Exotic decays of Higgs boson to light long-lived mediators @ HL-LHC and FCC-hh

based on Biplob Bhattacherjee, Shigeki Matsumoto, RS,
arXiv:2111.02437, PRD 106 (2022) 9, 095018

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INDIAN INSTITUTE OF SCIENCE

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ICNFP 2022
Extended Session

Standard Model of particle physics (**SM**)

successfully explains many fundamental phenomena of particles

Still many pieces **missing from the SM**, like

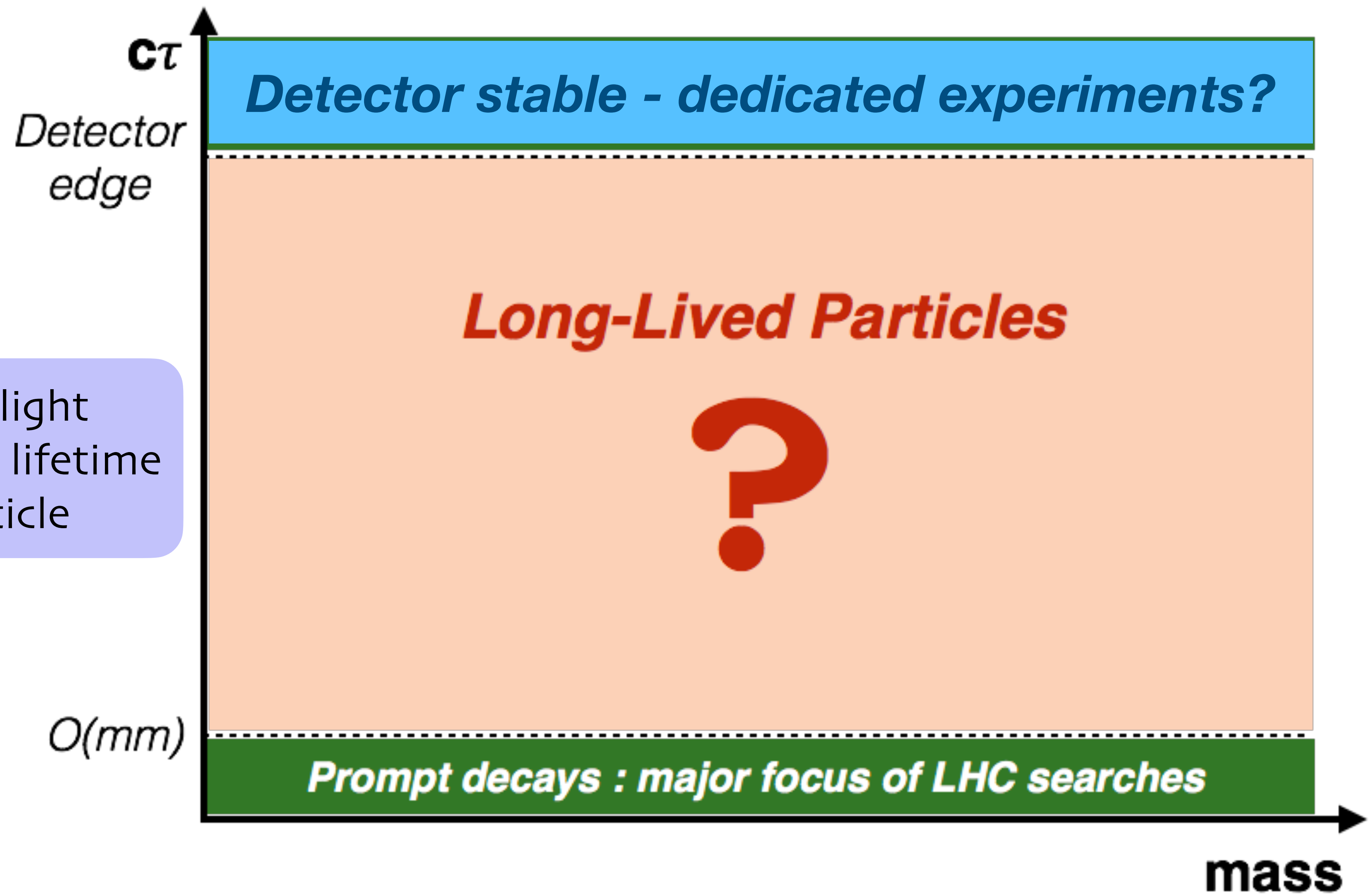
and many more...

We need to look beyond the SM (BSM)

Experiments are putting **stronger constraints on the nature of new physics**.

Most of the conventional LHC searches focus on **prompt decay** of particles.

like top quark, W/Z bosons in SM $\tau \sim 10^{-25}$ s



c: speed of light
τ: proper mean lifetime of the particle

Lifting up the assumption of prompt decays

open the door to the **Lifetime Frontier**

LLPs

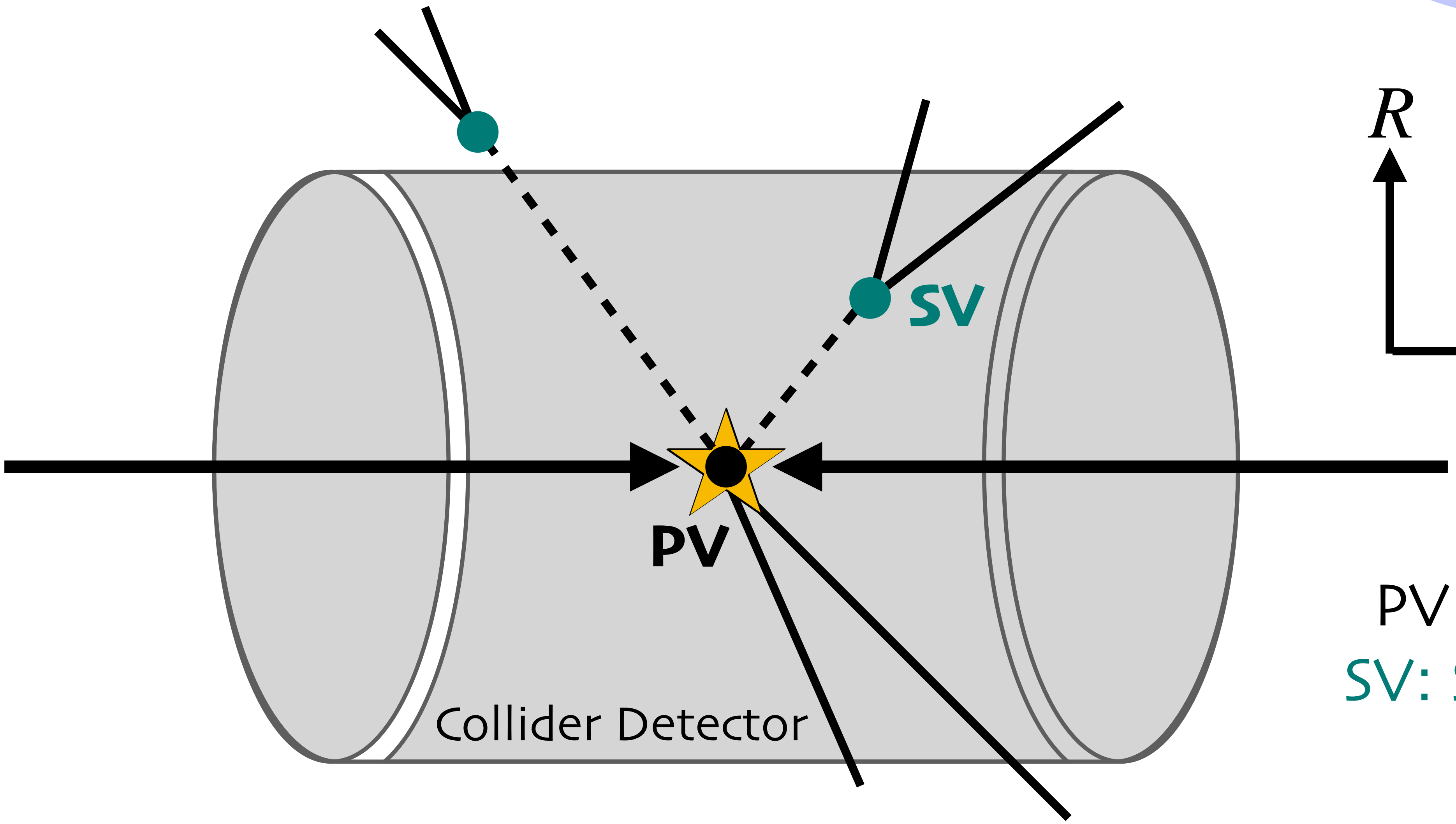
WHAT ARE LONG-LIVED PARTICLES?

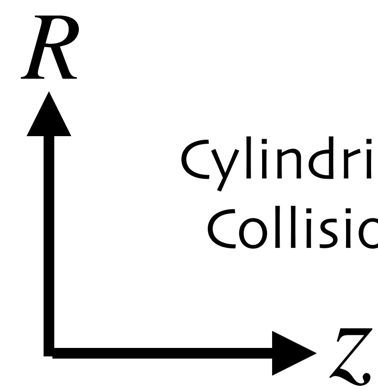
Particles with **large lifetimes (τ)**

— decays after traversing a macroscopic distance in the collider detectors

— or, decays outside the detector

$c\tau \gtrsim \mathcal{O}(\mathrm{mm})$





PV: Primary Vertex

SV: Secondary Vertex

Effect of magnetic field not shown

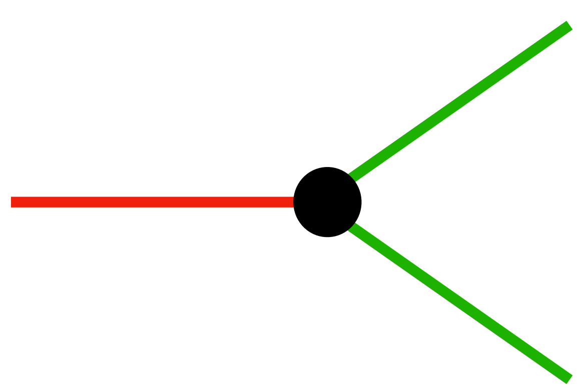
Reasons behind long lifetimes

?

$$\Gamma\left(\text{or } \frac{1}{\tau}\right) \propto |\,\text{Amplitude}\,|^2 \times (\text{Phase space factor})$$

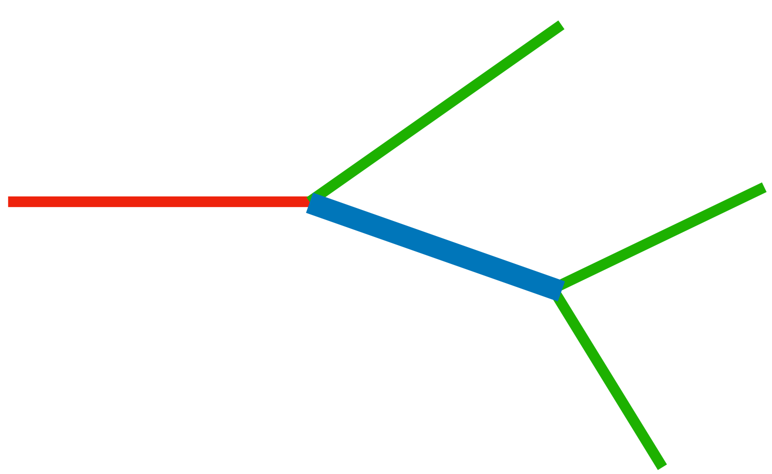
Small couplings

e.g., c and b quarks (SM),
RPV SUSY (BSM)



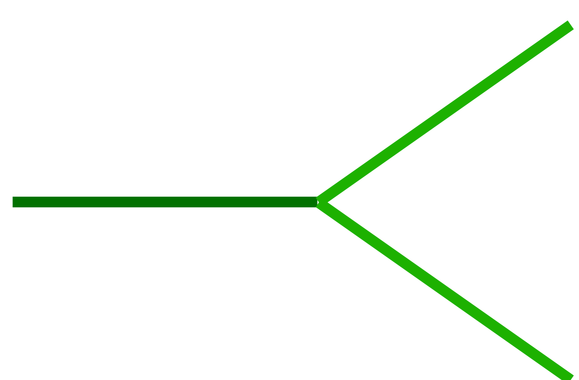
Heavy scales, $\Gamma \sim \dfrac{m^5}{M^4}$

e.g., muon (SM),
gluino in Split-SUSY (BSM)



Kinematic squeezing

e.g., neutron (SM),
compressed SUSY
scenarios (BSM)



LLP decays in colliders

Decay length in the detector

d is the **product** of $\beta\gamma$ and $c\tau$ **distributions**

LAB FRAME $\boxed{d = \beta\gamma c\tau}$

from PRODUCTION mode **from DECAY width**

$\boxed{\beta\gamma = \frac{p}{m} : \text{boost factor}}$

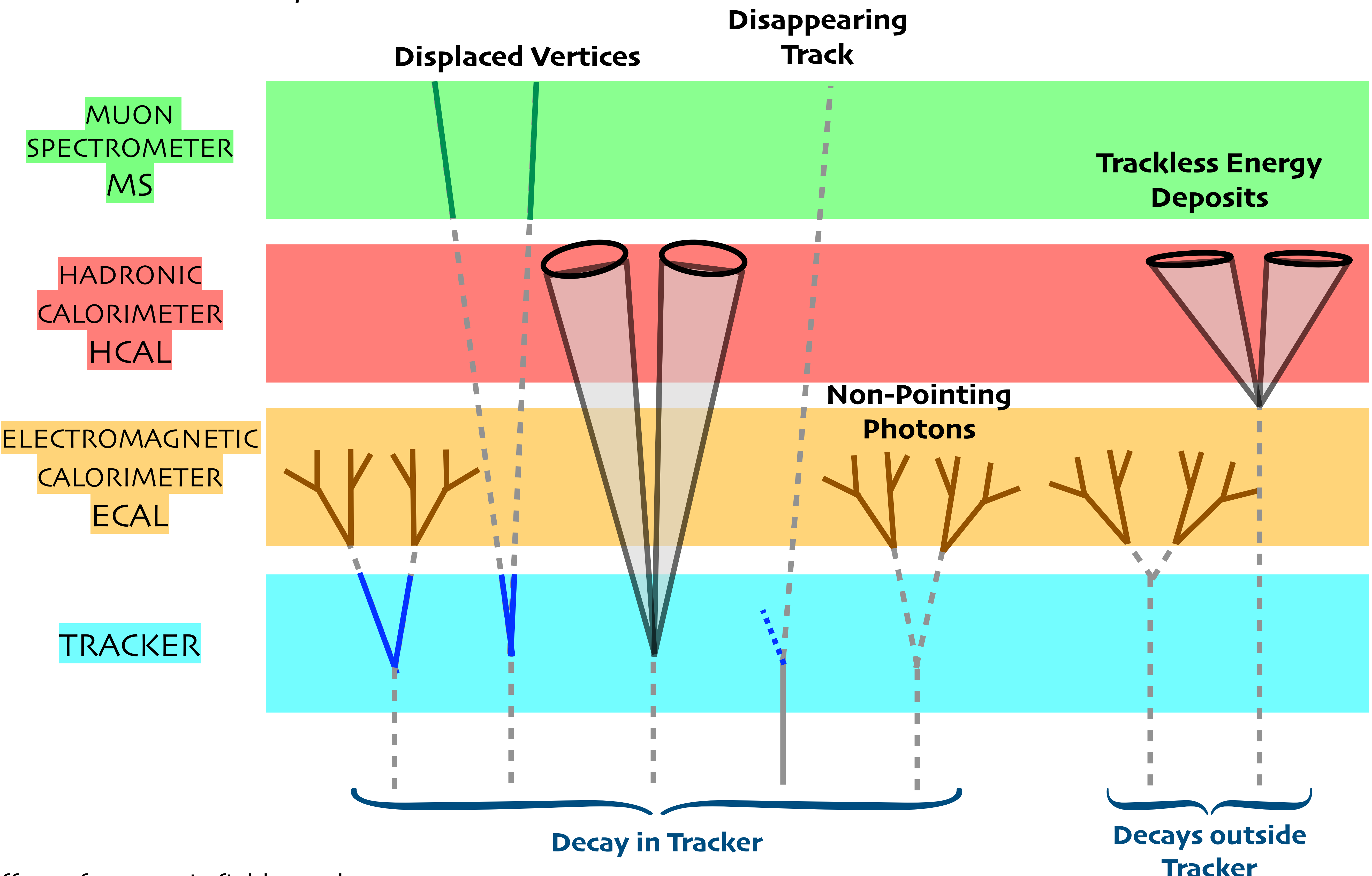
c : speed of light

τ : proper mean lifetime of the particle

Lighter particles ⇒ more displaced as compared to heavier ones for the same lifetime

