Searching for long-lived particles at the LHC and beyond:

ELEVENTH WORKSHOP OF THE LLP COMMUNITY

llp11

Long-Lived Light Mediators from Higgs Boson Decay

@ HL-LHC & FCC-hh

based on arXiv:2111.02437

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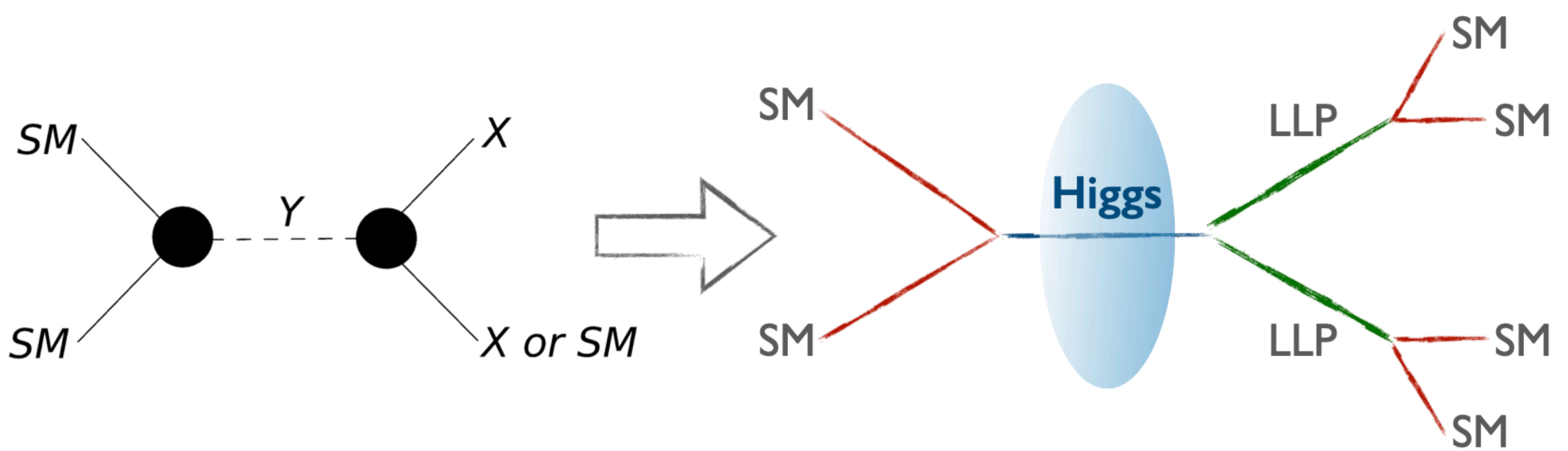
Long-lived particles in the Higgs portal

~ LLPs having dominant coupling to the SM Higgs boson ~



$m_{\rm LLP} \lesssim \frac{m_H}{2}$

LLPs can be produced from the *exotic decays of SM Higgs*

Theoretically	*Experimentally*
- leading renormalisable portal for new gauge-singlet particles to couple to the SM	- much scope to include couplings of Higgs to new physics - presence of multiple production modes

Motivated from many BSM models - like Dark Matter

LLP White Paper, arXiv:1903.04497

Mediator from a Dark Matter model

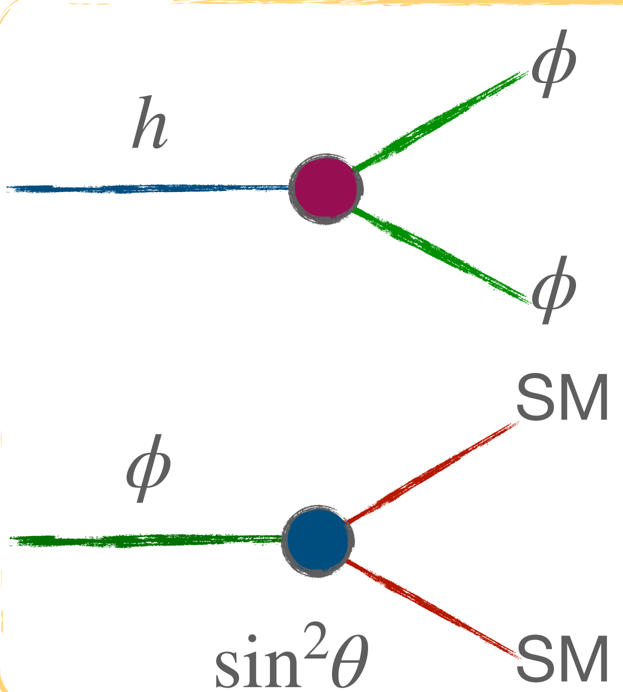
Shigeki Matsumoto, et al., *JHEP* 07 (2019) 050

Light *fermionic* WIMP with *light scalar mediator* → solves → small scale crisis in structure formation of the Universe → with → large and velocity-dependent scattering cross section between WIMPs

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu \Phi)^2 - A_{\Phi H}\Phi |H|^2 - \frac{\lambda_{\Phi H}}{2}\Phi^2 |H|^2 - \mu_1^3 \Phi - \frac{\mu_\Phi^2}{2}\Phi^2 - \frac{\mu_3}{3!}\Phi^3 - \frac{\lambda_\Phi}{4!}\Phi^4 + \mathcal{L}_{\rm DS}$$

Mixing highly constrained

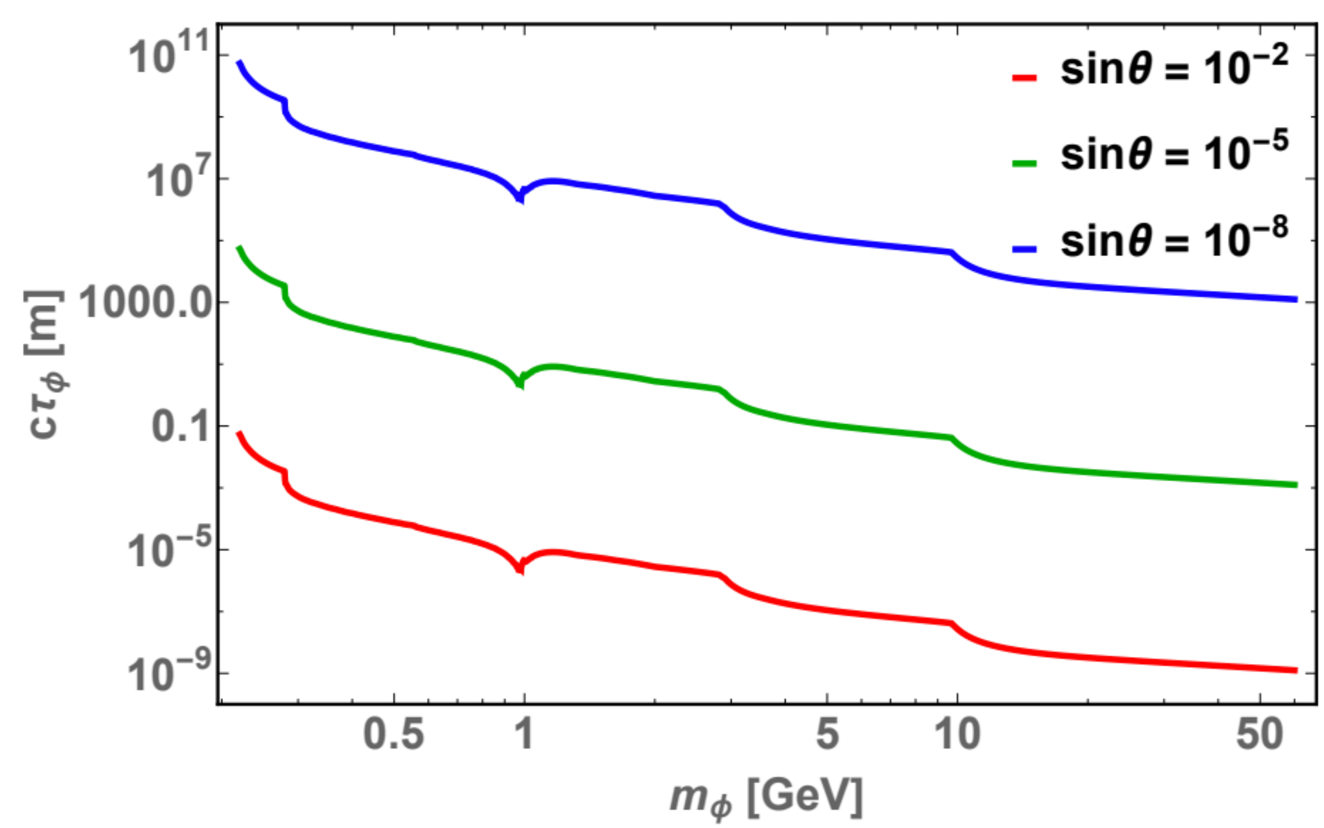
Not severely constrained so far



Production of ϕ has a different coupling than its decay

$\sin^2\theta \downarrow$ $c\tau_\theta \uparrow$

Long-lived mediator



Where to look for the LLPs?

A ***Muon Spectrometer (MS)***

- **A1** CMS MS [HL-LHC, 14 TeV, 3 ab^{-1}]
- **A2** FCC-hh MS [100 TeV, 30 ab^{-1}]

- Least affected by PU - farthest detector from the IP
- Large decay volume - compensates for its distance from the IP
- Sensitive to multiple decay modes

Apart from muons, MS of ATLAS and CMS are sensitive to other final states as well.

