Search for Long-lived Particles at Future Lepton Colliders Using Leptons and Jets

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2025/09/26

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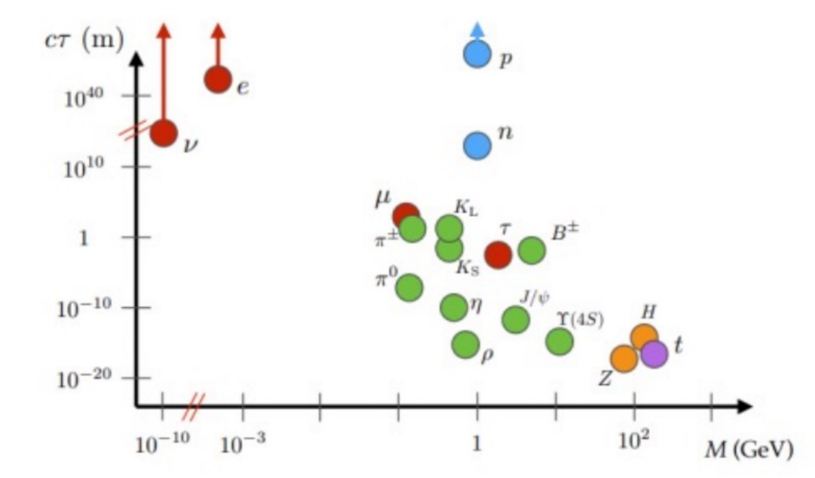
New Physics Beyond SM- LLPs

Long-lived particles (LLPs) are important ways to new physics

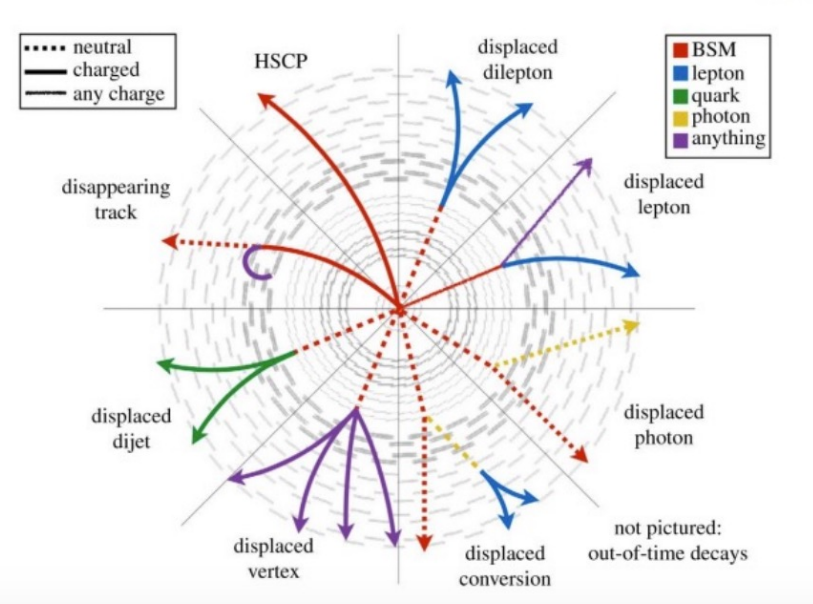
- Many particles in BSM models have a relatively long lifetime: weak coupling to SM particles, maybe new scalars, dark photons, ALP, SUSY….



JOURNAL OF PHYSICS G-NUCLEAR AND PARTICLE PHYSICS. 47(9) (2020)

LLP topology, a strong signature for detection:

- Displaced vertex with a long distance from the main vertex
- Different performance for neutral particles: a burst of energy appearing of nowhere and far away from the collision point



Potential on Lepton Collider:

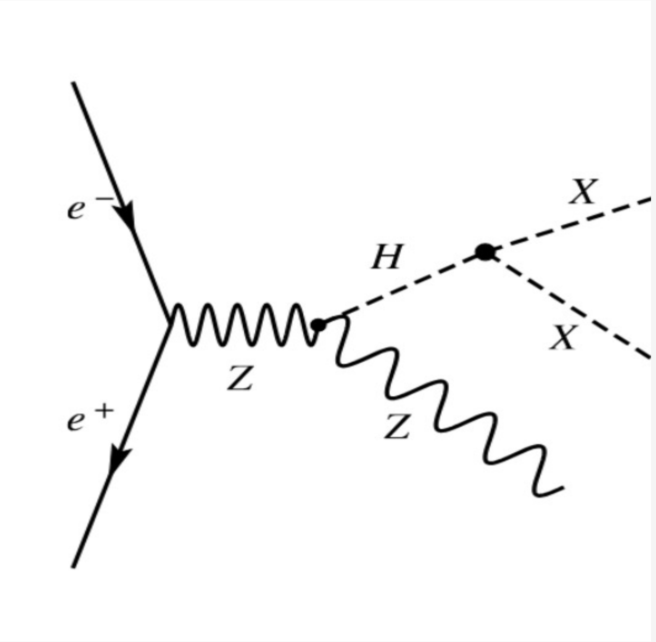
- The advantage of the lepton collider: clean environment
- Lepton pair or multi-jets with a displaced vertex
- Making use of deep learning techniques in jet channel: Image recognition and pattern identification

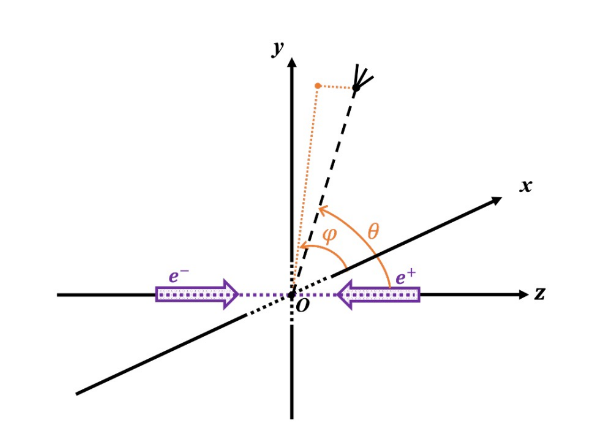
LLP at CEPC

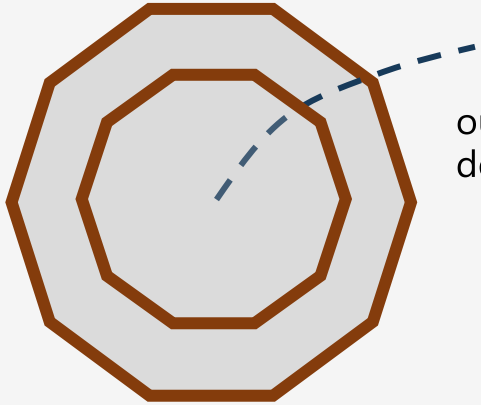
We consider two LLP final state scenrios in CEPC: **dilepton channel and jet chanel**

- We use the **full simulation** sample using CEPC official software to an integrated luminosity of 20 ab^{-1}

Long-lived particle production on CEPC







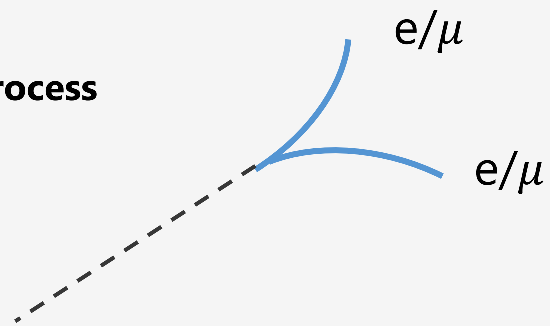
The acceptance for the decay vertex of LLPs: 0< r_{decay} <6 m

Acceptance (%)	Lifetime [ns]				
Mass [GeV]	0.001	0.1	1	10	100
1	100.00 ± 0.00	99.86 ± 0.01	48.76 ± 0.18	6.49 ± 0.09	0.67 ± 0.03
10	100.00 ± 0.00	100.00 ± 0.00	99.78 ± 0.01	46.80 ± 0.16	6.22 ± 0.08
50	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	99.31 ± 0.03	40.37 ± 0.16

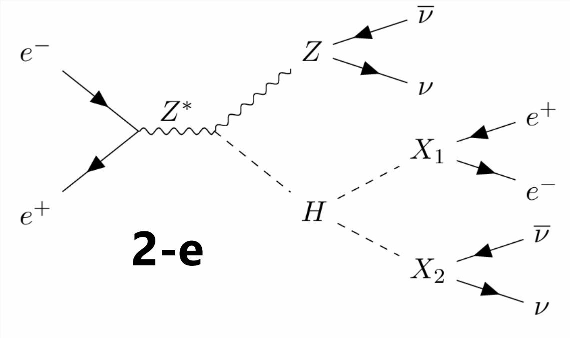
Dilepton Channel

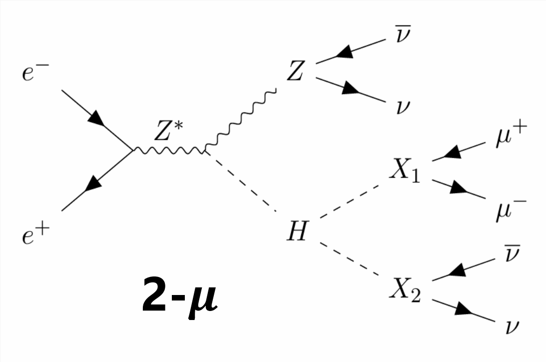
- Only one LLP decays to visible lepton pair
- Good acceptance if the decay length is within the reach of the CEPC detector
- Major background in dilepton final states are Bhabha process and ZZ process

LLP Process

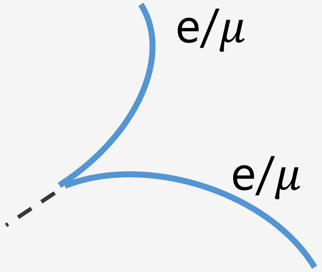


Long distance with IP



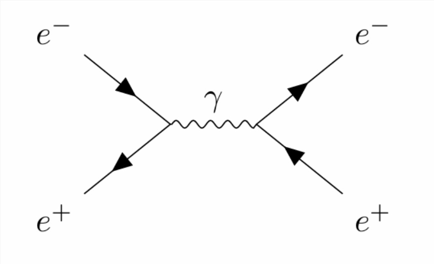


SM backgrounds

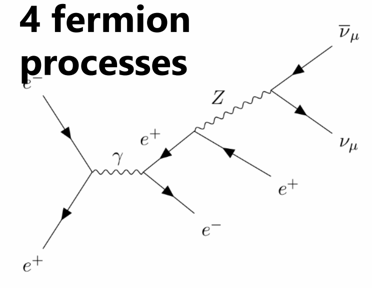


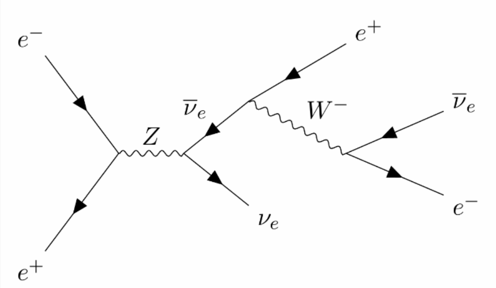
Short distance with IP

bhabha



4 fermion processes



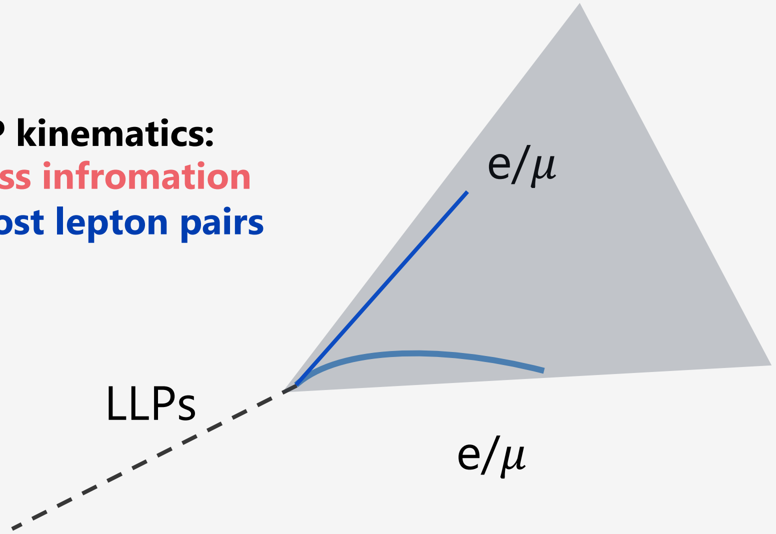


Signal Topology

- The most effective selections are the displaced vertex and invariant mass selection
- Timing information can also help in some cases