A Peek in to the Exotic Signatures of LLPs

not a complete list

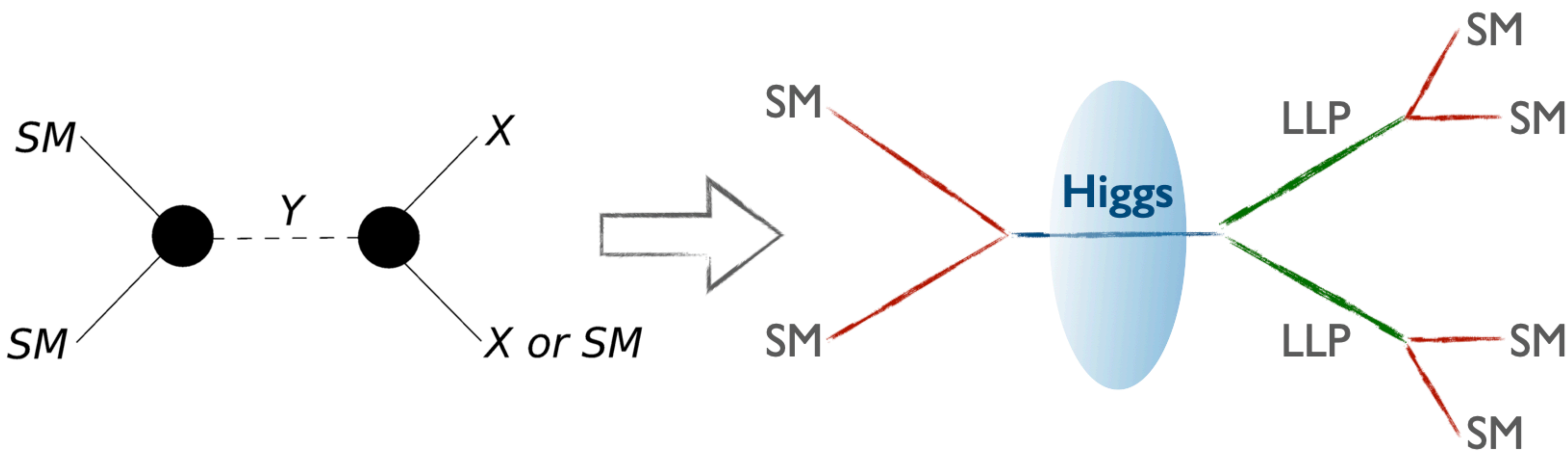


Effect of magnetic field not shown

Rhitaja Sengupta, IISc

Long-lived particles in the Higgs portal

~ LLPs having dominant coupling to the SM Higgs boson ~



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

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

Long-lived mediator from a minimal DM model

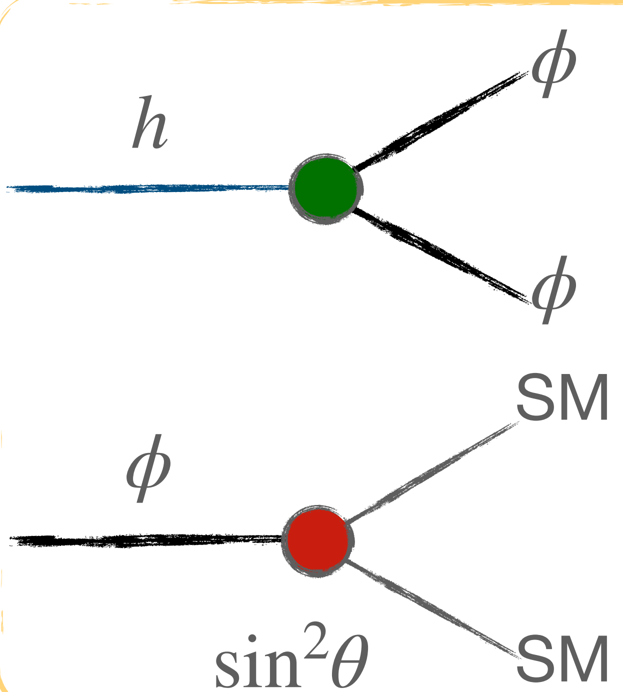
Shigeki Matsumoto, et al., *JHEP* 07 (2019) 050

Light Scalar Mediator

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

Mixing highly constrained

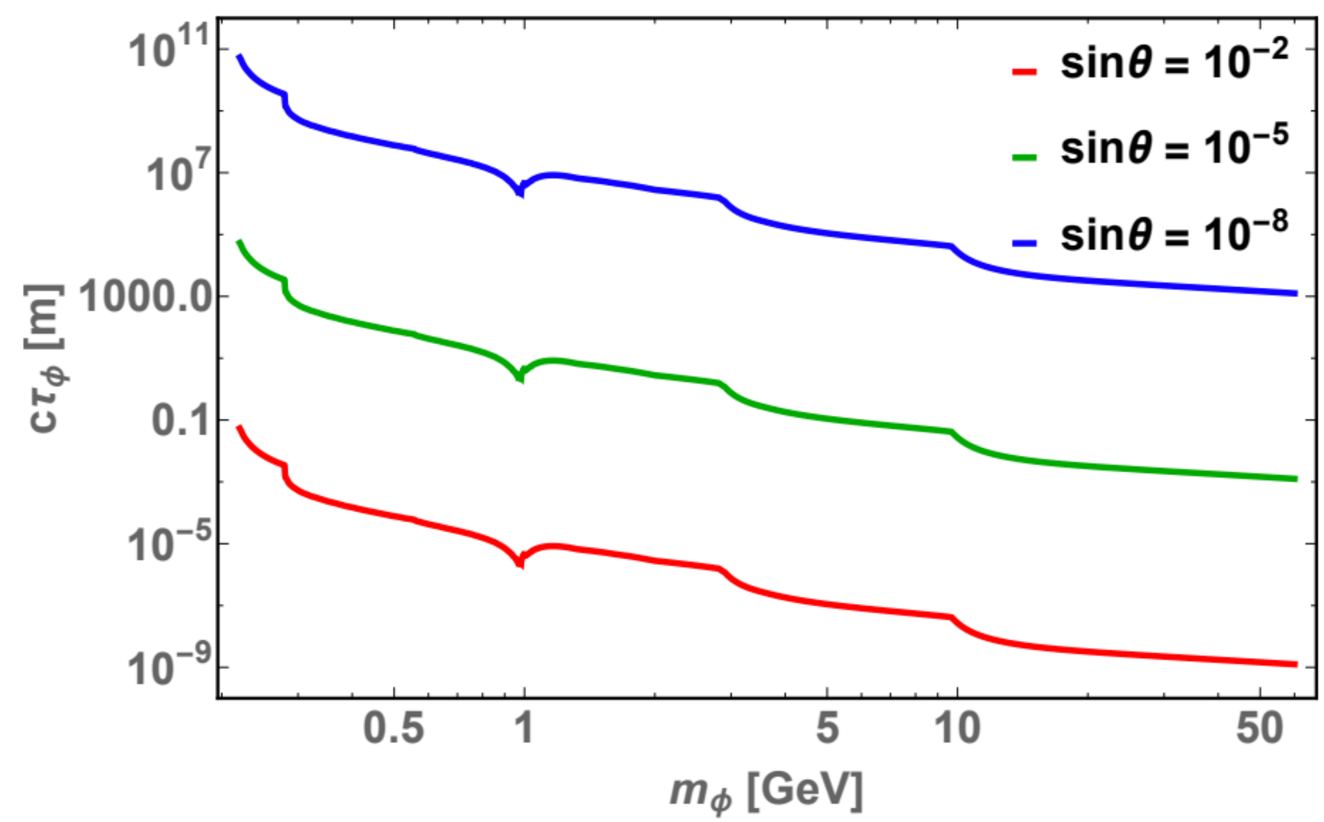
Not severely constrained so far



Production of ϕ has a different coupling than its decay

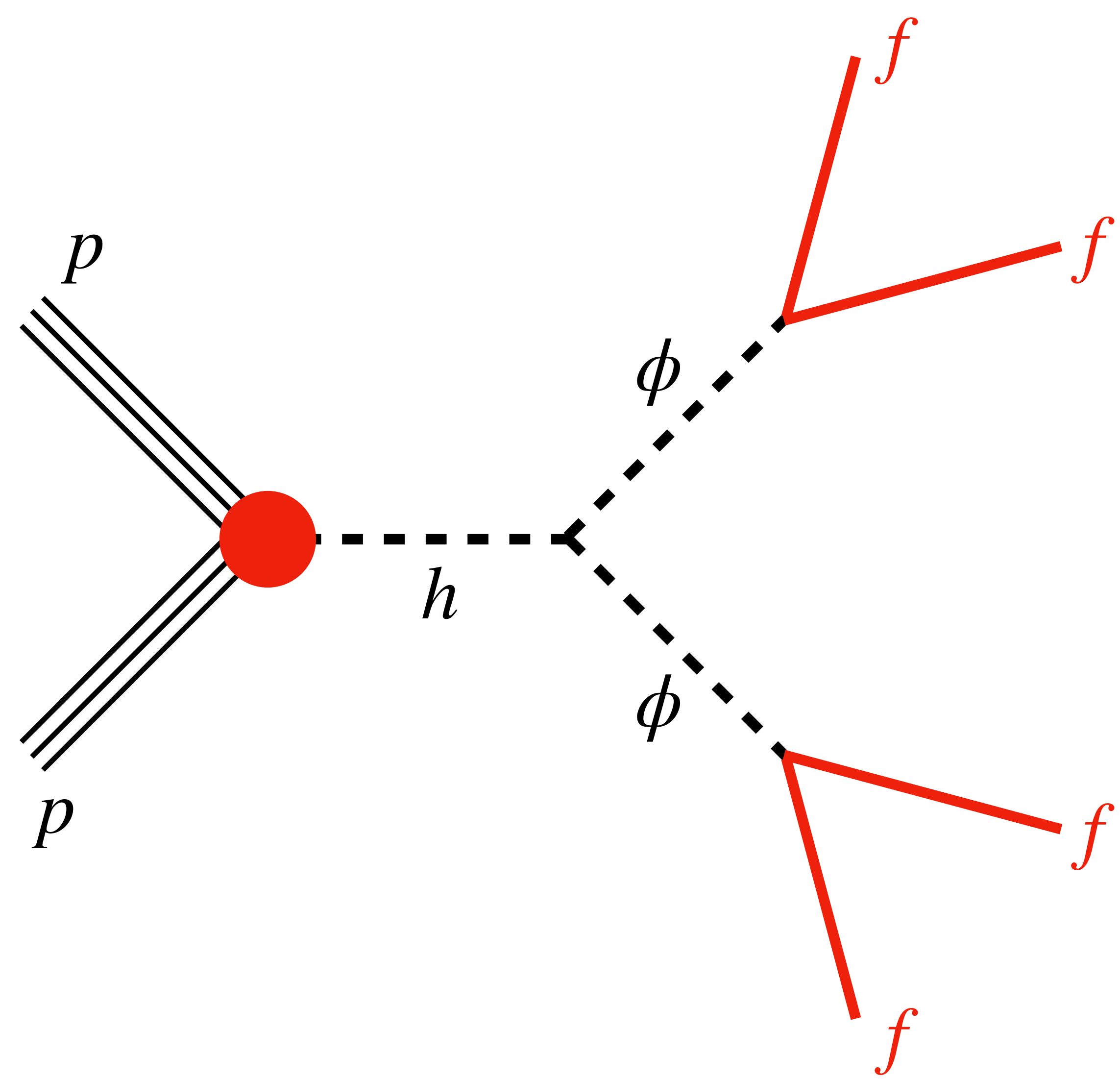
$\sin^2\theta \downarrow \quad c\tau_\theta \uparrow$

Long-lived mediator



Scalar LLPs from Higgs Boson Decay

ϕ: Long-lived mediator



- ? Production: From the decay of SM Higgs boson
- ? Decay: SM particles through mixing with SM Higgs boson, $\sin\theta$

Where to look for the LLPs?

Biplob Bhattacherjee, Shigeki Matsumoto, RS, arXiv:2111.02437, PRD 106 (2022) 9, 095018

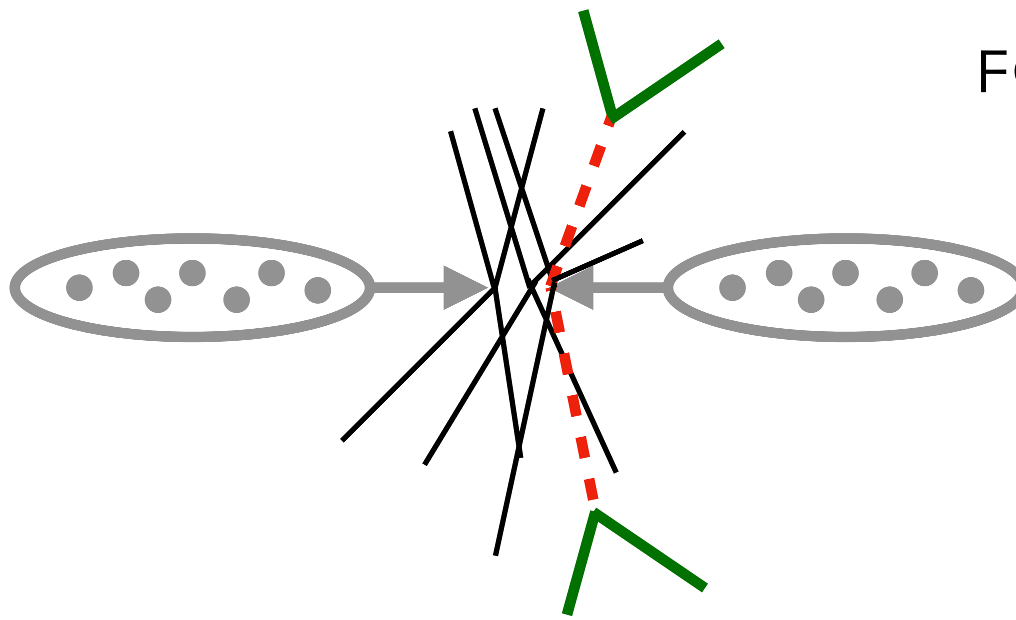
$\mathcal{Q}$: – **Prospect of HL-LHC/FCC-hh?**

Issue of pile-up (PU)

HL-LHC: High Luminosity LHC
14 TeV, 3 ab^{-1}

FCC: Future Circular Collider
100 TeV, 30 ab^{-1}

bunches of protons collide



interesting interaction accompanied by multiple pile-up interactions

Run-1/2 - around 30-50 interactions per bunch crossing

centre of mass energy of collision, integrated luminosity (# of collisions per unit area)

Where to look for the LLPs?

