Reinterpretation of CMS search for LLPs using endcap muon detectors

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(Re)interpreting the results of new physics searches at the LHC

12/15/2022

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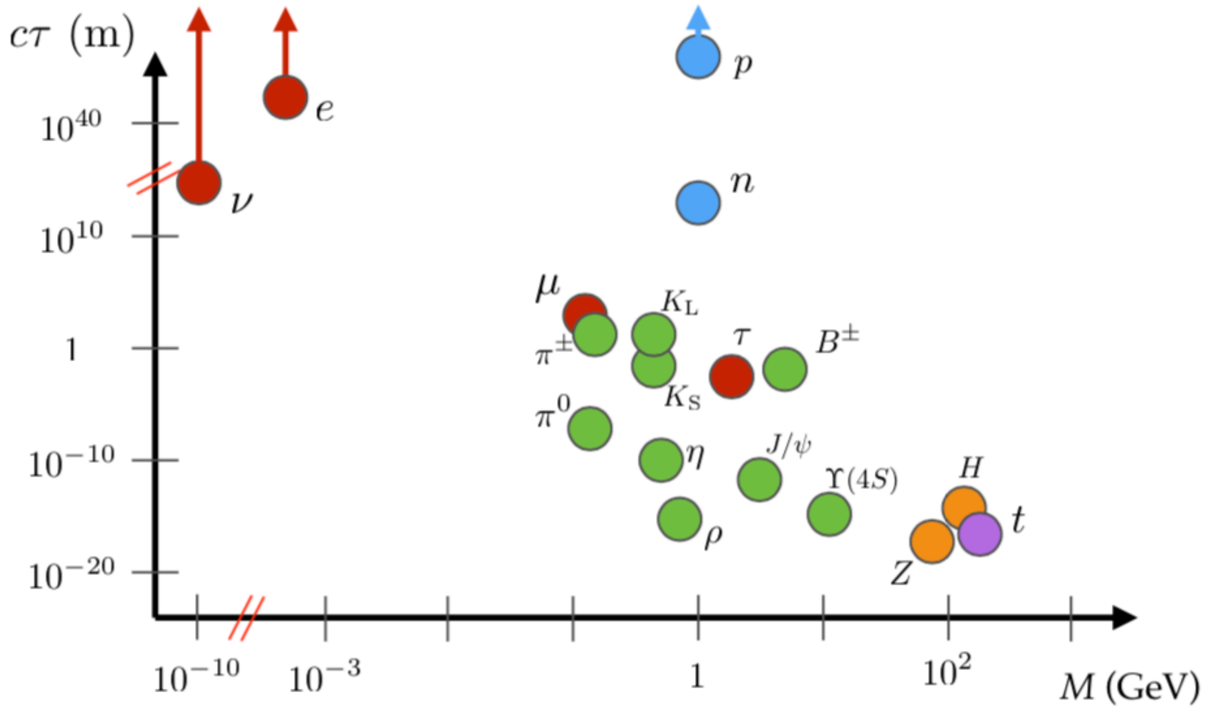
Caltech

Long-Lived Particles



$m \ll \Lambda$: Scale suppression

$$\tau^{-1} = \Gamma \sim y^2 (\frac{m}{\Lambda})^n \Phi$$

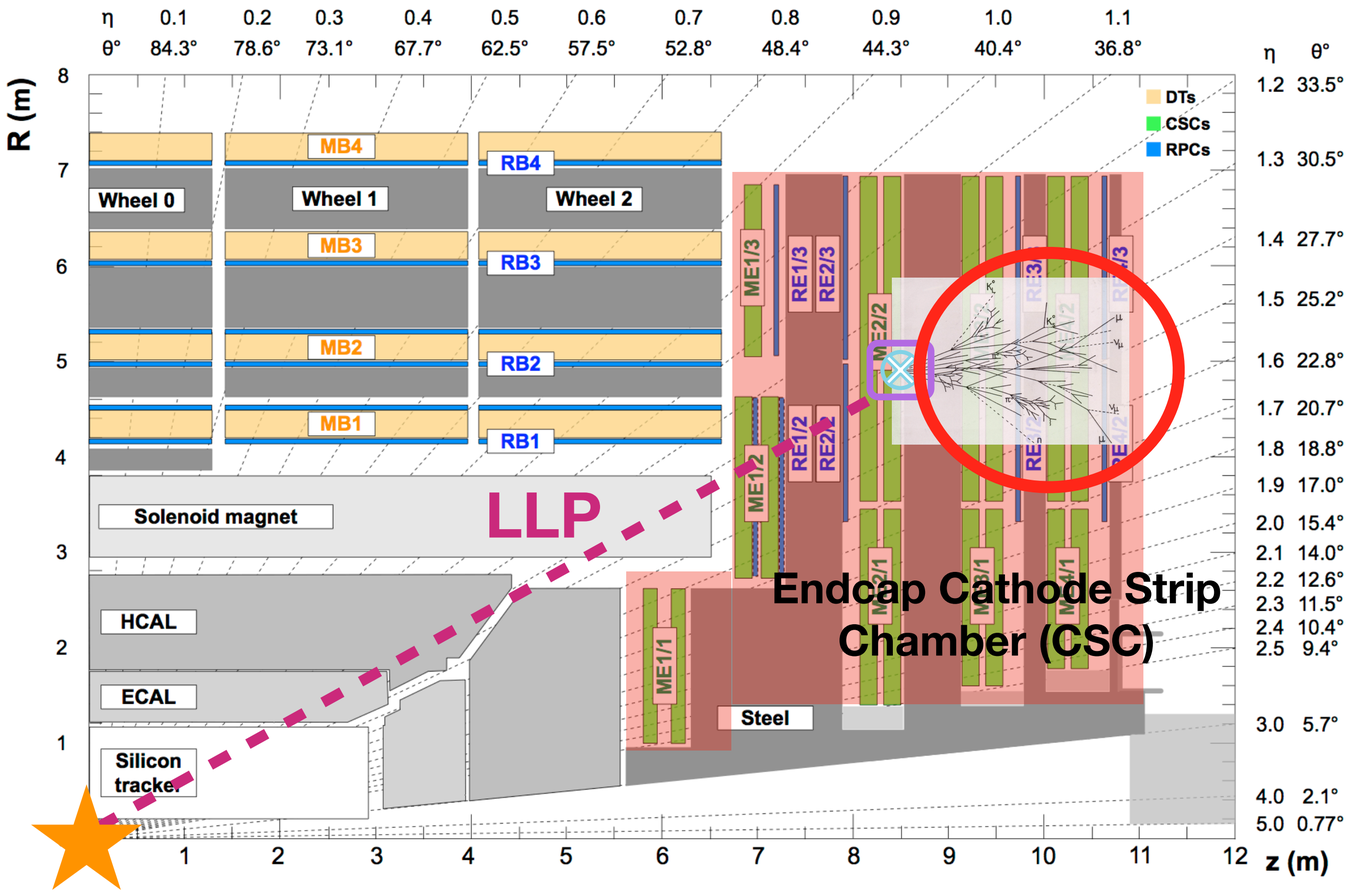
Small coupling

Small phase space

- Long-lived particles are common in SM as well as BSM theories
- Well motivated and predicted in many BSM models: SUSY, Heavy neutral leptons, Higgs portals …

Recent CMS Result: Muon System as a Sampling Calorimeter for LLPs

(Phys. Rev. Lett. 127, 261804)

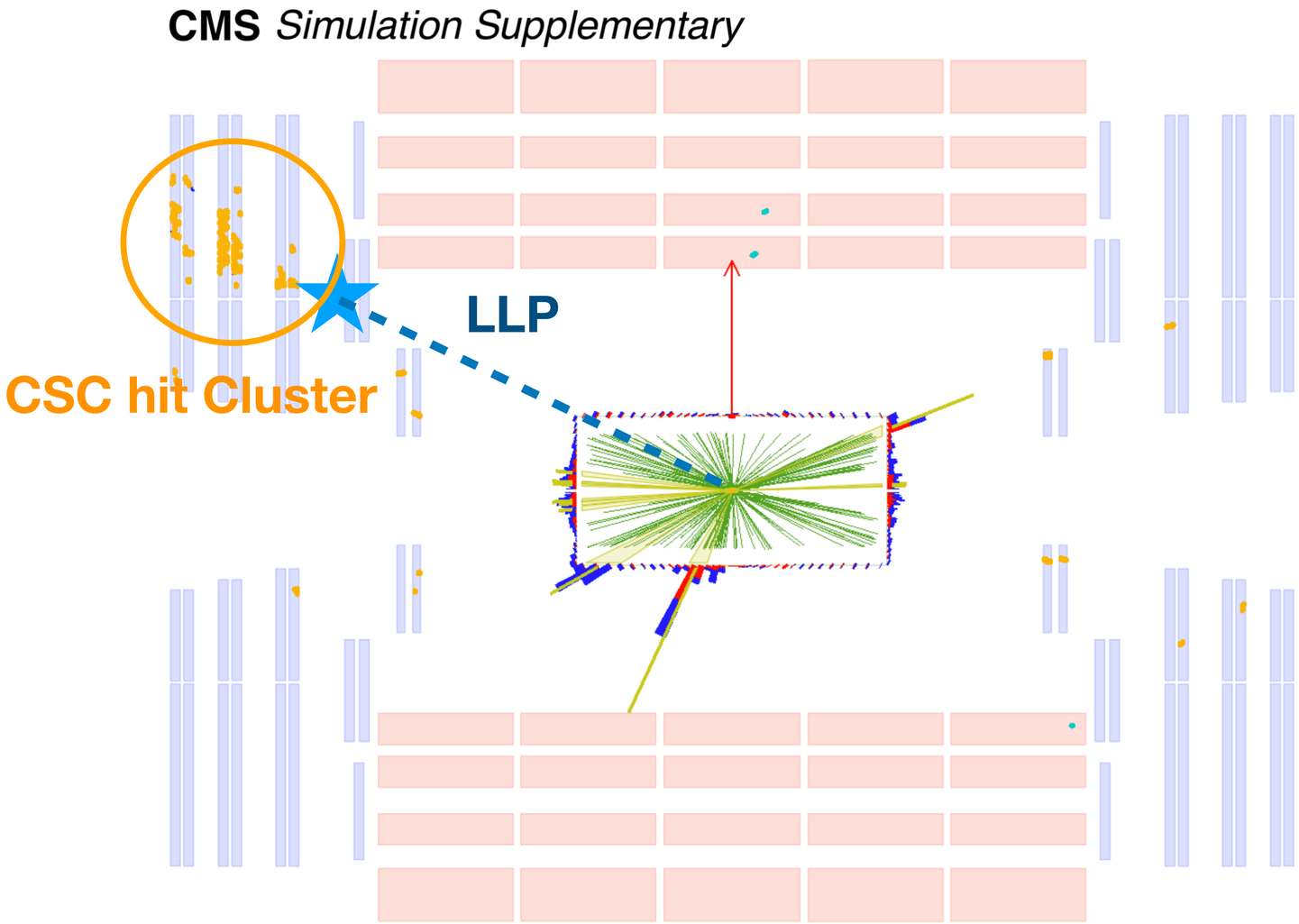


LLP decay and resulting particle shower is detected with a **large hit multiplicity**