Cut Flow
Jet veto
Displaced vertex: 2 tracks with distance between vertex and IP lower than 1 mm (3.5mm for LLP 1 GeV)
Lepton pair: exactly two opposite sign lepton
$\Delta\theta$: Two leptons back-to-back
Recoil mass(GeV): Z veto
Invariant mass(GeV): LLP signal mass selection
ΔT > 0.1 ns(0.05ns): LLP decay signal has large time difference

LLP kinematics:
mass infromation
Boost lepton pairs



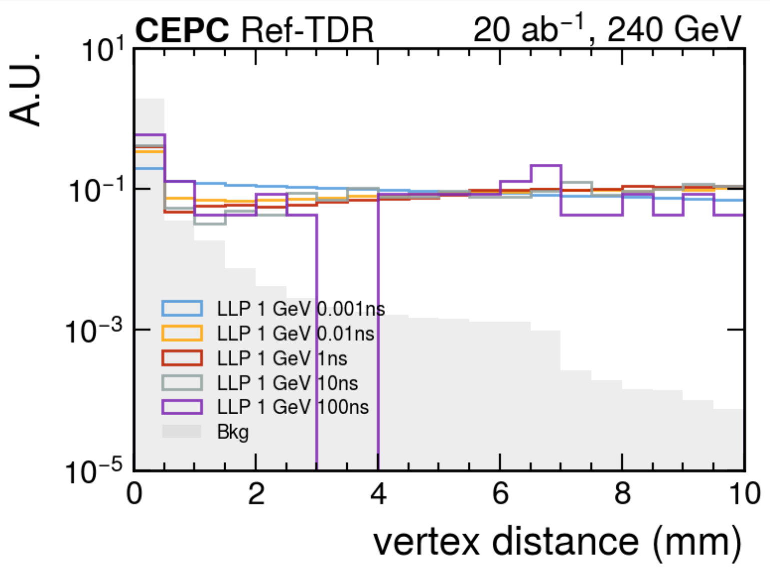
Lepton/neutrino:
Recoil mass
Particle ID

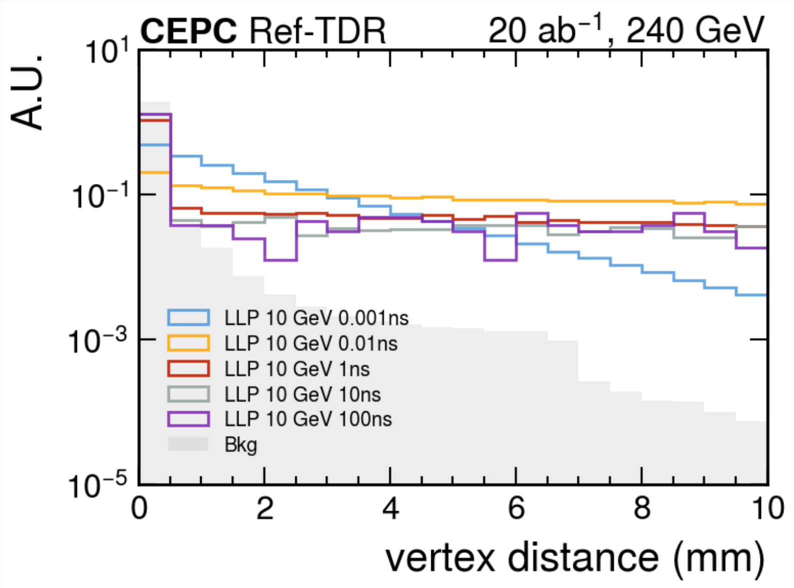
Displaced vertex:
vertex reconstuction
timing information

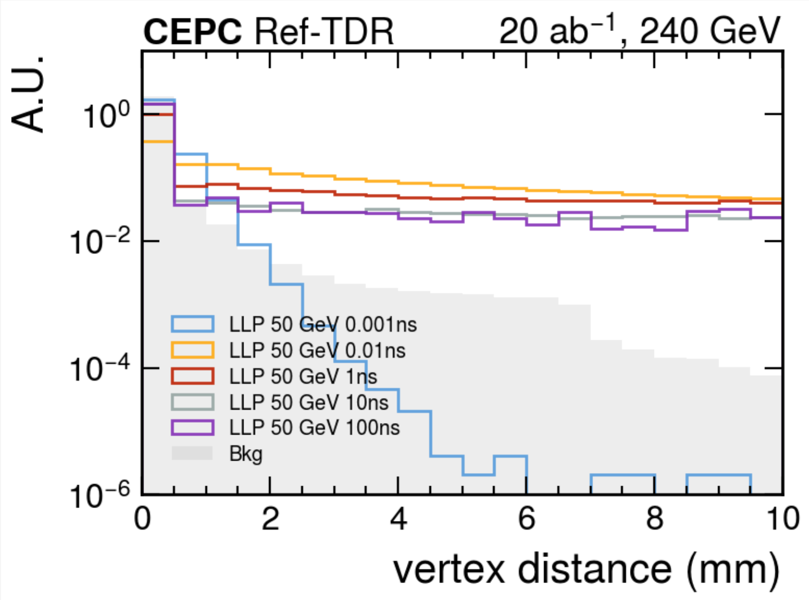
Displaced Vertex Reconstruction

- Using the tracks reconstructed from the tracker and TPC to find the prime vertex
- Most LLPs with lifetime over 0.1ns has obvious displaced vertex comparing to SM processes

Cuts	0.001 ns (%)	0.1 ns (%)	1ns (%)	10ns (%)	100ns (%)	eeH (%)	bhabha (%)	Single Z (%)	evW(%)
Jet veto + Zveto	99.98	99.93	99.91	99.97	99.98	6.56	64.05	99.36	99.81
2tracks+displaced vertex (>1 mm)	44.07	86.60	46.59	14.07	11.03	0.00	9.60	0.71	0.18

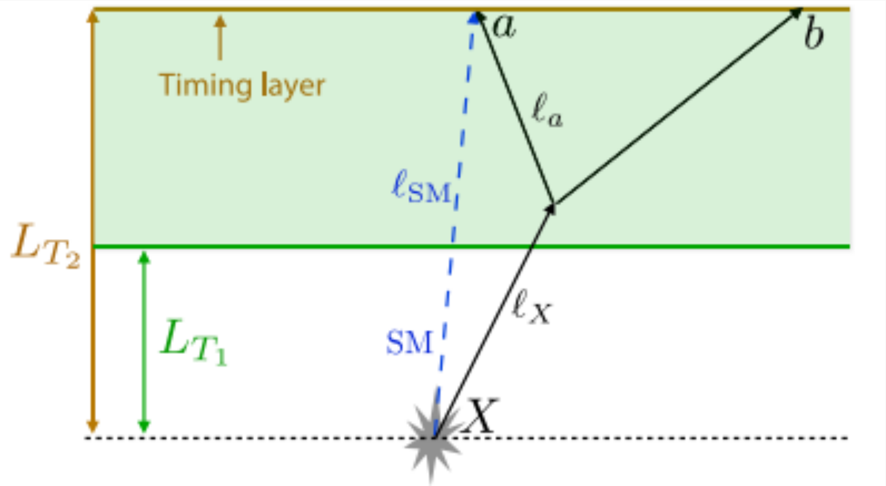






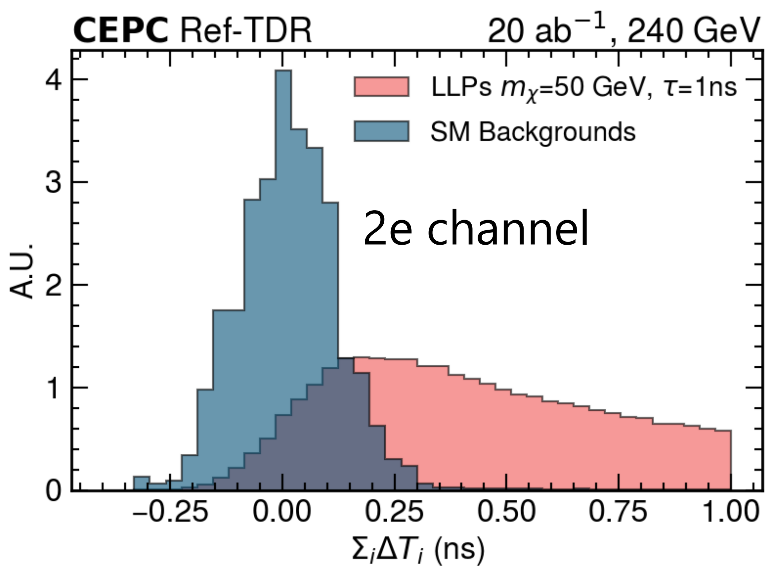
Timing Information

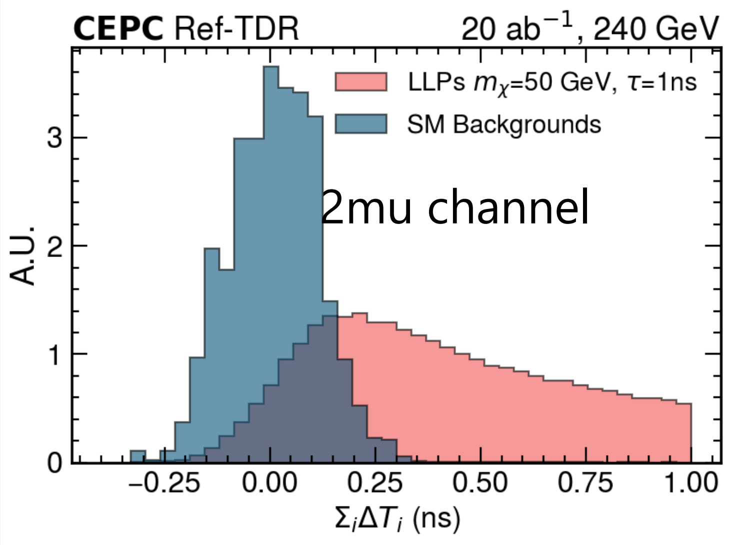
- The extended flight path of LLPs compared to SM particles makes timing information a distinctive signature
- The Time-of-Flight (TOF) detector with 1 ps timing resolution, provides precise hit time measurements for charged particles.



$$\Delta T = t_{hit,i} - r_{hit,i}/c$$

$t_{hit,i}$: hit time of the i-th component in the object cluster recorded by the detector
$r_{hit,i}$: i-th Euclidean distance to the IP
c : light speed in vacuum.

