Light scalar Long-Lived Particle searches@FCC

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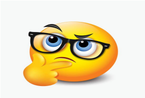
Outline

Based on: ***Phys.Rev.D* 110 (2024) 1, 015036**, **Arxiv:2503.08780**

Biplob Bhattacherjee, Camellia Bose, Herbi K. Dreiner, **NG** , Shigeki Matsumoto, Rhitaja Sengupta, Prabhat Solanki

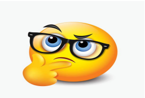
- Introduction to LLP
- Current(Proposed) LLP Searches
- LLP@FCC-hh
- LLP@FCC-ee

Introduction to LLP

Why LLP? 

Most of the conventional searches at LHC assumes that the New BSM particle decays promptly.

But is it really necessary to assume this?

Why LLP? 

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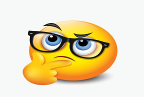
NO!!!

What if the NP particles have longer lifetime? $\rightarrow$ open the door to the Lifetime Frontier.

Why LLP? 

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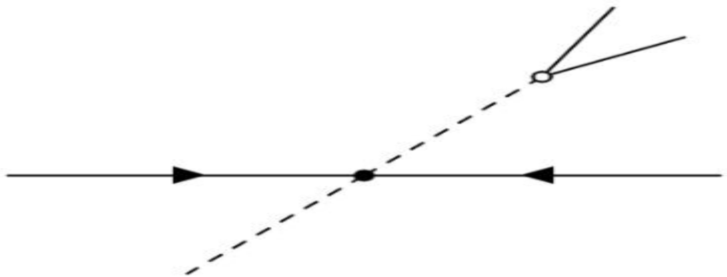

$c\tau \gtrsim O$ (few mm)

How to detect LLP ?

Production

1. Production rate
(like meson or Higgs

etc)

2. Boost Factor ($\beta\gamma$)

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Decay

1. Proper decay Length (cτ)
2. Decay Products

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Decay

1. Proper decay Length ($c\tau$)
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Detection

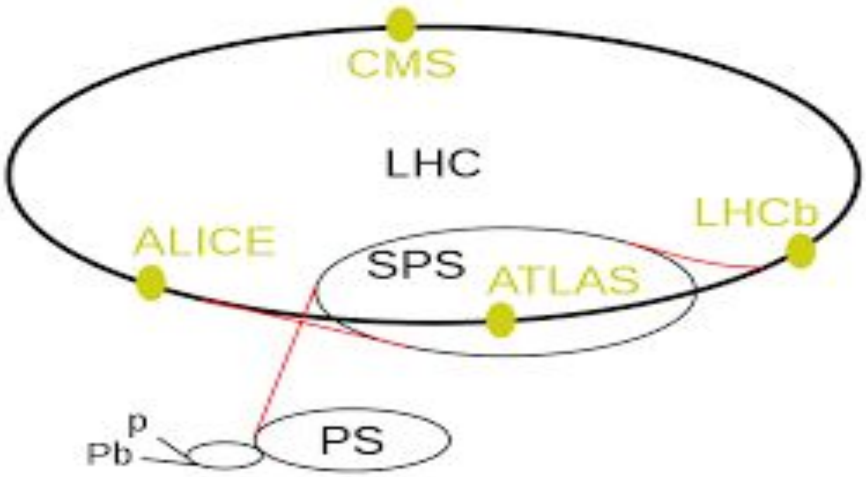
Where it decays?

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

Current(Proposed) LLP Searches

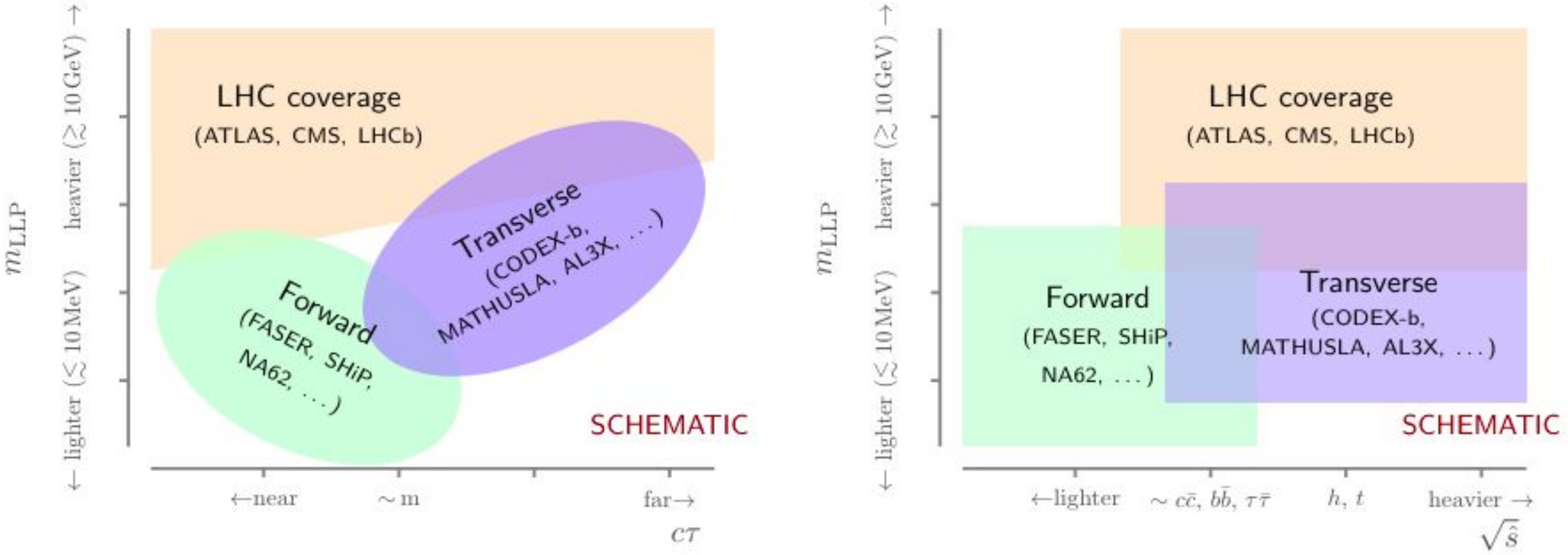
LLP@Hadron Collider

https://en.wikipedia.org/wiki/Large_Hadron_Collider



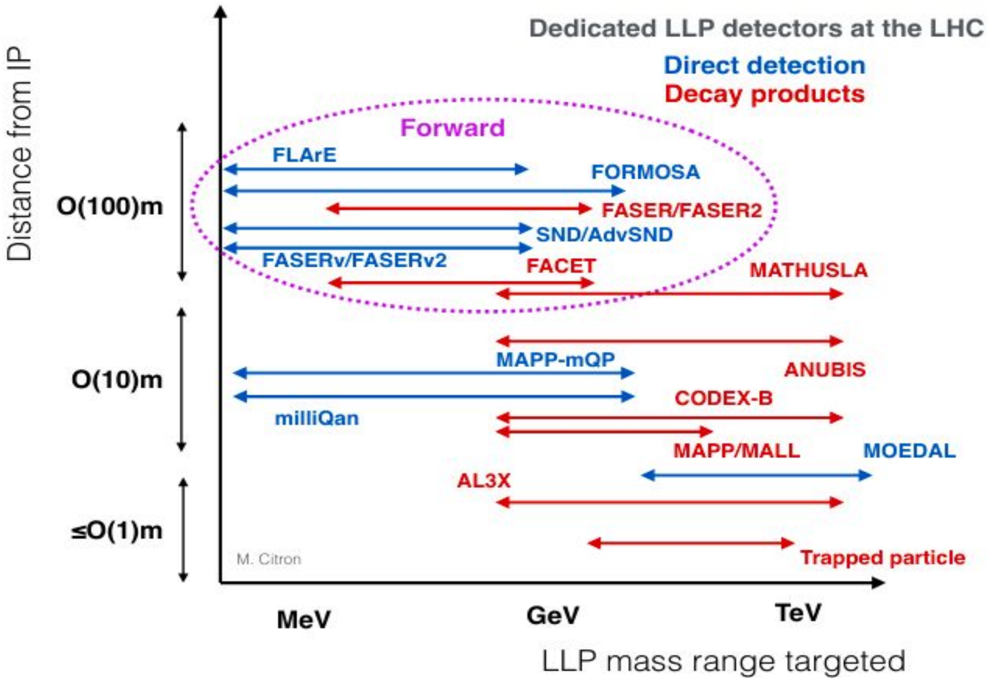
Reach and coverage of LLP experiments

[1911.00481]

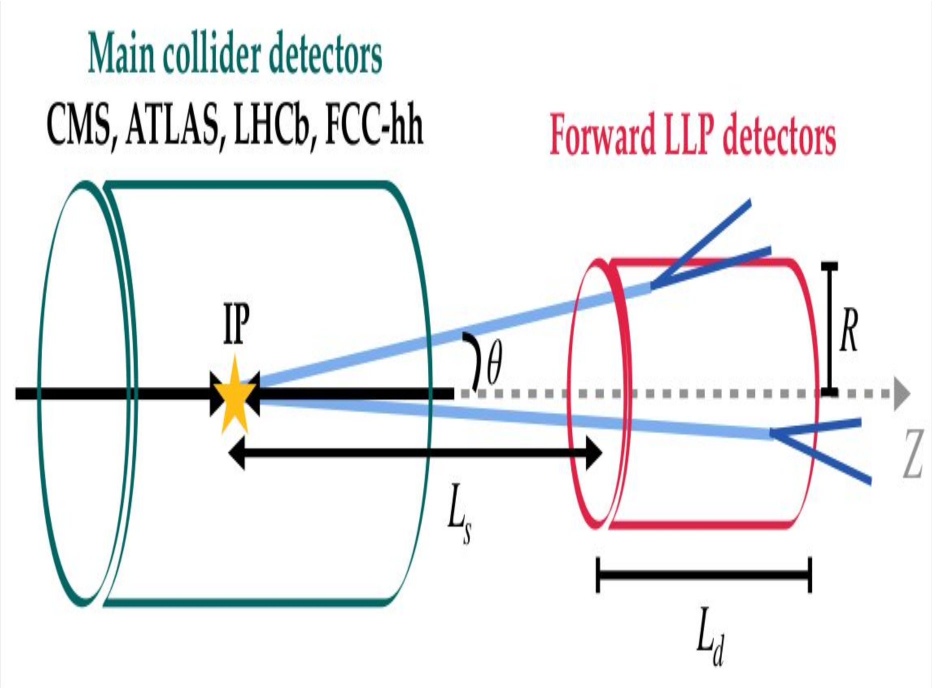


Dedicated detectors for LLP

[Snowmass Report 2209.13128]



Forward Detectors



ForwArd Search ExpeRiment FASER/FASER 2

480 m from ATLAS

R= 10 cm, L_d=1.5 m, L =150 fb^{-1}/
R=1 m, L_d=5m, L =3000 fb^{-1} (2026-2035)

Forward Physics Facility(FPF)

620 m from ATLAS, L_d= 10/15/20 m
(~2029) [2203.05090]

Forward Detectors

Forward-Aperture CMS ExTension (FACET)

Extension of CMS detector

R= 50 cm, L_d=18 m

Sensitive for masses > 1 GeV,

cτ in the range [0.1-100]m

[2201.00019]

Monopole and Exotics Detector at the LHC (MOEDAL)-(MoEDAL Apparatus for Penetrating Particles)MAPP detector

Forward region of LHCb (∼50 m)

10 × 10 array of 100 scintillator each of size 10 cm × 10 cm × 75 cm

[2209.03988]

Transverse Detectors

Massive Timing Hodoscope for Ultra Stable neutraL pArticles (MATHUSLA)

Surface detector above CMS interaction point 14 TeV HL-LHC

60.0 m < x < 85.0 m, -50.0 m < y < 50.0 m, 68.0 m < z < 168.0 m

L =3000 fb^{-1}

Sensitive for masses > 10 GeV,

cτ >100m

[2308.05860]

COmpact Detector for EXotics at LHCb (CODEX-b)

roughly 25 meters from the LHCb interaction point

10 m × 10 m × 10 m , L =300 fb^{-1}

cτ >1m

[1911.00481]

Transverse Detectors

AL3X(Alex)

12 m long cylinder, with inner radius 0.85 m and outer radius 5 m near ALICE

$L = 100\ fb^{-1}$

[1810.03636]

AN Underground Belayed In-Shaft search experiment(ANUBIS)

Near ATLAS

20 m away from IP, $c\tau$ in the range $[0.1\text{-}10^6]$m

[2401.11604]

Fixed Target Experiments

Search for Hidden Particles(SHiP)

Near CERN SPS fixed target experiment

Approved in 2024

2×10^{20} proton-target collisions (PoT) are foreseen in 5 years of operation.

Sensitive for masses < 10 GeV

[1504.04855]

NA62, NA64

And many more!!!!

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And many more!!!!

No proposal for 100 TeV FCC-hh!!!

LLP@FCC-hh

Model

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mu_\Phi^2\Phi^2 - \frac{1}{4}\lambda_\Phi\Phi^4 - \epsilon\Phi^2|H|^2,$$

After EWSB $\Longrightarrow$

$$h_{125} = \Phi\sin\theta + h\cos\theta,$$

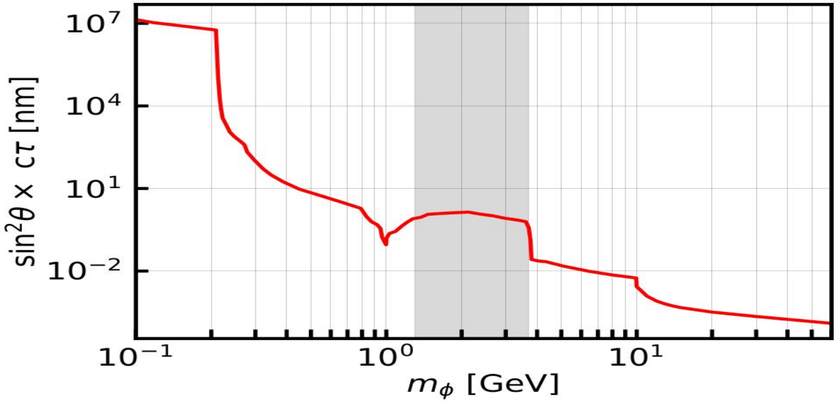
$$\phi = \Phi\cos\theta - h\sin\theta,$$

$$\mathcal{L}_{\mathrm{int}} = \phi\sin\theta\sum_f \frac{m_f}{v}\bar{f}f,$$

$$\Gamma_{\phi\to f\bar{f}} = \frac{N_c G_F m_\phi m_f^2 \sin^2\theta}{4\sqrt{2}\pi}\left(1-\frac{4m_f^2}{m_\phi^2}\right)^{3/2}$$

If ϴ is small, Γ is small, cτ is large →Φ is LLP!!!

