Searches for
Long Lived Particles

Guglielmo Frattari, on behalf of the ATLAS, CMS & FASER collaborations

12th Edition of the Large Hadron Collider Physics Conference

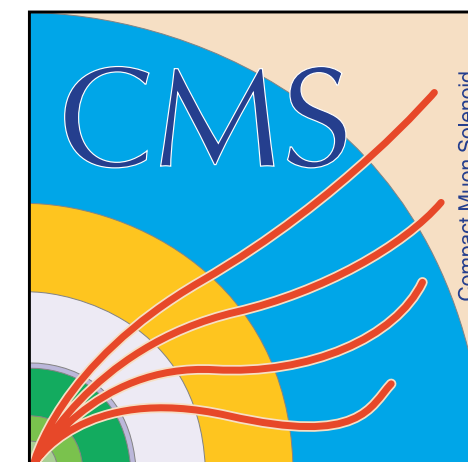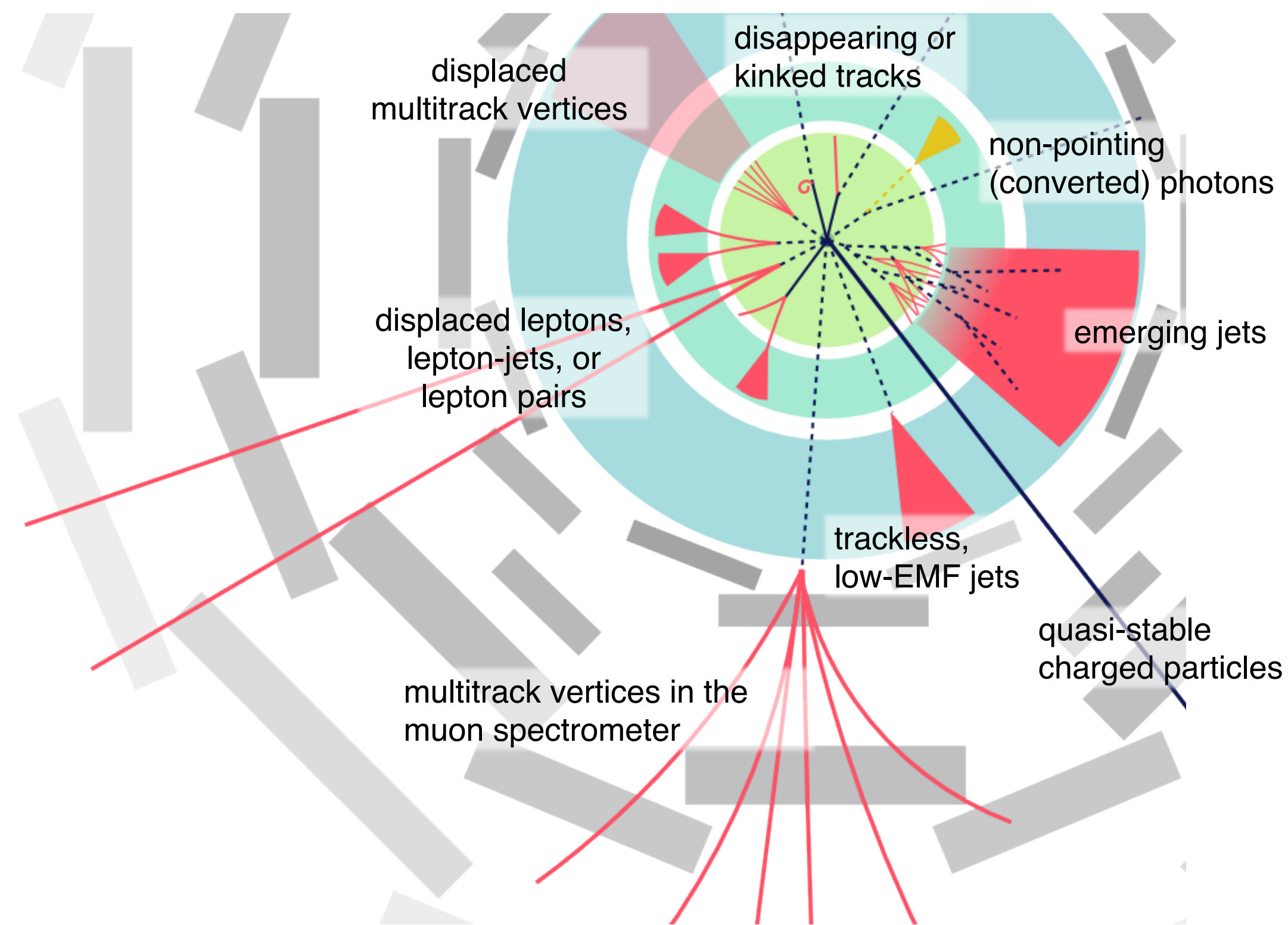Boston, 3 June 2024

LLPs: Long Lived Particles

Unique experimental challenge for LHC experiments!

- **unconventional signatures:** require dedicated reconstruction & analysis methods to enhance sensitivity

- motivated by many BSM theories - possible candidates to explain dark matter nature, neutrino masses, ..

Outline of the talk

Highlight of recent searches done in ATLAS, CMS and FASER
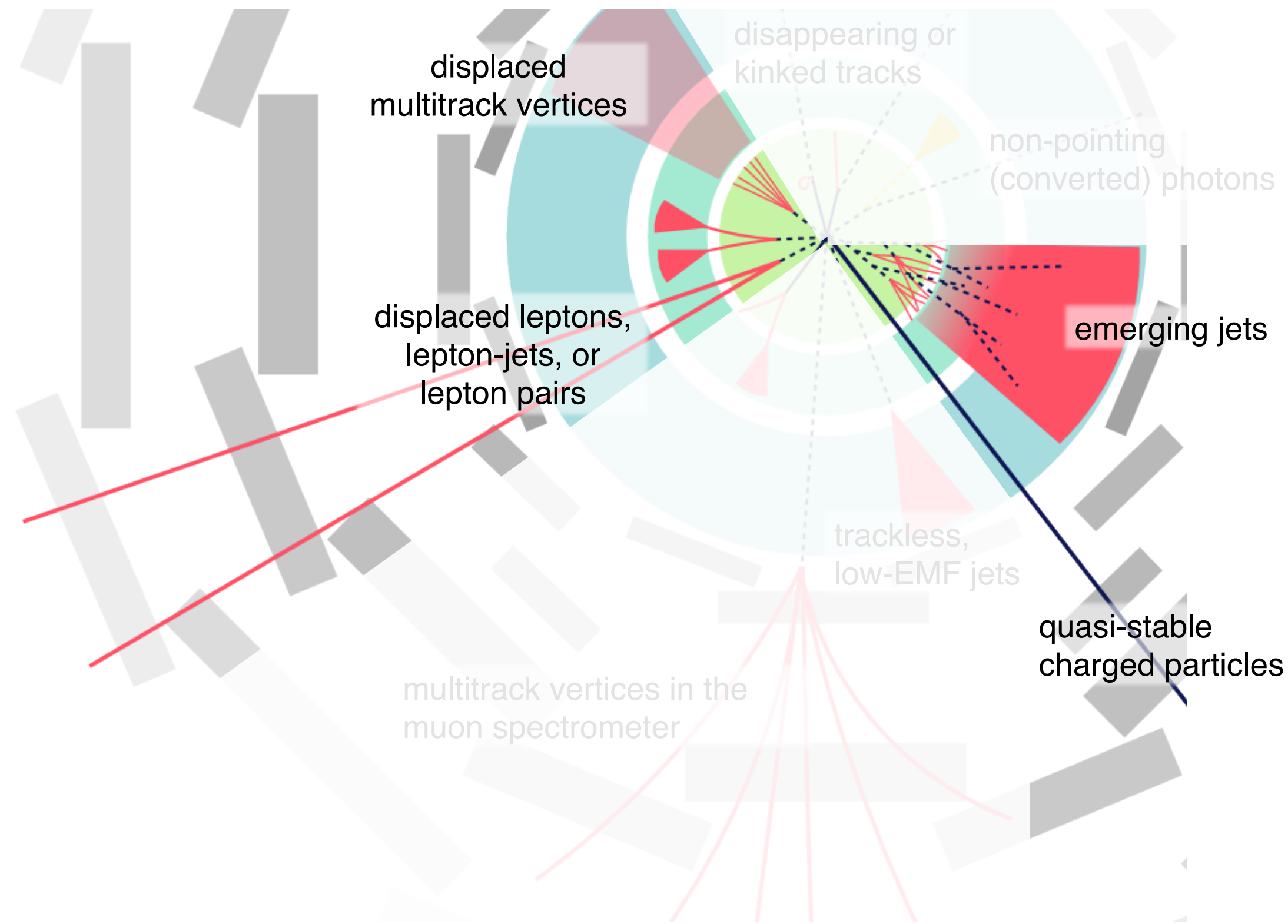
Low-mass neutral long-lived scalars

- Search with displaced vertices and jets in ATLAS and CMS
- Displaced vertices with muons at CMS using data from LHC run 3
- Long-lived axion-like-particles search with FASER

Heavy neutral leptons

- Recent result from CMS using the B-parking dataset

Massive charged long-lived particles with large ionization

- Followup ATLAS analysis after the 3.3σ excess result
- Recent CMS result targeting the same phase space

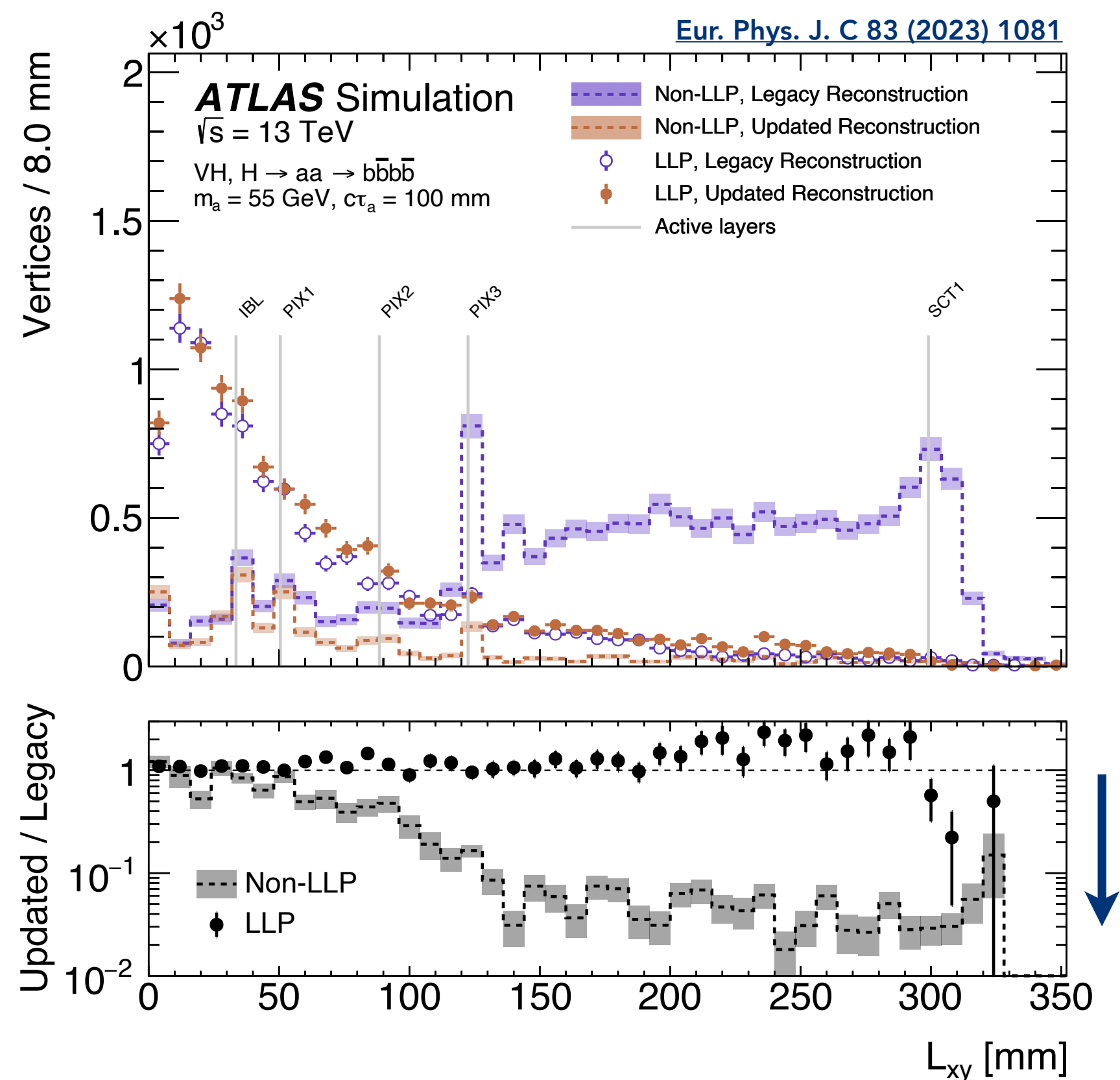**Emerging jets**

- Recent new result from CMS
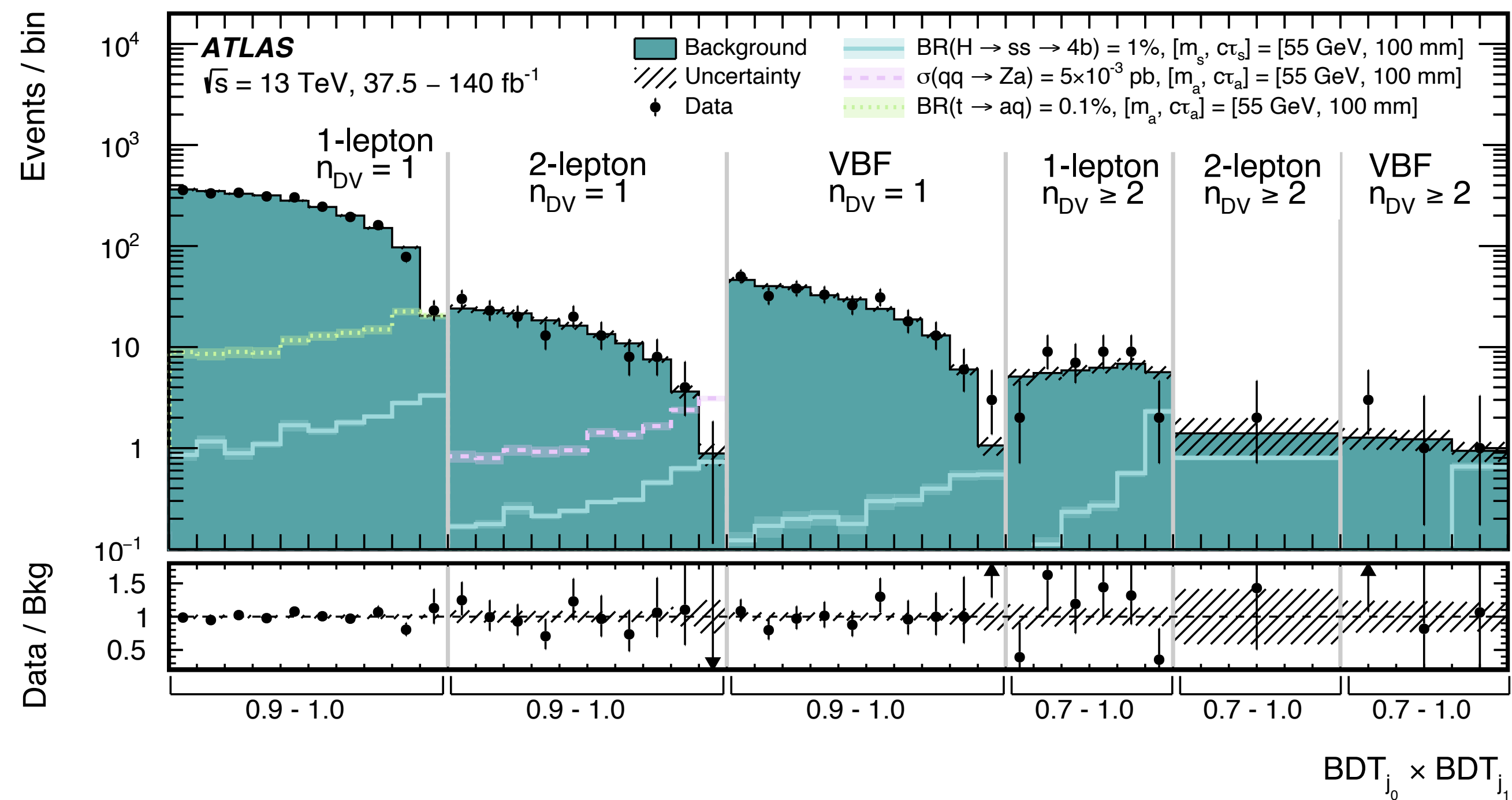
LLPs search with displaced vertices in

 ATLAS EXPERIMENT

- using LHC run 2 data with **improved displaced tracks reconstruction**

- search for **≥2 *displaced*-jets**, and **≥1** matched to a **displaced vertex (DV)**

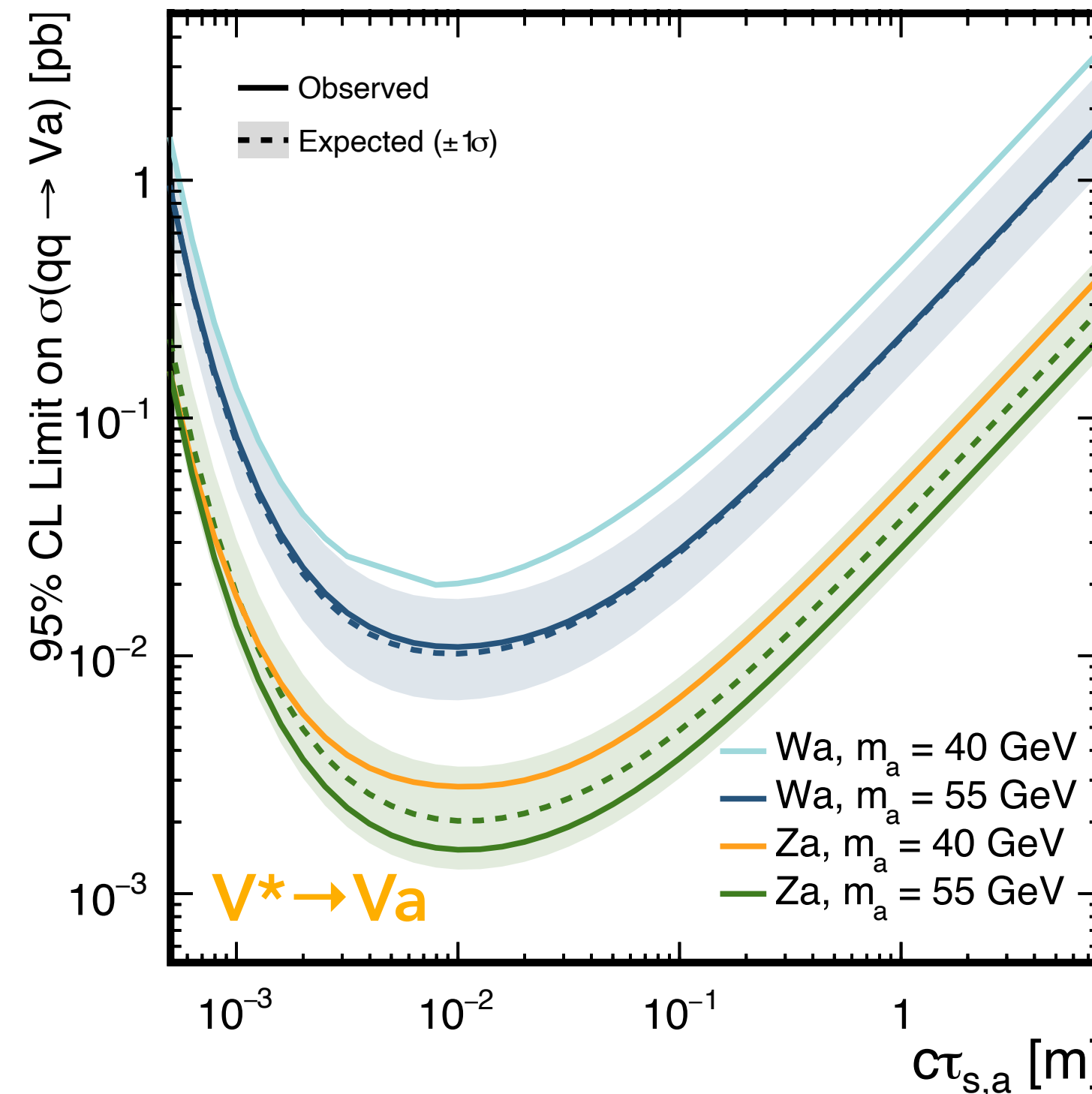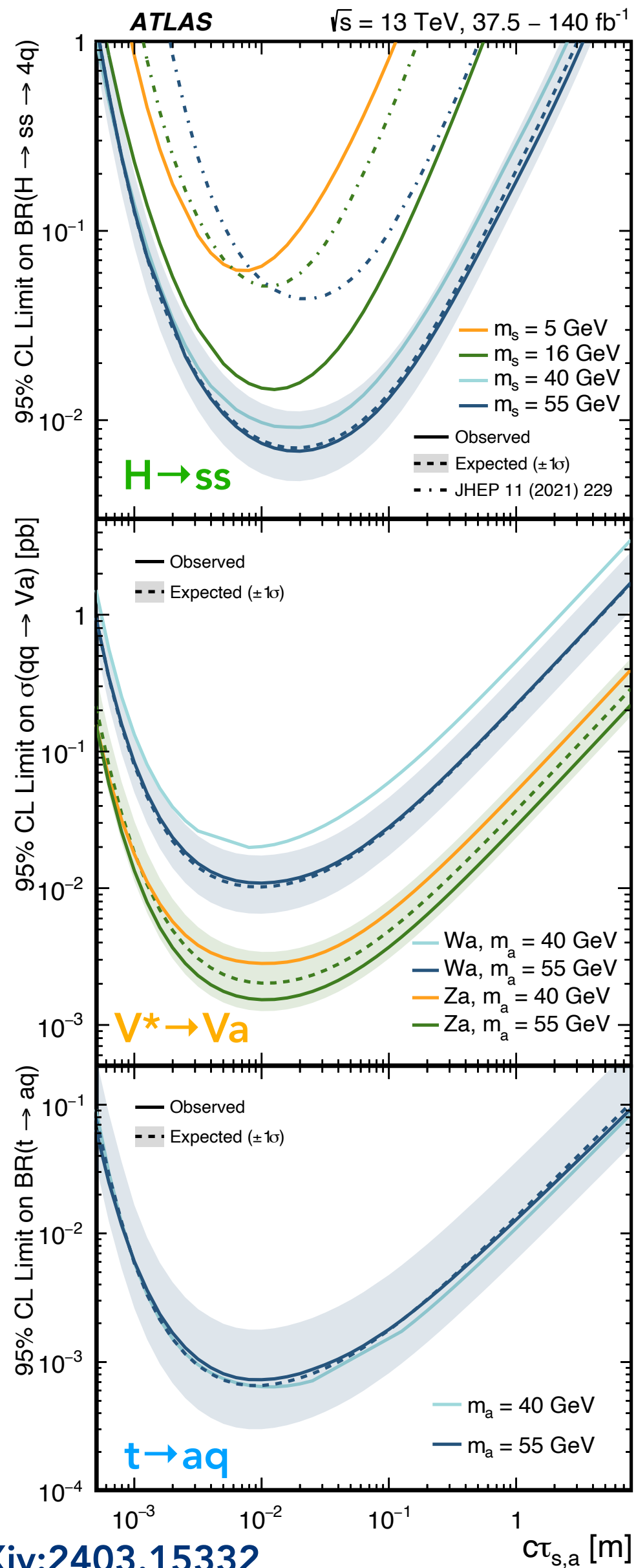- 6 analysis categories: **topology** (*VH*-like, *VBF*-like) × n_{DV}

