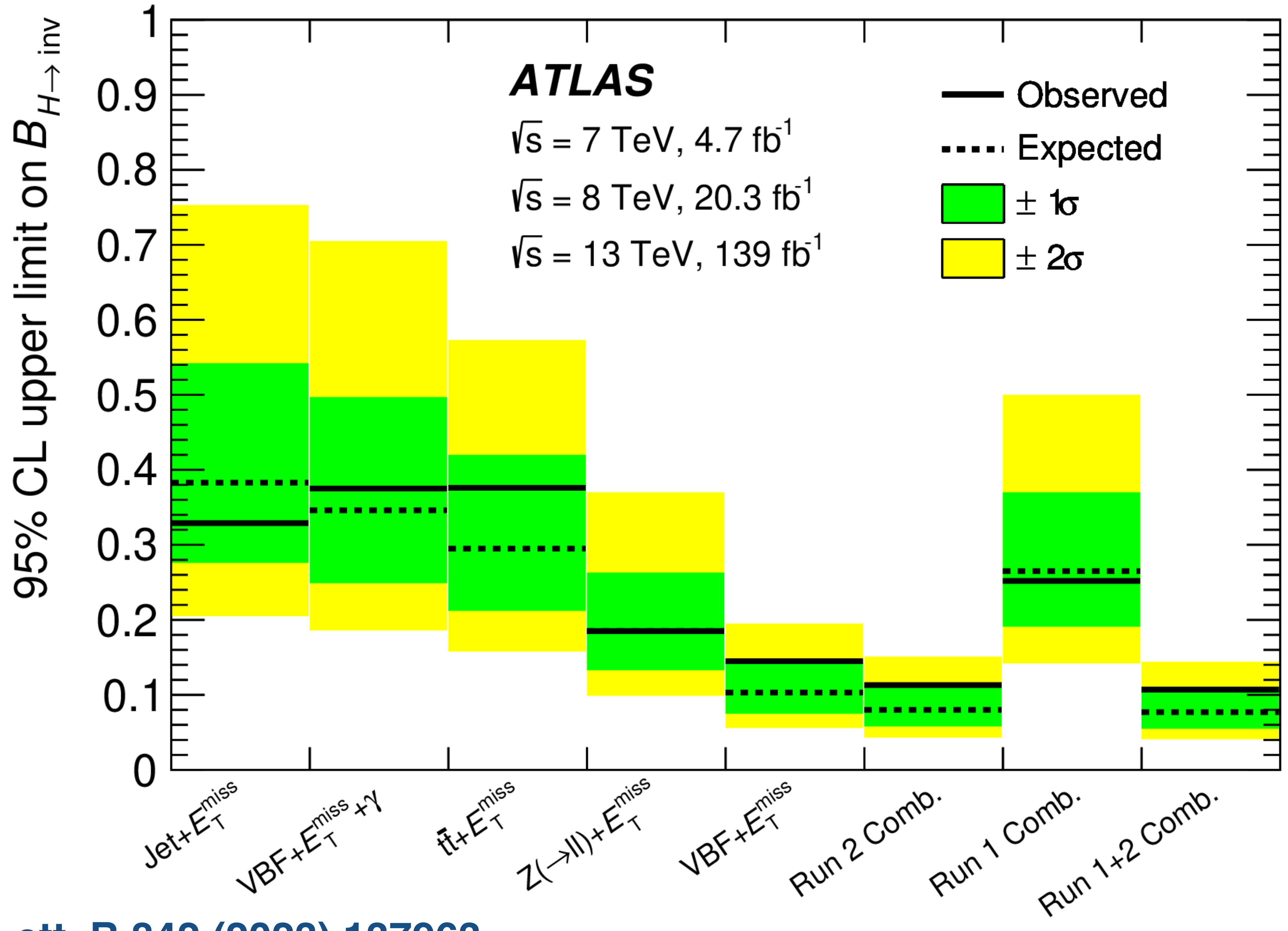
Dark sector searches with the CMS experiment

CMS EXO-23-005

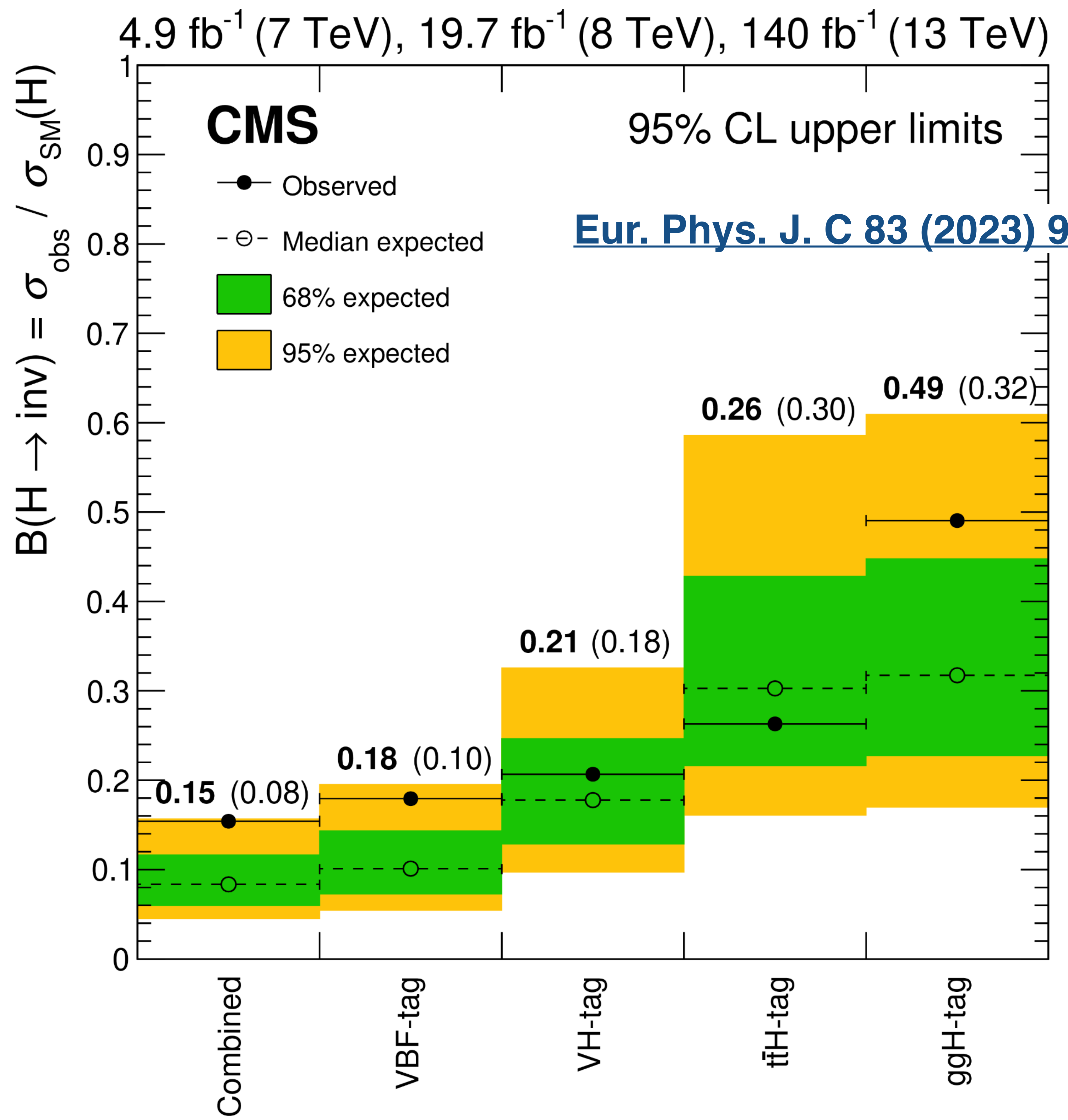
A lot of results from ATLAS & CMS covering different models in the recent years. I will only cover a select few.

H → invisible

- In SM: $\mathscr{B}(H_{125} \to \text{inv})$ is 0.1%
  - Can be larger in BSM models with Higgs coupling to Dark Sectors.
- Latest combination results from ATLAS and CMS for Run 1 + Run 2
  - Combining ggF, VBF, VH, ttH production modes
  - **Sensitivity is mostly driven by VBF channel**



Phys. Lett. B 842 (2023) 137963

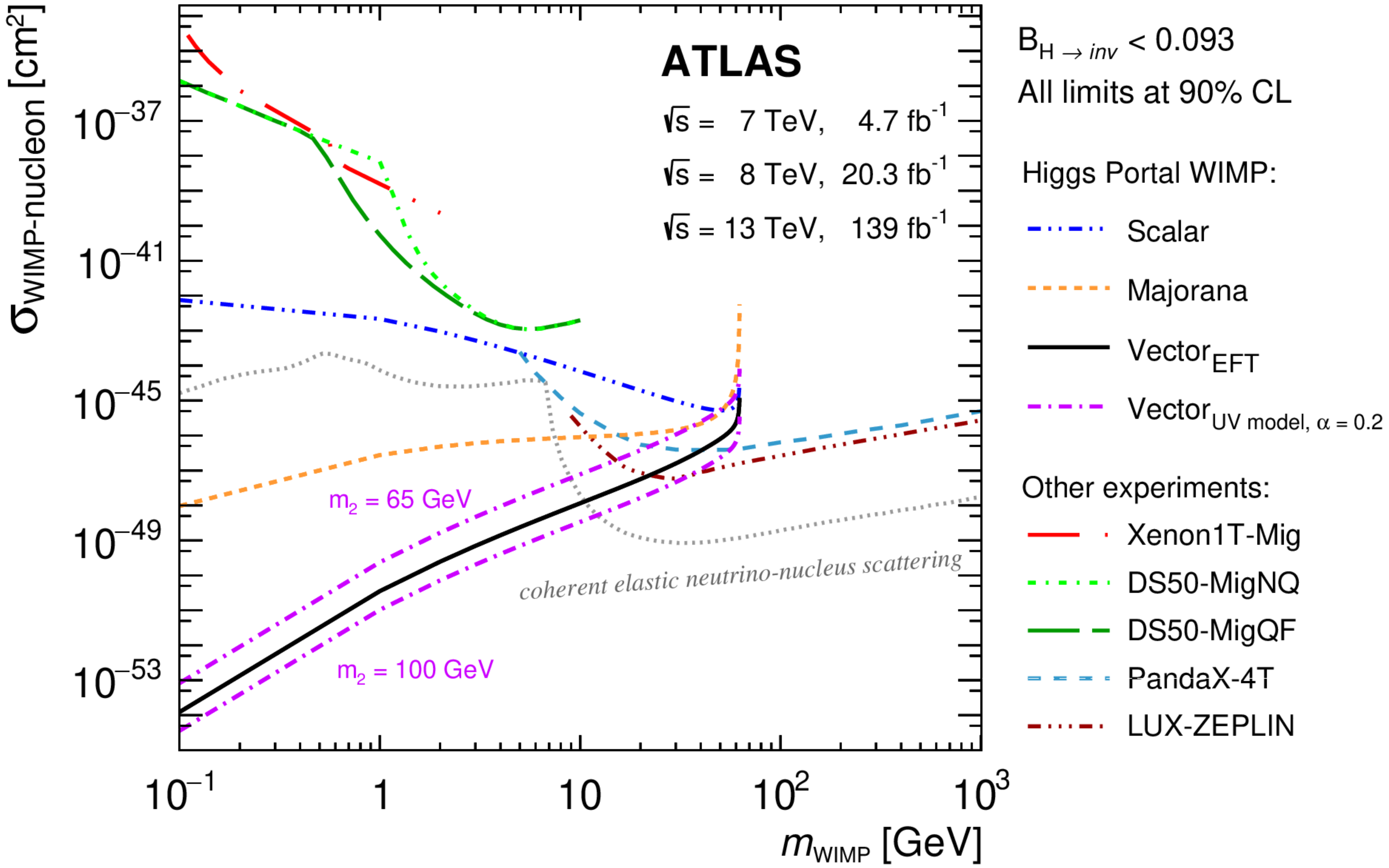


Eur. Phys. J. C 83 (2023) 933

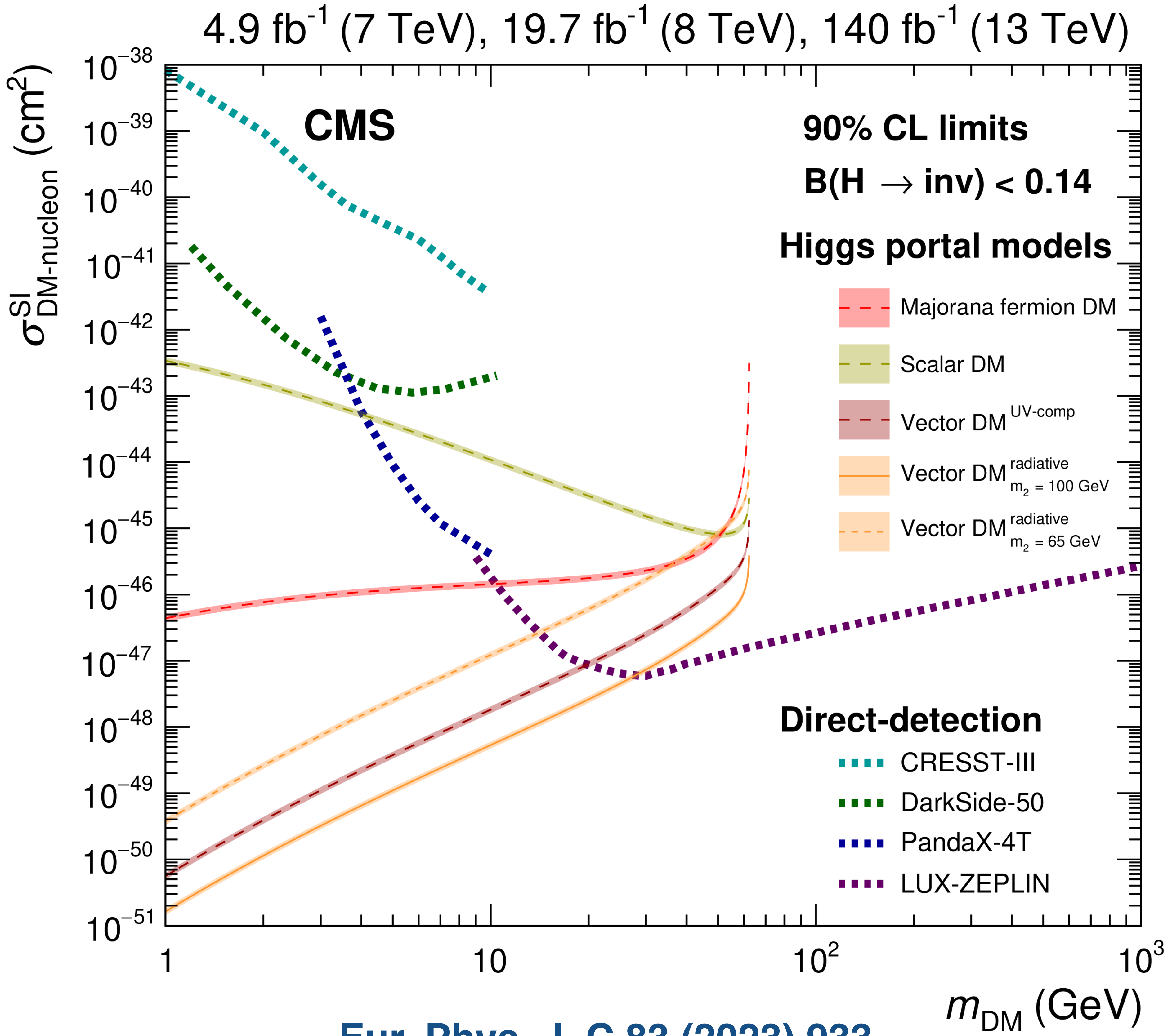
- Combined upper limit on $\mathscr{B}(H_{125} \to \text{inv})$:
  - **ATLAS: < 11% (8%) observed (expected)**
  - **CMS: < 15% (8%) observed (expected)**

H → invisible

- The upper limits can be interpreted in context of Higgs portal models to dark sectors
  - Translates into limits on **m_{DM} and DM-nucleon cross sections** for comparison to other DM experiments.
- **ATLAS & CMS are more competitive in low DM mass phase space**



[Phys. Lett. B 842 (2023) 137963]



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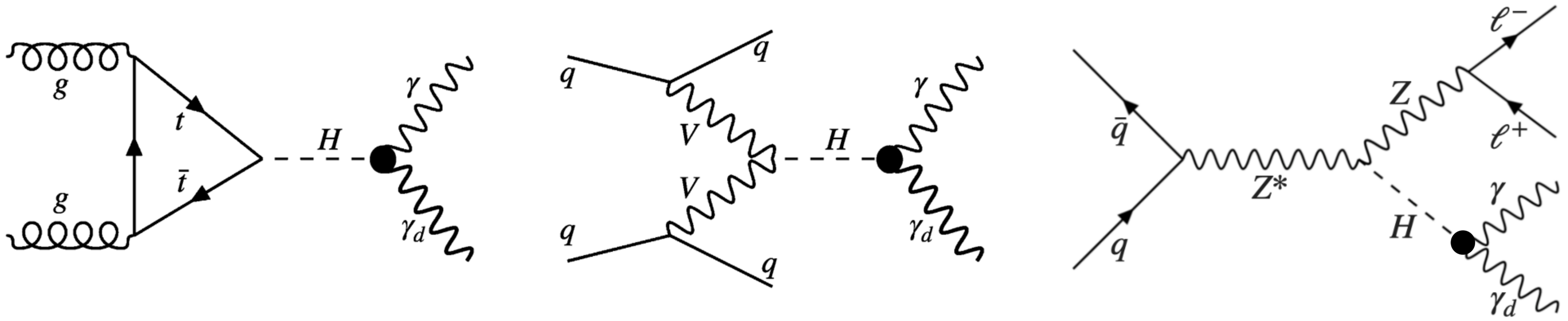
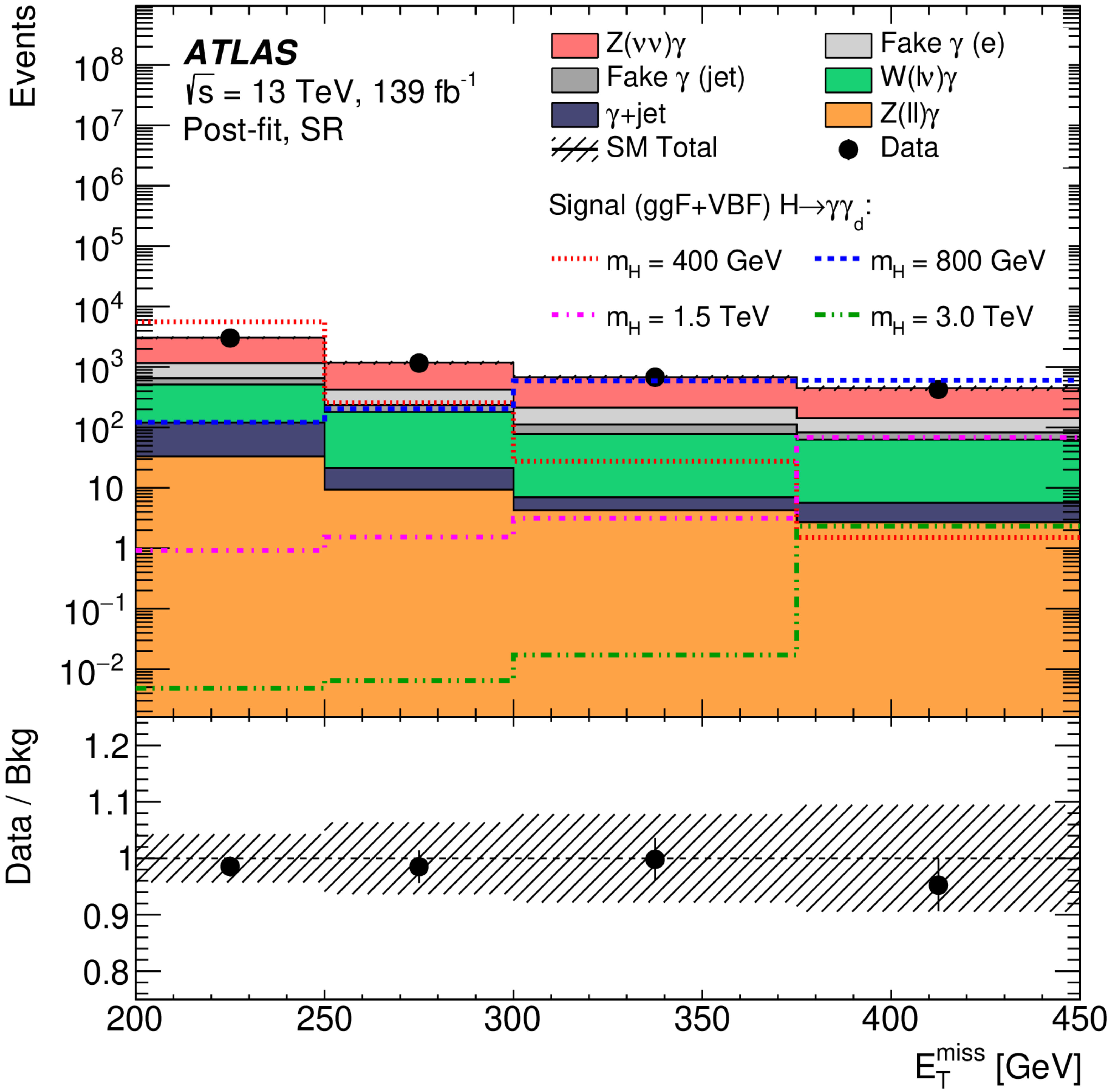
Massless Dark Photons





- Recent ATLAS combination result on massless dark photon searches.
- Targeting H $\rightarrow \gamma\gamma_d$ in ggF, VBF, and ZH production modes
  - **ggF**: $\gamma + E_T^{miss}$ signature using photon triggers
  - **VBF**: $\gamma + E_T^{miss}$ + VBF jets signature using E_T^{miss} triggers
  - **ZH**: $\gamma + E_T^{miss}$ + Z $\rightarrow ll$ signature using lepton triggers

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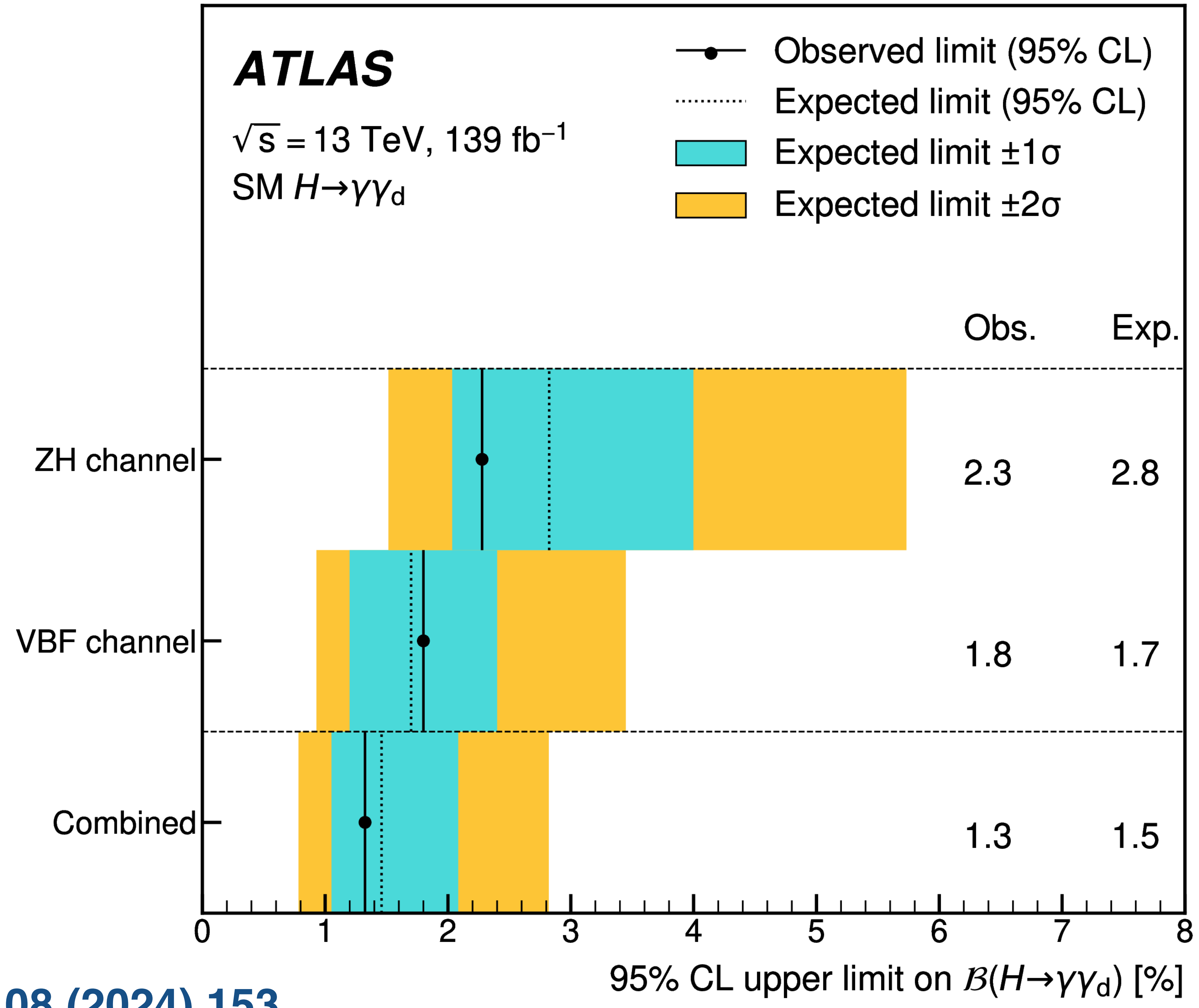
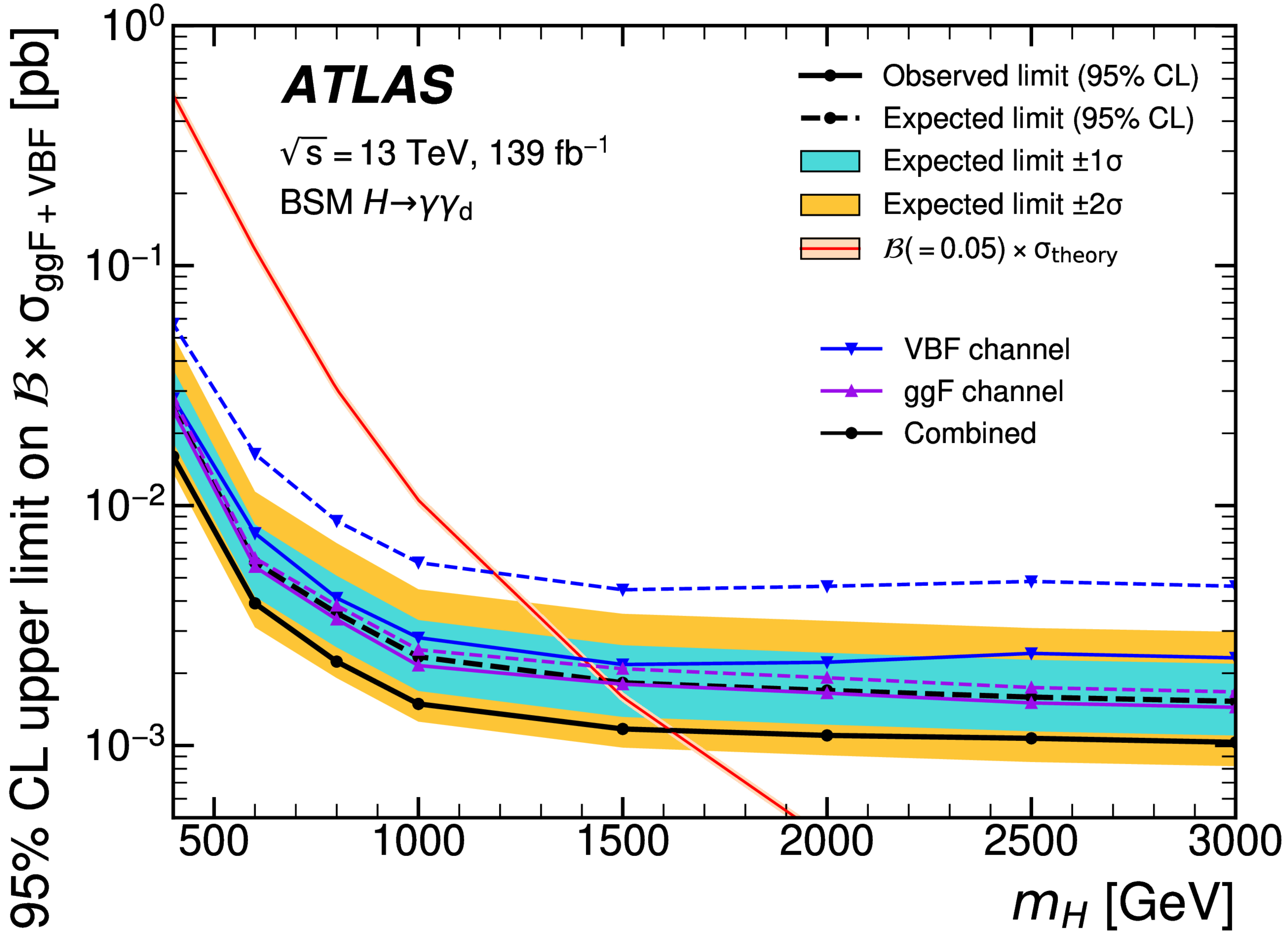
Massless Dark Photons