- Excellent **background suppression** from shielding material
- Steel interleaved with active chambers → **sampling calorimeter**

Experimental Signature: Displaced Showers in the Muon System

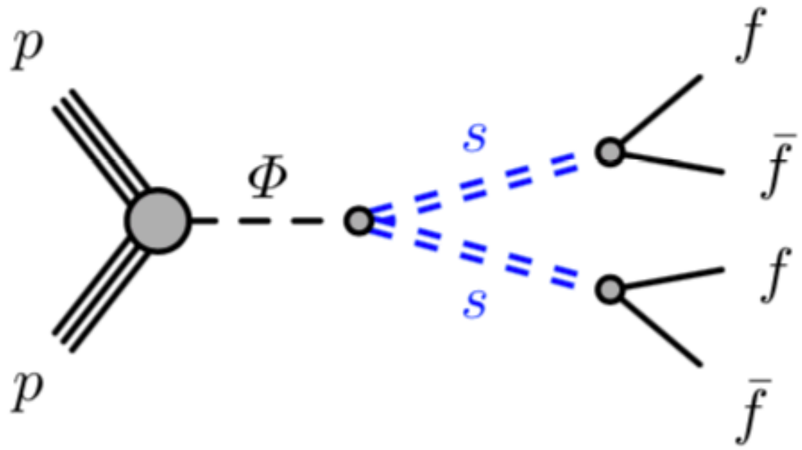
- Large **cluster of CSC hits (>100 hits)** in the muon system with no jets or tracks
- Muon system acts as a **sampling calorimeter:** sensitive to a broad range of decays



CMS Search Result

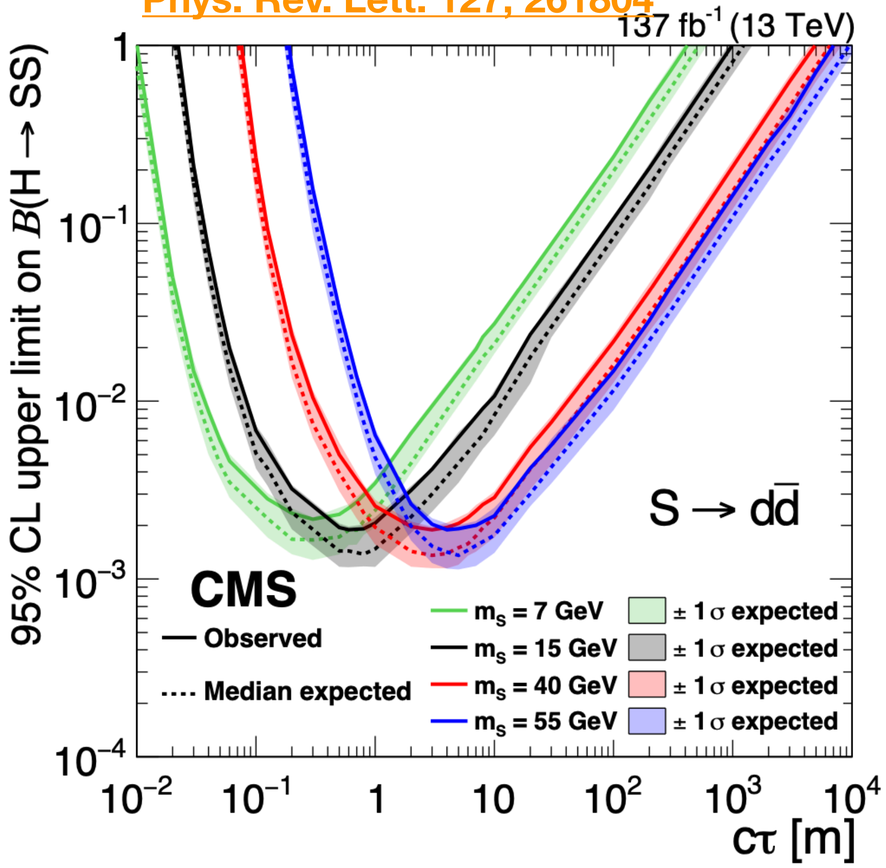
- The CMS paper interpreted the search result in Higgs-portal to scalar LLP
- Along with the CMS result, we released a set of detector response function parameterized using only gen-level LLP information that would allow for recasting of the analysis with other models: https://www.hepdata.net/record/104408

- **3 events observed**
- **2 ±1 background events predicted**



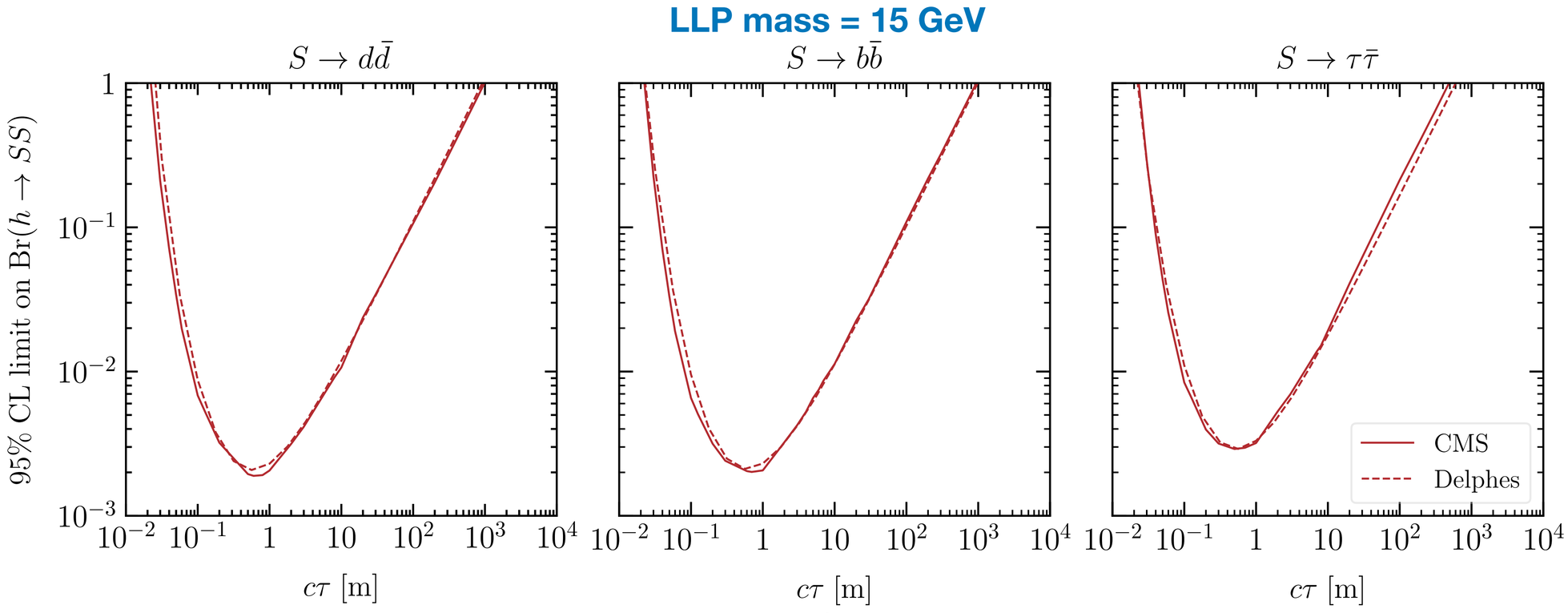
Twin Higgs model as benchmark model

Phys. Rev. Lett. 127, 261804



Delphes Module for Recasting

- Integrated the CSC cluster objects with the detector response functions as official Delphes classes and modules: https://github.com/delphes/delphes/pull/103
  - Validated that we are able to reproduce the limits from CMS for all 3 decay modes to within 30%
- We recasted the CMS analysis in a number of models: dark scalar, dark photon, ALPs, inelastic DM, hidden valley models, and HNL
  - Will focus on dark scalar, hidden valley, and HNL today
- We also invite everyone to use the new Delphes module for CSC clusters to reinterpret the analysis for any other model that predicts LLPs!
  - GMSB, RPV, split SUSY, milli-charged particles, charged LLP (stau) …



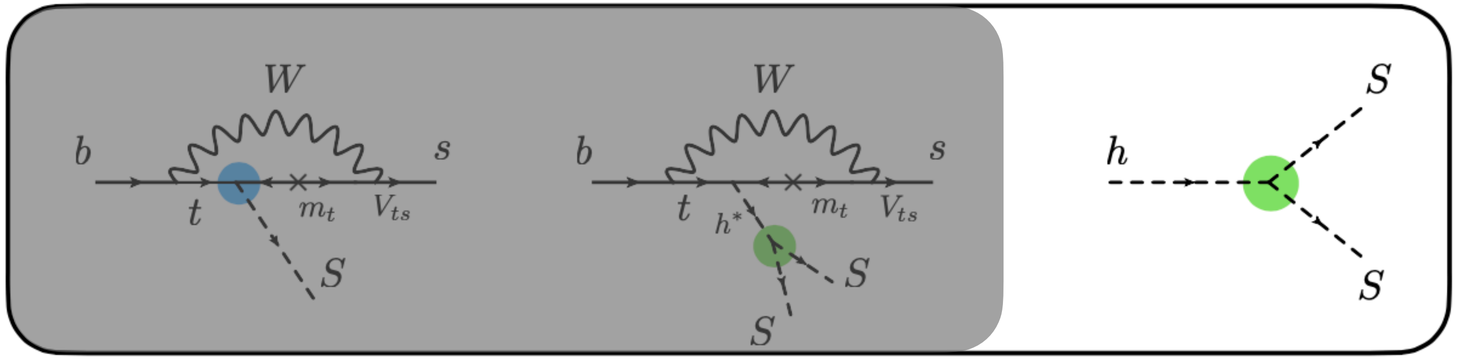
Light Scalar Model

$$\mathcal{L}_{SH} = \mathcal{L}_{\rm SM} + \overbrace{\frac{1}{2}\partial_\mu \hat{S}\,\partial^\mu \hat{S} - \frac{\mu_S^2}{2}\hat{S}^2}^{\mathcal{L}_{\rm DS}} - \overbrace{\left(A_{HS}\,\hat{S} + \lambda_{HS}\,\hat{S}^2\right)\hat{H}^\dagger \hat{H}}^{\text{Higgs portal}}$$