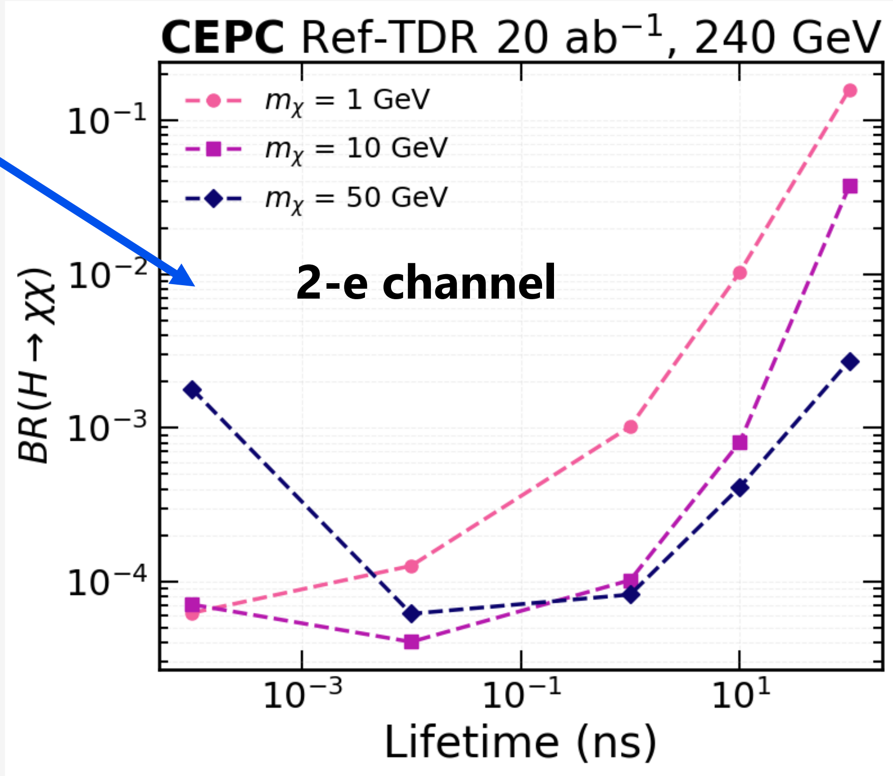


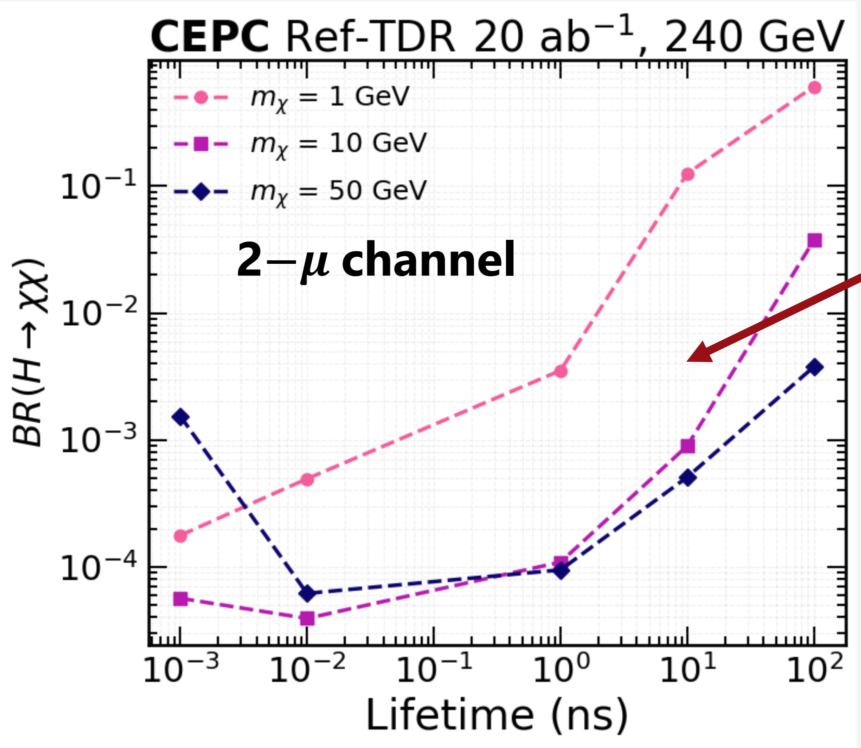


Expected Limit for Dilepton Channel

- The signal efficiency for dilepton channel reaches up to 40% in both channels at $m\chi$ = 10 GeV under background-free conditions
- Assuming the branch ratio BR(X-> ll) is 0.2. Best BR(H->LLPs->leptons) limit reaches to 4*10^{-5}
- The search sensitivity to lighter LLPs such as those with $m\chi$ = 1 GeV degrades because their decays produce softer, more collimated, and more prompt-like signatures

Lower efficiency in small lifetime: more prompt-like signals



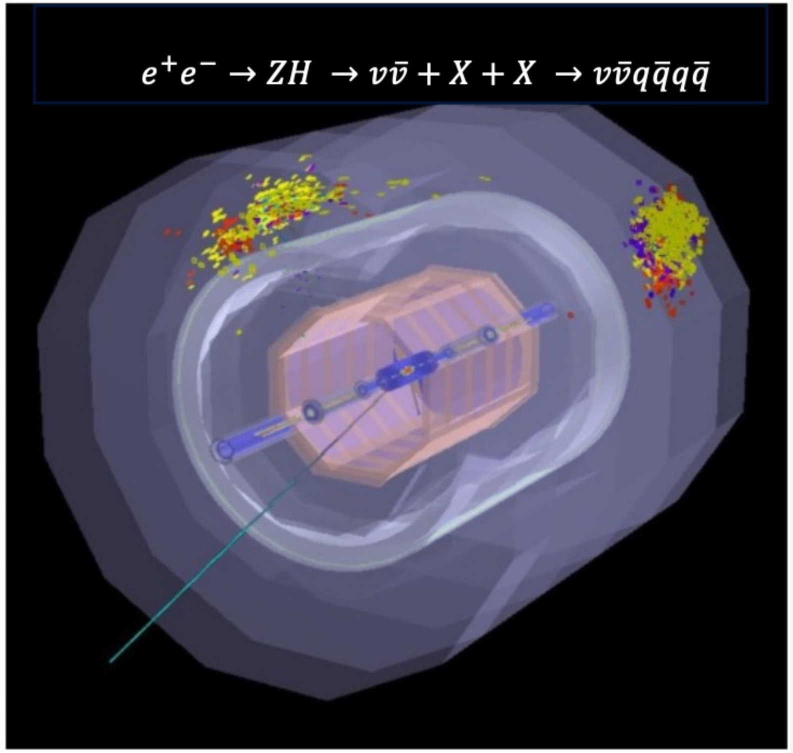


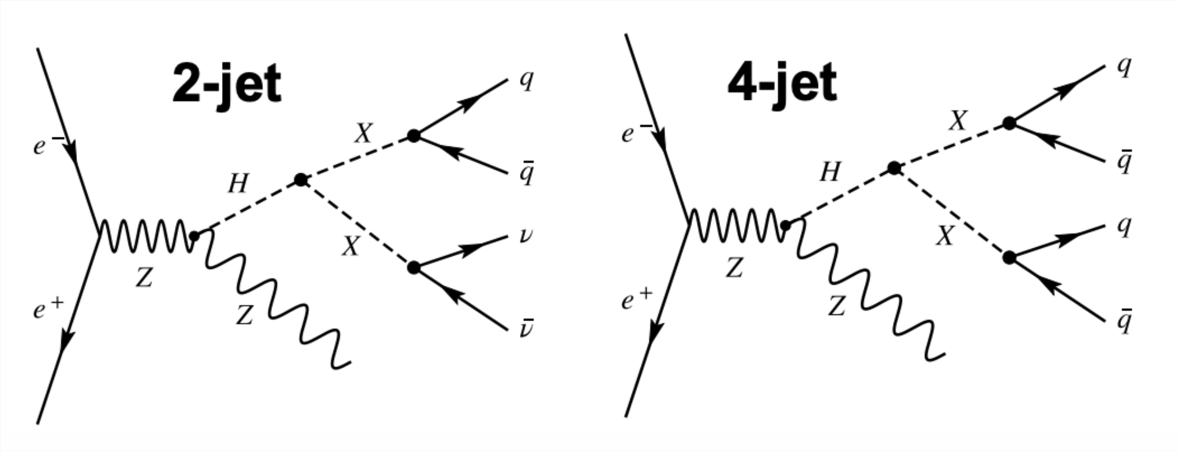
The efficiency in large lifetime region is limited by the detector length

LLP at CEPC Jet channel

Accepted by Frontiers of Physics (2025) 2401.05094

We consider two LLP jet final state cases in CEPC: **2-jet and 4-jets final state**

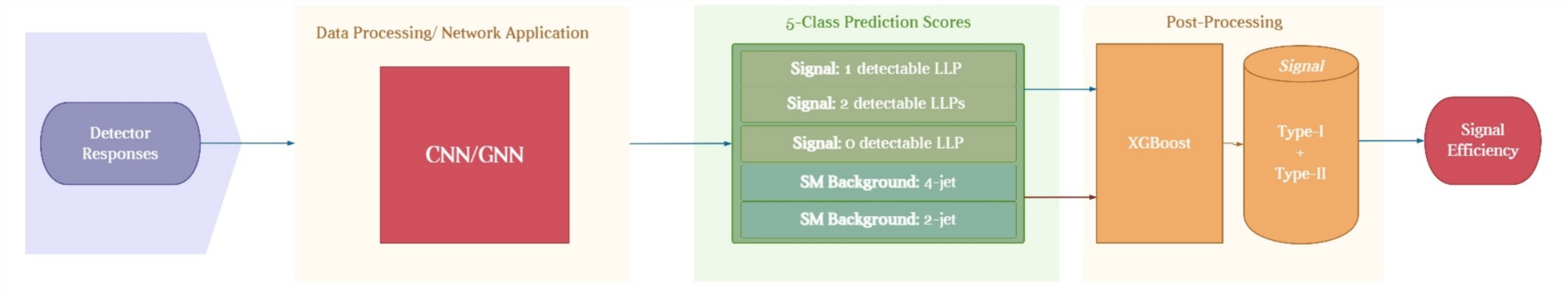




- The displaced vertex means that need a specfic trigger and algothrim for jet reconstruction
- The classification can be improved by machine learning!

Analysis Strategy

Advanced neural networks trained with low-level detector information:



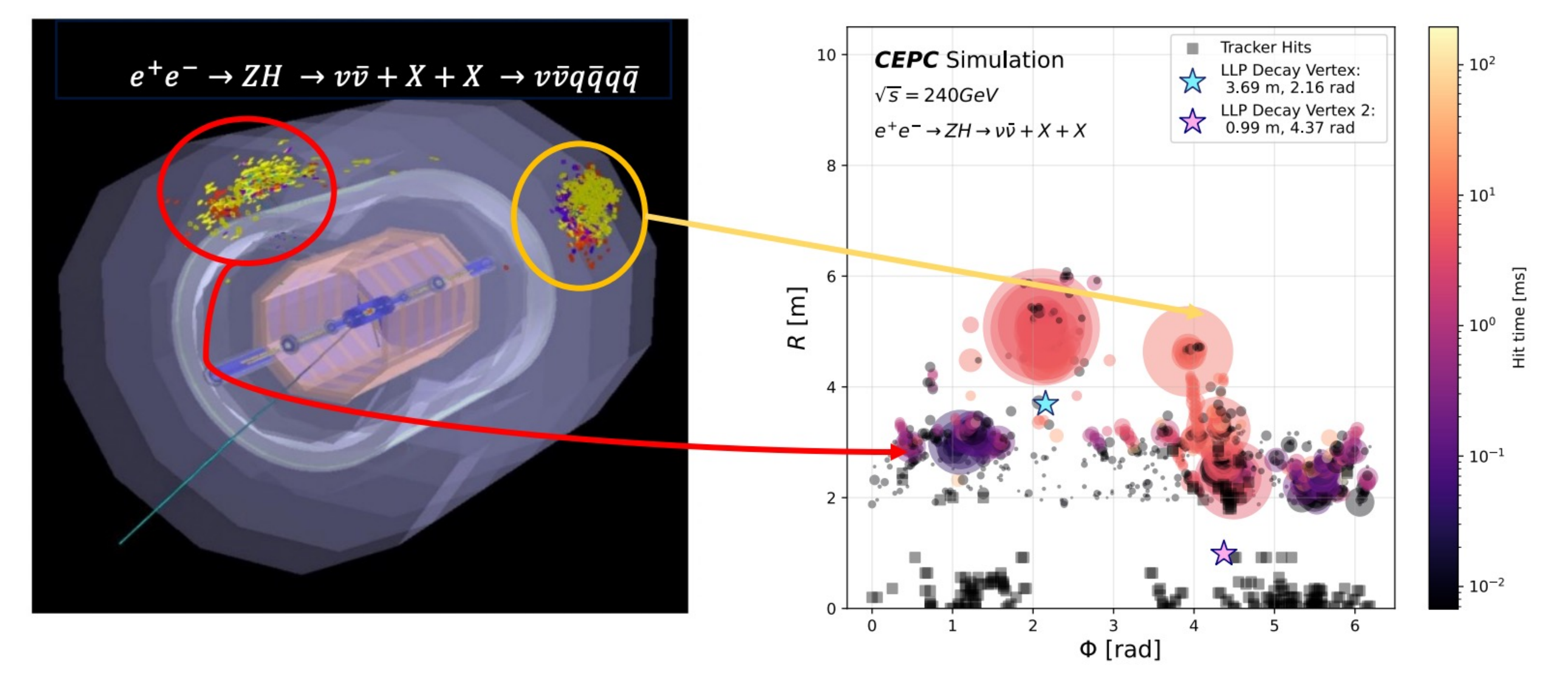
- End-to-end strategy: No need for vertex reconstruction and object reconstruction
- The input information from the detectors is all calibrated and considering detector resolution
- Universal treatment for all decay channel

Signal: LLP events
Background: SM process

Post-Processing: converting 5-class output to a 2-class classfication task

CNN: ResNet

- Converting the detector information to 2D image
- Use ResNet18 model with the cross-entropy loss



