Higgs portal long-lived particle searches at the FCC-hh

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Why no hints of new physics yet?

Experiments are putting **stronger constraints on the nature of new physics, especially for the conventional scenarios**

1. New physics appears at a scale beyond LHC or HL-LHC's reach

   Extend mass reach by increasing centre of mass energy or with higher precision

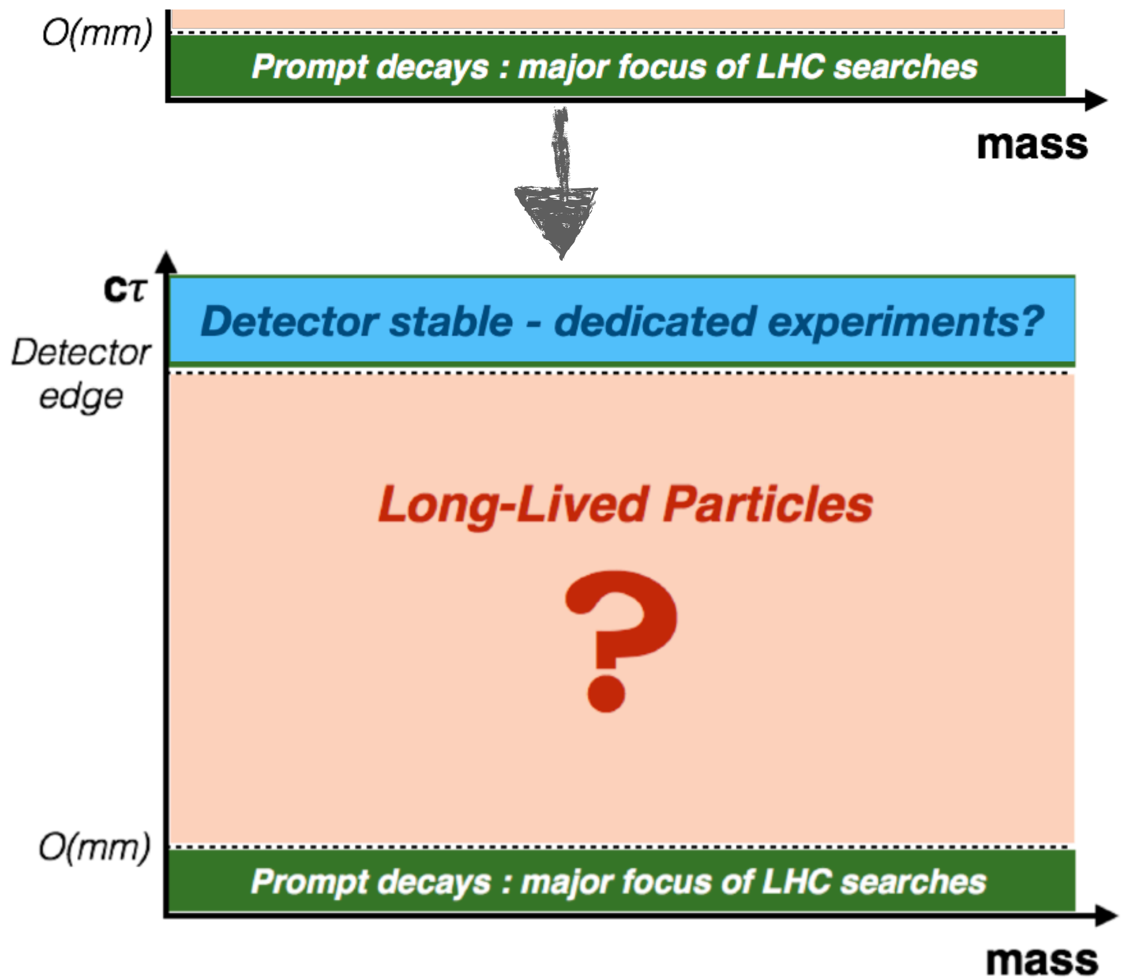
2. Scale is within LHC's reach, but the process is very rare or have large backgrounds

   Increase luminosity or more sophisticated analyses to reduce backgrounds

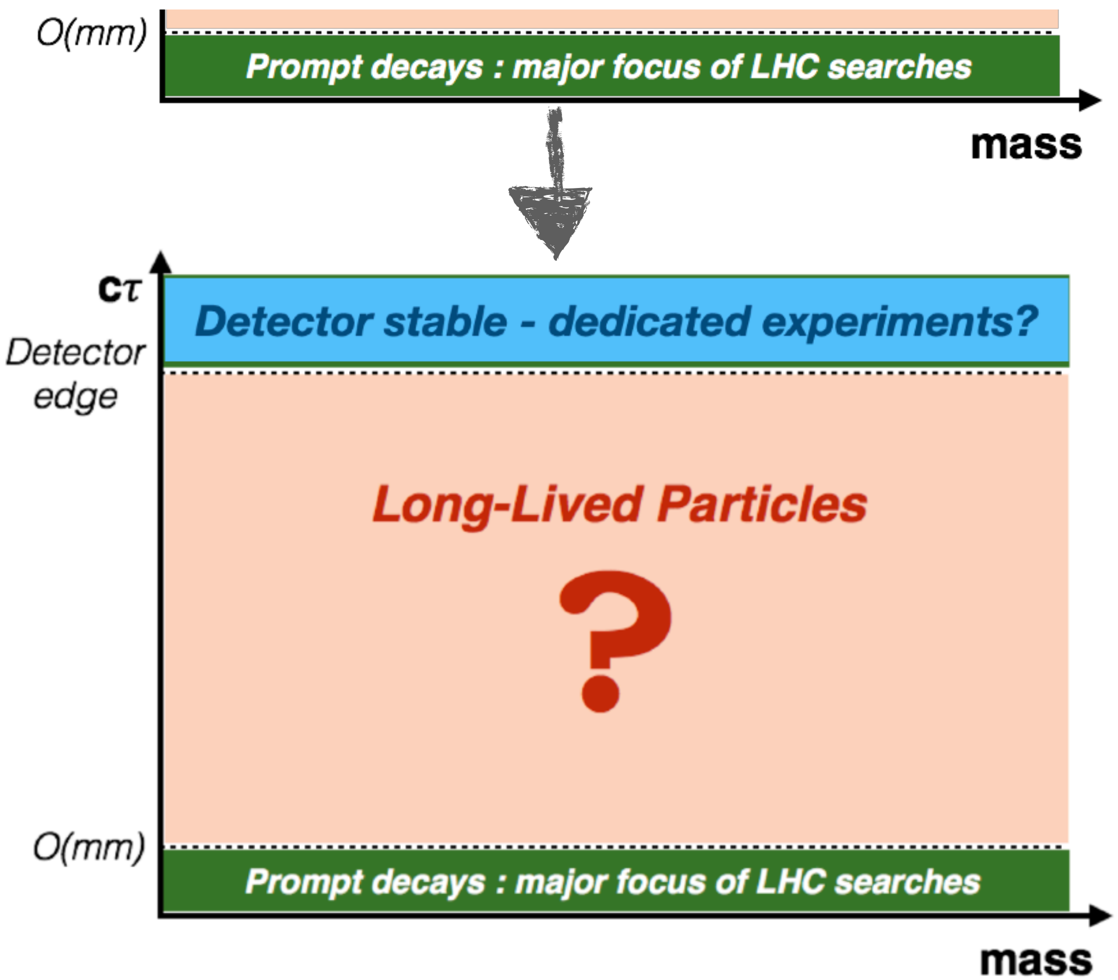
3. Their signatures are so unusual that they are overlooked in the present searches

   More inclusive or smarter trigger strategies

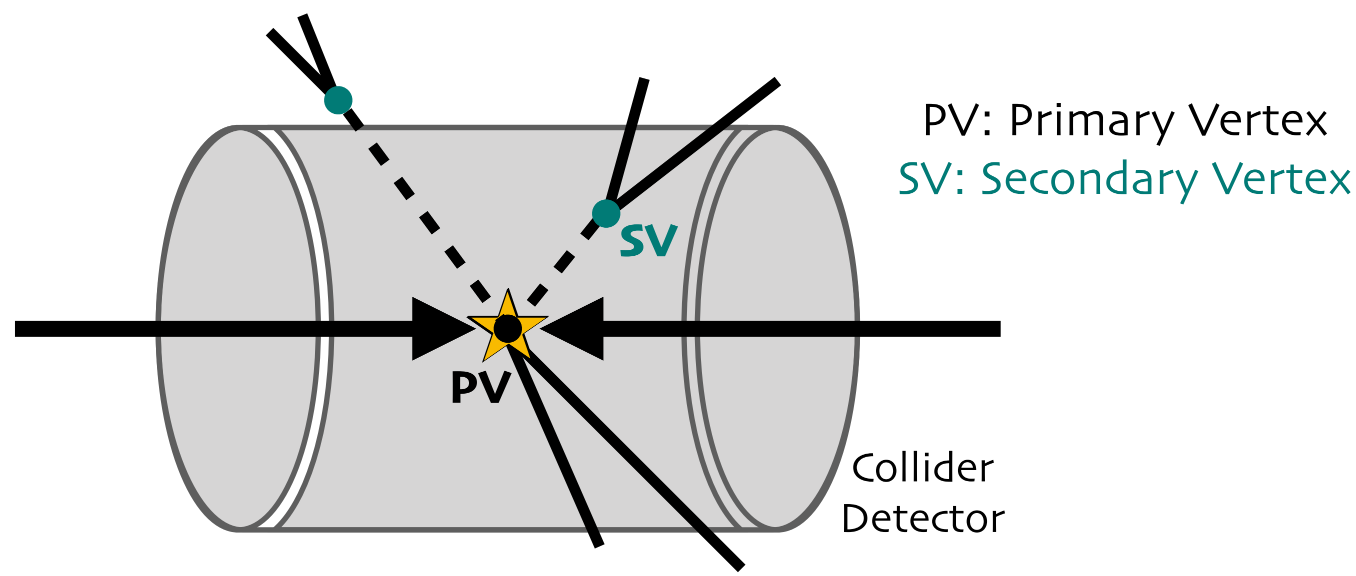
What are we missing?



Long-lived particles



Particles having lifetimes such that they have **macroscopic decay lengths** $> \mathcal{O}(\text{mm})$ inside the detector.



Keys to Longevity:

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

Heavy scales, $\Gamma \sim \left(\frac{m}{M}\right)^{\#}$

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

Small couplings

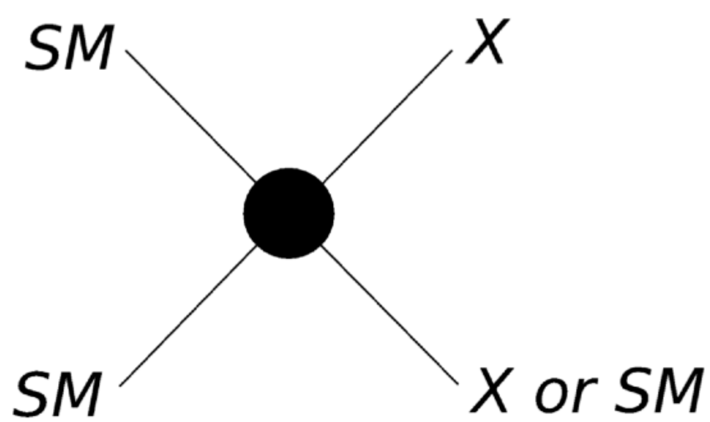
e.g., c and b quarks (SM), RPV SUSY (BSM)

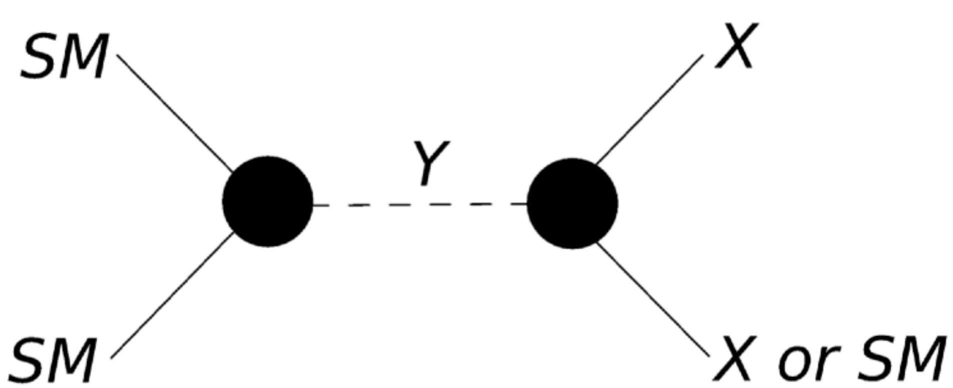
Kinematic squeezing

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

Long-lived particles

PRODUCTION



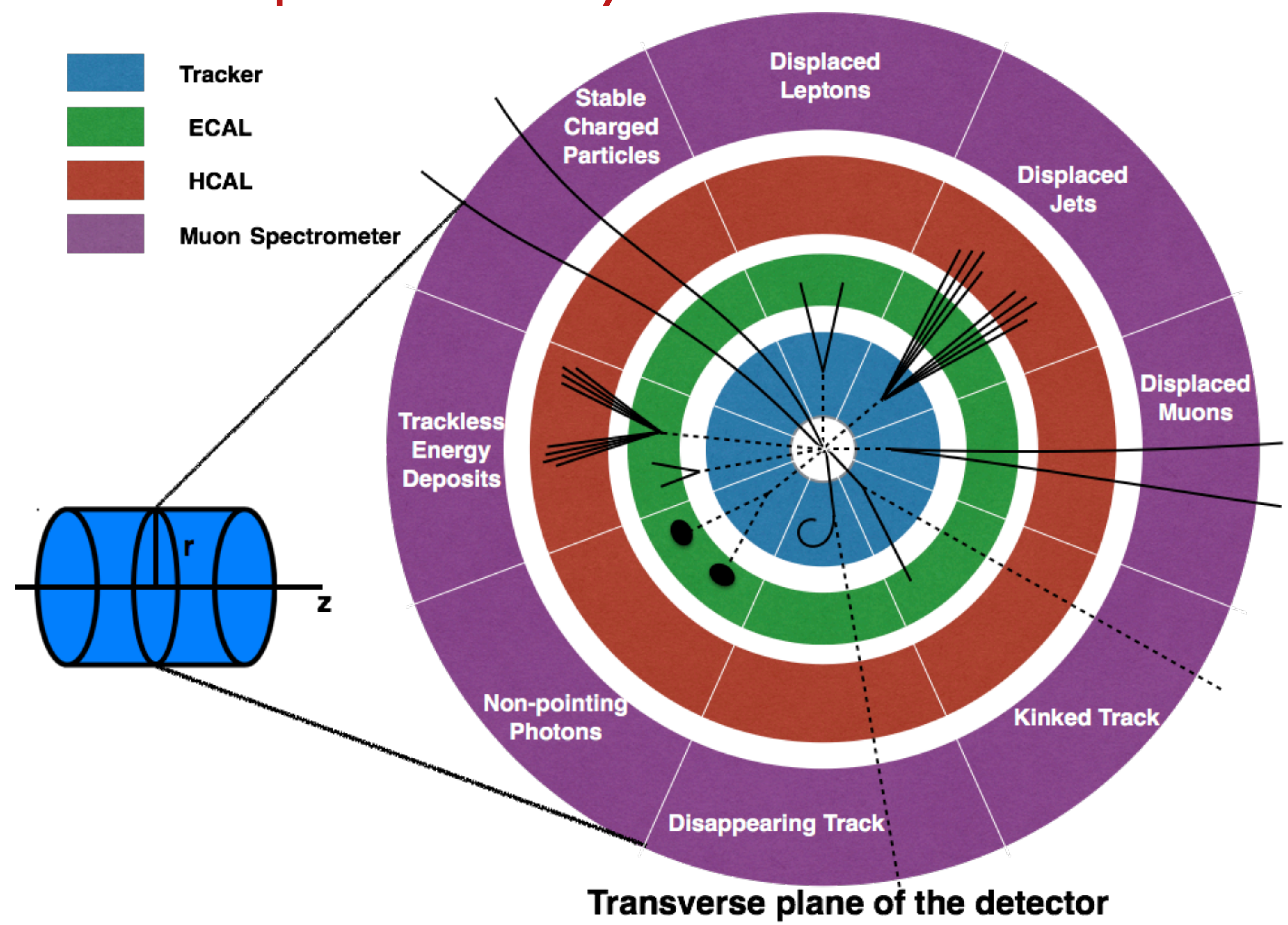


DECAY

Decay length in the detector (lab frame): $d = \beta\gamma c\tau$

where $\beta\gamma = \dfrac{p}{m}$ is the boost factor, c is the speed of light, τ is the proper lifetime of the particle

Signatures of LLP depend on **where the particle decays** inside the detector



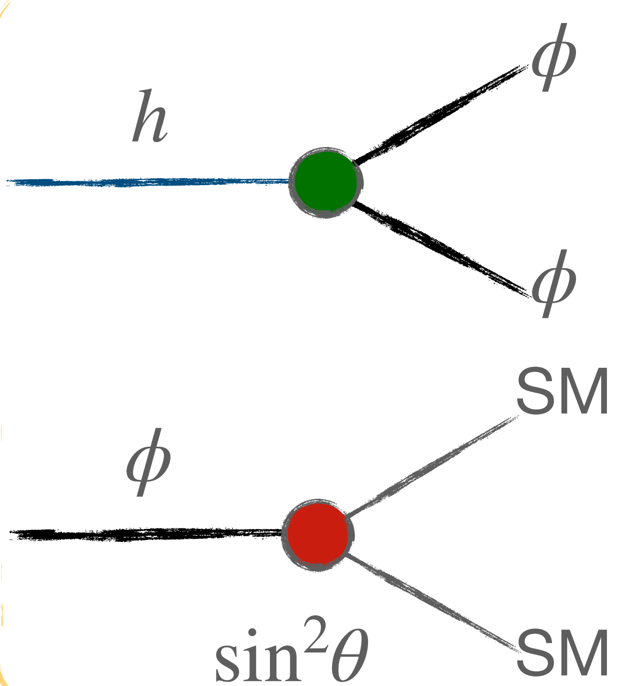
Long-lived particles in the Higgs portal

Light Scalar Mediator

$$\mathcal{L} \subset -m_\phi^2 \phi^2 - \sin\theta \, \frac{m_f}{v} \phi \bar{f} f - \lambda_{h\phi\phi} h\phi\phi + \ldots$$