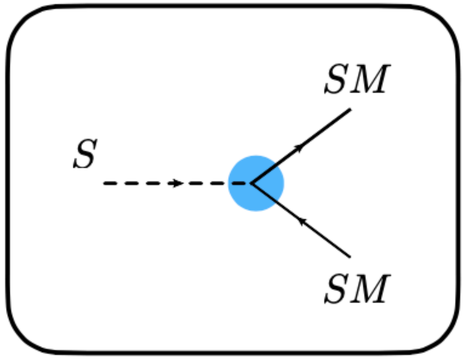
controls the $\hat{H} - \hat{S}$ mixing

controls $Br(H \to SS)$

production



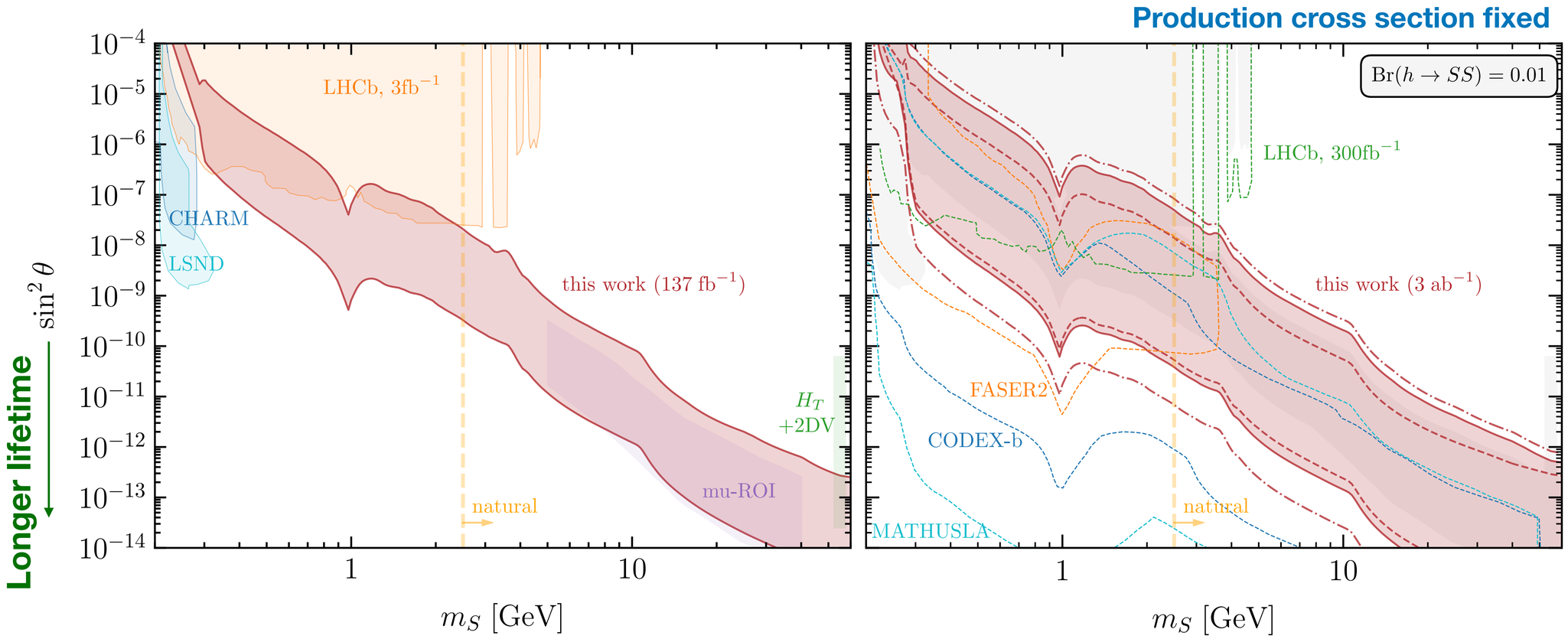
decay



No reach in this analysis
(due to MET > 200 GeV cut)

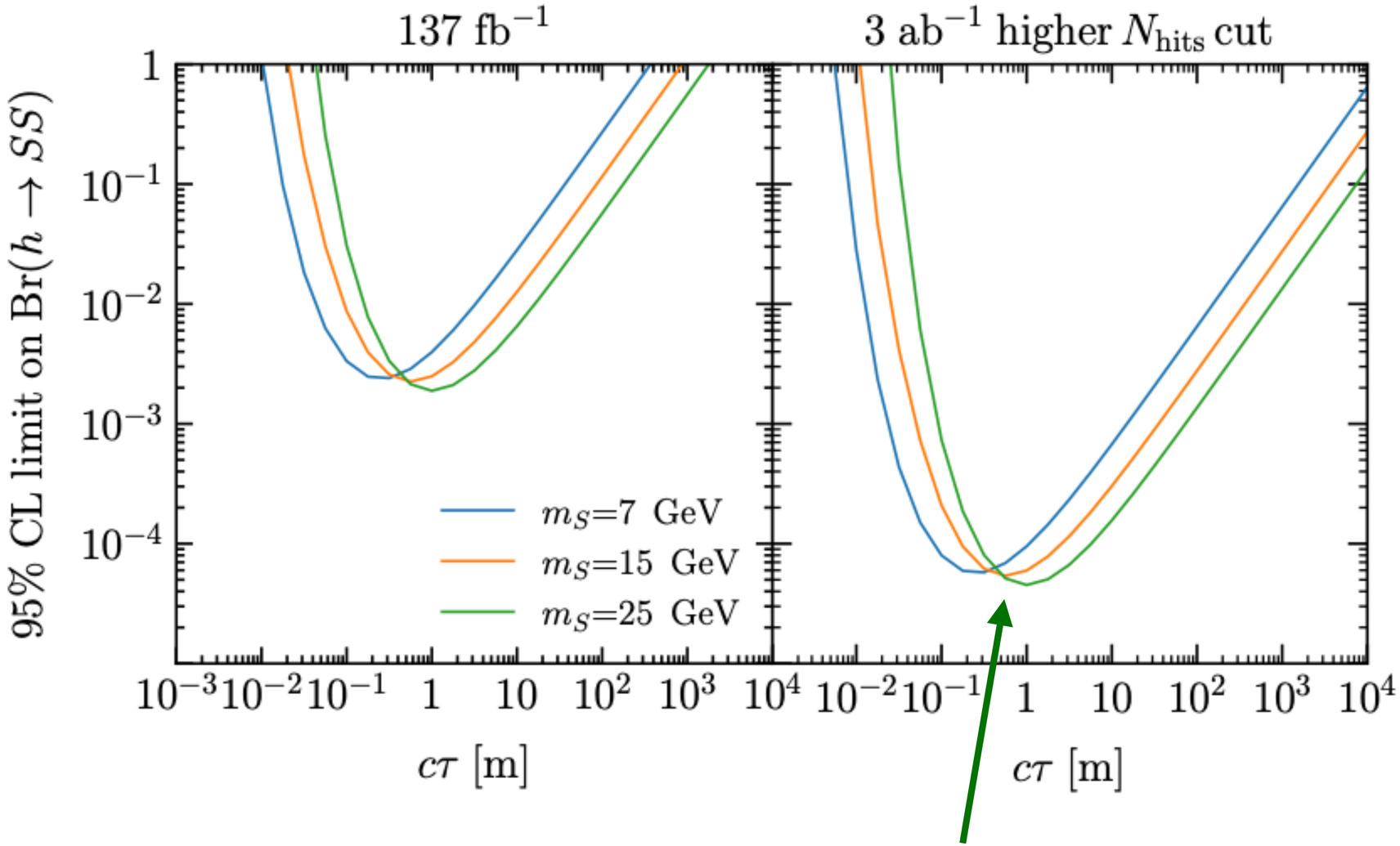
Production and decay channels are decoupled

Light Scalar Reinterpretation



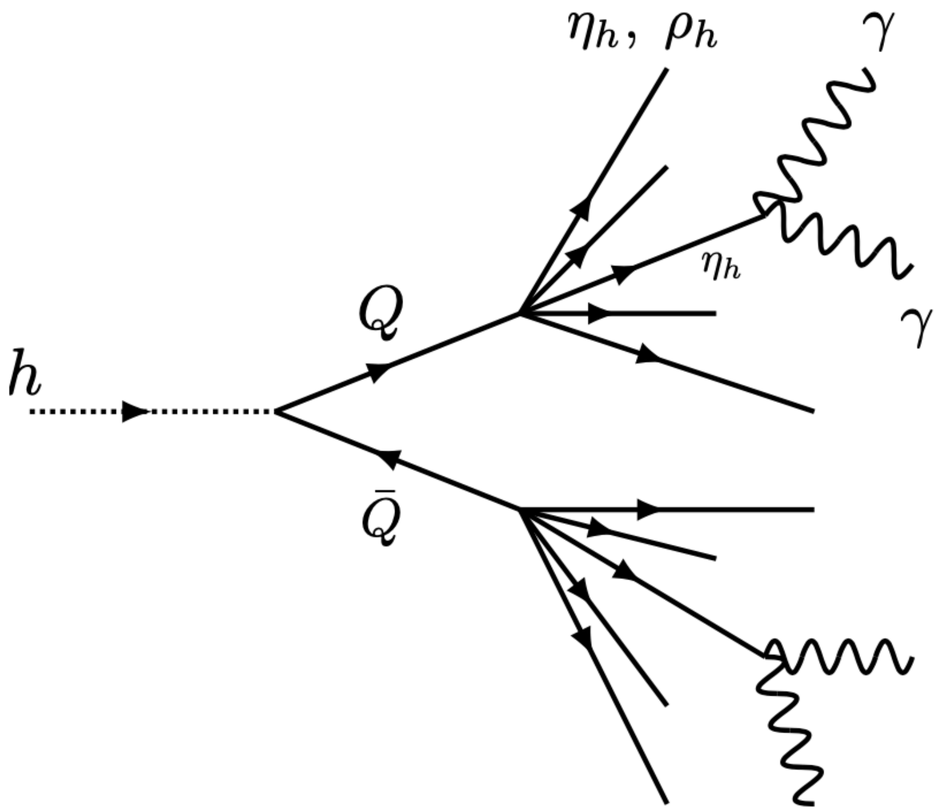
- m_S controls the decay mode and affects the acceptance
- 3 search strategies considered for phase 2:
  - Solid line : same analysis strategy and simply scale the result by luminosity
  - Dot-dashed line: increase N_{hit} cut until 0 bkg is achieved
  - Dotted line: remove MET cut and require 2 CSC clusters

Light Scalar Model



- With Phase 2 Projection, we will be able to reach **BR(h → SS) ~ 5e-5** at lifetime of a few meters, complementary to dedicated LLP experiments that are most sensitive to cτ of 10 - 100 m

