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Search for Long-lived Particles in the multi-lepton channel with the CEPC Detector

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2025/11/06

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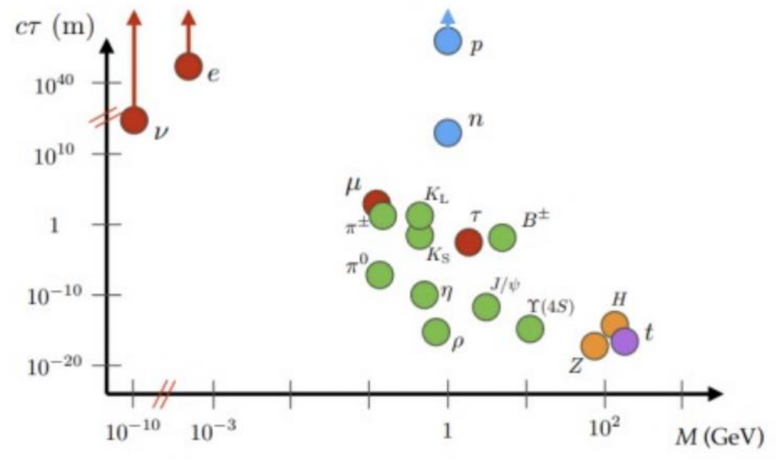
New Physics Beyond SM- LLPs

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

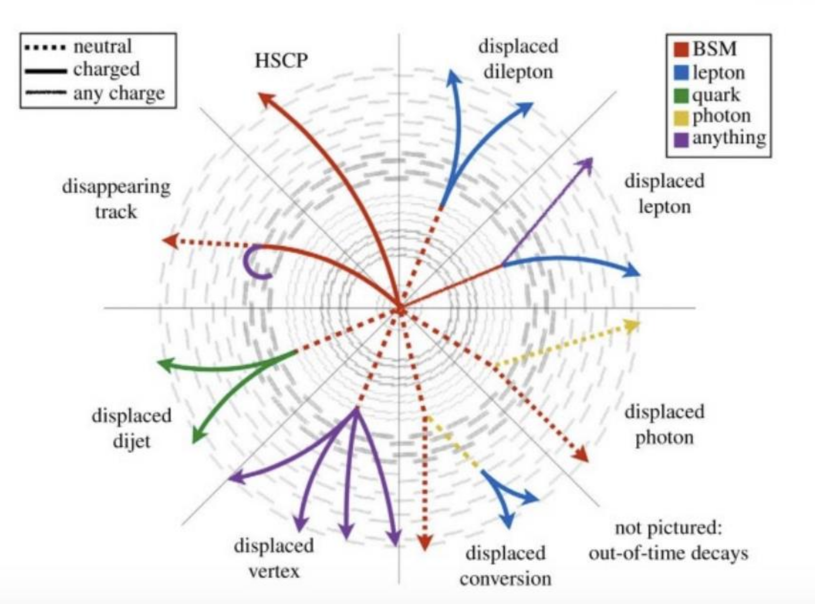
- Many particles in BSM models have a relatively long lifetime: weak coupling to SM particles, maybe new scalars, dark photons, ALP, SUSY….



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:

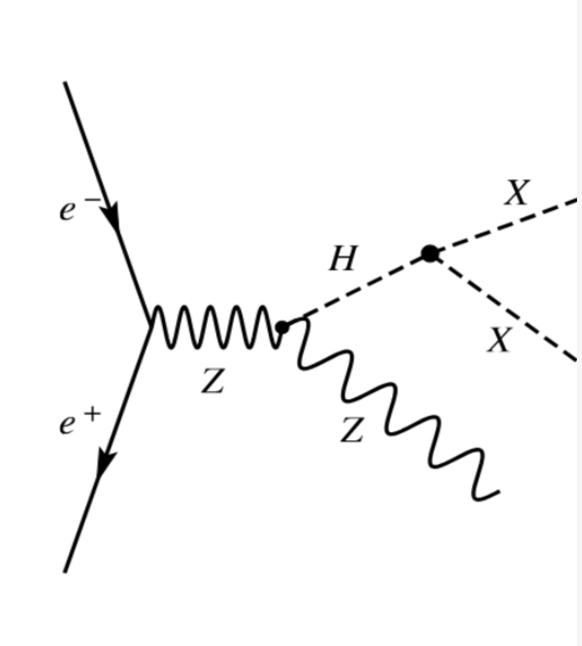
- The advantage of the lepton collider: clean environment
- Lepton pair or multi-jets with a displaced vertex
- Making use of deep learning techniques in jet channel: Image recognition and pattern identification

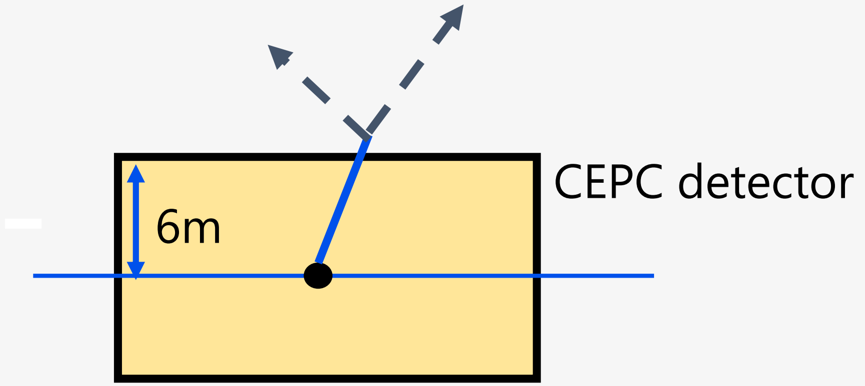
LLP at CEPC

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

- We use the **full simulation** sample using CEPC official software to an integrated luminosity of 21.6 ab^{-1}

Long-lived particle production on CEPC





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

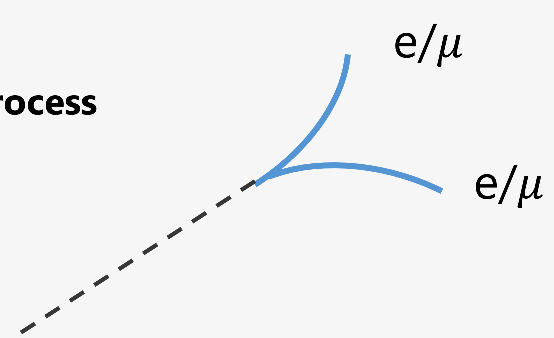
Acceptance (%)	Lifetime [ns]				
Mass [GeV]	0.001	0.1	1	10	100
1	100.00 ± 0.00	99.86 ± 0.01	48.76 ± 0.18	6.49 ± 0.09	0.67 ± 0.03
10	100.00 ± 0.00	100.00 ± 0.00	99.78 ± 0.01	46.80 ± 0.16	6.22 ± 0.08
50	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	99.31 ± 0.03	40.37 ± 0.16

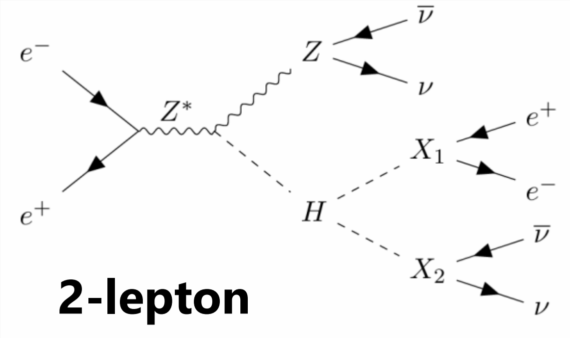
Lepton Channel

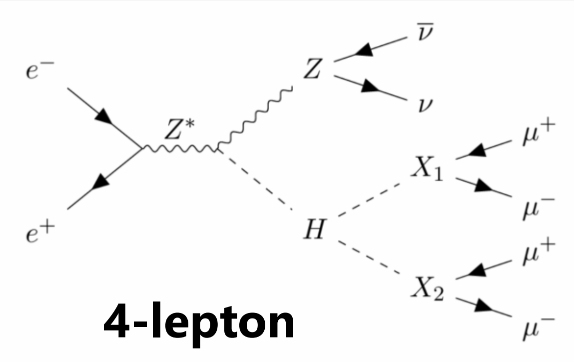
- One or two LLPs decay to visible lepton pair when Z decays to neutrinos to form 2-lepton and 4-lepton channel
- Major backgrounds are Bhabha process (2 leptons) and ZZ process (4 leptons)

LLP Process

Long distance with IP

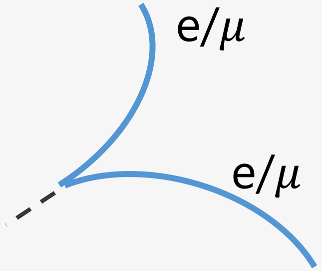




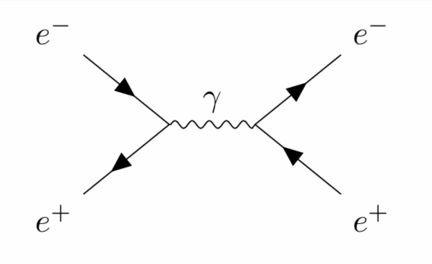


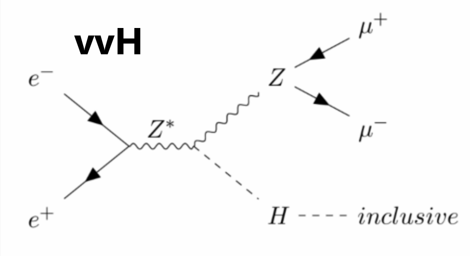
SM backgrounds

Short distance with IP

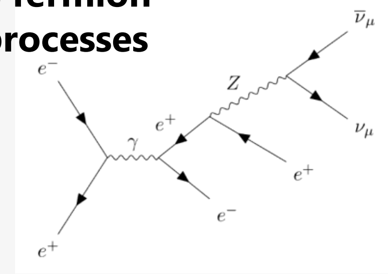


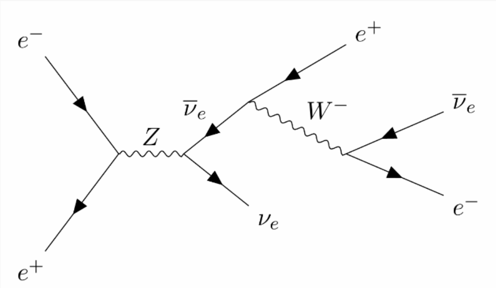
bhabha





4 fermion processes

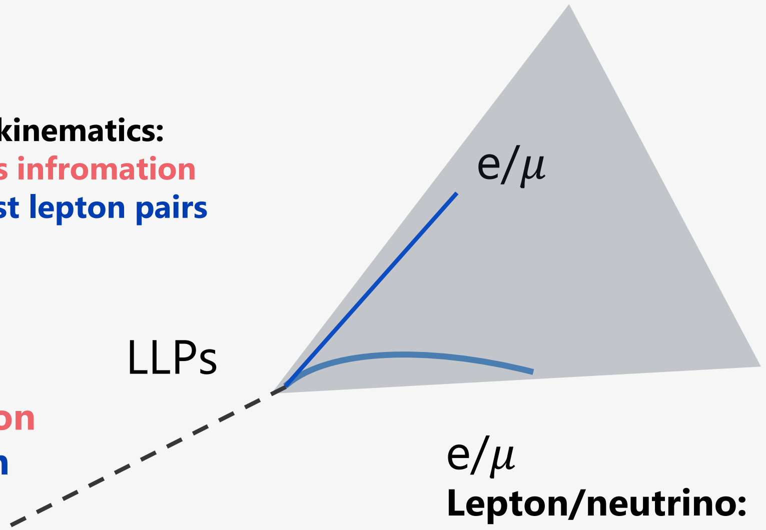




Analysis Strategy

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

LLP kinematics:
mass infromation
Boost lepton pairs



Displaced vertex:
vertex reconstuction
timing information

Lepton/neutrino:
Recoil mass
Particle ID

Preprocessing
Jet veto + lepton ID WP selection

Selection-based method

Displaced vertex: 2 tracks with distance between vertex and IP lower than 1 mm (3.5mm for LLP 1 GeV)
$\Delta\theta$: 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