- **ATLAS** can reconstruct **displaced vertices in the MS**.
- Due to the presence of iron yokes, **CMS** can see a **cluster of hits** in the MS for electrons, photons and hadrons

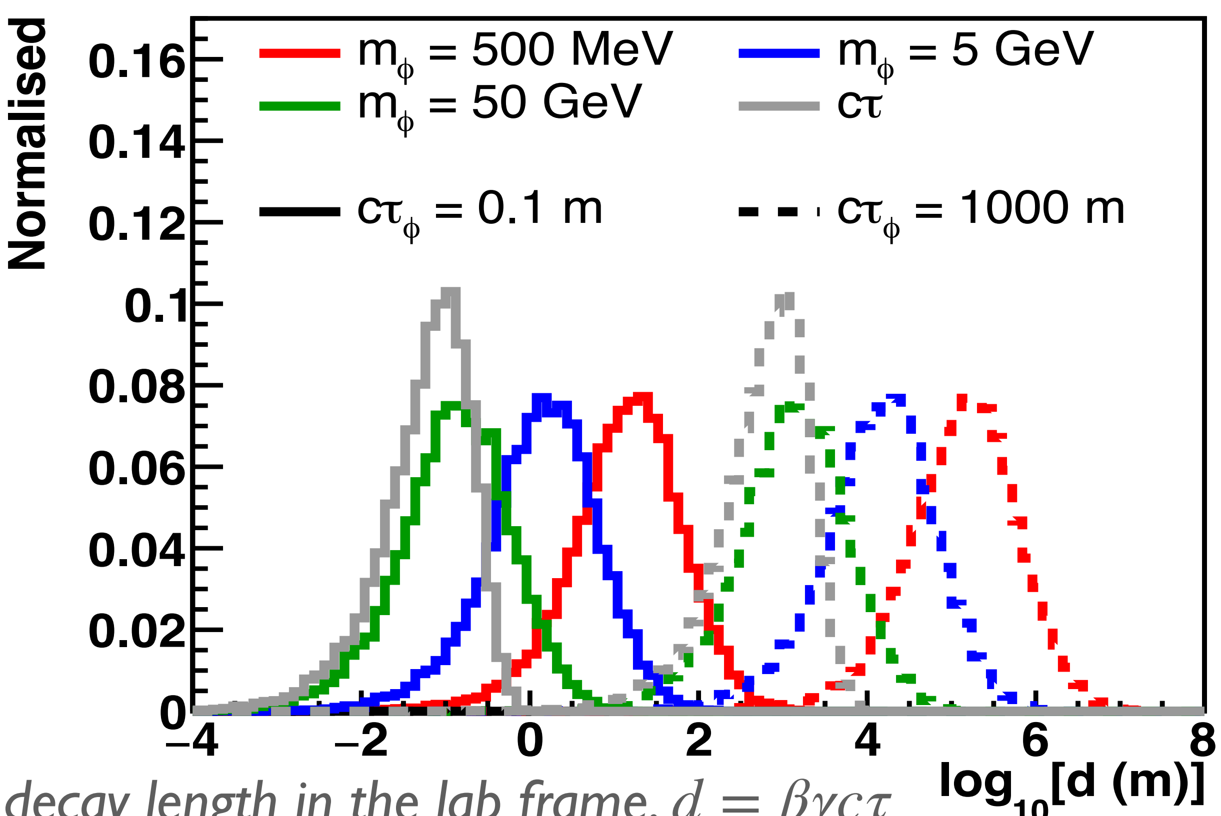
ATLAS, *PRD* 99 no. 5, (2019) 052005 — ATLAS, ATL-PHYS-PUB-2019-002
ATLAS, *PRD* 101 no. 5, (2020) 052013 — CMS, *PRL* 127 (2021) 26, 261804

B ***Dedicated transverse LLP detectors***

mostly centrally produced in Higgs decays - especially lighter LLPs

- **B1** MATHUSLA and CODEX-b [HL-LHC, 14 TeV]
- **B2** **DELIGHT** [FCC-hh, 100 TeV, 30 ab^{-1}]

New Proposal
This work



Distribution of decay length in the lab frame, $d = \beta\gamma c\tau$

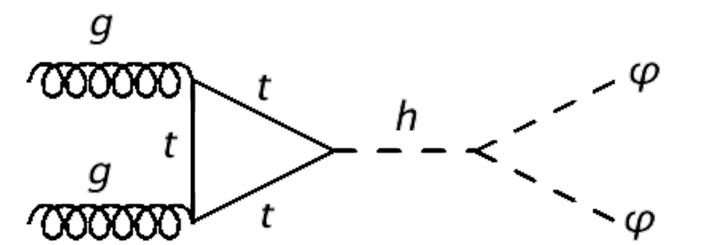
Analysis Strategy for Decays in MS

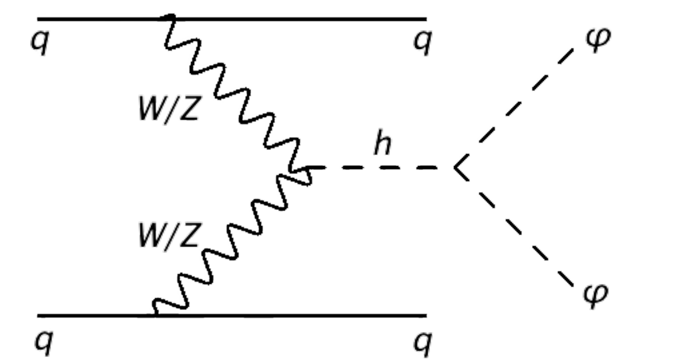
Triggers based on PROMPT objects

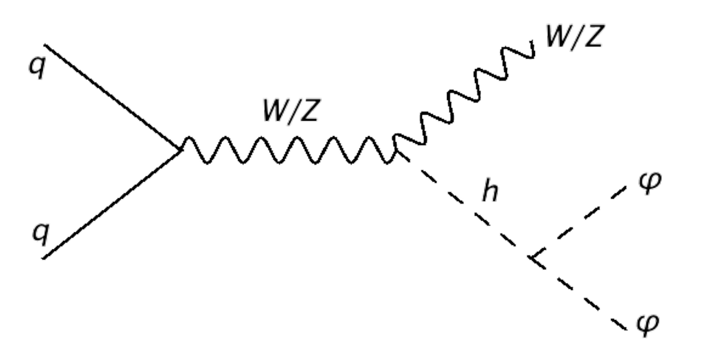
P^H : a hard set of cuts from Phase-II CMS L1 trigger menu

CMS-TDR-021

P^S : a softer set of cuts assuming thresholds on prompt objects can be reduced in the presence of displaced activity in the MS





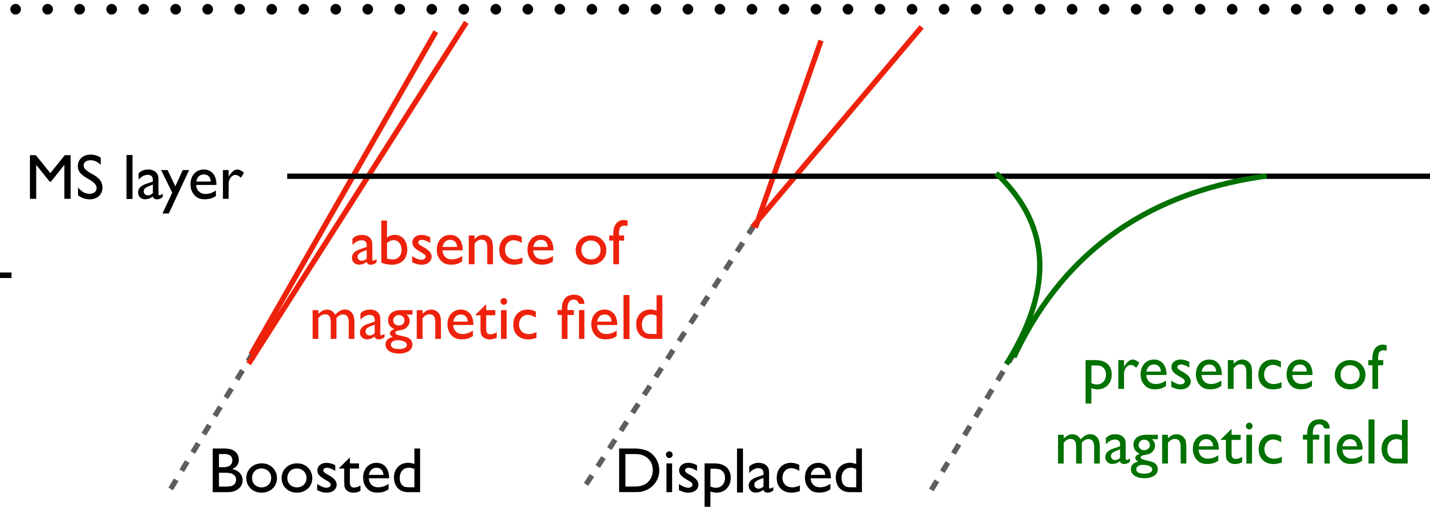


Trigger	In P^H_{Mode}	In P^S_{Mode}	Mode
Single jet	$p_T^j > 180\,\text{GeV},\ \lvert\eta_j\rvert < 2.4.$	$p_T^j > 90\,\text{GeV},\ \lvert\eta_j\rvert < 2.4.$	ggF, VBF, Vh-jet.
Di-jet	$p_T^j > 112\,\text{GeV},\ \lvert\eta_j\rvert < 2.4,\ \Delta\eta < 1.6.$	$p_T^j > 90\,\text{GeV},\ \lvert\eta_j\rvert < 2.4,\ \Delta\eta < 1.6.$	
VBF jet	$p_T > 70\,\text{GeV}$ for Leading jet, $p_T > 40\,\text{GeV}$ for Sub-leading jet, $\lvert\eta_j\rvert < 5,\ \eta_{j_1} \times \eta_{j_2} < 0,\ \Delta\eta > 4.0,$ $\Delta\phi < 2.0,$ $m_{jj} > 1000\,\text{GeV}.$	$p_T > 60\,\text{GeV}$ for Leading jet, $p_T > 30\,\text{GeV}$ for Sub-leading jet, $\lvert\eta_j\rvert < 5,\ \eta_{j_1} \times \eta_{j_2} < 0,\ \Delta\eta > 4.0,$ $\Delta\phi < 2.0,$ $m_{jj} > 500\,\text{GeV}.$	
Single electron	$p_T^e > 36\,\text{GeV},\ \lvert\eta\rvert < 2.4.$	$p_T^e > 18\,\text{GeV},\ \lvert\eta\rvert < 2.4.$	Vh-lep.
Double electron	$p_T^{e_1} > 25\,\text{GeV},\ p_T^{e_2} > 12\,\text{GeV},\ \lvert\eta\rvert < 2.4.$	$p_T^{e_1} > 12\,\text{GeV},\ p_T^{e_2} > 12\,\text{GeV},\ \lvert\eta\rvert < 2.4.$	
Single muon	$p_T^{\mu} > 22\,\text{GeV},\ \lvert\eta\rvert < 2.4.$	$p_T^{\mu} > 11\,\text{GeV},\ \lvert\eta\rvert < 2.4.$	
Double muon	$p_T^{\mu_1} > 15\,\text{GeV},\ p_T^{\mu_2} > 7\,\text{GeV},\ \lvert\eta\rvert < 2.4.$	$p_T^{\mu_1} > 7\,\text{GeV},\ p_T^{\mu_2} > 7\,\text{GeV},\ \lvert\eta\rvert < 2.4.$	

Triggers based on DISPLACED objects

Implemented magnetic field till muon spectrometer in Delphes for correct $\Delta\phi$ – important in boosted and displaced cases

ΔR plots



Analysis Strategy for Decays in MS

Triggers based on DISPLACED objects (contd.)