Hidden Valley Models

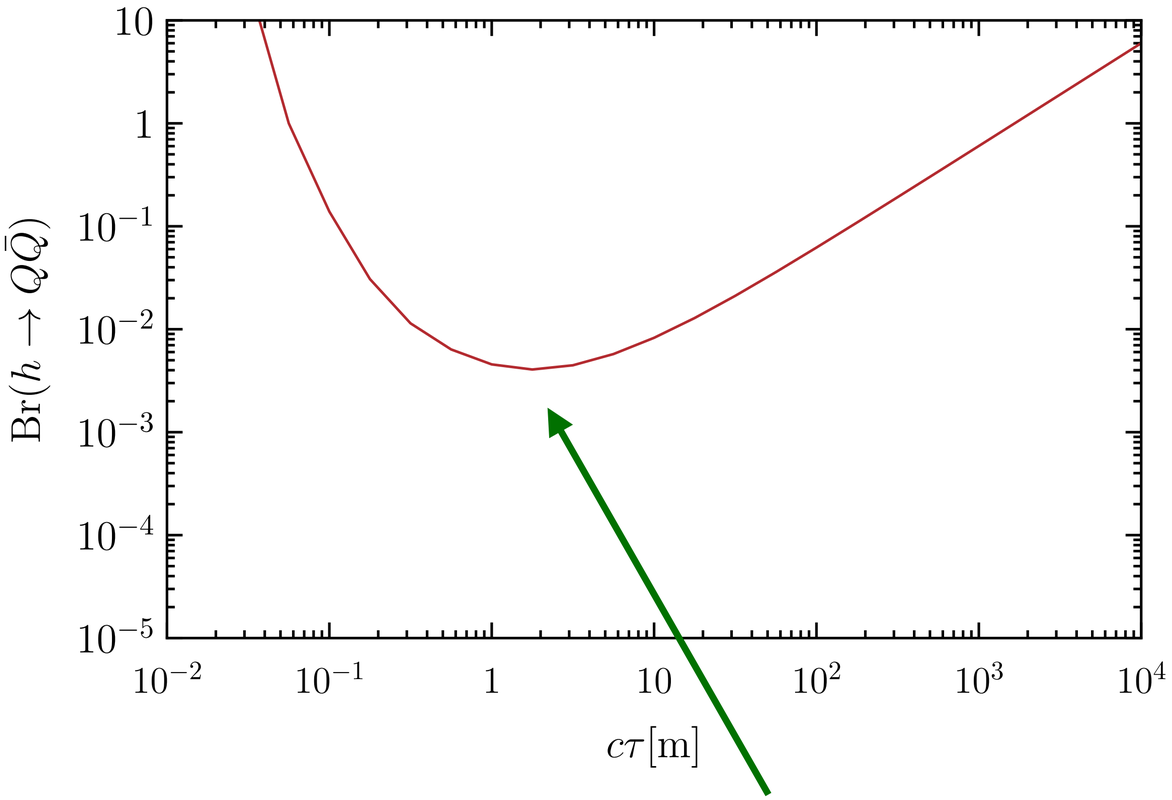


- We assume ρ_h to decay into $\eta_h\eta_h$, targeting high LLP multiplicity
- η_h is the LLP and decays to $\gamma\gamma$ to be conservative and it's hard to probe with other searches

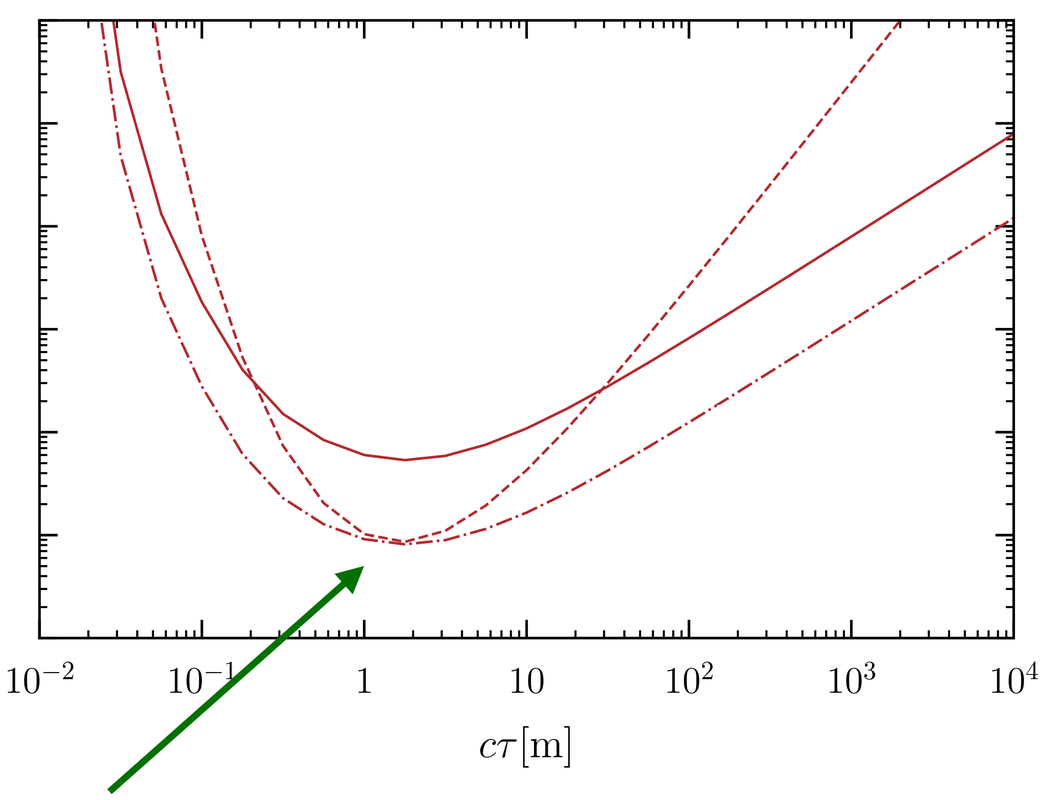
Hidden Valley Reinterpretation

LLP mass = 8 GeV

Run 2 recast (137 fb^{-1})

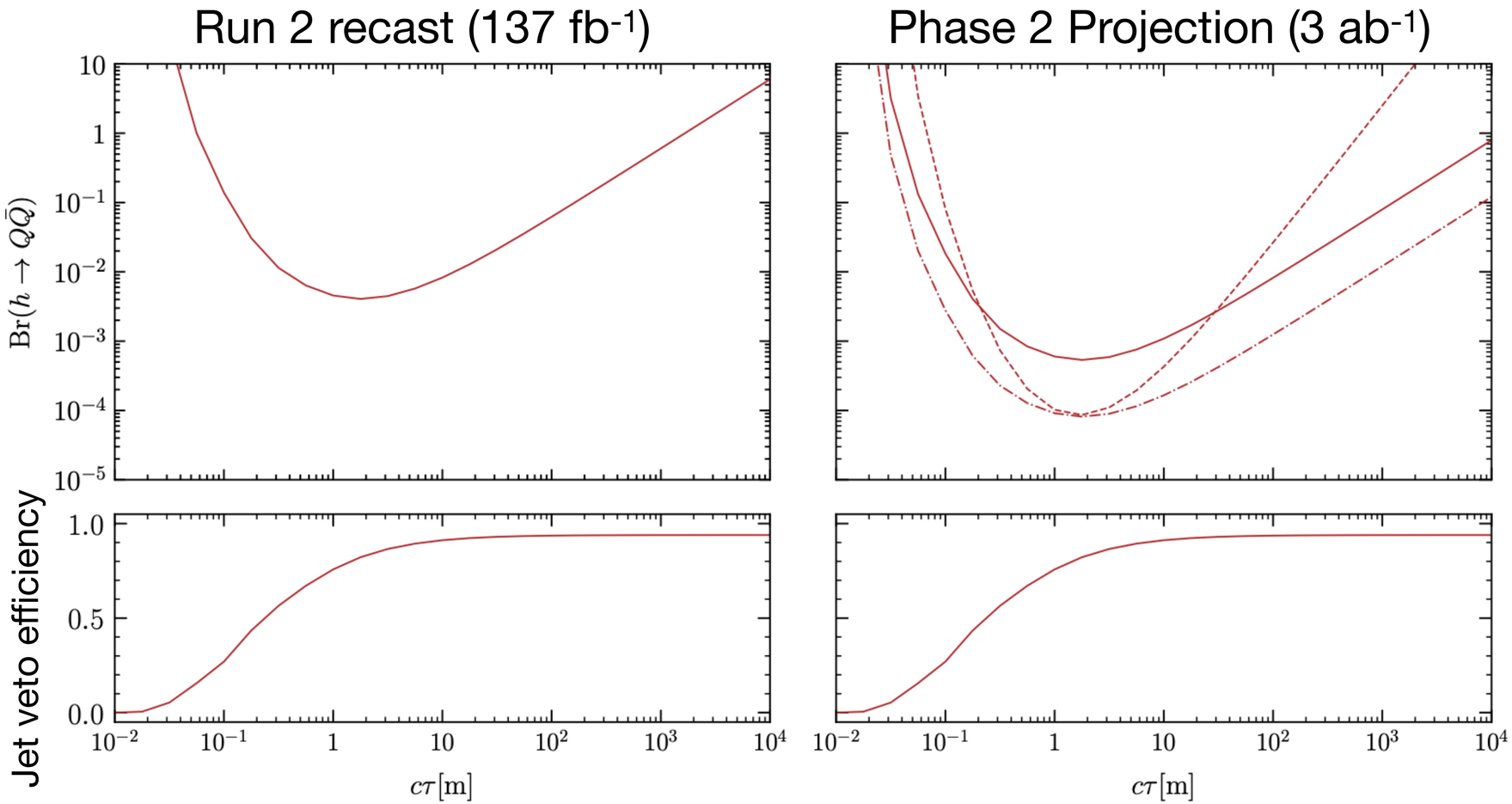


Phase 2 Projection (3 ab^{-1})



- Reaching BR 3e-3 with 137fb^{-1} and 1e-4 with 3ab^{-1}
- Currently there are no other experiments that set limit on this model

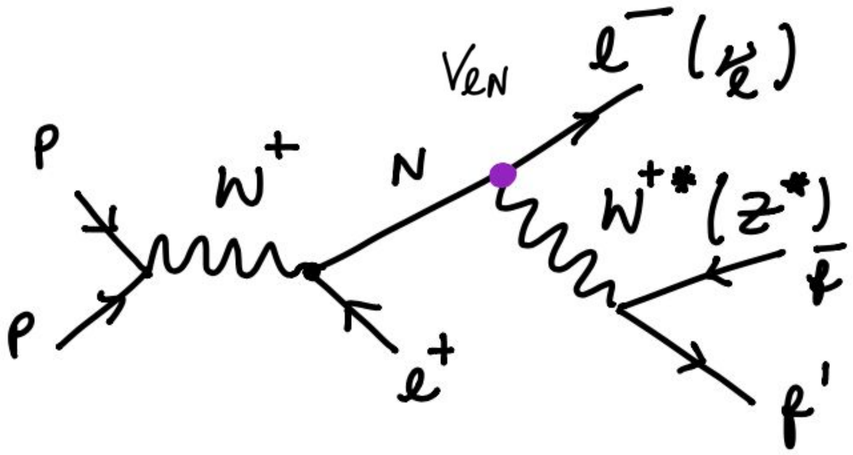
Hidden Valley Reinterpretation



- At low lifetime, the current search strategy limits the sensitivity by applying a jet veto, where the LLPs that decay in muon system are vetoed by LLPs decayed in tracker that create jets in the same direction
  - In this model, LLPs originating from the same dark quark usually come from the same direction
- At long lifetime, higher LLP multiplicity results in more stringent limit than the scalar model

Heavy Neutral Leptons

G. Cottin



$$\Gamma \sim G_F^2 \, m_N^5 \, |V_{eN}|^2$$

Small mixing & ~ GeV scale HNL ⟹ LLP!