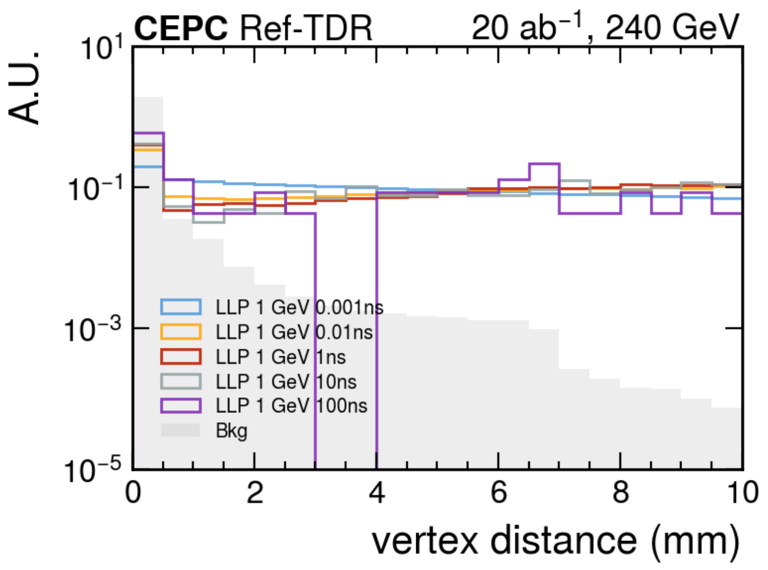
Machine learning method

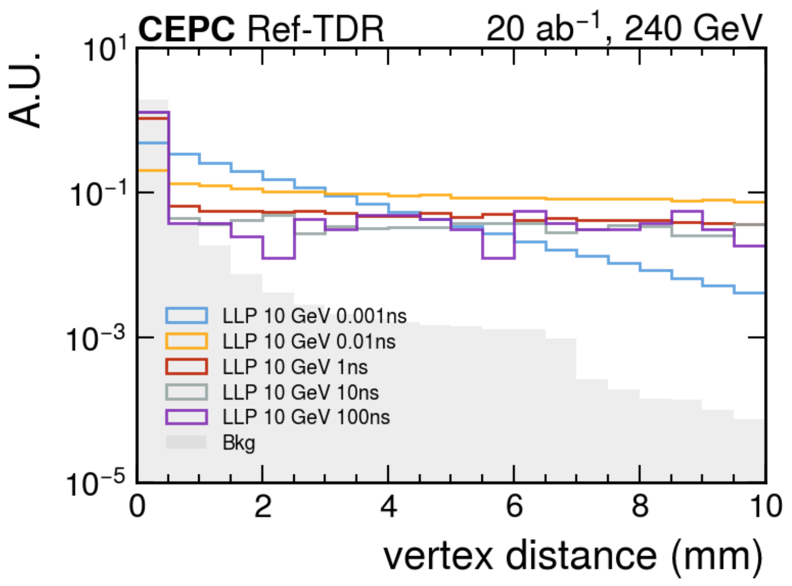
- XGBoost with the kinematics of the letptons as input
- KFold for optimization
- Variables are similar as selection based method

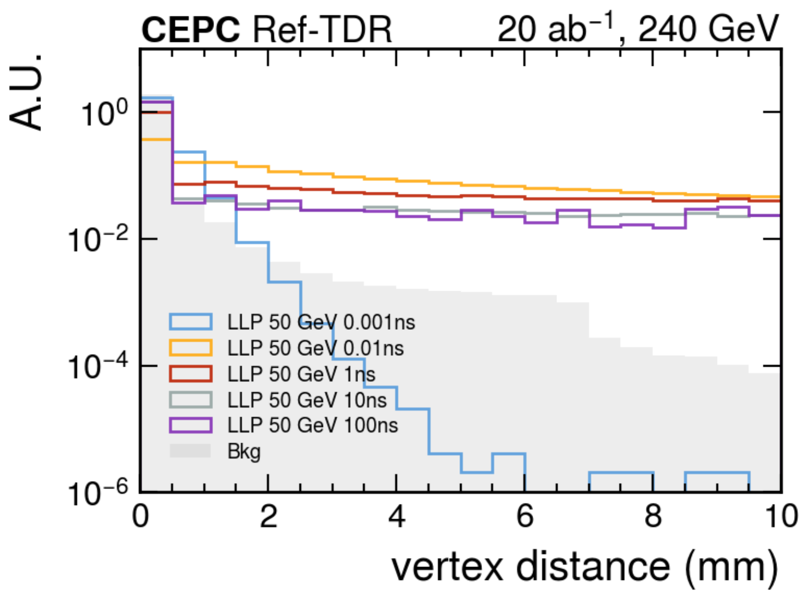
Displaced Vertex Reconstruction

- Using the tracks reconstructed from the tracker and TPC to find the prime vertex
- Most LLPs with lifetime over 0.1ns has 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**

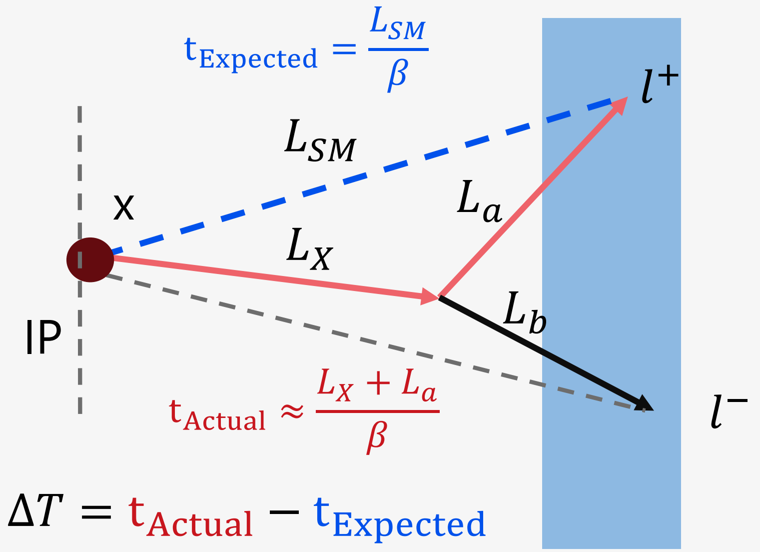






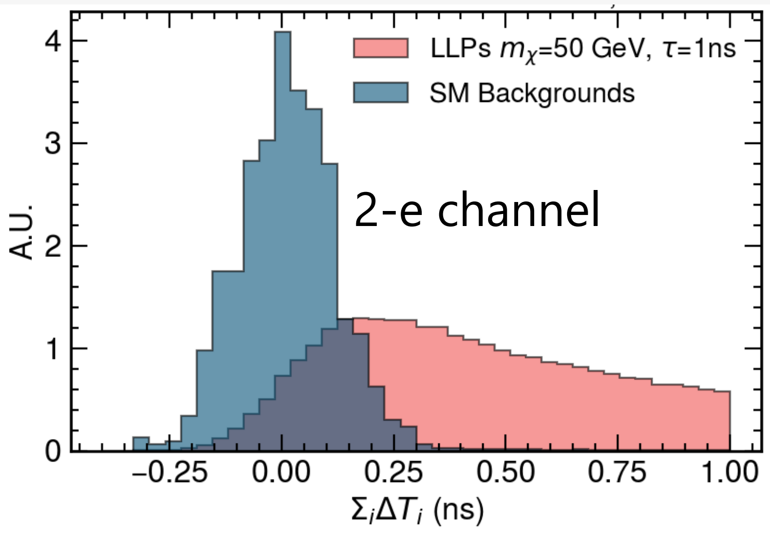
Timing Information

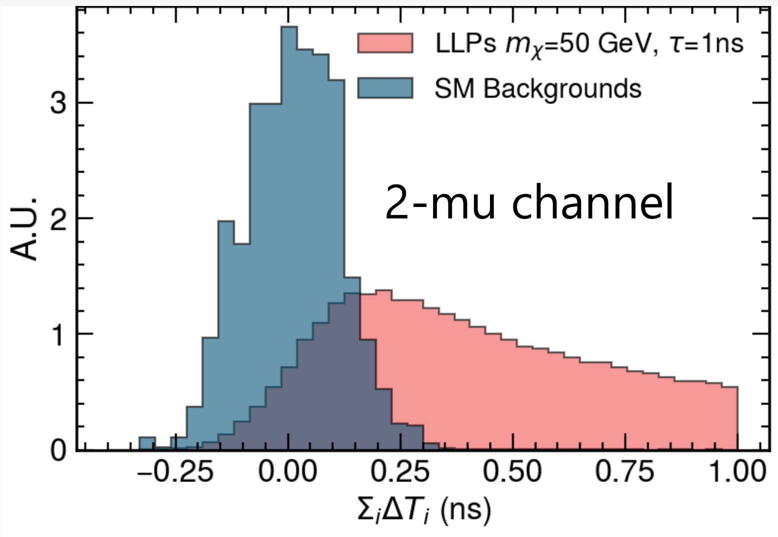
- The extended flight path of LLPs compared to SM particles makes timing information a distinctive signature
- The OTK with 50 ps timing resolution, provides precise hit time measurements for charged particles.



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

$t_{hit,i}$: 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.





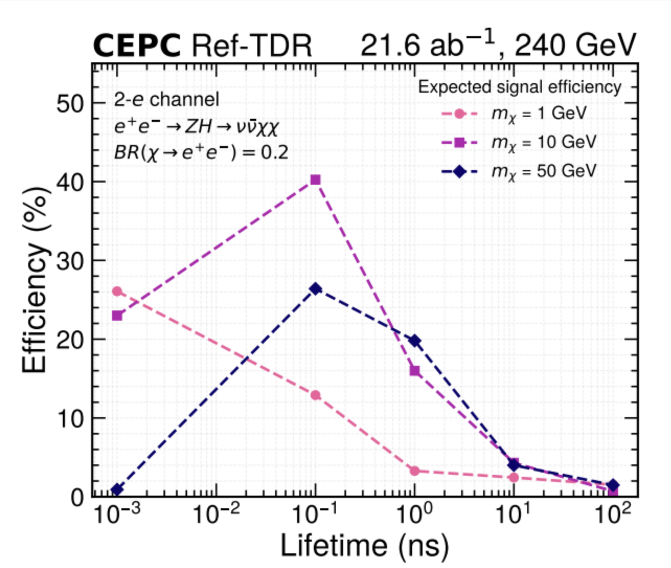
Selection-based Result

- The signal efficiency for 2-lepton channel reaches up to 40% in both channels at $m\chi$ = 10 GeV under **background-free** conditions
- The search sensitivity to heavier LLPs such as those with $m\chi$ = 50 GeV degrades because their decays produce softer, more collimated, and more prompt-like signatures

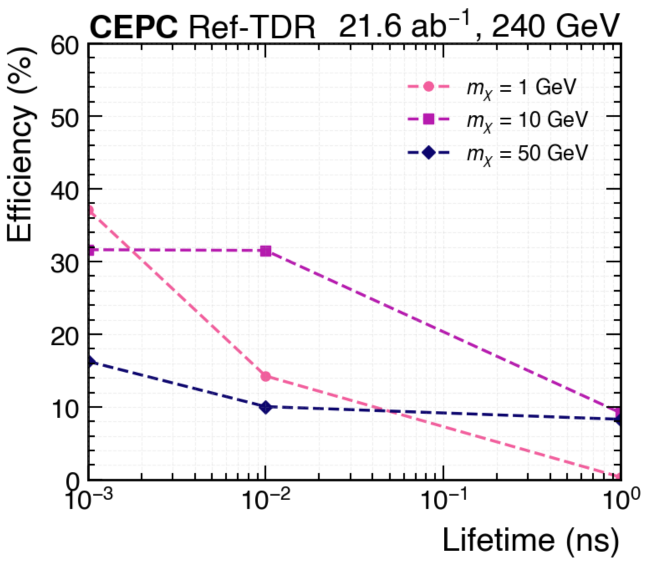
2-lepton cut-flow

Selection	Category	Criteria
Jet veto	2-e and 2-μ channels	nPFO < 20
Lepton ID	2-e and 2-μ channels	two oppositely charged leptons satisfying **BEST WP**
Lepton momentum	2-e and 2-μ channels	$p_\ell > 3$ GeV
Polar angle difference	2-e and 2-μ channels	$1° < \Delta\theta_{\ell\ell} < 60°$
Z veto	2-e and 2-μ channels	$\lvert M_{\ell\ell} - 90 \rvert > 5$ GeV
Recoil mass	2-e channel 2-μ channel	$M_{\text{recoil}} > 130$ GeV $M_{\text{recoil}} > 140$ GeV
Vertex displacement	$m_\chi = 1$ GeV $m_\chi = 10, 50$ GeV	$d_{vtx} > 3.5$ mm $d_{vtx} > 1$ mm
Invariant mass window	$m_\chi = 1$ GeV $m_\chi = 10, 50$ GeV	$\lvert M_{\ell\ell} - m_\chi \rvert < 0.6$ GeV $\left\lvert \frac{M_{\ell\ell} - m_\chi}{m_\chi} \right\rvert < 10\%$
Time-of-flight delay	$m_\chi = 1$ GeV and 2-μ channel	$\Delta T > 0.05$ ns