- VBF and ZH channel results are combined under SM Higgs assumption
  - Observed $\mathscr{B}(H_{125} \rightarrow \gamma\gamma_d)$ is 1.3%
- ggF and VBF results are combined under BSM Higgs hypothesis
  - Assuming $\mathscr{B}(H_{BSM} \rightarrow \gamma\gamma_d) = 5\,\%$, observed exclusion of $m_H <$ 1.6 TeV





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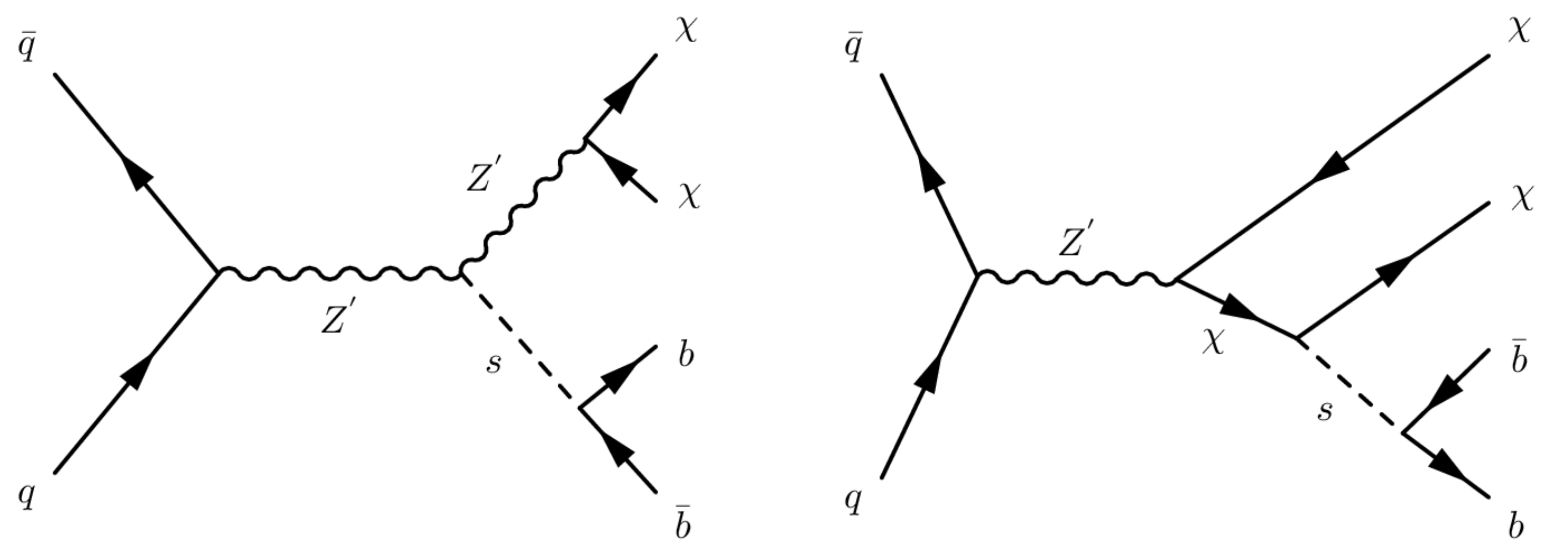
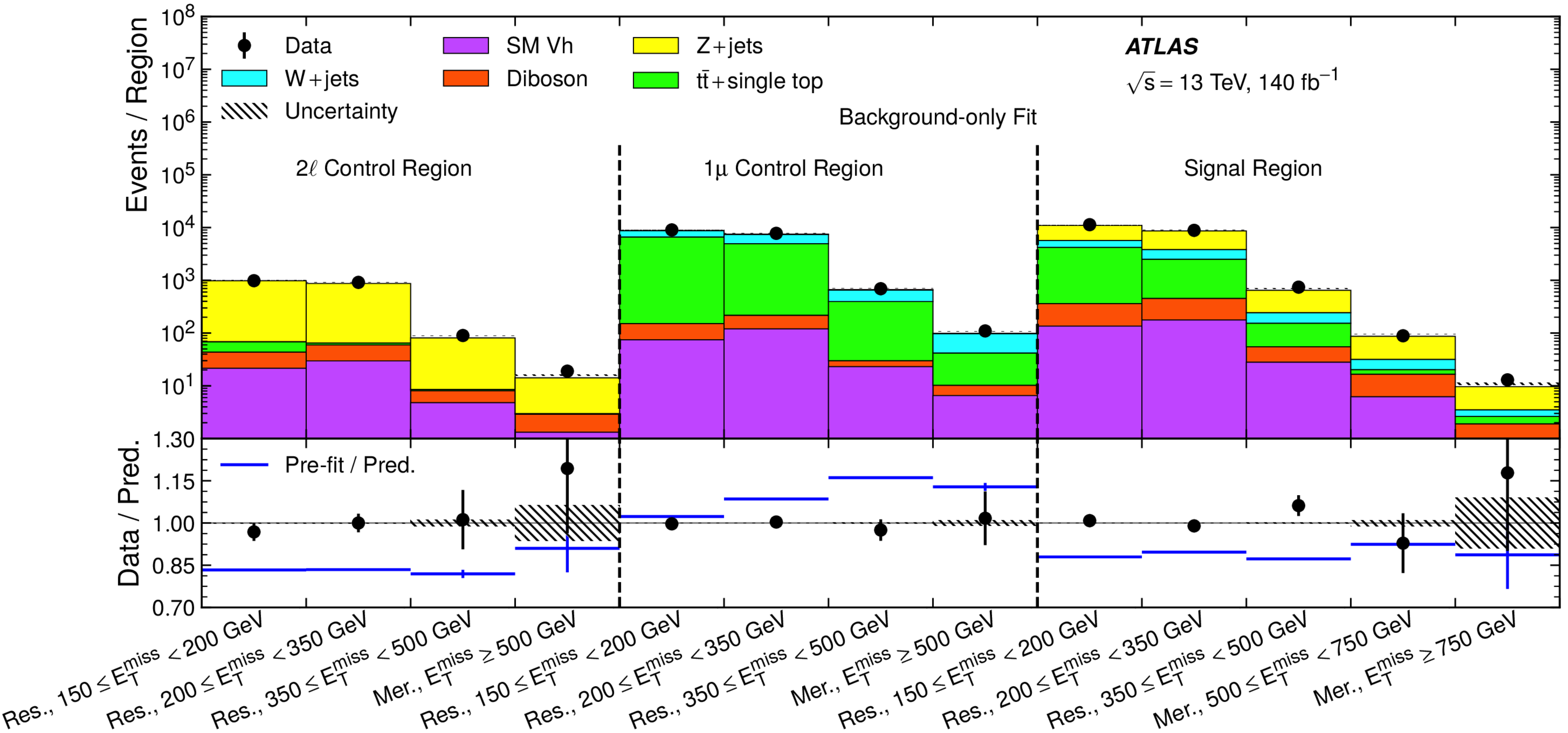
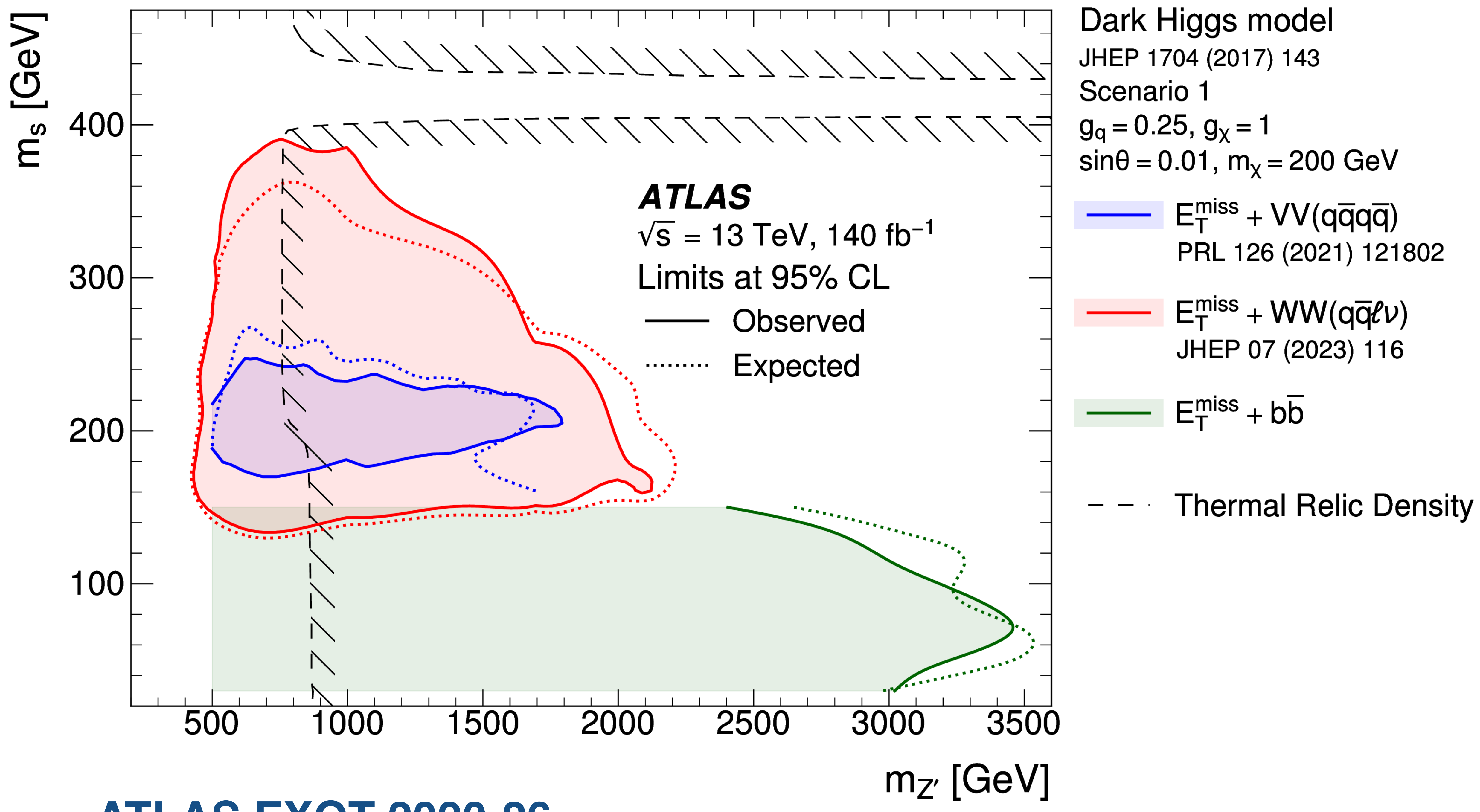
Dark Higgs

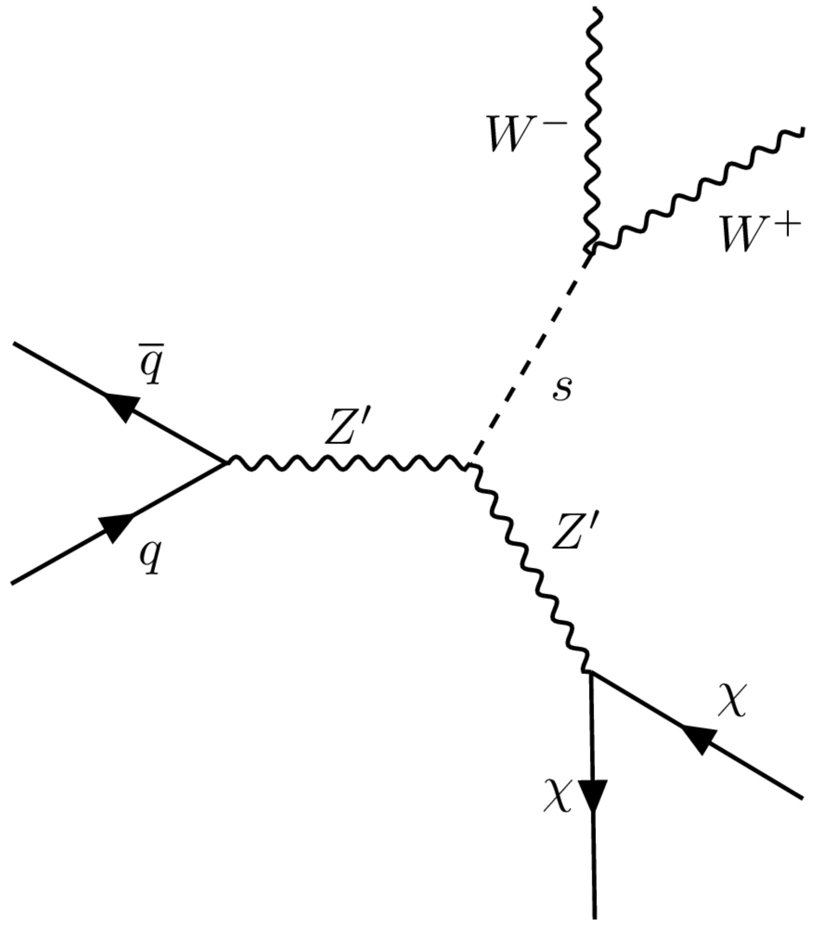
- ATLAS search for $X + E_T^{miss}$ for a massive dark Higgs boson (s) with $s \to b\bar{b}$, and a new $U(1)'$
- **Resolved** and **boosted** categories based on E_T^{miss}
- 1μ and $2l$ CRs to constrain the backgrounds
- New NN based $X \to b\bar{b}$ tagging algorithm to enhance the sensitivity
- Results are interpreted for 3 scenarios, based on g_χ, g_q, $\sin(\theta)$, m_χ
  - Excludes $m_{Z'} < 3.4$ TeV for the benchmark scenario with $m_s = 70$ GeV

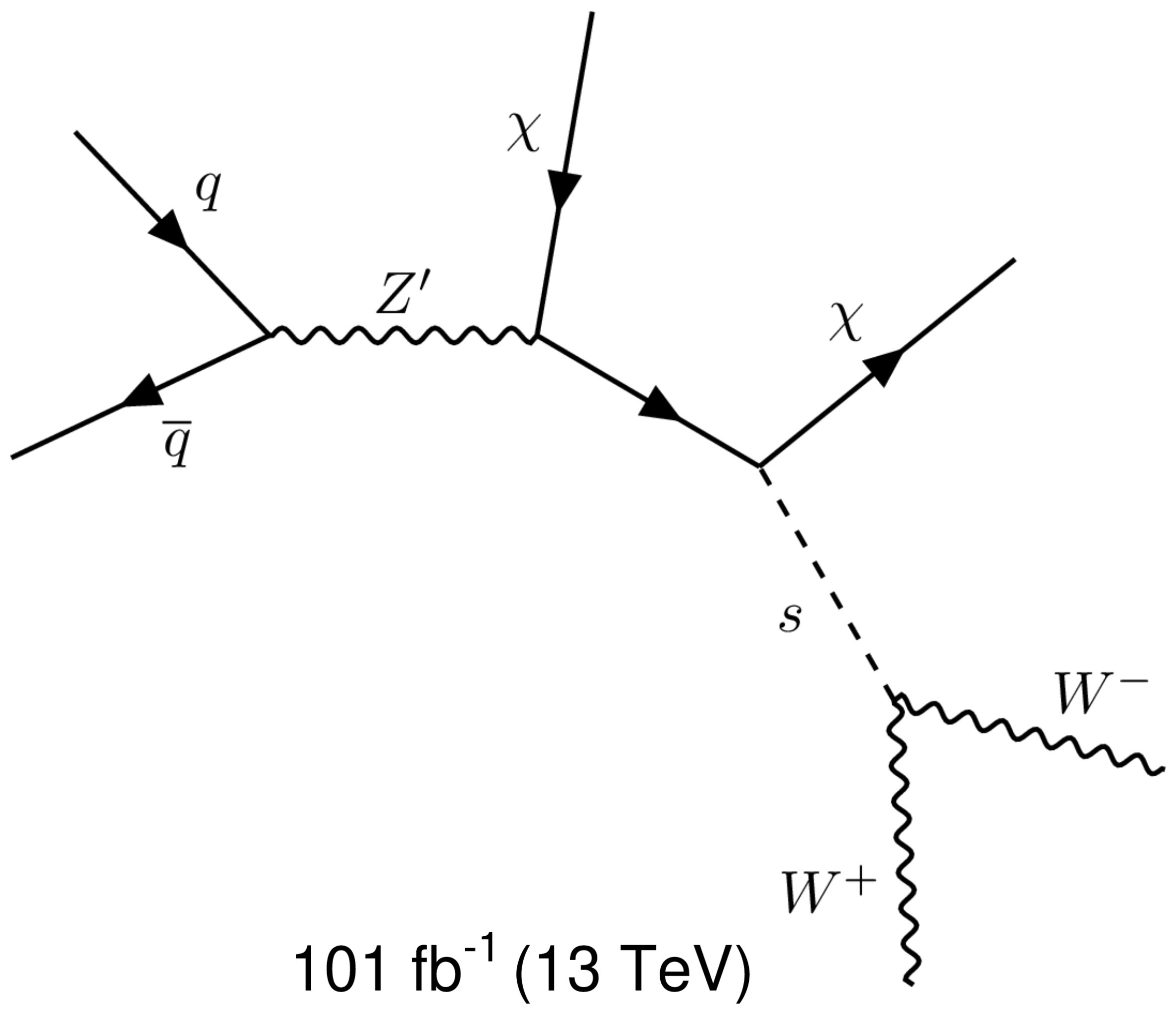




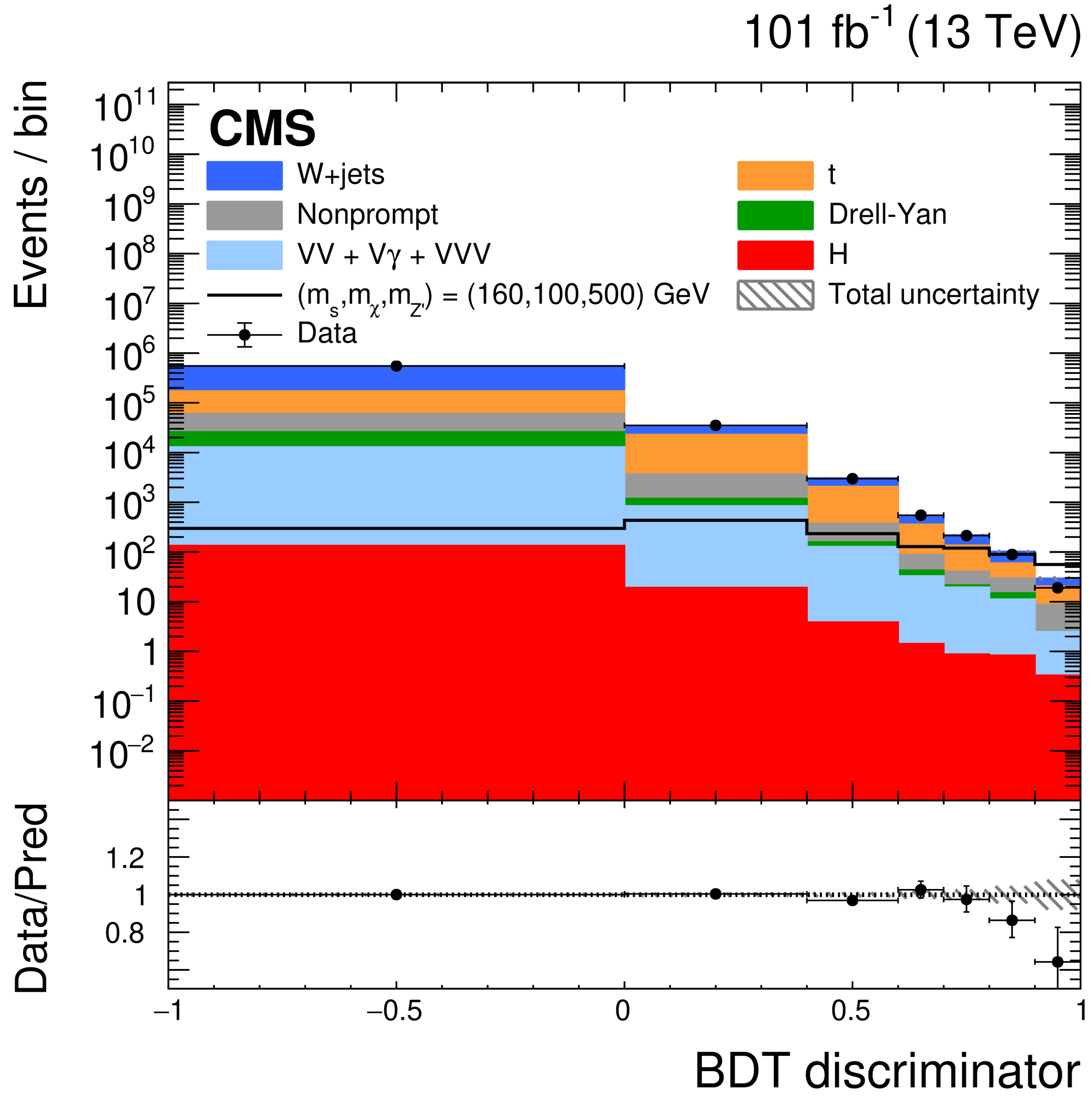


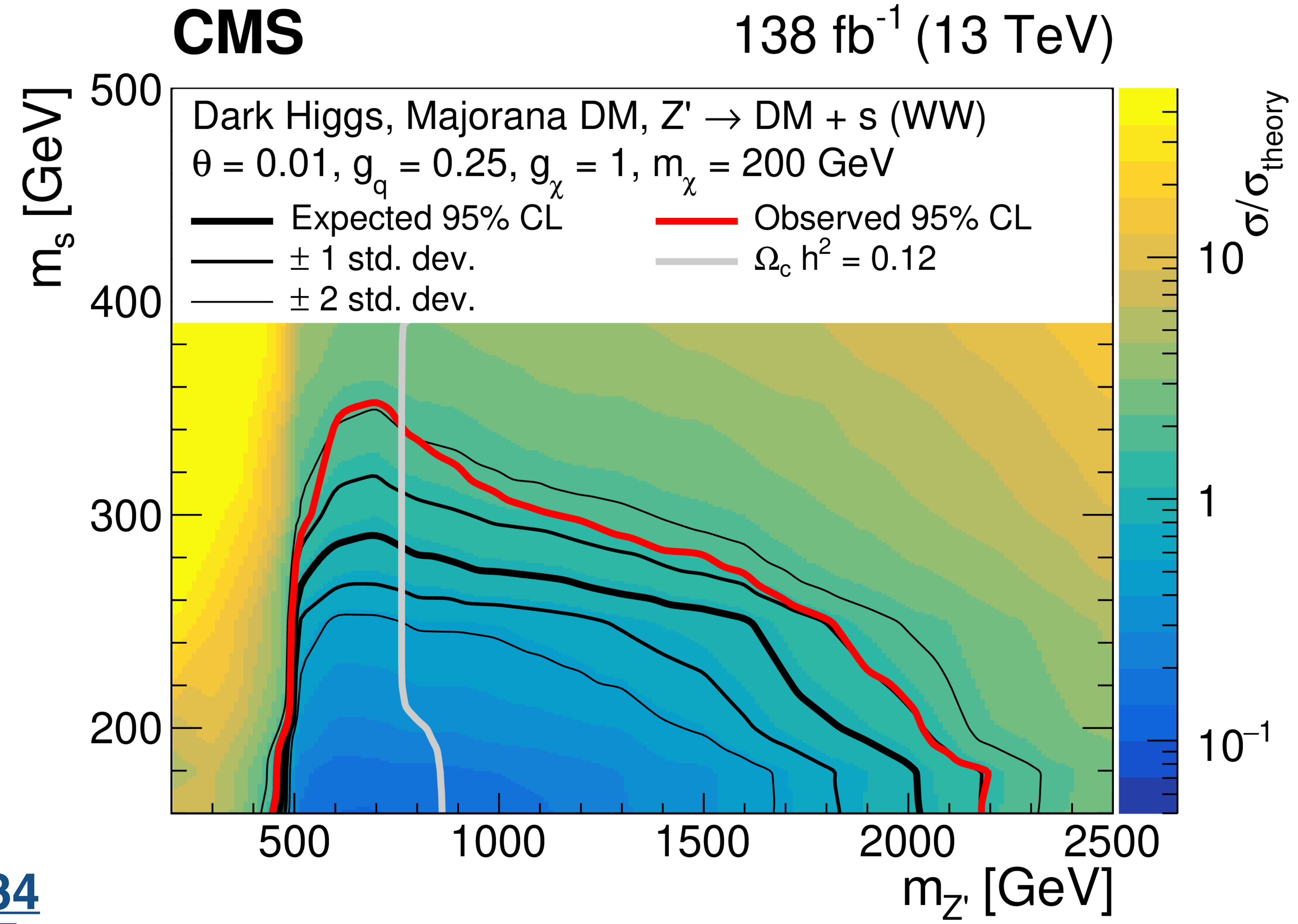
ATLAS EXOT-2020-26





- CMS search for $X + p_T^{miss}$ for a massive dark Higgs boson (s) with $s \to W^+W^-$, and a new $U(1)'$
  - Targets $m_s > 160$ GeV
  - Both $WW \to 2l2\nu$ and $WW \to l\nu qq$ are considered using single and double lepton triggers
- $WW \to 2l2\nu$: m_{ll} and transverse mass of l_{min} + p_T^{miss} system $m_T^{l_{min},p_T^{miss}}$
- $WW \to l\nu qq$: BDT discriminator using 13 kinematic features
- Results are interpreted for a similar benchmark scenario to ATLAS with different m_χ values
  - For $m_\chi = 200$ GeV, $m_{Z'} < 2.2$ TeV is excluded for $m_s = 160$ GeV