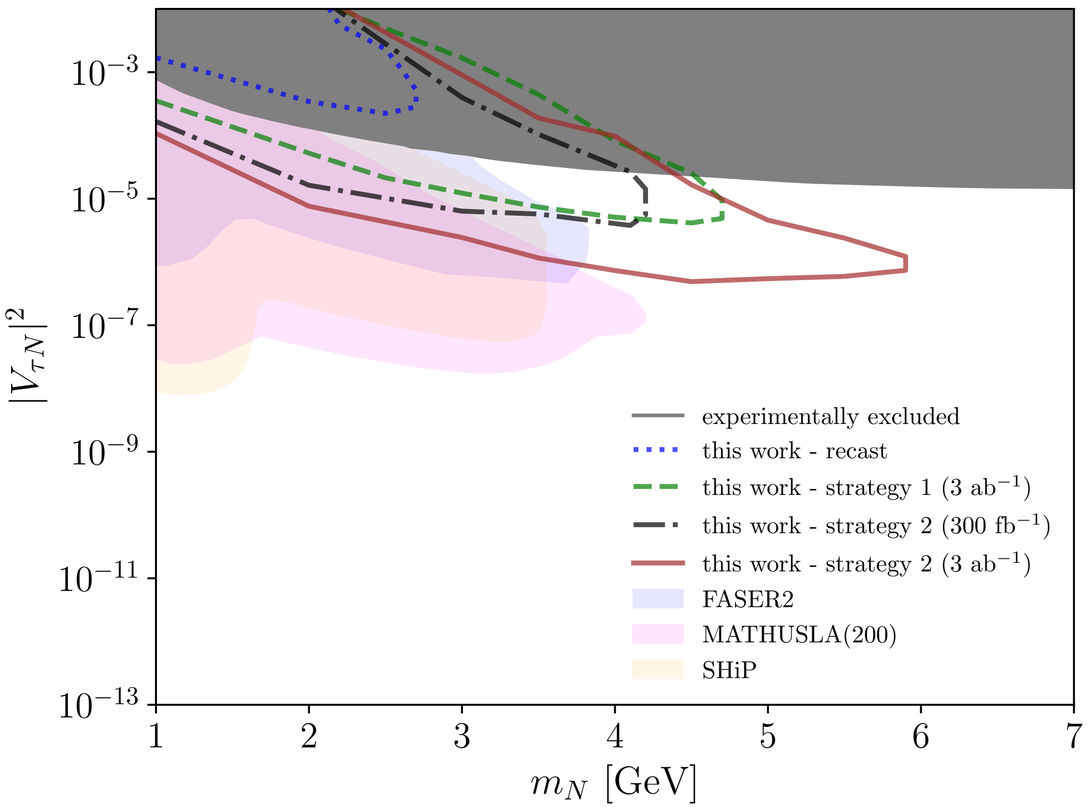
- Latest HNL searches at the LHC use prompt lepton triggers (e/μ) and displaced vertex signature targeting leptonic decays of W*/Z*
- Tau mixing is not covered yet at the LHC
- **Muon detector shower: target HNLs decaying in the muon system, sensitive to particle showers from the displaced lepton and inclusive W*/Z* decays**