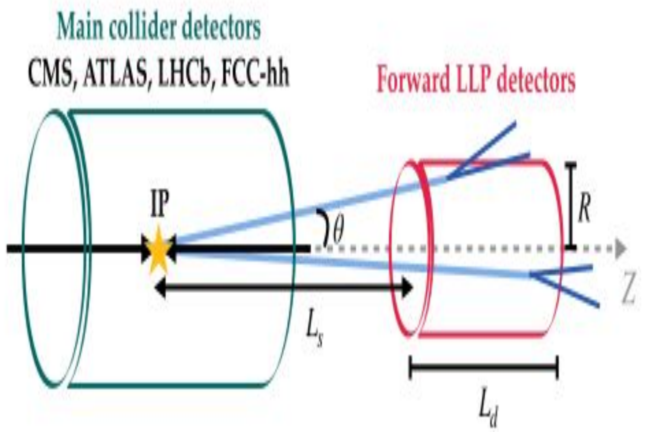
Model



- **Φ** to be very light, mass range varying from 100 MeV to Few GeV.
- It can come from various meson decays.
- **B ➡ K Φ** ✅

$$\mathrm{Br}(B \to X_s \phi) = 5.7 \sin^2\theta \left(1 - \frac{m_\phi^2}{m_b^2}\right)^2,$$

Analysis setup and validation



$$P_{\rm decay} = \frac{\left(1 - e^{\frac{-L_1}{|D_z|}}\right)}{e^{\frac{L_s}{|D_z|}}},$$

$$\epsilon_{\rm LLP} = \frac{\sum_i P^i_{\rm decay}}{N_{\rm events}},$$

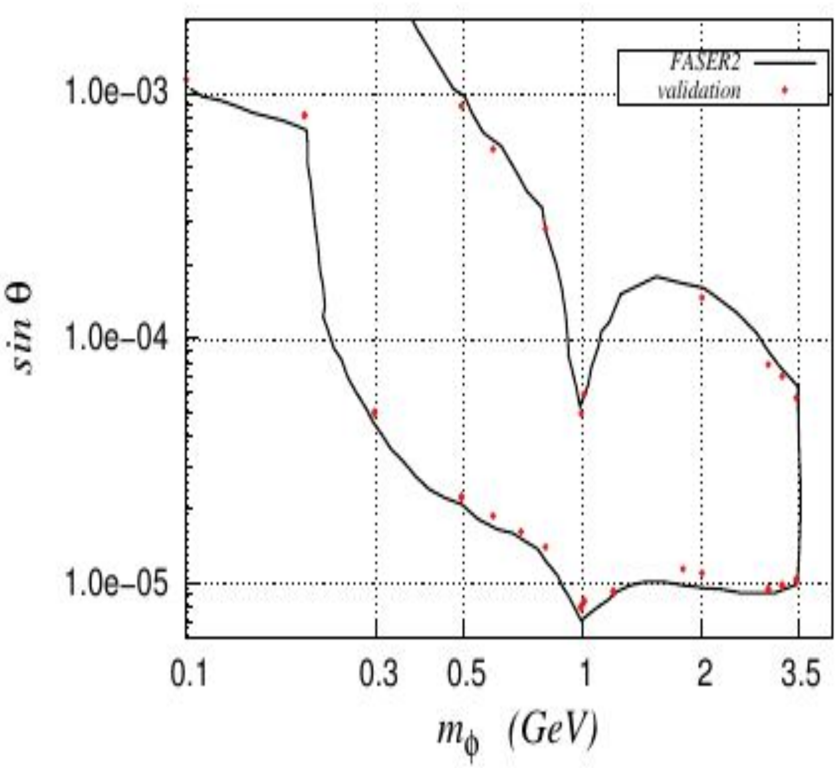
$$N_{\rm detector} = \sigma_{bb} \times \mathcal{B}r(B \to X_s\phi) \times \epsilon_{\rm LLP} \times \mathcal{L}$$

Analysis setup and validation

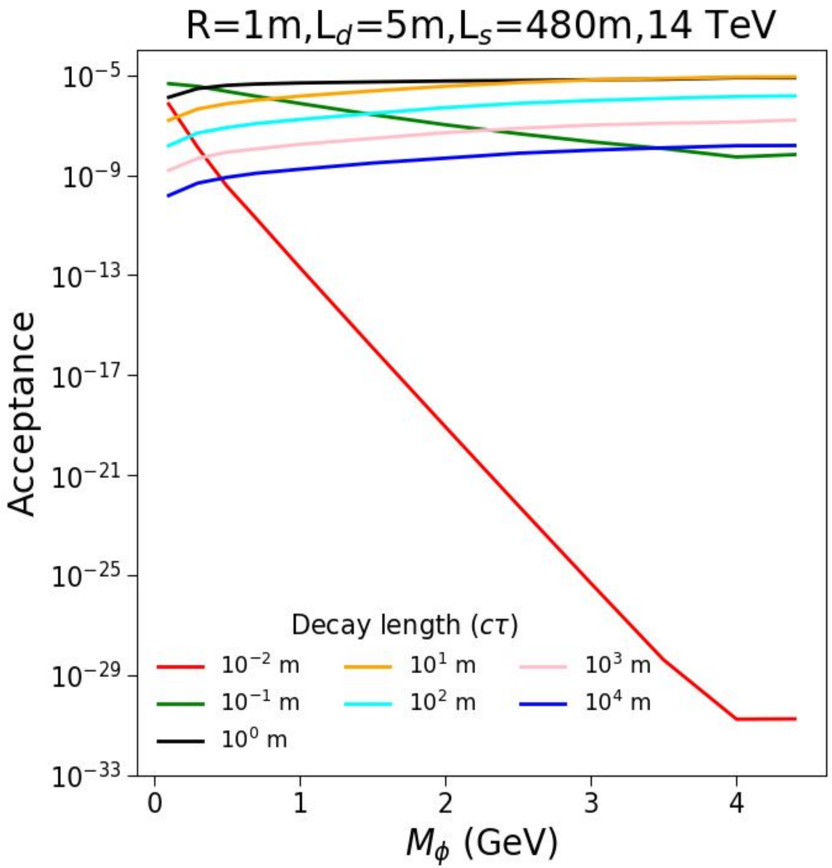
σ_{bb} = 9.4* 10^{11} fb

LLP decays to the visible particles with 100% branching ratio and will be detected in the detector only if the momentum > 100 GeV.

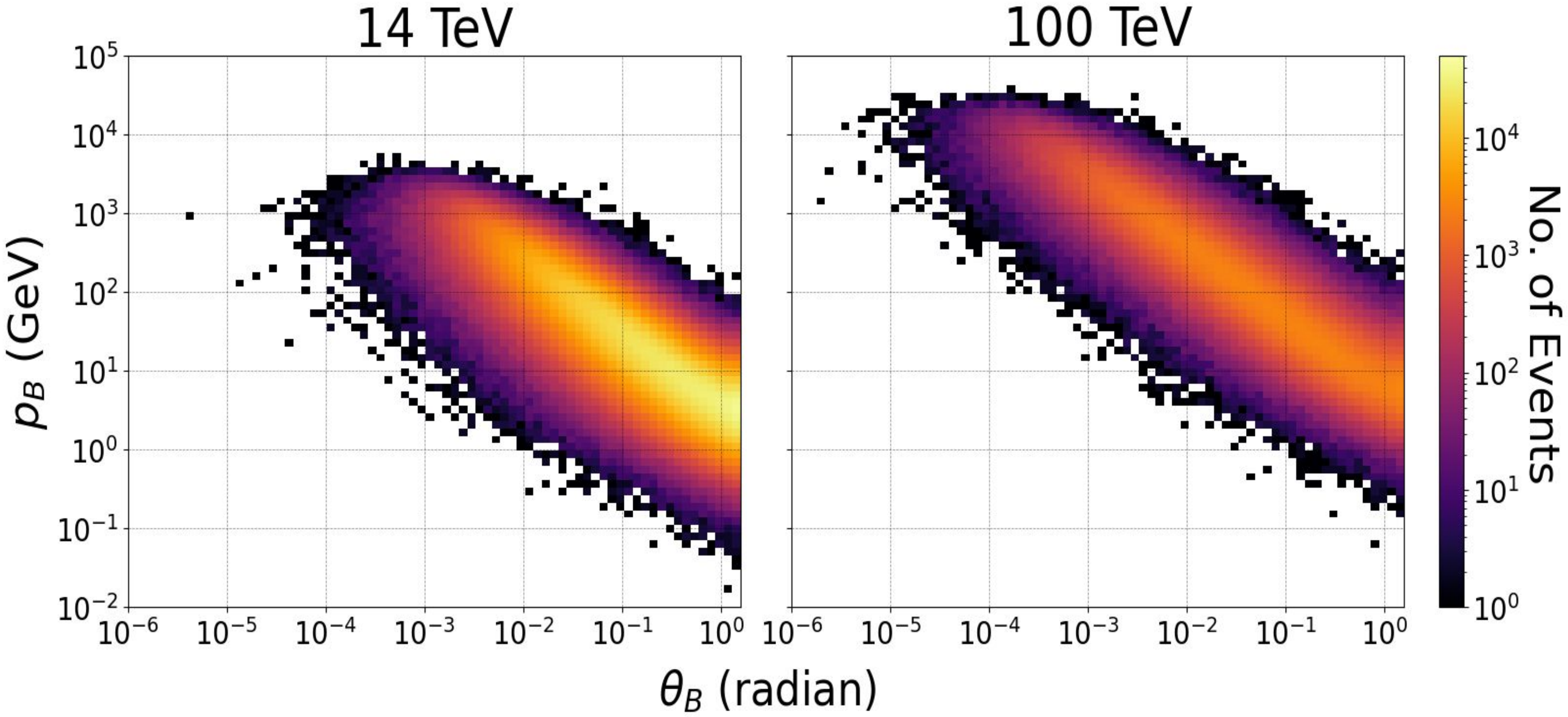
Validation done with FASER and FORESEE package[2105.07077]



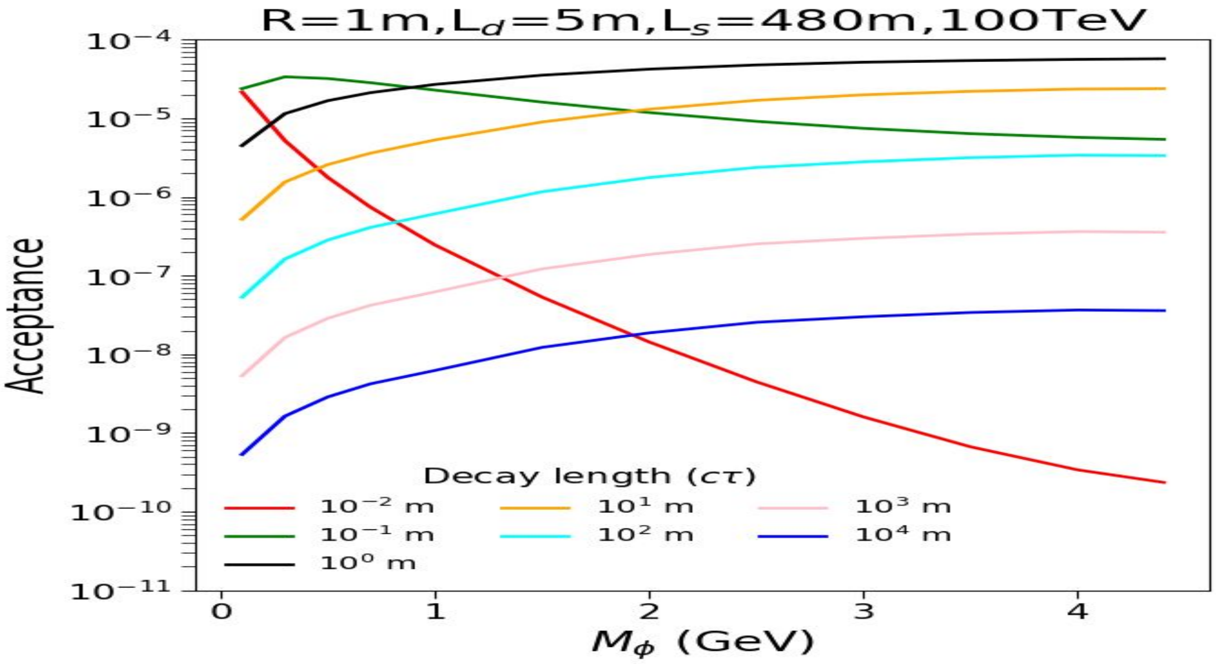
- For small ($c\tau \sim 10^{-2}$ m) and a mass greater than or equal to 1 GeV, the signal acceptance drops significantly.
- **Investigate the sensitivity of the dark Higgs boson model at FCC-hh !!!**.



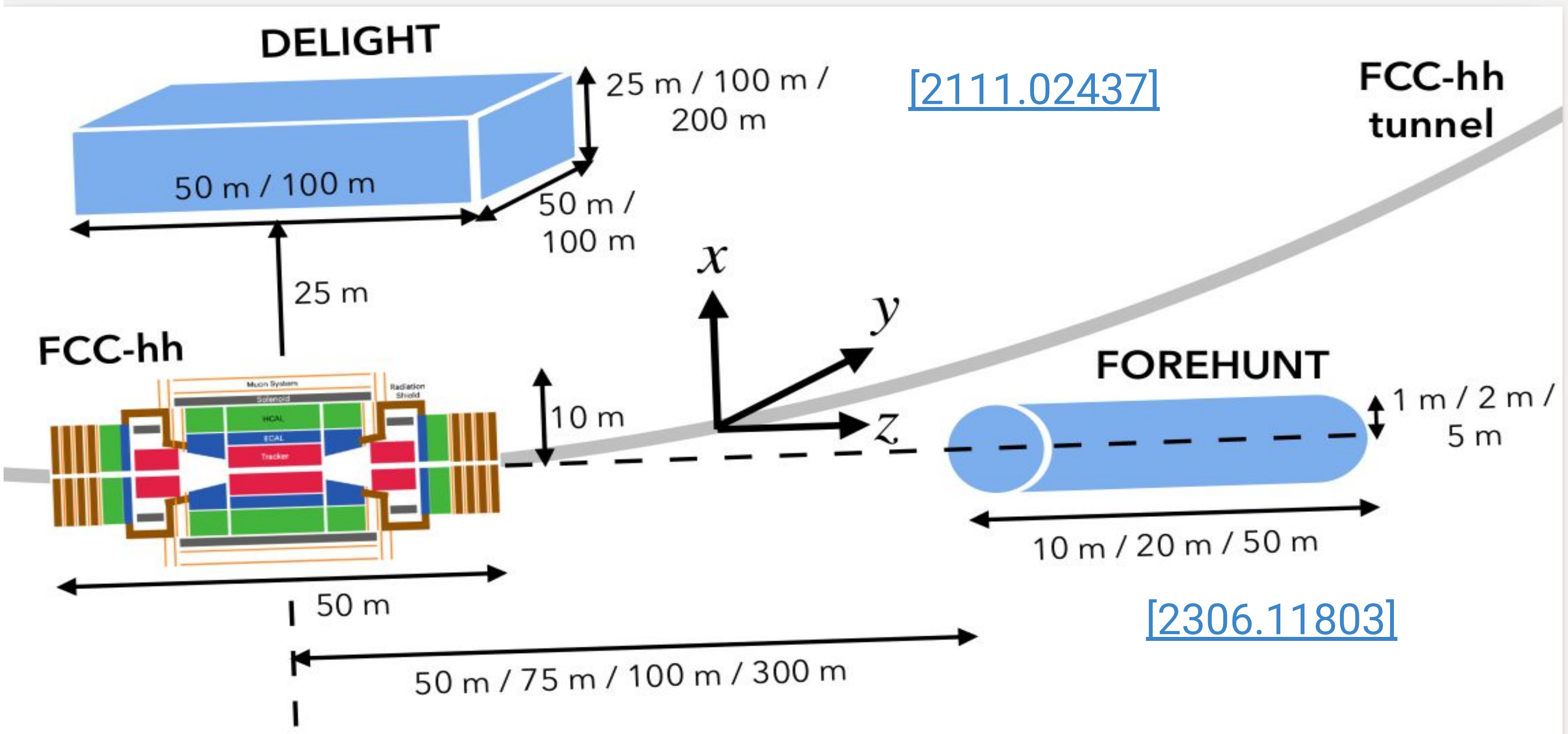
Dedicated detectors @100 TeV



Forward detectors @100 TeV



Schematic diagrams of the detectors



[2111.02437]