- **BDT displaced jet tagger** event-level discriminant: $BDT_{j0} \times BDT_{j1}$

- **per-jet vertex match probability** to estimate background in 6 SR

Improved Large Radius Tracking

factor ≥10 reduced fakes at large displacement

LLPs search with displaced vertices in
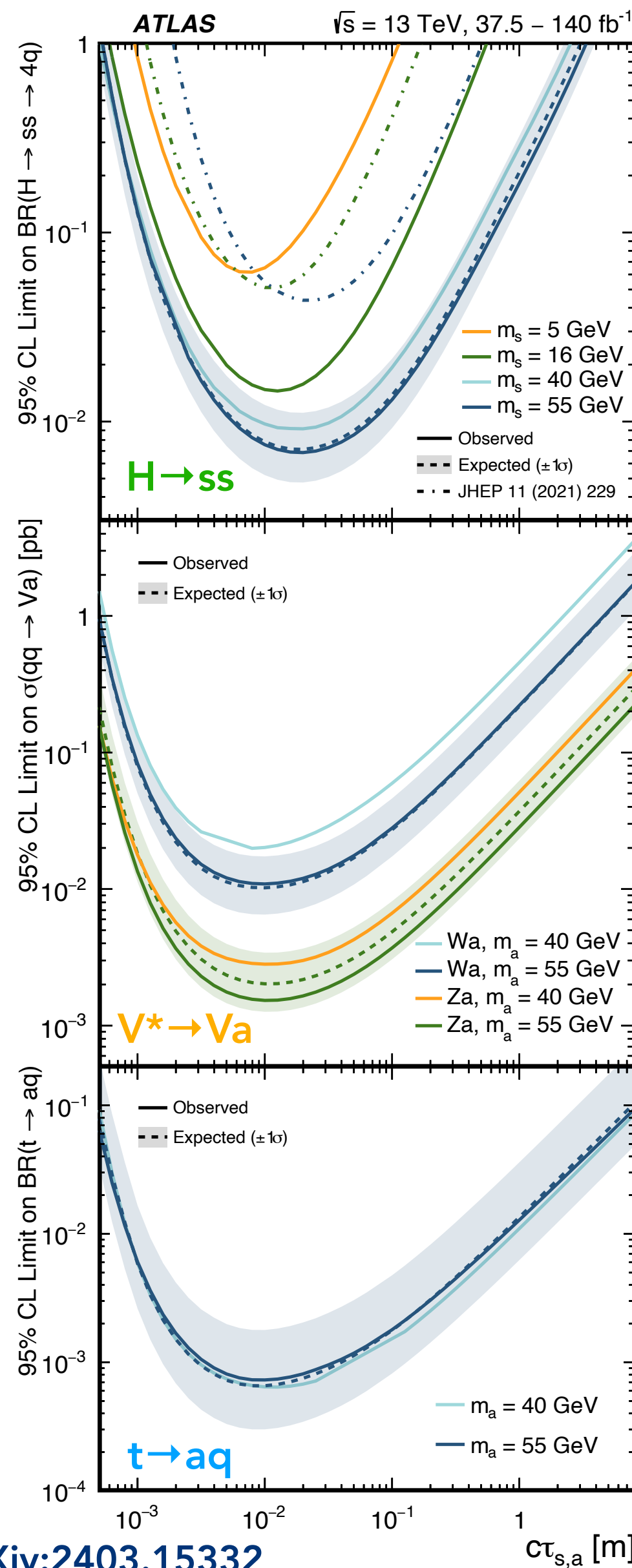

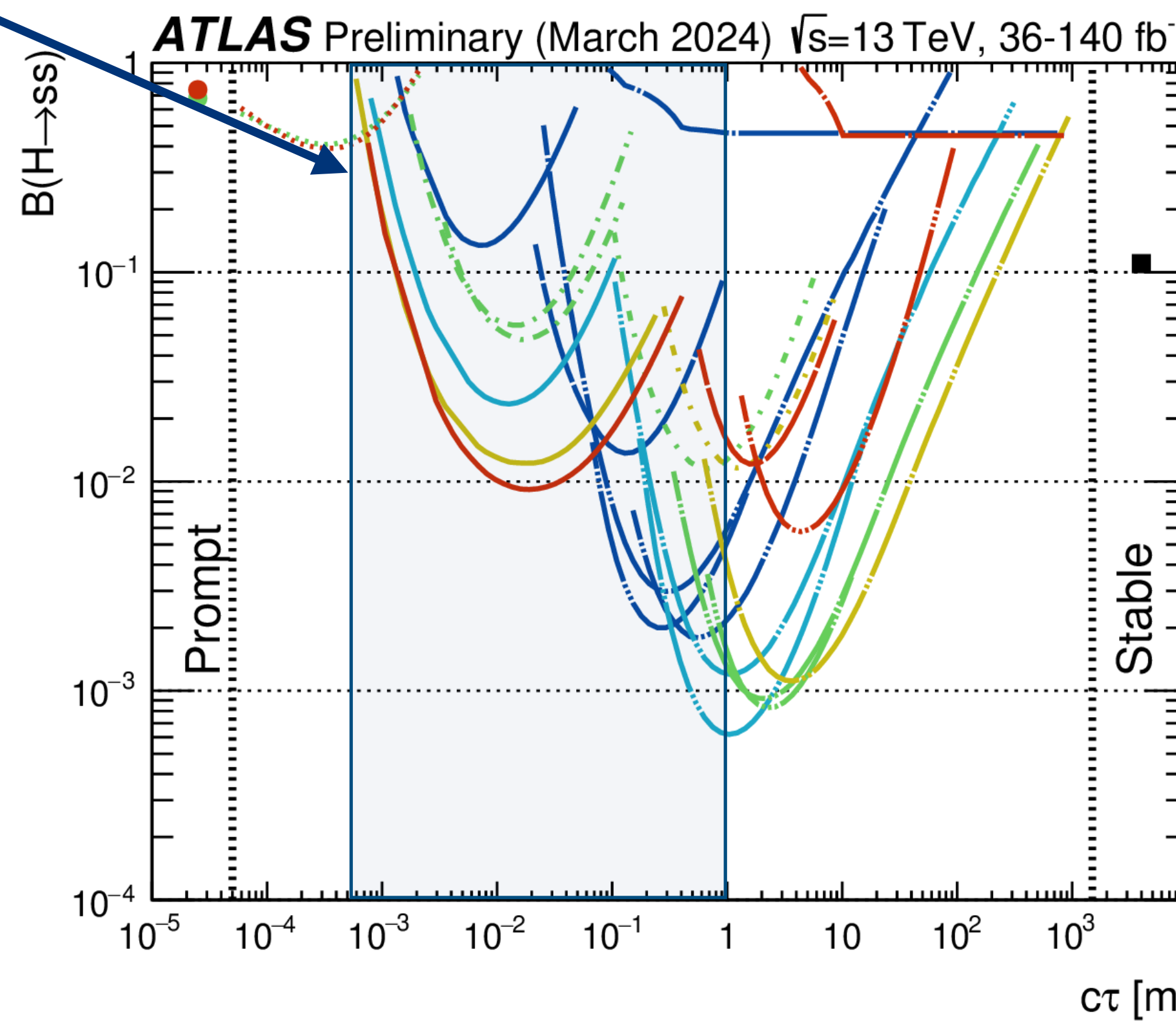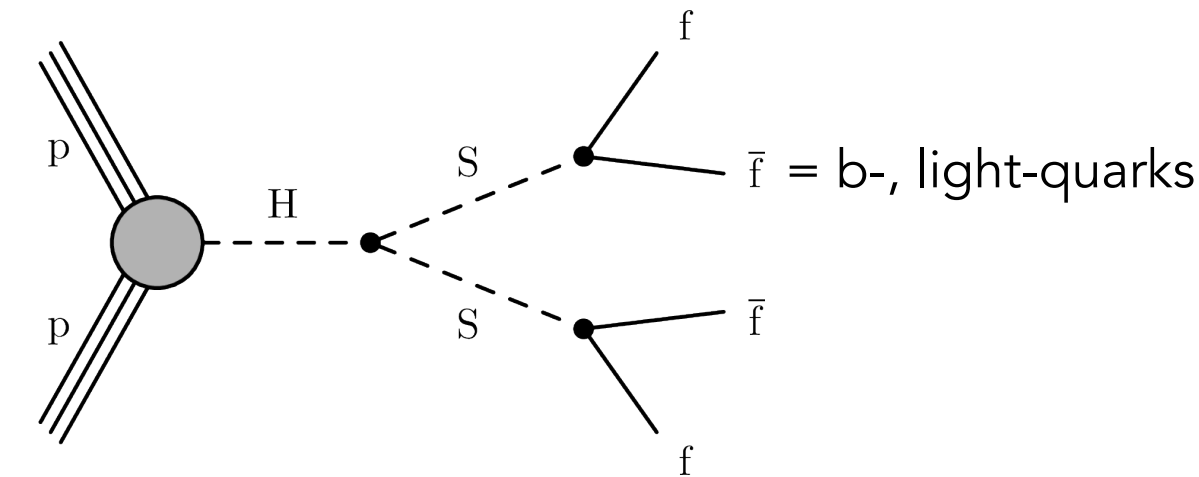Axion-like particles (ALPs) in *Va* production

New interpretation
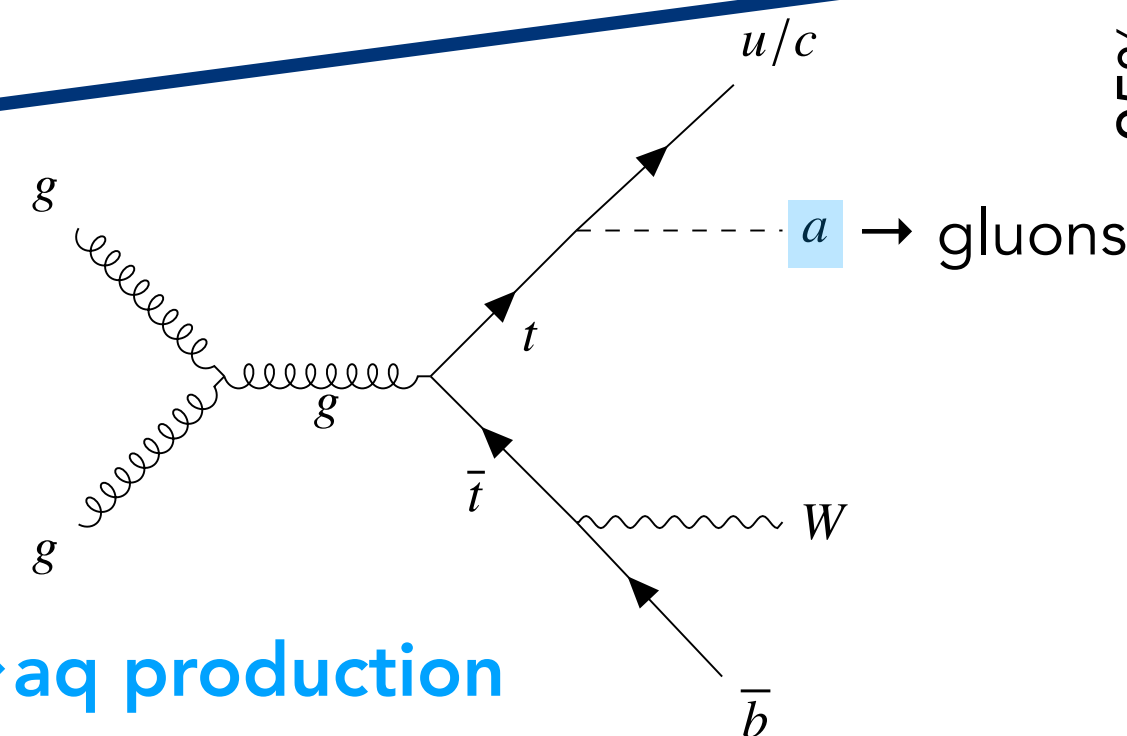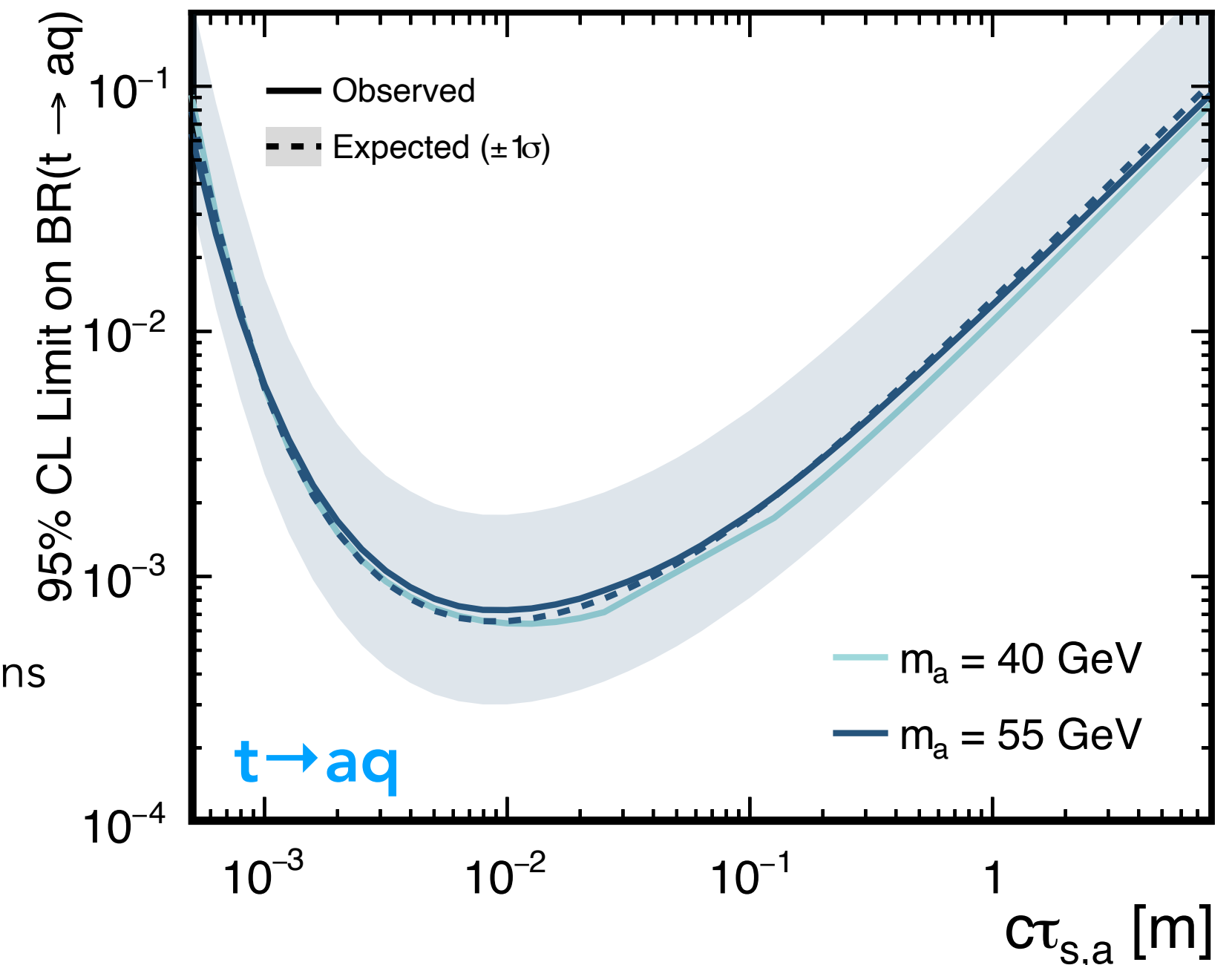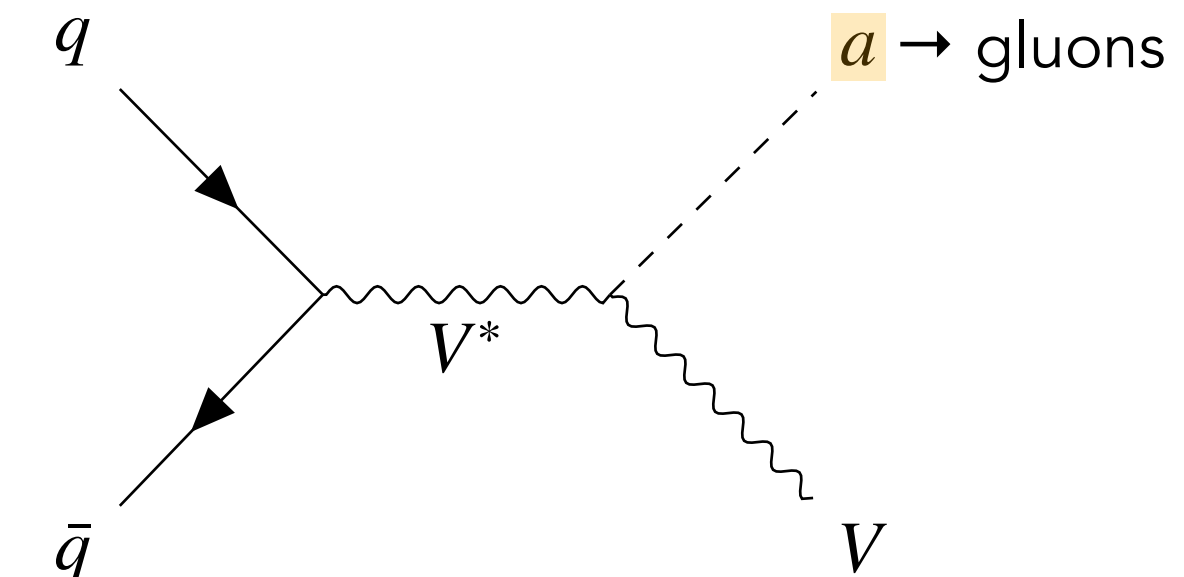
ALPs from t→aq production

New interpretation

LLPs search with displaced vertices in ATLAS
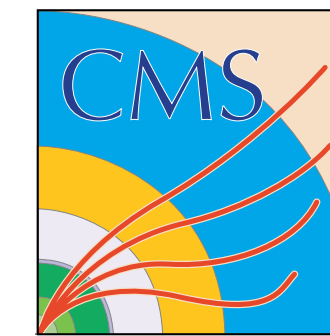
Neutral scalar LLPs from Higgs boson decay
HSS model