Cross Entropy Loss: $loss = -[\omega_0 * y_0 \log(x_0) + \omega_1 * y_1 \log(x_1) + \omega_2 * y_2 \log(x_2)]$

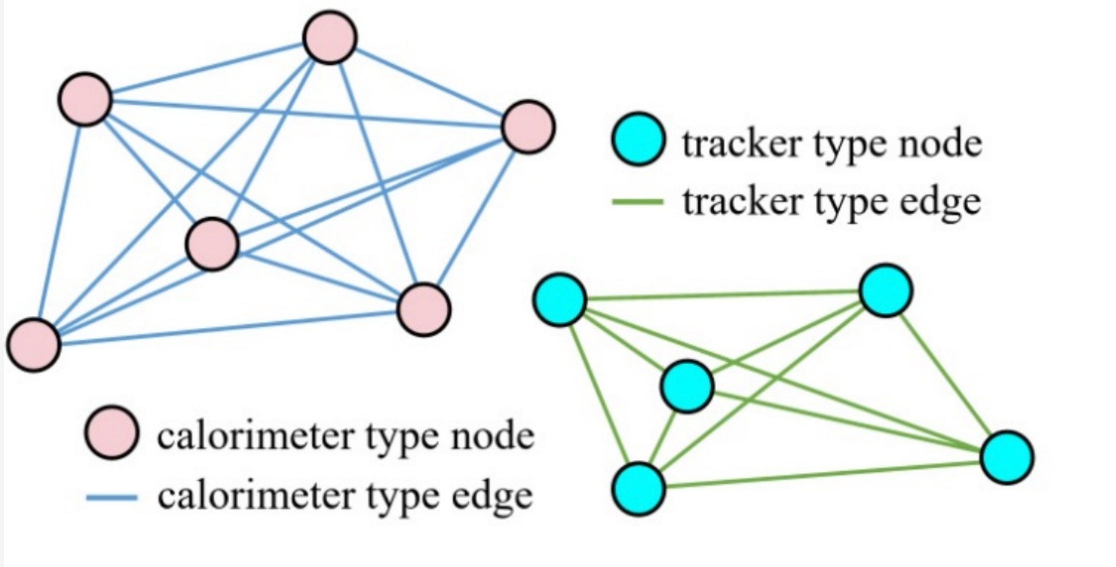
Class 0: 2-fermion bkg $\omega_0 = 0.5$	Class 1: 4-fermion bkg $\omega_1 = 0.25$	Class 2: LLP Signal $\omega_2 = 0.25$

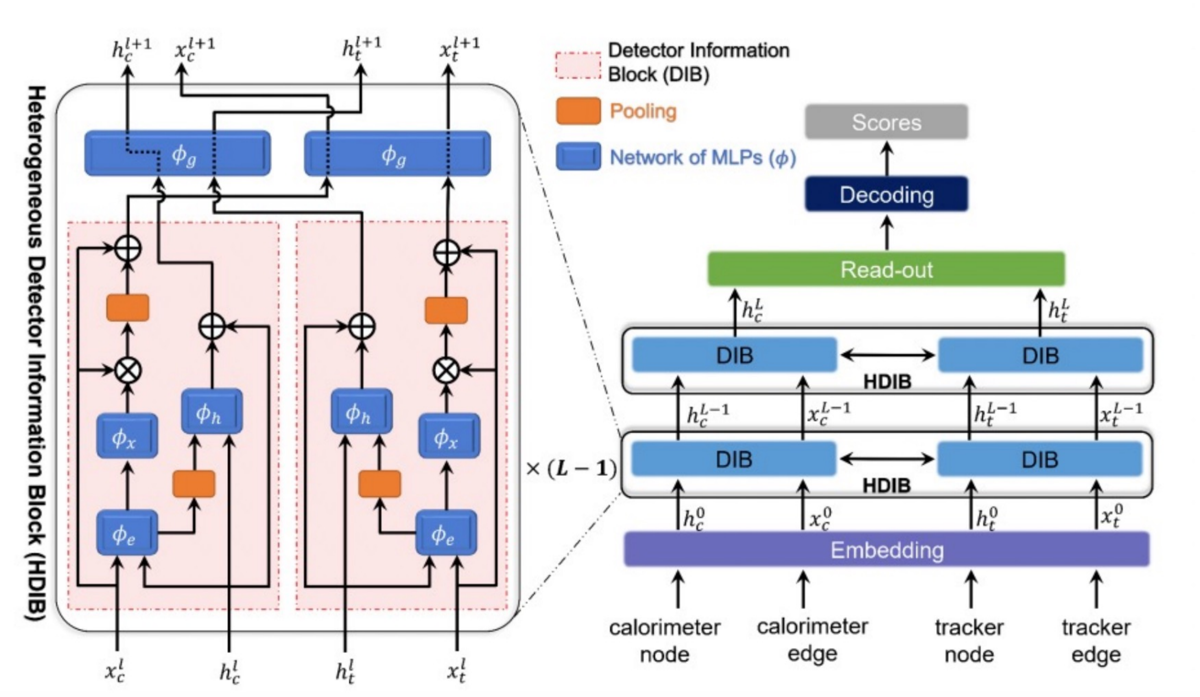
GNN

The representation of the information in the calorimeter and tracker to point-cloud dataset

- Simple clustering is used to reduce graph complexity and extract the main information
- Nodes of the same detector type are interconnected comprehensively

Features of nodes: calorimeter-type and tracker-type.
Features of edges: interaction between neighbor nodes



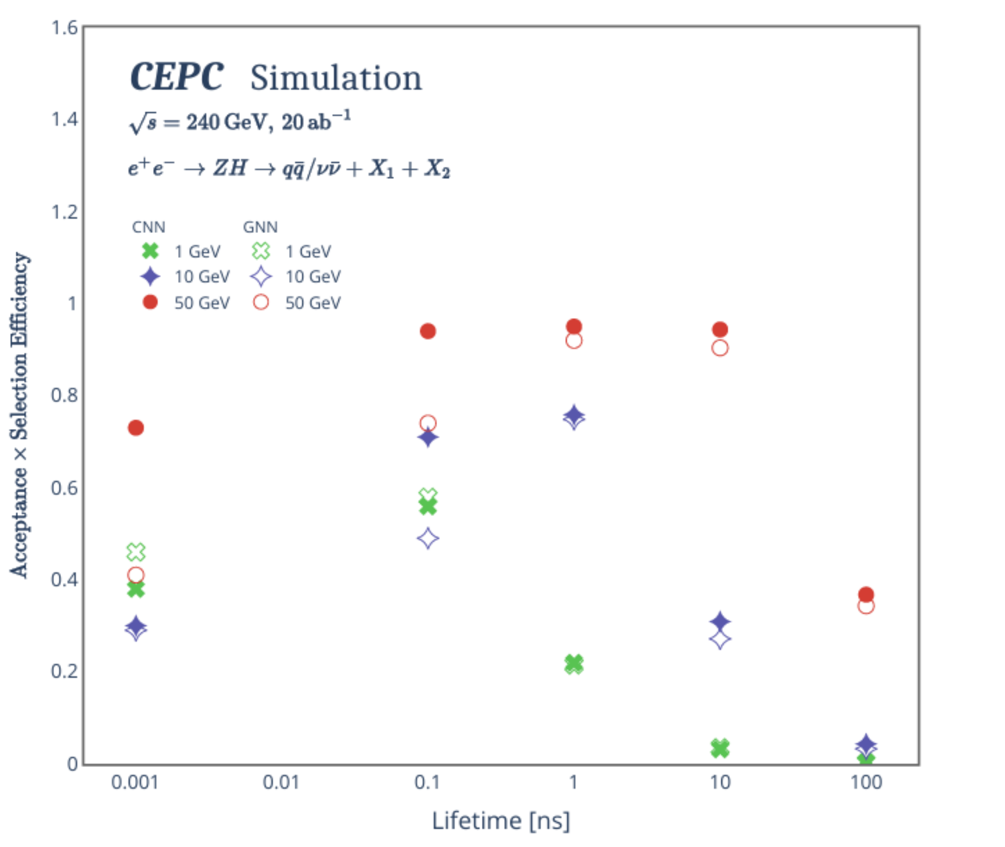


ML- Bases Analysis Result

- Both CNN and GNN achieve high signal efficiencies with background-free
- The performance is consistent across different LLP mass and lifetime considerations.
- Systematics uncertainties of 3.5%
  - Luminosity and neutral network training uncertainties
  - ZH process cross section uncertainty
  - Pile-up and cosmic rays background are neglected

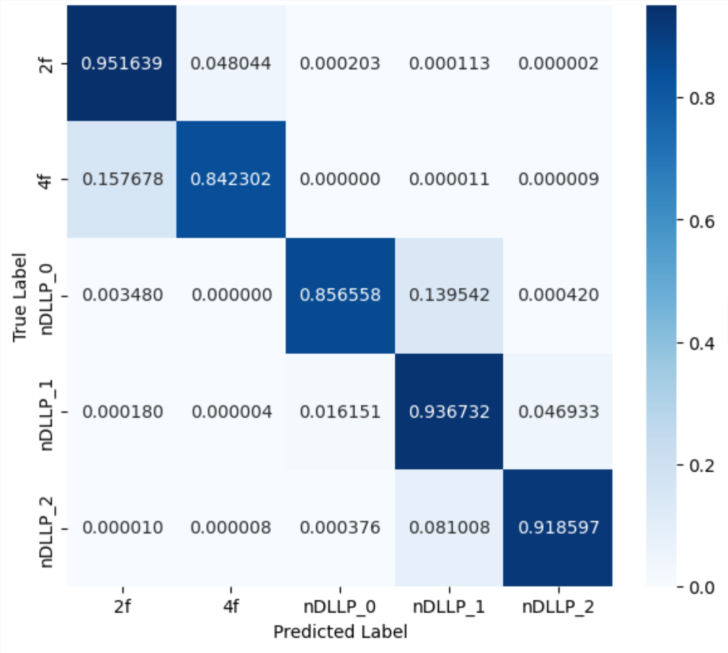
Approach	Efficiency (%)	Lifetime [ns]				
	Mass [GeV]	0.001	0.1	1	10	100
CNN	1	38 ± 0.1	56 ± 0.1	45 ± 0.2	48 ± 0.6	52 ± 1.9
	10	30 ± 0.1	71 ± 0.1	76 ± 0.1	66 ± 0.1	69 ± 0.5
	50	73 ± 0.1	94 ± 0.1	$\boxed{95 \pm 0.0}$	95 ± 0.0	91 ± 0.1
GNN	1	46 ± 0.1	58 ± 0.1	44 ± 0.2	54 ± 0.6	43 ± 1.8
	10	29 ± 0.1	49 ± 0.1	75 ± 0.1	58 ± 0.2	52 ± 0.5
	50	41 ± 0.1	74 ± 0.1	92 ± 0.1	91 ± 0.1	85 ± 0.1

Best efficiency at 95% (50 GeV, 1ns)

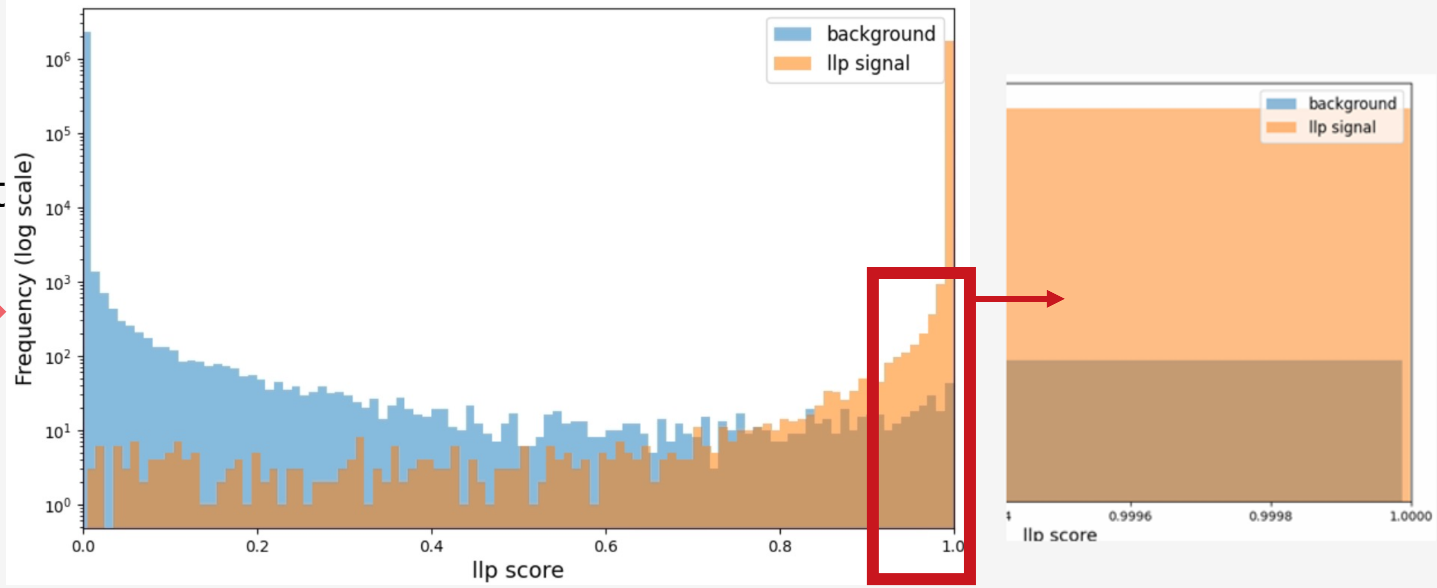


XGBoost?