Biplob Bhattacherjee, Shigeki Matsumoto, RS, arXiv:2111.02437, PRD 106 (2022) 9, 095018

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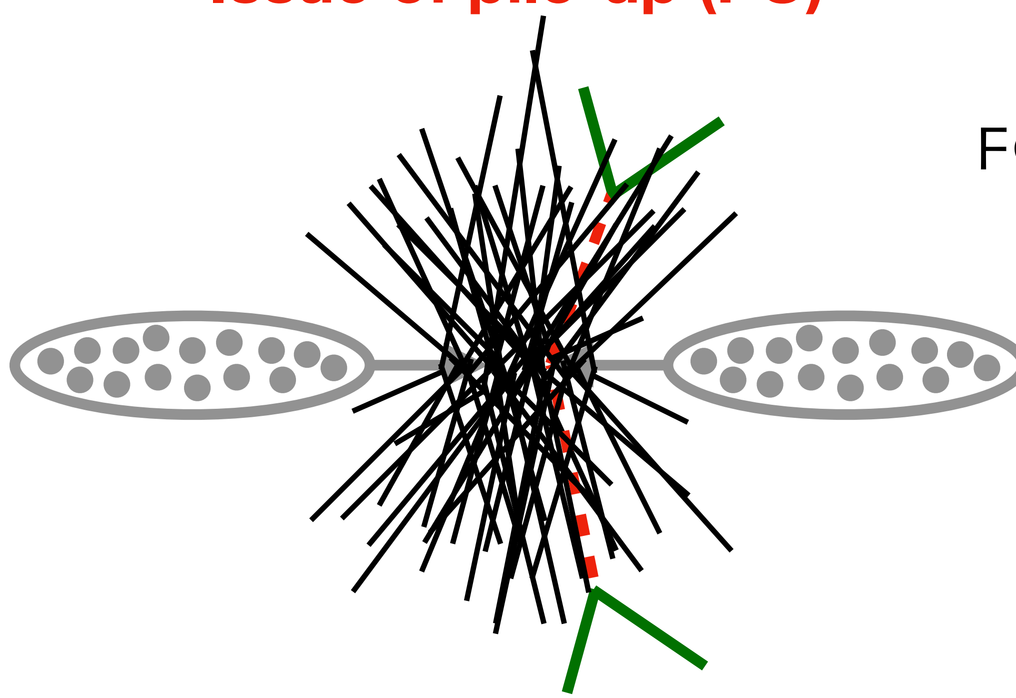
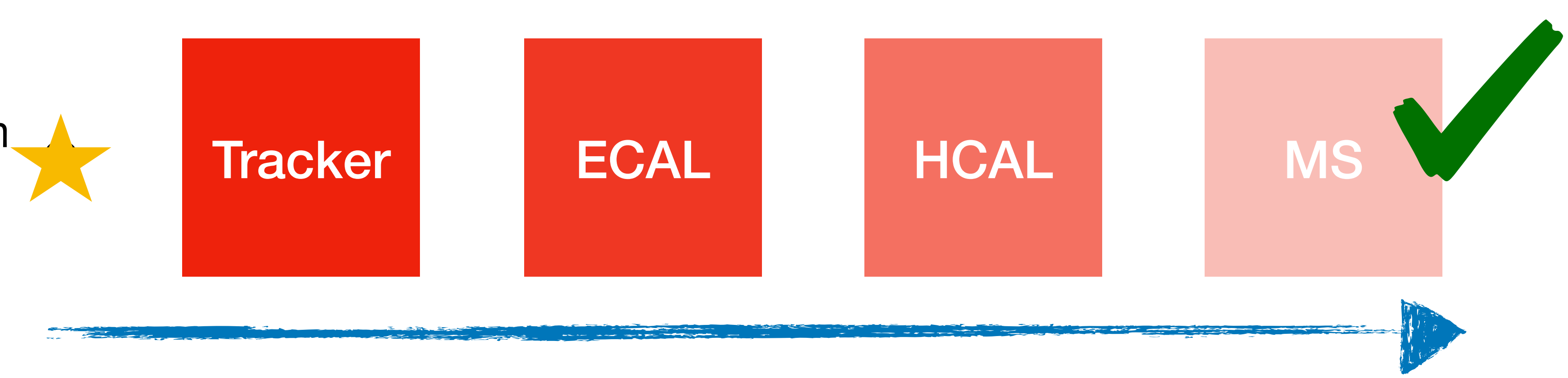


to increase luminosity, number of protons per bunch increased

Increased Luminosity = Increased pile-up

HL-LHC - 140/200 mean PU interactions per bunch crossing expected

Interaction Point (IP)



Where to look for the LLPs?

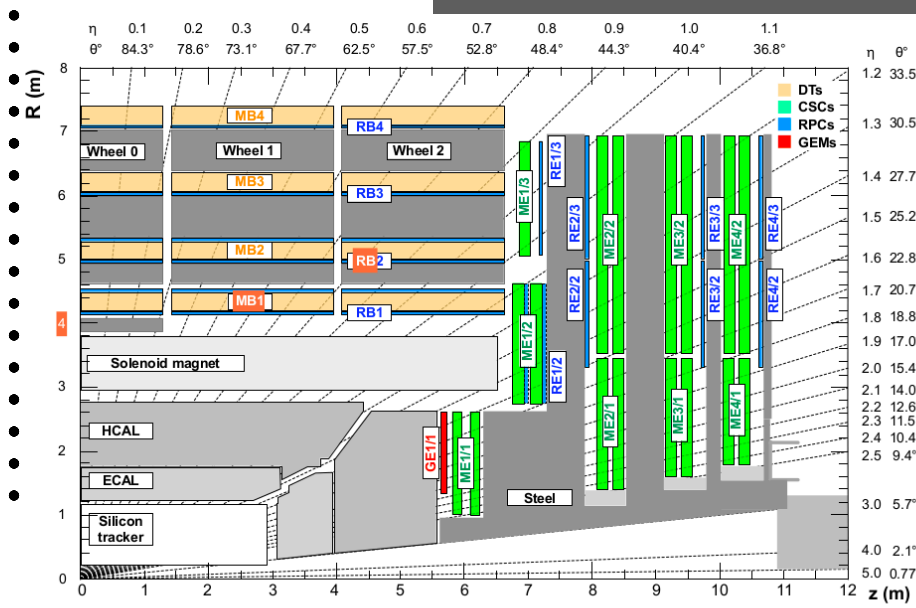
A ***Muon Spectrometer (MS)***

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

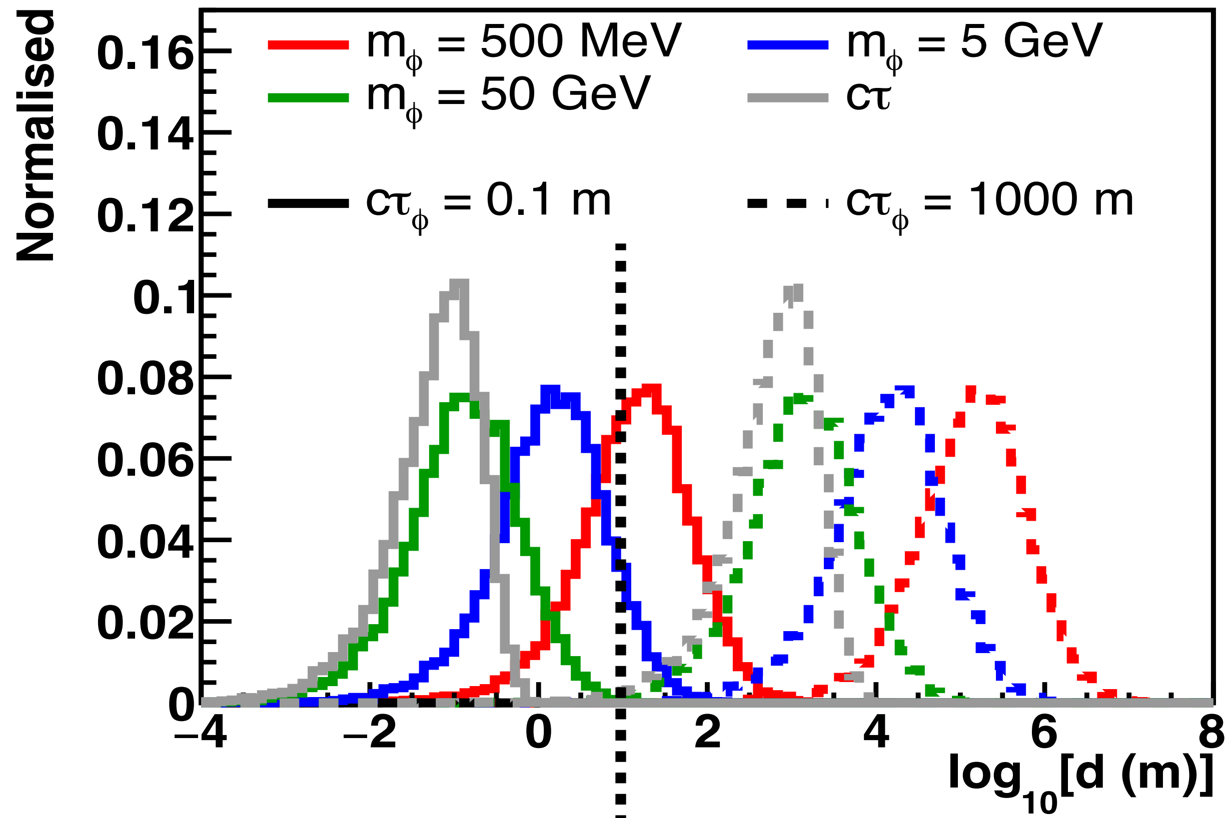
- Least affected by PU - farthest detector from the IP
- Large decay volume - compensates for its distance from the IP
- Sensitive to multiple decay modes

How do particles other than muons look in the MS?

ATLAS	CMS
displaced vertices in the MS	$e^{\pm}, \gamma$, hadrons — iron yokes — **cluster of hits in the MS**
ATLAS, *PRD* 99 no. 5, (2019) 052005	CMS, *PRL* 127 (2021) 26, 261804
ATLAS, *PRD* 101 no. 5, (2020) 052013	
ATLAS, ATL-PHYS-PUB-2019-002	



Where to look for the LLPs?



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

ATLAS and CMS main detectors can probe

after $\mathcal{O}(10)$ m, ATLAS and CMS main detectors lose sensitivity

B ***Dedicated transverse LLP detectors***

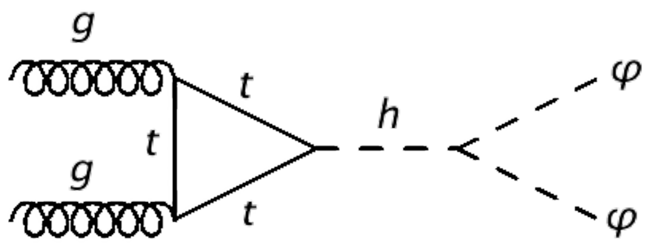
mostly centrally produced in Higgs decays - especially lighter LLPs