Hidden Sector, $m_H = 125$ GeV
Selected *ATLAS* results
95% CL observed limits

Searches:
- **Muon System (2 Vtx Only), 139 fb^{-1}**
  Phys. Rev. D 106 (2022) 032005
- **Muon System (1 Vtx + 2 Vtx), 36 fb^{-1}**
  Phys. Rev. D 99 (2019) 052005
- **Calorimeter, 139 fb^{-1}**
  JHEP 06 (2022) 005
- **Tracker+Muon System, 36 fb^{-1}**
  Phys. Rev. D 101 (2020) 052013
- **Tracker, 139 fb^{-1}**
  JHEP 11 (2021) 229
- **Tracker (b-tag), 36 fb^{-1}**
  JHEP 10 (2018) 031
- **Monojet, 139 fb^{-1}**
  ATL-PHYS-PUB-2021-020
- **H→ inv, 7-8-13 TeV combination**
  ATLAS-CONF-2020-052
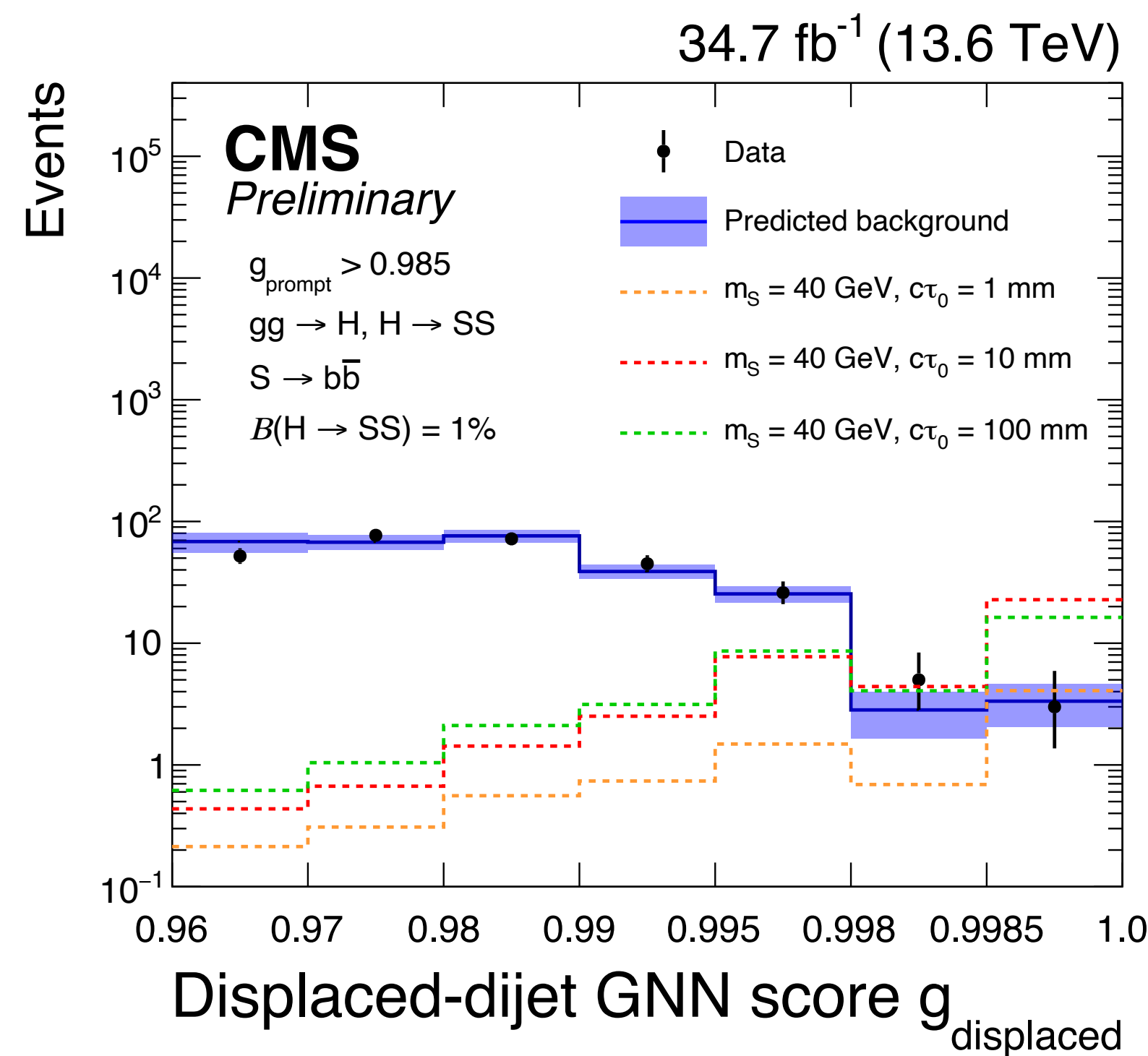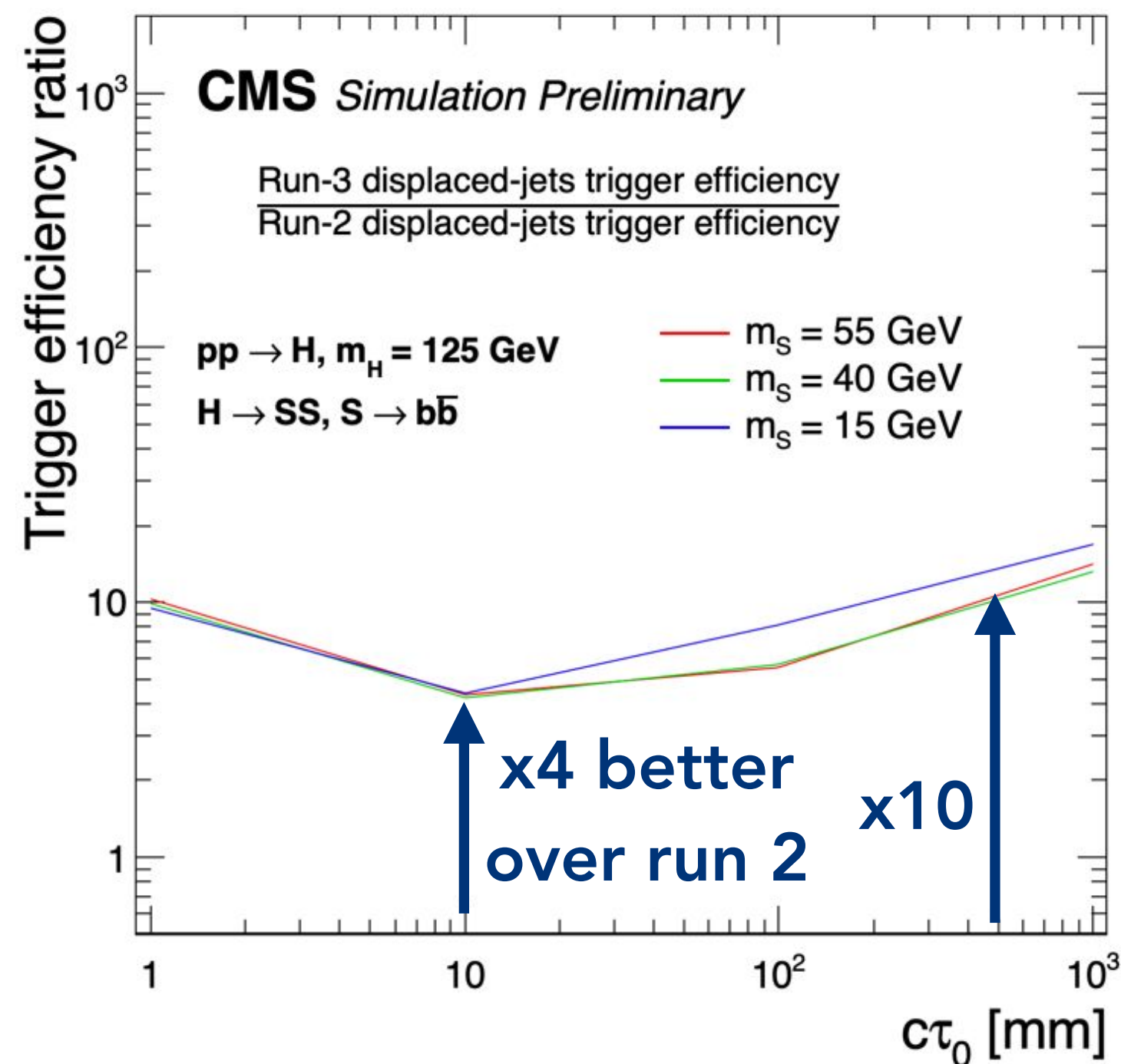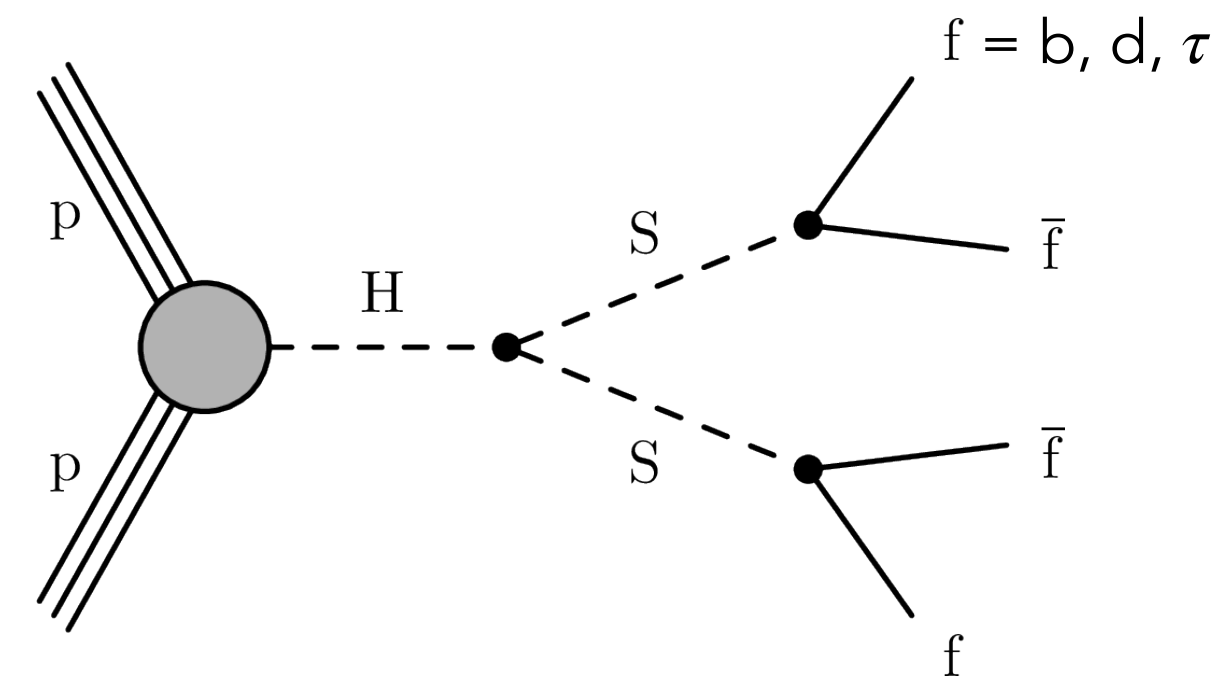- **Tracker, 37.5-140 fb^{-1}**
  arXiv:2403.15332

LLP masses:
- 5-8 GeV
- 15-20 GeV
- 25-35 GeV
- 40 GeV
- 45-60 GeV
- Any

Factor 10 ÷ 20 improvement on previous existing limits **using same signature**

LLPs to displaced jets with Run 3 data at

- target LLPs from Higgs boson decays or heavy neutral scalars

- use **improved displaced-jet triggers**:

  - requirements on large transverse momentum jets

    + presence of 'prompt' & 'displaced' tracks

f = b, d, τ

x4 better over run 2

x10

34.7 fb^{-1} (13.6 TeV)

CMS *Preliminary*

$g_{prompt} > 0.985$

$gg \to H, H \to SS$

$S \to b\bar{b}$

$B(H \to SS) = 1\%$

- Data
- Predicted background
- $m_S = 40$ GeV, $c\tau_0 = 1$ mm
- $m_S = 40$ GeV, $c\tau_0 = 10$ mm
- $m_S = 40$ GeV, $c\tau_0 = 100$ mm

Displaced-dijet GNN score $g_{displaced}$

- use of two **Graph Neural Network (GNN)**

  based LLP taggers:

  - 'displaced'-GNN

  - 'prompt'-GNN

- data-driven estimate using orthogonal

  control regions (ABCD method)

LLPs to displaced jets with Run 3 data at

- **first LHC limits** on displaced-hadronic tau signature

H→SS, S→$b\bar{b}$
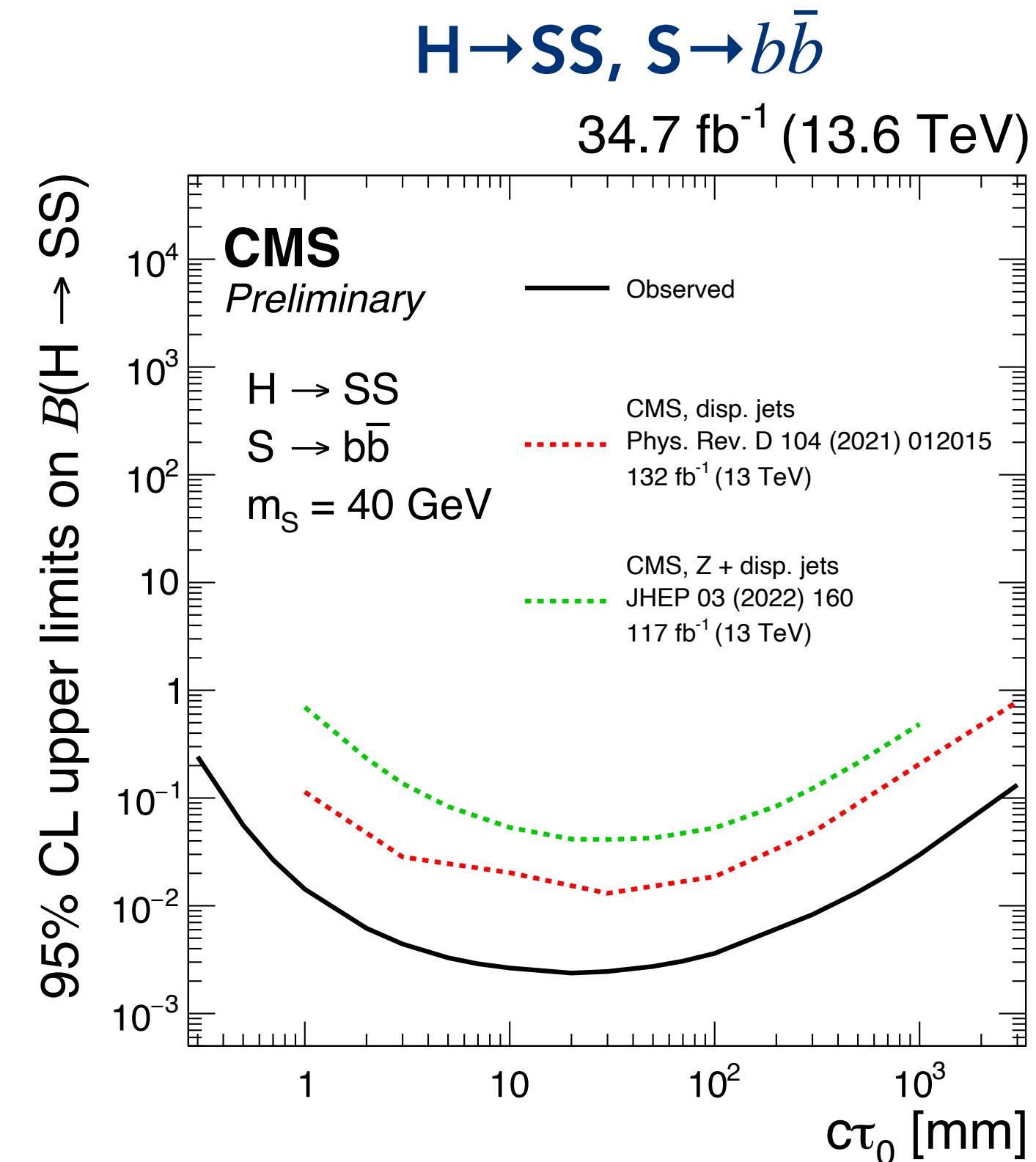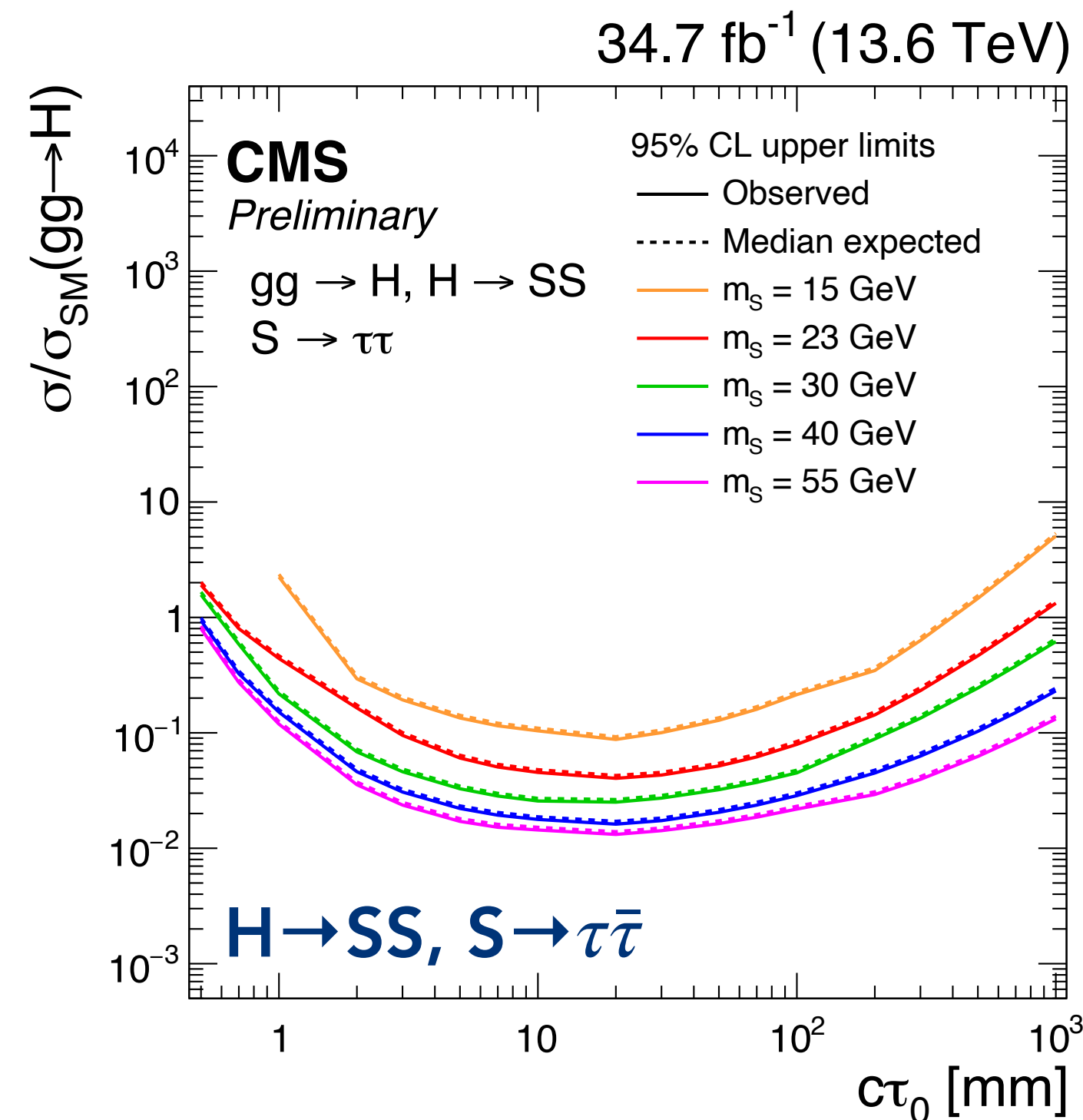
- new **most stringent limits** on H→SS model **for LLP masses ≥16 GeV**

  - outperforms ATLAS with a fraction of the dataset - **34.7/fb @ 13.6 TeV** vs 140/fb @ 13 TeV

- additional interpretations of the results in H→SS→light quarks, Fraternal Twin Higgs & Folded SUSY scenarios

LLPs to displaced muons with Run 3 data at
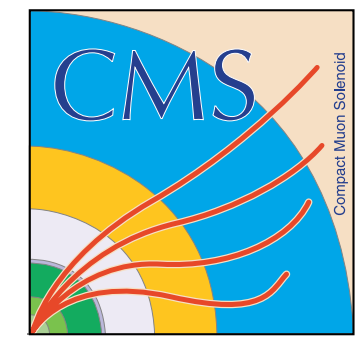
- search for **di-muon displaced vertices** produced in LLP decays
  - low mass LLPs, $m_{LLP} < 60$ **GeV**, from Higgs boson or heavy scalar decays

- **new dedicated triggers** to increase sensitivity
  - lower p_T threshold possible introducing a cut on transverse displacement (d_0)
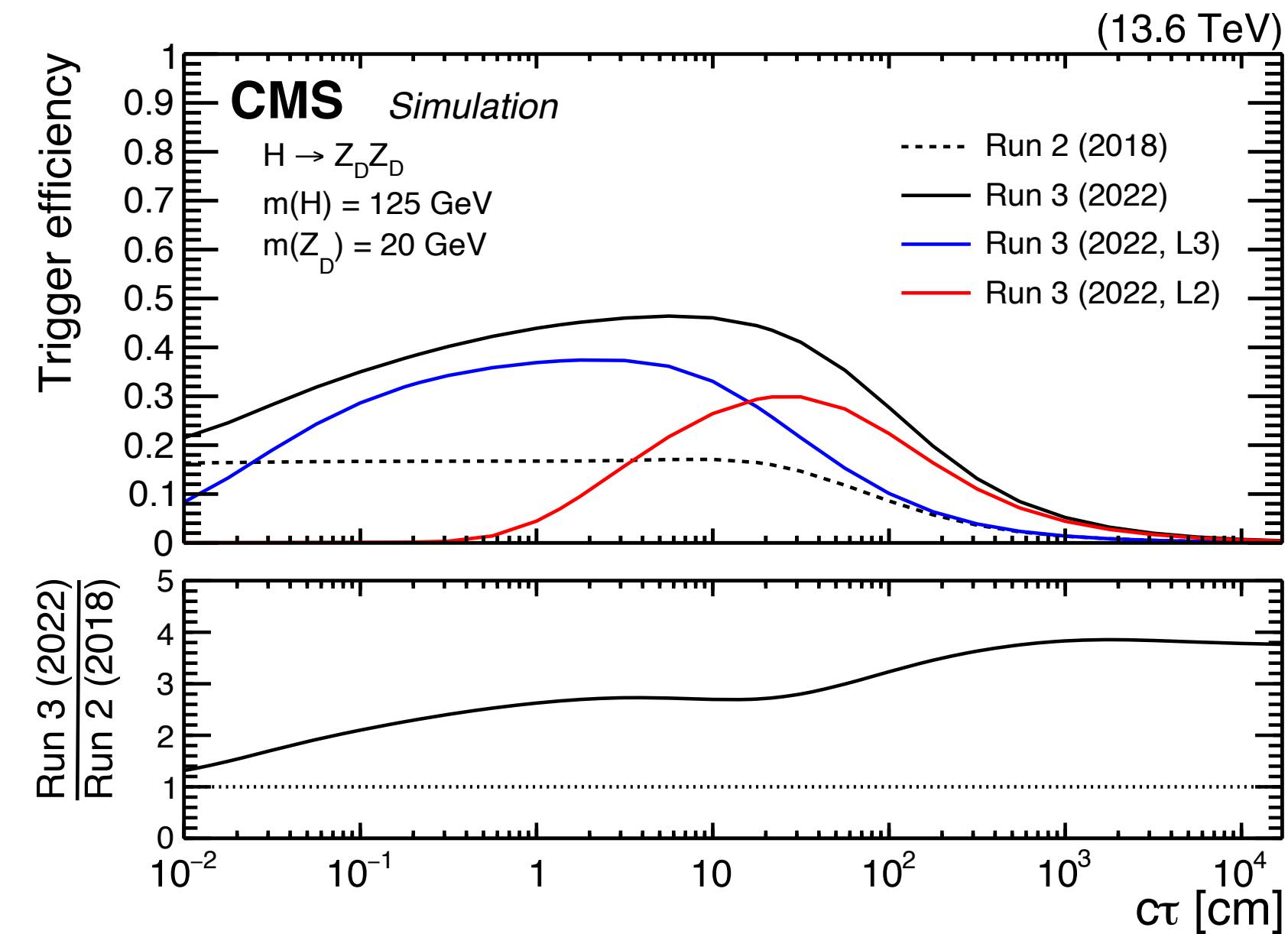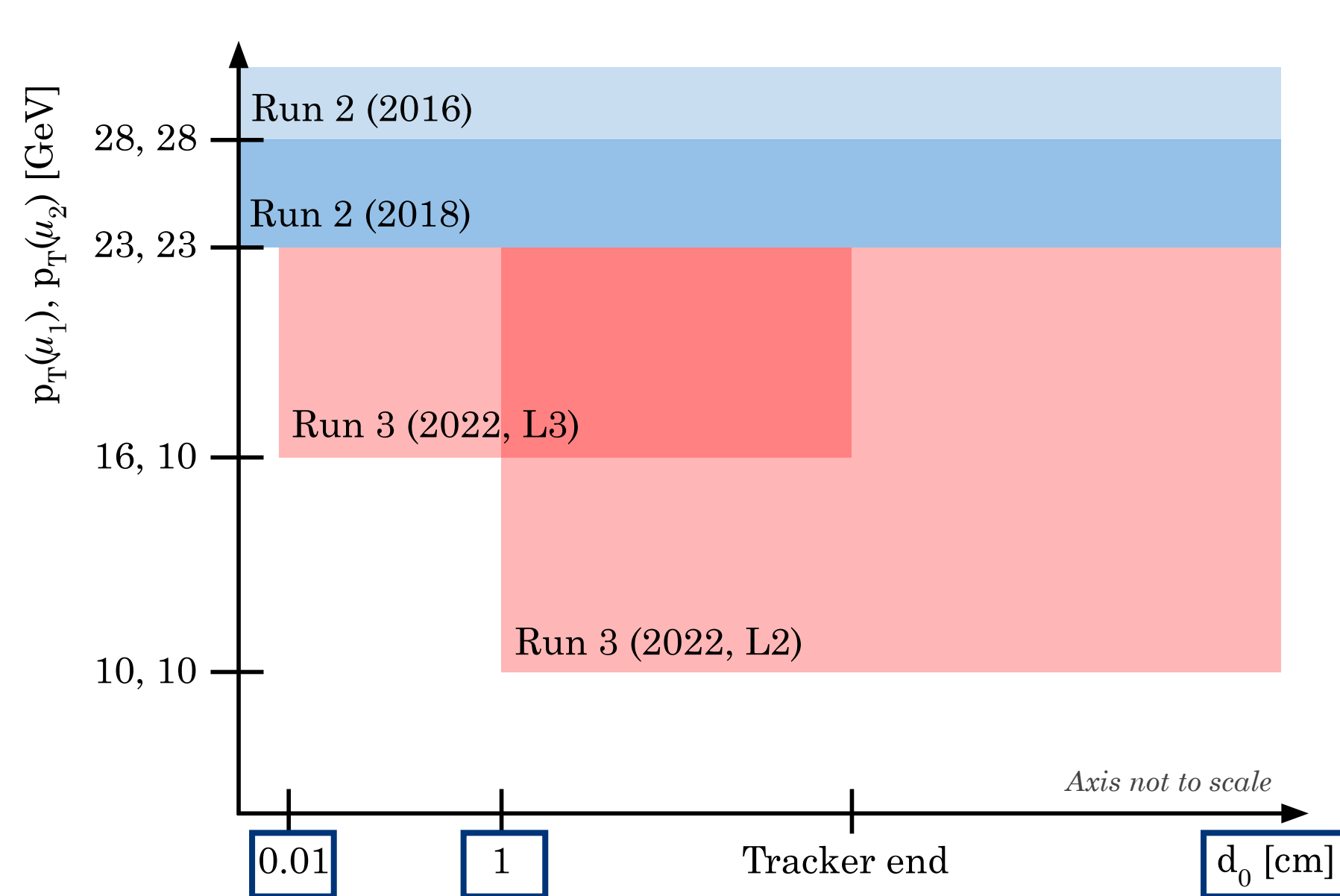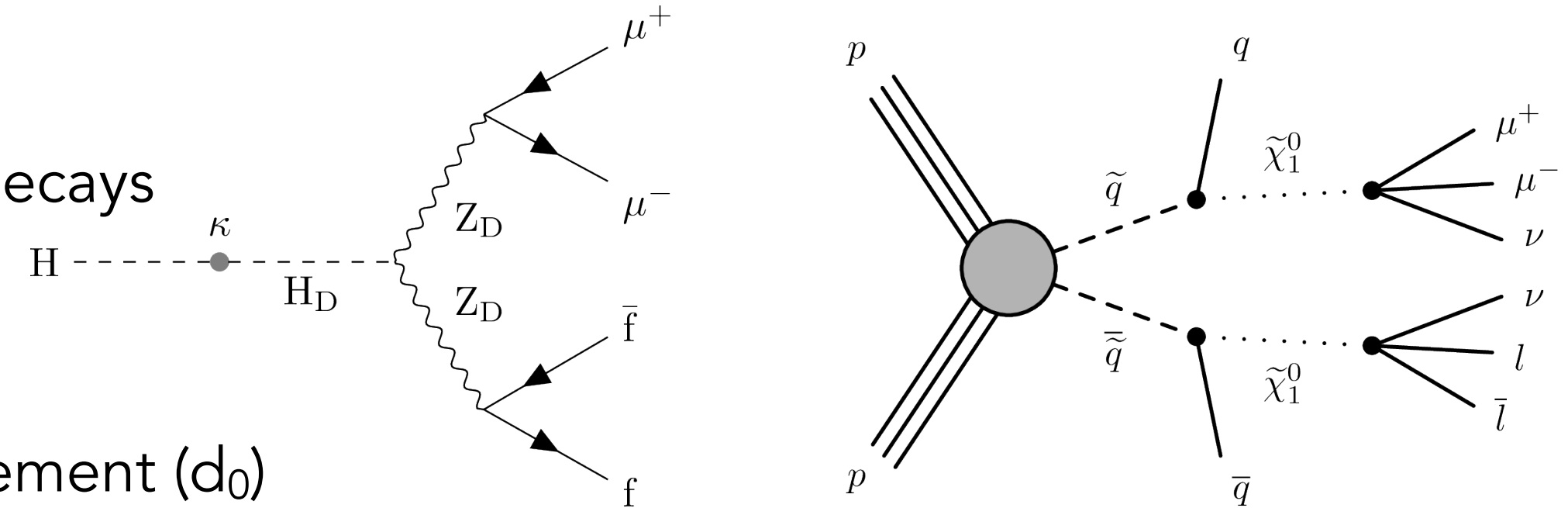
Factor **1.4 to 4** improvement over Run 2

