The Future of Long-Lived Particles

from the decay of Higgs boson

at HL-LHC and FCC-hh

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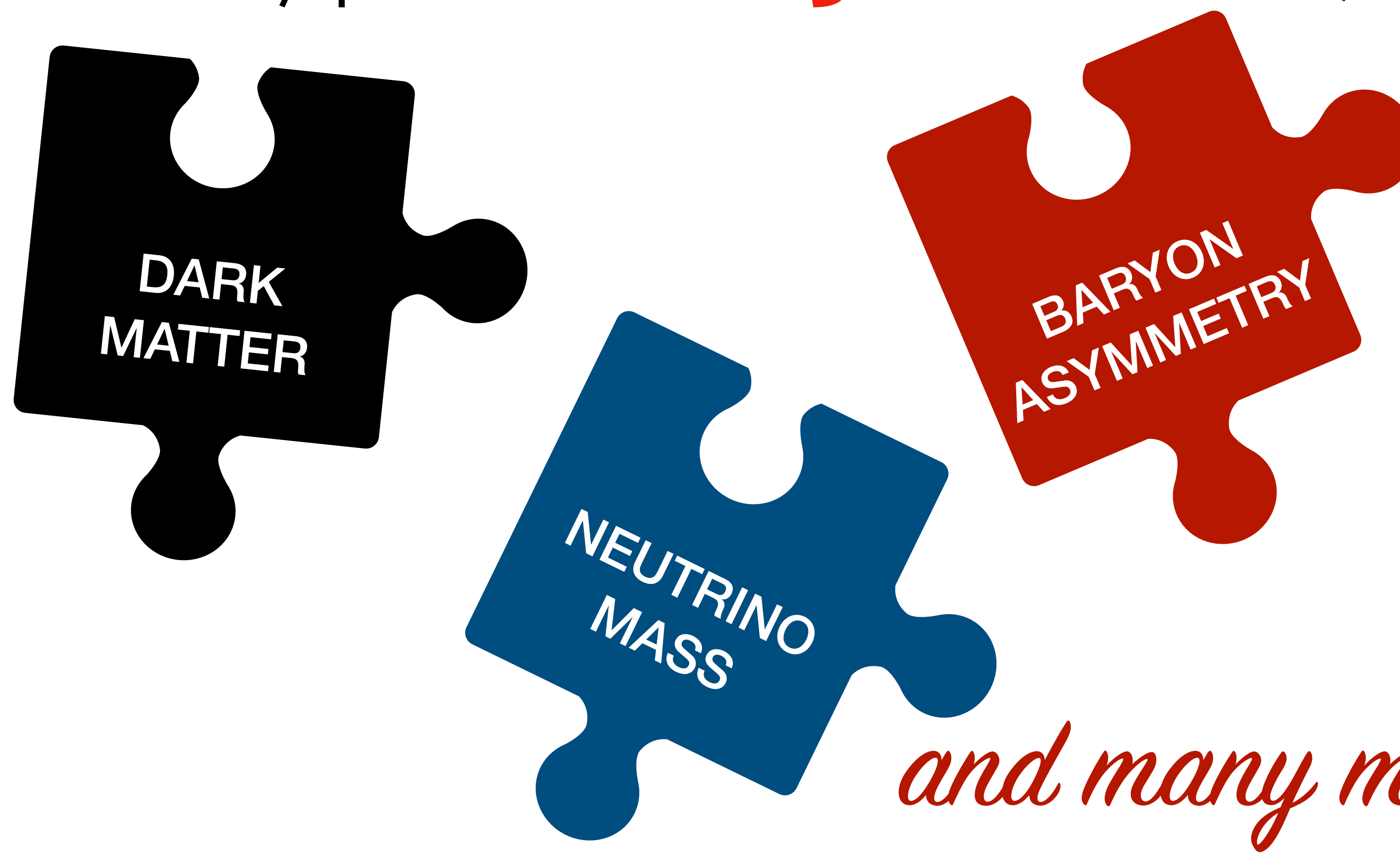
Standard Model of particle physics (**SM**)

successfully explains many fundamental phenomena of particles

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



and many more...

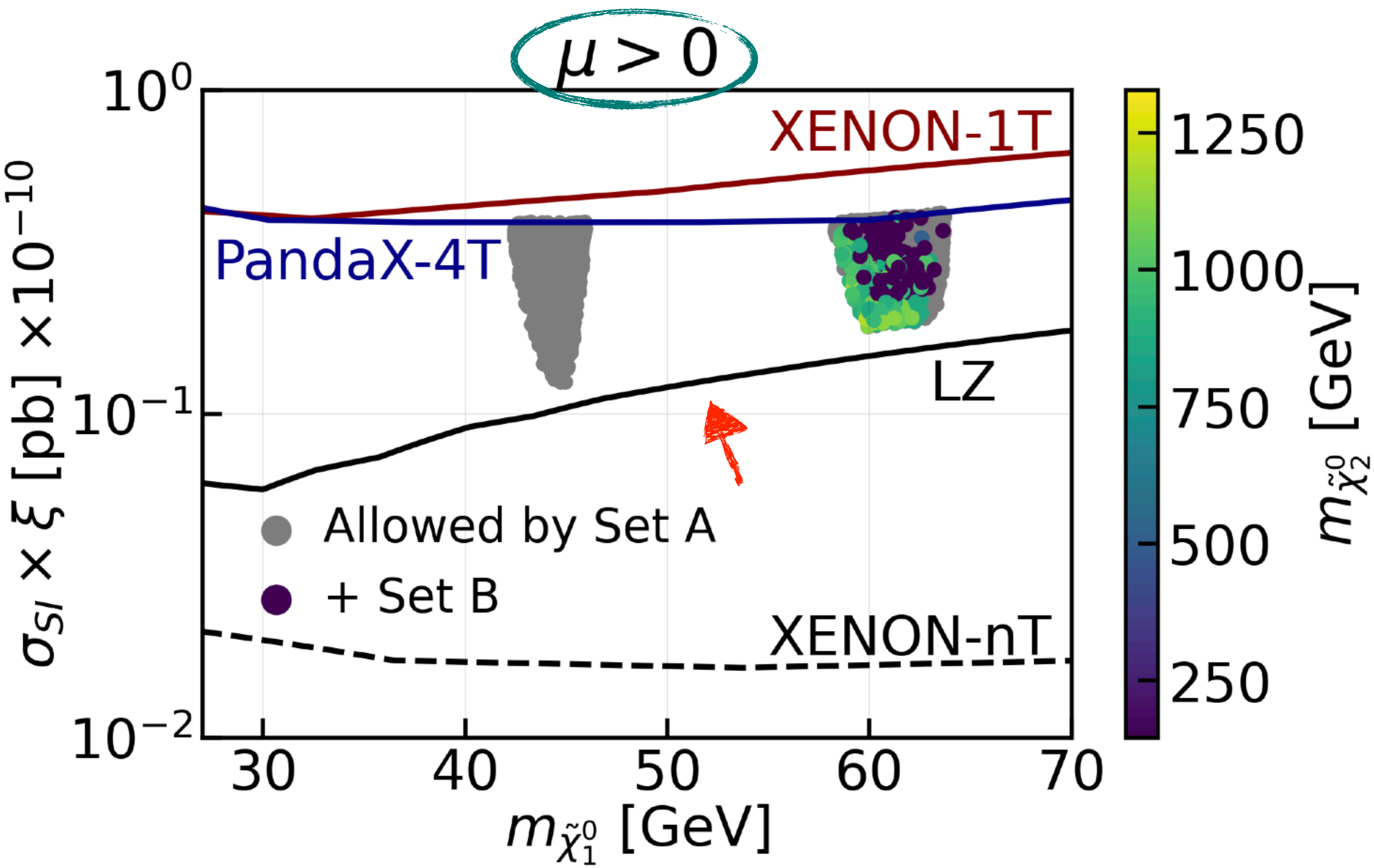
We need to look beyond the SM (BSM)

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

For instance, let us look at the current status of the **light neutralino ($m_\chi \leq m_h/2$) thermal dark matter in the context of pMSSM**

Bino-like LSP (DM), Higgsino-like NLSP

Rahool Kumar Barman, Genevieve Belanger, Biplob Bhattacherjee, Rohini Godbole, RS, arXiv:2207.06238



Set A: constraints from
LEP
flavor observables
Higgs constraints
relic density and
the DD experiments
XENON-1T, PICO-60 and
PandaX-4T
Set B: electroweakino
constraints from the LHC

The recent LZ result excludes the entire parameter space allowed so far for $\mu > 0$

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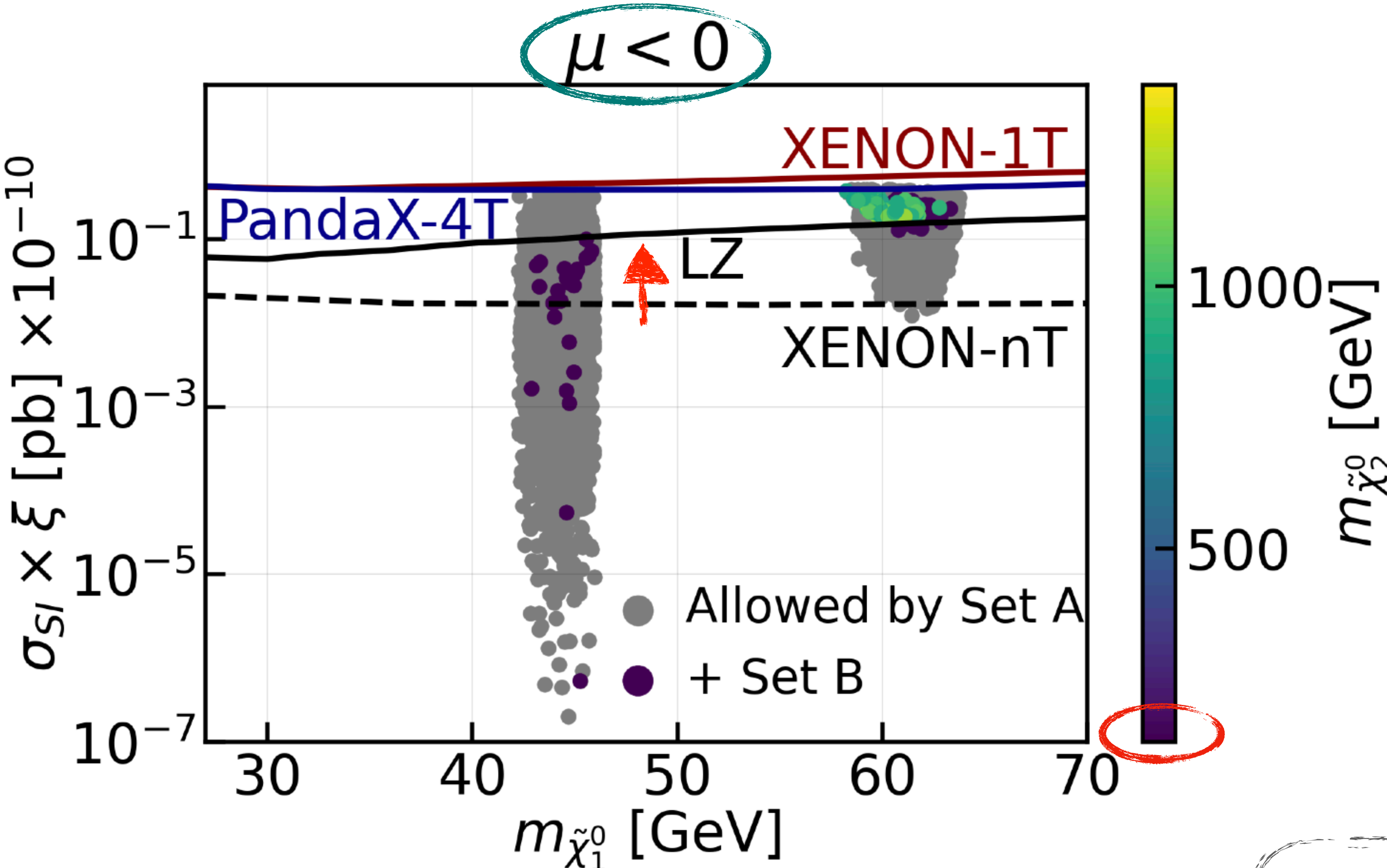


Set A: constraints from LEP flavor observables Higgs constraints relic density and the DD experiments XENON-1T, PICO-60 and PandaX-4T

Set B: electroweakino constraints from the LHC

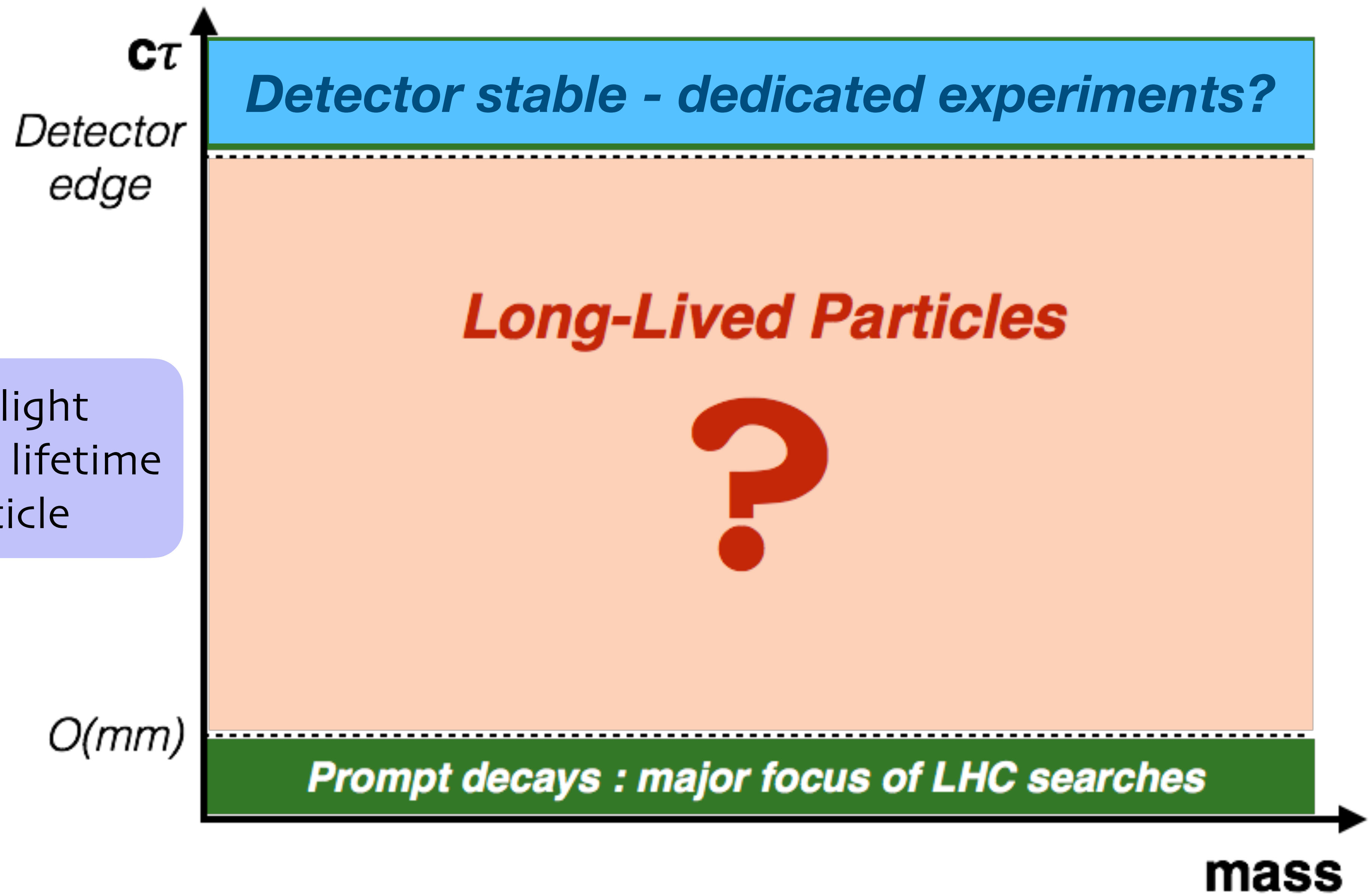
The recent LZ result only leaves very **light higgsinos** of mass 130-140 GeV (Z-funnel) and 149-155 GeV (h-funnel) allowed for $\mu < 0$

TAKEAWAY MESSAGE:

Recent experimental results have strongly constrained conventional scenarios

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

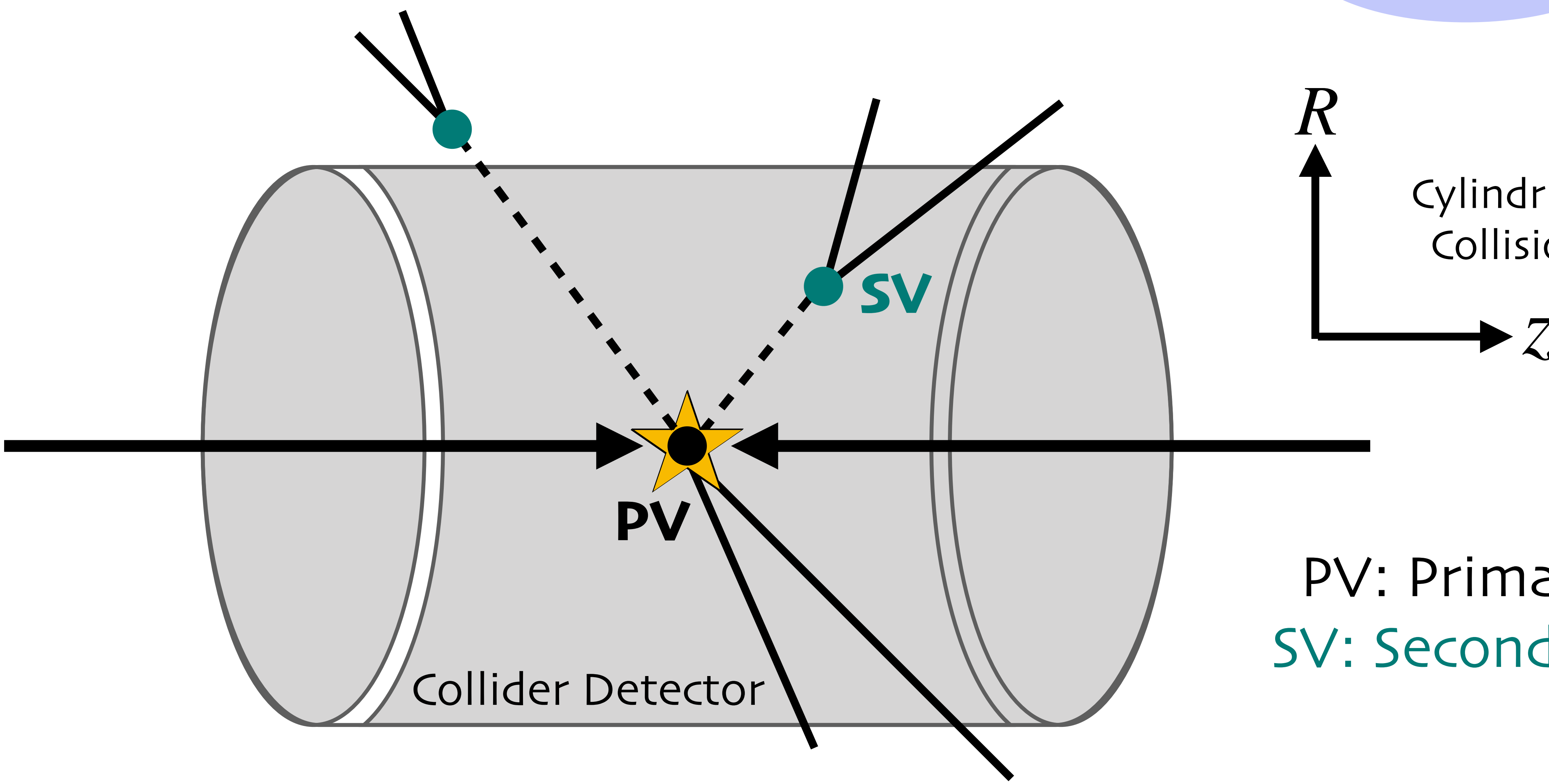
open the door to the **Lifetime Frontier**

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

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



Cylindrical coordinates
Collision along z axis

PV: Primary Vertex
SV: Secondary Vertex

Effect of magnetic field not shown

WHY EXPLORE LLPs?

well motivated in many BSM scenarios **largely unexplored**

IDEA NOT NEW

RECENT FOCUS

11 LLP Workshops - starting from 2016

Collaborative efforts from theorists and experimentalists worldwide

LLP White Paper: arXiv:1903.04497

Future collider experiments all including LLPs in their physics case

Multiple dedicated experiments for LLPs being proposed

OUTLINE

- LLPs in colliders
- A study of LLPs in Higgs portal @ HL-LHC and FCC-hh
- A few other aspects of LLP searches
  - Triggering
  - Image recognition techniques for displaced jets
  - Lifetime estimation

OUTLINE

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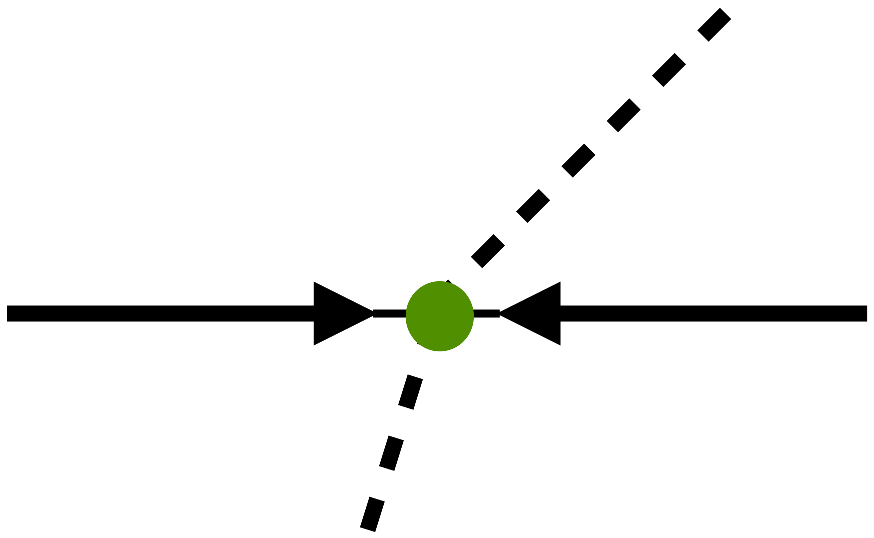
The 3 major ingredients

THEORY

PRODUCTION

- Production rate, σ
- Boost and direction



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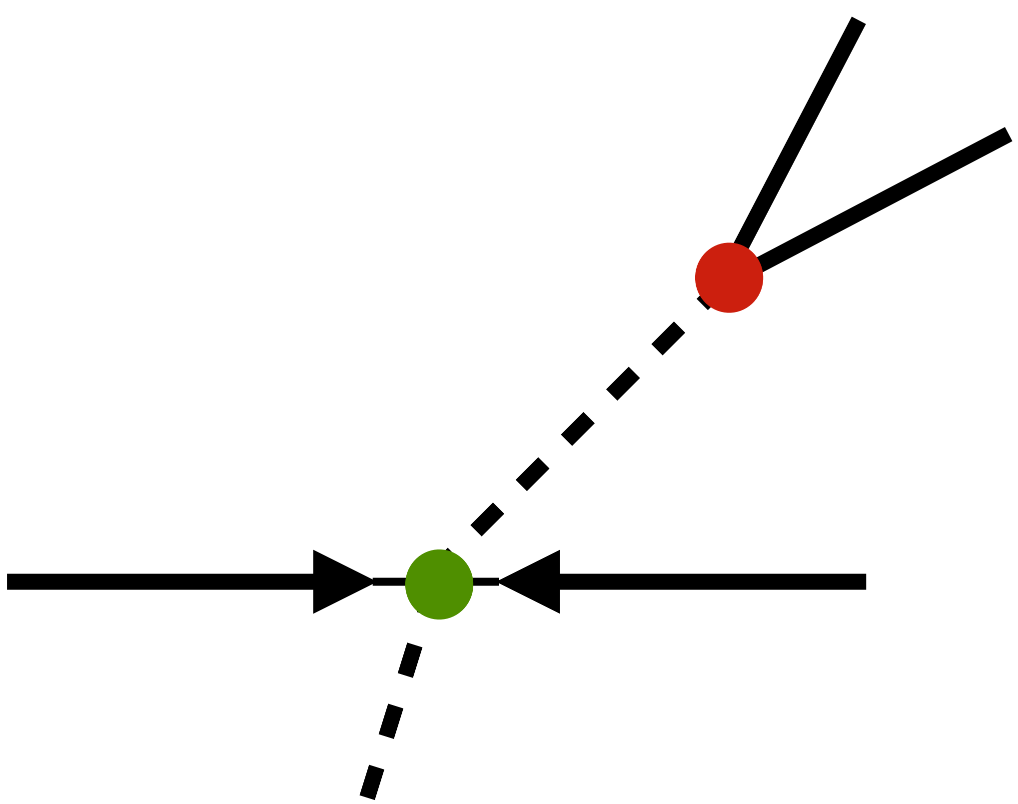
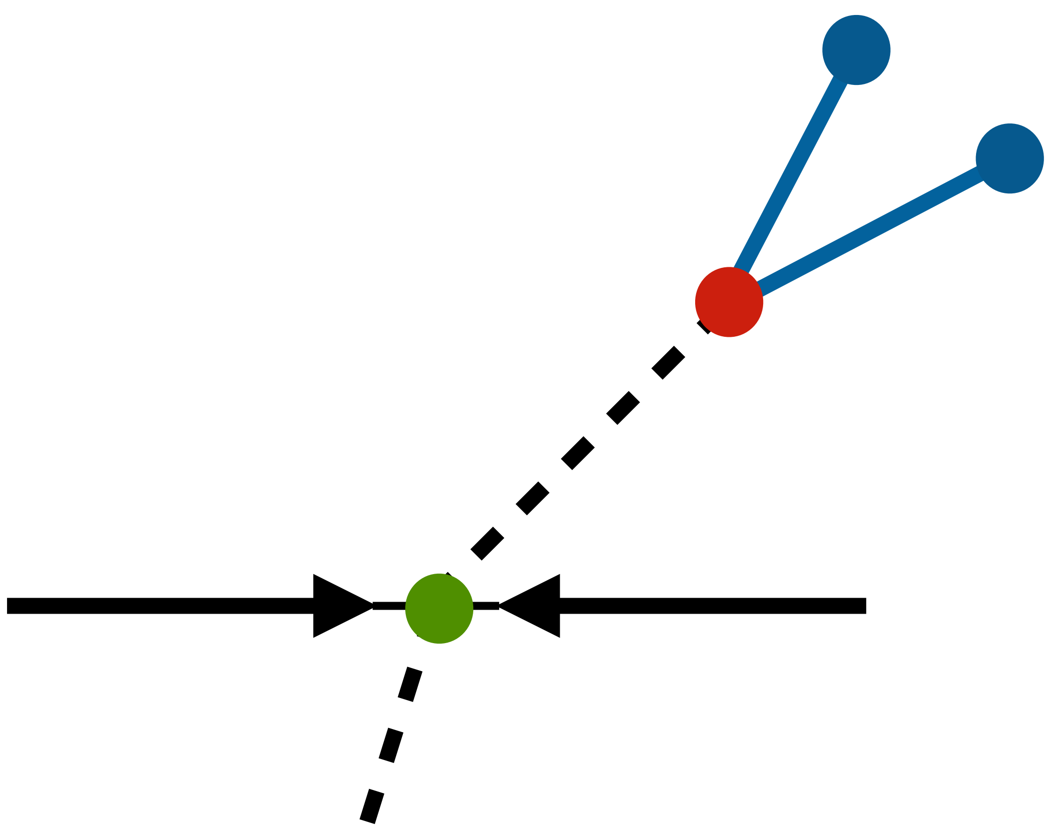
THEORY
DECAY

- Decay width, Γ or Lifetime, τ
- Decay modes



The 3 major ingredients

THEORY PRODUCTION	THEORY DECAY	EXPERIMENT DETECTION
- Production rate, σ - Boost and direction	- Decay width, Γ or Lifetime, τ - Decay modes	depends on - what it decays into - where it decays



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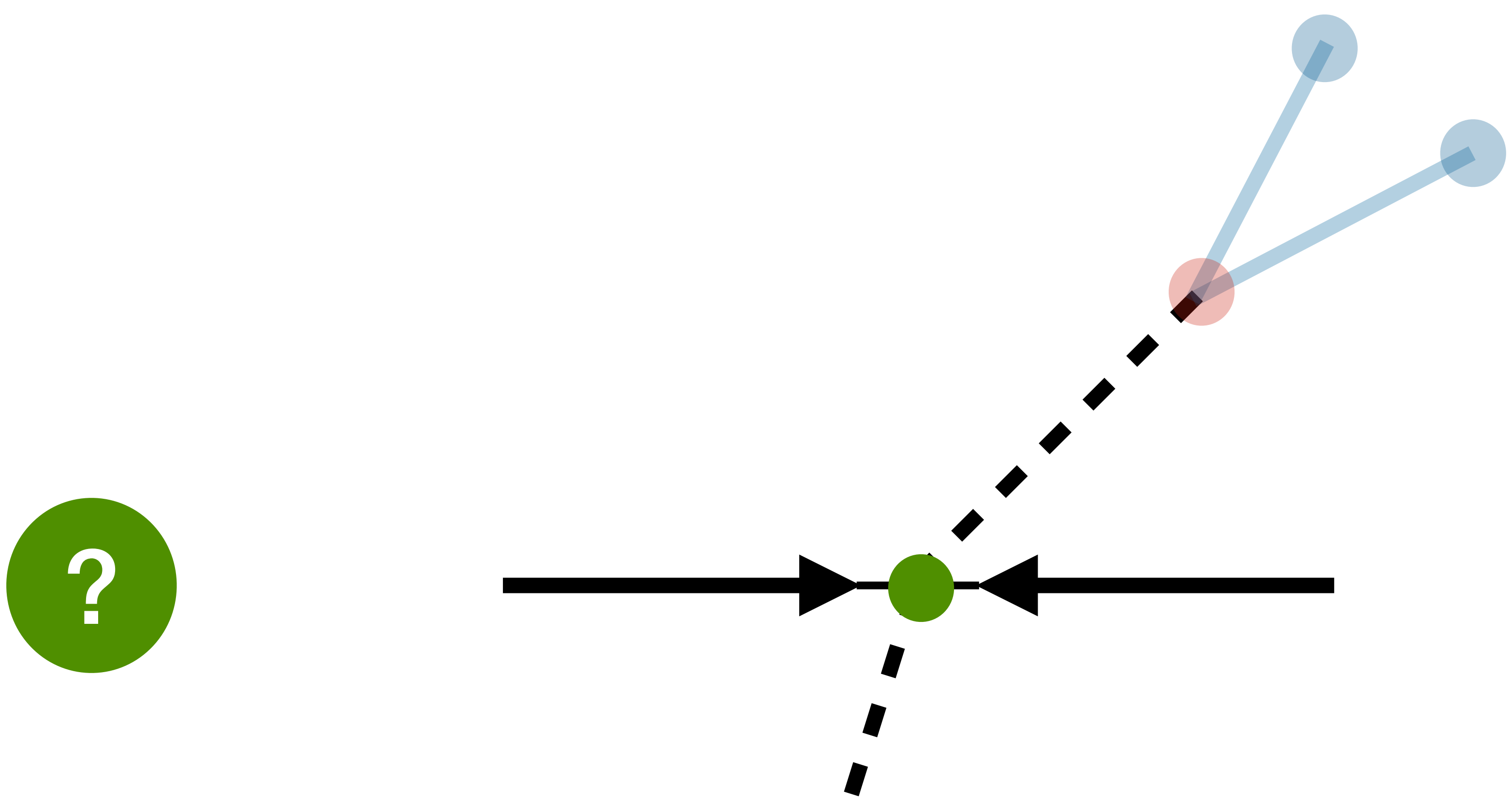
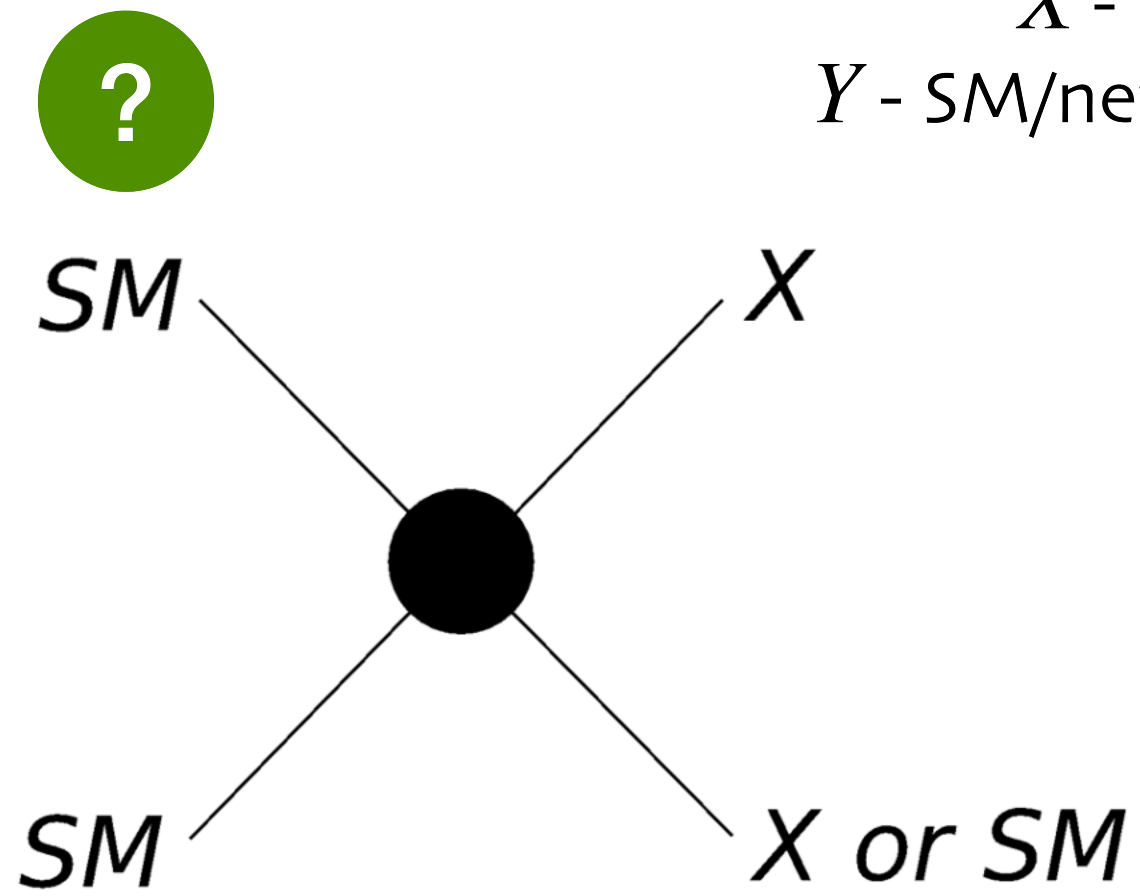