[2306.11803]

FORward Experiment for HUNdred TeV(FOREHUNT)

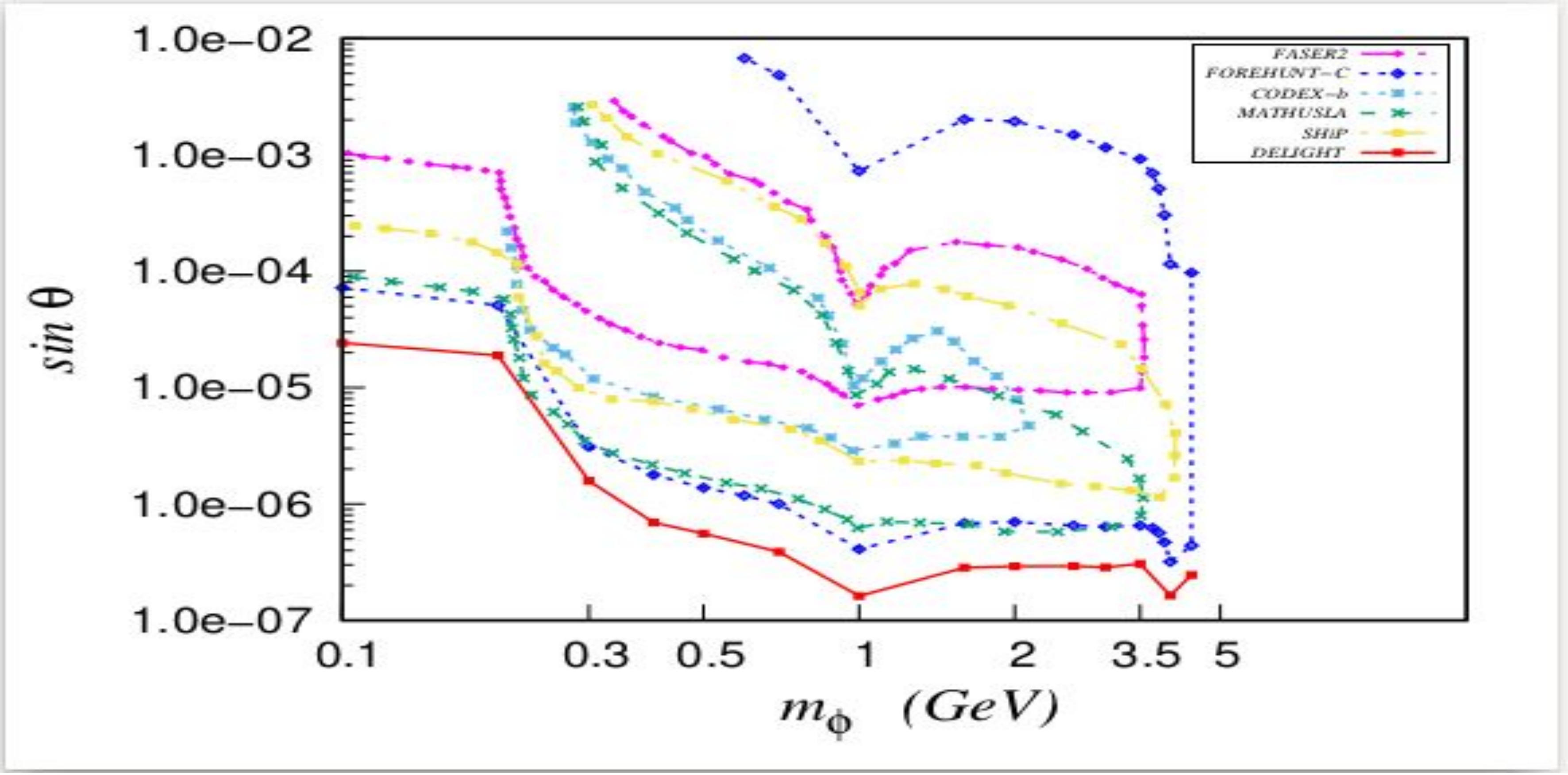
Detector configuration @100 TeV	Radius (R) [m]	Length (L_d) [m]	Position (Z) [m]
FOREHUNT-A	1	10	50
FOREHUNT-B	2	20	50
FOREHUNT-C	5	50	50
FOREHUNT-D	2	20	75
FOREHUNT-E	5	50	75
FOREHUNT-F	5	50	100

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

- DELIGHT-A: 25.0 m $< x <$ 50.0 m; 0.0 m $< y <$ 100.0 m; −50.0 m $< z <$ 50.0 m.
- DELIGHT-B: 25.0 m $< x <$ 125.0 m; 0.0 m $< y <$ 100.0 m; −50.0 m $< z <$ 50.0 m.
- DELIGHT-C: 25.0 m $< x <$ 225.0 m; 0.0 m $< y <$ 50.0 m; −25.0 m $< z <$ 25.0 m.

Because of the larger size, DELIGHT-B gives the best sensitivity to detect LLP.

Sensitivity for the dark Higgs model



LLP@FCC-ee

[FCC-CDR]

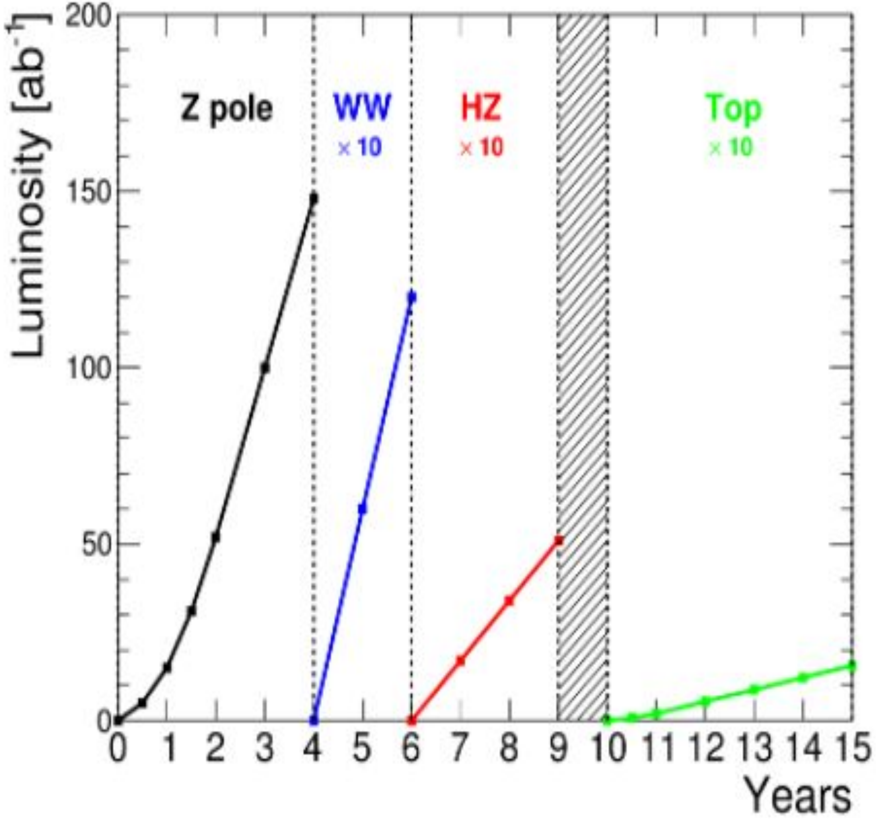
- Z pole (91.2 GeV)
- W + W − threshold

  (161 GeV)

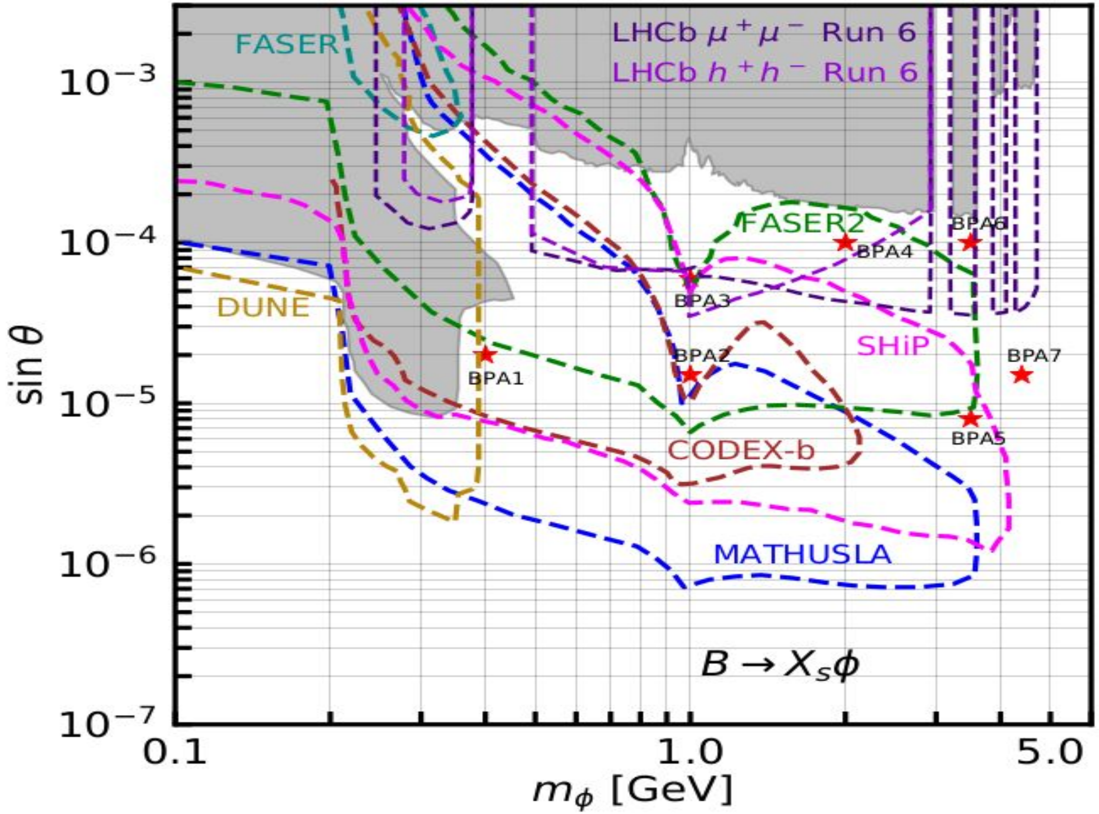
- HZ production peak

  (240 GeV)

- $t\bar{t}$ threshold (350/365 GeV)



Current status



Choice of BPs

Benchmark	m_ϕ (GeV)	$\sin\theta$	$c\tau$ (mm)	Dominant decay modes	Potential experiments to probe			
					FASER2	LHCb (projected)	MATHUSLA	SHIP
BPA1	0.4	2.0×10^{-5}	39666.6	$\pi^+\pi^-$: 76% $\mu^+\mu^-$: 10%	×	×	✓	✓
BPA2	1.0	1.5×10^{-5}	554.3	$\pi^+\pi^-$: 50% K^+K^- : 50%	✓	×	×	✓
BPA3	1.0	6×10^{-5}	34.6	$\pi^+\pi^-$: 50% K^+K^- : 50%	×	×	×	×
BPA4	2.0	10^{-4}	135.2	$\pi^+\pi^-$: 41% K^+K^- : 41% $\mu^+\mu^-$: 12%	✓	✓	×	×
BPA5	3.5	8×10^{-6}	10285.4	$\pi^+\pi^-$: 53% K^+K^- : 21% $\mu^+\mu^-$: 5%	×	×	×	✓
BPA6	3.5	10^{-4}	65.8	$\pi^+\pi^-$: 53% K^+K^- : 21% $\mu^+\mu^-$: 5%	×	✓	×	×
BPA7	4.4	1.5×10^{-5}	95.0	$c\bar{c}$: 65% $\tau^+\tau^-$: 20%	×	×	×	×

Innovative Detector for an Electron-Positron Accelerator (IDEA)

$$N = \sigma_{b\bar{b}} \times 2 \times \mathrm{Br}(B \to X_s\phi) \times \mathcal{L} \times \mathcal{A} \times \epsilon,$$

σ_{bb}=9.05 nb

$\mathscr{L}$=150 ab^{-1}

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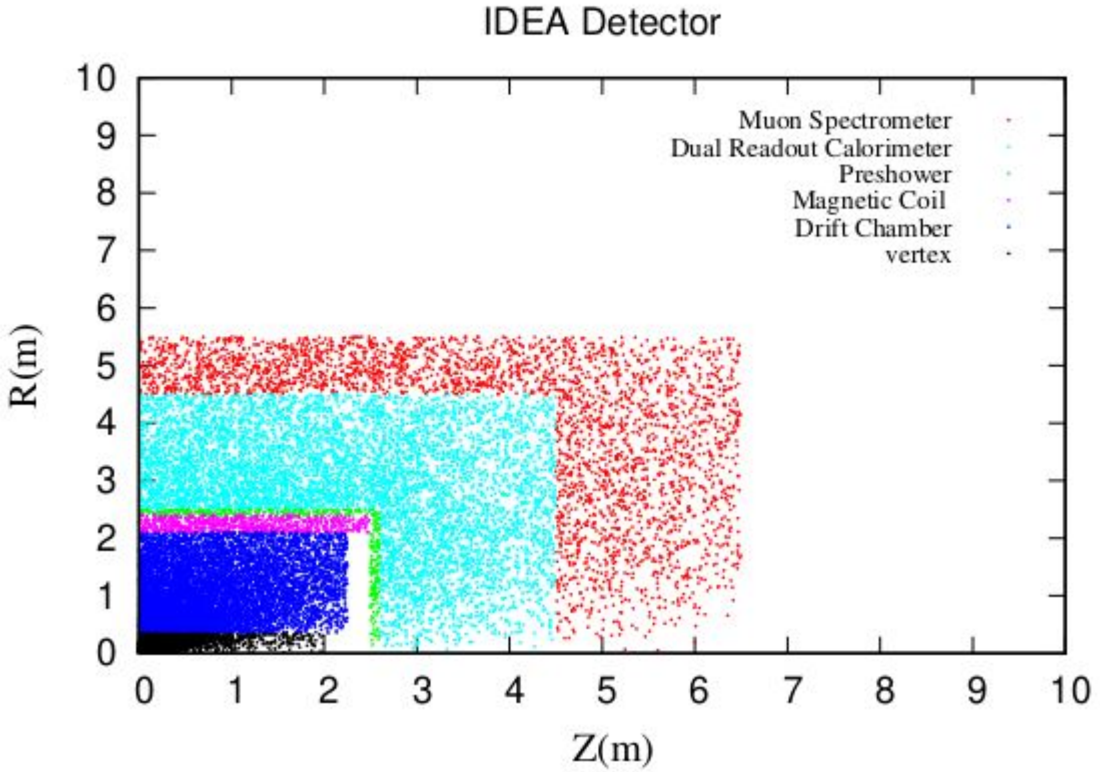