Mixing highly constrained

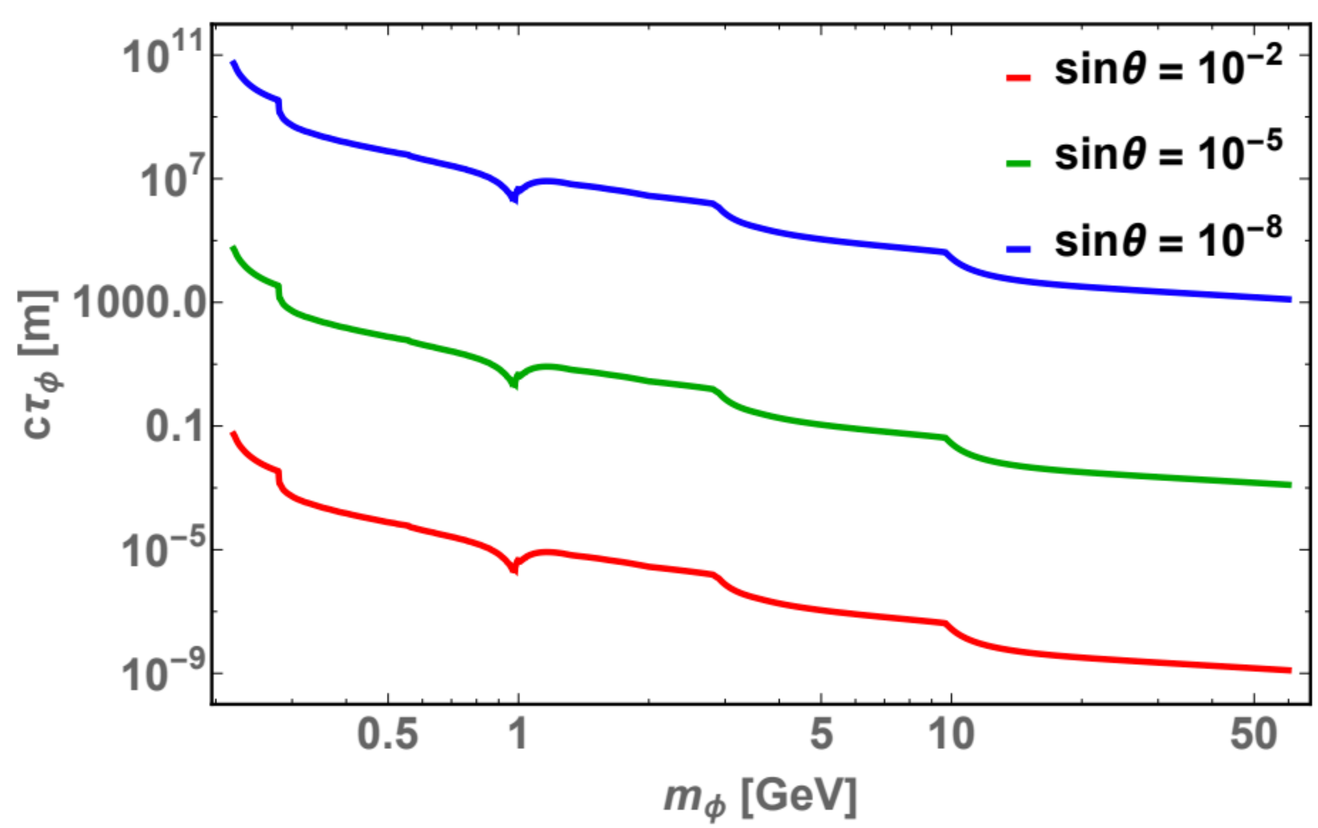
Not severely constrained so far



Production of ϕ has a different coupling than its decay

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

Long-lived mediator



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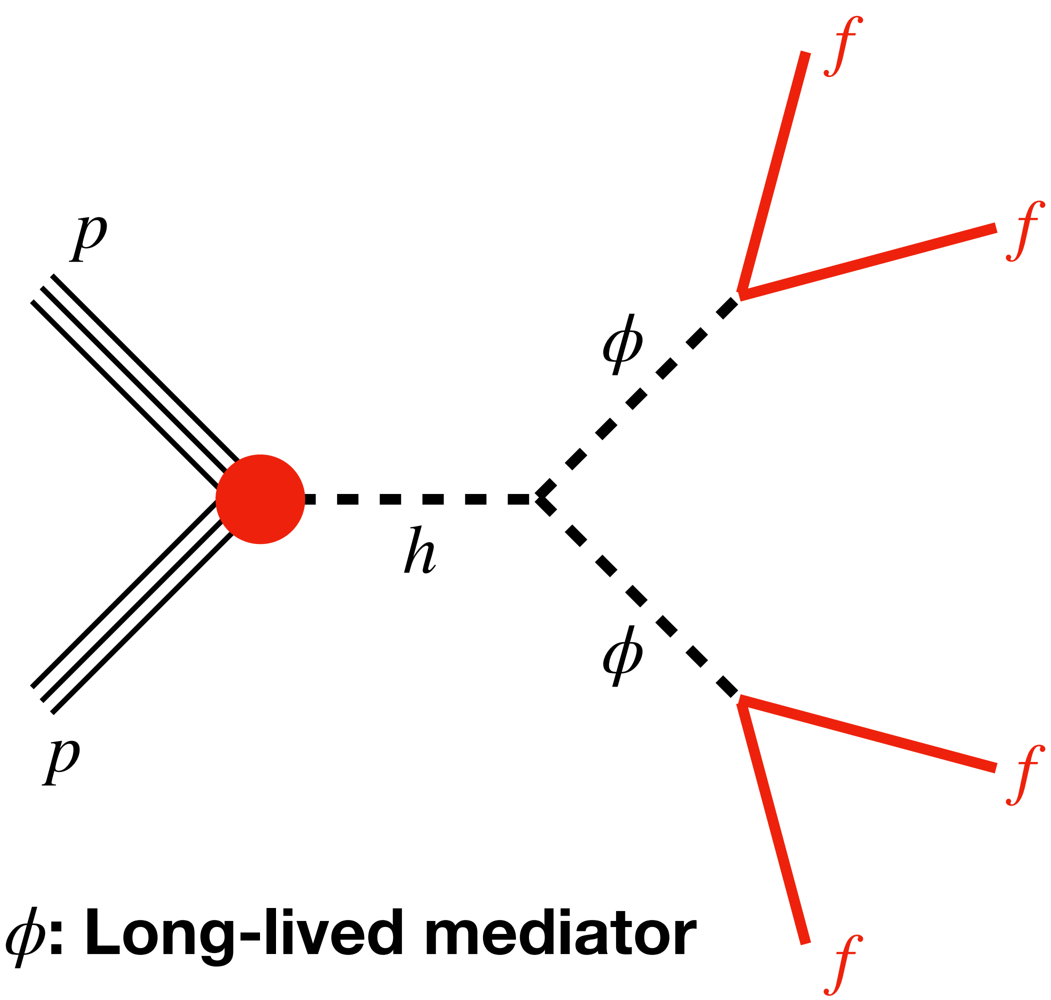
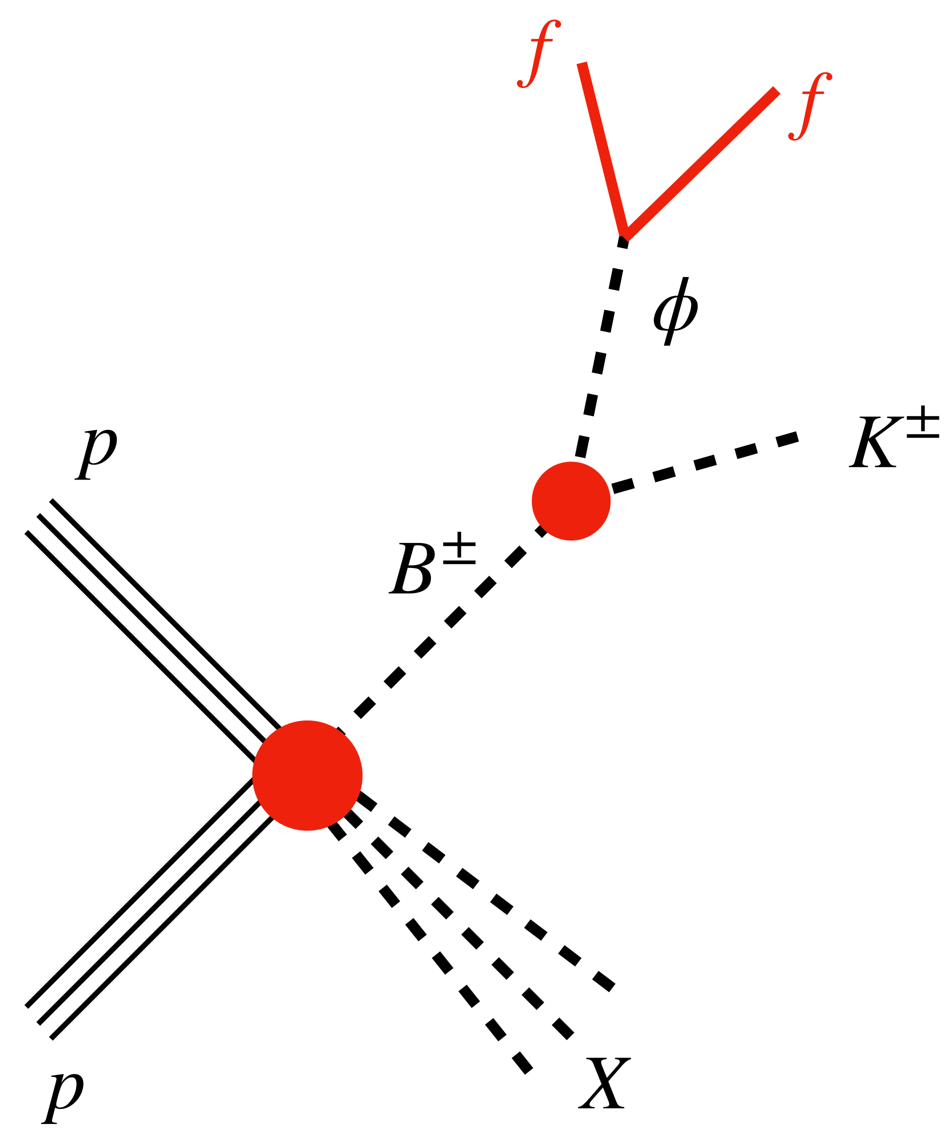


ϕ: Long-lived mediator



Light Long-Lived Particles

produced from decay of SM particles, like the Higgs boson, $m_{LLP} \leq m_h/2$

Triggering?

Difficult to trigger if there are no associated prompt hard particles

Primary vertex identification?

More chances of incorrect assignment of primary vertex

$$\beta\gamma = \frac{p}{m}$$

High boost for small m

Displaced vertices?

Larger decay length in the detector - secondary vertex reconstruction difficult as efficiency of Tracker decreases with increasing displacement

Delayed decay products?

Relativistic LLP - no significant time delay in decay products

Decays in the MS?

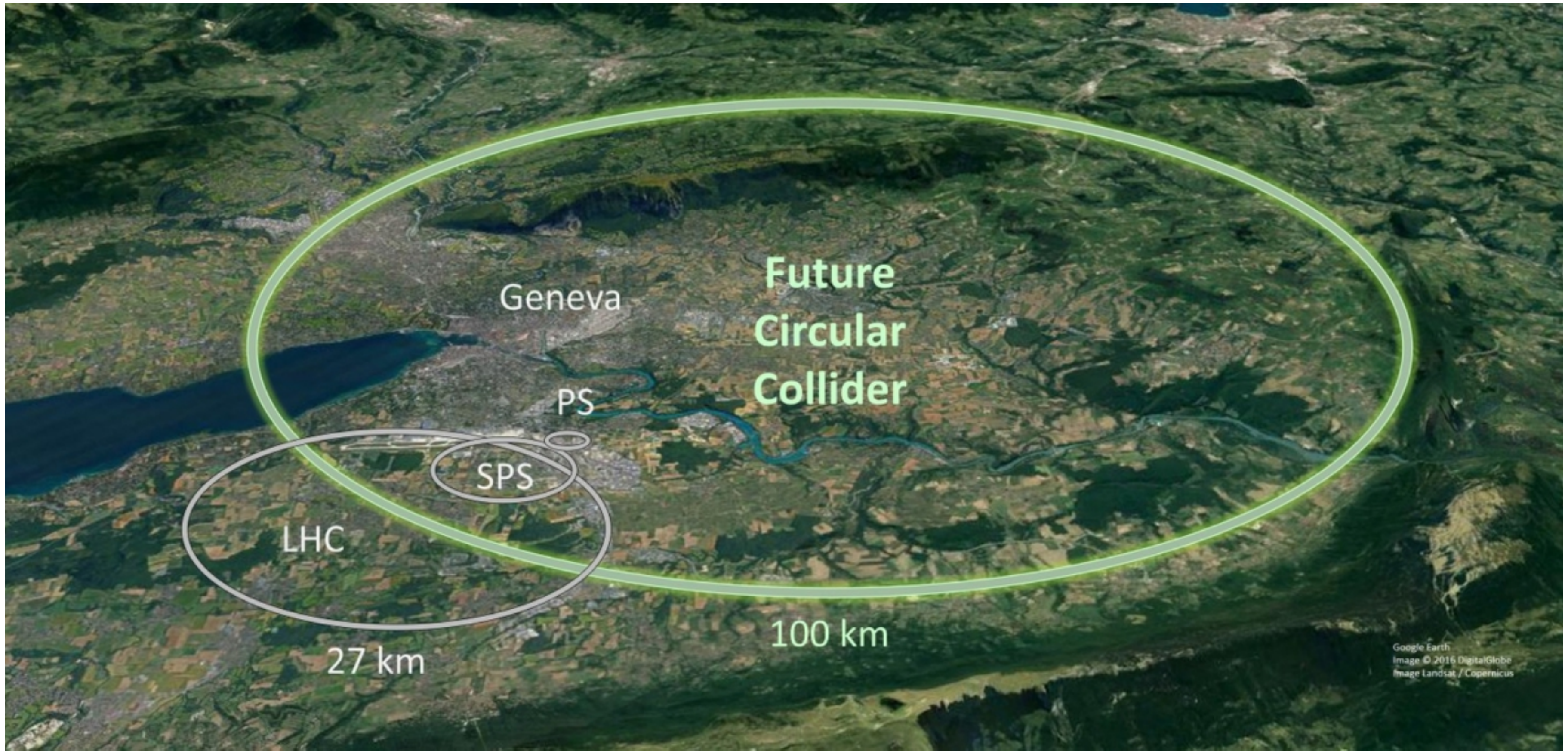
Decays outside the collider detector?

This talk

The Future Circular Hadronic Collider: FCC-hh

The FCC-ee 100 km tunnel is designed to host subsequently a future circular hadron collider (FCC-hh) of increased centre-of-mass energy:

100 TeV compared to the 14 TeV HL-LHC



FCC study, CERN

Why do we need a hadron collider at such a high centre-of-mass energy?

Discovery after indirect evidence

Even when precision measurements provides indirect evidence of particles, we need to produce them directly to understand its properties

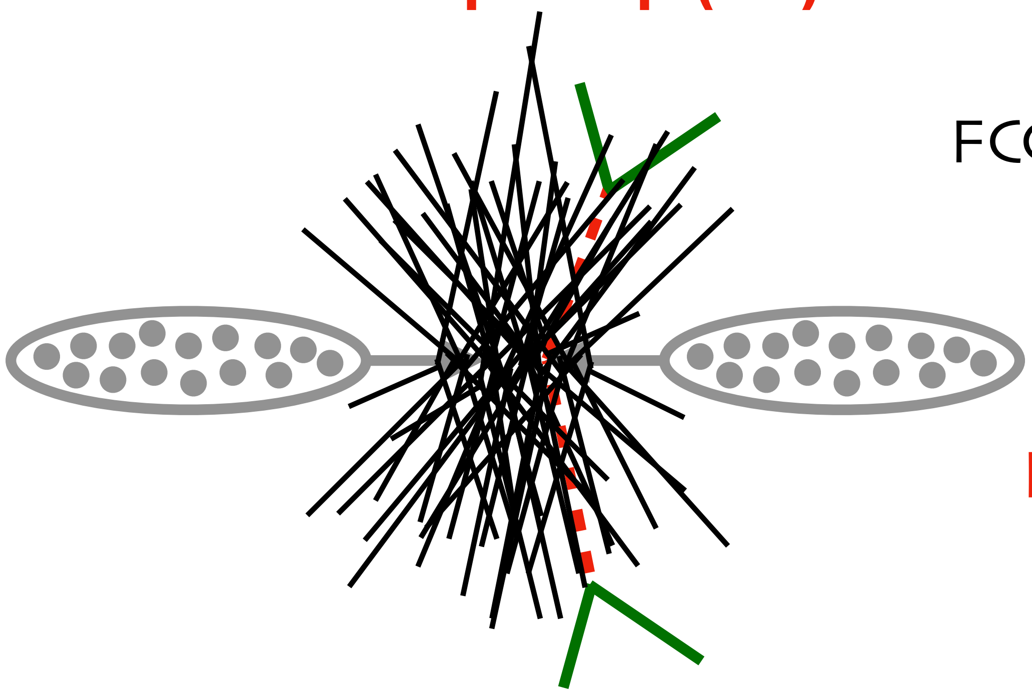
FCC-ee will be sensitive to new phenomena at scales of tens of TeV

With the current technology, direct particle production at this scale can only be achieved by a hadron collider of around 100 TeV energy range

Huge enhancement in the Higgs production -
benefit for any new physics coupled to the Higgs boson

High luminosity machine: $30\ ab^{-1}$

High pile-up environment



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

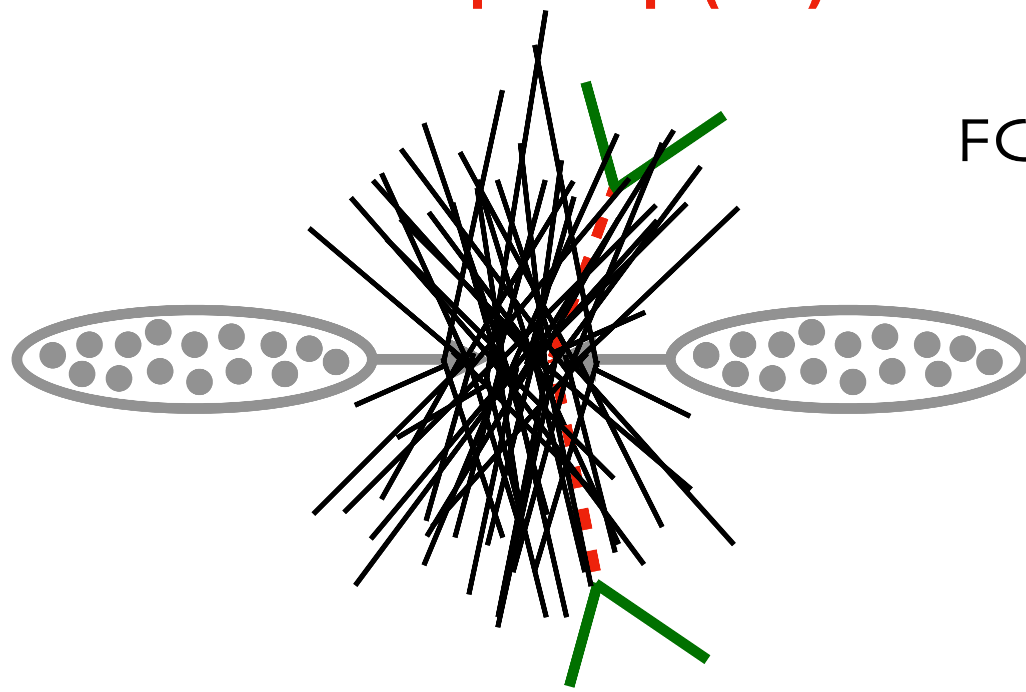
Increased Luminosity = Increased pile-up

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

FCC-hh - ~1000 mean PU interactions

Moving farther away from the IP

Issue of pile-up (PU)



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

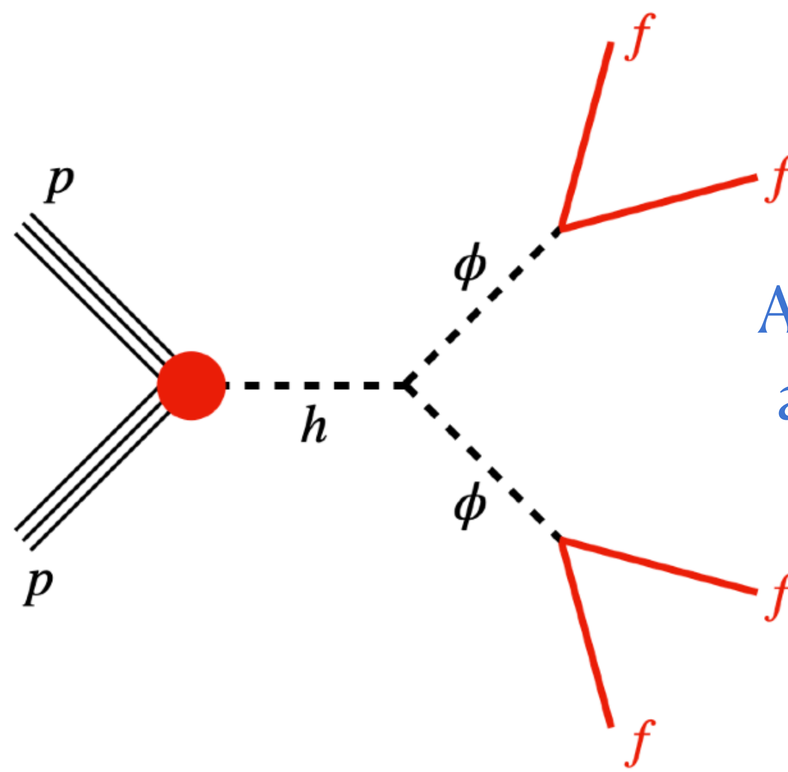
FCC-hh - ~1000 mean PU interactions

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

Decays in the Muon Spectrometer

Bhattacherjee, Matsumoto, RS,
PRD 106 (2022) 9, 095018

Trigger using prompt object associated with the production of the LLP



Analysis looks for displaced activity in the MS from the LLP decay

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

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

CMS MS @ HL-LHC

Observation of 50 events required

Backgrounds

$\text{Br}(h \to \phi\phi) \times \text{Br}(\phi \to \mu^+\mu^-) < 1.1 \times 10^{-5}$ for $m_\phi = 60\,\text{GeV}, c\tau = 0.5\,\text{m}$

$\text{Br}(h \to \phi\phi) \times \text{Br}(\phi \to b\bar{b}) < 5.9 \times 10^{-5}$ for $m_\phi = 60\,\text{GeV}, c\tau = 5\,\text{m}$

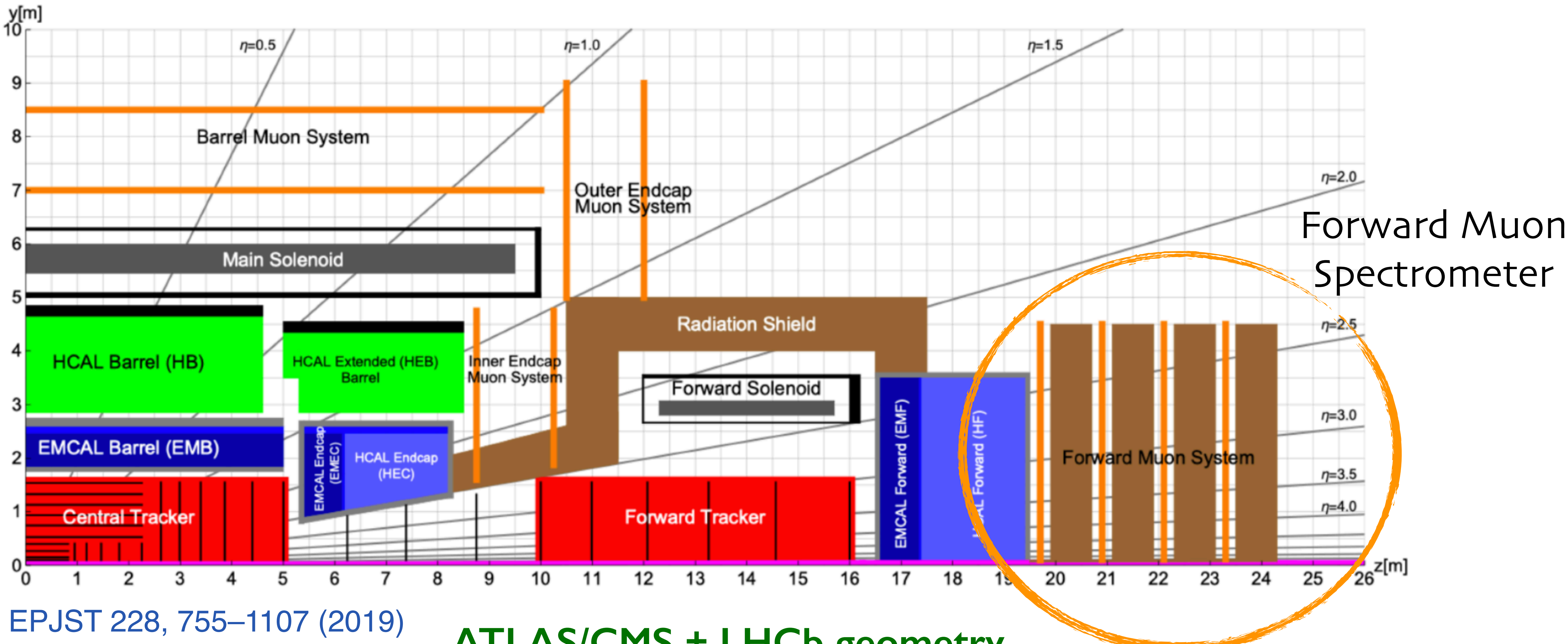
Muon Spectrometer only analysis - sensitive to higher decay lengths