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

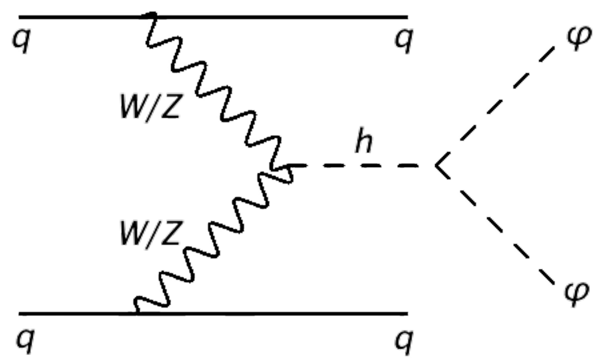
New Proposal
This work

Analysis Strategy for Decays in MS

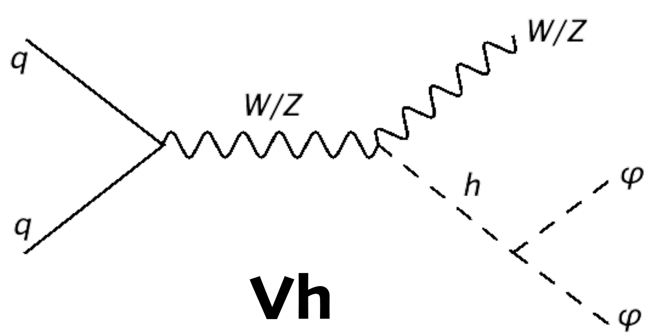
Production



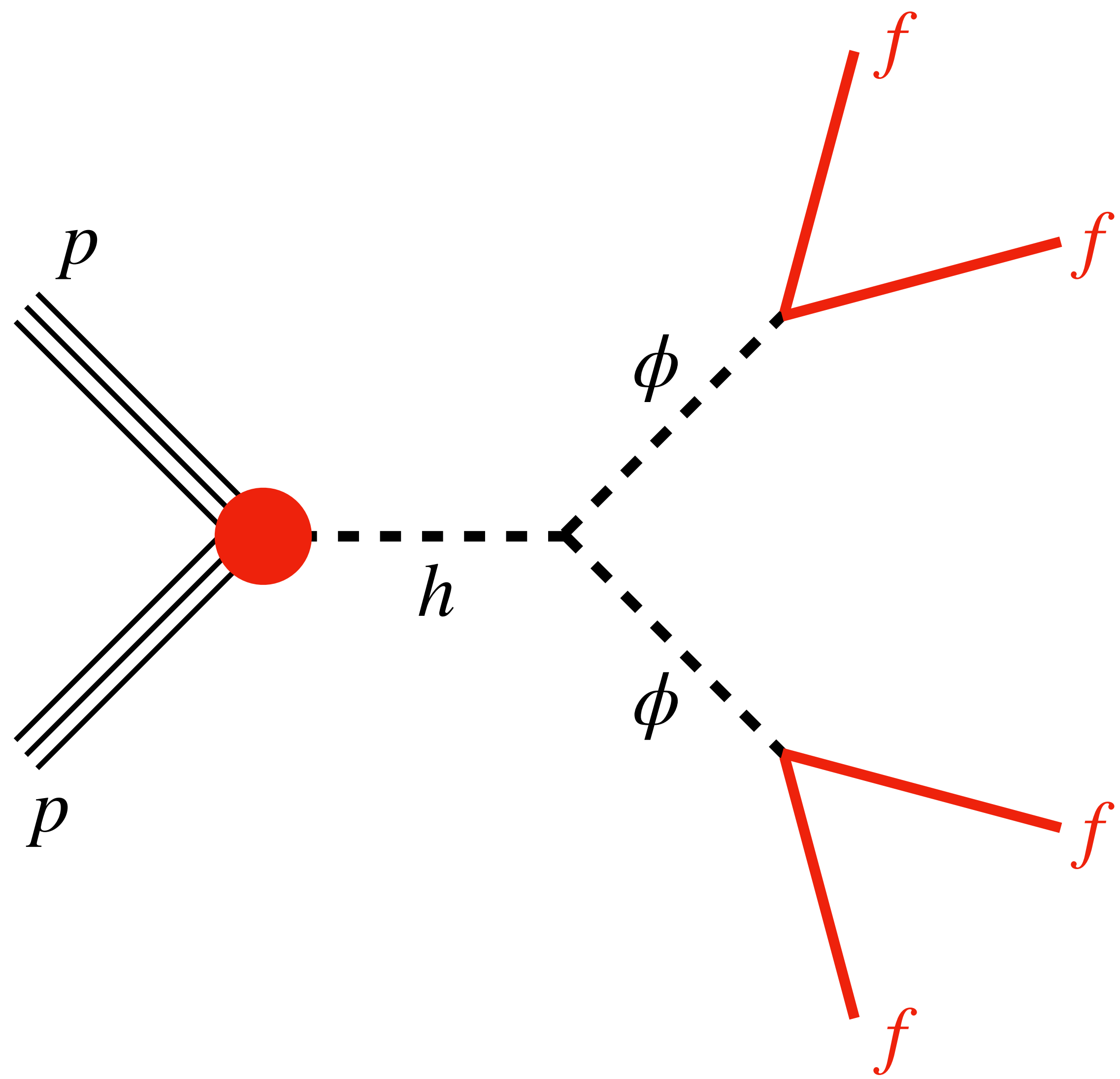
ggF



VBF



Vh



Decay

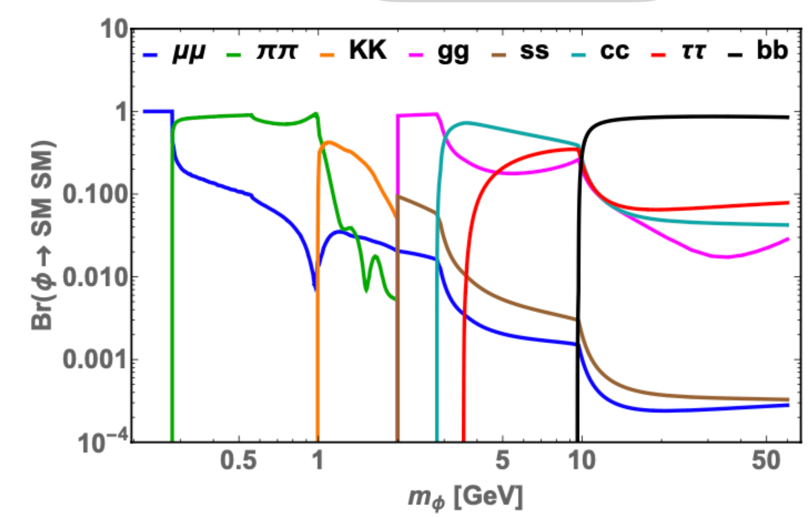
$\mu^+\mu^-$ $\quad s\bar{s}$

$\pi^+\pi^-$ $\quad c\bar{c}$

K^+K^- $\quad \tau^+\tau^-$

gg $\quad b\bar{b}$

[Branching Fraction]

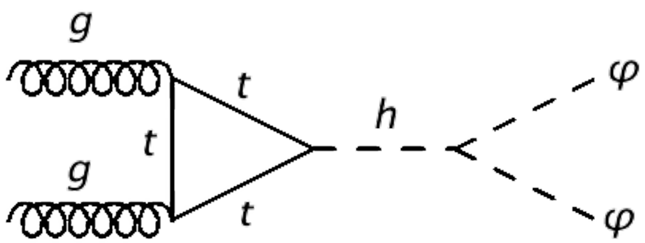


Prompt objects associated with production

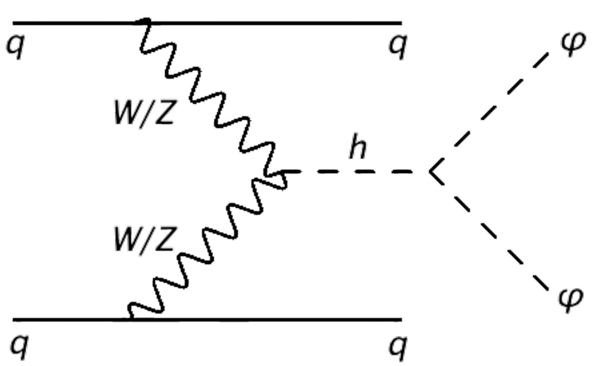
Displaced objects from the LLP decay

Analysis Strategy for Decays in MS

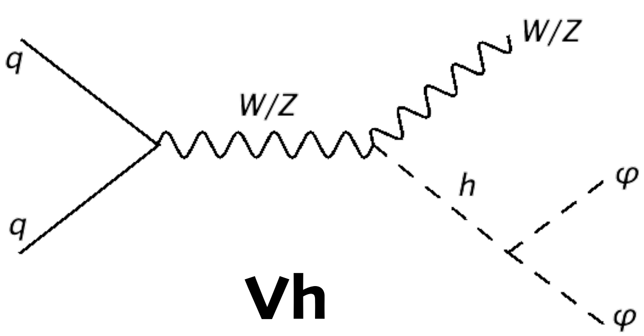
Production



ggF



VBF



Vh

Prompt objects
associated with production

Selection cuts on PROMPT OBJECTS

prompt jets, electrons, muons

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

ggF, VBF, Vh-jet

Vh-lep

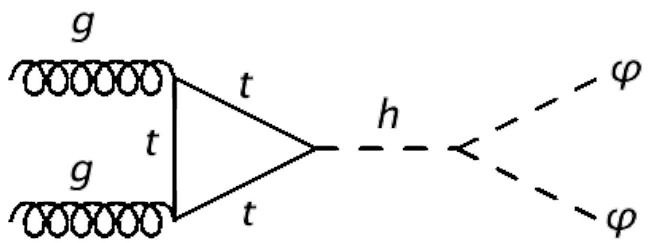
P^H : Hard set of cuts on prompt objects

cuts from Phase-II CMS L1 trigger menu

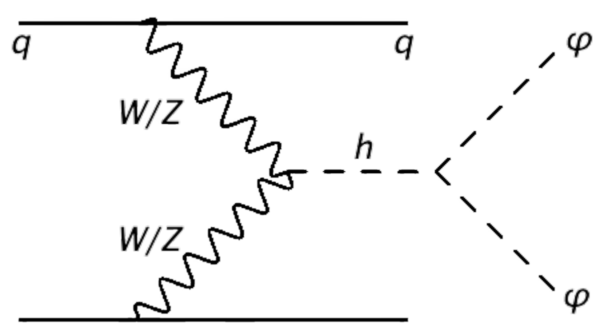
CMS-TDR-021

Analysis Strategy for Decays in MS

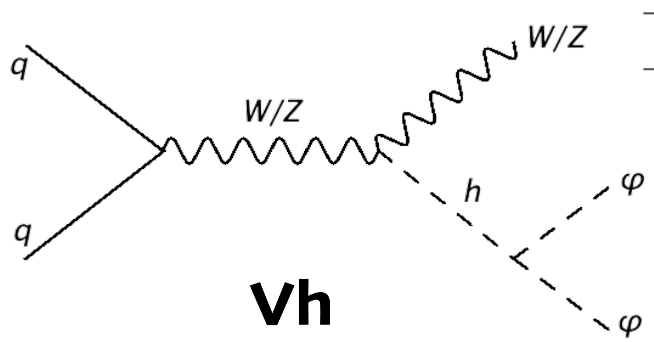
Production



ggF



VBF



Vh

Prompt objects
associated with production

Selection cuts on PROMPT OBJECTS

prompt jets, electrons, muons

Trigger	In P^H_{Mode}	In P^S_{Mode}
Single jet	$p_T^j > 180\,\text{GeV},\ \lvert\eta_j\rvert < 2.4.$	$p_T^j > 90\,\text{GeV},\ \lvert\eta_j\rvert < 2.4.$
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	$p_T^e > 36\,\text{GeV},\ \lvert\eta\rvert < 2.4.$	$p_T^e > 18\,\text{GeV},\ \lvert\eta\rvert < 2.4.$
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	$p_T^{\mu_1} > 15\,\text{GeV},\ p_T^{\mu_2} > 7\,\text{GeV},\ \lvert\eta\rvert < 2.4.$	$p_T^{\mu_1} > 7\,\text{GeV},\ p_T^{\mu_2} > 7\,\text{GeV},\ \lvert\eta\rvert < 2.4.$

ggF, VBF, Vh-jet

Vh-lep

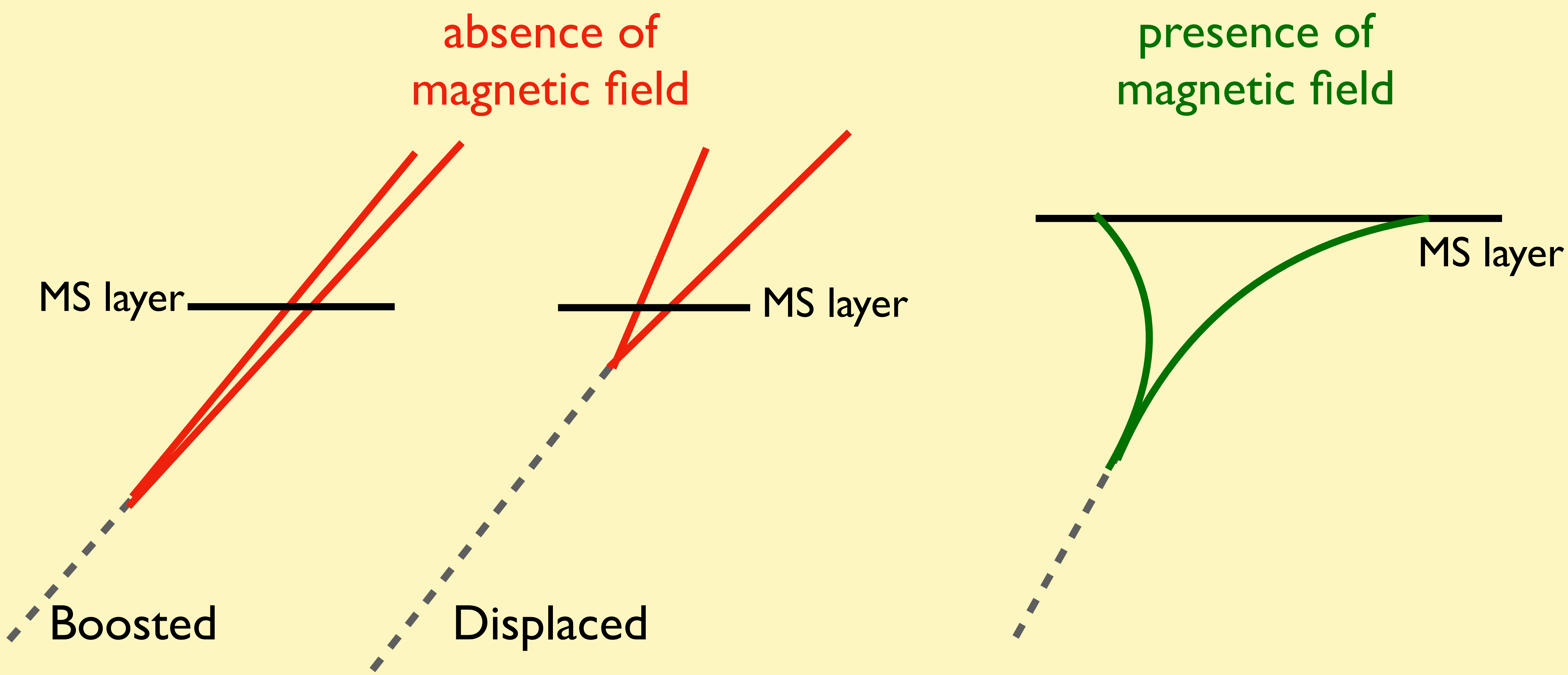
P^S : Soft set of cuts on prompt objects

assuming thresholds on prompt objects can be reduced in the presence of displaced activity in the MS

Analysis Strategy for Decays in MS

CMS: Magnetic field till MS (changes sign after HCAL and reduced in magnitude from 3.8 T to 0.5 T)

Delphes (fast detector simulation): Magnetic field till Tracker



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

Delta R

Analysis Strategy for Decays in MS

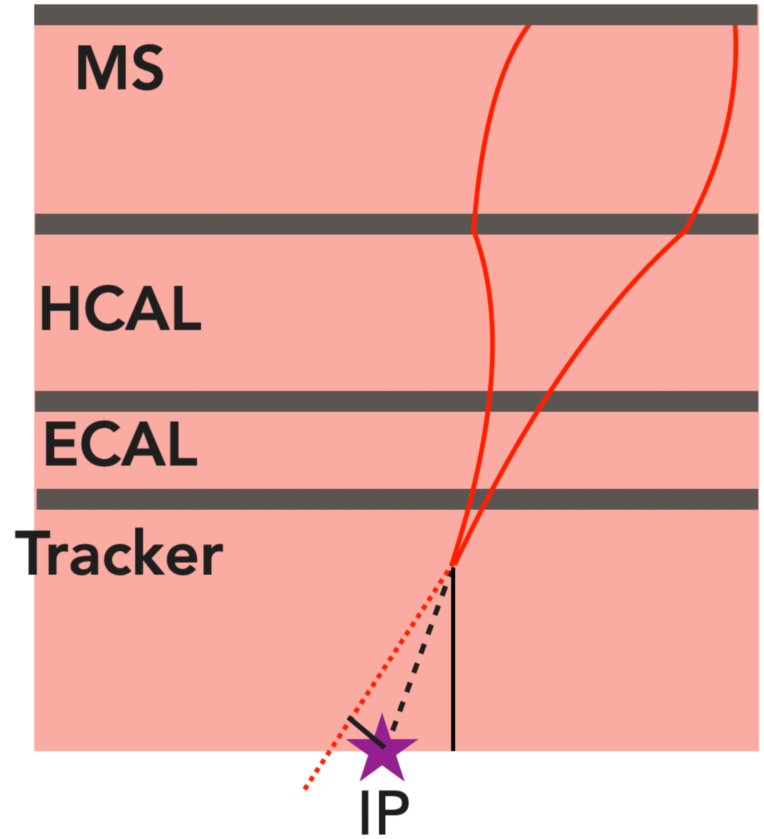
Selection cuts on DISPLACED OBJECTS

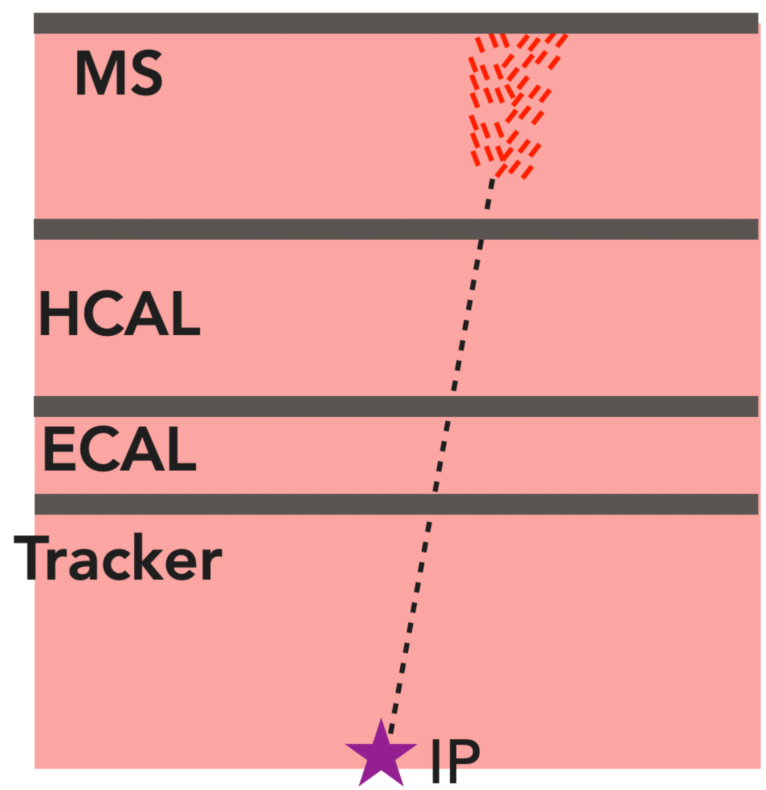
Displaced muons $\mu^+\mu^-$ hard soft

	D^H_μ	D^S_μ
Muons	$p_T^\mu > 20\,\mathrm{GeV}$	$p_T^\mu > 10\,\mathrm{GeV}$
	$n_\mu \geq 2$	$n_\mu \geq 2$
	$\lvert\eta^\mu\rvert < 2.8$	$\lvert\eta^\mu\rvert < 2.8$
	$\lvert d_0^\mu\rvert > 2\,\mathrm{mm}$	$\lvert d_0^\mu\rvert > 2\,\mathrm{mm}$
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 jets 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 $\lvert d_z\rvert < 9\,\mathrm{m}$
	$n^{\mathrm{ch}}_{\mathrm{dSV}} \geq 5$	$n^{\mathrm{ch}}_{\mathrm{dSV}} \geq 3$
	$\sum p_{T,dSV} > 50\,\mathrm{GeV}$	$\sum p_{T,dSV} > 20\,\mathrm{GeV}$
	$\Delta\phi_{\max} > 0.2$	$\Delta\phi_{\max} > 0.1$
Event	$n_{\mathrm{cluster}} \geq 1$, $n_{\mathrm{cluster}} = 2$	$n_{\mathrm{cluster}} \geq 1$, $n_{\mathrm{cluster}} = 2$