- **background processes:** mis-reconstructed prompt muons, muons in jets → data driven estimate from independent CRs

LLPs to displaced muons with Run 3 data at CMS
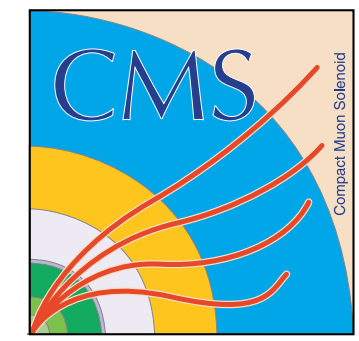
- 2 analysis categories based on muon reconstruction:
  - using both **tracker & muon spectrometer** (TMS)
  - standalone muon spectrometer (STA)

- **partial Run 3 result competitive with full Run 2 result**
  - new analysis better for $c\tau \gtrsim 100$ cm for almost all masses
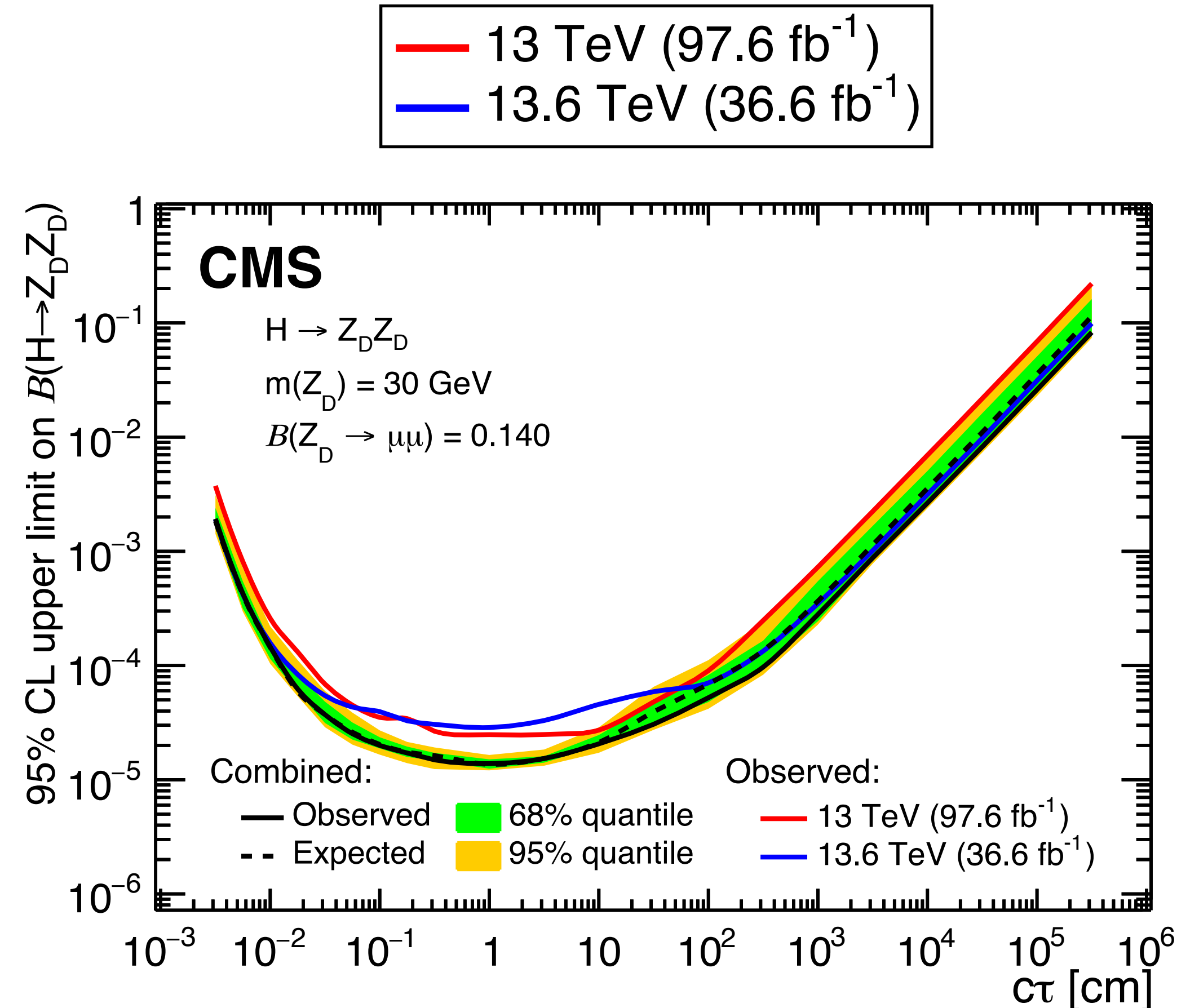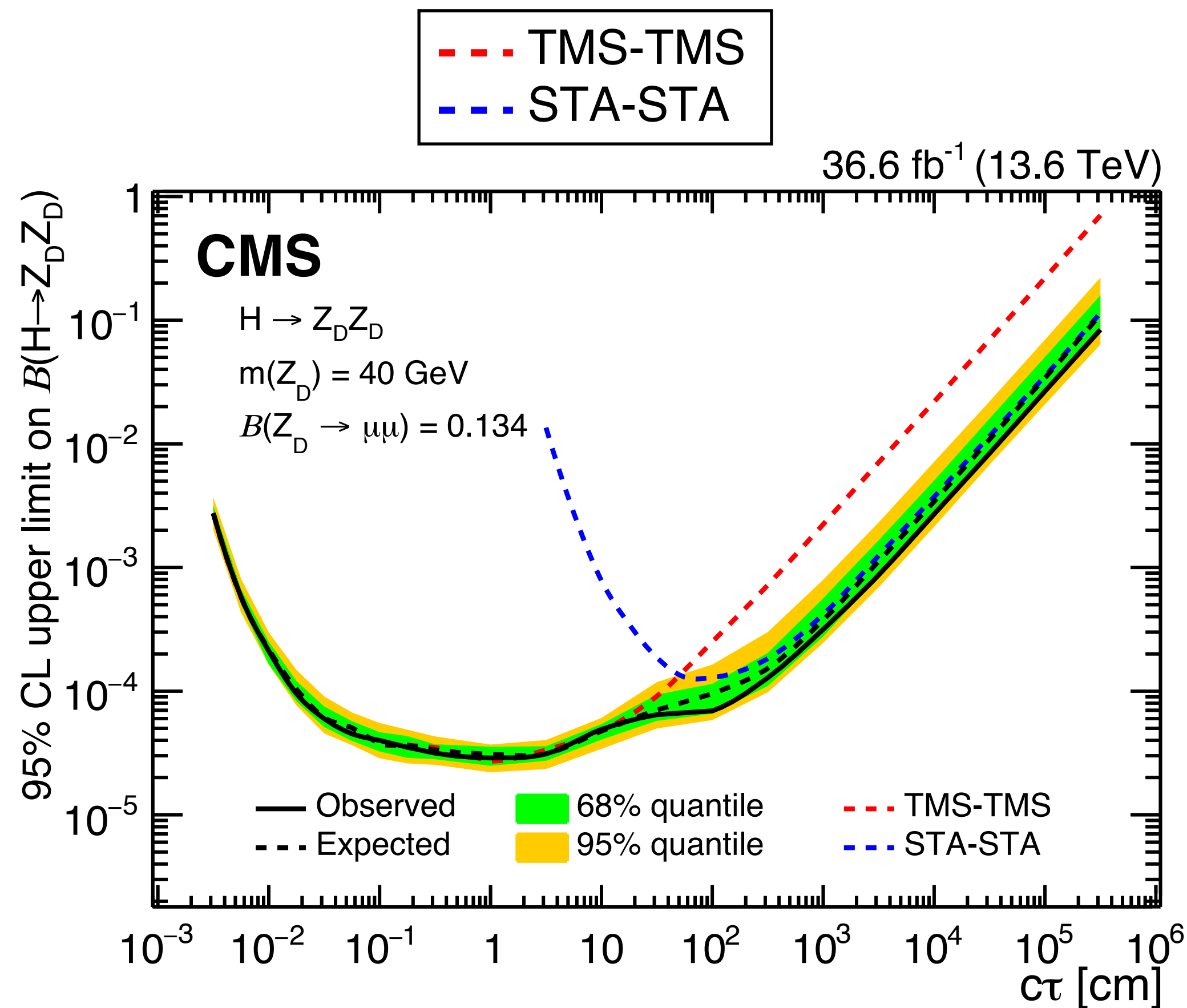
Search for long-lived ALPs with FASER

- experiment situated 500m from ATLAS collision point, aligned with the beam collision axis
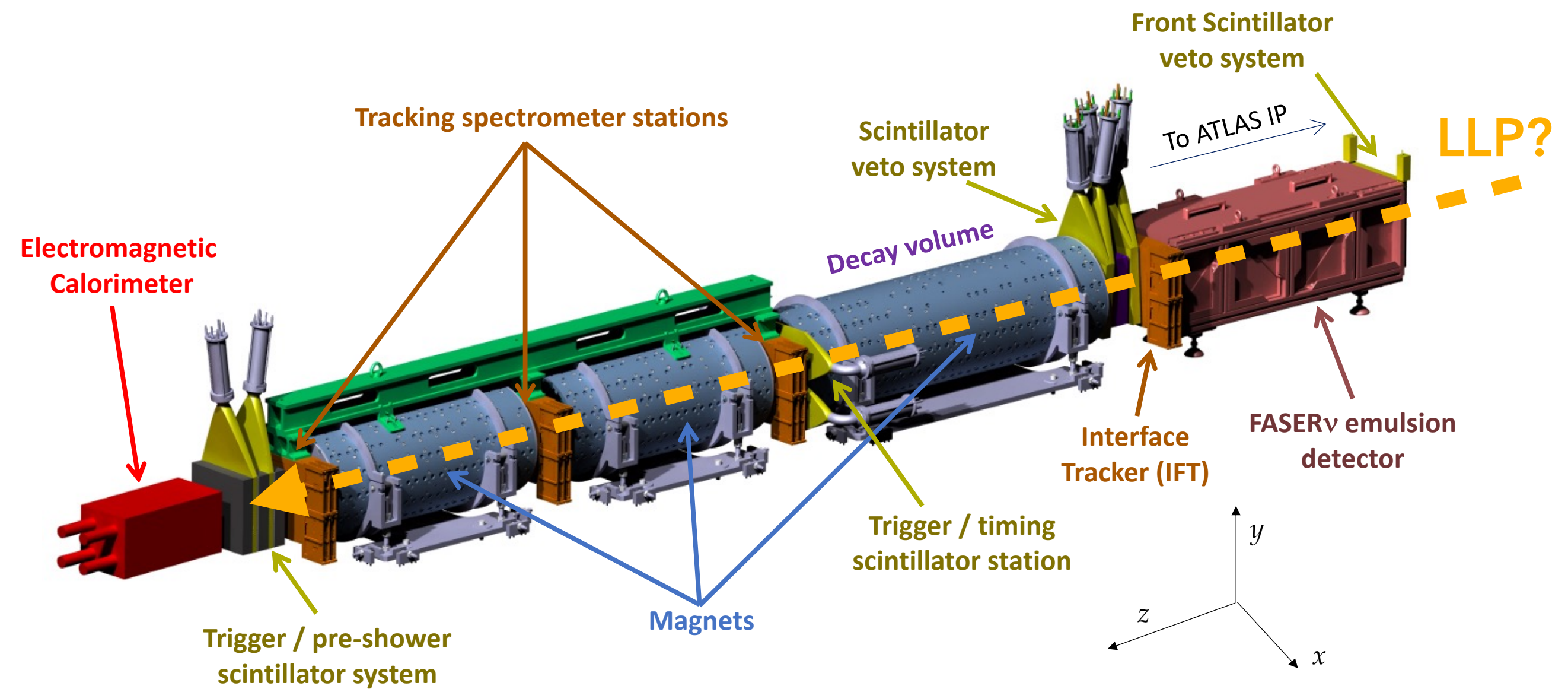
- sensitive to **long-lived axion-like-particles (ALPs)** produced with $\mathcal{O}(\text{TeV})$ boost along the beam line and decaying inside the detector into photon pairs

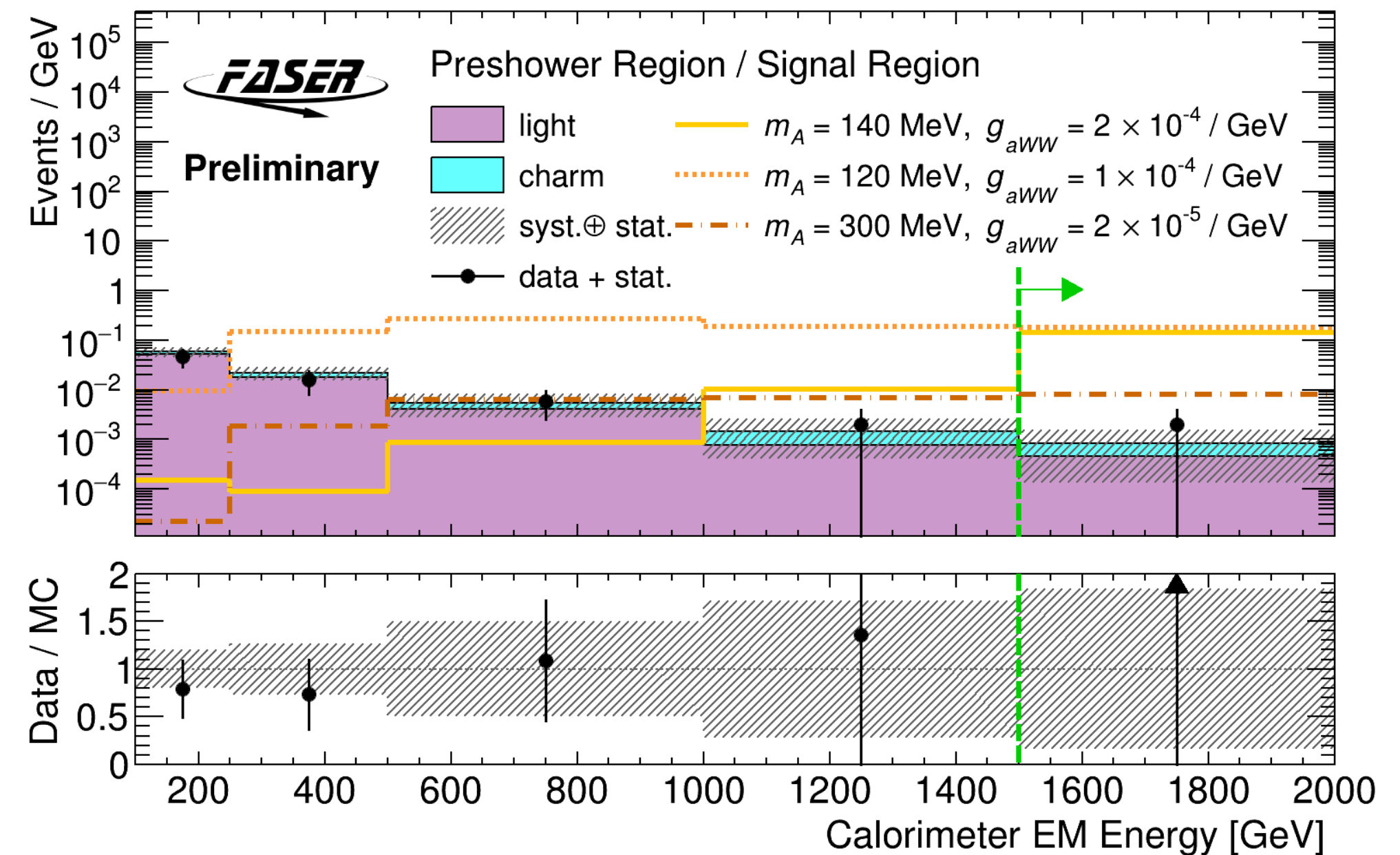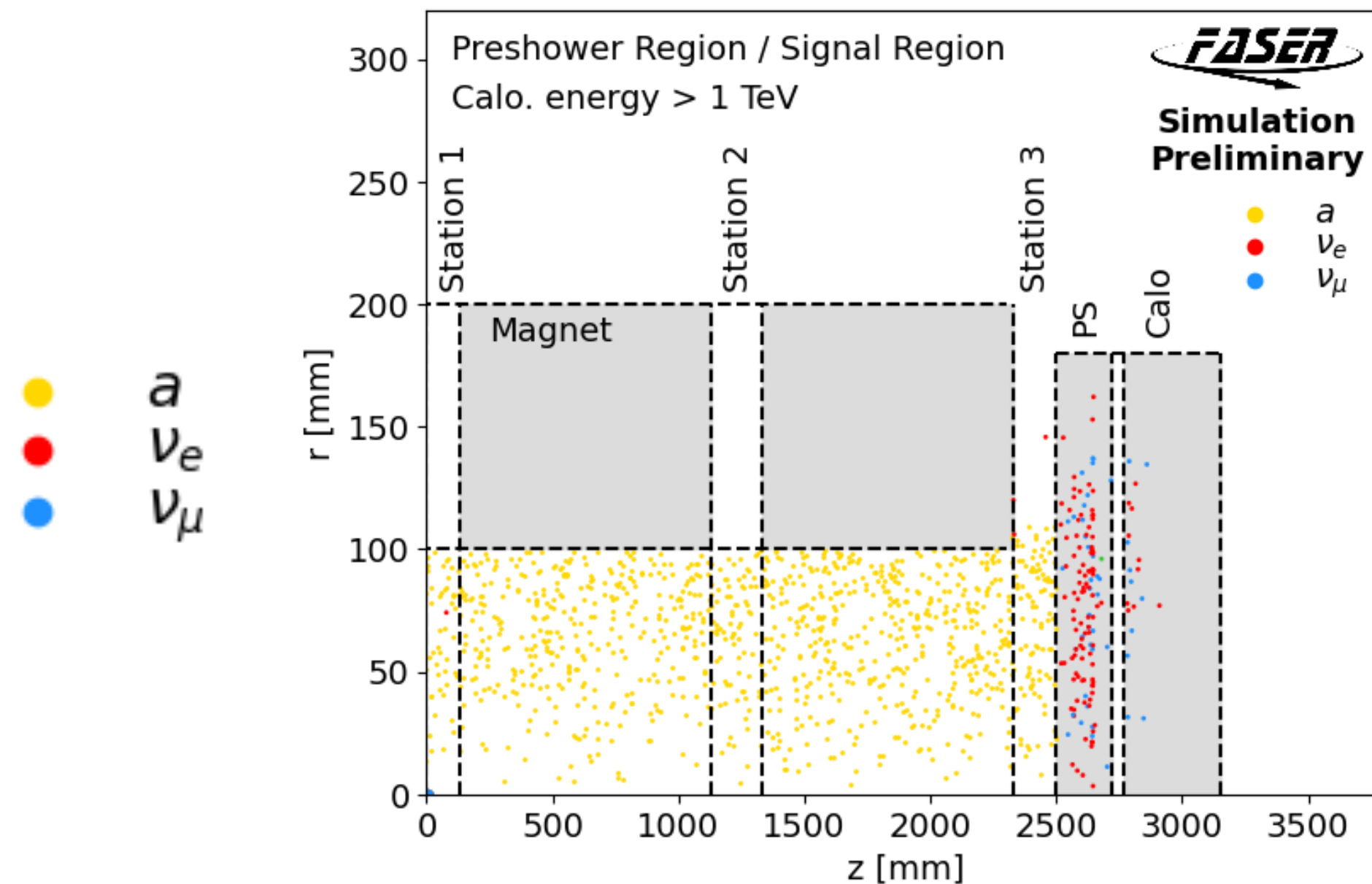# Search for long-lived ALPs with FASER

