Far Detectors Can Enhance the Physics Discovery Potential at the CEPC

Kechen Wang (王科臣)
Wuhan University of Technology

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Based on Zeren Simon Wang, and **K. Wang**,
PRD 101 (2020) no.7, 075046, PRD 101 (2020) no. 11, 115018

OUTLINE

Long-lived Particles

Proposed FDs @ pp colliders

FDs @ e^-e^+ colliders

→ geometry, shape, volume, position, ...

Physics implications

→ exotic Higgs decays

→ heavy neutral leptons

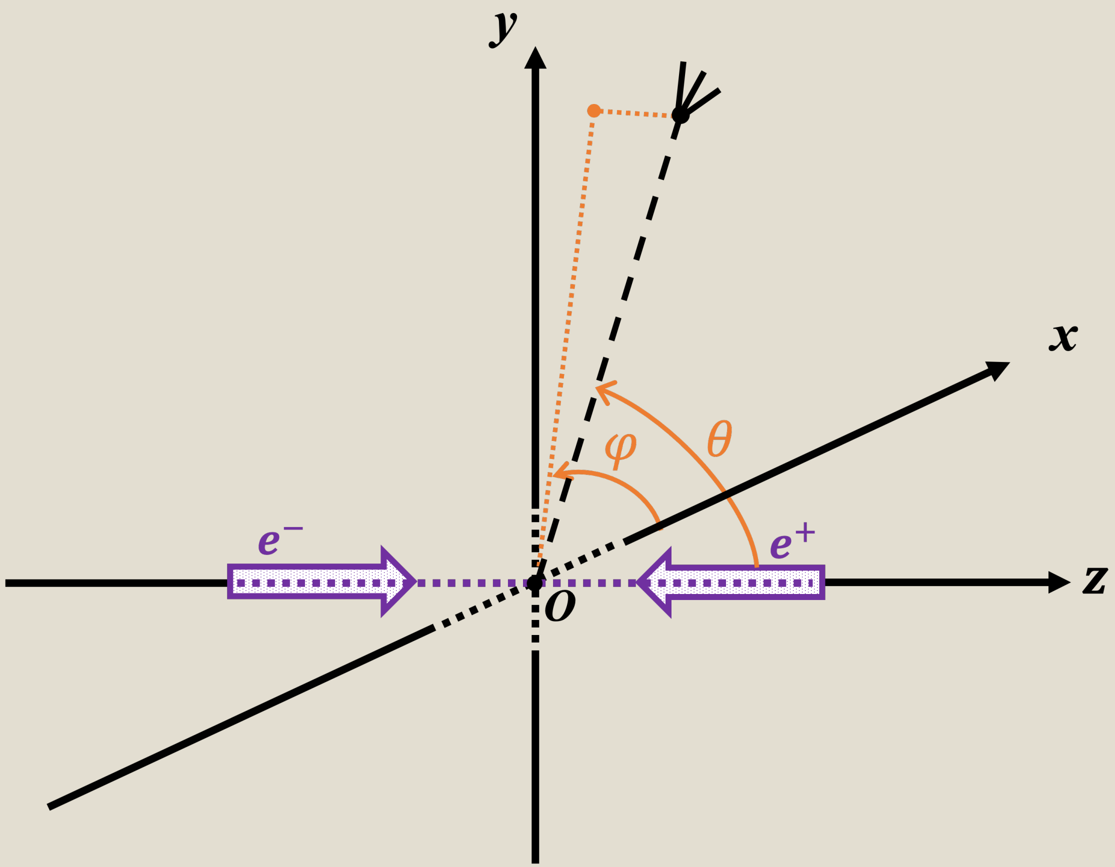
→ lightest neutralinos in RPV-SUSY

Conclusion & Discussion

Theory Motivation

New particles become long-lived because of:
→ feeble couplings to SM particles
→ phase space suppression
→ approximate symmetry
→ heavy mediators, ...

Relatively long decay length



The discovery of LLPs could explain some fundamental problems:
neutrino mass, dark matter, baryogenesis, naturalness, ...

LLPs are important targets when searching for BSM physics.

Exponential Decay

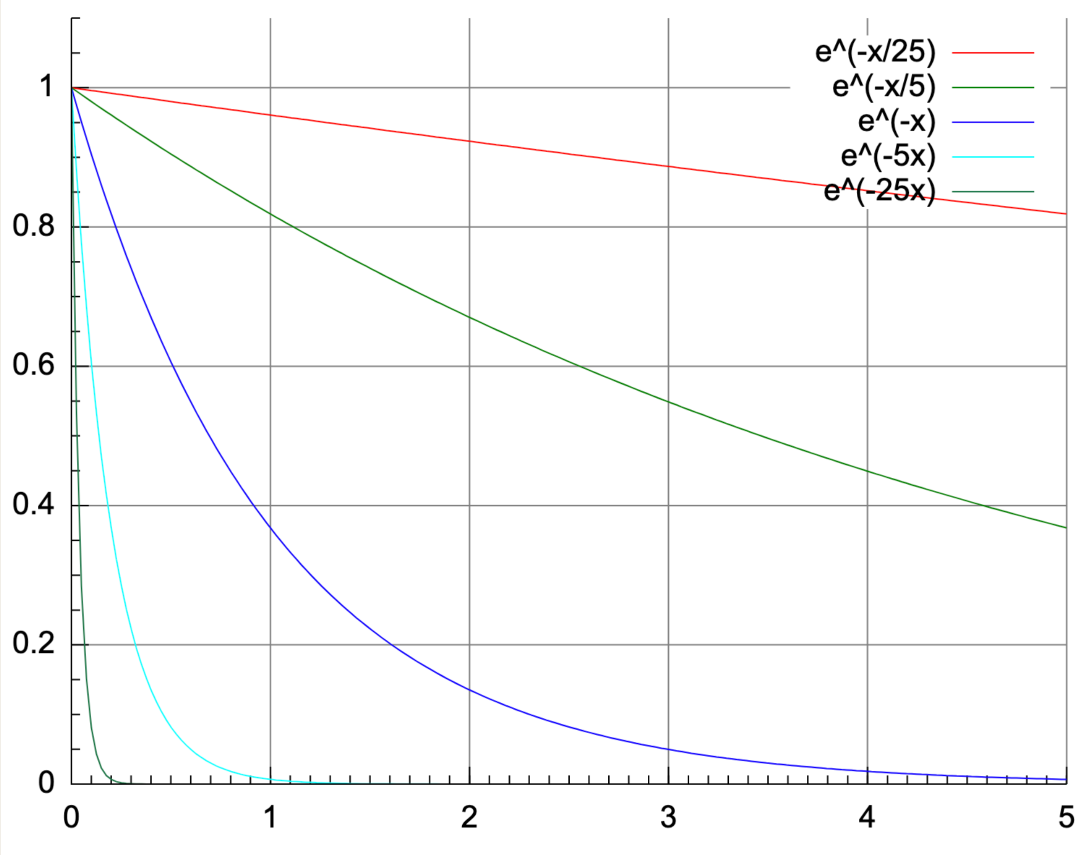
When a LLP produced at 0,

Probability of still existing (does not decay) at L

$P(L) = e^{-L/\lambda}$, λ – decay length

Probability of decaying between L_1 and L_2 ($L_1 < L_2$)