HNL Reinterpretation

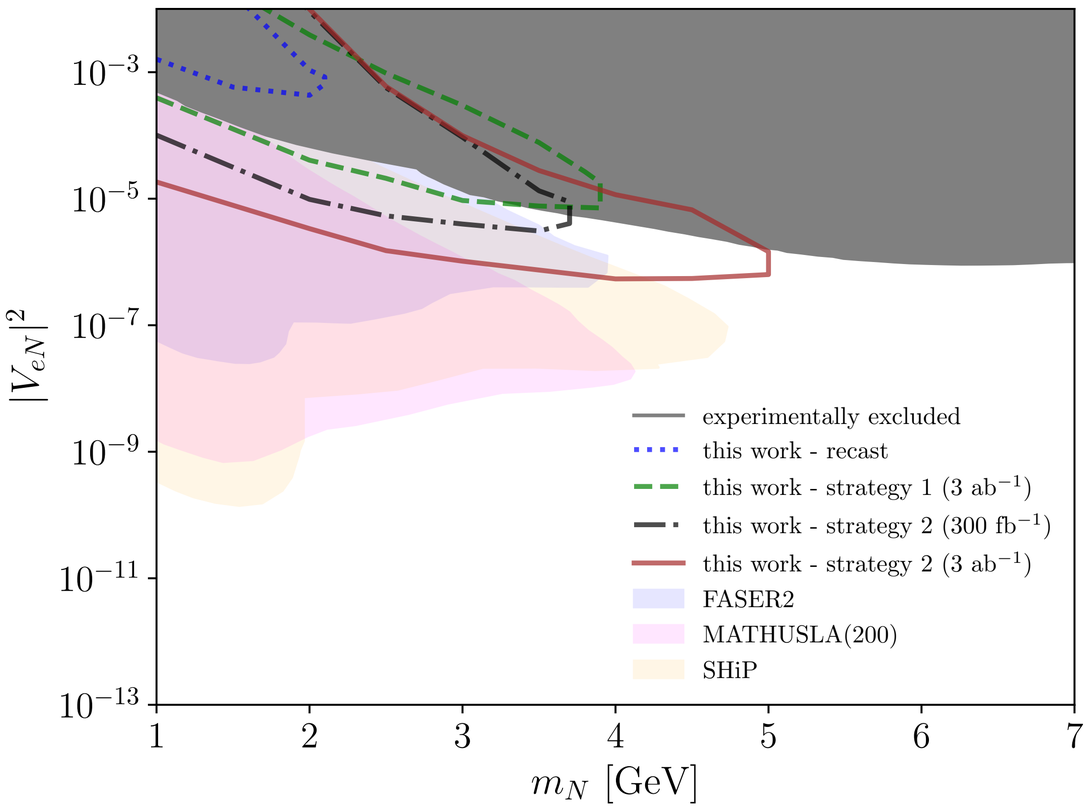
Giovanna's talk at LLP11

Paper on arXiv

τ-type



Electron-type

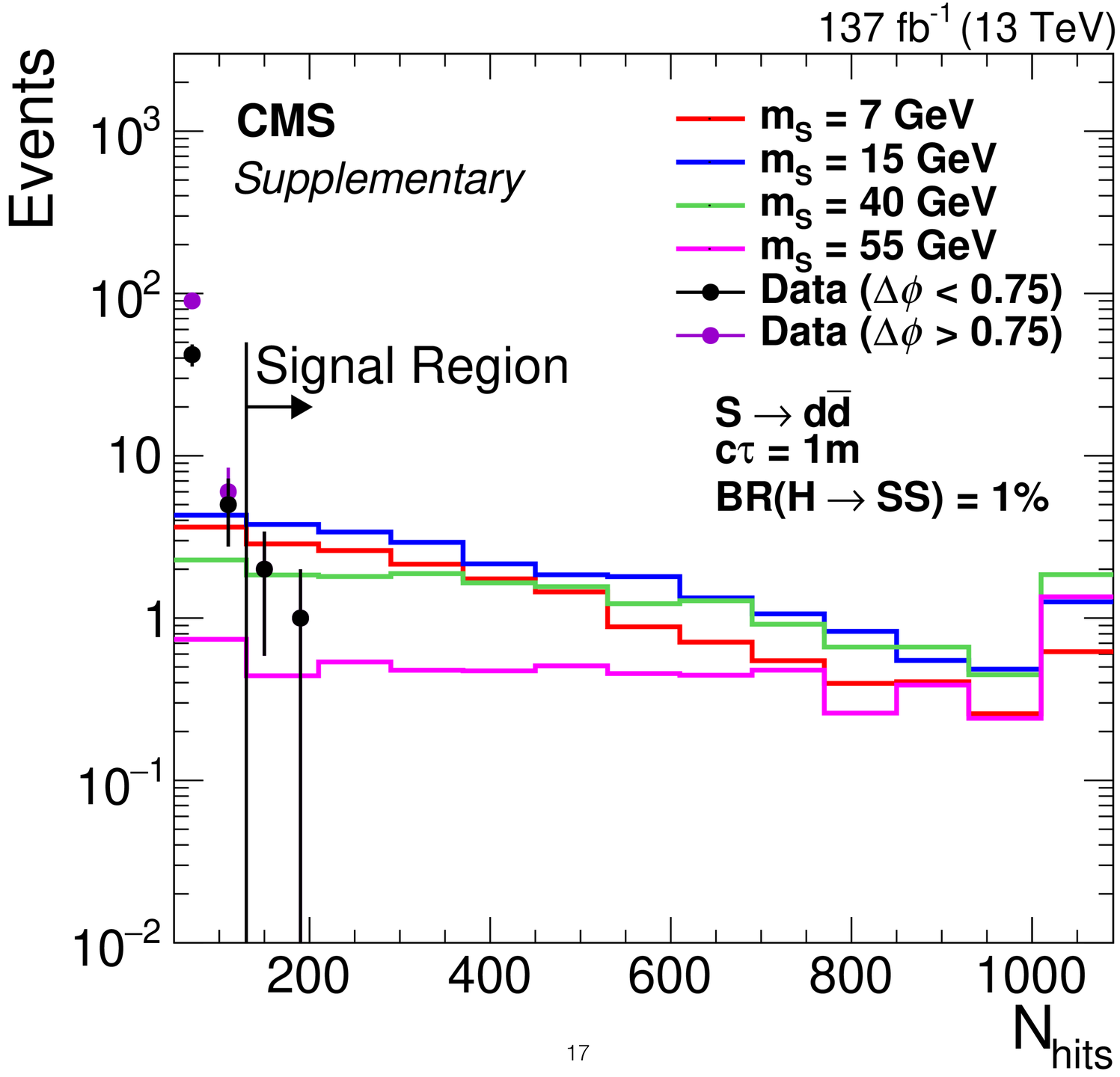


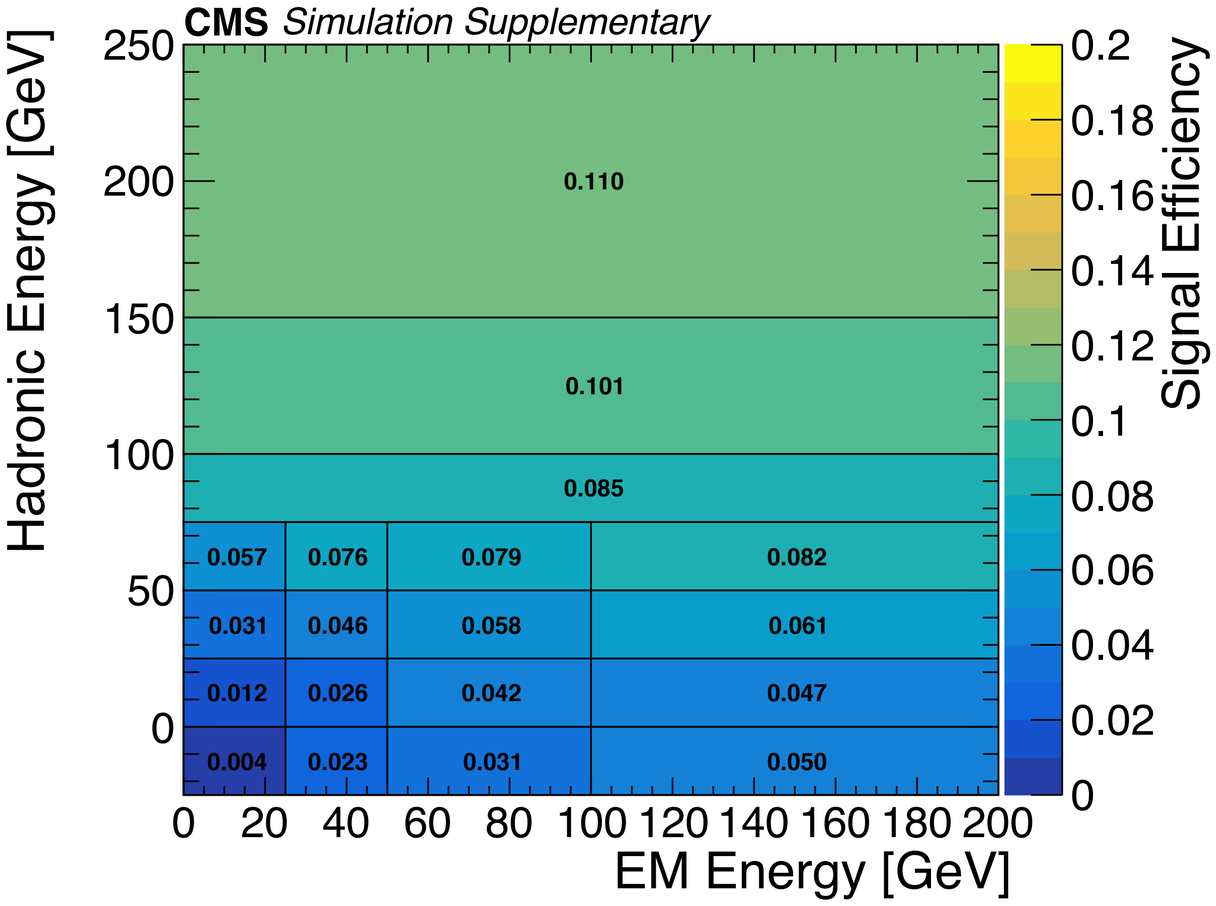
- **Can reach mixings as low as ~5 x 10^{-7} and HNL masses between 1 and 6 GeV for both electron and τ-type**
  - Strategy 1 : Maintains high MET trigger but with a tighter N_{hit} cut.
  - Strategy 2: Lower MET cut > 50 GeV and increased N_{hit}. Enabled by the new dedicated trigger for Run 3

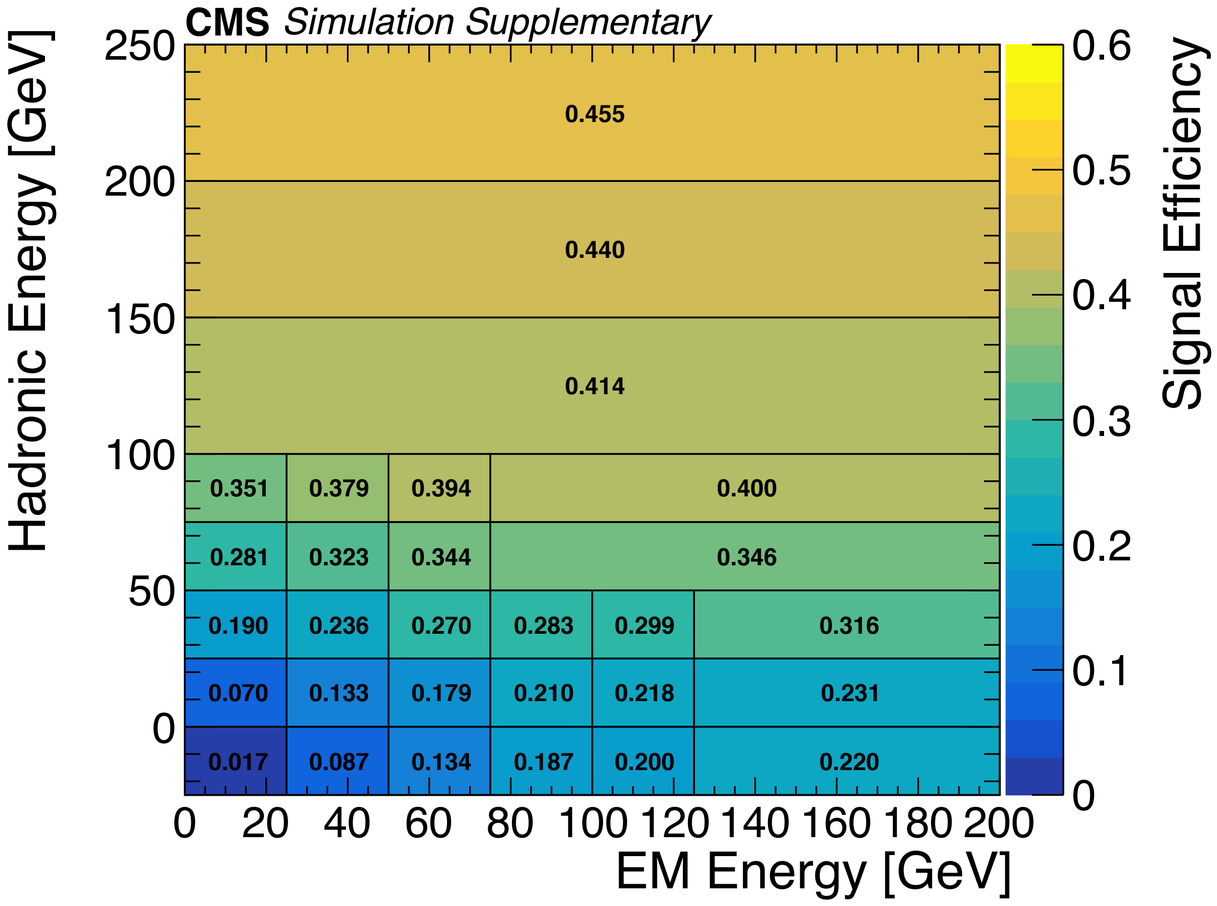
Summary

- Presented reinterpretation and sensitivity projections in a number of benchmark models, significantly extending the physics scope of recent CMS result
- We highlight a few representative models: dark scalar model, heavy neutral leptons, and hidden valley models
- For most benchmark models, the analysis covers previously unconstrained regions of the parameter space and is complementary to dedicated LLP experiments
  - New dedicated trigger in run3 would also open up possibilities for more models and search strategies
- **We invite anyone interested to use the new Delphes class/module to reinterpret the analysis with their favorite model**
  - Example code on delphes repo: https://github.com/delphes/delphes/blob/master/examples/ExampleCscCluster.py