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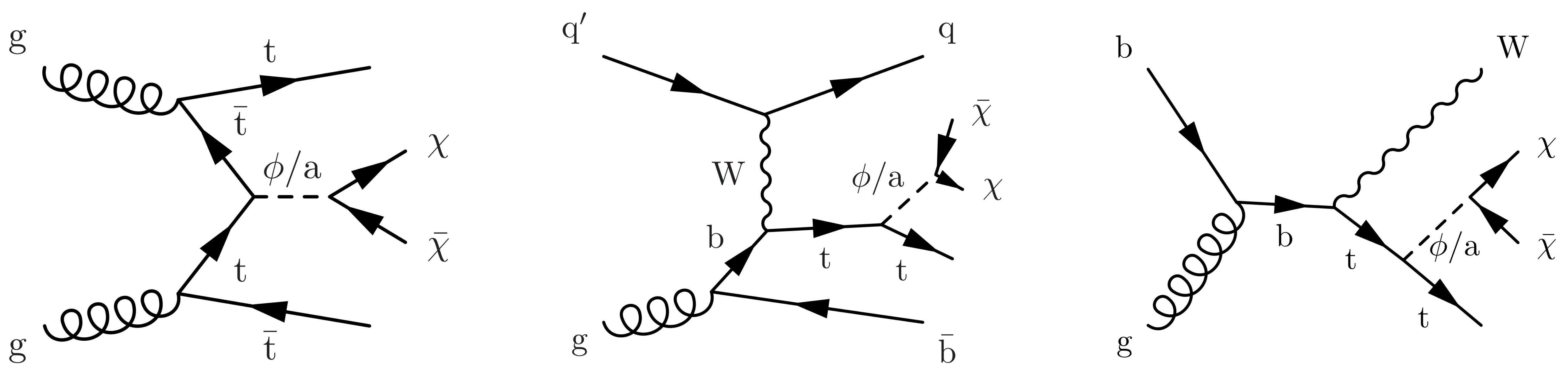
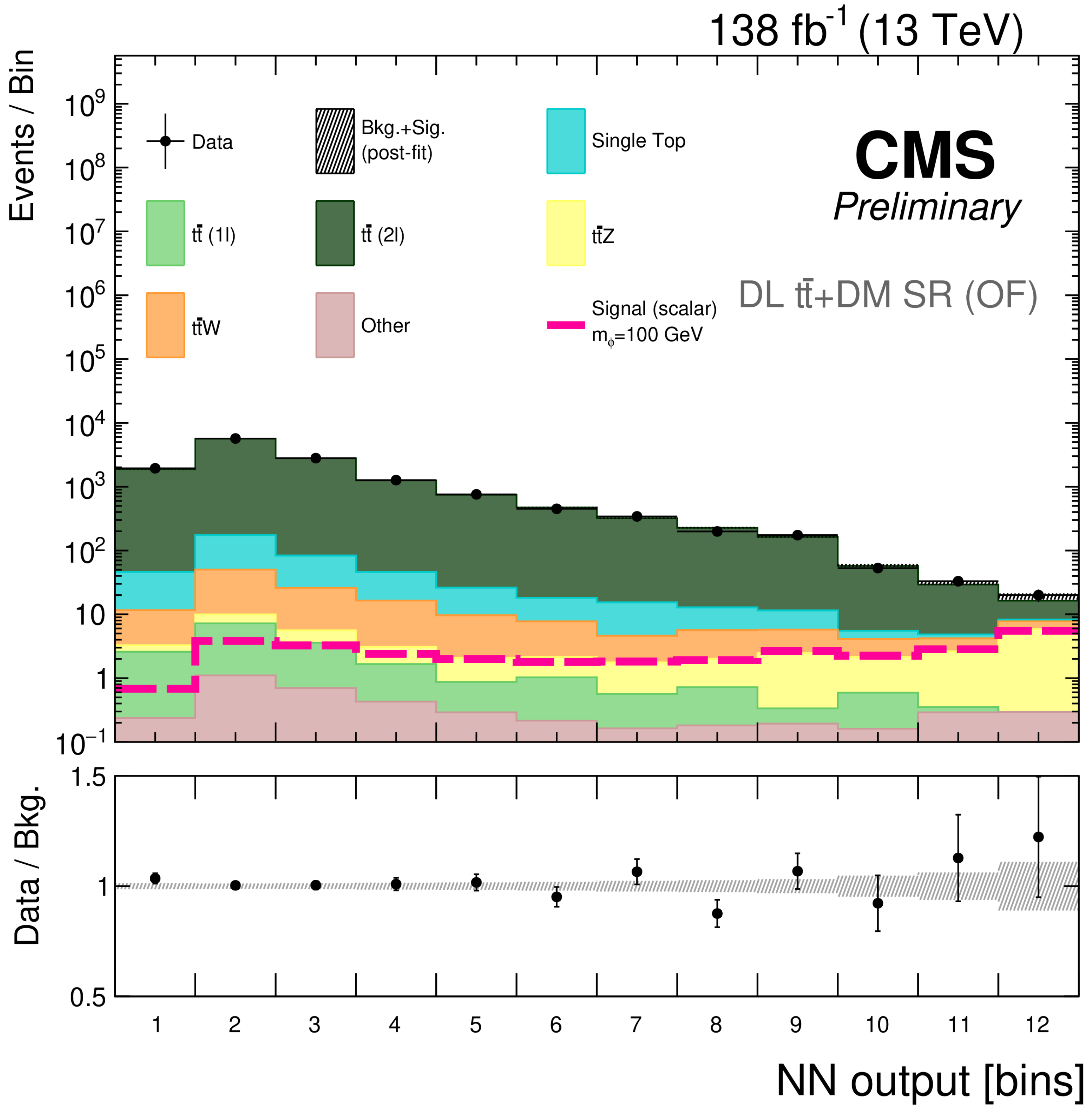
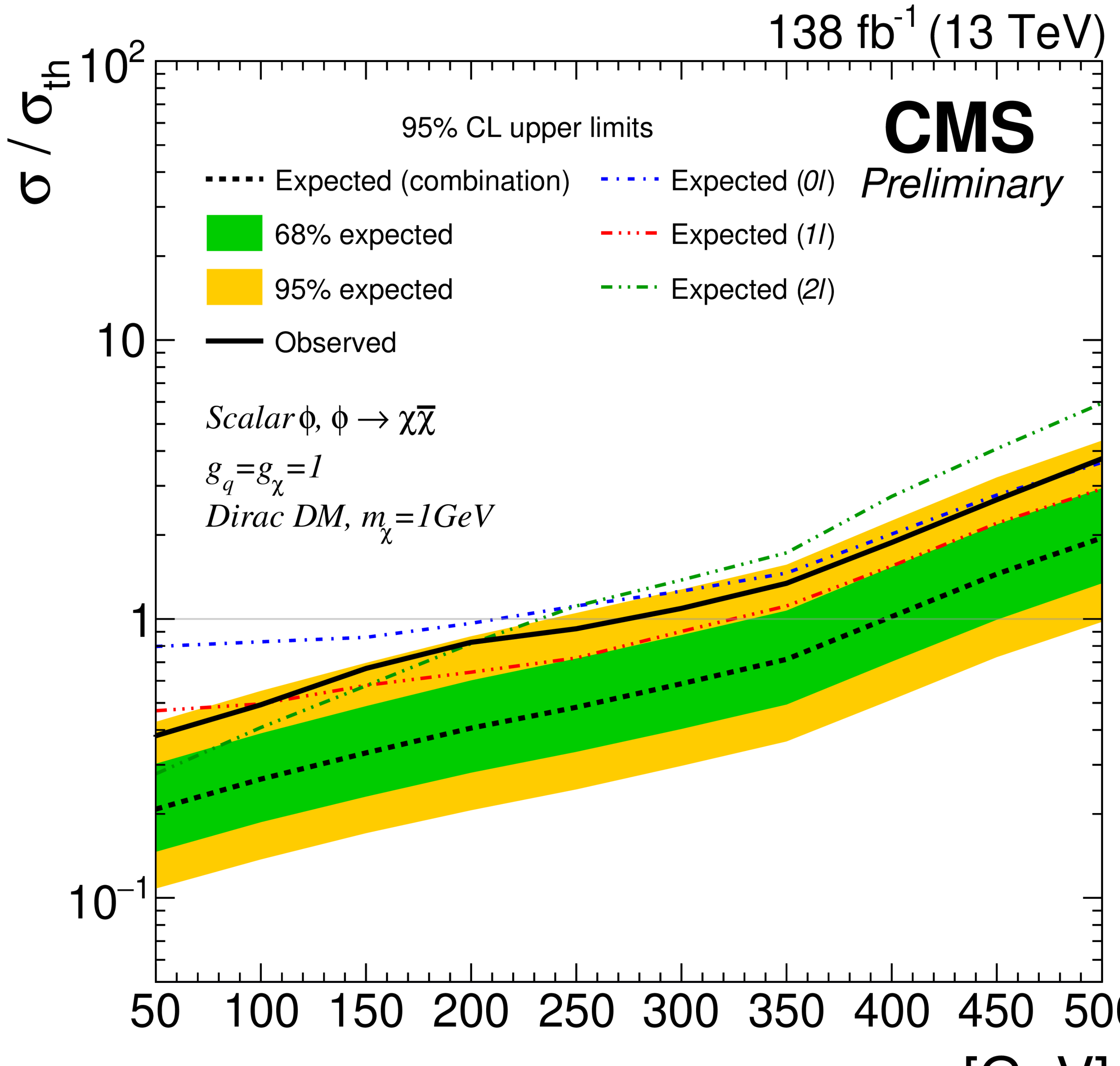
$t\bar{t} + p_T^{miss}$



- CMS search for $t\bar{t} + p_T^{miss}$ for simplified models with scalar and pseudo-scalar portals
  - Yukawa-like couplings to SM quarks with top couplings favored
  - Considering all hadronic, semi-leptonic, and dileptonic channels
  - Both $t\bar{t} + p_T^{miss}$ and $t + p_T^{miss}$ are probed
- **All hadronic and semi-leptonic**: p_T^{miss} discriminator
- **dileptonic**: NN based discriminator using kinematic variables
- Scalar (pseudo-scalar) masses are excluded below 280 (290) GeV

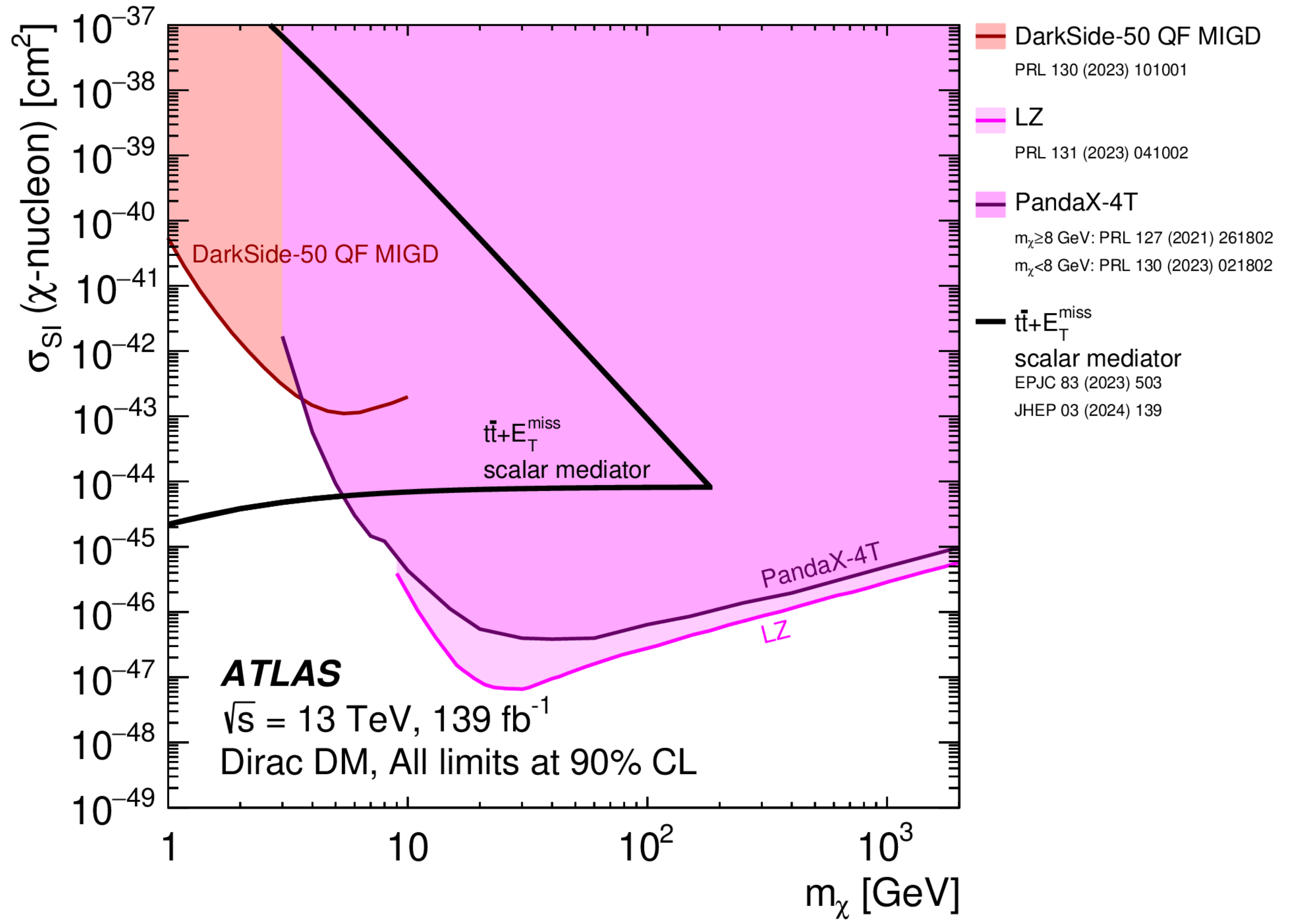


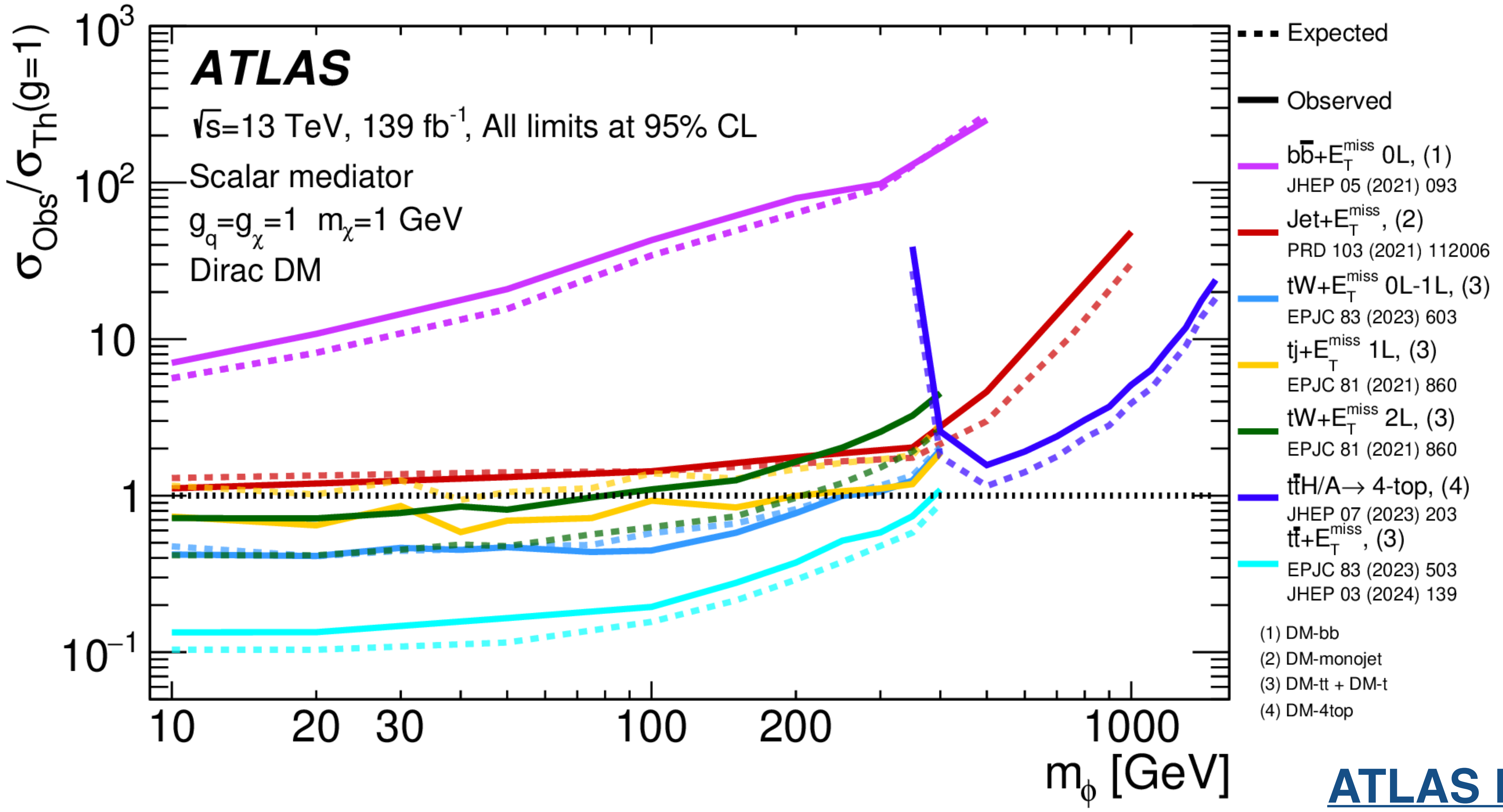


[CMS EXO-22-014]

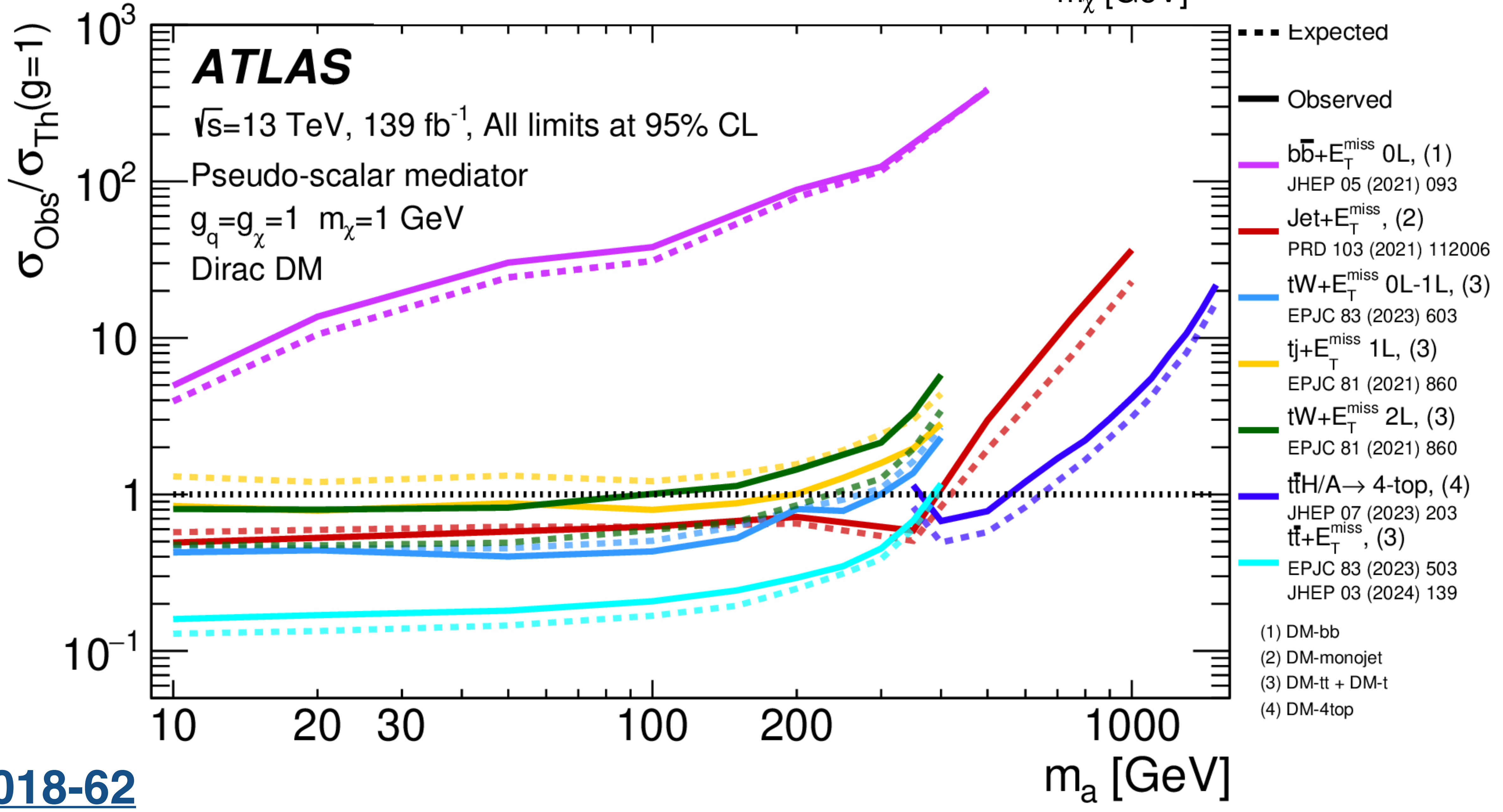
Scalar and Pseudo-Scalar Mediators

- Recent ATLAS result combining multiple searches for DM models with s-channel mediators
  - Combining results for **scalar, pseudo-scalar, vector, and axial-vector mediators**
- Most stringent limits on scalar and pseudo-scalar mediators are obtained from $t\bar{t} + E_T^{miss}$ final state excluding mediator masses up to 400 GeV
  - After $m_{mediator} > 350$ GeV, $t\bar{t}t\bar{t}$ limits become dominant
- The upper limits from $t\bar{t} + E_T^{miss}$ are also converted to DM-nucleon scattering cross sections and compared to DD experiments



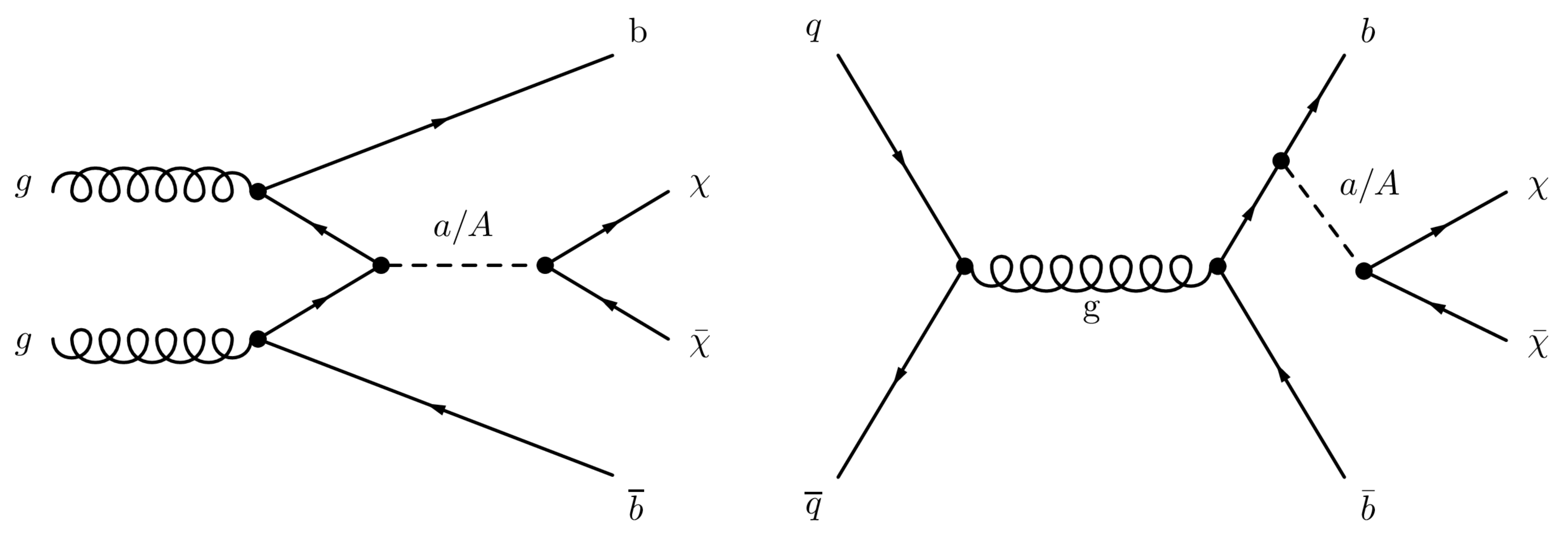


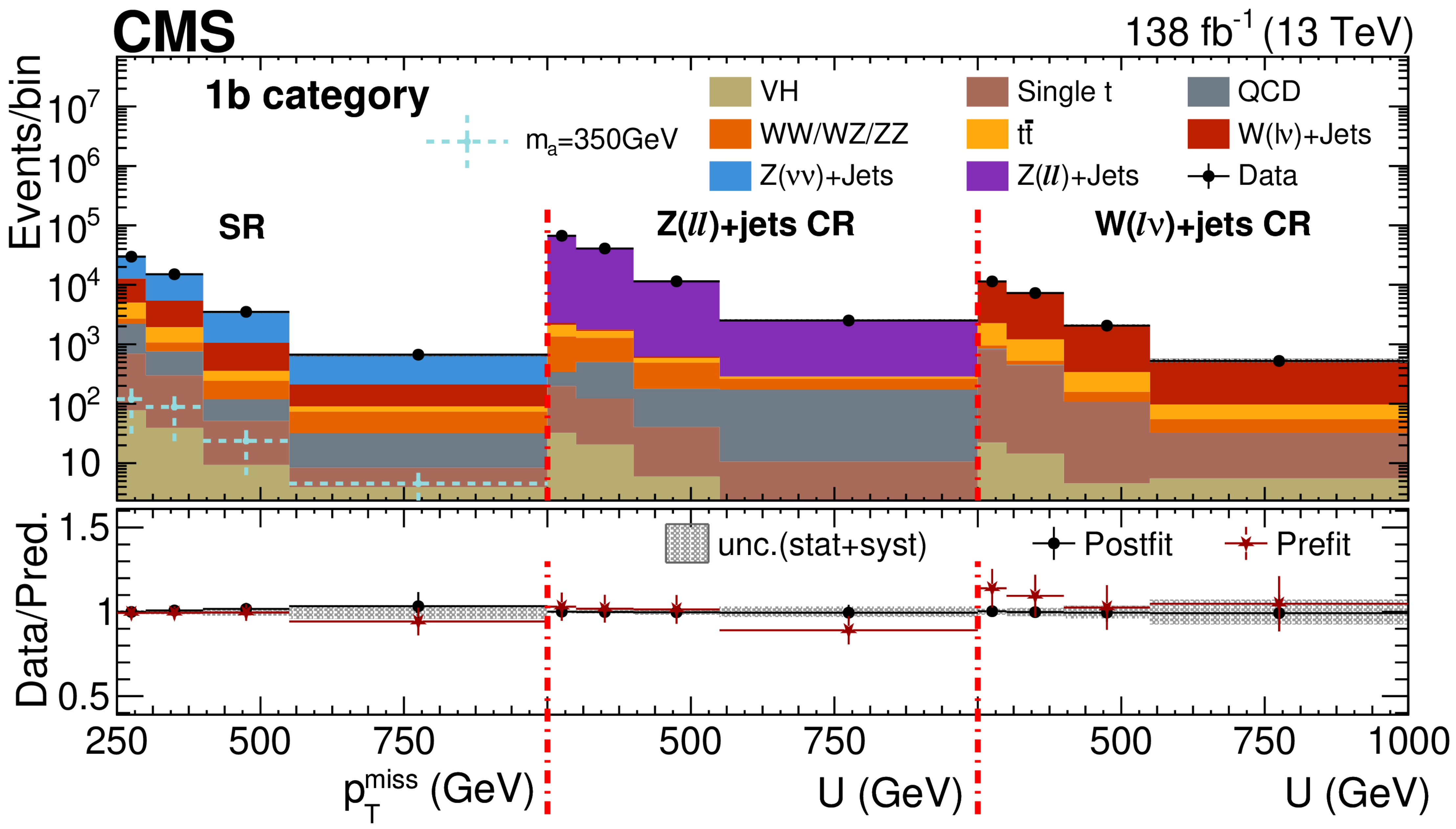
[ATLAS EXOT-2018-62]