Possible backgrounds

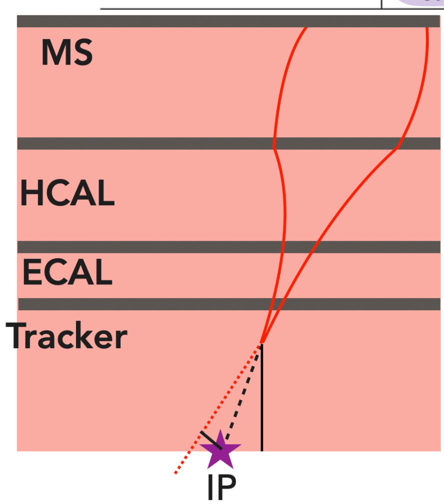
Performed analyses for final states $\mu^+\mu^-, \pi^+\pi^-, K^+K^-, gg, s\bar{s}, c\bar{c}, \tau^+\tau^-, b\bar{b}$ at the CMS MS for a range of LLP masses between 0.5 GeV and 60 GeV with $c\tau = [0.01,\ 5\times 10^7]$ m

Displaced muons — $\mu^+\mu^-$ — hard — soft

	D^H_μ	D^S_μ
Muons	$p_T^\mu > 20\,\mathrm{GeV}$	$p_T^\mu > 10\,\mathrm{GeV}$
	$n_\mu \geq 2$	$n_\mu \geq 2$
	$\lvert\eta^\mu\rvert < 2.8$	$\lvert\eta^\mu\rvert < 2.8$
	$\lvert d_0^\mu\rvert > 1\,\mathrm{mm}$	$\lvert d_0^\mu\rvert > 1\,\mathrm{mm}$
Muon pair from the same dSV	$d_T > 1\,\mathrm{cm}$	$d_T > 1\,\mathrm{cm}$
	$d_T < 6\,\mathrm{m}\ \&\ \lvert d_z\rvert < 9\,\mathrm{m}$	$d_T < 6\,\mathrm{m}\ \&\ \lvert d_z\rvert < 9\,\mathrm{m}$
	$\Delta\phi_{\mu\mu} > 0.01$	$\Delta\phi_{\mu\mu} > 0.01$
Event	$n_{vtx} \geq 1$ or $n_{vtx} = 2$	$n_{vtx} \geq 1$ or $n_{vtx} = 2$

MS cluster — $b\bar{b}$ — hard — soft

	D^H_{jets}	D^S_{jets}
Electrons, photons, hadrons	$p_T > 0.5\,\mathrm{GeV}$	$p_T > 0.5\,\mathrm{GeV}$
	$\lvert\eta\rvert < 2.8$	$\lvert\eta\rvert < 2.8$
MS cluster from same dSV ($< 1\,\mathrm{cm}$)	$d_T > 4\,\mathrm{m}$ or $\lvert d_z\rvert > 7\,\mathrm{m}$	$d_T > 4\,\mathrm{m}$ or $\lvert d_z\rvert > 7\,\mathrm{m}$
	$d_T < 6\,\mathrm{m}$ and $\lvert d_z\rvert < 9\,\mathrm{m}$	$d_T < 6\,\mathrm{m}$ and $\lvert d_z\rvert < 9\,\mathrm{m}$
	$n^{\mathrm{ch}}_{\mathrm{dSV}} \geq 5$	$n^{\mathrm{ch}}_{\mathrm{dSV}} \geq 3$
	$\sum p_{T,dSV} > 50\,\mathrm{GeV}$	$\sum p_{T,dSV} > 20\,\mathrm{GeV}$
	$\Delta\phi_{\max} > 0.3$	$\Delta\phi_{\max} > 0.2$
Event	$n_{\mathrm{cluster}} \geq 1,\ n_{\mathrm{cluster}} = 2$	$n_{\mathrm{cluster}} \geq 1,\ n_{\mathrm{cluster}} = 2$



$\mathrm{Br}(h \to \phi\phi) < 3\times 10^{-6}$ for $m_\phi = 60\,\mathrm{GeV}$, $c\tau = 0.5\,\mathrm{m}$

at least one displaced activity ⇒ harder set of cuts is used to suppress backgrounds

$D^H(\geq 1\mathrm{vtx})$

$D^H(= 2\mathrm{vtx})$

2 displaced activities with harder set of cuts expected to have significantly low background rates

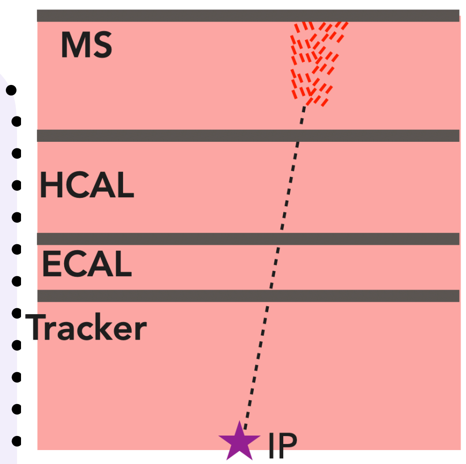
cuts on the prompt & displaced objects relaxed ⇒ combination expected to keep backgrounds in control

$P^S \times D^S$ $(\geq 1\mathrm{vtx})$

$P^H \times D^S$ $(\geq 1\mathrm{vtx})$

harder set of cuts on the prompt objects allows to relax cuts on displaced objects

assumed observation of 50 events

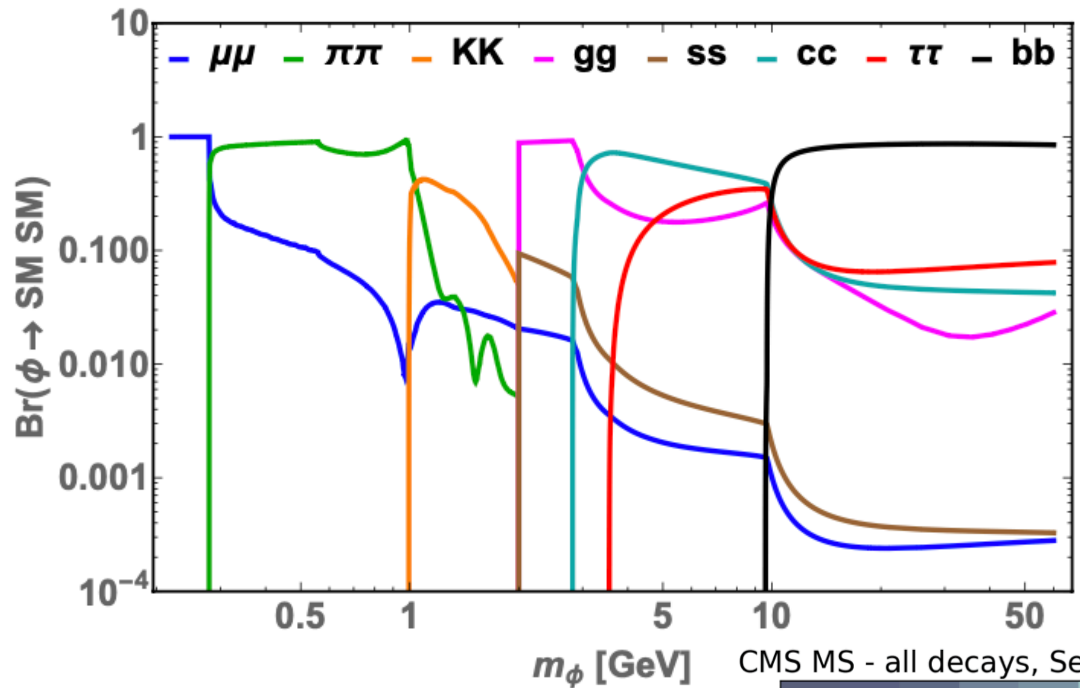


$\mathrm{Br}(h \to \phi\phi) < 1.7\times 10^{-5}$ for $m_\phi = 60\,\mathrm{GeV}$, $c\tau = 5\,\mathrm{m}$