2-lepton results



4-lepton results



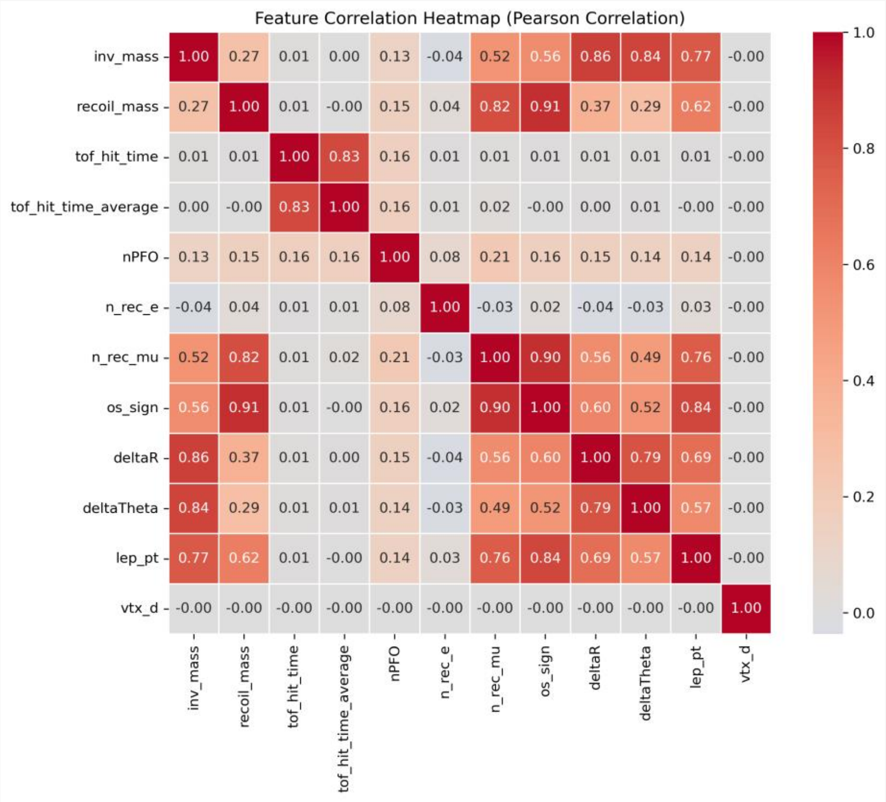
MVA can help to further improve signal efficiency, see next slide

MVA Training and Optimation

- Using XGBoost, optimized with K-Fold method
- The training variables for XGBoost for lepton channels are those used in the selection based after PID
- Adding PFO momentum information in addition to selection-based input variables

Input variables:

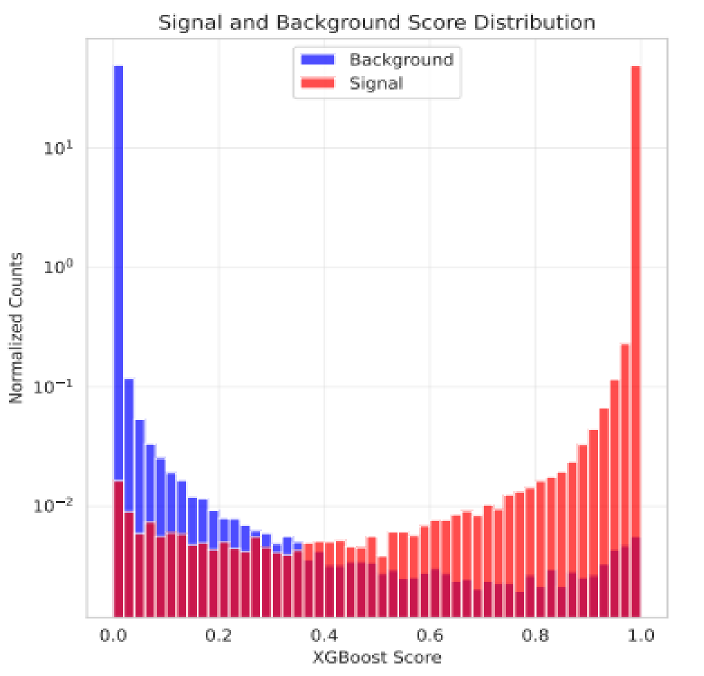
Displaced vertex with 2 tracks: the distance in (x,y,z) plane
Particle Kinematics: $\Delta\theta$, $\Delta\phi$, momentum information
Number of particle-flow objects
Invariant mass between paring leptons
Timing information: the sum ΔT of the hit on TOF

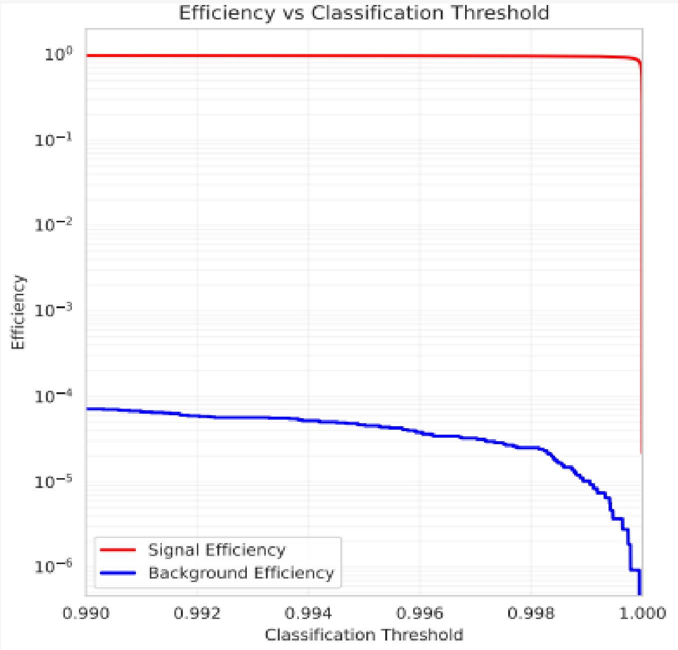


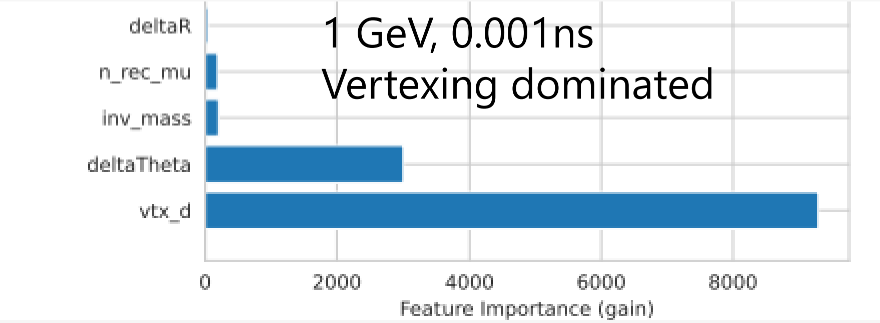
For the 4-lepton channel: the 4 leptons are paring to 2 groups by the invariant between two particles

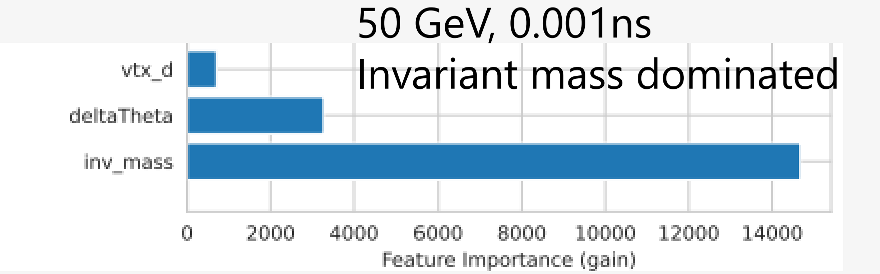
MVA Performance

- Achieve background-free
- Invariant mass has more importance in low lifetime samples, while vertexing information is more effective for long life-time LLPs