Xgboost is used to convert a 5-class classification task to 2-class classification task



XGBoost

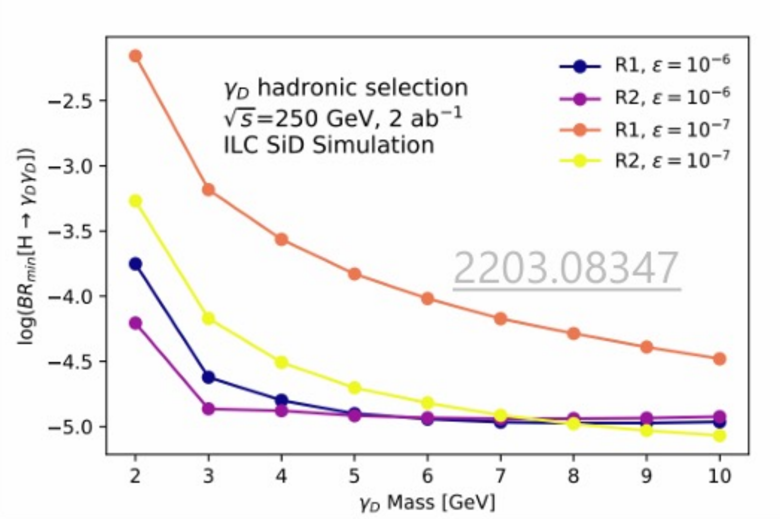


Signal efficiency@ 50 GeV 10ns: 92%

Signal efficiency@ 50 GeV 10ns: 95%
Background-free achieveable

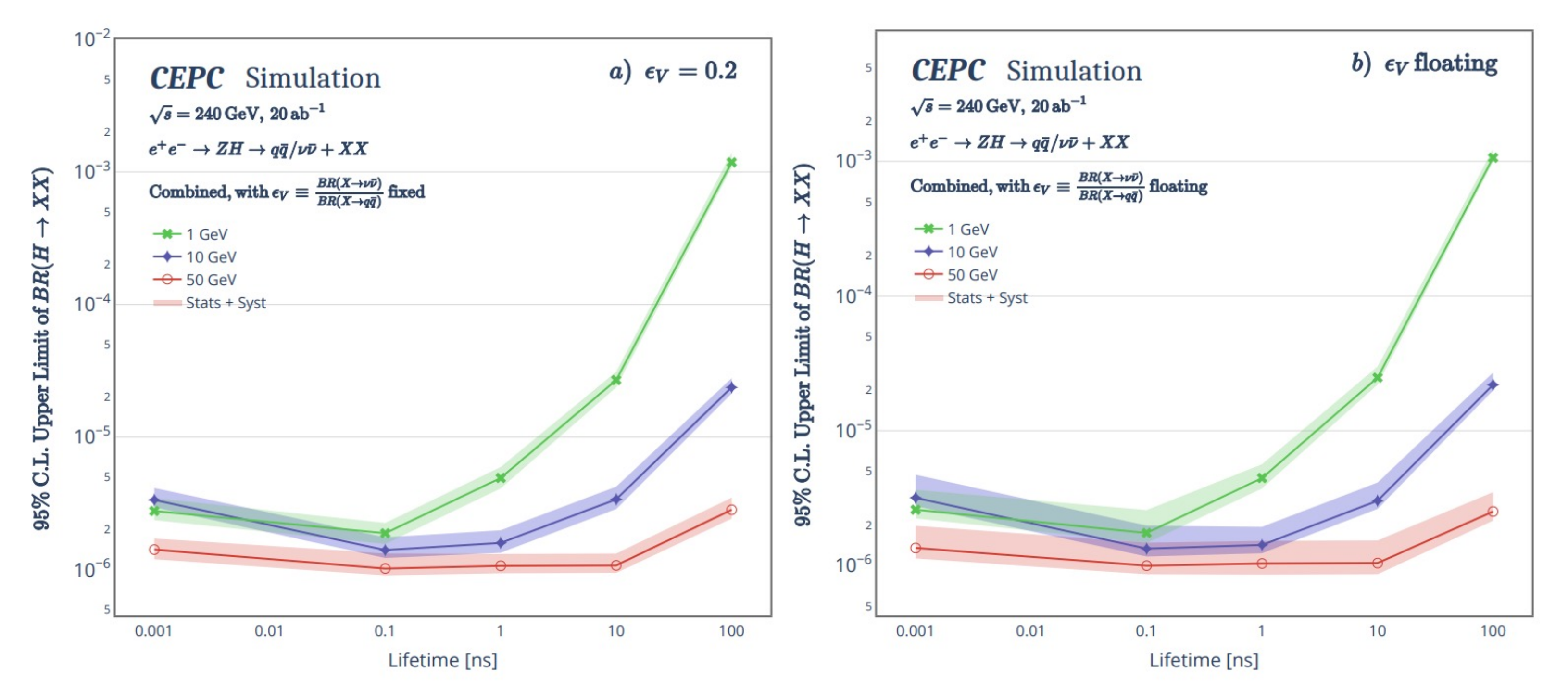
LLP Search Limits

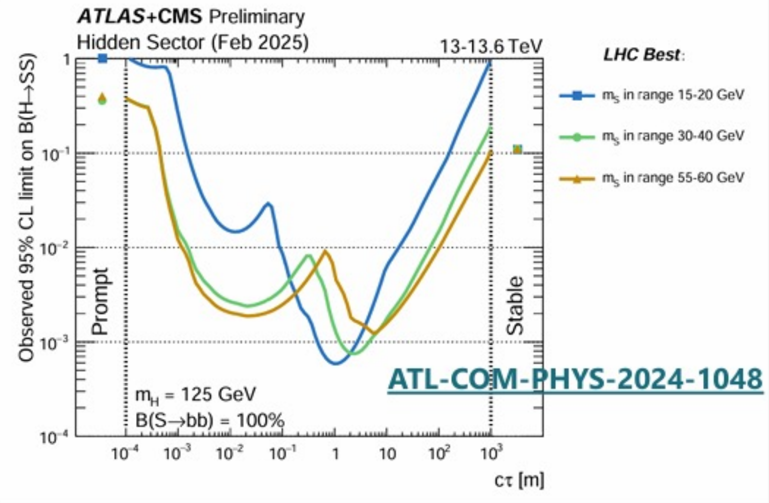
- The best expected limit of BR(H → XX) achieves 10^{-6}
- Outperforming the current limit from ATLAS and CMS by 2 - 3 orders of magnitude
- An order of magnitude better than the ILC's when the lifetime of LLP is over 1ns



ILC Best limit: ~10^{-5}

$$\epsilon_V = BR(X\to\bar{\nu}\nu)/BR(X\to\bar{q}q)$$

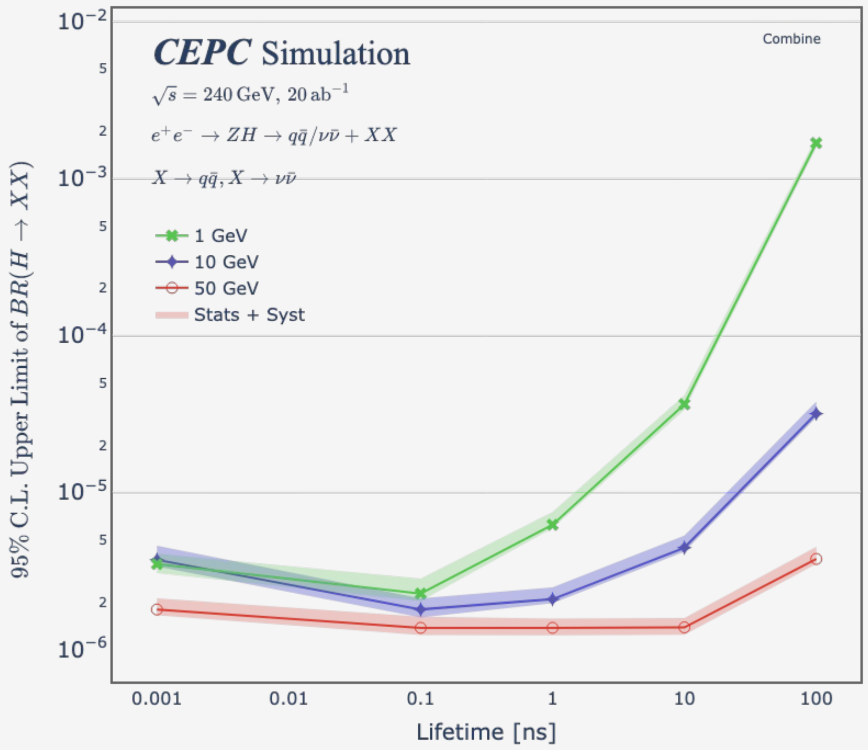




LHC Best limit: ~10^{-3}

Combine Limit

- Combining the dilepton channel, 2-jet and 4-jet channel
- Assuming the decay branching ratio of the LLPs is similar as Z boson
  - 2-jet and 4-jet channel accounts for 77% in the total final states
  - Dilepton channel accounts for 2.5% (without tau channel)
- Expected limit reaches 10^{-6} due to jet final states dominated
  - Comparing to previous jet-only channel assumption, best limit get ~1% better



Combination

Limit in unit of 10^{-6}

CNN	0.001ns	0.1ns	1ns	10ns	100ns
1 GeV	3.63	2.30	6.32	33.1	1522.1
10 GeV	4.37	1.84	2.03	4.35	30.59
50 GeV	1.82	1.37	1.37	1.38	3.54

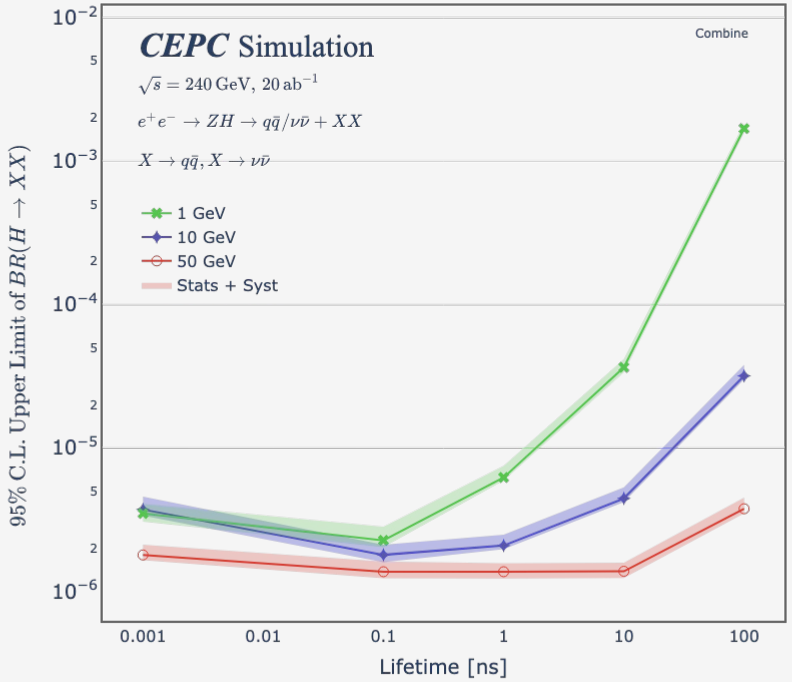
Jet-only

Limit in unit of 10^{-6}

CNN	0.001ns	0.1ns	1ns	10ns	100ns
1 GeV	3.67	2.32	6.38	33.2	1529.7
10 GeV	4.41	1.86	2.05	4.38	30.03
50 GeV	1.84	1.37	1.38	1.39	3.69