The FCC-hh Muon Spectrometer

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

FCC-hh Reference Detector

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



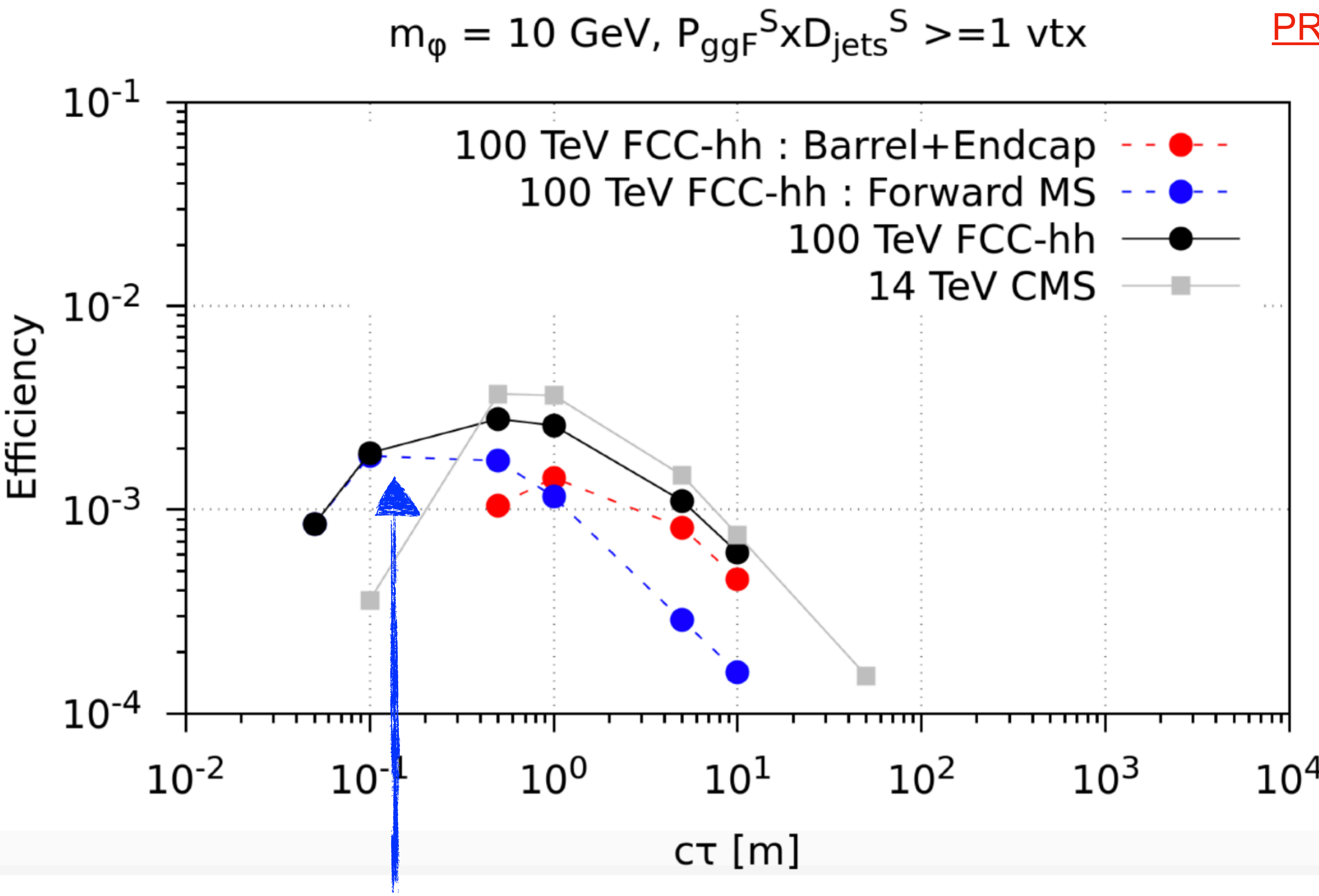
EPJST 228, 755–1107 (2019)

ATLAS/CMS + LHCb geometry

ANY BENEFIT?

The FCC-hh Muon Spectrometer

Bhattacherjee, Matsumoto, RS, PRD 106 (2022) 9, 095018



Forward MS increases sensitivity to lower decay lengths

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

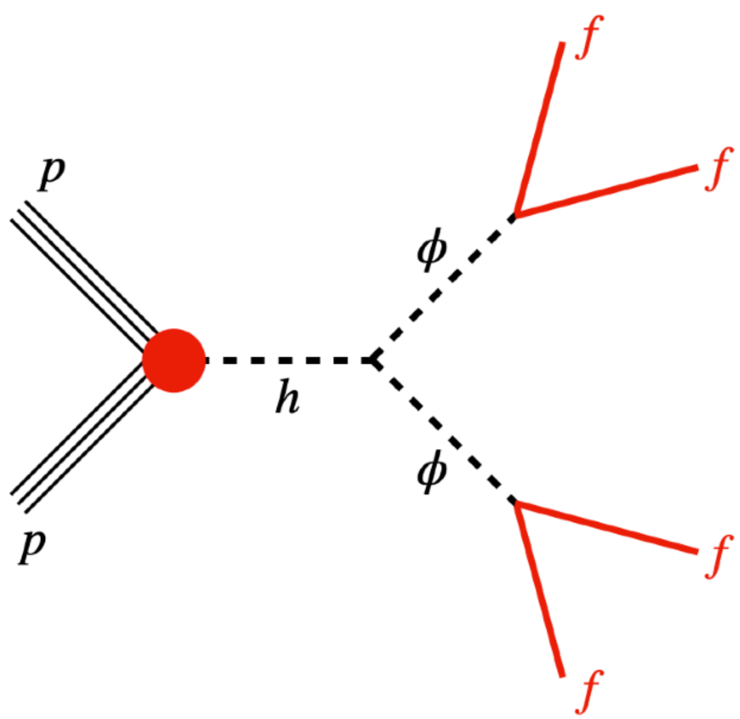
$$d = \beta\gamma c\tau$$

$\downarrow$ $\uparrow$

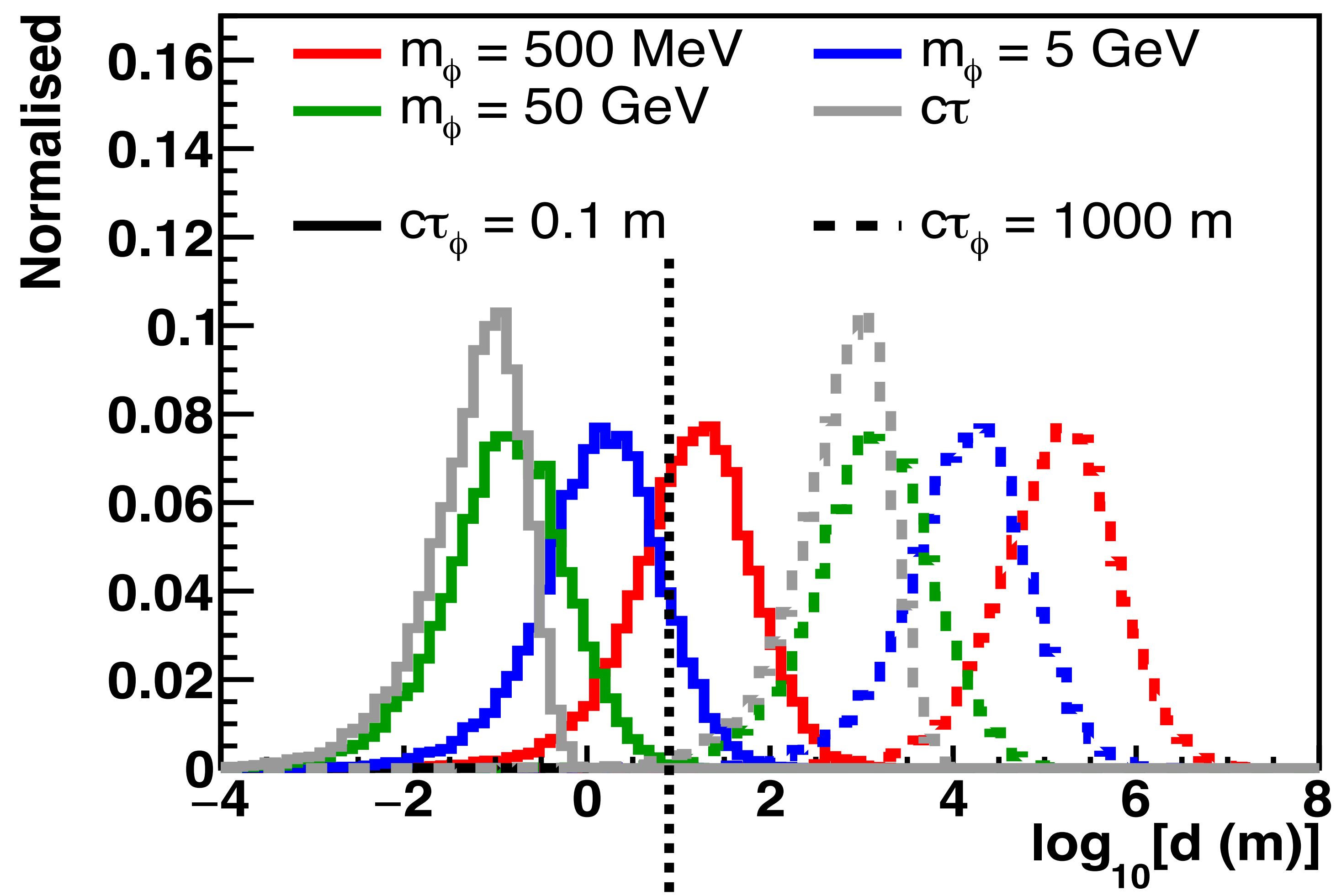
More boost in the forward direction

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

What about LLPs traveling farther?



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

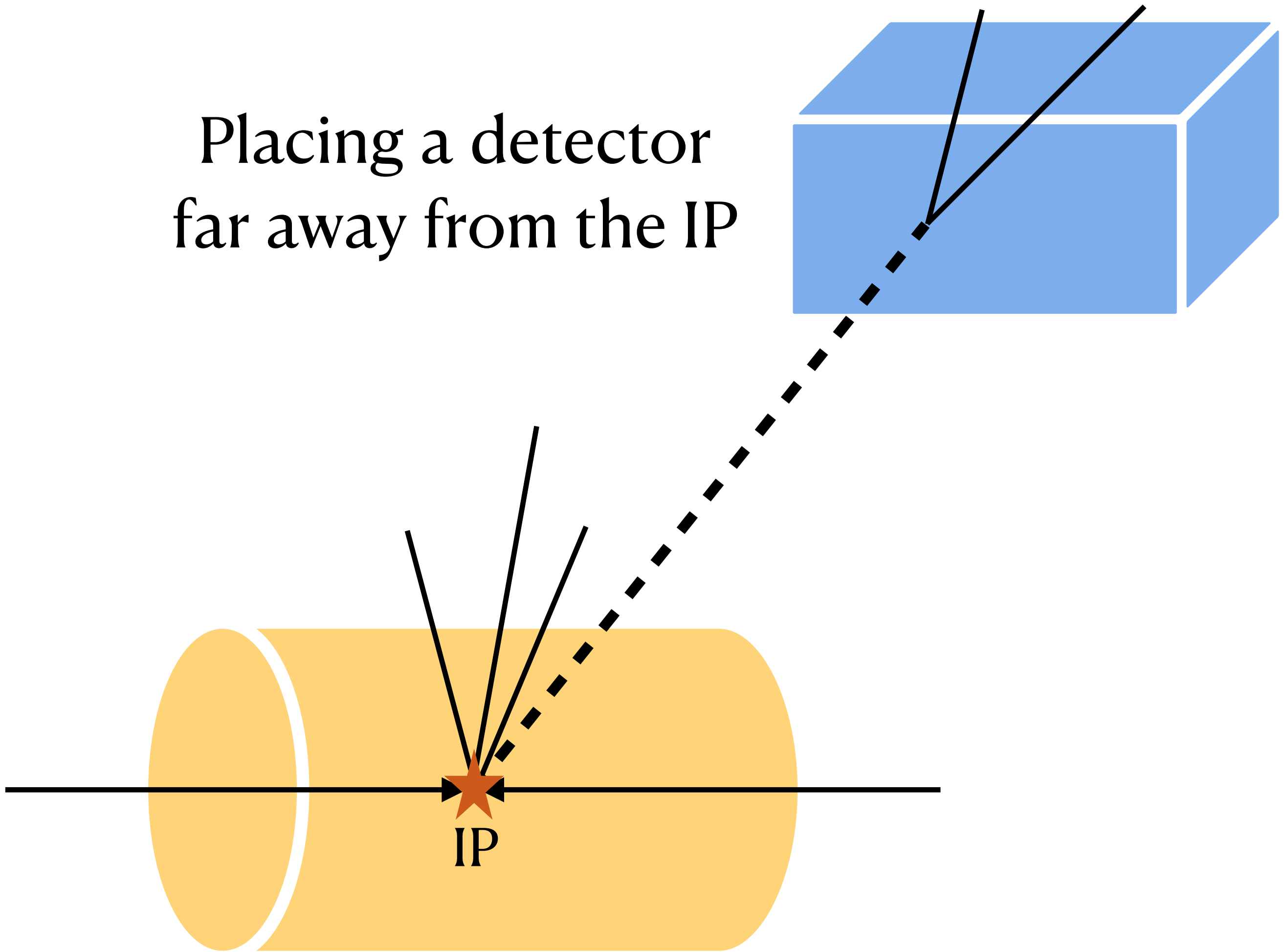


ATLAS and CMS main detectors can probe

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

Dedicated detectors for LLPs

Placing a detector far away from the IP



Small solid angle coverage

Dedicated detectors for LLPs

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Small solid
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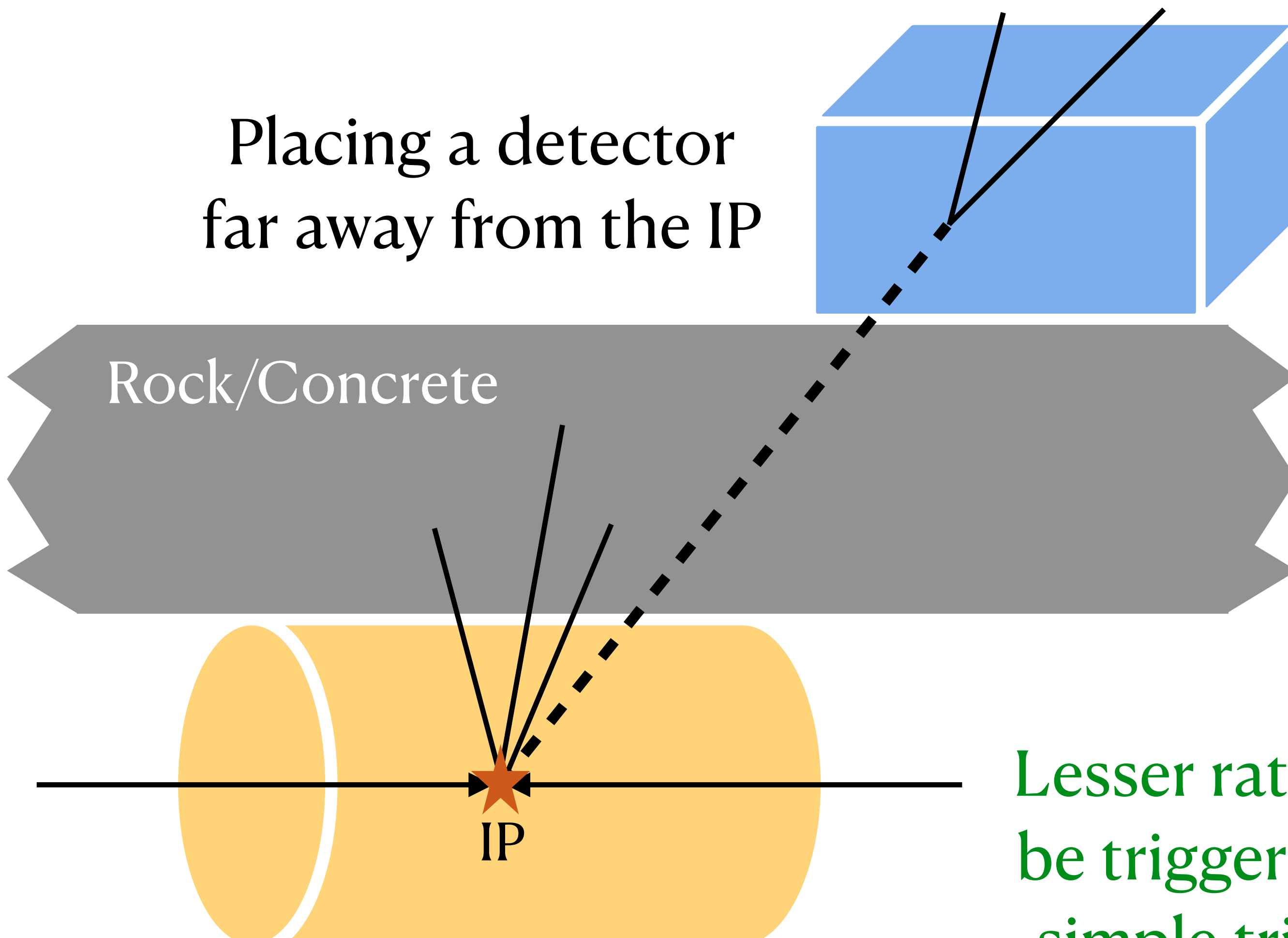


Shielding - reduces
backgrounds
drastically

Lesser rate - can
be triggerless or
simple triggers

Dedicated
detectors can
be used to
trigger on main
detectors

Multiple detector
components?
Mostly RPCs.
Calorimeter can be present,
like in FASER

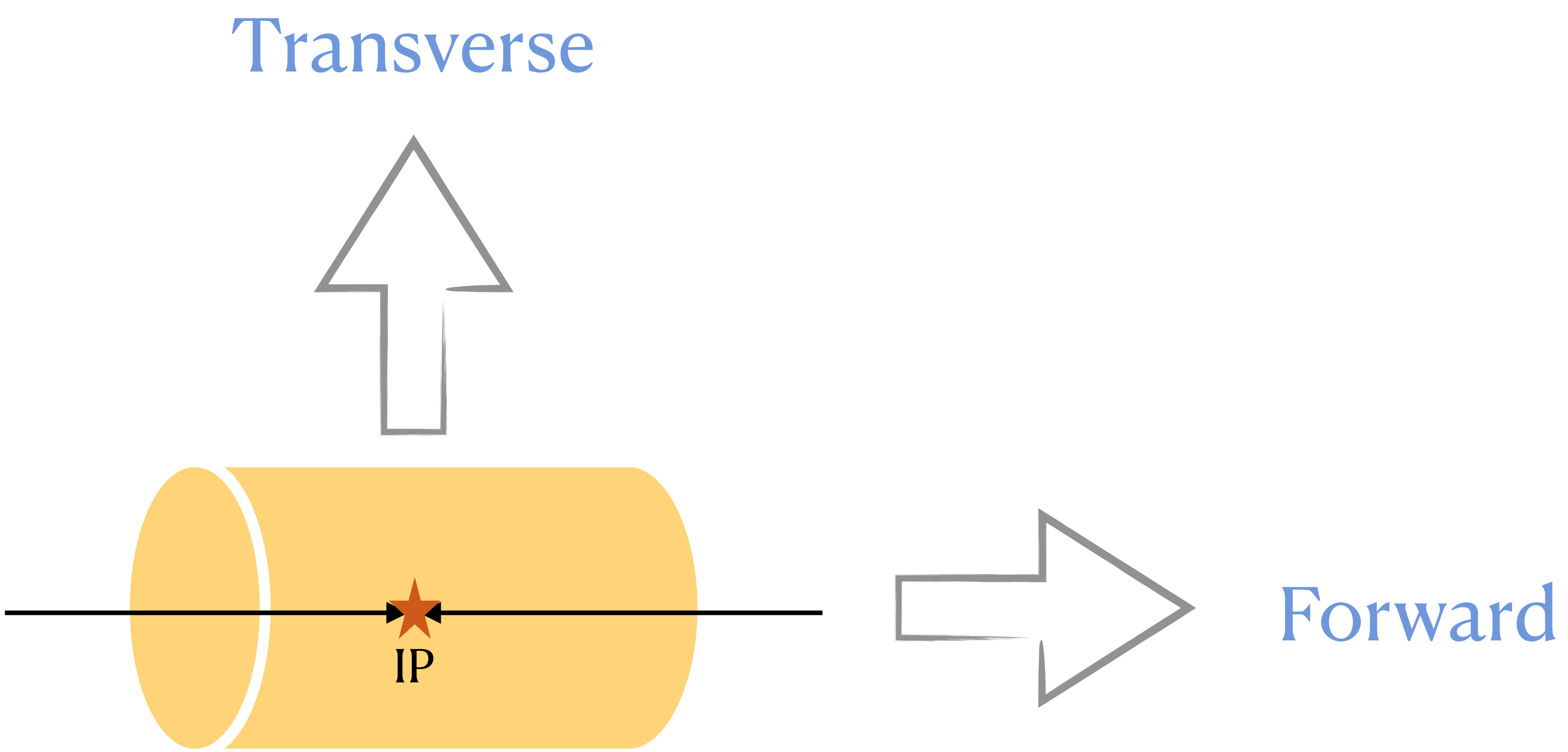
Reconstruction of LLP
properties possible?

