The Exotic World of
LONG-LIVED PARTICLES

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THEORIE/PHENO SEMINAR

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**Laboratoire de Physique Subatomique et de Cosmologie
(LPSC)
Grenoble, France**

OUTLINE

- Motivation

- LLPs in colliders

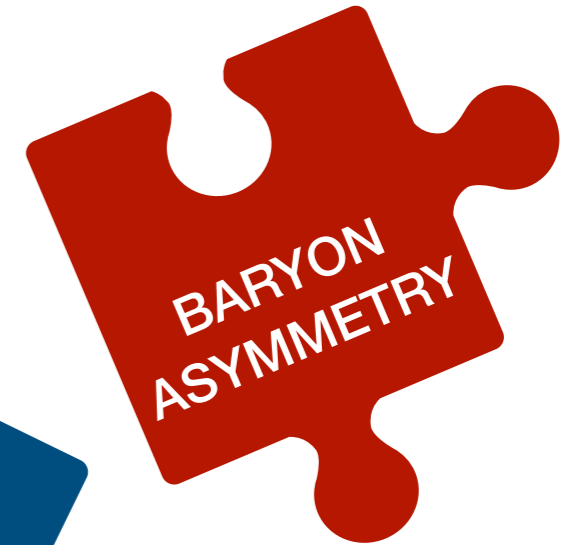- Specific aspects of LLP searches in colliders

OUTLINE

➡️ **Motivation**

○ LLPs in colliders

○ Specific aspects of LLP searches in colliders

Standard Model of particle physics (**SM**)
successfully explains many fundamental phenomena of particles

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

DARK MATTER

NEUTRINO MASS

BARYON ASYMMETRY
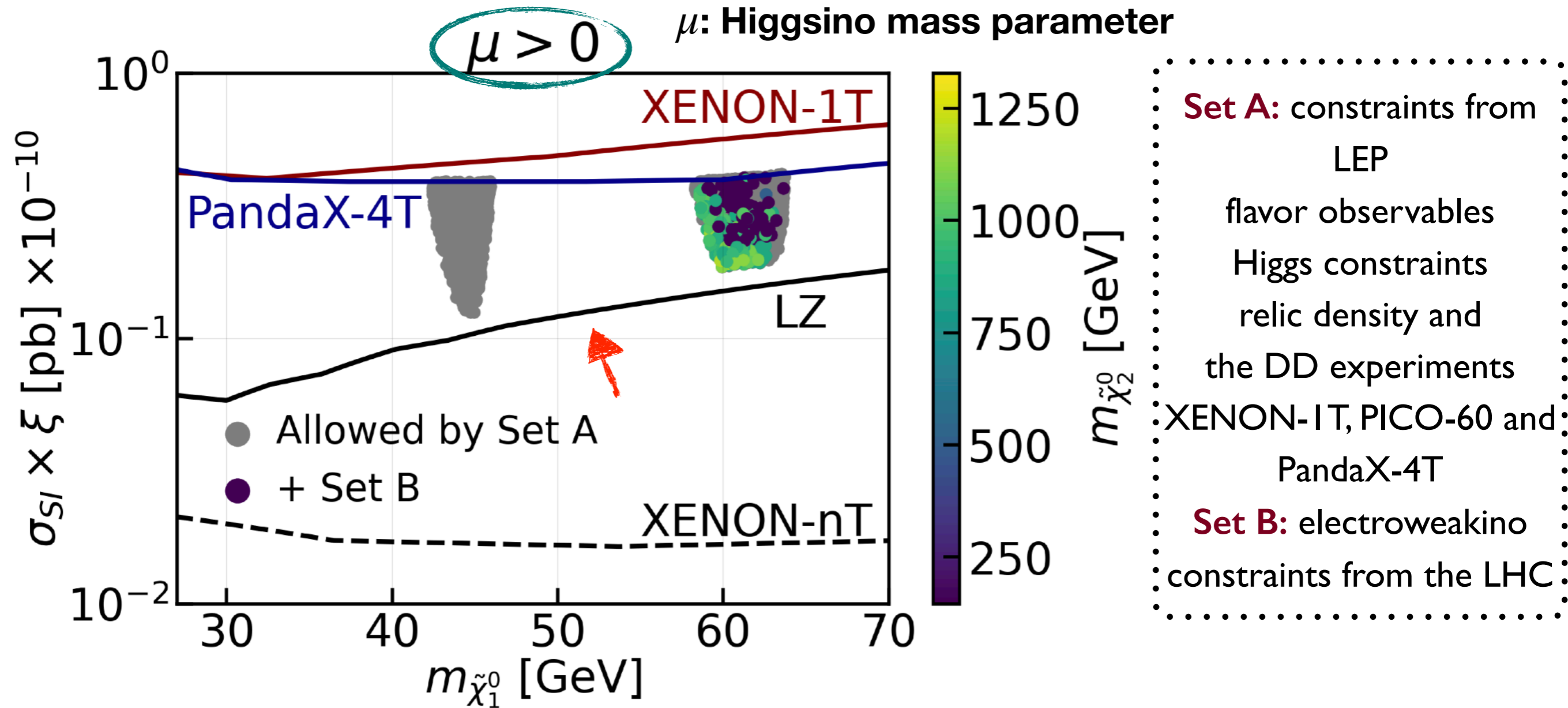
and many more...

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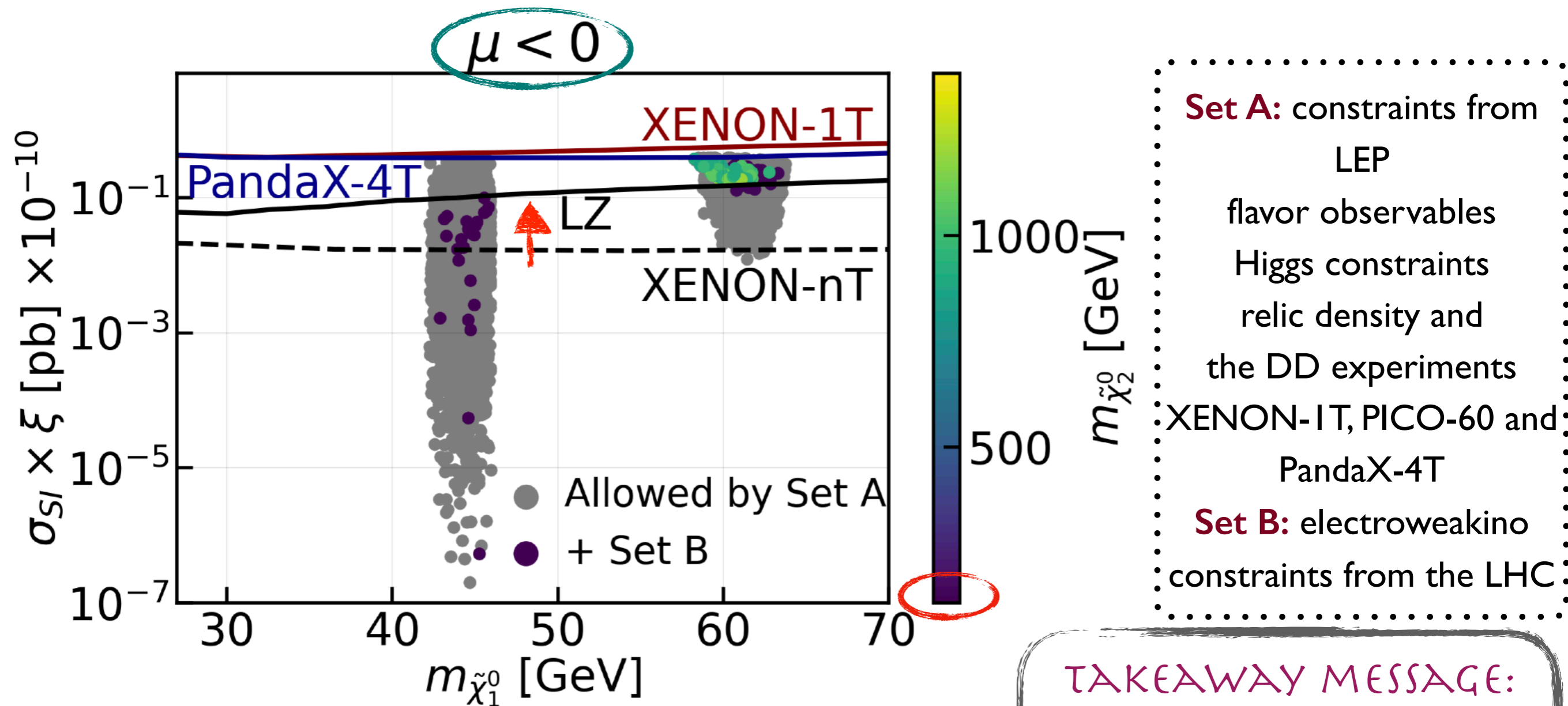
Bino-like LSP (DM), Higgsino-like NLSP

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

μ: **Higgsino mass parameter**

$\mu > 0$

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

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

$\mu < 0$

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

$O(mm)$

Prompt decays : major focus of LHC searches

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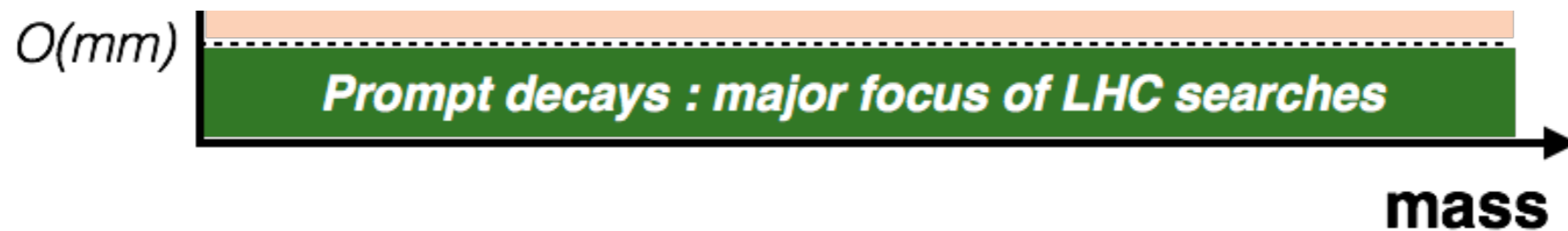
Most of the conventional LHC searches focus on **prompt decay** of particles.

like top quark, W/Z bosons in SM $\tau \sim 10^{-25}$ s
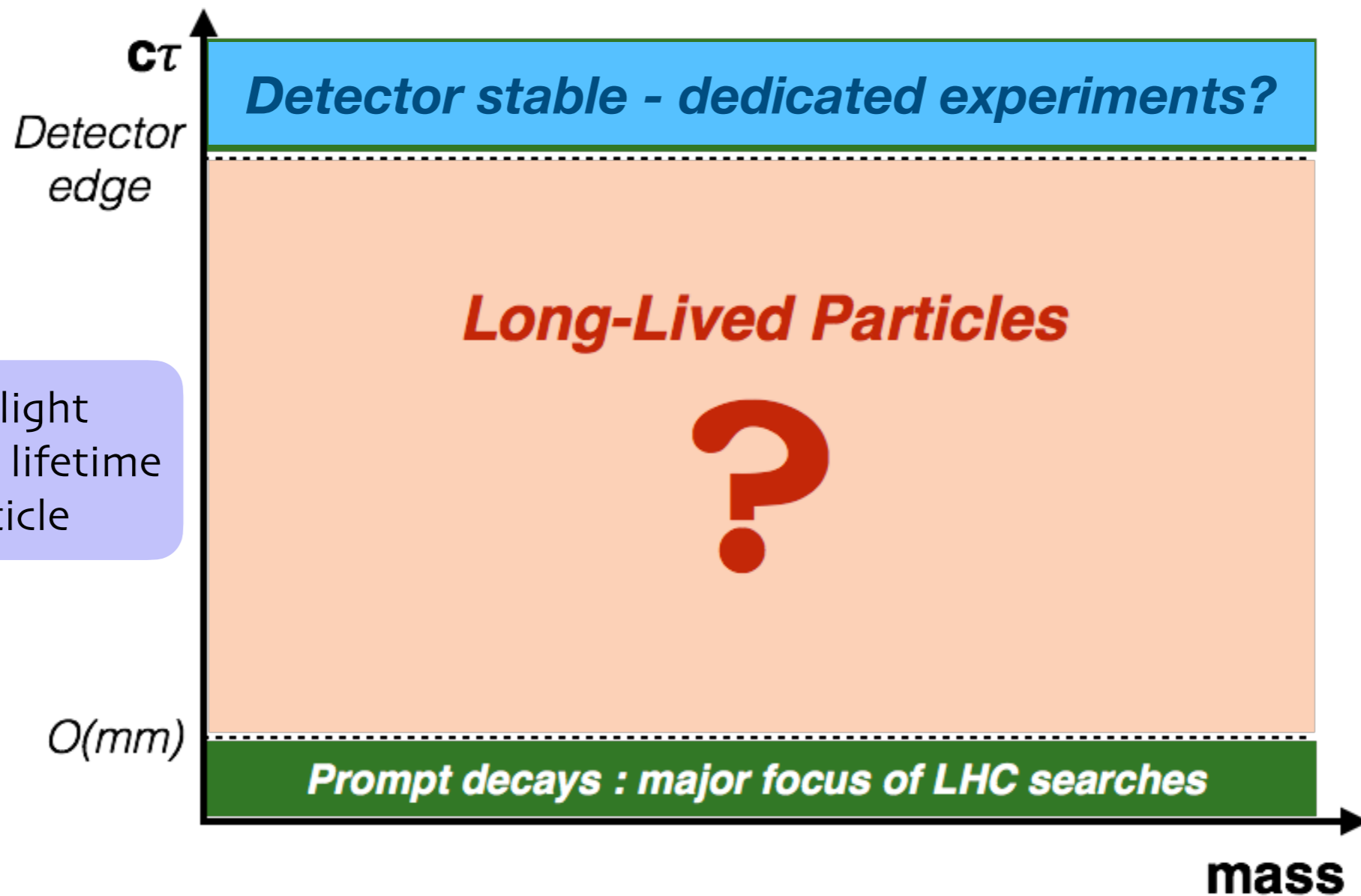
Lifting up the assumption of prompt decays

open the door to the **Lifetime Frontier**

LLPs

Particles with **large lifetimes (τ)**
— decays after traversing a macroscopic distance in the collider detectors
— or, decays outside the detector

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

R

Cylindrical coordinates
Collision along z axis

z

SV

PV

Collider Detector

PV: Primary Vertex
SV: Secondary Vertex

Effect of magnetic field not shown

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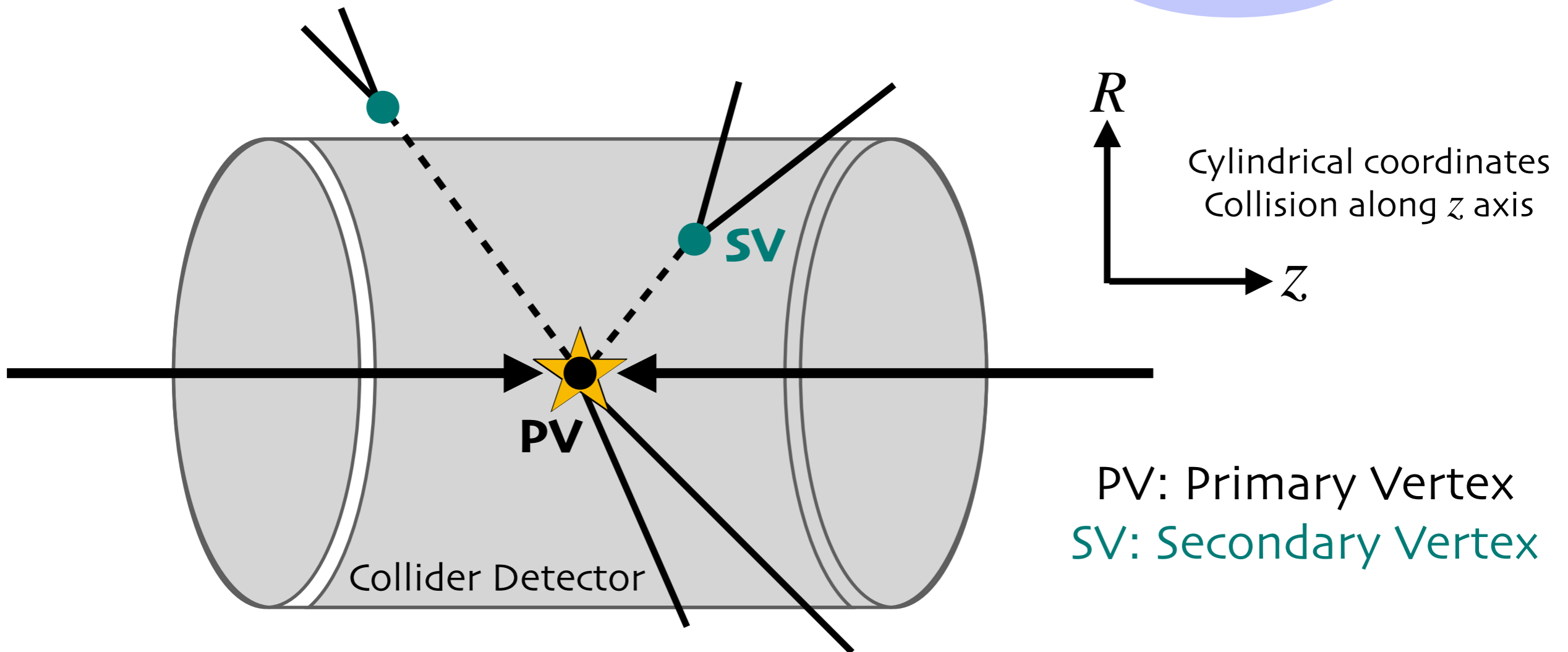
WHY EXPLORE LLPs?

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

IDEA NOT NEW

RECENT FOCUS

12 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
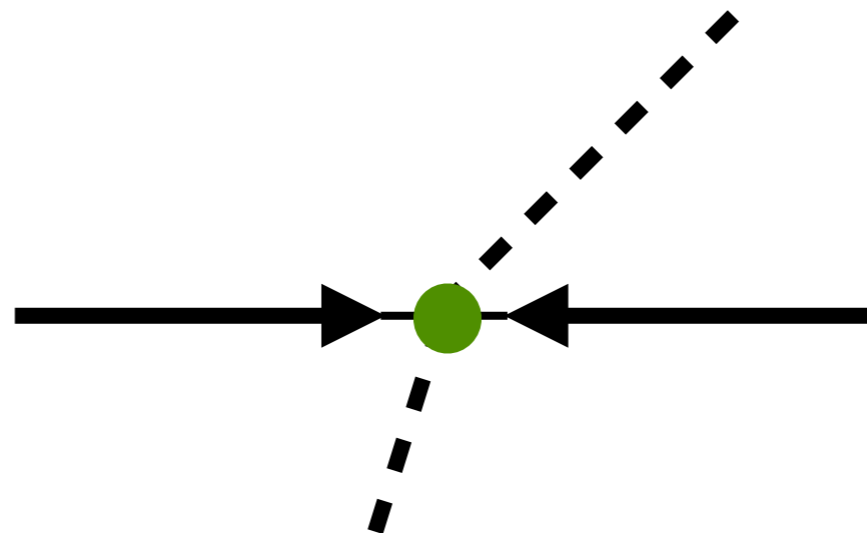
OUTLINE

○ Motivation

➡ **LLPs in colliders**

○ Specific aspects of LLP searches in colliders

The 3 major ingredients

PRODUCTION

- Production rate, σ
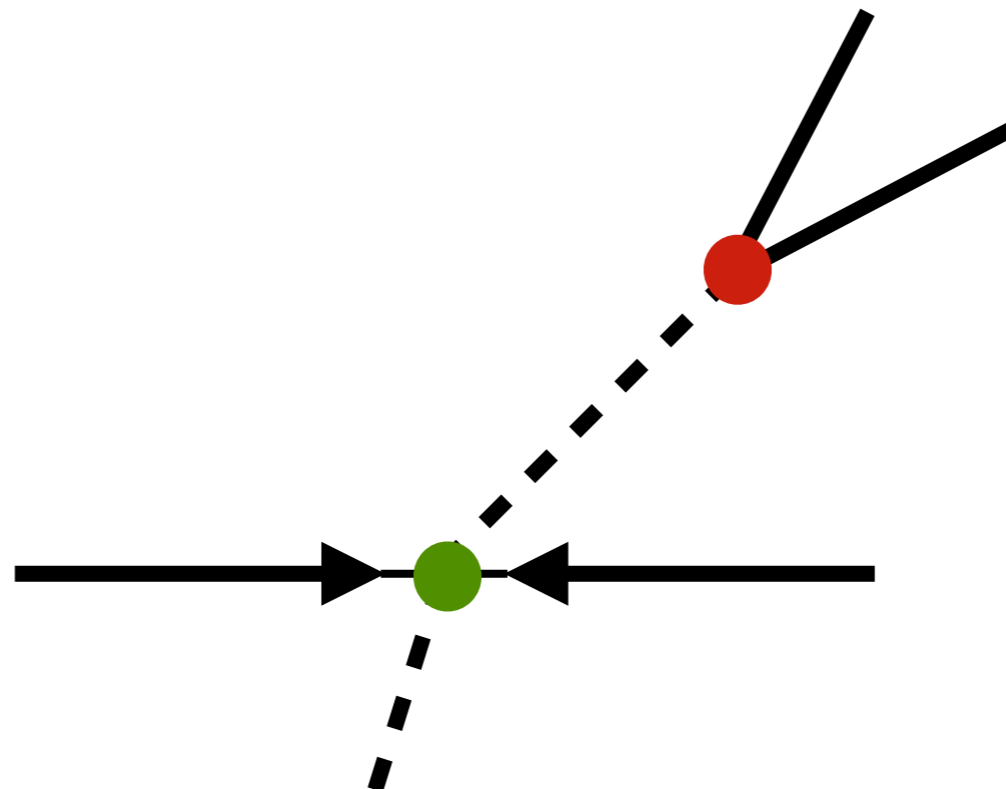- Boost and direction

The 3 major ingredients

PRODUCTION

DECAY

- Production rate, σ
- Boost and direction

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

The 3 major ingredients

PRODUCTION

DECAY

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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The 3 major ingredients

PRODUCTION

THEORY
DECAY

EXPERIMENT
DETECTION

- Production rate, σ
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depends on
- what it decays into
- where it decays

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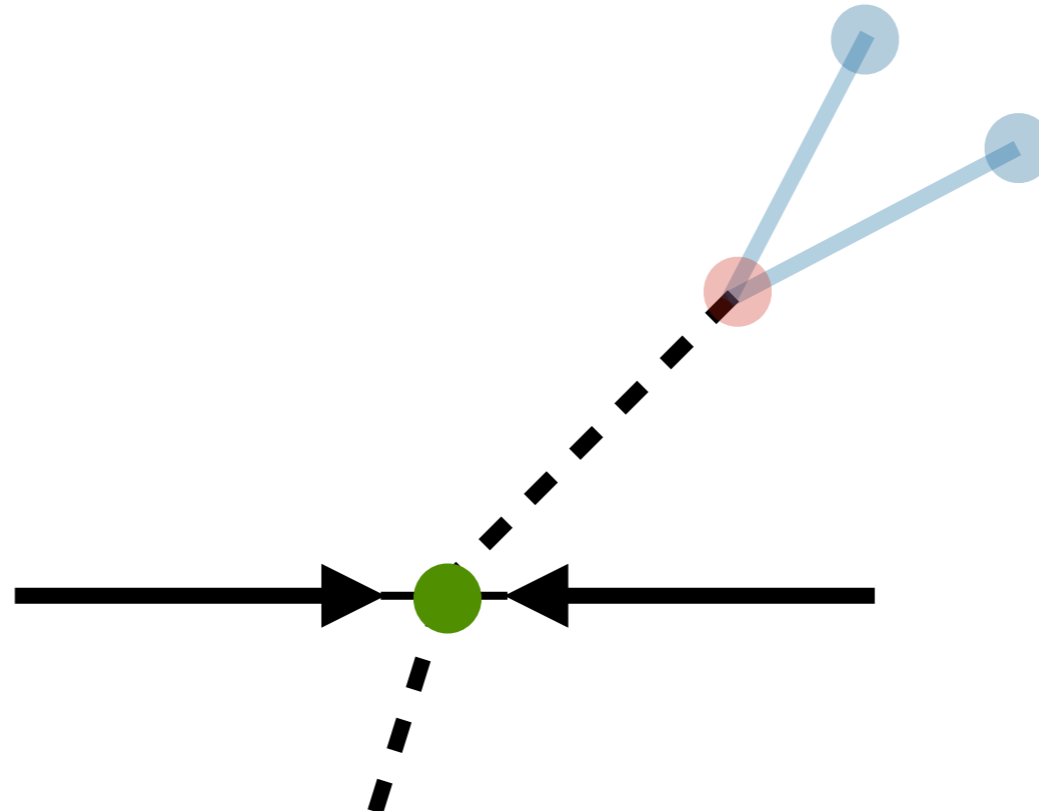
Production of LLPs in colliders

X - LLP
Y - SM/new particle

Direct Production
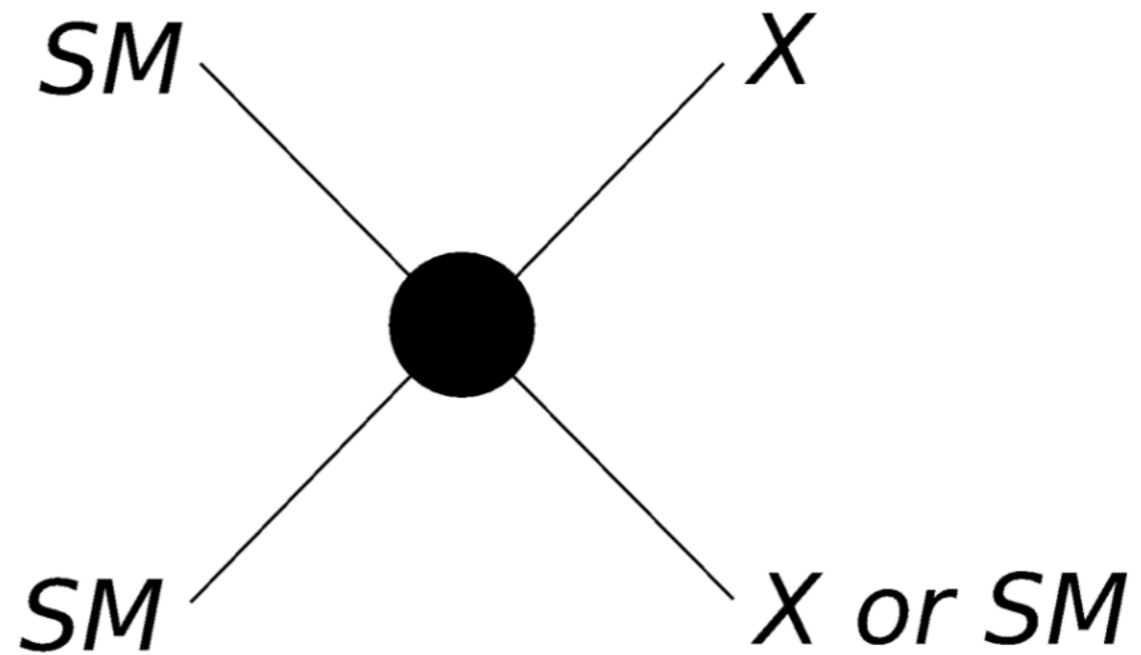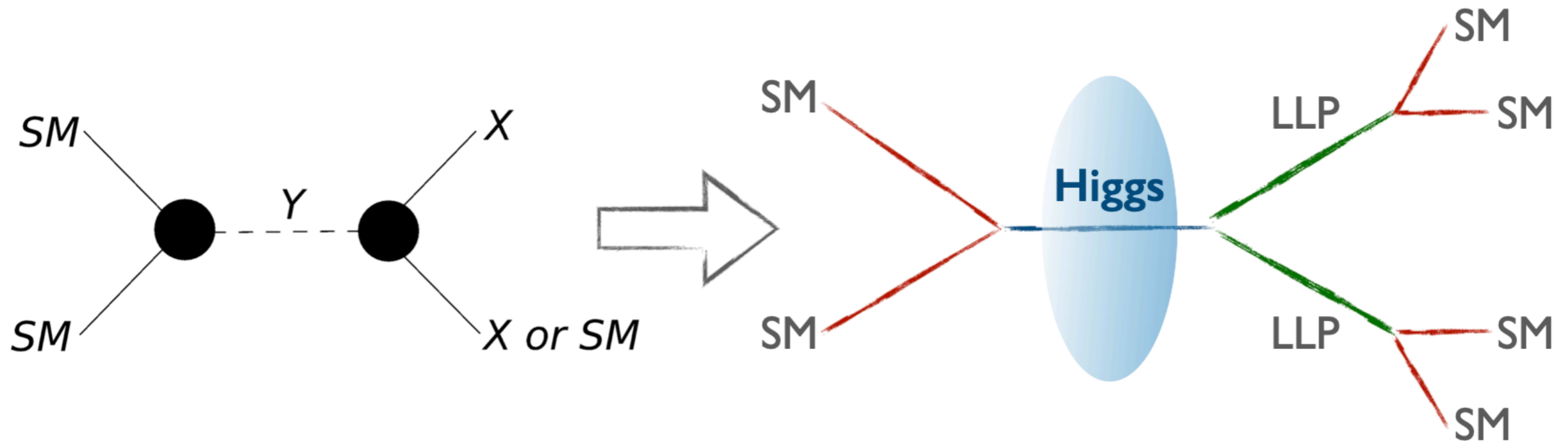

From the decay of a resonance

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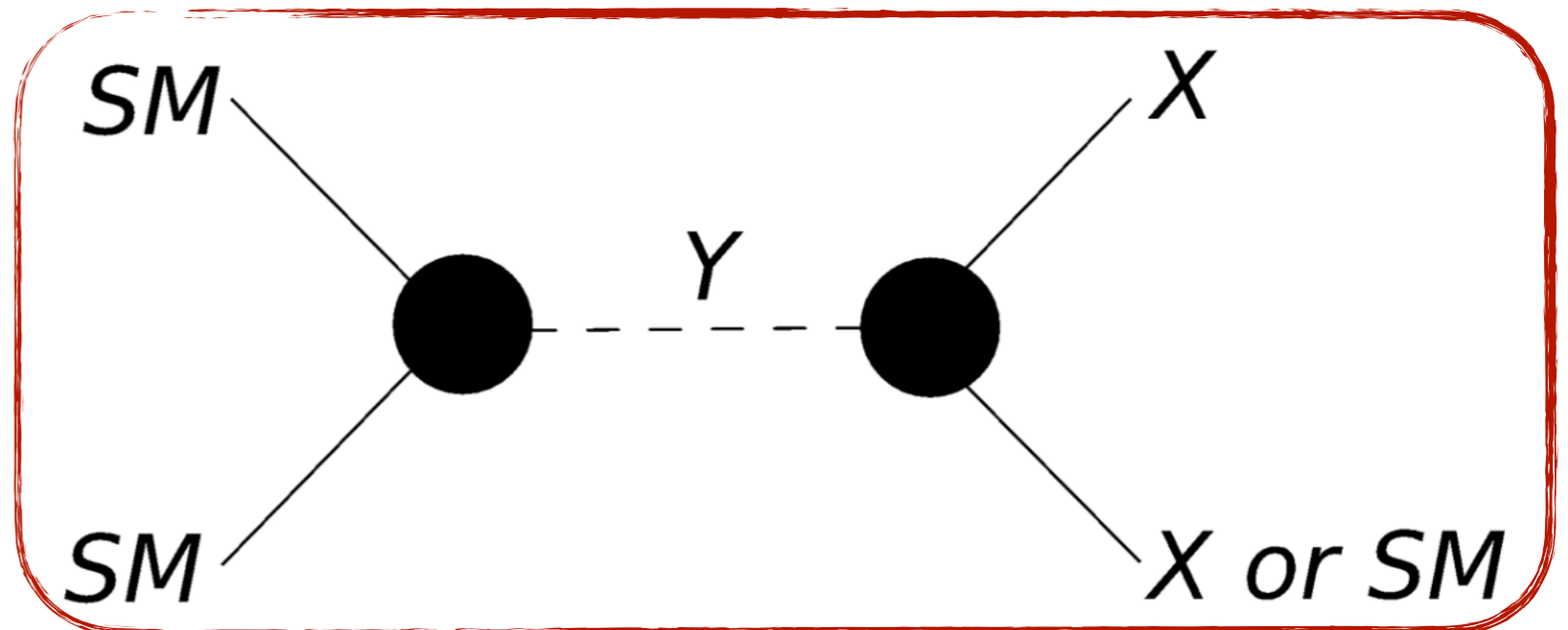
Long-lived particles in the Higgs portal

~ 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*

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The 3 major ingredients

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DETECTION

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depends on
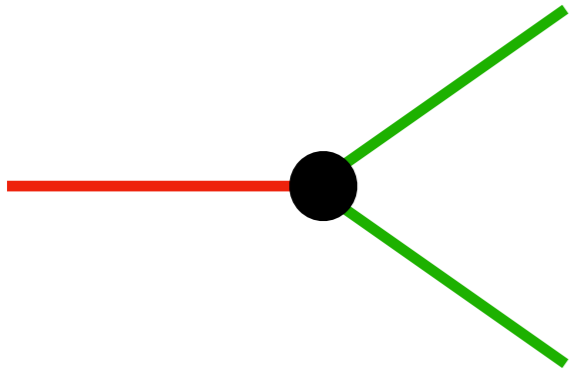- what it decays into
- where it decays

?