IDEA detector

Detector component	R_{in} (mm)	R_{out} (mm)	Z_{in}^{half} (mm)	Z_{out}^{half} (mm)
Silicon pixel detector (VTX)	17	340	400	2000
Drift chamber (DCH)	345	2020	2125	2125
Solenoid	2100	2400	2500	2500
Preshower	2400	2500	2500	2600
Dual-readout calorimeter (DRC)	2500	4500	2600	4500
Muon system (MS)	4500	5500	4500	6500

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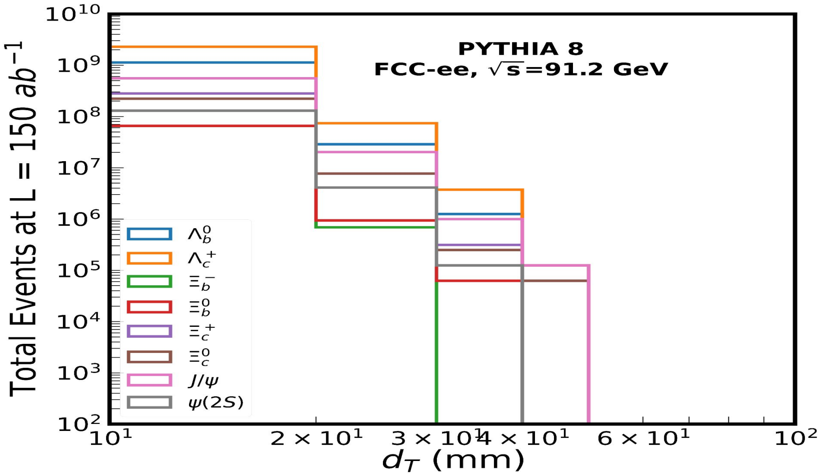
Benchmark	Number of LLP decays for $\mathcal{L} = 150\,{\rm ab}^{-1}$						
	VTX	DCH	Solenoid	Preshower	DRC	MS	Outside
BPA1	5	17	1	1	21	13	6175
BPA2	315	720	31	28	485	228	1348
BPA3	32750	16977	184	134	1014	84	50
BPA4	42924	47166	861	834	8534	1937	1611
BPA5	2	6	0	0	8	5	188
BPA6	22573	10029	32	24	124	4	0
BPA7	42	28	0	0	1	0	0

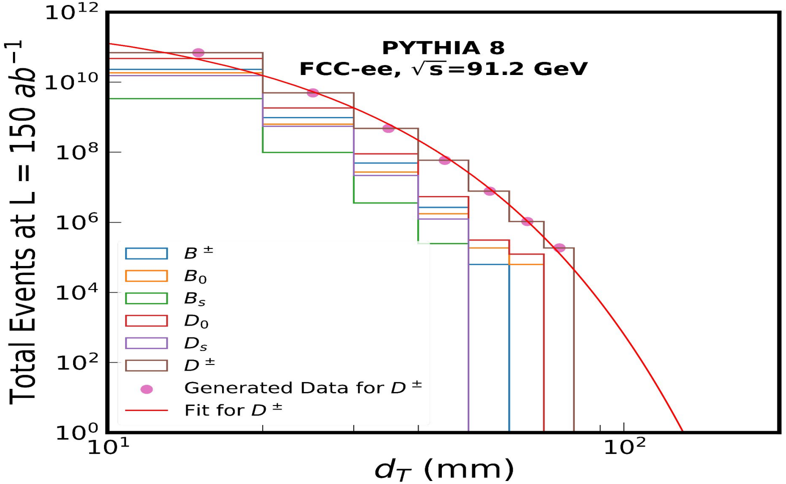
[efficiency]

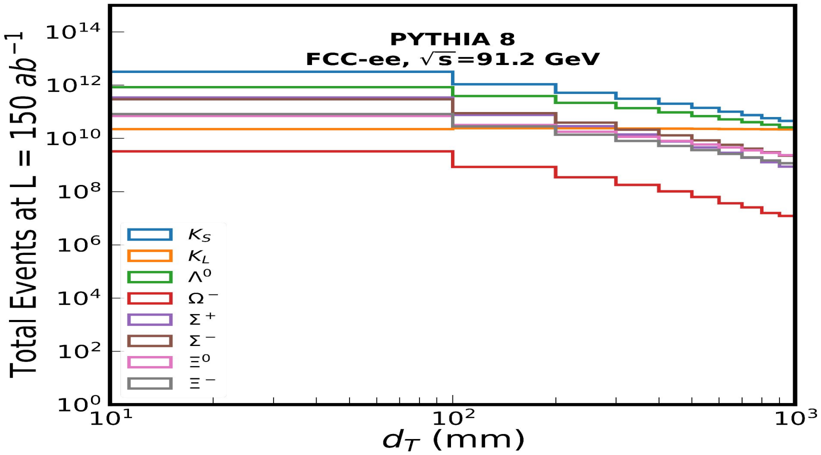
Detector component	Particles	Energy threshold (GeV)	Efficiency
Vertex detector (VTX) Drift Chamber (DCH)	charged particles	$0.1 < E < 0.3$ $0.3 < E < 0.5$ $E > 0.5$	0.06 0.65 0.997
Solenoid Preshower	$e^{\pm}$, $\mu^{\pm}$, charged hadrons γ	$E > 0.5$ $E > 0.10$	0.98
DR calorimeter		$E > 0.5$	0.98
Muon system	$\mu^{\pm}$	$E > 0.10$	0.98

SM backgrounds

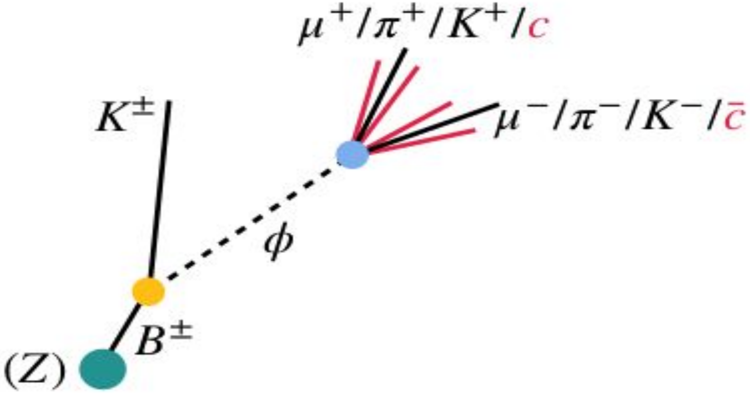
Mesons	m (GeV)	$c\tau$ (mm)	Baryons	m (GeV)	$c\tau$ (mm)
K_L	0.498	15330	Ξ^0	1.315	87.1
K_S	0.498	26.84	Λ	1.116	78.9
$B^{\pm}$	5.279	0.491	Ξ^-	1.322	49.1
B^0	5.279	0.459	Σ^-	1.197	44.34
B_S^0	5.367	0.439	Ω^-	1.672	24.61
$D^{\pm}$	1.869	0.312	Σ^+	1.189	24.04
$D_S^{\pm}$	1.968	0.150	Λ_b^0	5.619	0.369
D^0	1.865	0.123	Ξ_b^-	5.791	0.364
			Ξ_b^0	5.788	0.364
			Ξ_c^+	2.468	0.132
			Λ_c^+	2.286	0.06
			Ξ_c^0	2.471	0.0336

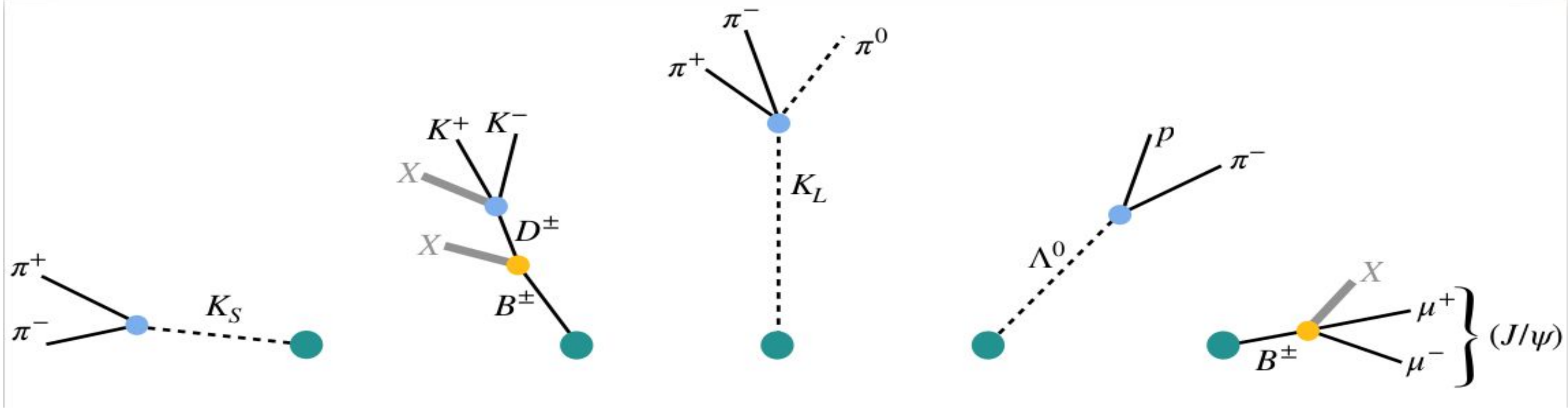

PYTHIA 8
FCC-ee, √s=91.2 GeV
Total Events at L = 150 ab⁻¹
d_T (mm)
Λ_b^0
Λ_c^+
Ξ_b^-
Ξ_b^0
Ξ_c^+
Ξ_c^0
J/ψ
ψ(2S)


PYTHIA 8
FCC-ee, √s=91.2 GeV
Total Events at L = 150 ab⁻¹
d_T (mm)
B^±
B_0
B_s
D_0
D_s
D^±
Generated Data for D^±
Fit for D^±


PYTHIA 8
FCC-ee, √s=91.2 GeV
Total Events at L = 150 ab⁻¹
d_T (mm)
K_S
K_L
Λ^0
Ω^-
Σ^+
Σ^-
Ξ^0
Ξ^-

Analysis Strategy

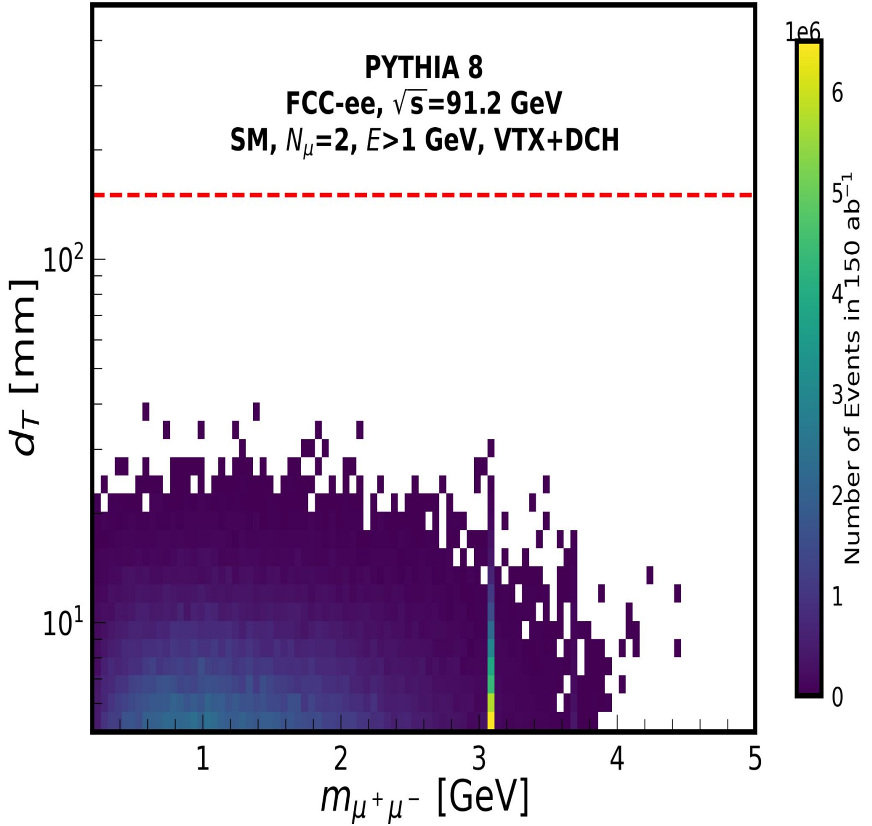




Important variables

- detector element based on the location of the vertex, D_{vtx}
- number of charged particles created at the vertex, N_{ch}
- total energy of the particles produced at the vertex, E
- transverse displacement of the vertex from the origin d_T , number of muons (N_μ), pions (N_π), kaons (N_K) originating at the vertex
- invariant mass of the final state particles associated with the vertex, m_{vtx}
- the impact parameter of the vertex, d_0

Di-muon final state

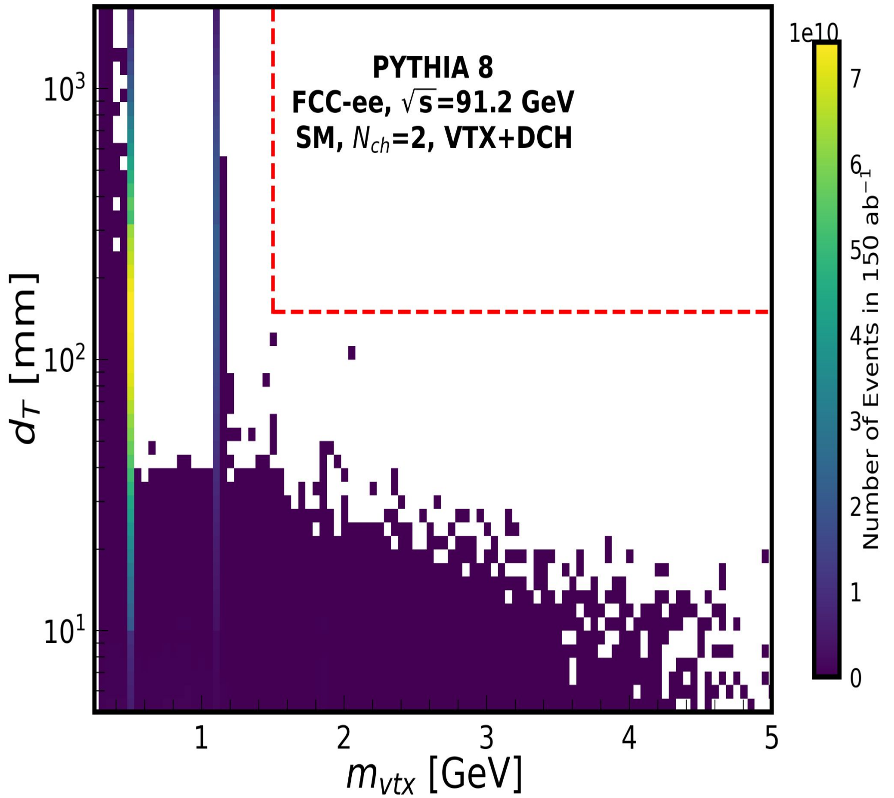


Final cuts for the dimuon final state
$D_{\rm vtx} \equiv$ out to the MS
$N_{\rm chg} = 2$
$N_\mu = 2$
$E > 2\,{\rm GeV}$
$d_T > 150\,{\rm mm}$