Far Barrel Detector (FBD)

- To improve the sensitivity for the LLP with large displaced vertex, far detector are consider to capture the decay products of LLPs

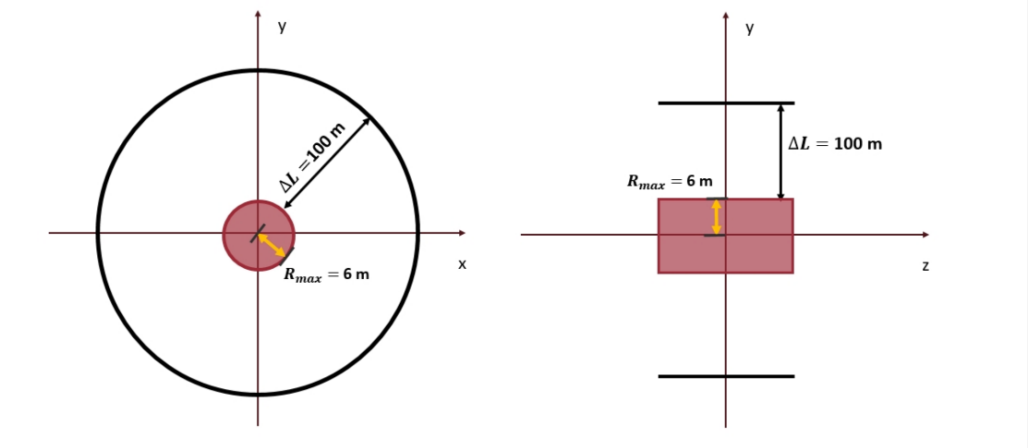


- The gain attributable to the FBD, located 100 meters outside the near detector, can be estimated by comparing the LLP signal yields (background free)

- Deriving the gain factor for estimation in the long-lifetime region

$$F_{gain} = \frac{\Delta\Omega}{4\pi}\left(\frac{1-e^{-\frac{L+\Delta L}{d}}}{1-e^{-\frac{L}{d}}} - 1\right) + 1$$

L is the length of the muon to IP
d is the exptected decay length of LLP
$\frac{\Delta\Omega}{4\pi}$ is the angular acceptance
ΔL is the gap between the FBD and the MD

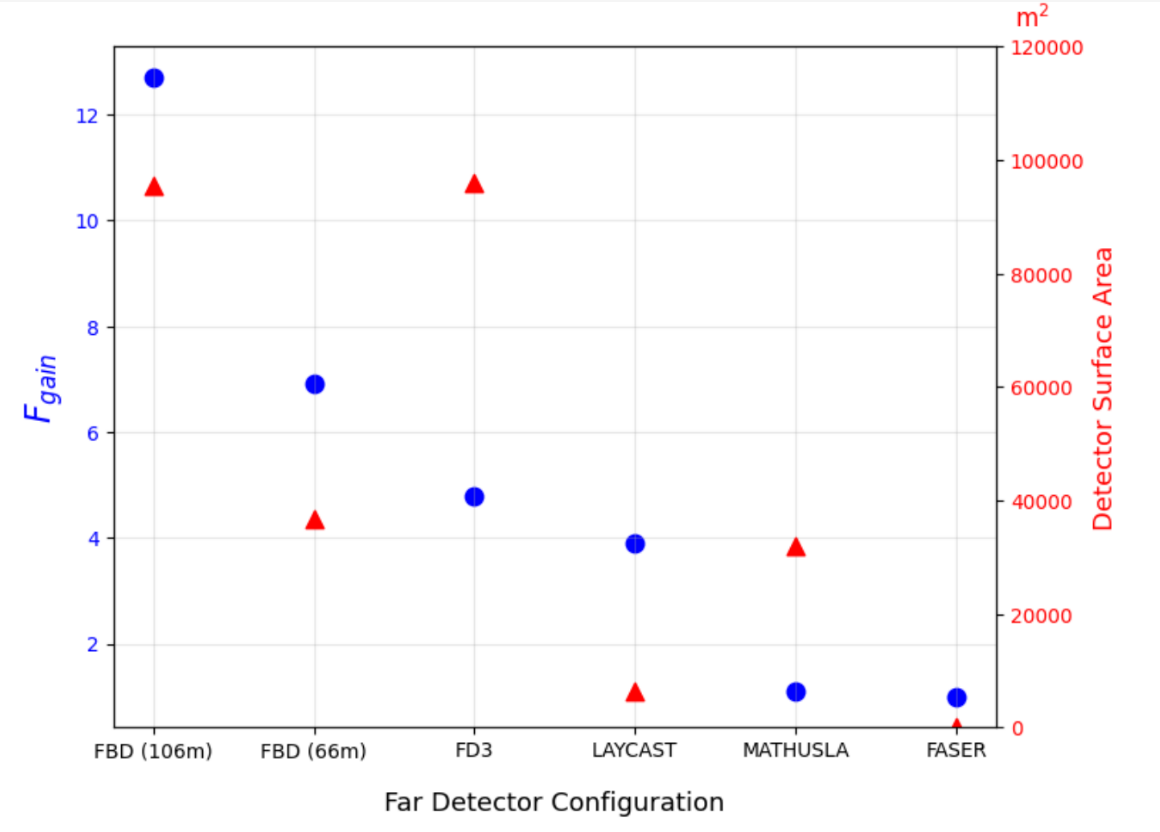


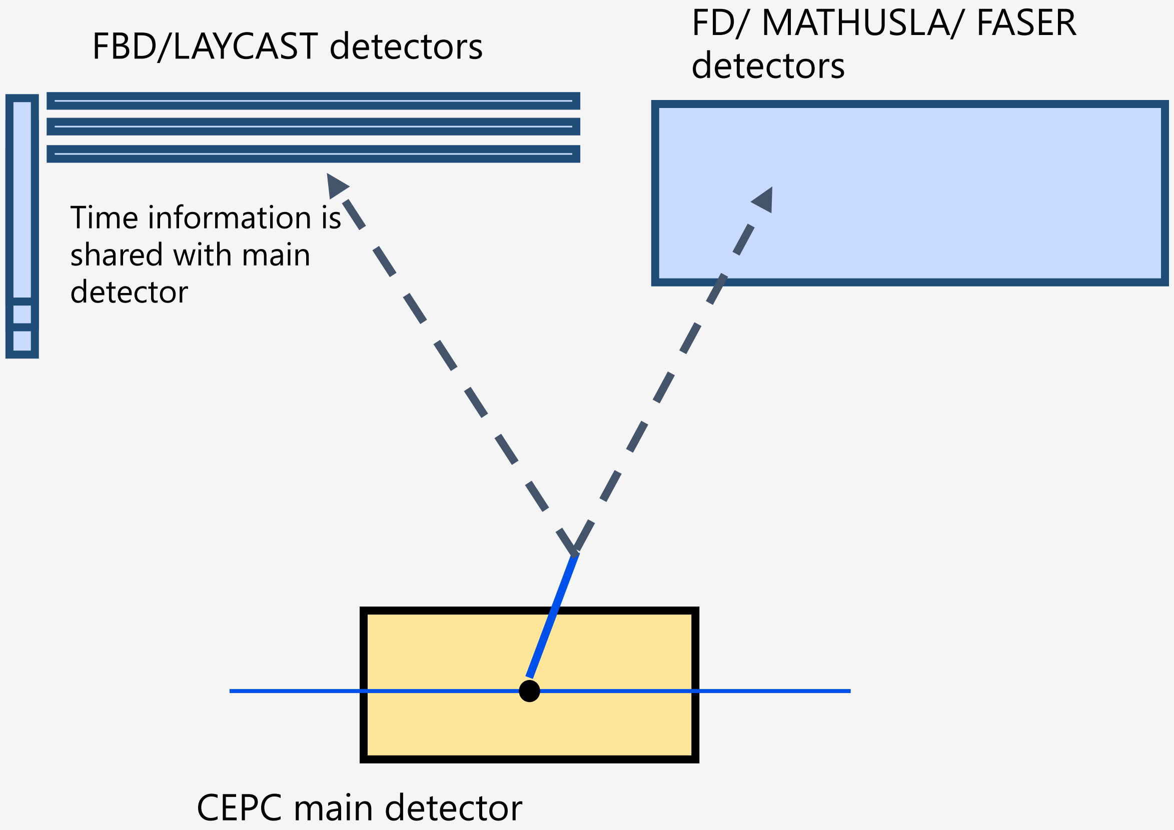
F_{gain}	Lifetime [ns]				
Mass [GeV]	0.001	0.1	1	10	100
1	1	1	2.8	9.9	13.7
10	1	1	1	2.9	10.1
50	1	1	1	1.1	3.3

Far Detector for Long-live Particle

[Accepted by Chinese Physics C (2025), 2505.24810]

- Different type of the far detectors are compared. The cost is represented by the surface area
- Far barrel detector design has the best LLP gain factor of 13.7 due to good angular acceptance and combined detection with near detector sharing time information





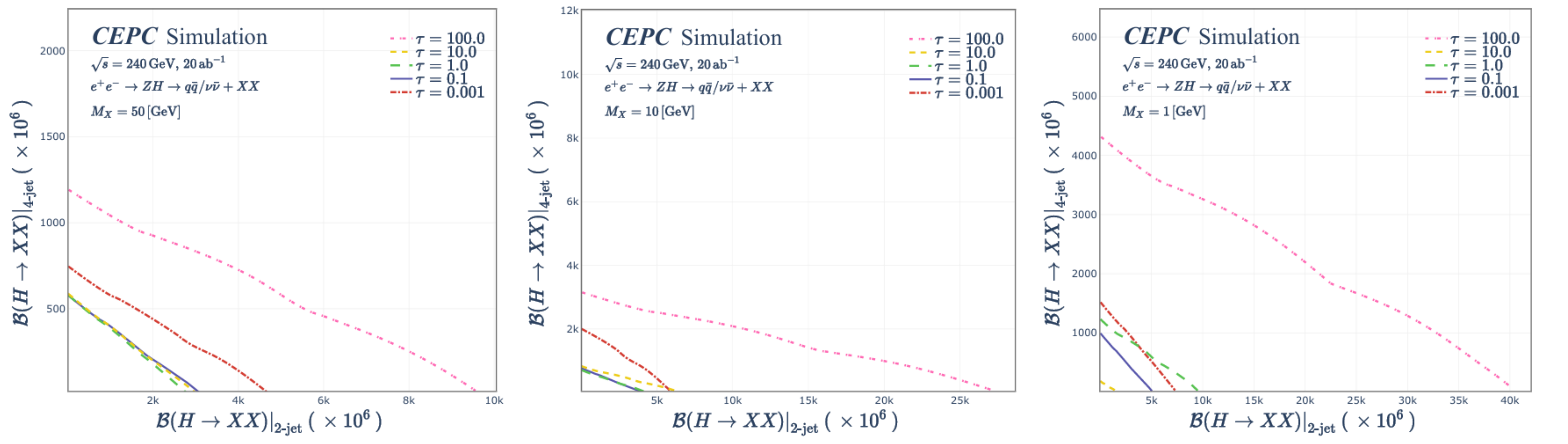
Summary

- **LLP Searches at Lepton Colliders** in the **dilepton** and **jet** channels benefit from the clean environment and distinctive detector signatures.
- **Dilepton channel (**2-e and 2-μ**): traditional cut-based method**
  - Cut-based analysis using **off-axis vertex reconstruction** and **particle ID**
    - Signal efficiency up to **40%**.
  - Lepton+jet channel should be included in future combinations.
- **Jet channel** (2-jet and 4jet)**: significant enhancement from deep learning techniques**
  - Low-level detector information without full reconstruction
  - Signal efficiency as high as 95% (while traditional method reaches to 25%)
- Best exclusion limit on BR(H→LLPs) @ 20 ab^{-1} after combination reaches **10^{-6}**
  - The jet channel plays the dominant role in the overall sensitivity in current assumption
  - **Far barrel detectors** improve sensitivity in the long-lifetime regime