Reasons behind long lifetimes

?

$$\Gamma\left(\text{or } \frac{1}{\tau}\right) \propto |\text{Amplitude}|^2 \times (\text{Phase space factor})$$
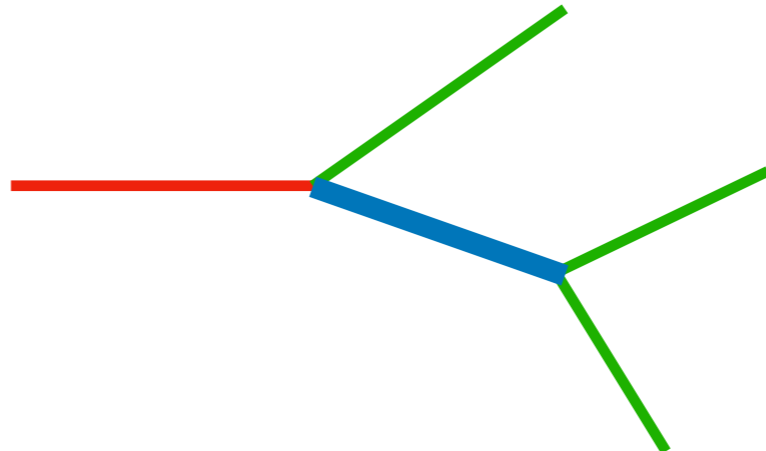
Small couplings
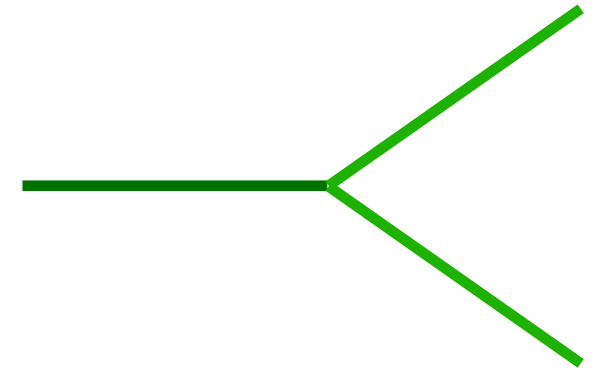e.g., c and b quarks (SM),
RPV SUSY (BSM)

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)

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Long-lived mediator from a minimal DM model

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

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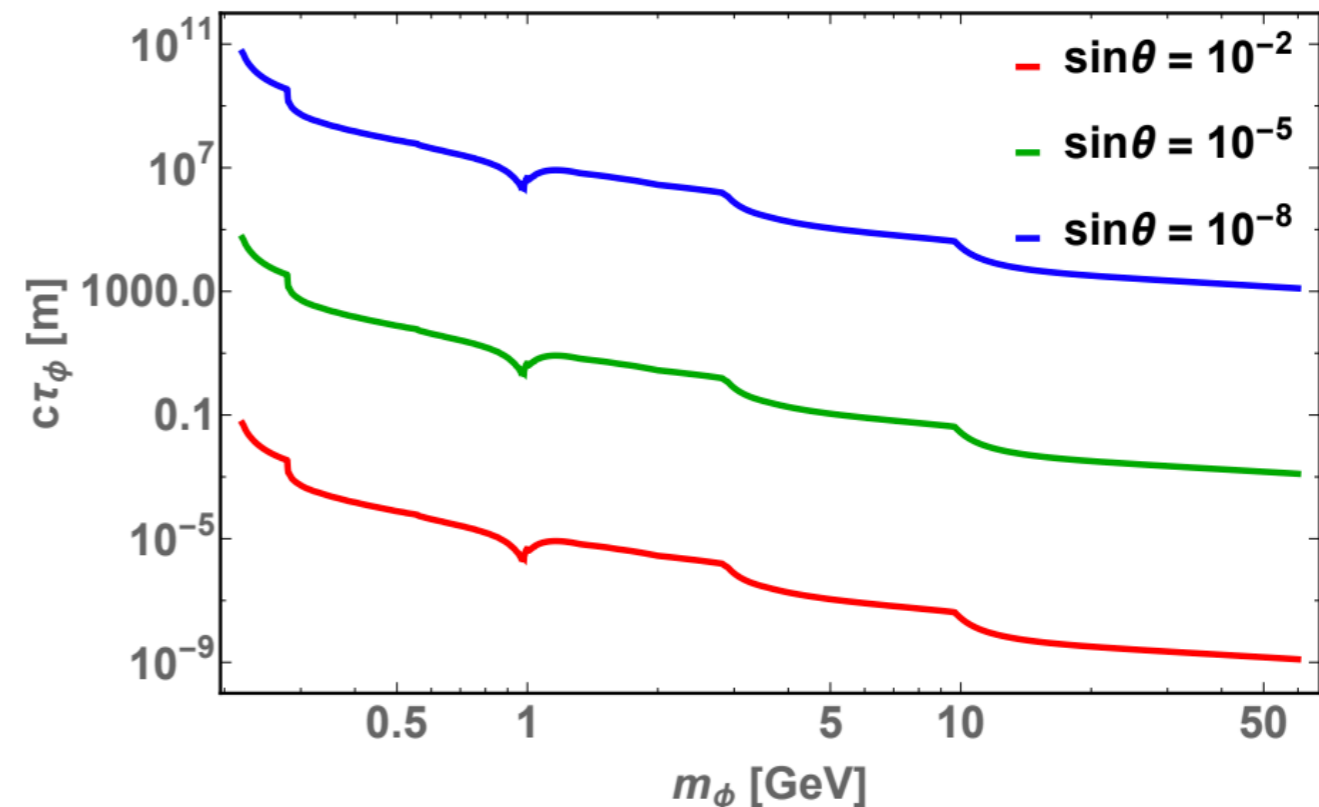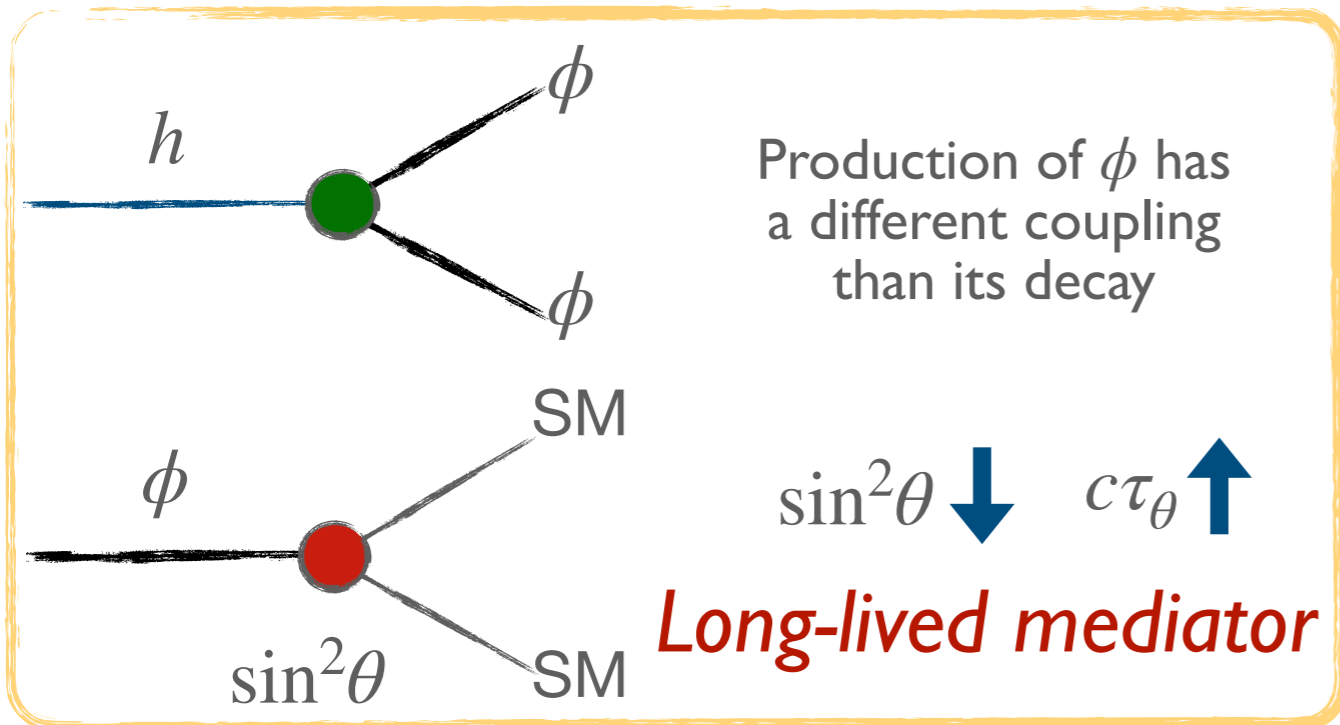
LLP decays in colliders

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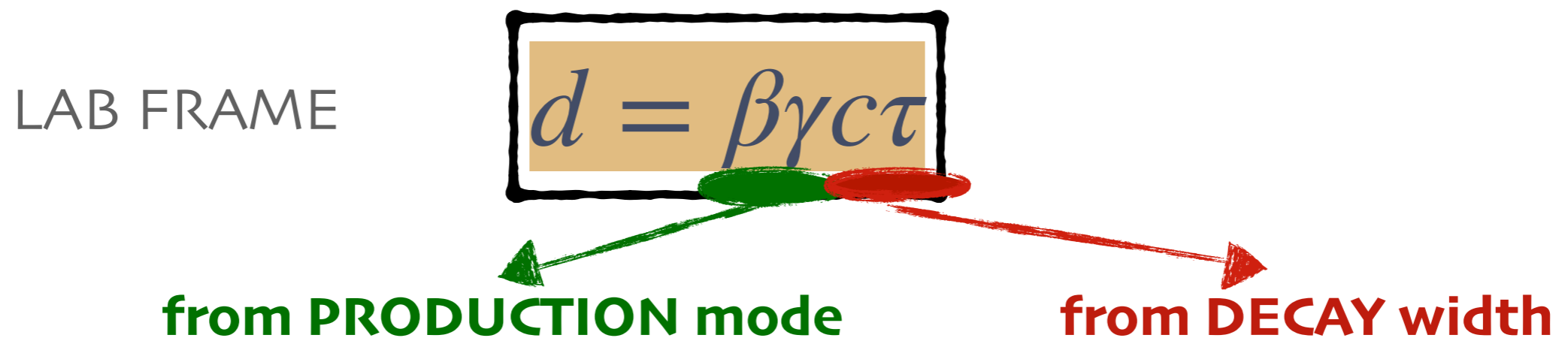
$\beta\gamma = \dfrac{p}{m}$: boost factor

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

PRODUCTION

DECAY

EXPERIMENT
DETECTION

- Production rate, σ
- Boost and direction

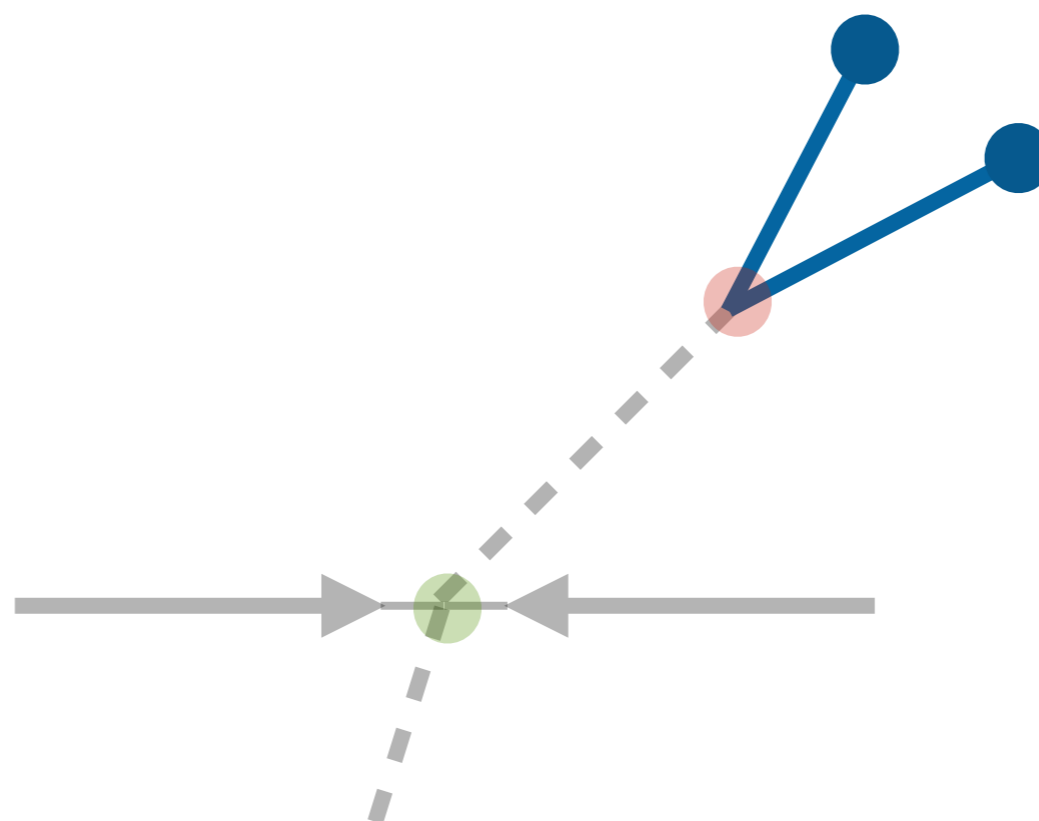- Decay width, Γ or Lifetime, τ
- Decay modes

depends on
- what it decays into
- where it decays

similar for prompt decays as well

?

The 3 major ingredients

PRODUCTION

DECAY

EXPERIMENT
DETECTION

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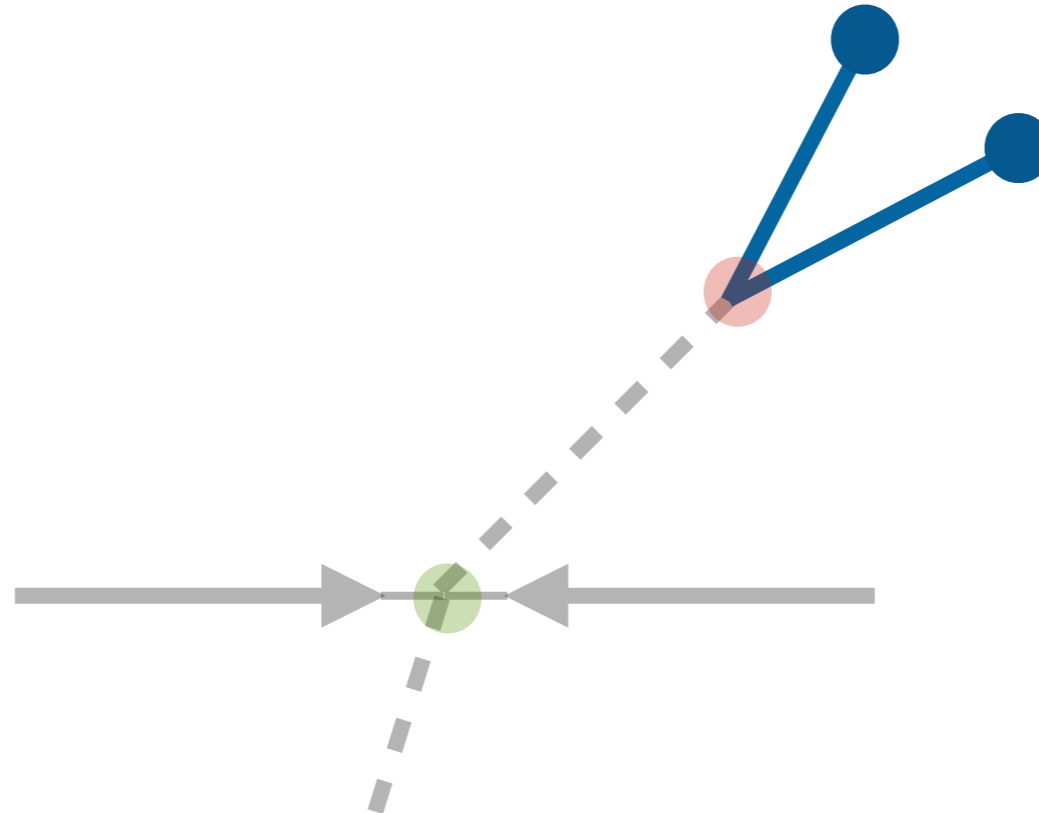
Decay position of the LLP
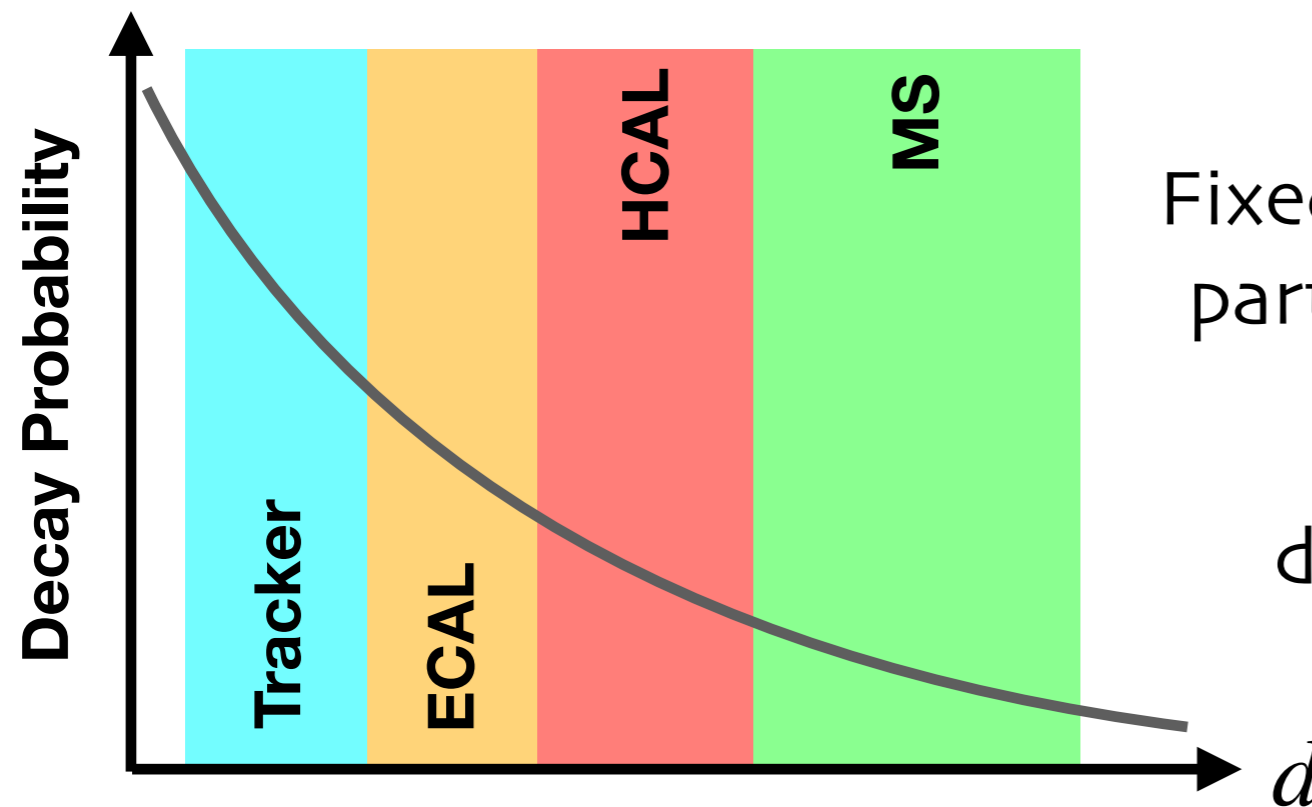
Fixed m and $c\tau$ of a BSM particle with a particular production and decay mode

$\Downarrow$

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	**DECAYS WHERE?**
2 electrons $\Rightarrow$ energy deposits in the ECAL with associated tracks in the Tracker	**Tracker:** displaced vertex **ECAL:** trackless energy deposit **HCAL/MS: ?**

A Peek in to the Exotic Signatures of LLPs

not a complete list
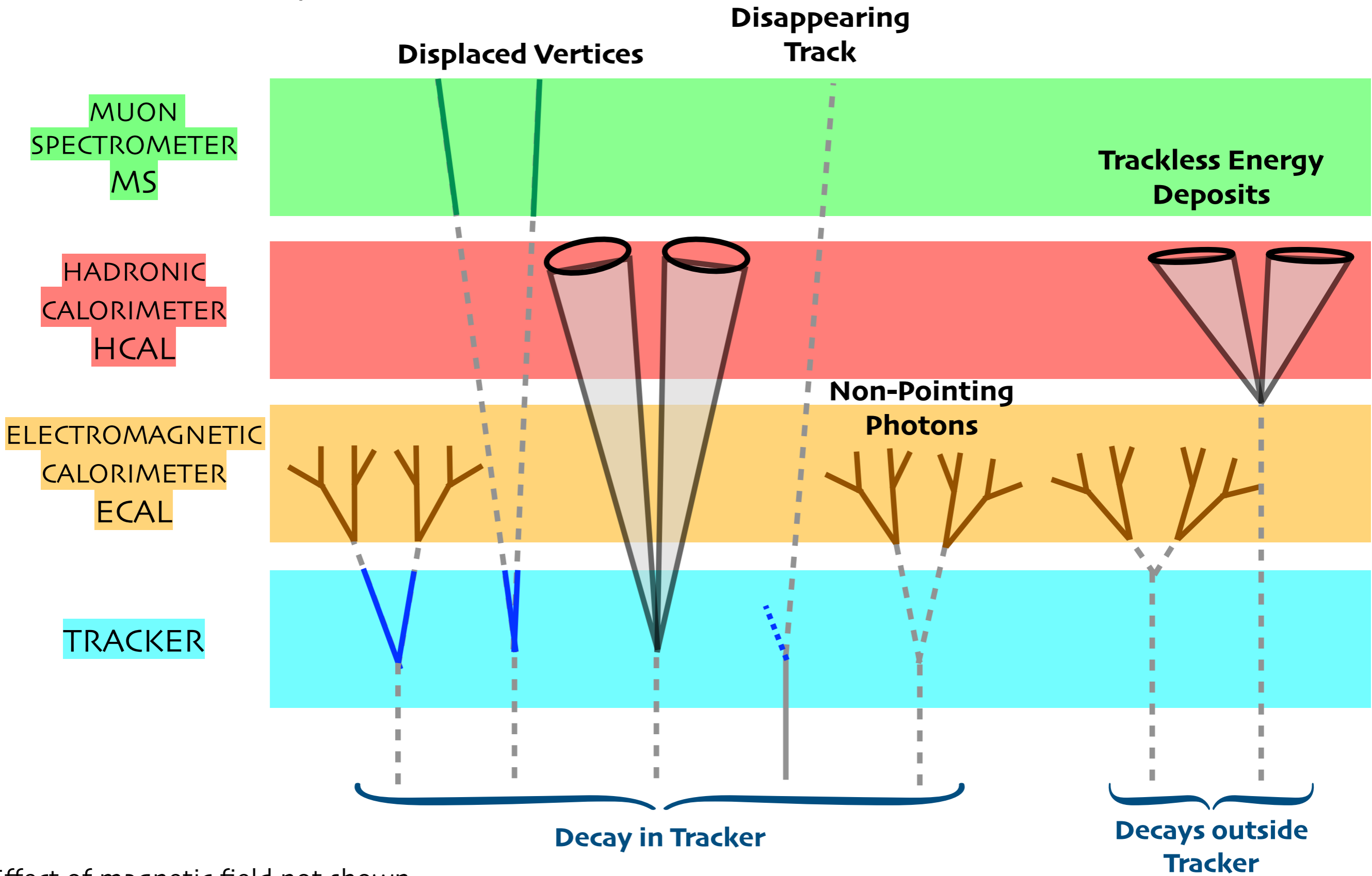
Disappearing Track

Displaced Vertices

MUON SPECTROMETER MS

HADRONIC CALORIMETER HCAL

ELECTROMAGNETIC CALORIMETER ECAL

TRACKER

Trackless Energy Deposits

Non-Pointing Photons

Decay in Tracker

Decays outside Tracker

Effect of magnetic field not shown

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OUTLINE

○ Motivation

○ LLPs in colliders

➡ **Specific aspects of LLP searches in colliders**

▪ **Triggering**

▪ Searches in **main collider detectors**

▪ **Dedicated detectors**

▪ **Machine Learning** and LLPs

Shankha Banerjee, Biplob Bhattacherjee, Andreas Goudelis, Björn Herrmann, Dipan Sengupta, RS, Eur.Phys.J.C 81 (2021) 2, 172 ➡ ▪ **Parameter estimation** of LLPs

OUTLINE

○ Motivation

○ LLPs in colliders

➤ Specific aspects of LLP searches in colliders

■ **Triggering**

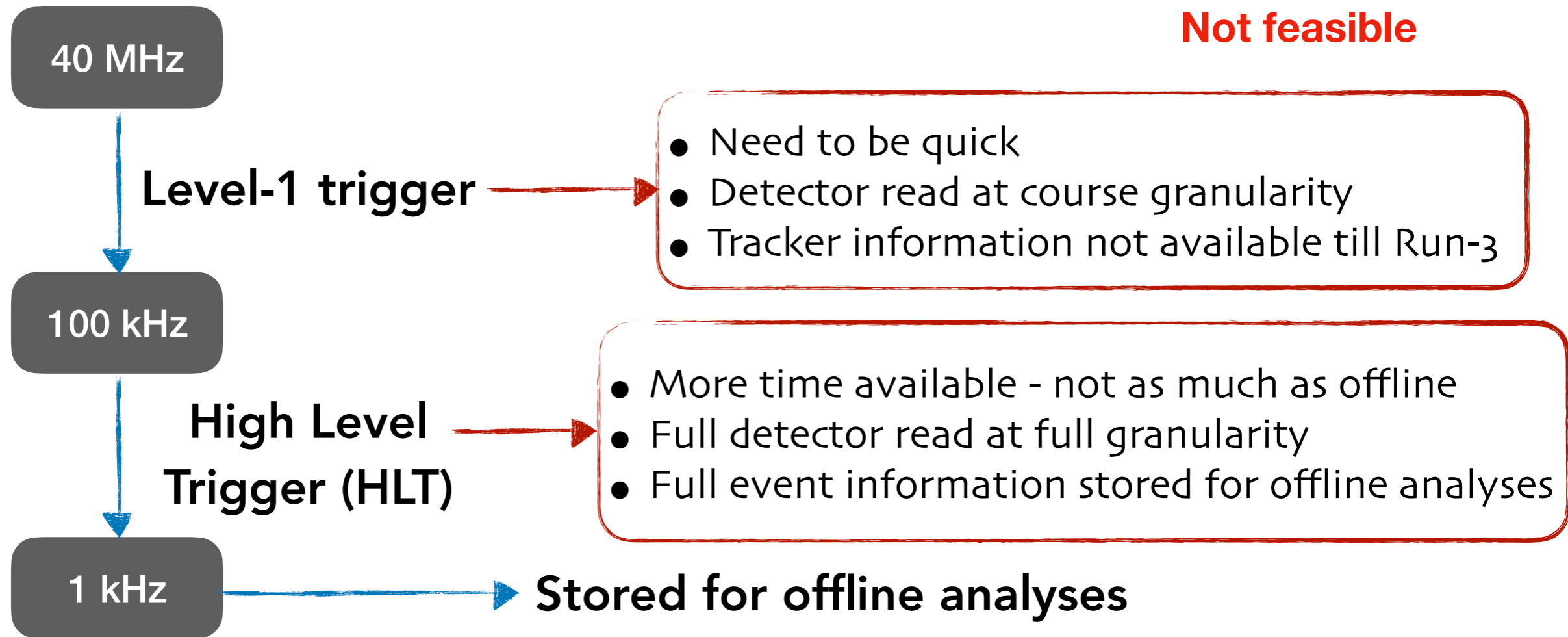■ Searches in **main collider detectors**

■ **Dedicated detectors**

■ **Machine Learning** and LLPs

■ **Parameter estimation** of LLPs

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

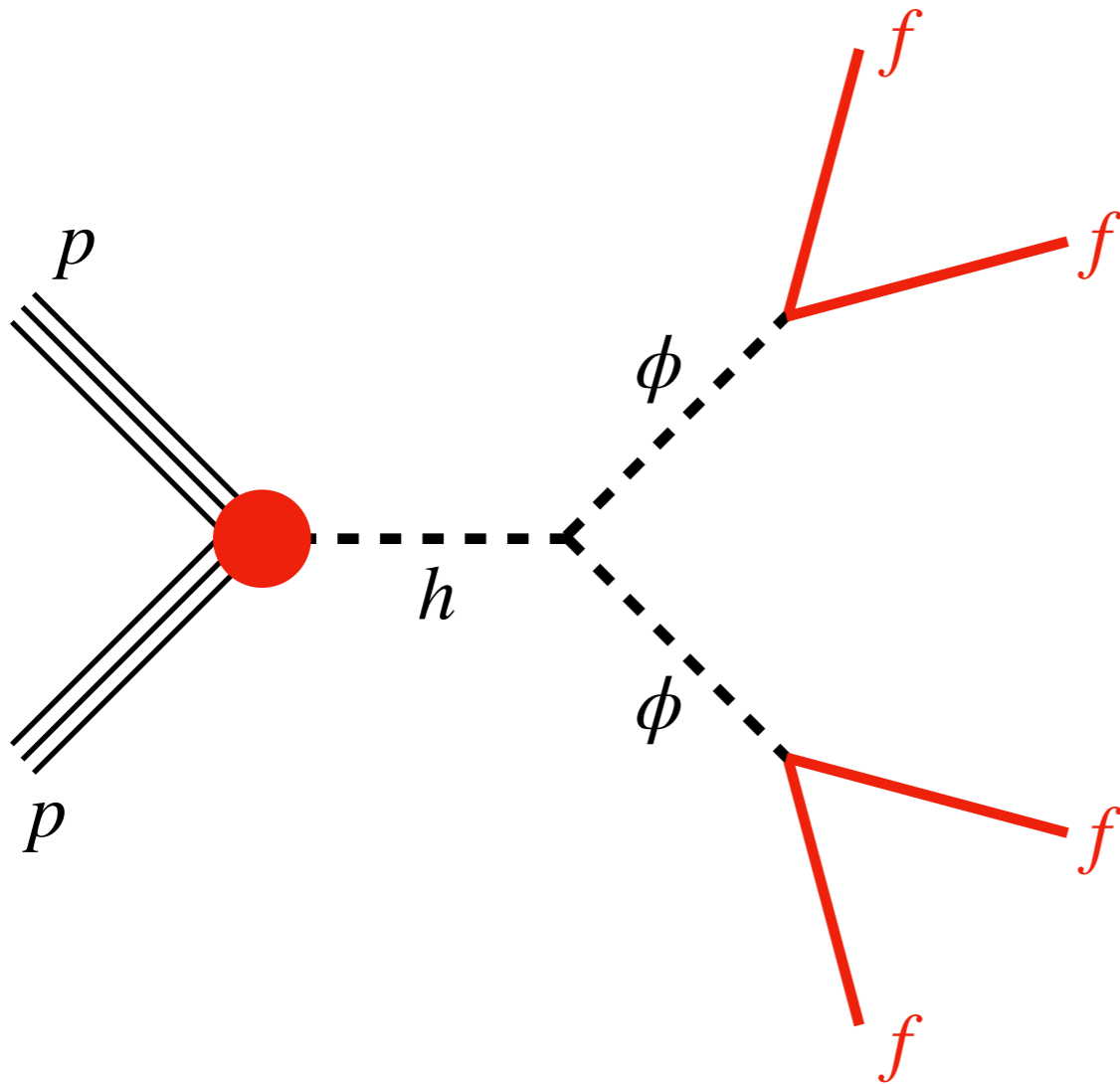**Stored for offline analyses**

1kHz x 1 MB ~ 1 GB/sec

Dedicated L1 Triggers important for LLPs

Biplob Bhattacherjee, Swagata Mukherjee, RS, Prabhat Solanki, <u>JHEP 08 (2020) 141</u>
Biplob Bhattacherjee, Tapasi Ghosh, RS, Prabhat Solanki, <u>JHEP 08 (2022) 254</u>

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Scalar LLPs from Higgs Boson Decay

ϕ: **Long-lived mediator**

Where to look for the LLPs?