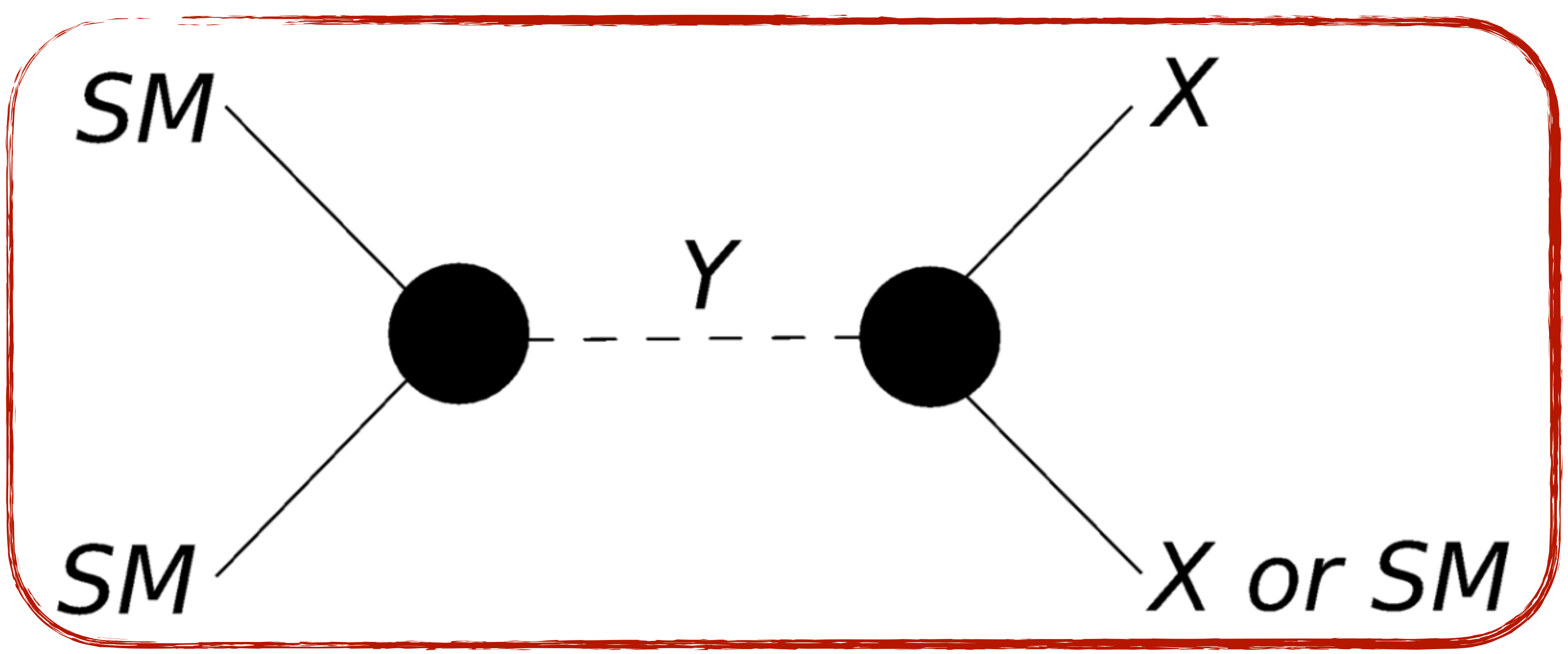
Production of LLPs in colliders

X - LLP
Y - SM/new particle

Direct Production

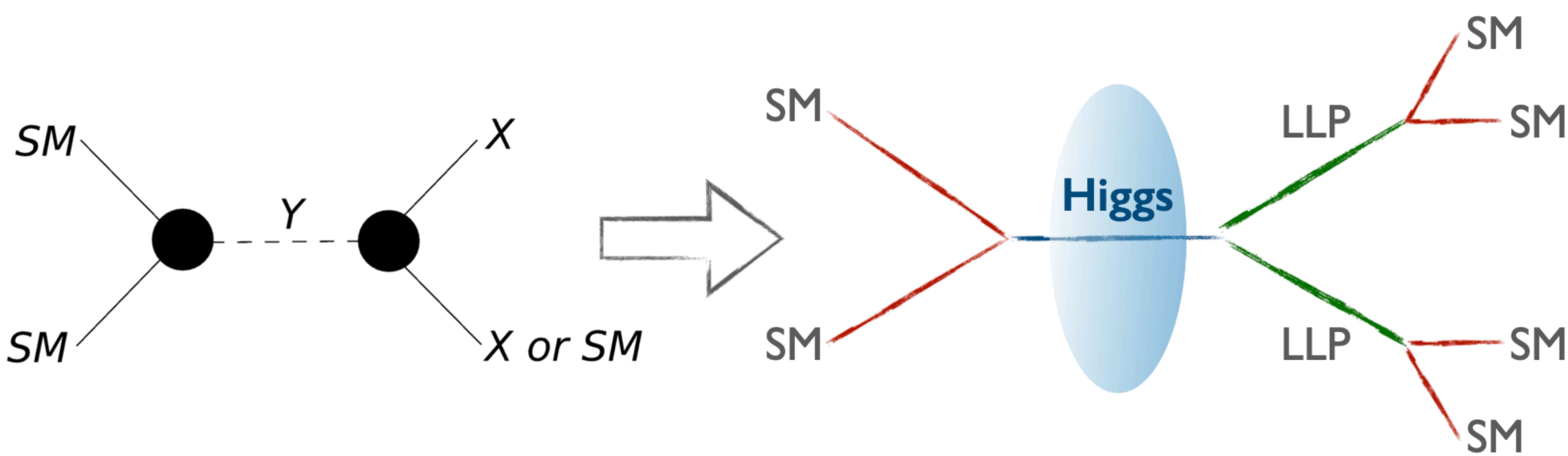


From the decay of a resonance



Long-lived particles in the Higgs portal

~ LLPs having dominant coupling to the SM Higgs boson ~



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

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

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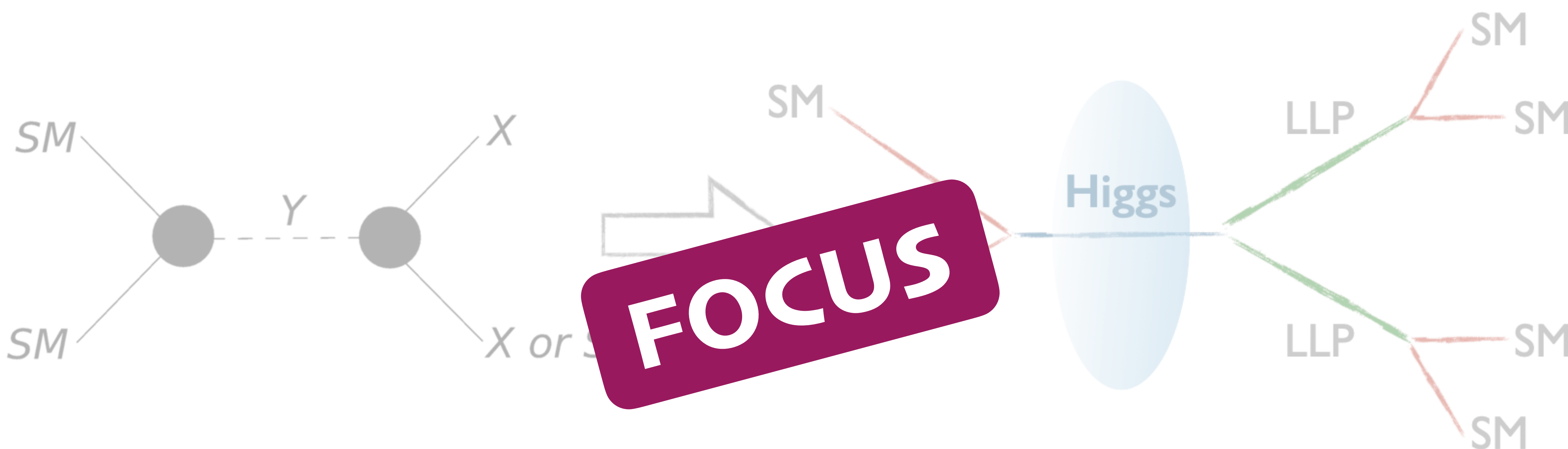

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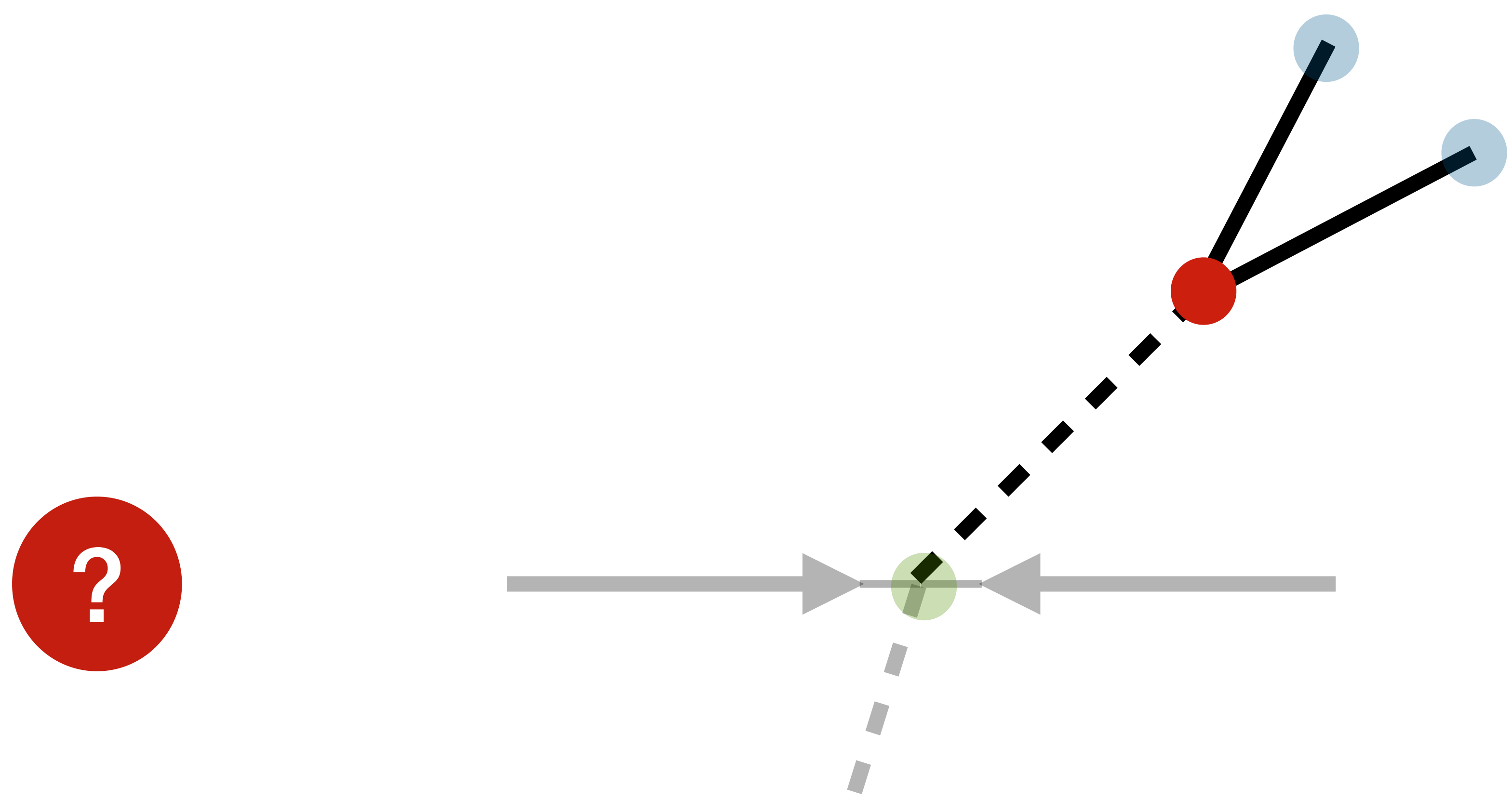


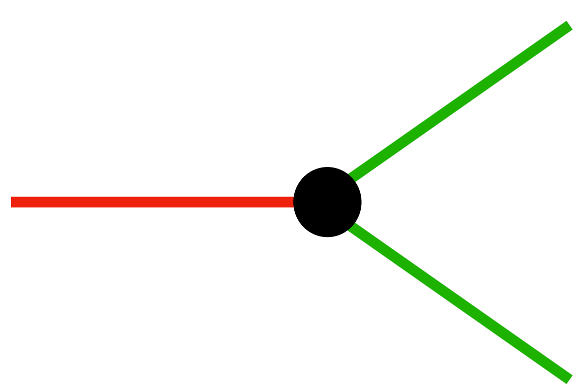
Reasons behind long lifetimes

?

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

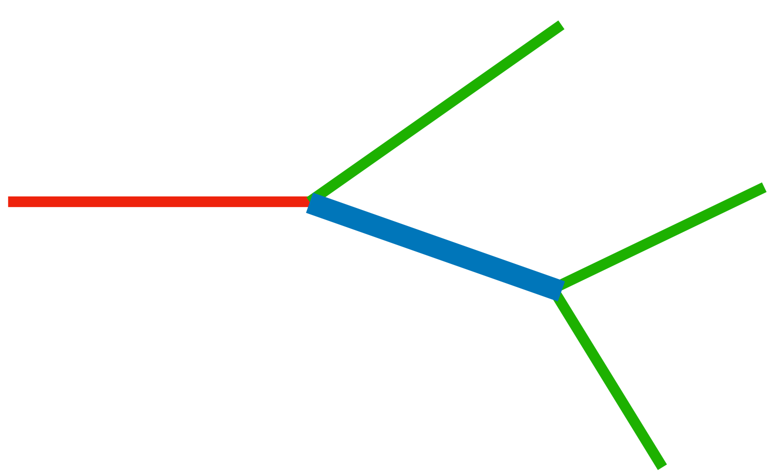
Small couplings

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



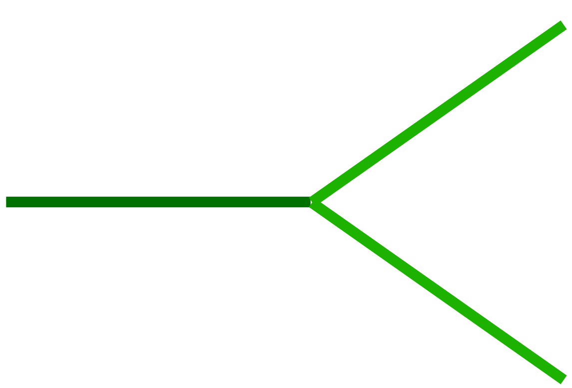
Heavy scales, $\Gamma \sim \frac{m^5}{M^4}$

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



Kinematic squeezing

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



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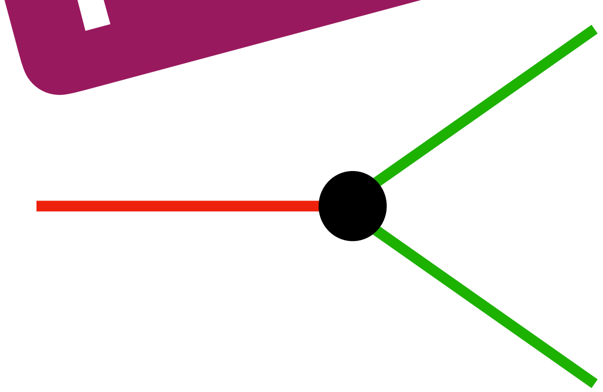
BS...

FOCUS



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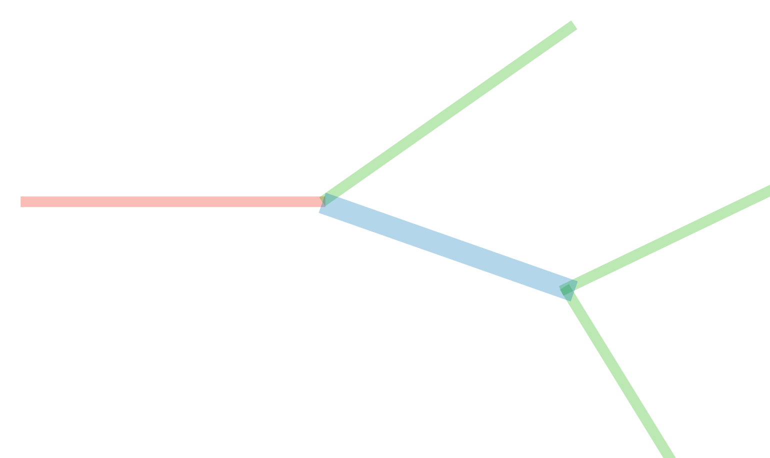

Kinematic squeezing

e.g., neutron (SM),

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scenarios (BSM)

Long-lived mediator from a minimal DM model

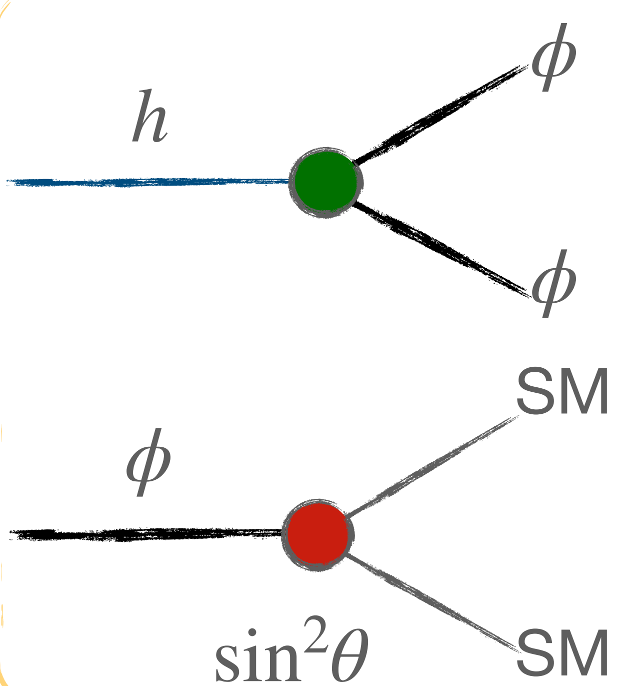
Shigeki Matsumoto, et al., *JHEP* 07 (2019) 050

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

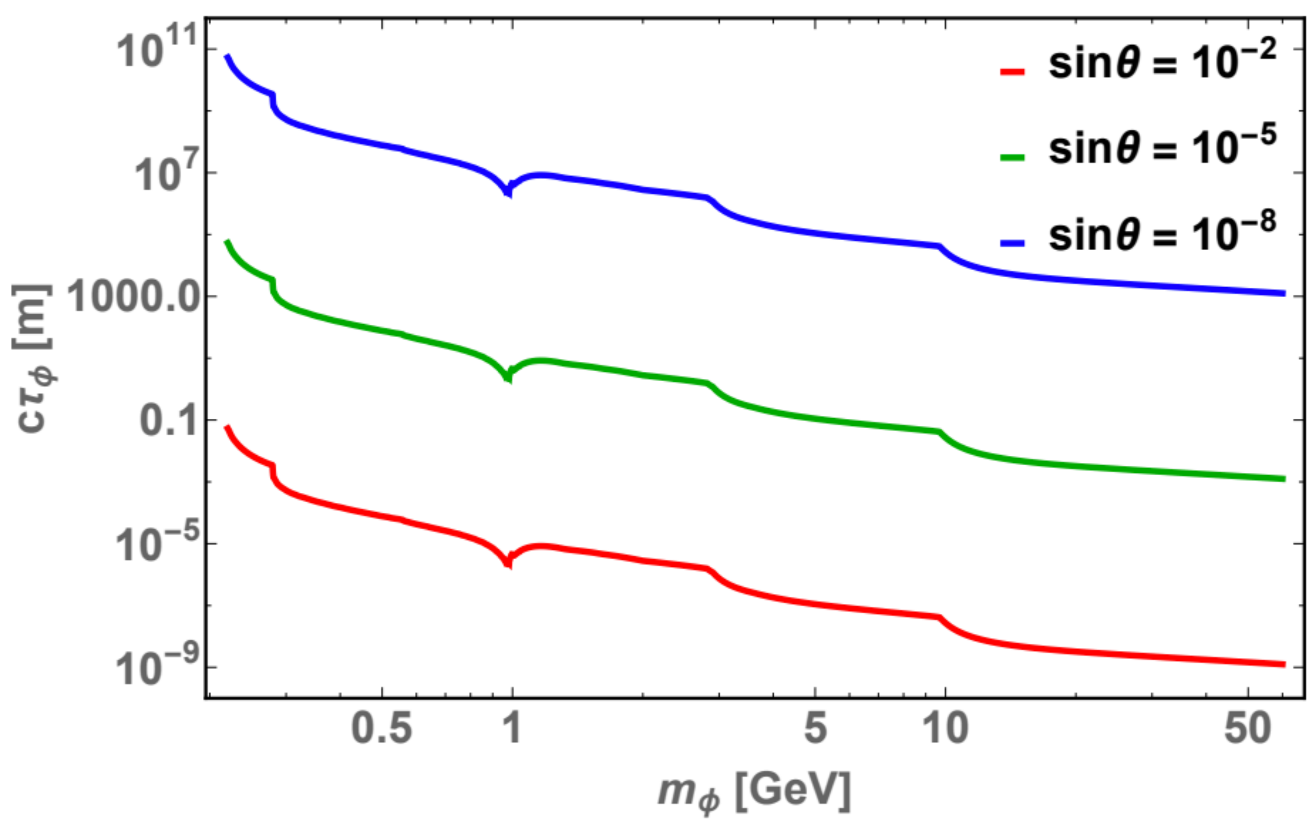
Not severely constrained so far



Production of ϕ has a different coupling than its decay

$\sin^2\theta$ ↓ $c\tau_\theta$ ↑

Long-lived mediator



LLP decays in colliders

Decay length in the detector

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

LAB FRAME

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

from PRODUCTION mode **from DECAY width**

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

c : speed of light

τ : proper mean lifetime of the particle

Lighter particles $\Rightarrow$ more displaced as compared to heavier ones for the same lifetime

The 3 major ingredients

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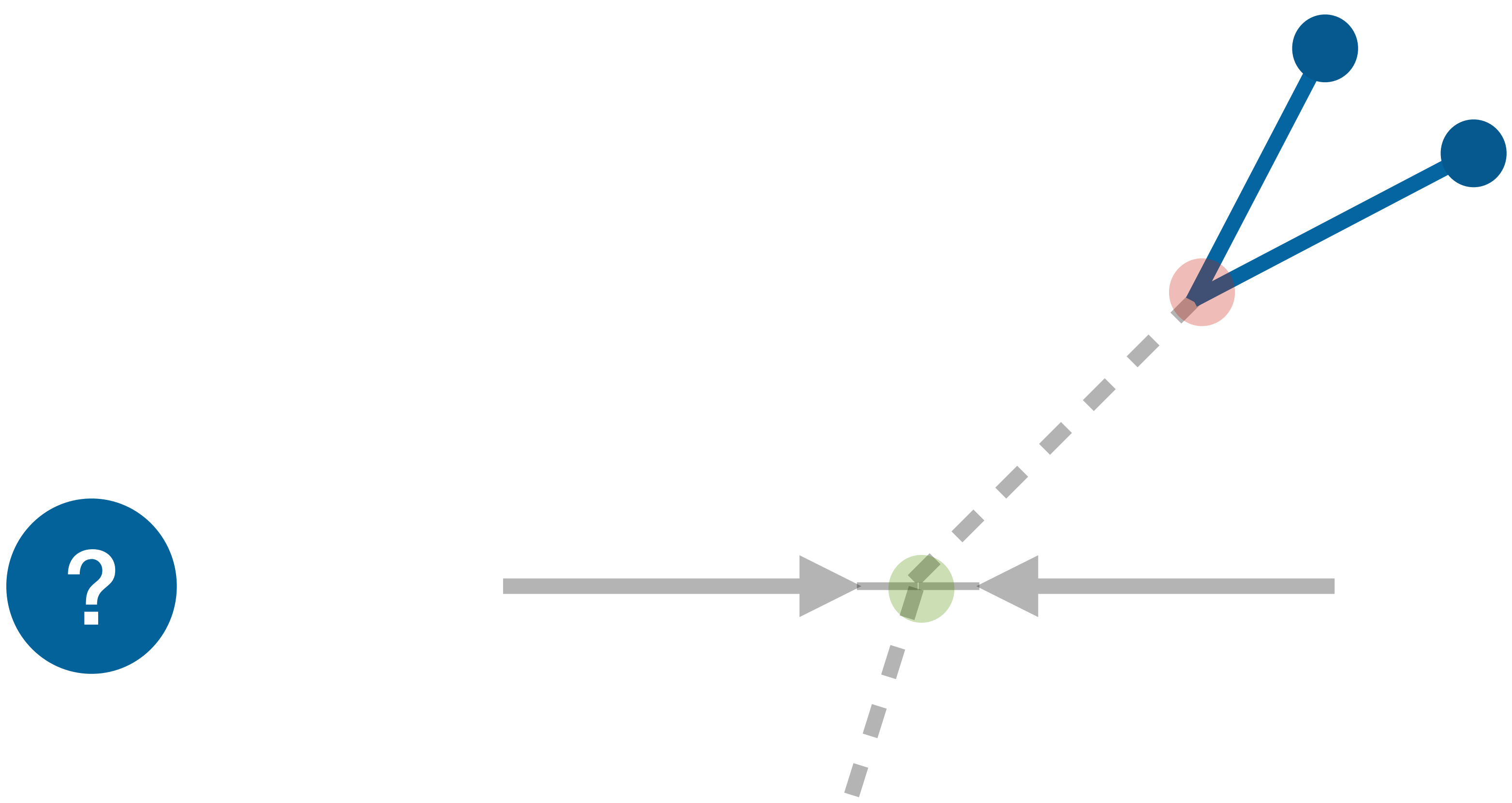
- Production rate, σ - Boost and direction	- Decay width, Γ or Lifetime, τ - Decay modes	depends on - what it decays into - where it decays

similar for prompt decays as well



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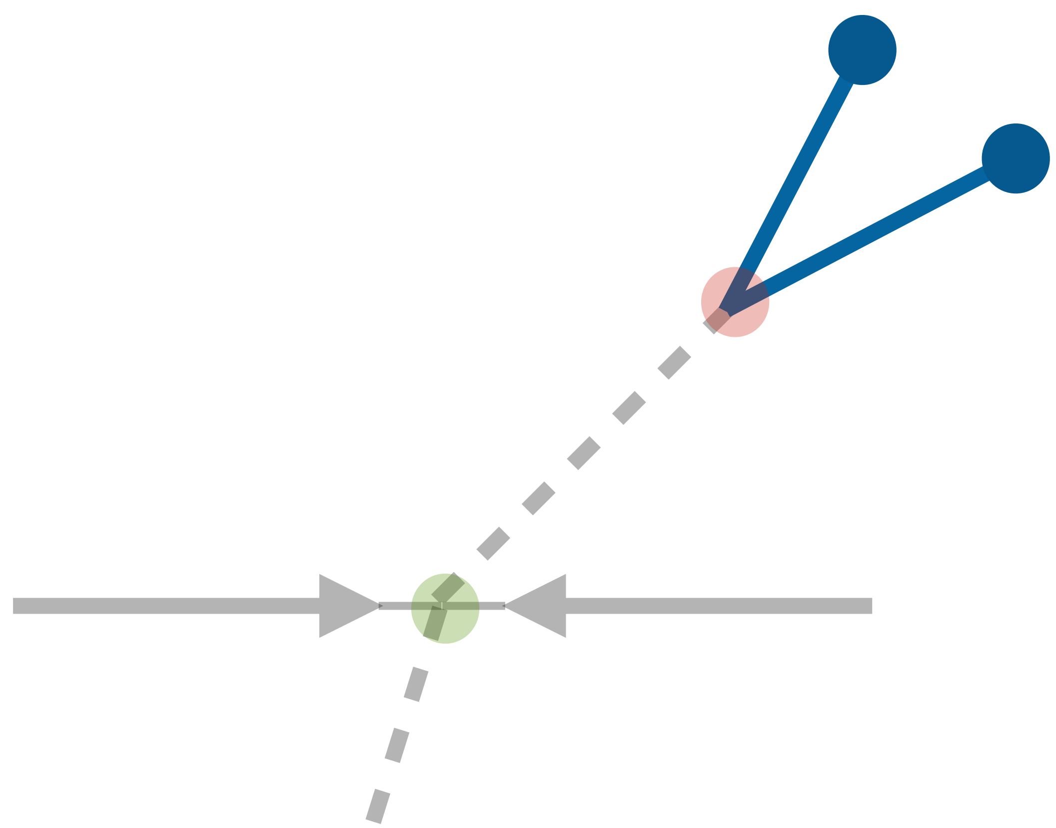
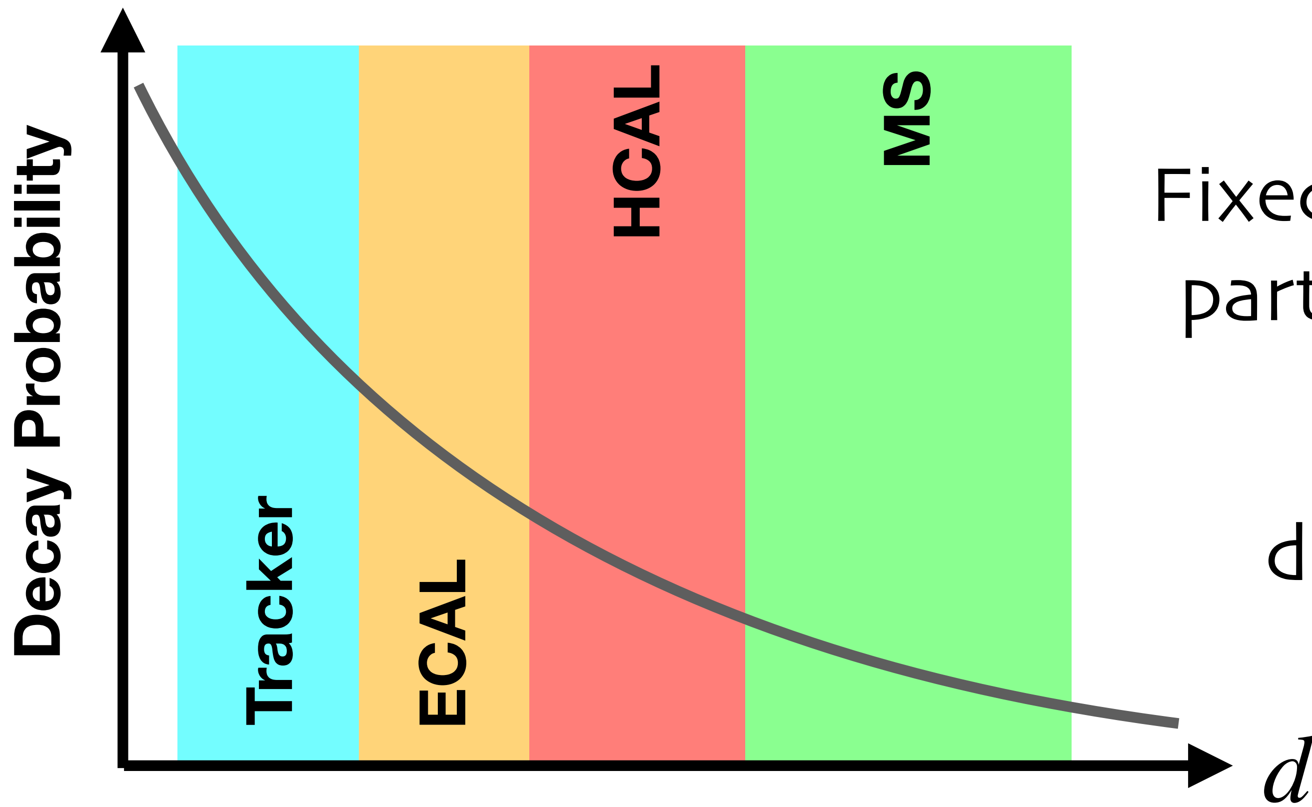


Decay position of the LLP



Fixed m and $c\tau$ of a BSM particle with a particular production and decay mode

$\Downarrow$

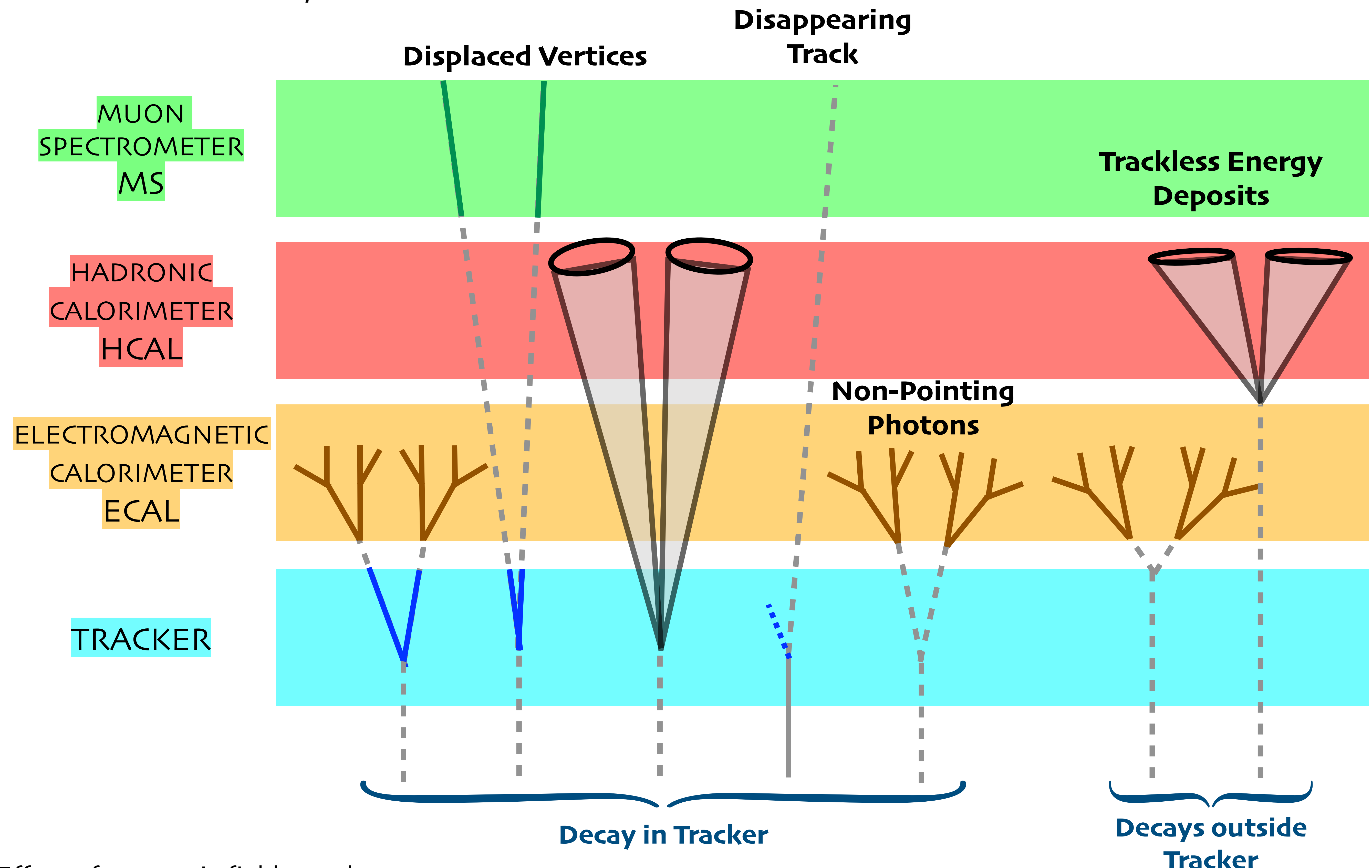
different probabilities to decay in different parts of the detector

Say, a BSM particle decays to two electrons

Prompt scenario	**LLP**
Final state signature fixed 2 electrons $\Rightarrow$ energy deposits in the ECAL with associated tracks in the Tracker	**DECAYS WHERE?** **Tracker:** displaced vertex **ECAL:** trackless energy deposit **HCAL/MS:** ?