Jared Barron and David Curtin,
JHEP 12 (2020) 061

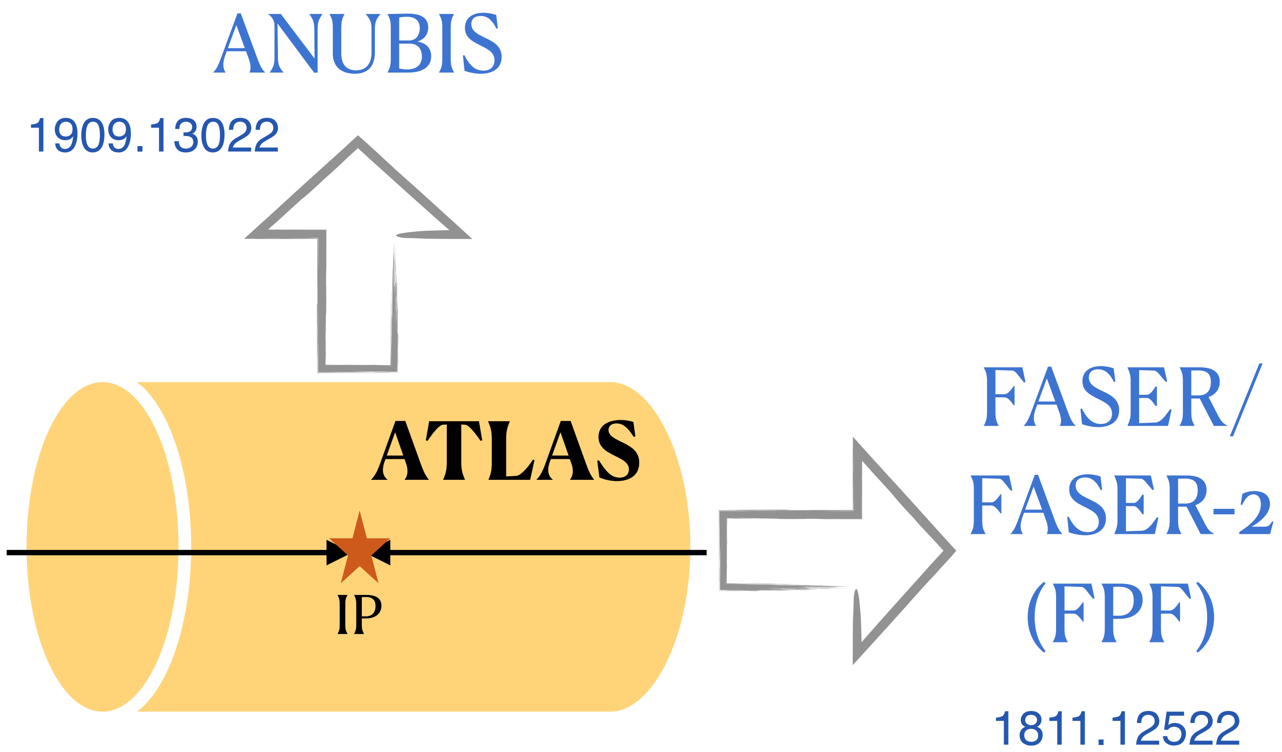
Transverse and forward detectors for (HL-)LHC

Limited solid angle coverage →

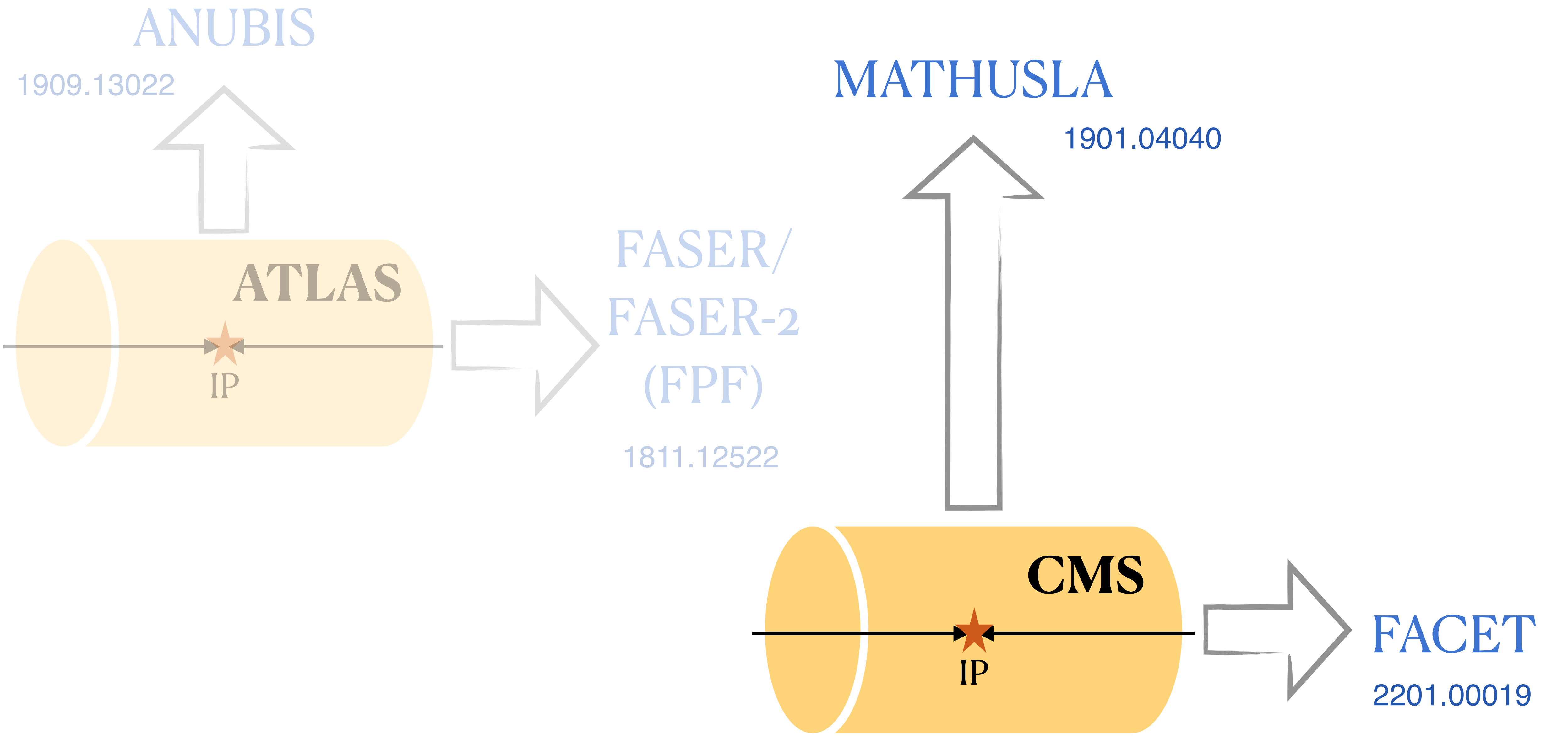
*need dedicated detectors in both the **transverse** and **forward** directions for capturing LLPs with different kinematic distributions.*



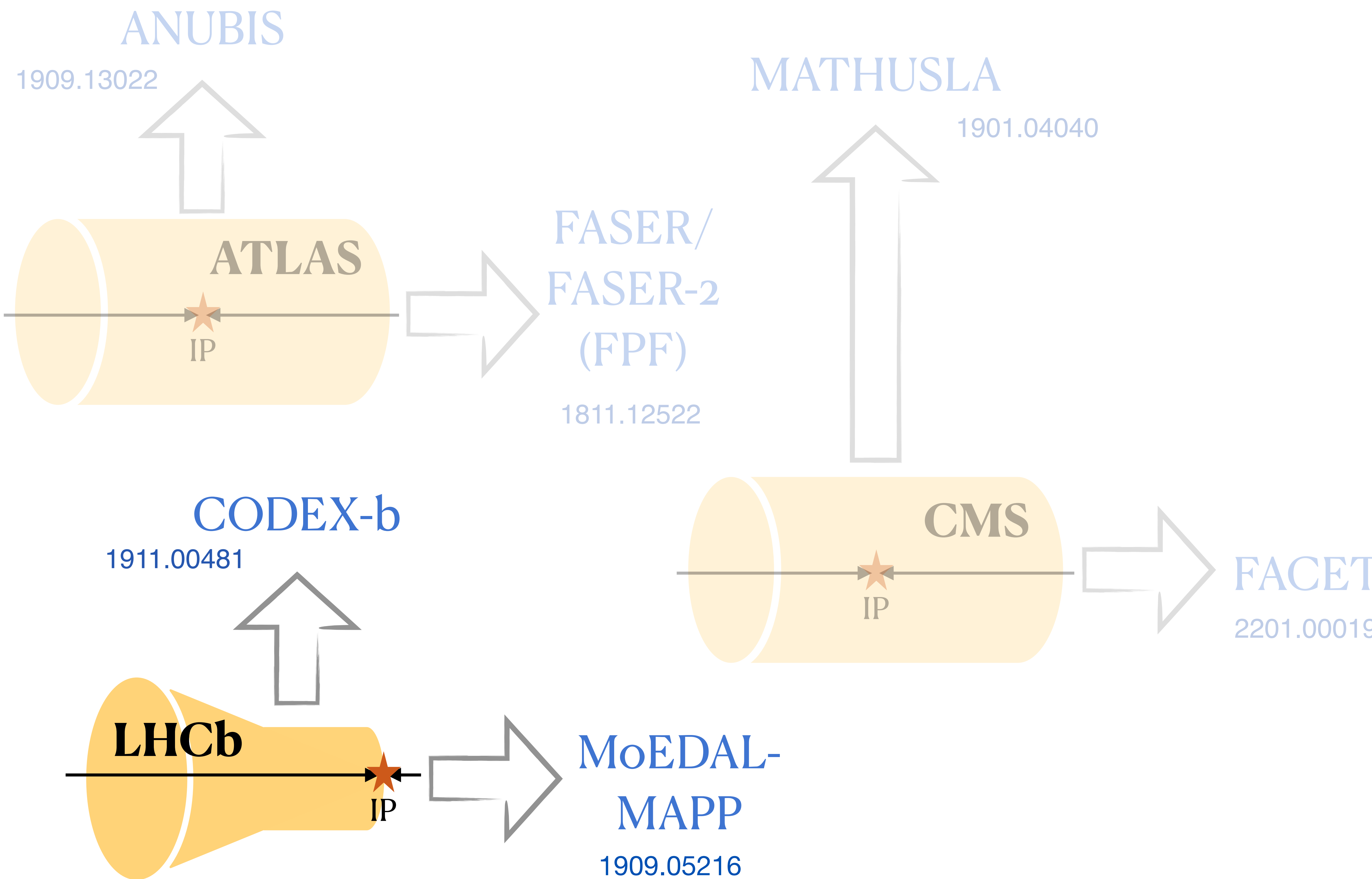
Transverse and forward detectors for (HL-)LHC



Transverse and forward detectors for (HL-)LHC

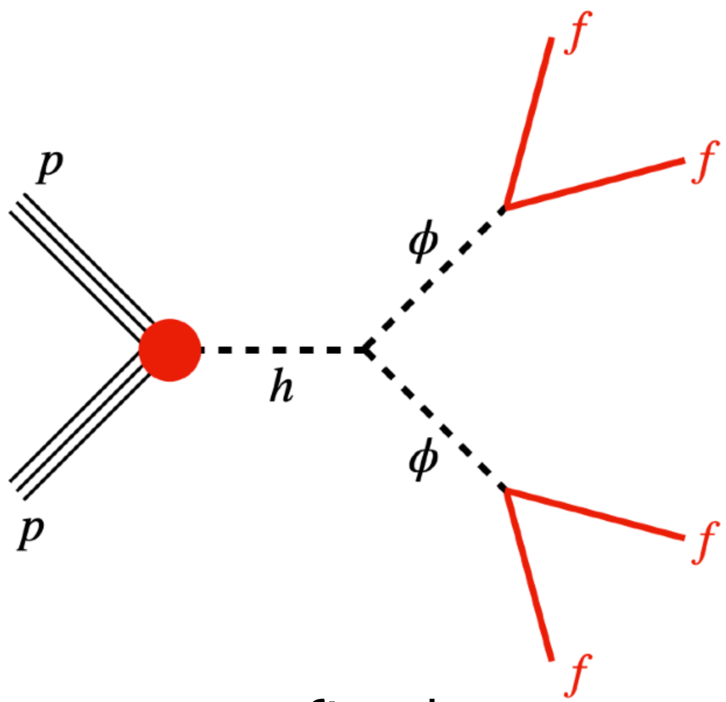


Transverse and forward detectors for (HL-)LHC

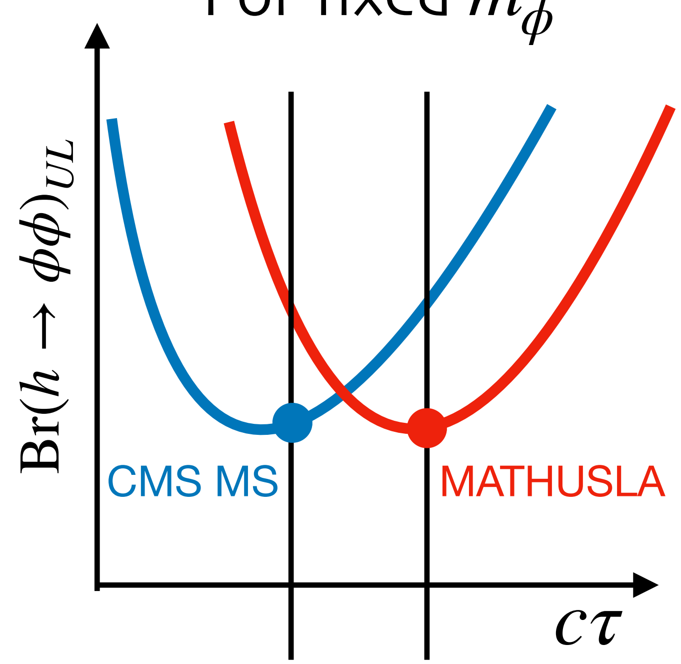


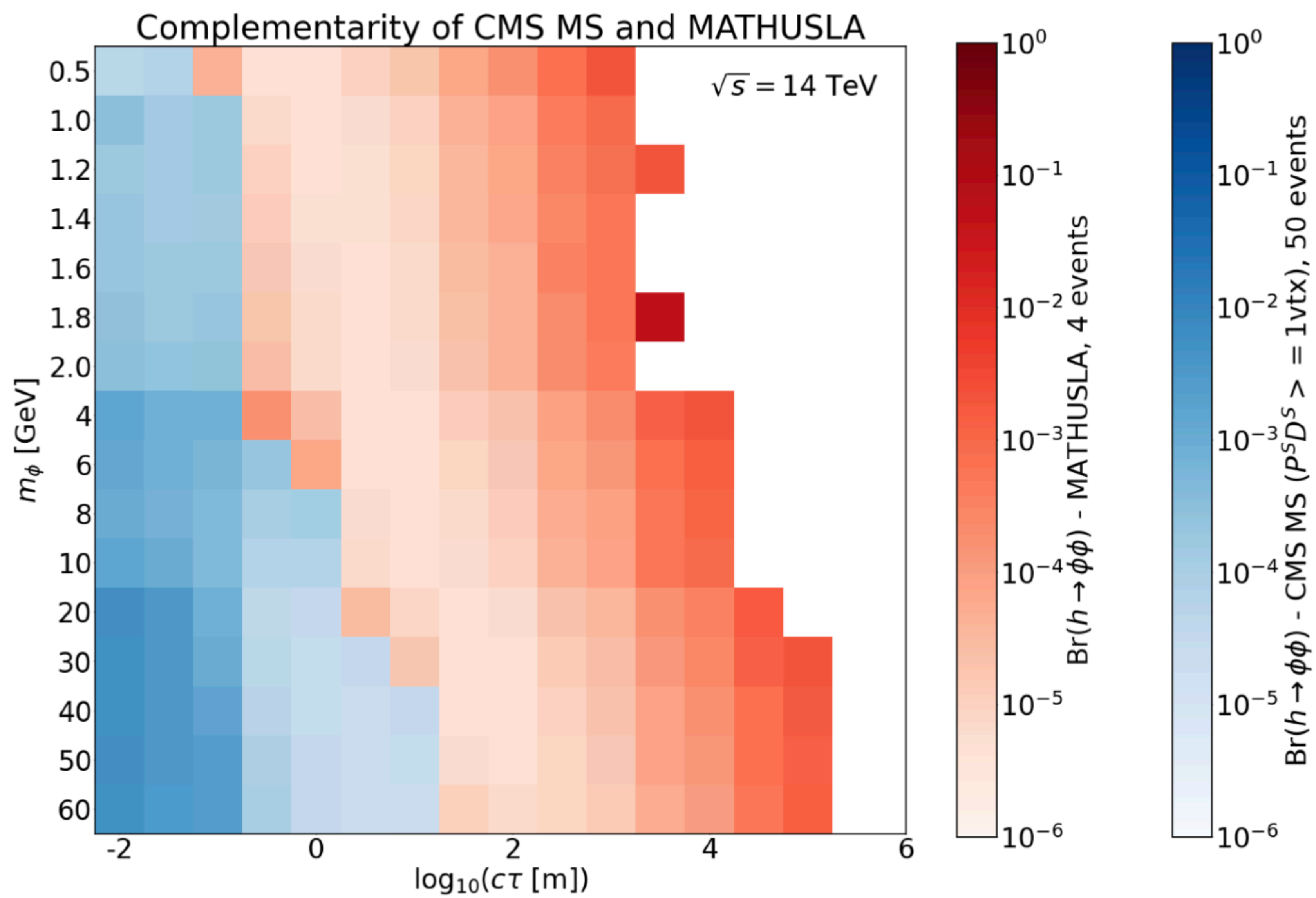
Complementary role of dedicated detectors

Bhattacherjee, Matsumoto, RS, PRD 106 (2022) 9, 095018



For fixed m_ϕ





CMS MS + MATHUSLA:

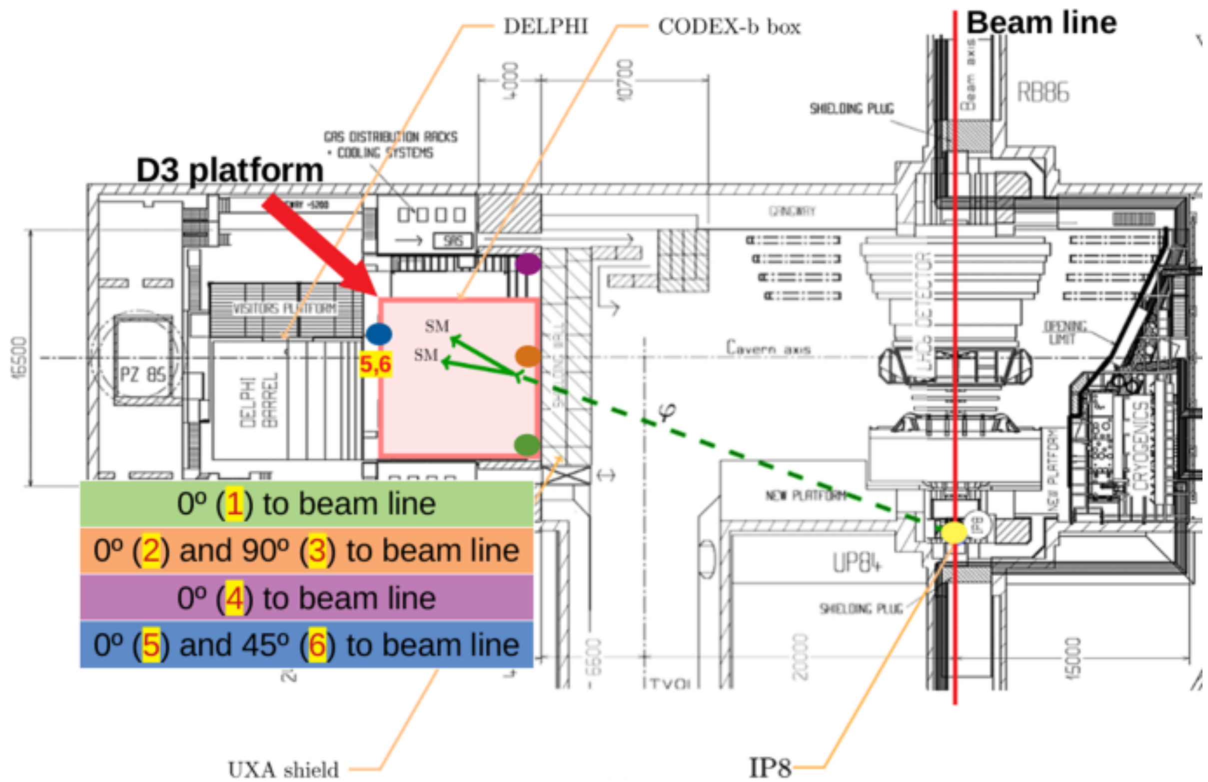
can probe $c\tau \lesssim 10^5\,\mathrm{m}$ for $m_\phi = 60\,\mathrm{GeV}$,

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

Why should we talk about dedicated detectors at FCC-hh now?