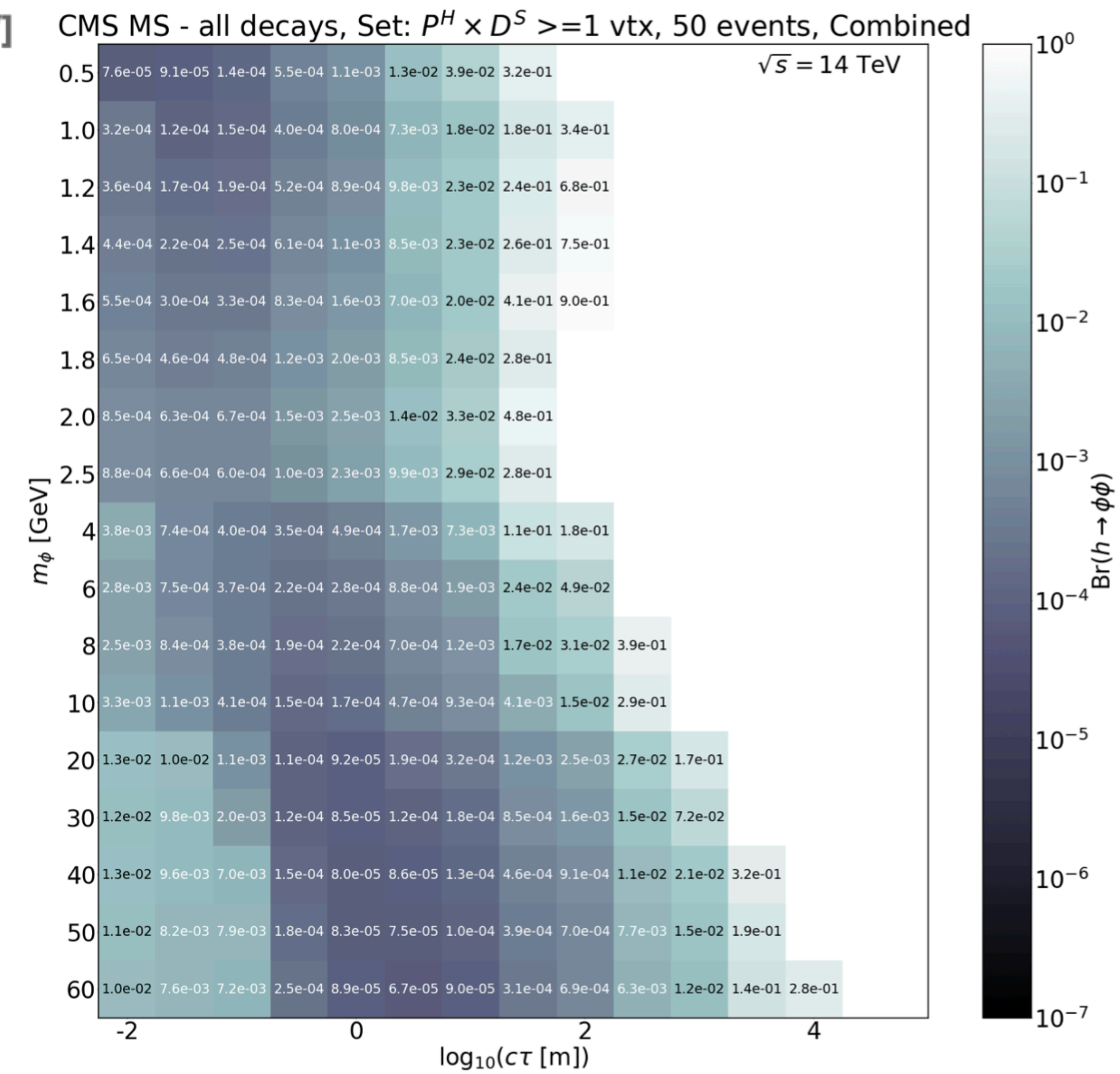
A1 CMS MS

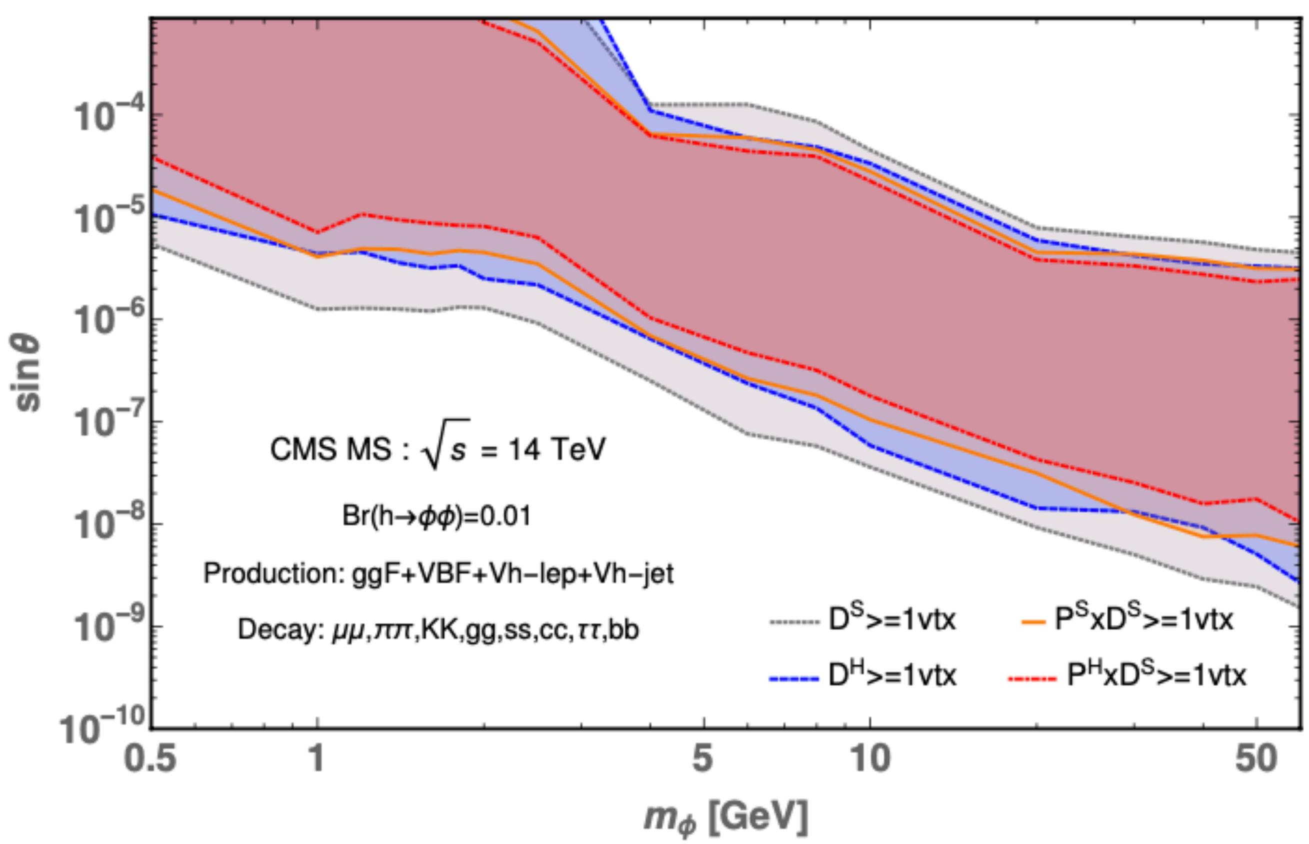
Presented limits assuming 100% branching to each decay mode
$\mu^+\mu^-, \pi^+\pi^-, K^+K^-,$
$gg, s\bar{s}, c\bar{c}, \tau^+\tau^-, b\bar{b}$

+



combined as per branching of minimal model

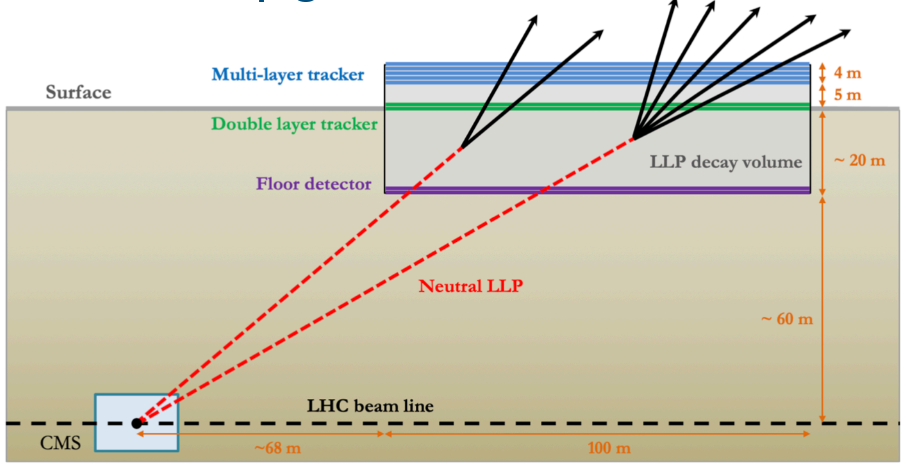




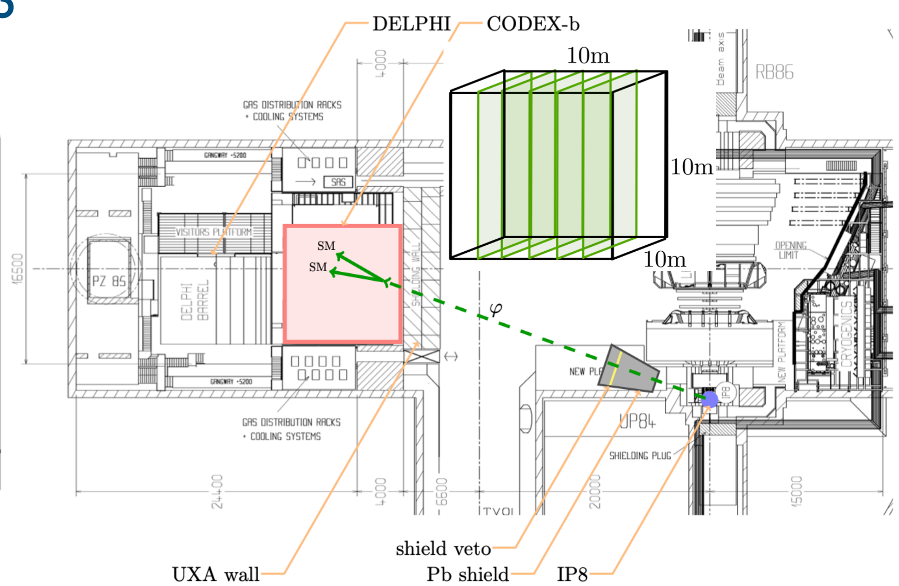
for fixed value of $\mathrm{Br}(h \to \phi\phi)$,
translated limit on $c\tau$ to limit on $\sin\theta$