A Peek in to the Exotic Signatures of LLPs

not a complete list



Effect of magnetic field not shown

Rhitaja Sengupta, IISc

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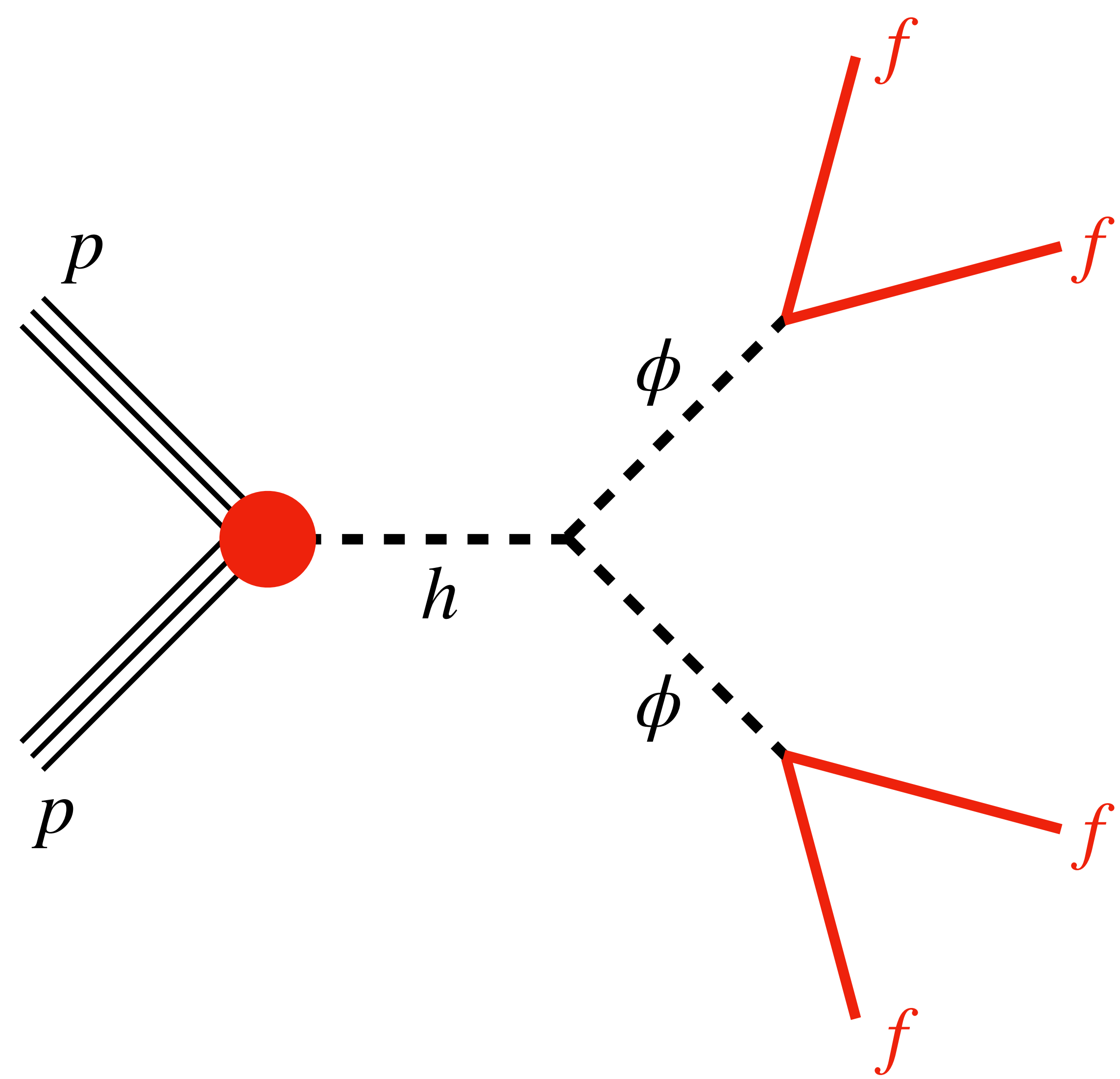
Scalar LLPs from Higgs Boson Decay

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?

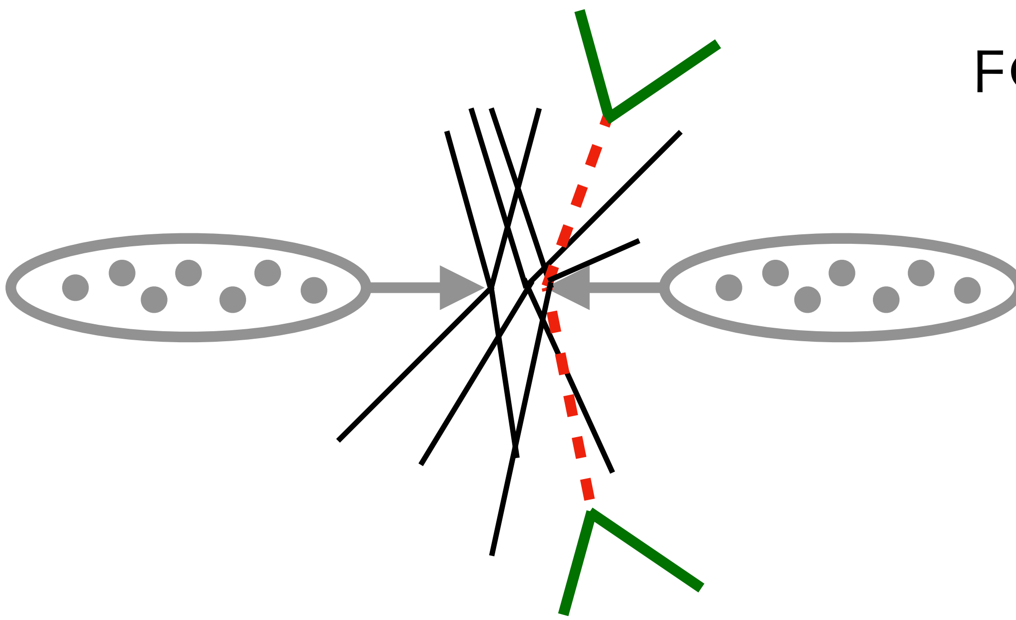
Biplob Bhattacherjee, Shigeki Matsumoto, RS, arXiv:2111.02437, PRD xxx, xxxxxx (2022)

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)

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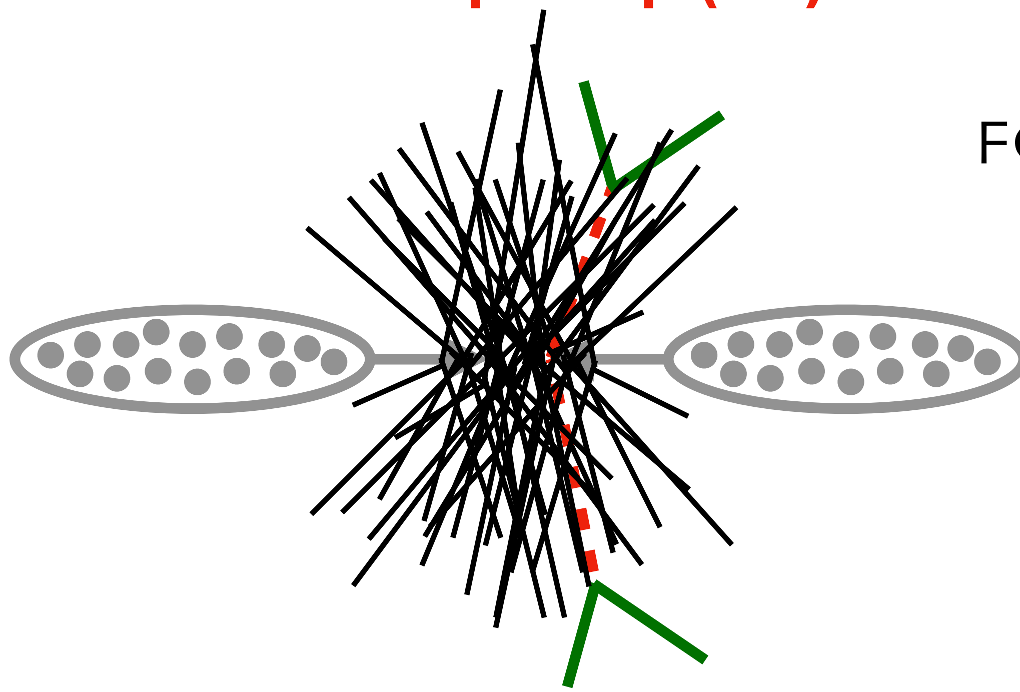


HL-LHC: High Luminosity LHC
14 TeV, 3 ab^{-1}

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

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

Where to look for the LLPs?

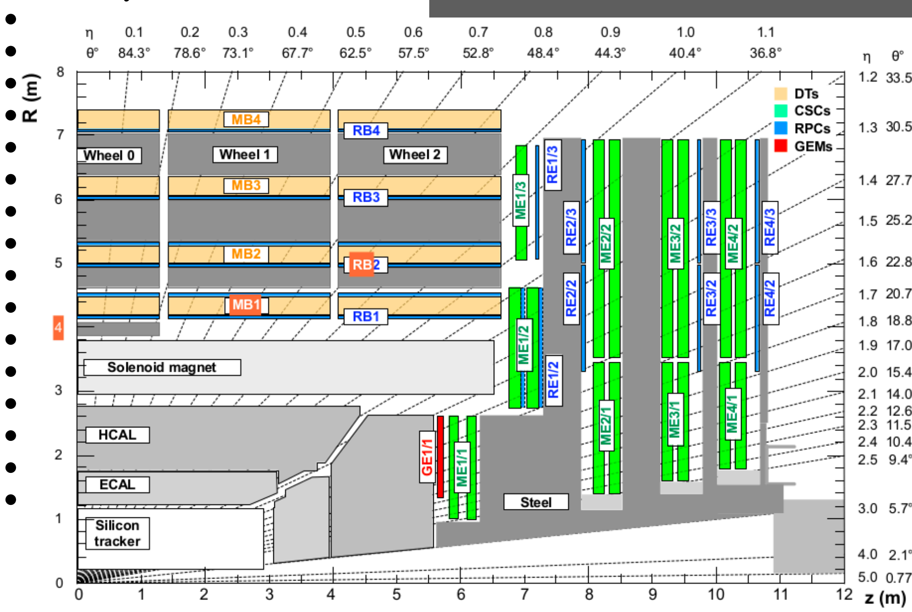
A ***Muon Spectrometer (MS)***

- **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	



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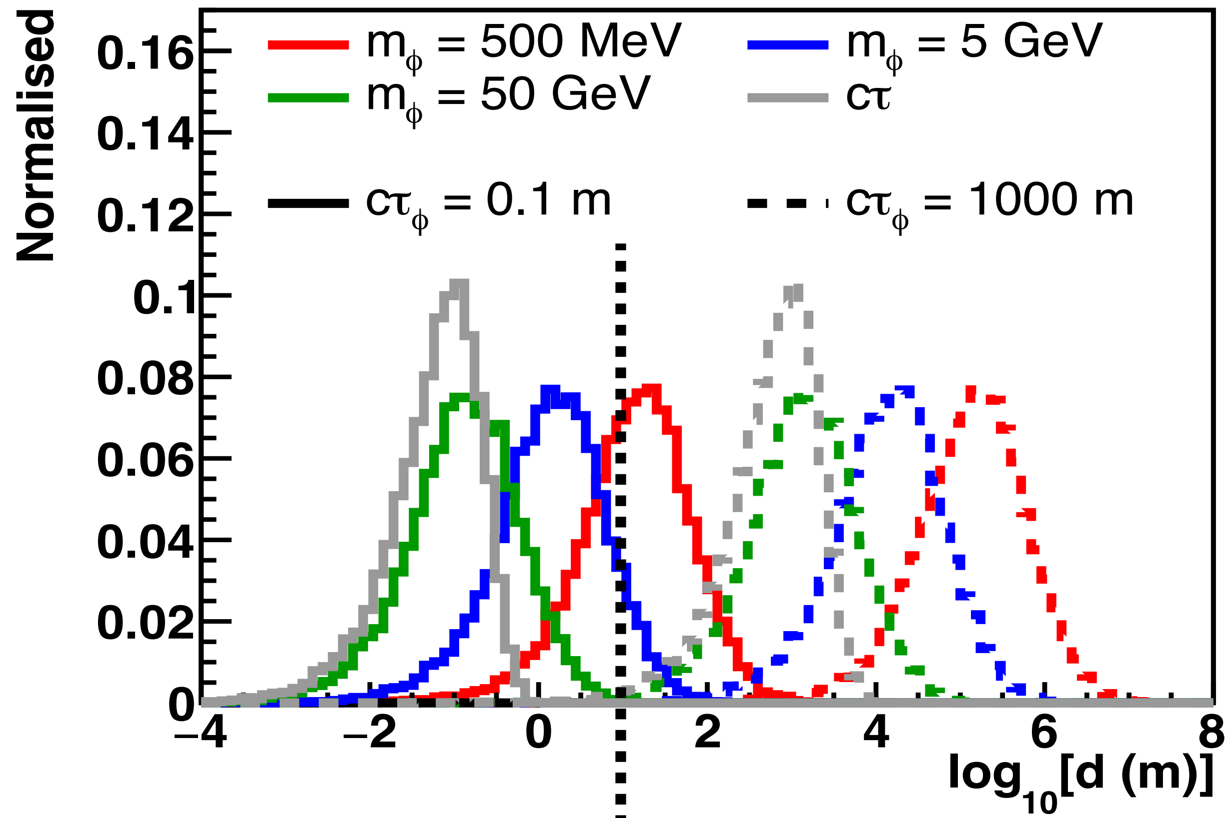


Distribution of decay length in the lab frame, $d = \beta\gamma c\tau$

ATLAS and CMS main detectors can probe

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

B ***Dedicated transverse LLP detectors***

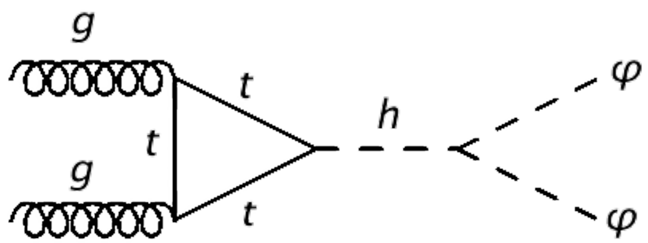
mostly centrally produced in Higgs decays - especially lighter LLPs

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

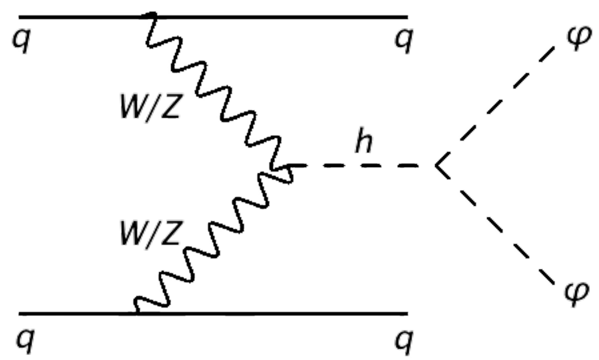
New Proposal
This work

Analysis Strategy for Decays in MS

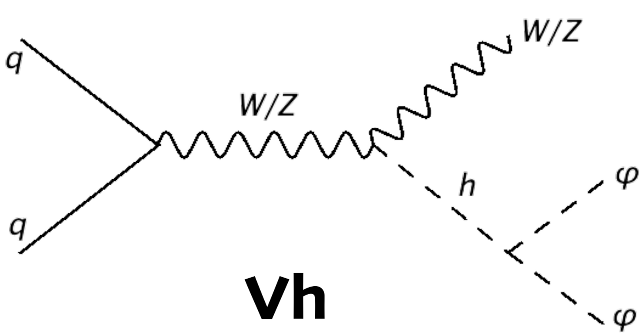
Production



ggF



VBF



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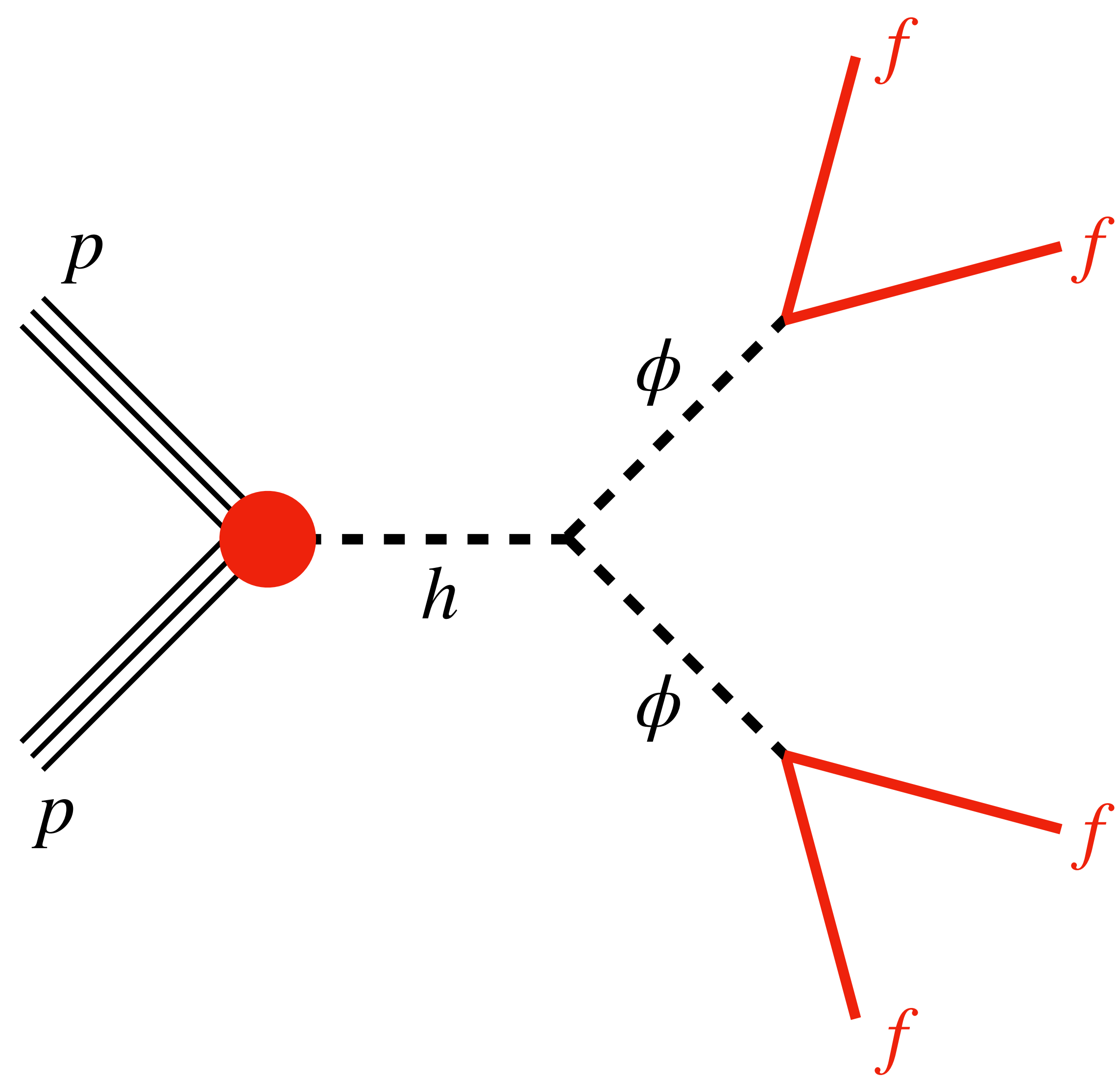
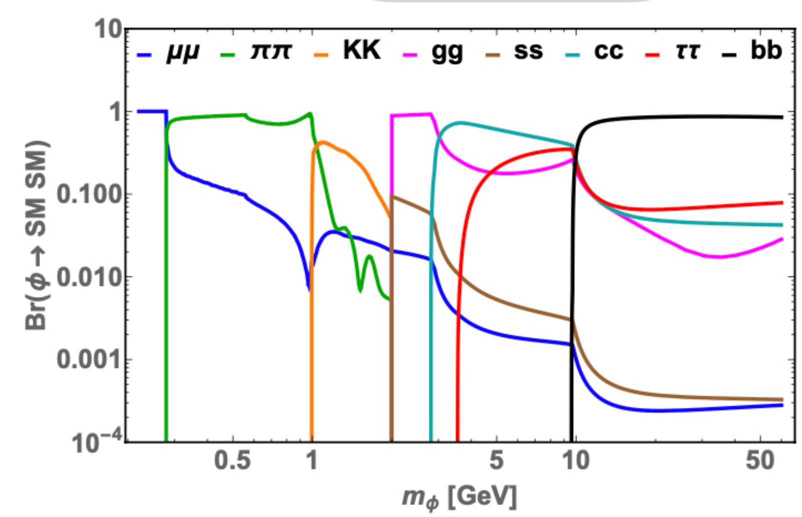


Decay

$\mu^+\mu^-$	$s\bar{s}$
$\pi^+\pi^-$	$c\bar{c}$
K^+K^-	$\tau^+\tau^-$
gg	$b\bar{b}$

Branching Fraction



Prompt objects associated with production

Displaced objects from the LLP decay

Analysis Strategy for Decays in MS

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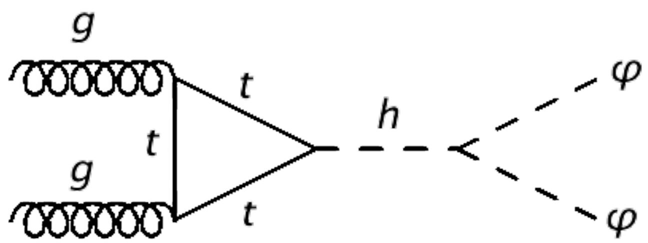

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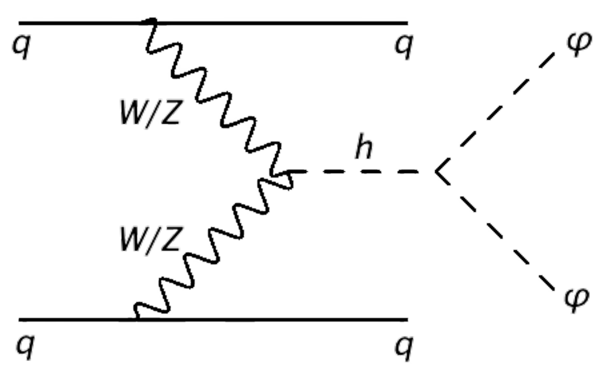

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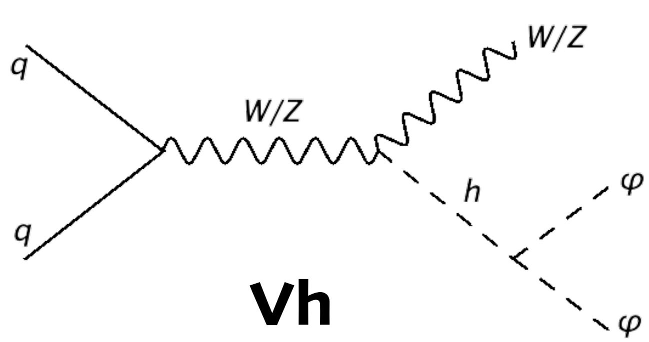

Vh

Prompt objects associated with production

Selection cuts on PROMPT OBJECTS

prompt jets, electrons, muons

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

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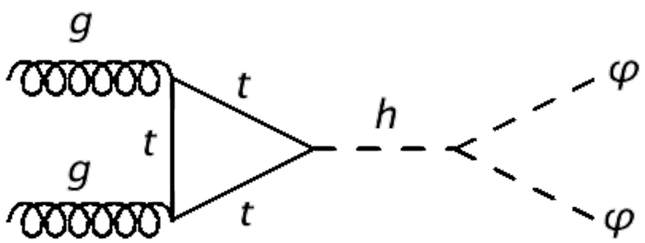

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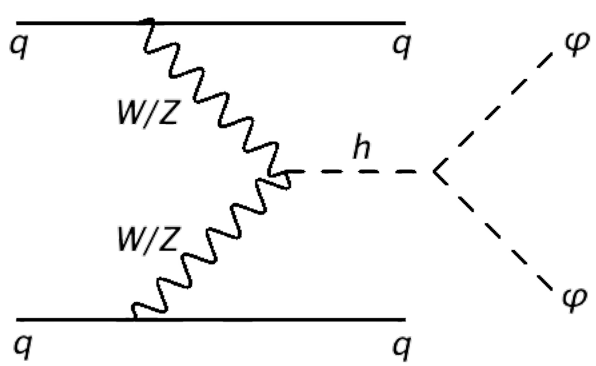

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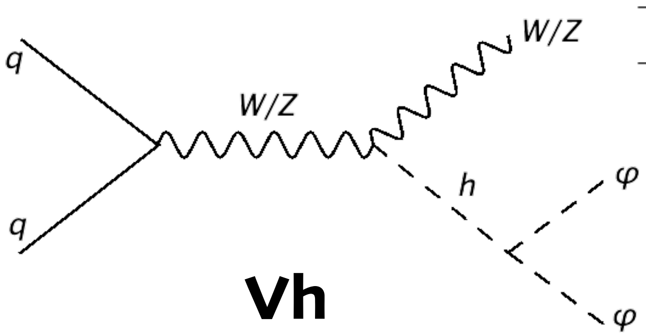

Vh

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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 (Single jet, Di-jet, VBF jet)

Vh-lep (Single electron, Double electron, Single muon, Double muon)

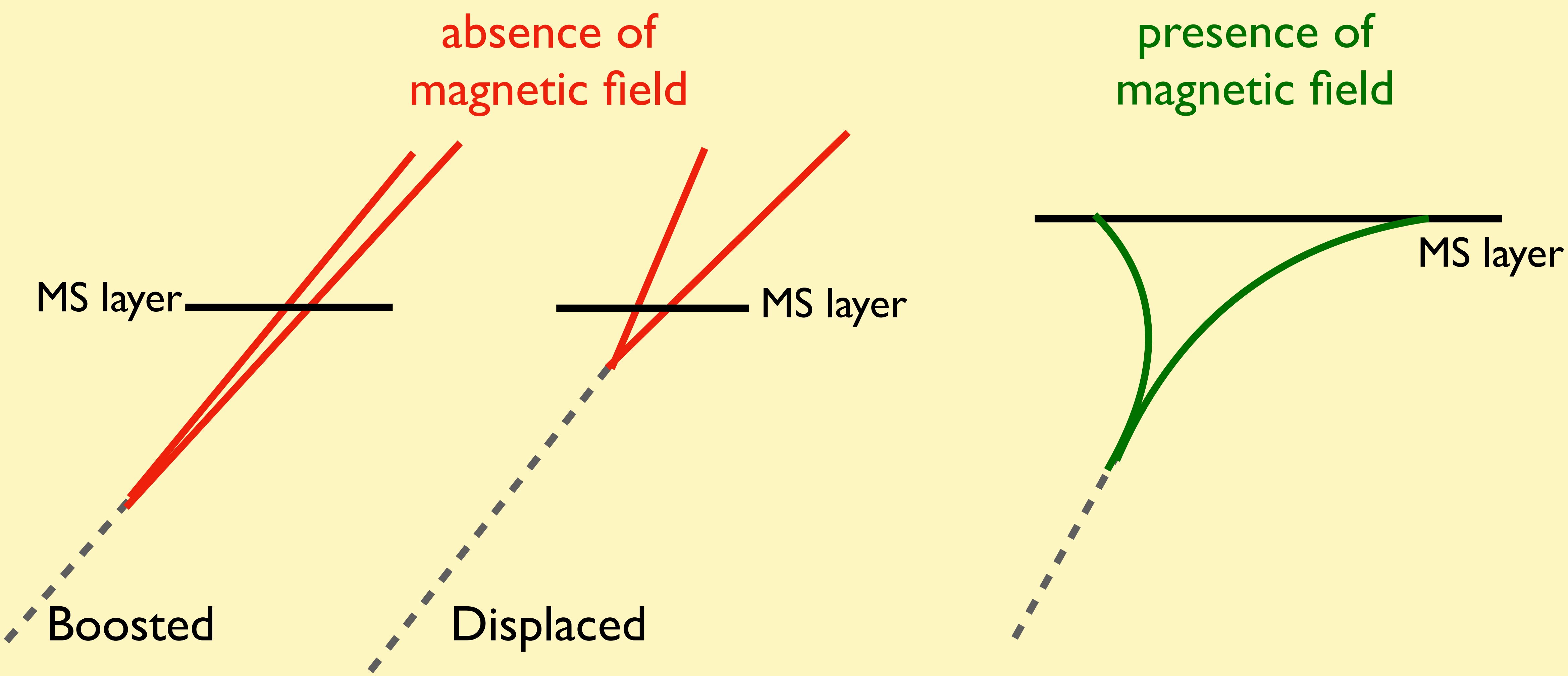
P^S : Soft set of cuts on prompt objects

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

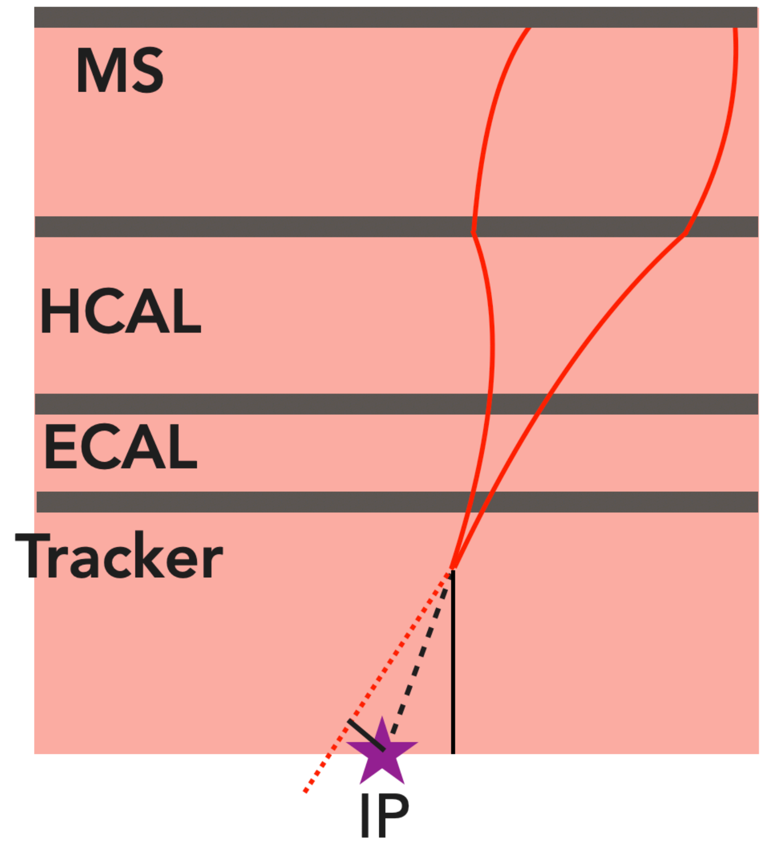
Selection cuts on DISPLACED OBJECTS

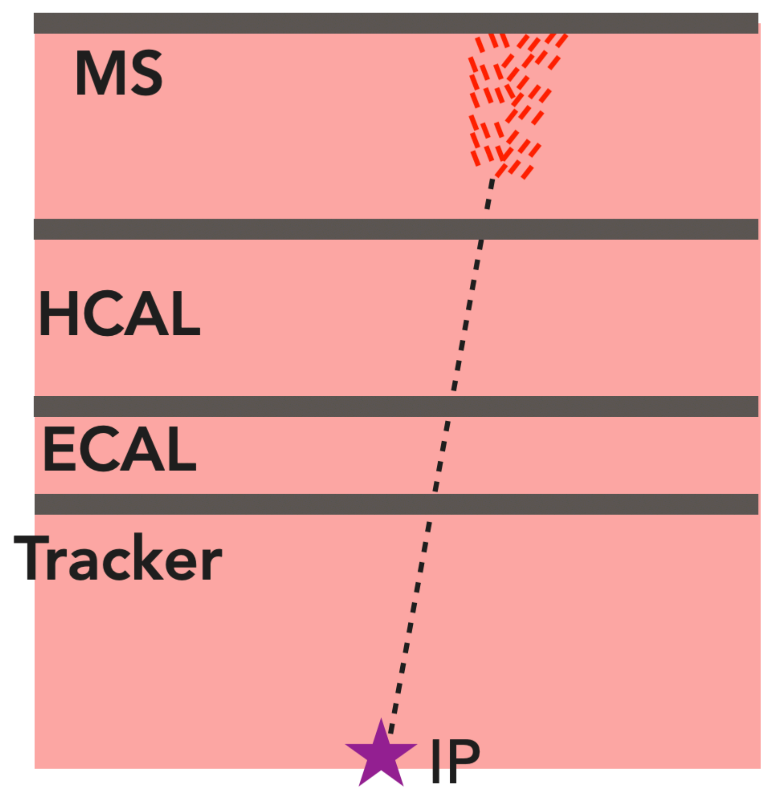
Displaced muons $\mu^+\mu^-$ — hard / soft