HL-LHC Upgrades

1. **L1 Tracking**
2. **MIP Timing Detector (MTD)**
3. **ECAL Timing**

Decays before the ECAL

? Production: From the decay of SM Higgs boson

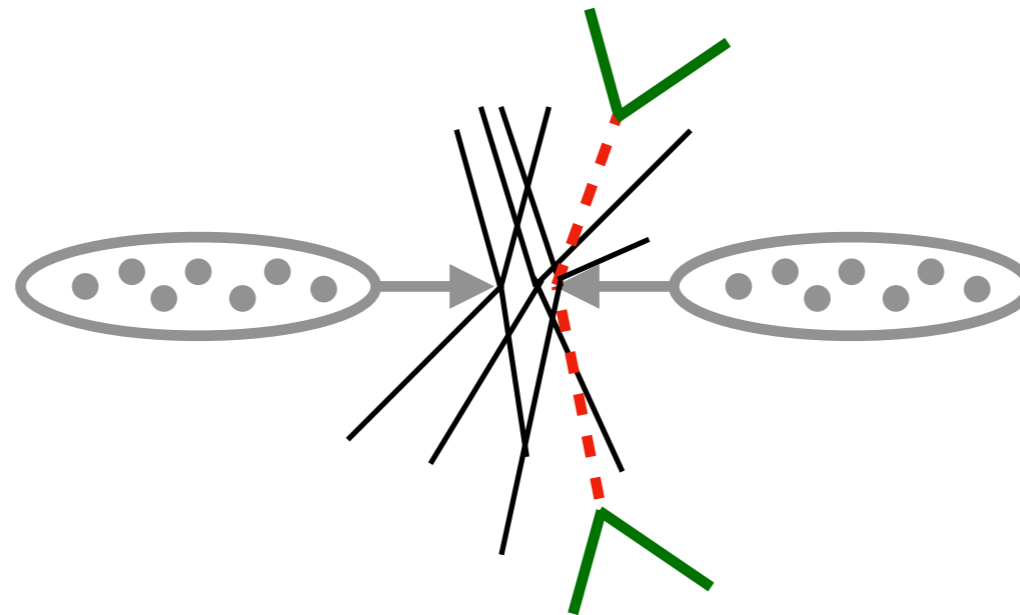**?** Decay: SM quarks through small coupling - **displaced jets**

Issue of Pile-Up (PU)

HL-LHC: High Luminosity LHC

14 TeV, 3 ab^{-1}

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

bunches of protons collide

**interesting interaction
accompanied by multiple
pile-up interactions**
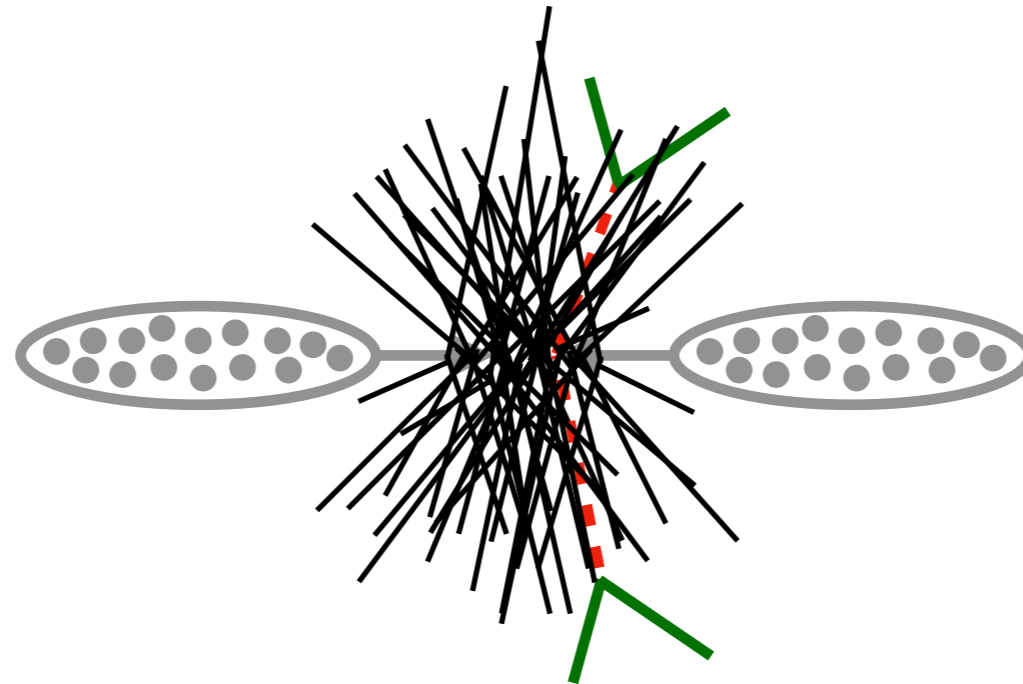
Run-1/2 - around 30-50 interactions per bunch crossing

Issue of Pile-Up (PU)

HL-LHC: High Luminosity LHC

14 TeV, 3 ab^{-1}

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

to increase luminosity, number of protons per bunch increased
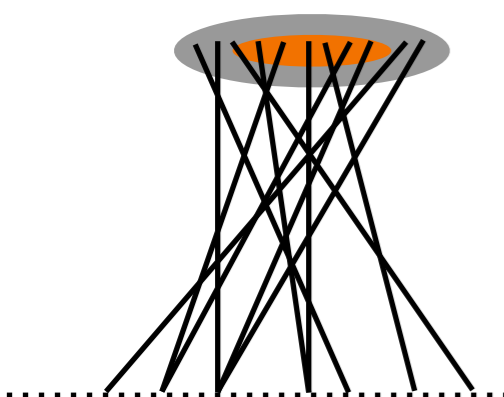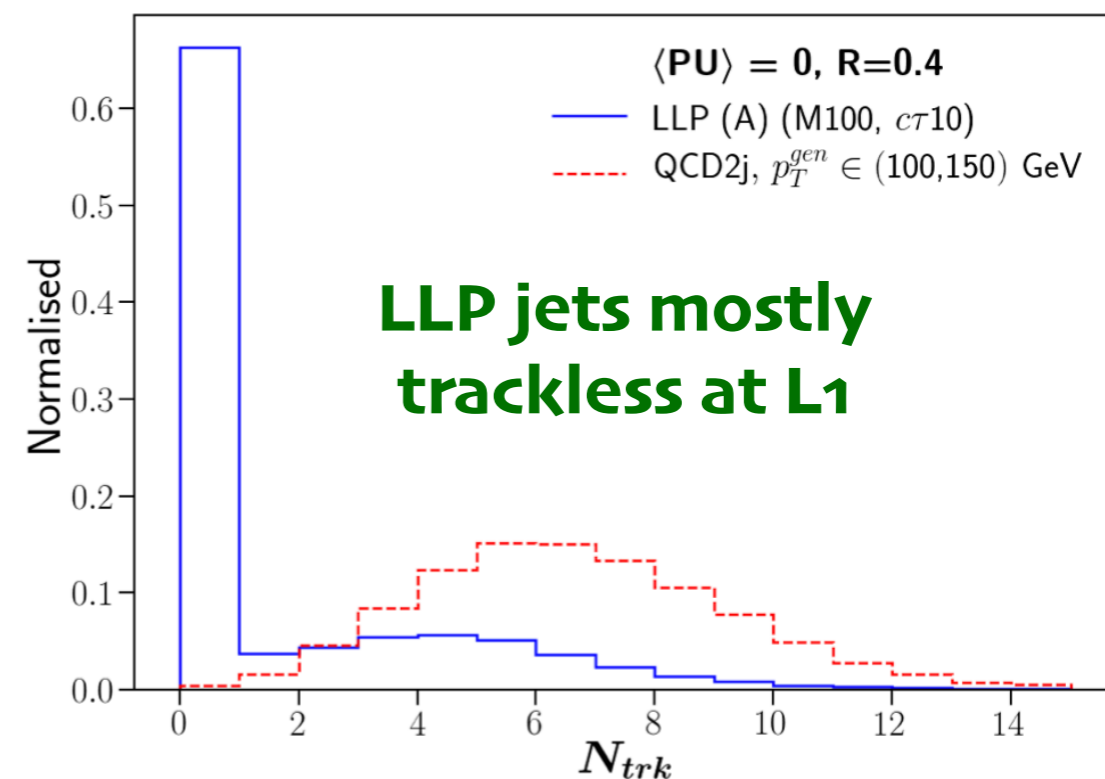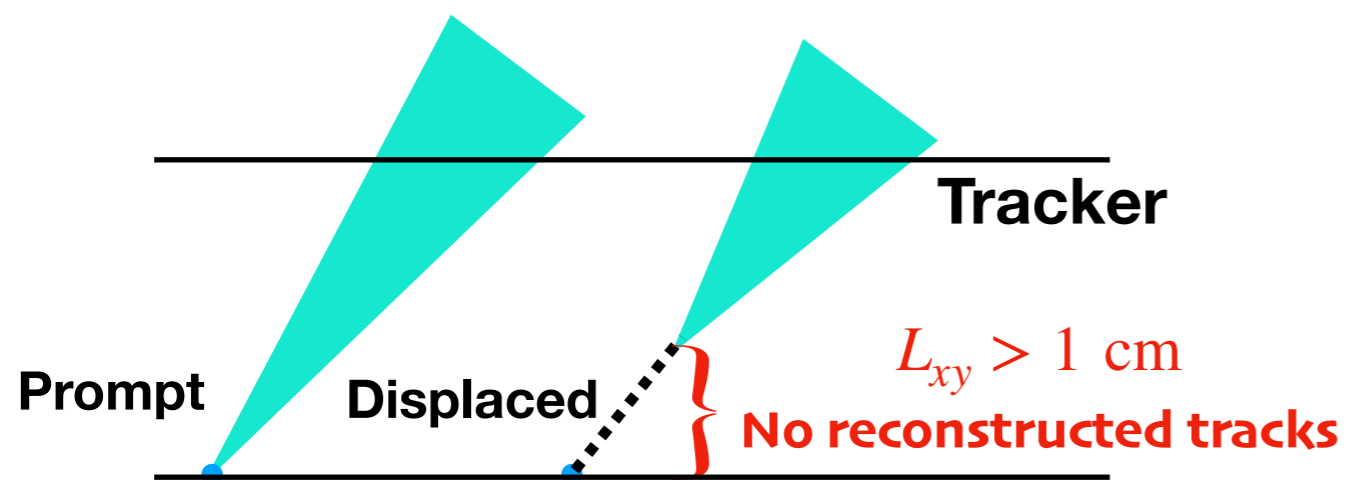
Increased Luminosity = Increased pile-up

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

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

Tracker

Prompt **Displaced**

$L_{xy} > 1$ cm
No reconstructed tracks

LLP jets mostly trackless at L1
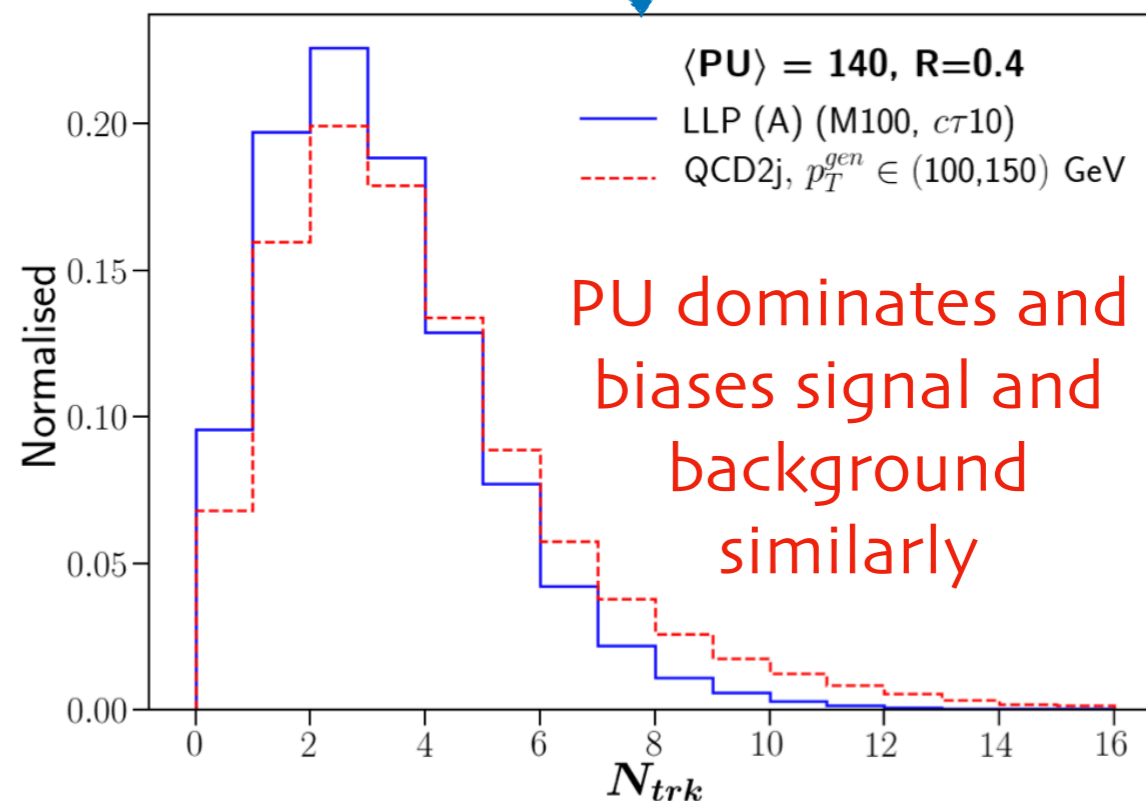
PU contribution, being more uniform, reduces with reduced cone-size
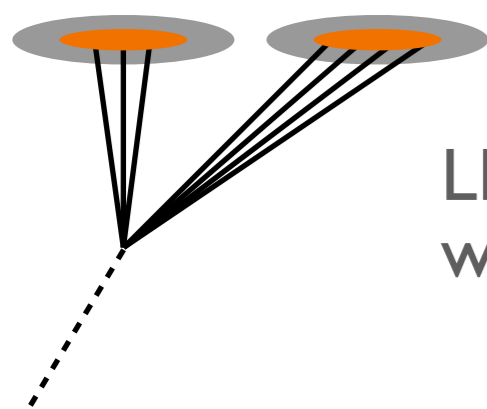
LLP signals not affected with reduced cone-size

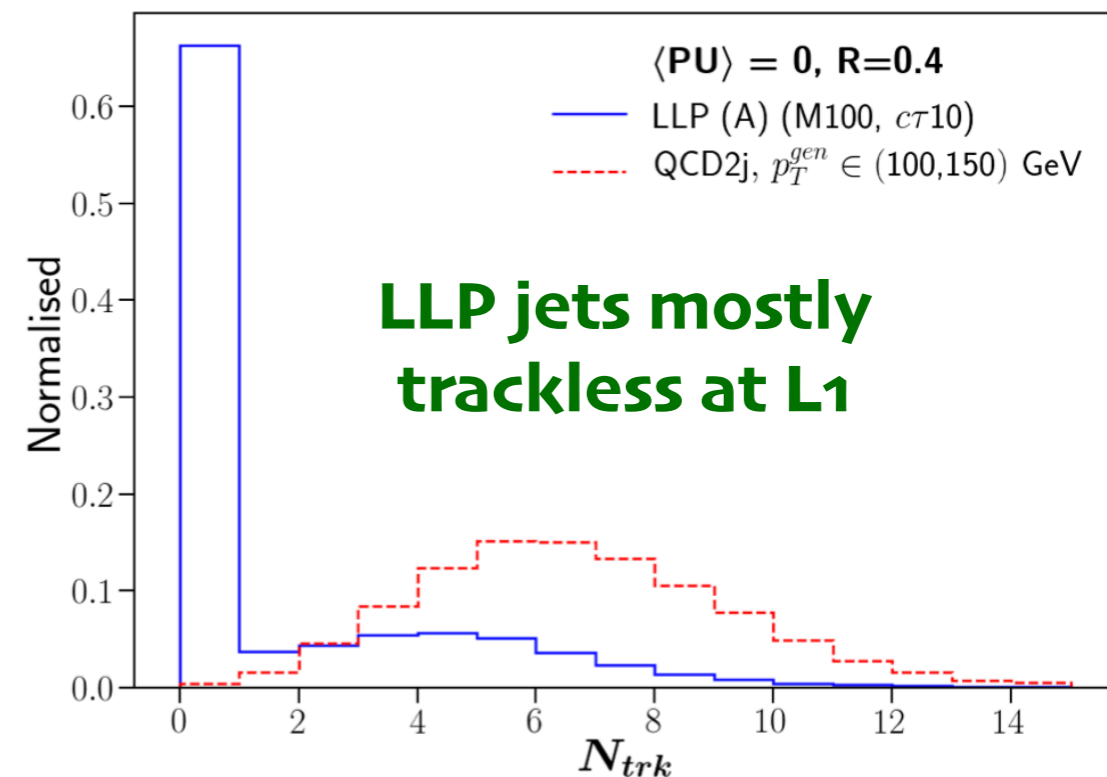PU dominates and biases signal and background similarly

L1 Tracking

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

T. James, CERN-THESIS-2018-241

Tracker

Prompt   **Displaced**

$L_{xy} > 1$ cm
No reconstructed tracks

⟨PU⟩ = 0, R=0.4
LLP (A) (M100, $c\tau10$)
QCD2j, $p_T^{gen} \in (100,150)$ GeV

LLP jets mostly trackless at L1

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

⟨PU⟩ = 140, R=0.2
LLP (A) (M100, $c\tau10$)
QCD2j, $p_T^{gen} \in (100,150)$ GeV

Difference restored to some extent

⟨PU⟩ = 140, R=0.4
LLP (A) (M100, $c\tau10$)
QCD2j, $p_T^{gen} \in (100,150)$ GeV

PU dominates and biases signal and background similarly

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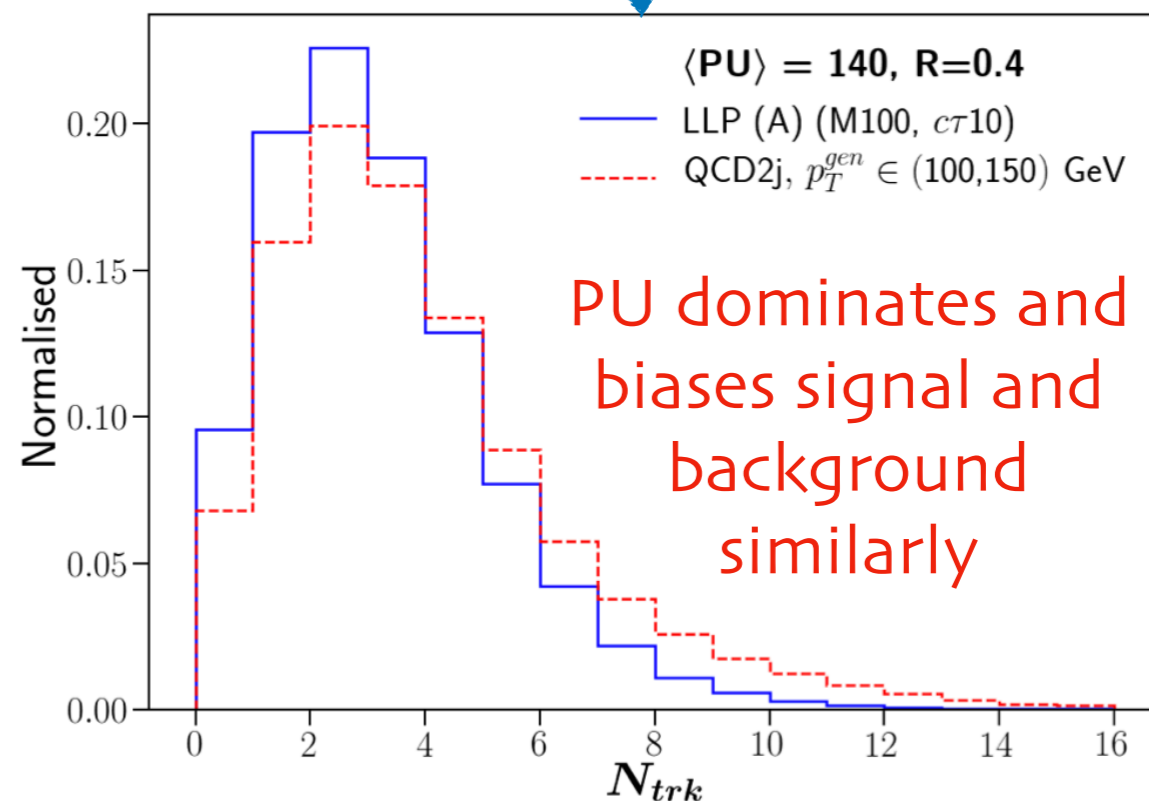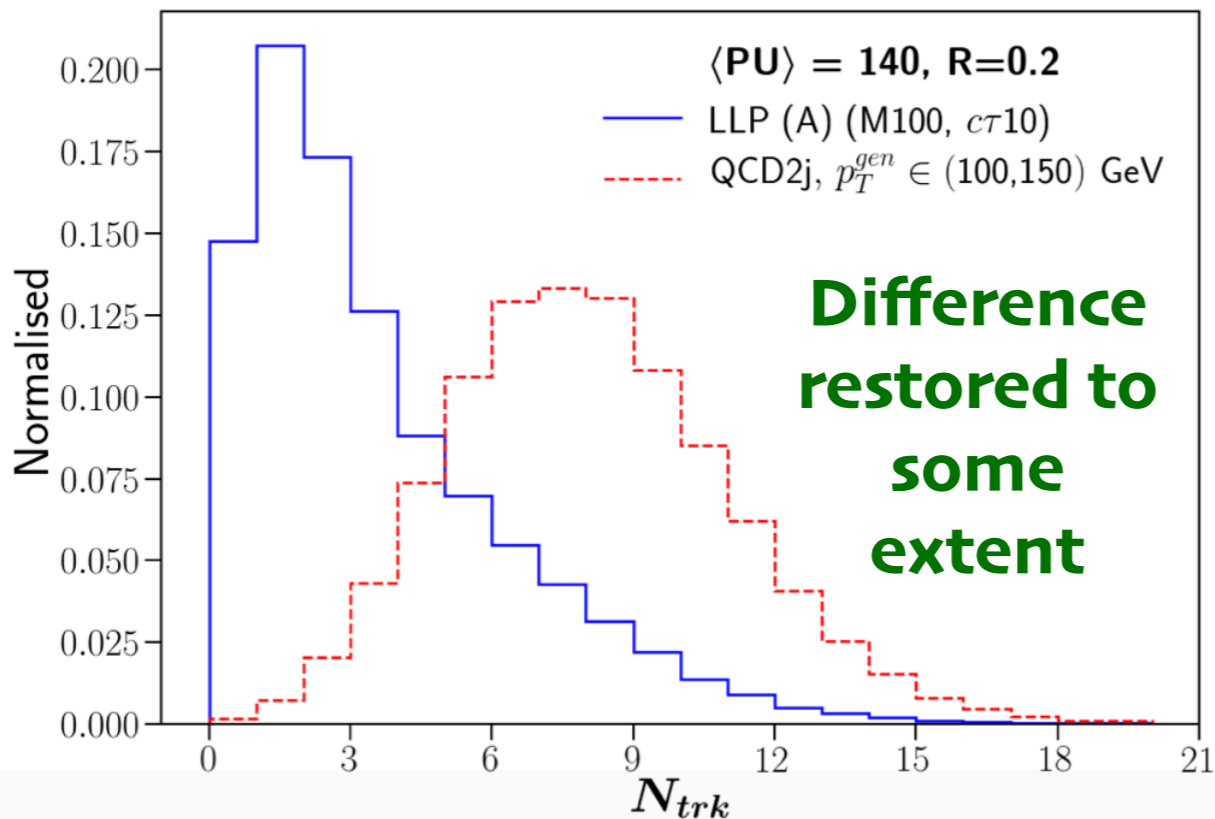
Tracking variables:

$$N_{\text{trk}} \mid \sum p_T \mid z_{\text{j\_vtx}} \mid \Delta z_{\text{j\_vtx}} \mid p_{T(\text{vtx})}^{\text{miss}} \mid n_{z_{\text{trk\_max}}} \mid \Delta z_{\text{trk\_max}} \mid \sum p_T^{z_{\text{trk\_max}}} \mid \sum p_T^{z_a \neq z_{\text{trk\_max}}} \mid \frac{\sum p_T^{z_{\text{trk\_max}}}}{\sum p_T} \mid S(\frac{|z_i|}{\sum |z_i|}) \mid$$

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

Train a Boosted Decision Tree (BDT)

Performance improves with decreasing lifetime

Performance improves with decreasing mass

LLP (C) (M10)
($c\tau$=10) AUC = 93.5
($c\tau$=100) AUC = 87.2

LLP (C) (M30)
($c\tau$=10) AUC = 83.9
($c\tau$=100) AUC = 82.7

Scenario
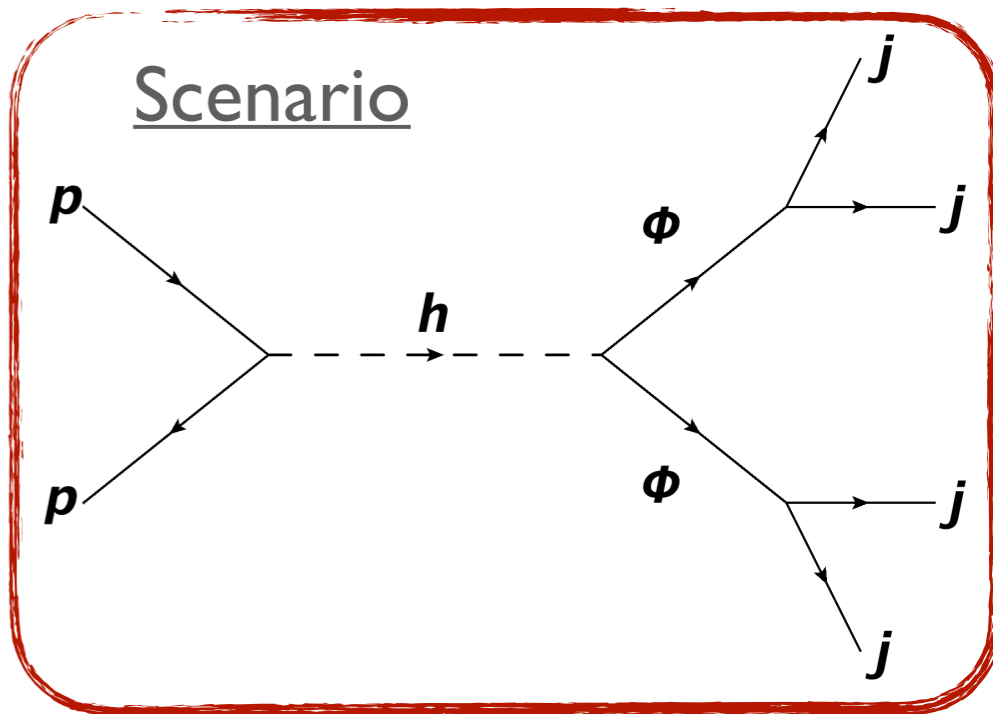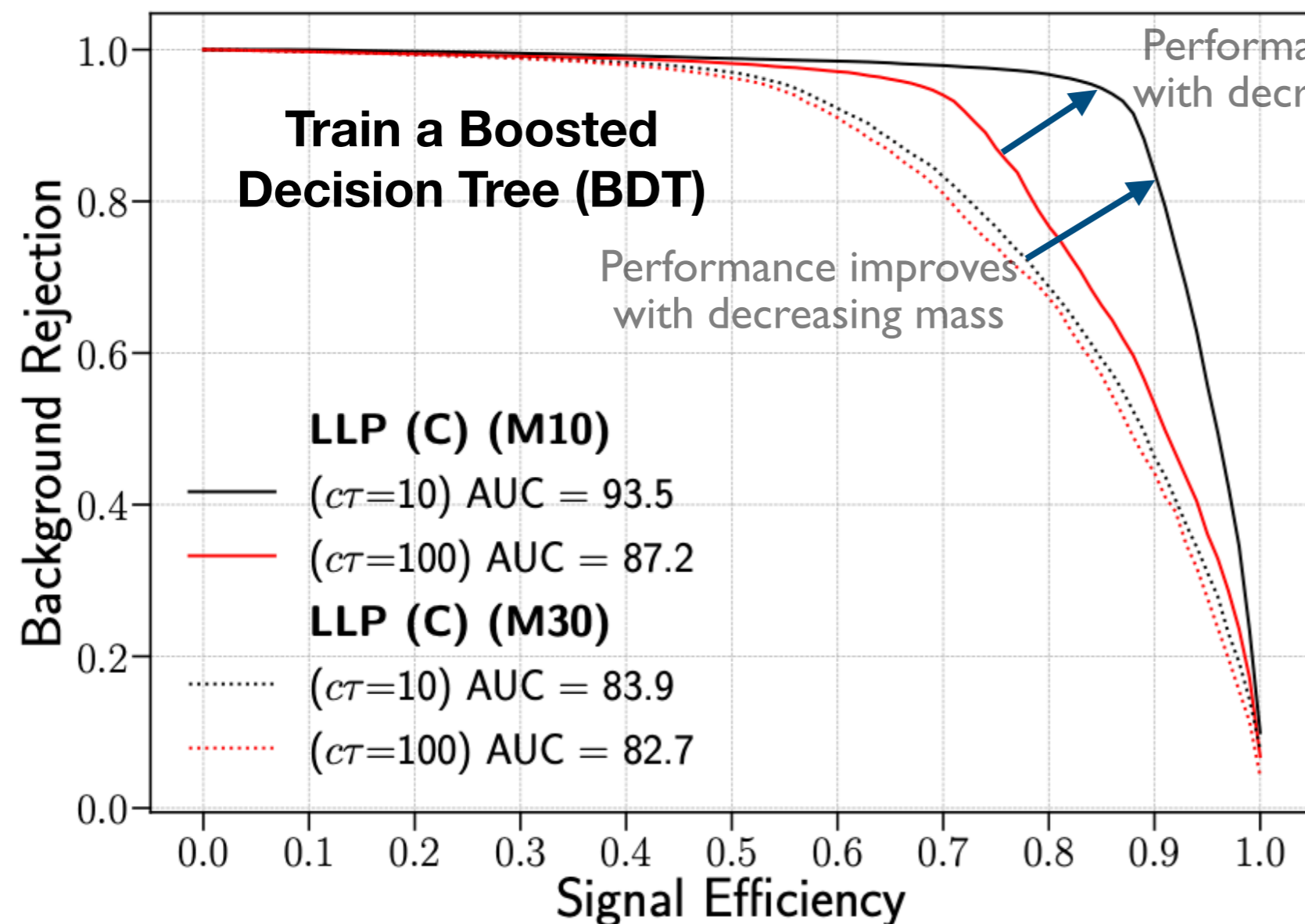
Timing @ MTD

MTD: 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

Timing layer

fast

Timing layer

slow

Decay products of LLPs delayed

Timing:
- p_T
- η
- $N_{\mathrm{MTD}}^{(0.2)}$
- $T_{\mathrm{Med}}^{(0.2)}$
- $\Delta T_{\mathrm{Med,PV}}^{(0.2)}$
- $N_{\mathrm{MTD}}^{(0.2),\mathrm{NT}}$
- $\Delta T_{\mathrm{Med,PV}}^{(0.2),\mathrm{NT}}$

LLP (C) (M10)
($c\tau$=10) AUC = 92.2
($c\tau$=100) AUC = 84.4

LLP (C) (M30)
($c\tau$=10) AUC = 80.2
($c\tau$=100) AUC = 78.1

(Plot: Background Rejection vs Signal Efficiency)

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)
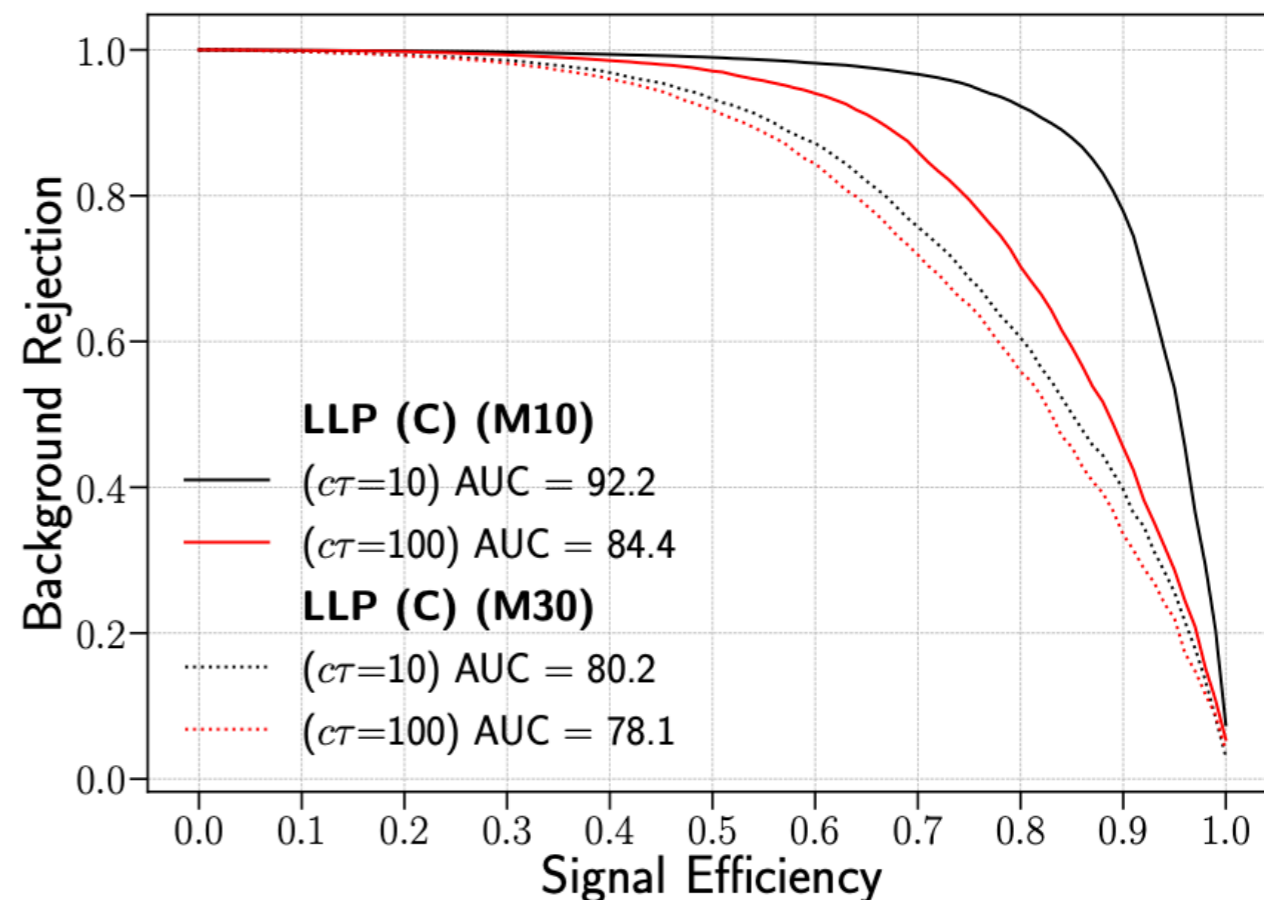
Will MTD be available at L1?