$P(\Delta L) = e^{-L_1/\lambda} - e^{-L_2/\lambda}$



Signatures of LLPs in ND

When $\lambda \sim \mathcal{O}(1)$ m,

Mainly decay inside the near detector

Appear as displaced vertex

Various final states depending on different decay products

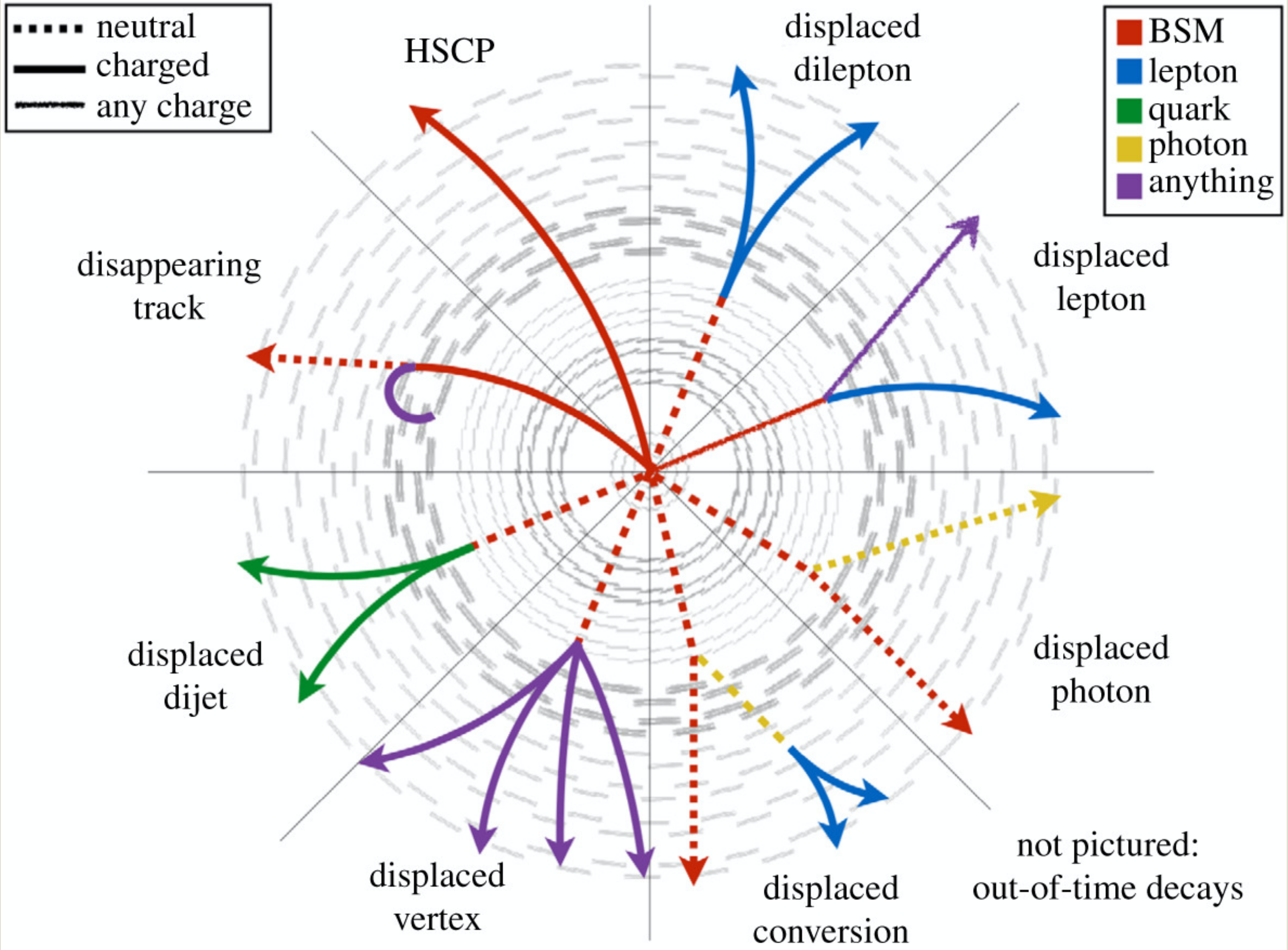


Figure from [A. De Roeck, Phil. Trans. Roy. Soc. Lond. A 377, 20190047 (2019)]

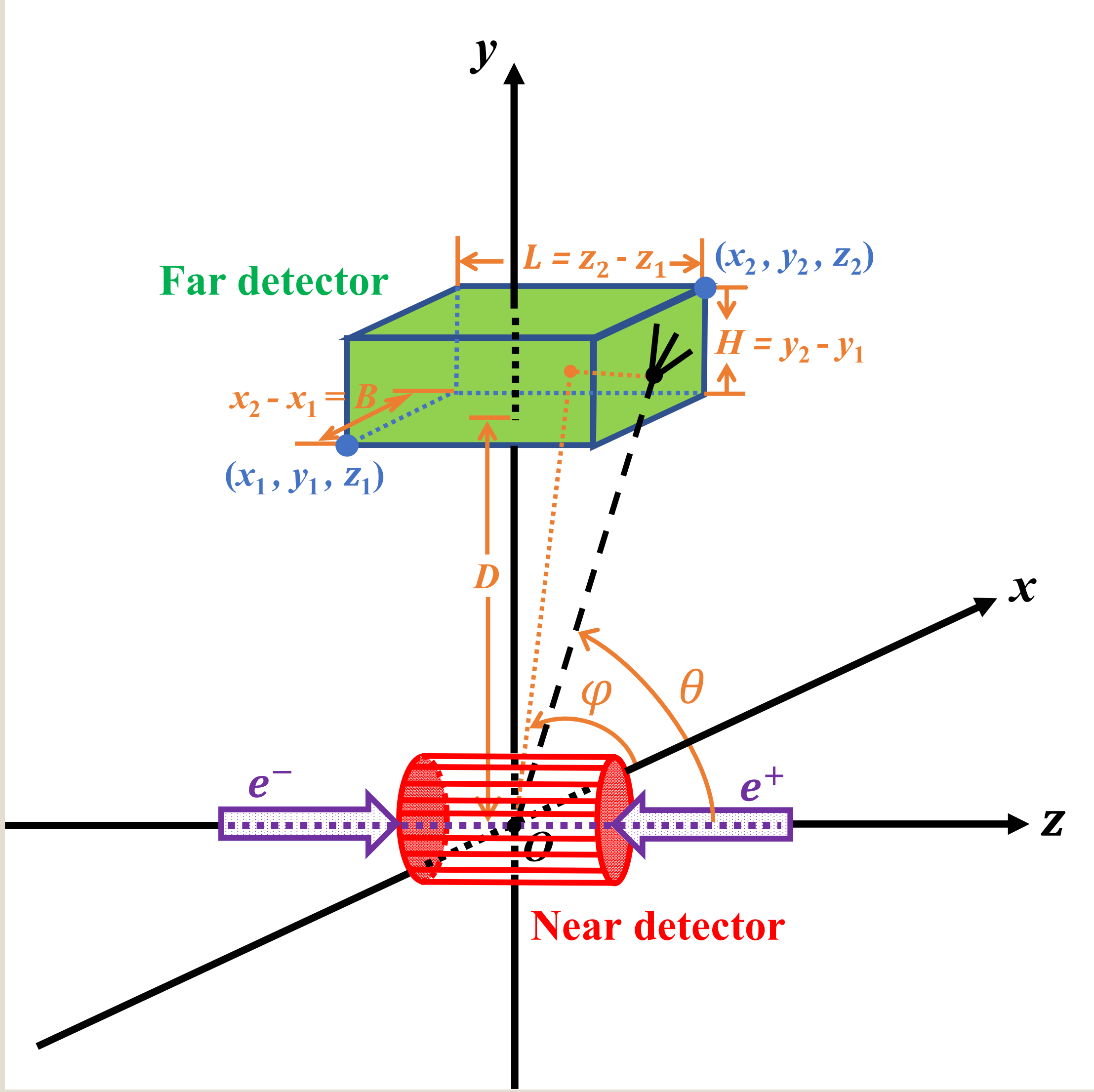
Signatures of LLPs in FD

When $\lambda \sim \mathcal{O}(100)$ m,

Mainly travel through and acts as missing energy in the near detector.

Far detector is more likely to observe the decay process, and reconstruct the time, position, direction, momentum, mass, etc.

Far detector can enhance the discovery potential for LLPs with very long decay length.



MATHUSLA

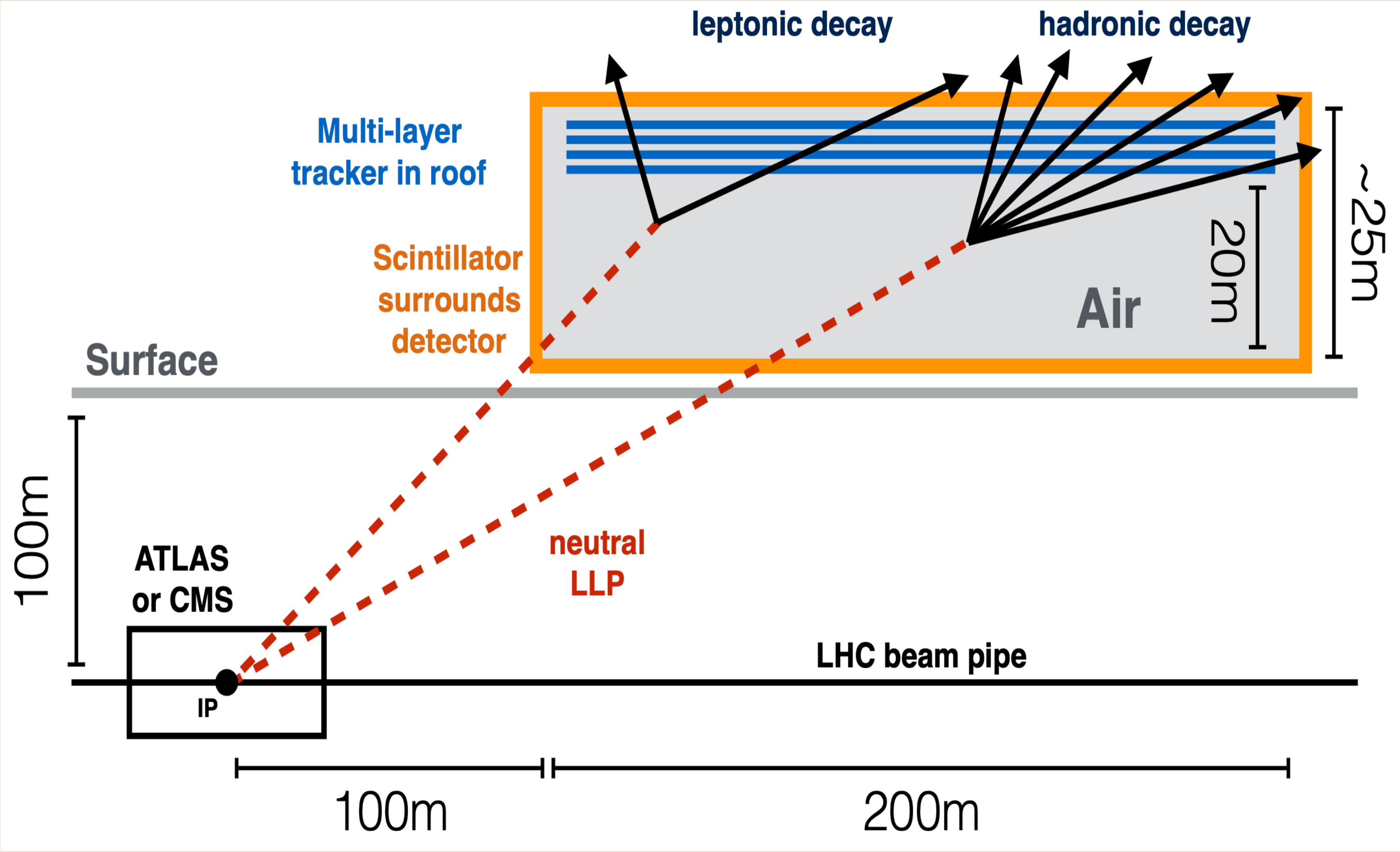


Figure from [D. Curtin et al., Rept. Prog. Phys. 82, 116201 (2019)]

Vertical slice through MATHUSLA. Gray-filled orange box – the detector.

Shape: a cuboid with a bottom area of 200 m × 200 m and a height of 25 m.

Location: on the ground above the IP, 100 m shifted along the beam directions.