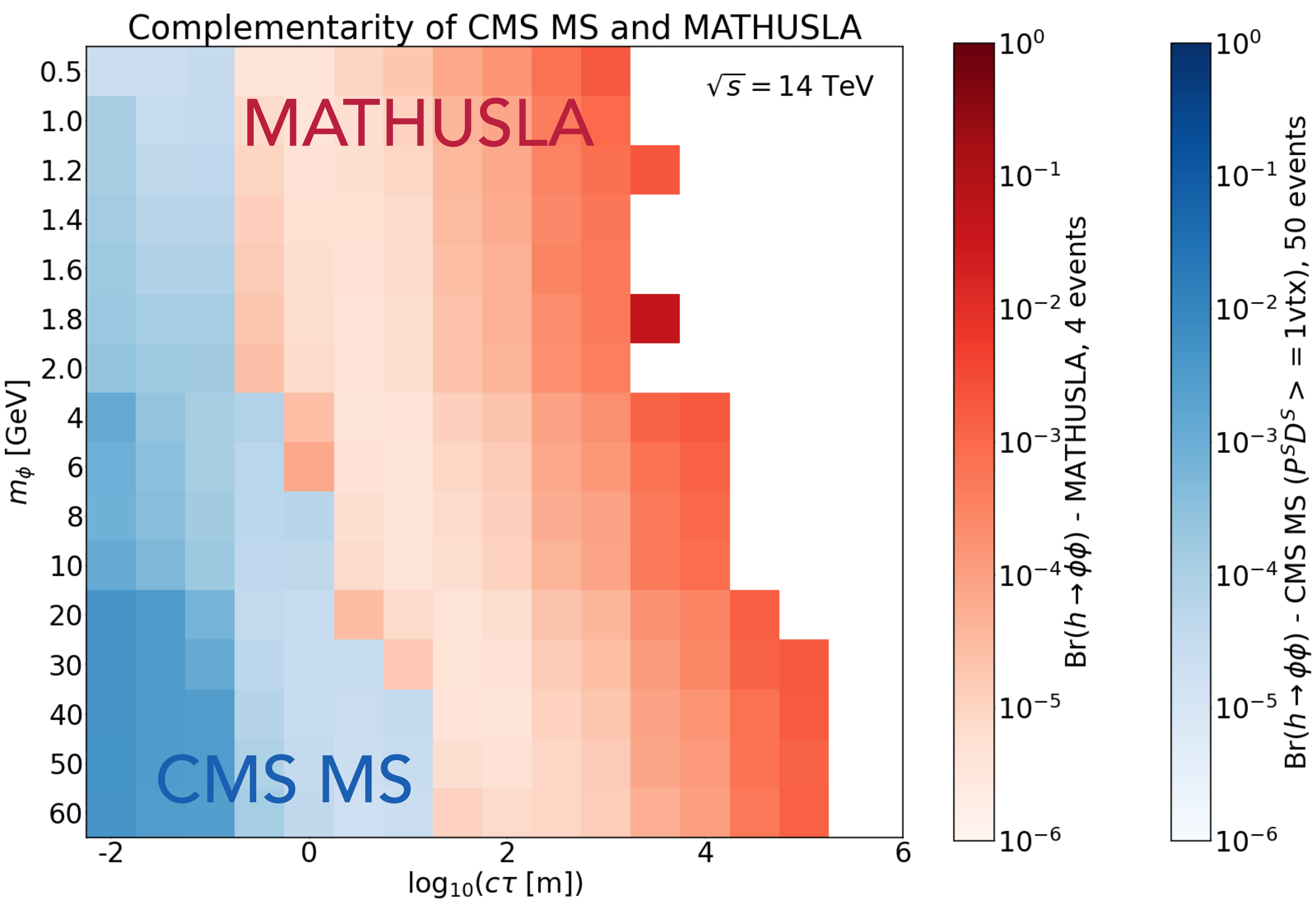
B1 MATHUSLA and CODEX-b

Cristiano Alpigiani, et al., arXiv:2009.01693



Giulio Aielli, et al., arXiv:1911.00481





CODEX-b, $10 \times 10 \times 10$ m^3
300 fb^{-1}

$(0.5\ \mathrm{GeV},\ 3.3 \times 10^{-4},\ 0.5\ \mathrm{m})$

$(50\ \mathrm{GeV},\ 5.3 \times 10^{-4},\ 50\ \mathrm{m})$

CODEX-b, $20 \times 10 \times 10$ m^3
1000 fb^{-1}

$(0.5\ \mathrm{GeV},\ 7.0 \times 10^{-5},\ 0.5\ \mathrm{m})$

$(50\ \mathrm{GeV},\ 1.1 \times 10^{-4},\ 50\ \mathrm{m})$

MATHUSLA,
$100 \times 100 \times 25$ m^3, 3000 fb^{-1}

$(0.5\ \mathrm{GeV},\ 4.1 \times 10^{-6},\ 1\ \mathrm{m})$

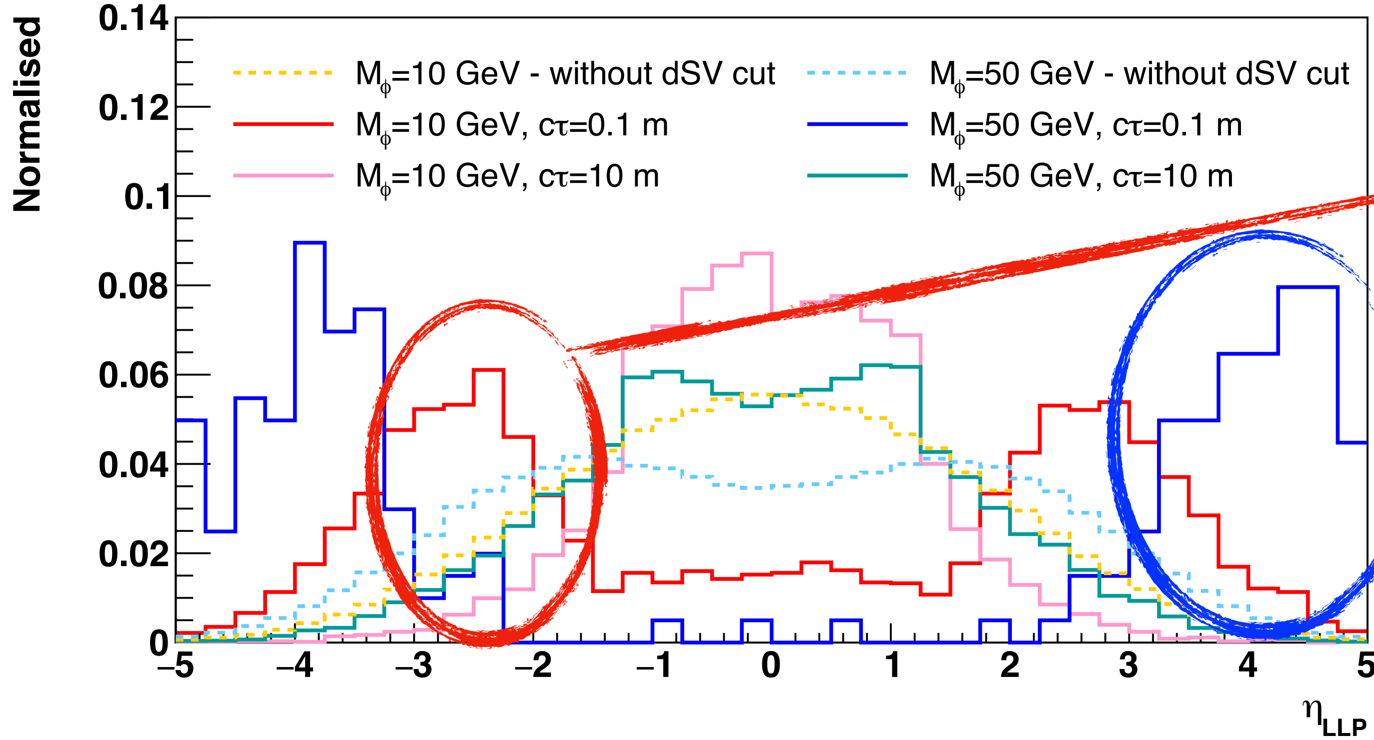
$(50\ \mathrm{GeV},\ 4.6 \times 10^{-6},\ 100\ \mathrm{m})$

$(m_\phi, \mathrm{Br}(h \to \phi\phi)_{UL}, c\tau)$

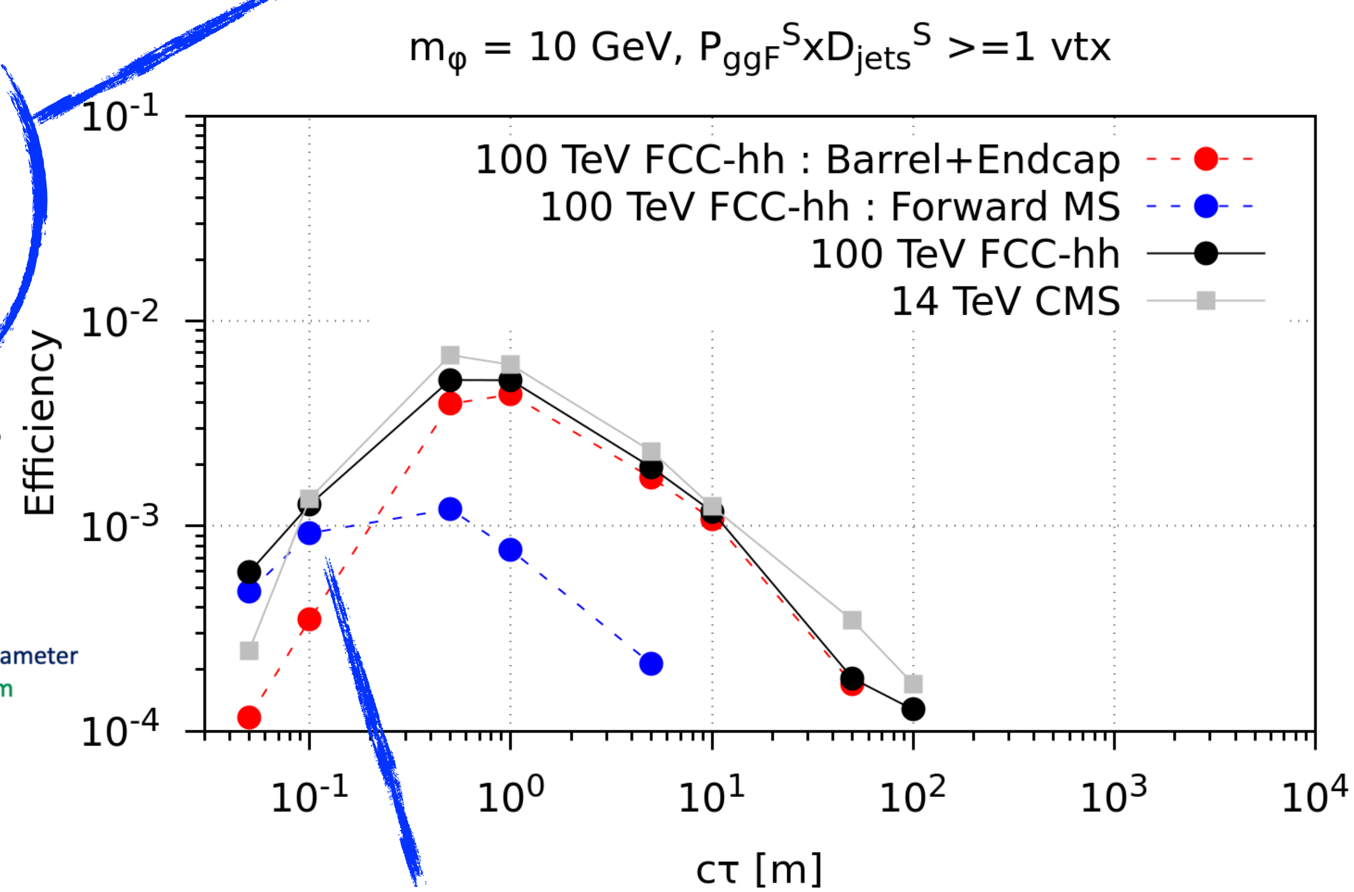
CMS MS + MATHUSLA:
can probe $c\tau \lesssim 10^5\ \mathrm{m}$ for $m_\phi = 60\ \mathrm{GeV}$, without any gap if $\mathrm{Br}(h \to \phi\phi) \gtrsim 0.1\ \%$