	D_μ^H	D_μ^S
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_{jets}^H	D_{jets}^S
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 $\lvert d_z\rvert < 9\,\mathrm{m}$
	$n_{\mathrm{dSV}}^{\mathrm{ch}} \geq 5$	$n_{\mathrm{dSV}}^{\mathrm{ch}} \geq 3$
	$\sum p_{T,\,dSV} > 50\,\mathrm{GeV}$	$\sum p_{T,\,dSV} > 20\,\mathrm{GeV}$
	$\Delta\phi_{\max} > 0.2$	$\Delta\phi_{\max} > 0.1$
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

Observation of 50 events required

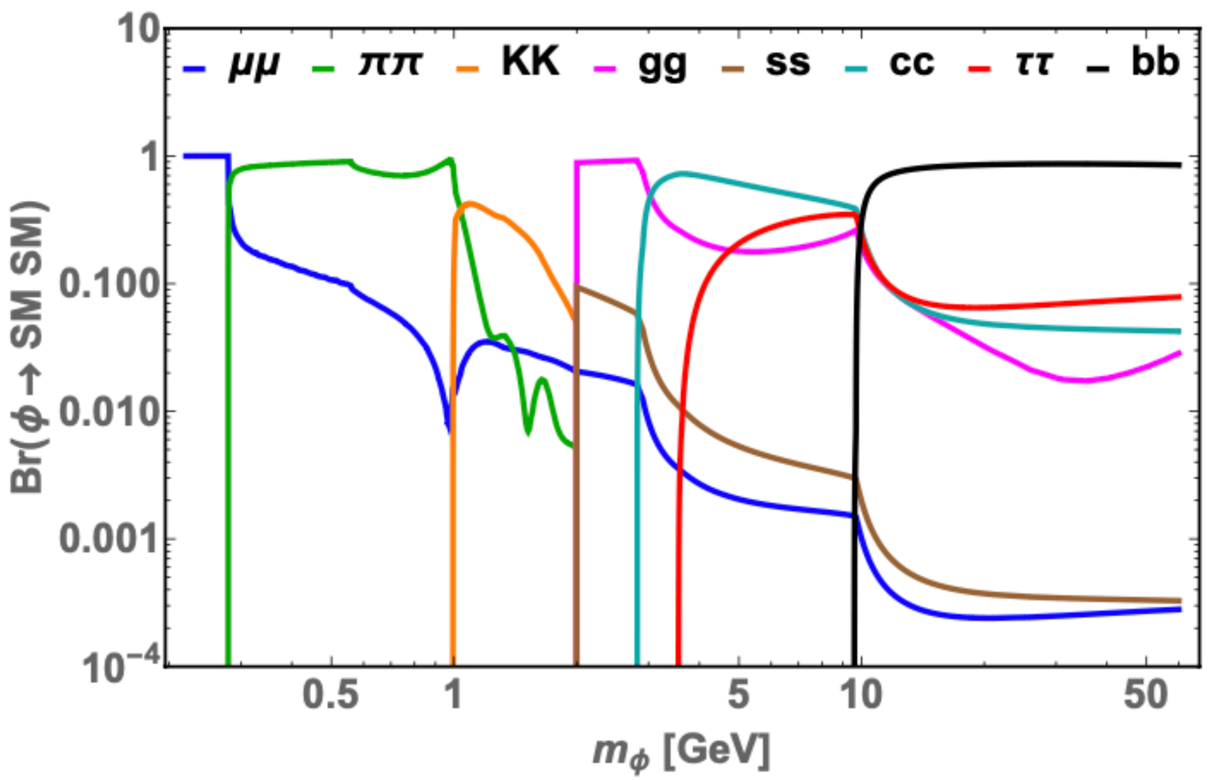
Backgrounds

For $\phi \to \mu^+\mu^-$ (100%),
$\text{Br}(h \to \phi\phi) < 3.1 \times 10^{-6}$
for $m_\phi = 60\,\text{GeV}, c\tau = 0.5\,\text{m}$

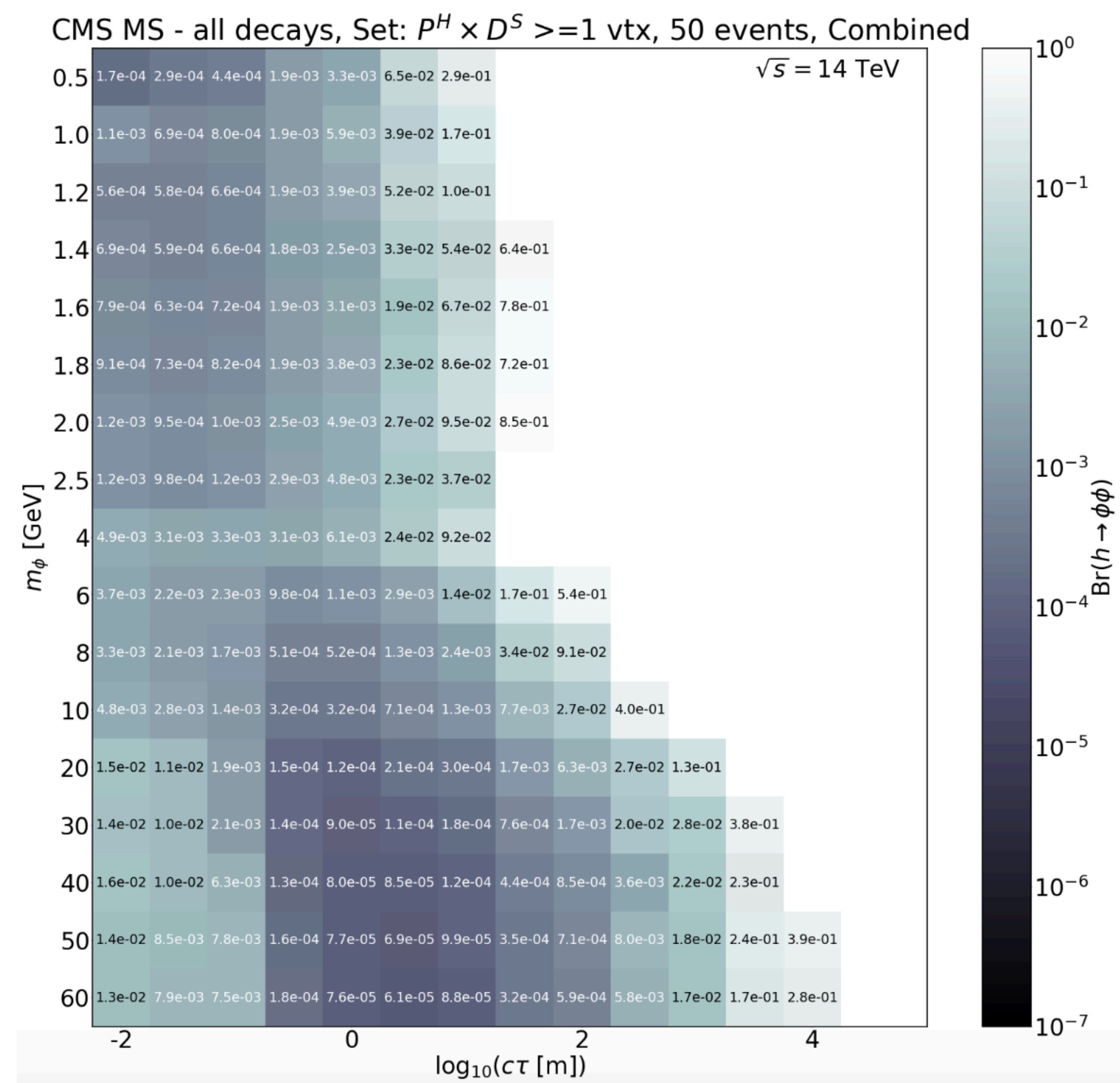
For $\phi \to b\bar{b}$ (100%),
$\text{Br}(h \to \phi\phi) < 1.7 \times 10^{-5}$
for $m_\phi = 60\,\text{GeV}, c\tau = 5\,\text{m}$

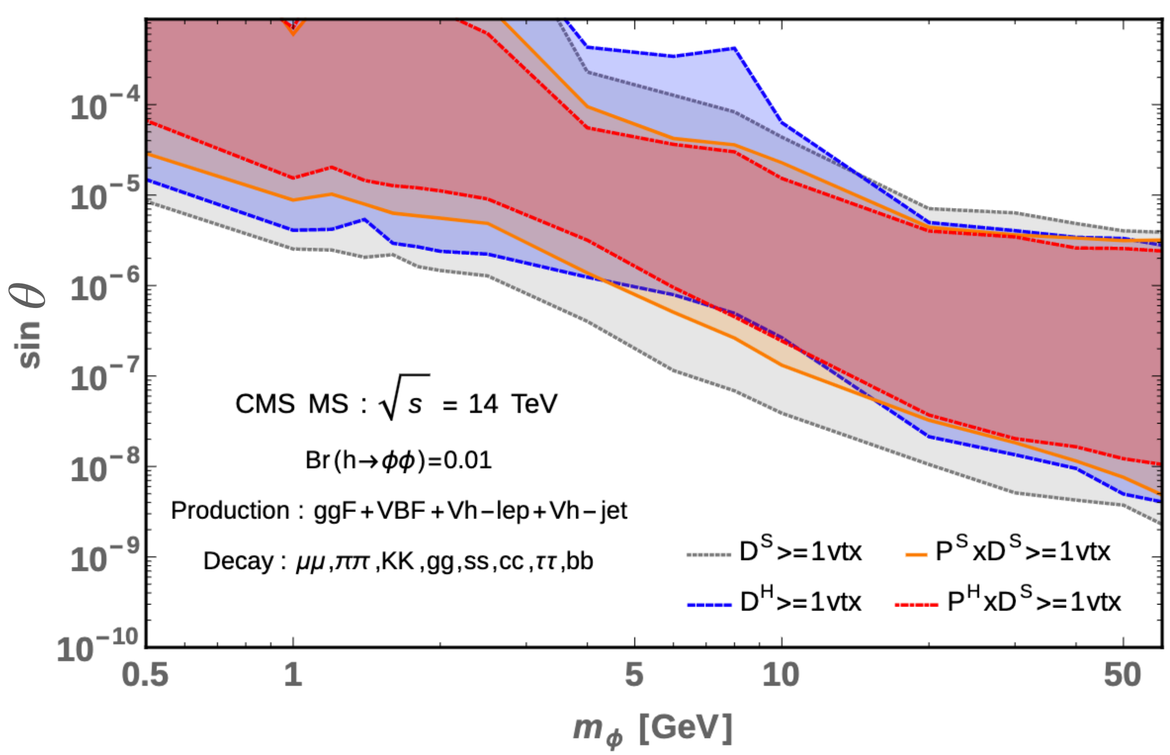
Muon Spectrometer only analysis - sensitive to higher decay lengths

A1 CMS MS



combined as per branching of minimal model



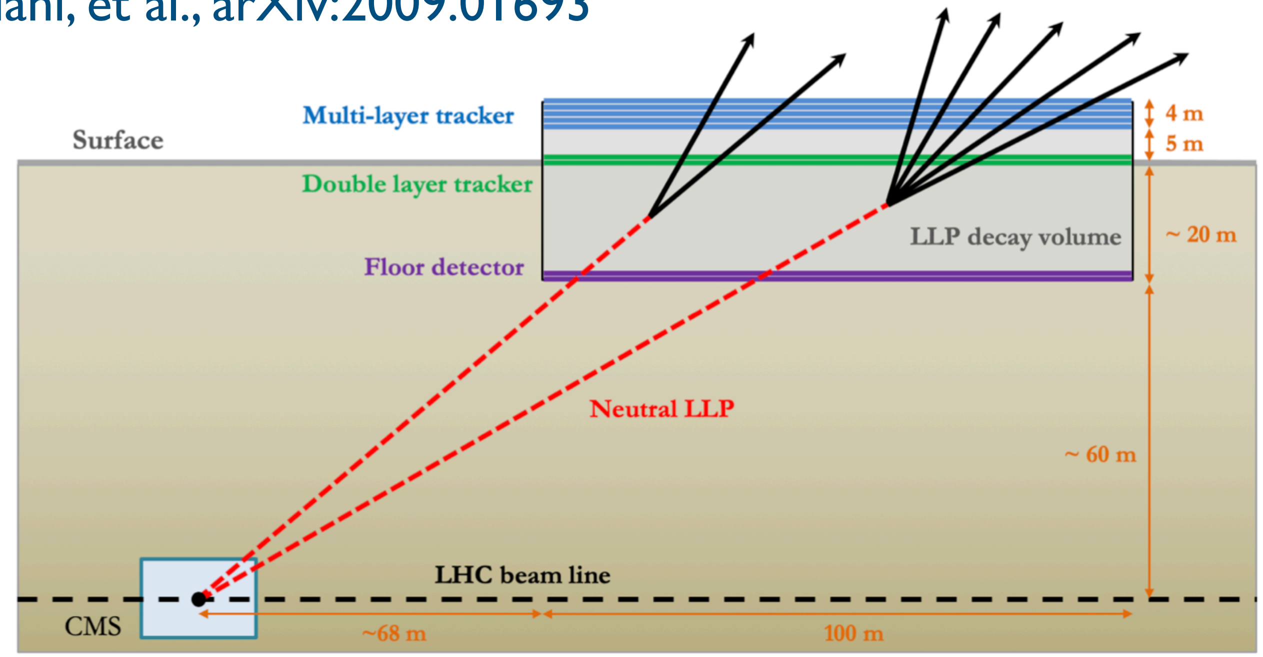


for fixed value of $\mathrm{Br}(h \to \phi\phi)$,

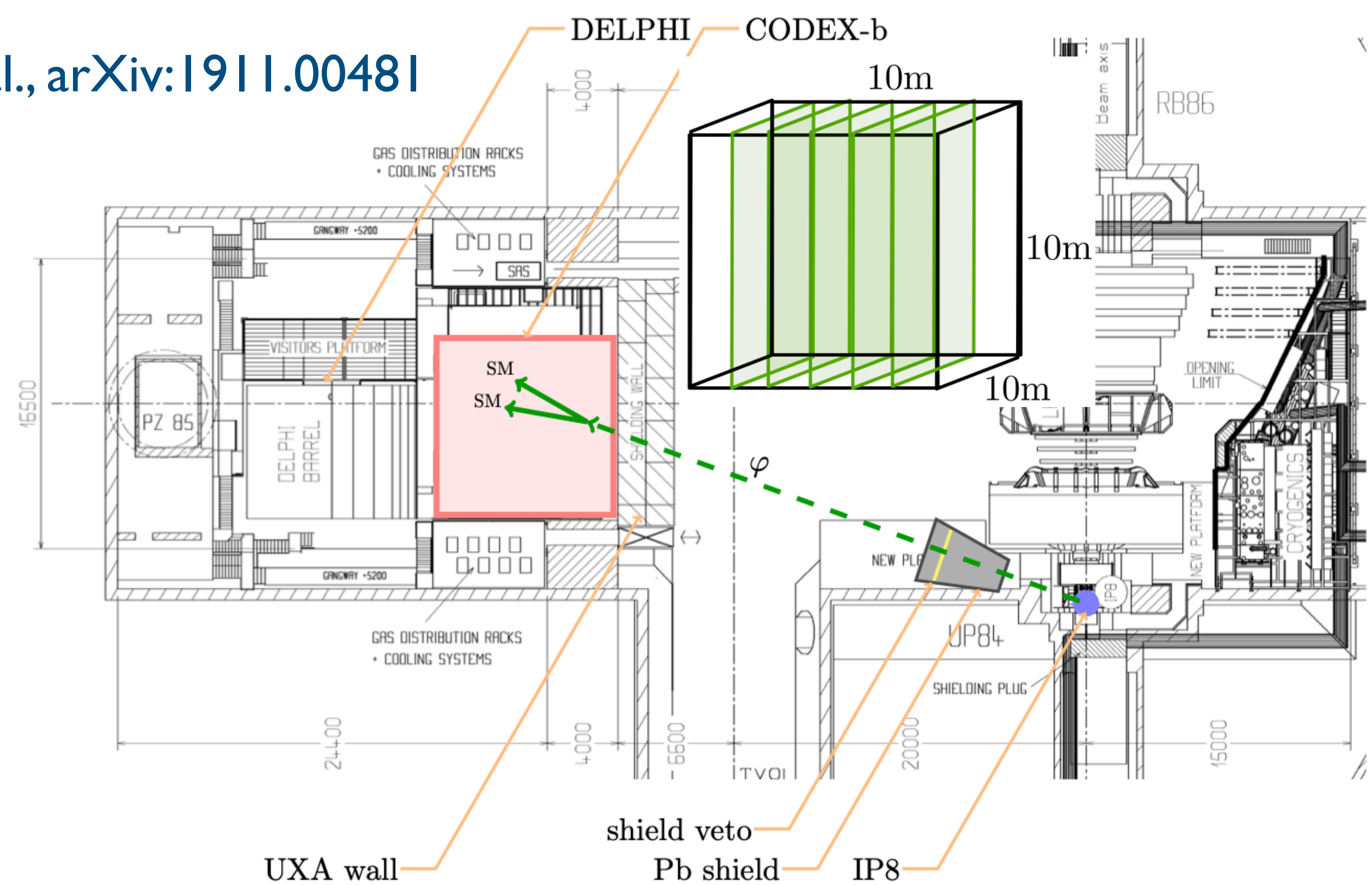
translated limit on $c\tau$ to limit on $\sin\theta$

B1 MATHUSLA and CODEX-b

Cristiano Alpigiani, et al., arXiv:2009.01693



Giulio Aielli, et al., arXiv:1911.00481



BACKGROUND FREE!

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

validated and extended analysis for our benchmarks

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

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

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

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

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

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

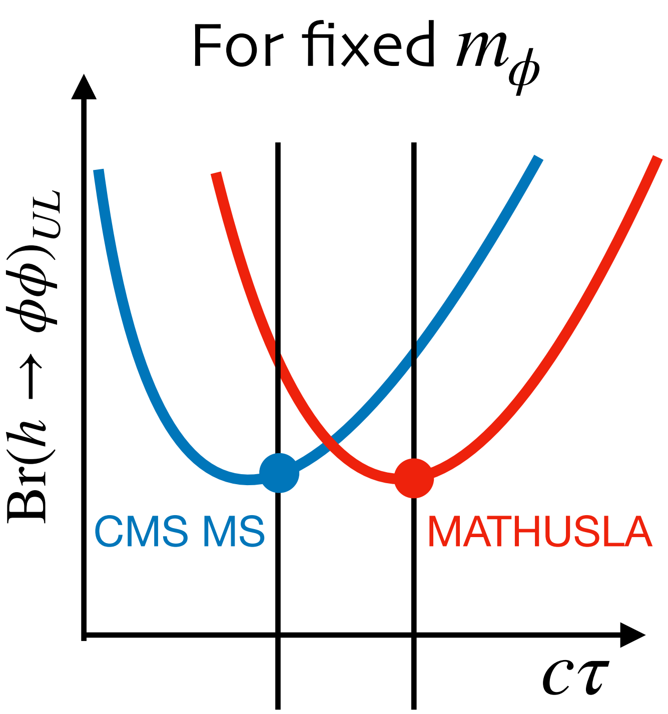
MATHUSLA,
$100 \times 100 \times 25\ \mathrm{m}^3,\ 3000\ \mathrm{fb}^{-1}$

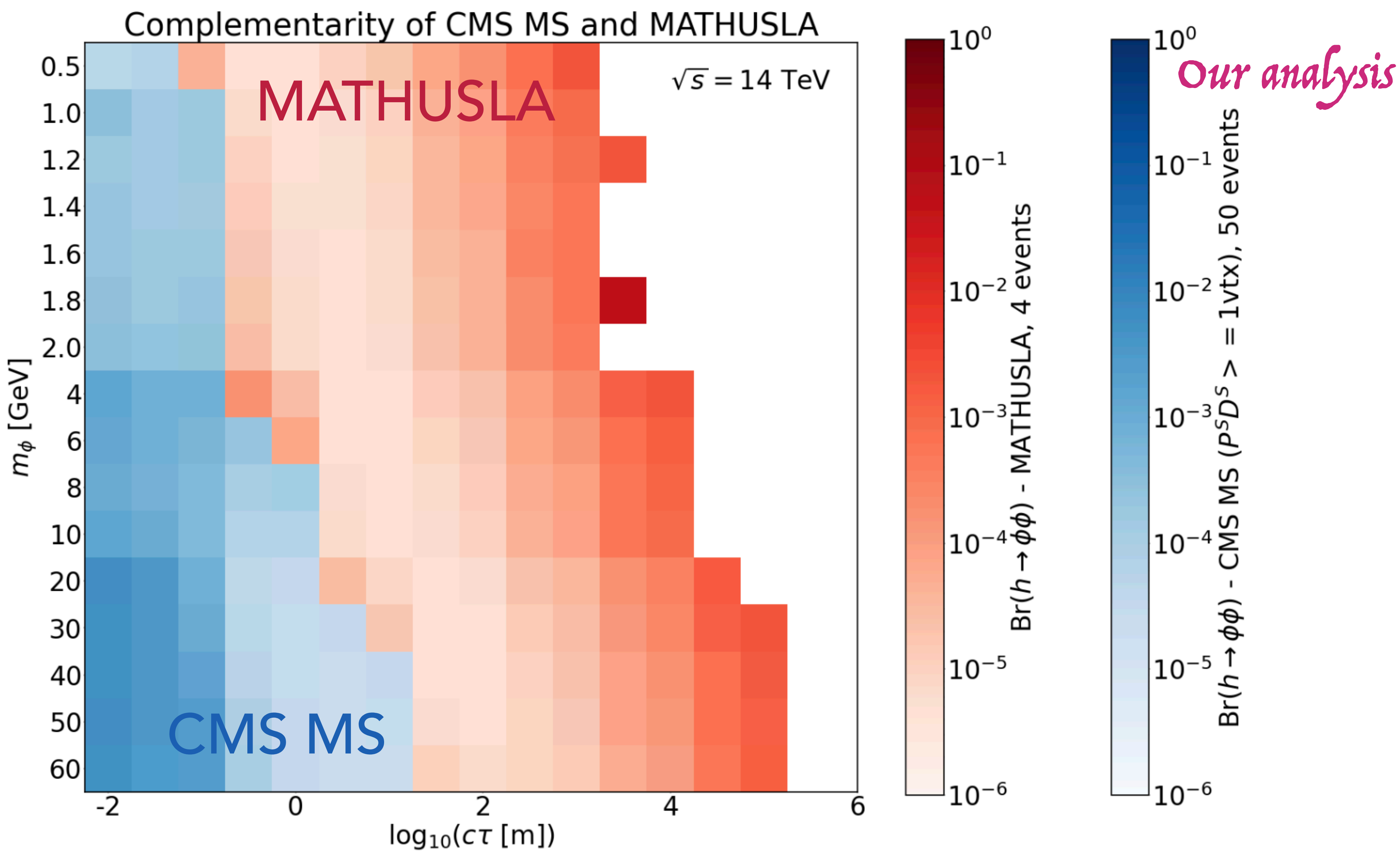
$(0.5\ \mathrm{GeV},\ 4.1 \times 10^{-6},\ 1\ \mathrm{m})$

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

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

CMS MS and MATHUSLA





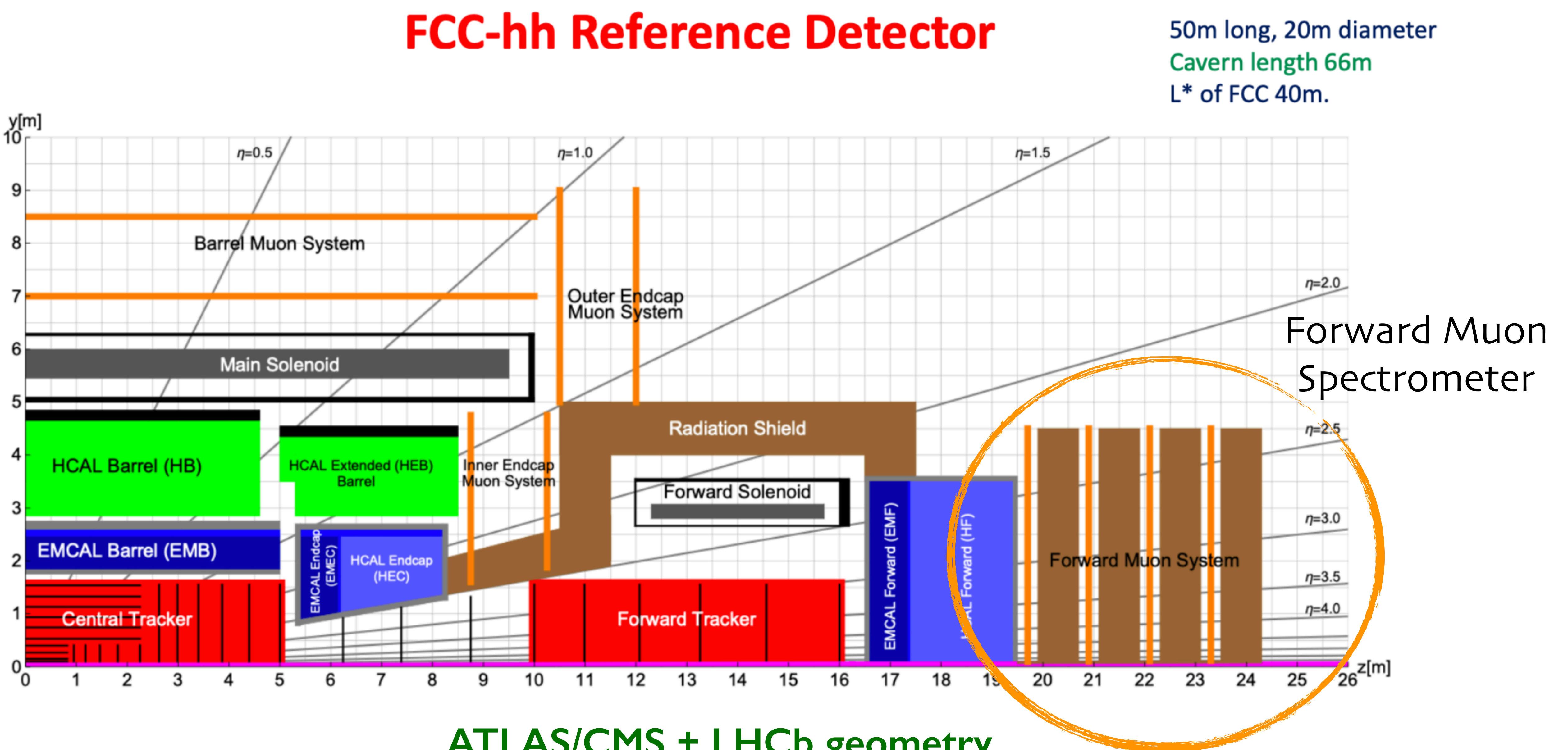
CMS MS + MATHUSLA:

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

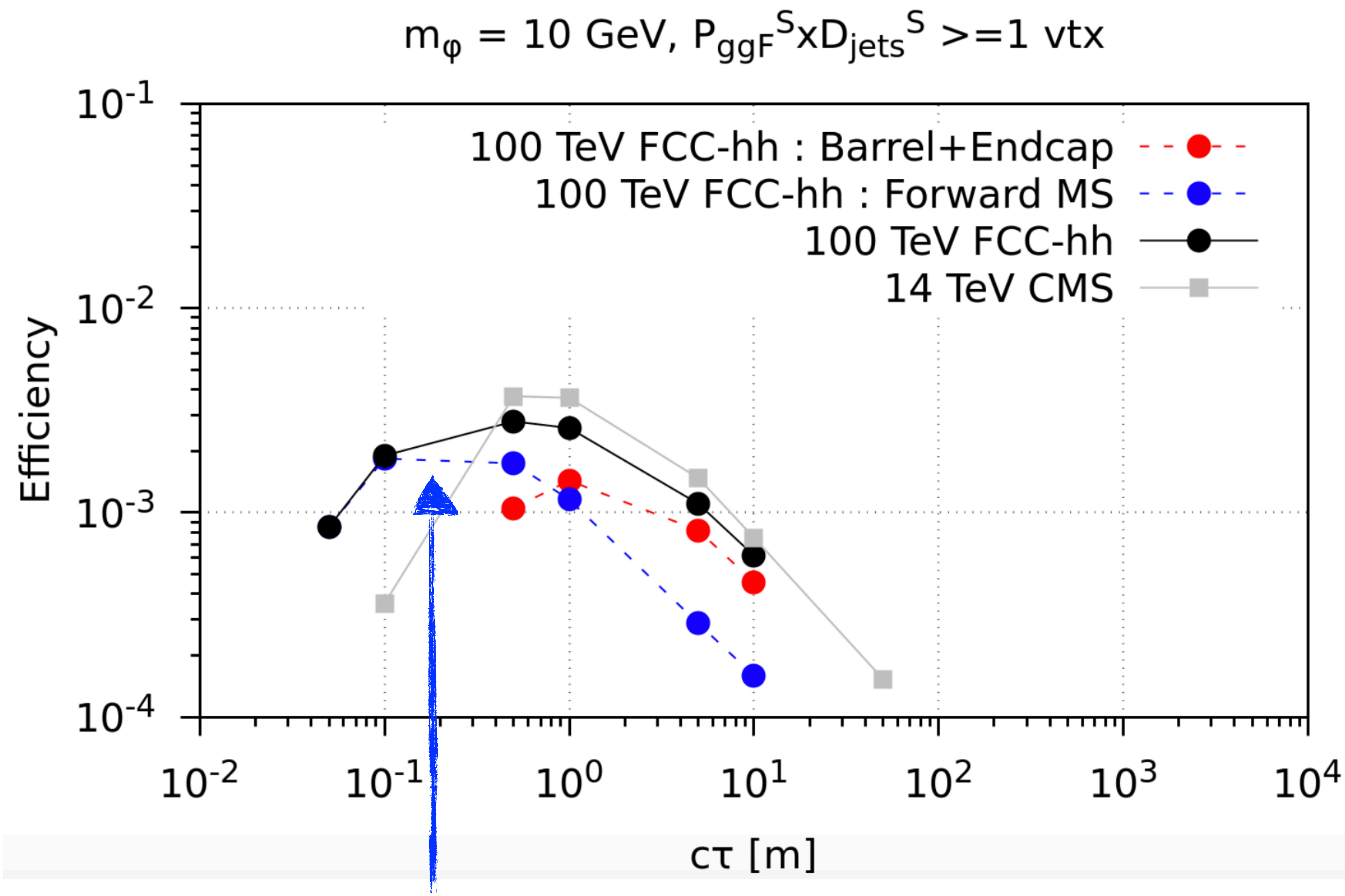
Performed similar analyses following the CMS MS one using the FCC-hh MS for final states $\mu^+\mu^-, c\bar{c}$, and $b\bar{b}$ for a range of LLP masses between 0.5 GeV and 60 GeV with $c\tau = [0.01,\ 5 \times 10^7]$ m



ATLAS/CMS + LHCb geometry

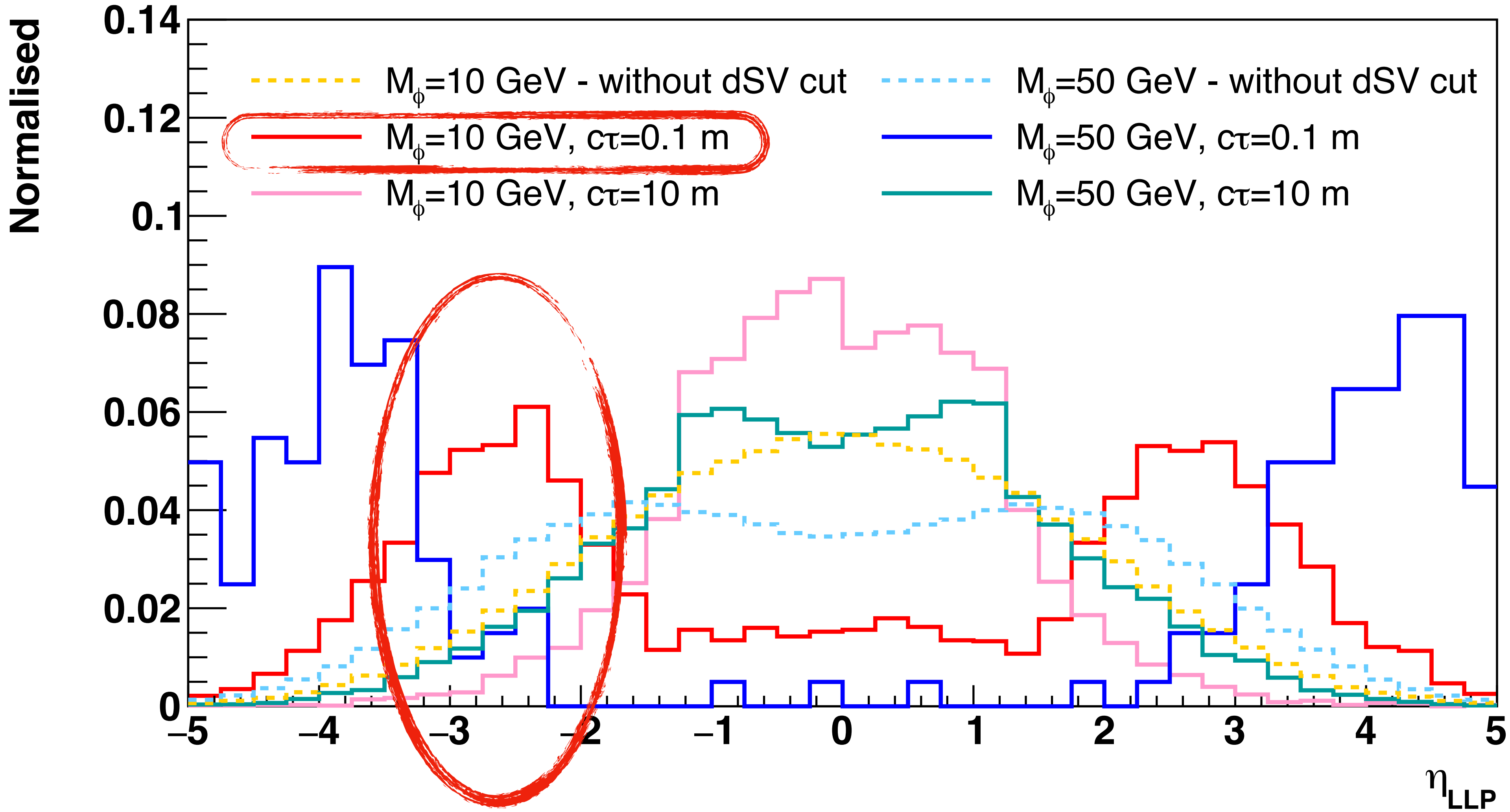
ANY BENEFIT?