Decay

$\mu^+\mu^-$

$\pi^+\pi^-$

K^+K^-

$\tau^+\tau^-$

gg

$s\bar{s}$

$c\bar{c}$

$b\bar{b}$

Displaced objects from the LLP decay

Analysis Strategy for Decays in MS

Combination of cuts using hard and soft selections on prompt and displaced objects

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

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

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

cuts on the prompt & displaced objects relaxed $\Rightarrow$
combination expected to keep backgrounds in control

CMS MS @ HL-LHC

$\mathrm{Br}(h \to \phi\phi) \times \mathrm{Br}(\phi \to \mu^+\mu^-)$
$< 3.1 \times 10^{-6}$
for $m_\phi = 60\,\mathrm{GeV}, c\tau = 0.5\,\mathrm{m}$

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

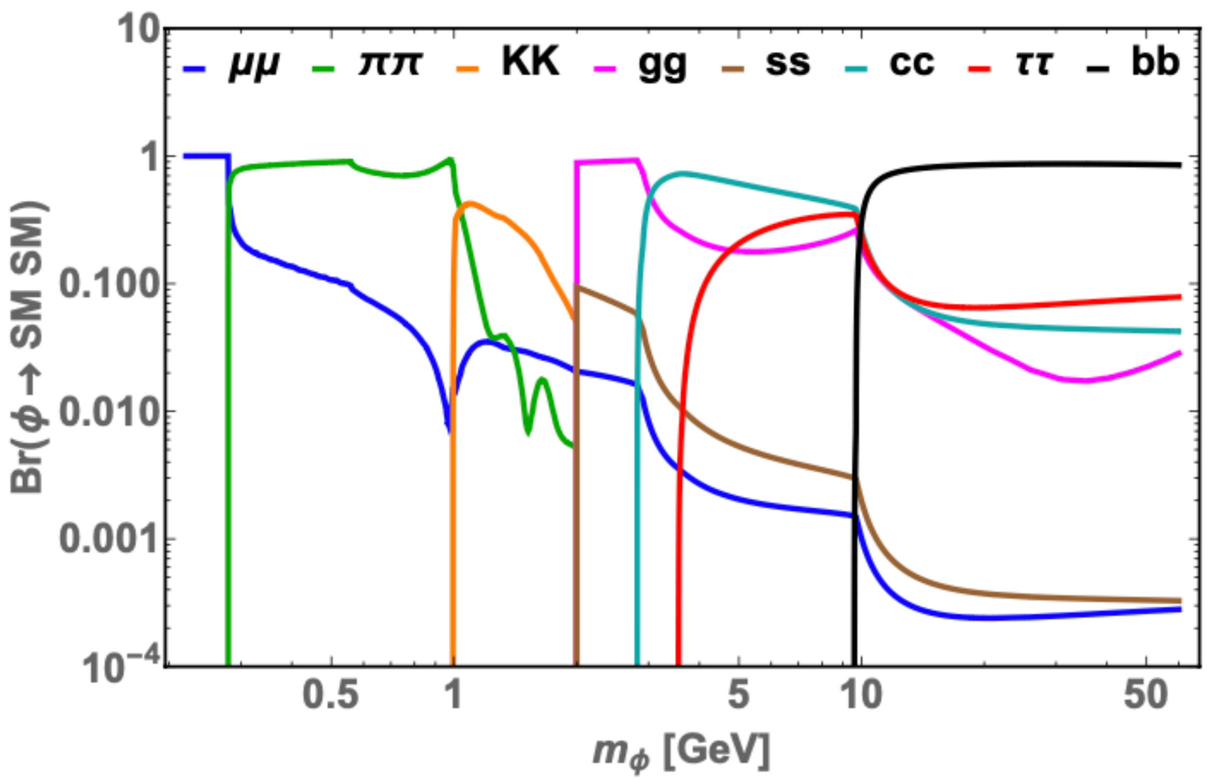
Observation of 50 events required

Backgrounds

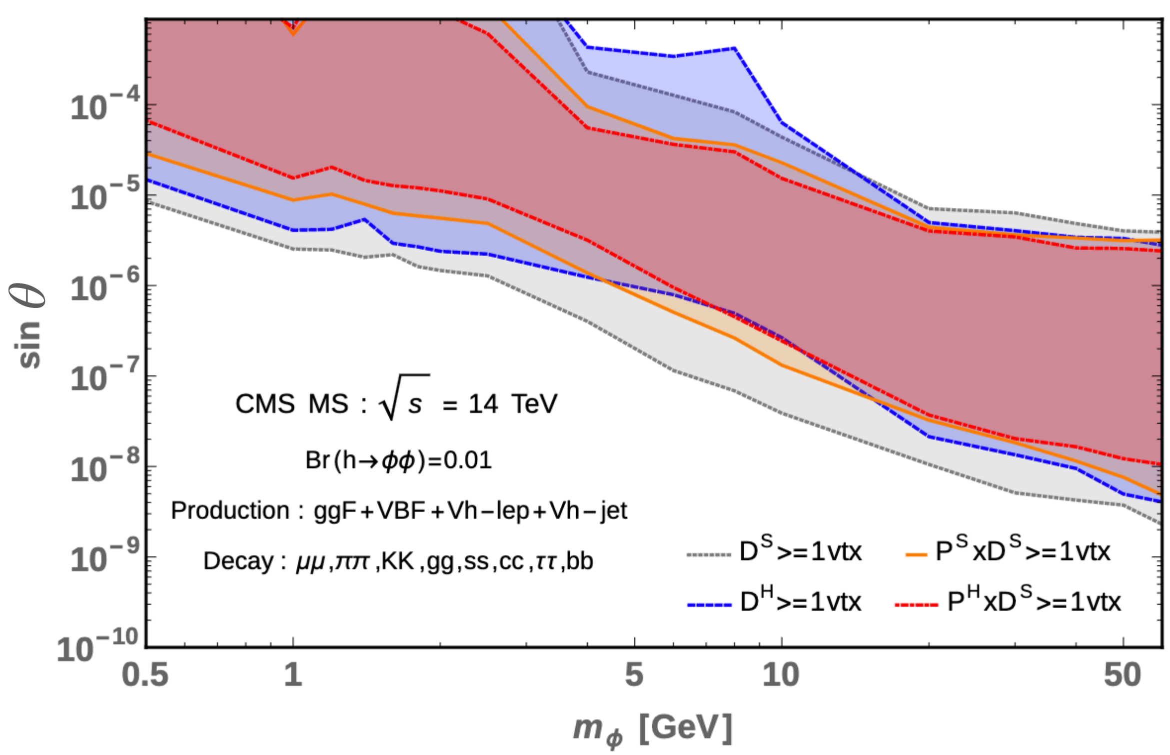
Muon Spectrometer only analysis - sensitive to higher decay lengths