FASER

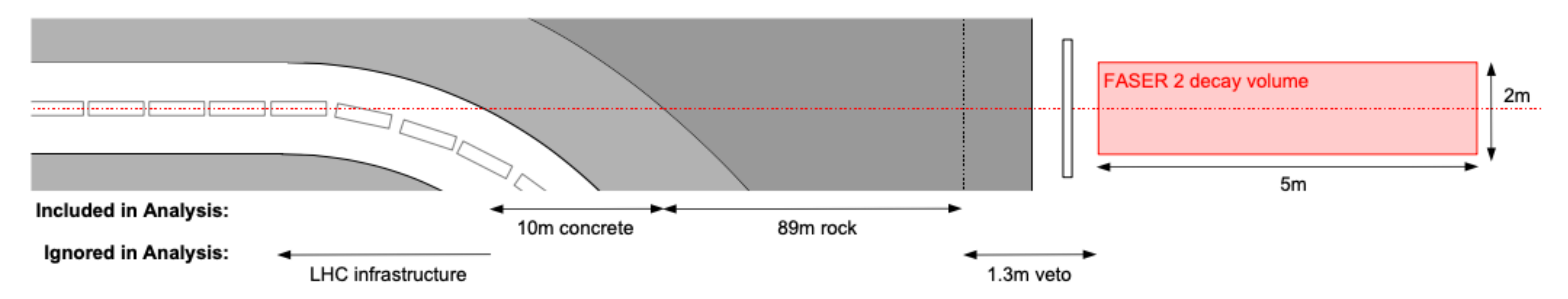


Figure from [K. Jodlowski, F. Kling, L. Roszkowski, and S. Trojanowski, arXiv:1911.11346].

Horizontal slice through FASER.
Pink box – the detector.

Shape: a cylinder with a bottom circle of 2 m in diameter and 5 m in length.

Location: directly in front of the LHC tunnel along the beam direction, ~ 480 m away from the ATLAS IP.

CODEX-b

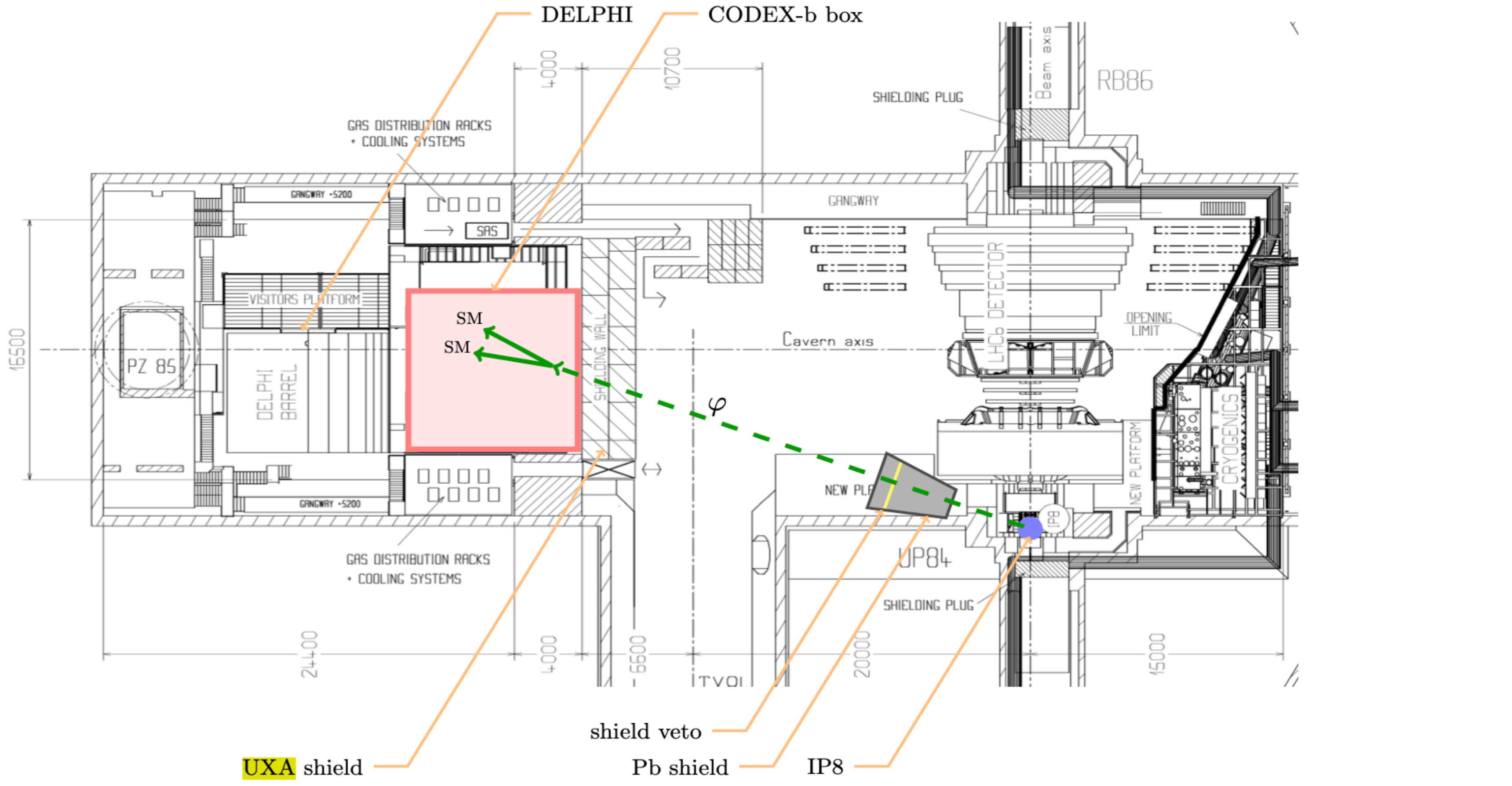


Figure 10: Layout of the LHCb experimental cavern UX85 at point 8 of the LHC [113], overlaid with the proposed CODEX-b location.

Figure from [arXiv:1901.09966]

FD (pink area) ~ 25 m from IP8, 10×10×10 m^3 volume; 3 m thick concrete UXA shield wall; 4.5 m of Pb shield

Inspirations

FDs @ pp can have different positions, geometry sizes, ...

Enhance the discovery potential of LLPs with $\lambda \sim \mathcal{O}(100)$ m

[see for example, D. Curtin et al., Rept. Prog. Phys. 82, 116201 (2019)]

Naturally questions arises:

Can we install similar FDs at future lepton colliders ?

If we can, what's the best design of such far detectors ?

Geometry, shape, volume, position, ...

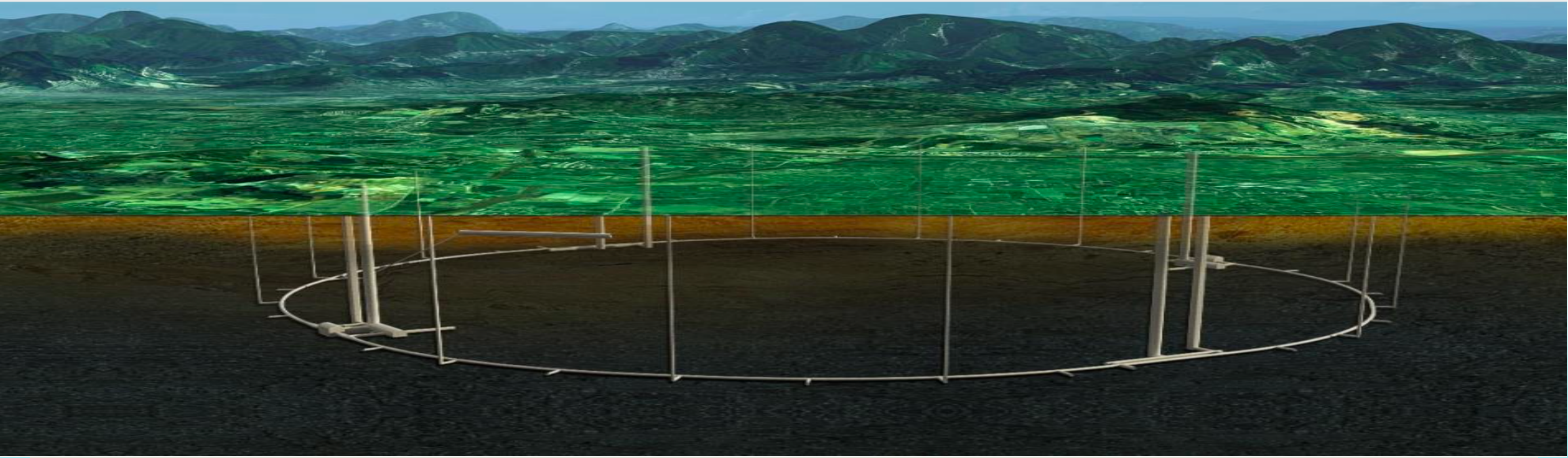
Optimized by its physical discovery potential !

What's the physics implications, if they are installed ?

We proposed to install FDs @ ee colliders, and investigate the preliminary designs.