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

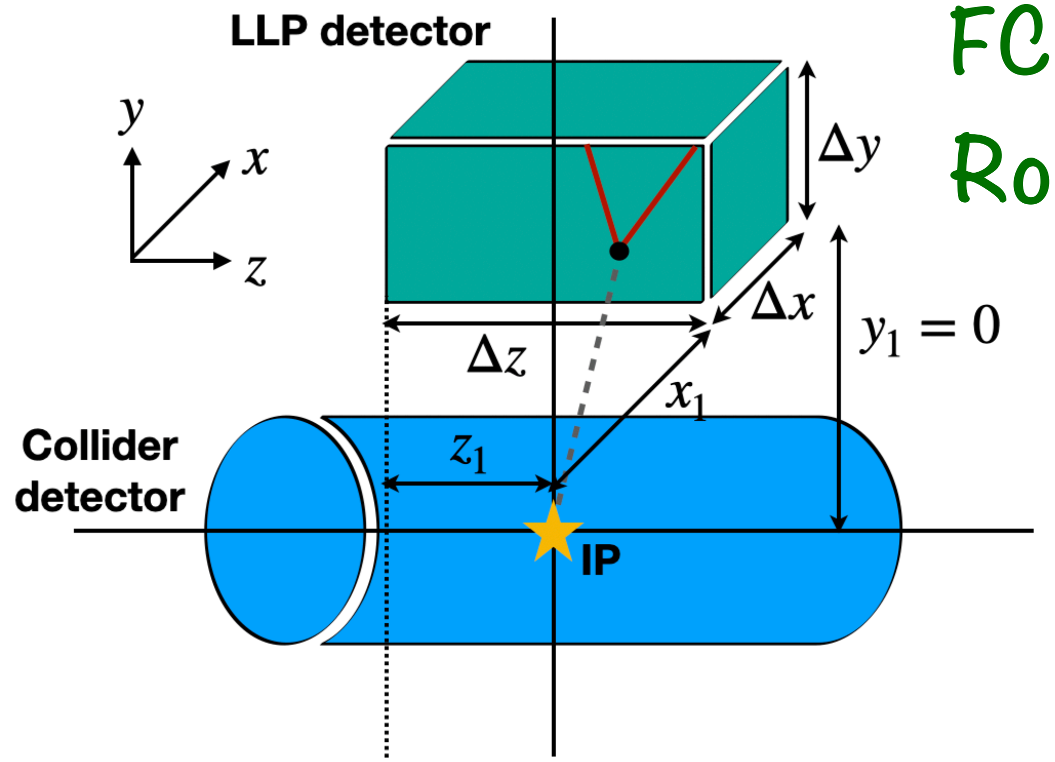
Lower decay lengths, otherwise, difficult due to more background in the Tracker

New Proposal
This work

B2 DELIGHT for FCC-hh

DELIGHT

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



FCC-hh design under study

Room for optimisation

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

Proposal for FCC-ee/CEPC - HECATE

Marcin Chrzaszcz, et al., arXiv:2011.01005

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. $\Delta x \times \Delta y \times \Delta z = 200 \times 50 \times 50\,\mathrm{m}^3$.

New Proposal
This work

B2 DELIGHT for FCC-hh

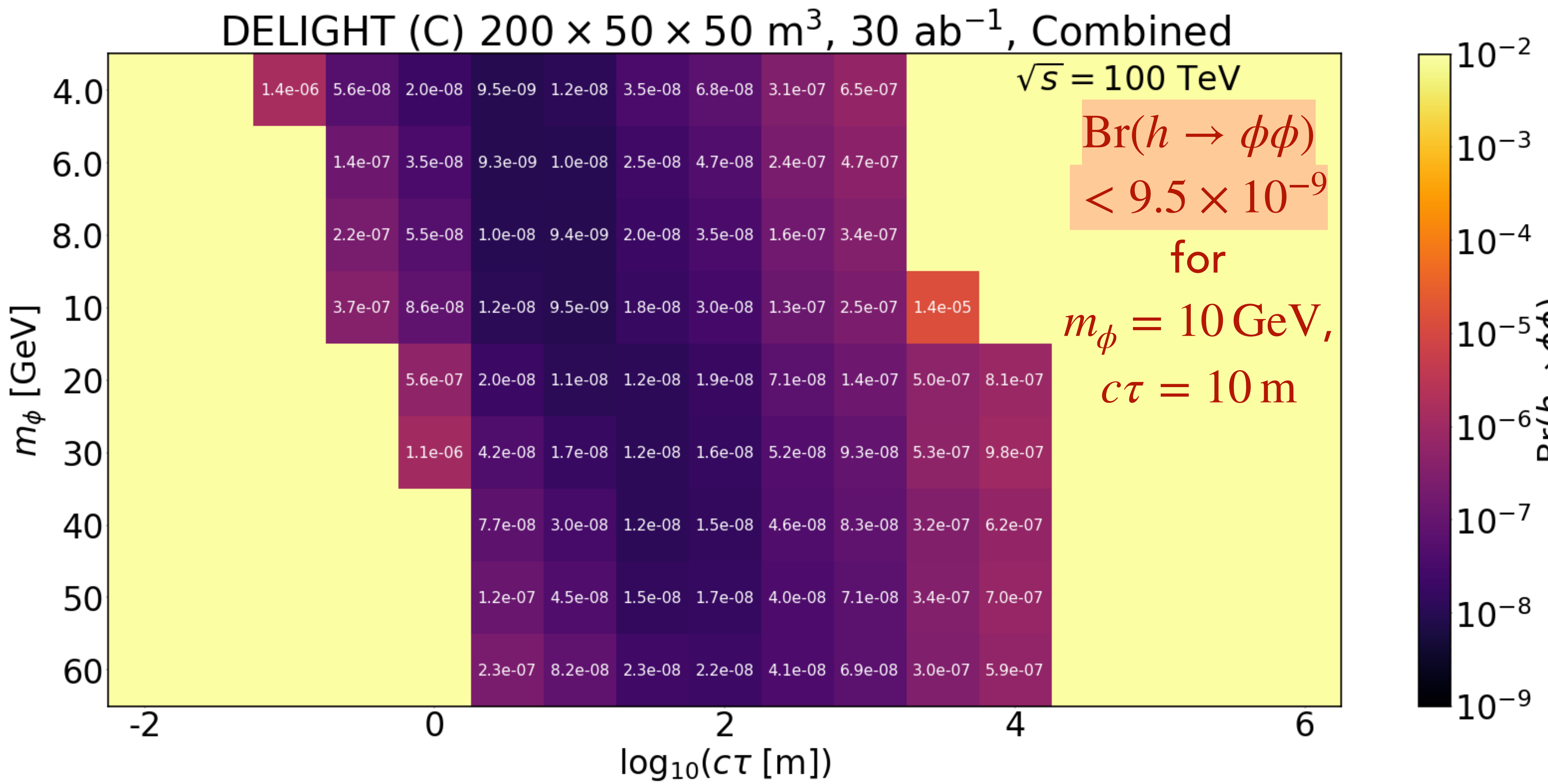
FCC-hh design under study
Room for optimisation

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

OUTLINE

- LLPs in colliders
- A study of LLPs in Higgs portal @ HL-LHC and FCC-hh
- **A few other aspects of LLP searches**
  - **Triggering**
  - Image recognition techniques for displaced jets
  - Lifetime estimation

Triggering: What, Why, How?

Selecting interesting events from the many pp interactions and storing them for further analysis

pp **collisions rate at LHC: 40 MHz, event size ~ 1 MB** $\Rightarrow$ **40000 GB/sec**

Not feasible

40 MHz

Level-1 trigger →

- Need to be quick
- Detector read at course granularity
- Tracker information not available till Run-3

100 kHz

High Level Trigger (HLT) →

- More time available - not as much as offline
- Full detector read at full granularity
- Full event information stored for offline analyses

1 kHz → **Stored for offline analyses**

1kHz x 1 MB ~ 1 GB/sec

Dedicated L1 Triggers important for LLPs

Biplob Bhattacherjee, Swagata Mukherjee, RS, Prabhat Solanki, JHEP 08 (2020) 141

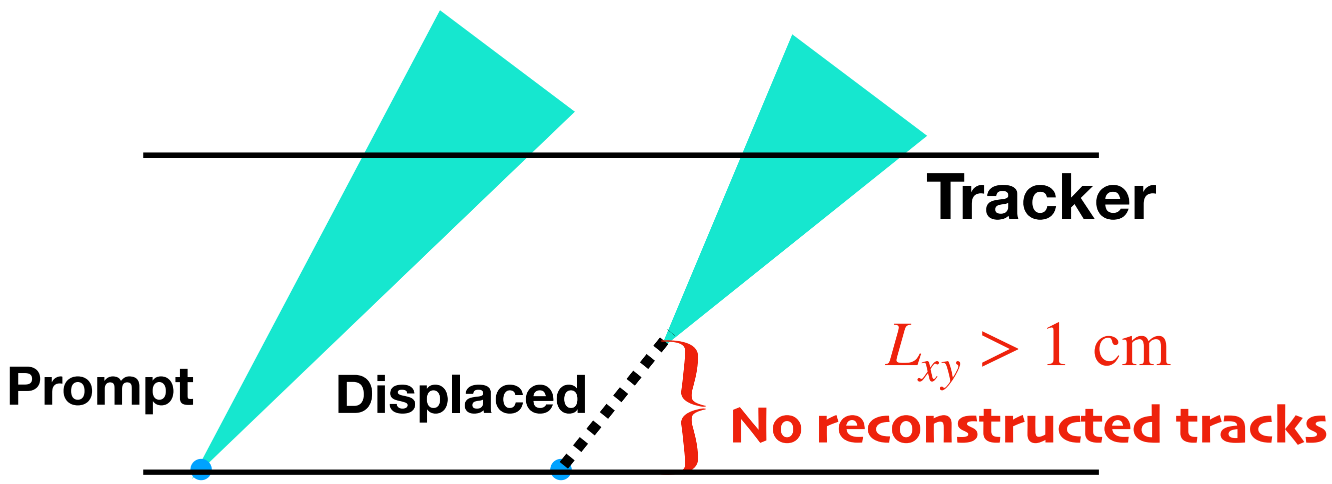
Biplob Bhattacherjee, Tapasi Ghosh, RS, Prabhat Solanki, JHEP 08 (2022) 254

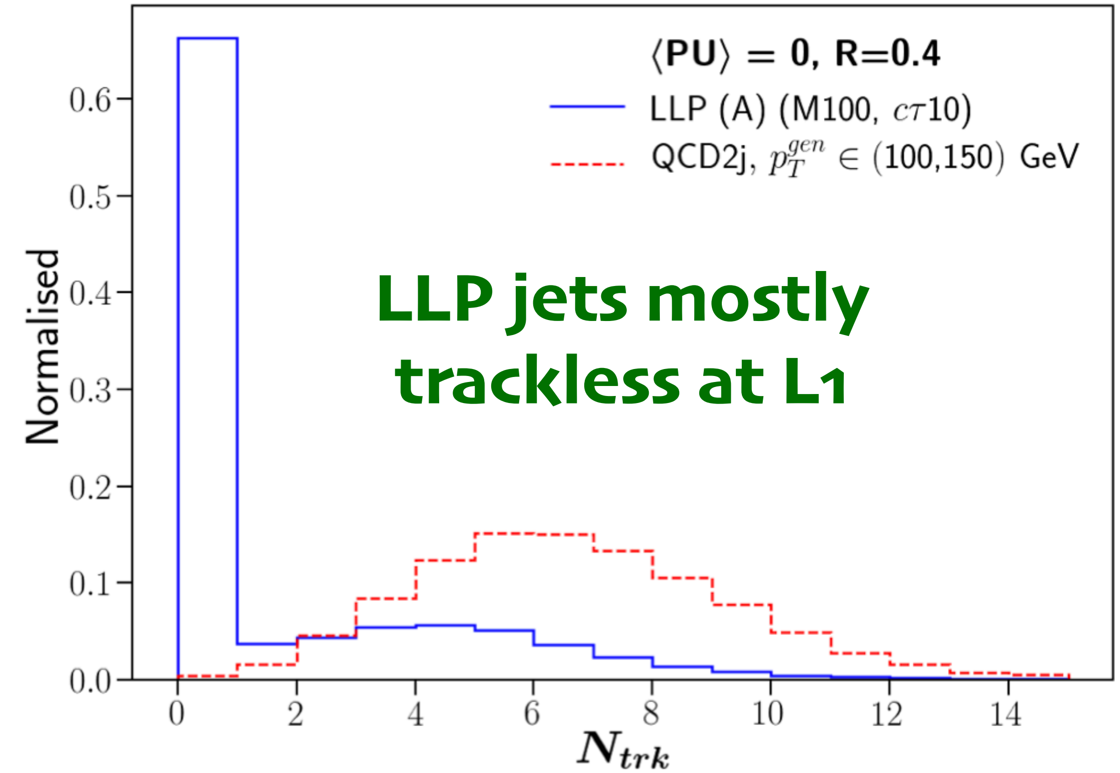
L1 Tracking

L1 track:

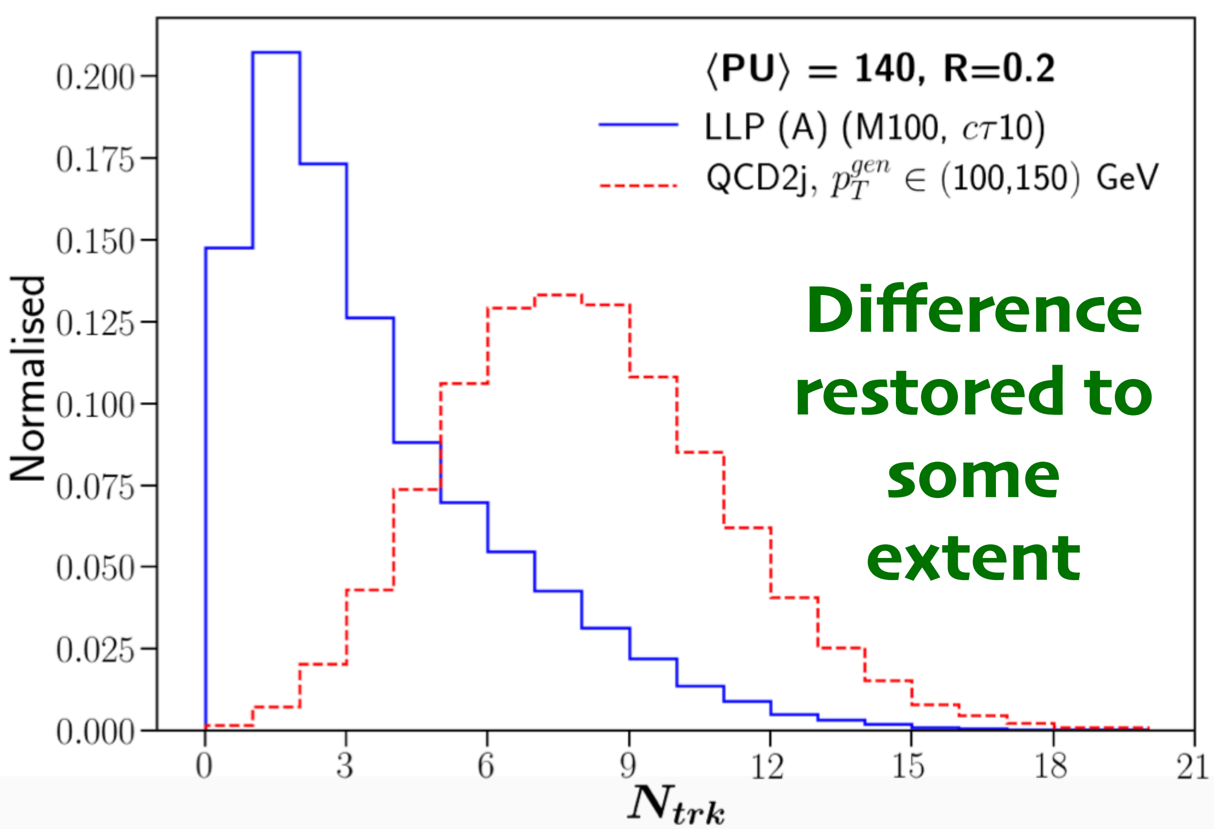
$p_T > 2$ GeV, $|\eta| < 2.5$,
$L_{xy} < 1$ cm, $|z_0| < 30$ cm

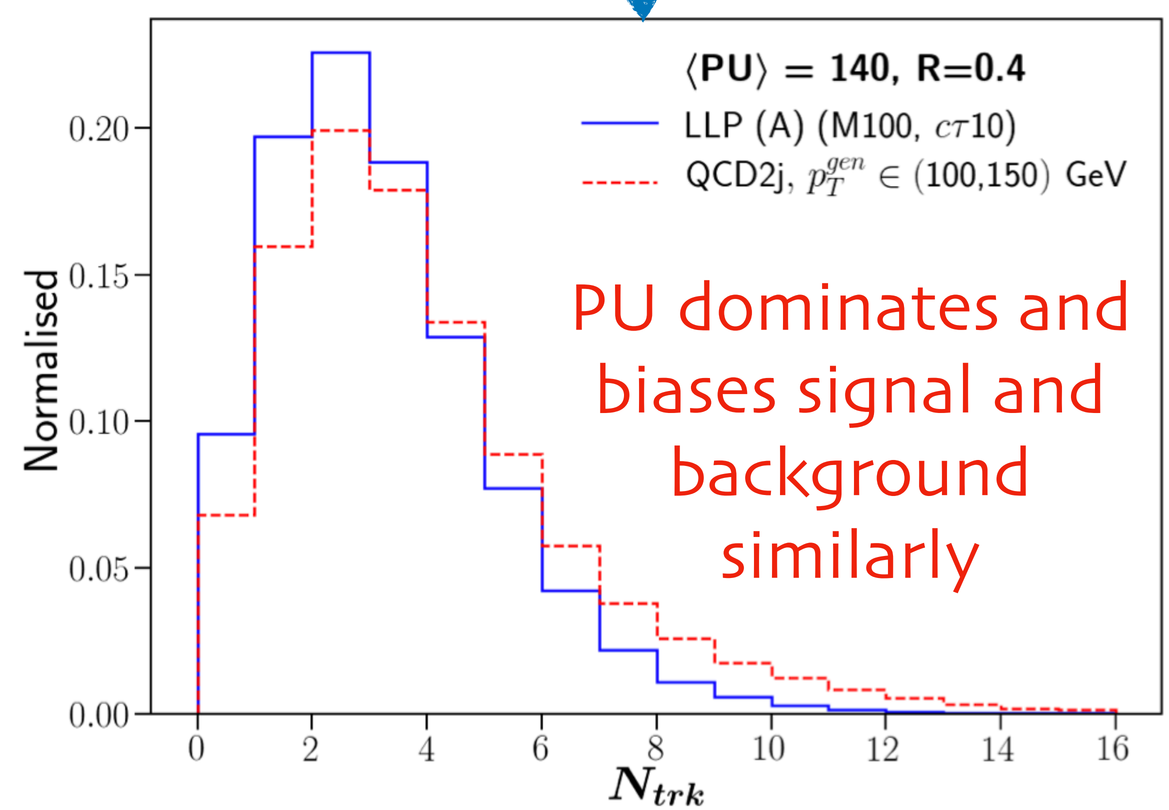
T. James, CERN-THESIS-2018-241





Reduce cone-size from $R = 0.4 \rightarrow R = 0.2$



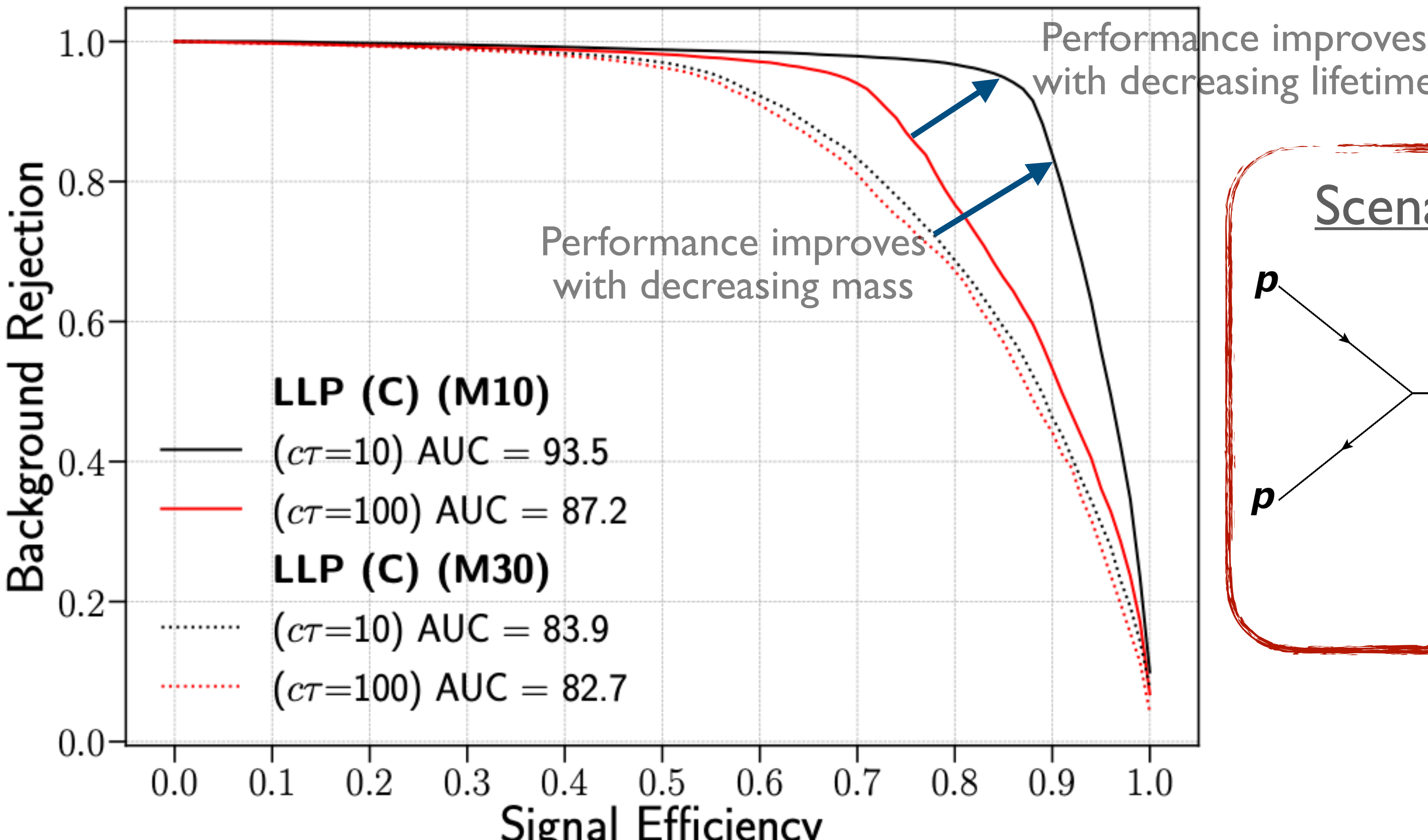


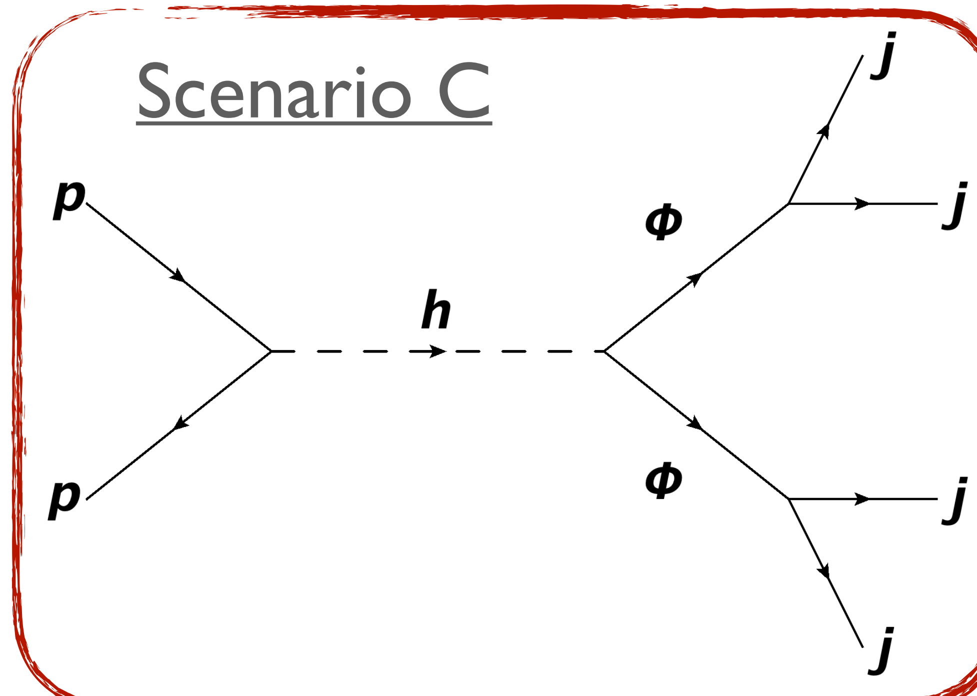
L1 Tracking

Tracking variables:

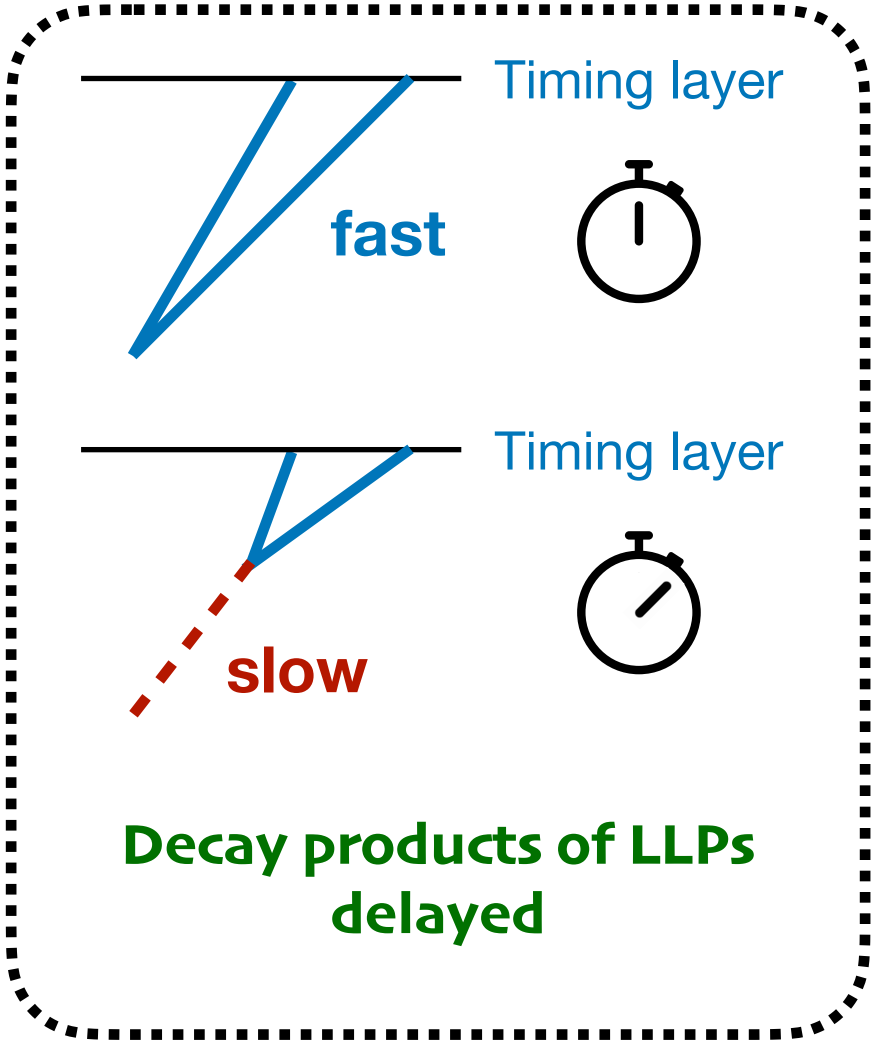
$$N_{\rm trk} \mid \sum p_T \mid z_{\rm j\_vtx} \mid \Delta z_{\rm j\_vtx} \mid p^{\rm miss}_{T({\rm vtx})} | n_{z_{\rm trk\_max}} \mid \Delta z_{\rm trk\_max} \mid \sum p_T^{z_{\rm trk\_max}} | \sum p_T^{z_a \neq z_{\rm trk\_max}} | \frac{\sum p_T^{z_{\rm trk\_max}}}{\sum p_T} | S\left(\frac{|z_i|}{\sum |z_i|}\right) |$$

$$S(z_i + 301) \mid S\left(\frac{z_i + 301}{\sum (z_i + 301)}\right) \mid S(p_{T,i}) \mid S\left(\frac{p_{T,i}}{\sum p_{T,i}}\right) \mid \text{Same vars with trks within } \Delta R = 0.2 \mid \frac{N_{\rm trk}}{N^{(0.2)}_{\rm trk}} \mid \frac{\sum p_T}{\sum p_T^{(0.2)}}$$





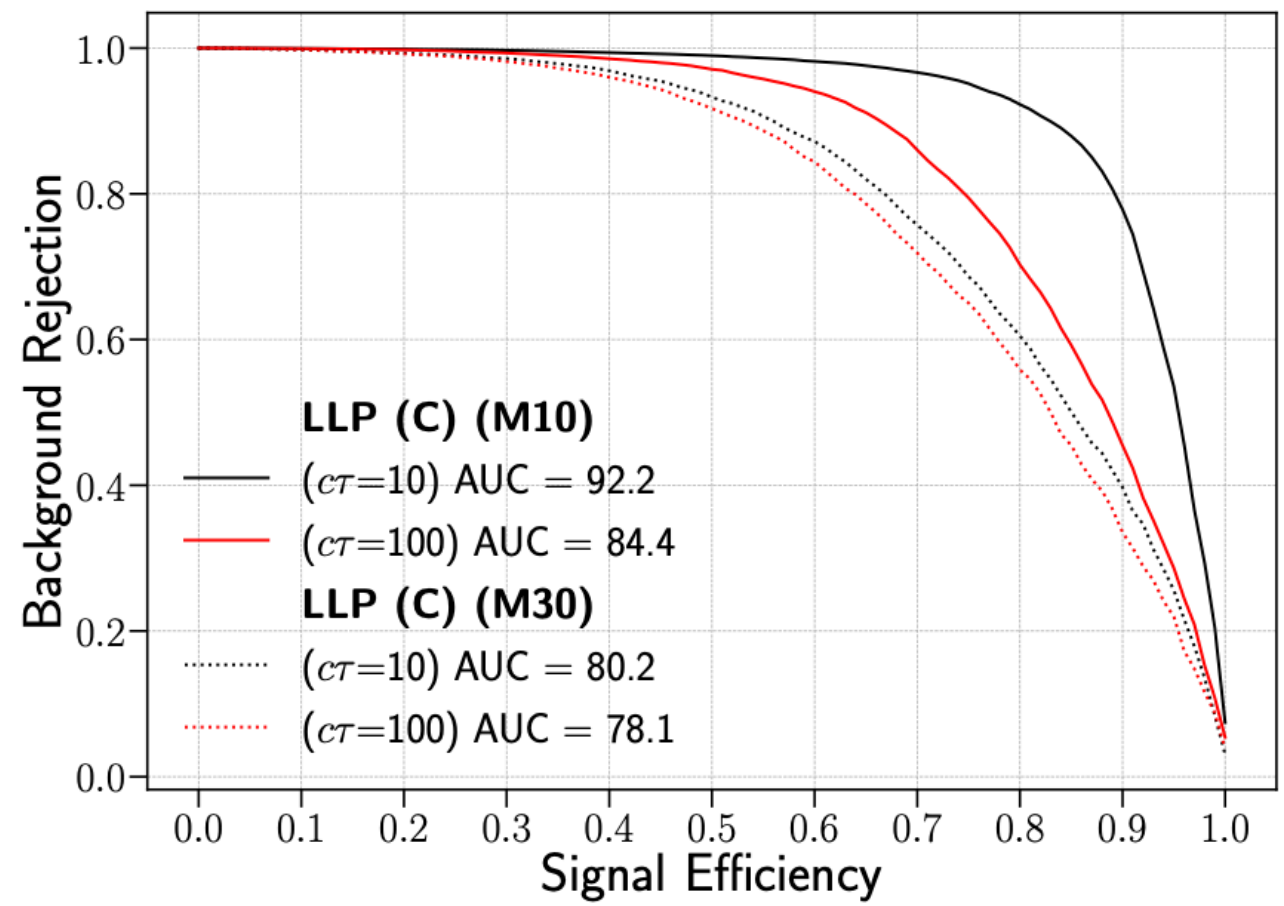
Timing @ MTD



<u>MTD:</u> Timing of charged particles with $p_T > 0.7$ GeV upto $|\eta| = 1.5$; $p > 0.7$ GeV for $1.5 < |\eta| < 3.0$ with 30 ps resolution

<u>Timing:</u>

- p_T
- η
- $N^{(0.2)}_{\mathrm{MTD}}$
- $T^{(0.2)}_{\mathrm{Med}}$
- $\Delta T^{(0.2)}_{\mathrm{Med,PV}}$
- $N^{(0.2),\mathrm{NT}}_{\mathrm{MTD}}$
- $\Delta T^{(0.2),\mathrm{NT}}_{\mathrm{Med,PV}}$



Jets - many particles - timing?