Backups

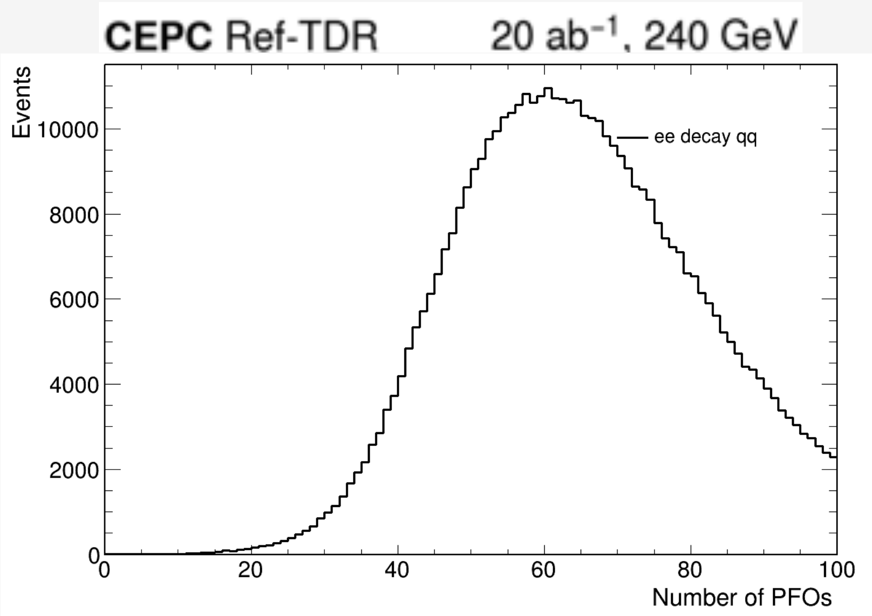
LLP 2D Limits

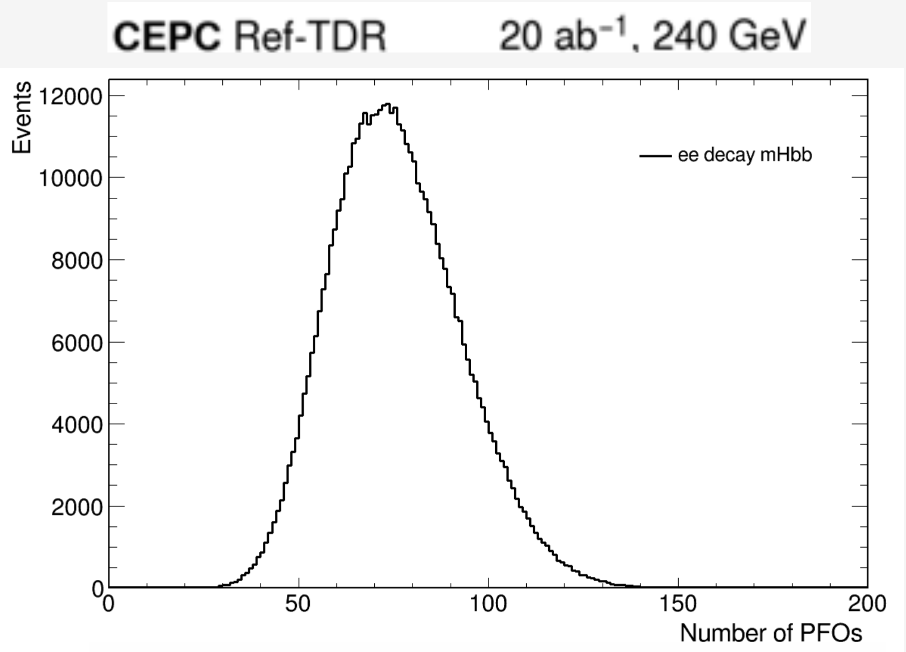
- We also provide the 2D likelihood for 95% Confidence Level upper limit on BR(H → XX) with 2 jets and 4 jets final state
- Keep ϵv= BR(X→$\nu\nu$)/BR(X→qq) float during limit extraction
- Higher mass and shorter lifetime scenarios have better sensitivities

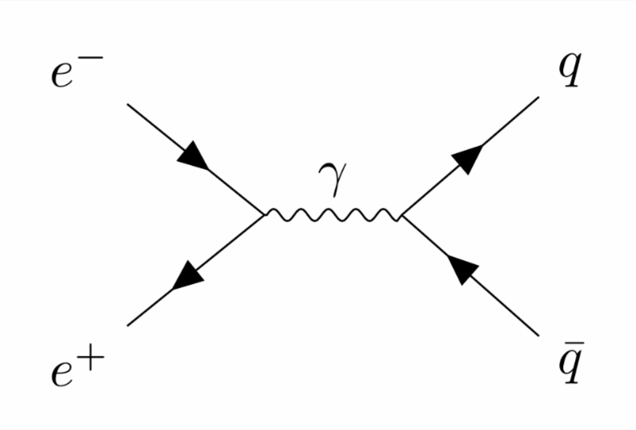


Jet Veto

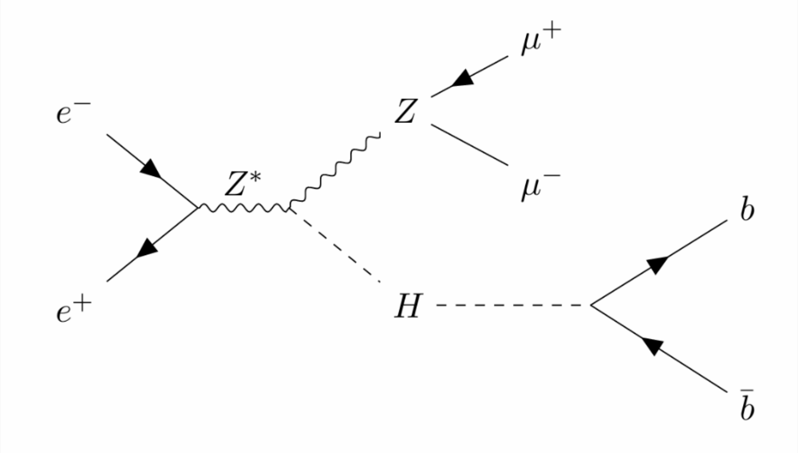
The jet veto is done by the number of particle flow objects







Jet Veto:
nPFO<20

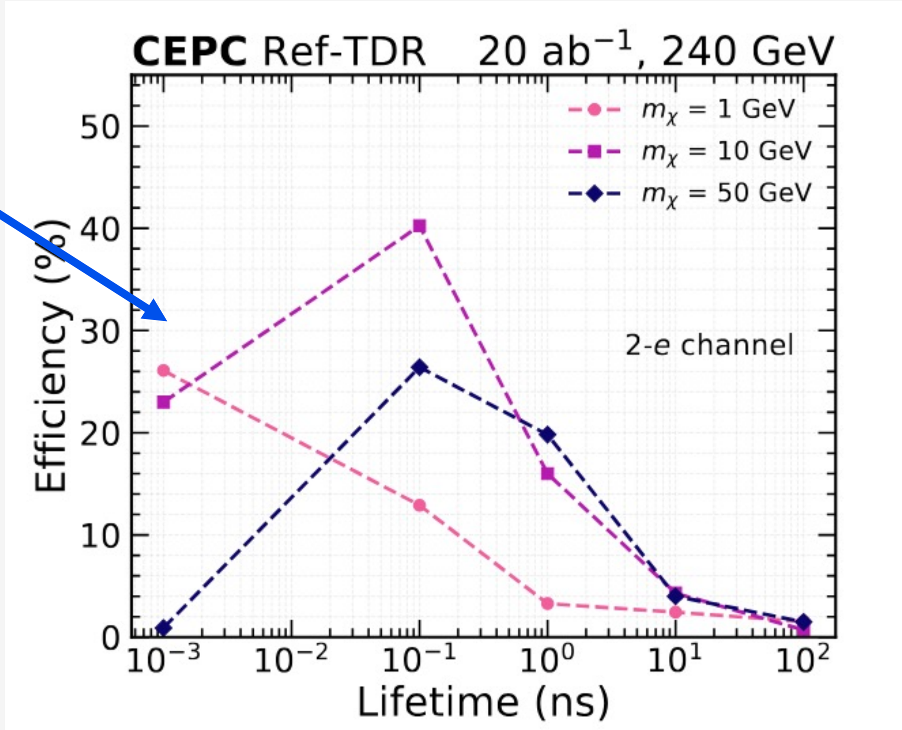


Signal Efficiency

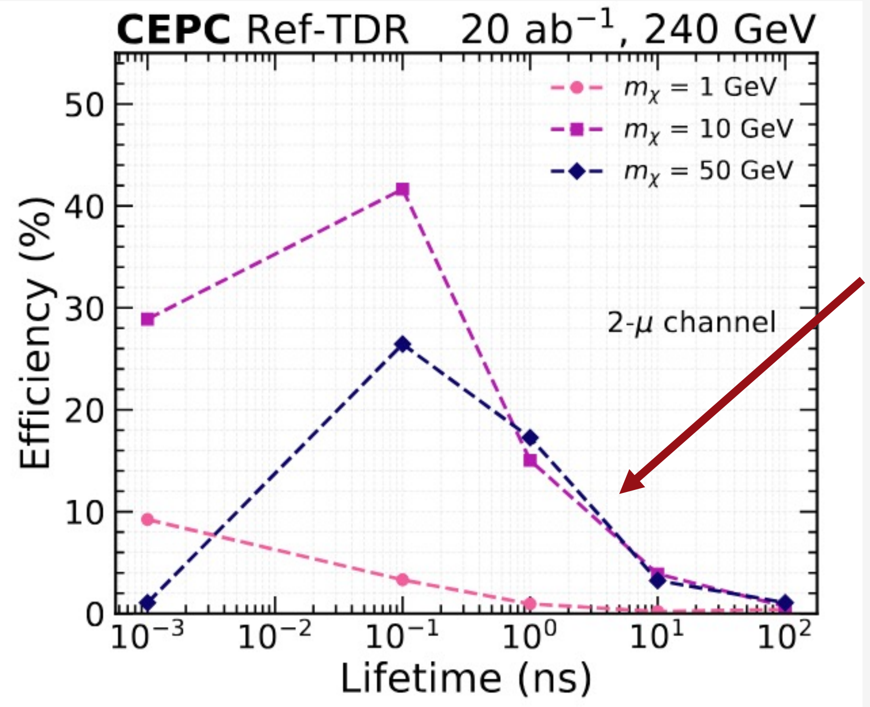
- The signal efficiency for dilepton channel reaches up to 40% in both channels at $m\chi$ = 10 GeV under background-free conditions

Lower efficiency in small lifetime: more prompt-like signals

LLP signal efficiency for 2-e channel



LLP signal efficiency for $2-\mu$ channel



The efficiency in large lifetime region is limited by the detector length

GNN Input Variables

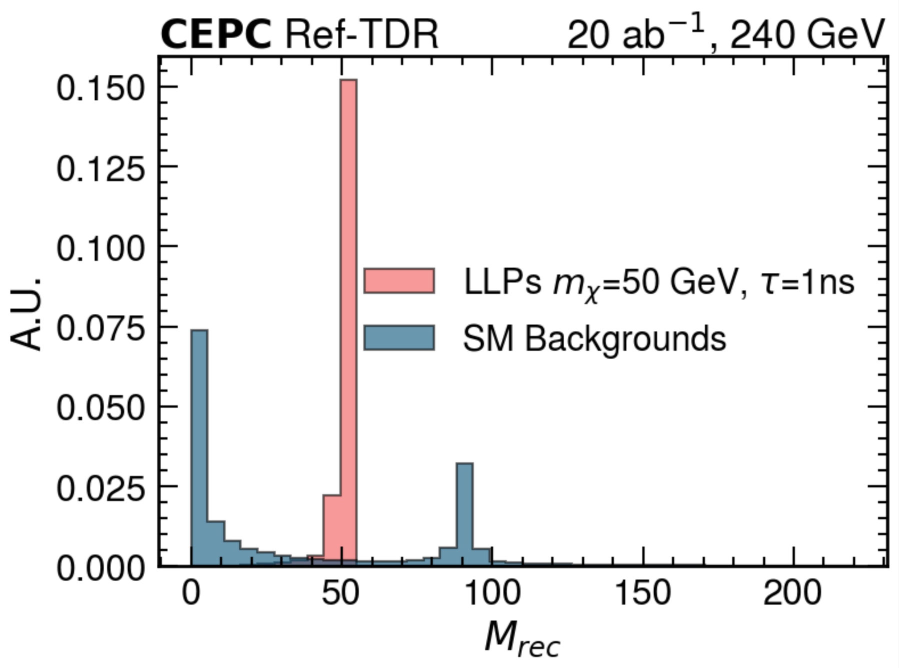
Features	Variable	Definition
calorimeter type node i	$\lvert x_i^\mu \rvert$	the space-time interval
	$\lvert p_i^\mu \rvert$	the invariant mass
	N_i	the number of hits
	η_i	$\frac{1}{2}\ln\frac{1+\frac{p_z}{p}}{1-\frac{p_z}{p}}$
	ϕ_i	$\arctan\frac{p_y}{p_x}$
	$\mathcal{R}_i$	$\sqrt{\eta^2+\phi^2}$
calorimeter type edge between node i and j	$x_i^\mu x_{j\mu}$, $p_i^\mu p_{j\mu}$, $x_i^\mu p_{j\mu}$, $p_i^\mu x_{j\mu}$ $\lvert x_i^\mu - x_j^\mu \rvert$, $\lvert p_i^\mu - p_j^\mu \rvert$, $\eta_i-\eta_j$, $\phi_i-\phi_j$, $\mathcal{R}_i-\mathcal{R}_j$	
tracker type node i	$\lvert r \rvert$	euclidean distance
	N_i	the number of hits
	η_i	$\frac{1}{2}\ln\frac{1+\frac{z}{r}}{1-\frac{z}{r}}$
	ϕ_i	$\arctan\frac{y}{x}$
	$\mathcal{R}_i$	$\sqrt{\eta^2+\phi^2}$
tracker type edge between node i and j	$\lvert r_i - r_j \rvert$, $r_i r_j$, $\eta_i-\eta_j$, $\phi_i-\phi_j$, $\mathcal{R}_i-\mathcal{R}_j$	