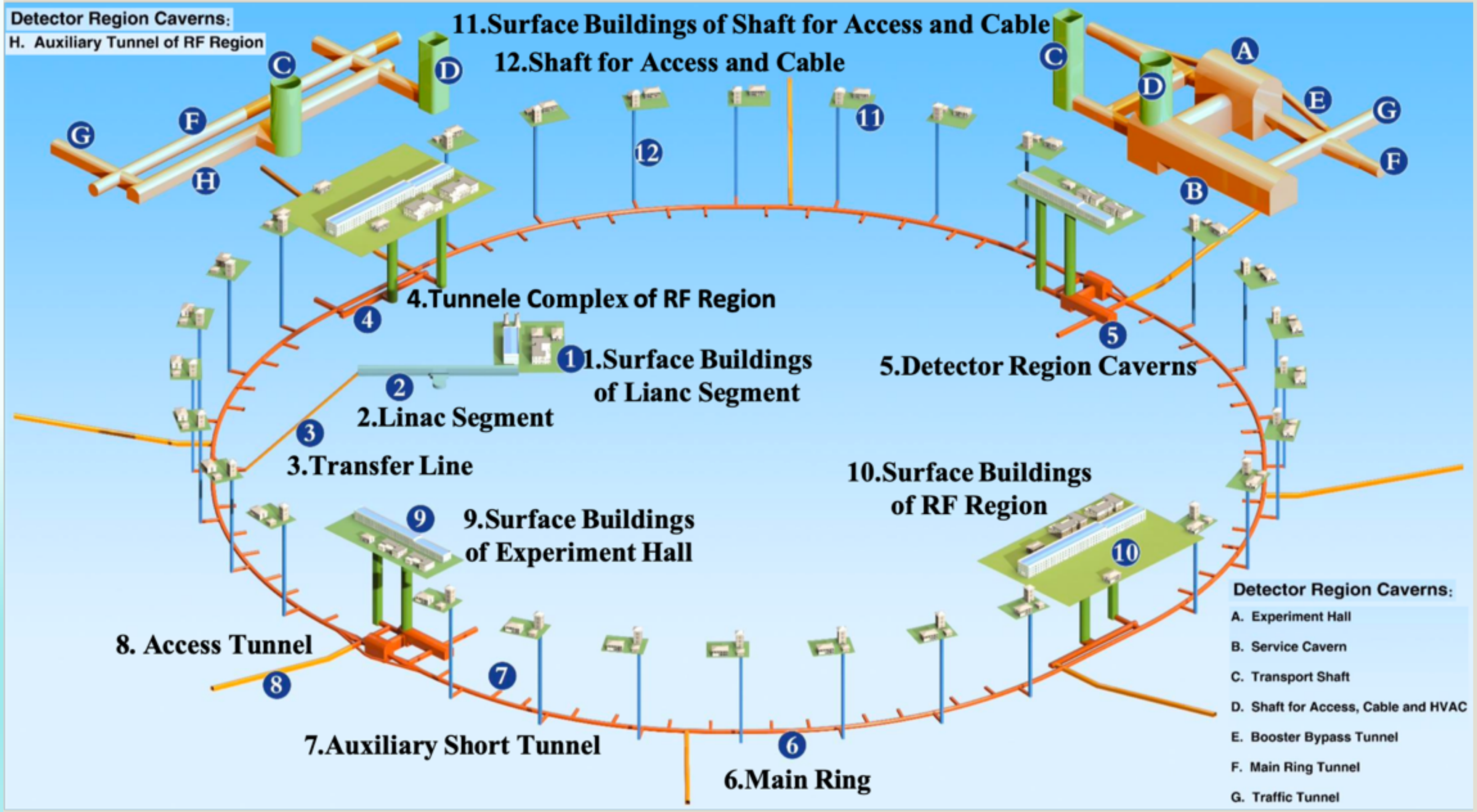
Site Selection of CEPC

CEPC Civil Engineering



FDs can be placed on the ground above the IPs.

CEPC Civil Engineering



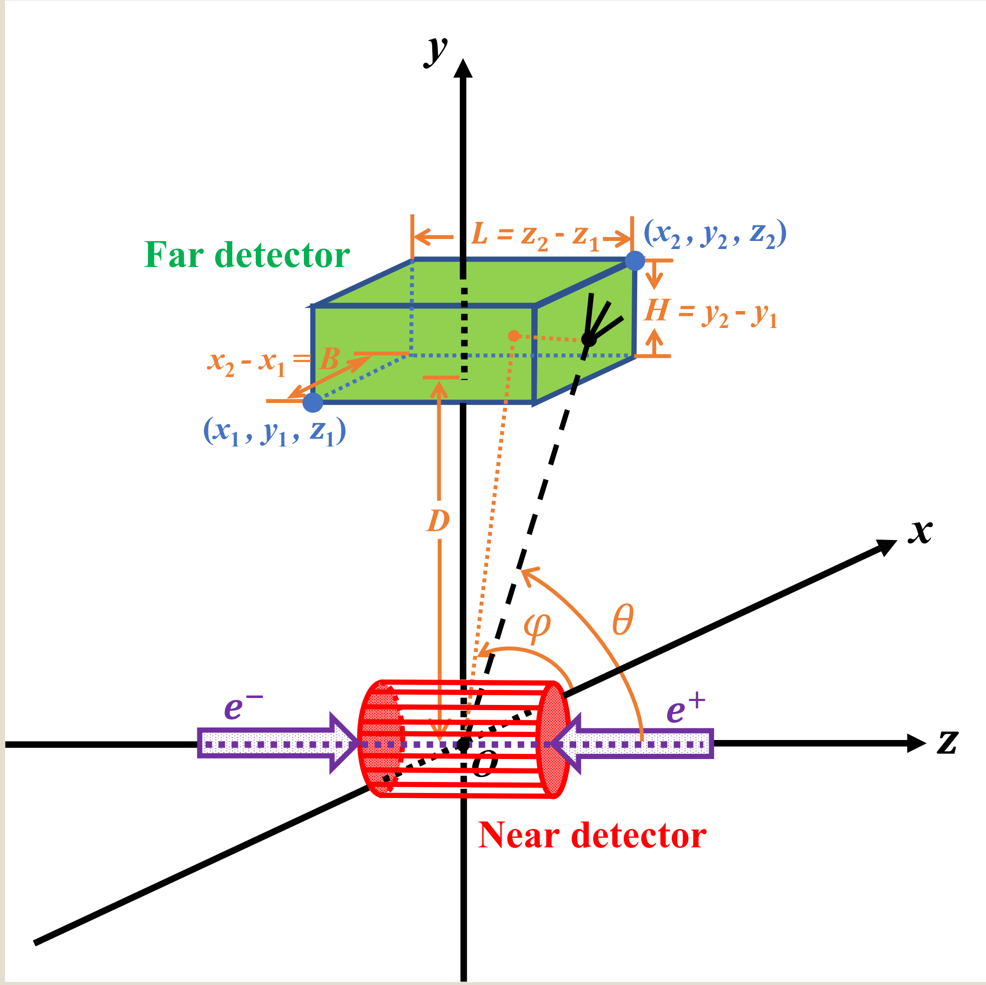
FDs can also be placed inside the experiment hall if the hall is big enough.

Or, FDs can be placed in a cavern or shaft near the experiment hall.

Figure based on [Lei Ye, Workshop on the Circular Electron-Positron Collider, Oxford, (2019)], see updated results from Yu Xiao, Ke Huang, Zhichao Zhang's talks in this workshop.

Different Designs of FDs

	V [m^3]	B [m]	H [m]	L [m]	(x_1, y_1, z_1) [m]	(x_2, y_2, z_2) [m]	D [m]
FD1	5.0×10^3	10	10	50	(5, -5, -25)	(15, 5, 25)	5
					(10, -5, -25)	(20, 5, 25)	10
FD2	8.0×10^5	200	20	200	(-100, 50, 50)	(100, 70, 250)	50
					(-100, 100, 100)	(100, 120, 300)	100
FD3	8.0×10^5	200	20	200	(-100, 50, -100)	(100, 70, 100)	50
					(-100, 100, -100)	(100, 120, 100)	100
FD4	8.0×10^5	100	80	100	(-50, 50, -50)	(50, 130, 50)	50
					(-50, 100, -50)	(50, 180, 50)	100
FD5	3.2×10^6	200	80	200	(-100, 50, -100)	(100, 130, 100)	50
					(-100, 100, -100)	(100, 180, 100)	100
FD6	8.0×10^7	1000	80	1000	(-500, 50, -500)	(500, 130, 500)	50
					(-500, 100, -500)	(500, 180, 500)	100
FD7	8.0×10^5	2000	20	20	(-1000, 50, -10)	(1000, 70, 10)	50
					(-1000, 100, -10)	(1000, 120, 10)	100
FD8	8.0×10^5	20	20	2000	(-10, 50, -1000)	(10, 70, 1000)	50
					(-10, 100, -1000)	(10, 120, 1000)	100



Simple shape: cuboid, similar to MUTHUSLA
Varying: position & geometry size

Physics Scenarios

		Exotic Higgs Decays	Heavy Neutral Leptons	Light Neutralinos in RPV SUSY
scenario		$h \to XX$	$Z \to N\nu$	$Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$
LLP		X	N	$\tilde{\chi}_1^0$
production $e^- e^+ \to$		Zh (main) $\nu\bar{\nu}h, e^- e^+ h$ (VBF)	Z	
$\sqrt{s}$ [GeV]		240	91.2	
N_h	CEPC FCC-ee	1.14×10^6 [16] 5.6 ab^{-1}, 7 years, 2 IPs	-	
N_Z	CEPC	-	7.0×10^{11} [16] 16 ab^{-1}, 2 years, 2 IPs	
	FCC-ee		5.0×10^{12} [20] 150 ab^{-1}, 4 years, 2 IPs	

has been updated to 1.5×10^{12}

Signal Calculation

$$N_{\rm LLP}^{\rm obs} = N_{\rm LLP}^{\rm prod} \cdot \langle P[\text{LLP in f.v.}]\rangle \cdot \text{Br}(\text{LLP} \to \text{visible})$$