Median of the time differences of all particles associated with the jet (within $\Delta R = 0.2$ of the jet axis) w.r.t to photons starting from the reconstructed Primary Vertex (PV)

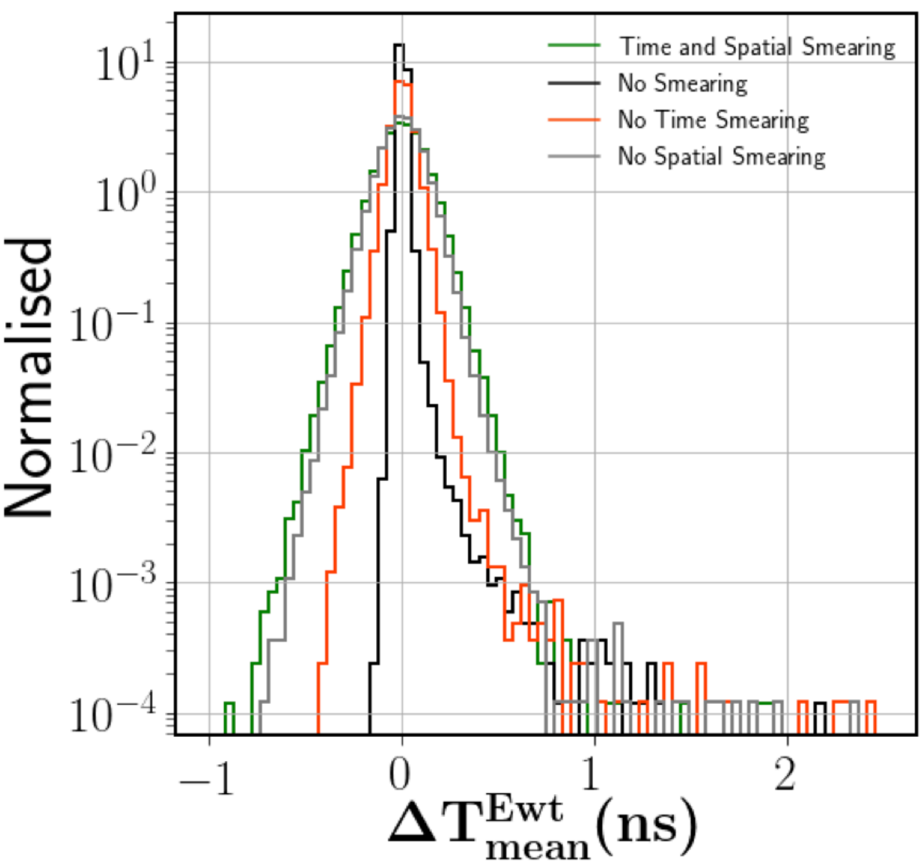
Will MTD be available at L1?

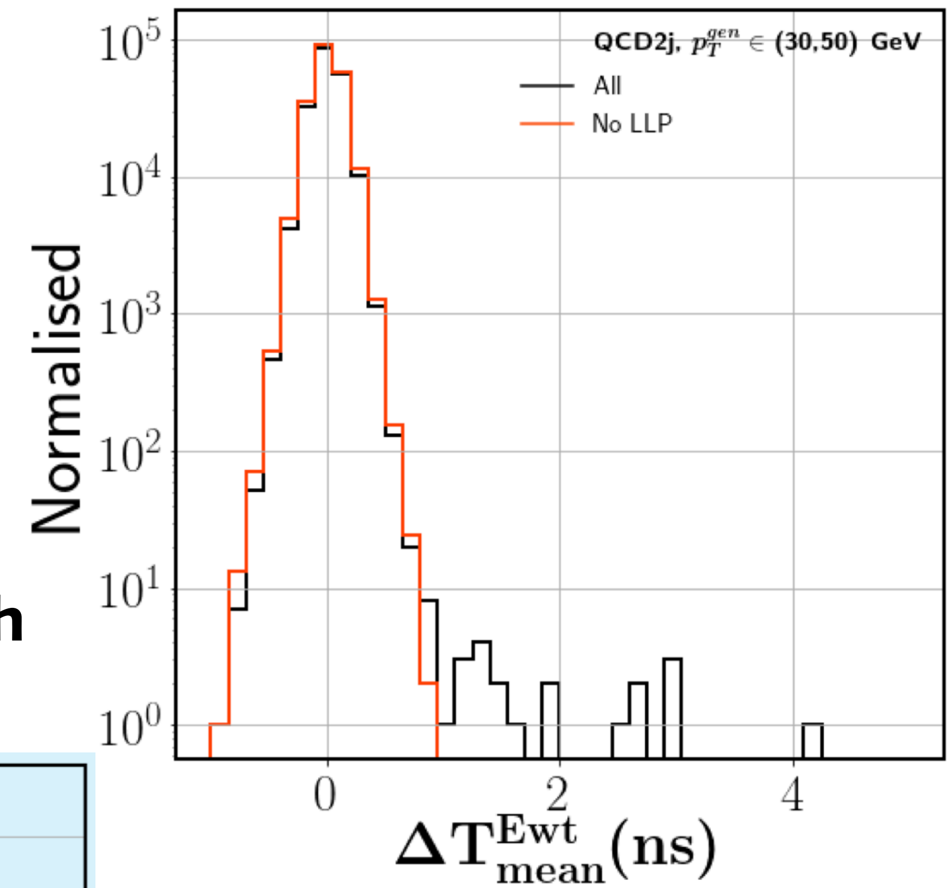
Regional timing - separately or in combination with L1 track trigger

Applying timing BDT on events passing the tracking BDT score corresponding to 70% bkg rej. (T2), we can reduce the **background rate by a factor of 4 with little loss in the signal efficiency**.

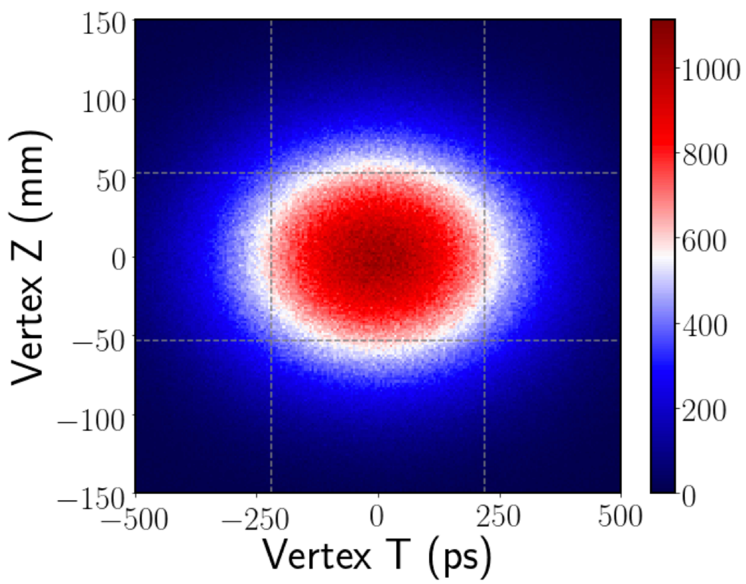
Timing @ ECAL

Factors affecting timing of a jet



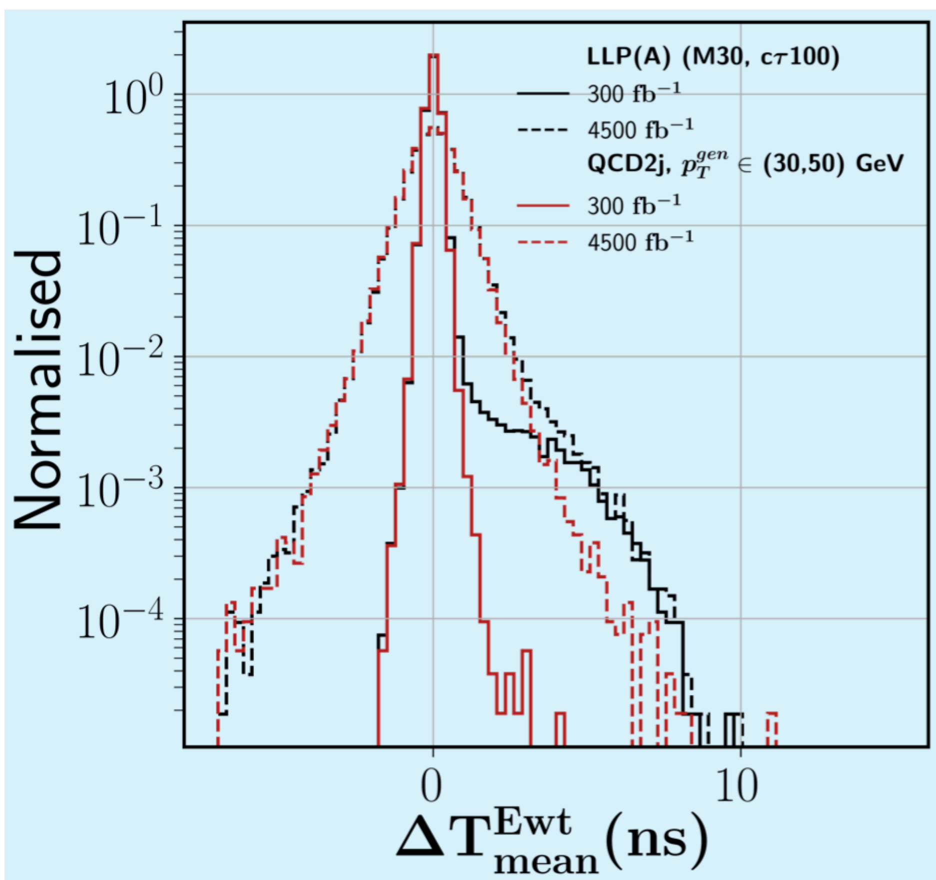


LLPs in SM



Spread of vertices in the z and t directions

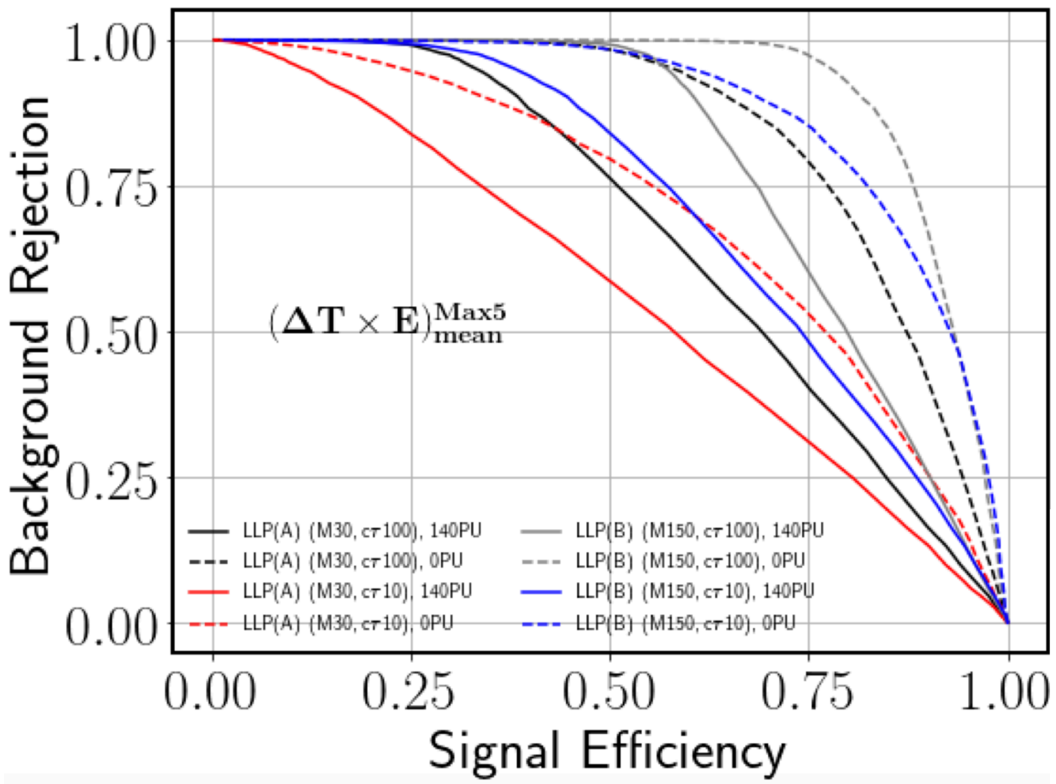
Degrading resolution with increasing luminosity



Timing @ ECAL

$$\Delta T_{Mean}, \Delta T_{Median}, \Delta T_{RMS}, \Delta T^{Ewt}_{Mean}, \Delta T^{ETwt}_{Mean}, \Delta T^{Max5}_{Mean}, (\Delta T \times E)^{Max5}_{Mean}, \Delta T^{Max10}_{Mean}, (\Delta T \times E)^{Max10}_{Mean}, \sum \Delta T$$

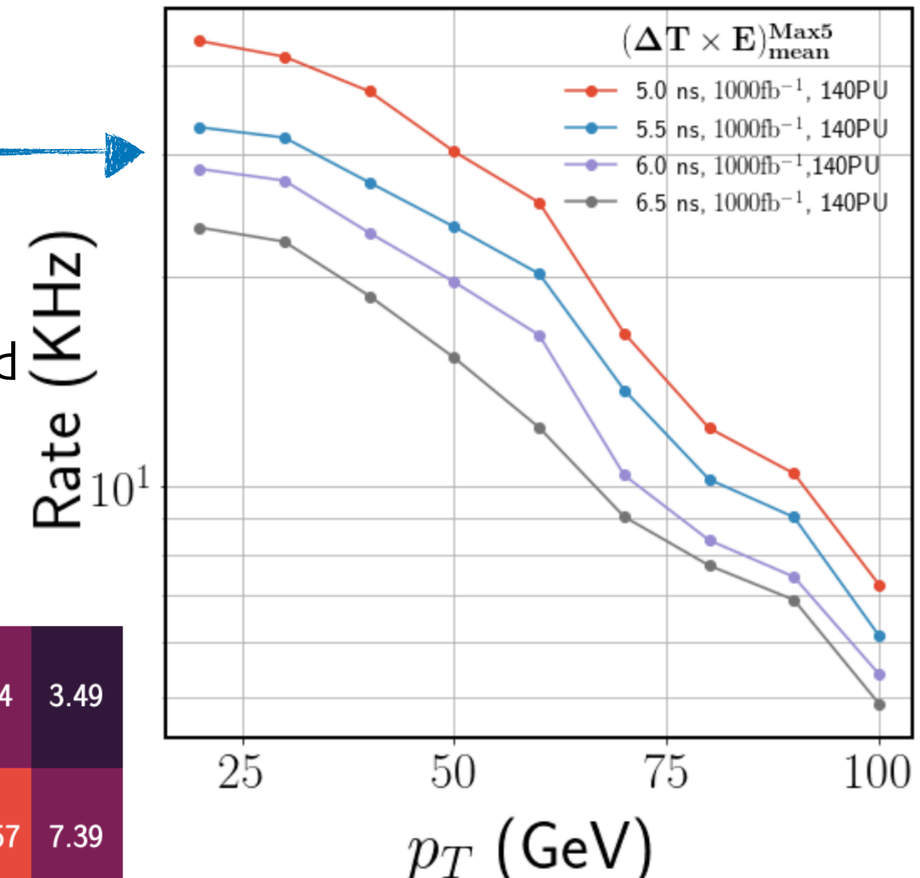
$$(\Delta T \times E)^{Max5}_{Mean}$$

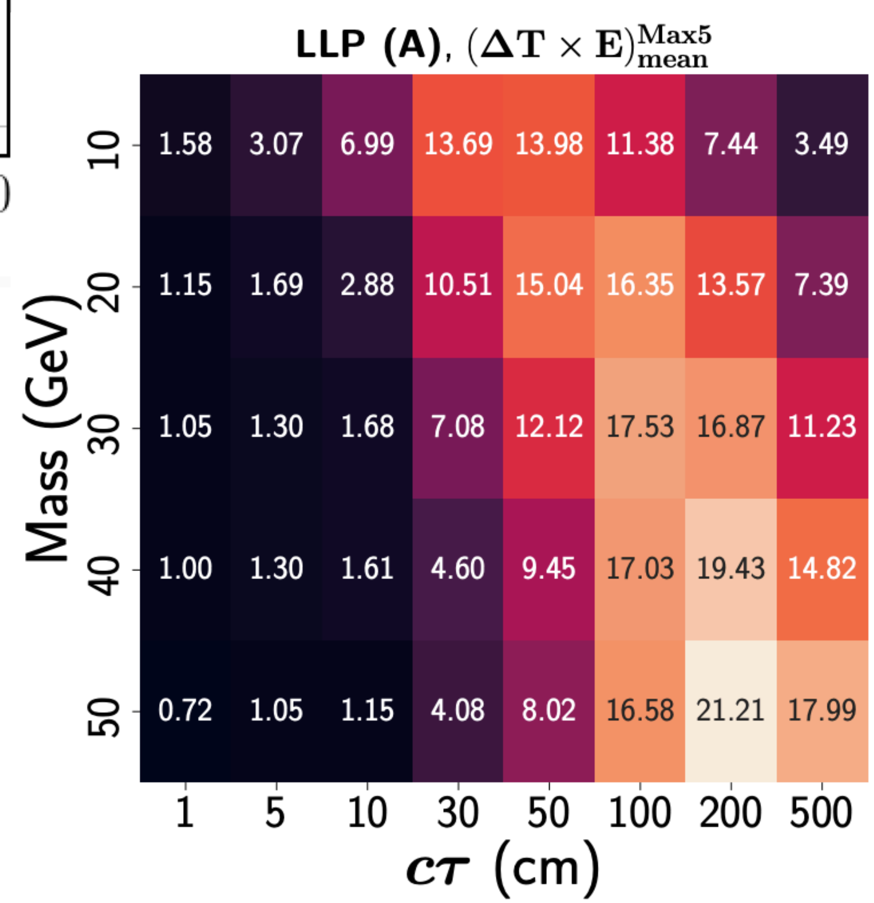


Select cuts that maintain **30 kHz rate**

"STITCHING" algorithm to combine QCD dijet background to minimum bias events

K. Ehatäht et al, arXiv:2106.04360





Inclusion of L1 **displaced tracking** (efficient till $d_0 < 8$ cm) increases sensitivity for low lifetimes

Signal efficiency grid demanding at least one jet with $p_T > 35$ GeV and $(\Delta T \times E)^{Max5}_{Mean} > 5.5$ ns

OUTLINE

- LLPs in colliders
- A study of LLPs in Higgs portal @ HL-LHC and FCC-hh
- **A few other aspects of LLP searches**
  - Triggering
  - **Image recognition techniques for displaced jets**
  - Lifetime estimation

Displaced Jet Images

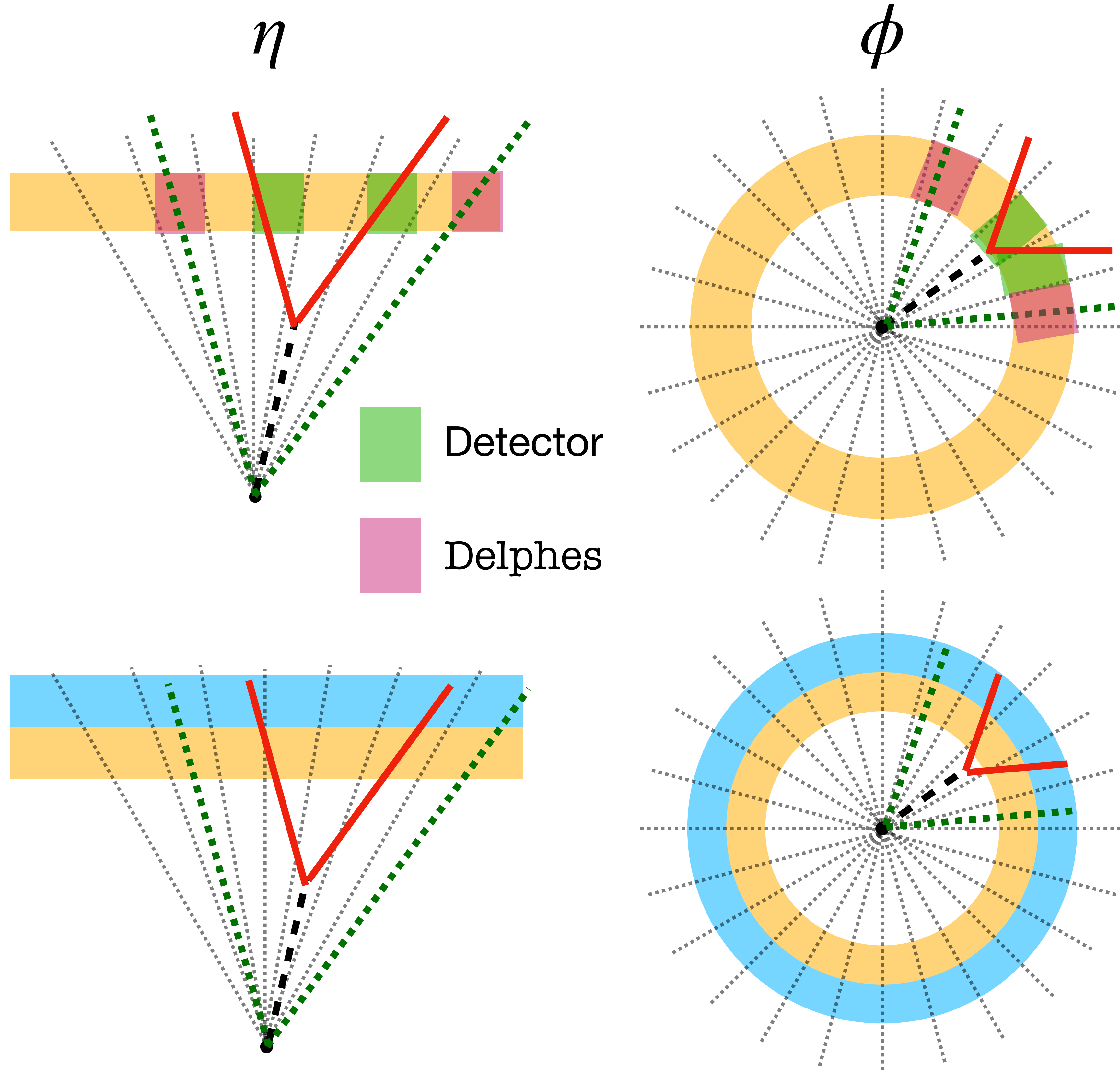
Biplob Bhattacherjee, Swagata Mukherjee, RS, JHEP 11 (2019) 156

In experiment, particle's η-ϕ corresponds to the η-ϕ of the detector cell where it deposits its energy

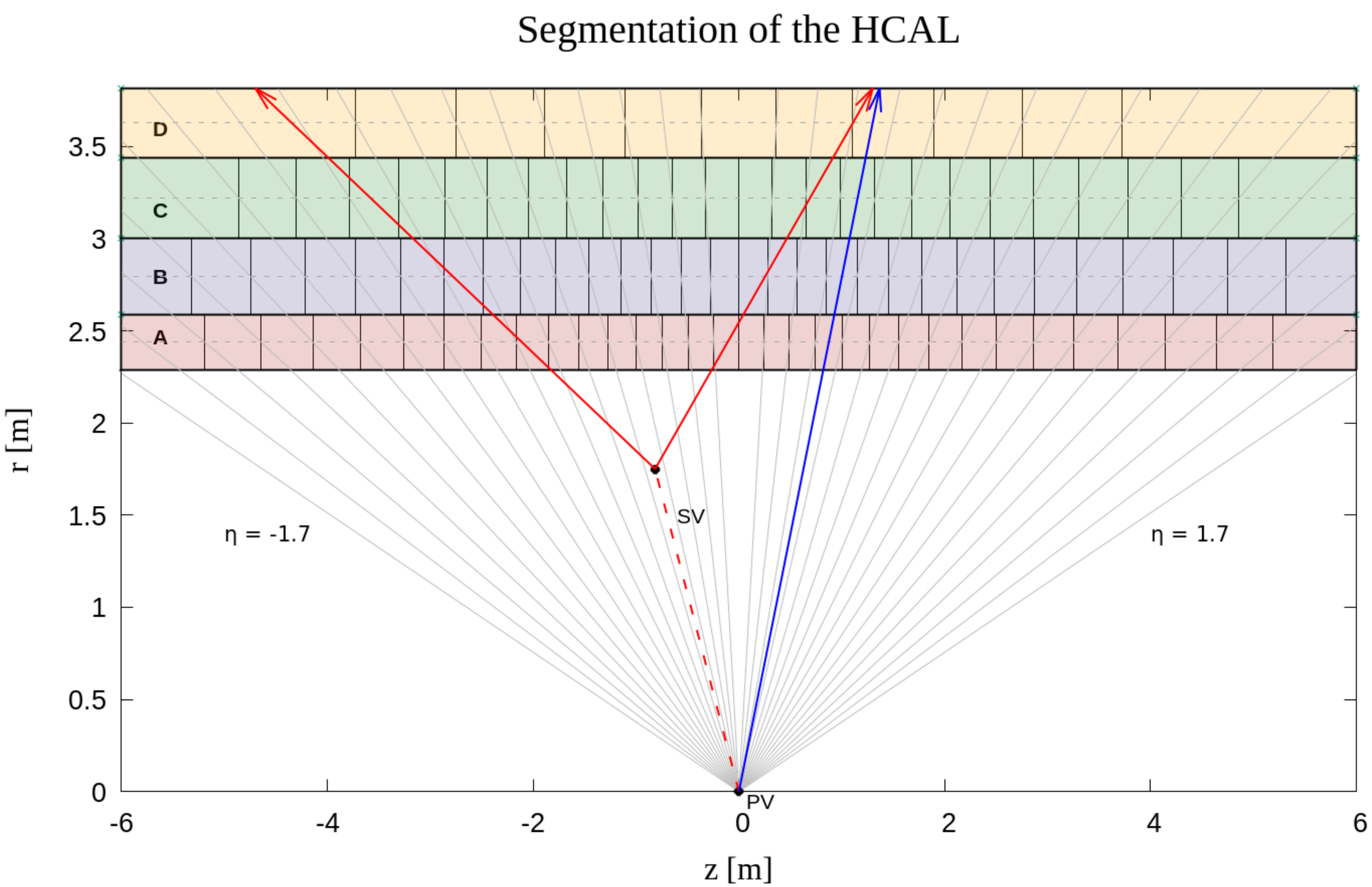
Mismatch of **displaced particle's η-ϕ** direction with η-ϕ **segmentation of the detector**

To understand the mismatch, **layered structure/depth segmentation** needed

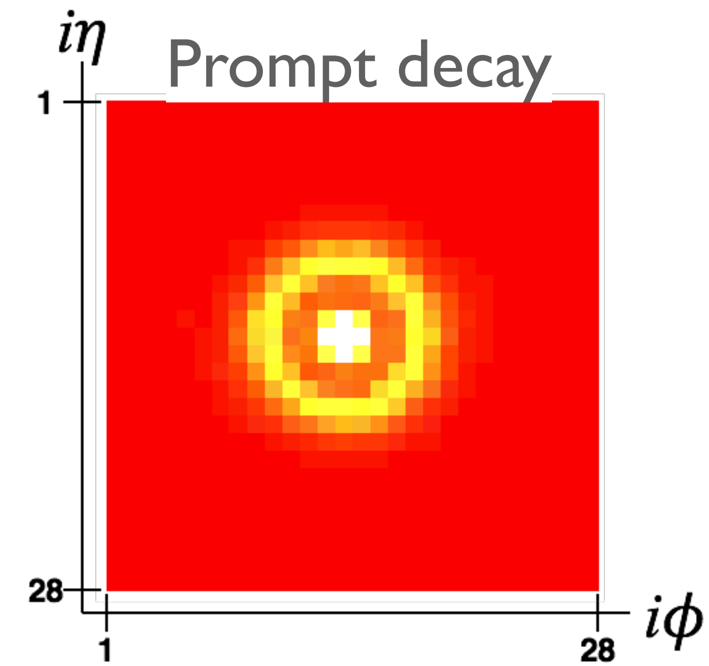
Absent in fast detector simulations (eg. `Delphes`)

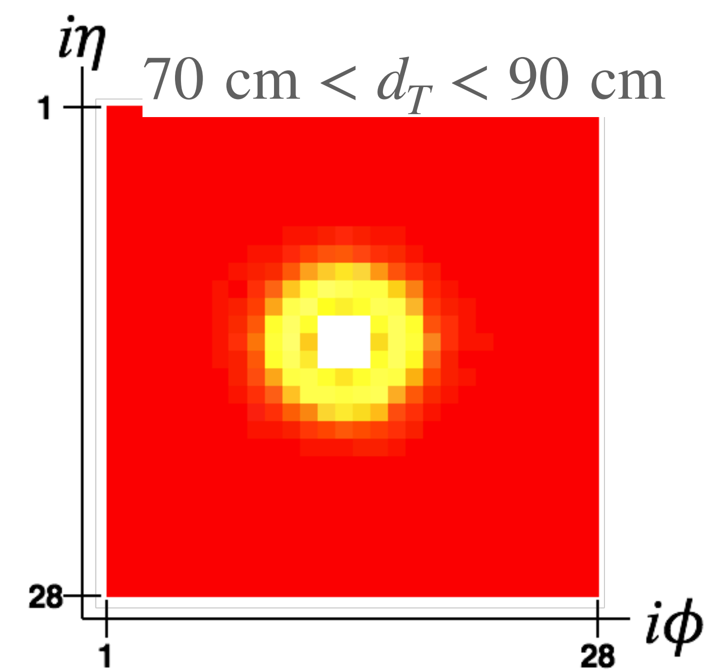


Displaced Jet Images



$\Delta R \sim \frac{2m_Z}{p_T^Z}$ p_T^Z almost fixed due to window cut on $\sum E$