- using **57/fb** of data collected during **2022 & 2023**

- ALPs produced in B/K meson decays, **decaying subsequently into photon pairs**

- signature: high energy deposit in the ECAL and no signal in veto scintillators

  Main background: neutrinos interactions with detector material

- events categorised based on energy released in **calorimeter & pre-shower layers**
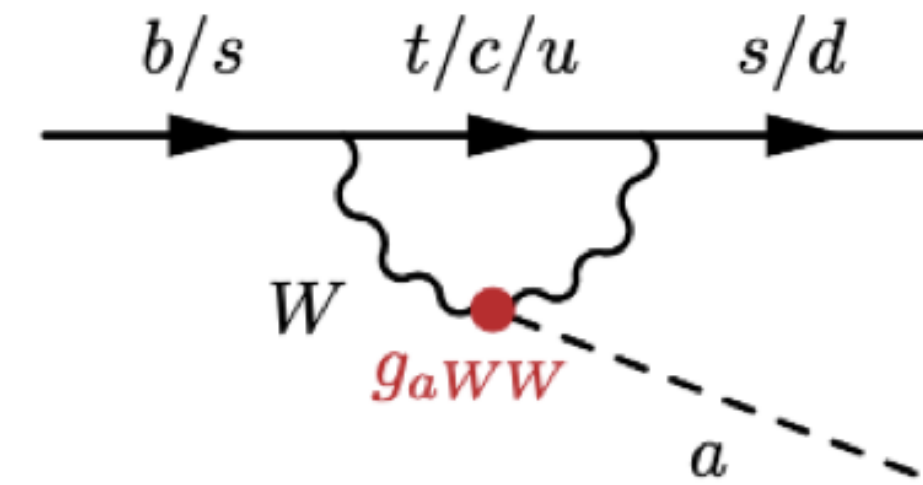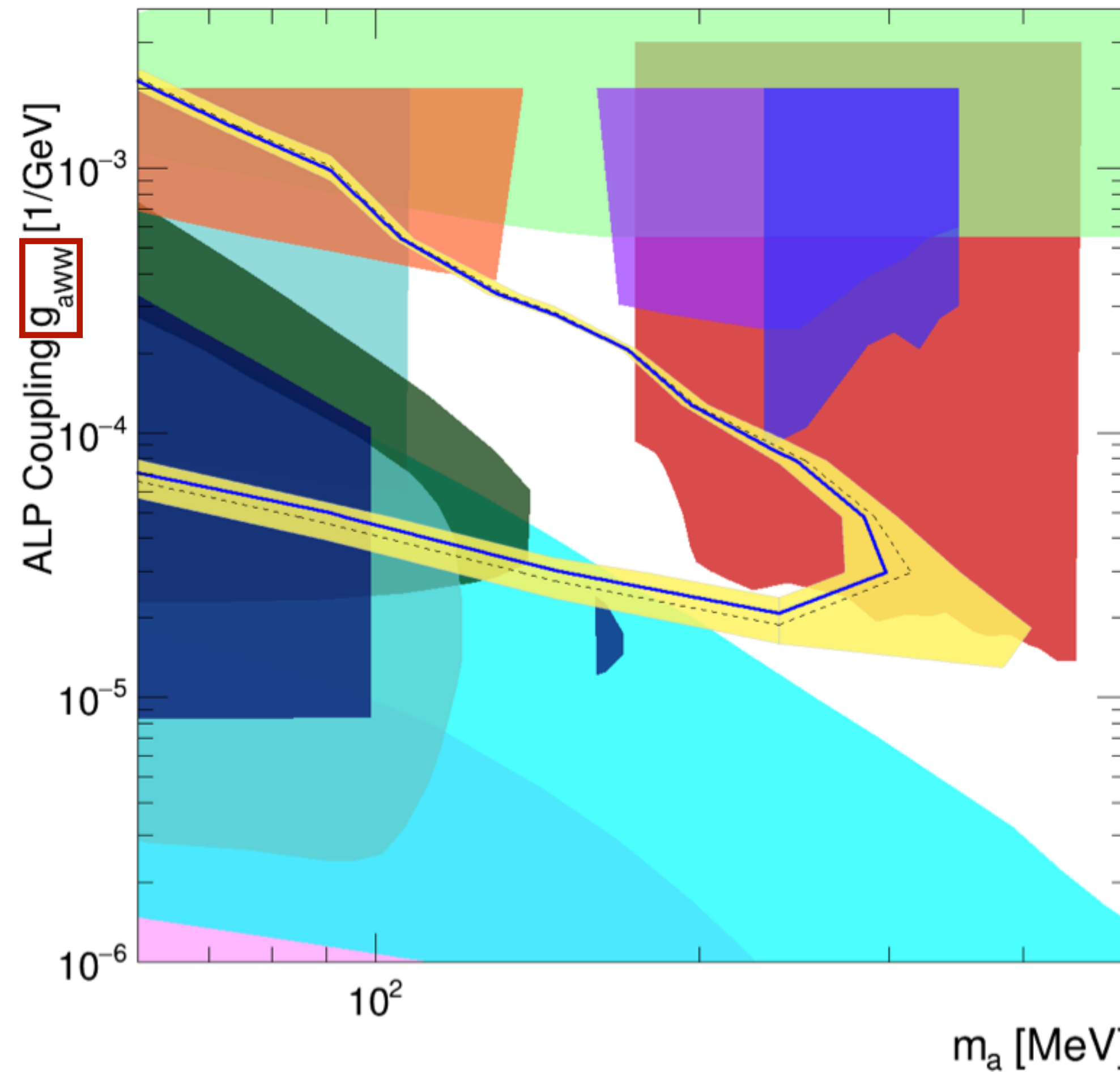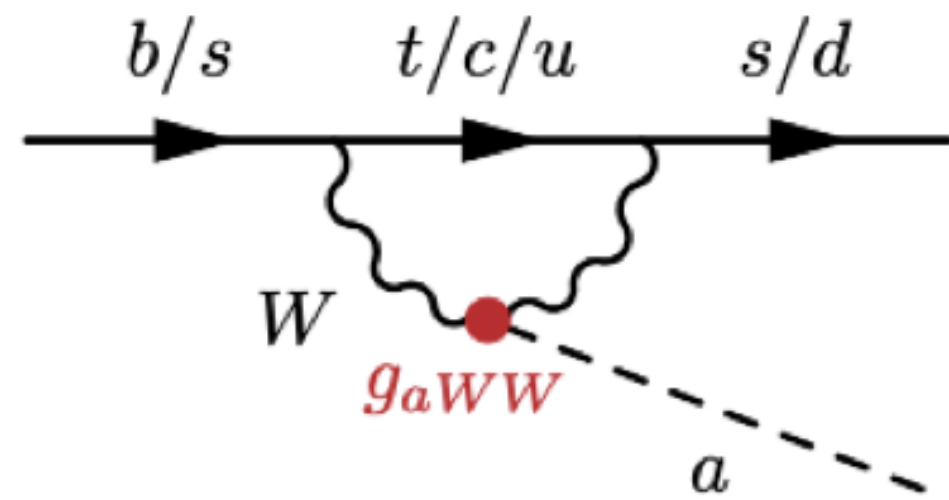
Bkg prediction: 0.42 ± 0.38 ; **1 observed event**
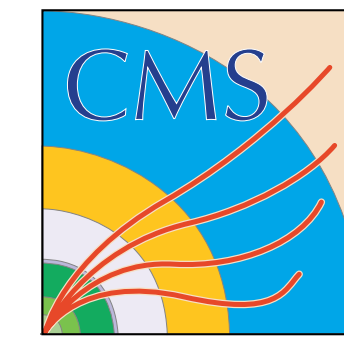
Search for long-lived ALPs with FASER

Unique sensitivity in unexplored regions of the parameter space, ALPs masses in the range **[60, 300] MeV**

Search for HNLs in B-meson decays at

- unique dataset (41.6/fb): **B parking, O(10B) $b\bar{b}$ events**

  - **lower μ trigger thresholds**, delayed reconstruction

- targets low mass Heavy Neutral Leptons (HNLs) from B-mesons

 - signature: **displaced vertex with lepton + track**
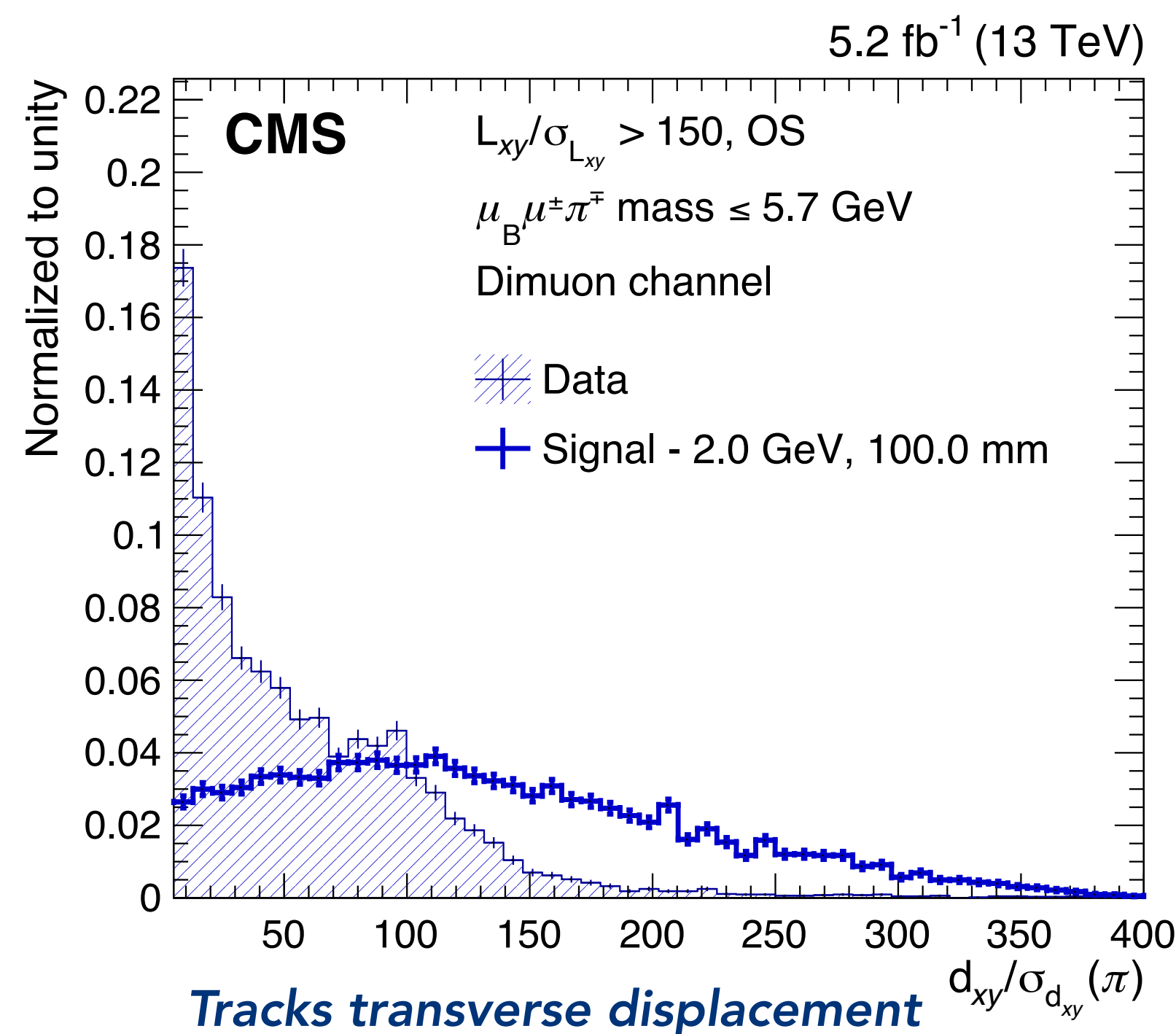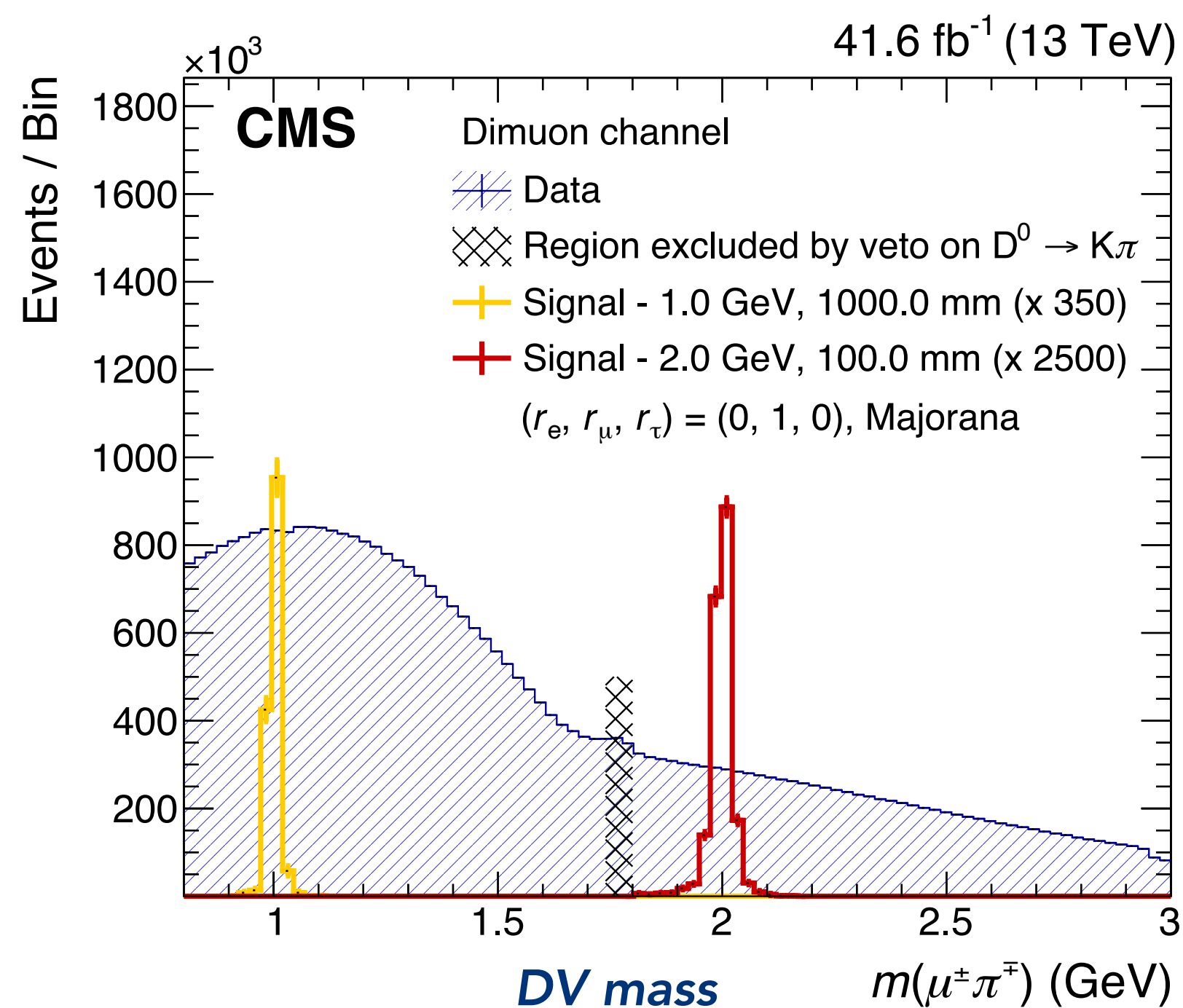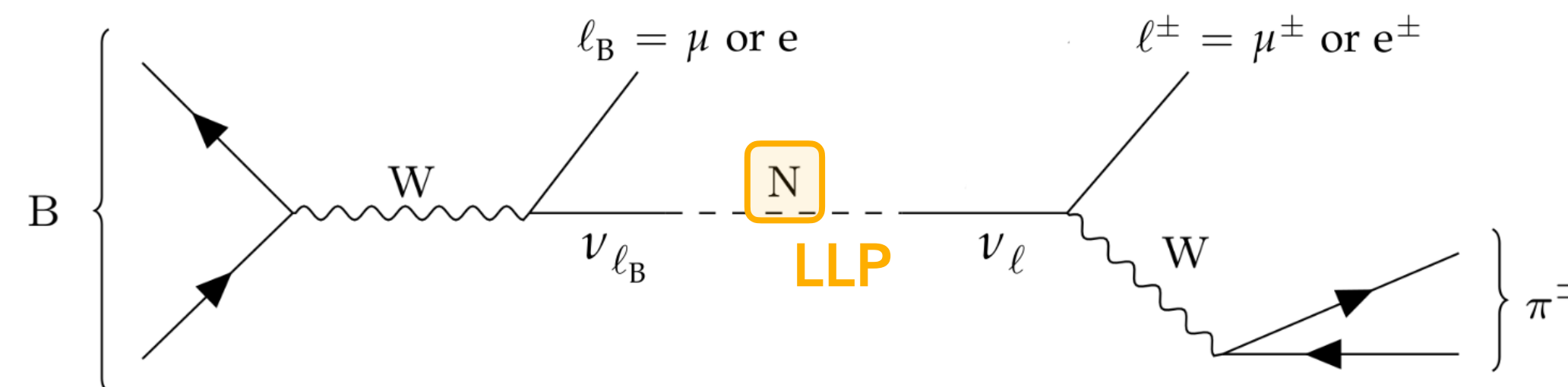
- parameterised Neural Network to enhance sensitivity

