Searching for leptophilic composite asymmetric dark sector at e^+ e^- colliders

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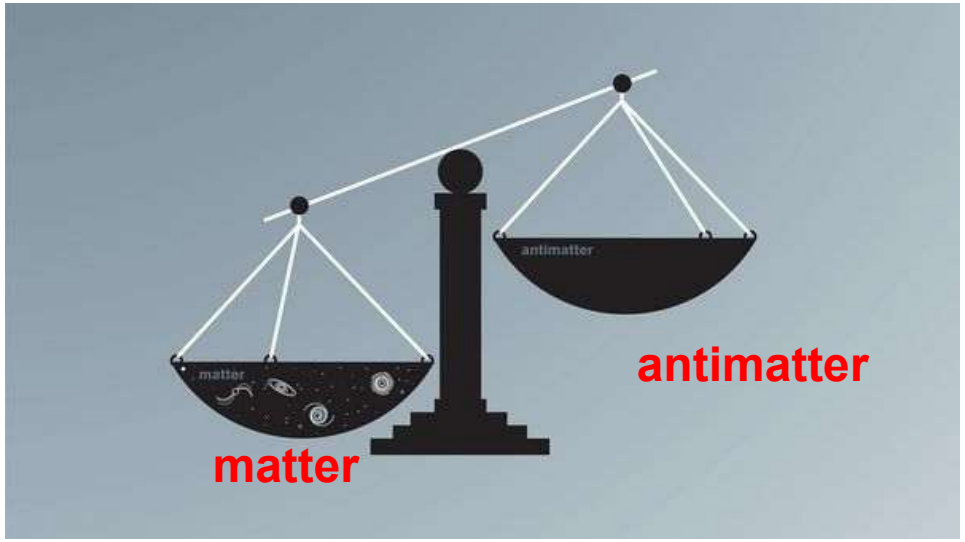
Reference: arXiv:2509.12504v1 [hep-ph] 15 Sep 2025

The 2025 International Workshop on the High Energy Circular Electron Positron Collider

Problem:
The particle nature of dark matter and the origin of matter-antimatter asymmetry



$$\eta(B) \equiv \frac{n_B - n_{\bar{B}}}{s} \simeq 10^{-10}$$

$$\Omega_{DM}/\Omega_B \approx 5$$

a common origin for both abundances

Composite ADM

Dark sector

bi-charged scalar mediator (X)

SM sector

baryophilic: dark quark← X → SM quark

leptophilic : dark quark ← X → SM lepton

Model and methods

coupling strength between q_d and leptons

$$\mathcal{L} \supset \overline{q_d}(i\not{D} - m_{q_d})q_d + (D_\mu X)^\dagger (D^\mu X) - m_X^2 X^\dagger X - \frac{1}{4} G^{d,\mu\nu} G^d_{\mu\nu} - (\kappa X \overline{q_d}_L l_R + \text{H.c.})$$

Integrating out the heavy mediator

$$D_\mu = \partial_\mu - i g_d G^d_\mu$$

g_d : SU(3)d gauge coupling
G^d_μ: dark gluon field

$$\mathcal{L}_{\text{dim-6}} \supset \frac{\kappa^2}{m_X^2} (\overline{q_d}_L \ell_R)(\overline{\ell_R} q_{dL})$$