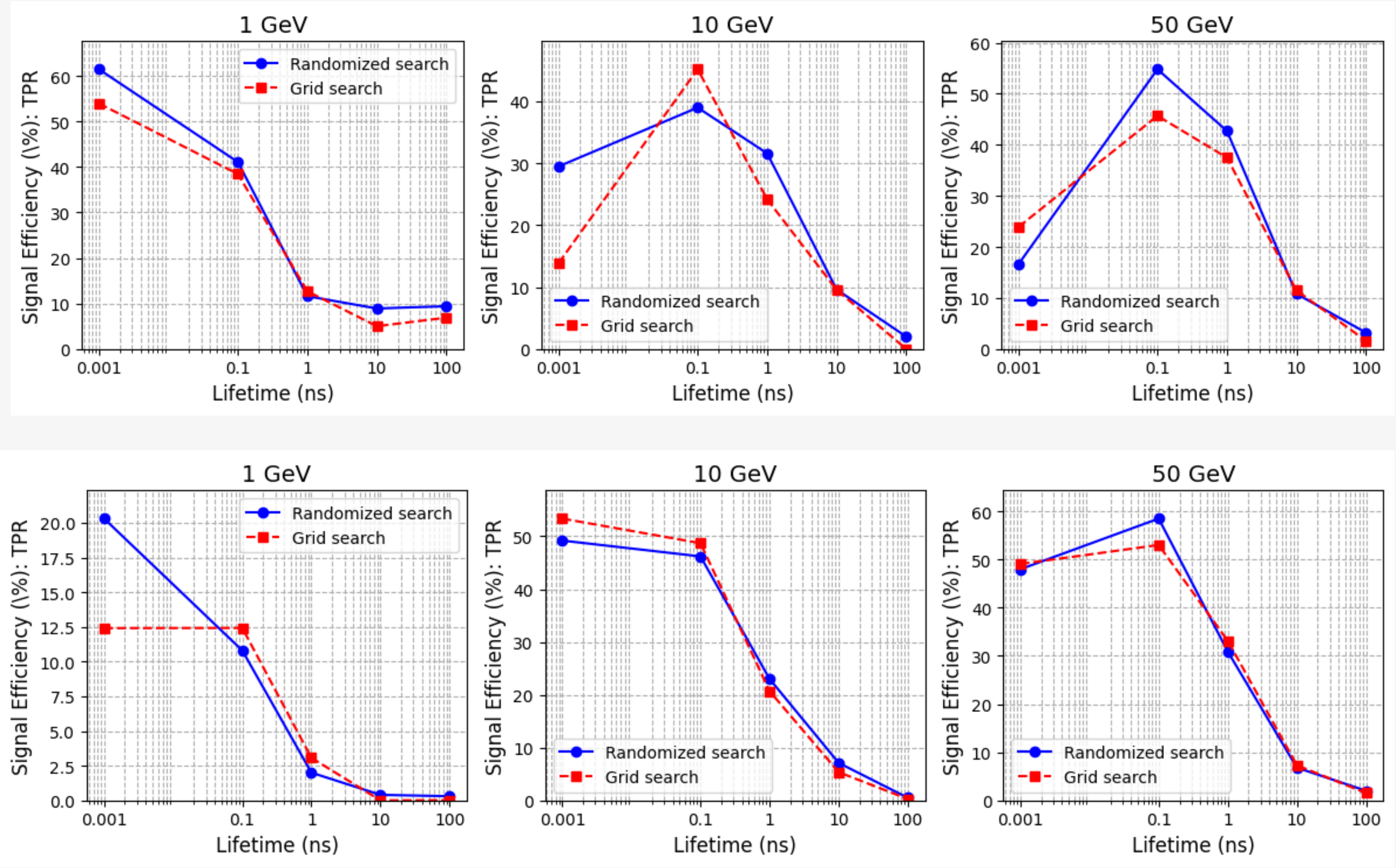






Different Optimization Methods for XGBoost

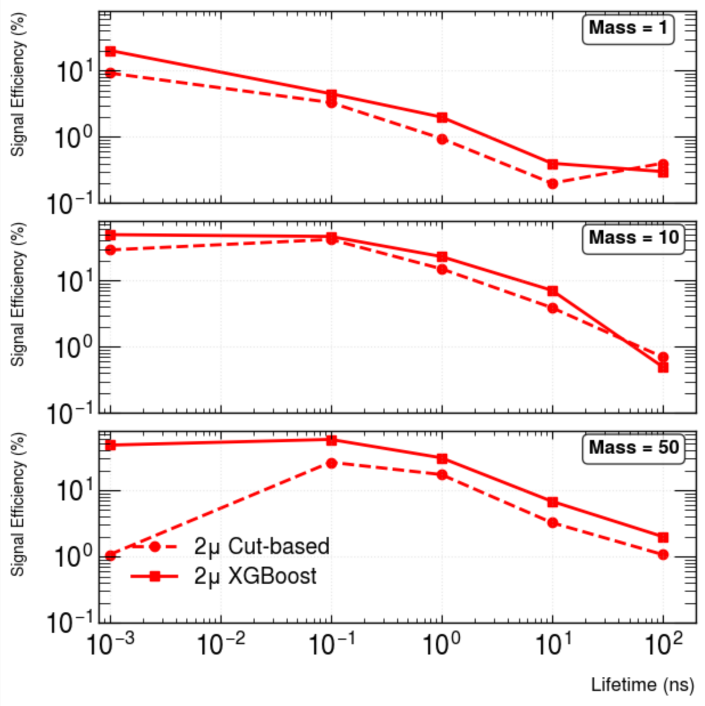
- Tried with different optimization methods: randomized search versus grid search
  - Similar performance between two methods
  - Choose randomized search as the default

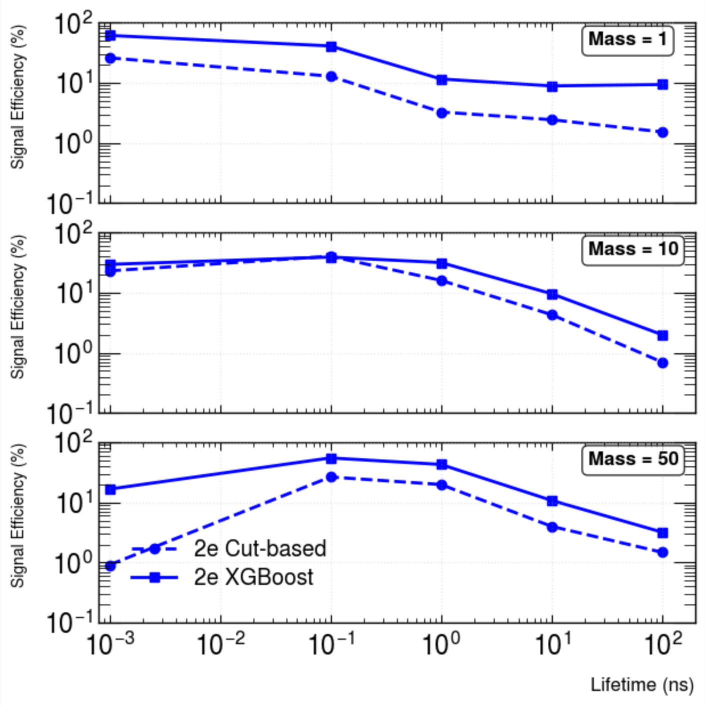


Comparsion between Selection-based and MVA Method

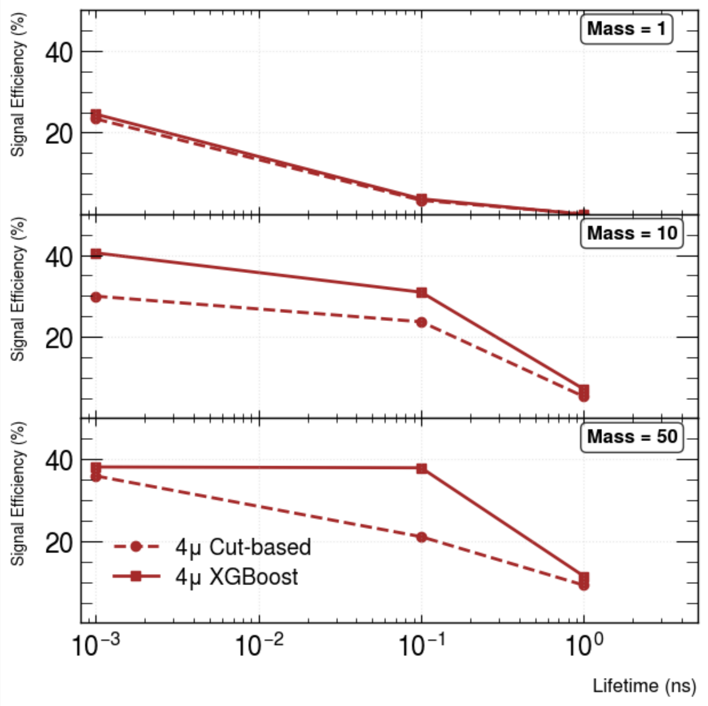
- MVA method improves signal efficiency for dilepton channel by 100%-300% at $m\chi$ = 50 GeV under **background-free** conditions
- 4-lepton channel is improved by 100% at $m\chi$ = 10 GeV

2-lepton results



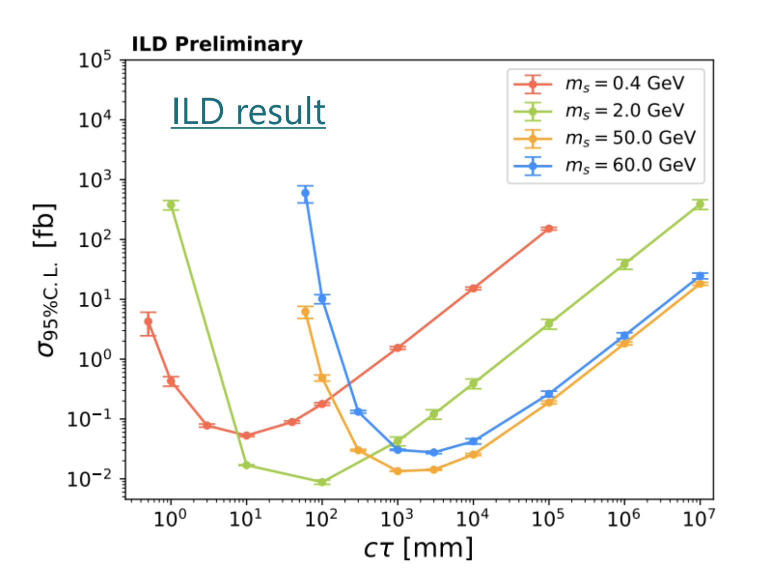


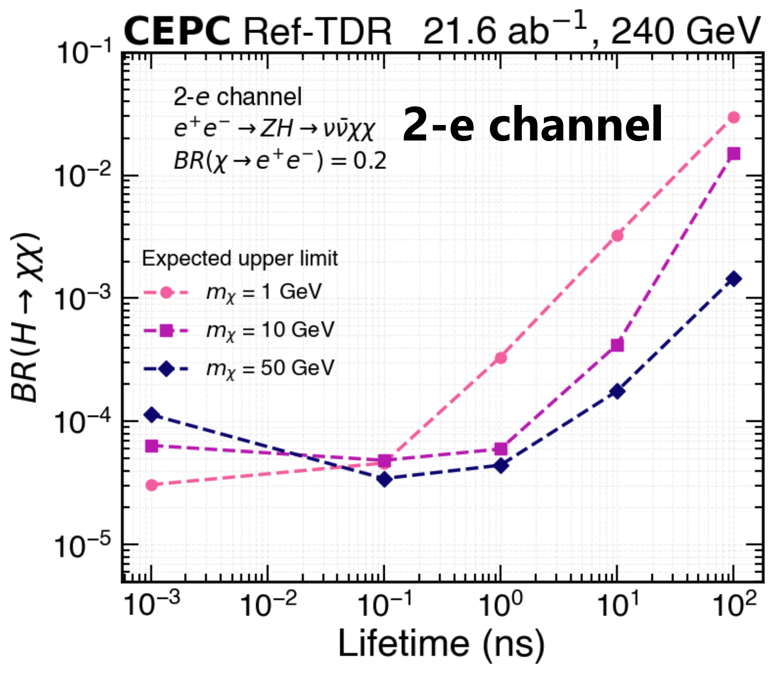
4-lepton results

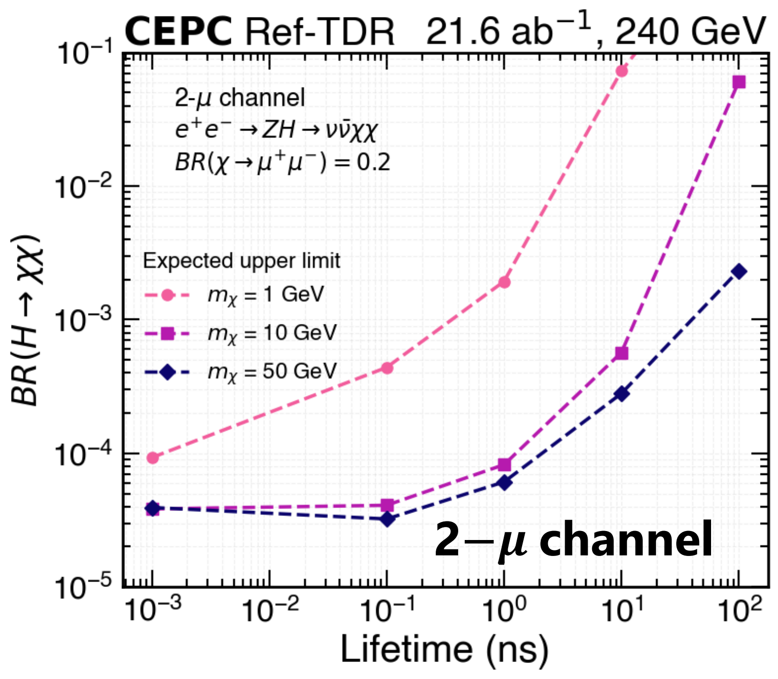


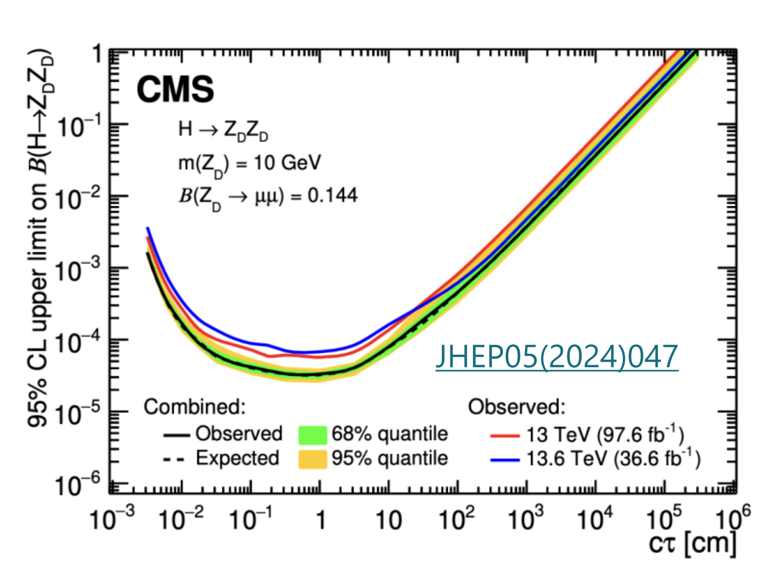
Expected Limit for Lepton Channel

- Assuming the branch ratio BR(X-> ll) is 0.2
- Best BR(H->LLPs) limit reaches to $3*10^{-5}$
- Advantage: short life-time region
- An order of magnitude better than the ILD and LHC result in short life time region