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.**
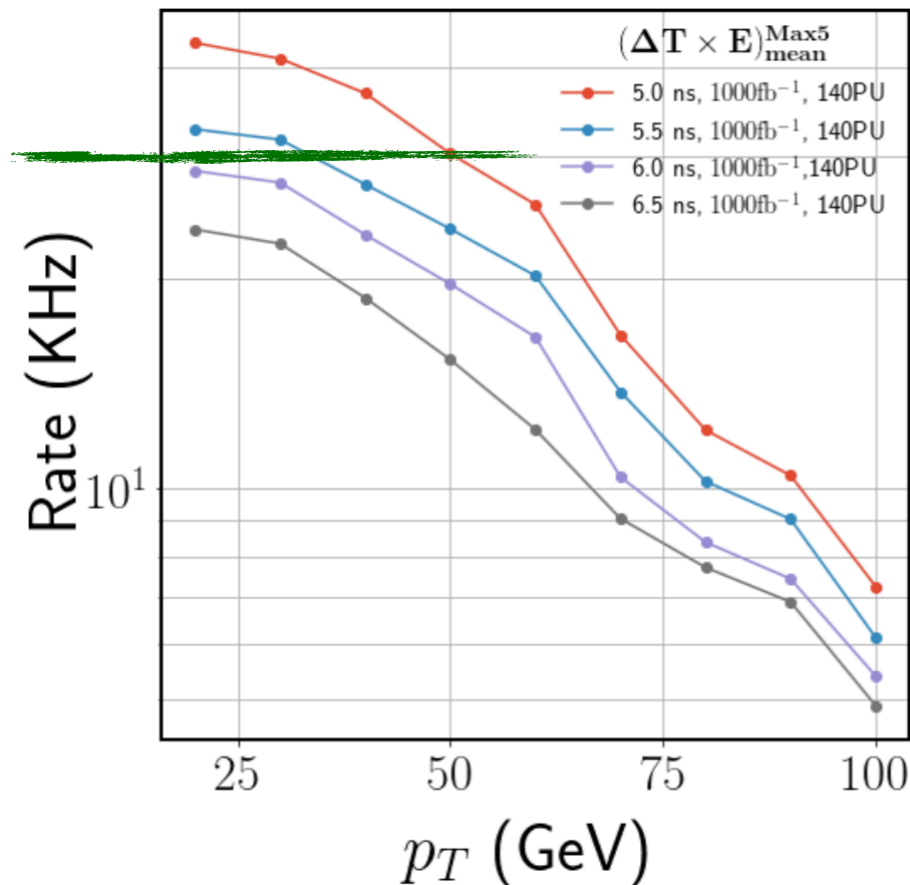
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Timing @ ECAL

$\Delta T_{Mean}, \Delta T_{Median}, \Delta T_{RMS}, \Delta T_{Mean}^{Ewt}, \Delta T_{Mean}^{ETwt}, \Delta T_{Mean}^{Max5},$

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

Spread of vertices in the z and t directions

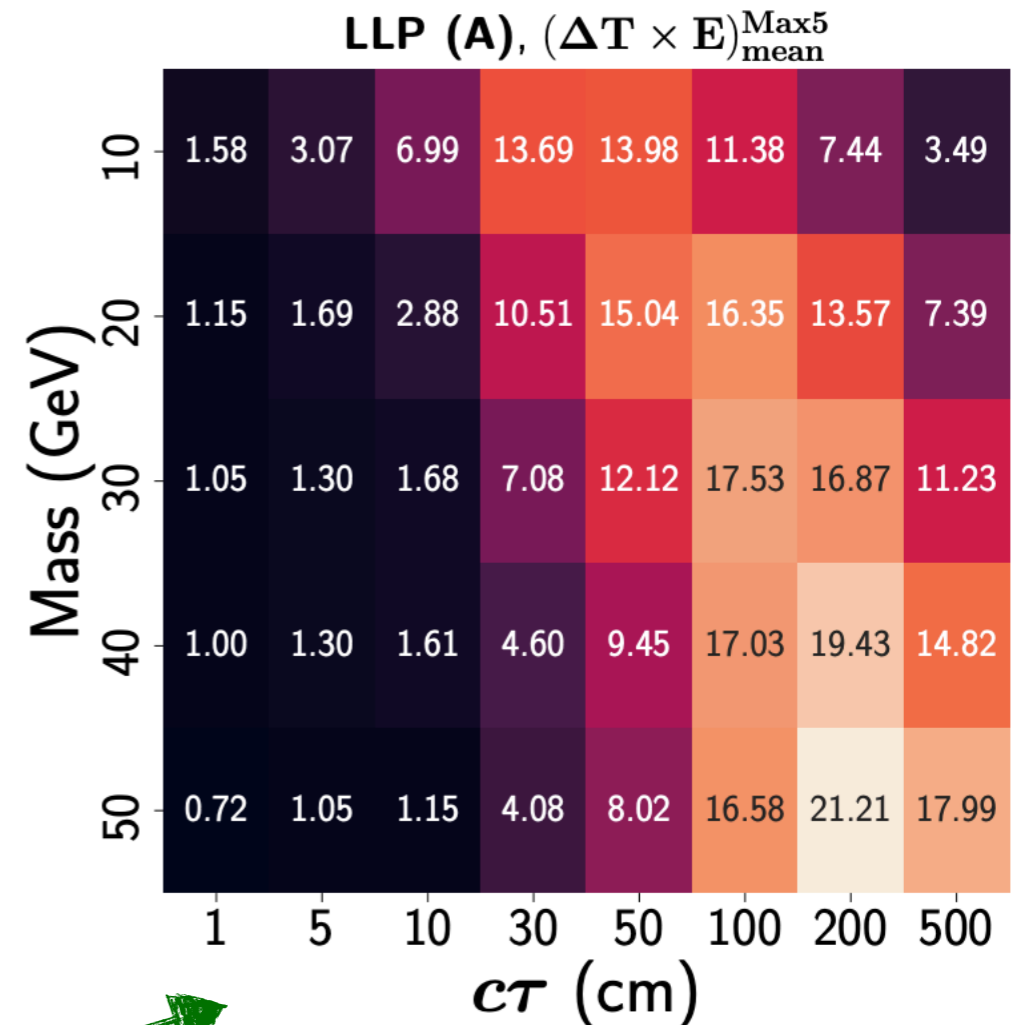Degrading resolution with increasing luminosity

LLPs in SM

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

Average timing of the 5 ECAL crystals having maximum value of $\Delta T \times E$

LLP (A), $(\mathbf{\Delta T \times E})_{mean}^{Max5}$

Select cuts that maintain **30 kHz rate**

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

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

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

K. Ehaẗaht et al, arXiv:2106.04360

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➤ **Specific aspects of LLP searches in colliders**
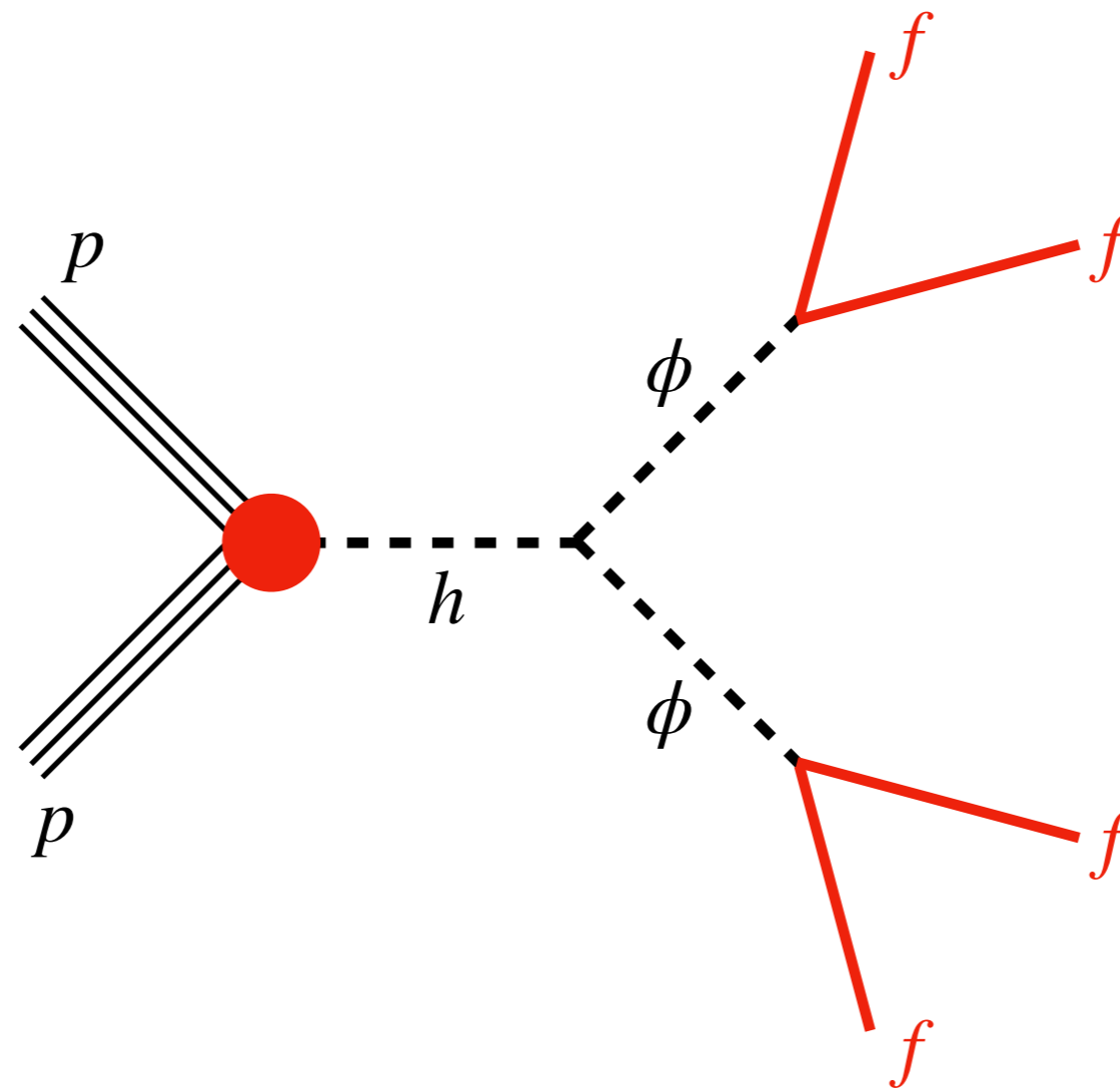
■ Triggering

■ Searches in **main collider detectors**

■ **Dedicated detectors**

■ Machine Learning and LLPs

■ Parameter estimation of LLPs

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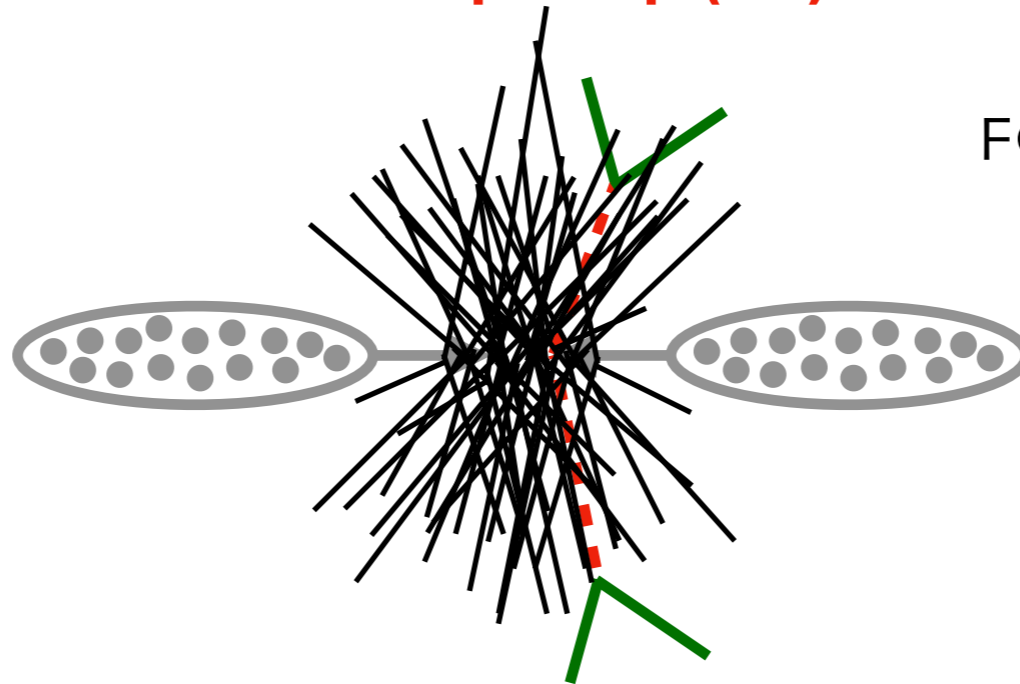
$\mathcal{Q}:$ – **Prospect of HL-LHC/FCC-hh?**

Issue of pile-up (PU)

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

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

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
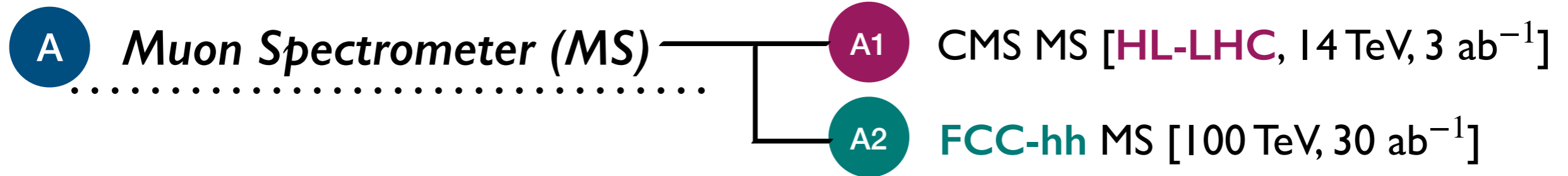
Interaction Point (IP) ★ | Tracker | ECAL | HCAL | MS ✓

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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
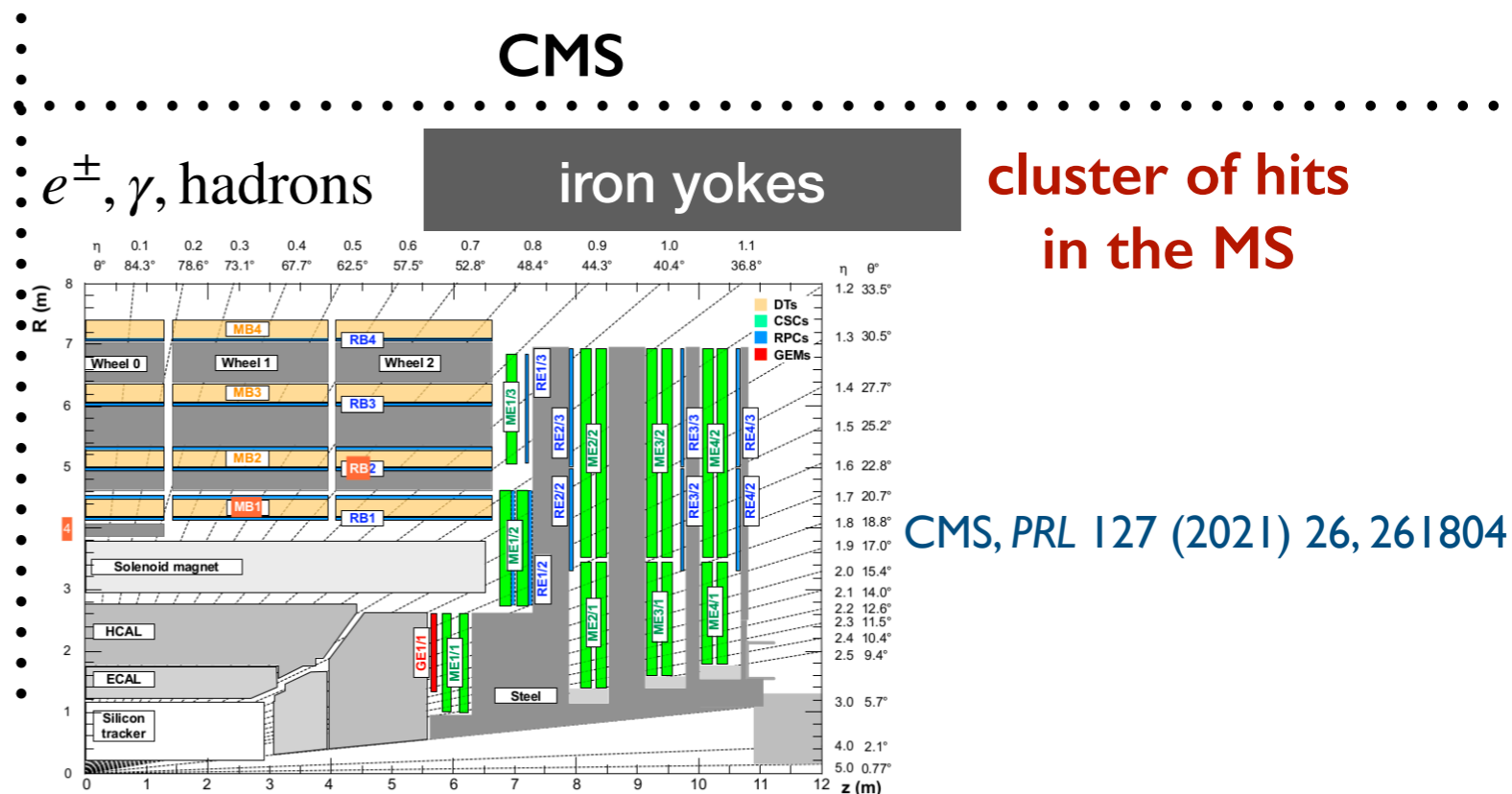
How do particles other than muons look in the MS?

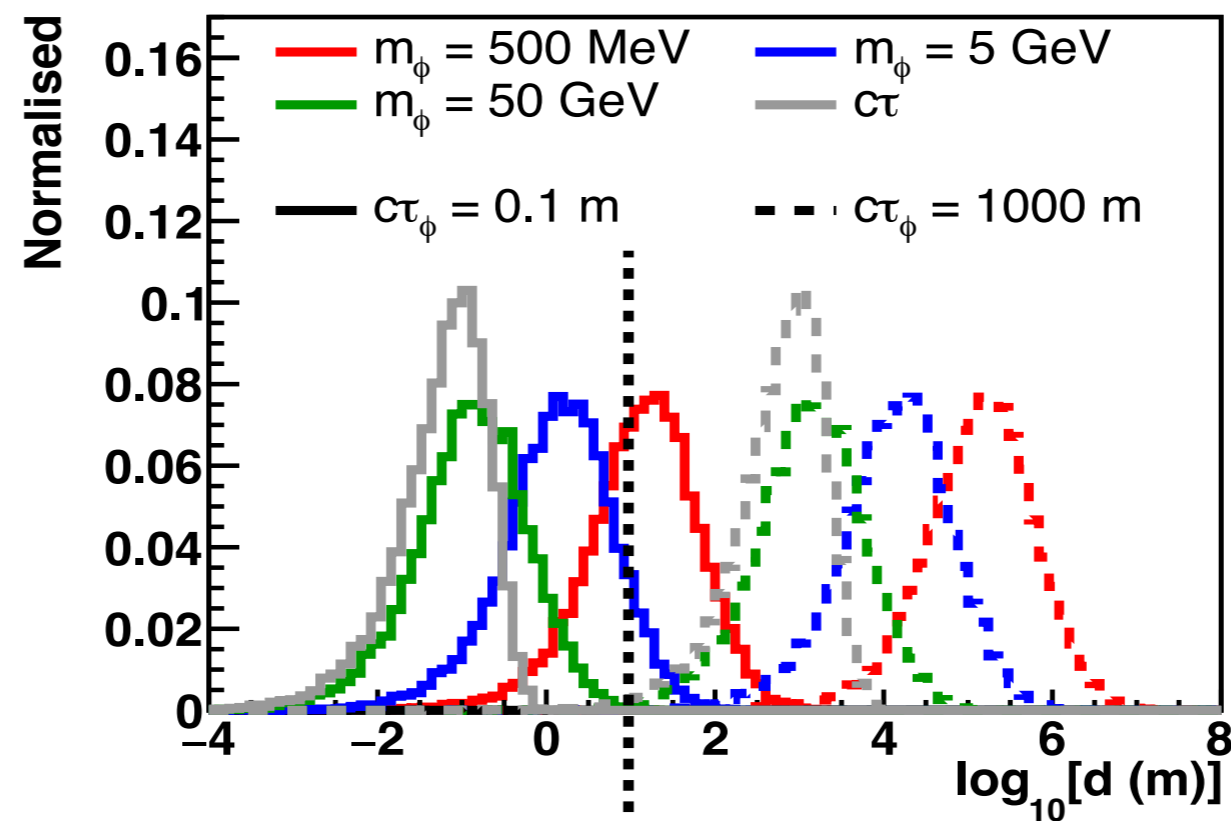| ATLAS	CMS

displaced vertices in the MS

ATLAS, *PRD* 99 no. 5, (2019) 052005

ATLAS, *PRD* 101 no. 5, (2020) 052013

ATLAS, ATL-PHYS-PUB-2019-002

$e^{\pm}, \gamma,$ hadrons   iron yokes   cluster of hits in the MS

CMS, *PRL* 127 (2021) 26, 261804

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

B   *Dedicated transverse LLP detectors*

mostly centrally produced in Higgs decays - especially lighter LLPs

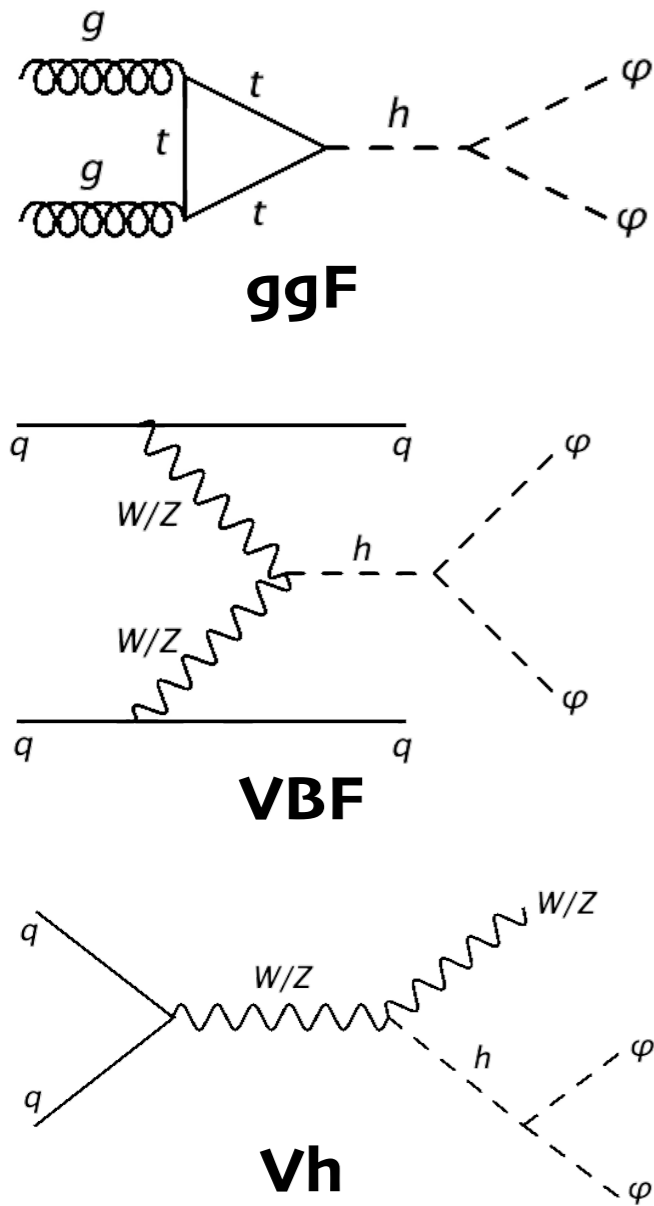**B1**   MATHUSLA and CODEX-b [**HL-LHC**, 14 TeV]

B2   **DELIGHT** [**FCC-hh,** 100 TeV, 30 ab^{-1}]   New Proposal This work

Analysis Strategy for Decays in MS

Production

ggF

VBF

Vh
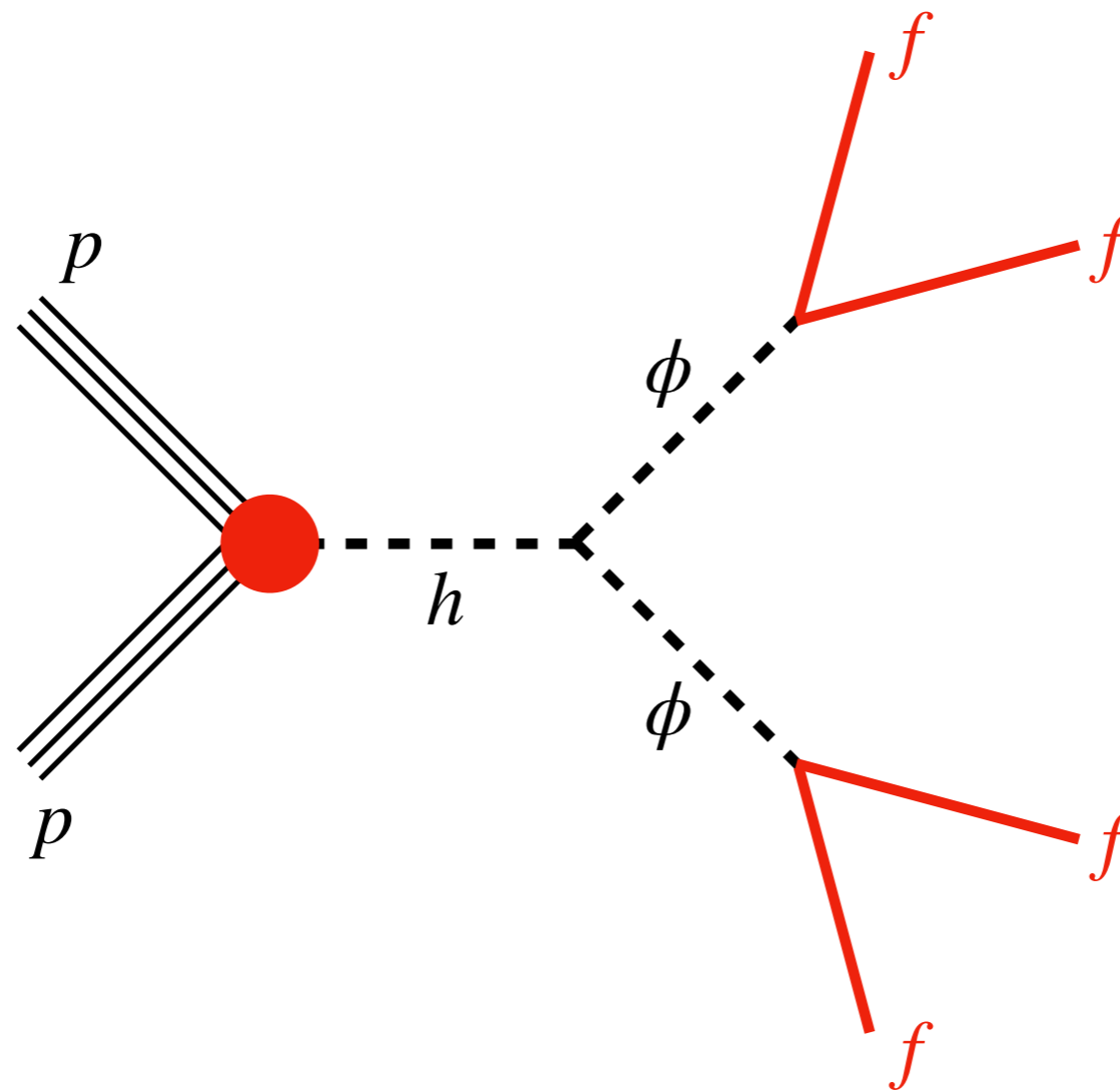
Decay

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

Branching Fraction

Prompt objects associated with production

Displaced objects from the LLP decay
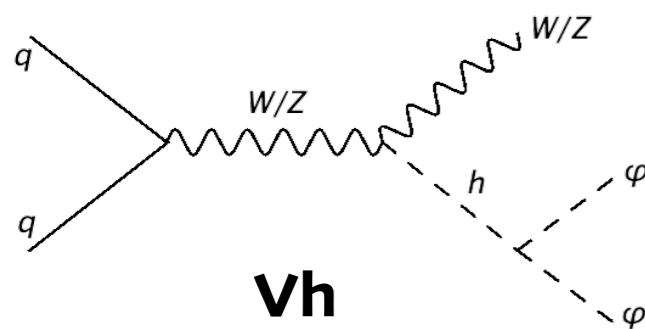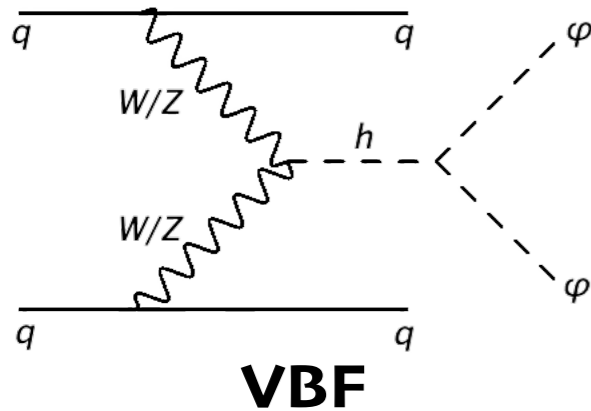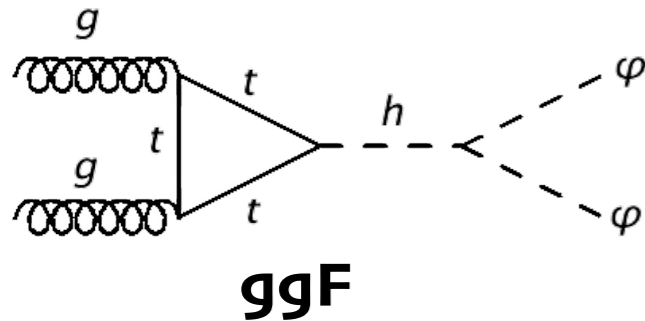
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Analysis Strategy for Decays in MS

Production

ggF

VBF

Vh

Prompt objects
associated with
production

Selection cuts on PROMPT OBJECTS
prompt jets, electrons, muons

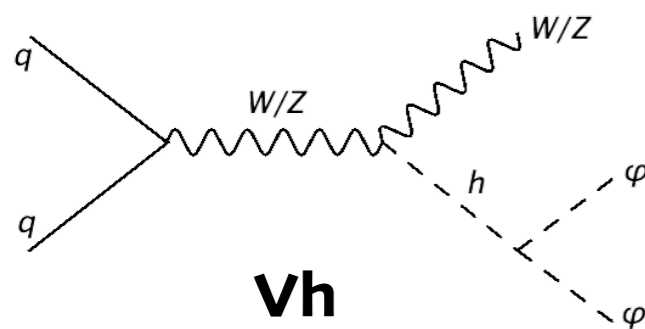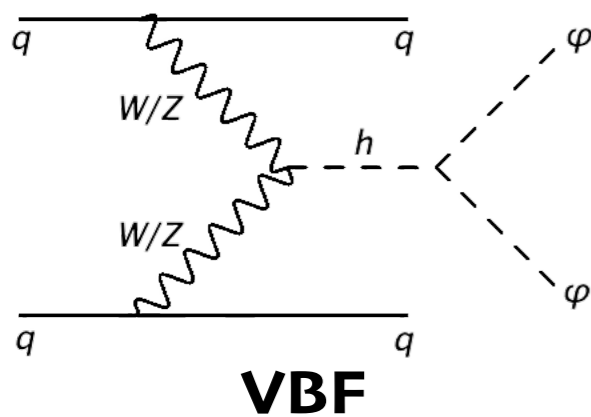| Trigger	In P_{Mode}^{H}
Single jet	$p_T^j > 180\,\text{GeV}$, $|\eta_j| < 2.4$.
Di-jet	$p_T^j > 112\,\text{GeV}$, $|\eta_j| < 2.4$, $\Delta\eta < 1.6$.
VBF jet	$p_T > 70\,\text{GeV}$ for Leading jet, $p_T > 40\,\text{GeV}$ for Sub-leading jet, $|\eta_j| < 5$, $\eta_{j_1} \times \eta_{j_2} < 0$, $\Delta\eta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

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

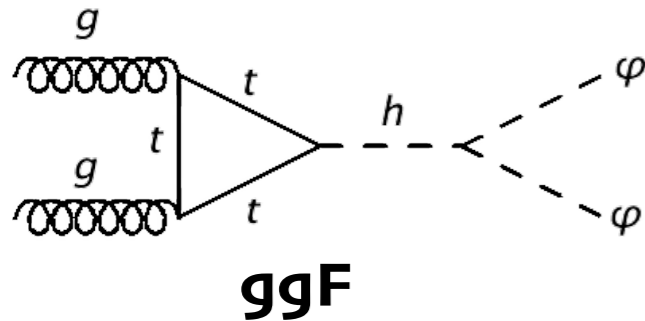| Trigger	In P^H_{Mode}	In P^S_{Mode}
Single jet	$p^j_T > 180\,\text{GeV}, |\eta_j| < 2.4.$	$p^j_T > 90\,\text{GeV}, |\eta_j| < 2.4.$
Di-jet	$p^j_T > 112\,\text{GeV}, |\eta_j| < 2.4, \Delta\eta < 1.6.$	$p^j_T > 90\,\text{GeV}, |\eta_j| < 2.4, \Delta\eta < 1.6.$
VBF jet	$p_T > 70\,\text{GeV}$ for Leading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

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

Rhitaja Sengupta, IISc

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

absence of magnetic field

presence of magnetic field

MS layer

MS layer

MS layer
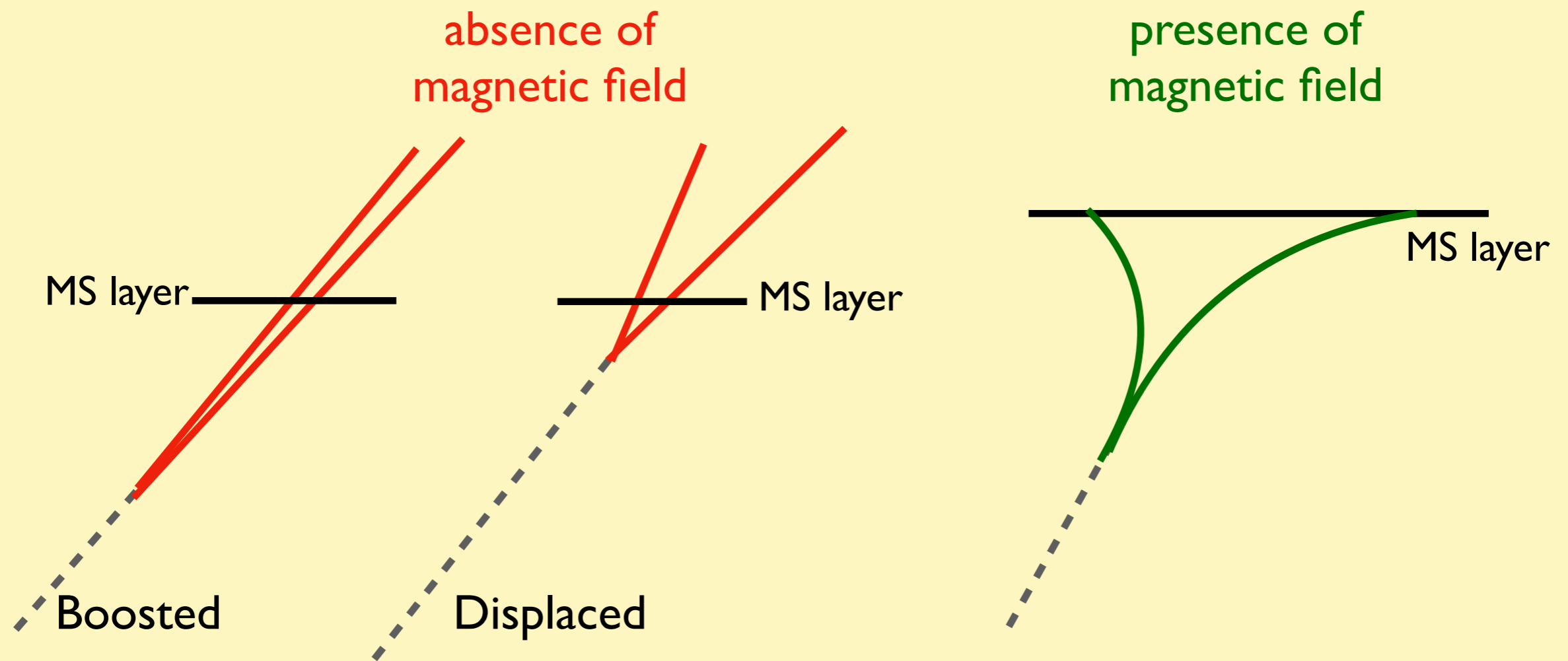
Boosted

Displaced

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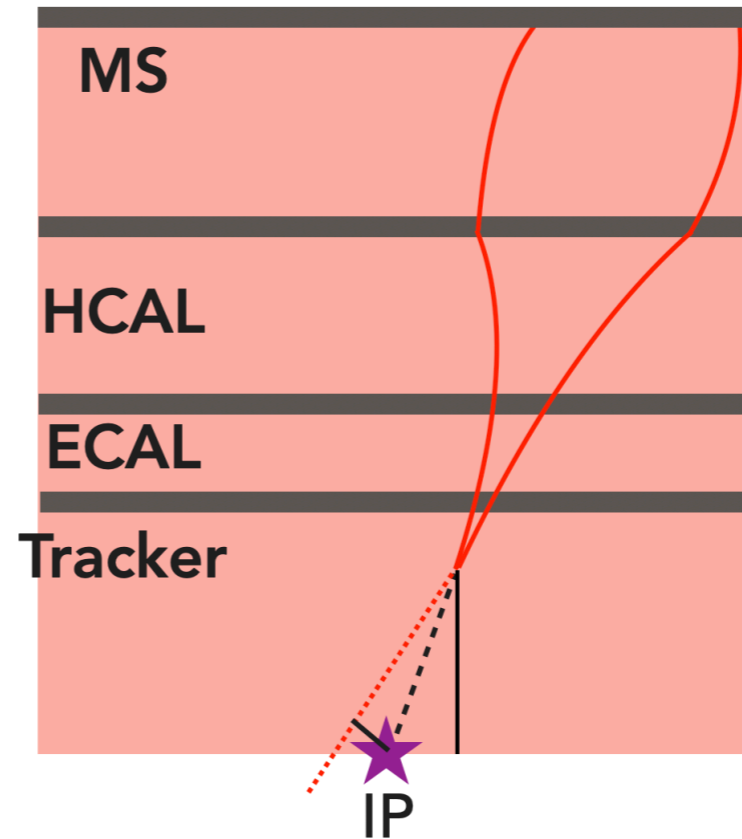
Delta R