For LHC or HL-LHC, the dedicated detectors are accommodated in empty shafts or available halls around the main detectors

For example, see for CODEX-b



EPJC 80, 1177 (2020)

But this might not be optimal for the LLP models beyond the SM

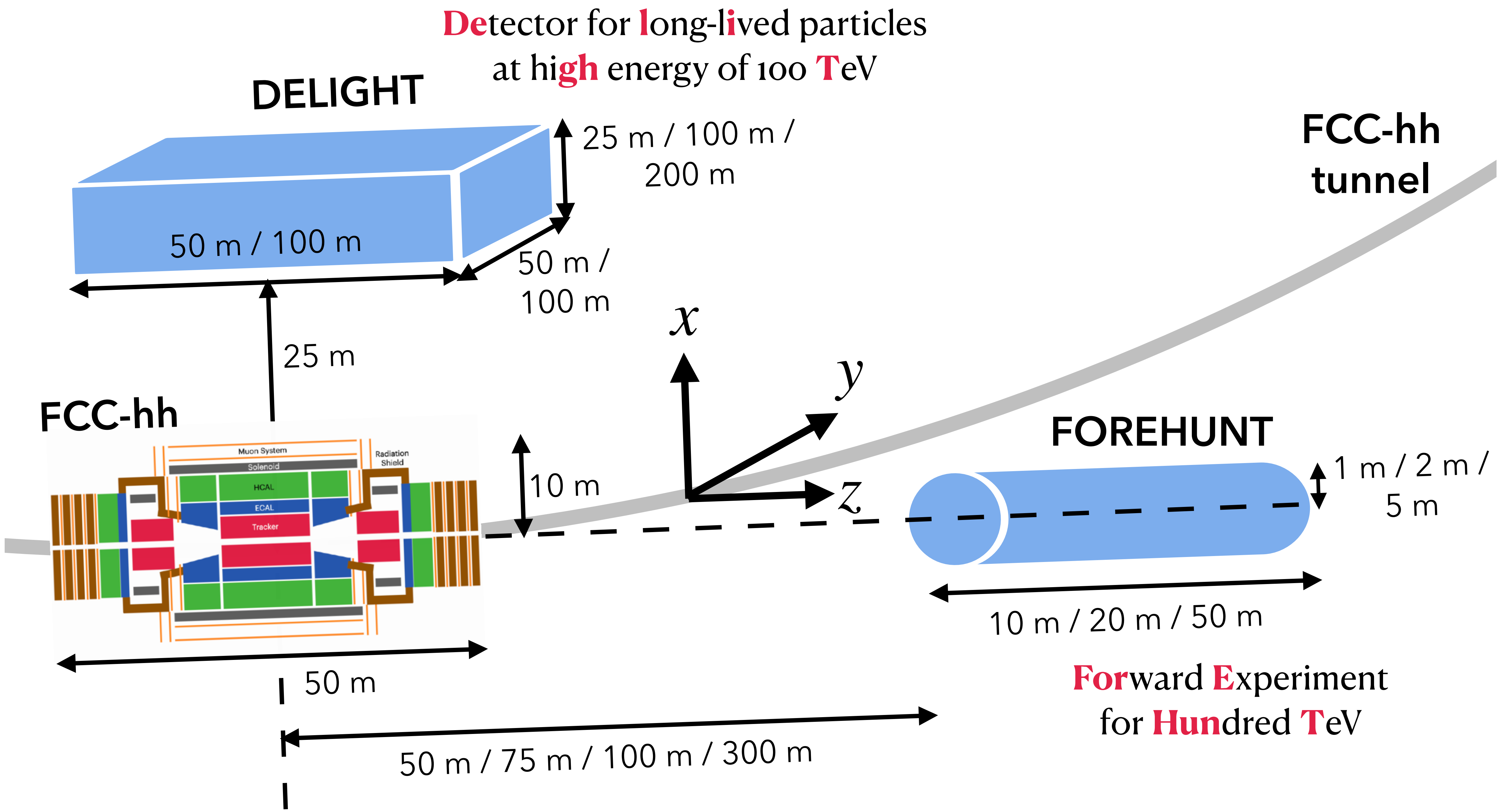
The Future Colliders are in their conceptual design phase now

⇒

Optimise and integrate dedicated LLP detectors with the main detector design

Proposal for DELIGHT and FOREHUNT @ FCC-hh

FCC-hh design under study — Room for optimisation



Proposal for DELIGHT and FOREHUNT @ FCC-hh

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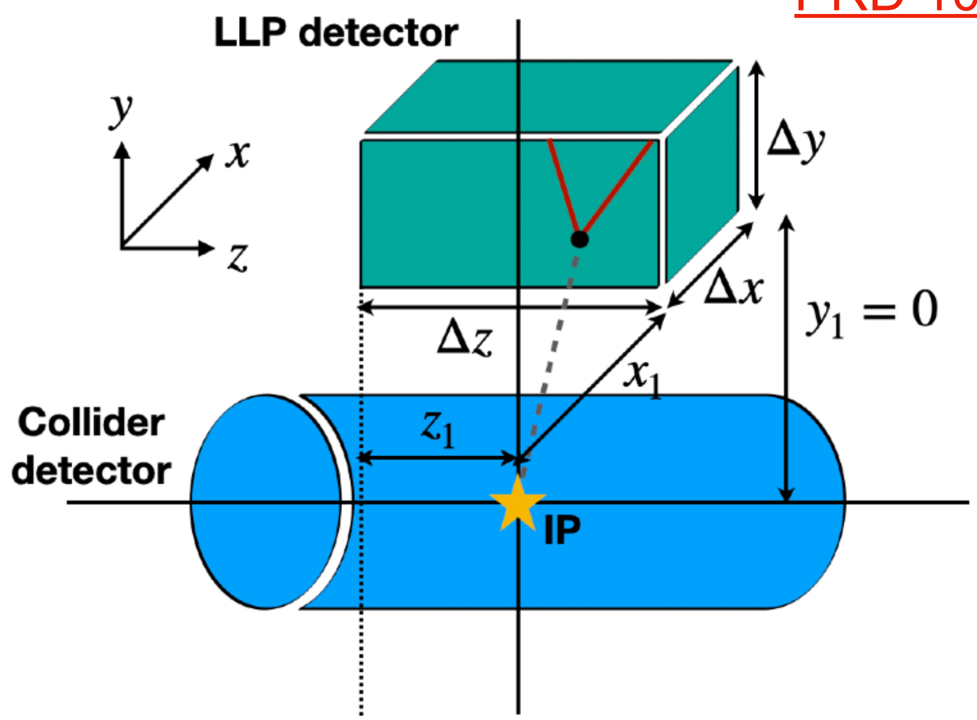
Bhattacherjee, Matsumoto, RS, PRD 106 (2022) 9, 095018

(A) Transverse detector:

DELIGHT

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



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

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

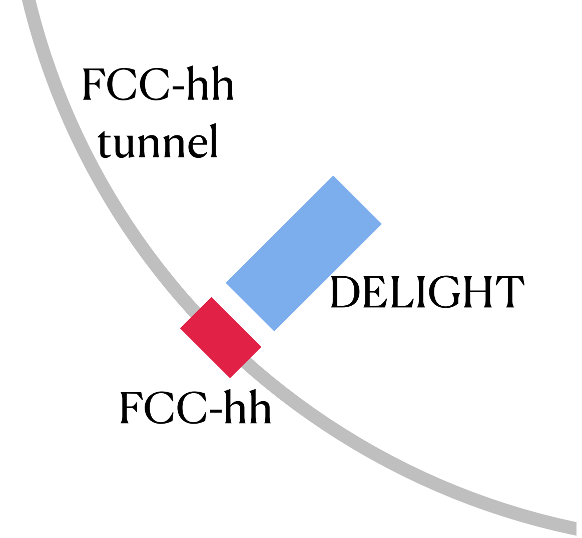
DELIGHT (B): Four times bigger than the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 100 \times 100 \times 100\,\mathrm{m}^3$.

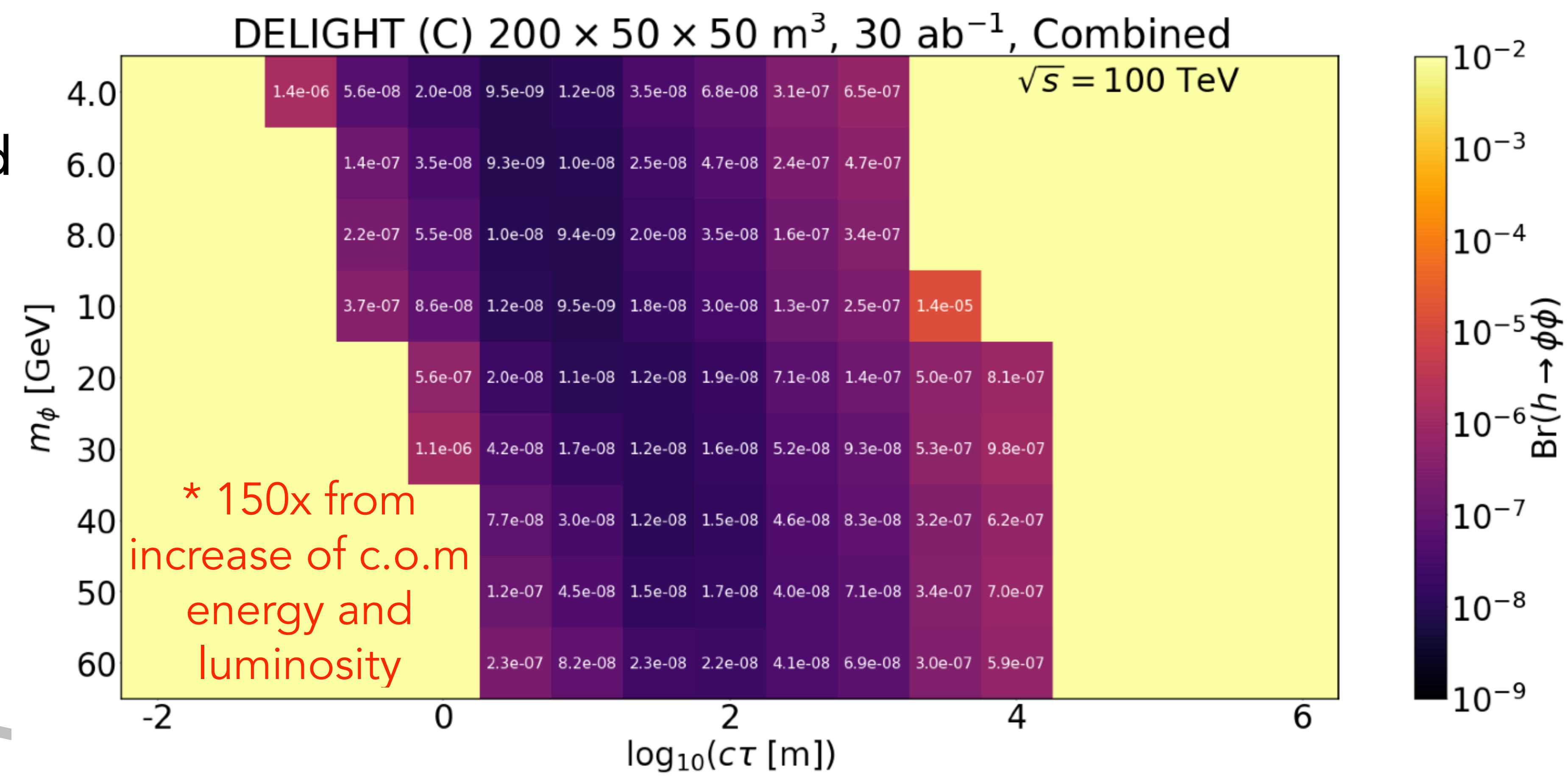
DELIGHT (C): Twice the decay volume as the MATHUSLA detector with different dimensions, i.e. $\Delta x \times \Delta y \times \Delta z = 200 \times 50 \times 50\,\mathrm{m}^3$.

LLPs from Higgs boson decay in DELIGHT

- 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

Improvement by 430* × compared to MATHUSLA





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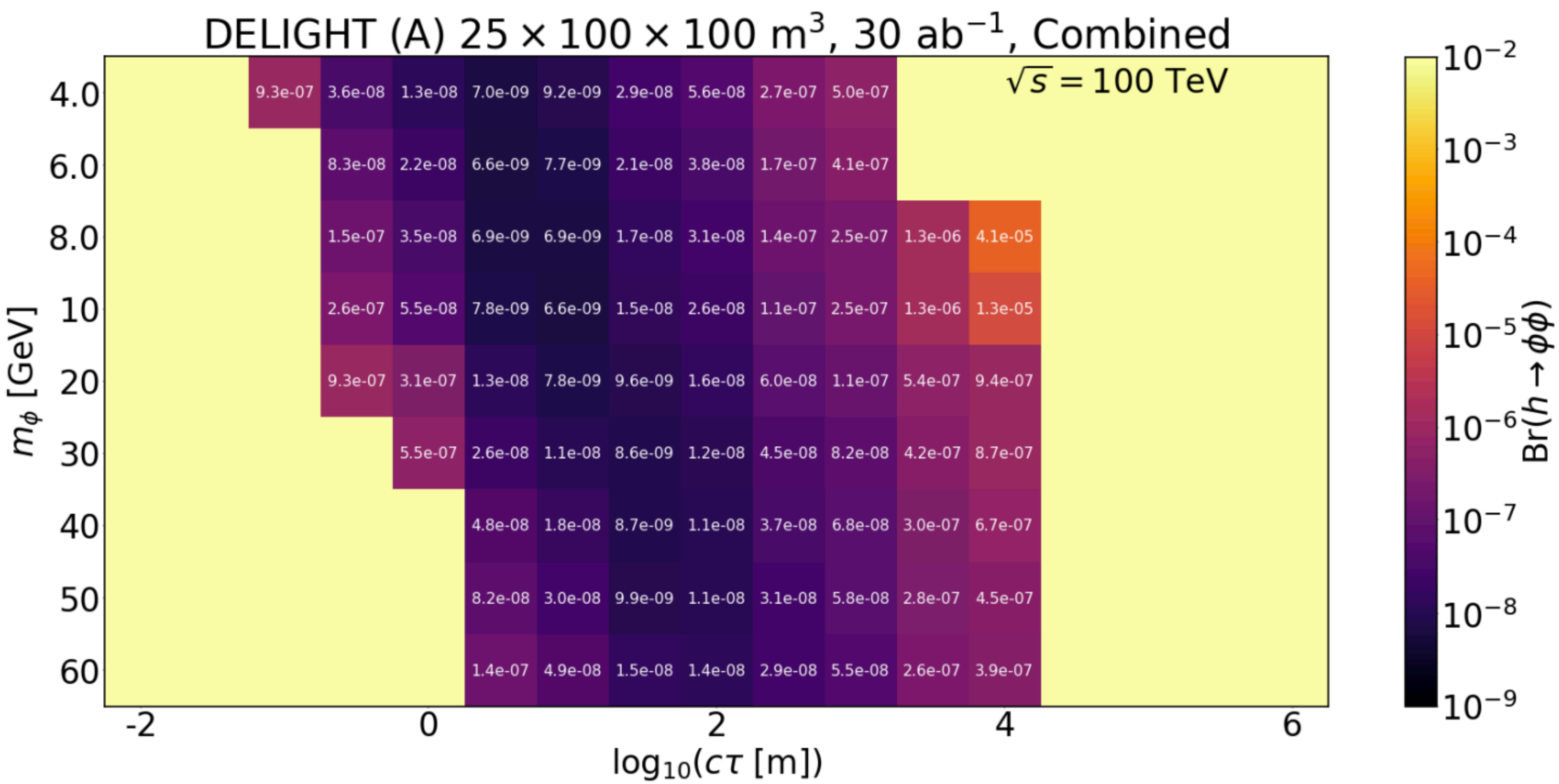


Similar or slightly better performance than DELIGHT-C

Even though decay volume is half of DELIGHT-C

Cross-sectional area towards the IP four times larger - increased solid angle coverage

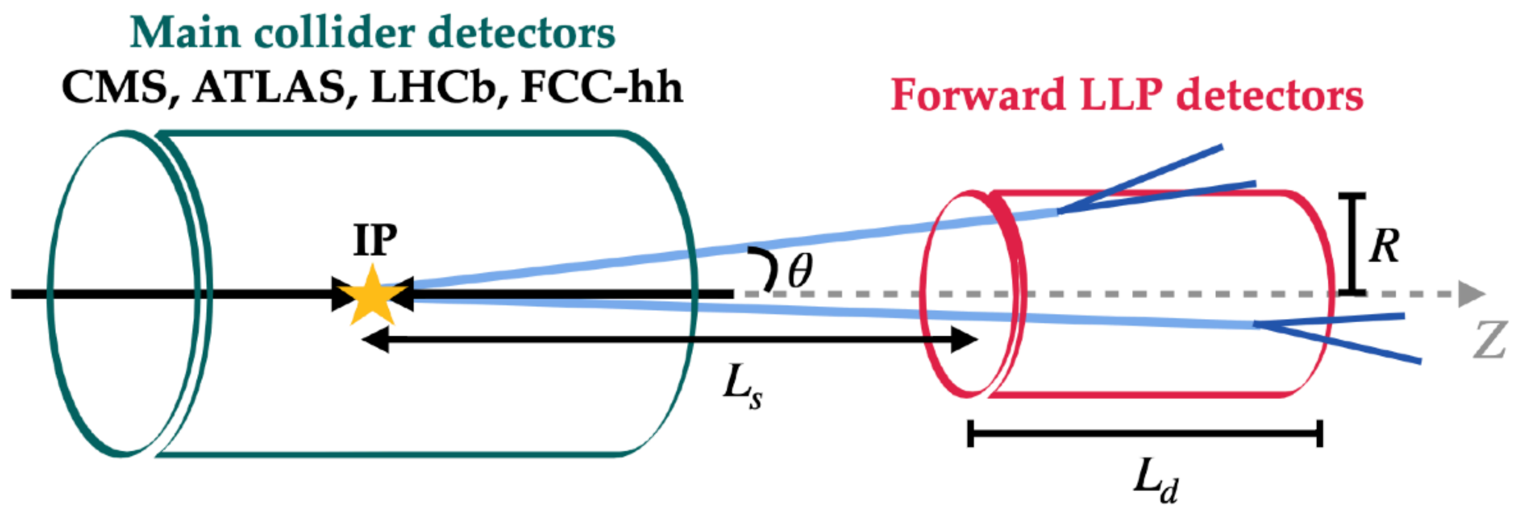
Proposal for DELIGHT and FOREHUNT @ FCC-hh

FCC-hh design under study — Room for optimisation

(B) Forward detector:

FOREHUNT

Forward **E**xperiment
for **Hun**dred **T**eV



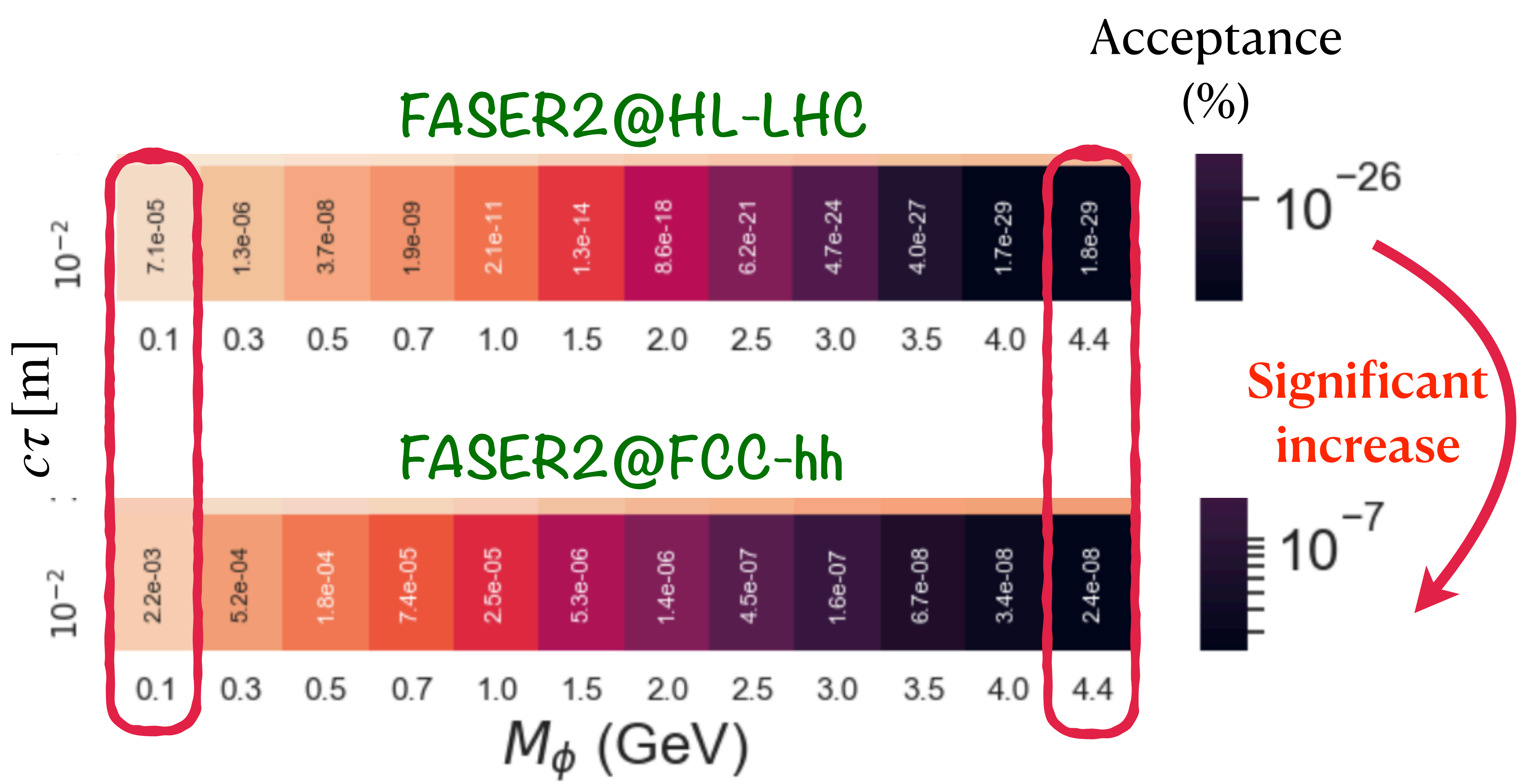
L_s
R
L_d

Bhattacherjee, Dreiner, Ghosh, Matsumoto, RS, Solanki,
PRD 110 (2024) 1, 015036

FASER-2 @ HL-LHC vs FASER-2 @ FCC-hh

$B^{\pm} \rightarrow K^{\pm}\phi$

FASER2 $L_s = 480$ m, $R = 1$ m, $L_d = 5$ m, $p_\phi > 100$ GeV



B-mesons more energetic at 100 TeV collider

↓

The LLP coming from *B*-meson decay has larger boost

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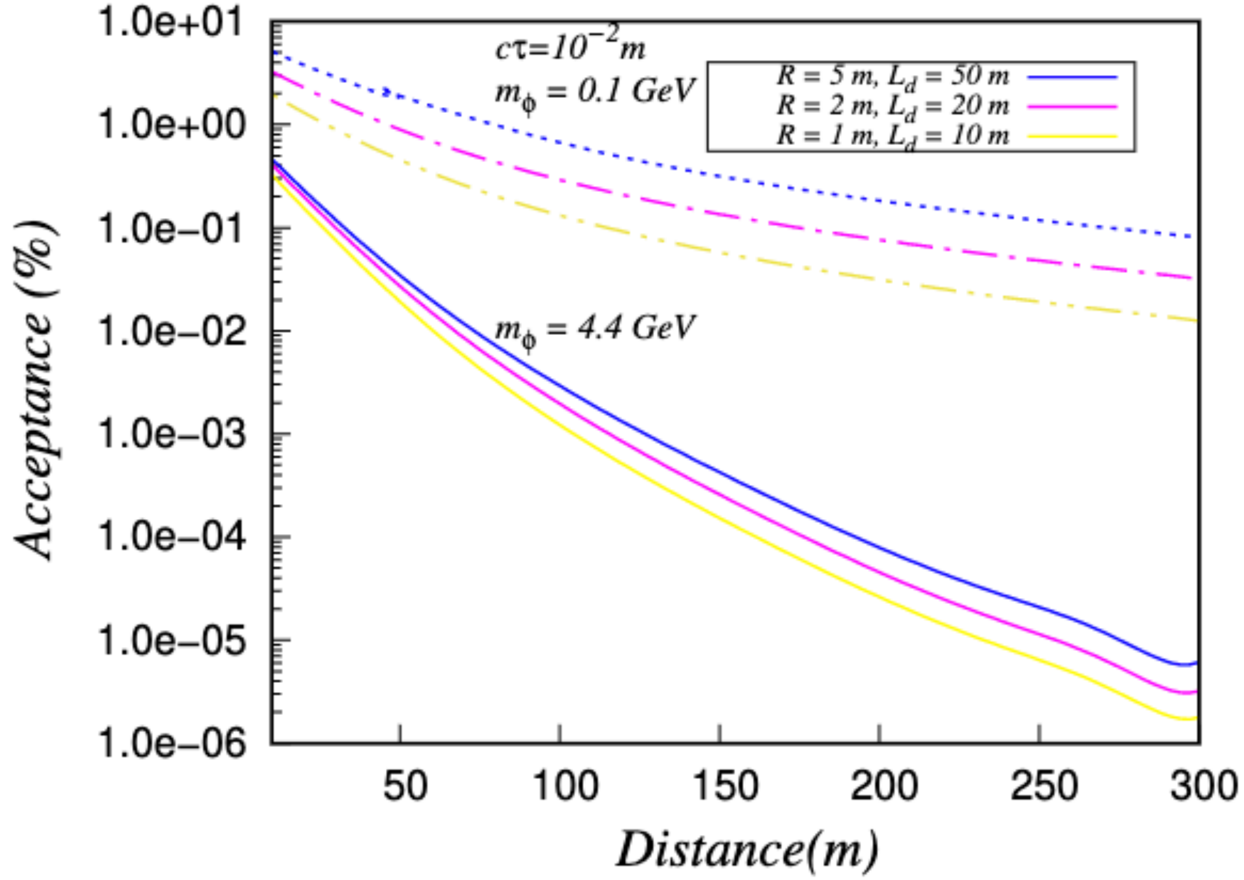
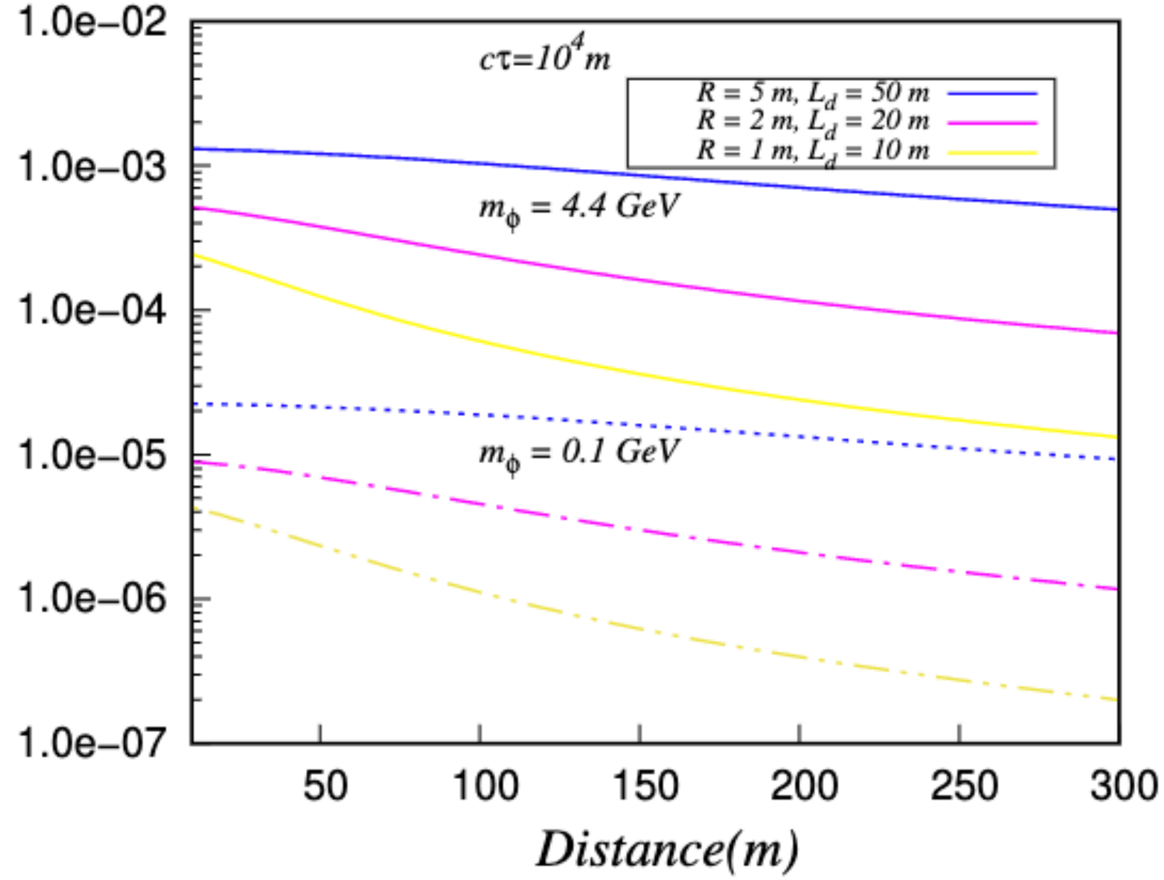
Increased efficiency for smaller decay lengths and heavier masses

Optimising FOREHUNT for LLPs from B-meson decay

$c\tau = 10^{-2}$ m



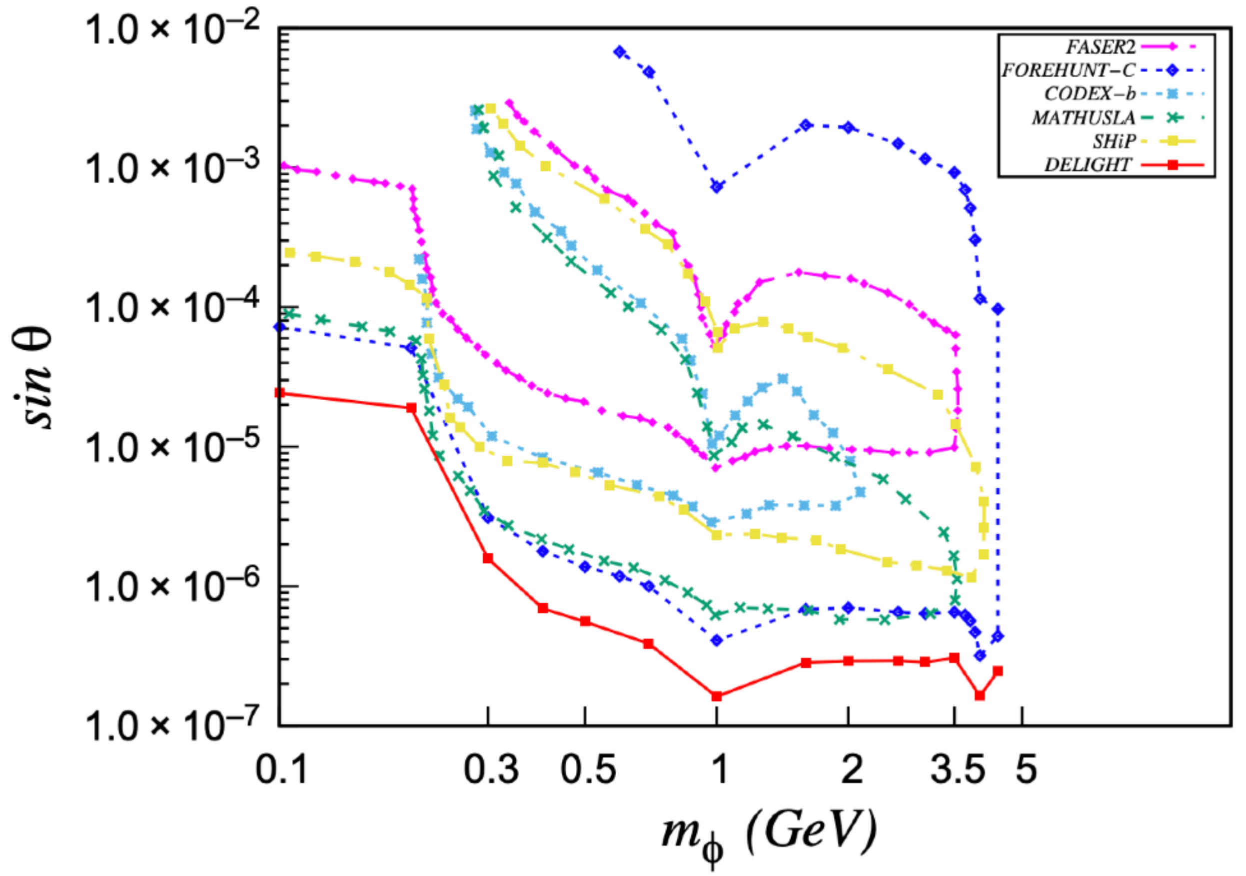
$c\tau = 10^{4}$ m

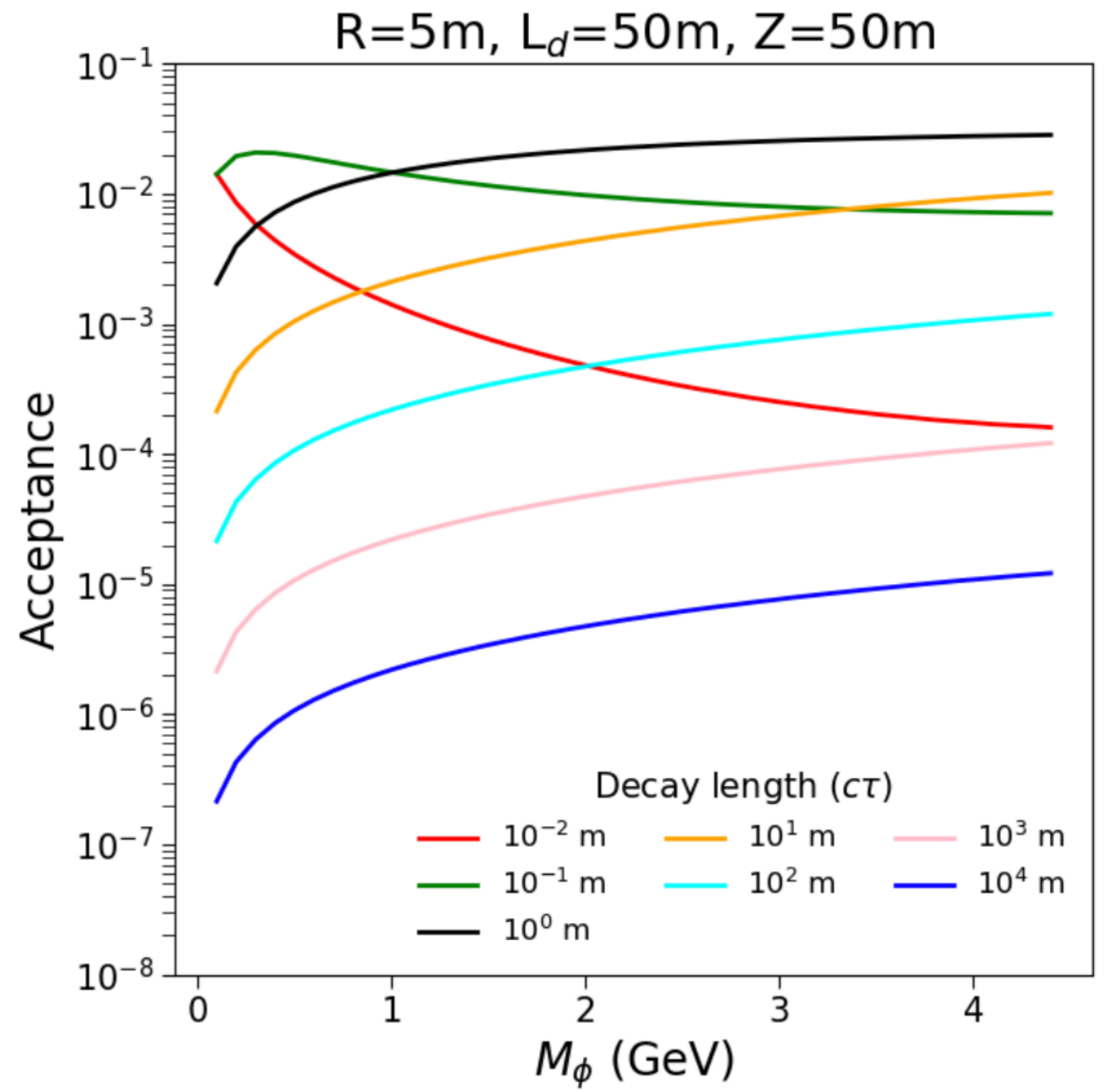


- Decrease of acceptance with increasing distance of the detector is **more prominent for smaller decay length**
- Small decay length: higher acceptance for lighter LLP
  Large decay length: higher acceptance for heavier LLP

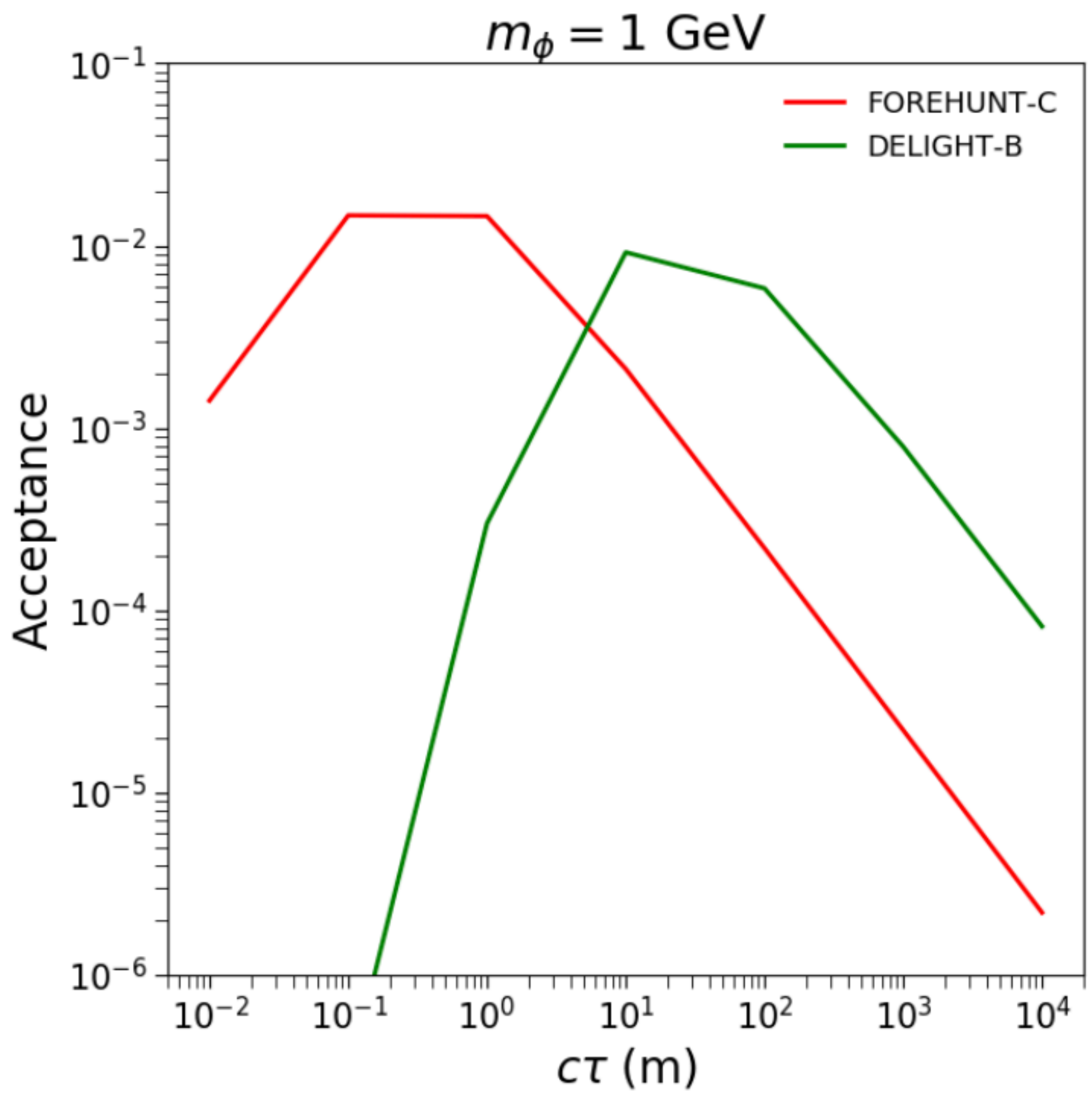
LLPs from B-meson decay in FOREHUNT

Detector Configuration @100 TeV	Radius (R)	Length (L_d)	Position (Z)
FOREHUNT-A	1 m	10 m	50 m
FOREHUNT-B	2 m	20 m	50 m
FOREHUNT-C	5 m	50 m	50 m
FOREHUNT-D	2 m	20 m	75 m
FOREHUNT-E	5 m	50 m	75 m
FOREHUNT-F	5 m	50 m	100 m





LLPs from B-meson decay in FOREHUNT and DELIGHT



LLPs more in *forward direction* for lower $c\tau$ at a particular distance from the interaction point