Di-muon final state

Benchmarks	Dimuon analysis for decays out to the MS			
	m_ϕ (GeV)	$c\tau$ (mm)	Number of events	
BPA1	0.4	39666.6	3	(5)
BPA4	2.0	135.2	9352	(12273)
BPA5	3.5	10285.4	1	(2)
BPA6	3.5	65.8	915	(1639)

Di-pion & Di-kaon final state



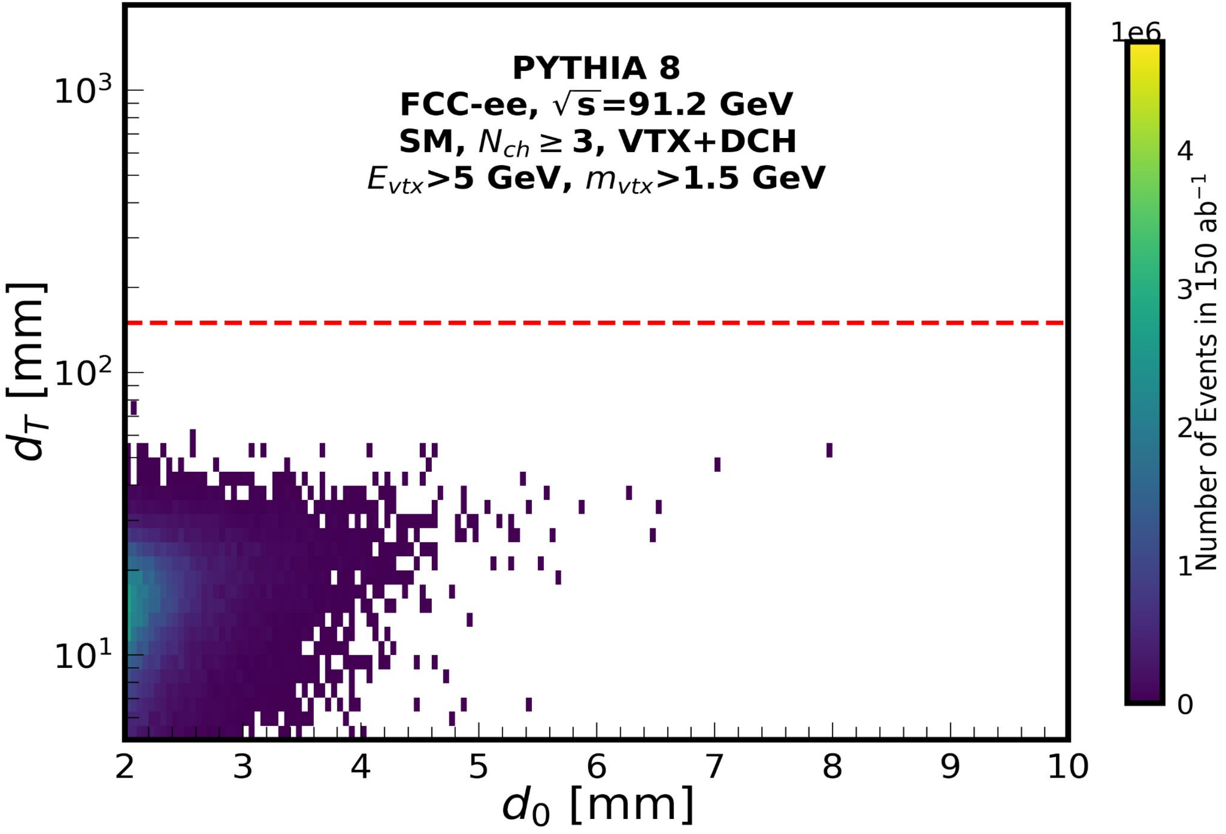
Final cuts for the di-pion/di-kaon final state	
$m_\phi \gtrsim 1.5\,\mathrm{GeV}$	All benchmarks
$D_{\mathrm{vtx}} \in$ VTX or DCH $N_{\mathrm{ch}} = 2$ $N_{\pi/K} = 2$ $E > 1\,\mathrm{GeV}$ $d_T > 150\,\mathrm{mm}$	$D_{\mathrm{vtx}} \in$ MS $N_{\mathrm{ch}} = 2$ $E > 5\,\mathrm{GeV}$

Di-pion & Di-kaon final state

Benchmarks	VTX + DCH analysis			
	m_ϕ (GeV)	$c\tau$ (mm)	Number of events	
			$\phi \to \pi^+\pi^-$	$\phi \to K^+K^-$
BPA4	2.0	135.2	26202	26970
BPA5	3.5	10385.4	4	2
BPA6	3.5	65.8	9495	3822

Benchmarks	Muon Spectrometer analysis		
	m_ϕ (GeV)	$c\tau$ (mm)	Number of events
BPA1	0.4	39666.6	4
BPA2	1.0	554.3	206
BPA3	1.0	34.6	78
BPA4	2.0	135.2	1515
BPA5	3.5	10285.4	4
BPA6	3.5	65.8	3

$c\bar{c}$ final state



$c\bar{c}$ final state

Benchmark	m_ϕ (GeV)	$c\tau$ (mm)
BPA7	4.4	95.0
Final cuts for the $c\bar{c}$ final state	Number of events	
$D_{\text{vtx}} \in$ VTX or DCH, $N_{\text{ch}} \geq 3$, $E > 5\,\text{GeV}$, $m_{\text{vtx}} > 1.5\,\text{GeV}$ + $d_T > 100\,\text{mm}$, $d_0 > 10\,\text{mm}$	6	
$D_{\text{vtx}} \in$ VTX or DCH, $N_{\text{ch}} \geq 3$, $E > 5\,\text{GeV}$, $m_{\text{vtx}} > 1.5\,\text{GeV}$ + $d_T > 150\,\text{mm}$, $d_0 > 10\,\text{mm}$	6	
$D_{\text{vtx}} \in$ VTX or DCH, $N_{\text{ch}} \geq 3$, $E > 5\,\text{GeV}$, $m_{\text{vtx}} > 1.5\,\text{GeV}$ + $d_T > 250\,\text{mm}$, $d_0 > 20\,\text{mm}$	3	

Benchmark	Number of LLP decays for $\mathcal{L} = 150\,\text{ab}^{-1}$						
	VTX	DCH	Solenoid	Preshower	DRC	MS	Outside
BPA1	5	17	1	1	21	13	6175
BPA2	315	720	31	28	485	228	1348
BPA3	32750	16977	184	134	1014	84	50
BPA4	42924	47166	861	834	8534	1937	1611
BPA5	2	6	0	0	8	5	188
BPA6	22573	10029	32	24	124	4	0
BPA7	42	28	0	0	1	0	0

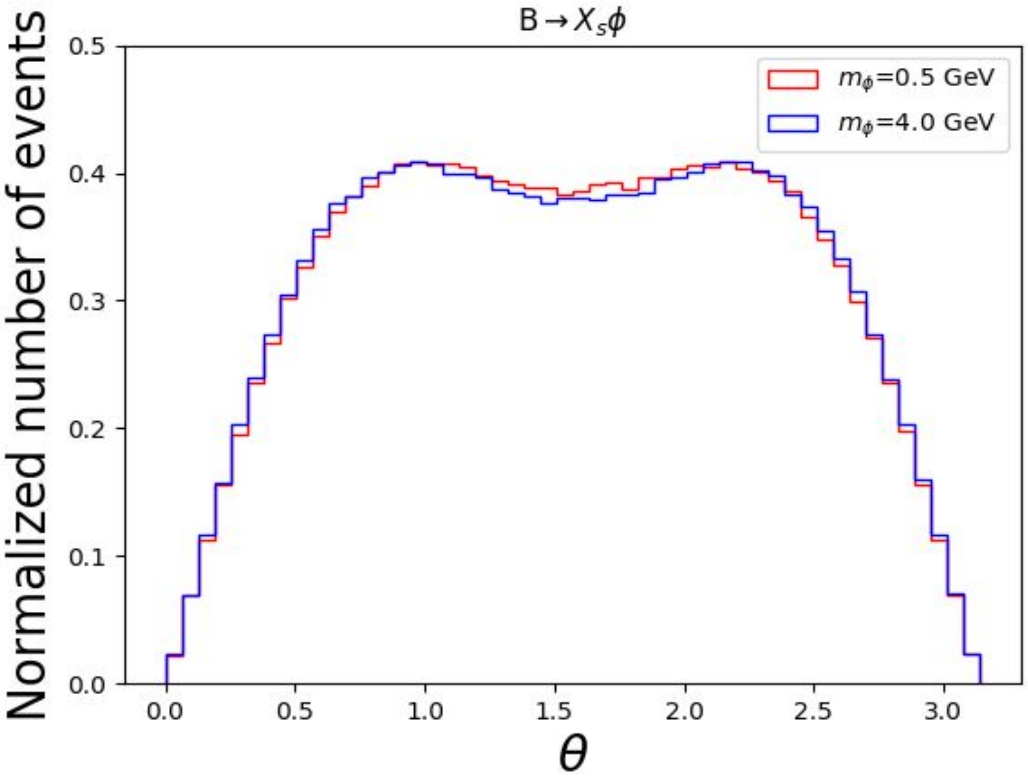
Dedicated detectors for FCC-ee

- HECATE (HErmetic Cavern TrackEr) [2011.01005]

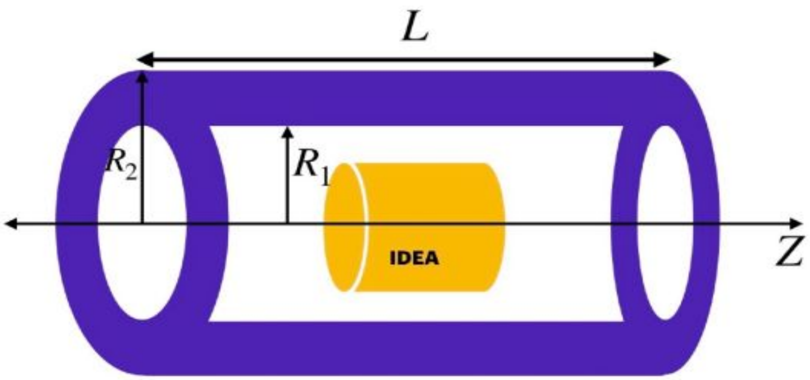
- near and far detectors [1911.06576]

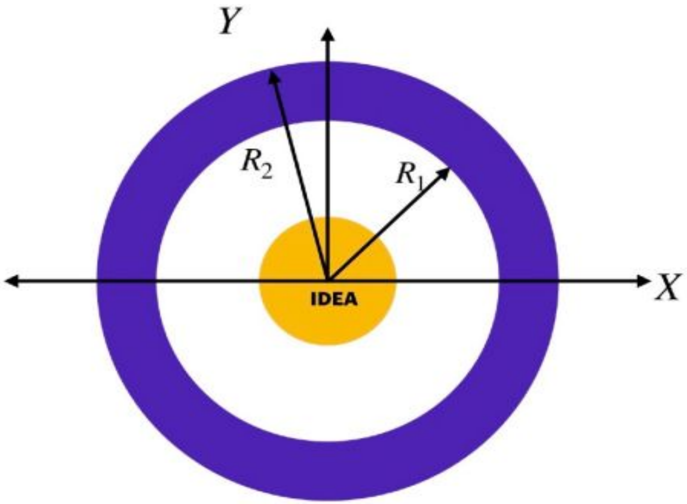
- LAYered CAvern Surface Tracker (LAYCAST) [2406.05770]

Dedicated detectors for FCC-ee



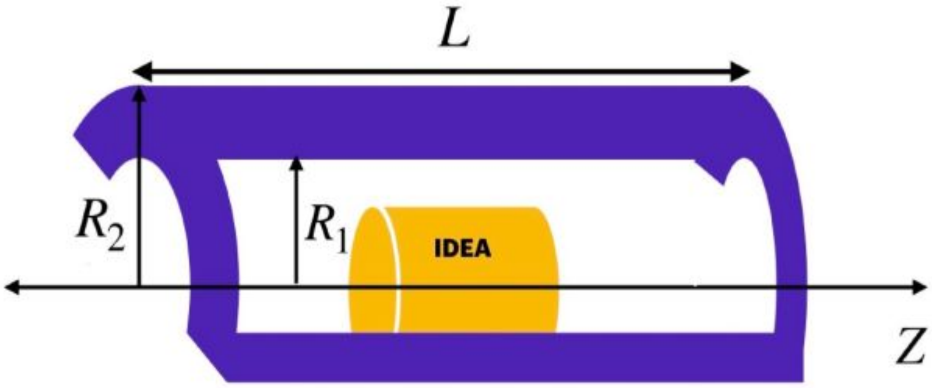
Dedicated detectors for FCC-ee (A1)

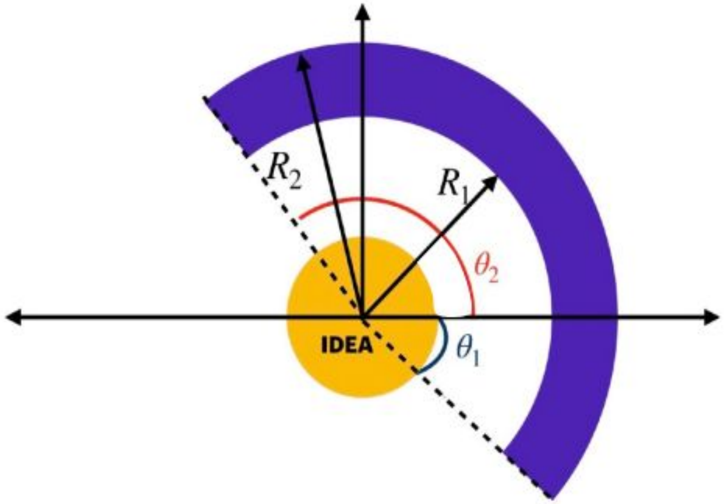




Detector	R_1 (m)	R_2 (m)	L (m)
A1	6	11	20

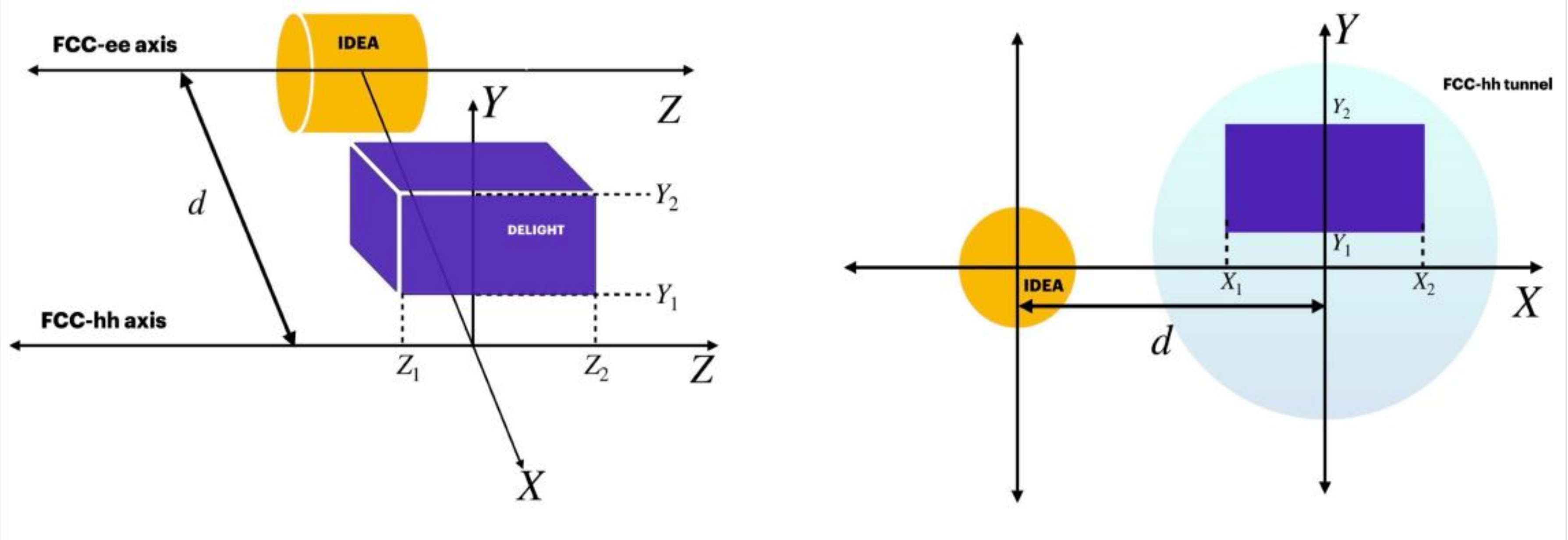
Dedicated detectors for FCC-ee (B4)





Detector	R_1 (m)	R_2 (m)	L (m)	θ_1 (°)	θ_2 (°)
B4	6	11	20	-45	135

Dedicated detectors for FCC-ee (G2)



Detector	d (m)	X_1 (m)	X_2 (m)	Y_1 (m)	Y_2 (m)	Z_1 (m)	Z_2 (m)
G2	10	−50	50	25	125	−50	50

Dedicated detectors for FCC-ee

Benchmarks	Dedicated detector analysis				
	m_ϕ (GeV)	$c\tau$ (mm)	A1	B4	G2
BPA1	0.4	39666.6	38	21	87
BPA5	3.5	10285.4	11	6	15

Conclusion

- Detection prospect of light LLPs coming from B-meson decays at the FCC-hh and FCC-ee for dark Higgs boson.