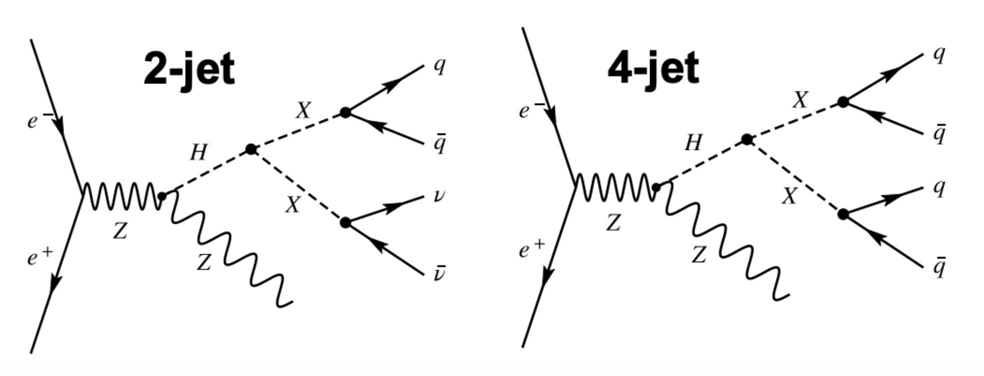


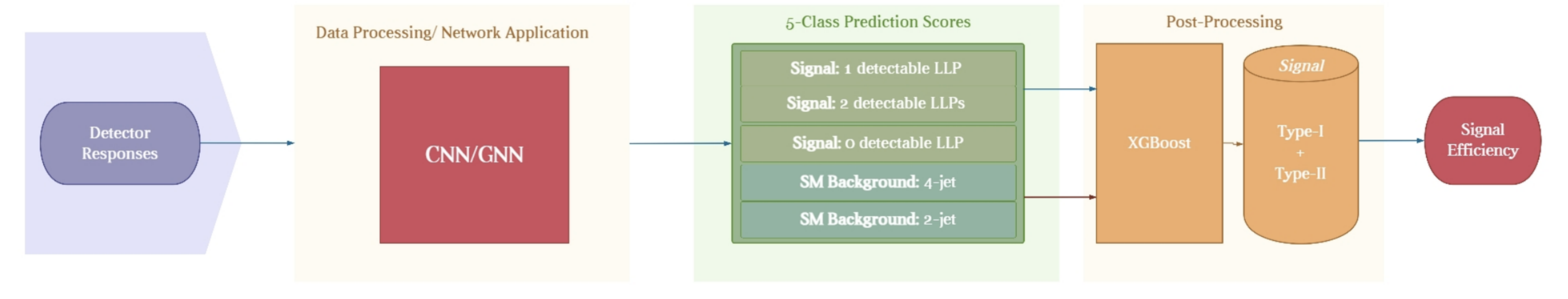


Accepted by Frontier Physics (2025) 2401.05094

LLPs at CEPC Jet channel

We consider two LLP jet final state cases in CEPC:
2-jet and 4-jet final state
Advanced neural networks trained with low-level detector information:





- 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

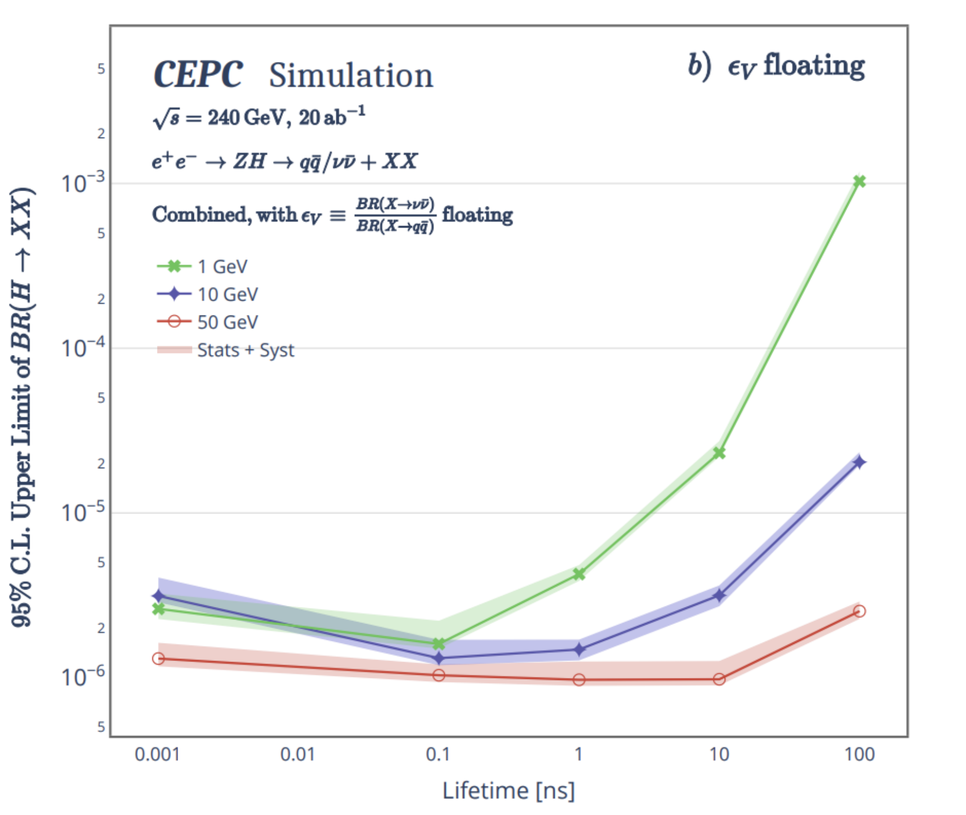
Post-Processing: converting 5-class output to a 2-class classfication task

ML-Based Analysis Result

- Both CNN and GNN achieve high signal efficiencies with background-free
- The performance is consistent across different LLP mass and lifetime considerations.
- The best expected limit of BR(H → XX) achieves 10^{-6}

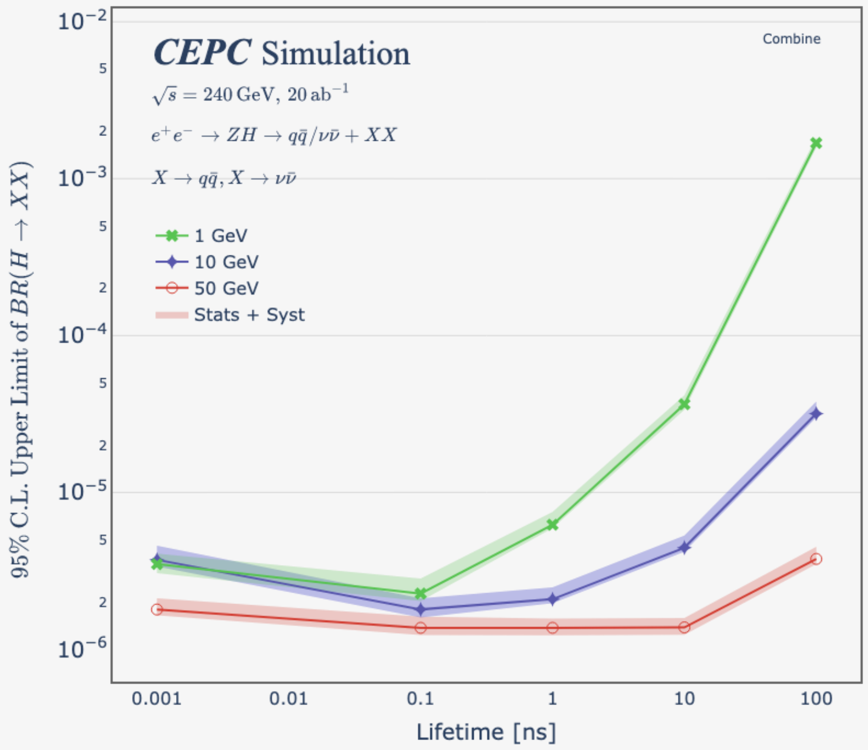
Approach	Efficiency (%)	Lifetime [ns]				
	Mass [GeV]	0.001	0.1	1	10	100
CNN	1	38 ± 0.1	56 ± 0.1	45 ± 0.2	48 ± 0.6	52 ± 1.9
	10	30 ± 0.1	71 ± 0.1	76 ± 0.1	66 ± 0.1	69 ± 0.5
	50	73 ± 0.1	94 ± 0.1	95 ± 0.0	95 ± 0.0	91 ± 0.1
GNN	1	46 ± 0.1	58 ± 0.1	44 ± 0.2	54 ± 0.6	43 ± 1.8
	10	29 ± 0.1	49 ± 0.1	75 ± 0.1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



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
  - Combined limit improves jet-only limit by ~1%



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

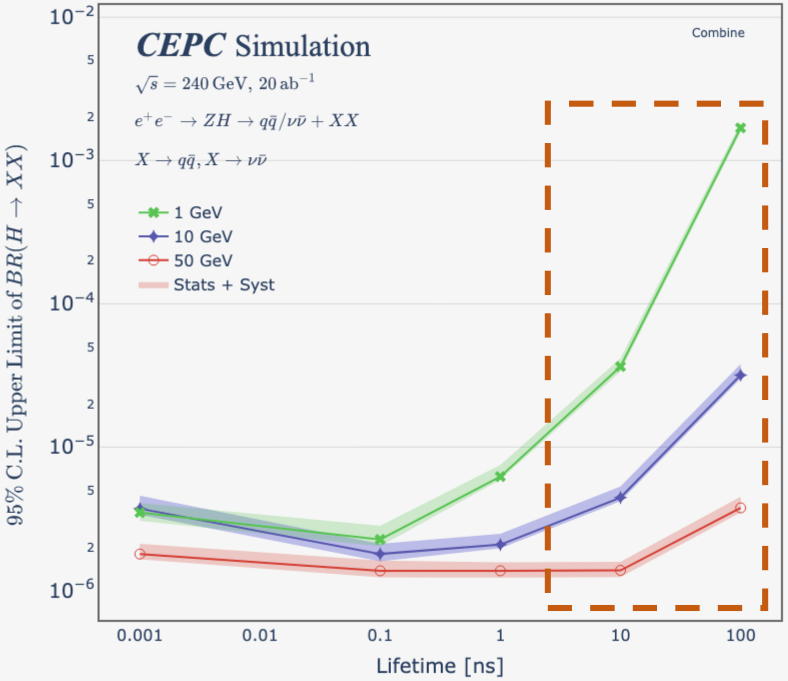
Summary

- **LLP Searches at Lepton Colliders** in the **lepton** and **jet** channels benefit from the clean environment and distinctive detector signatures.
- **Lepton channel (**2l and 4l**):**
  - Selection-based: using **off-axis vertex reconstruction** and **particle ID,** with signal efficiency up to **40%**.
  - Machine learning method: improve the performance by **100%** in overall
  - Lepton+jet channel should be included in future combinations.
- **Jet channel** (2-jet and 4-jet)**: 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($H \rightarrow$LLPs) @ 20 ab^{-1} after combination reaches **10^{-6}**
  - The jet channel plays the dominant role in the overall sensitivity in current assumption