  - leptons, tracks, and DV properties e.g. **tracks transverse displacement** (d_{xy})
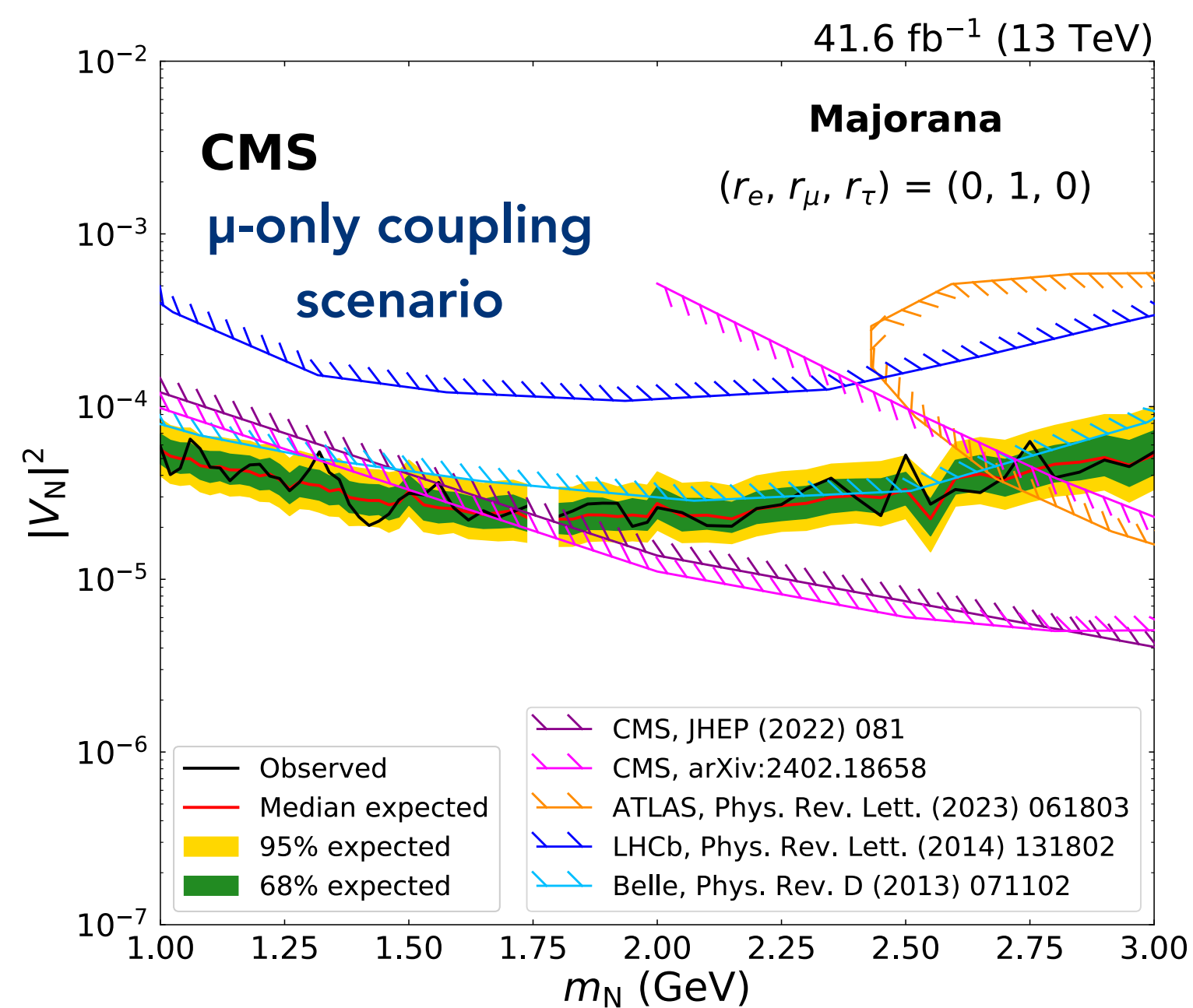
- training with signal MC & a subset of data
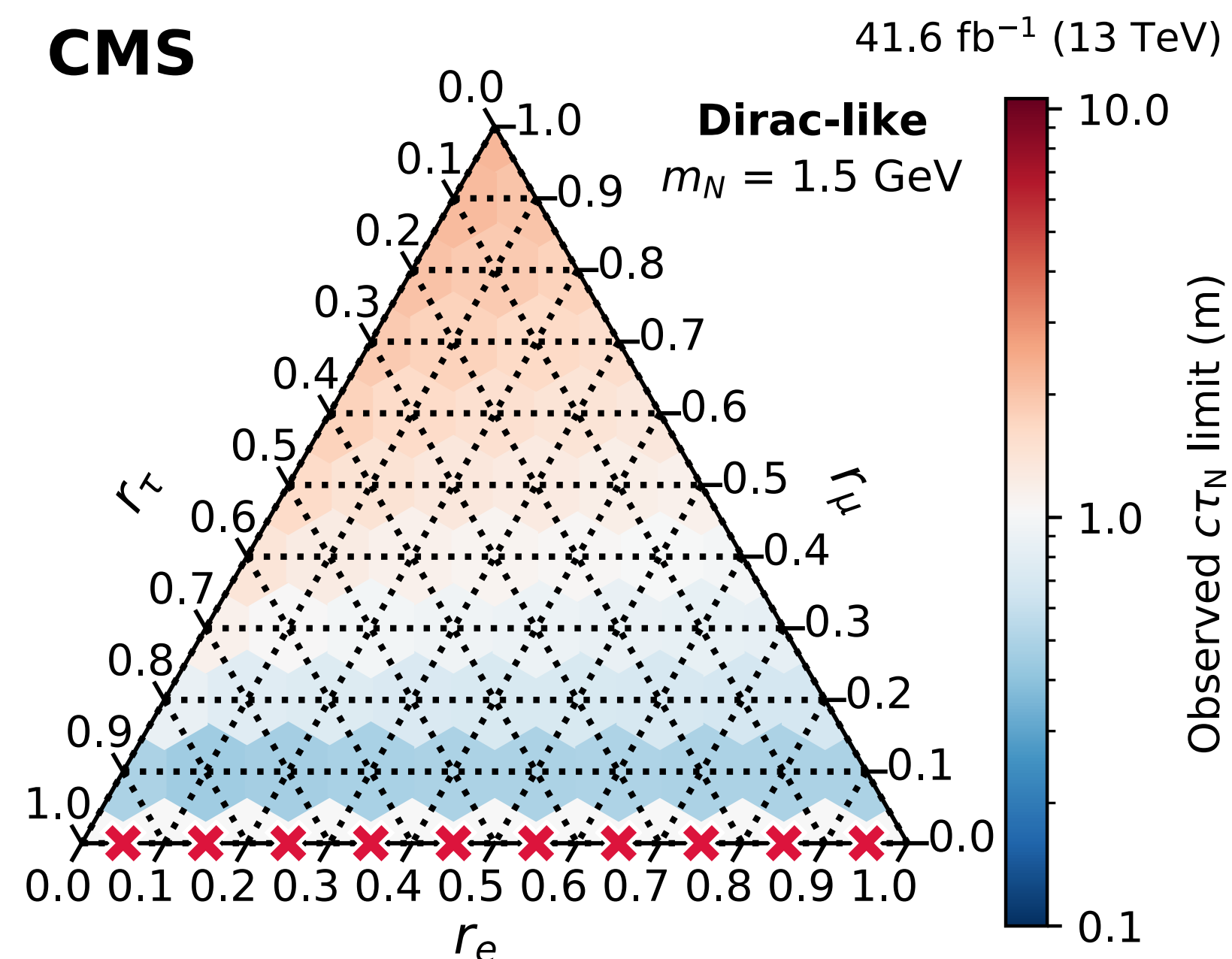
Search for HNLs in B-meson decays at
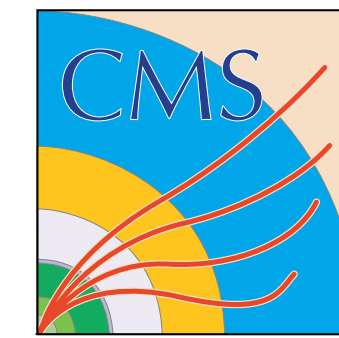
- bump-hunt in 24 mutual exclusive categories
  - (μμ, μe, eμ) channels **x** transverse displacement of the DV **x** DV invariant mass
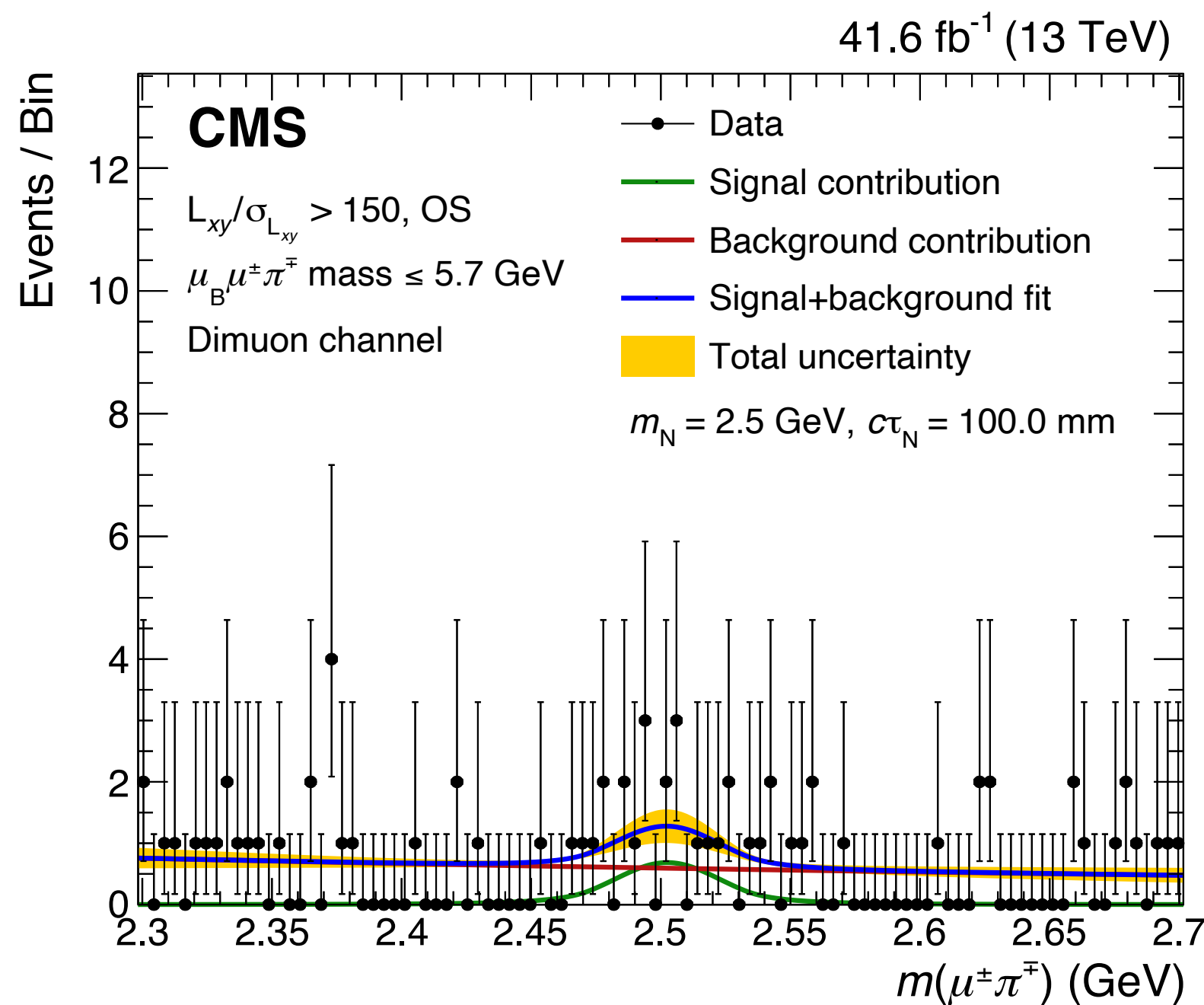

Discriminant variable: **DV mass**

Best sensitivity for HNL masses
below 1.75 GeV

Results interpretation in **multiple scenarios** of HNL nature & coupling to SM

Search for massive charged LLPs

- signature of many new physics models at LHC energies; key characteristic: **high p_T isolated track** with

  - **large ionization (dE/dx)** measured in the pixel detector

  - **long time of flight (ToF)** measured with the calorimeter or muon chambers

- observable: particle mass, from β and track p_T measurements
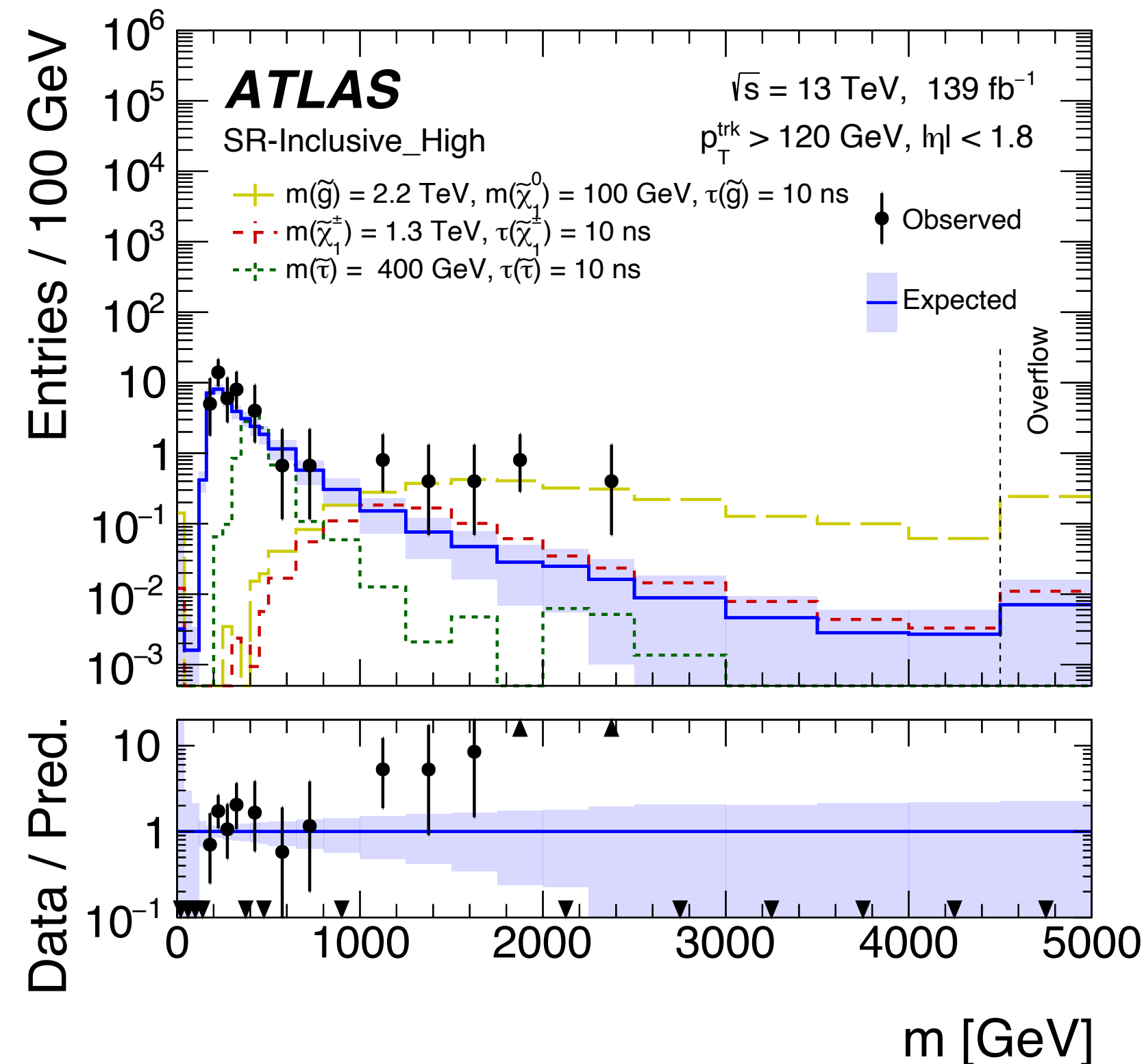
Previously found 3.3σ excess by ATLAS

(JHEP 06 (2023) 158)
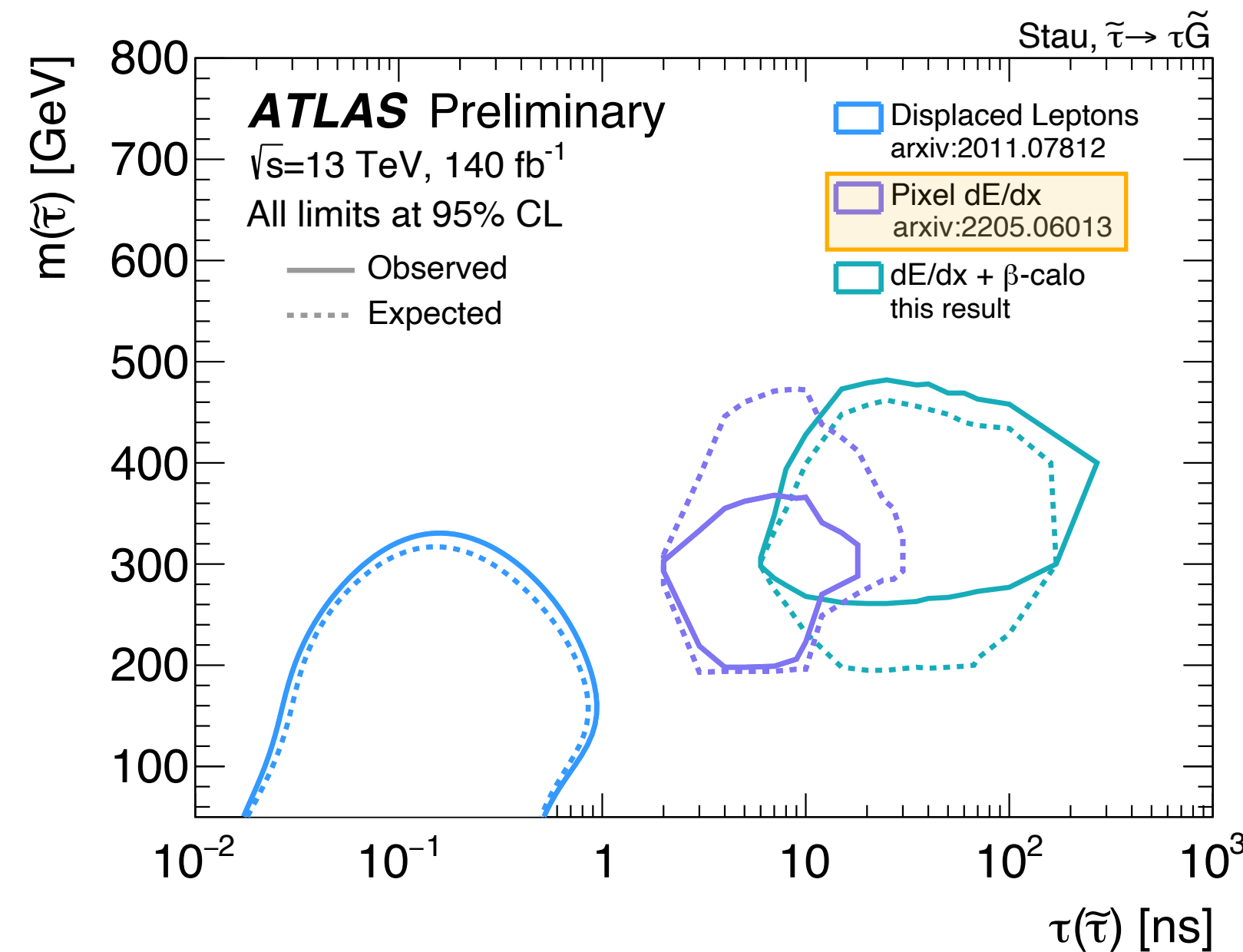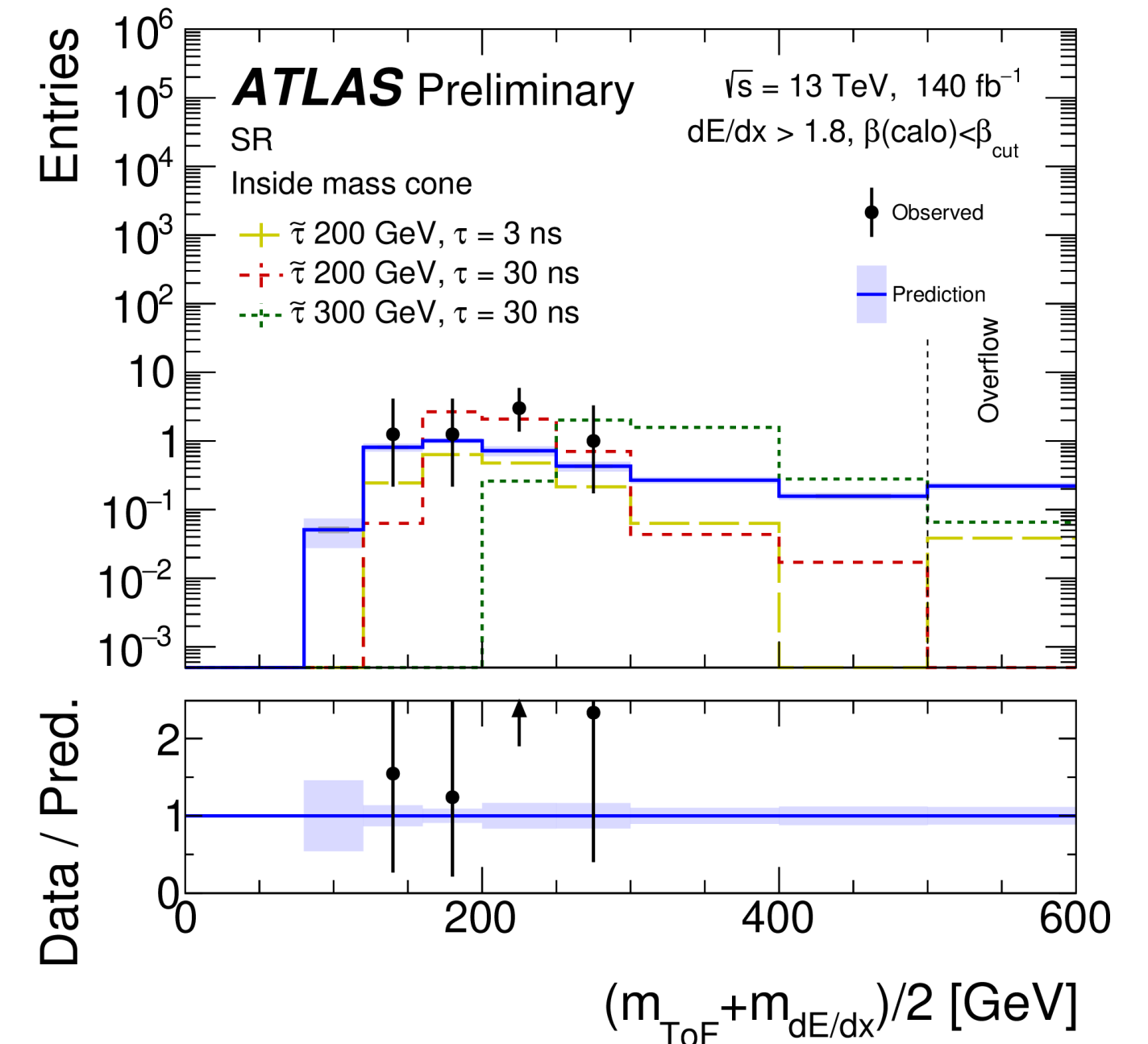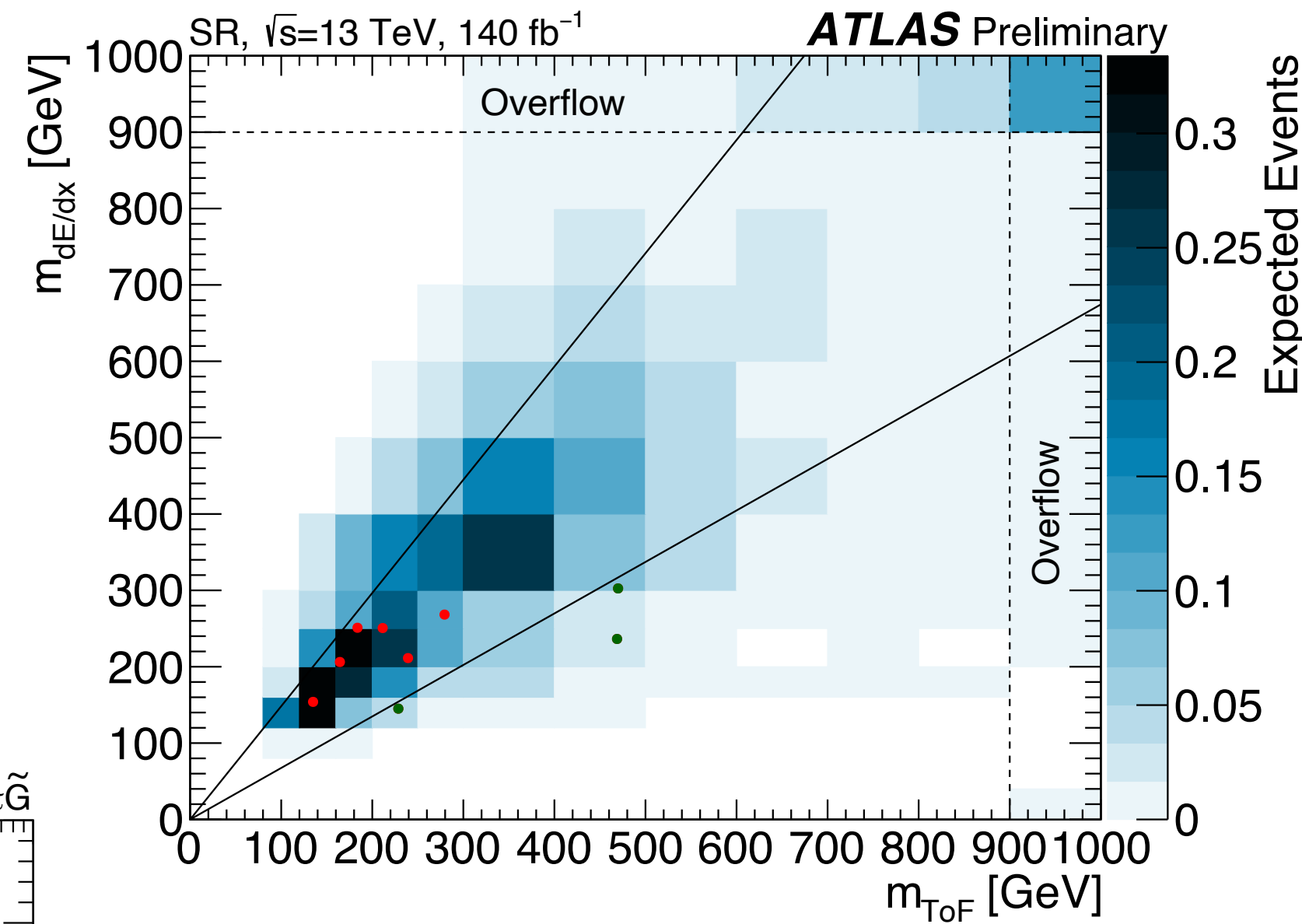
- 0.4 ± 0.7 events predicted, **7 observed**