A2 FCC-hh MS

Performed similar analyses following the CMS MS one using the FCC-hh MS for final states $\mu^+\mu^-$, $c\bar{c}$, and $b\bar{b}$ for a range of LLP masses between 0.5 GeV and 60 GeV with $c\tau = [0.01,\ 5\times10^7]$ m



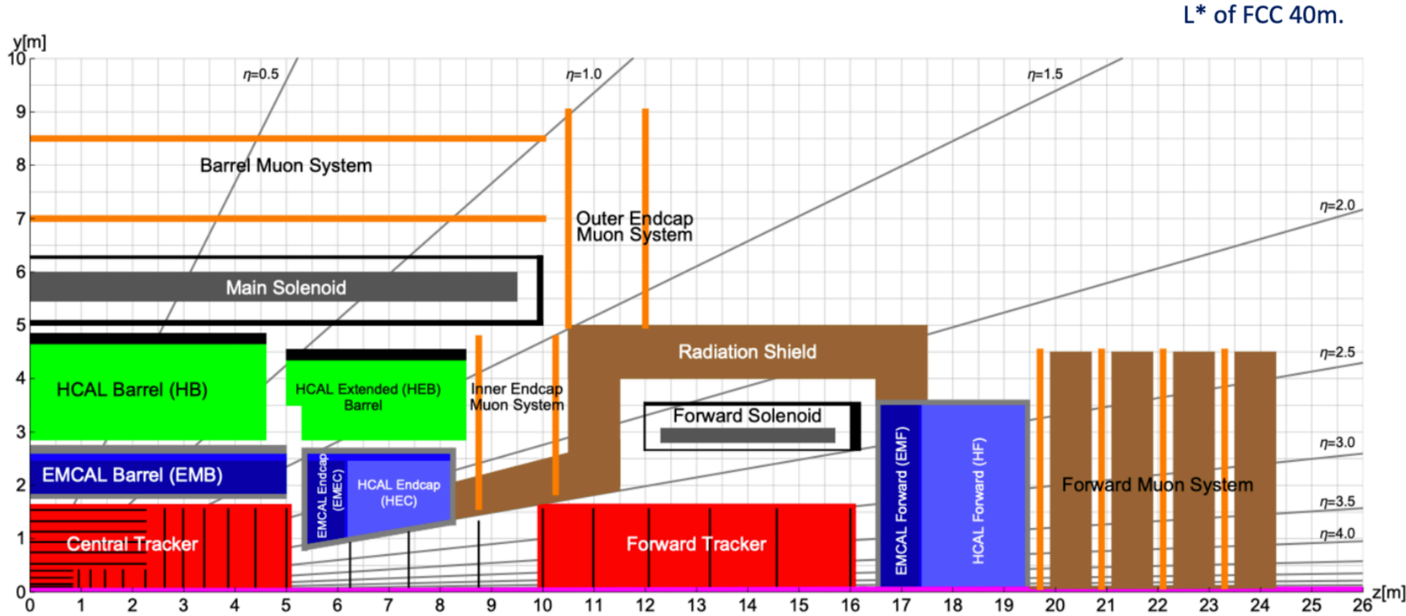
LLPs more in *forward direction* for lower $c\tau$ when decay is restricted within MS



ATLAS/CMS + LHCb geometry

FCC-hh Reference Detector

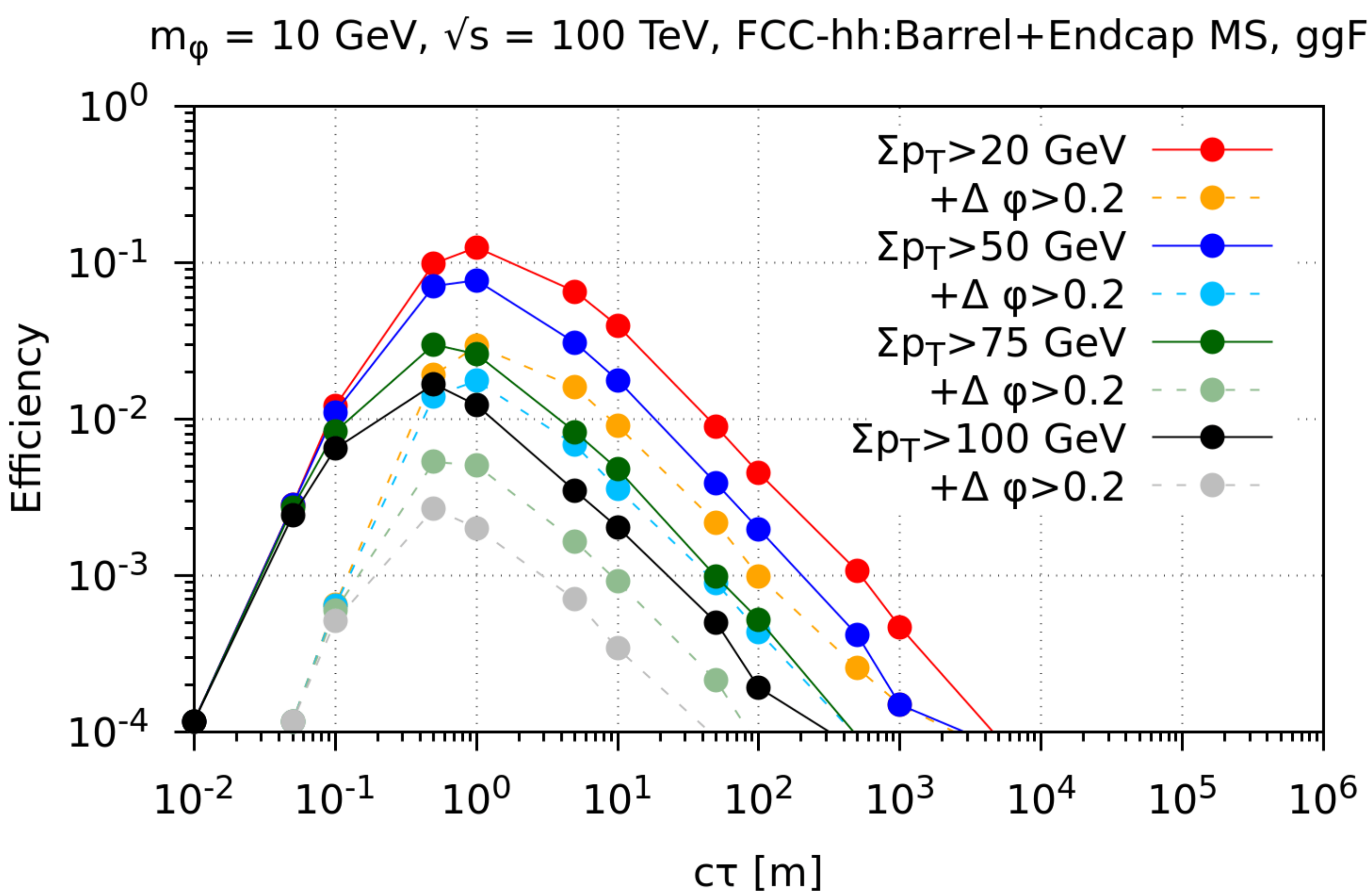
50m long, 20m diameter
Cavern length 66m
L* of FCC 40m.