dark pions decay into SM leptons

dark pion decay constant

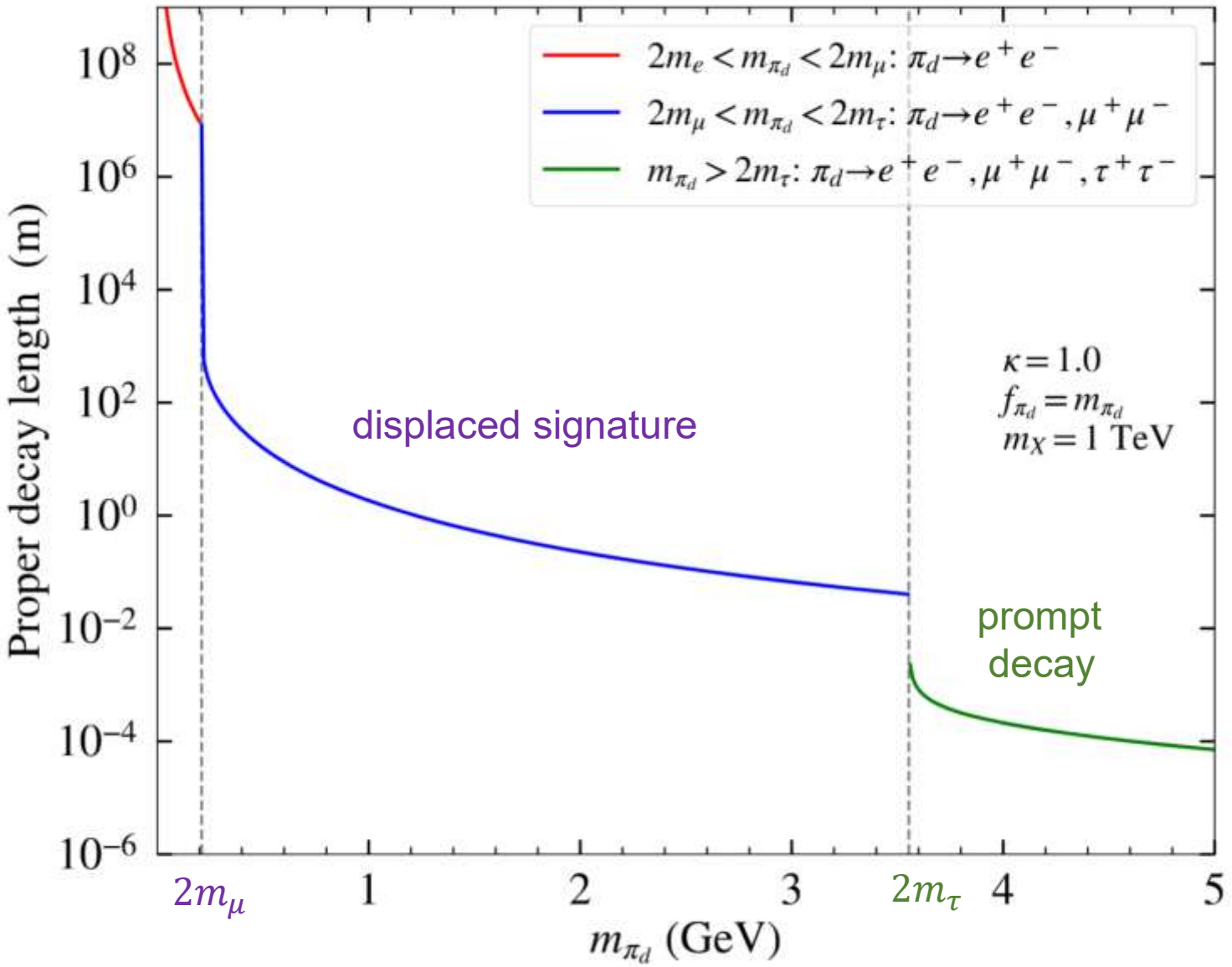
$$\Gamma(\pi_d \to \bar{\ell}\ell) = \frac{\kappa^4 f_{\pi_d}^2 m_\ell^2 m_{\pi_d}}{32\pi m_X^4}\sqrt{1-\frac{4m_\ell^2}{m_{\pi_d}^2}},$$

with $\ell = e, \mu, \tau.$

$$c\tau_0 = \frac{c\hbar}{\Gamma_{\pi_d}}$$

For different $m_{\pi d}$,
we focus on the two ranges :
$2m_e < m_{\pi d} < 2m_\mu$ and
$2m_\mu < m_{\pi d} < 2m_\tau$