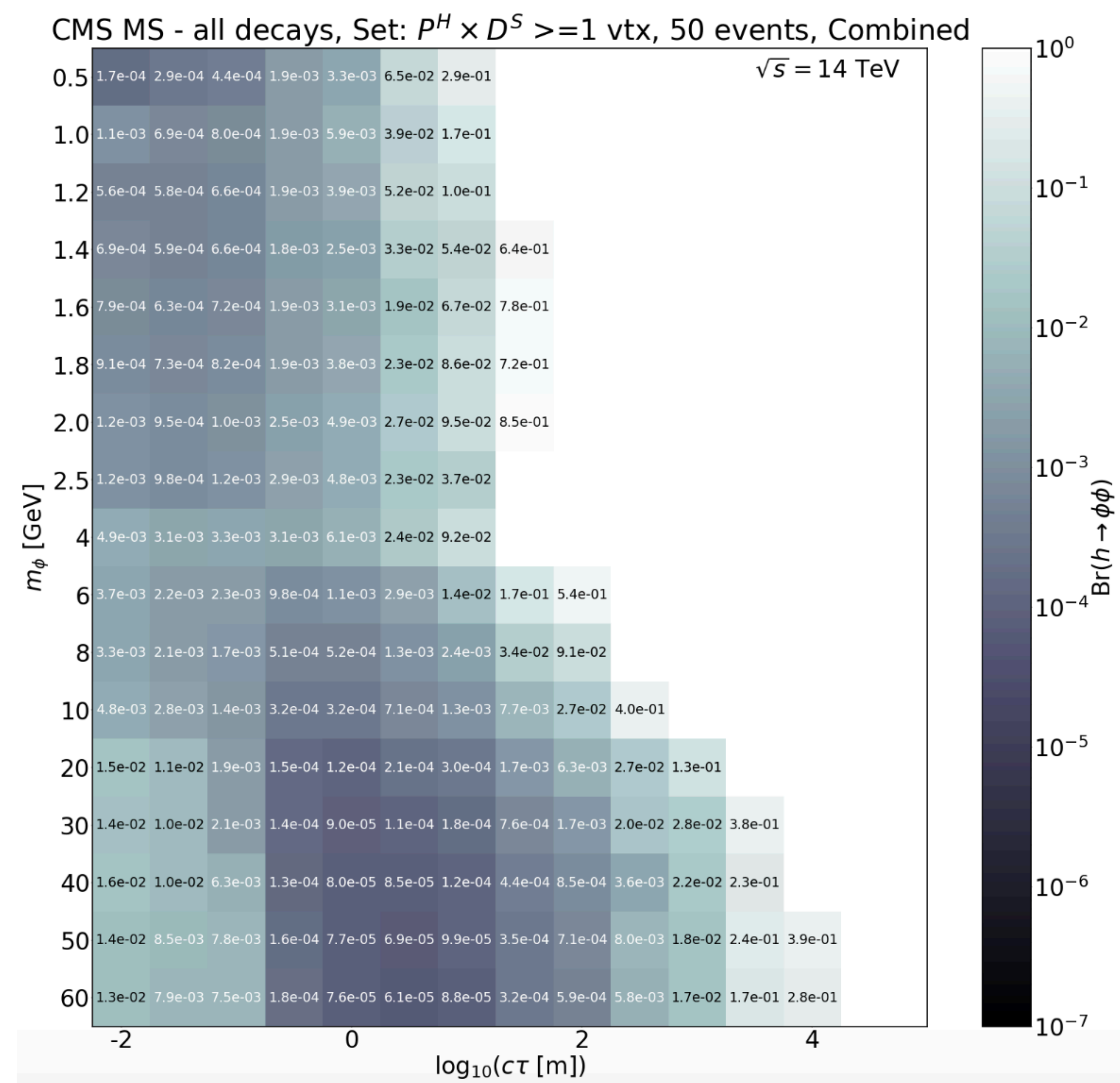
A1

CMS MS



combined as per branching of minimal model



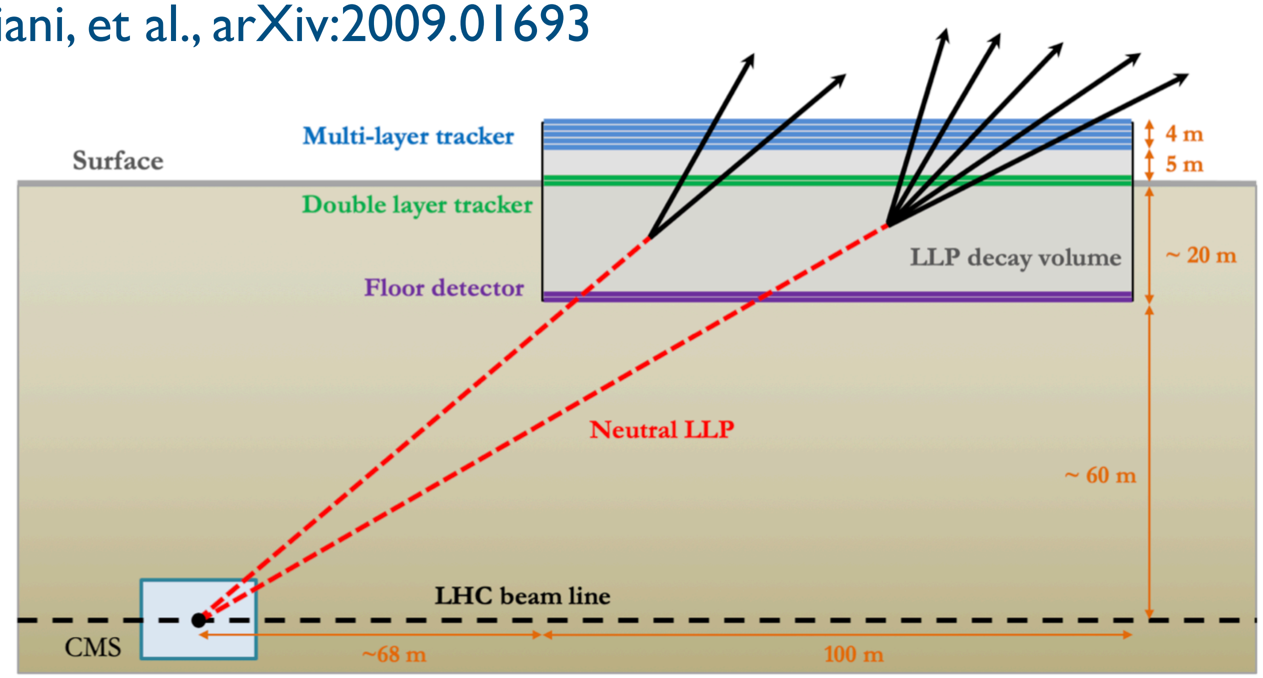


for fixed value of Br($h \to \phi\phi$),

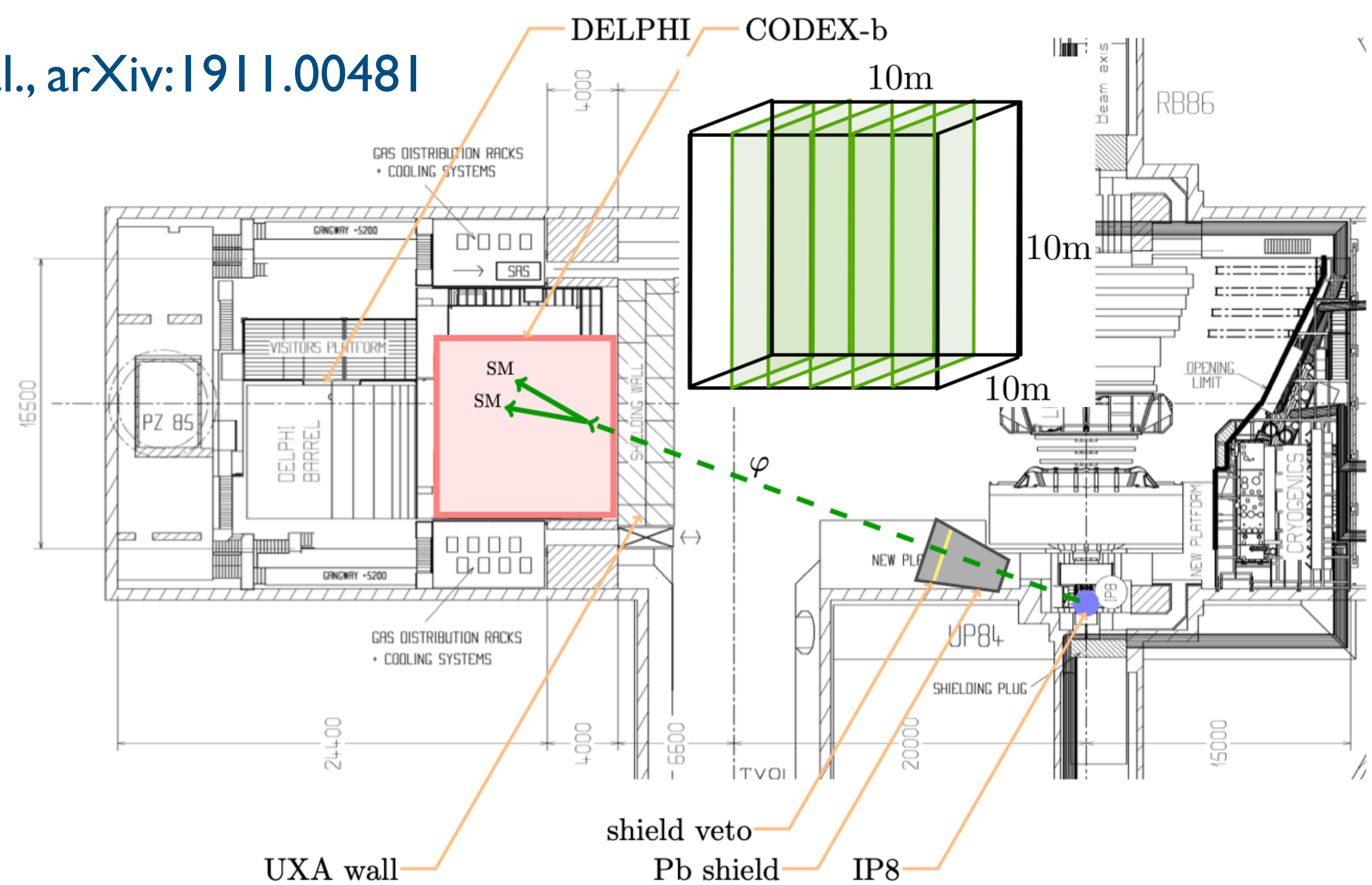
translated limit on $c\tau$ to limit on $\sin\theta$

B1 MATHUSLA and CODEX-b

Cristiano Alpigiani, et al., arXiv:2009.01693



Giulio Aielli, et al., arXiv:1911.00481



BACKGROUND FREE!

observation of few events (~4) enough to claim discovery

validated and extended analysis for our benchmarks

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

(0.5 GeV, 3.3×10^{-4}, 0.5 m)

(50 GeV, 5.3×10^{-4}, 50 m)

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

(0.5 GeV, 7.0×10^{-5}, 0.5 m)

(50 GeV, 1.1×10^{-4}, 50 m)

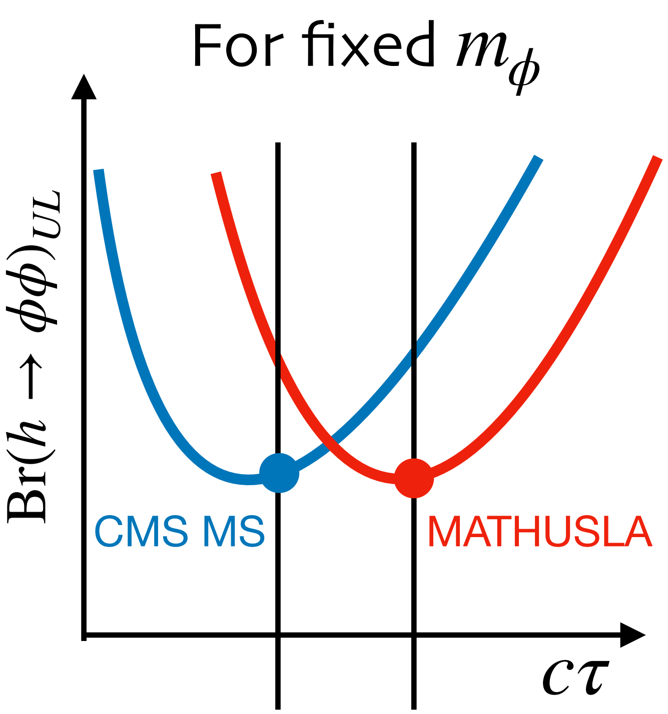
MATHUSLA,
$100 \times 100 \times 25$ m^3, 3000 fb^{-1}

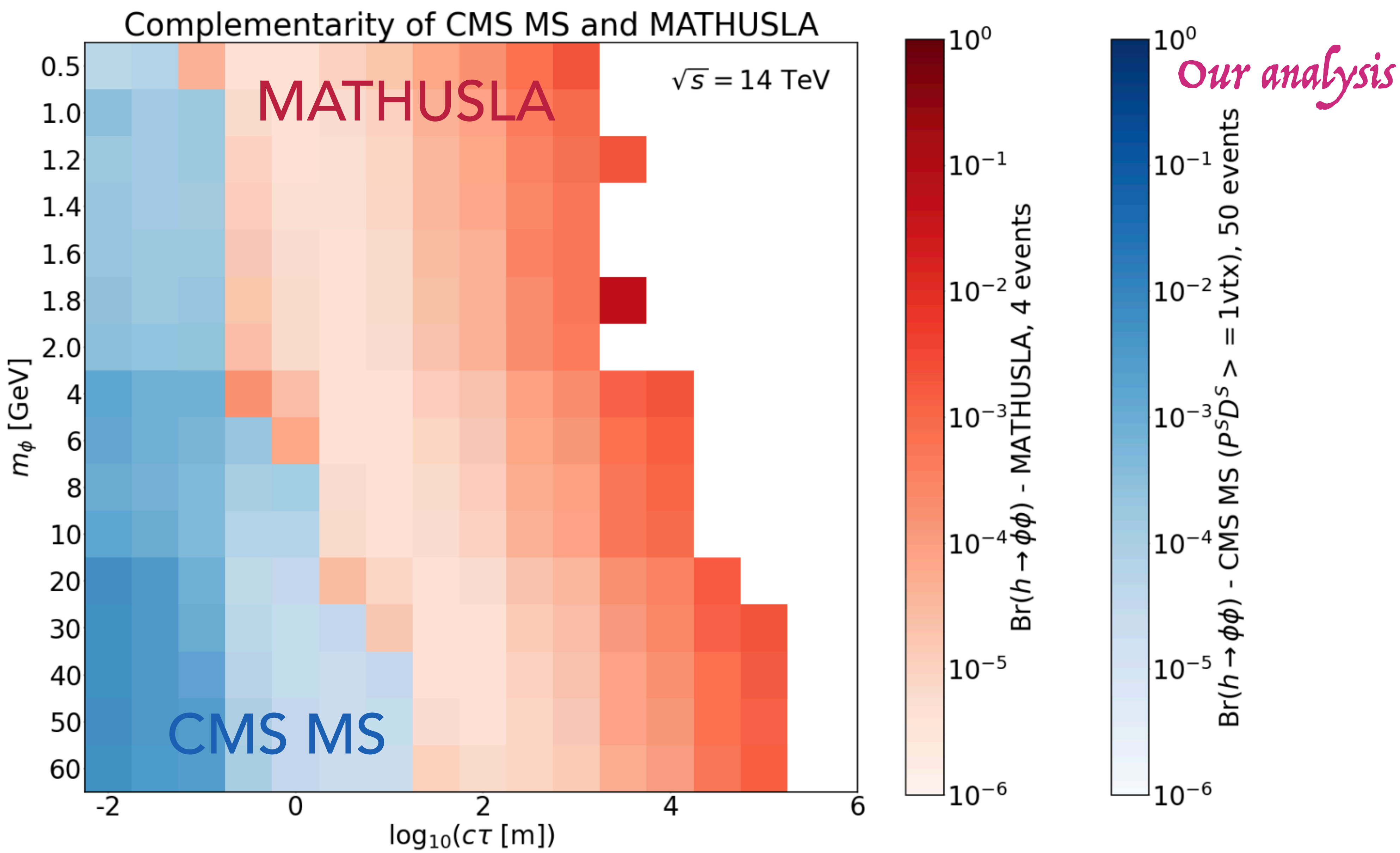
(0.5 GeV, 4.1×10^{-6}, 1 m)

(50 GeV, 4.6×10^{-6}, 100 m)

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

CMS MS and MATHUSLA





CMS MS + MATHUSLA:

can probe $c\tau \lesssim 10^5\,\mathrm{m}$ for $m_\phi = 60\,\mathrm{GeV}$,

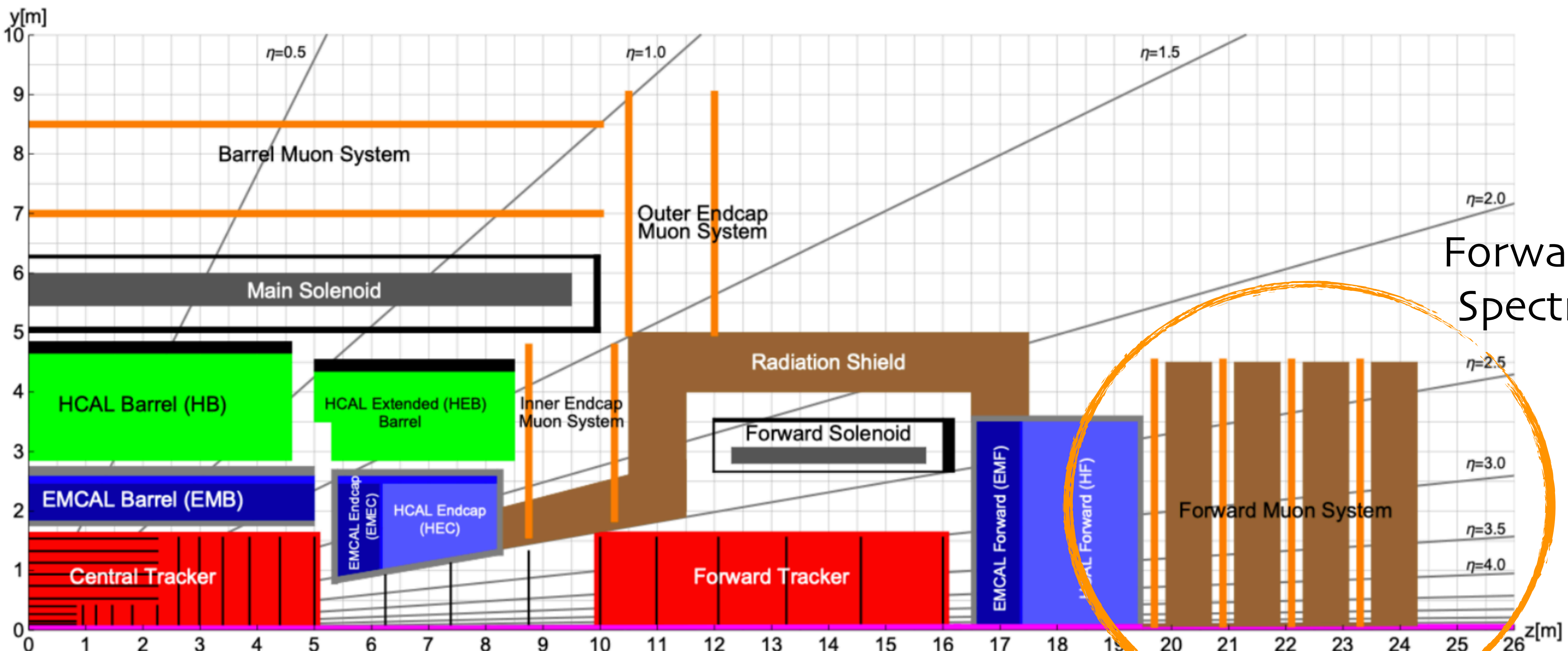
without any gap if $\mathrm{Br}(h \to \phi\phi) \gtrsim 0.1\,\%$

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

FCC-hh Reference Detector

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

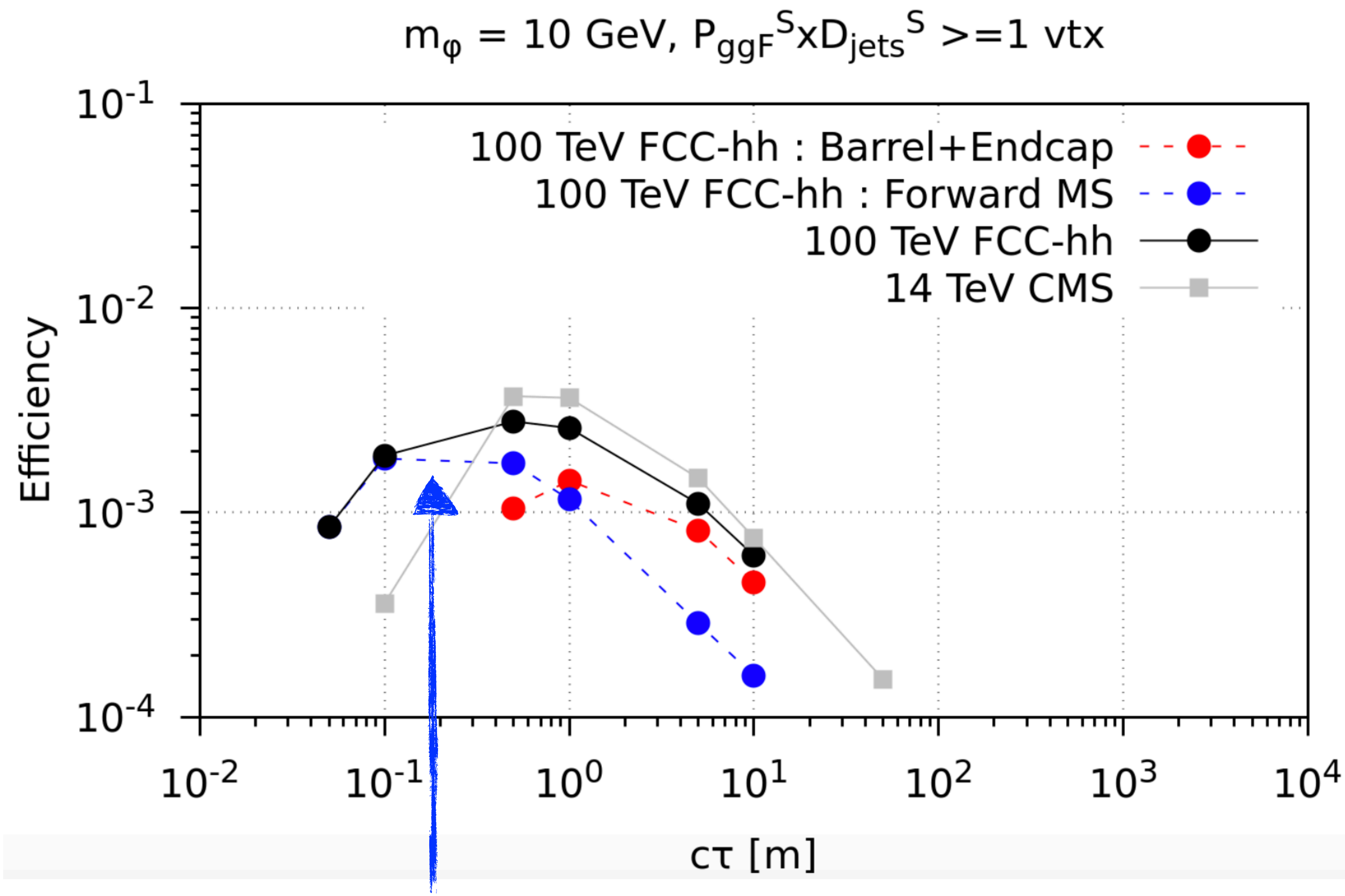


ATLAS/CMS + LHCb geometry

ANY BENEFIT?