Average over 50 000 images

$X(\text{LLP}) \to Z(\text{SM}) + Y(\text{Invisible})$

$Z \to jj, \quad [m_X = 800 \text{ GeV}]$

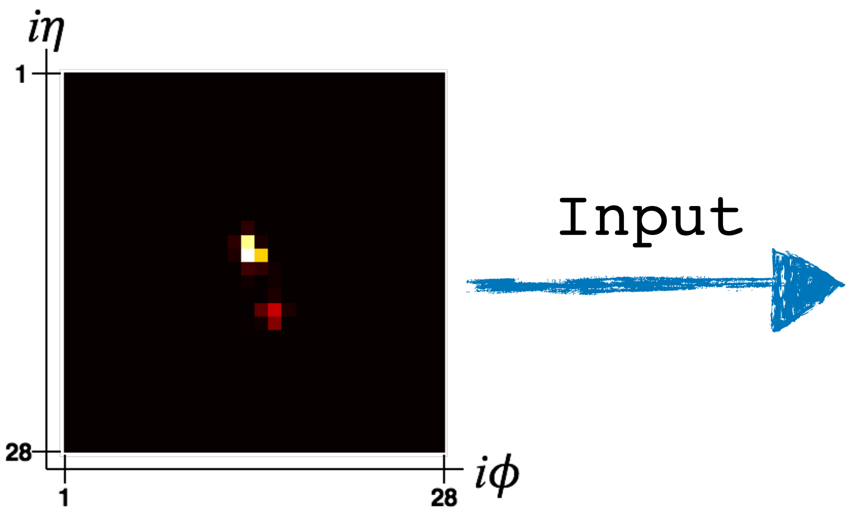
Displaced Z boson

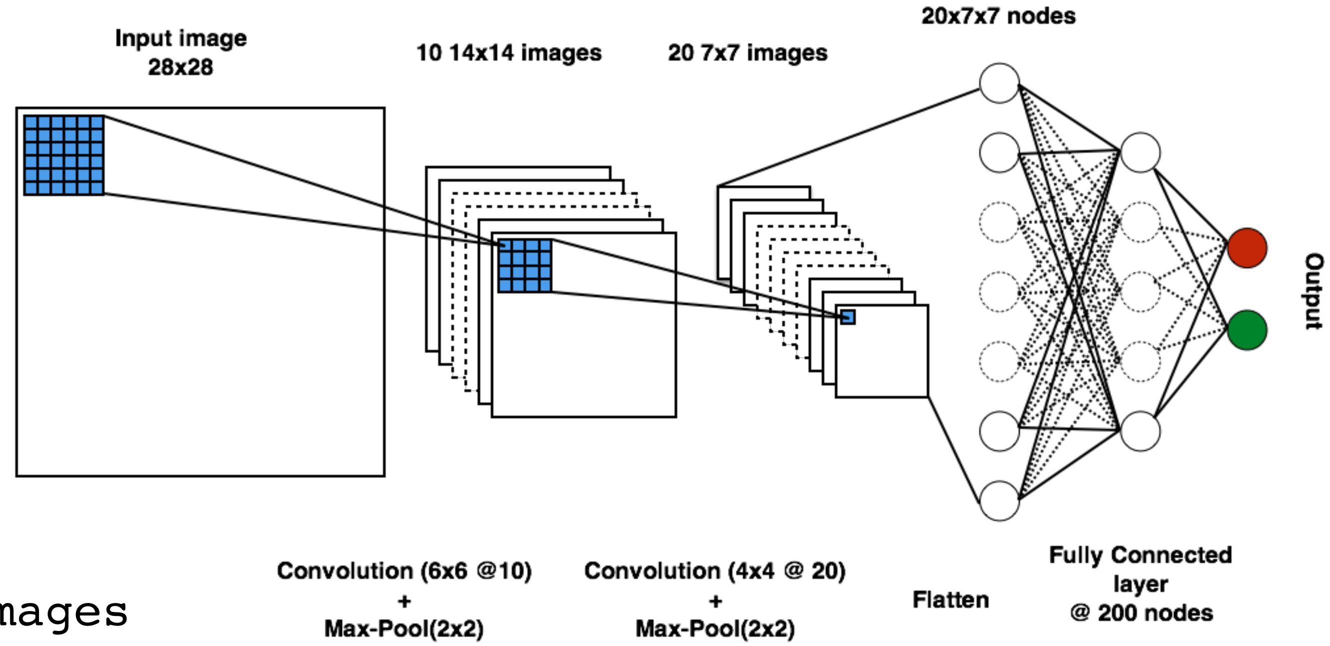
GMSB SUSY

$\tilde{\chi}_1^0 \to Z\tilde{G}$

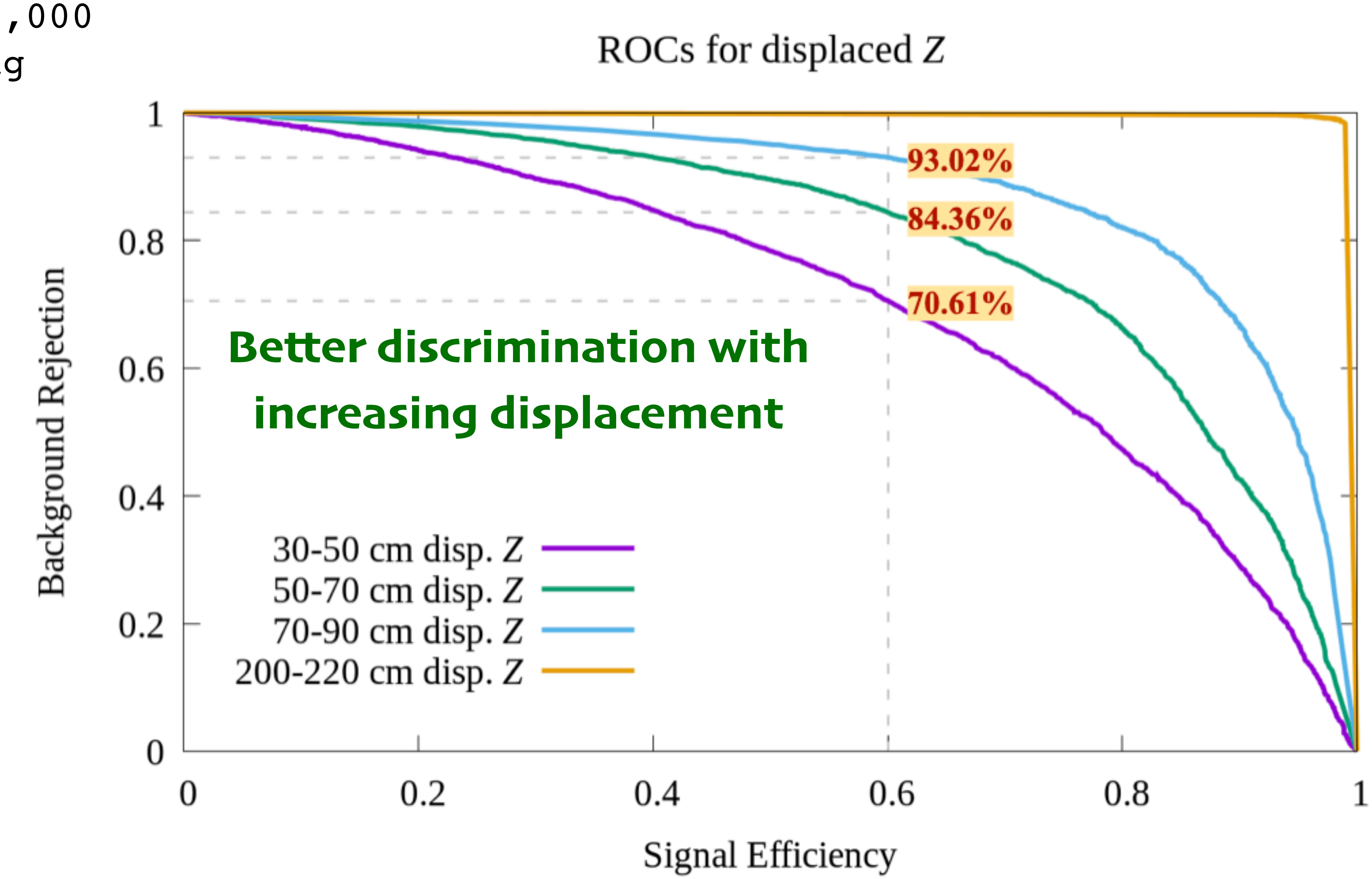
Neutralino width suppressed by SUSY breaking scale

Displaced Jet Images

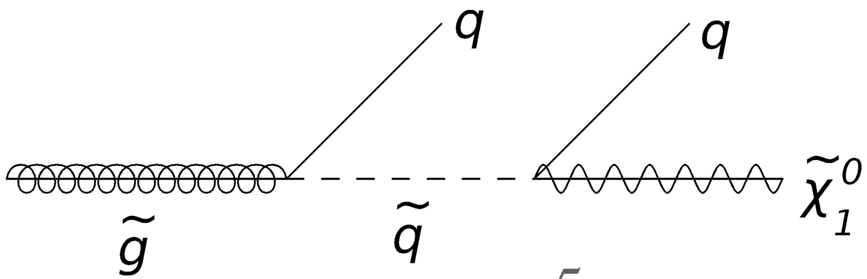




- Minimal preprocessing of images
- 60,000 images for training, 20,000 each for validation and testing
- Batch size: 200
- Adam Optimizer
- Activation by RELU
- Learning rate: 0.001
- Dropout: 50%
- Training stopped at the epoch with minimum validation loss



Stopped R-hadrons

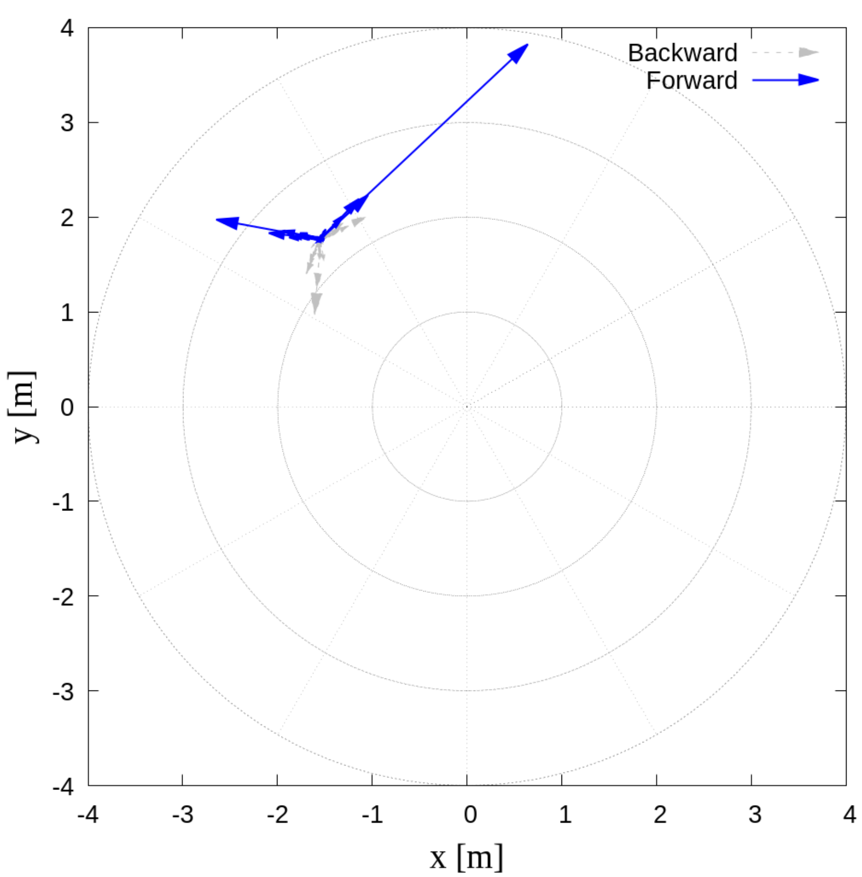


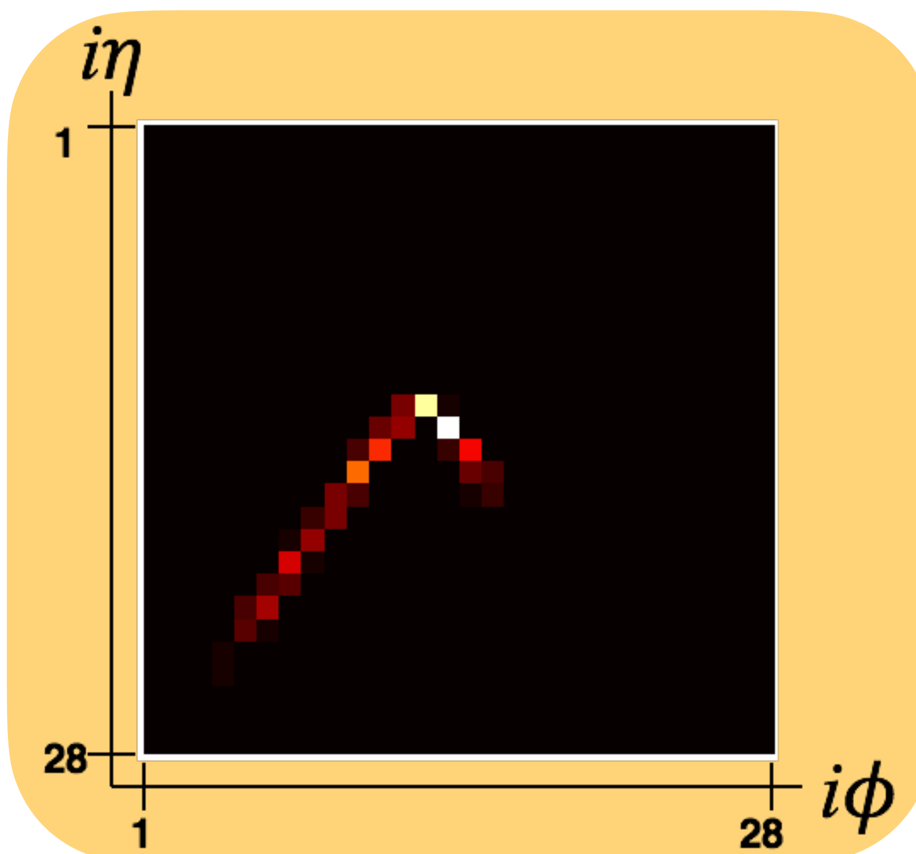
$$\Gamma_{\tilde{g}} \sim \frac{m_{\tilde{g}}^5}{m_{\tilde{q}}^4}$$

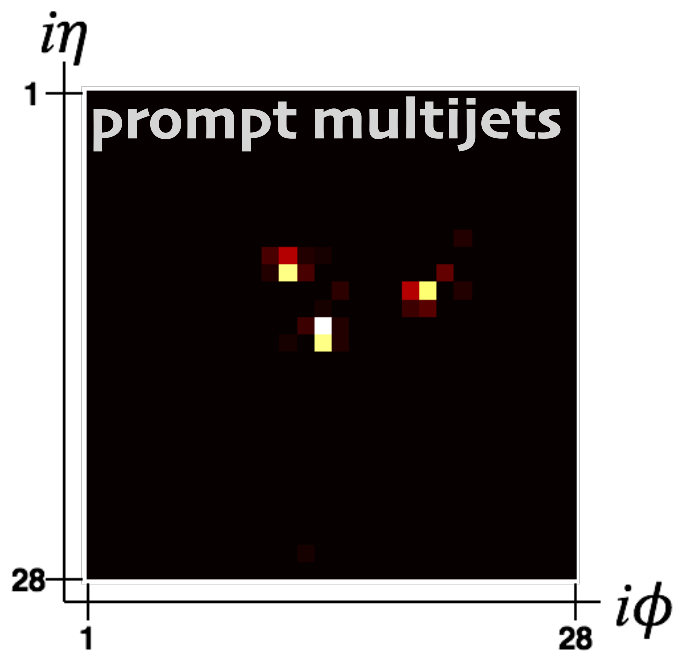
- $\Gamma_{\tilde{g}} < \Lambda_{QCD} \Rightarrow$ hadronizes before decaying "***R*-hadrons**"
- lose energy via ionization while traversing the detector $\Rightarrow$ **stop before decaying**
- can decay seconds, days, or even weeks later
- **out-of-time energy deposits in the calorimeter in empty bunch-crossings**

Shankha Banerjee, Geneviève Bélanger, Biplob Bhattacherjee, Fawzi Boudjema, Rohini M. Godbole, and Swagata Mukherjee, Phys. Rev. D 98, 115026

$X \to jjj, X$ decays at rest, $m_X = 1$ TeV







Significantly different energy deposition pattern

OUTLINE

- LLPs in colliders
- A study of LLPs in Higgs portal @ HL-LHC and FCC-hh
- **A few other aspects of LLP searches**
  - Triggering
  - Image recognition techniques for displaced jets
  - **Lifetime estimation**

Problem with lifetime estimation of LLPs

Q: **In the optimistic scenario where we discover LLPs, how to estimate it's lifetime?**

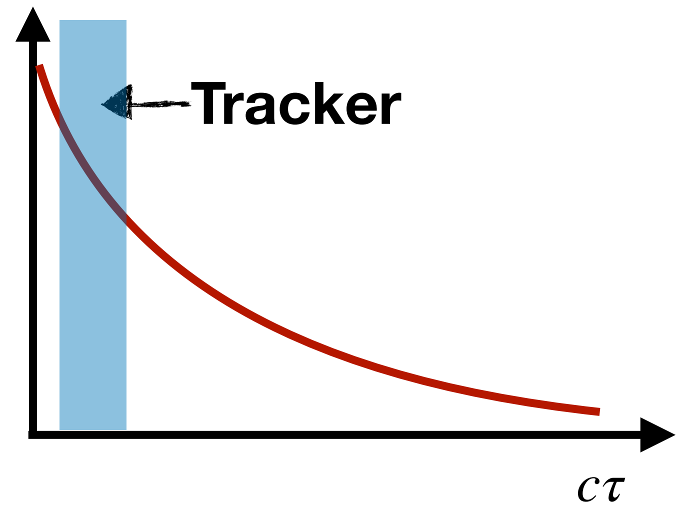
Shankha Banerjee, Biplob Bhattacherjee, Andreas Goudelis, Björn Herrmann, Dipan Sengupta, RS, Eur.Phys.J.C 81 (2021) 2, 172

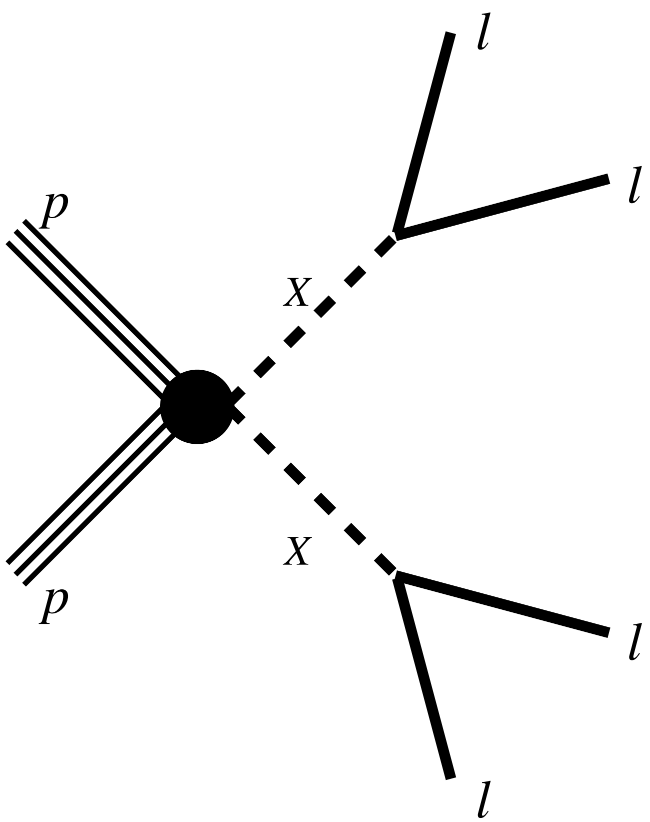
Each event $d = \beta\gamma c\tau$

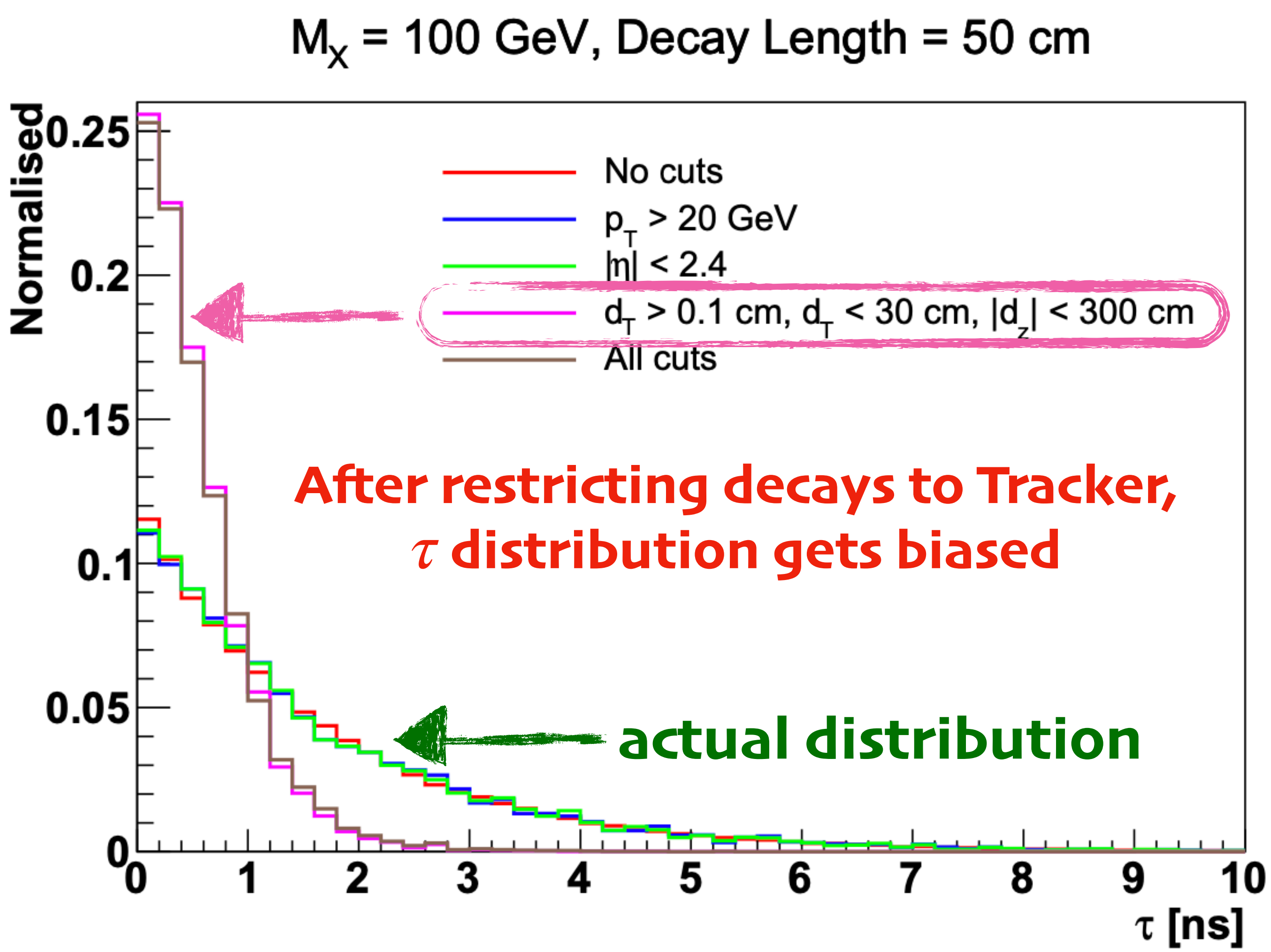
known (d) **unknown** (τ)

known ($\beta\gamma$)

Fit the exponential distribution of $c\tau$ and find out the proper mean lifetime of the particle







- Tracker can precisely identify the position of the SV
- Better measurement of $\beta\gamma$ if the LLP decays within Tracker

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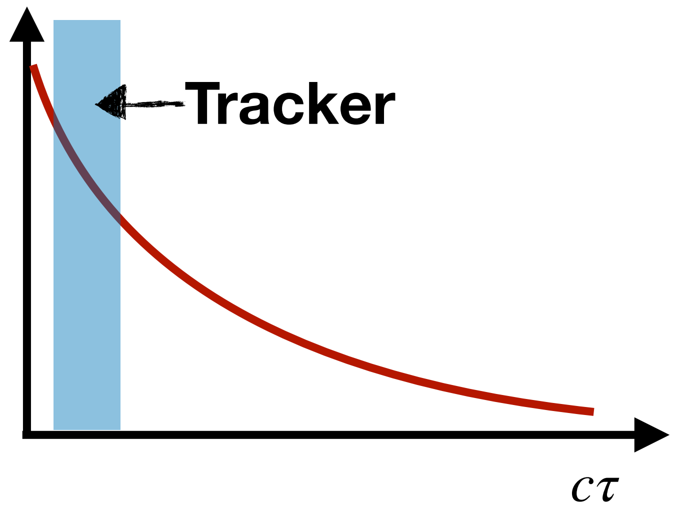
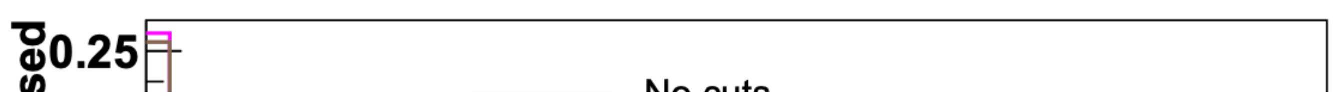
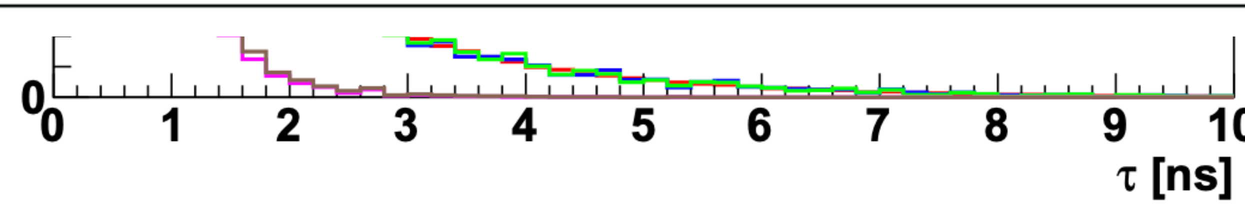


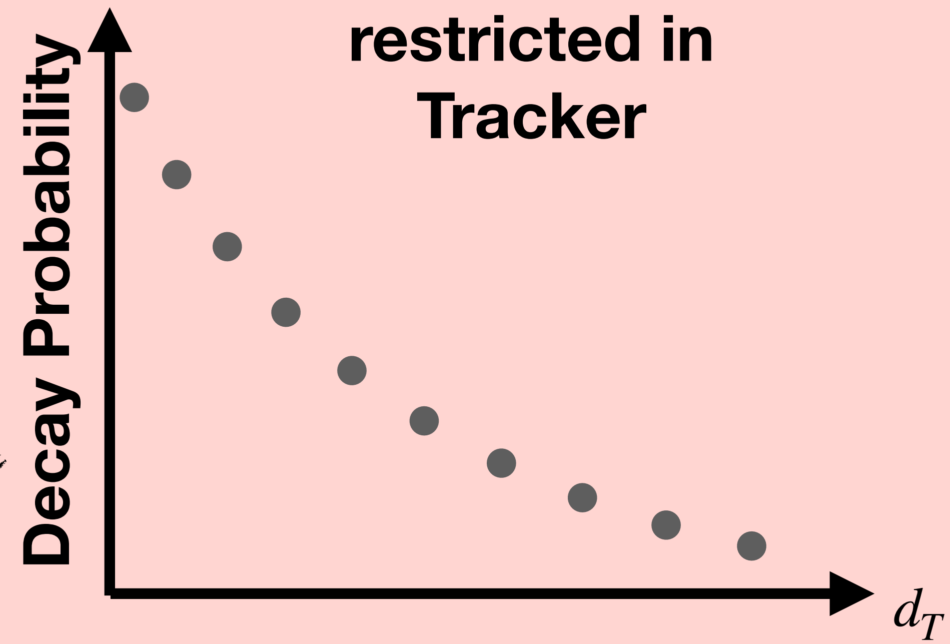


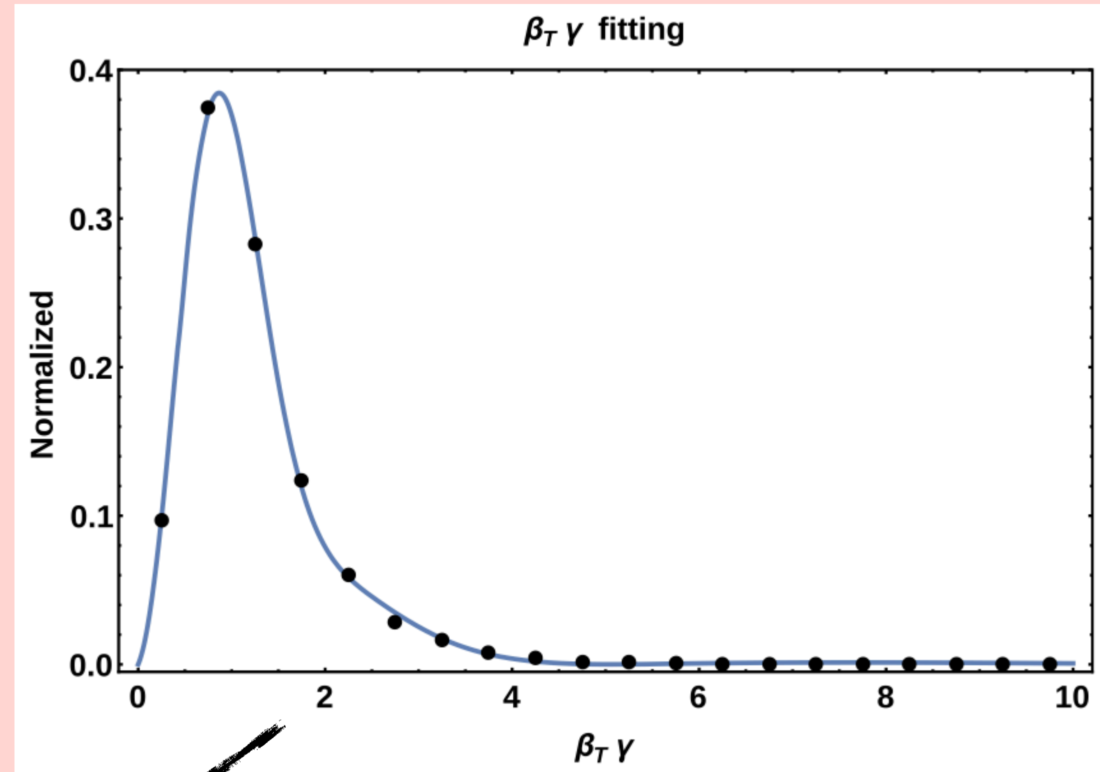
M_X [GeV]	DL [cm]	Reconstructed DL		
		Without cuts [cm]	With BC [cm]	With EC [cm]
100	10	9.95 ± 0.10	9.91 ± 0.13 [6117]	7.81 ± 0.10 [5375]
100	50	49.74 ± 0.51	49.55 ± 0.64 [6117]	15.25 ± 0.29 [2590]
100	100	99.48 ± 1.01	98.82 ± 1.29 [6117]	18.12 ± 0.45 [1539]
1000	10	9.97 ± 0.10	10.02 ± 0.10 [9546]	8.88 ± 0.08 [9050]
1000	50	49.88 ± 0.49	50.09 ± 0.51 [9546]	19.61 ± 0.26 [5227]
1000	100	99.85 ± 0.99	100.15 ± 1.02 [9546]	22.37 ± 0.35 [3233]