Backups

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



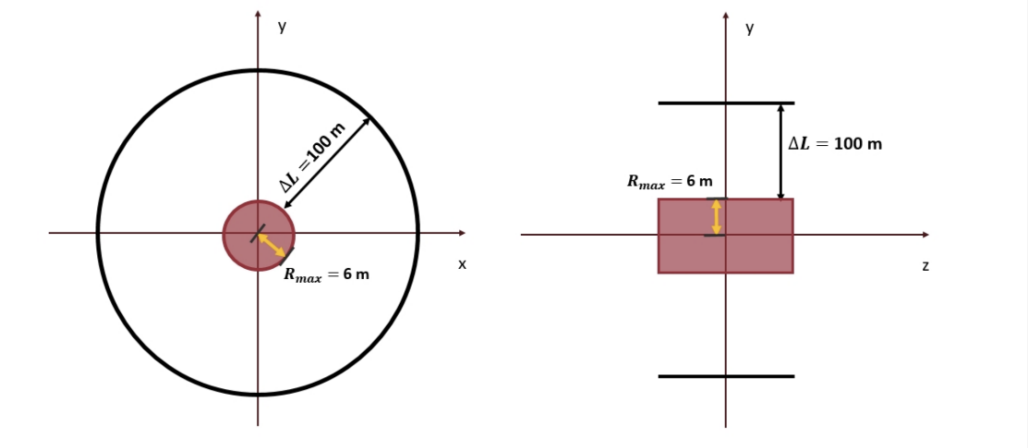
Improving this part

- 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

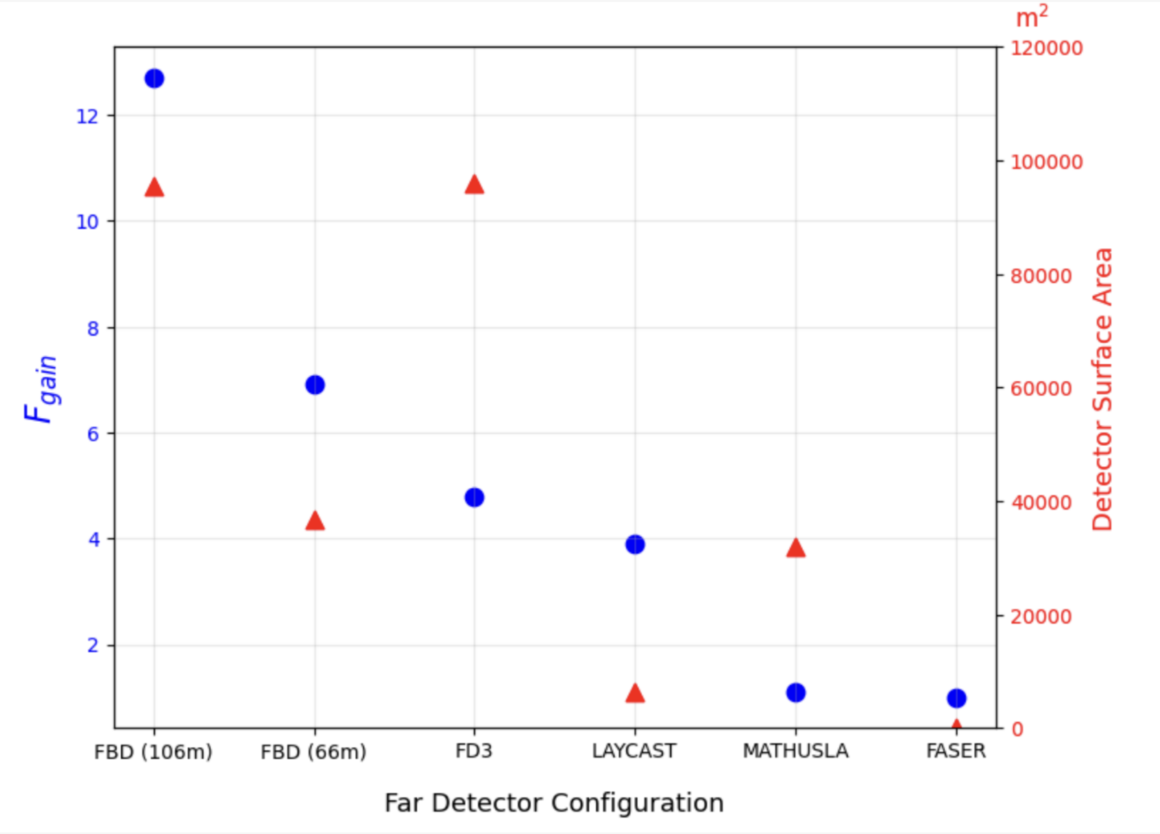


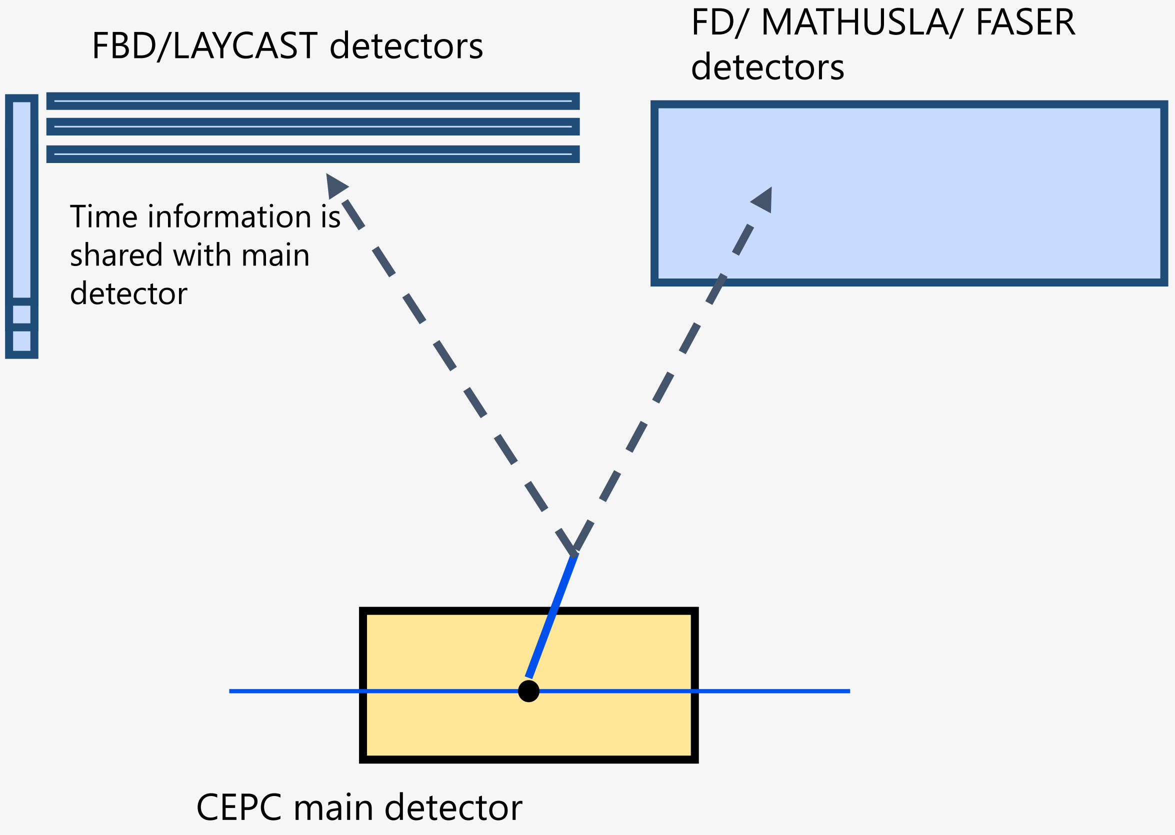
F_{gain}	Lifetime [ns]				
Mass [GeV]	0.001	0.1	1	10	100
1	1	1	2.8	9.9	13.7
10	1	1	1	2.9	10.1
50	1	1	1	1.1	3.3

Far Detector for Long-live Particle

Accepted by Chinese Physics C (2025), 2505.24810

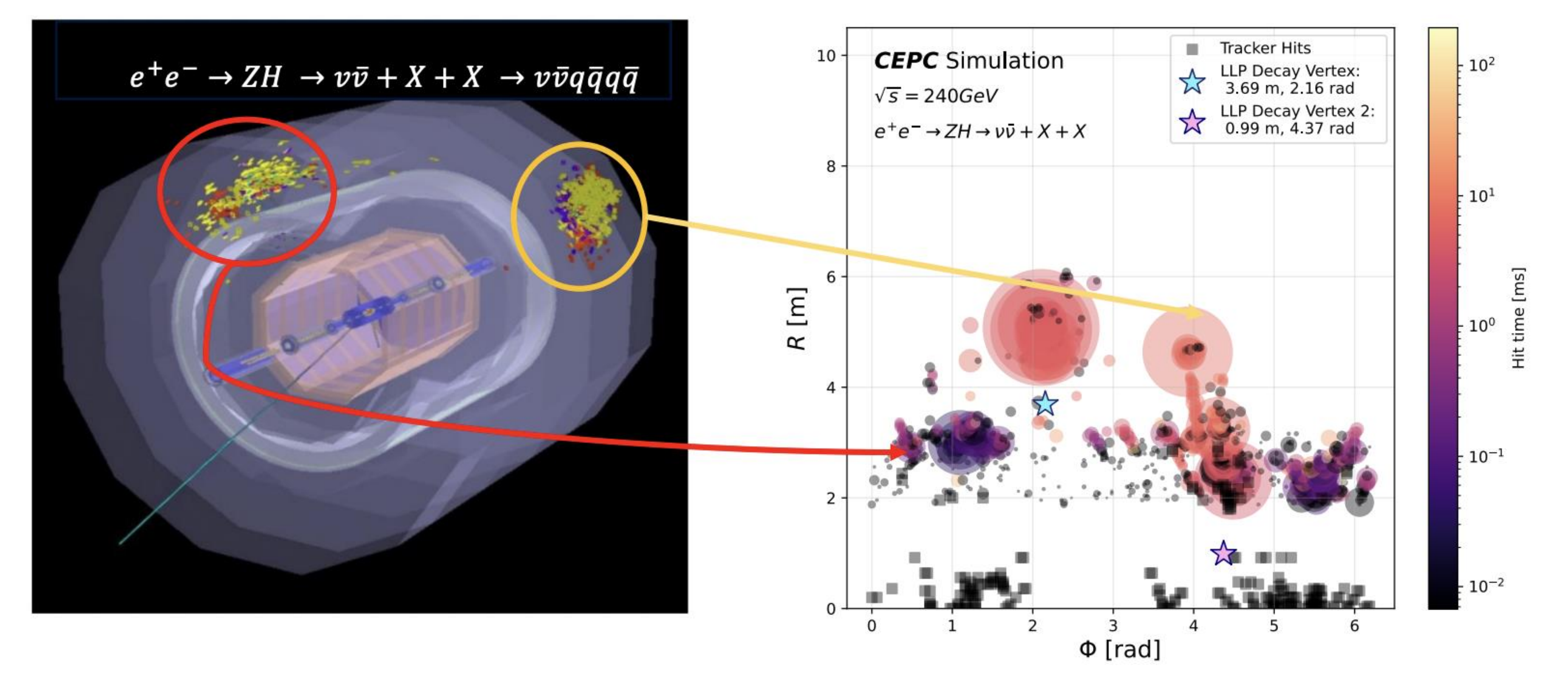
- Different type of the far detectors are compared. The cost is represented by the surface area
- Far barrel detector design has the best LLP gain factor of 13.7 due to good angular acceptance and combined detection with near detector sharing time information





CNN: ResNet

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

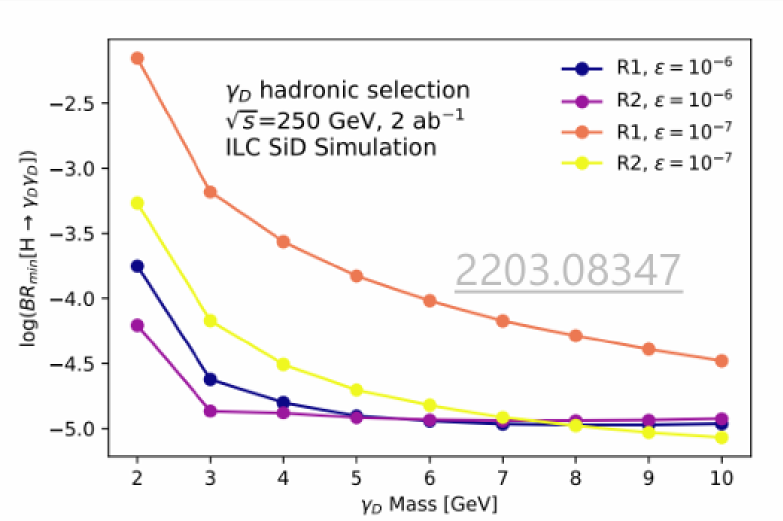


Cross Entropy Loss: $loss = -[\omega_0 * y_0 \log(x_0) + \omega_1 * y_1 \log(x_1) + \omega_2 * y_2 \log(x_2)]$