- Compared to FASER2, FOREHUNT enhance the sensitivity by a factor of 20 for the dark Higgs model. → DELIGHT performs even well.

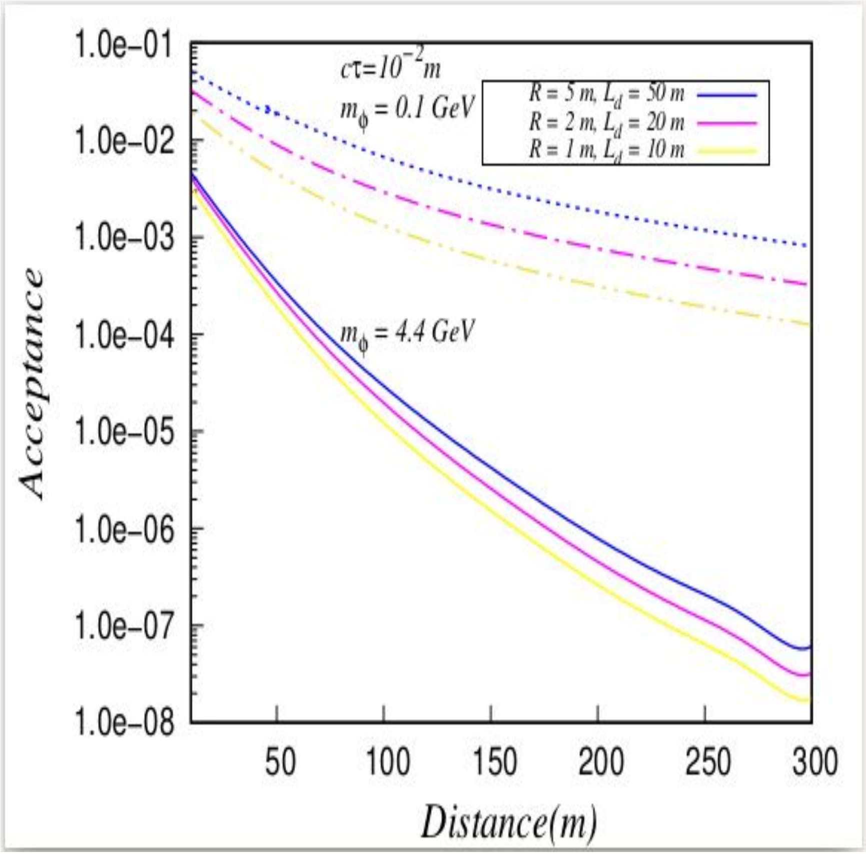
- We quote the expected number of signal events at FCC-ee after the analysis cuts for each benchmark for their dominant decay modes.

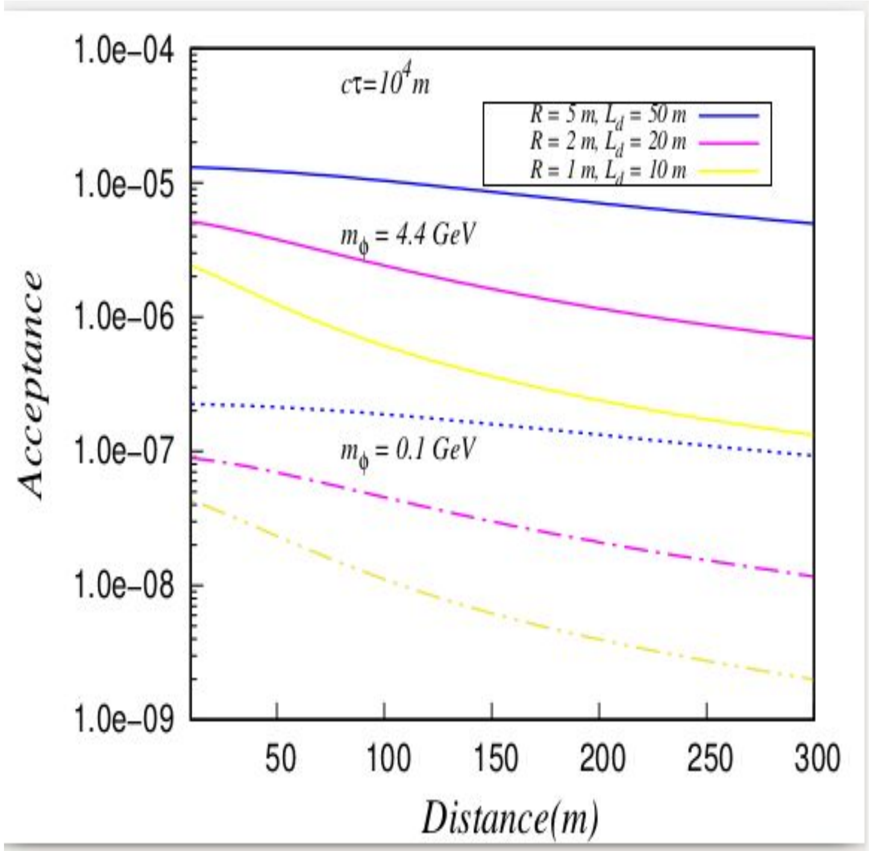
- Finally, we extensively study possible dedicated LLP detector options for the FCC-ee.

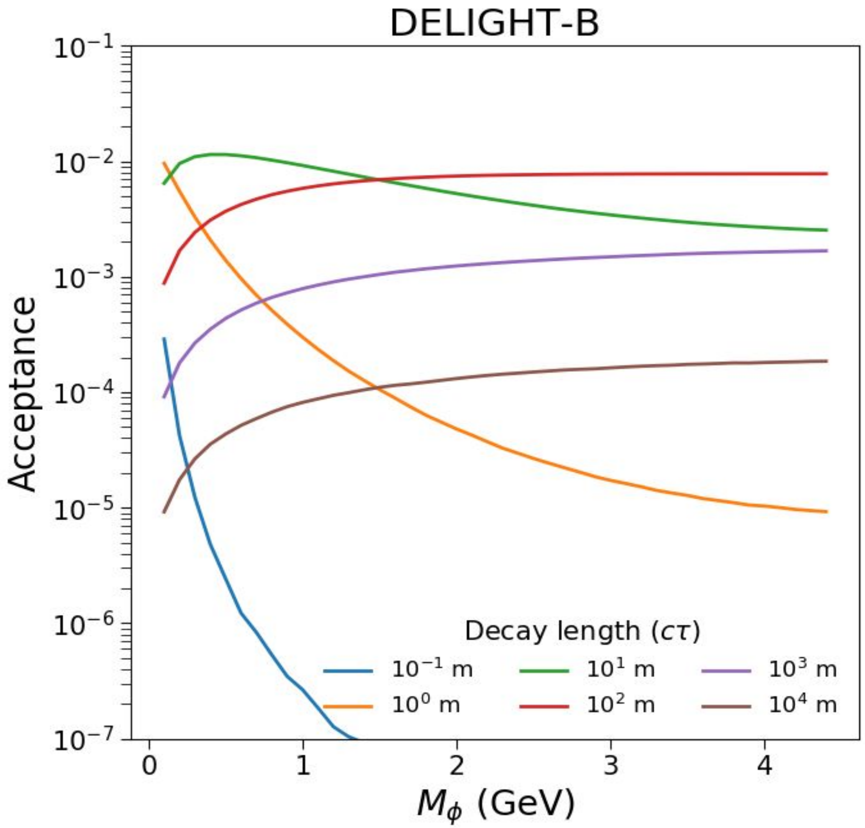

THANK YOU

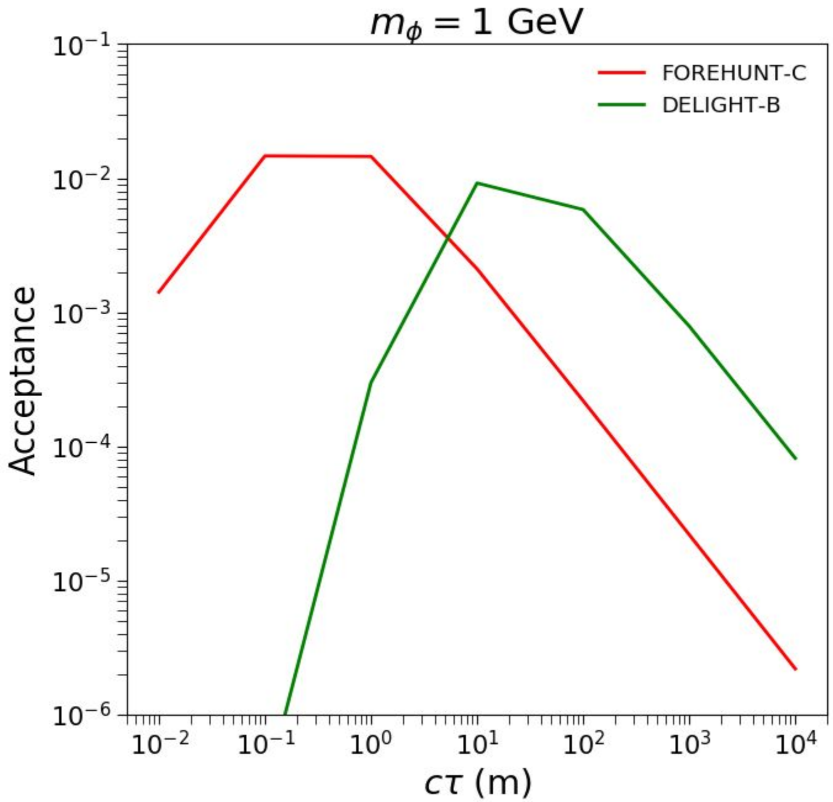
Backup Slides

Optimization



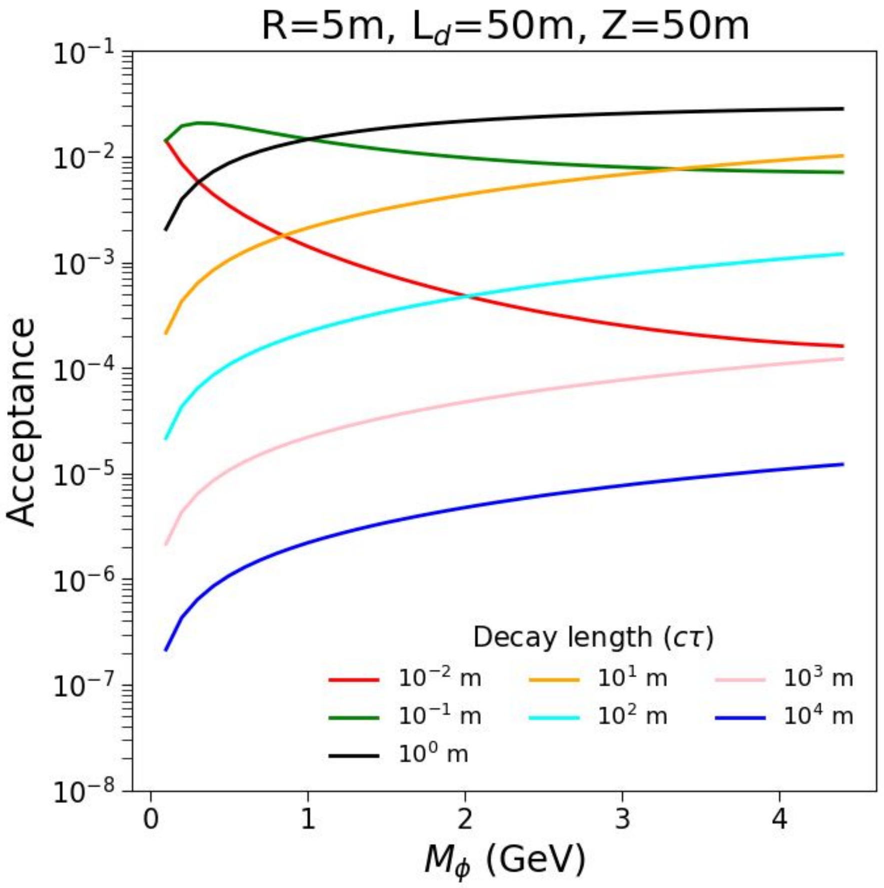



DELIGHT-B
Acceptance
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
1
2
3
4
M_ϕ (GeV)
Decay length ($c\tau$)
10^{-1} m
10^{0} m
10^{1} m
10^{2} m
10^{3} m
10^{4} m


$m_\phi = 1$ GeV
Acceptance
FOREHUNT-C
DELIGHT-B
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
$c\tau$ (m)

- Huge improvement over all mass and cτ (~ 100) compared to FASER2 like configuration at 100 TeV.

- The enhancement comes from the increase in size as well as the placement of the detector near to IP.