Ways to estimate the correct lifetime

From experiment





COMPARE

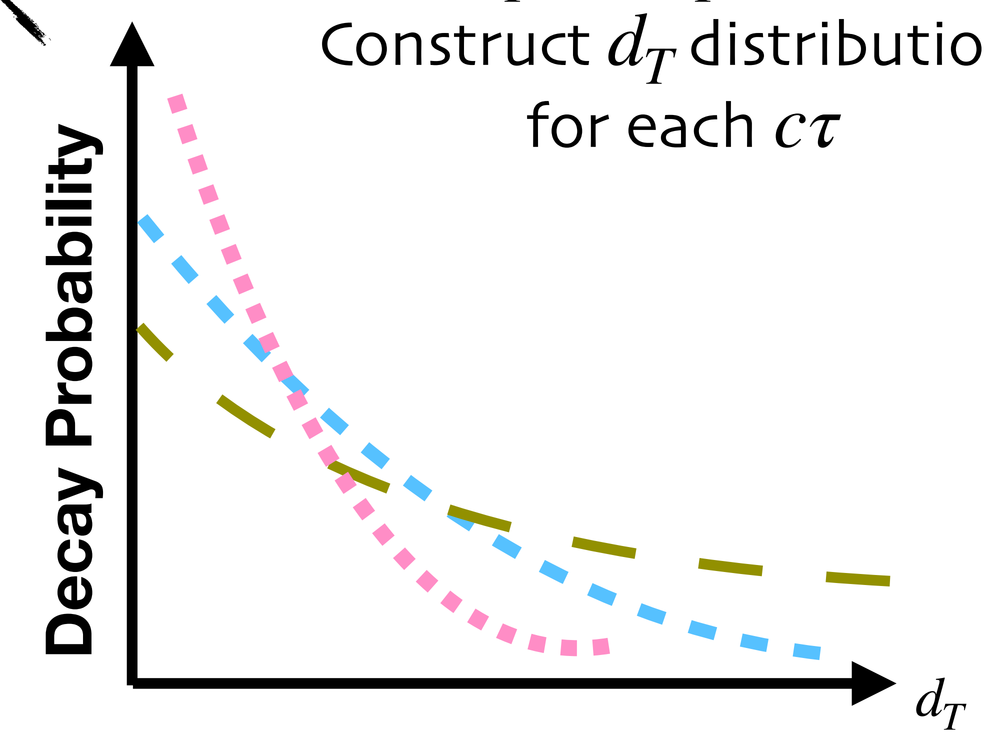
Generate random numbers

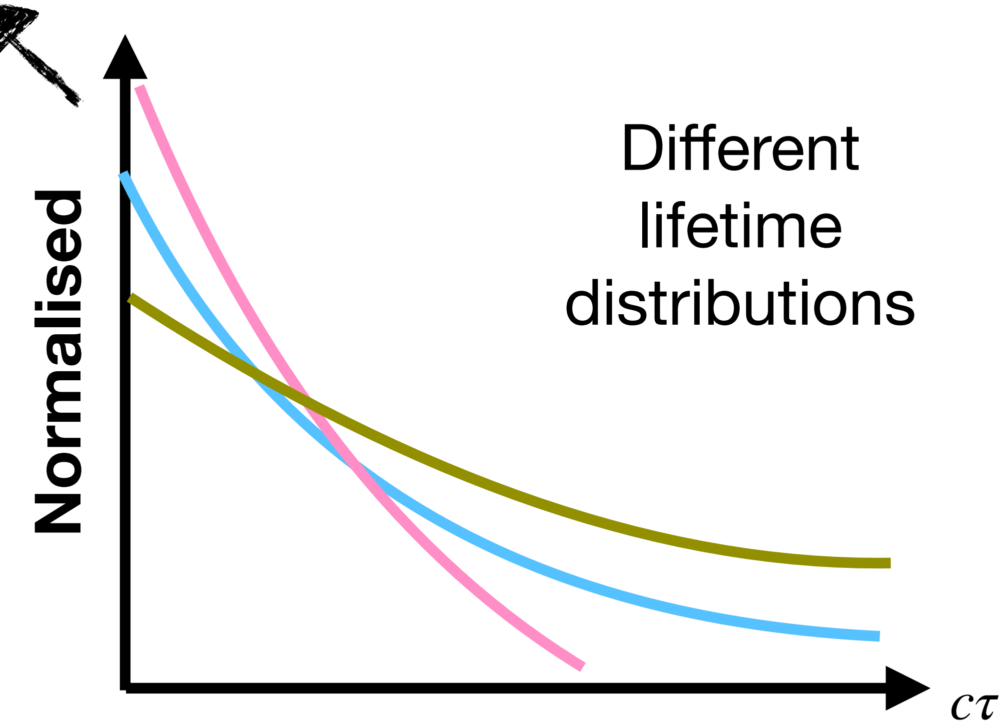
$d_T = (\beta_T\gamma)(c\tau)$

Construct d_T distributions for each $c\tau$

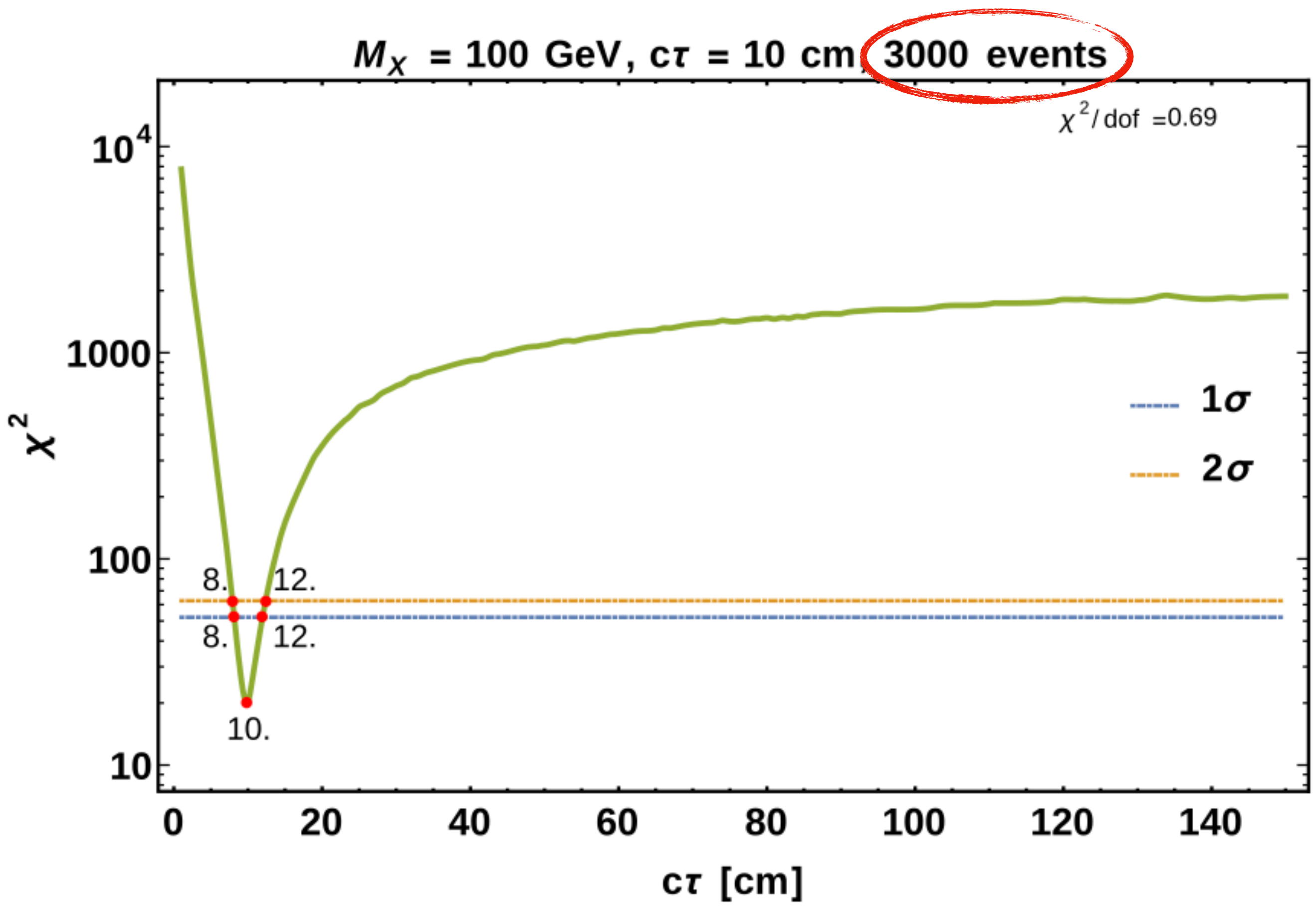
Model-independent method

See paper for model-dependent





Ways to estimate the correct lifetime

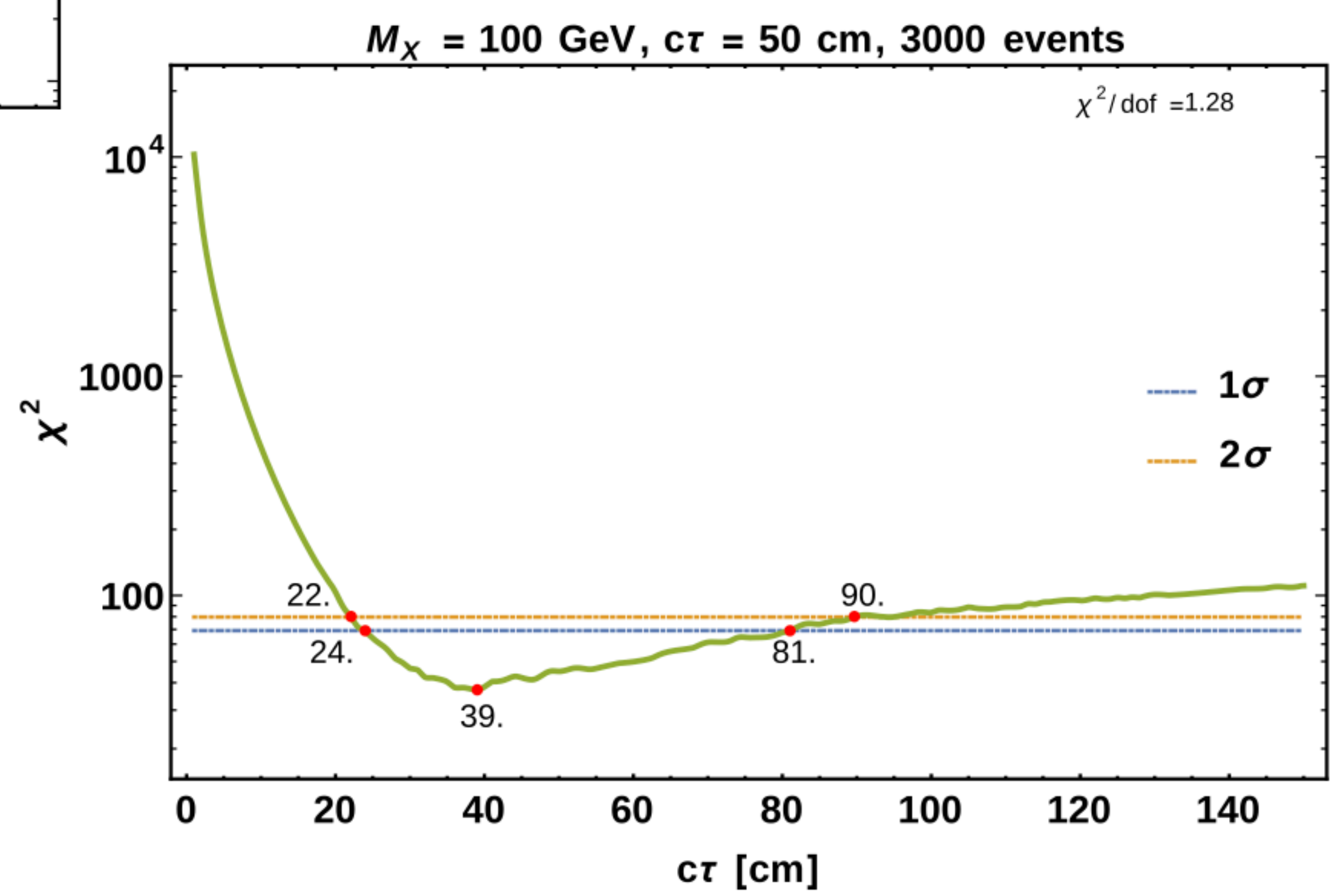


Cross-section: 1 fb

HL-LHC 3000 fb^{-1}

$$\chi^2 = \sum_{i=1}^{N} \frac{(n_{\rm th} - n_{\rm exp})^2}{\sigma^2}$$

Statistical Data Analysis,
Glen Cowan



Performed Machine Learning (ML) based regression - similar performance

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

IS IT SIMPLE OR CHALLENGING?

SM background - mostly prompt - difficult to mimic the exotic signatures of LLPs

SM long-lived particles like b-hadrons, c-hadrons, K_S or Λ

Real Particles Produced via Interactions with the Detector

Real Particles Originating from Outside the Detector

Cosmic muons

Fake signatures

Detector noise

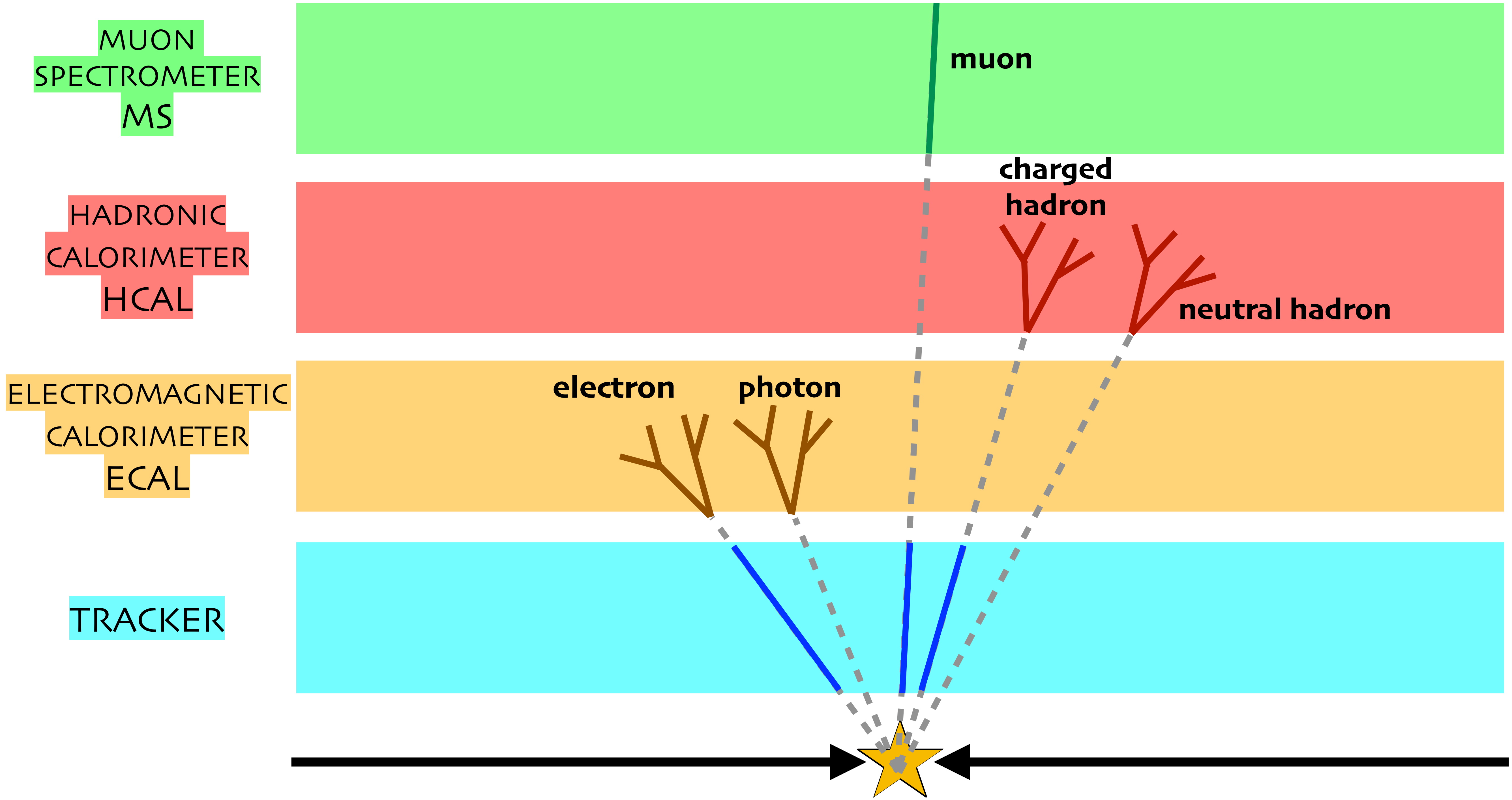
Randomly merged vertices/ random tracks crossing each other

Chances to miss real signal unless carefully searched

Non-standard and unusual backgrounds
Simulation very technical

How do prompt particles look in the detector?

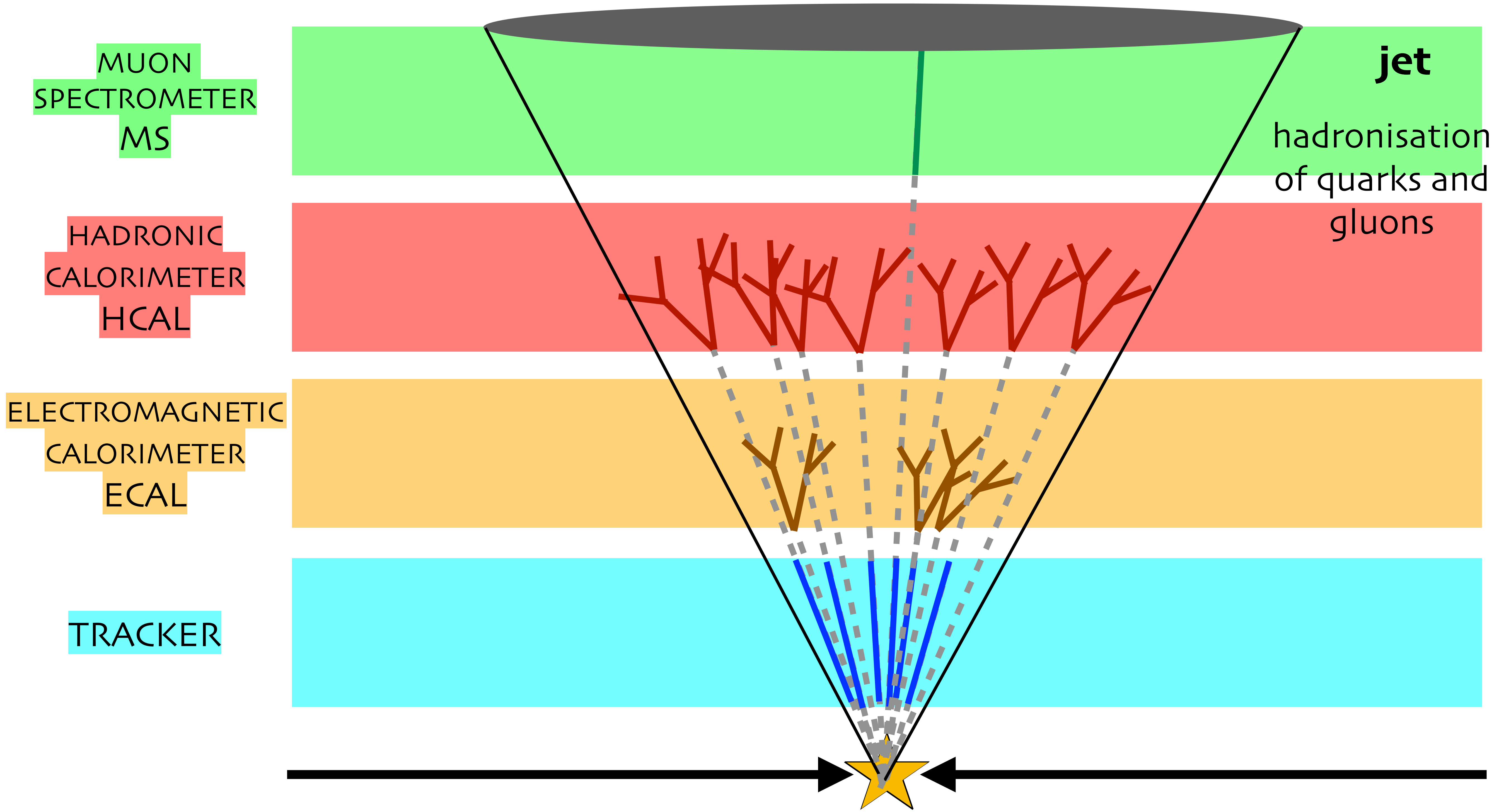
Different particles leave different signatures in collider detectors



Effect of magnetic field not shown

How do prompt particles look in the detector?

Different particles leave different signatures in collider detectors



Effect of magnetic field not shown

Different decay modes of a particle

different final states in the collider detector

Major **physics objects** in the collider detectors:

- electron (e)
- muon (μ)
- photon (γ)
- jet (j)
- missing transverse energy (MET)

Define **final states** in terms of these physics objects, like:

- 2 leptons (e/μ)
- 2 photons + jets ($2\gamma + \geq 1j$)
- 3 leptons (e/μ) + MET
- *and so on…*

Probability to observe each final state for production of BSM particles

BRANCHING FRACTION — *theory*

DETECTOR EFFICIENCY & ACCEPTANCE — *experiment*

Till this point, the story is similar for LLPs

However, there is one more factor affecting the signature of LLPs

References for the branching ratio of the mediator particle

The decay of a light Higgs Boson

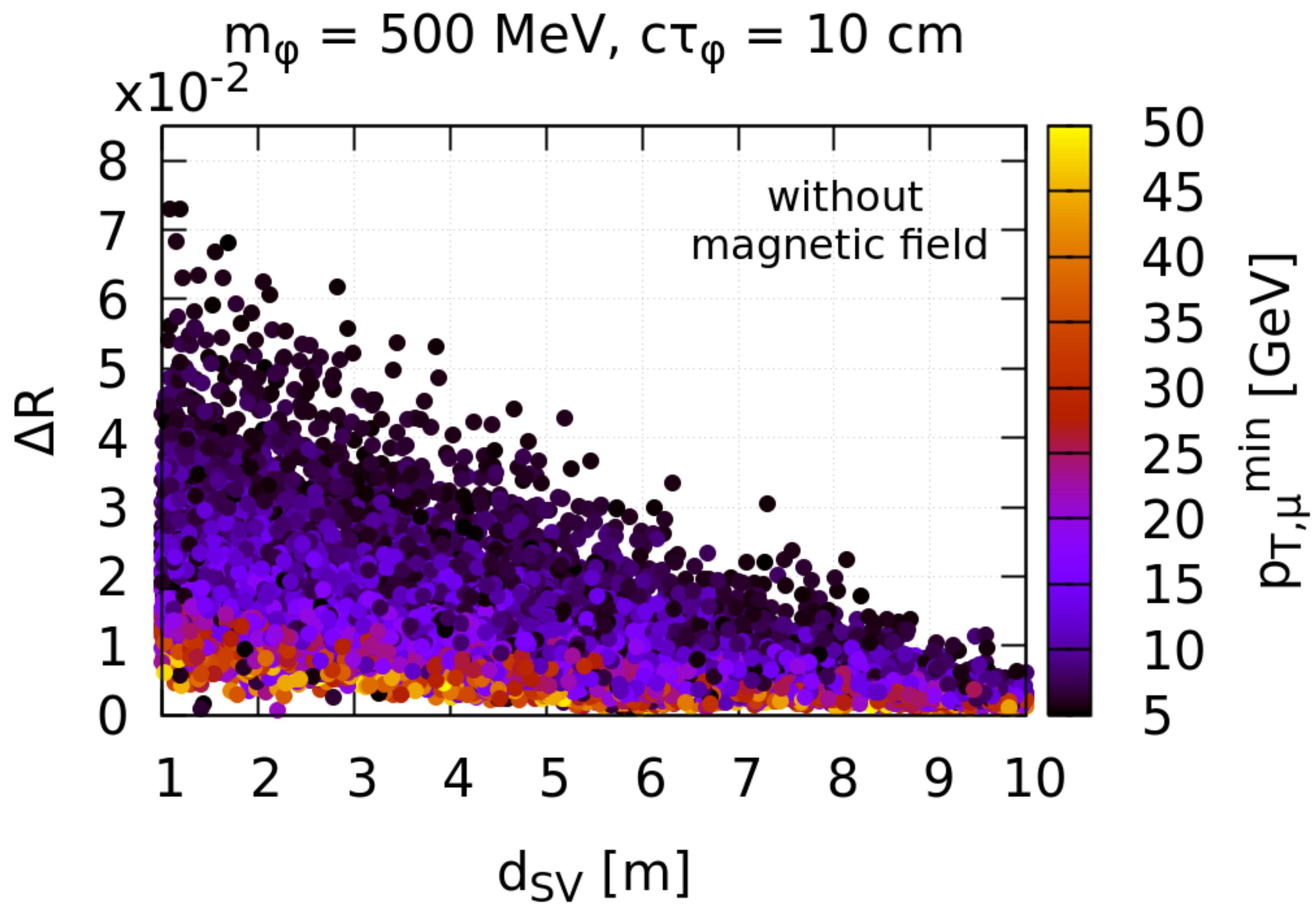
J. F. Donoghue, J. Gasser and H. Leutwyler, Nucl. Phys. B 343, 341 (1990)

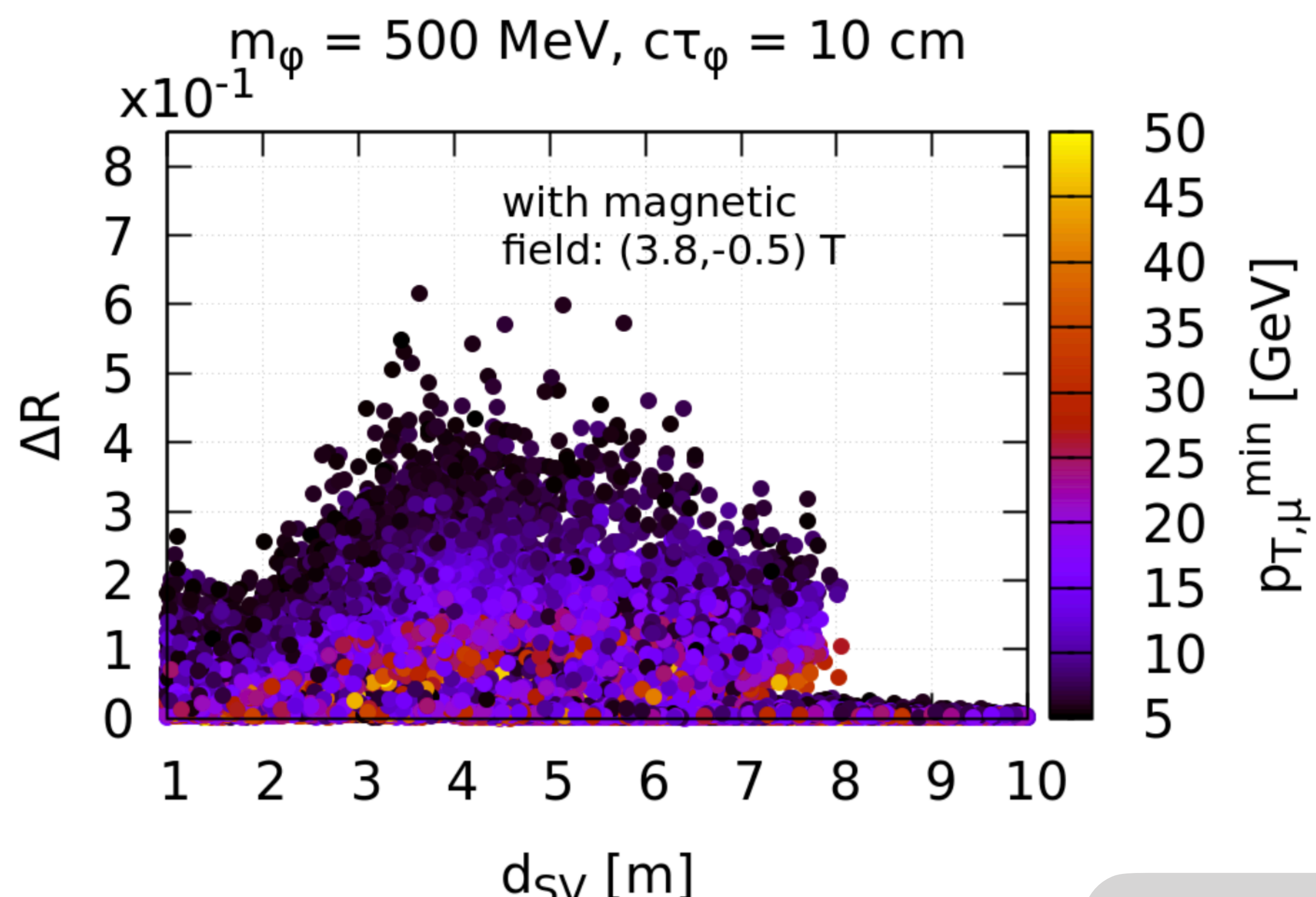
Decay and Detection of a Light Scalar Boson Mixing with the Higgs

Martin Wolfgang Winkler 1809.01876

After 2 GeV - HDECAY

Back


m_φ = 500 MeV, $c\tau_\varphi$ = 10 cm
x10^{-2}
without
magnetic field
ΔR
d_{SV} [m]
$p_{T,\mu}^{min}$ [GeV]


m_φ = 500 MeV, $c\tau_\varphi$ = 10 cm
x10^{-1}
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.

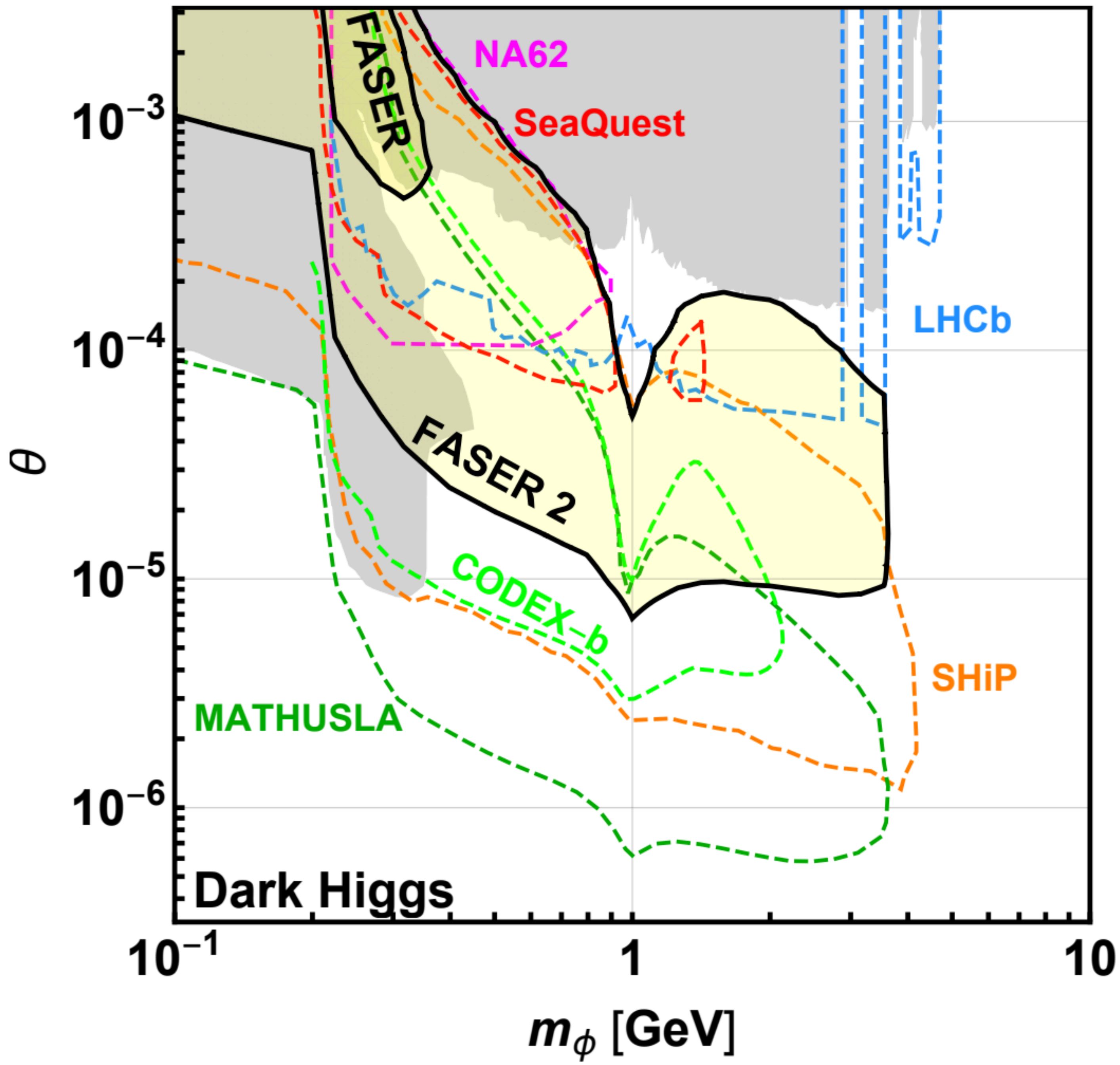
MS cluster

- 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

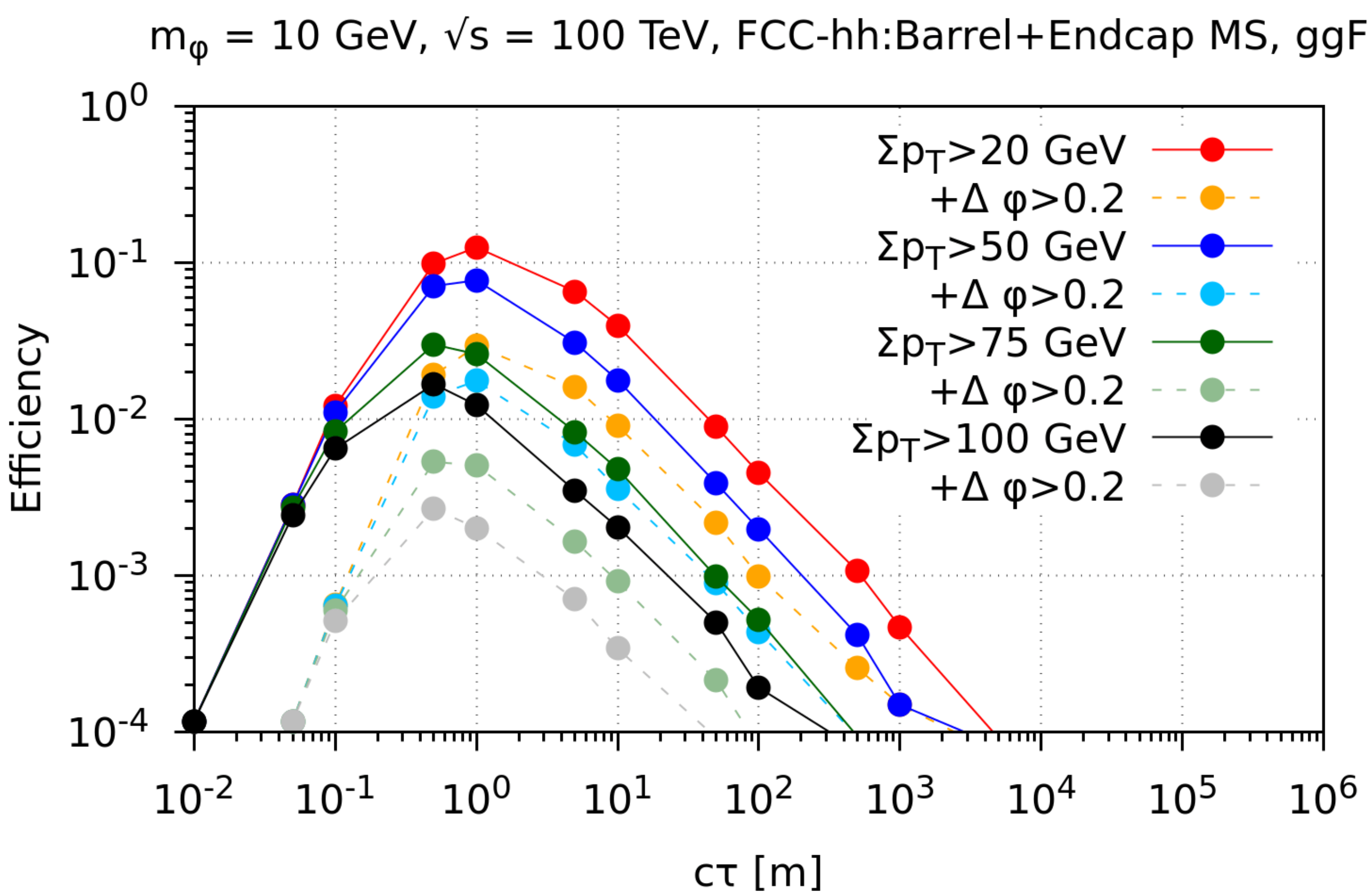
Our obtained limits can be scaled accordingly

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

Triggers using L1 Tracking

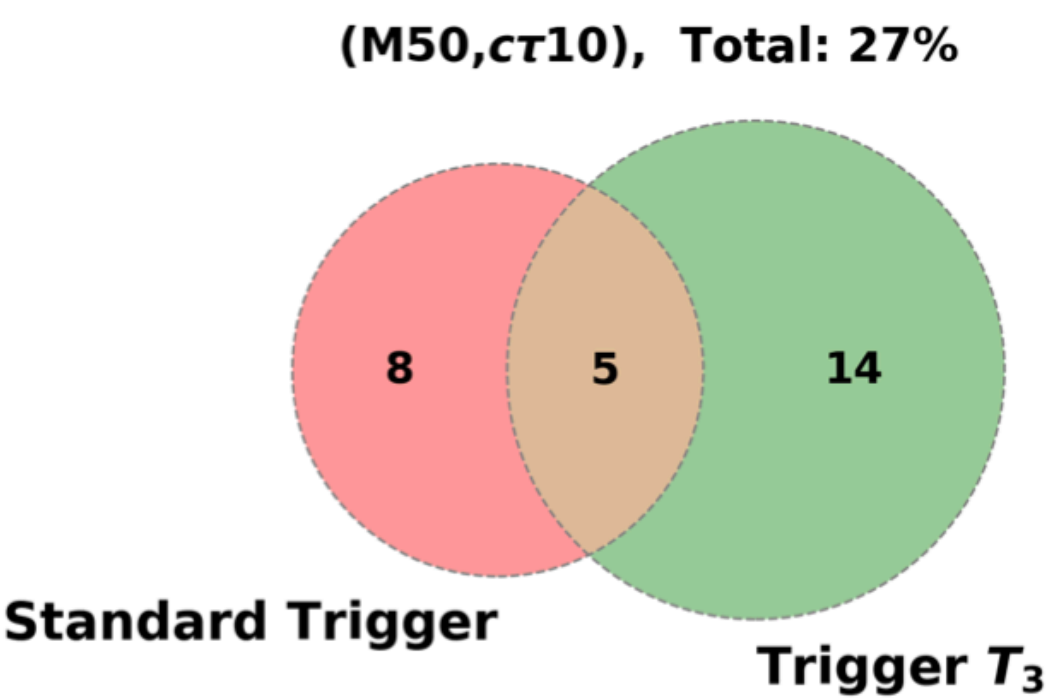
Max L1 trigger bandwidth for HL-LHC: 750 kHz

- **T_1**: at least one $R = 0.2$ jet with $p_T > 60$ GeV;
- **T_2**: T_1 + that jet passes the BDT threshold corresponding to a background rejection of 98% or 70%;
- **T_3**: T_1 + no other jet from the same z-vertex (i.e., Δz with all other jets is greater than 1 cm) + T_2;

$T_3 \rightarrow$ Bkg rejection $\downarrow$	QCD2j $p_T^{gen} \in (50, 100)$ GeV rate (kHz)	LLP (M50,$c\tau$10) efficiency (%)	LLP (M100,$c\tau$10) efficiency (%)
98% Table	1046 → 14	13	60
70% Table	1046 → 190	19	73

We can choose the ROC point depending on the trigger bandwidth constraints.

$$\mathcal{R}_B = \sigma\ (\text{nb}) \times \mathcal{L}\ (\text{nb}^{-1}\text{Hz}) \times \epsilon_B$$



- **Provides high signal efficiency for higher mass LLPs with reasonable rates.**
- **Mostly exclusive to standard triggers – improves signal efficiency for lower mass LLPs as well.**