Average Decay Probabilities in FD

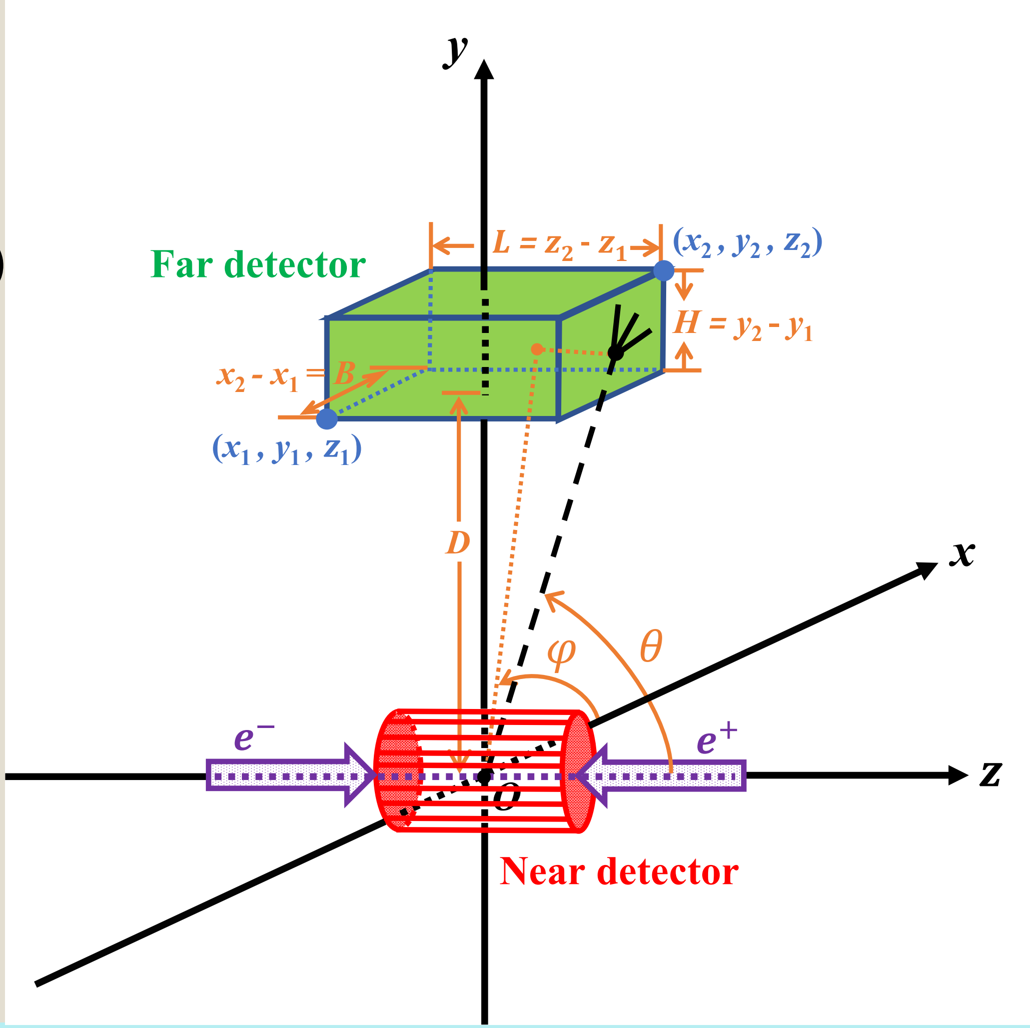
$$P(\Delta L) = e^{-L_1/\lambda} - e^{-L_2/\lambda},$$

probability of decaying between L_1 and L_2 $(L_1 < L_2)$

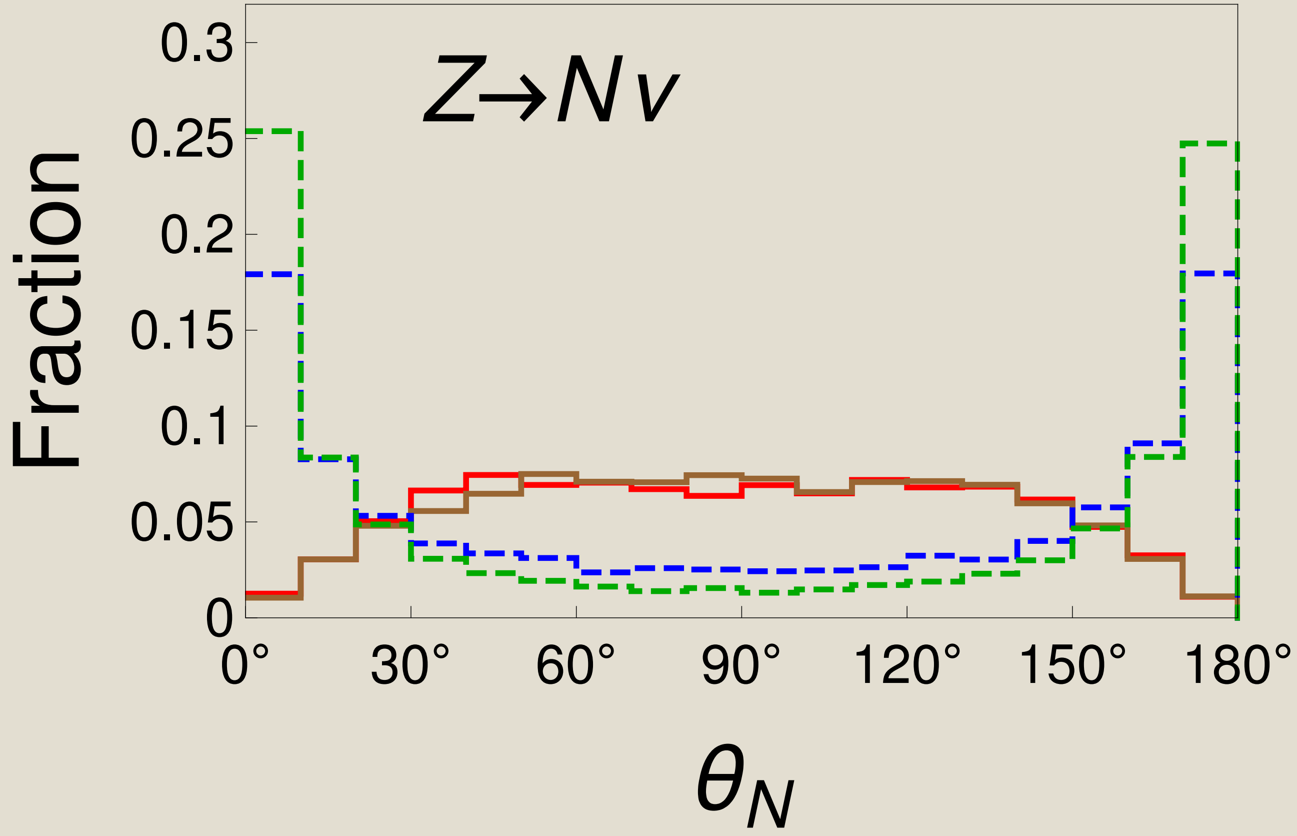
in the lab. frame:

$$\lambda = \beta c\, \gamma\tau = \frac{p}{E}\frac{E}{m} c\tau = \frac{p}{m} c\tau$$

Depends on theory model parameters (kinematics, mass, lifetime) & geometry of FD



Kinematical Distributions



@ pp: very forward direction
@ ee: more in the transverse direction

- e^-e^+ 91.2 GeV: m_N= 1 GeV
- e^-e^+ 91.2 GeV: m_N= 40 GeV
- LHC 14 TeV: m_N=1 GeV
- LHC 14 TeV: m_N=40 GeV

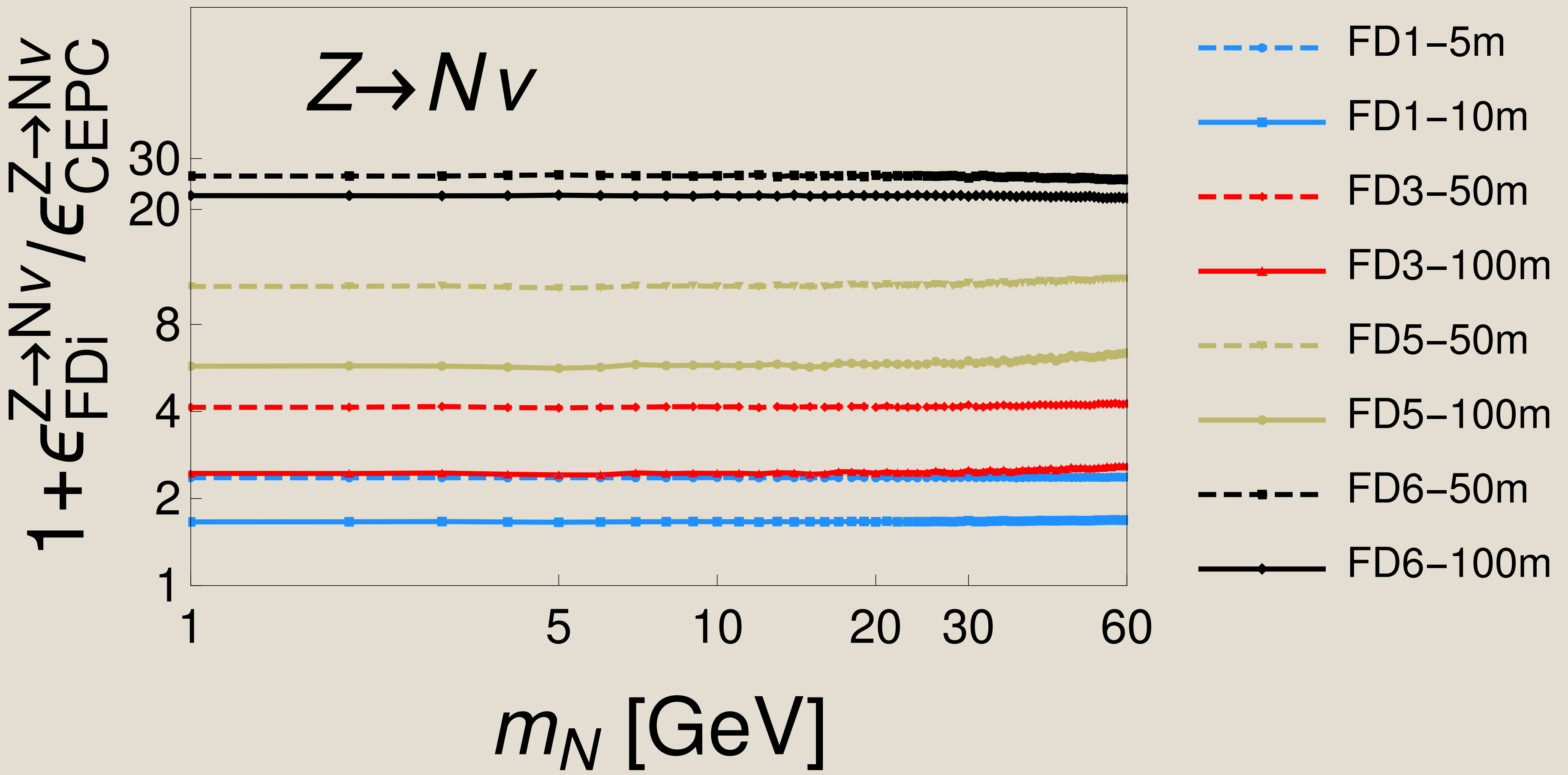
FDs in the very forward direction like FASER may not work at ee colliders.
Better to be installed in the central region.