Forward MS increases sensitivity to lower decay lengths

Otherwise lower decay lengths difficult due to more background

FCC-hh MS



$\sqrt{s}$ [TeV]	Process	Cross section [pb]
14	ggF	50.35
	VBF	4.172
	Vh	2.387 (Wh:1.504, Zh:0.8830)
100	ggF	740.3
	VBF	82.00
	Vh	27.16 (Wh:15.90, Zh:11.26)

- Cross-section increases by a factor of **~15**
- Integrated luminosity is expected to increase by a factor of **10**
- Overall improvement w.r.t HL-LHC given efficiency remains the same **~150**

100 TeV - increase energy threshold

High granular detector - relax $\Delta\phi$ cut

$\sum p_T >$	20 GeV	50 GeV	100 GeV
$\Delta\phi > 0.2$	$\times 75$	$\times 34.5$	$\times 4.5$
No $\Delta\phi$ cut	$\times 250$	$\times 150$	$\times 24$

improvement factors w.r.t. HL-LHC

New Proposal
This work

Proposal for FCC-ee/CEPC - HECATE

Marcin Chrzaszcz, et al., arXiv:2011.01005

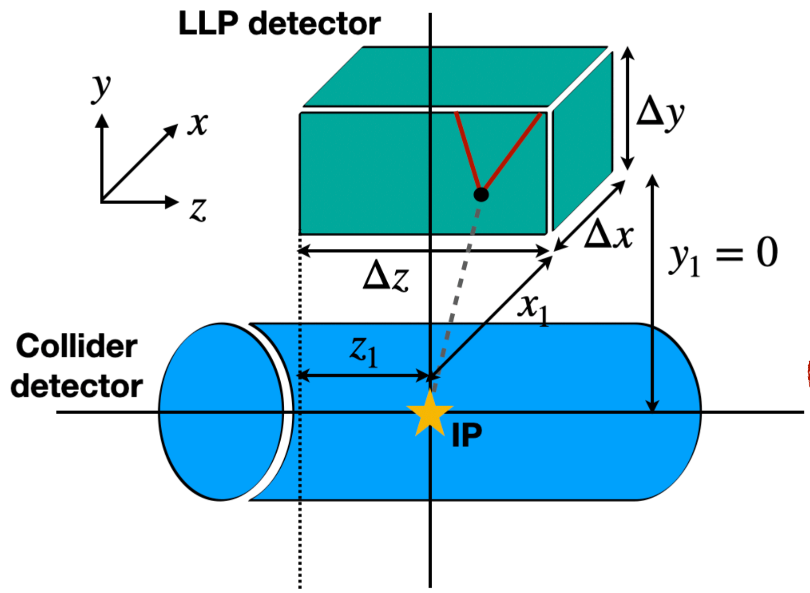
B2 DELIGHT for FCC-hh

FCC-hh design under study
Room for optimisation

DELIGHT

Detector for **l**ong-l**i**ved particles at **high** energy of 100 **T**eV

$x_1 = 25$ m
$y_1 = 0$ m
$z_1 = -\Delta z/2$



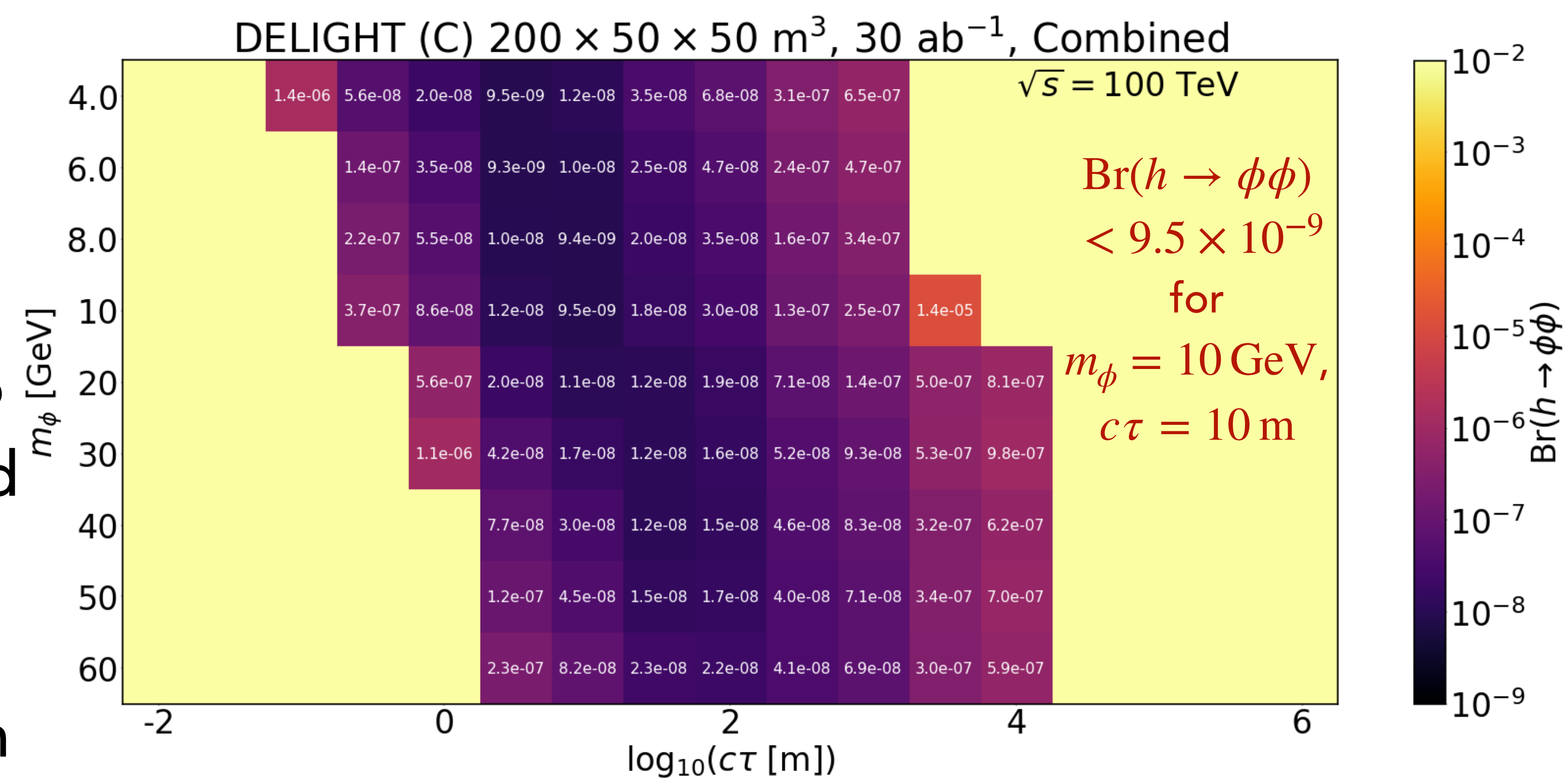
DELIGHT (A): The same as the dimensions of the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 25 \times 100 \times 100\,\mathrm{m}^3$.

DELIGHT (B): Four times bigger than the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 100 \times 100 \times 100\,\mathrm{m}^3$.

DELIGHT (C): Twice the decay volume as the MATHUSLA detector with different dimensions, i.e. $\Delta x \times \Delta y \times \Delta z = 200 \times 50 \times 50\,\mathrm{m}^3$.

- long tunnel-like detector - better shielding against cosmic rays
- closer to IP - use of materials with high shielding power & active veto components to reduce background
- RPCs and possibility of a calorimeter element
- integration with the trigger system of FCC-hh

FURTHER STUDIES



Improvement by $\times 430$ compared to MATHUSLA

Summary

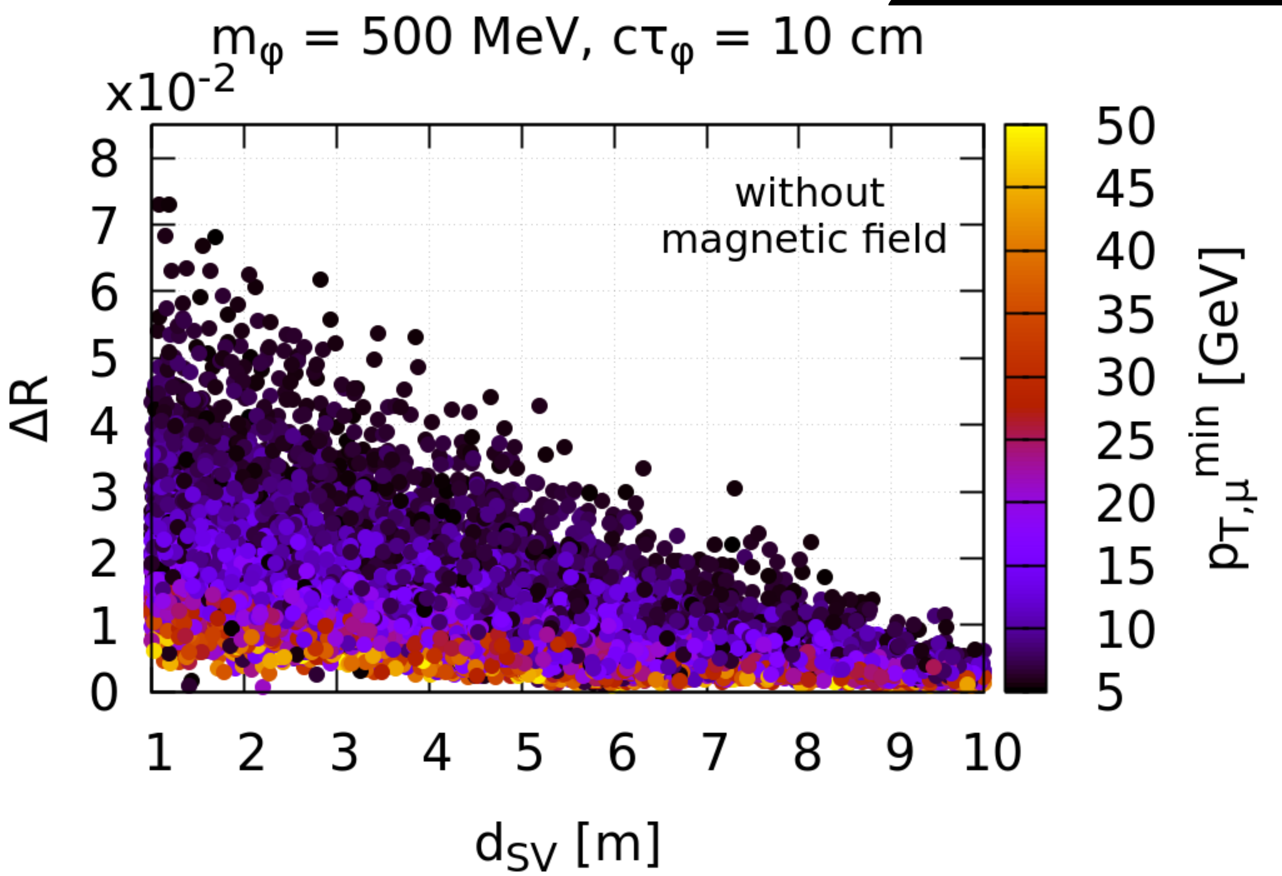
- Studied the landscape of **long-lived light mediators from exotic decays of SM Higgs boson** using the
  - **CMS Muon Spectrometer** at **HL-LHC**
  - Dedicated transverse LLP detectors like **MATHUSLA** and **CODEX-b** at HL-LHC
  - **Muon Spectrometer** (both transverse and forward) at **FCC-hh**
  - New proposal for dedicated LLP detector for FCC-hh - **DELIGHT**
- Combination of the three dominant production modes of SM Higgs boson - **ggF, VBF and Vh**, and multiple decay modes - $\mu^+\mu^-, \pi^+\pi^-, K^+K^-, gg, s\bar{s}, c\bar{c}, \tau^+\tau^-, b\bar{b}$