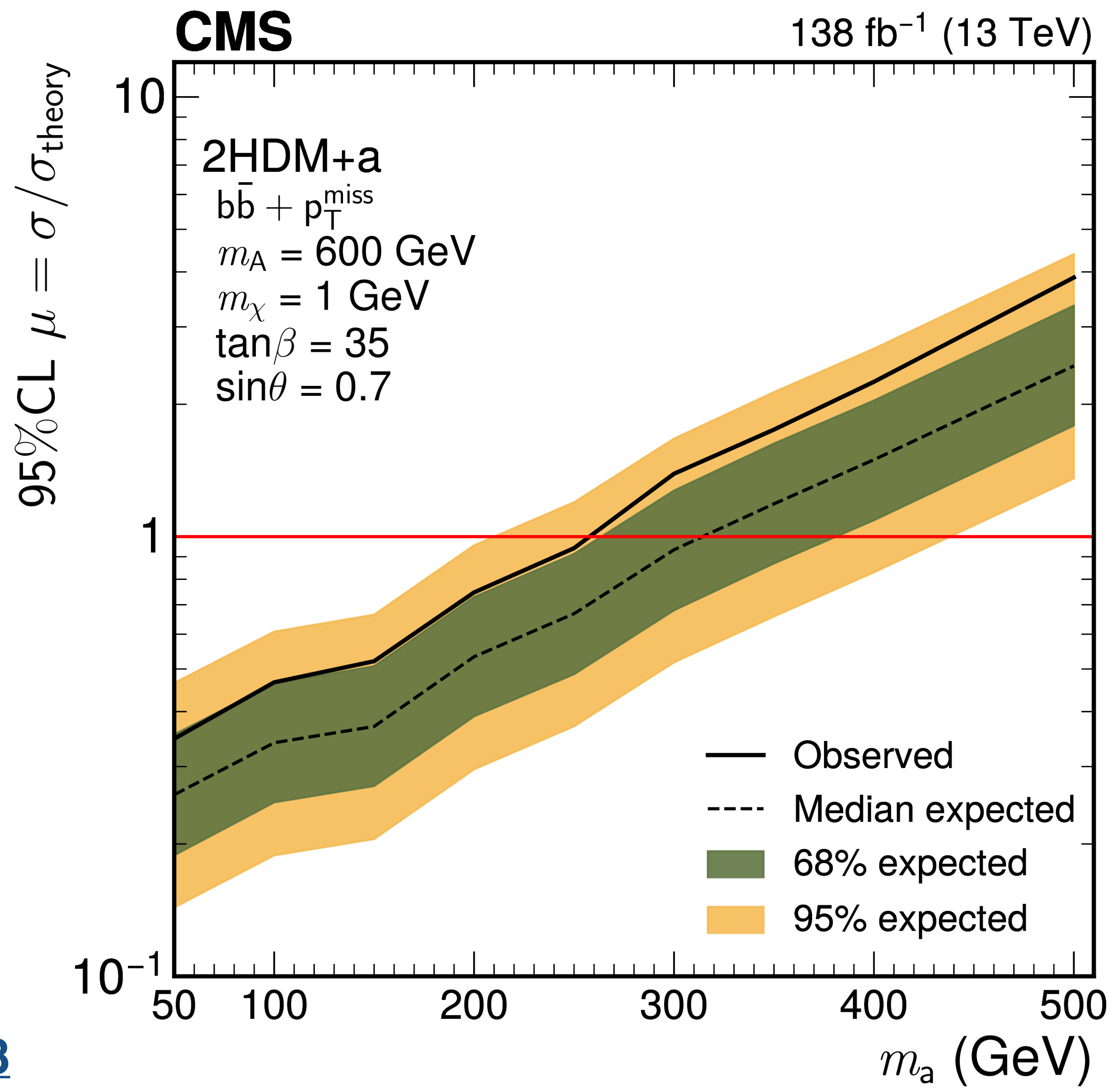


2HDM+a Signatures: $b\bar{b} + p_T^{miss}$

- CMS search for $b\bar{b} + p_T^{miss}$ motivated by 2HDM+a models
  - $A/a - b$ coupling is enhanced for large $\tan(\beta)$
- $1b$ or $2b$ signal regions with large p_T^{miss} and CRs to constrain $Z +$ jets, $W +$ jets, and $t\bar{t}$ backgrounds
- $1b$ SR: p_T^{miss} (or $U = |\vec{p}_T^{miss} + \sum \vec{p}_T^{\ell}|$ for CRs) as discriminator
- $2b$ SR: $\cos\Theta^* = |\tanh\left(\frac{\eta_{j1} - \eta_{j2}}{2}\right)|$ as discriminator
- For a 2HDM+a model, $m_a < 260$ GeV is excluded at high $\tan(\beta)$ phase space



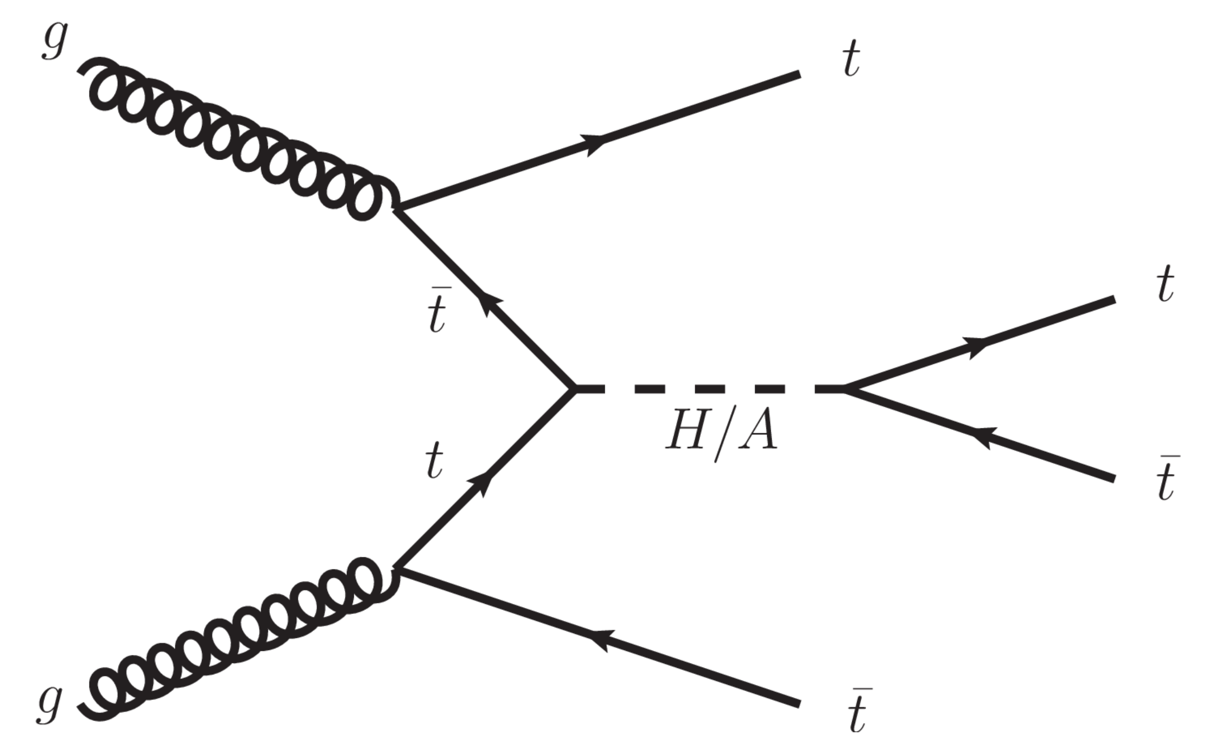


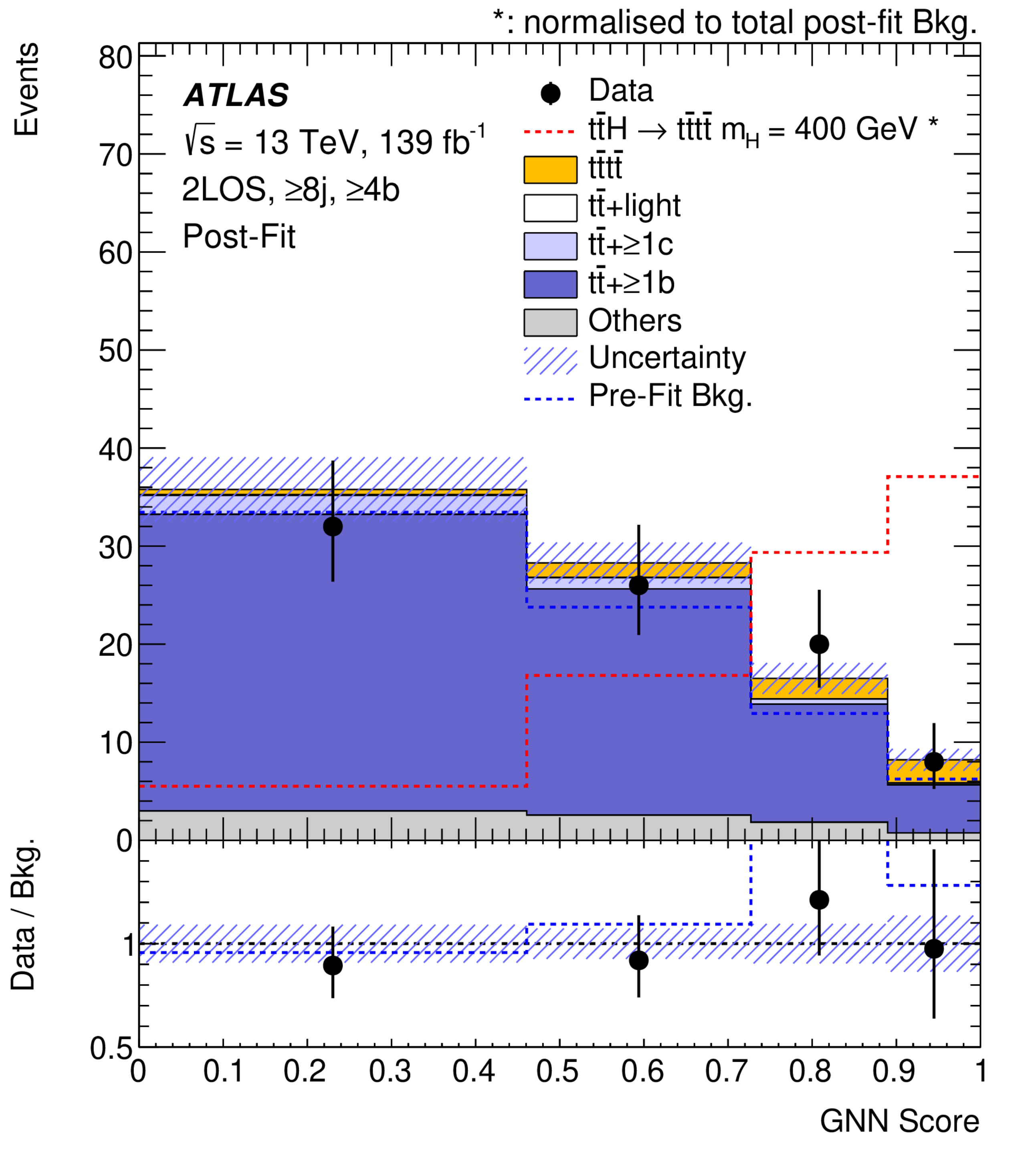


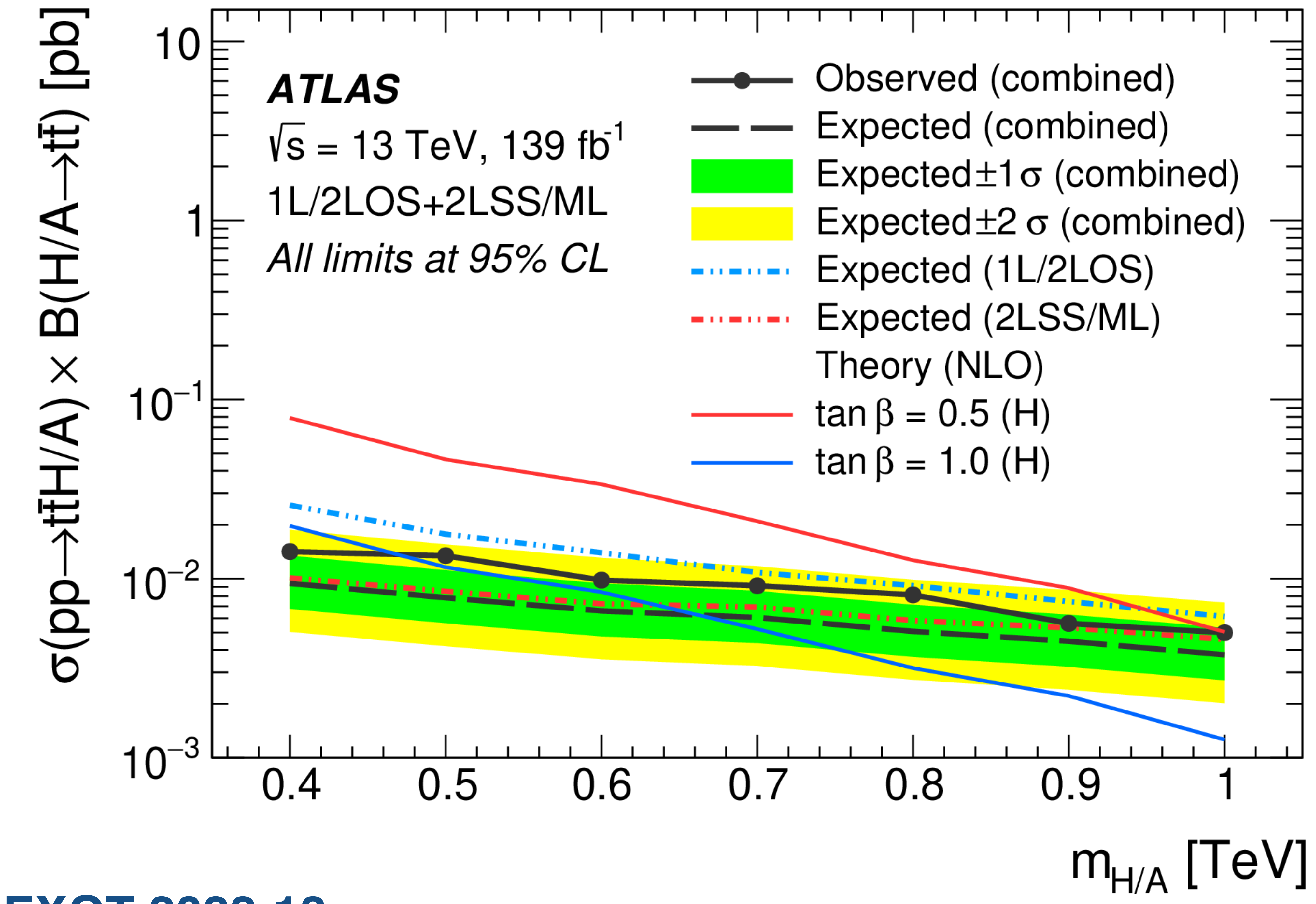
CMS SUS-23-008

2HDM Signatures: $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$

- ATLAS search for a heavy scalar (H) or pseudo-scalar (A) in $t\bar{t}t\bar{t}$ final state
  - For $m_{H/A} > 500$ GeV and $\tan\beta \sim 1$ dominant decay is $t\bar{t}$
- 1L channel: One lepton (e or μ) and >7 jets
- 2LOS channel: Two opposite charge leptons and >5 jets
- Channels further split into categories based on # of b-tagged jets
- Signal and background classification using GNNs parametrised in $m_{H/A}$
- Results are combined with a previous search with 2 same-sign leptons (2LSS) or multi leptons (ML) channels for a 2HDM model setting upper limits on the cross-sections as a function of $m_{H/A}$







ATLAS EXOT-2022-13

2HDM Signatures: $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$

- ATLAS search for a heavy scalar (H) or pseudo-scalar (A) in $t\bar{t}t\bar{t}$ final state
  - For $m_{H/A} > 500$ GeV and $\tan\beta \sim 1$ dominant decay is $t\bar{t}$
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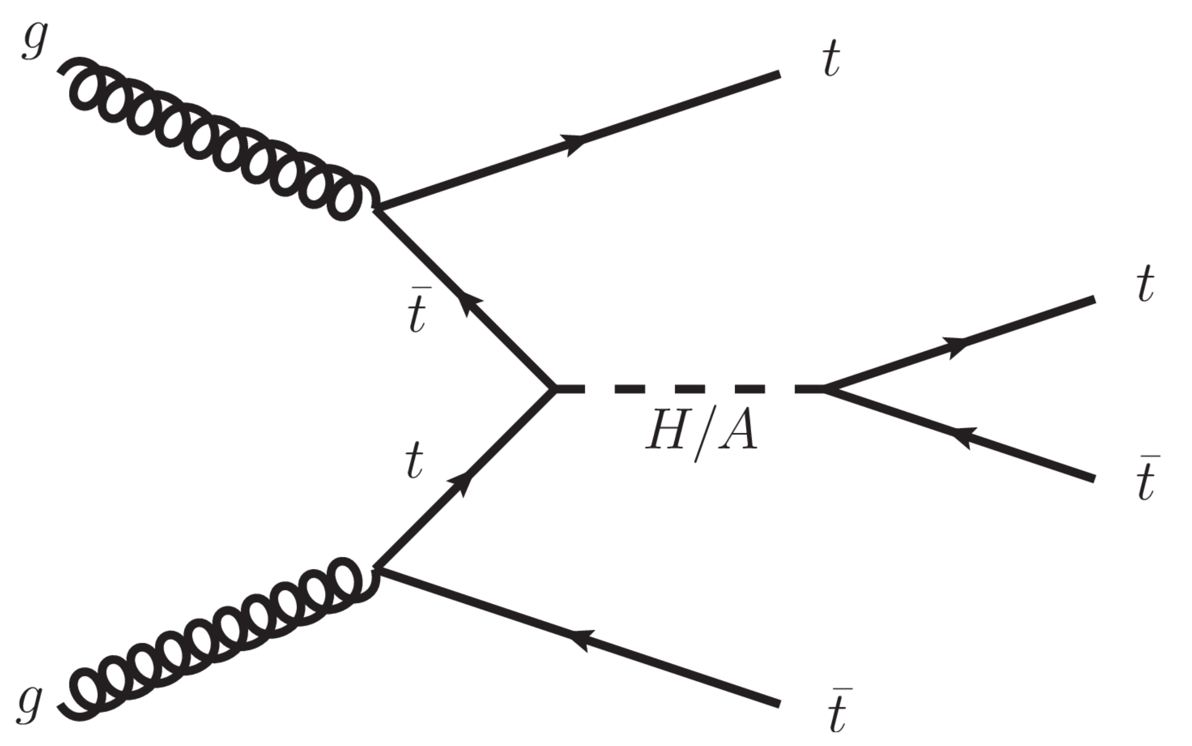
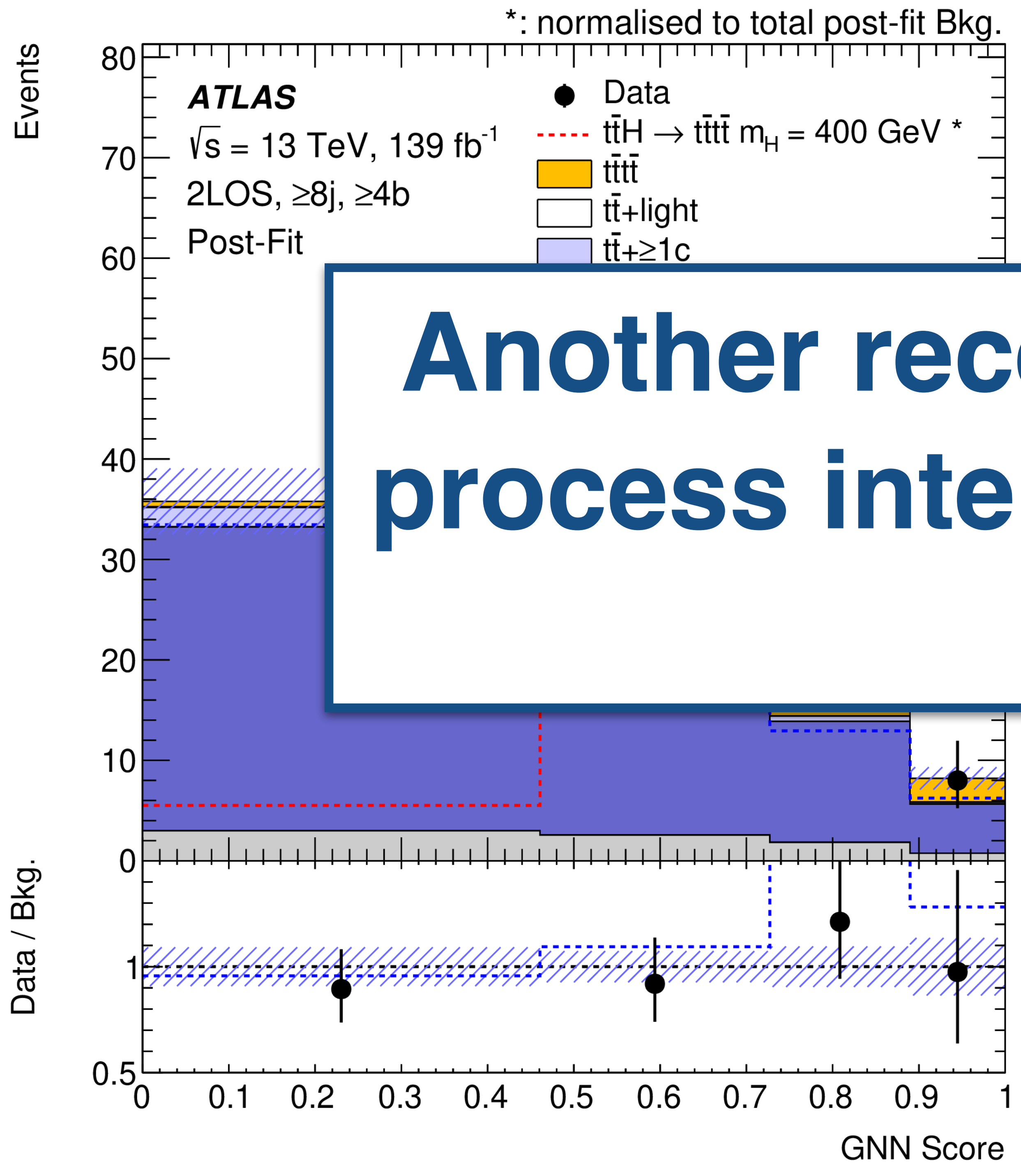
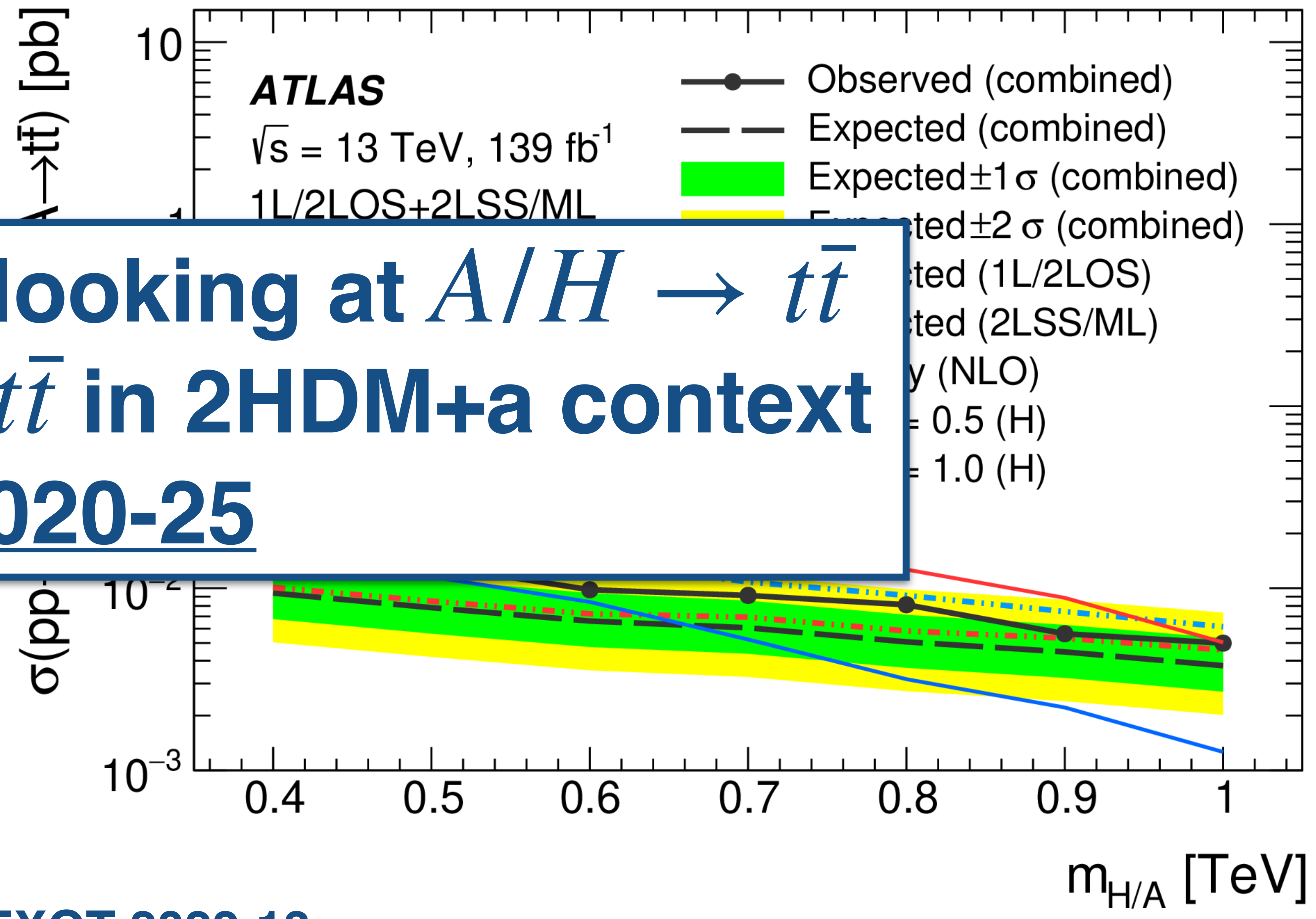