Average Decay Probabilities

	D [m]	$\epsilon^{h\to XX} \cdot c\tau$ [m]	$\epsilon^{Z\to N\nu} \cdot c\tau$ [m]	$\epsilon^{Z\to \tilde{\chi}_1^0\tilde{\chi}_1^0} \cdot c\tau$ [m]	$\frac{\epsilon^{h\to XX}}{\epsilon^{h\to XX}_{\text{CEPC}}}+1$	$\frac{\epsilon^{Z\to N\nu}}{\epsilon^{Z\to N\nu}_{\text{CEPC}}}+1$	$\frac{\epsilon^{Z\to \tilde{\chi}_1^0\tilde{\chi}_1^0}}{\epsilon^{Z\to \tilde{\chi}_1^0\tilde{\chi}_1^0}_{\text{CEPC}}}+1$
FD1	5	4.7×10^{-2}	6.7×10^{-2}	6.6×10^{-2}	2.4	2.4	2.3
	10	2.4×10^{-2}	3.2×10^{-2}	3.2×10^{-2}	1.7	1.7	1.7
FD2	50	3.5×10^{-2}	6.3×10^{-2}	6.3×10^{-2}	2.0	2.3	2.3
	100	1.9×10^{-2}	3.3×10^{-2}	3.3×10^{-2}	1.6	1.7	1.7
FD3	50	1.1×10^{-1}	1.5×10^{-1}	1.5×10^{-1}	4.3	4.1	4.1
	100	5.8×10^{-2}	7.0×10^{-2}	7.0×10^{-2}	2.7	2.4	2.4
FD4	50	1.7×10^{-1}	1.9×10^{-1}	1.9×10^{-1}	5.9	4.9	4.8
	100	6.5×10^{-2}	7.1×10^{-2}	7.1×10^{-2}	2.9	2.5	2.5
FD5	50	3.7×10^{-1}	4.8×10^{-1}	4.8×10^{-1}	12.2	10.8	10.8
	100	2.0×10^{-1}	2.3×10^{-1}	2.3×10^{-1}	6.9	5.7	5.7
FD6	50	8.2×10^{-1}	1.2	1.2	25.0	26.2	26.2
	100	7.1×10^{-1}	1.0	1.0	21.9	22.3	22.4
FD7	50	2.5×10^{-2}	2.7×10^{-2}	2.9×10^{-2}	1.7	1.6	1.6
	100	1.3×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	1.4	1.3	1.3
FD8	50	3.0×10^{-2}	4.6×10^{-2}	4.8×10^{-2}	1.9	1.9	2.0
	100	1.5×10^{-2}	2.3×10^{-2}	2.3×10^{-2}	1.4	1.5	1.5

LLPs of mass 1 GeV

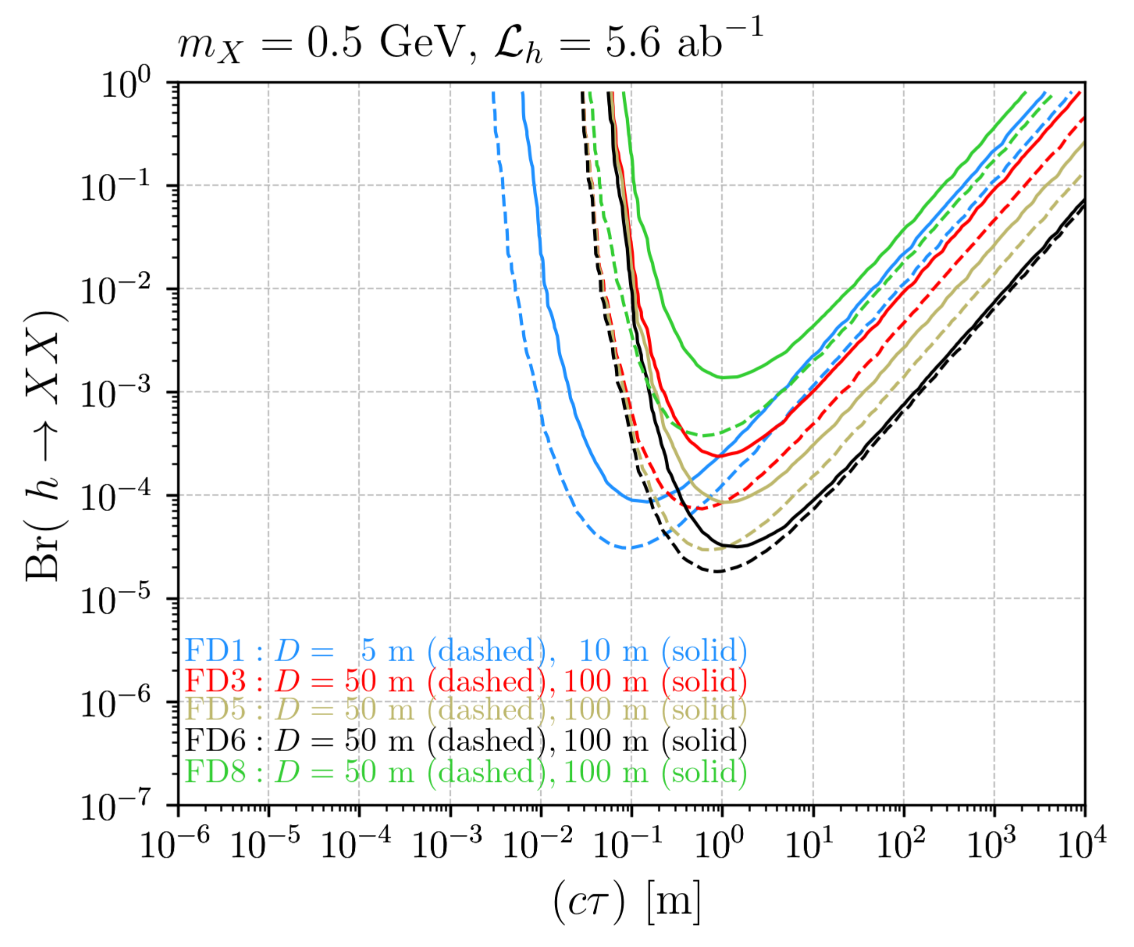
Average Decay Probabilities

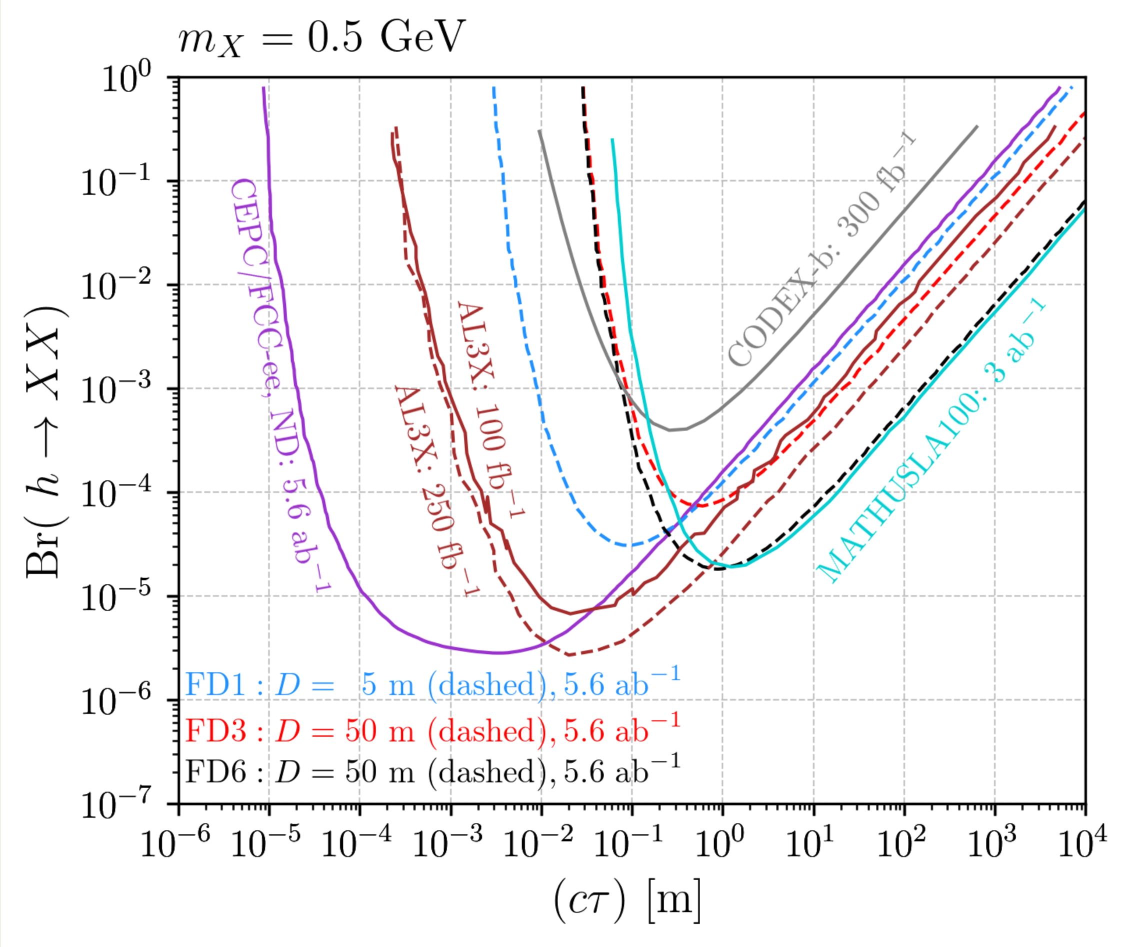


The gain factor has a small dependence on the LLP mass.