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

↓

↑

More boost in the forward direction

For smaller decay lengths, FOREHUNT performs better than DELIGHT

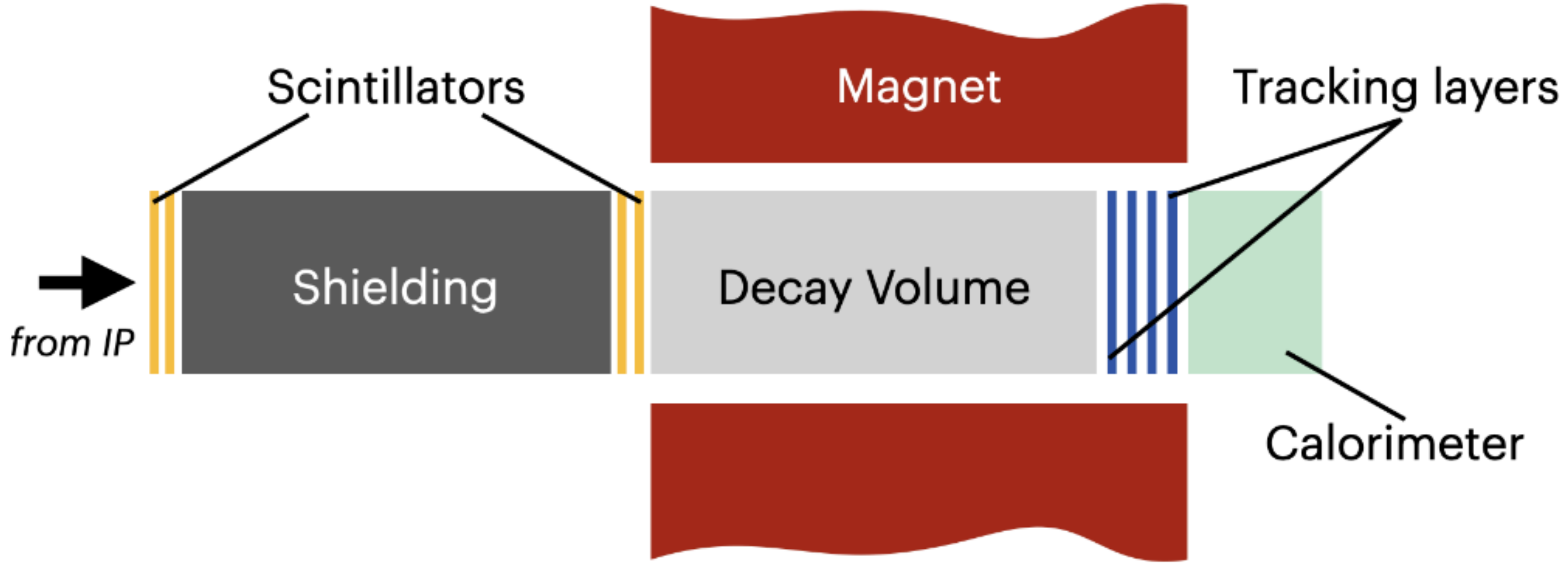
Complementarity between forward and transverse detectors

Backgrounds and possible detector design

1 Muons from the IP

2 Neutral hadrons

3 Neutrinos

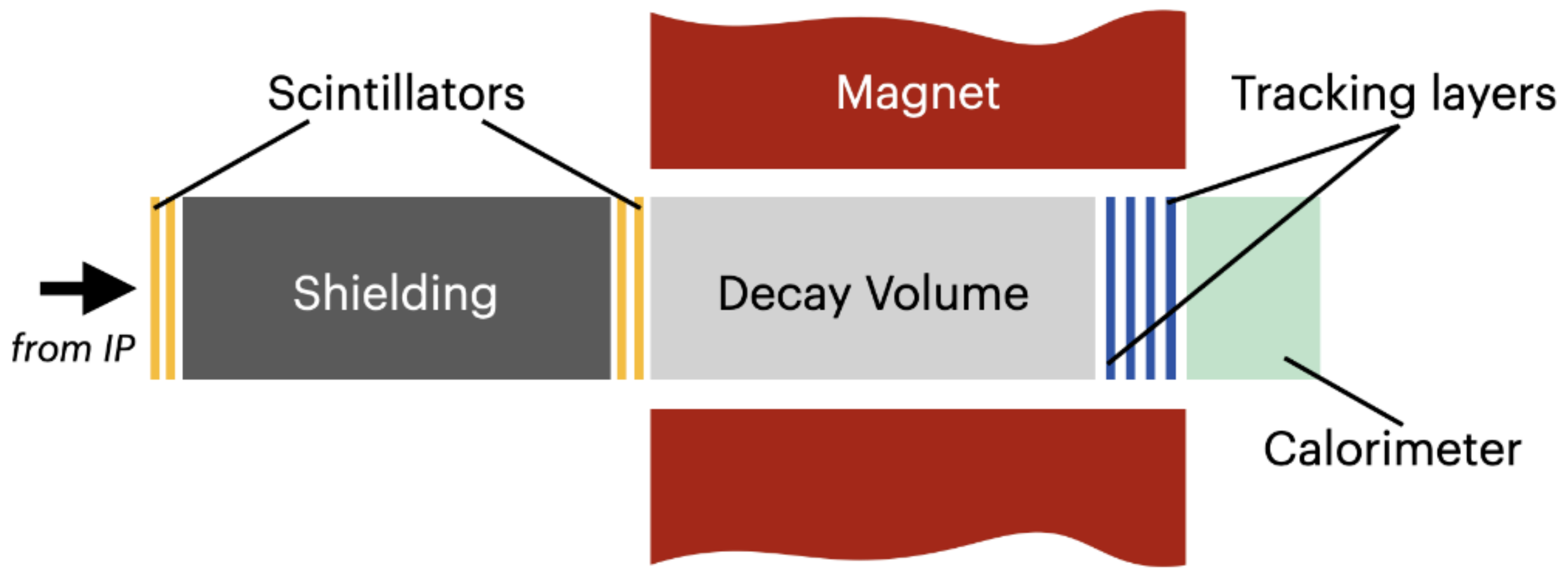


Backgrounds and possible detector design

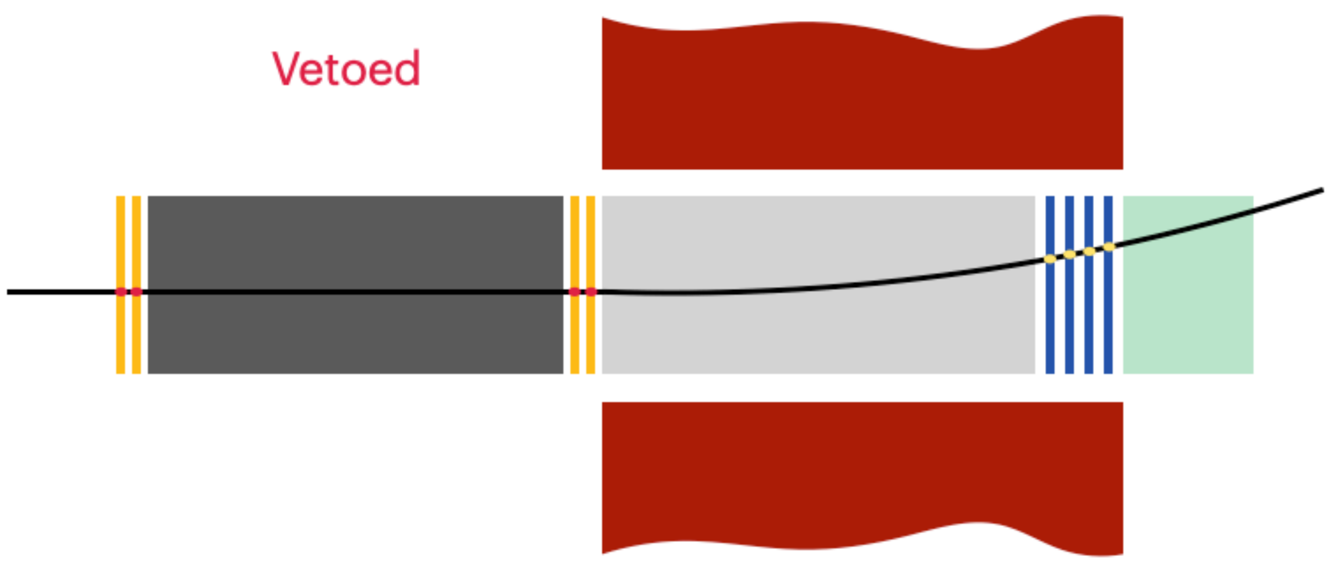
1 Muons from the IP

2 Neutral hadrons

3 Neutrinos



Muons from the IP



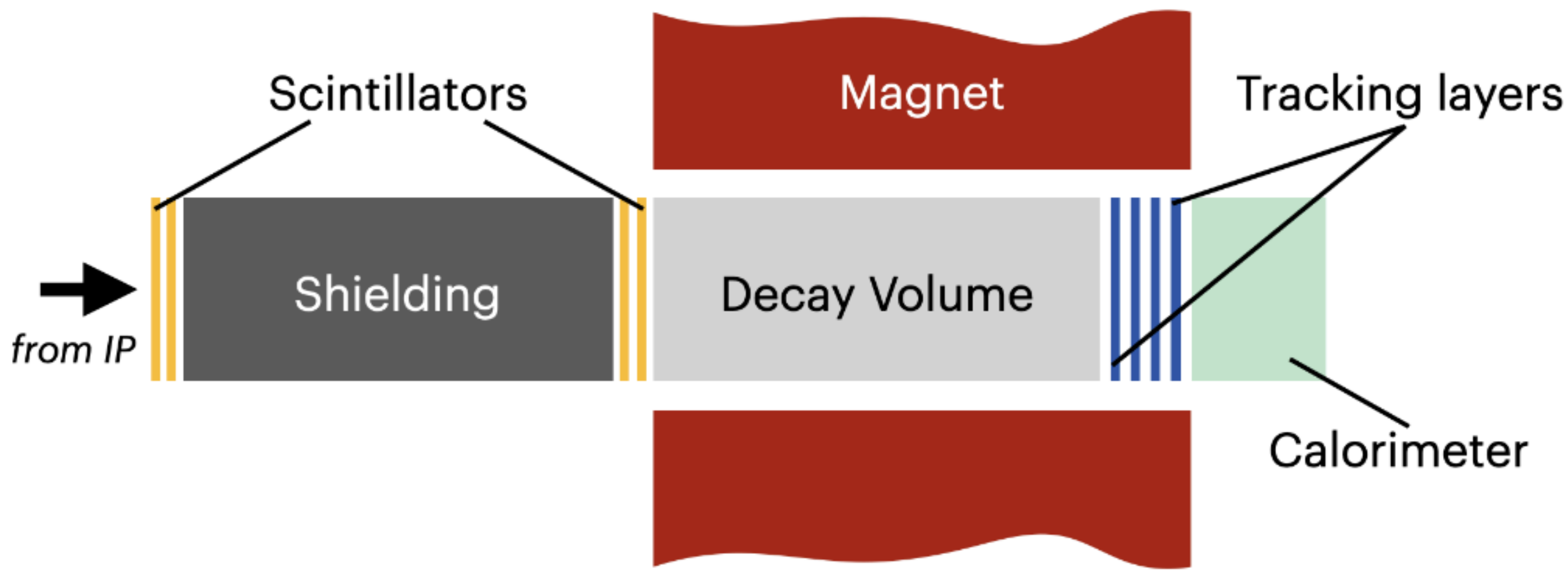
Veto events with hits in any of the four scintillator planes

Backgrounds and possible detector design

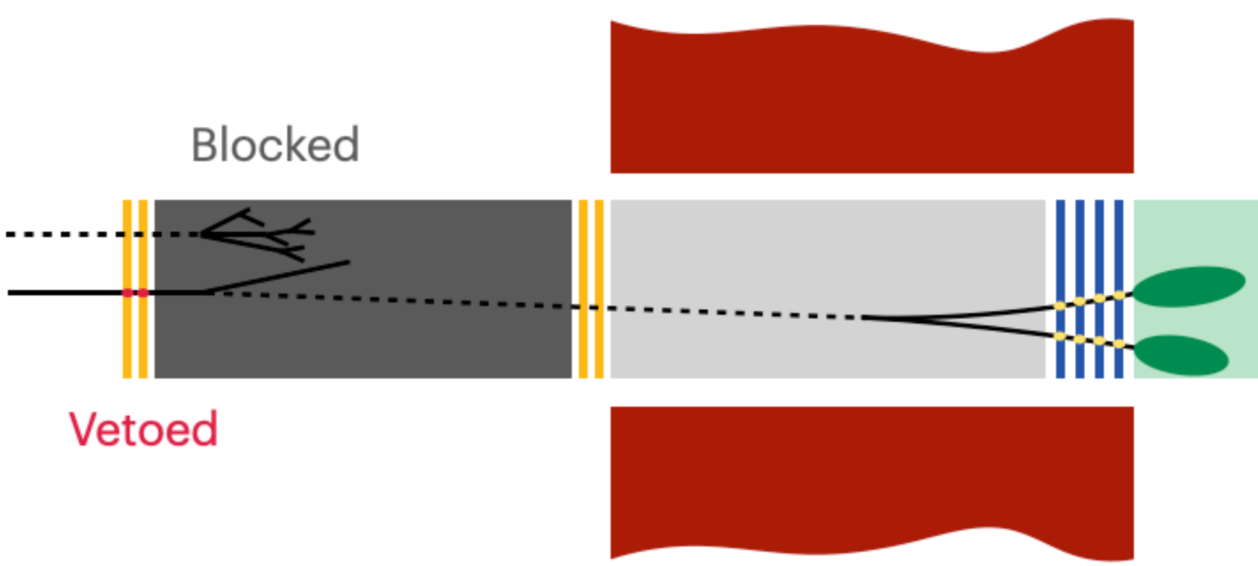
1 Muons from the IP

2 Neutral hadrons

3 Neutrinos



Neutral hadrons



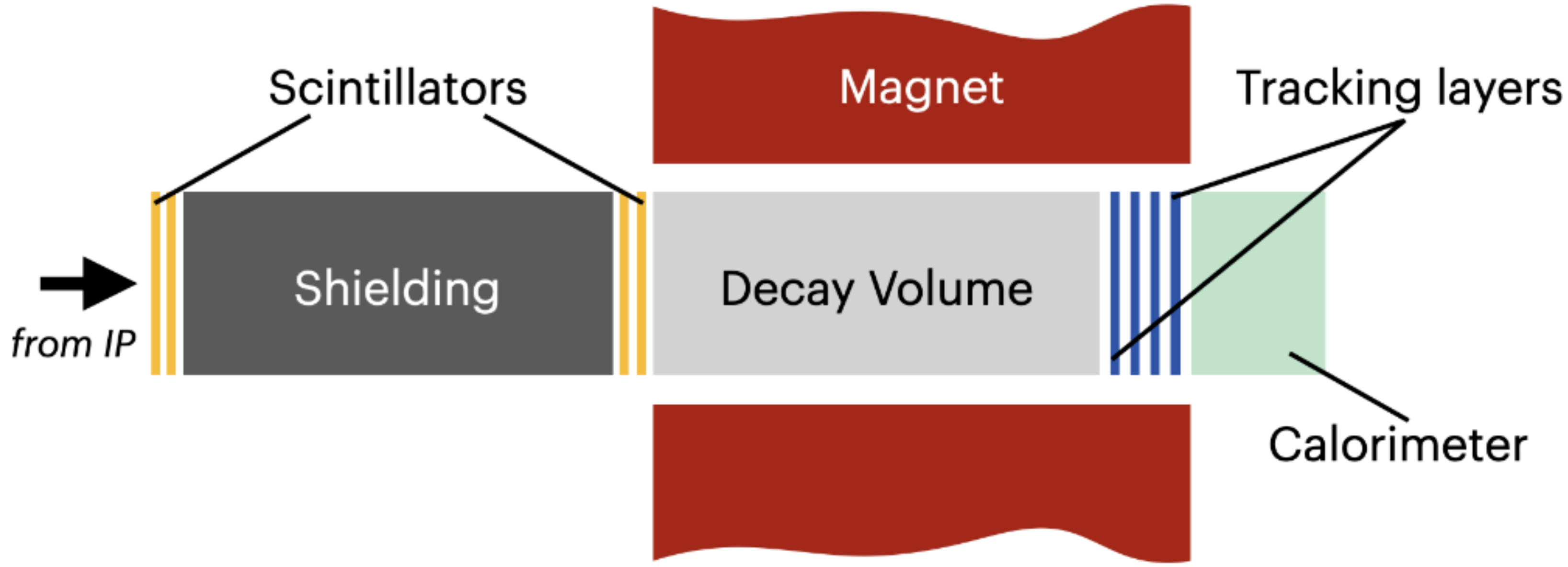
Veto events with hits in any of the four scintillator planes

Backgrounds and possible detector design

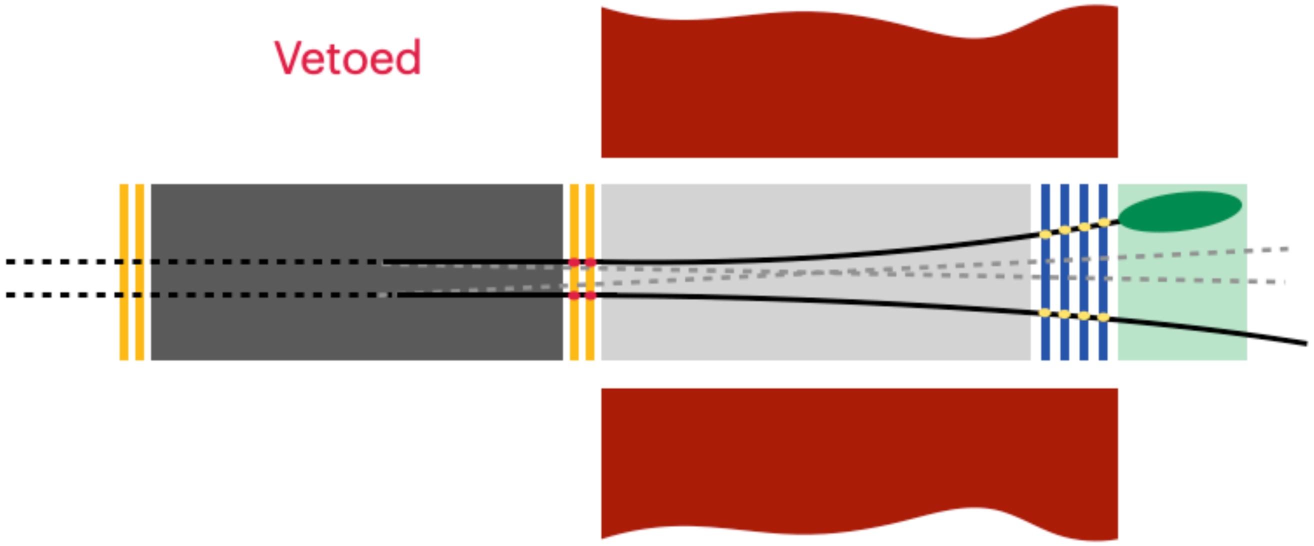
1 Muons from the IP

2 Neutral hadrons

3 **Neutrinos**



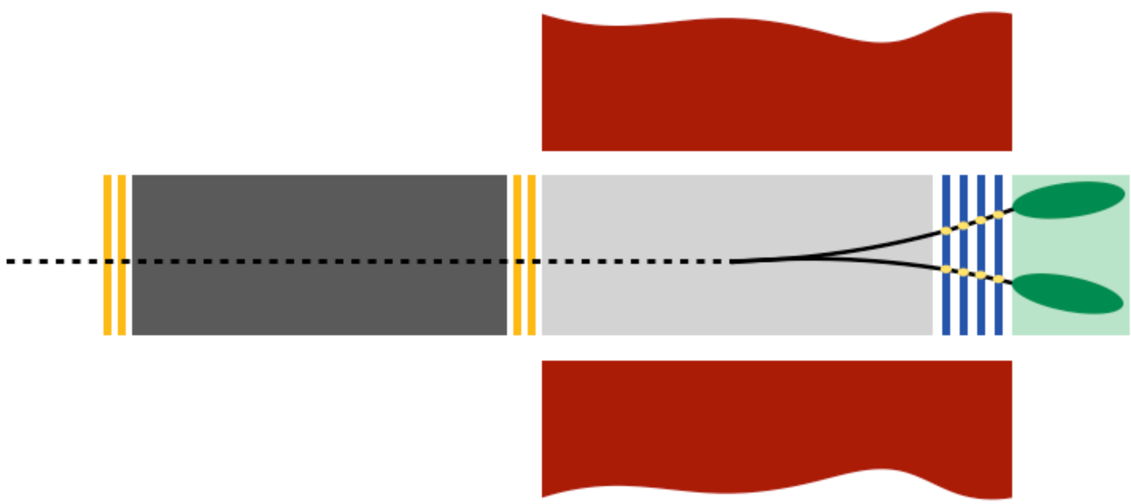
Neutrino interactions



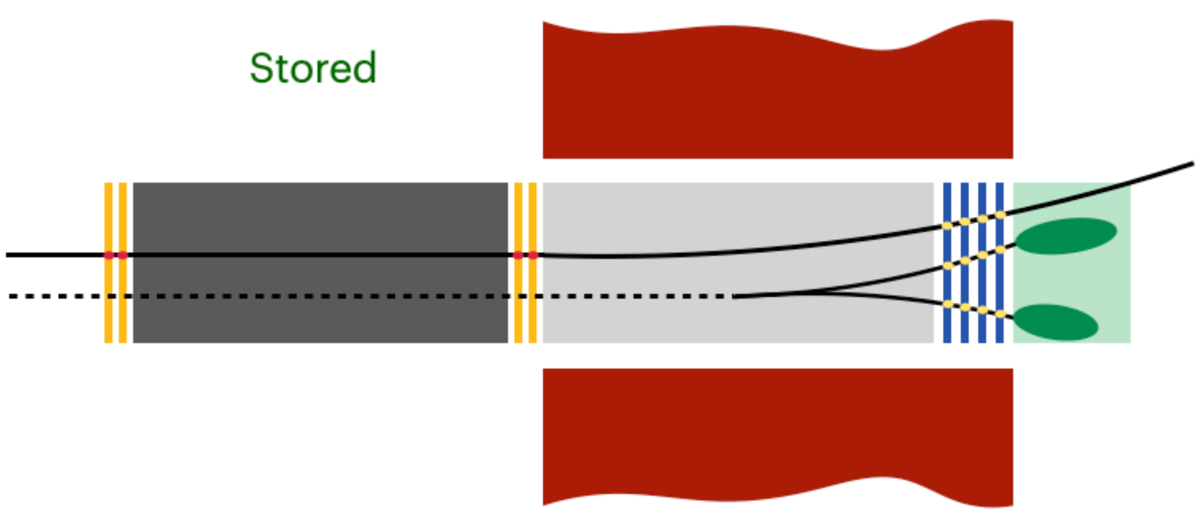
Veto events with hits in any of the four scintillator planes