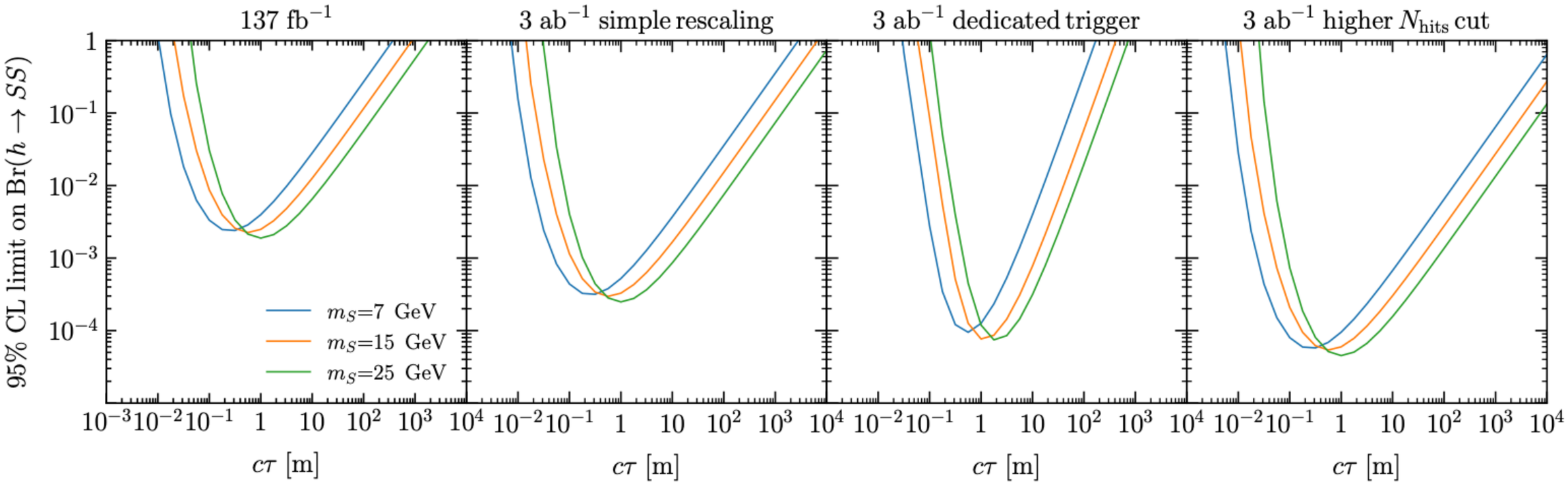
BACKUP SLIDES

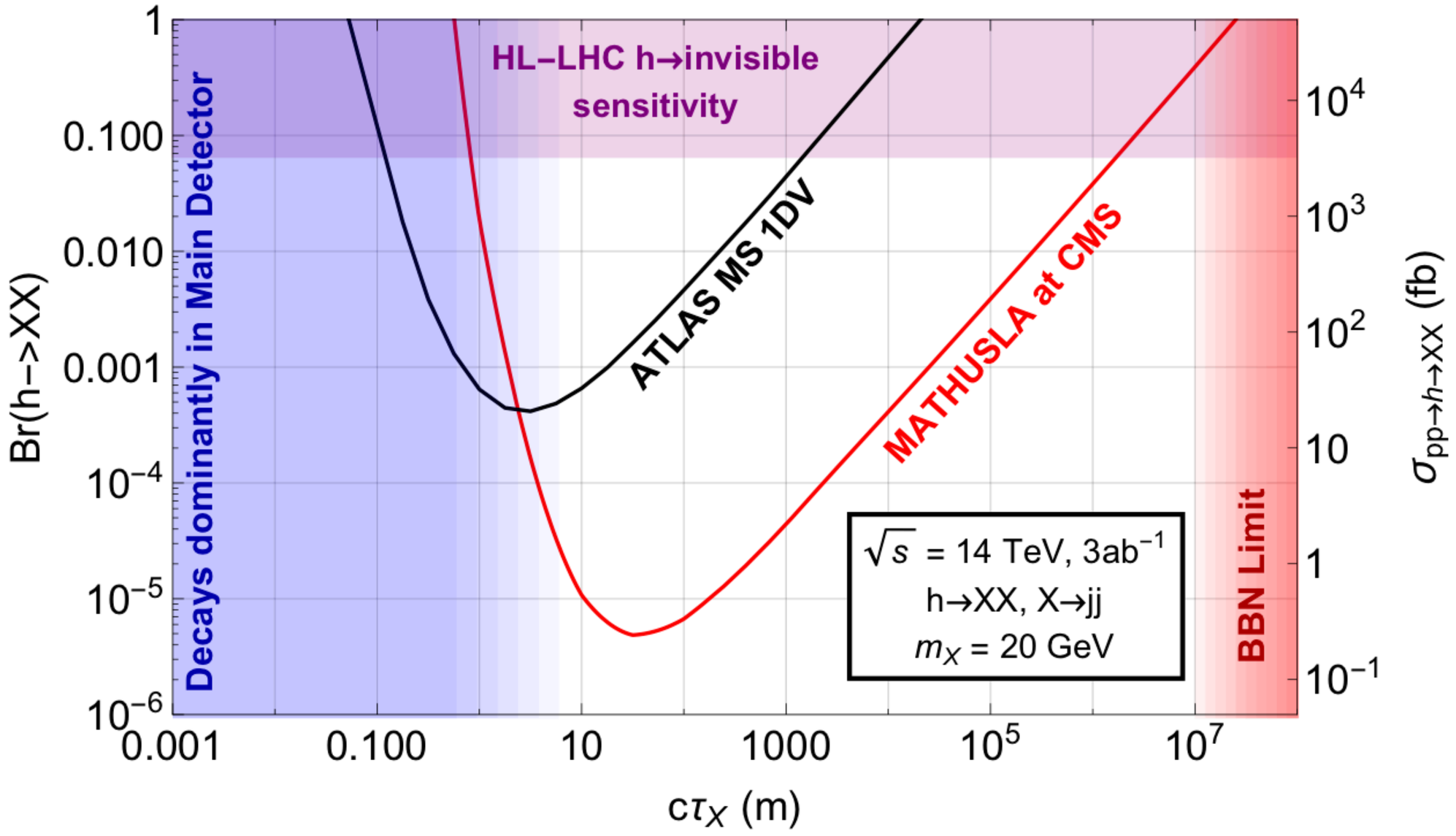

137 fb^{-1} (13 TeV)
CMS
Supplementary
Events
m_S = 7 GeV
m_S = 15 GeV
m_S = 40 GeV
m_S = 55 GeV
Data ($\Delta\phi$ < 0.75)
Data ($\Delta\phi$ > 0.75)
Signal Region
$S \to d\bar{d}$
$c\tau$ = 1m
BR($H \to SS$) = 1%
10^3
10^2
10
1
10^{-1}
10^{-2}
200
400
600
800
1000
N_{hits}

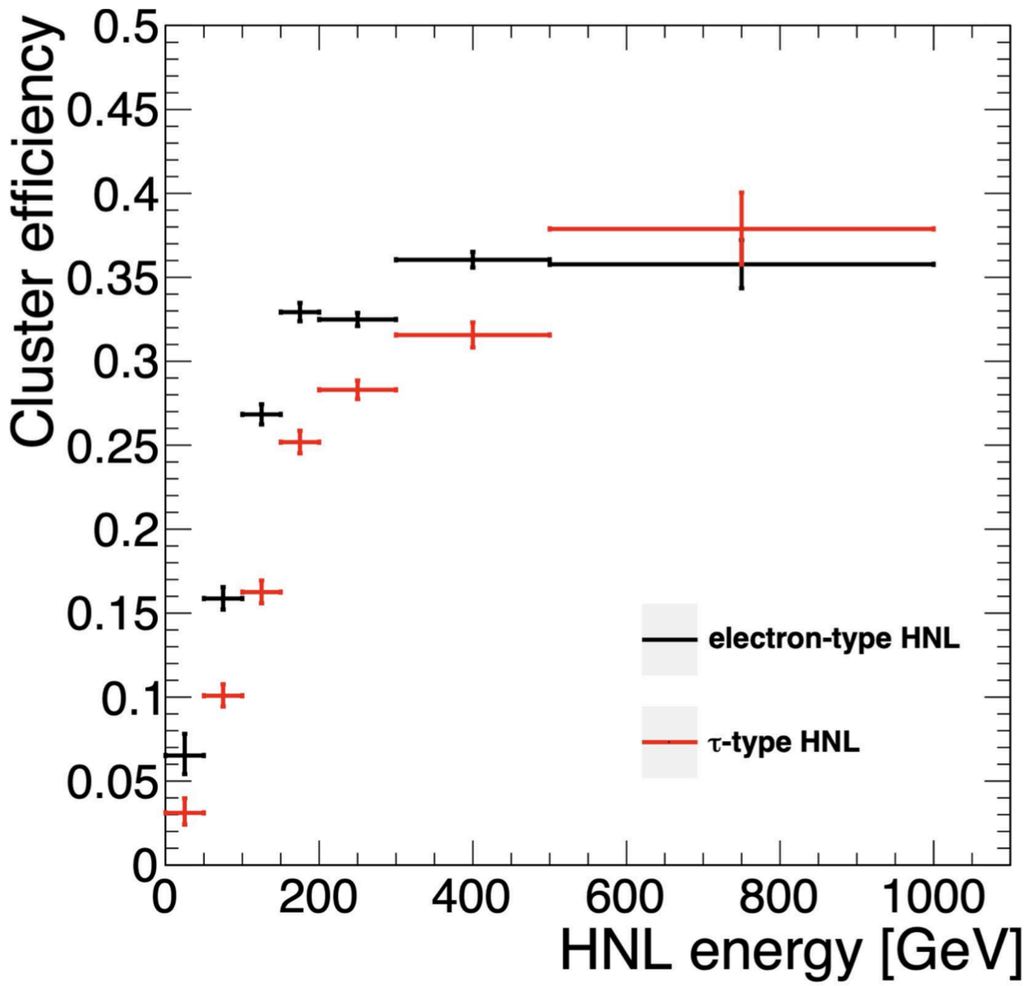

CMS Simulation Supplementary
Hadronic Energy [GeV]
EM Energy [GeV]
Signal Efficiency
0.110
0.101
0.085
0.057 0.076 0.079 0.082
0.031 0.046 0.058 0.061
0.012 0.026 0.042 0.047
0.004 0.023 0.031 0.050


CMS Simulation Supplementary
Hadronic Energy [GeV]
EM Energy [GeV]
Signal Efficiency
0.455
0.440
0.414
0.351 0.379 0.394 0.400
0.281 0.323 0.344 0.346
0.190 0.236 0.270 0.283 0.299 0.316
0.070 0.133 0.179 0.210 0.218 0.231
0.017 0.087 0.134 0.187 0.200 0.220

Light Scalar Model

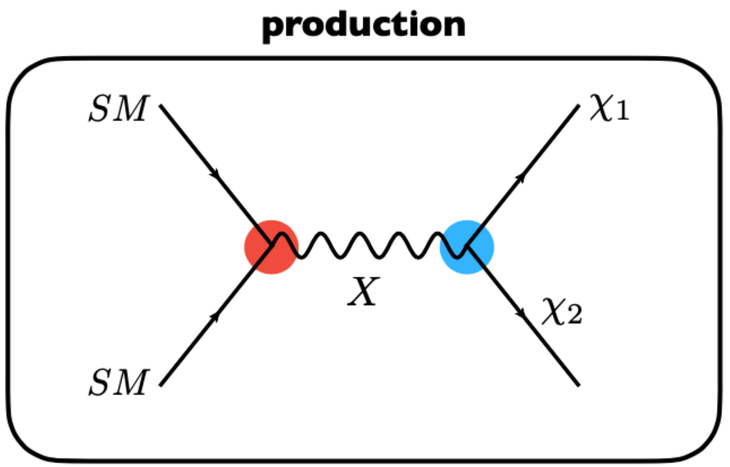


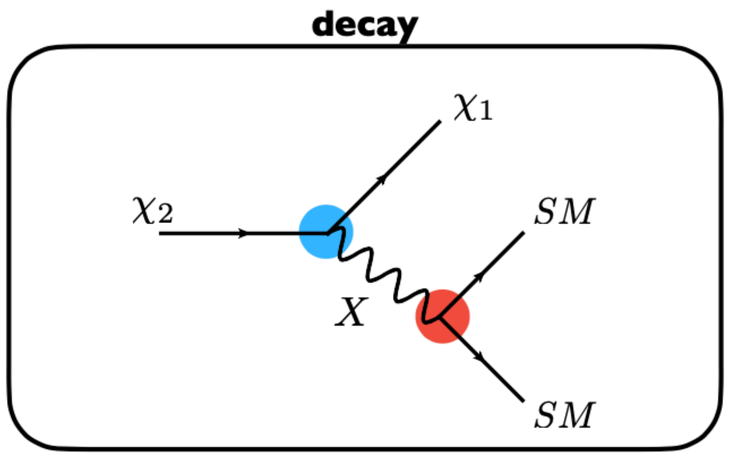

HL–LHC h→invisible sensitivity
Decays dominantly in Main Detector
ATLAS MS 1DV
MATHUSLA at CMS
BBN Limit
$\sqrt{s}$ = 14 TeV, 3ab^{-1}
h→XX, X→jj
m_X = 20 GeV
Br(h–>XX)
$c\tau_X$ (m)
$\sigma_{pp\to h\to XX}$ (fb)
1
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
0.001
0.100
10
1000
10^5
10^7
10^4
10^3
10^2
10
1
10^{-1}