Exotic Higgs Decays

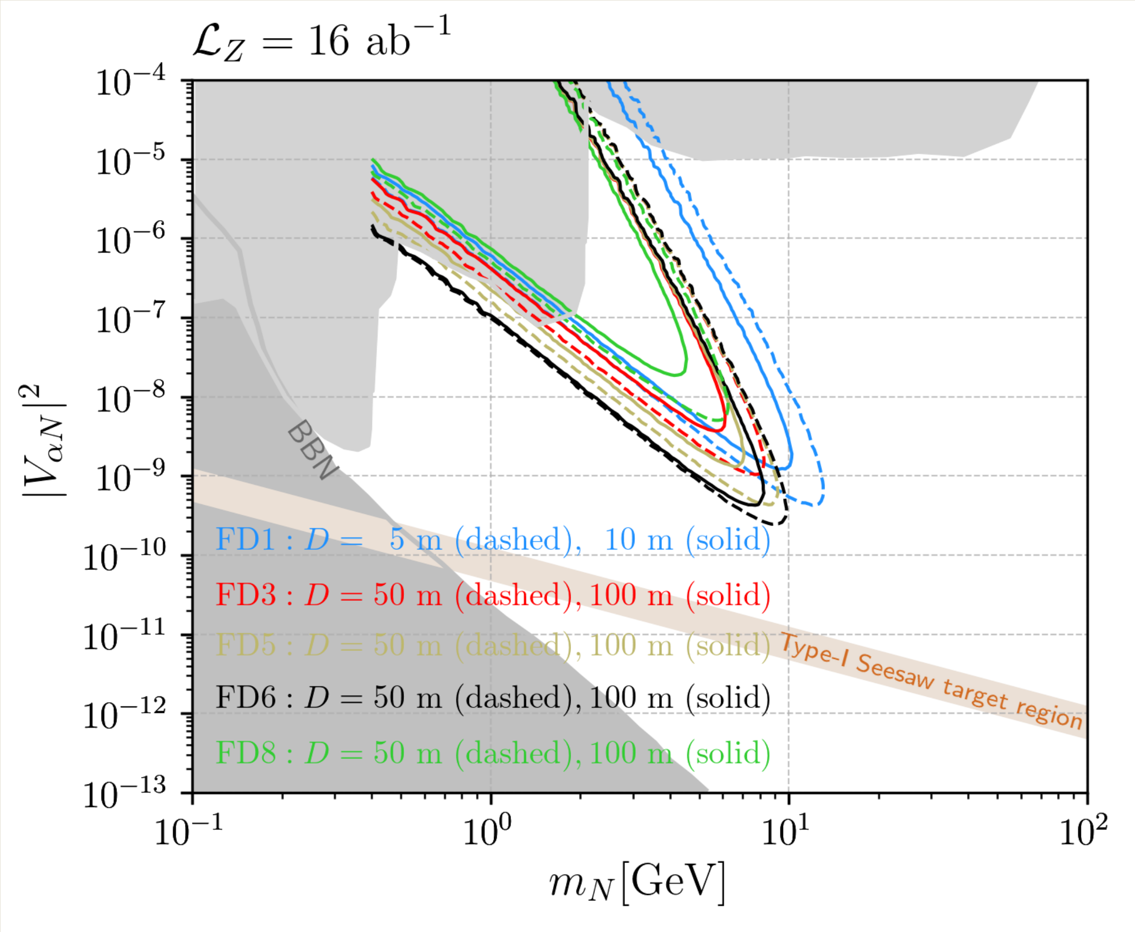
$h \to XX$ @ $\sqrt{s} = 240$ GeV

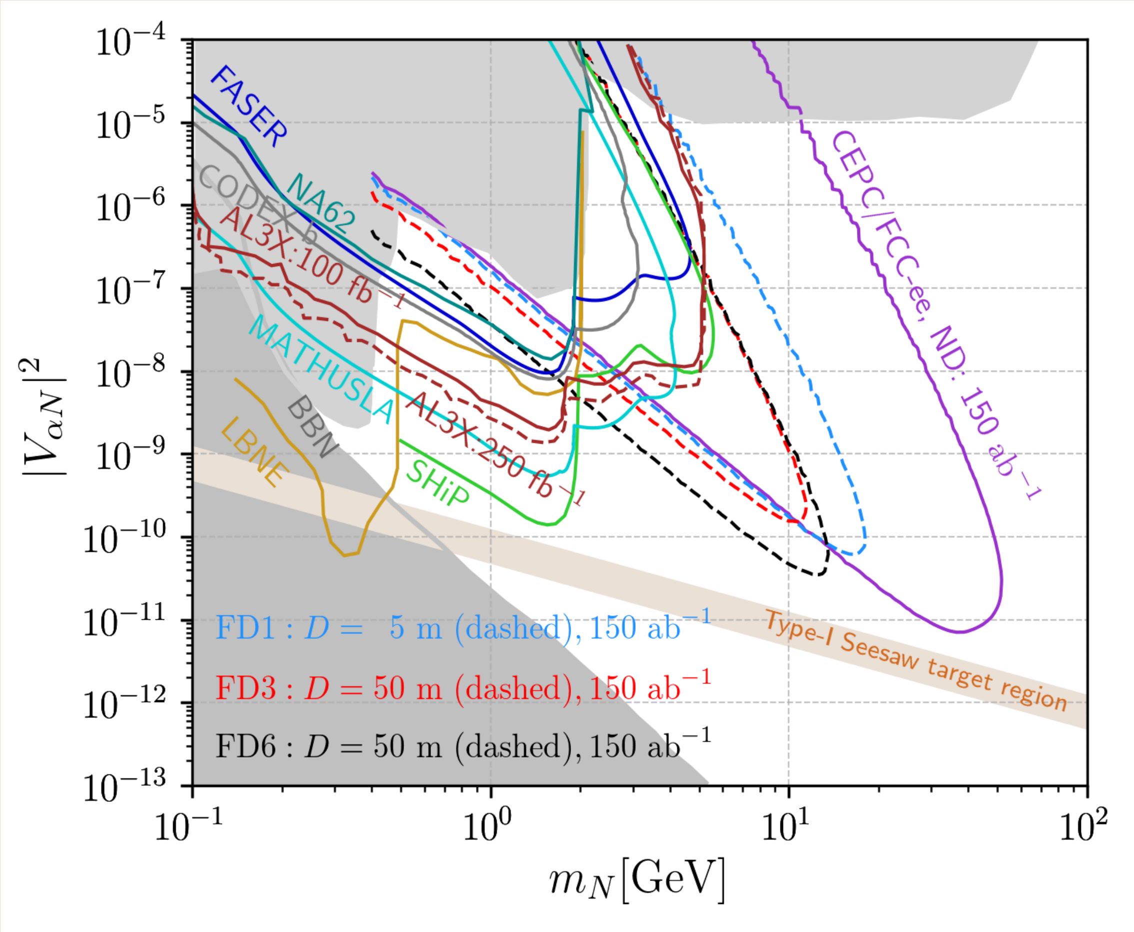




Heavy Neutral Leptons

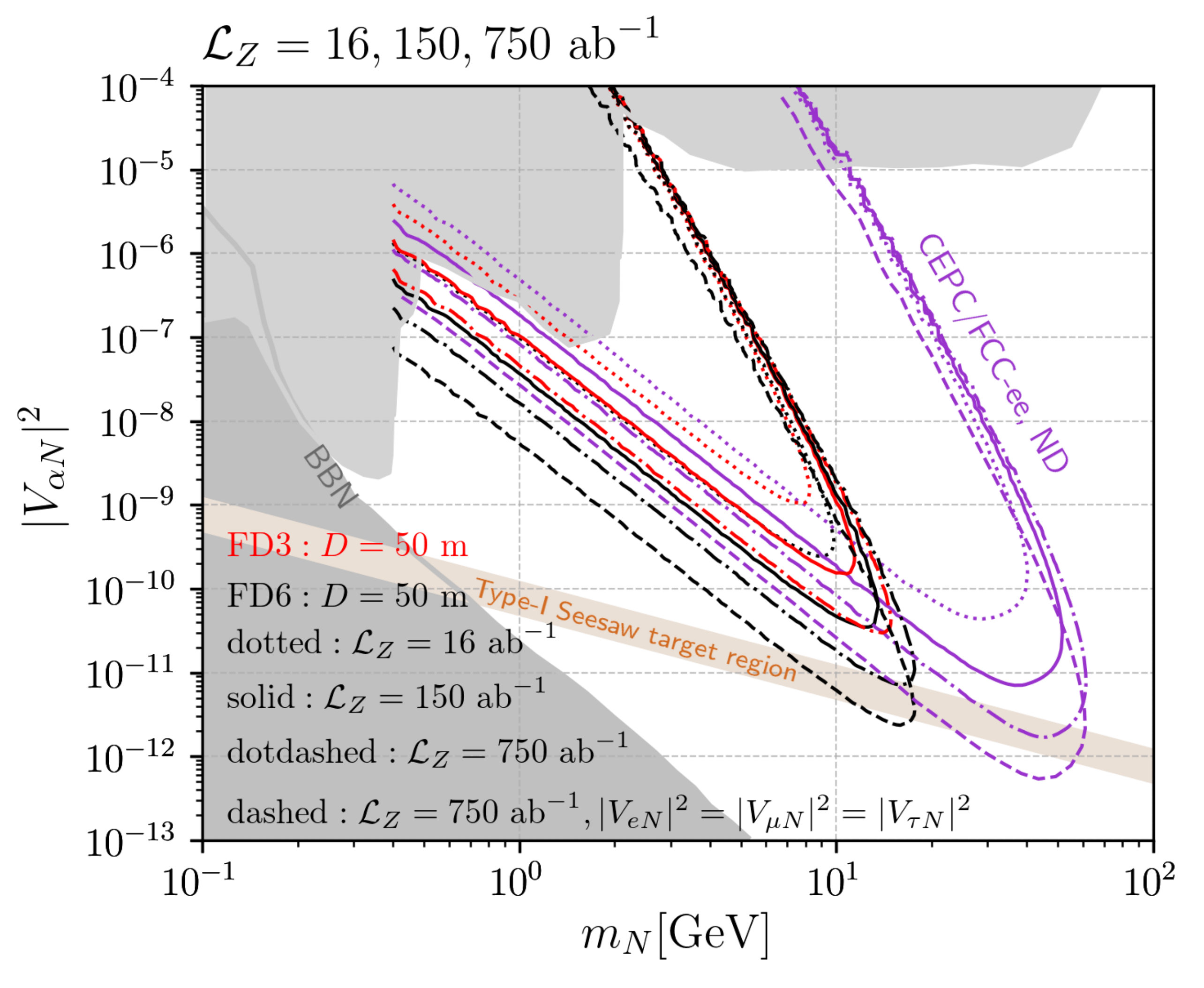
$Z \to N\nu$ @ $\sqrt{s} = 91.2$ GeV





Heavy Neutral Leptons

$Z \to N\nu$ @ $\sqrt{s} = 91.2$ GeV

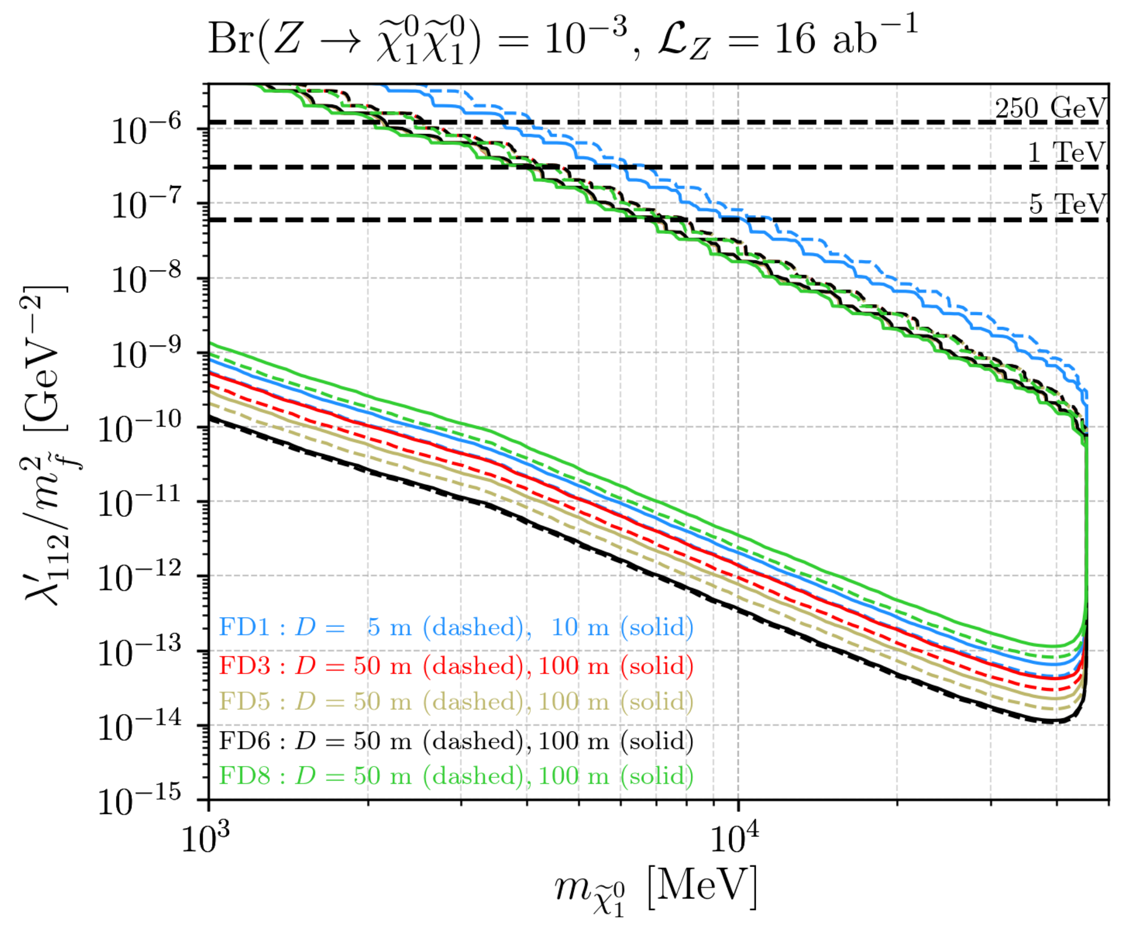


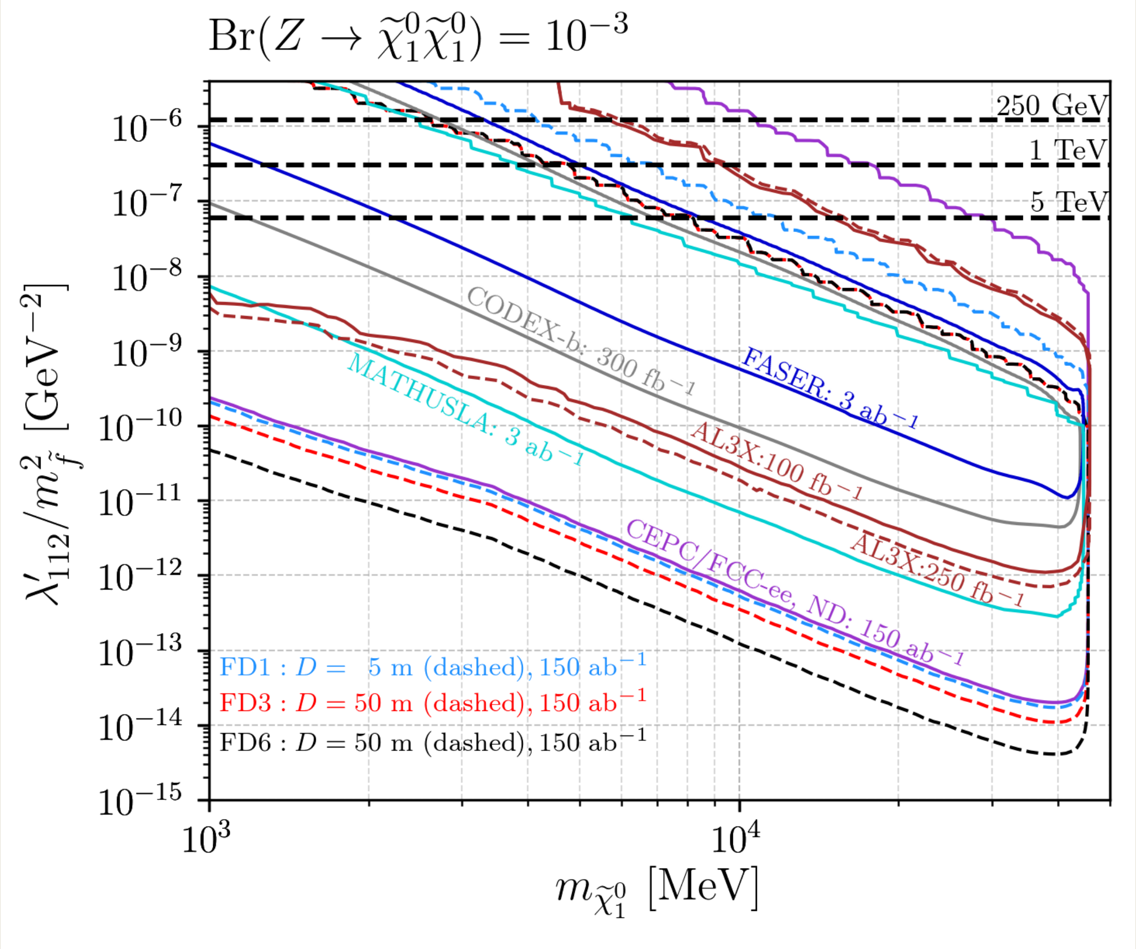
750 ab^{-1}, 10 years, 4 IPs;
or to increase the instantaneous luminosity;
or to relax the theoretical assumptions

Can test the Type-I seesaw directly!

Light Neutralinos in RPV-SUSY

$Z \to \tilde{\chi}_1^0 \, \tilde{\chi}_1^0$ @ $\sqrt{s} = 91.2$ GeV





Conclusion

We proposed to installed FDs @ ee colliders such as CEPC and FCC-ee.

We investigate the preliminary FD designs including volume, geometry size, distance to the IP, etc.

Unlike LHC, LLPs @ ee colliders are much less boosted in the forward direction, thus FD is better to be installed in the central region.

Such far detectors at future lepton colliders can extend and complement the sensitivity reaches of previous collider experiments for $Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$, $Z \to N\nu$, $h \to XX$ physics scenarios.

In light of its significance in physics, we suggest the construction of such far detectors should be considered as one possible option for the CEPC, FCC-ee and other future lepton colliders.

Discussion

To realize such FDs, more pre-studies are needed.

For example:

Investigate the physics potential and optimize the designs in the context of more physics scenarios, different center-of-mass energies, background analysis.

Take into account more realistic factors, including the availability of the space, the technology, cost and shielding of the detectors, the reusing possibility at the SppC/FCC-hh.

Consider other applications: probing neutrinos, cosmic rays, etc.

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