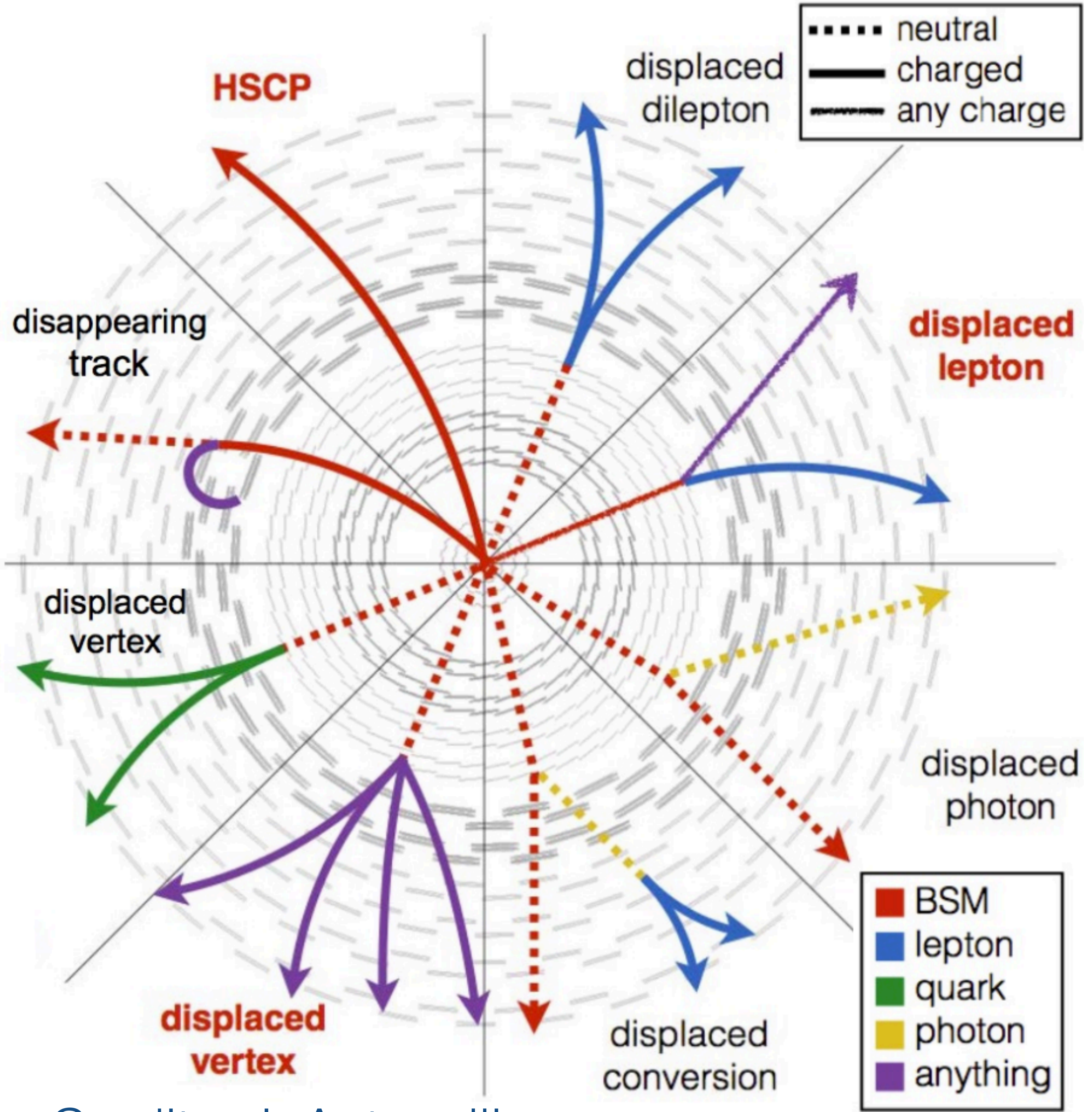


Another recent ATLAS result looking at $A/H \rightarrow t\bar{t}$ process interference with SM $t\bar{t}$ in 2HDM+a context
ATLAS EXOT-2020-25

ATLAS EXOT-2022-13

LLPs in Dark Sectors

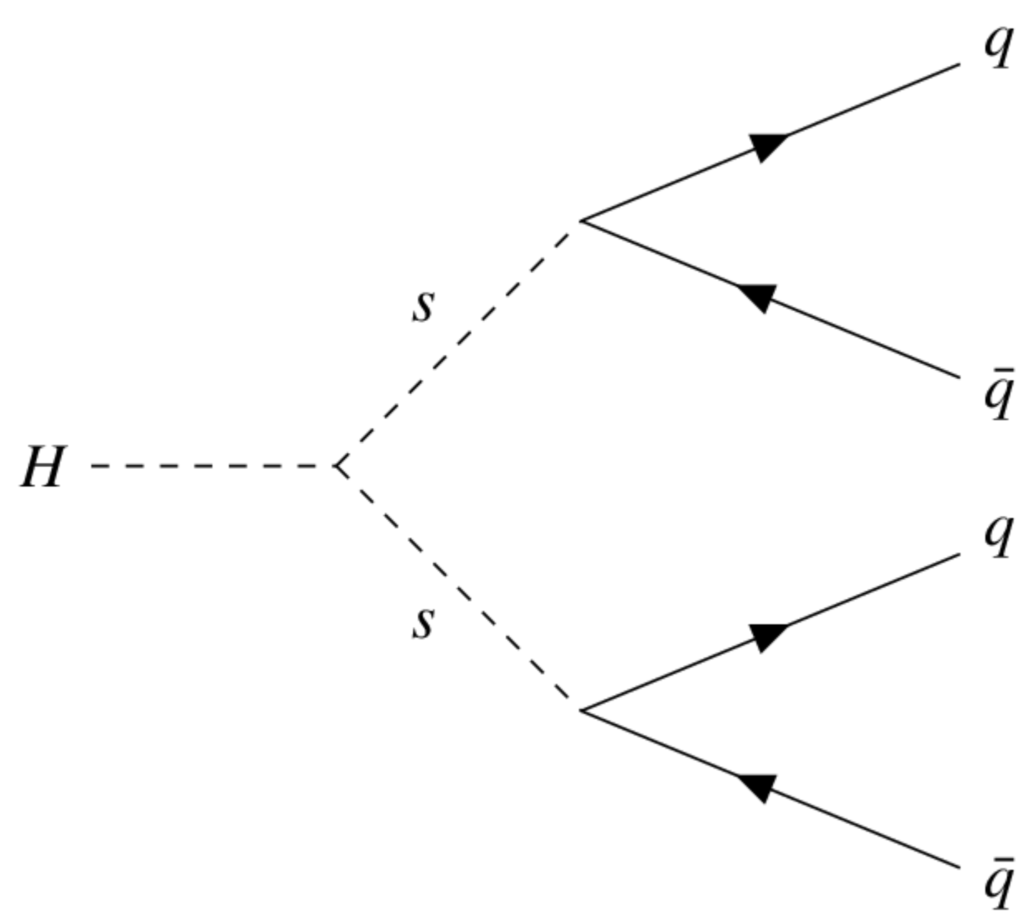
- Structure of DS can lead to new and rich phenomenology
- Very weak couplings to SM and low masses, compressed spectra:
  - **Long-lived particles (LLPs)**
- Unconventional detector signatures and unusual backgrounds
  - Dedicated strategies for **triggering, reconstruction, and background estimation** are often necessary

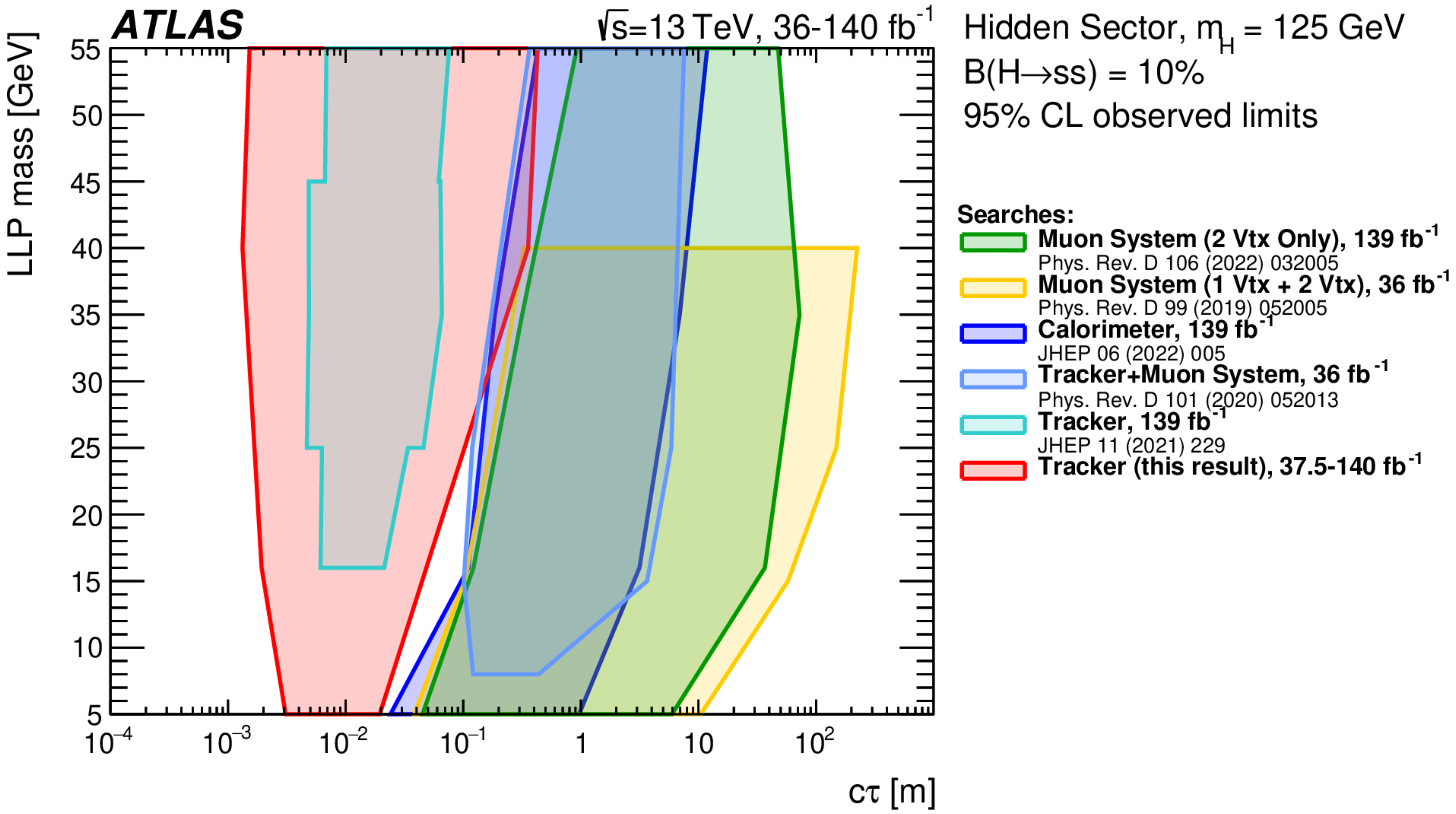


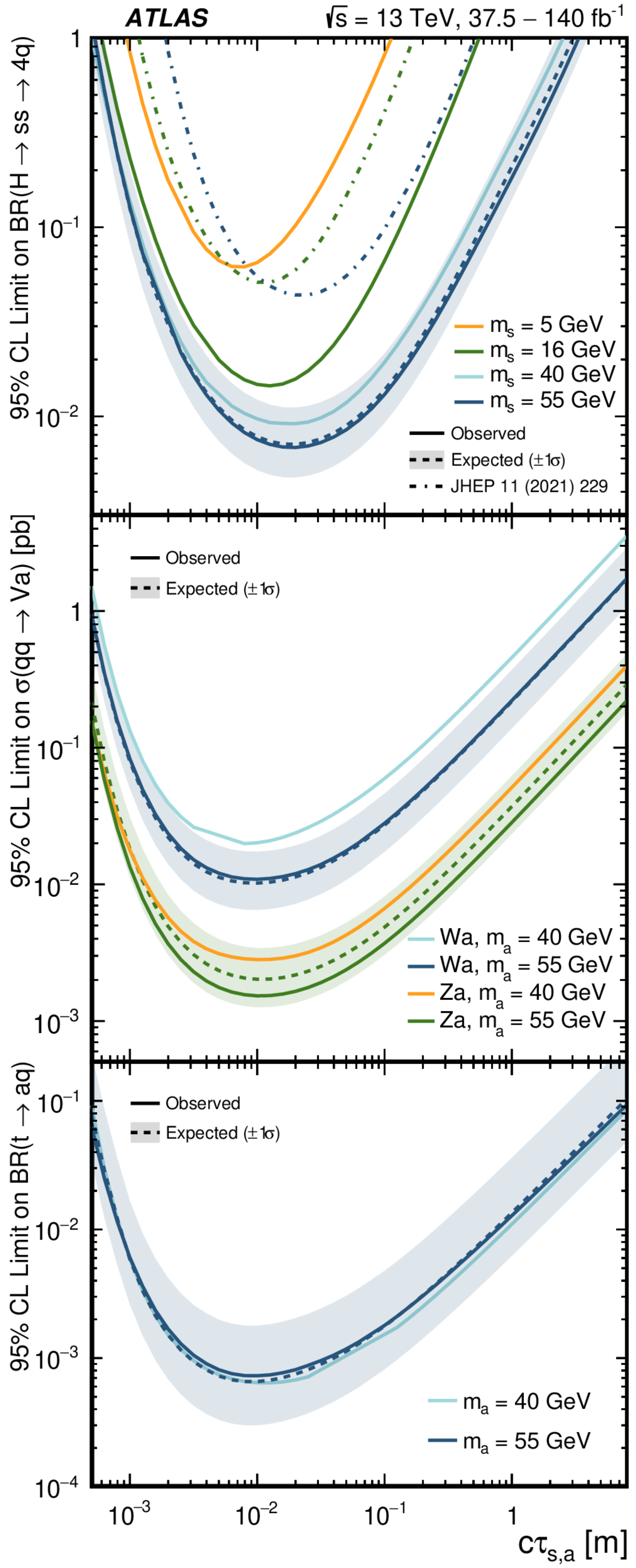
Credits: J. Antonelli

Displaced Vertices

- ATLAS search for hadronically decaying neutral LLPs leading to displaced vertices (DV)
  - Higgs portal (w/ VH and VBF production): $H \to ss \to q\bar{q}q\bar{q}$
  - ALP coupling to W/Z or up-type quarks
- Displaced and prompt jets are identified with a **BDT classifier using jet level features**. Selected displaced jets are associated to reconstructed DVs
- Higgs portal benchmark limits are stronger than previous results by **up to a factor of 20**
  - Driven by improvements in **large-impact parameter track reconstruction, addition of 1-lepton and VBF regions, and inclusion of $n_{DV} = 1$ SR.**
- For $H \to ss \to 4b$ BR > 1% are excluded for $m_s = 55$ GeV and $6 < c\tau_s < 68$ mm
- $\mathscr{B}(H \to ss \to 4c) >$ 10% excluded for $m_s = 5$ GeV and $3 < c\tau_s < 20$ mm