- events compatible with β ≃ 1 & being

  reconstructed as muons

# Search for massive charged LLPs in ATLAS EXPERIMENT

- followup analysis

- mass calculated with p_T of the track +

  - **dE/dx** in pixel detector *and*

  - **ToF** measurement in calorimeter

- analysis selection defined using

  both measurements

- bkg predictions obtained in a data-driven way

- no significant excess observed, derived limits on simplified

  LLP models

Complementary exclusion contours with
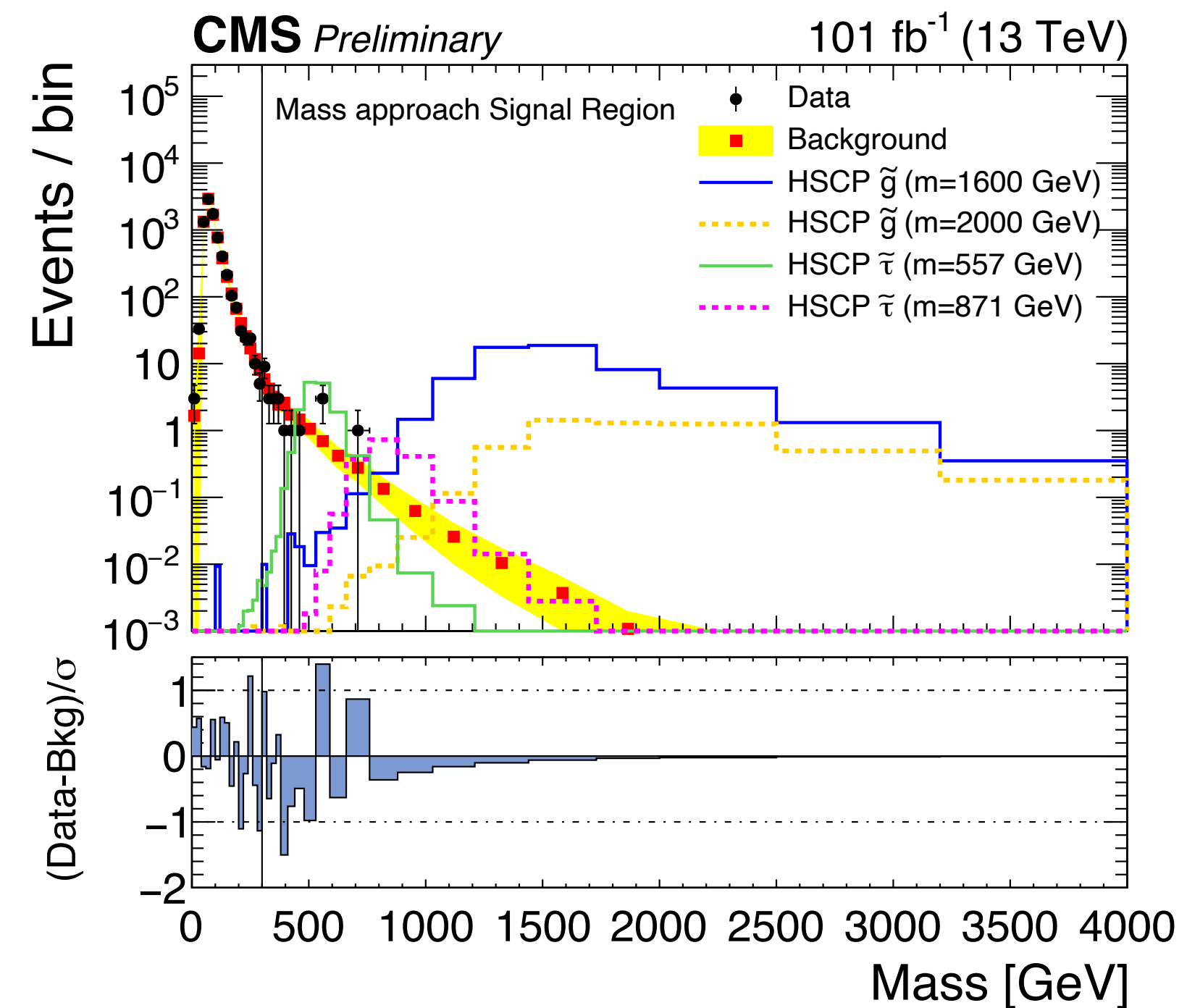**previous search** for long-lived staus

Search for massive charged LLPs in
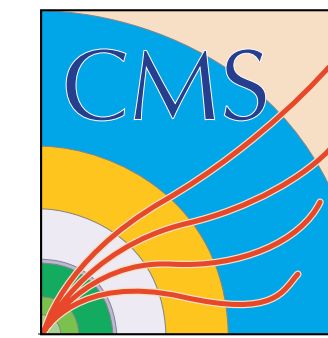
- search for 1 isolated high pT muon with large ionisation & missing energy
  - **dE/dx measured separately in pixel & strips detector** allowing background suppression
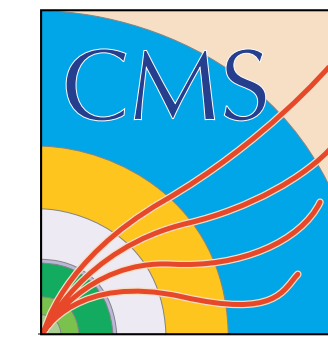- two search methods:

dE/dx measurement
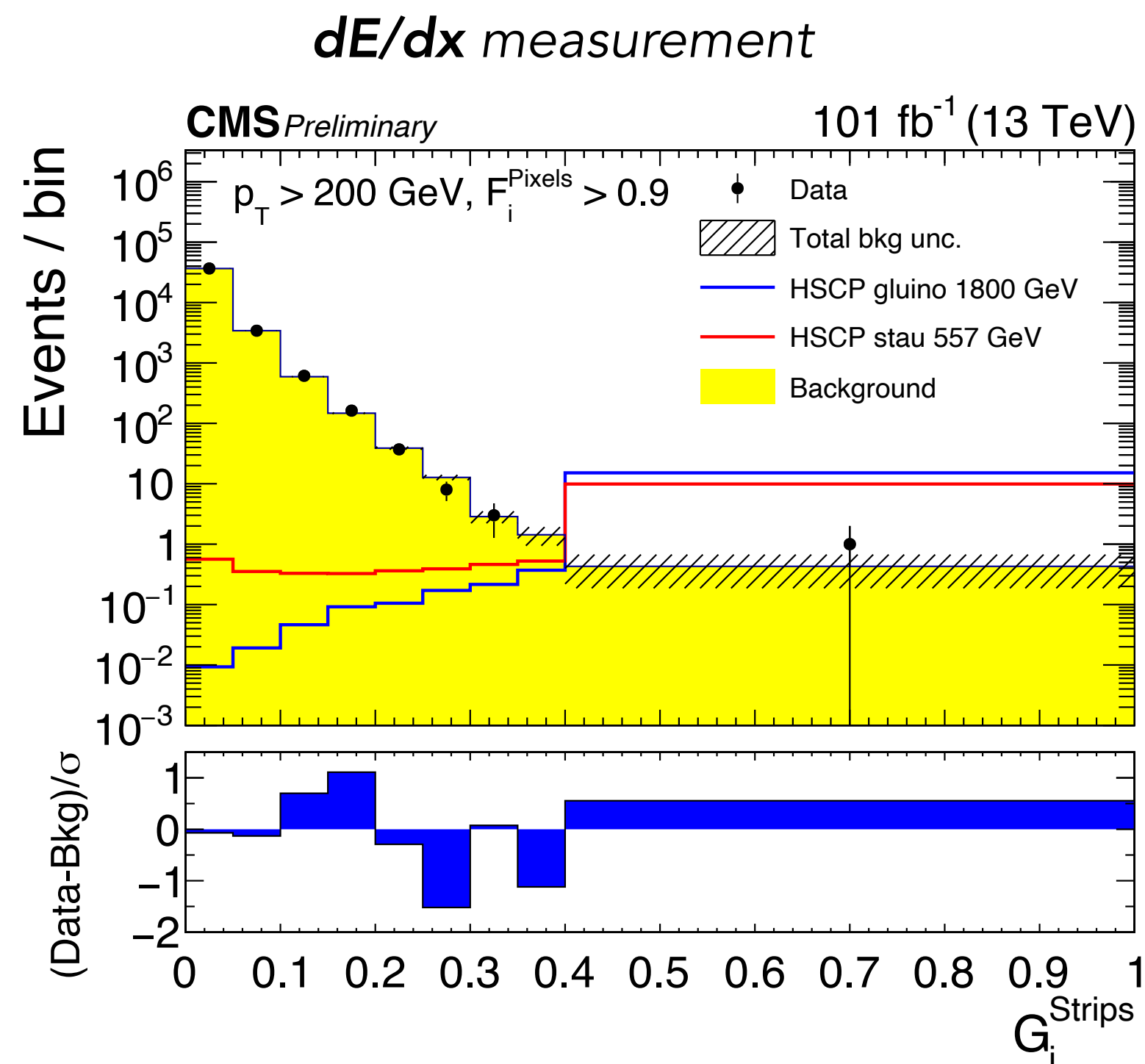
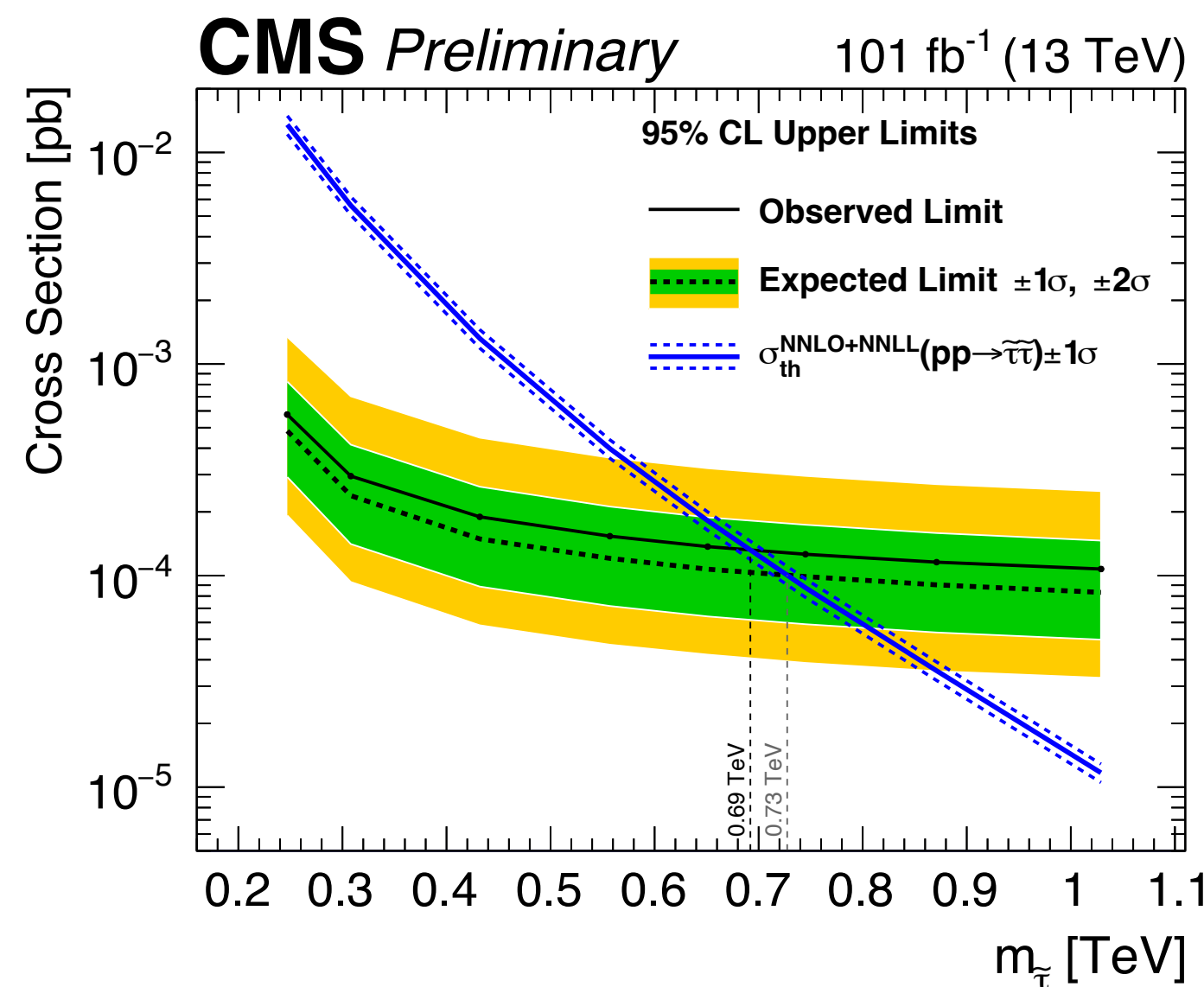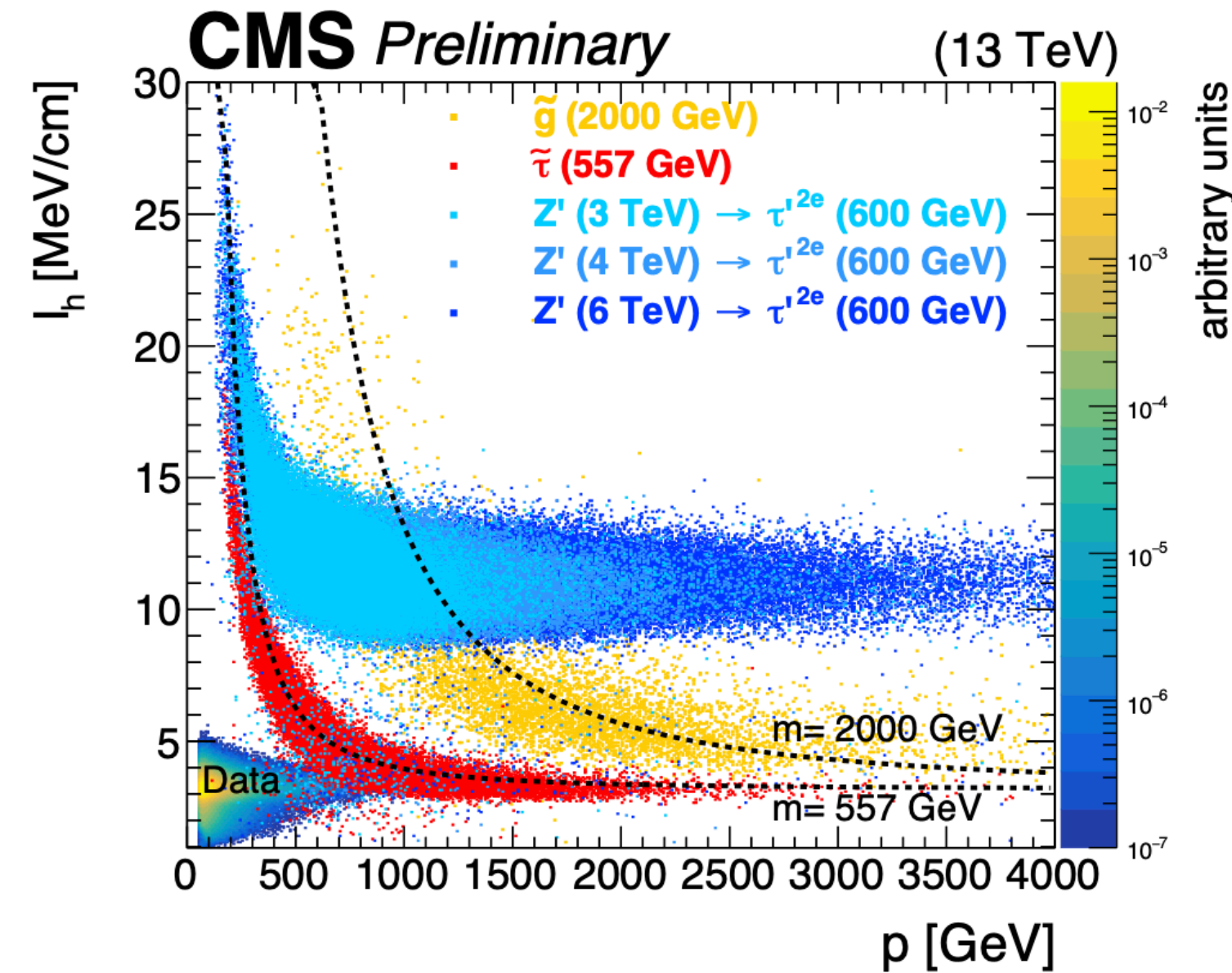**mass method**: from ionization variable + track p_T

- 60-80% overlap of events in the SR between the two approaches
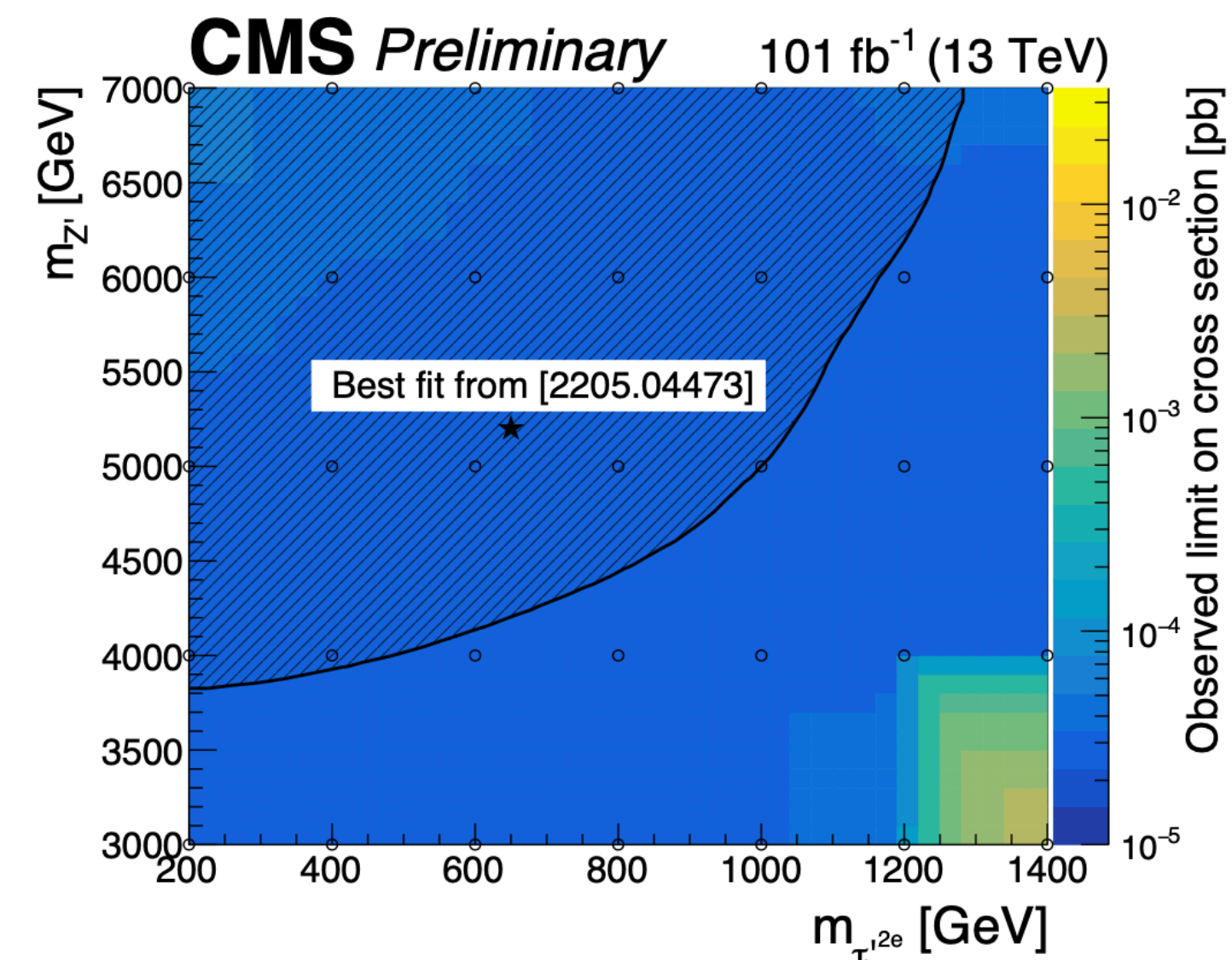- similar sensitivity to new physics models

Search for massive charged LLPs in
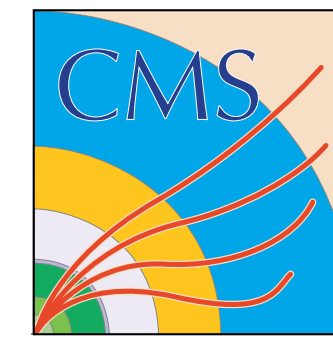
- no data excess found