Signal and backgrounds

LLP signal

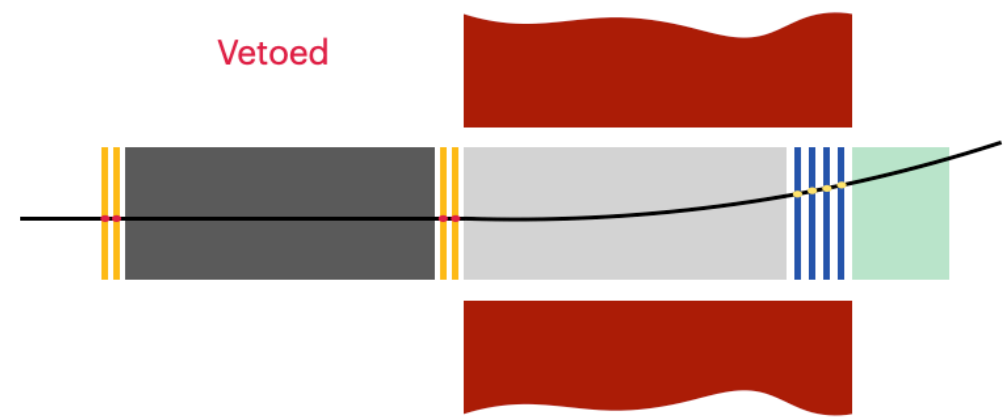


Muons from the IP with a coincident signal

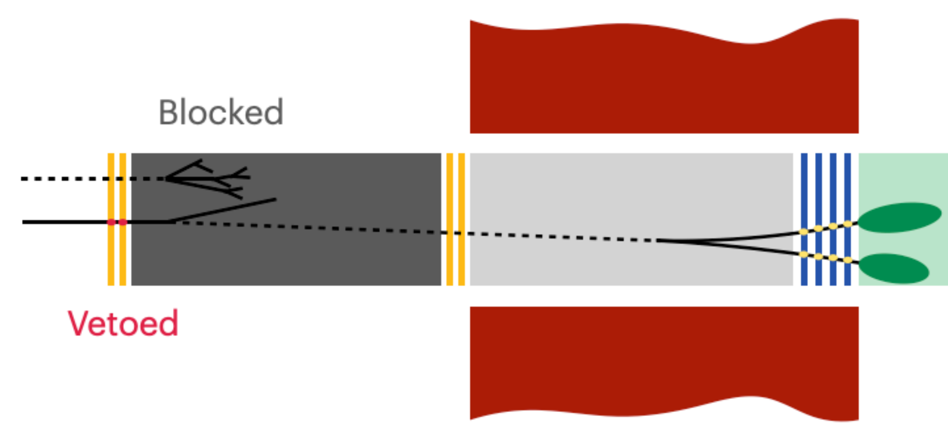


Veto events with hits in any of the four scintillator planes which do not have any calorimeter deposit other than ones which are consistent with the direction of the muon track inferred from the scintillator hits.

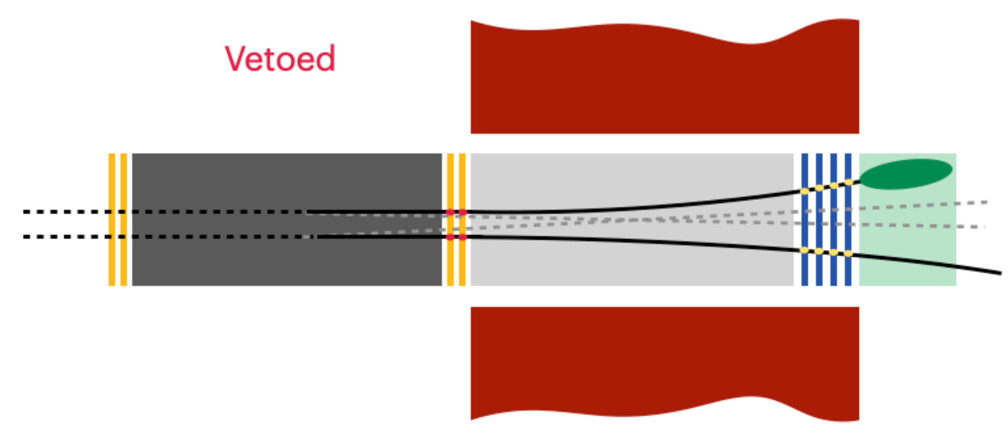
Muons from the IP



Neutral hadrons



Neutrino interactions



More on FOREHUNT

(A) Bending and width of the beampipe

- Placing the detector at 50 m might still contain the beampipe within it - reduces acceptance

(C) Multiple detectors in the forward direction

- A second detector at 300 m increases overall signal acceptance by 50%
- Energy threshold of the second detector can be reduced as the first detector plays the role of an active veto

(B) Off-axis forward detector

- In case placement along the beamline close to the IP is not feasible, place the detector off-axis – 1 m off-axis reduces acceptance by a factor of 2
- Placing the detector 300 m along the beamline is better than shifting it 5 m off-axis

(D) Elements of the detector

- Layers of RPCs: for 5 m radius of the detector, cost per layer of RPC would be around 245 k€
- Triplet RPC layers: 0.1 cm spatial and 0.4 ns temporal resolutions 1909.13022
- Possibility of adding calorimeter and integration with FCC-hh trigger system being studied

Summary

- General-purpose and dedicated detectors together play a key role in the LLP search programs.
- The forward muon spectrometer of FCC-hh will improve sensitivity to light LLPs with small lifetimes.
- Exploring dedicated LLP detectors for future colliders is timely and important to understand their roles.
- We propose designs for a **transverse detector, DELIGHT**, and those of a **forward detector, FOREHUNT**, for the FCC-hh - optimise them for light LLPs coming from Higgs boson or B-meson decays.
- Both the transverse and forward detectors at FCC-hh **significantly improve** the sensitivity of light LLPs in **complementary regions of phase-space**.
- **Further investigations on their feasibility and optimal designs** are crucial for finalising the FCC-hh collider design for the LLP physics case.

Thank you for your attention

BACK UP

Backgrounds for LLP searches

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

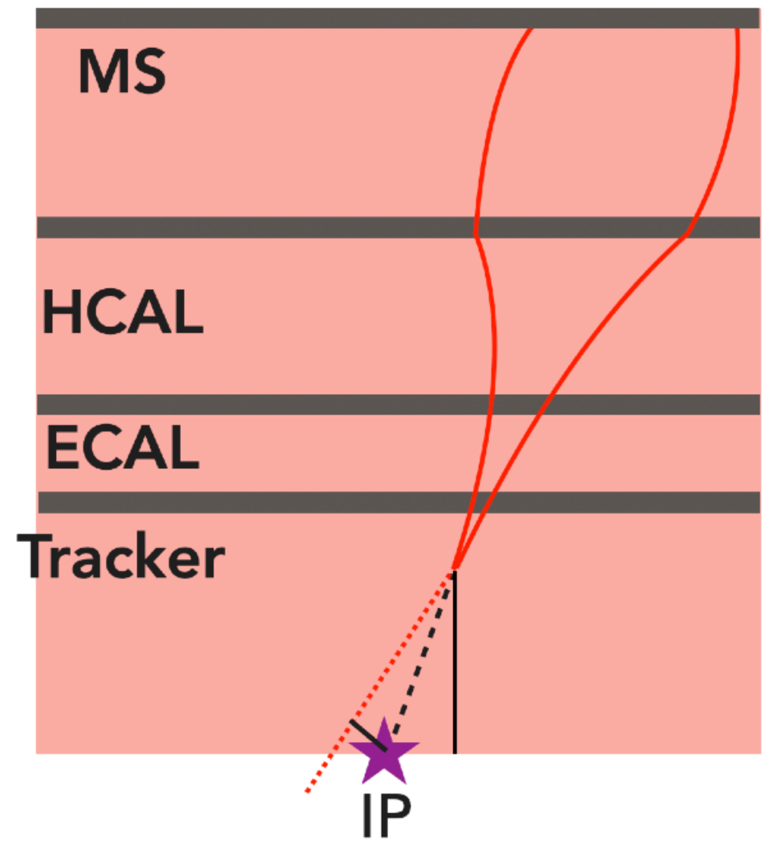
Non-standard and unusual backgrounds
Simulation very technical

Analysis strategy in the MS

Selection cuts on DISPLACED OBJECTS

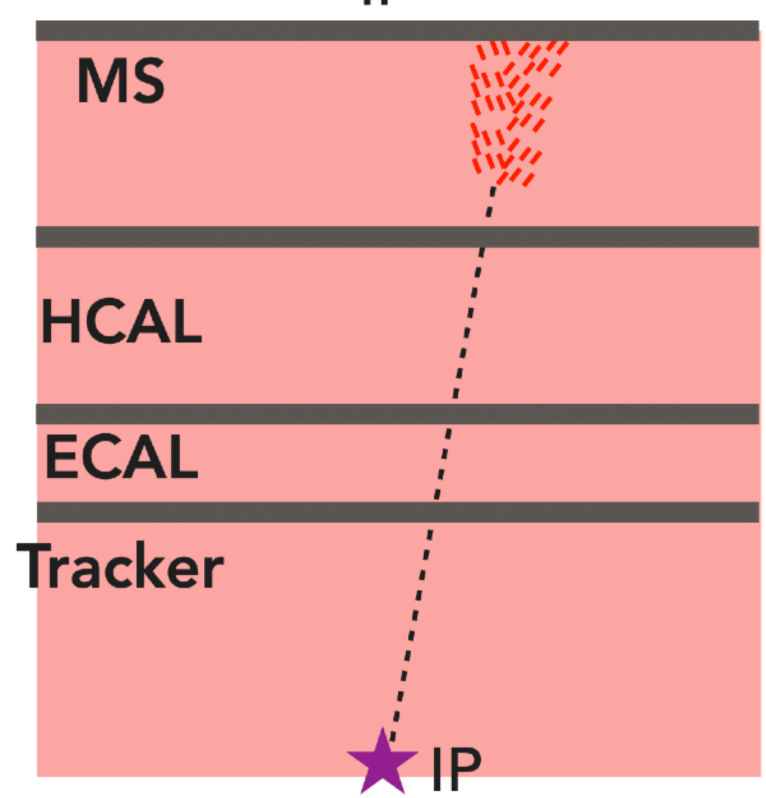
Displaced muons $\mu^+\mu^-$ — hard / soft

	D^H_μ (hard)	D^S_μ (soft)
Muons	$p^\mu_T > 20\,\mathrm{GeV}$	$p^\mu_T > 10\,\mathrm{GeV}$
	$n_\mu \geq 2$	$n_\mu \geq 2$
	$\lvert\eta^\mu\rvert < 2.8$	$\lvert\eta^\mu\rvert < 2.8$
	$\lvert d^\mu_0\rvert > 2\,\mathrm{mm}$	$\lvert d^\mu_0\rvert > 2\,\mathrm{mm}$
Muon pair from the same dSV	$d_T > 1\,\mathrm{cm}$	$d_T > 1\,\mathrm{cm}$
	$d_T < 6\,\mathrm{m}$ & $\lvert d_z\rvert < 9\,\mathrm{m}$	$d_T < 6\,\mathrm{m}$ & $\lvert d_z\rvert < 9\,\mathrm{m}$
	$\Delta\phi_{\mu\mu} > 0.01$	$\Delta\phi_{\mu\mu} > 0.01$
Event	$n_{vtx} \geq 1$ or $n_{vtx} = 2$	$n_{vtx} \geq 1$ or $n_{vtx} = 2$



MS cluster jets — hard / soft

	D^H_{jets} (hard)	D^S_{jets} (soft)
Electrons, photons, hadrons	$p_T > 0.5\,\mathrm{GeV}$	$p_T > 0.5\,\mathrm{GeV}$
	$\lvert\eta\rvert < 2.8$	$\lvert\eta\rvert < 2.8$
MS cluster from same dSV ($< 1\,\mathrm{cm}$)	$d_T > 4\,\mathrm{m}$ or $\lvert d_z\rvert > 7\,\mathrm{m}$	$d_T > 4\,\mathrm{m}$ or $\lvert d_z\rvert > 7\,\mathrm{m}$
	$d_T < 6\,\mathrm{m}$ and $\lvert d_z\rvert < 9\,\mathrm{m}$	$d_T < 6\,\mathrm{m}$ and $\lvert d_z\rvert < 9\,\mathrm{m}$
	$n^{\mathrm{ch}}_{\mathrm{dSV}} \geq 5$	$n^{\mathrm{ch}}_{\mathrm{dSV}} \geq 3$
	$\sum p_{T,dSV} > 50\,\mathrm{GeV}$	$\sum p_{T,dSV} > 20\,\mathrm{GeV}$
	$\Delta\phi_{\max} > 0.2$	$\Delta\phi_{\max} > 0.1$
Event	$n_{\mathrm{cluster}} \geq 1$, $n_{\mathrm{cluster}} = 2$	$n_{\mathrm{cluster}} \geq 1$, $n_{\mathrm{cluster}} = 2$



Decay

$\mu^+\mu^-$

$\pi^+\pi^-$

K^+K^-

$\tau^+\tau^-$

gg

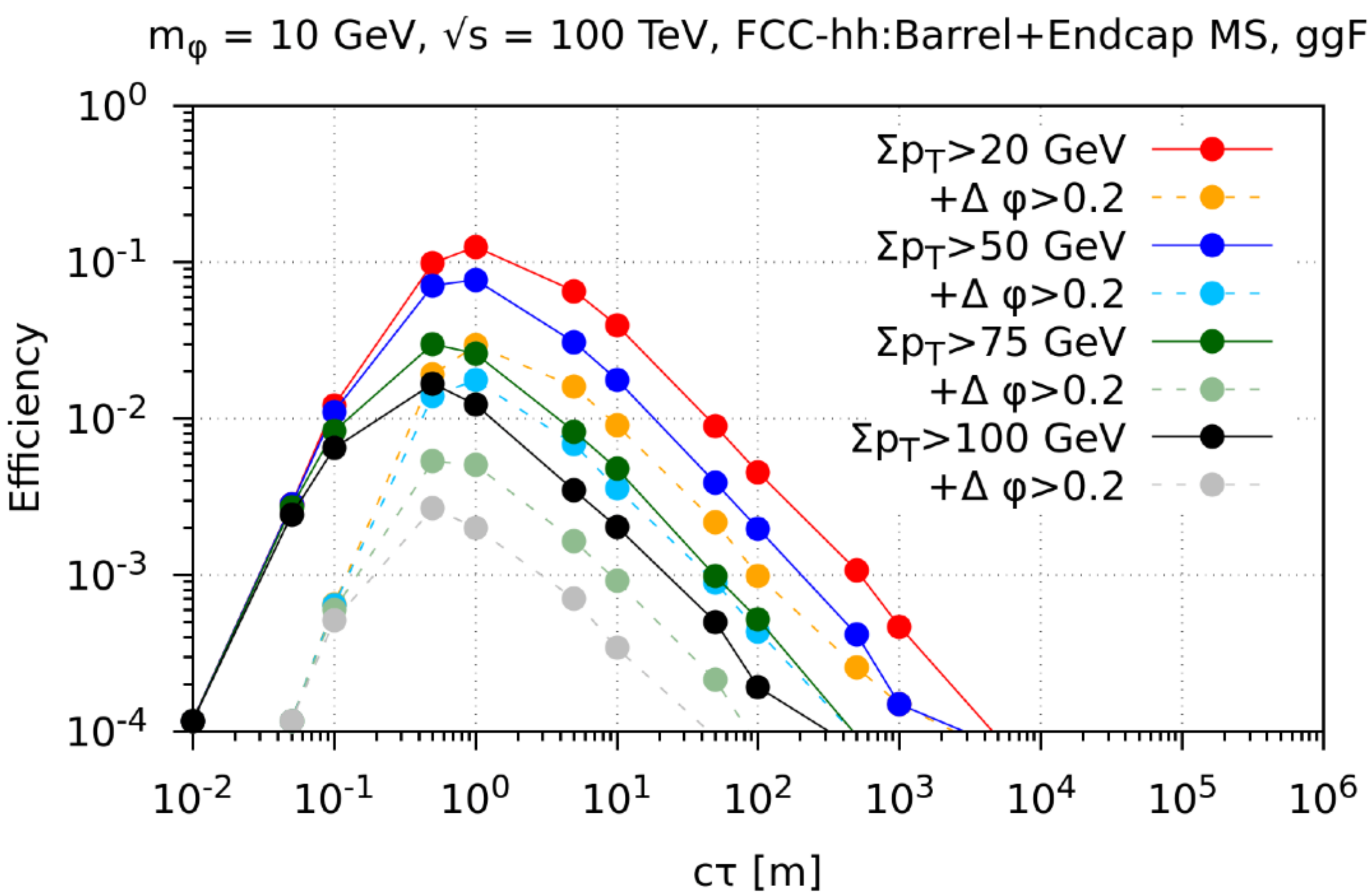
$s\bar{s}$

$c\bar{c}$

$b\bar{b}$

Displaced objects from the LLP decay

FCC-hh MS thresholds



$\sqrt{s}$ [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

Comparison of various detector acceptances

m_ϕ (GeV)	$c\tau$ (m)	FASER2 ($p_\phi > 100$GeV)	CODEX-b ($E_\phi > 1$GeV)	MATHUSLA ($E_\phi > 1$GeV)	FOREHUNT-C ($p_\phi > 100$GeV)	DELIGHT-B ($E_\phi > 1$GeV)
0.1	10^1	$1.6\times10^{-5}\%$	$1.0\times10^{-2}\%$	$1.3\times10^{-1}\%$	$2.1\times10^{-2}\%$	$\mathbf{6.5\times10^{-1}}\%$
0.1	10^4	$1.5\times10^{-8}\%$	$1.1\times10^{-5}\%$	$2.1\times10^{-4}\%$	$2.1\times10^{-5}\%$	$\mathbf{9.2\times10^{-4}}\%$
2.0	10^1	$3.6\times10^{-4}\%$	$1.8\times10^{-2}\%$	$4.4\times10^{-2}\%$	$4.4\times10^{-1}\%$	$\mathbf{5.3\times10^{-1}}\%$
2.0	10^4	$4.8\times10^{-7}\%$	$1.9\times10^{-4}\%$	$3.4\times10^{-3}\%$	$4.7\times10^{-4}\%$	$\mathbf{1.5\times10^{-2}}\%$
4.4	10^1	$8.6\times10^{-4}\%$	$9.2\times10^{-3}\%$	$1.3\times10^{-2}\%$	**1.0**%	$2.5\times10^{-1}\%$
4.4	10^4	$1.5\times10^{-6}\%$	$2.3\times10^{-4}\%$	$5.0\%\ \times10^{-3}\%$	$1.2\times10^{-3}\%$	$\mathbf{1.9\times10^{-2}}\%$

Multiple forward detectors

m_ϕ (GeV)	$c\tau$ (m)	acceptance for first detector at z=50 m	acceptance for second detector at z=100 m	acceptance for second detector at z=300 m
0.1	10^{-1}	1.4%	0.56%	0.29%
4.4	10^{-1}	0.7%	0.22%	$1.9\times10^{-2}\%$
0.1	10^4	$2.1\times10^{-5}\%$	$1.9\times10^{-5}\%$	$9.3\times10^{-6}\%$
4.4	10^4	$1.2\times10^{-3}\%$	$1.0\times10^{-3}\%$	$4.9\times10^{-4}\%$

Reduced threshold for the second detector

m_ϕ (GeV)	$c\tau$ (m)	FOREHUNT-C ($p_\phi > 50$ GeV, z=100 m)	FOREHUNT-C ($p_\phi > 50$ GeV, z=200 m)	FOREHUNT-C ($p_\phi > 50$ GeV, z=300 m)
0.1	10^1	$3.3\times10^{-2}\%$	$1.8\times10^{-2}\%$	$1.1\times10^{-2}\%$
0.1	10^4	$3.3\times10^{-5}\%$	$1.8\times10^{-5}\%$	$1.2\times10^{-5}\%$
2.0	10^1	$6.0\times10^{-1}\%$	$3.0\times10^{-1}\%$	$2.0\times10^{-1}\%$
2.0	10^4	$7.4\times10^{-4}\%$	$4.4\times10^{-4}\%$	$3.0\times10^{-4}\%$
4.4	10^1	1.1%	$5.0\times10^{-1}\%$	$3.0\times10^{-1}\%$
4.4	10^4	$1.6\times10^{-3}\%$	$9.0\times10^{-4}\%$	$5.9\times10^{-4}\%$

Off-axis detectors

m_ϕ (GeV)	$c\tau$ (m)	1 m off-axis ($p_\phi > 100$ GeV)	5 m off-axis ($p_\phi > 100$ GeV)
0.1	10^{-1}	0.83%	$5.5\times10^{-2}\%$
4.4	10^{-1}	$1.53\times10^{-2}\%$	$1.2\times10^{-4}\%$
0.1	10^4	$1.5\times10^{-5}\%$	$8.7\times10^{-7}\%$
4.4	10^4	$8.4\times10^{-4}\%$	$1.7\times10^{-4}\%$