Not background-free Assumption

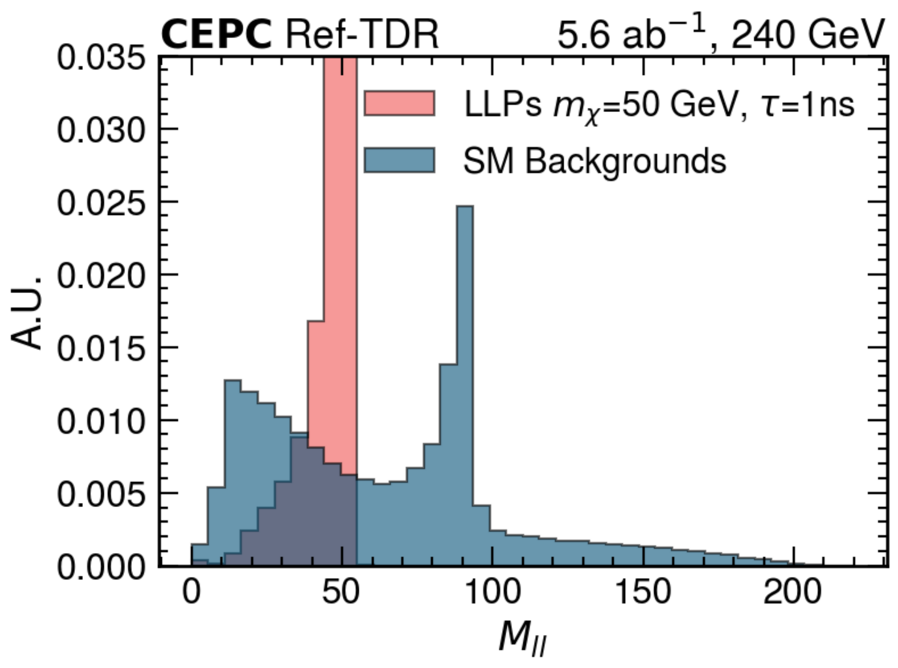
2 backgrounds assumption

Table 6: The 95% C.L. exclusion limit on BR($h \to XX$) for all signal channels with both fixed and floating ϵ_V with 2 backgrounds assumption. The limits include $\pm 1\sigma$ uncertainties after taking into account both statistical and systematic contributions.

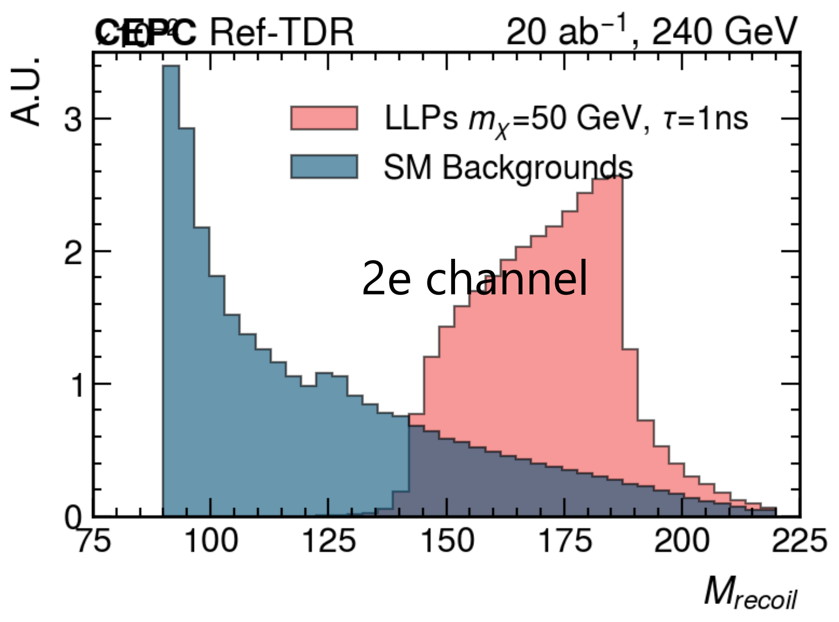
Scenario	$\mathcal{B}$ $(\times 10^{-6})$	Lifetime [ns]				
	Mass [GeV]	0.001	0.1	1	10	100
Fixed	1	$2.78^{+1.21}_{-0.54}$	$2.40^{+0.95}_{-0.55}$	$5.21^{+1.96}_{-1.47}$	$34.60^{+12.43}_{-10.17}$	$1285.89^{+496.57}_{-301.57}$
	10	$3.58^{+1.44}_{-0.87}$	$1.74^{+0.75}_{-0.42}$	$2.07^{+0.79}_{-0.50}$	$4.42^{+1.68}_{-1.06}$	$31.94^{+11.97}_{-8.64}$
	50	$1.84^{+0.74}_{-0.44}$	$1.54^{+0.59}_{-0.35}$	$1.68^{+0.64}_{-0.40}$	$1.69^{+0.64}_{-0.40}$	$4.04^{+1.54}_{-1.02}$
Floating	1	$5.62^{+15.39}_{-4.07}$	$2.63^{+4.82}_{-1.40}$	$2.80^{+11.86}_{-0.87}$	$17.54^{+82.75}_{-5.21}$	$675.25^{+3739.15}_{-195.72}$
	10	$3.75^{+11.82}_{-1.86}$	$4.04^{+10.78}_{-3.08}$	$1.08^{+4.85}_{-0.31}$	$2.30^{+10.34}_{-0.65}$	$16.74^{+76.53}_{-4.81}$
	50	$3.58^{+11.01}_{-2.59}$	$2.78^{+8.31}_{-1.93}$	$1.96^{+3.24}_{-1.10}$	$1.97^{+3.27}_{-1.10}$	$2.15^{+9.64}_{-0.71}$

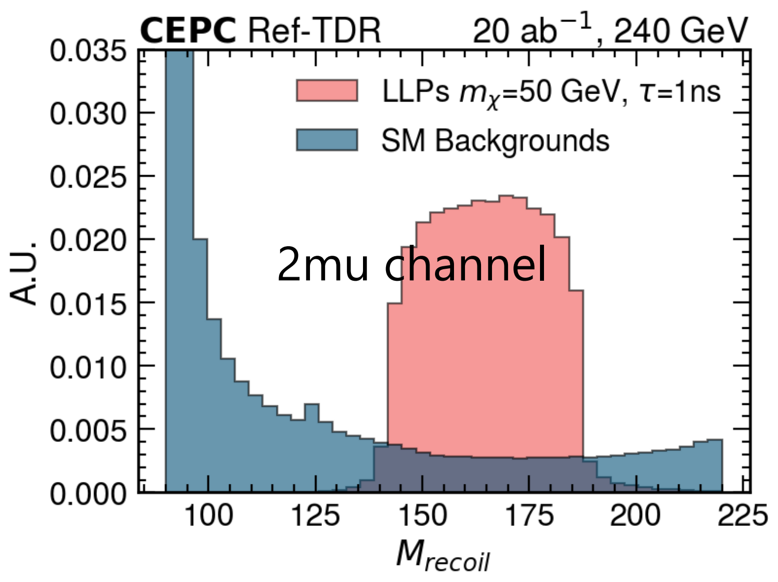


CEPC Ref-TDR
20 ab^{-1}, 240 GeV
LLPs m_χ=50 GeV, τ=1ns
SM Backgrounds
A.U.
0.150
0.125
0.100
0.075
0.050
0.025
0.000
0
50
100
150
200
M_{rec}



CEPC Ref-TDR
5.6 ab^{-1}, 240 GeV
LLPs m_χ=50 GeV, τ=1ns
SM Backgrounds
A.U.
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
50
100
150
200
M_{ll}


CEPC Ref-TDR
20 ab^{-1}, 240 GeV
A.U.
LLPs m_χ=50 GeV, τ=1ns
SM Backgrounds
2e channel
0
1
2
3
75
100
125
150
175
200
225
M_{recoil}


CEPC Ref-TDR
20 ab^{-1}, 240 GeV
A.U.
LLPs m_χ=50 GeV, τ=1ns
SM Backgrounds
2mu channel
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
100
125
150
175
200
225
M_{recoil}

The cut-flow for the electron channel, m_{llp} = 10 GeV

Cuts	0.001 ns (%)	0.1 ns (%)	1ns (%)	10ns (%)	100ns (%)	eeH (%)	barbar (%)	Single Z (%)	evW(%)
All Events	100.00	100.00	100.0	100.00	100.00	100.00	100.00	100.00	100.00
Jet veto	99.98	99.93	99.91	99.97	99.98	6.56	64.05	99.36	99.81
Z veto	99.98	99.93	99.91	99.97	99.98	5.21	63.50	79.58	93.33
2 tracks	83.99	88.3	47.78	14.53	11.39	0.13	24.51	56.80	75.73
displaced vertex (>1 mm)	44.07	86.60	46.59	14.07	11.03	0.00	9.60	0.71	0.18
recoil mass >140 GeV	29.79	55.68	27.84	8.71	1.34	0.00	0.20	0.30	0.07
2 electron after PID	29.7	55.68	27.84	8.71	1.34	0.00	0.20	0.30	0.07
OS	29.74	55.64	27.82	8.71	1.34	0.00	0.14	0.01	0.01
$1 < \Delta\theta < 60$	28.68	53.85	26.87	8.41	1.28	0.00	10^{-4}	10^{-5}	0.00
Invariant mass cut $abs(m_{ll}-10) < 1$ GeV	23.00	40.24	16.00	4.61	0.70	0.00	0.00	0.00	0.00

The cut-flow for the muon channel, m_{llp} = 1 GeV

Cuts	0.001ns (%)	0.01ns (%)	1ns (%)	10ns (%)	100ns (%)	vvHX (%)	mmHX (%)	barbar (%)	Signal Z (%)	ZZ (%)	WW(%)
All Events	100	100	100	100	100	100	100	100	100	100	100
Jet veto	100	100	100	100	100	8.04	7.7	97.94	99.67	99.42	99.94
Z veto	100	100	100	100	100	7.98	5.05	72.09	88.09	79.15	93.89
2 tracks	97.62	60.12	19.56	15.36	15.57	5.2	0.09	54.49	58.14	47.01	85.7
displaced vertex (>3.5 mm)	78.7	58.92	19.14	15.04	15.24	0.02	0	0.59	0.47	0.46	0.05
recoil mass >130 GeV	34.59	17.96	5.58	0.97	2.15	0.01	0	0.01	0.14	0.08	0
2 muon after PID	33.3	16.73	5.19	0.89	2.01	0	0	0.01	0.13	0.07	0
OS	33.3	16.73	5.19	0.89	2.01	0	0	0.01	0.13	0.07	0
$1 < \Delta\theta < 60$	24.24	12.55	3.93	0.69	1.37	0	0	0	0.002	0.002	0
Invariant mass cut abs(m_{ll}-1) < 0.6 GeV	24.24	12.55	3.93	0.69	1.37	0	0	0	10^{-4}	10^{-4}	0
ΔT > 0.05 ns	9.23	3.31	0.95	0.2	0.4	0	0	0	0	0	0

Networking Trianing Results