Analysis Strategy for Decays in MS

Selection cuts on DISPLACED OBJECTS

Decay

Displaced muons

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

	D_μ^H	D_μ^S
Muons	$p_T^\mu > 20\,\text{GeV}$	$p_T^\mu > 10\,\text{GeV}$
	$n_\mu \geq 2$	$n_\mu \geq 2$
	$|\eta^\mu| < 2.8$	$|\eta^\mu| < 2.8$
	$|d_0^\mu| > 2\,\text{mm}$	$|d_0^\mu| > 2\,\text{mm}$
Muon pair from the same dSV	$d_T > 1\,\text{cm}$	$d_T > 1\,\text{cm}$
	$d_T < 6\,\text{m}\ \&\ |d_z| < 9\,\text{m}$	$d_T < 6\,\text{m}\ \&\ |d_z| < 9\,\text{m}$
	$\Delta\phi_{\mu\mu} > 0.01$	$\Delta\phi_{\mu\mu} > 0.01$
Event	$n_{vtx} \geq 1$ or $n_{vtx} = 2$	$n_{vtx} \geq 1$ or $n_{vtx} = 2$

MS
HCAL
ECAL
Tracker

IP

$\mu^+\mu^-$

$\pi^+\pi^-$

K^+K^-

$\tau^+\tau^-$

gg

$s\bar{s}$

MS cluster

jets hard soft

	D_{jets}^H	D_{jets}^S
Electrons, photons, hadrons	$p_T > 0.5\,\text{GeV}$	$p_T > 0.5\,\text{GeV}$
	$|\eta| < 2.8$	$|\eta| < 2.8$
MS cluster from same dSV ($< 1\,\text{cm}$)	$d_T > 4\,\text{m}$ or $|d_z| > 7\,\text{m}$	$d_T > 4\,\text{m}$ or $|d_z| > 7\,\text{m}$
	$d_T < 6\,\text{m}$ and $|d_z| < 9\,\text{m}$	$d_T < 6\,\text{m}$ and $|d_z| < 9\,\text{m}$
	$n_{\text{dSV}}^{\text{ch}} \geq 5$	$n_{\text{dSV}}^{\text{ch}} \geq 3$
	$\sum p_{T,dSV} > 50\,\text{GeV}$	$\sum p_{T,dSV} > 20\,\text{GeV}$
	$\Delta\phi_{\text{max}} > 0.2$	$\Delta\phi_{\text{max}} > 0.1$
Event	$n_{\text{cluster}} \geq 1$, $n_{\text{cluster}} = 2$	$n_{\text{cluster}} \geq 1$, $n_{\text{cluster}} = 2$

MS
HCAL
ECAL
Tracker

IP

$c\bar{c}$

$b\bar{b}$

Displaced objects from the LLP decay

Rhitaja Sengupta, IISc
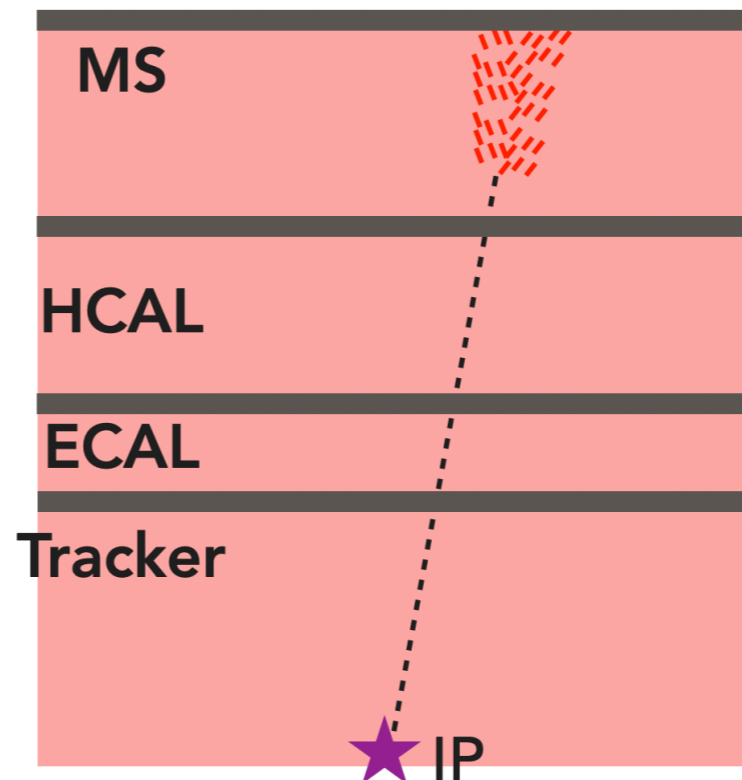
Analysis Strategy for Decays in MS

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
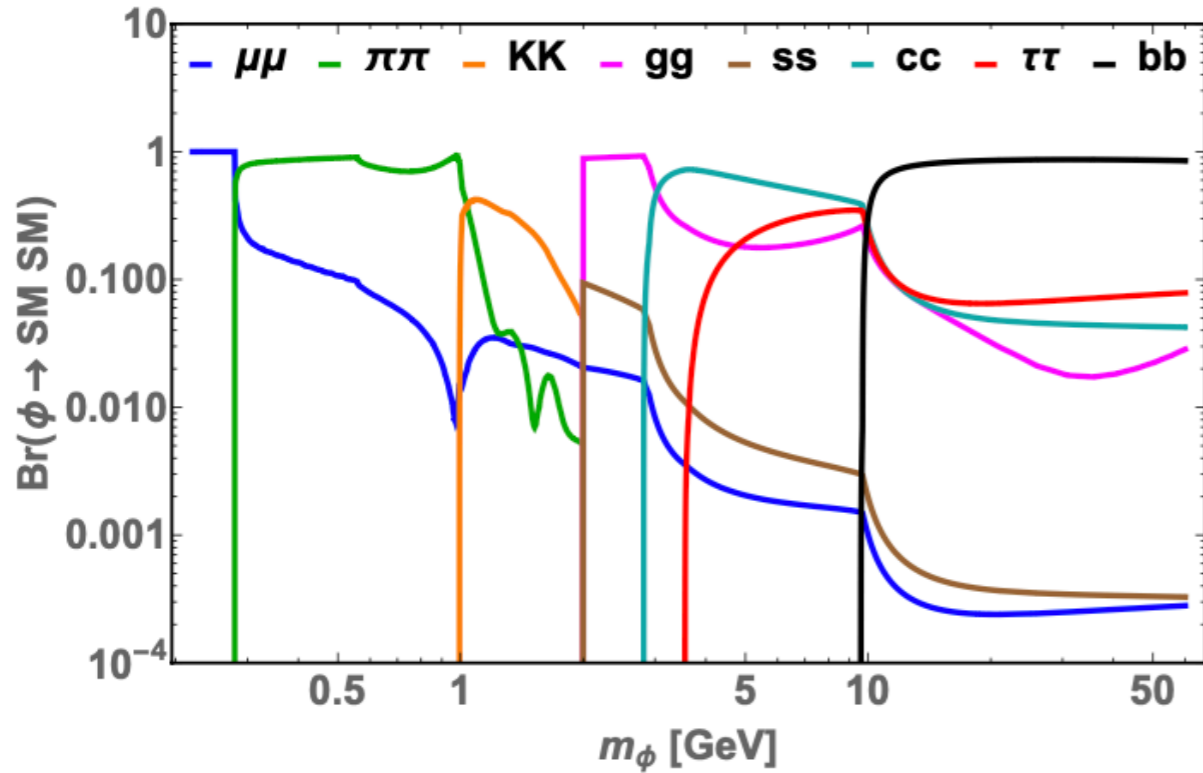events required

Backgrounds

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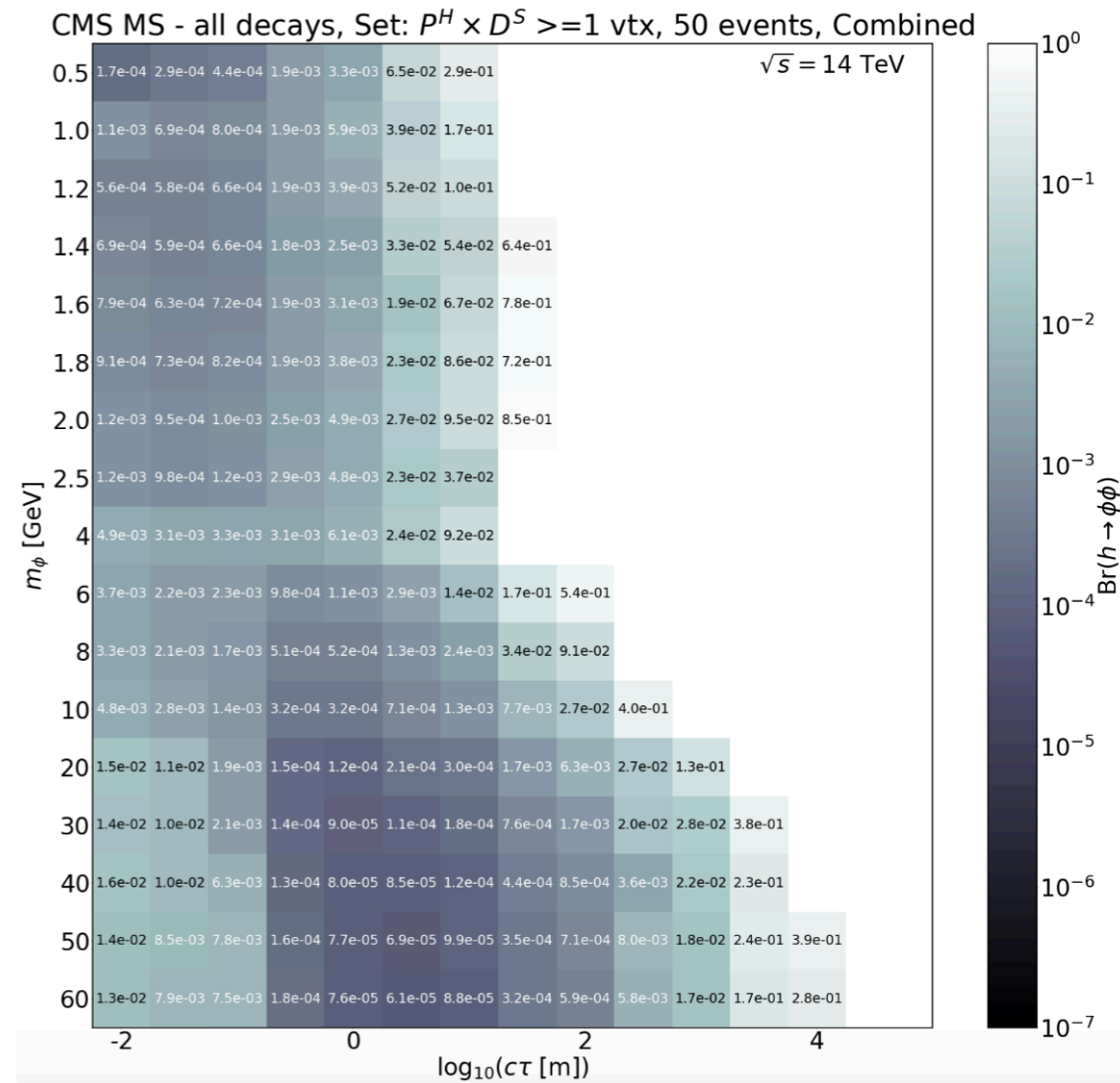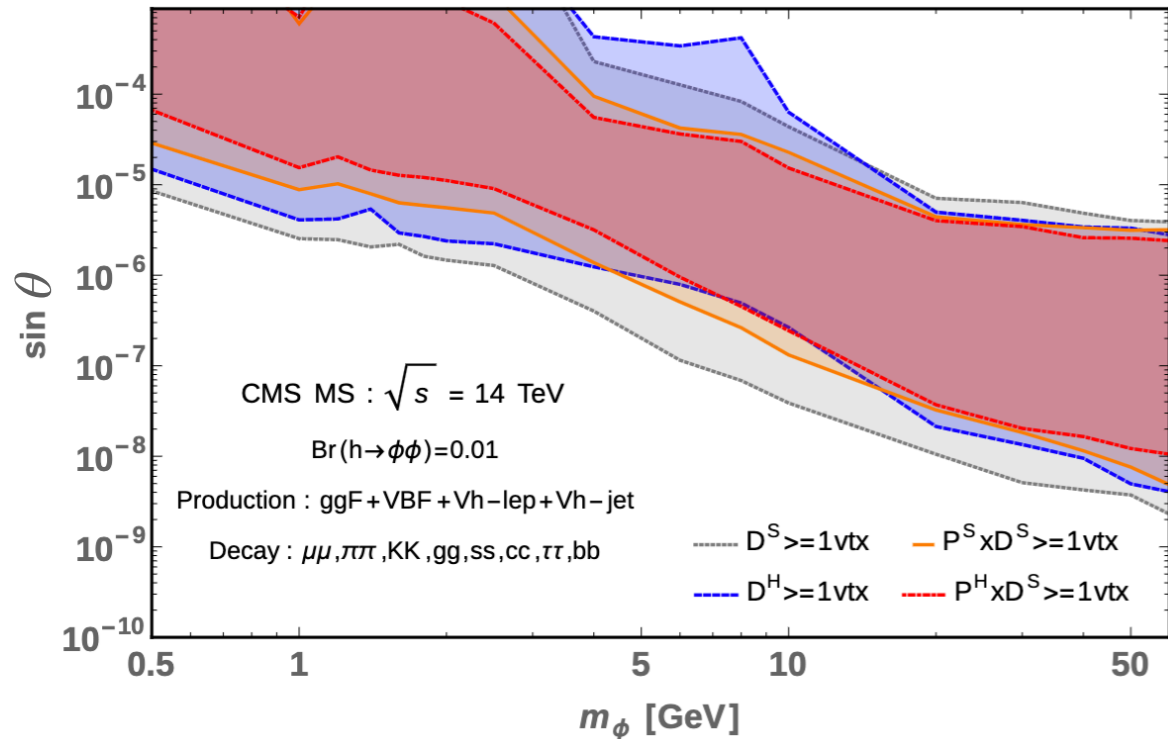for $m_\phi = 60\,\text{GeV}, c\tau = 0.5\,\text{m}$

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

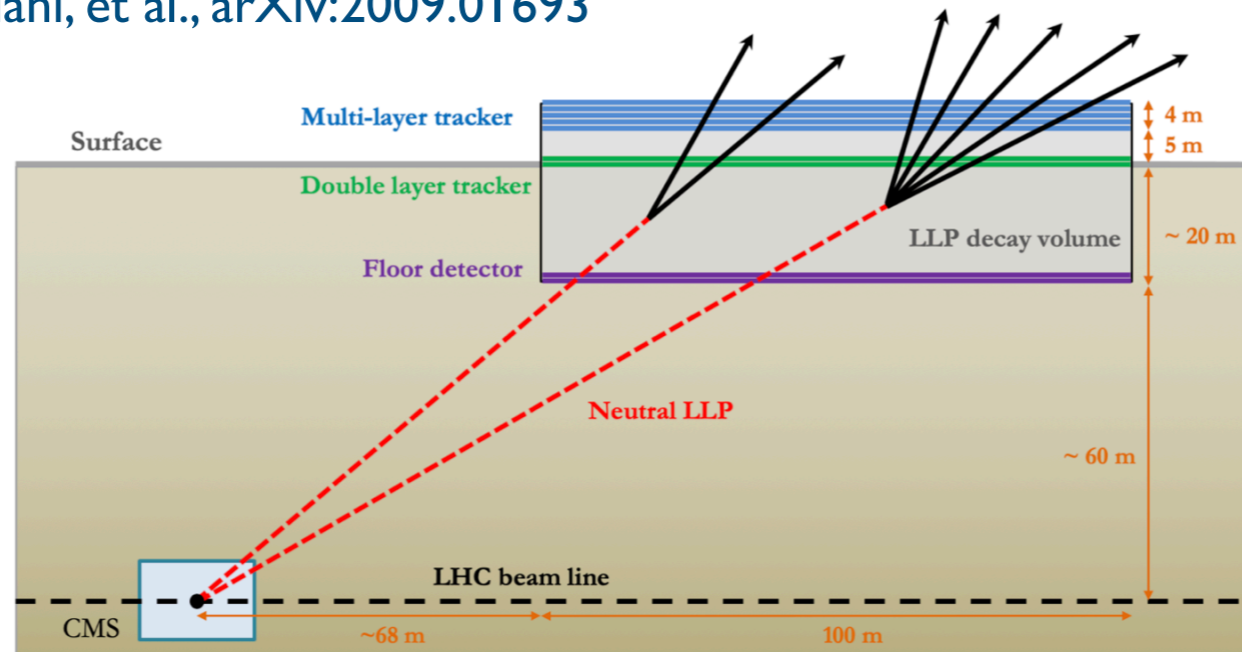Muon Spectrometer only analysis - sensitive to higher decay lengths

Rhitaja Sengupta, IISc

combined as per branching
of minimal model

CMS MS - all decays, Set: $P^H \times D^S \geq 1$ vtx, 50 events, Combined

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

BACKGROUND FREE!
**observation of few events (~4)
enough to claim discovery**

validated and extended
analysis for our benchmarks

Cristiano Alpigiani, et al., arXiv:2009.01693

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

$(0.5 \text{ GeV}, 3.3 \times 10^{-4}, 0.5 \text{ m})$
$(50 \text{ GeV}, 5.3 \times 10^{-4}, 50 \text{ m})$

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

$(0.5 \text{ GeV}, 7.0 \times 10^{-5}, 0.5 \text{ m})$
$(50 \text{ GeV}, 1.1 \times 10^{-4}, 50 \text{ m})$

Giulio Aielli, et al., arXiv:1911.00481

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

$(0.5 \text{ GeV}, 4.1 \times 10^{-6}, 1 \text{ m})$
$(50 \text{ GeV}, 4.6 \times 10^{-6}, 100 \text{ m})$
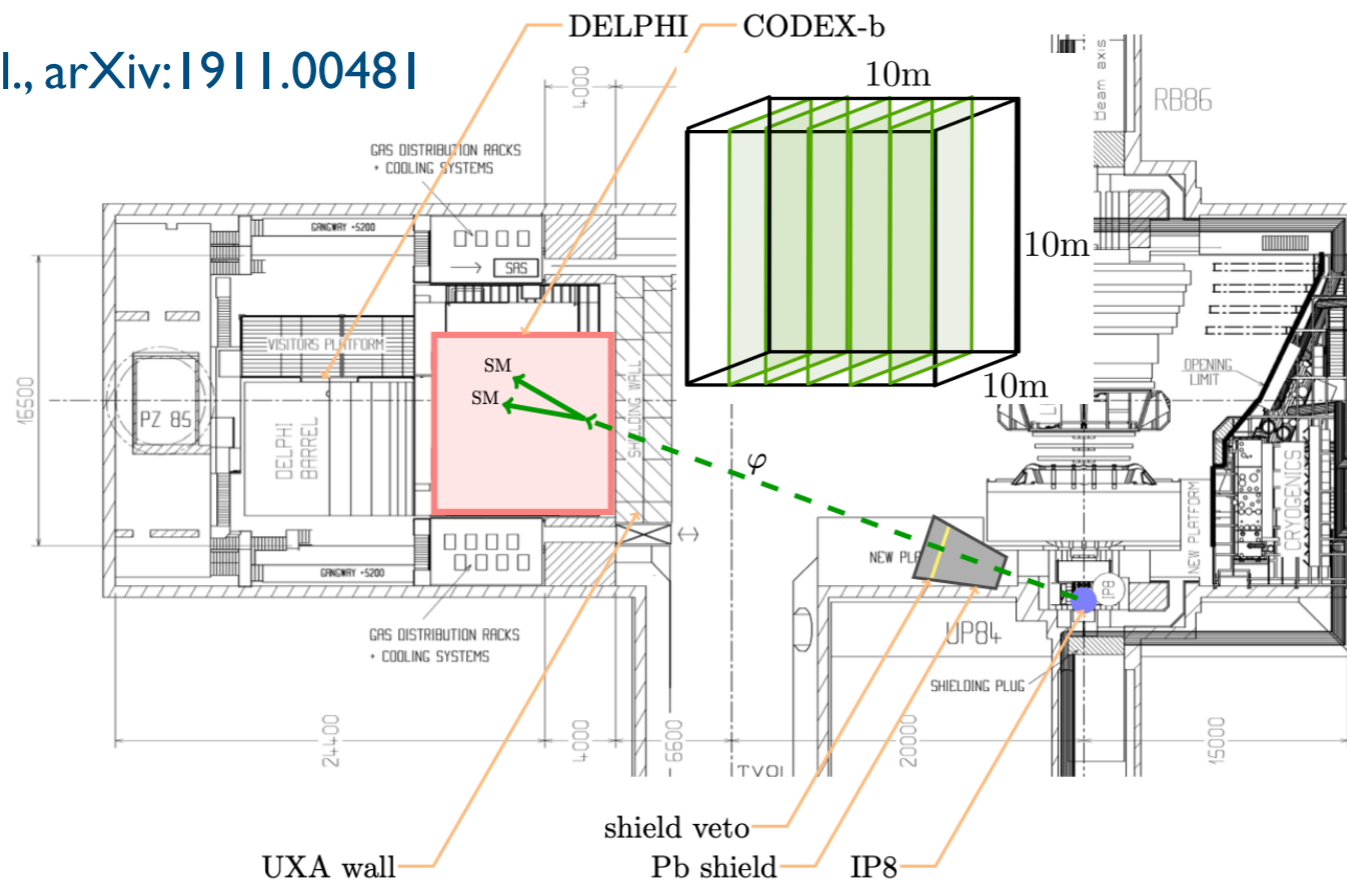
$(m_\phi, \text{Br}(h \to \phi\phi)_{UL}, c\tau)$

CMS MS and MATHUSLA

For fixed m_ϕ

Complementarity of CMS MS and MATHUSLA

$\sqrt{s} = 14$ TeV

MATHUSLA

CMS MS

Br$(h \to \phi\phi)$ - MATHUSLA, 4 events
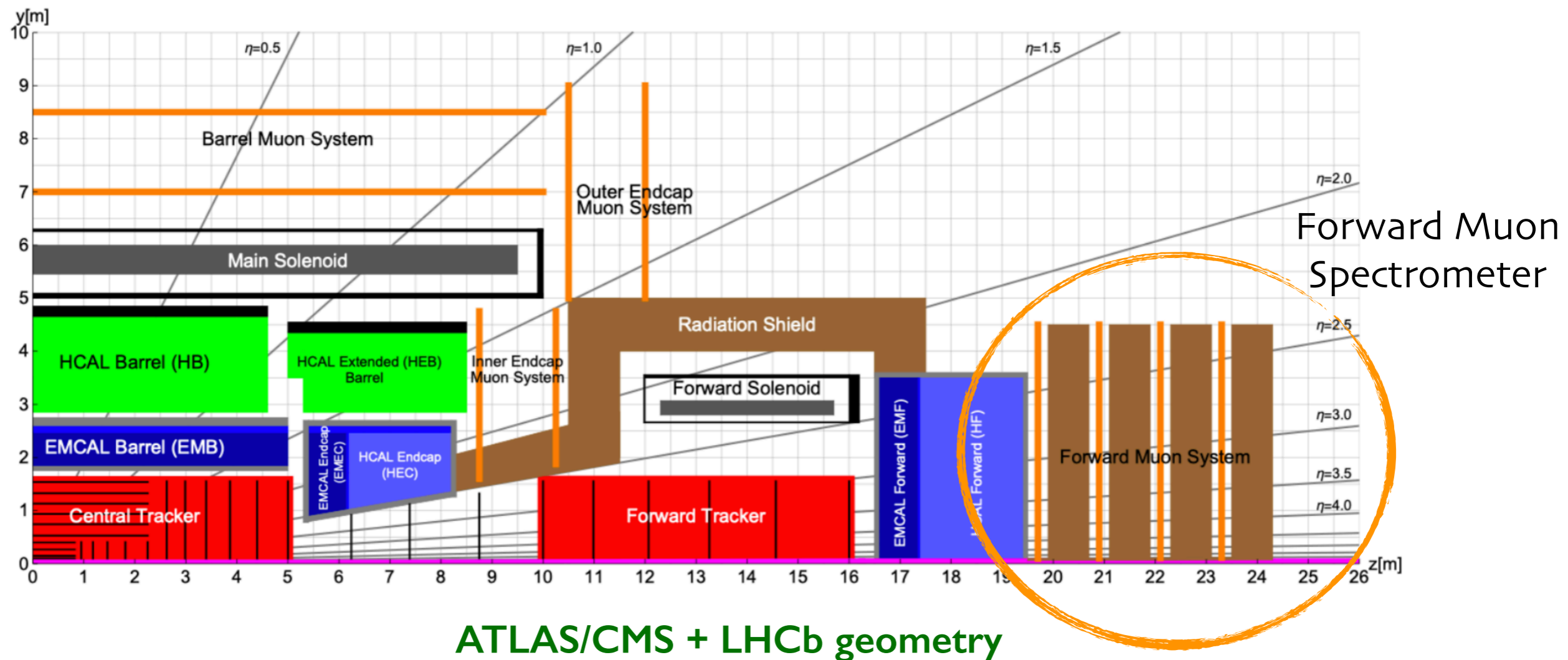
Our analysis

Br$(h \to \phi\phi)$ - CMS MS ($P^S D^S > = $ 1vtx), 50 events
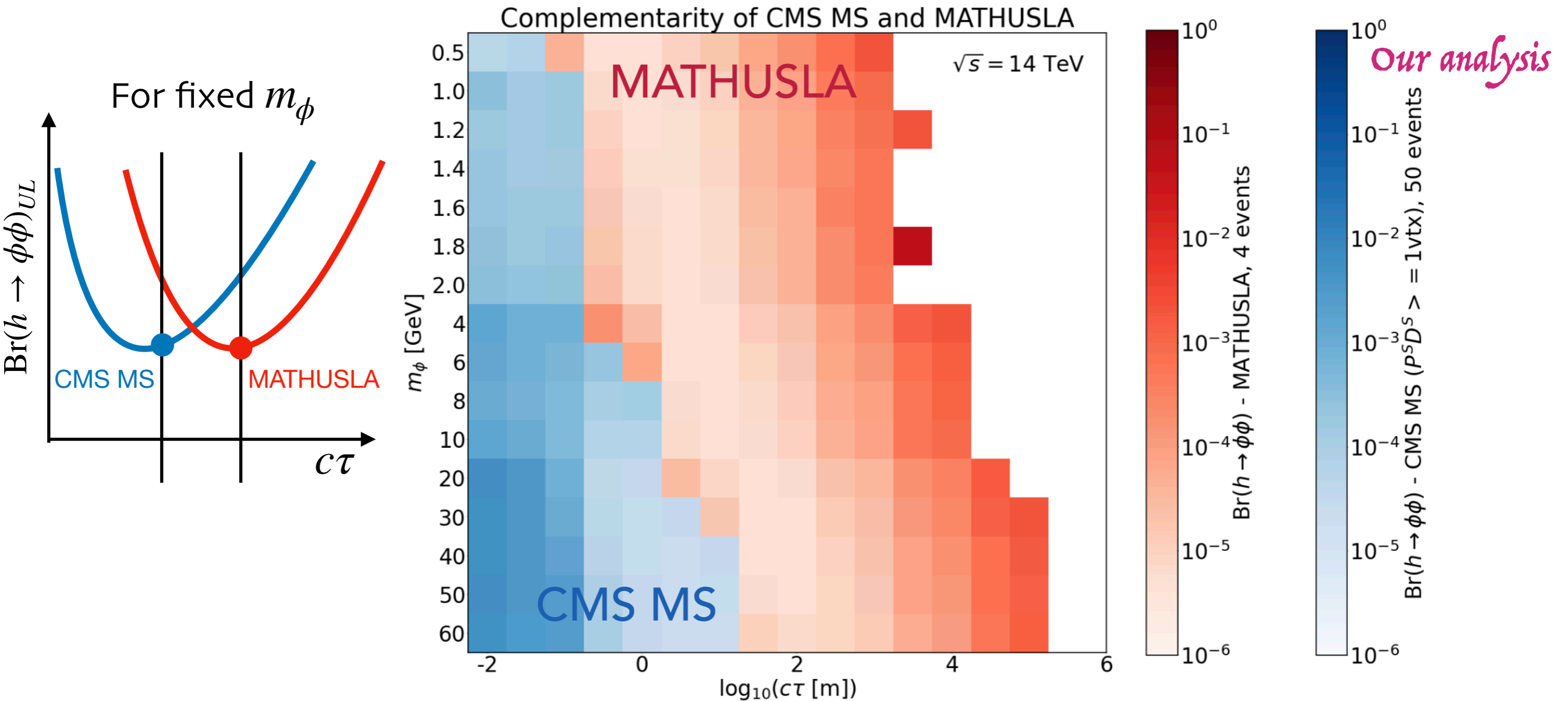
CMS MS + MATHUSLA:

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

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

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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
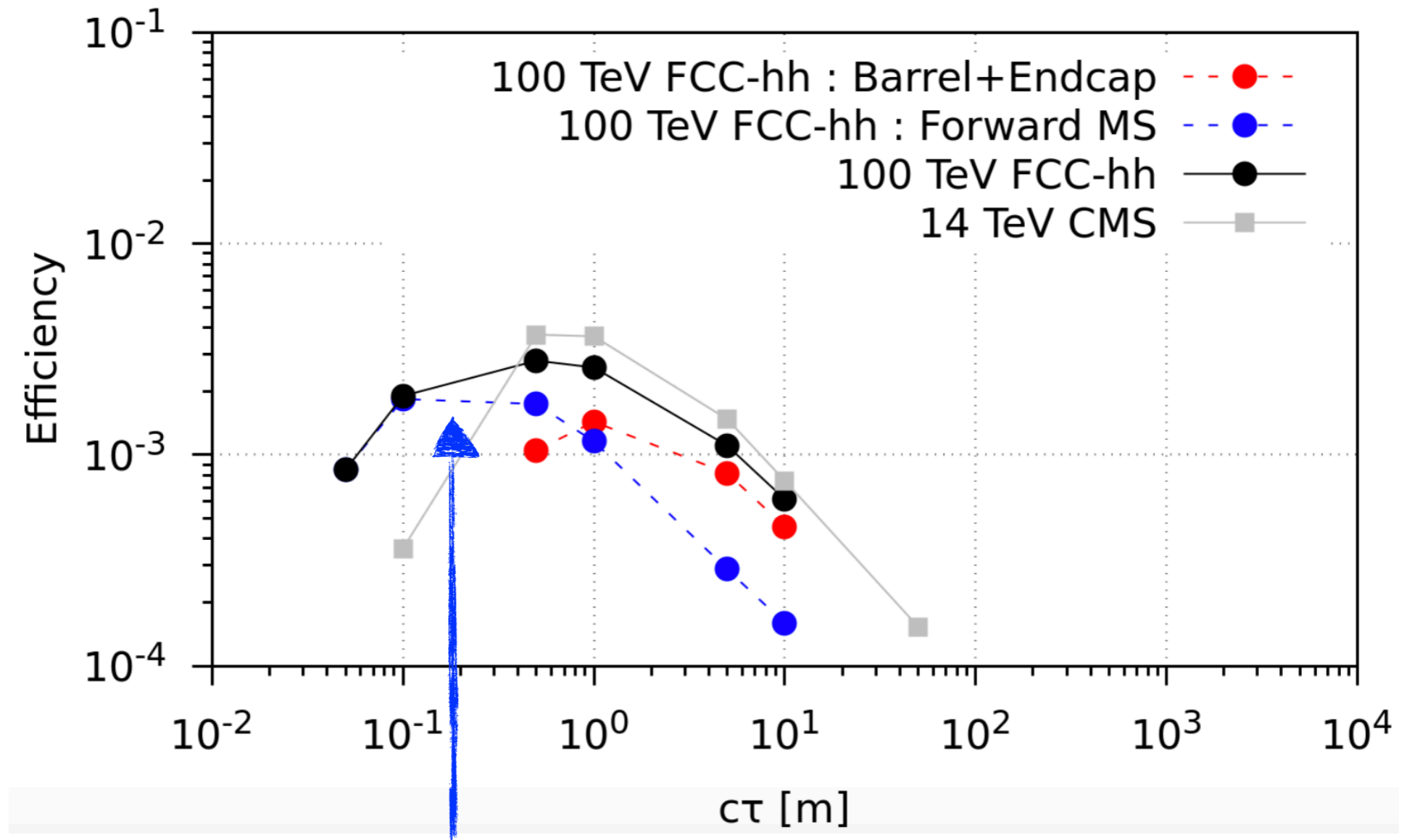

FCC-hh Reference Detector

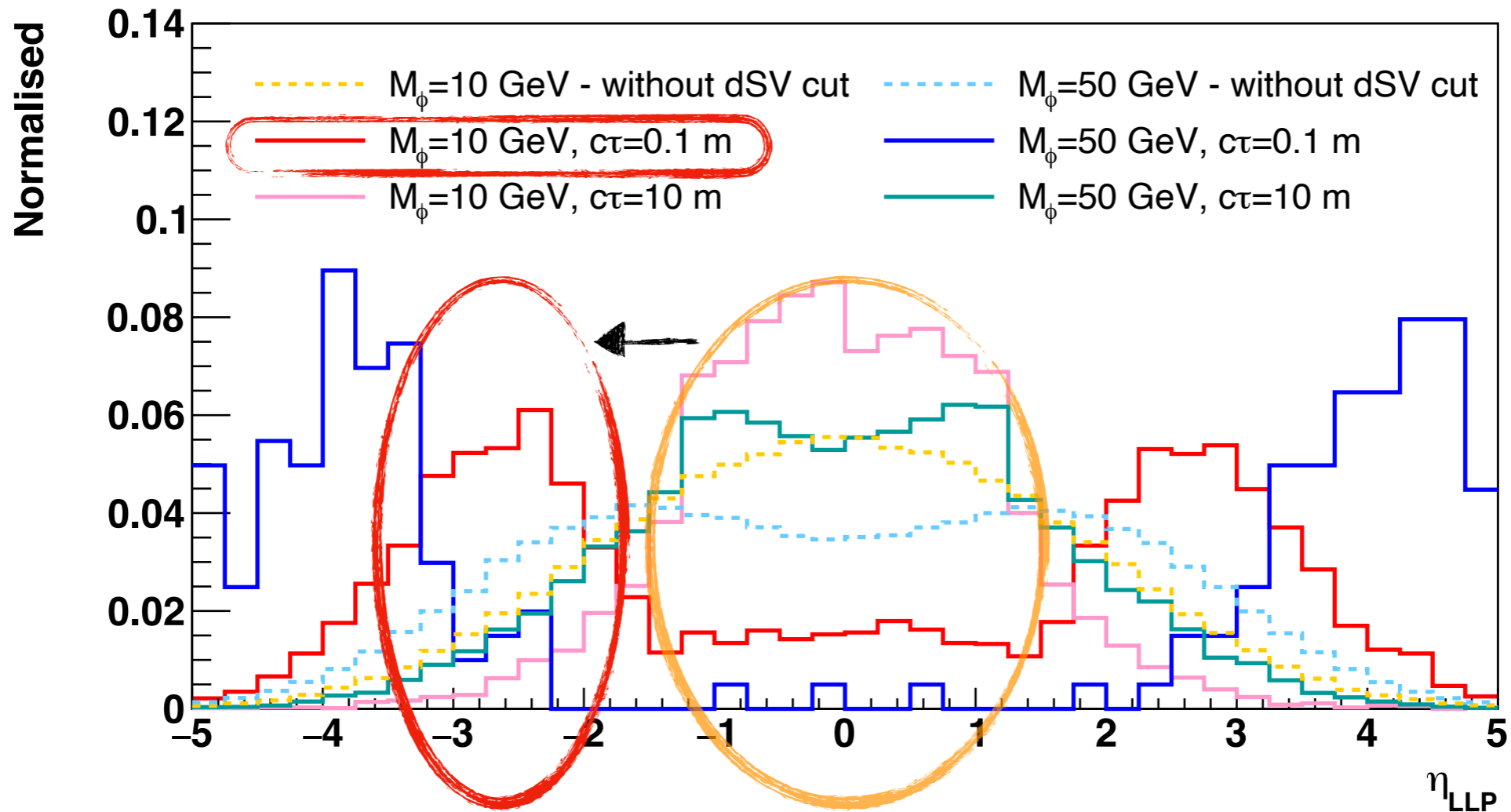50m long, 20m diameter
Cavern length 66m
L* of FCC 40m.