For further details please have a look at
B. Bhattacherjee, S. Matsumoto, and RS, arXiv:2111.02437 [hep-ph]

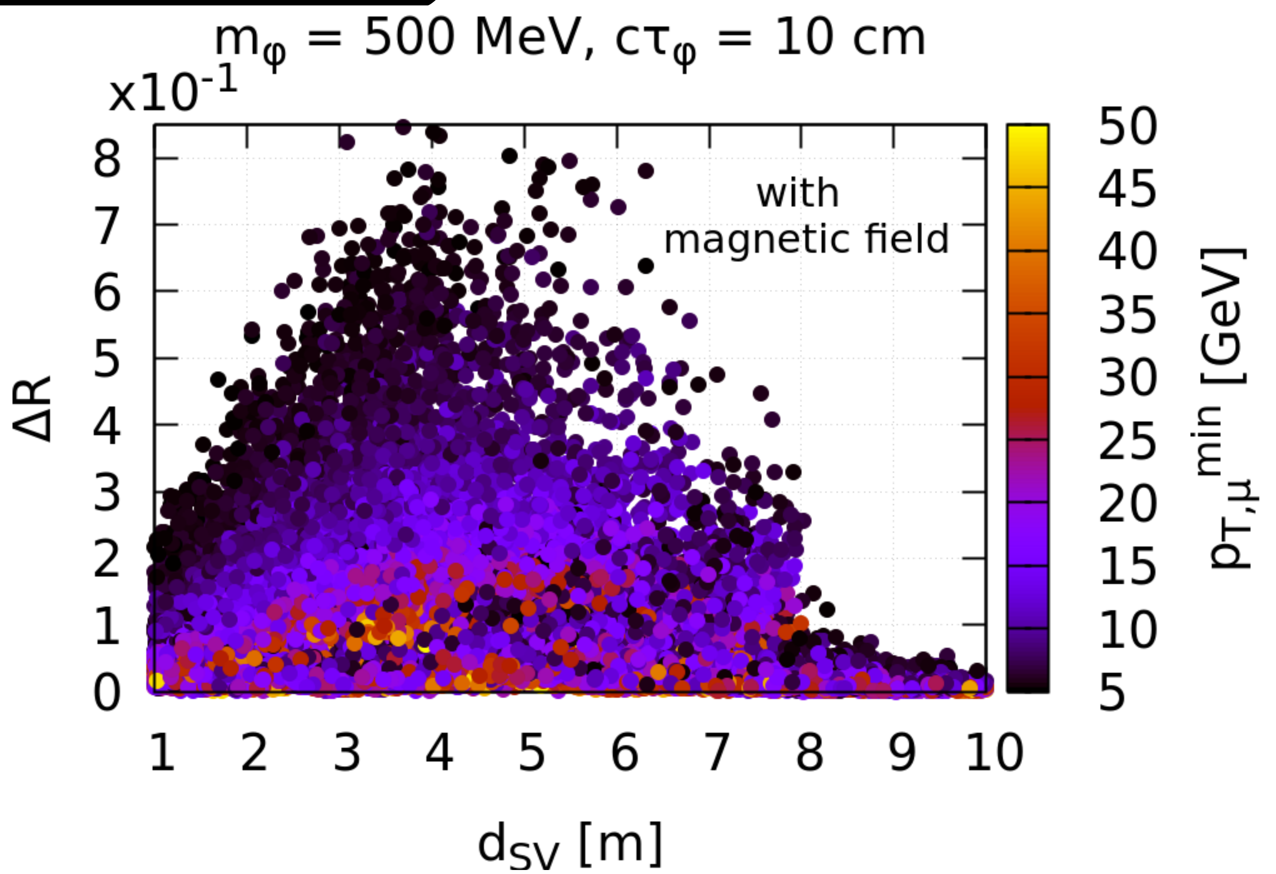
E-mail: rhitaja[at]iisc[dot]ac[dot]in

Thank you

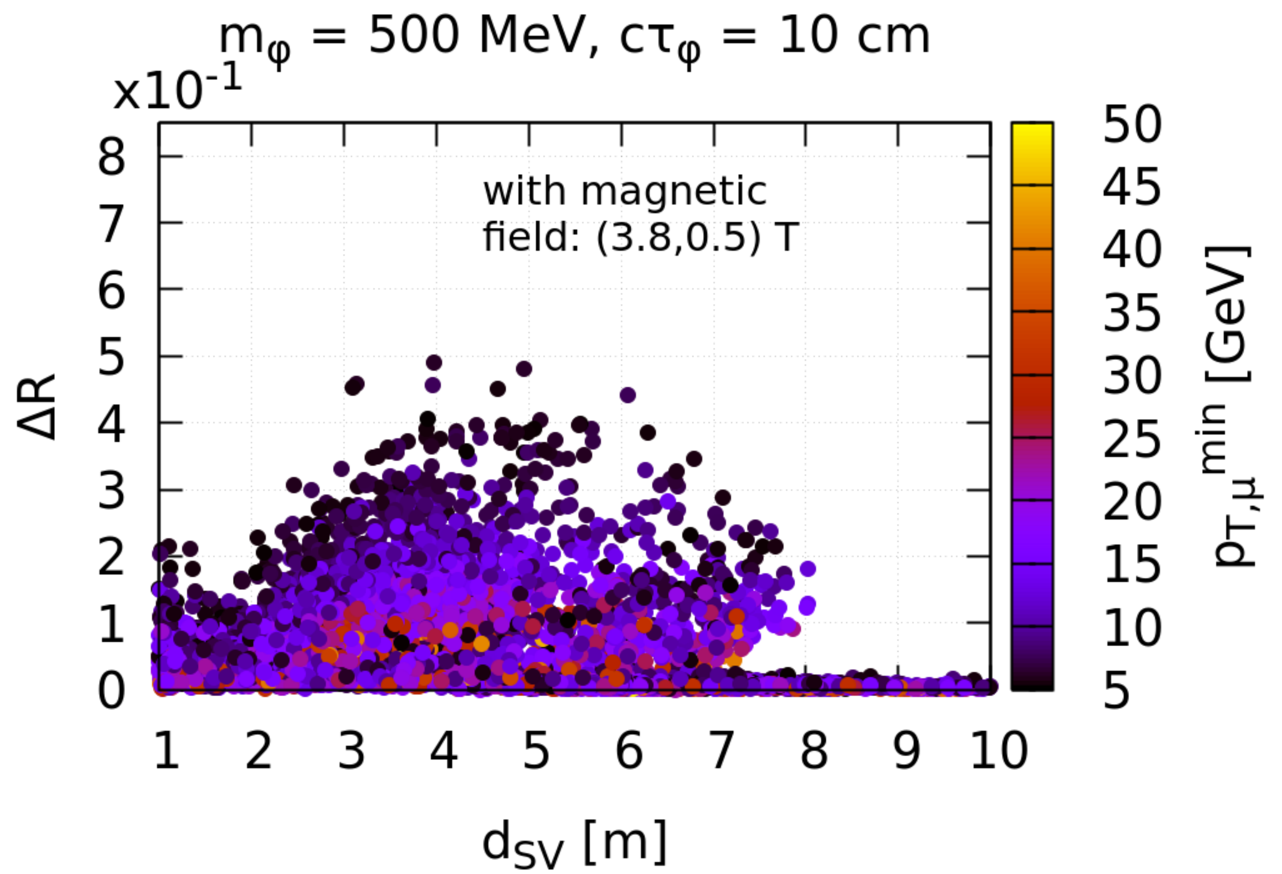
Back up



m_φ = 500 MeV, $c\tau_\varphi$ = 10 cm
without magnetic field
ΔR
d_{SV} [m]
$p_{T,\mu}^{min}$ [GeV]



m_φ = 500 MeV, $c\tau_\varphi$ = 10 cm
with magnetic field
ΔR
d_{SV} [m]
$p_{T,\mu}^{min}$ [GeV]



m_φ = 500 MeV, $c\tau_\varphi$ = 10 cm
with magnetic field: (3.8,0.5) T
ΔR
d_{SV} [m]
$p_{T,\mu}^{min}$ [GeV]

Back

Back up

Possible backgrounds

Displaced dimuons

- SM particles decaying into di-muons, such as J/ψ or Υ ⇒ very small decay lengths (~ few pm) ⇒ separated from signals with the d_0 or d_T cuts or masking the invariant mass of the two muons near the J/ψ and ϒ resonances.
- Cosmic muons ⇒ usually appear back-to-back in the detector ⇒ suppressed by rejecting back-to-back muon pairs with a $\Delta\phi$ cut ⇒ a suppression factor of 10^{-9} for cosmic muon events in the absence of pp collisions. CMS-PAS-FTR-18-002
- Muons from the beam halo ⇒ have very low transverse momentum ⇒ a cut of $p_T > 15$ GeV on displaced muons can suppress the beam halo background.

MS cluster

- Several long-lived hadrons in the SM can punch through the calorimeter from the transition regions and then decay, such as $K_S \rightarrow \pi^+\pi^-, \Lambda \rightarrow p\pi^-, \Sigma^+ \rightarrow p\pi^0/n\pi^+$, $\Sigma^- \rightarrow n\pi^-, \Xi \rightarrow \Lambda\pi^0, \Xi^- \rightarrow \Lambda\pi^-$ and $\Omega^- \rightarrow \Lambda K^-/\Xi\pi^-/\Xi^-\pi^0$ ⇒ demand at least 3-5 charged particles associated with a displaced vertex.
- Punch through of PU jets in the HL-LHC ⇒ can be suppressed either by vetoing events from the transition regions, or by checking for activities inside the calorimeters as well as the trackers associated with the activity in the MS. ATLAS, *PRD* 92 no. 1, (2015) 012010

We assume 50 events ⇒ a significance $(S/\sqrt{B})$ of 2σ can accommodate ~625 background events

Our obtained limits can be scaled accordingly

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