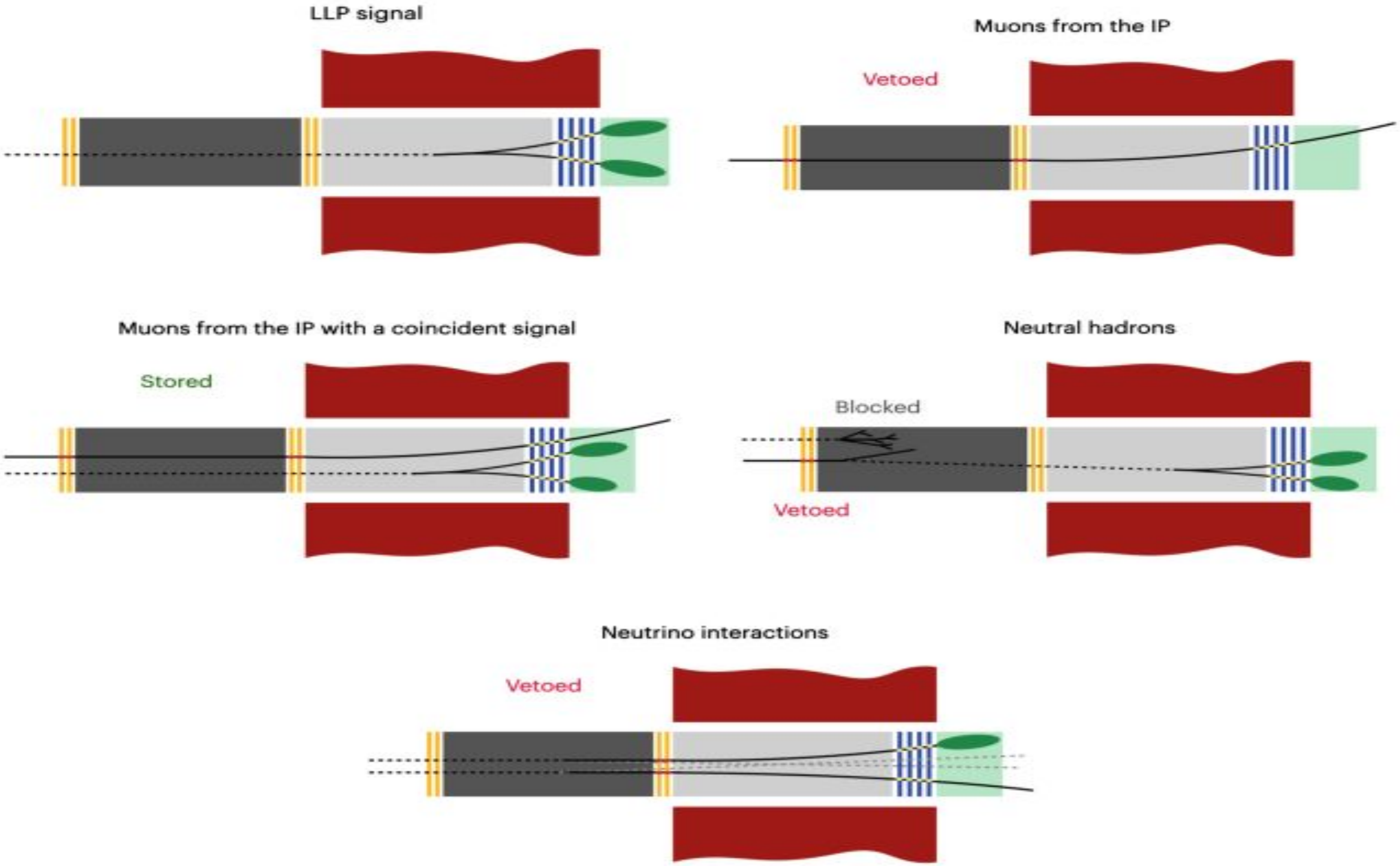


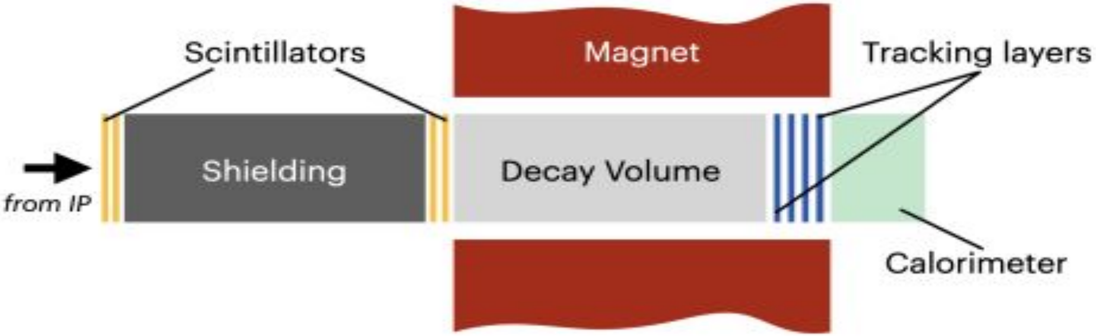
Backgrounds and detector design for FOREHUNT

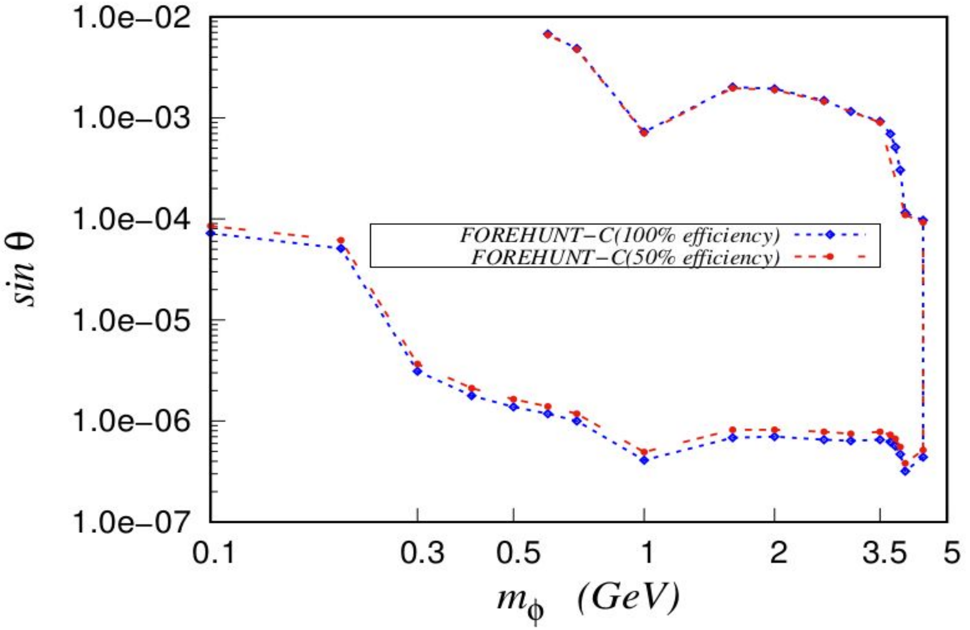
- **Muons from the IP**: 0 (10^9) at run 3, expected to increase by a factor of 2 at FCC-hh ➡ scintillator plates to veto this background.

- **Neutral Hadrons:** Like K_L,k_S can mimic the signal ➡ shielding before scintillators to reduce the background.

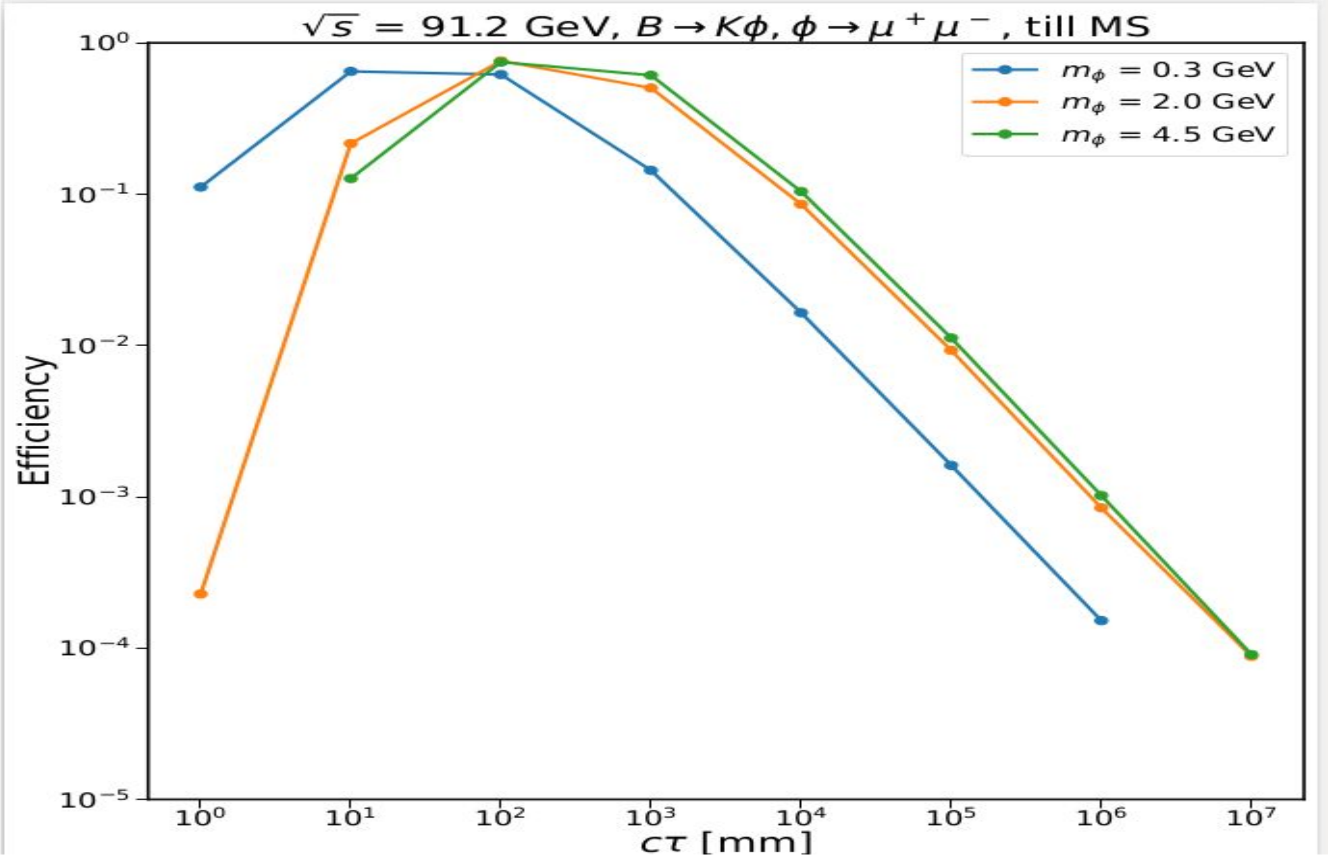
- **Neutrinos:** In case the neutrino interacts after the veto system, the number of such events can be further suppressed by demanding at least two reconstructed tracks coming from the same vertex, where the reconstructed vertex lies within the decay volume. The neutrino background can be further reduced by a higher cut on the calorimeter energy deposit.


LLP signal
Muons from the IP
Vetoed
Muons from the IP with a coincident signal
Stored
Neutral hadrons
Blocked
Vetoed
Neutrino interactions
Vetoed

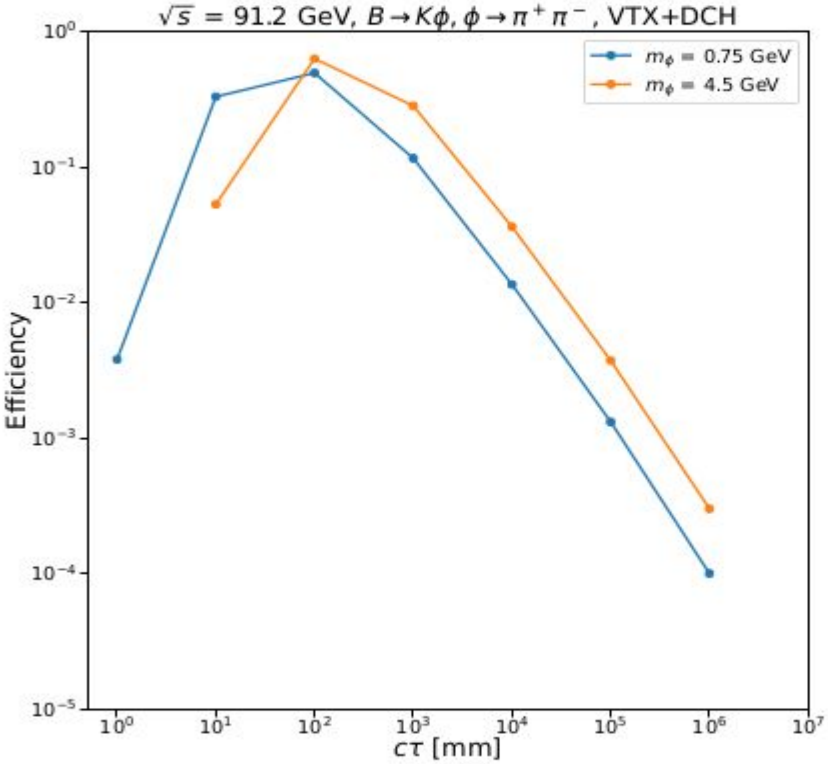

Scintillators
Magnet
Tracking layers
Shielding
Decay Volume
from IP
Calorimeter

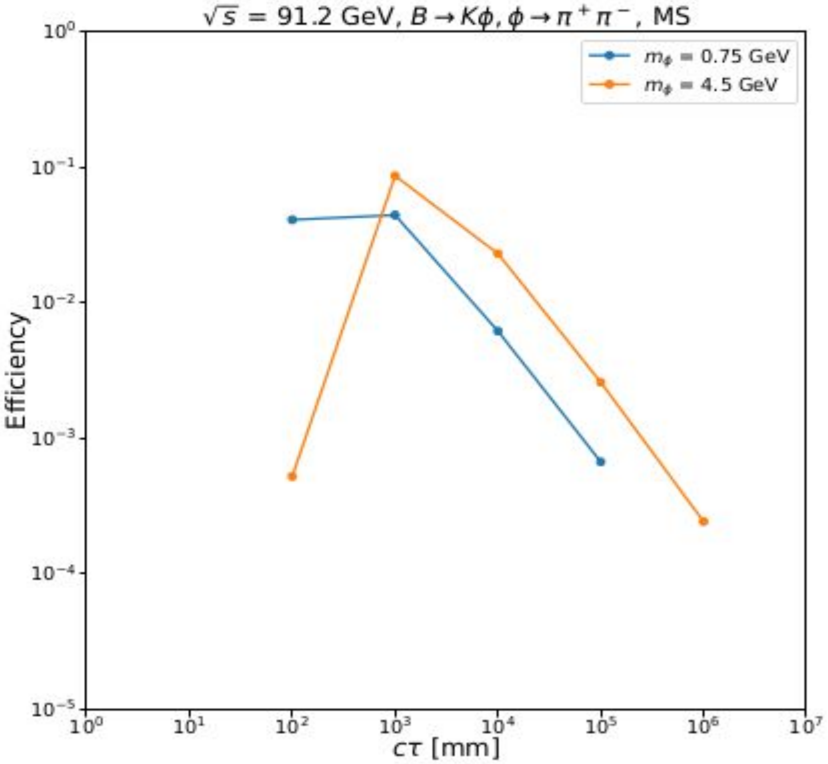

1.0e−02
1.0e−03
1.0e−04
1.0e−05
1.0e−06
1.0e−07
sin θ
FOREHUNT−C(100% efficiency)
FOREHUNT−C(50% efficiency)
0.1
0.3
0.5
1
2
3.5
5
m_φ (GeV)