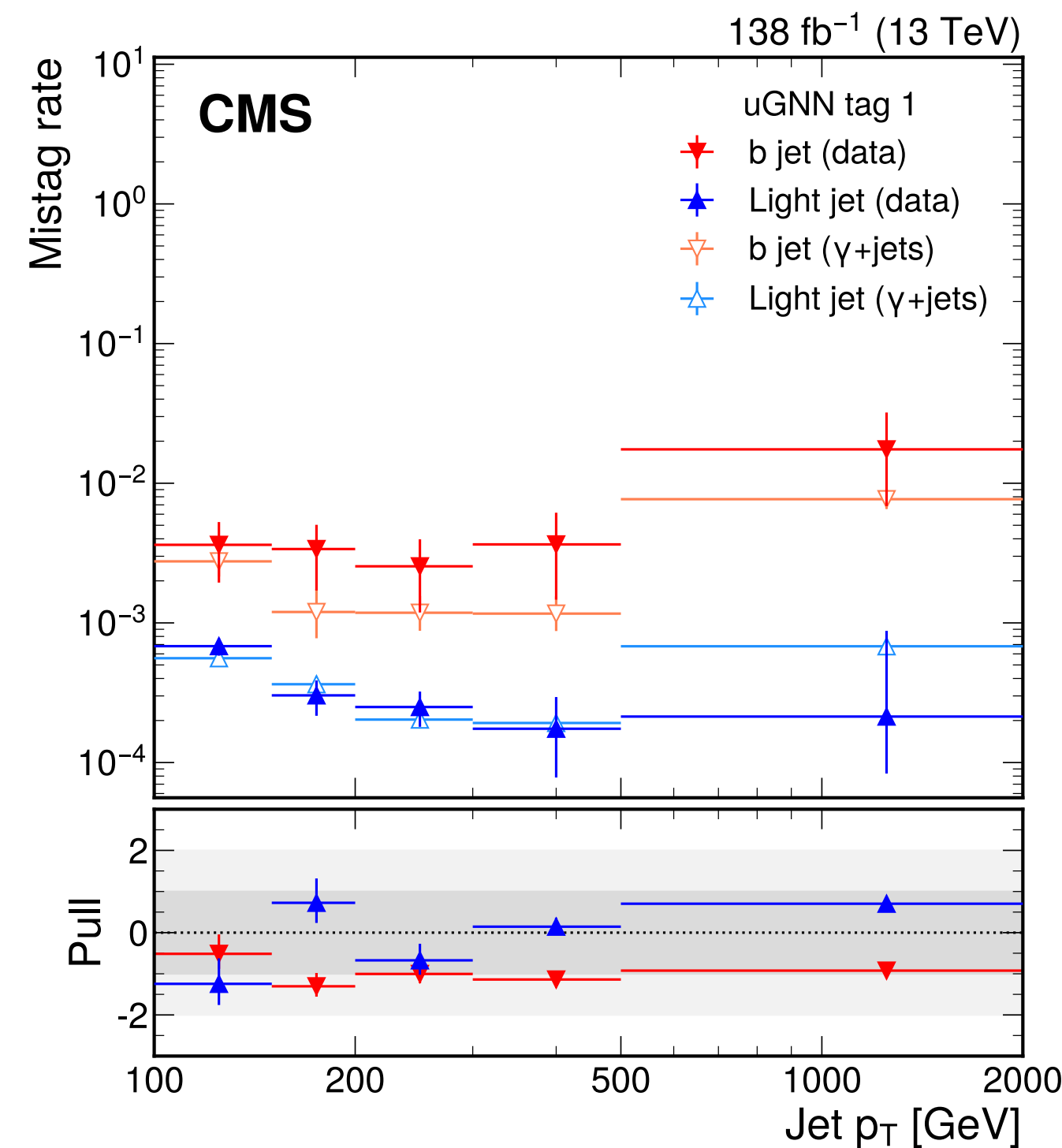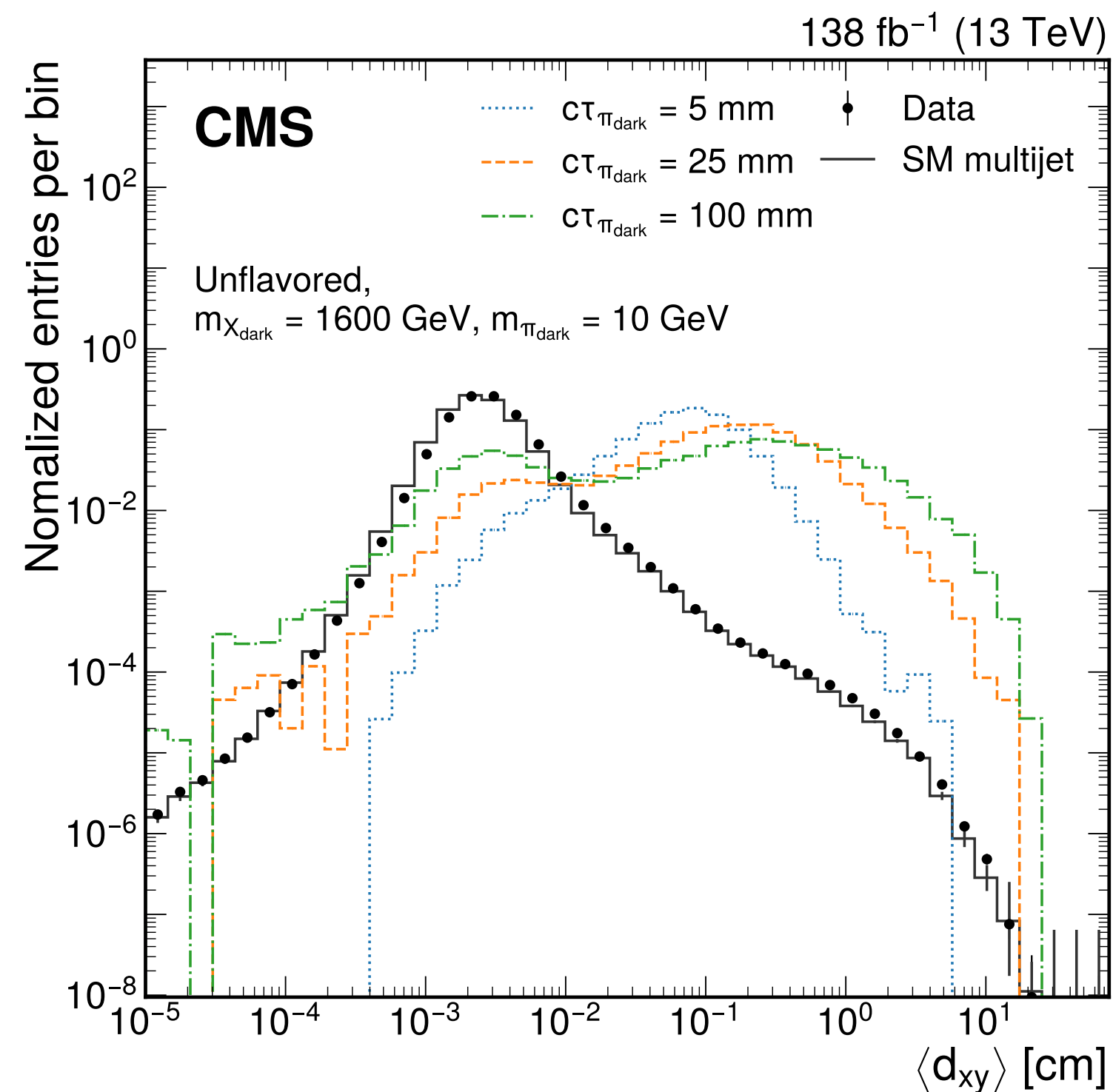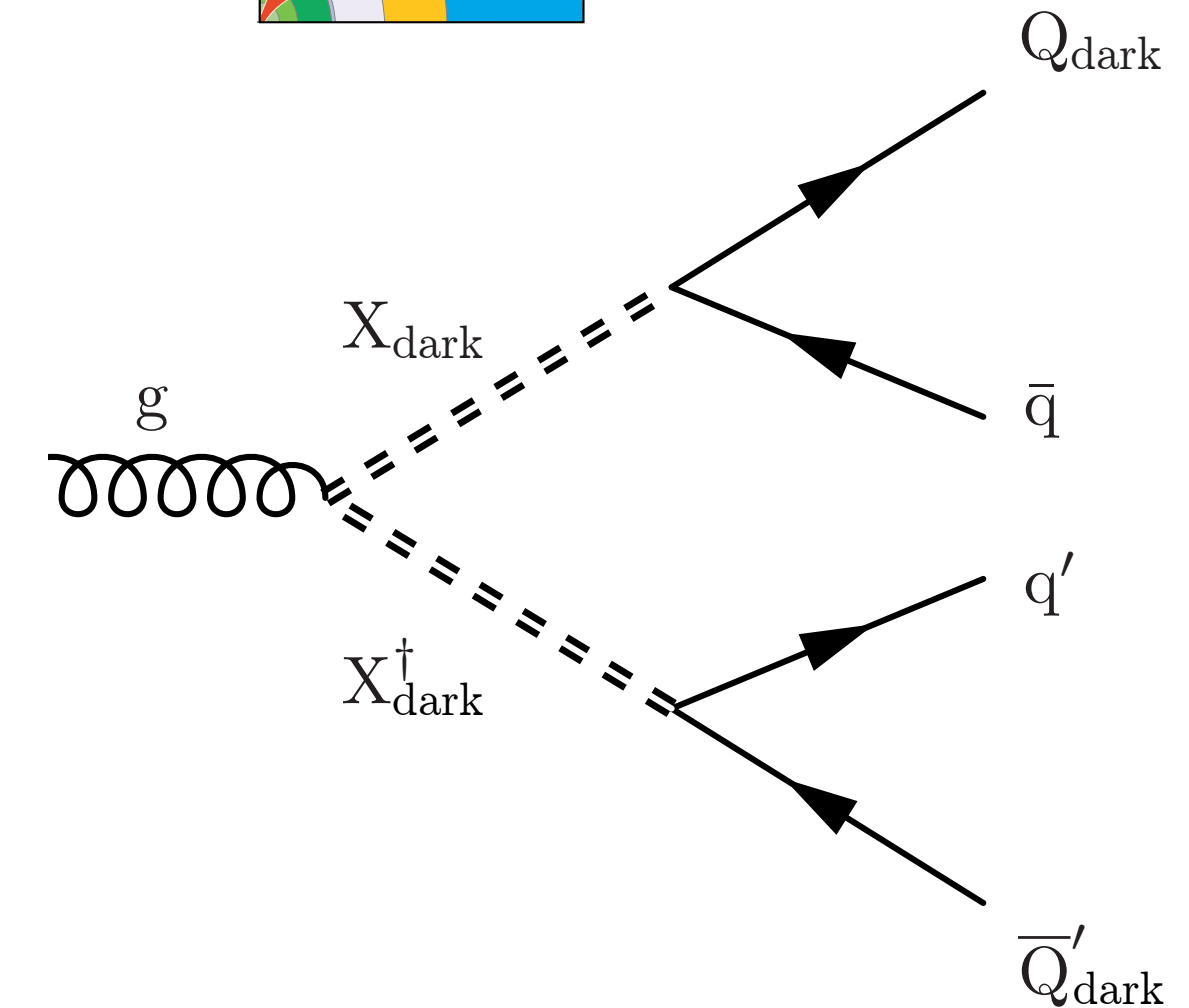- limits set on various models

Simplified stau model

*Z' model proposed to explain ATLAS excess*

Search for emerging jets at CMS

- pair production of scalars - X_{dark} - coupled to SM & dark sector

  - dark quark (Q_d) hadronisation → **long-lived dark mesons** producing *Emerging Jets*

- signature: **≥ 4 jets, large transverse momentum (HT), 2 jets tagged as Emerging Jets**

138 fb^{-1} (13 TeV)

CMS

$c\tau_{\pi_{dark}}$ = 5 mm   • Data
$c\tau_{\pi_{dark}}$ = 25 mm   — SM multijet
$c\tau_{\pi_{dark}}$ = 100 mm

Unflavored,
$m_{X_{dark}}$ = 1600 GeV, $m_{\pi_{dark}}$ = 10 GeV

Nomalized entries per bin

$\langle d_{xy} \rangle$ [cm]

138 fb^{-1} (13 TeV)

CMS

uGNN tag 1
b jet (data)
Light jet (data)
b jet (γ+jets)
Light jet (γ+jets)

Mistag rate

Pull

Jet p_T [GeV]

- **model-agnostic approach**:

  - tag EJ based on displaced tracks in jets

- **model-dependent approach**:

  - GNN to discriminate SM- & signal-like jets

- data-driven bkg estimate based on EJ mis-tag

Search for emerging jets at CMS
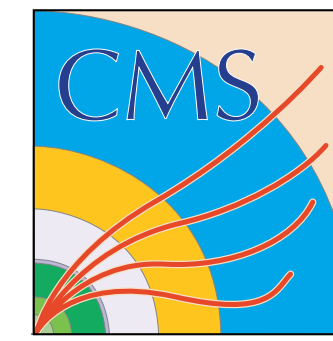
- exploring dark pion masses in [6,20] GeV range, dark scalar masses in [1,2.5] TeV
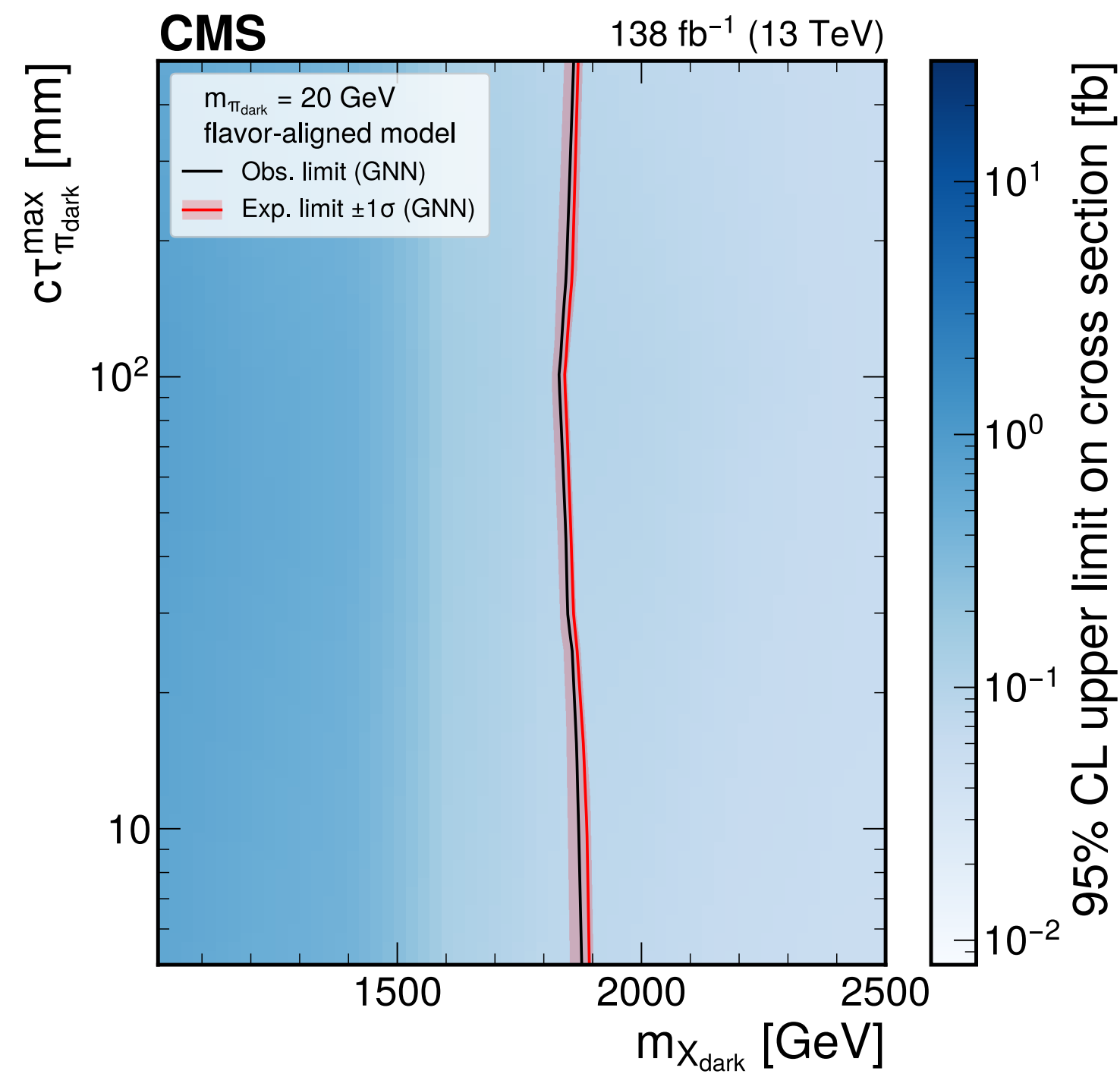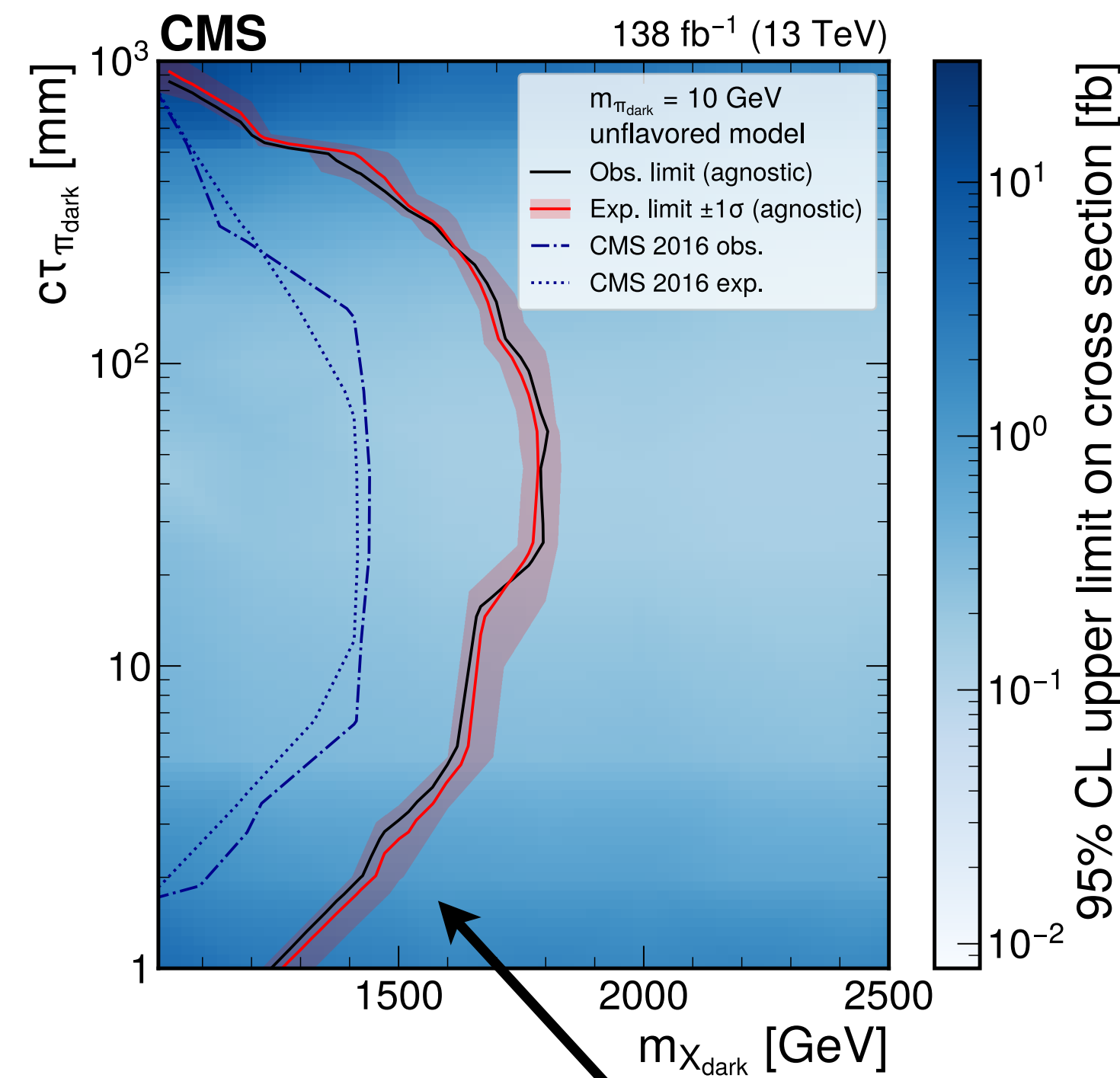
Flavor-aligned model

Unflavored model

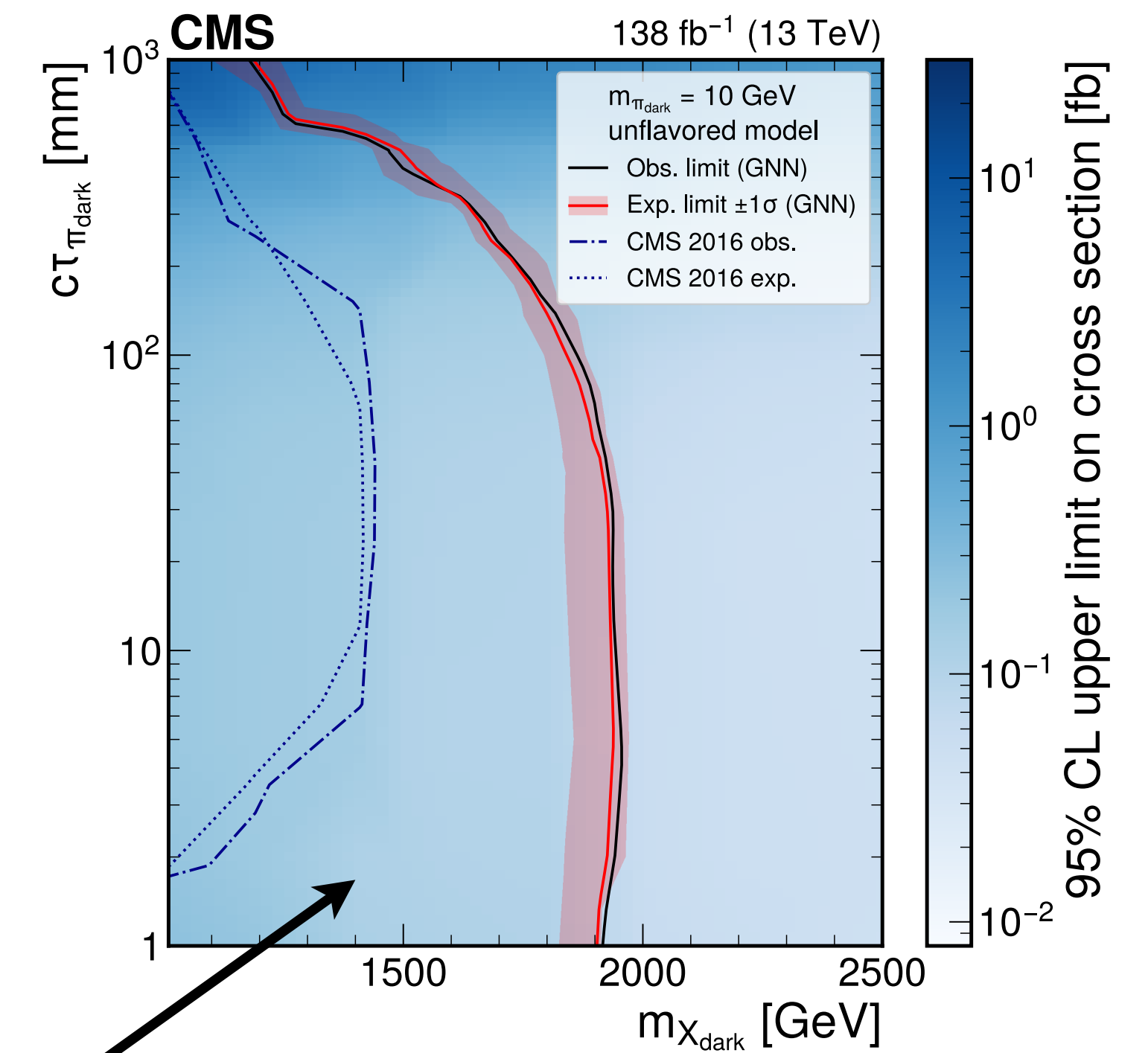**GNN** approach

Model-independent approach

GNN approach

First limits on this scenario

GNN-tagger keeps **high signal acceptance for low** $c\tau$

Summary

Searches for long-lived particles at LHC provides **unique challenges** for the experiments.

Development of **new triggers**, **innovative analysis methods** & **powerful NN discriminants** help in pushing the sensitivity.

Exciting times ahead with the Run 3 dataset **quickly growing!**

A selection of results from ATLAS, CMS and FASER has been presented, more details in the parallel sessions.

Additional material

FASER event display