Forward Muon Spectrometer

ATLAS/CMS + LHCb geometry

ANY BENEFIT?

$m_\varphi = 10$ GeV, $P_{ggF}^S x D_{jets}^S >= 1$ vtx

- 100 TeV FCC-hh : Barrel+Endcap
- 100 TeV FCC-hh : Forward MS
- 100 TeV FCC-hh
- 14 TeV CMS

Efficiency vs $c\tau$ [m]

Forward MS increases sensitivity to lower decay lengths

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
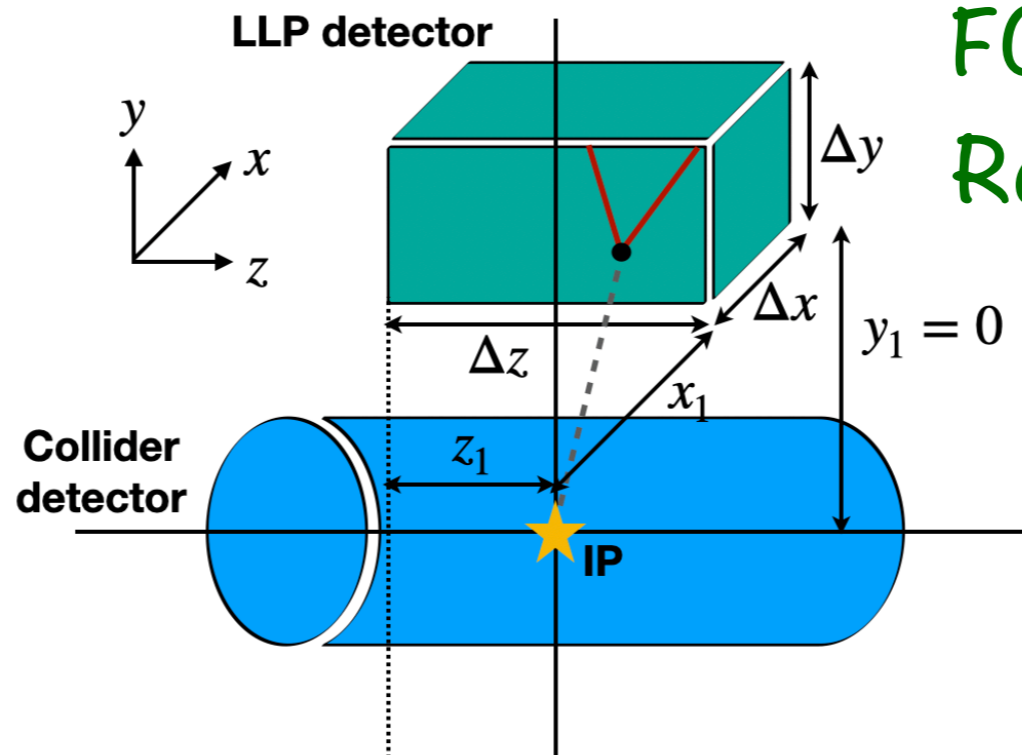
DELIGHT

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

Proposal for FCC-ee/CEPC - HECATE

Marcin Chrzaszcz, et al., arXiv:2011.01005

Near or Far detectors for ILC

Schäfer, Tillinger, Westhoff,

arXiv:2202.11714

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

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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

DELIGHT (C) $200 \times 50 \times 50$ m^3, 30 ab^{-1}, Combined

$\sqrt{s} = 100$ TeV

$\mathrm{Br}(h \to \phi\phi)$
$< 9.5 \times 10^{-9}$
for
$m_\phi = 10\,\mathrm{GeV}$,
$c\tau = 10\,\mathrm{m}$
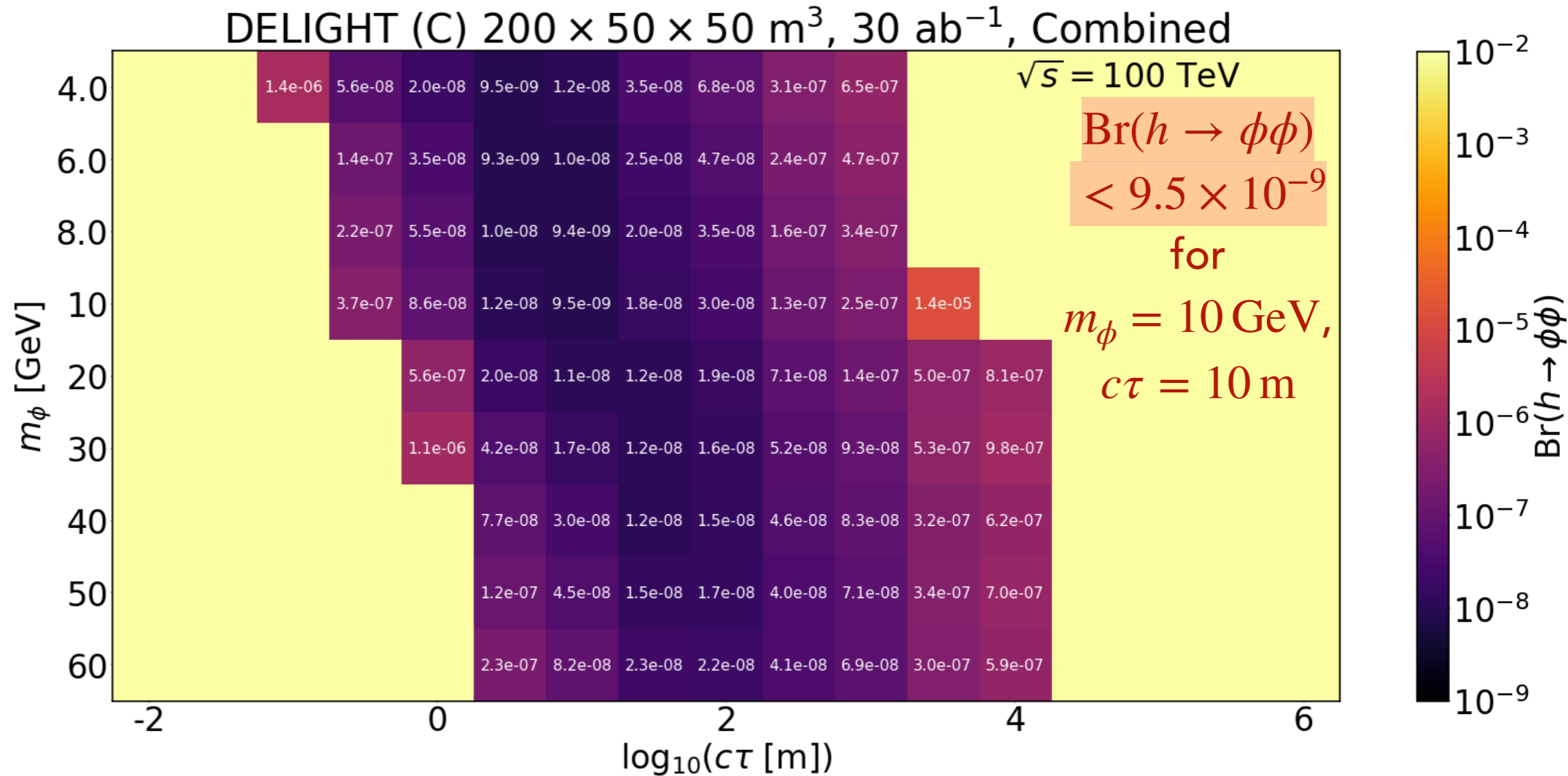
- long tunnel-like detector - better shielding against cosmic rays
- closer to IP - use of materials with high shielding power & active veto components to reduce background
- RPCs and possibility of a calorimeter element
- integration with the trigger system of FCC-hh

FURTHER STUDIES

OUTLINE

⭕ Motivation

⭕ LLPs in colliders

➡️ **Specific aspects of LLP searches in colliders**

◾ **Triggering**

◾ Searches in **main collider detectors**

◾ **Dedicated detectors**

◾ **Machine Learning** and LLPs

◾ **Parameter estimation** of LLPs

Displaced Jet Images

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

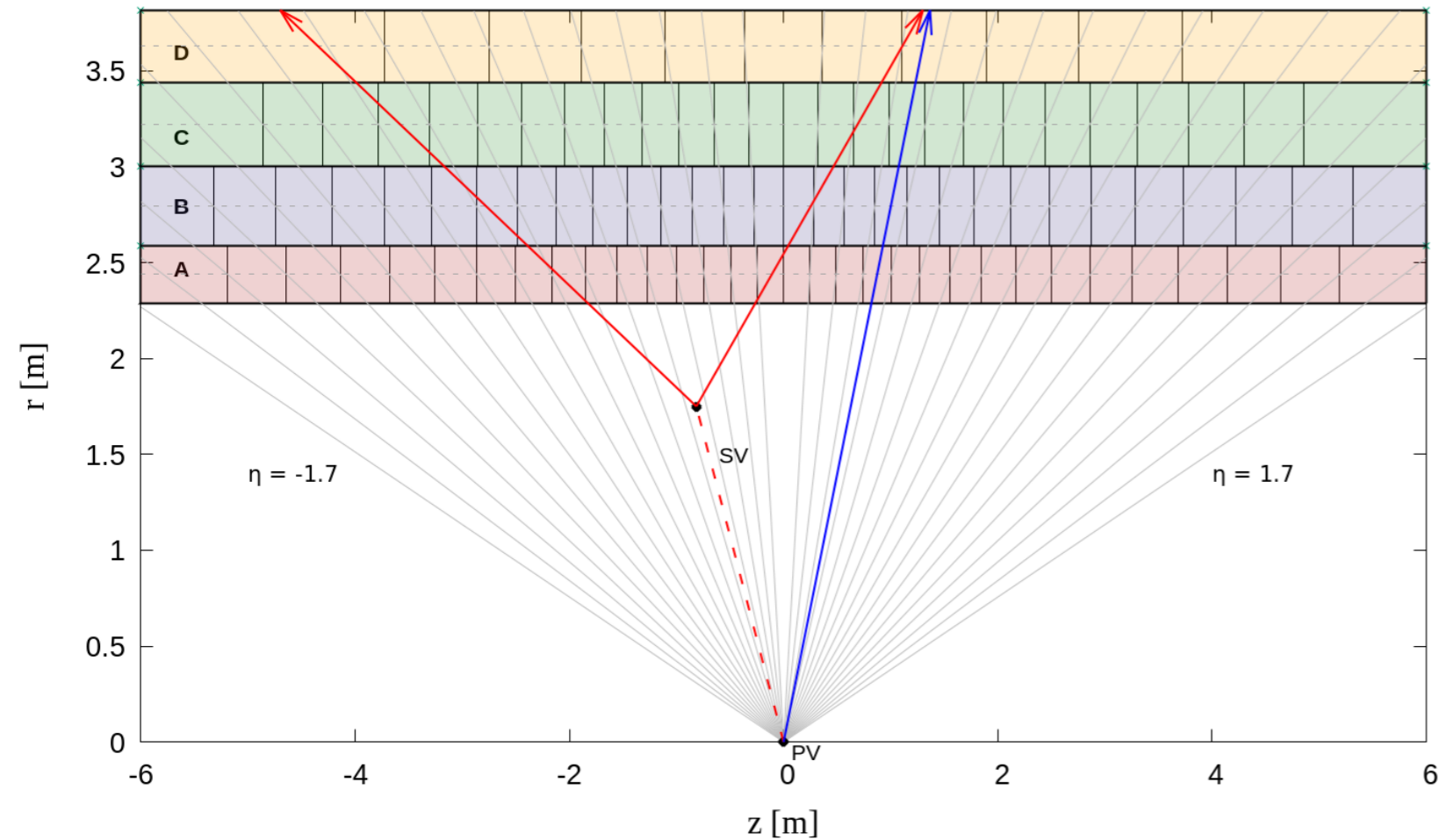**Mismatch** of **displaced particle's η-ϕ** direction with η-ϕ **segmentation of the detector**

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

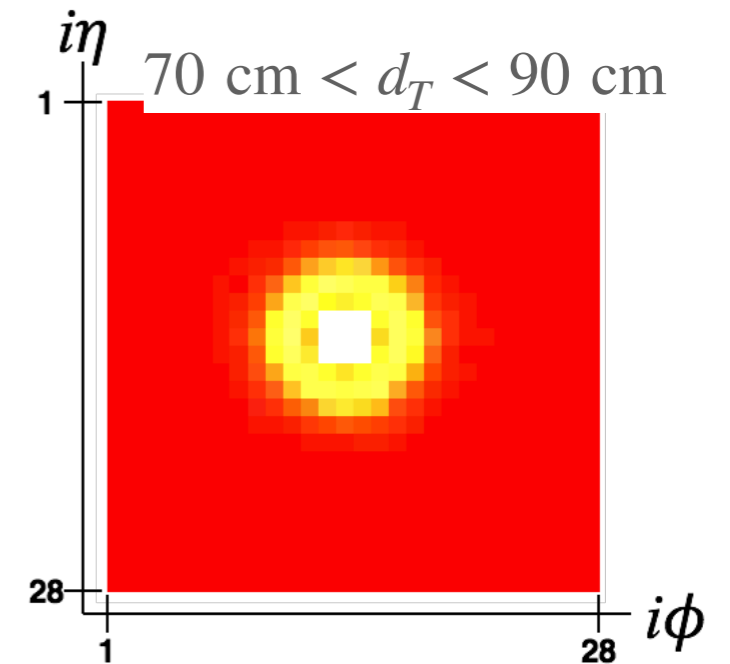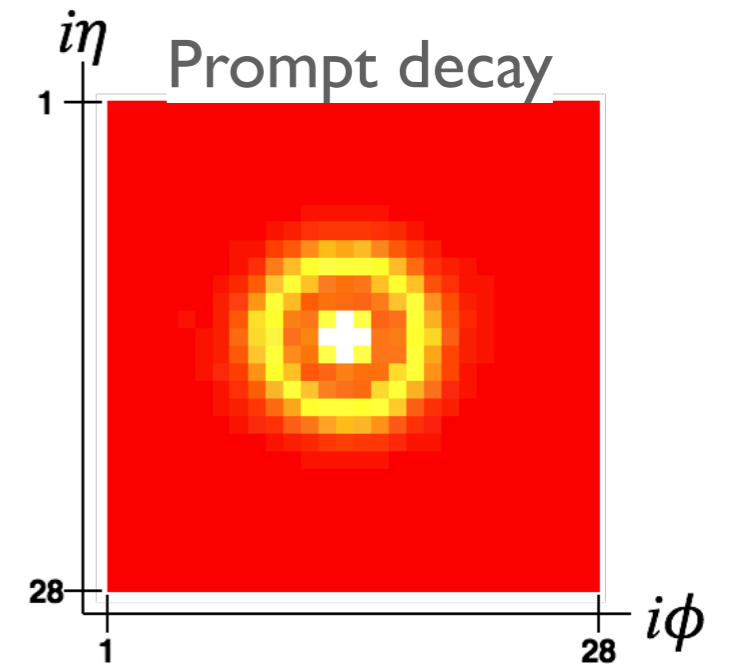**Absent** in fast detector simulations (eg. **Delphes**)

η

ϕ

Detector

Delphes
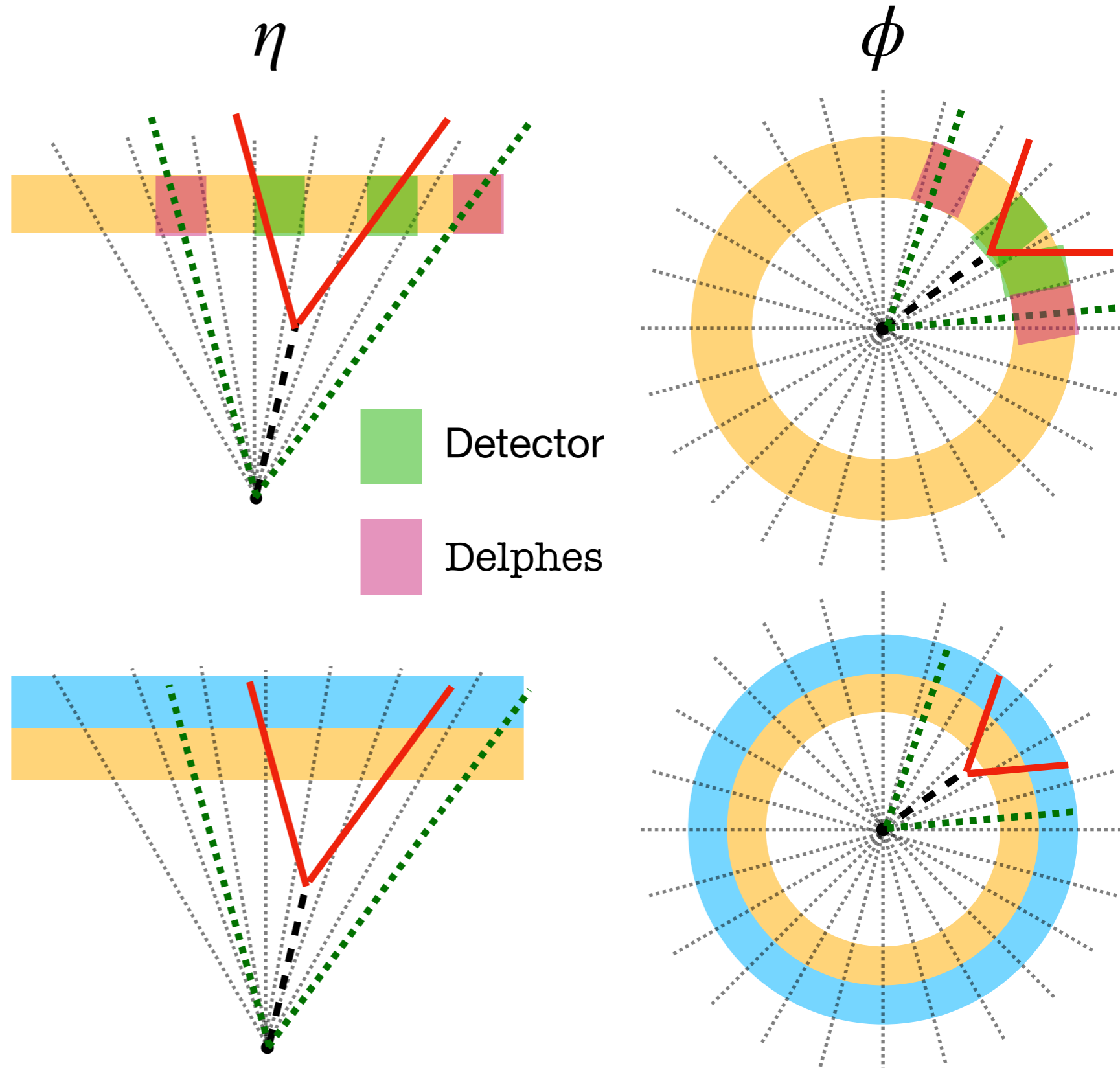
Displaced Jet Images

Segmentation of the HCAL

$$\Delta R \sim \frac{2m_Z}{p_T^Z}$$

p_T^Z almost fixed due to window cut on $\sum E$

Prompt decay

$70 \text{ cm} < d_T < 90 \text{ cm}$

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

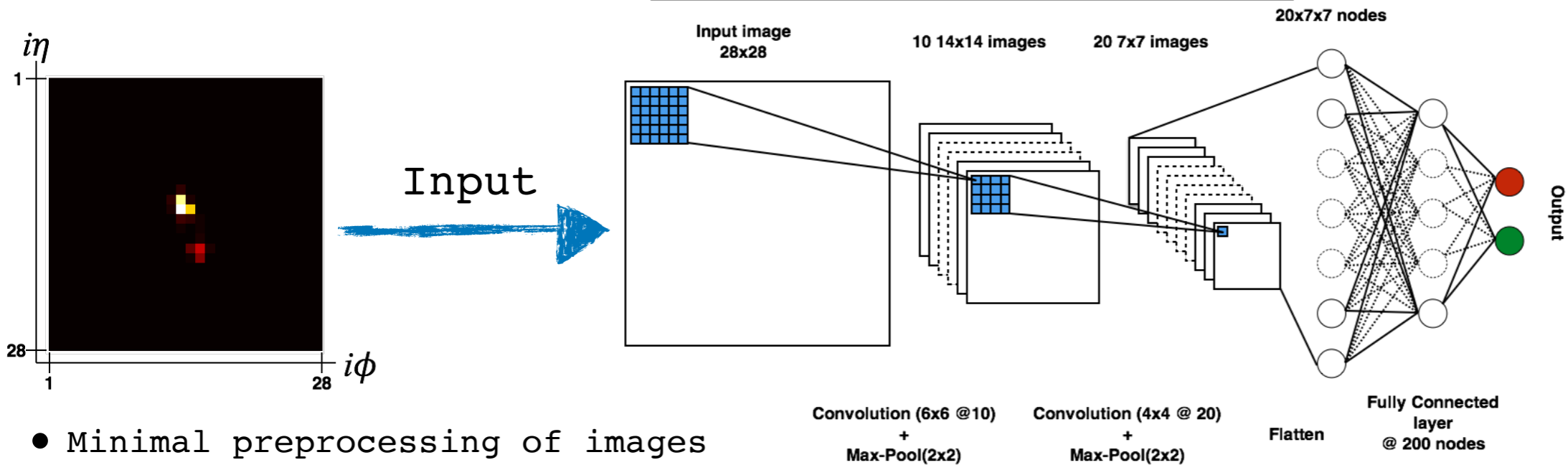**Displaced** Z **boson**

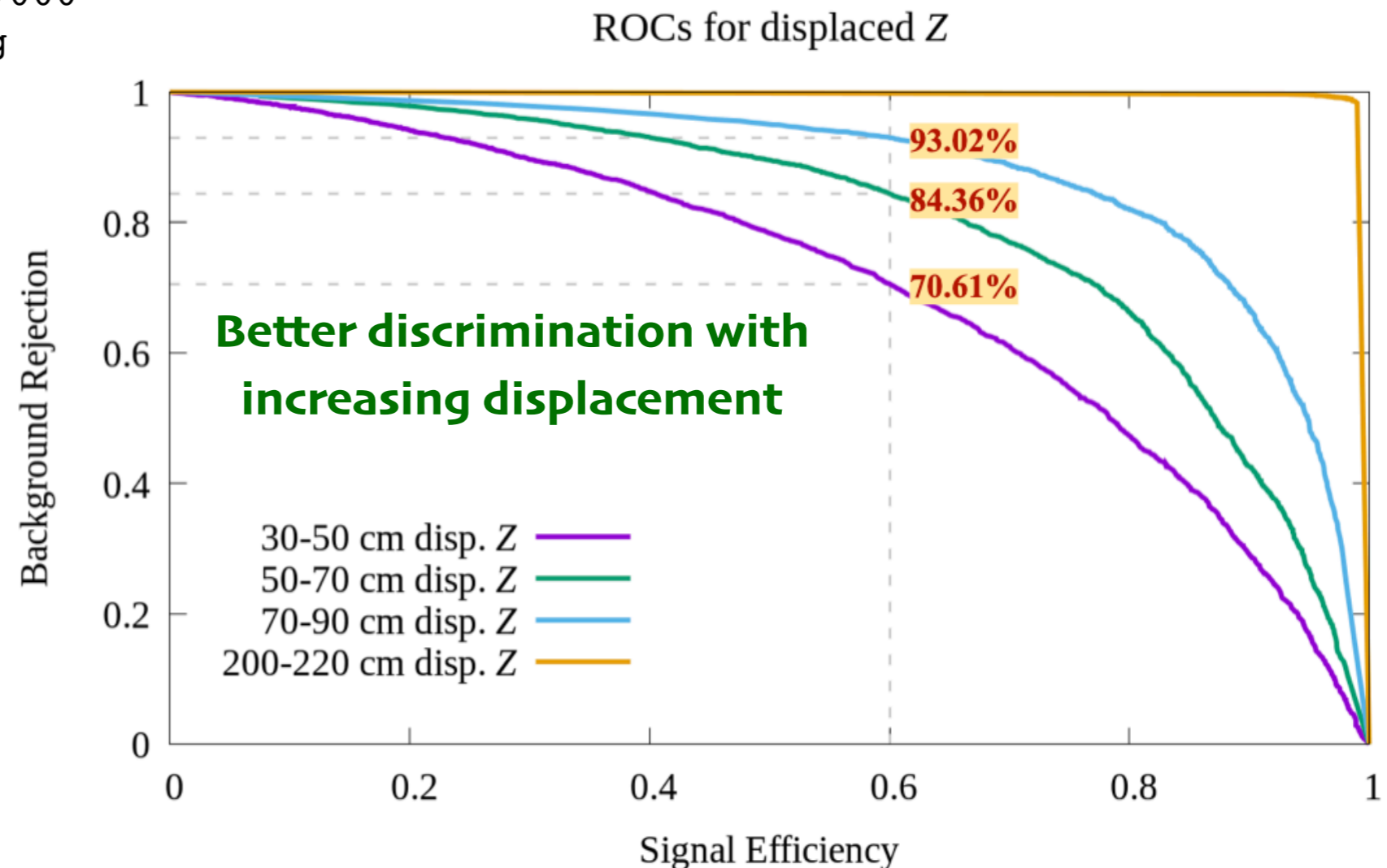$Z \rightarrow jj, \quad [m_X = 800 \text{ GeV}]$

GMSB SUSY
$\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$

Neutralino width suppressed by SUSY breaking scale

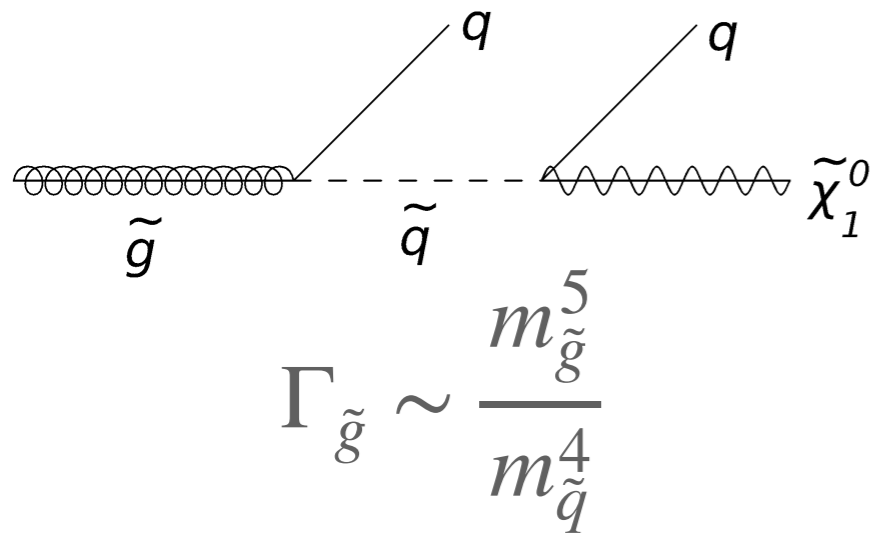Average over 50 000 images

Rhitaja Sengupta, IISc

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

ROCs for displaced Z

Better discrimination with increasing displacement

93.02%
84.36%
70.61%

30-50 cm disp. Z
50-70 cm disp. Z
70-90 cm disp. Z
200-220 cm disp. Z

Background Rejection

Signal Efficiency

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Stopped R-hadrons

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

- $\Gamma_{\tilde{g}} < \Lambda_{\text{QCD}} \Rightarrow$ 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

Transverse projection of stopped particle decay

prompt multijets
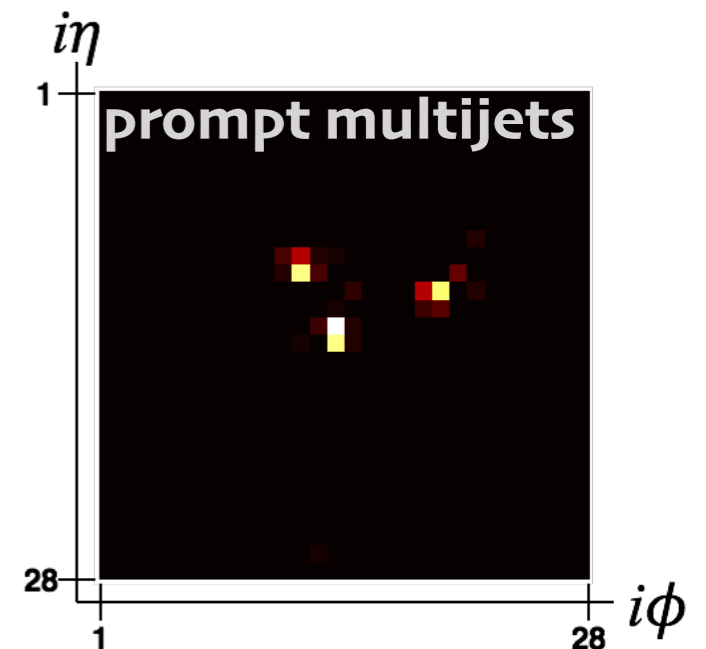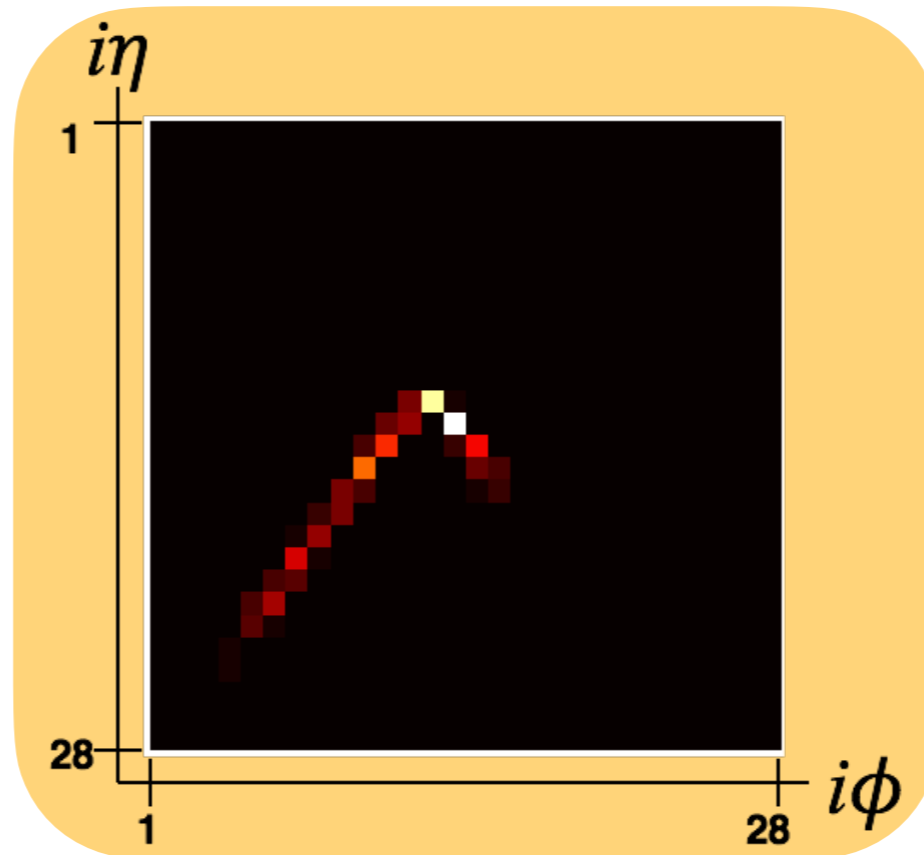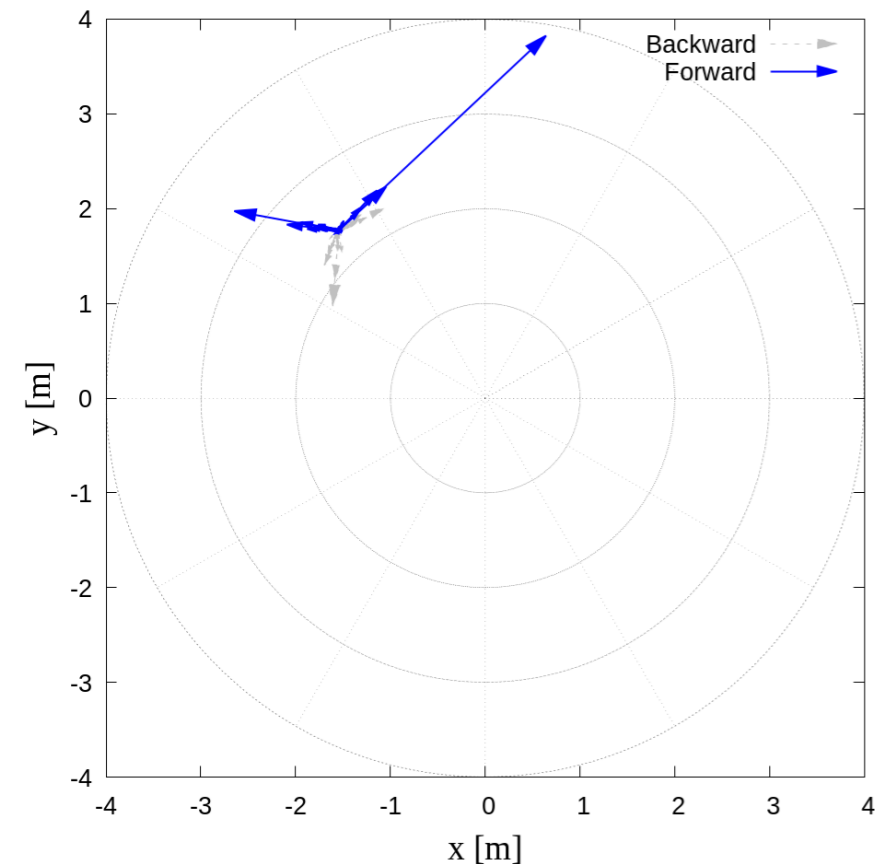
Significantly different energy deposition pattern