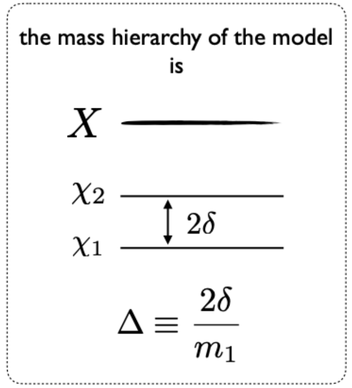

Cluster efficiency
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
200
400
600
800
1000
HNL energy [GeV]
electron-type HNL
τ-type HNL

Inelastic Dark Matter Model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + ie_D \hat{X}^\mu \bar{\chi}_1 \gamma^\mu \chi_2 - \frac{\epsilon}{2\cos\theta_W} \hat{X}_{\mu\nu} \hat{B}^{\mu\nu}$$

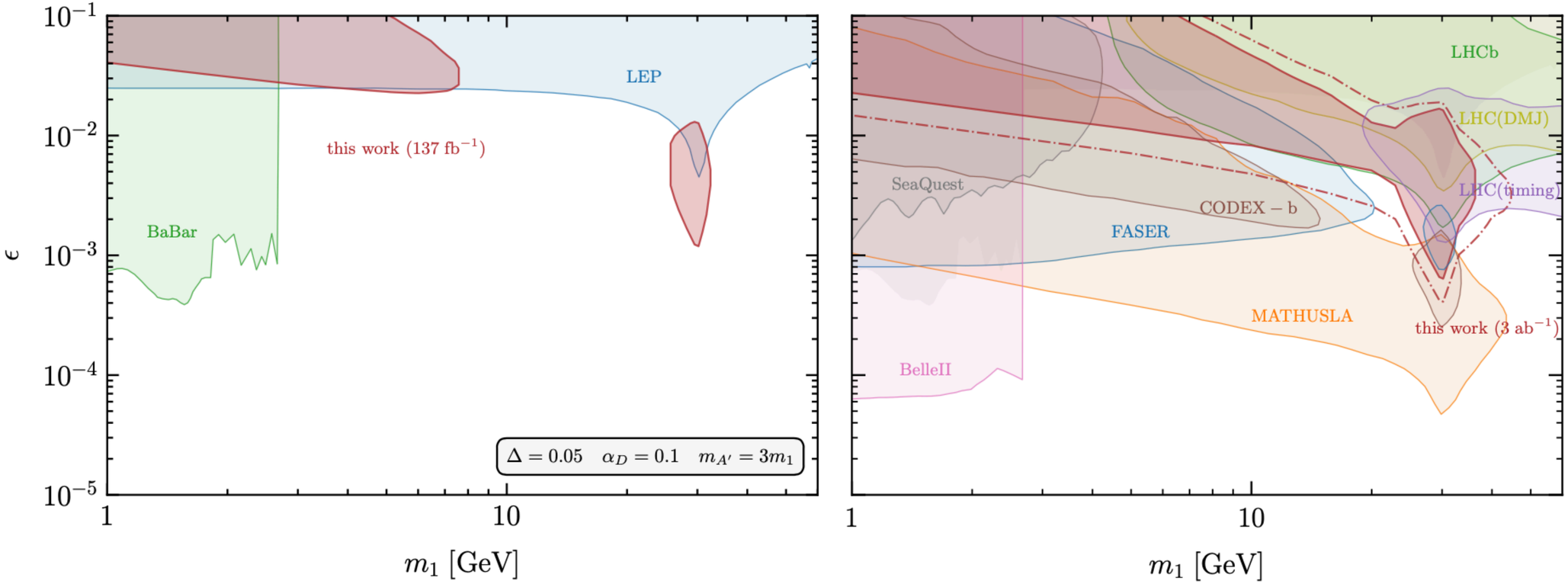






- χ_1 is stable and χ_2 is the long-lived
- LLP energy and MET are decoupled

iDM Reinterpretation

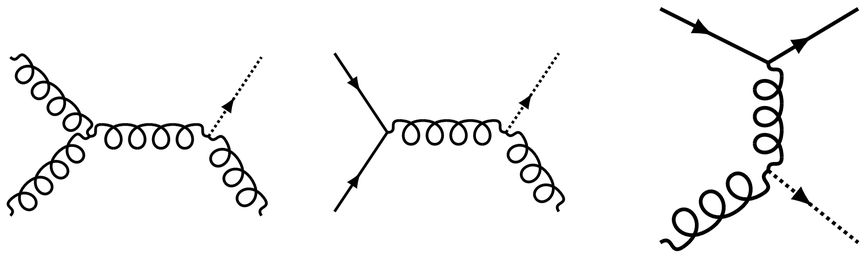


- ϵ controls the scalar lifetime and production
- Scalar mass controls the decay mode and affects the acceptance

ALPs

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)^2 + \frac{a}{4\pi f_a}\left(\alpha_s c_{GG}\, G^a_{\mu\nu}\,\widetilde{G}^{a,\mu\nu} + \alpha_2 c_{WW}\, W^a_{\mu\nu}\widetilde{W}^{a,\mu\nu} + \alpha_1 c_{BB}\, B_{\mu\nu}\widetilde{B}^{\mu\nu}\right) + \ldots$$

gluon-coupled ALP
$(c_{GG} \neq 0,\ c_{BB} = c_{WW} = 0)$



$a \to \gamma\gamma$

$a \to 3\pi$

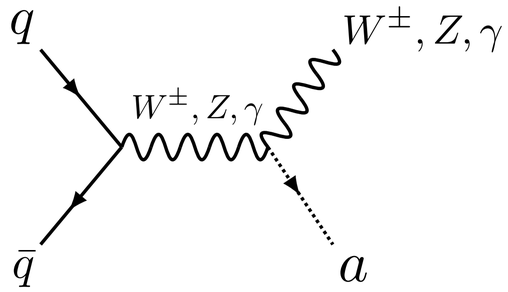
$a \to \eta\pi\pi$

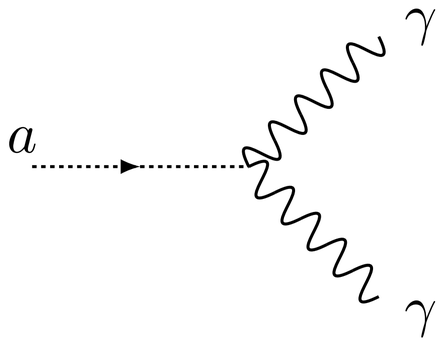
$a \to \pi\pi\gamma$

main production channels

main decay channels for current reach

photon-coupled ALP
$(c_{GG} \neq 0,\ c_{BB} = c_{WW} = 0)$

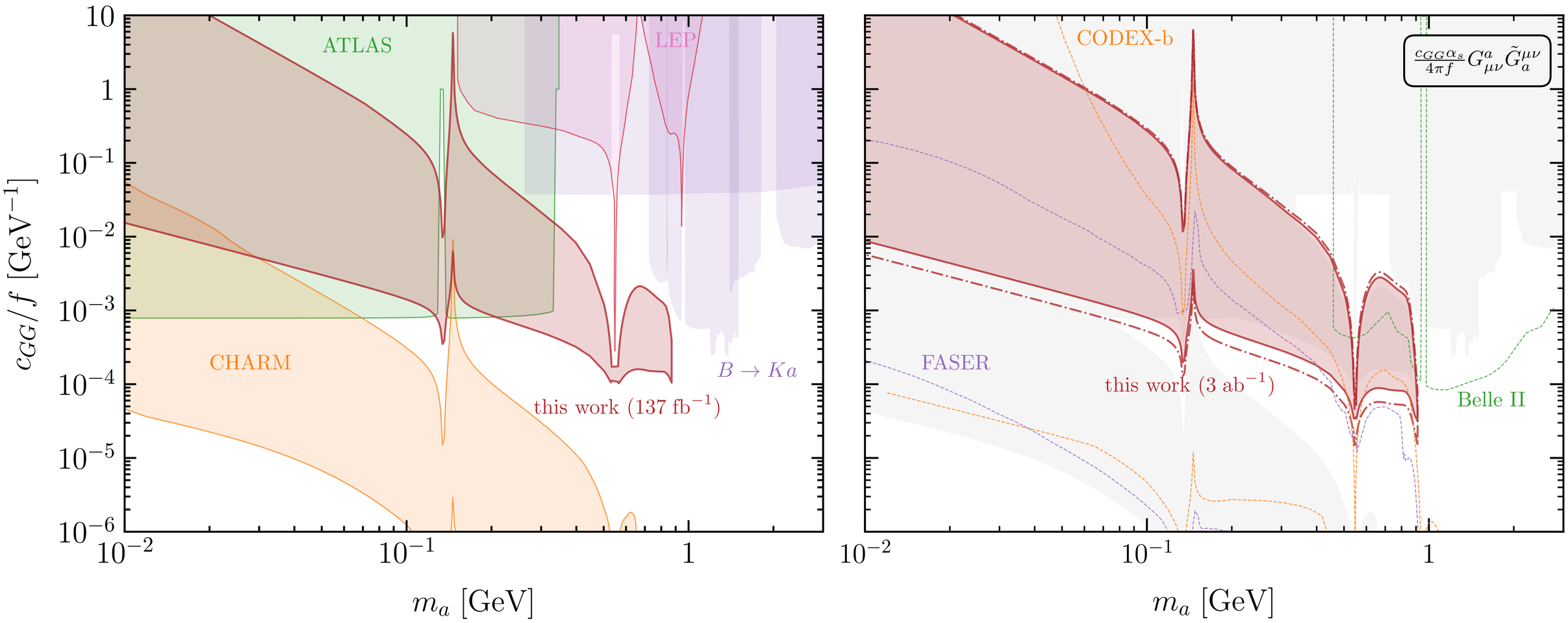




A. Mitridate

ALPs

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{4\pi f_a}\left(\alpha_s c_{GG}\, G^a_{\mu\nu}\,\widetilde{G}^{a,\mu\nu} + \alpha_2 c_{WW}\, W^a_{\mu\nu}\widetilde{W}^{a,\mu\nu} + \alpha_1 c_{BB}\, B_{\mu\nu}\widetilde{B}^{\mu\nu}\right) + \ldots$$



ALPs

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{4\pi f_a}\left(\alpha_s c_{GG}\, G^a_{\mu\nu}\,\widetilde{G}^{a,\mu\nu} + \alpha_2 c_{WW}\, W^a_{\mu\nu}\widetilde{W}^{a,\mu\nu} + \alpha_1 c_{BB}\, B_{\mu\nu}\widetilde{B}^{\mu\nu}\right) + \ldots$$

$c_{\gamma Z}$ tuned to 0