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

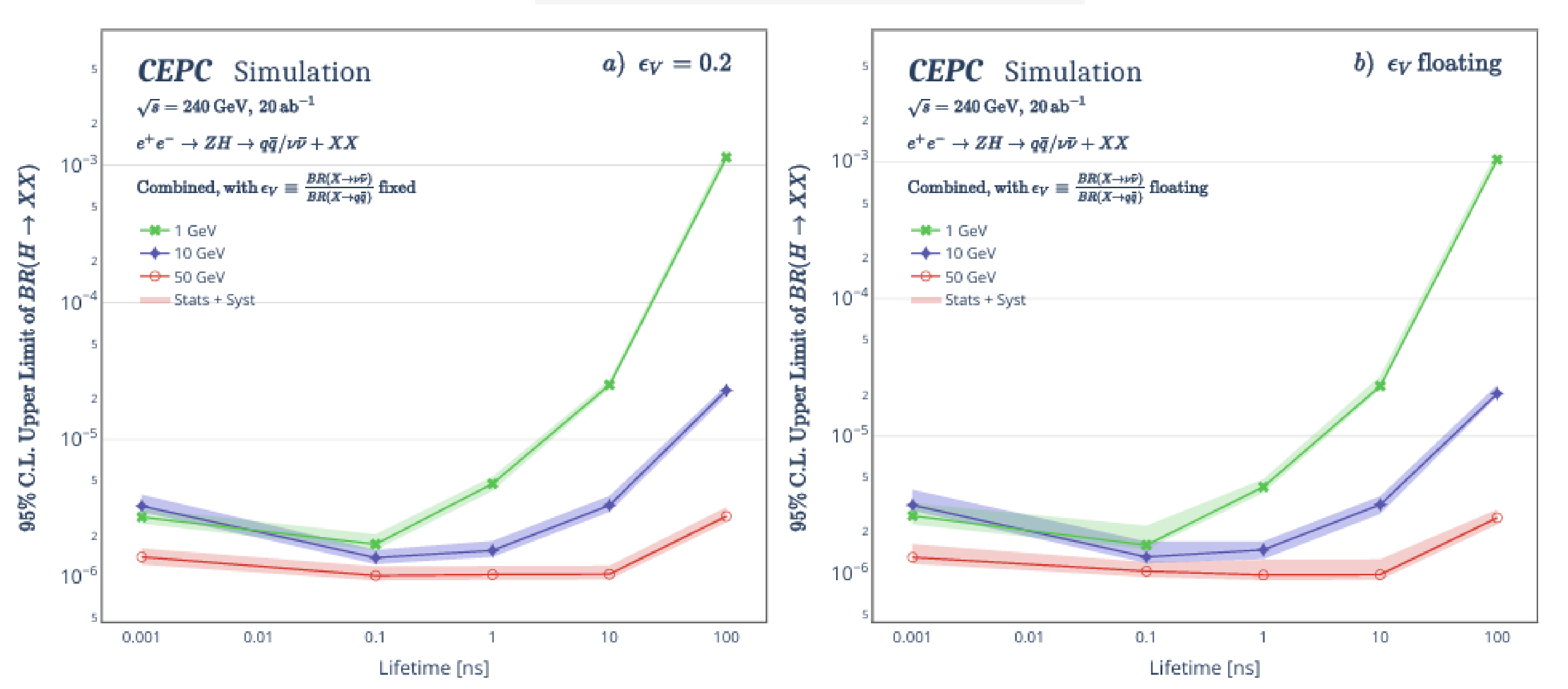
LLP Search Limits

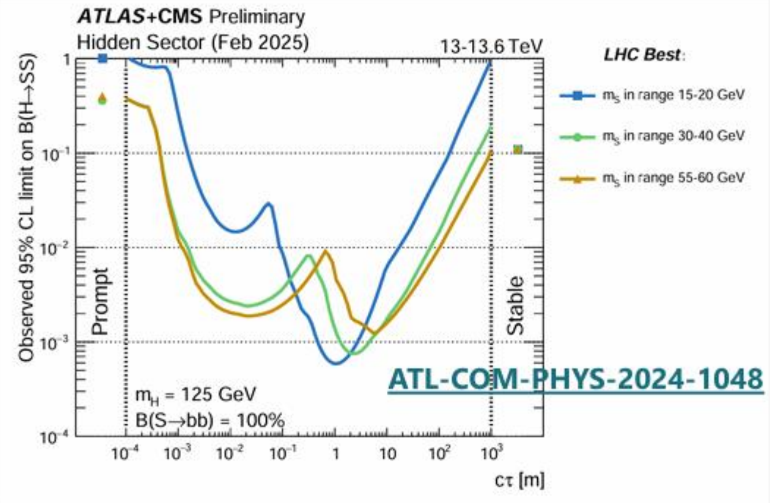
- The best expected limit of BR(H → XX) achieves 10^{-6}
- Outperforming the current limit from ATLAS and CMS by 2 - 3 orders of magnitude
- An order of magnitude better than the ILC's when the lifetime of LLP is over 1ns



ILC Best limit: ~10^{-5}

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





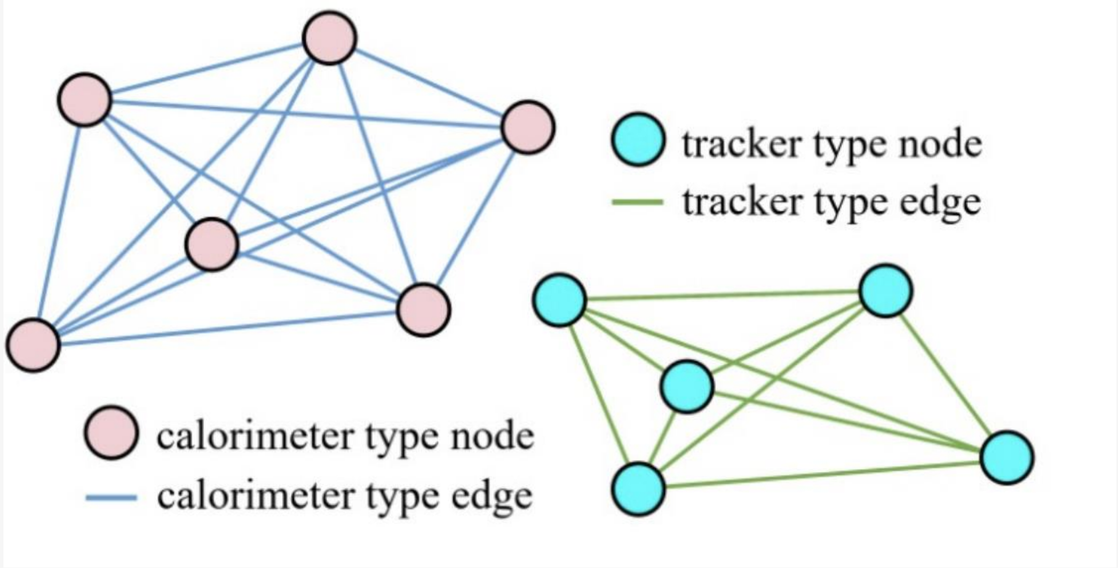
LHC Best limit: ~10^{-3}

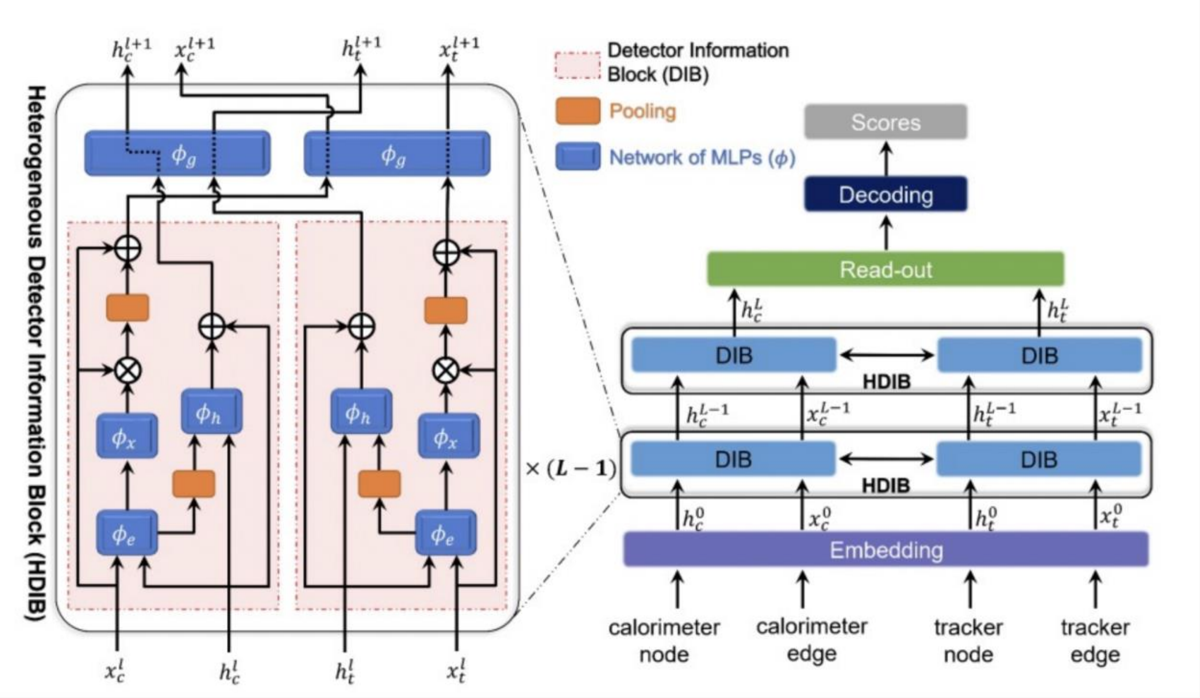
GNN

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

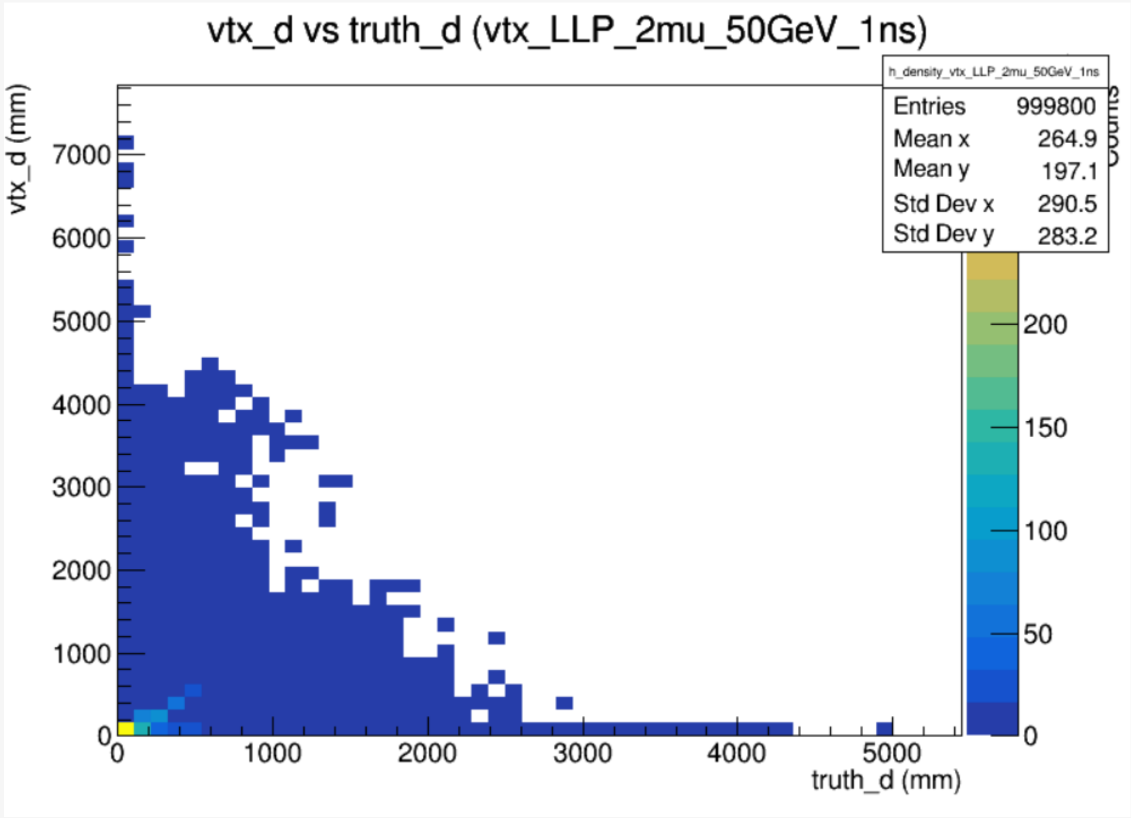
- Simple clustering is used to reduce graph complexity and extract the main information
- Nodes of the same detector type are interconnected comprehensively