Rhitaja Sengupta, IISc

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

OUTLINE

⭕ Motivation

⭕ LLPs in colliders

➡️ **Specific aspects of LLP searches in colliders**

■ Triggering

■ Searches in **main collider detectors**

■ **Dedicated detectors**

■ **Machine Learning** and LLPs

■ **Parameter estimation** of LLPs

Problem with lifetime estimation of LLPs

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

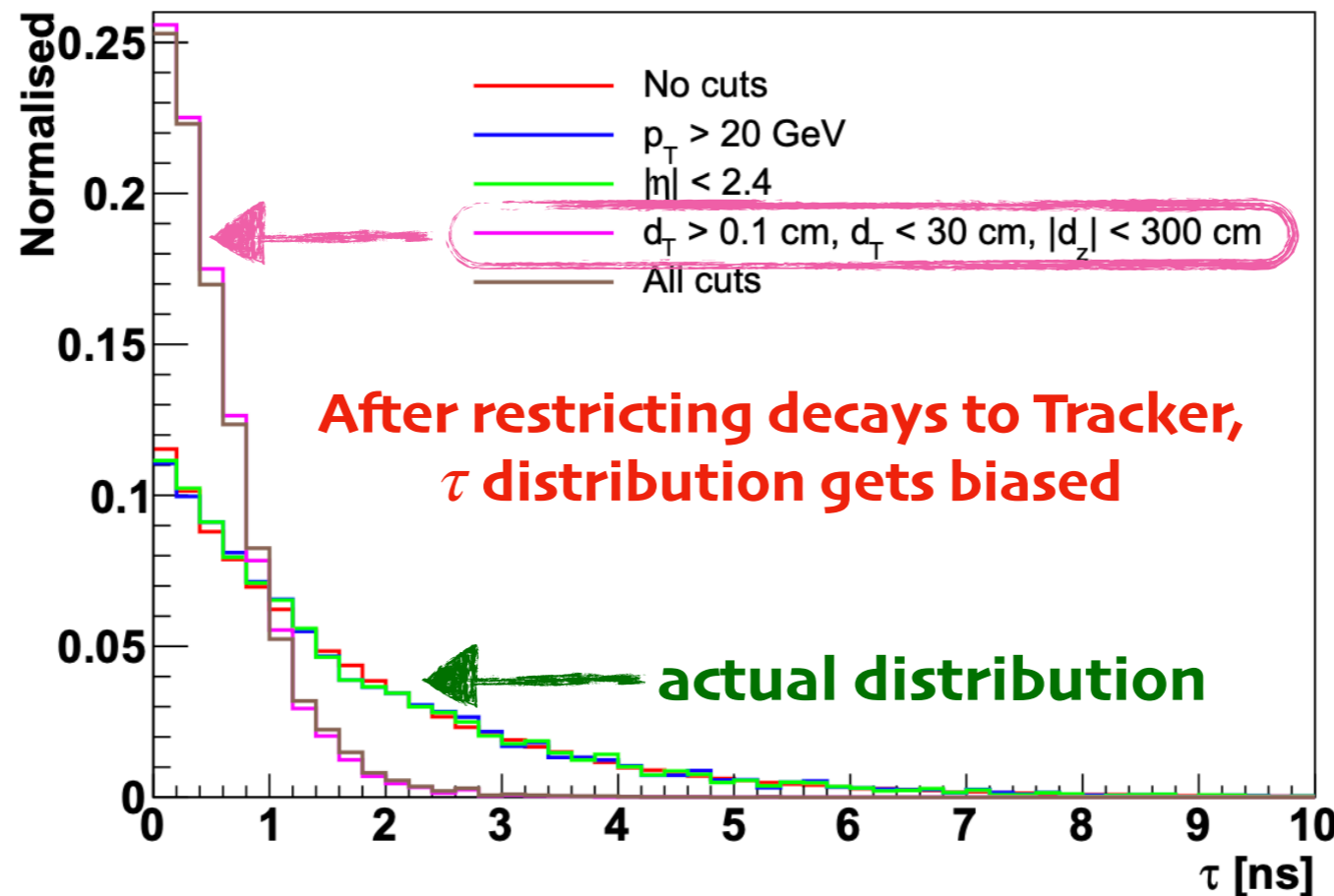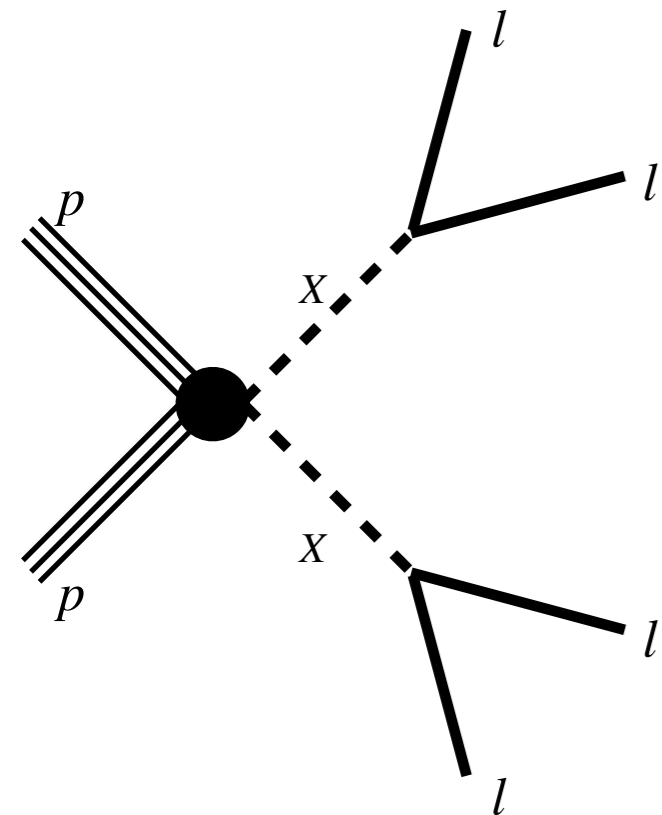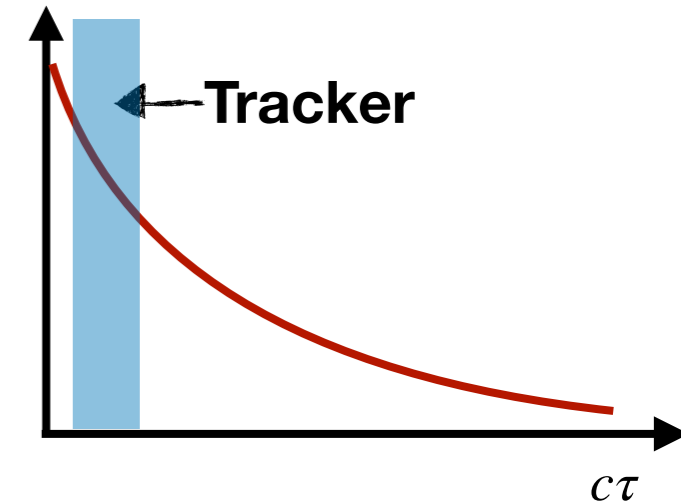**Each event**

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

known   **unknown**

known

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

M_X = 100 GeV, Decay Length = 50 cm

←**Tracker**

$c\tau$

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

After restricting decays to Tracker, τ distribution gets biased

actual distribution

Legend:
- No cuts
- p_T > 20 GeV
- $|\eta|$ < 2.4
- d_T > 0.1 cm, d_T < 30 cm, $|d_z|$ < 300 cm
- All cuts

Problem with lifetime estimation of LLPs

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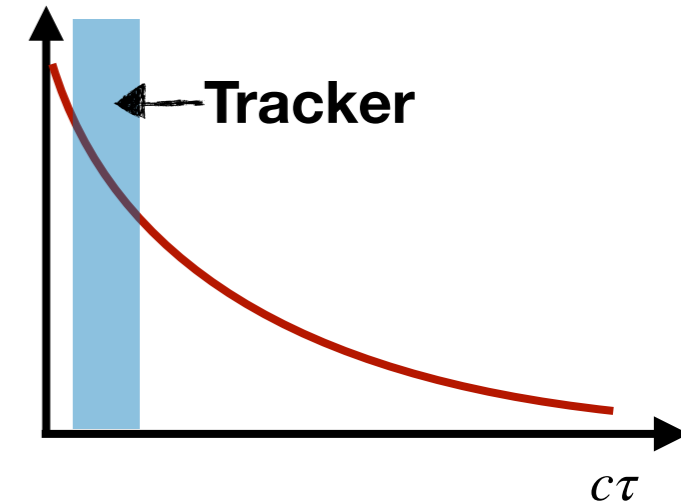
Each event

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

known   **unknown**

known

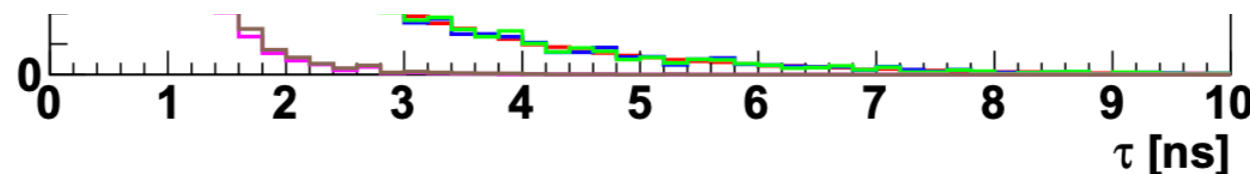Fit the exponential distribution of $c\tau$ and find out the proper mean lifetime of the particle

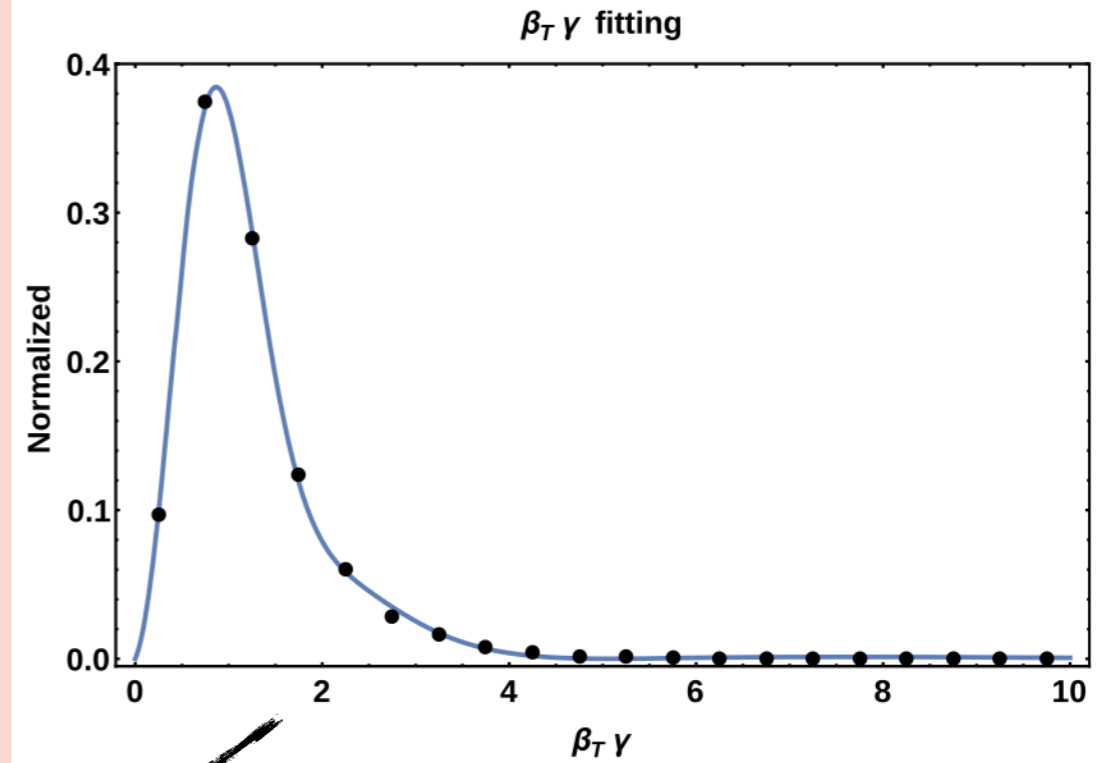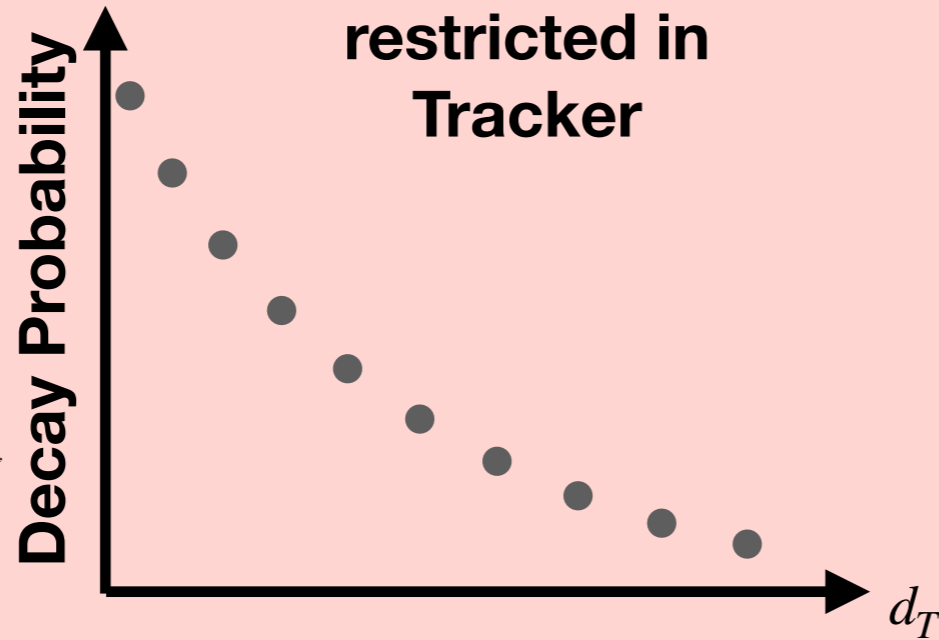←**Tracker**

$c\tau$

M_X = 100 GeV, Decay Length = 50 cm

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]

τ [ns]

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Ways to estimate the correct lifetime

From experiment

COMPARE

restricted in Tracker

Decay Probability

d_T

$\beta_T\gamma$ fitting

Normalized

$\beta_T\gamma$
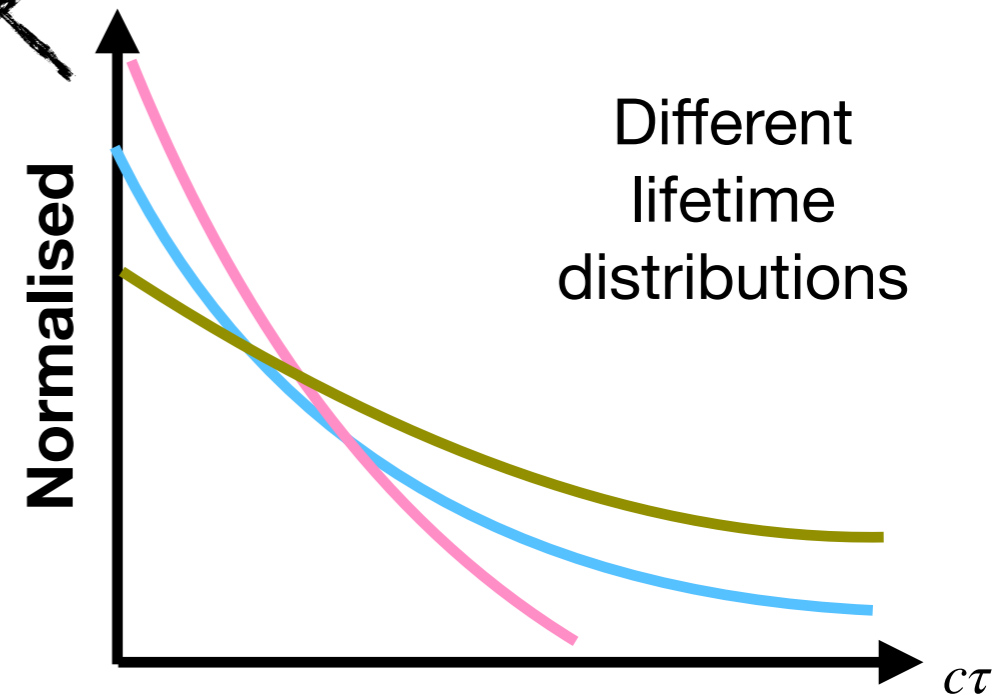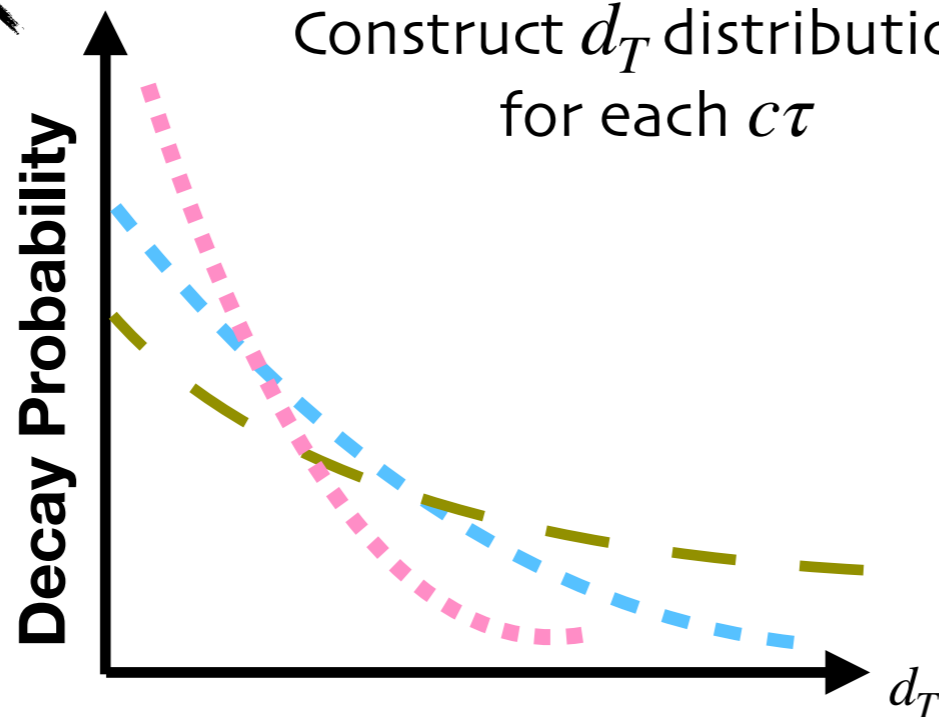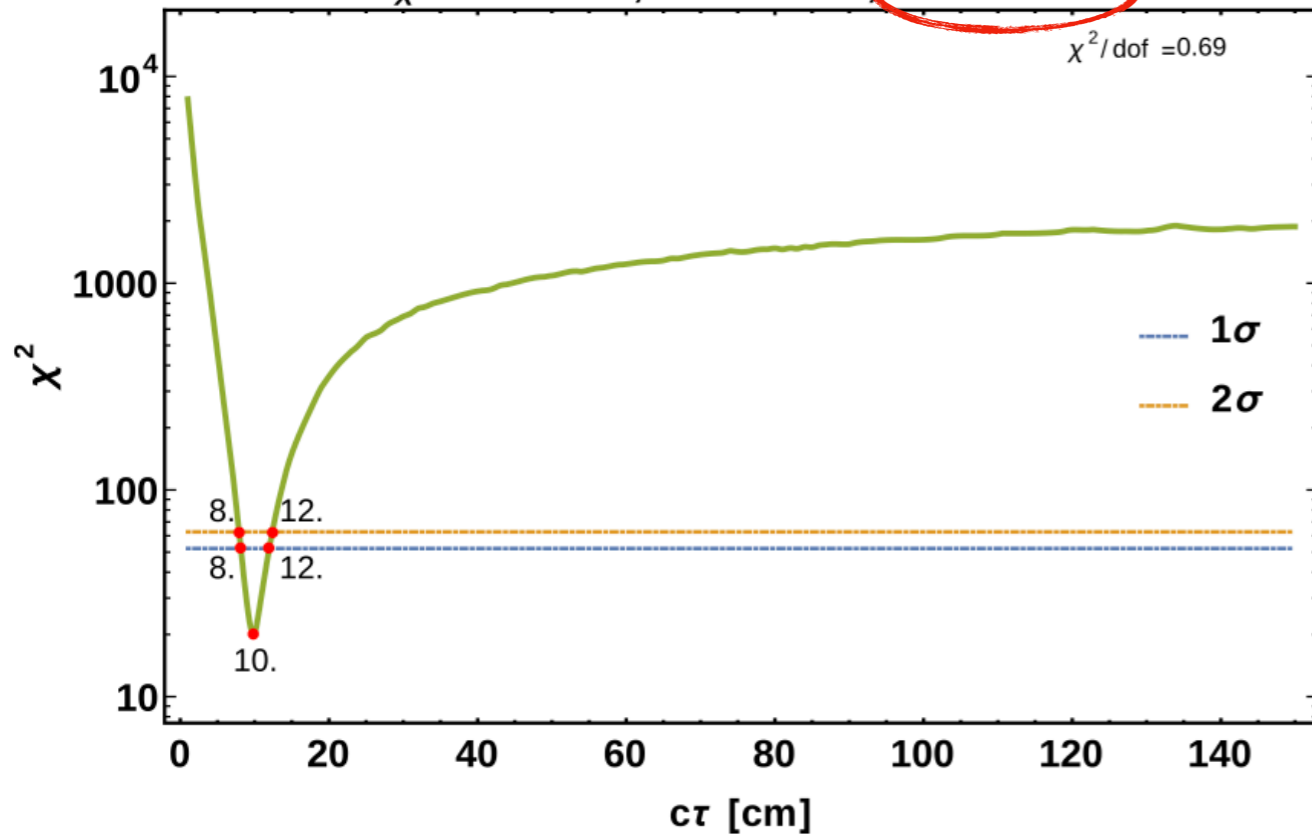
Generate random numbers
$$d_T = (\beta_T\gamma)(c\tau)$$
Construct d_T distributions for each $c\tau$

Model-independent method
See paper for model-dependent

Decay Probability

d_T

Different lifetime distributions

Normalised

$c\tau$

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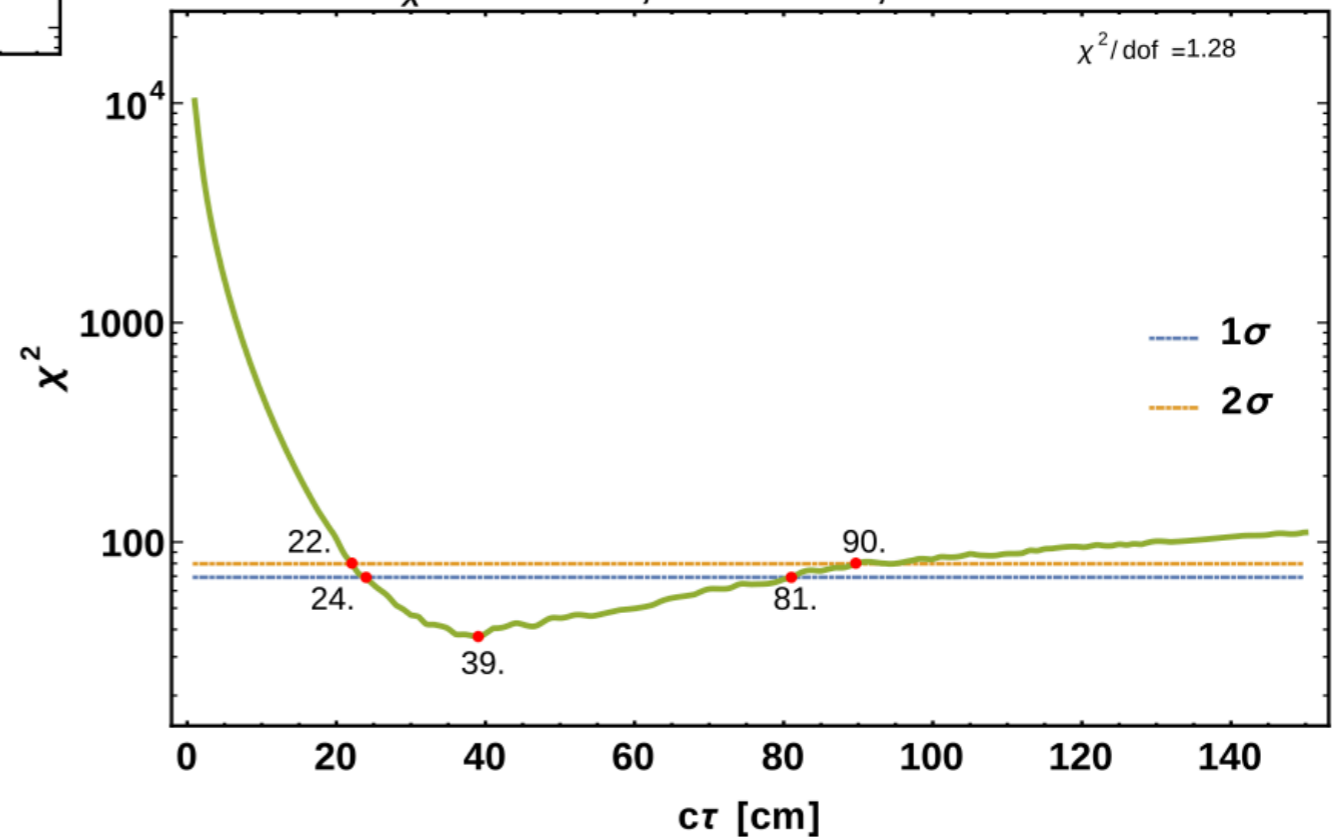# Ways to estimate the correct lifetime

Cross-section: 1 fb
HL-LHC 3000 fb^{-1}

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

Statistical Data Analysis,
Glen Cowan

Performed Machine Learning (ML) based regression - similar performance

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

MUON SPECTROMETER MS

HADRONIC CALORIMETER HCAL

ELECTROMAGNETIC CALORIMETER ECAL

TRACKER

muon

charged hadron

neutral hadron

electron   photon

Effect of magnetic field not shown

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How do prompt particles look in the detector?

Different particles leave different signatures in collider detectors

MUON SPECTROMETER MS

HADRONIC CALORIMETER HCAL

ELECTROMAGNETIC CALORIMETER ECAL

TRACKER

jet
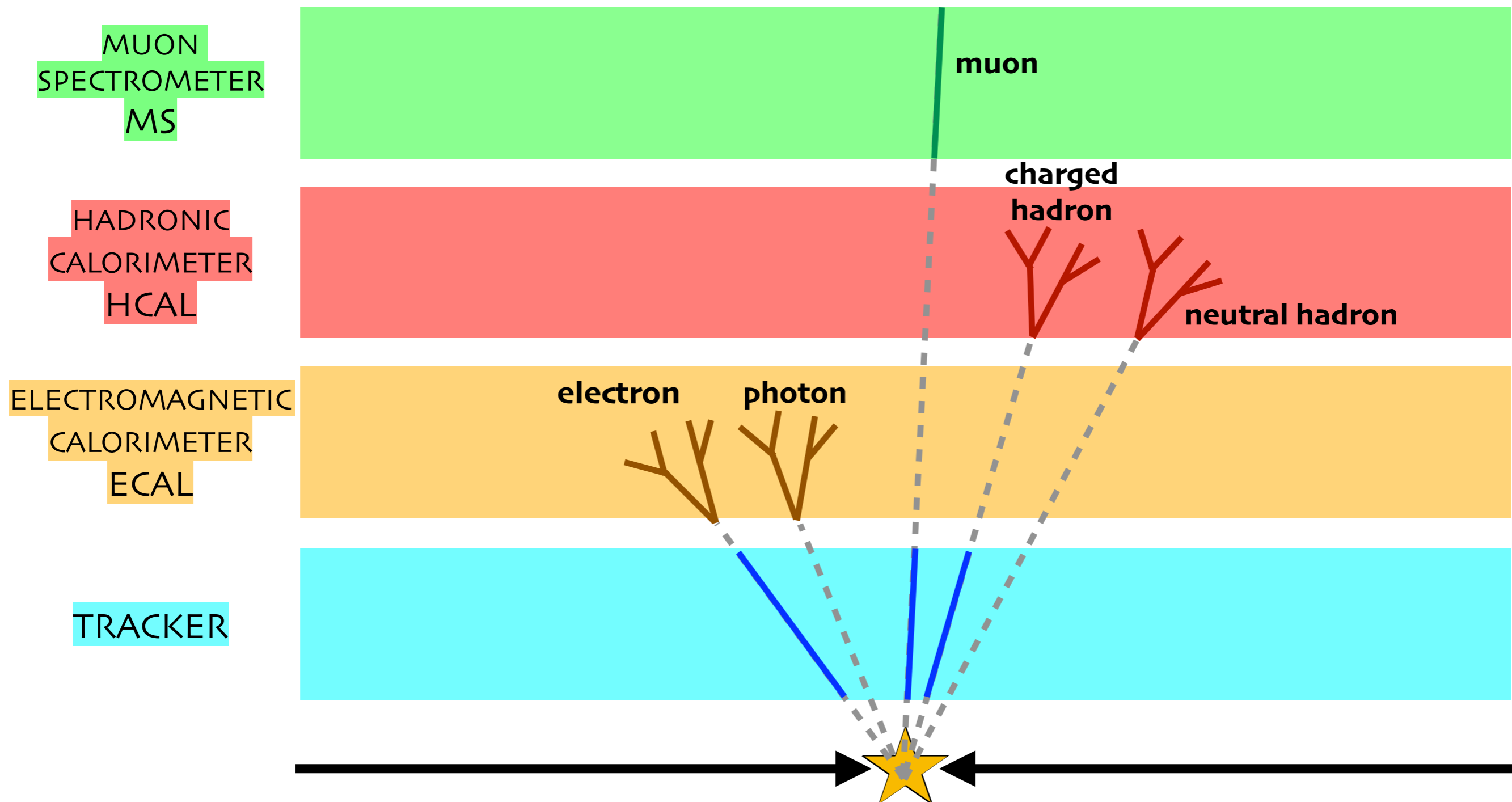
hadronisation of quarks and gluons

Effect of magnetic field not shown

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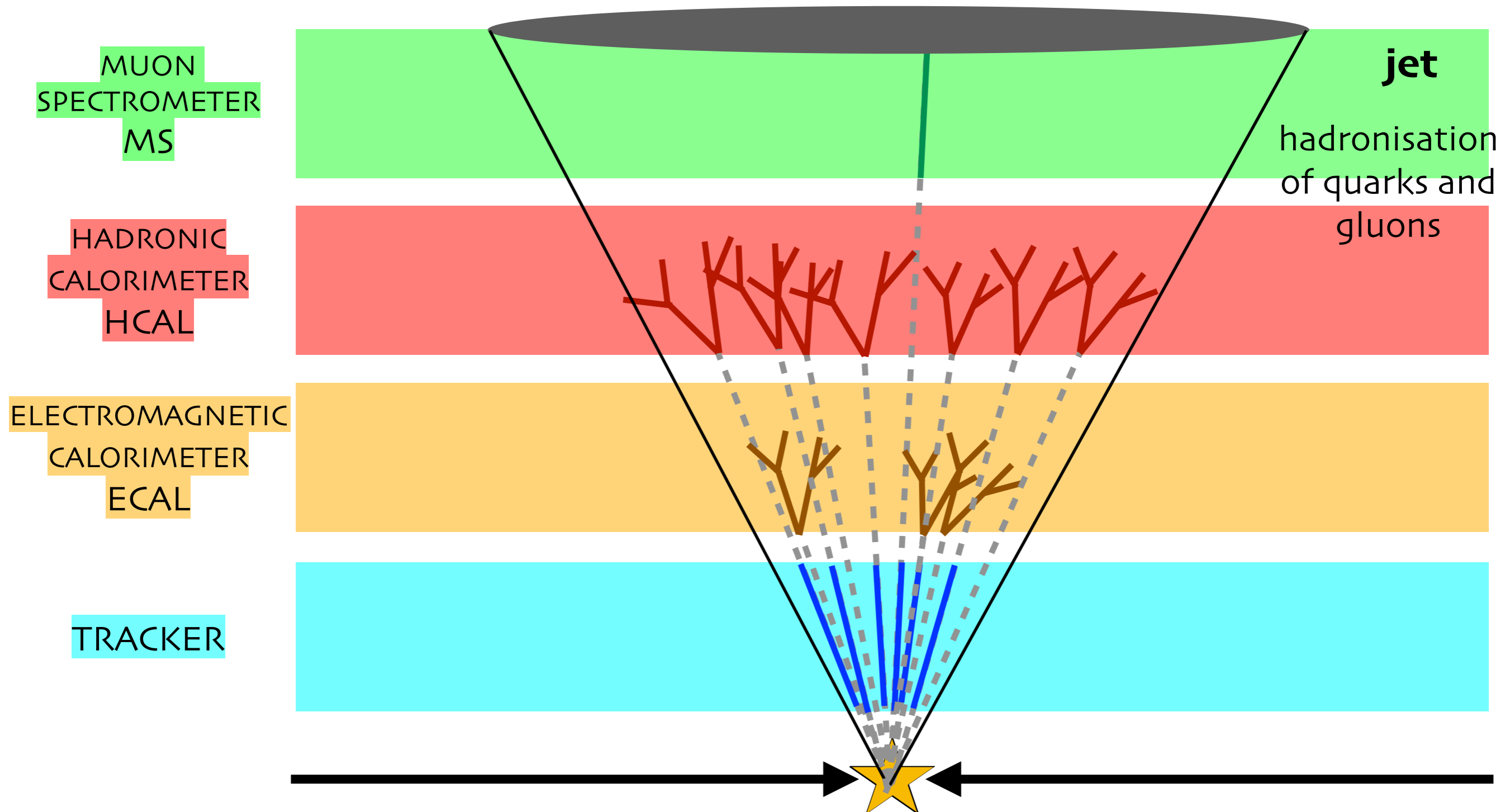
Different decay modes of a particle