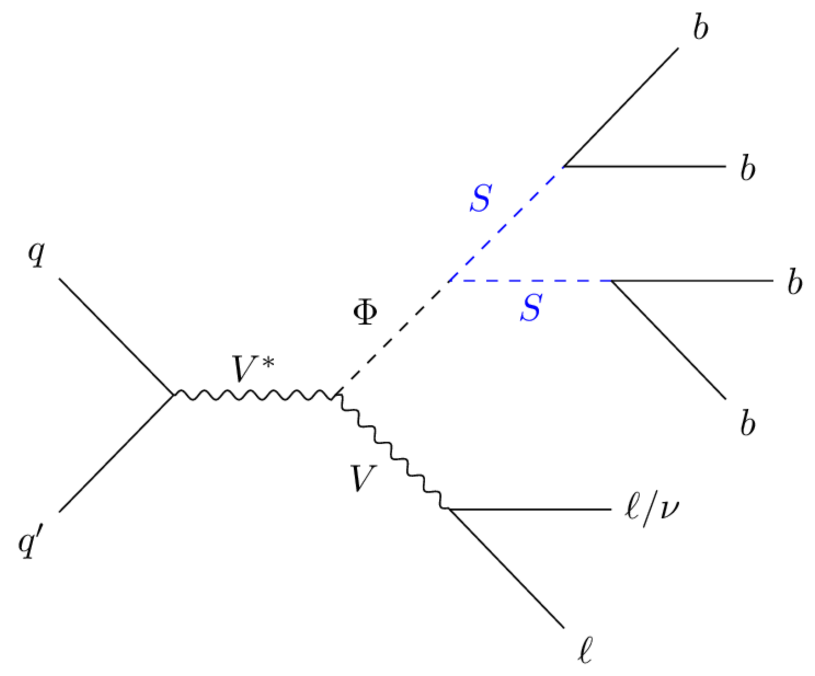


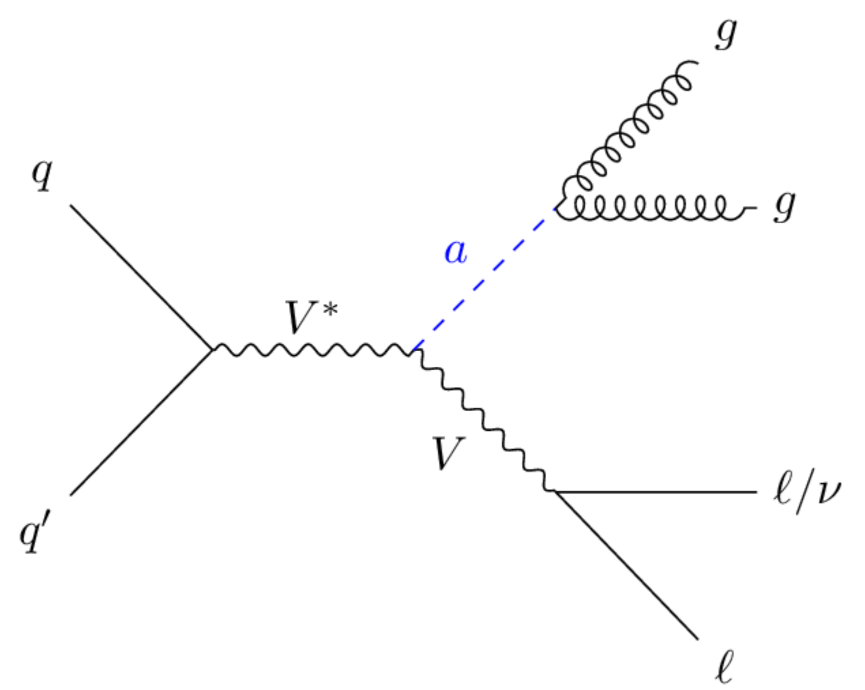


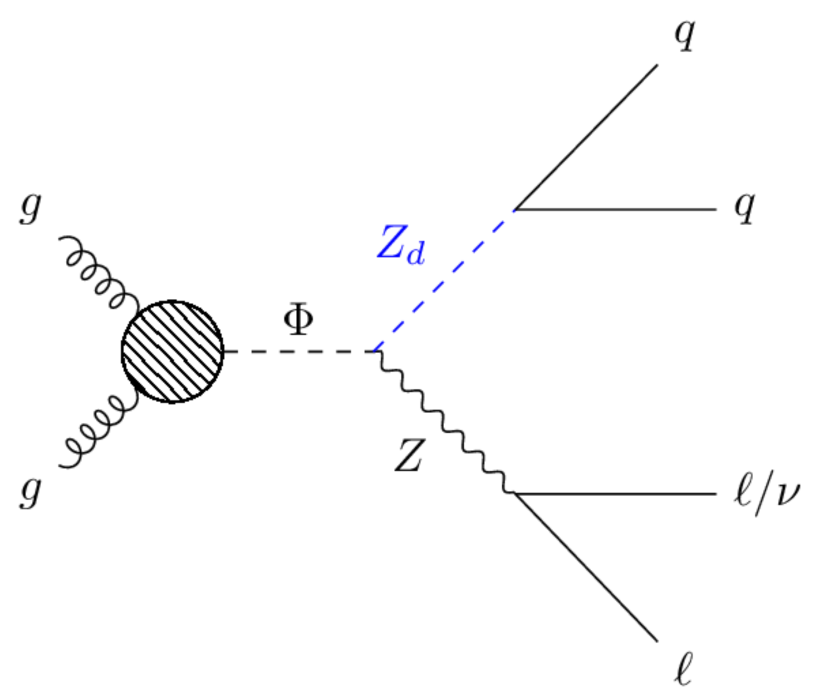


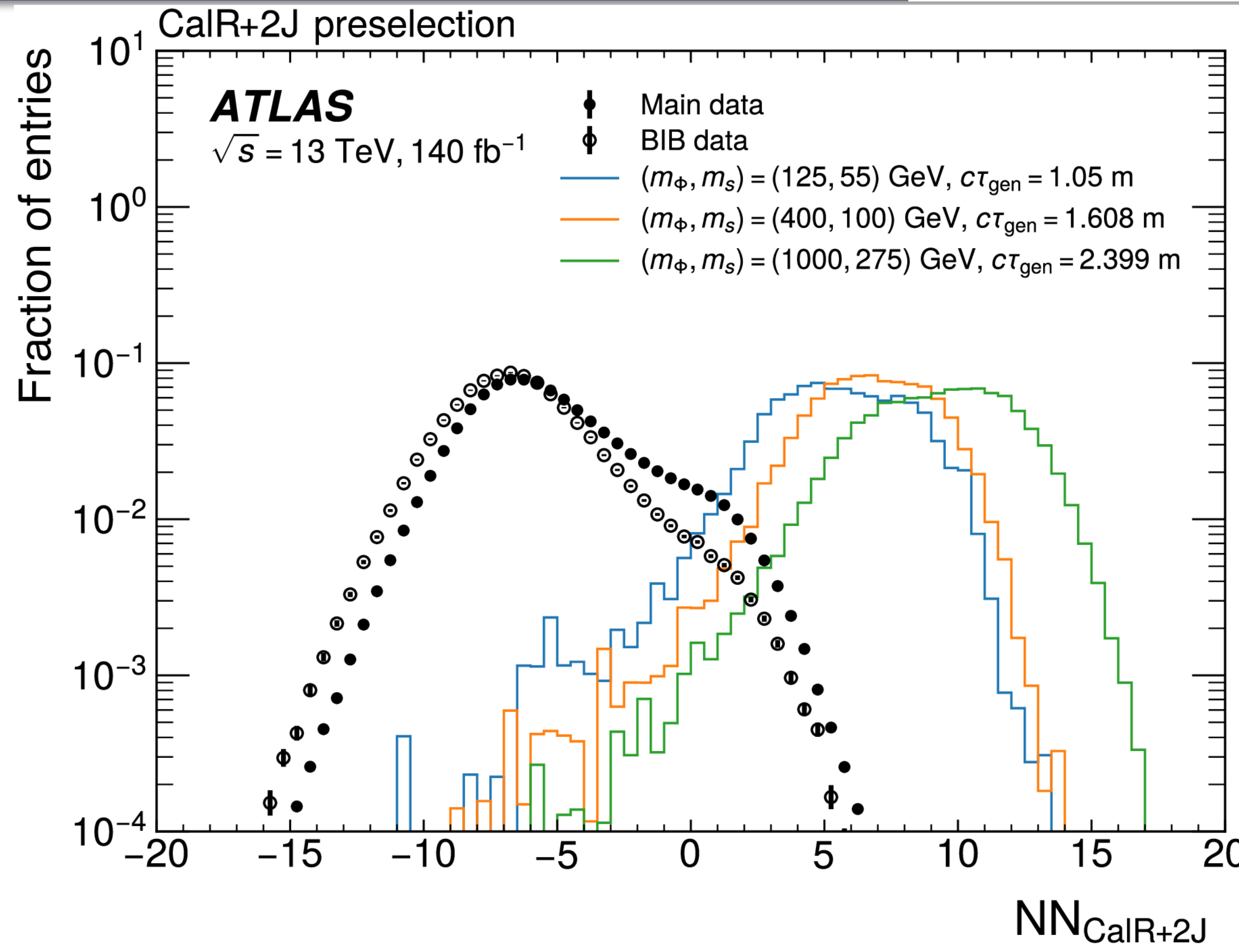
ATLAS EXOT-2021-32

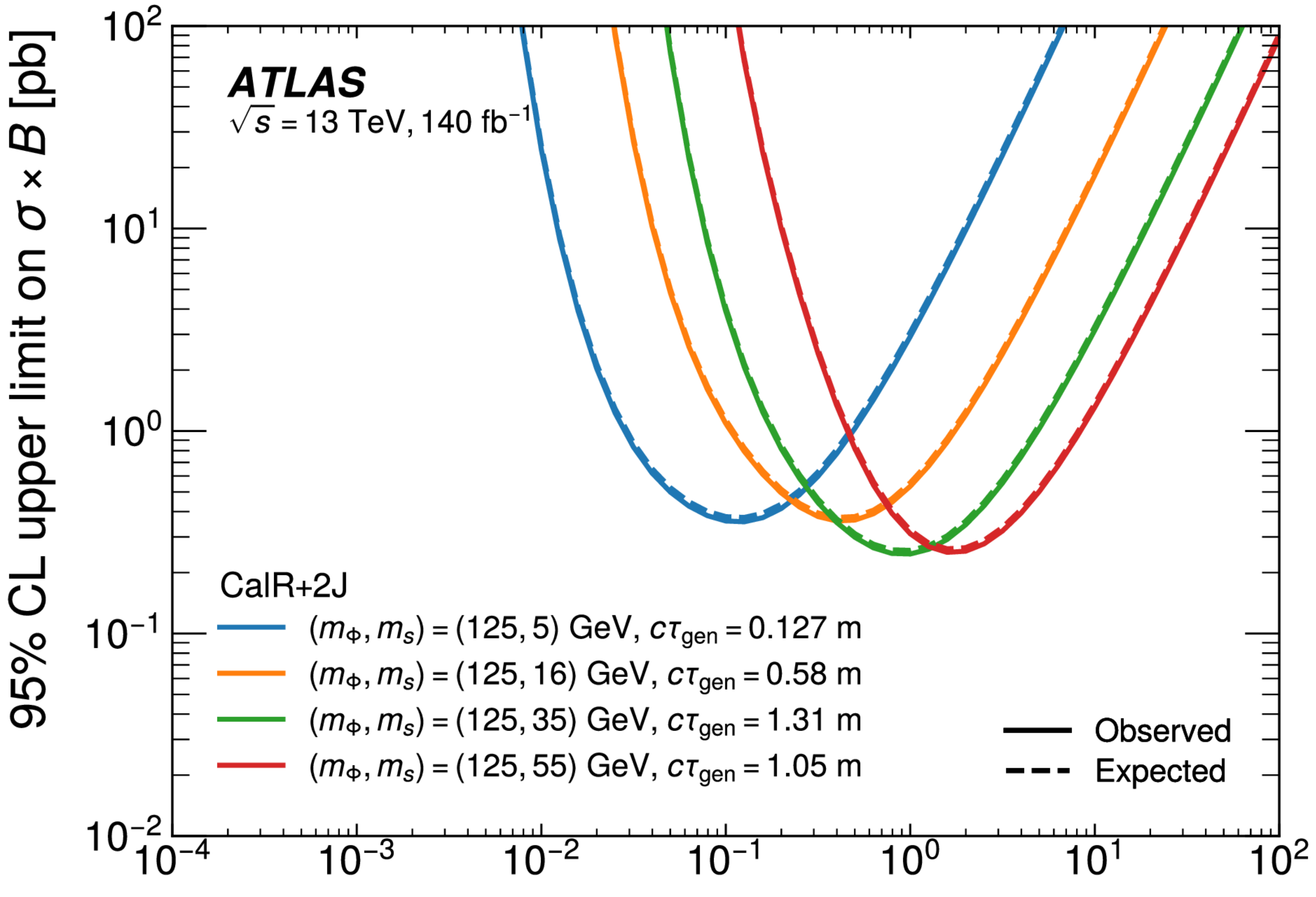
Displaced Calorimeter Jets









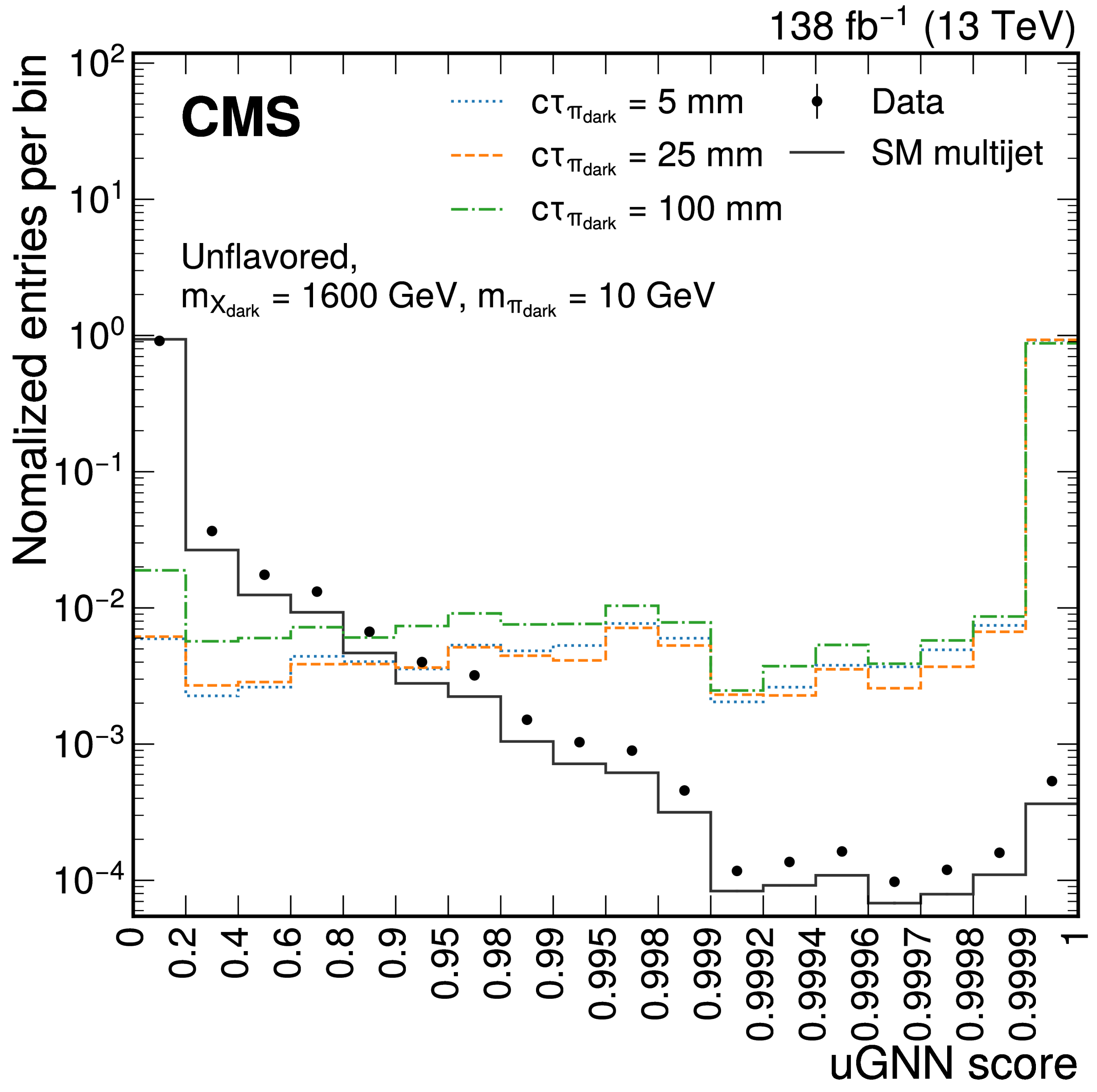


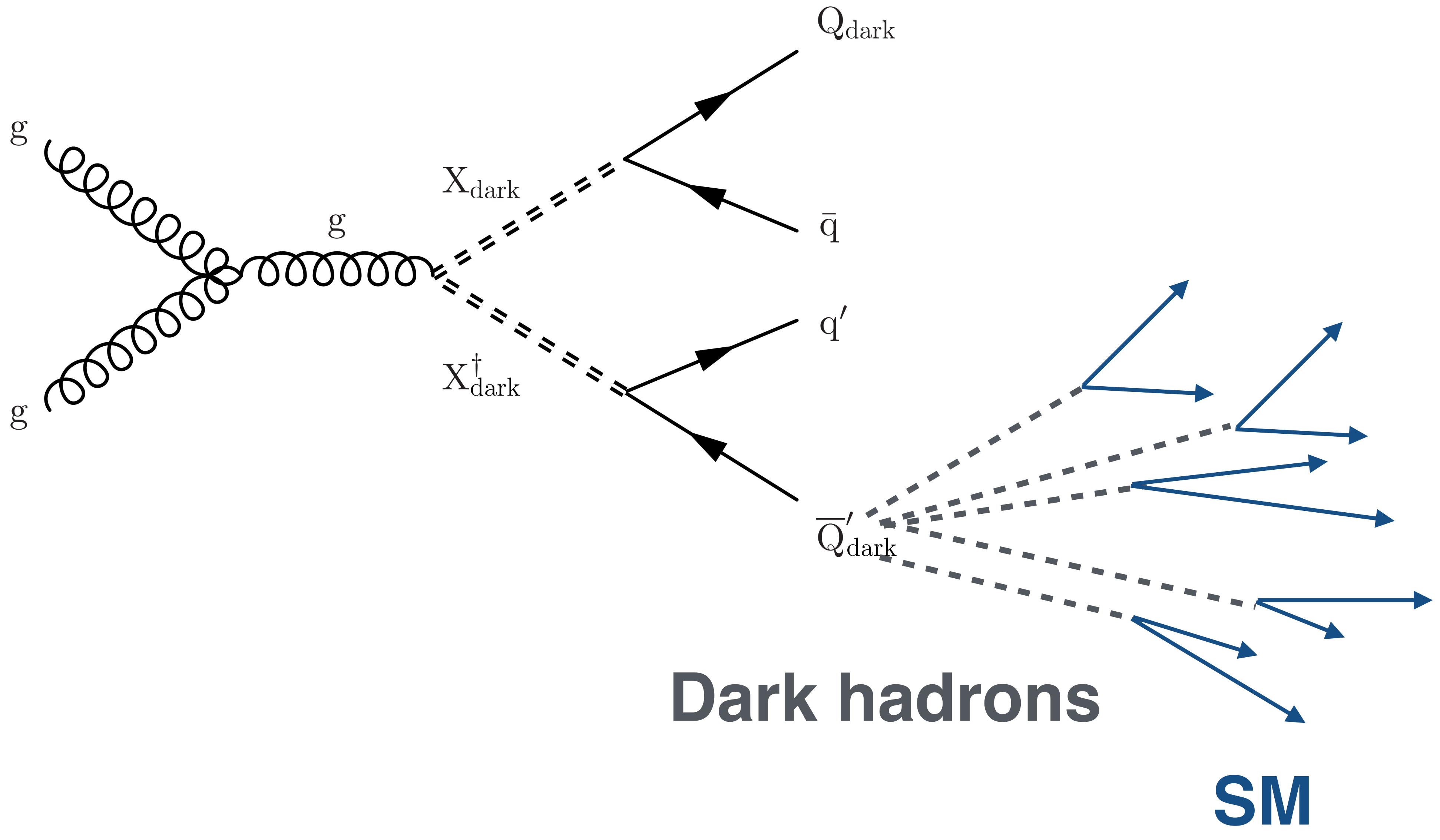
ATLAS EXOT-2022-04

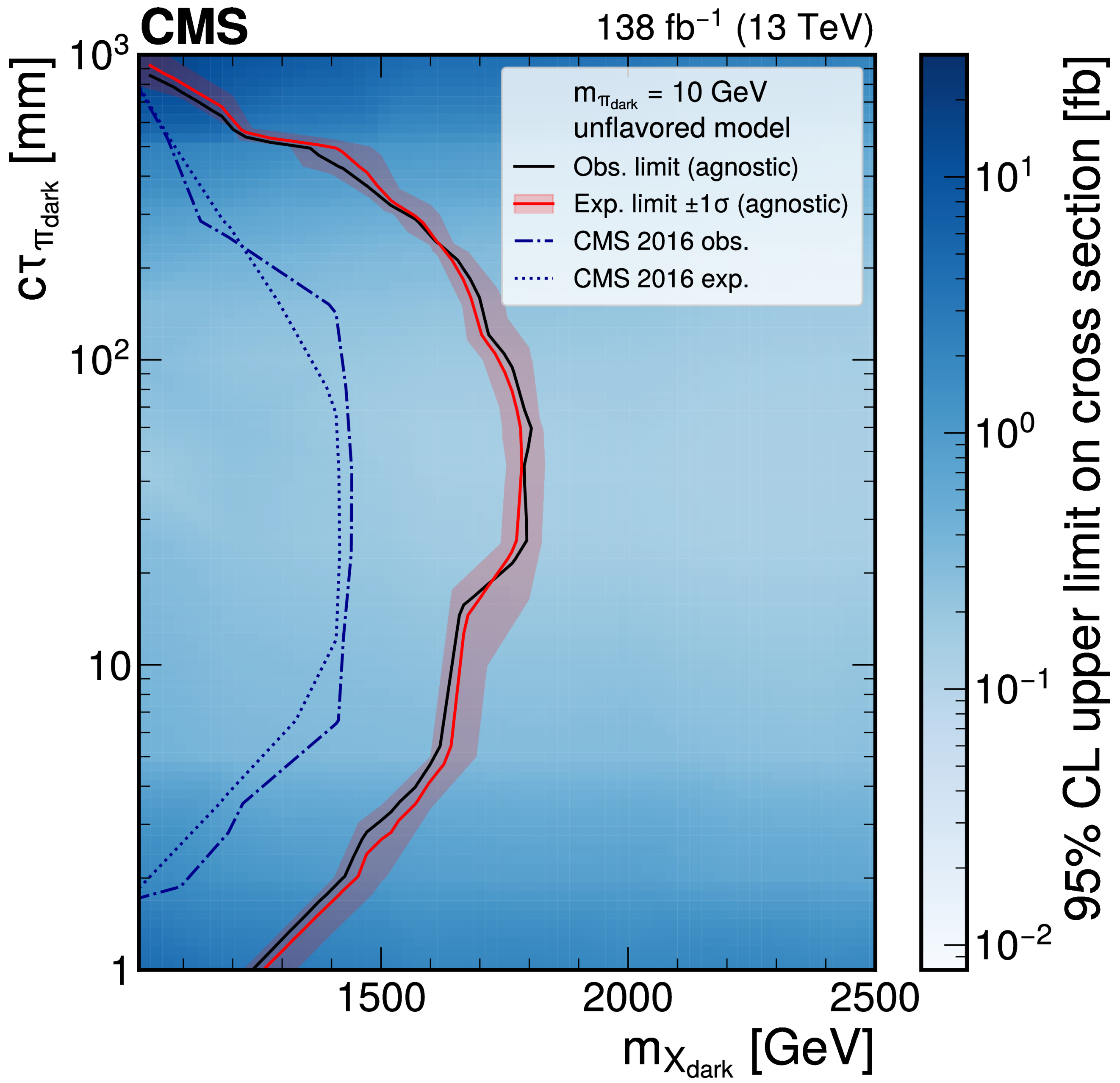
- ATLAS search for hadronically decaying neutral LLPs leading to displaced jets in calorimeter
  - Hidden Sector (w/ VH and ggF production): $\Phi \to ss \to q\bar{q}q\bar{q}$
  - ALP coupling to W/Z
  - Long-lived massive dark photon Z_d
- Neutral LLPs decaying after electromagnetic calorimeter → **High hadronic to electromagnetic energy ratio (CalRatio)**
- CalRatio + 2 jets, CalRatio + W, CalRatio + Z channels using CalRatio, single lepton, and dilepton triggers
- **Jet level NN classifier** to distinguish signal-like displaced jets from backgrounds
- **Event level NN and BDTs** are trained to separate signal and background events
- Hidden Sector model limits exclude $\mathscr{B}(\Phi \to ss) > 1\,\%$ for $30 < c\tau_s < 450$ cm **improving previous limits by a factor of 3.**
  - Extends sensitivity to longer lifetimes compared to displaced vertices search

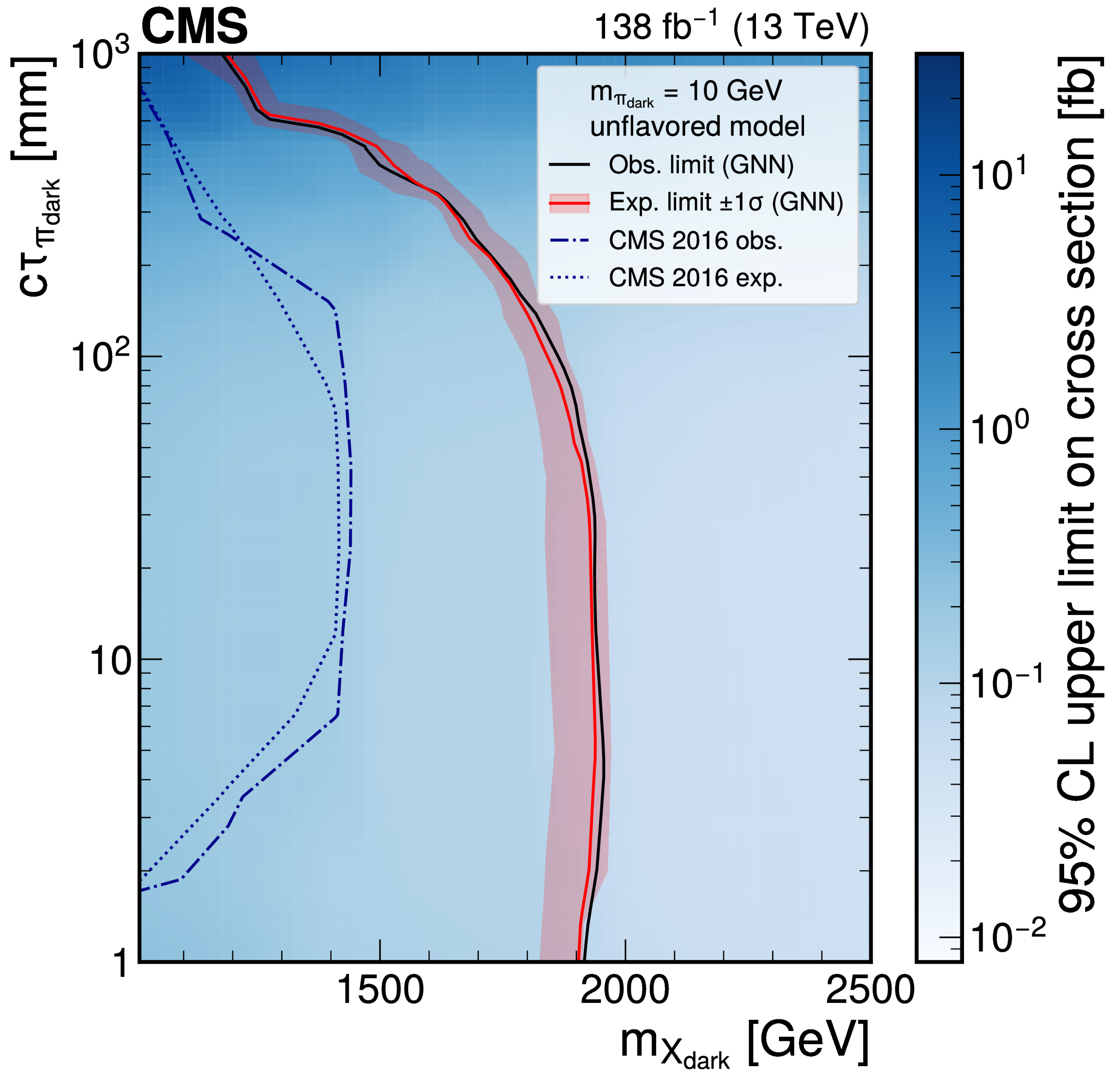
Emerging jets

- CMS search for emerging jets (EJ) in models with long-lived dark hadrons decaying to SM particles
  - **Multiple displaced vertices in a jet**
- Yukawa-like coupling between heavy mediator, dark quarks, and SM quarks
  - **Unflavored**: only couplings to down quark
  - **Flavor-aligned**: Universal coupling to $d/s/b$
- **Cut based** and **GNN based EJ tagging** used for both **model-agnostic** and **model specific** results
- Selecting events with high H_T, at least 4 jets with at least 2 EJ
- Unflavored: $m_{X_{dark}} < 1950$ GeV excluded for $c\tau_{\pi_{dark}} \approx 100$ mm and $m_{\pi_{dark}} = 10$ GeV
- Flavor-aligned: $m_{X_{dark}} < 1850$ GeV excluded for $c\tau_{\pi_{dark}} \approx 500$ mm and $m_{\pi_{dark}} = 10$ GeV









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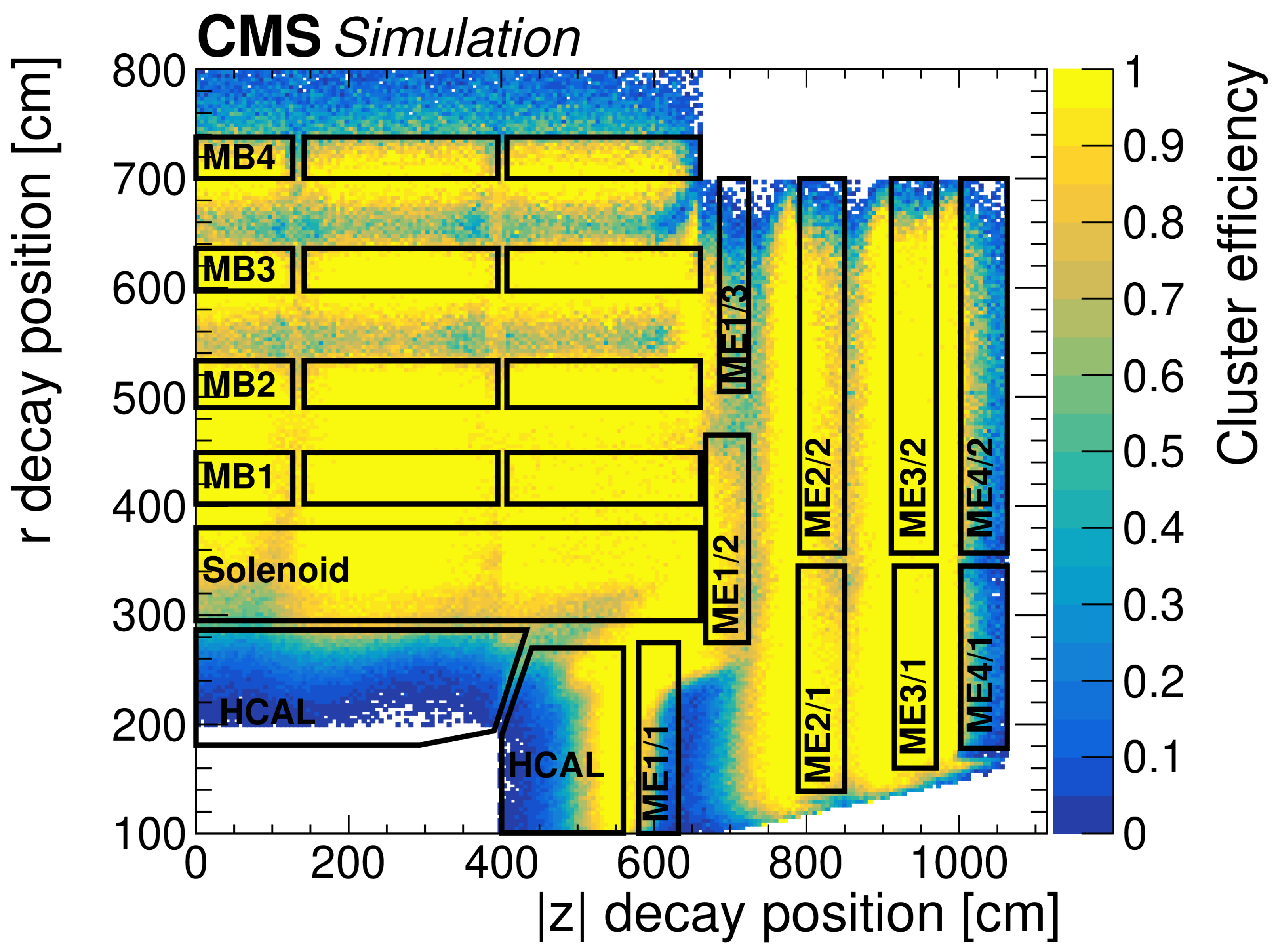
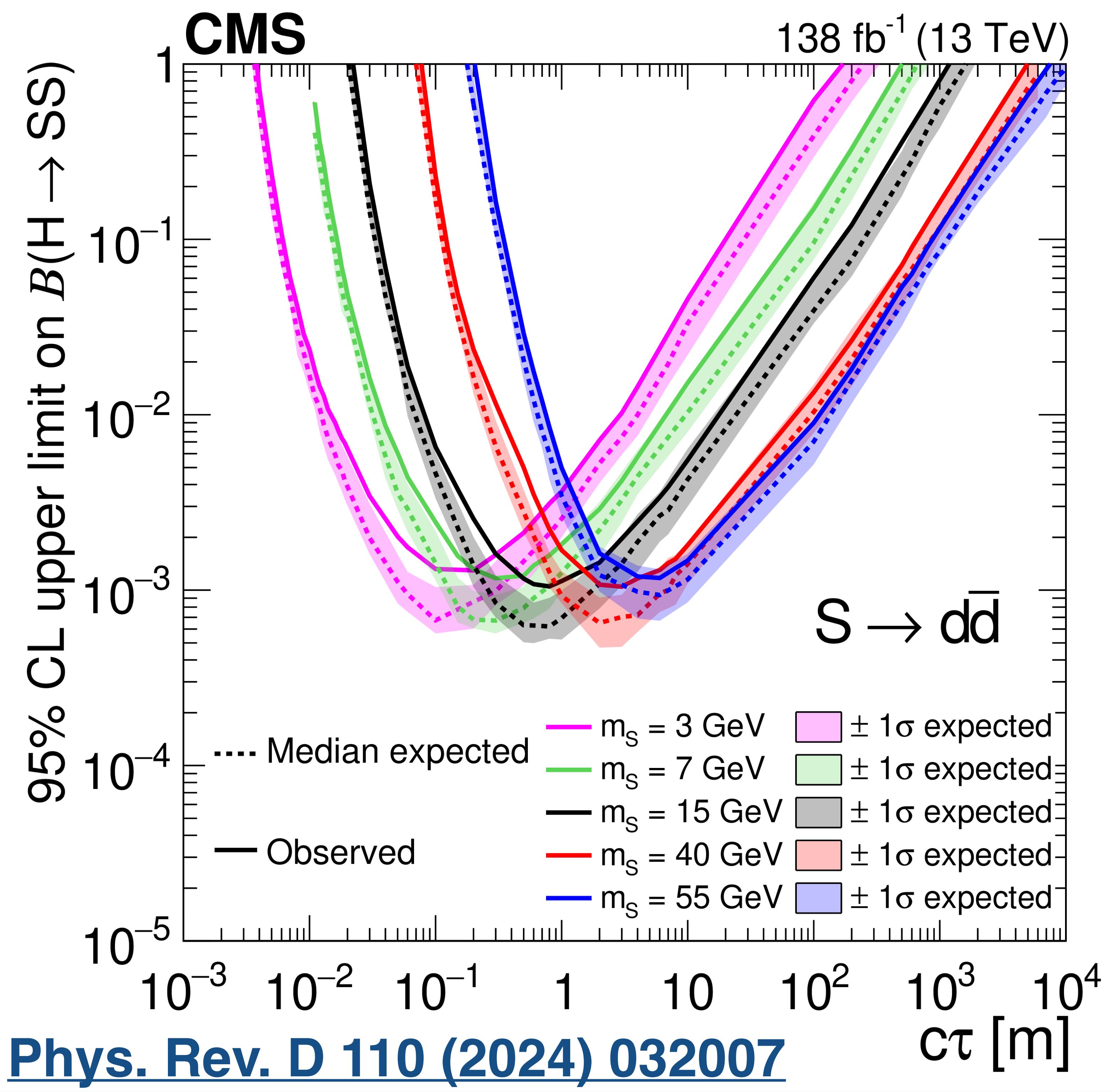
Muon showers

- CMS Run 2 search for particle showers by LLP decays in muon systems in models with both $H \rightarrow SS$ and $H \rightarrow \Psi\bar{\Psi}$
  - **Using muon detectors as sampling calorimeters,**
  - Trigger on p_T^{miss}, and form **clusters of hits in drift tubes (barrel) and cathode strip chambers (endcap)**
  - Number of hits in a cluster is used to discriminate signal and background
- Lower level of backgrounds compared to displaced vertex searches and equal sensitivity to different m_{LLP}
- Results are complementary with emerging jets search