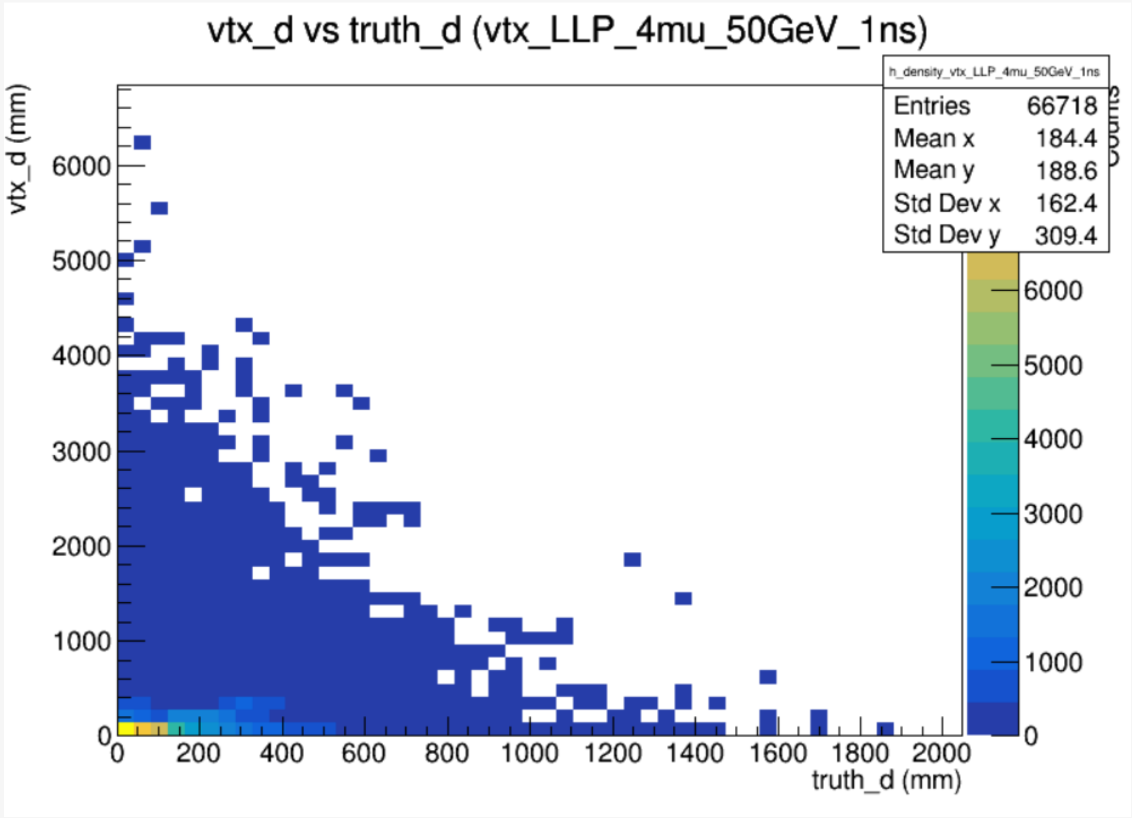
Features of nodes: calorimeter-type and tracker-type.
Features of edges: interaction between neighbor nodes





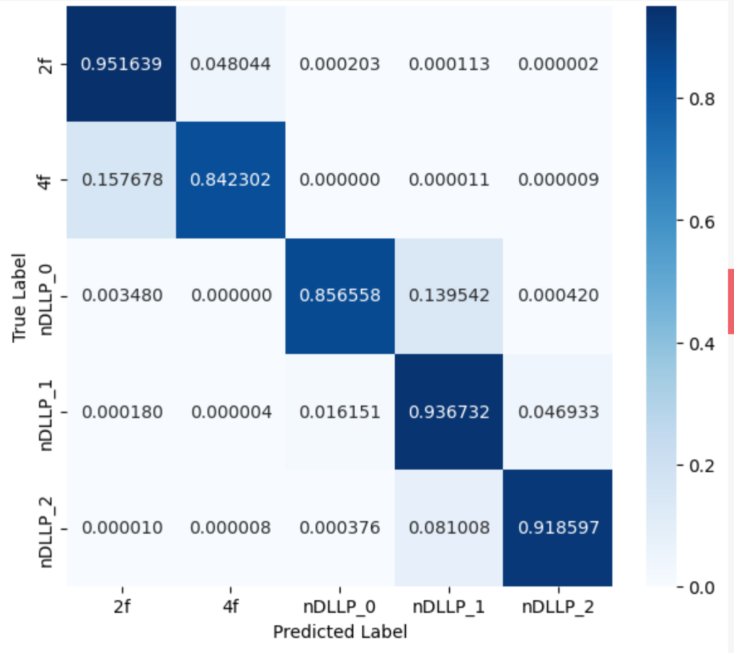
Vertex Rconstruction



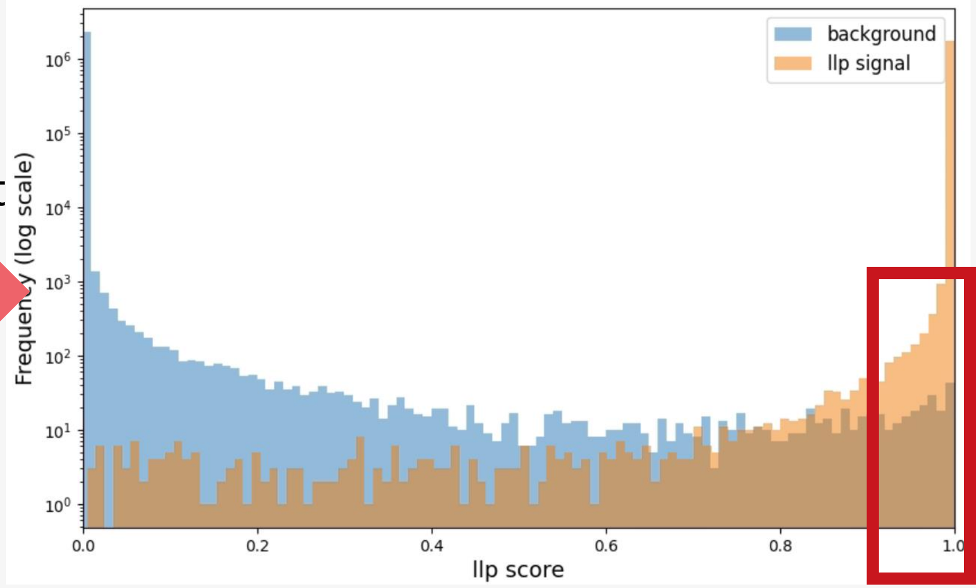


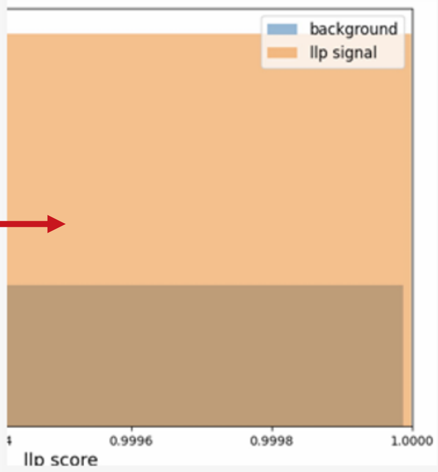
XGBoost?

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%

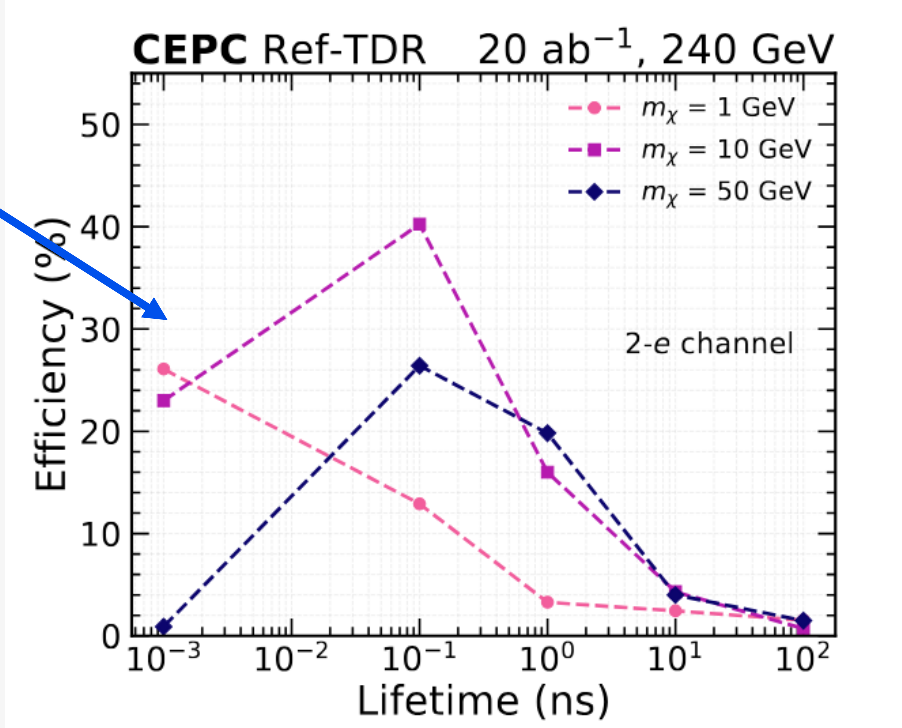
Background-free achieveable

Signal Efficiency with Selection Based Method

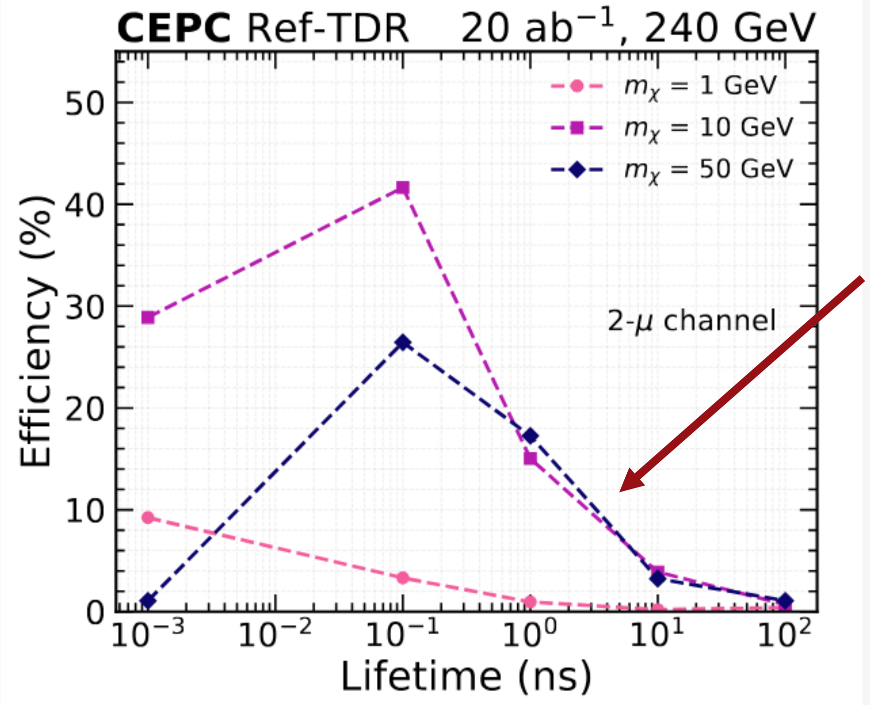
- The signal efficiency for dilepton channel reaches up to 40% in both channels at $m\chi$ = 10 GeV under background-free conditions

Lower efficiency in small lifetime: more prompt-like signals

LLP signal efficiency for 2-e channel



LLP signal efficiency for 2−μ channel



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

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