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
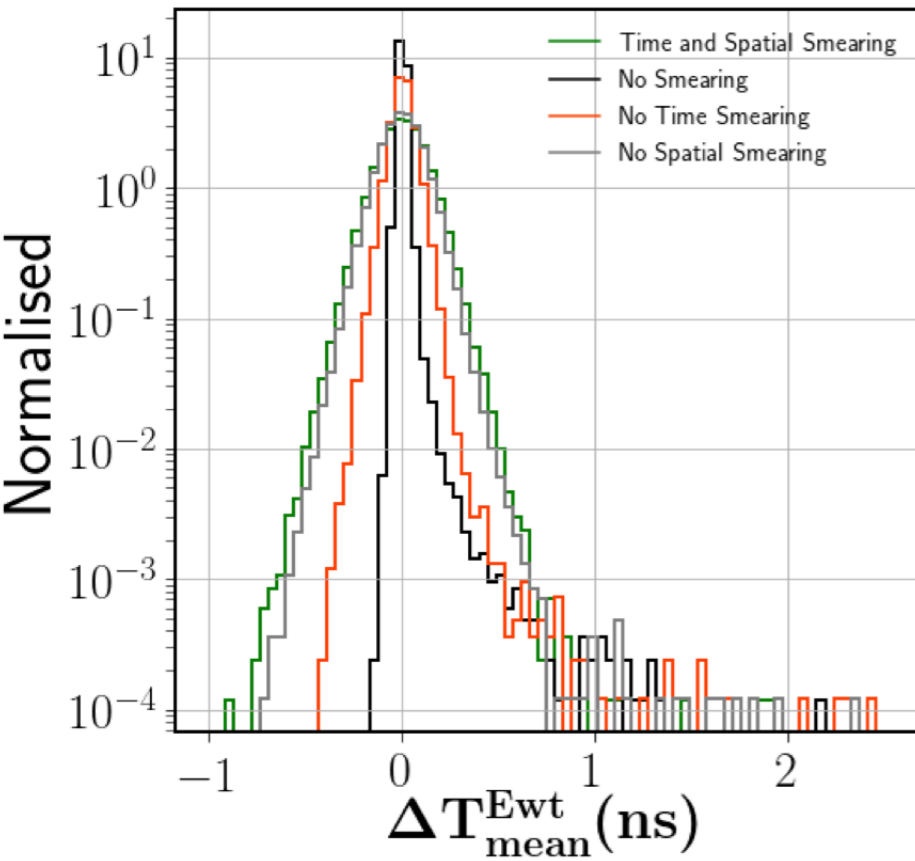
BRANCHING FRACTION — *theory*

DETECTOR EFFICIENCY & ACCEPTANCE — *experiment*

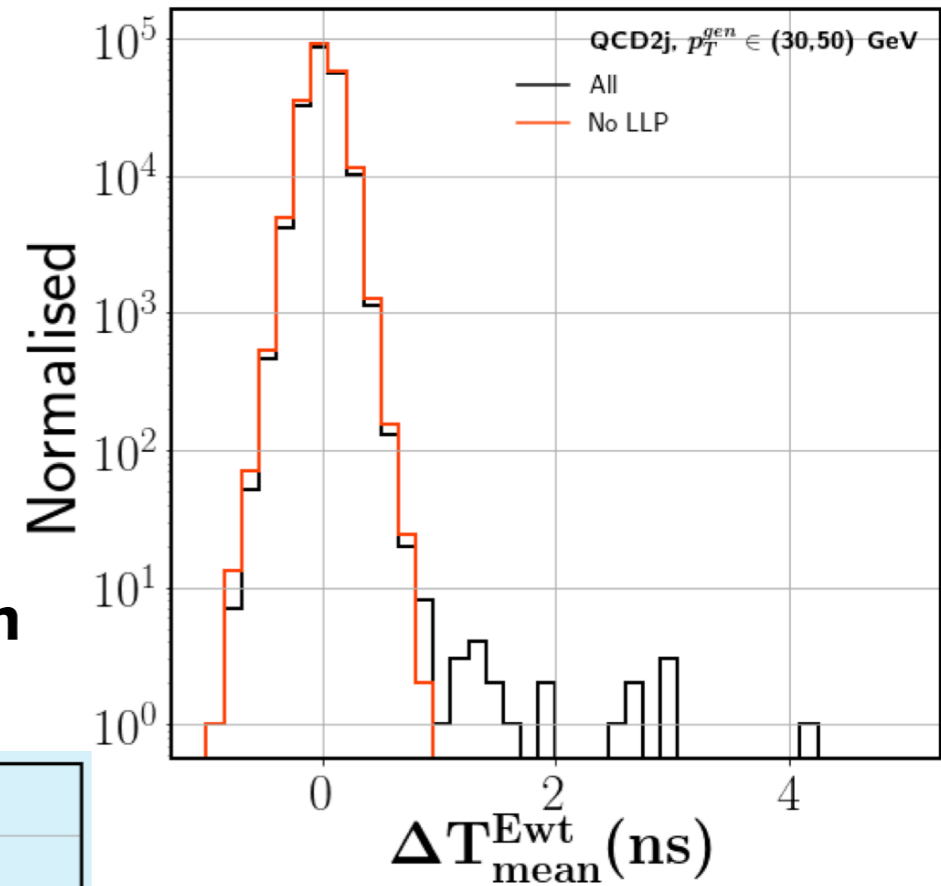Till this point, the story is similar for LLPs

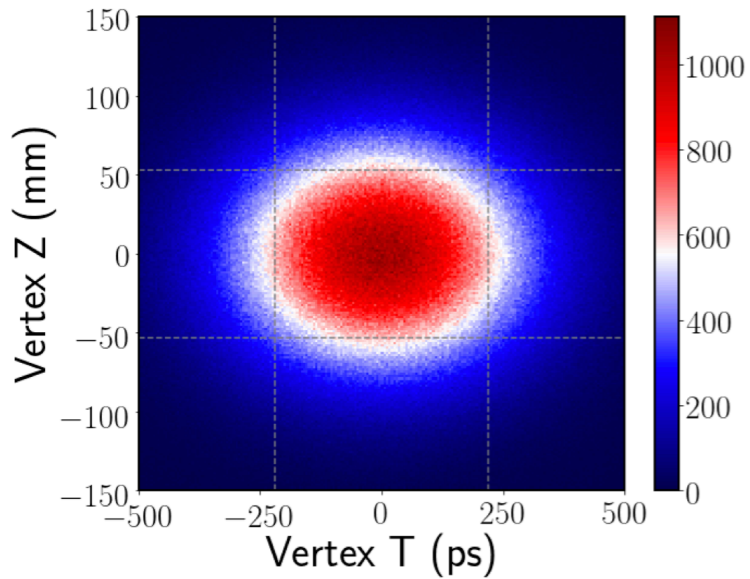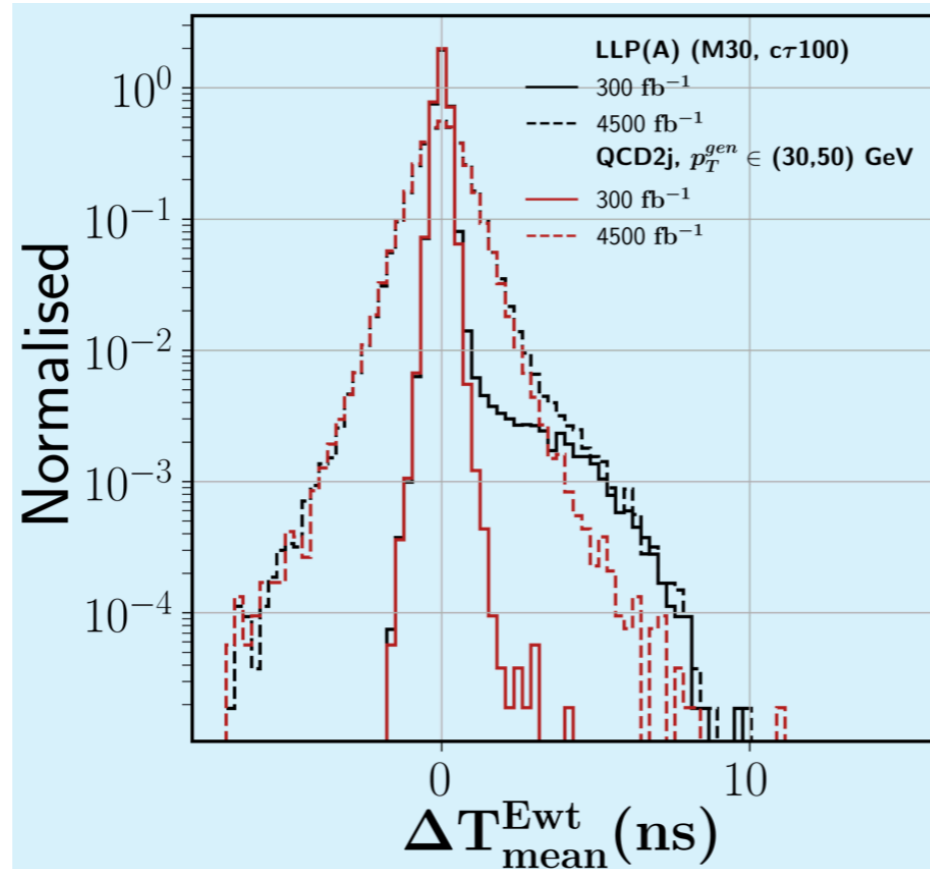**However, there is one more factor affecting the signature of LLPs**

Timing @ ECAL

Factors affecting timing of a jet

Degrading resolution with increasing luminosity
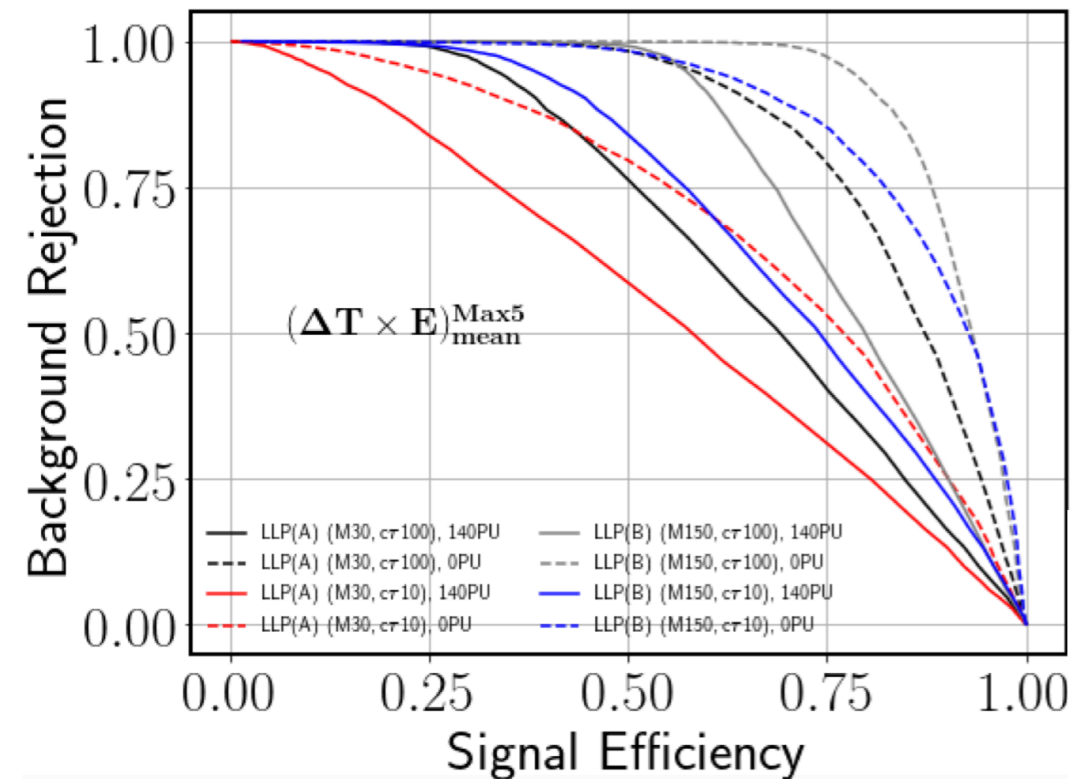

LLPs in SM

Spread of vertices in the z and t directions

Timing @ ECAL

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

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

Select cuts that maintain **30 kHz rate**

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

K. Ehat'aht et al, arXiv:2106.04360
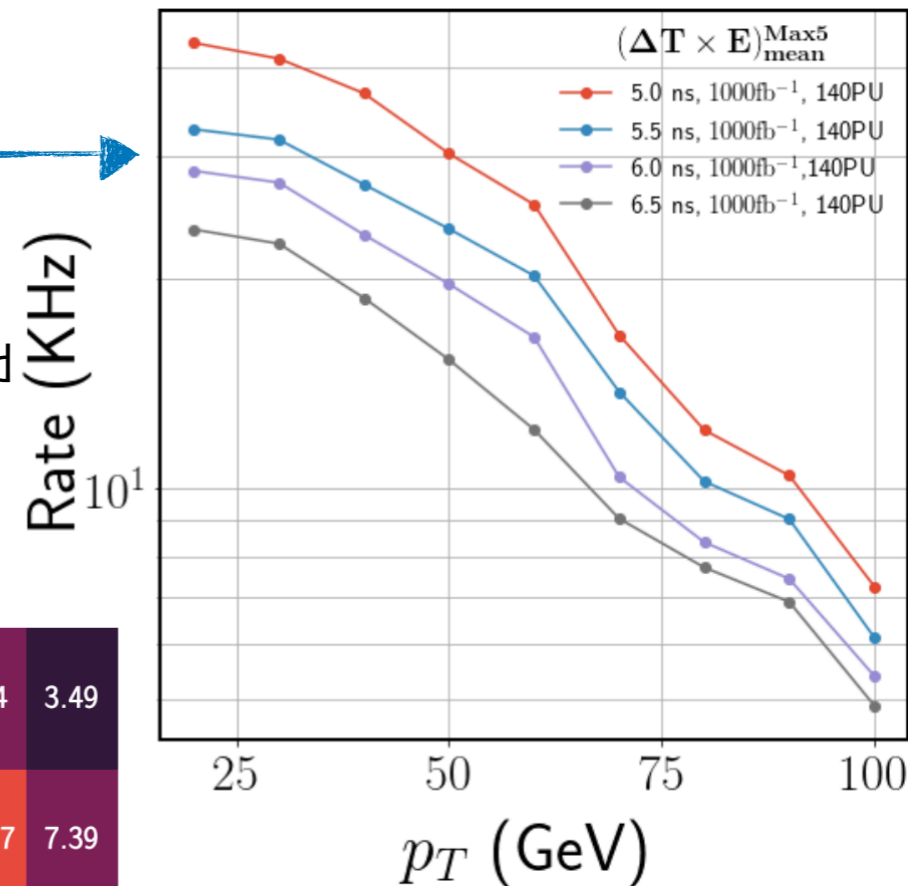
LLP (A), $(\Delta T \times E)_{mean}^{Max5}$
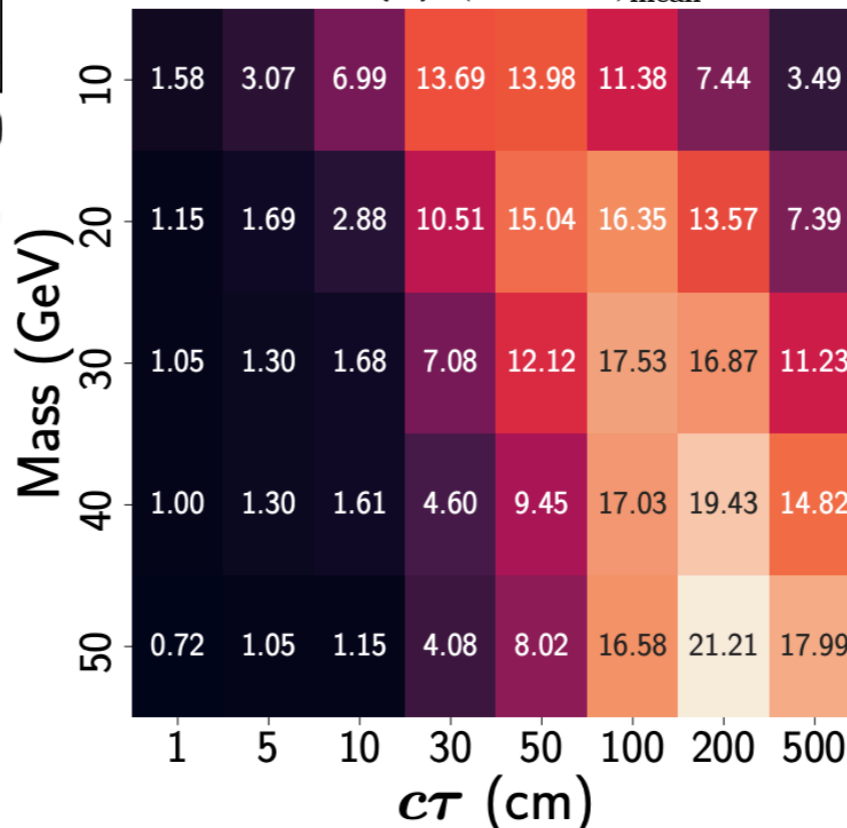
Inclusion of L1 **displaced tracking** (efficient till $d_0 < 8$ cm) increases sensitivity for low lifetimes

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

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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

$m_\varphi = 500$ MeV, $c\tau_\varphi = 10$ cm

without magnetic field
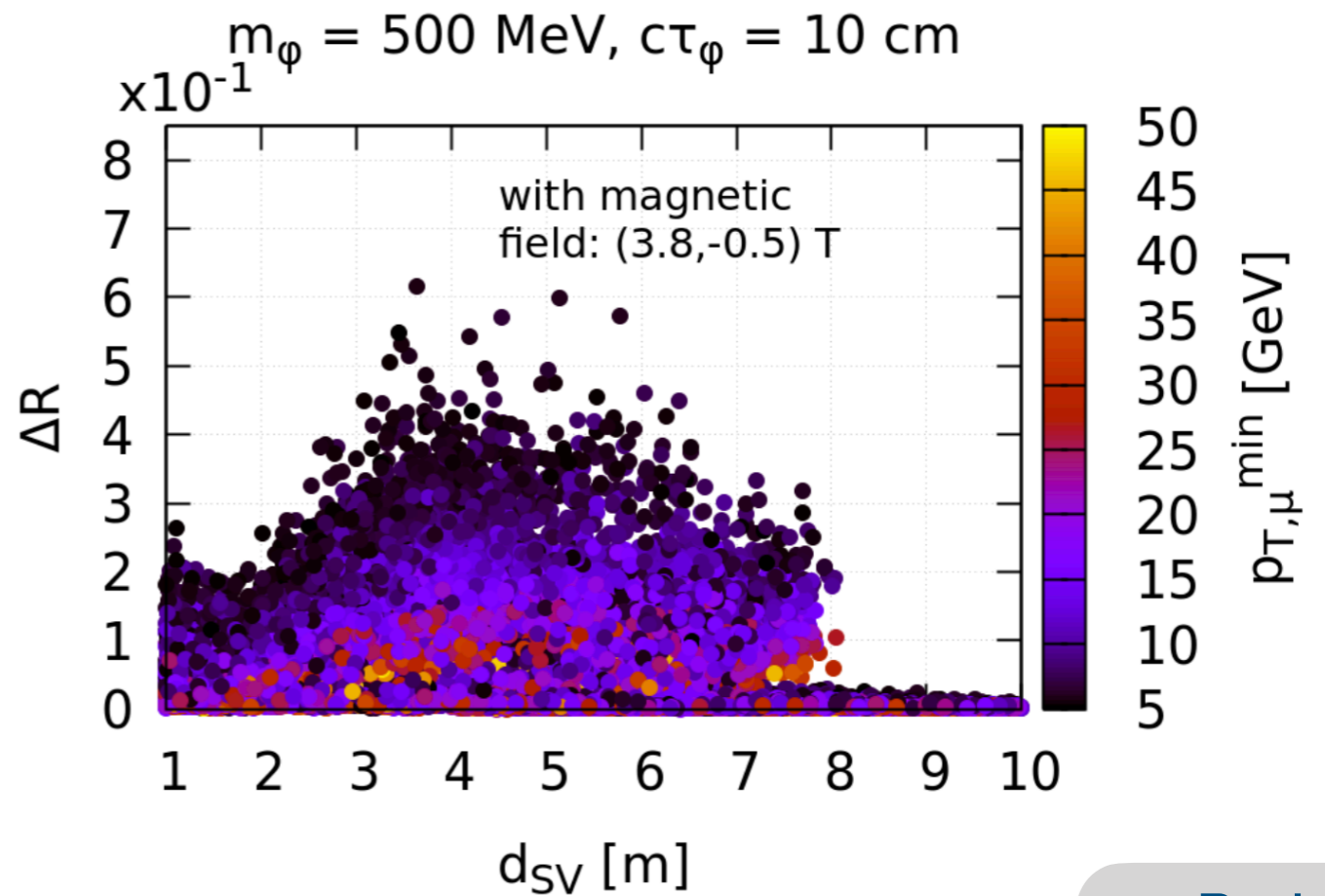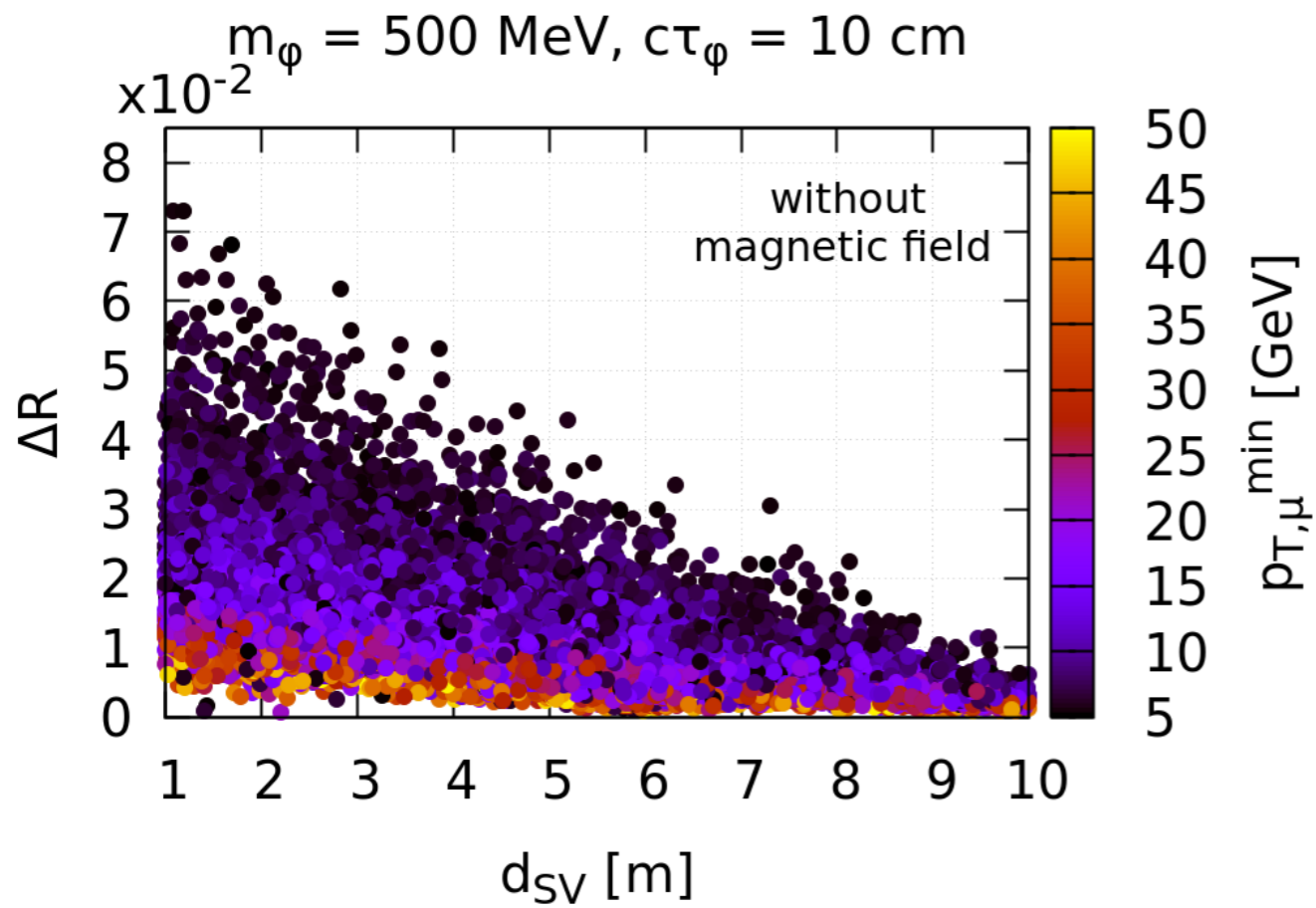
$m_\varphi = 500$ MeV, $c\tau_\varphi = 10$ cm

with magnetic field: (3.8,-0.5) T

Back

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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
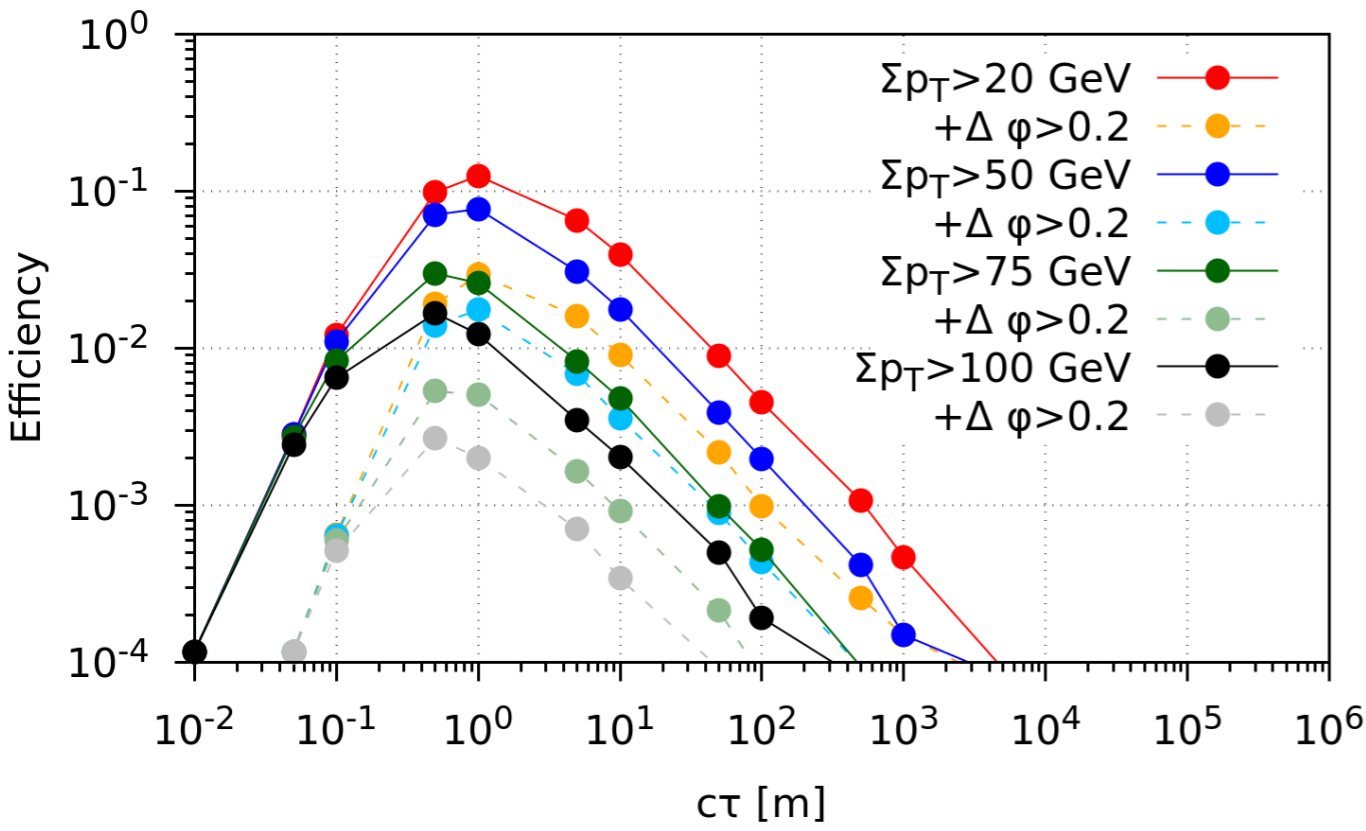
Our obtained limits can be scaled accordingly

Back

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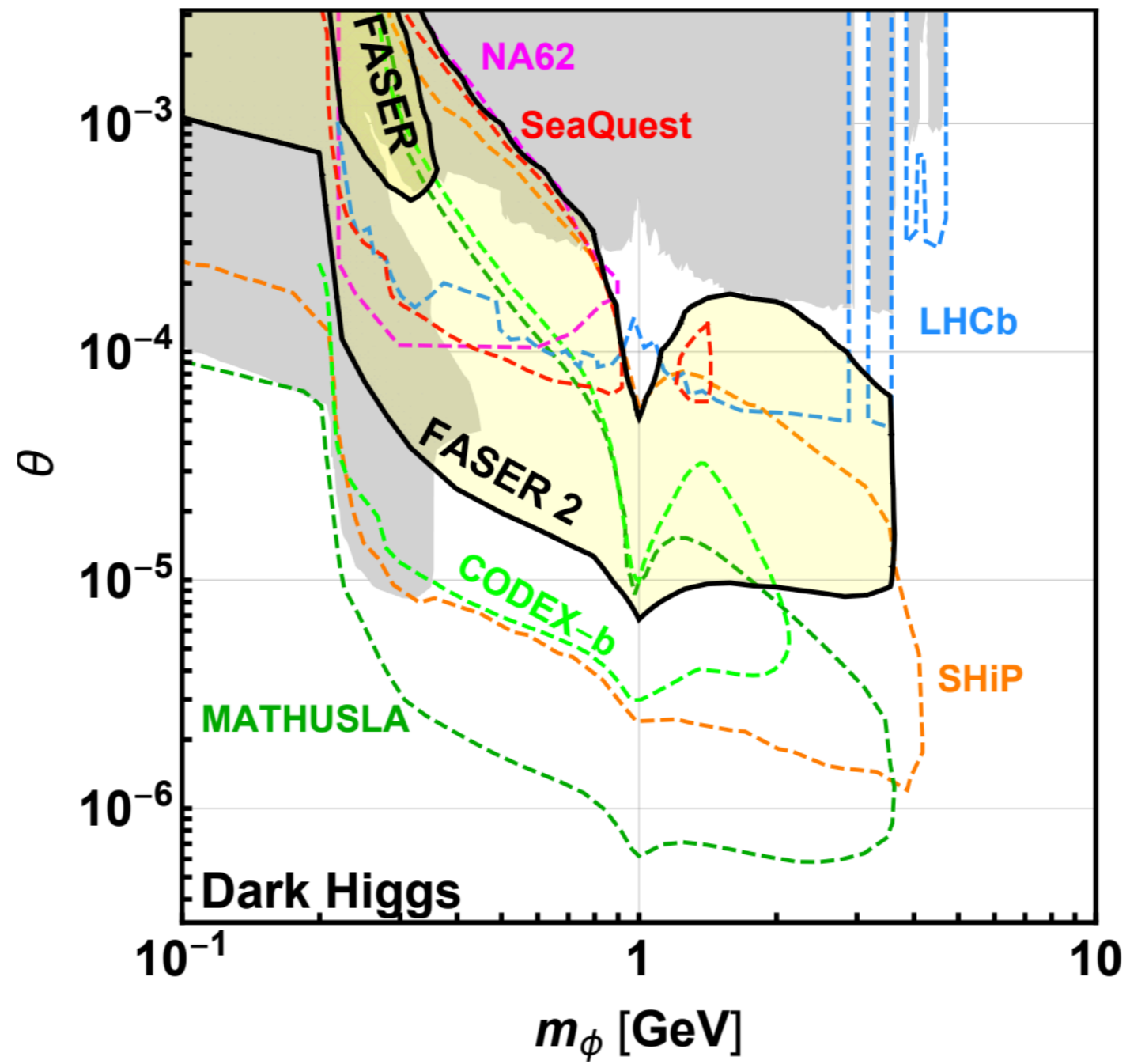
FASER: ForwArd Search ExpeRiment at the LHC, <u>arXiv:1901.04468.pdf</u>

$m_\varphi = 10$ GeV, $\sqrt{s} = 100$ TeV, FCC-hh:Barrel+Endcap MS, ggF

$\sqrt{s}$ [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 →

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

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

improvement factors w.r.t. HL-LHC

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Triggers using L1 Tracking

- **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	$1046 \rightarrow 14$	13	60
70% Table	$1046 \rightarrow 190$	19	73

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

(M50,$c\tau$10), Total: 27%

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

8   5   14
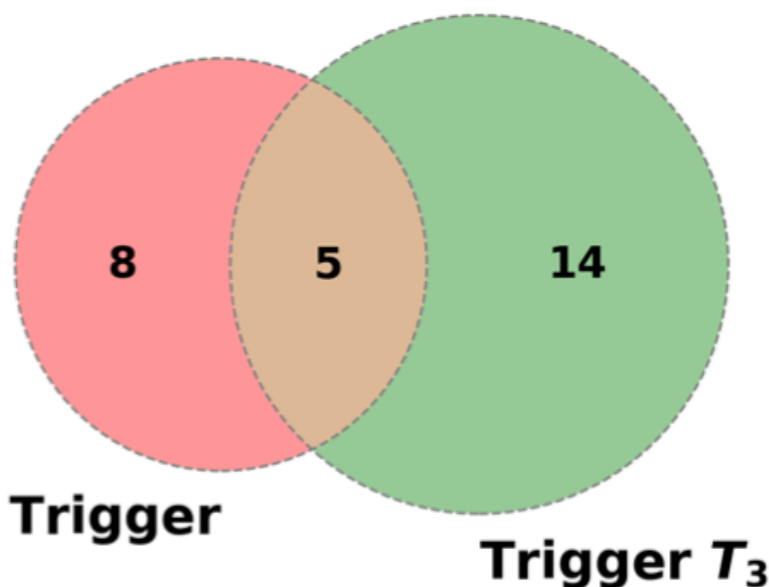
Standard Trigger

Trigger T_3

- **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.**