Di-muon final state

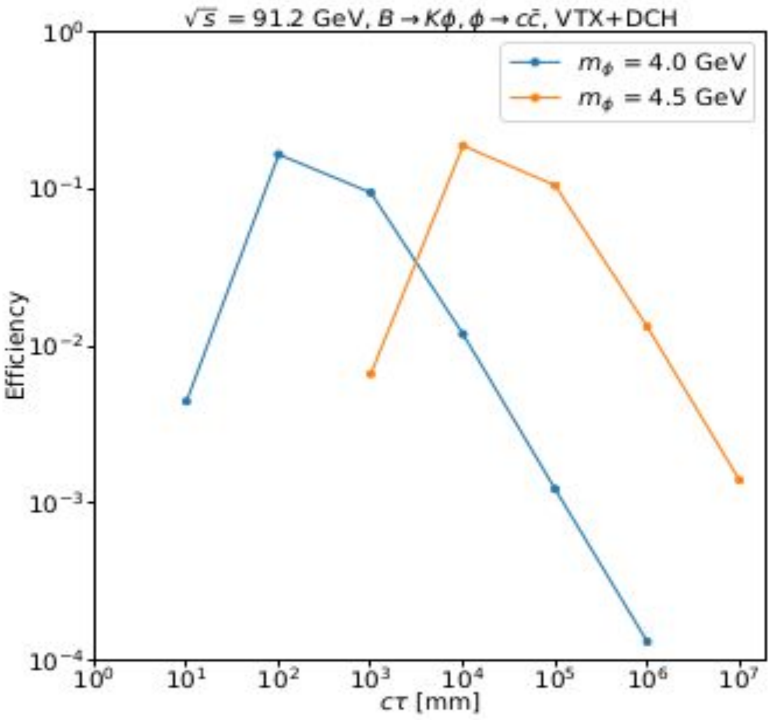


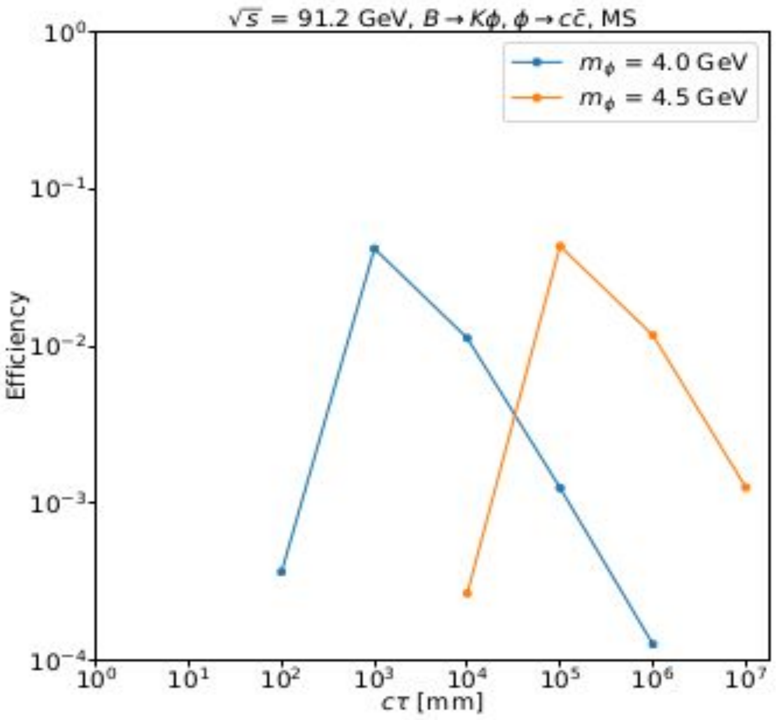
Di-pion & Di-kaon final state



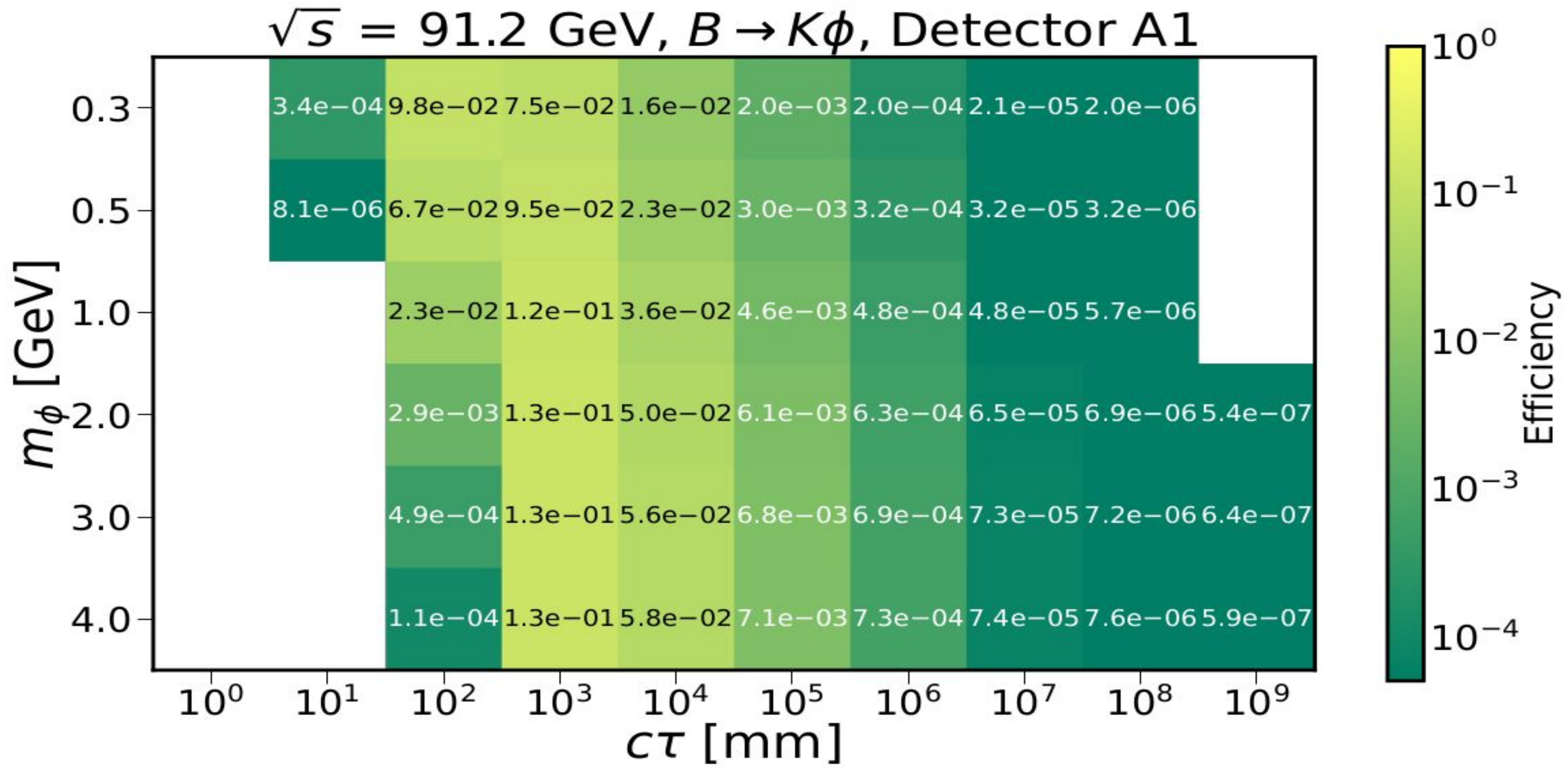


$c\bar{c}$ final state

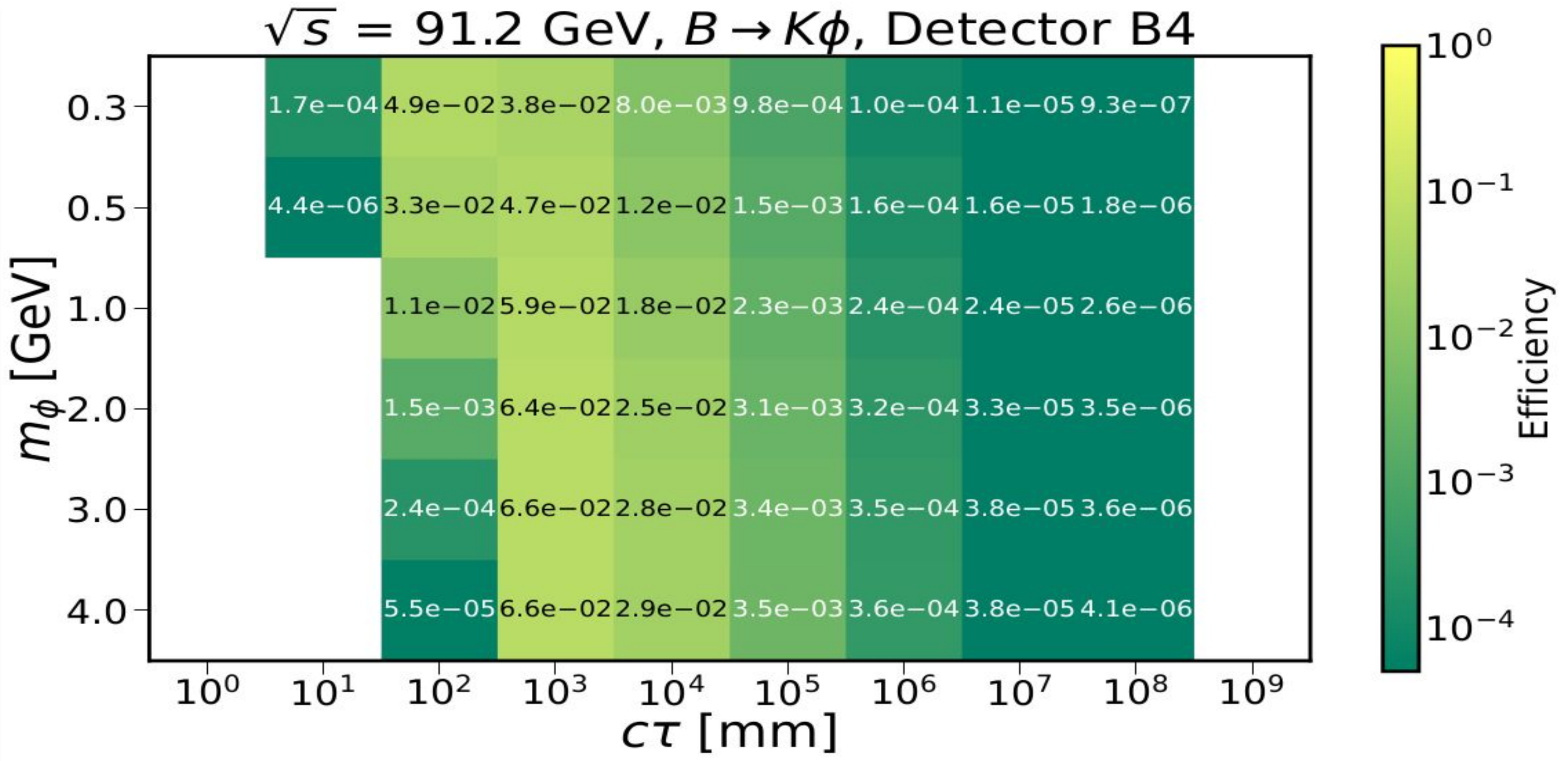




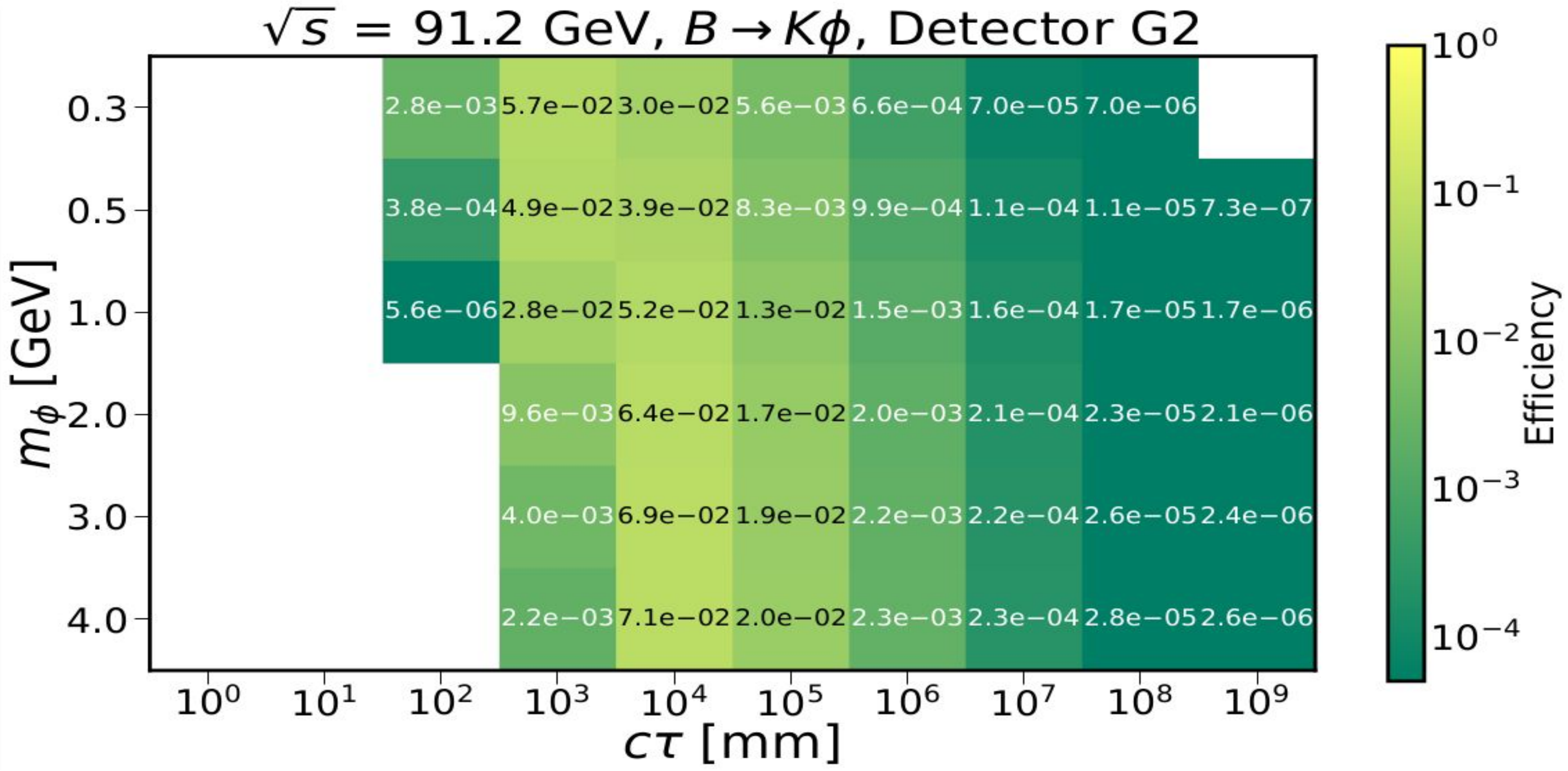
Dedicated detectors for FCC-ee



Dedicated detectors for FCC-ee



Dedicated detectors for FCC-ee



Dedicated detectors for FCC-ee