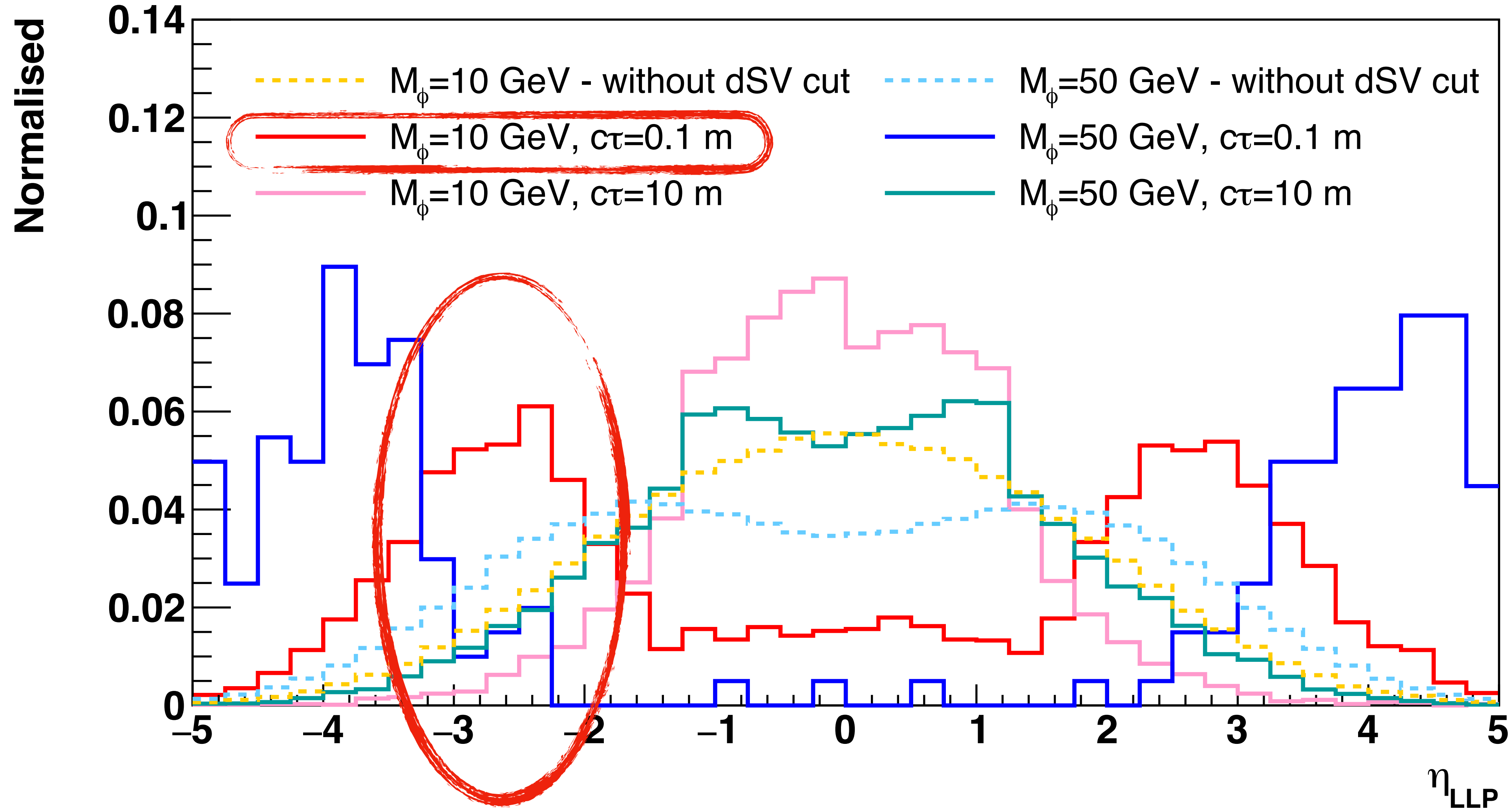
A2

FCC-hh MS



Forward MS increases sensitivity to lower decay lengths

A2 FCC-hh MS



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

$$d = \beta\gamma c\tau$$

↓

↑

More boost in the forward direction

Lower decay lengths, otherwise, difficult due to more background in the Tracker

New Proposal
This work

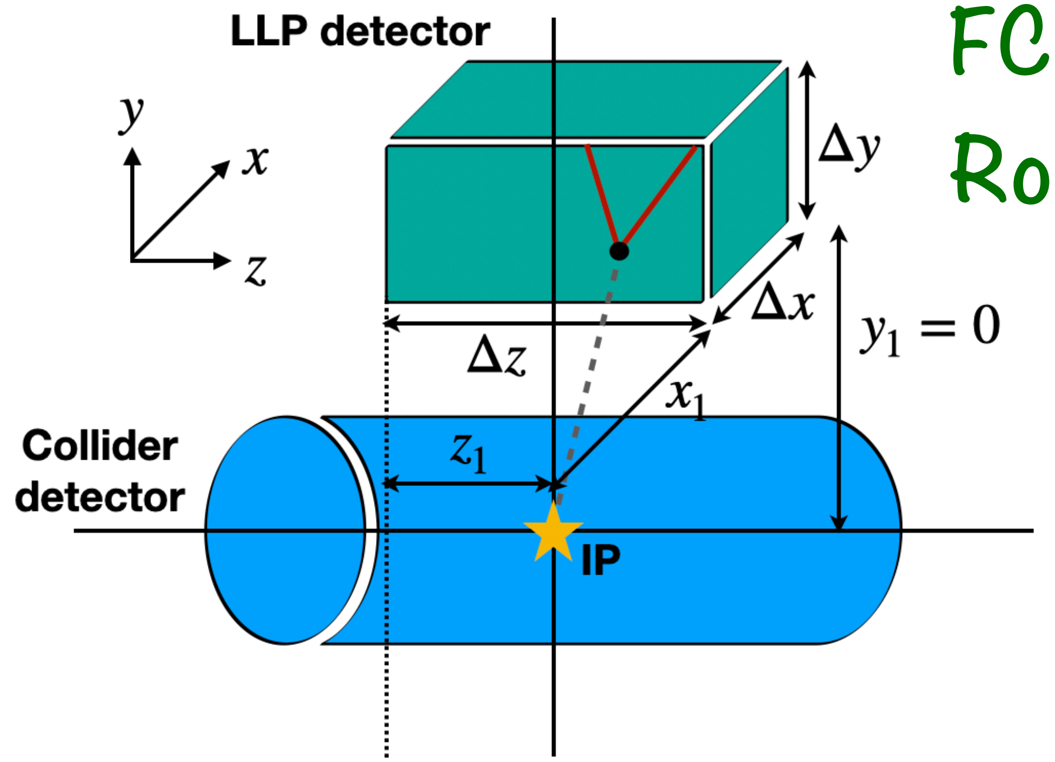
B2 DELIGHT for FCC-hh

DELIGHT

Detector for long-lived particles at high energy of 100 TeV

Proposal for FCC-ee/CEPC - HECATE

Marcin Chrzaszcz, et al., arXiv:2011.01005



FCC-hh design under study

Room for optimisation

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

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

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

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

New Proposal
This work

B2 DELIGHT for FCC-hh

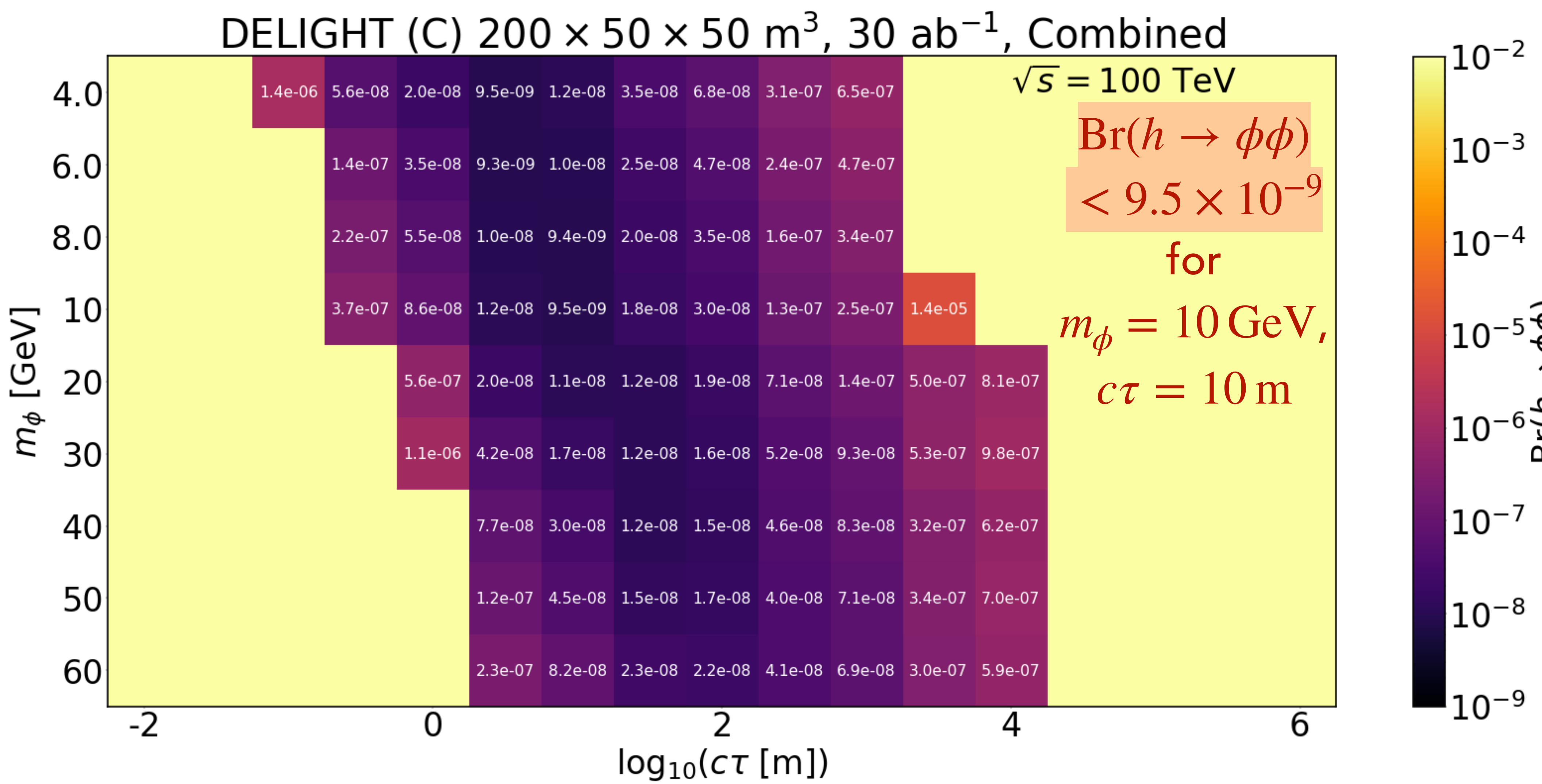
FCC-hh design under study
Room for optimisation

DELIGHT

Detector for long-lived particles at high energy of 100 TeV

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

Improvement by $\times 430$ compared to MATHUSLA



- 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

A Rich Program Ahead to Hunt Down LLPs

Collider Main Detectors	ATLAS	CMS	LHCb
Forward Detectors	FASER	Forward Physics Facility	MAPP-MoEDAL
Transverse Detectors	CODEX-b	MATHUSLA	ANUBIS
Charged LLPs	MoEDAL	MilliQan	

Keep looking out for new possibilities!