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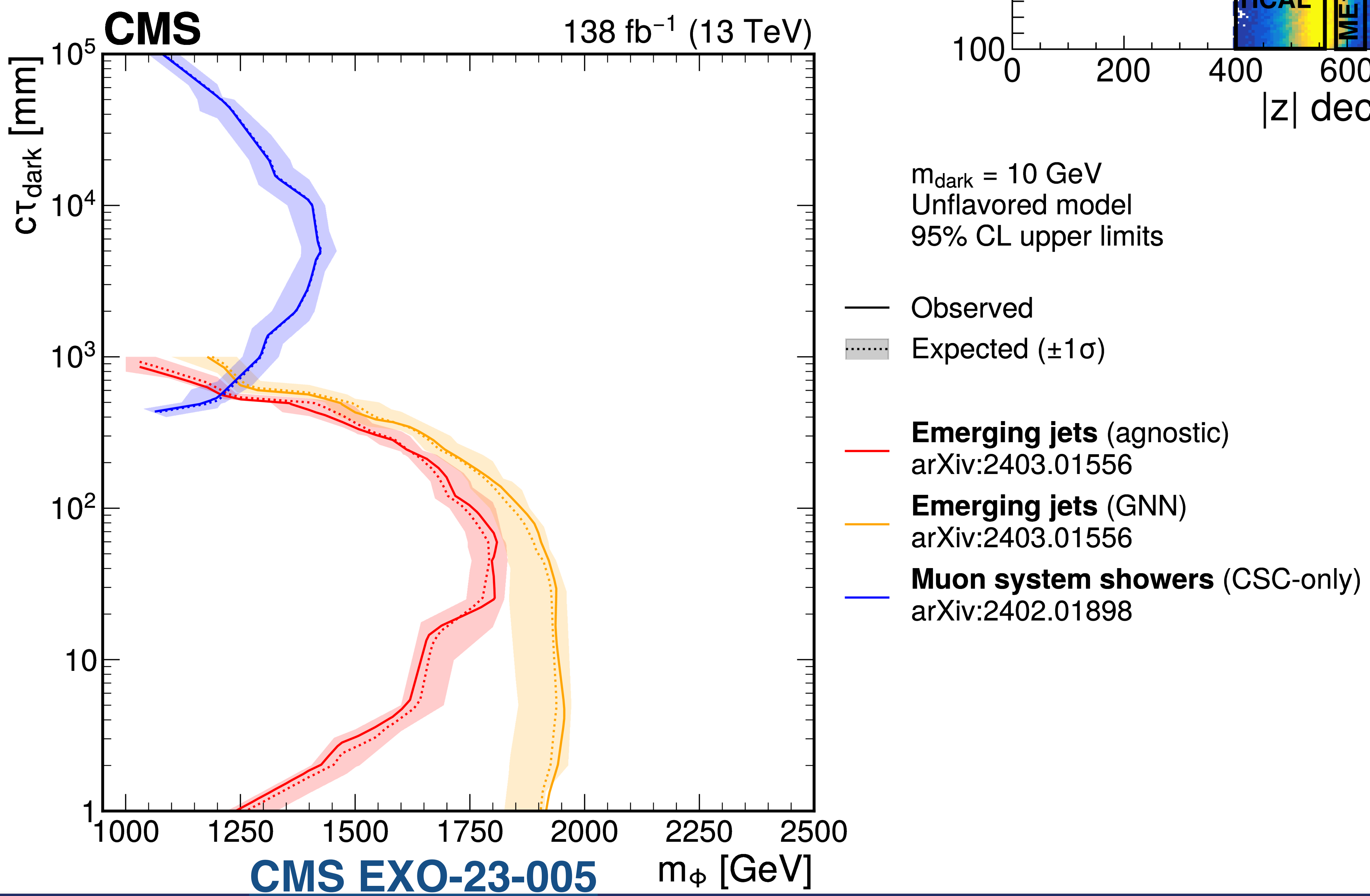
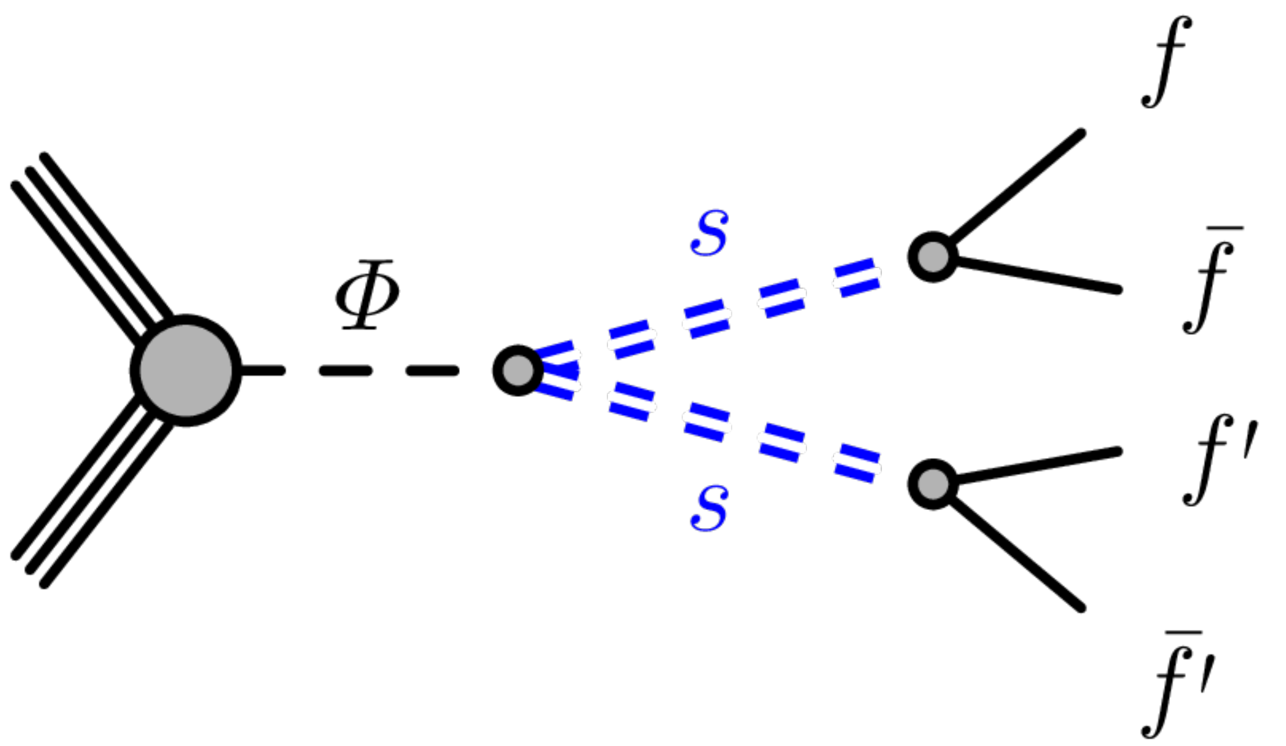
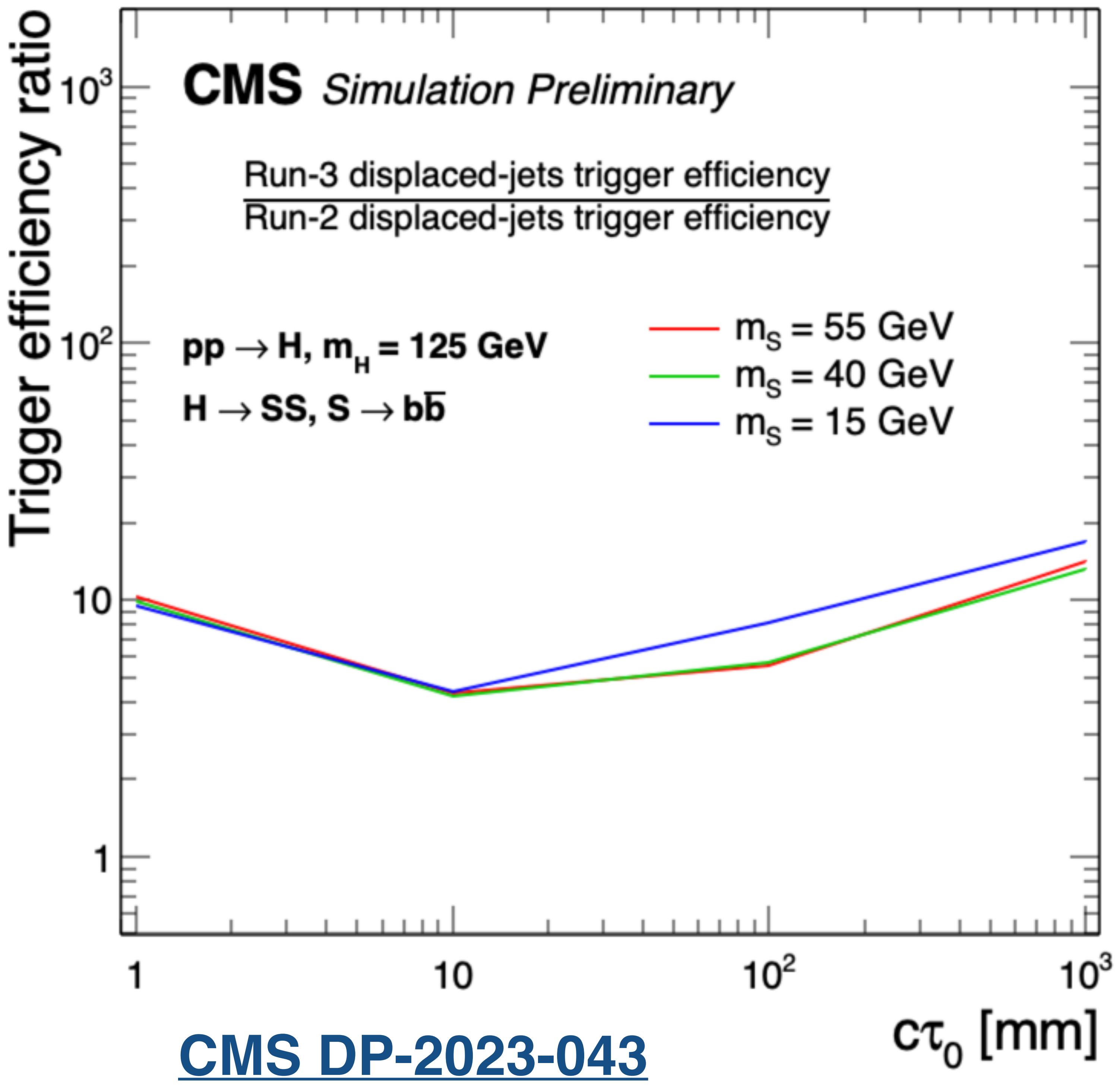


CMS EXO-23-005

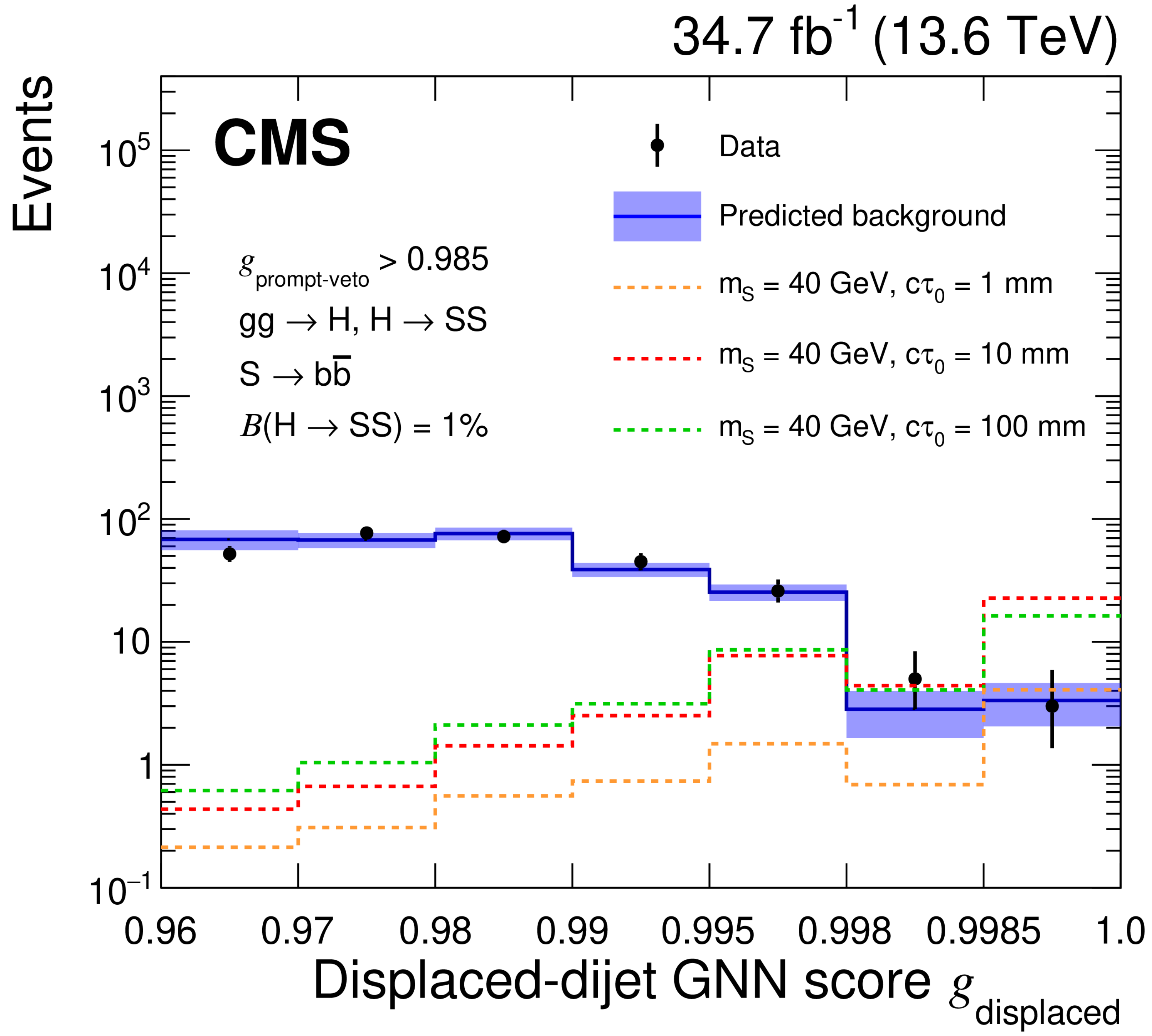
Displaced Jets in Tracker

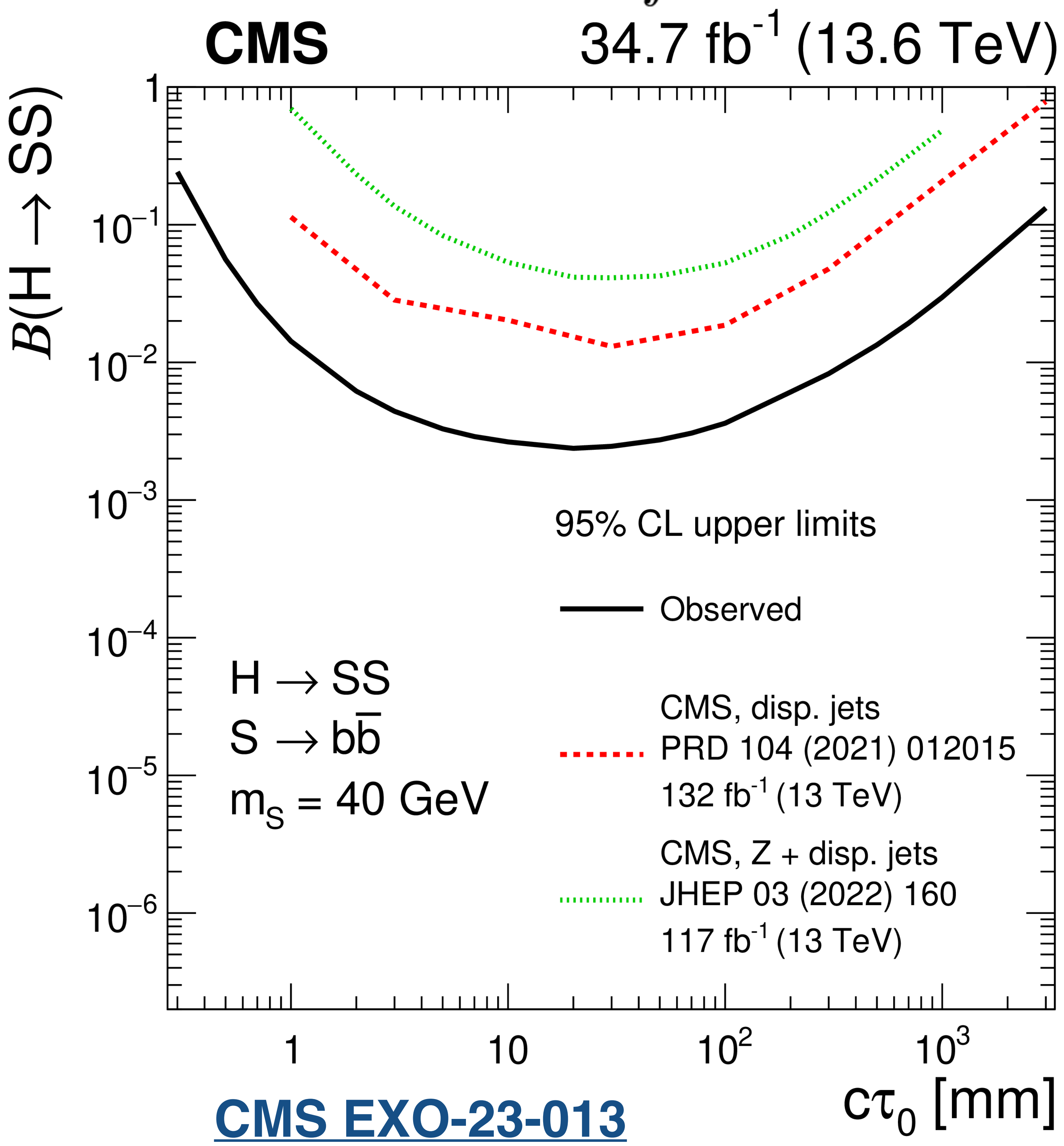
- CMS early Run 3 result for displaced jets using new trigger and reconstruction techniques
  - New displaced jet triggers: **factor 5-10 gain in efficiency compared to Run 2**
  - New **displaced vertex reconstruction** and **GNN based LLP taggers**
- Displaced dijet GNN score is used to define the signal region
- Limits are set on $H \to SS$ with $S \to b\bar{b}$, $S \to d\bar{d}$, and $S \to \tau\tau$
  - First displaced τ_h exclusion for decay lengths smaller than $\approx 1\text{m}$
  - **Order of magnitude better results than CMS Run 2 combination** with $\sim 1/4$ of the data





[CMS DP-2023-043](#)

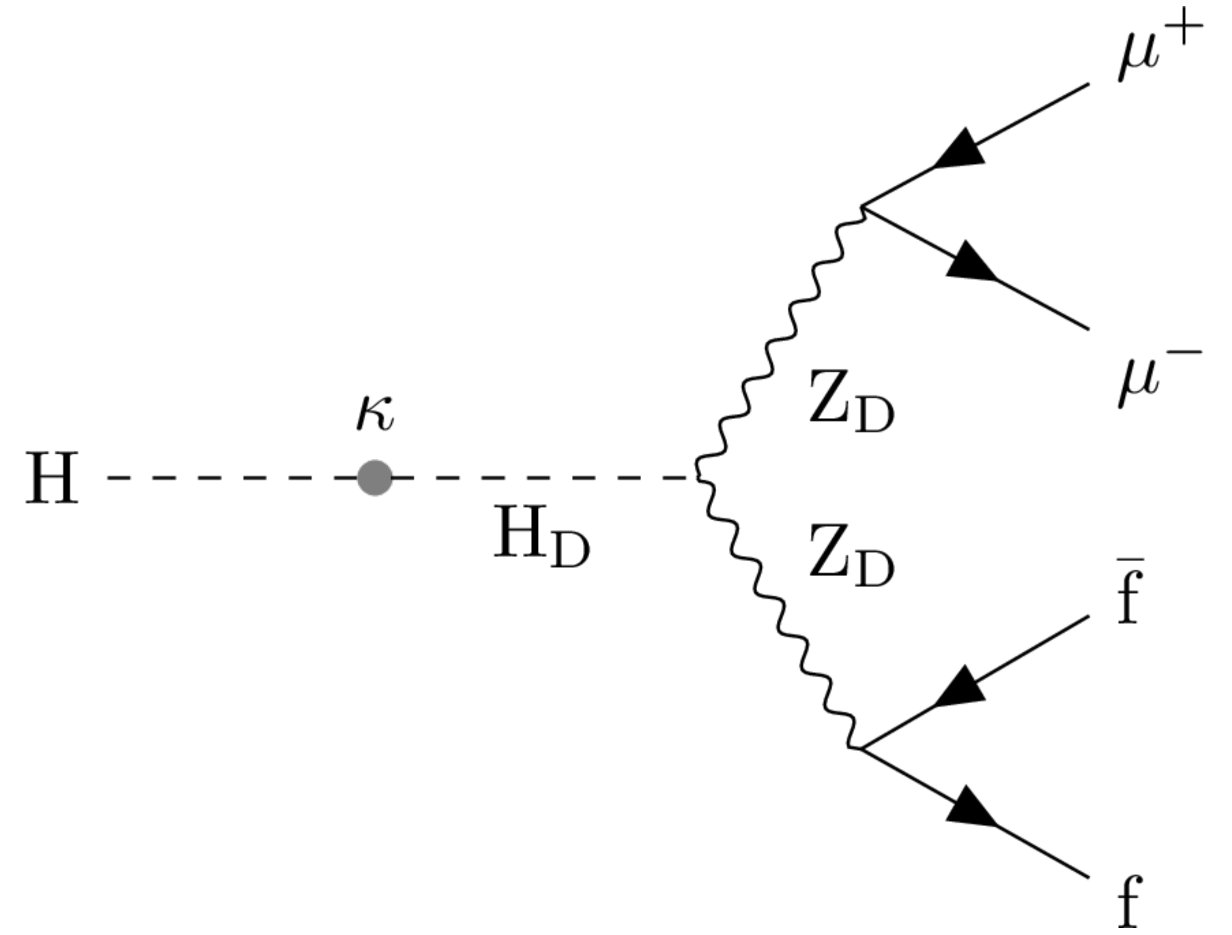


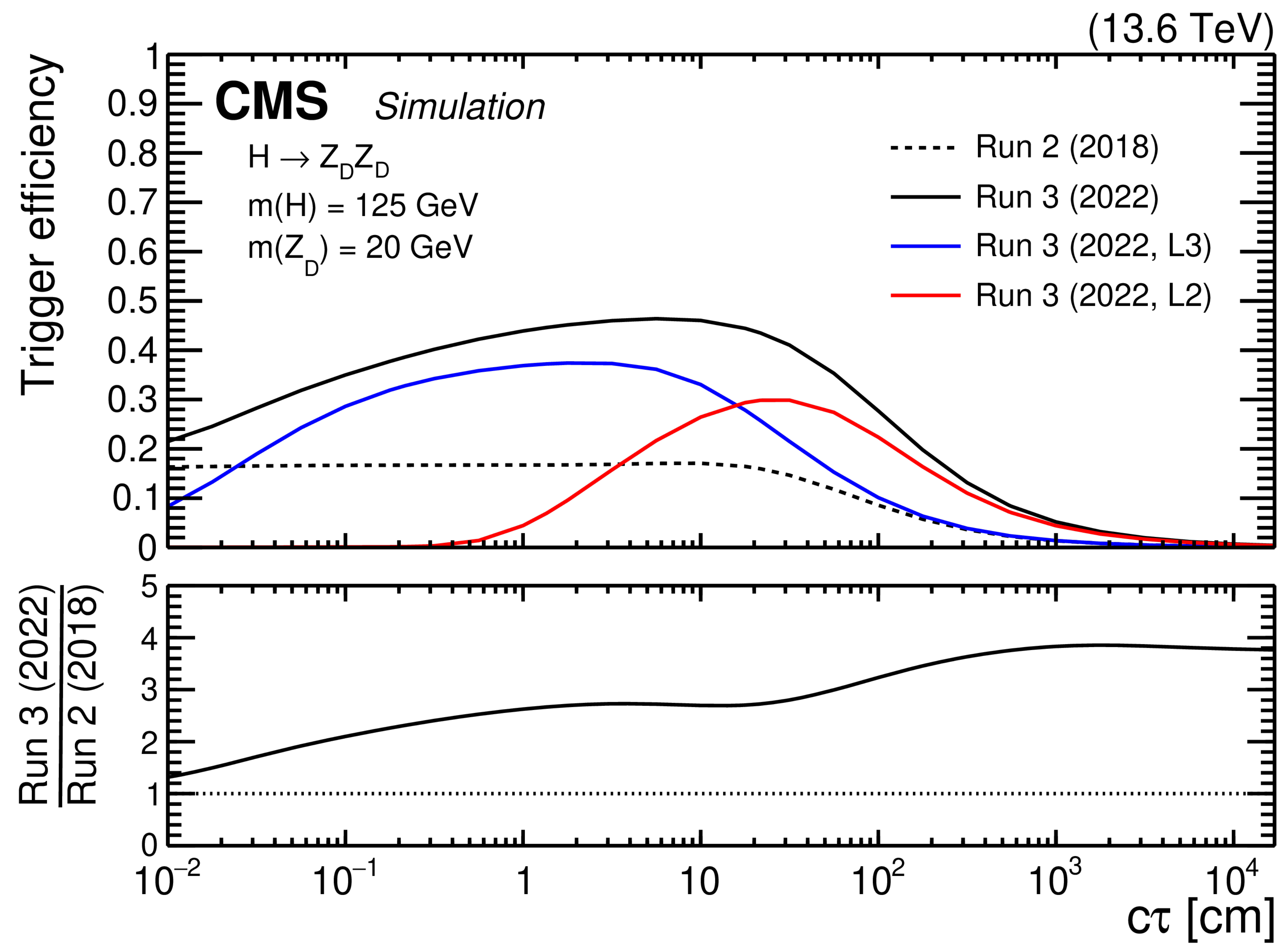


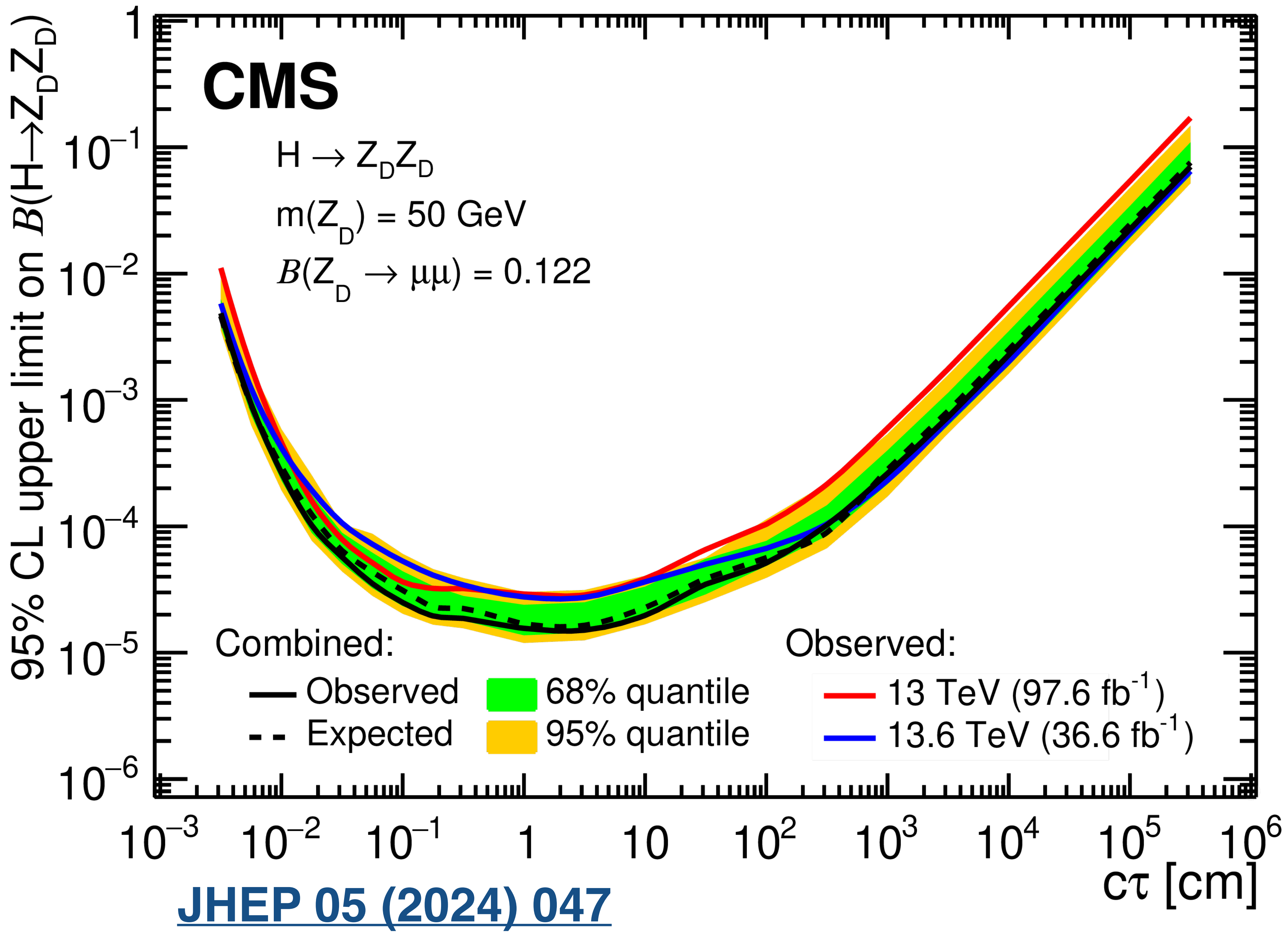
[CMS EXO-23-013](#)

Displaced Dimuons

- CMS early Run 3 result for displaced dimuons from LLP decays using new triggers
  - Improved trigger efficiency **up to a factor of 4 compared to Run 2**
- Using a combination of **tracker+muon system and muon system only muons**
- Sensitivity to a wide range of LLP $c\tau$
- Results are interpreted for HAHM and RPV SUSY models
  - **Run 3 limits are already better than Run 2 limits** with $\sim 1/3$ of the data for large $c\tau$