Thank you for your attention

BACK UP

References for the branching ratio of the mediator particle

The decay of a light Higgs Boson

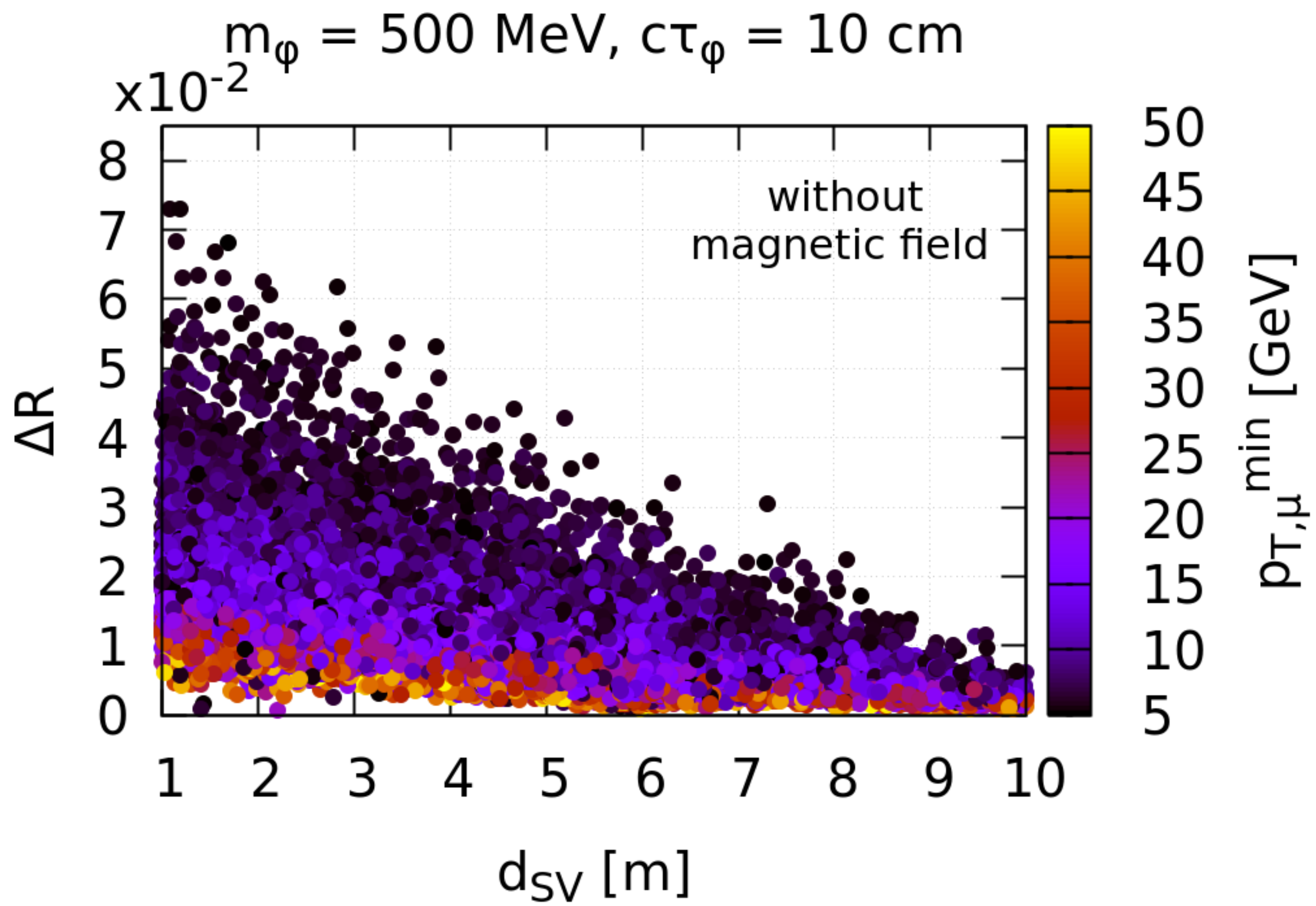
J. F. Donoghue, J. Gasser and H. Leutwyler, Nucl. Phys. B 343, 341 (1990)

Decay and Detection of a Light Scalar Boson Mixing with the Higgs

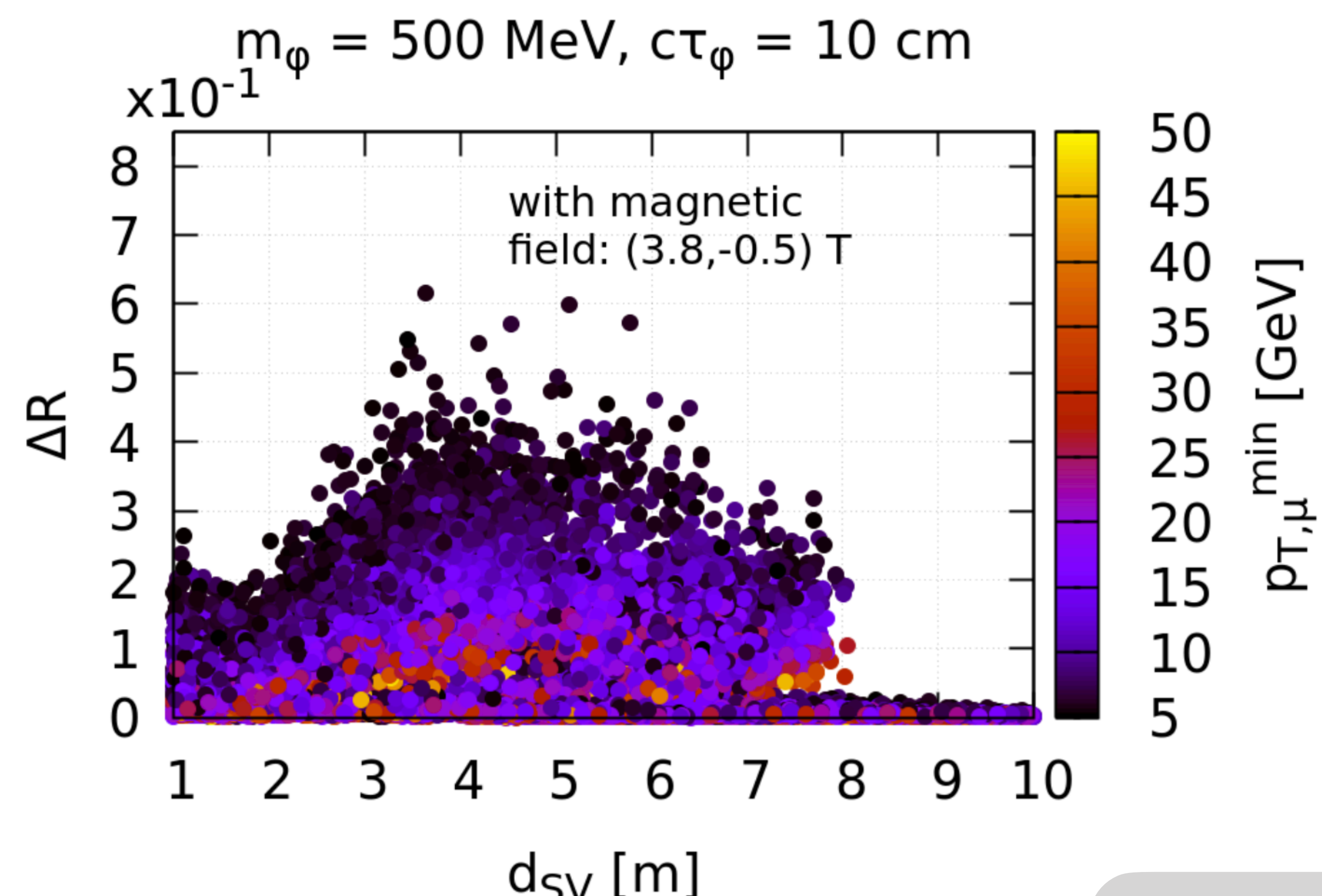
Martin Wolfgang Winkler **1809.01876**

After 2 GeV - HDECAY

Back



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: (3.8,-0.5) T
ΔR
d_{SV} [m]
$p_{T,\mu}^{min}$ [GeV]

Back

Possible backgrounds

Displaced dimuons

- SM particles decaying into di-muons, such as J/ψ or Υ $\Rightarrow$ very small decay lengths (~ few pm) $\Rightarrow$ 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 $\Rightarrow$ usually appear back-to-back in the detector $\Rightarrow$ suppressed by rejecting back-to-back muon pairs with a $\Delta\phi$ cut $\Rightarrow$ 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 $\Rightarrow$ have very low transverse momentum $\Rightarrow$ a cut of $p_T > 15$ GeV on displaced muons can suppress the beam halo background.

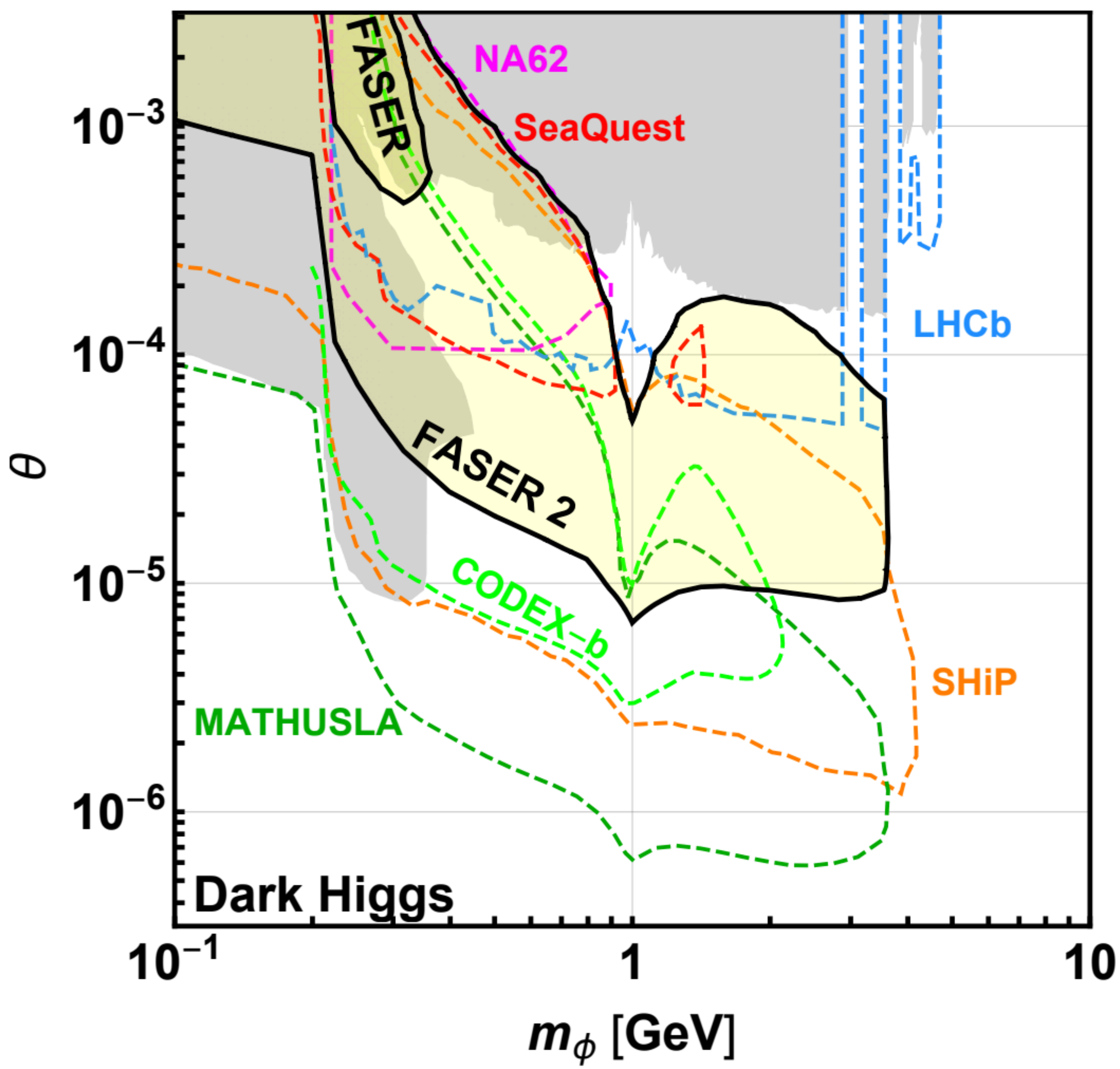
MS cluster

- Several long-lived hadrons in the SM can punch through the calorimeter from the transition regions and then decay, such as $K_S \to \pi^+\pi^-, \Lambda \to p\pi^-, \Sigma^+ \to p\pi^0/n\pi^+$, $\Sigma^- \to n\pi^-, \Xi \to \Lambda\pi^0, \Xi^- \to \Lambda\pi^-$ and $\Omega^- \to \Lambda K^-/\Xi\pi^-/\Xi^-\pi^0$ $\Rightarrow$ demand at least 3-5 charged particles associated with a displaced vertex.
- Punch through of PU jets in the HL-LHC $\Rightarrow$ 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 $\Rightarrow$ a significance $(S/\sqrt{B})$ of 2σ can accommodate ~625 background events

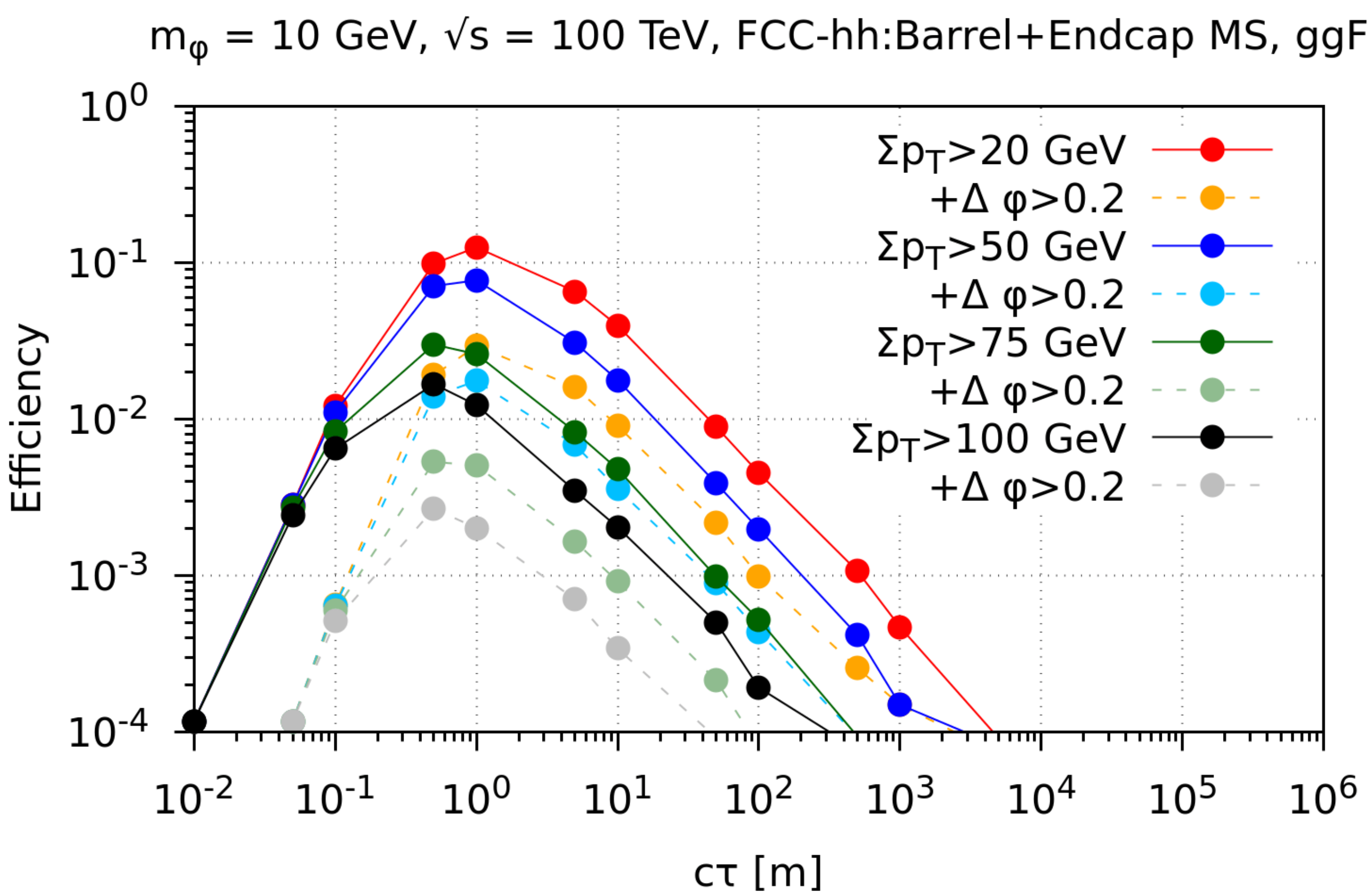
Our obtained limits can be scaled accordingly

Back



FASER: ForwArd Search ExpeRiment at the LHC, arXiv:1901.04468.pdf

A2 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