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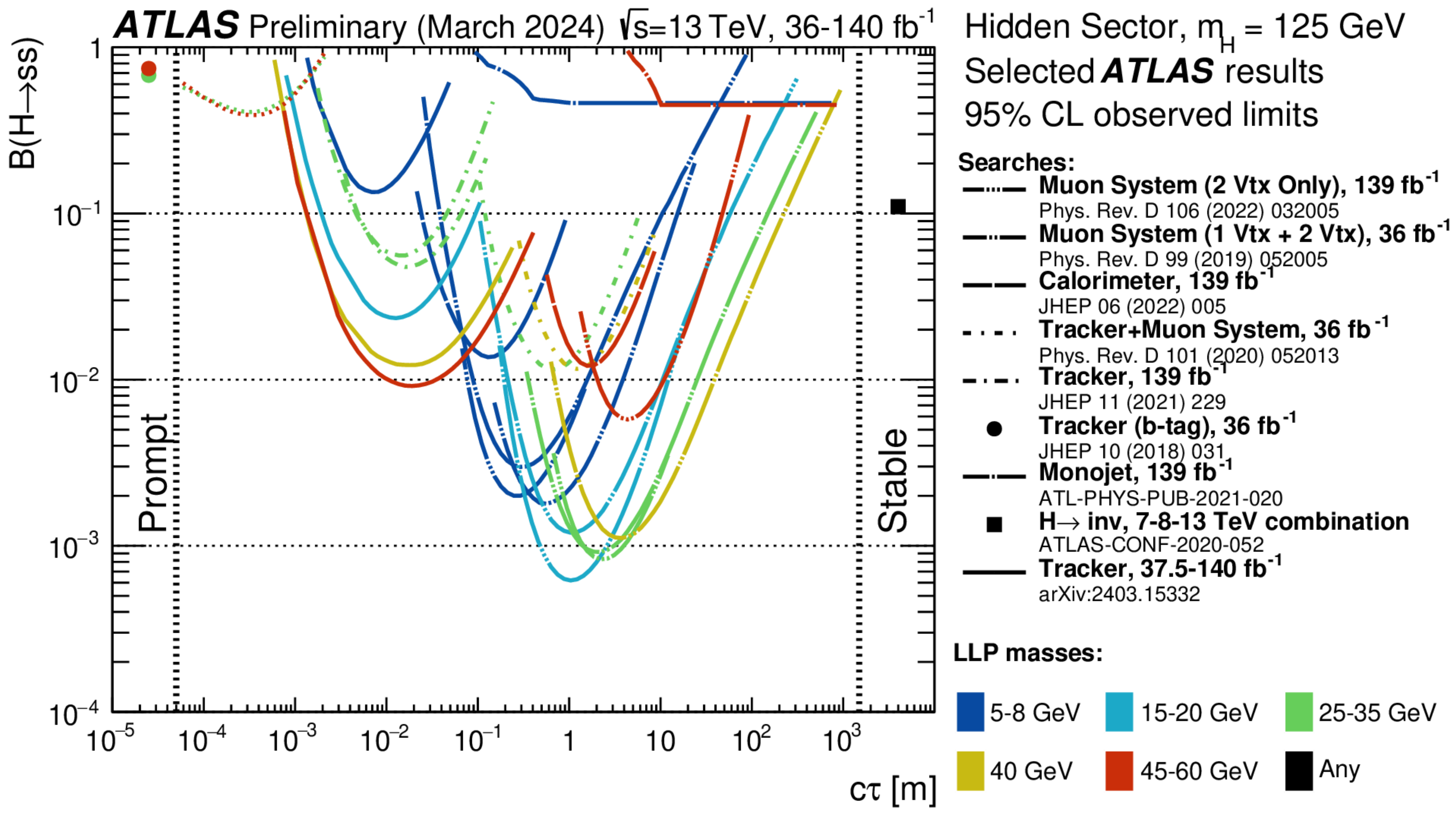
$H \to$ LLP Summary Plots

- A lot of different searches in ATLAS and CMS targeting $H \to$ LLP signatures
- Selection of the most sensitive results from Run 2 and early Run 3 are shown in summary plots spanning a large range of lifetimes
- **More Run 3 results will follow!**



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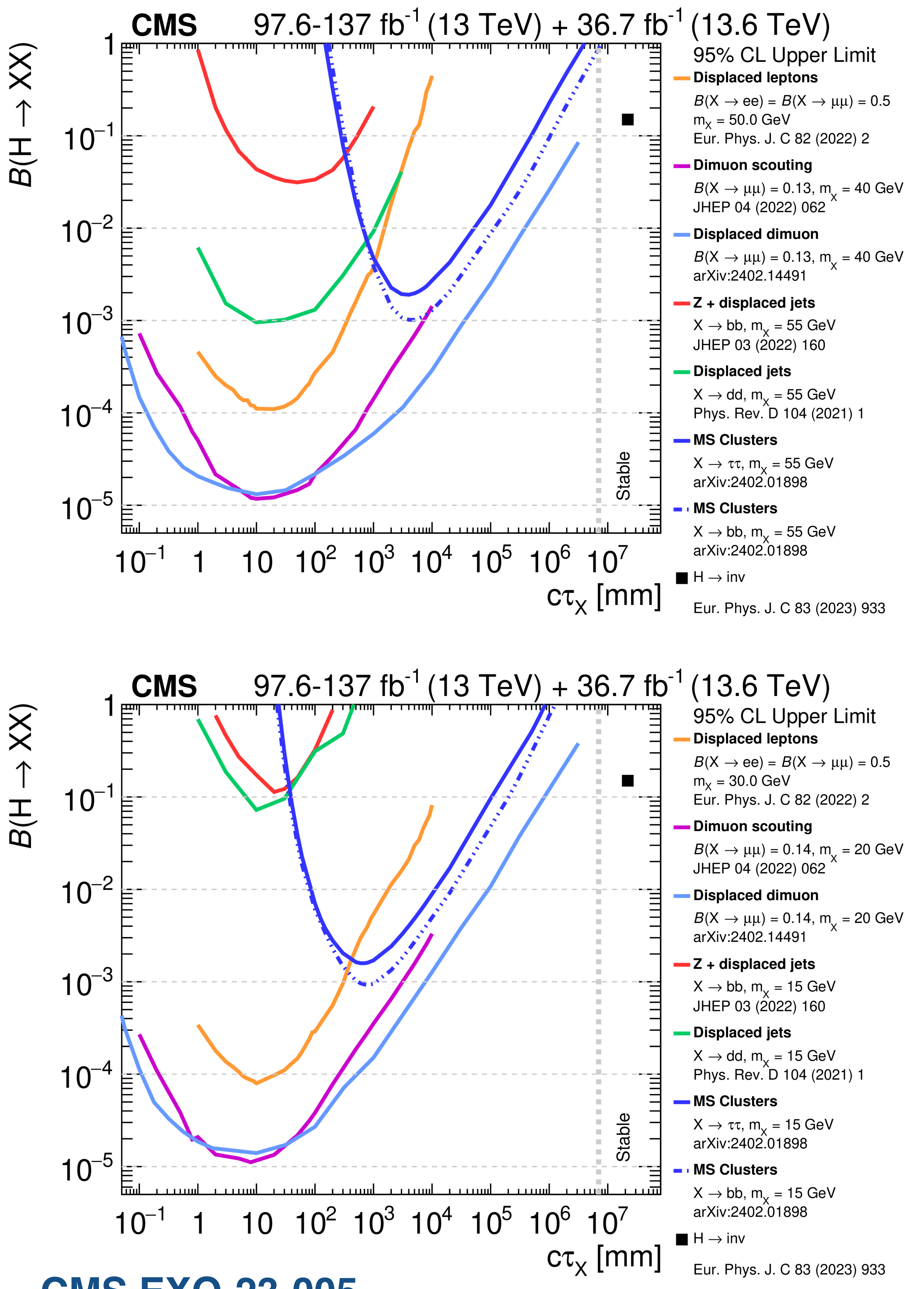


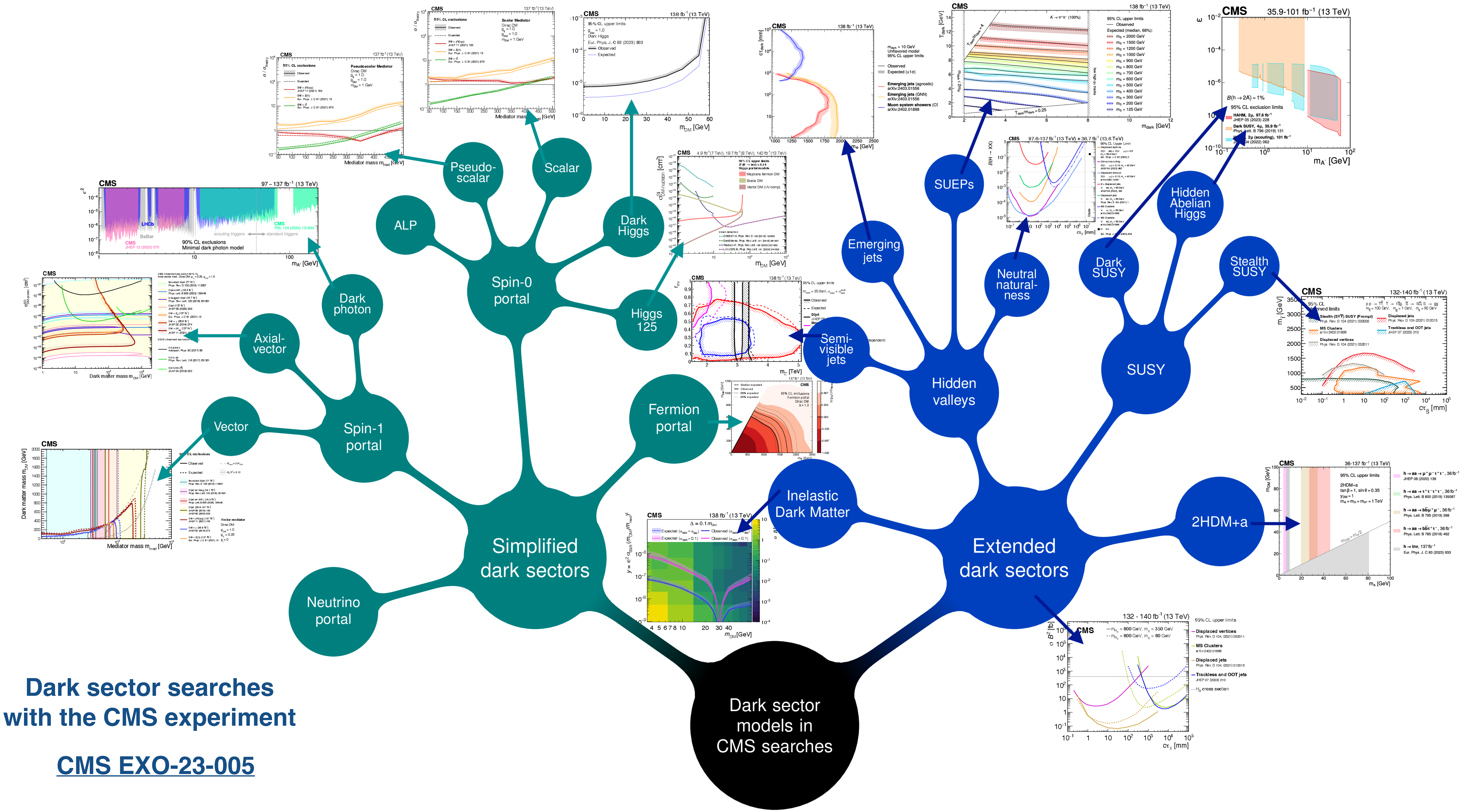
CMS EXO-23-005

Summary & Outlook

- Extensive search program at the LHC to investigate Higgs properties and dark sectors
- **Impressive results**, including combination results, **using full Run 2 dataset** from ATLAS and CMS exclude huge amounts of BSM parameter space
- **Innovative strategies in Run 3** to substantially increase sensitivity to unconventional final state signatures
  - **Exciting developments in triggering, reconstruction, and analysis techniques making extensive use of ML methods**
- Early Run 3 results already show the impact of new developments, improving on Run 2 results with a fraction of the dataset
- Many more searches are in progress with the Run 3 dataset
  - **Exciting new results are expected**
- HL-LHC era is around the corner with **significant improvements in detectors and trigger systems**
  - **Significantly improved sensitivities to unconventional final states**

BACKUP

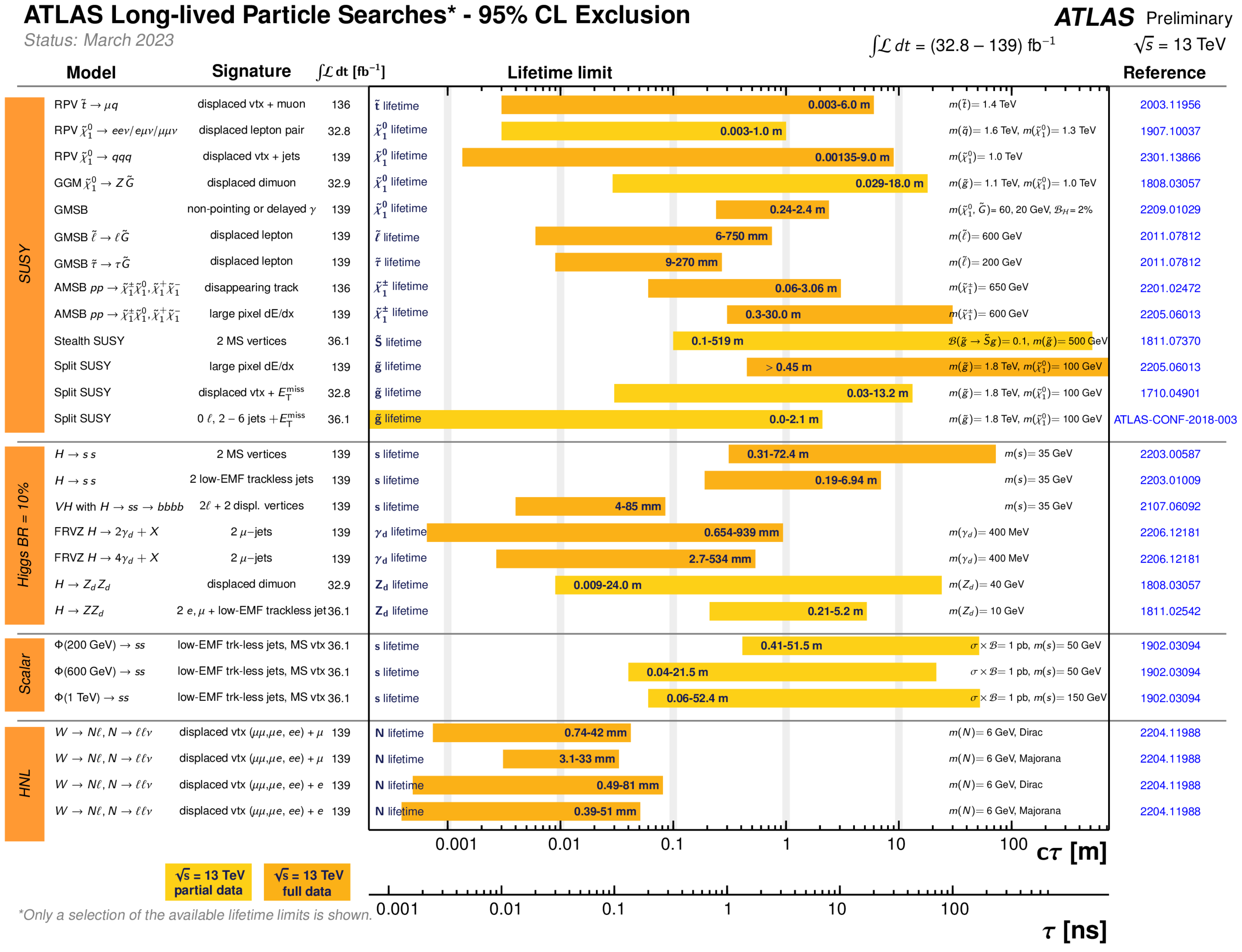
Dark Sector Summary

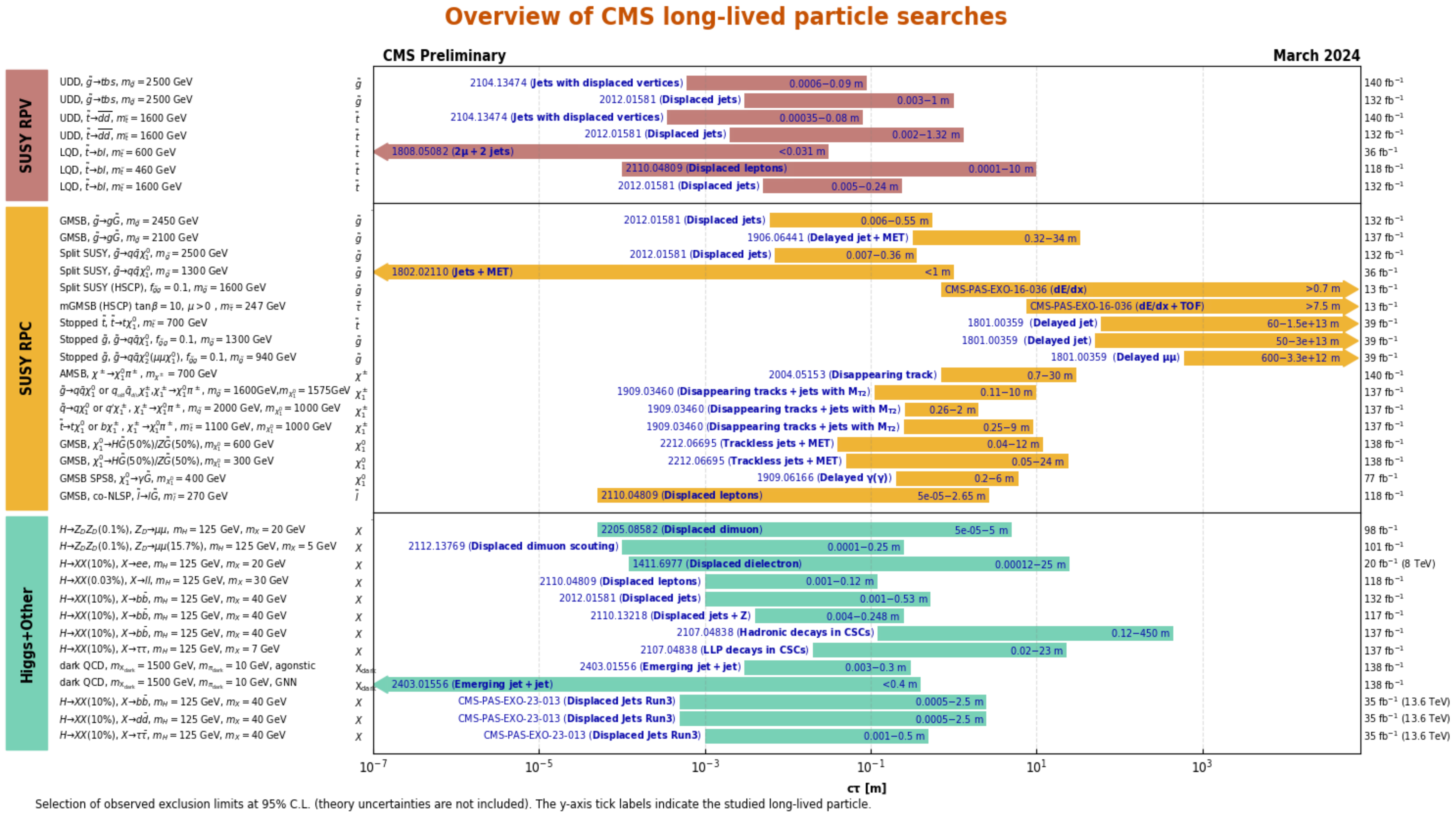


Dark sector searches with the CMS experiment

[CMS EXO-23-005]

LLP Summary Plots





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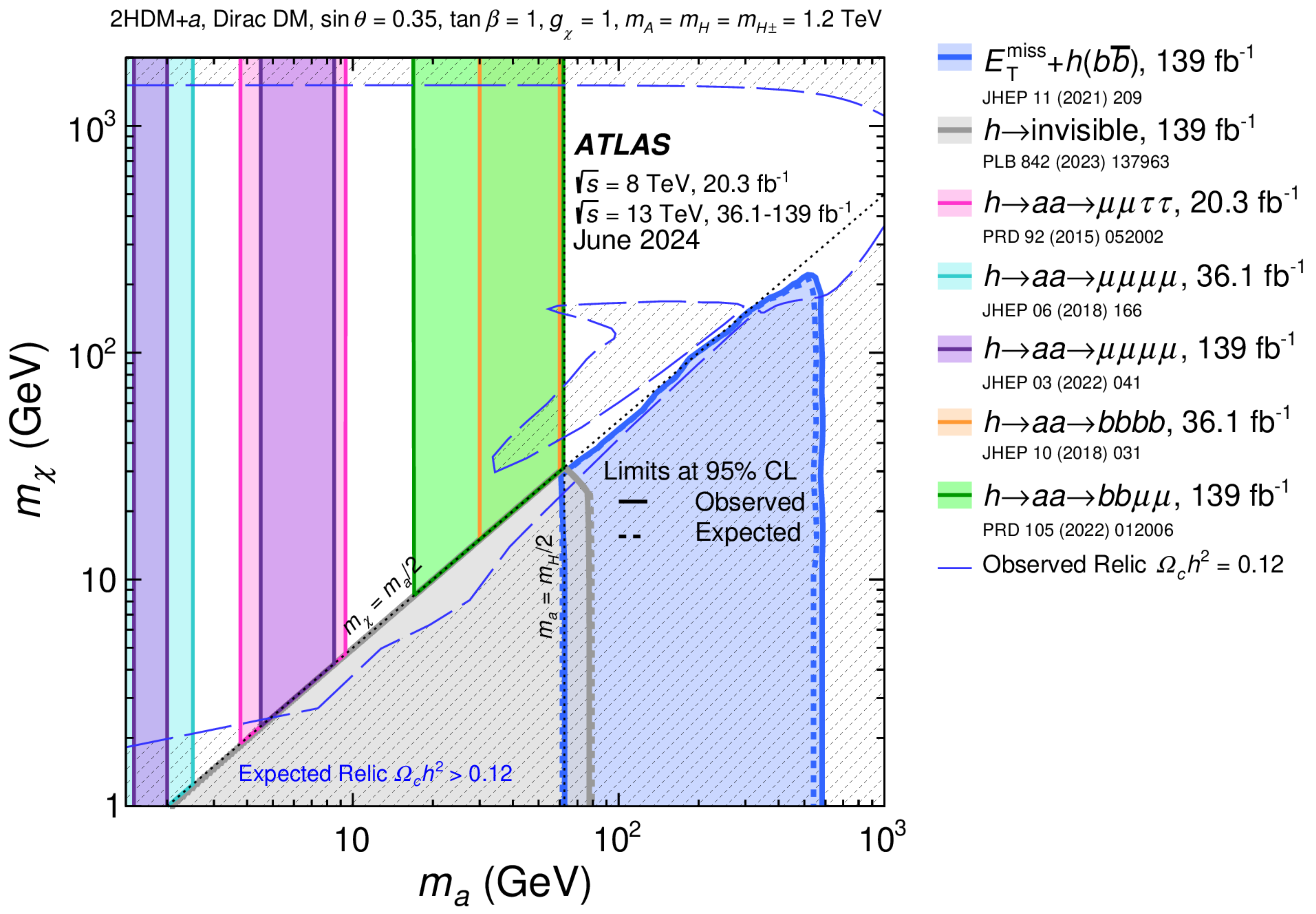
2HDM+a Summary Plots



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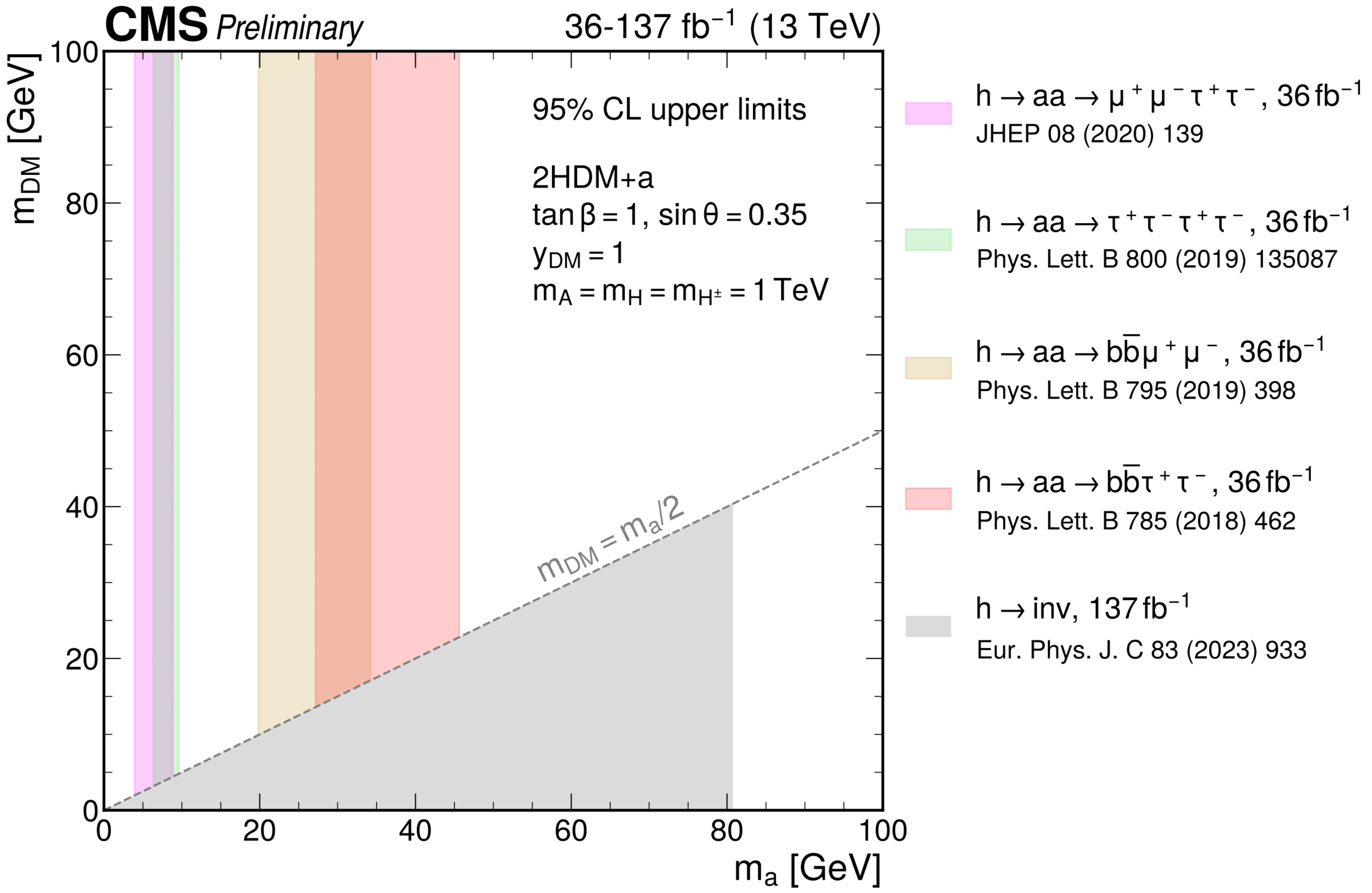

CMS EXO-23-005