invisible final states

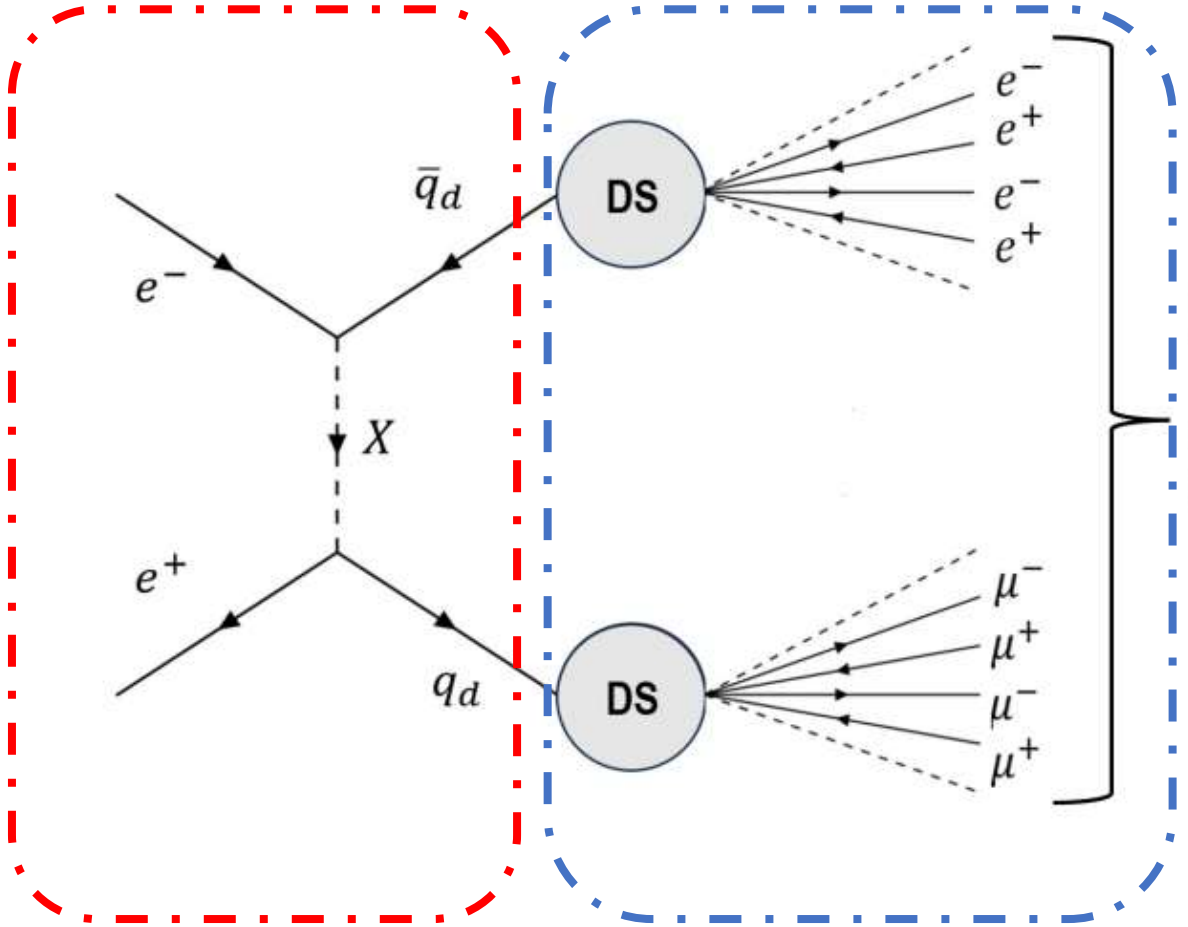


Specific process Feynman diagram and simulation method

Madgraph5

hard process
through t-channel:

$$e^+ e^- \rightarrow q_d \overline{q_d}$$

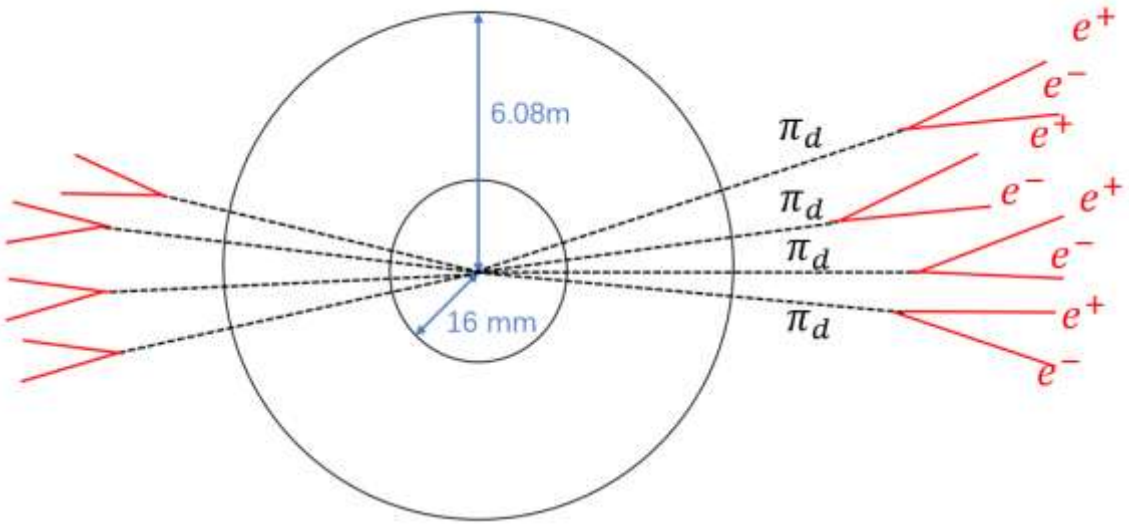


Pythia8 HV module:

showring, hadronization
and dark mesons decay

The mono-photon signature

For $2m_e < m_{\pi d} < 2m_\mu$: The llps decay into electrons and almost all of them fly out of the detector, leaving missing energy.



CEPC detector range

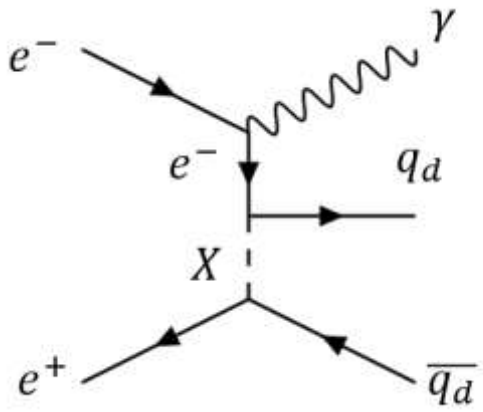
very long-lived

↓

invisible lepton jets

↓

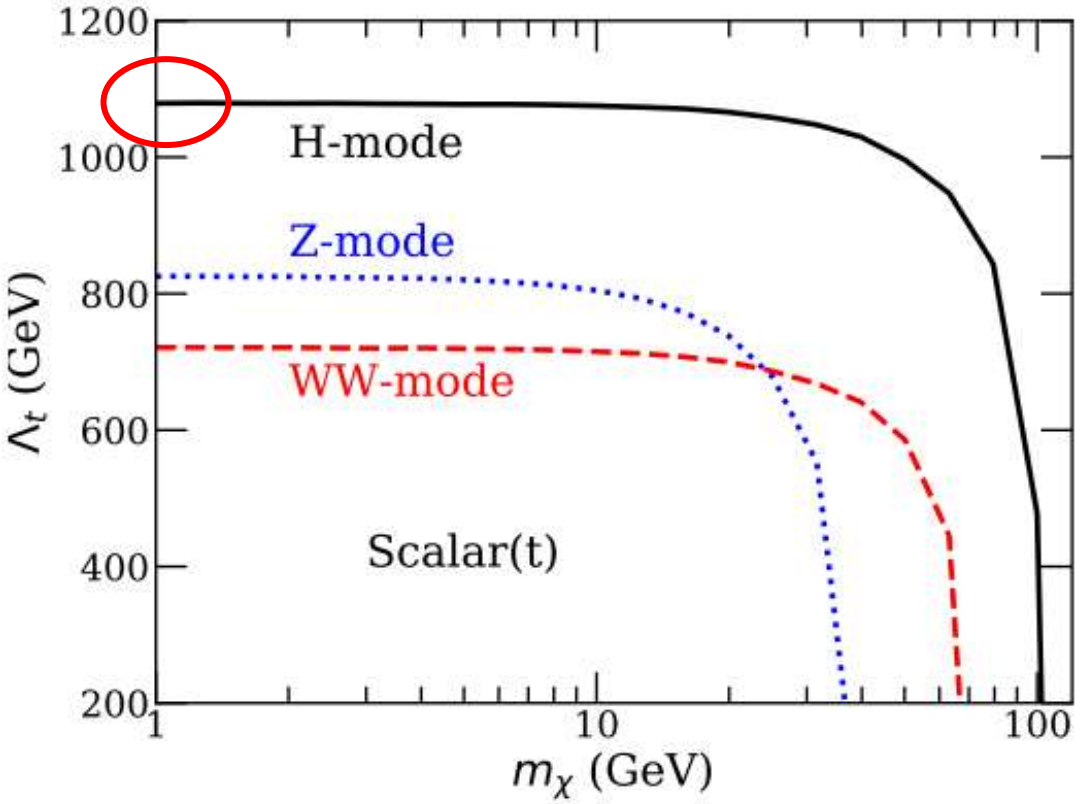
search by a ISR photon

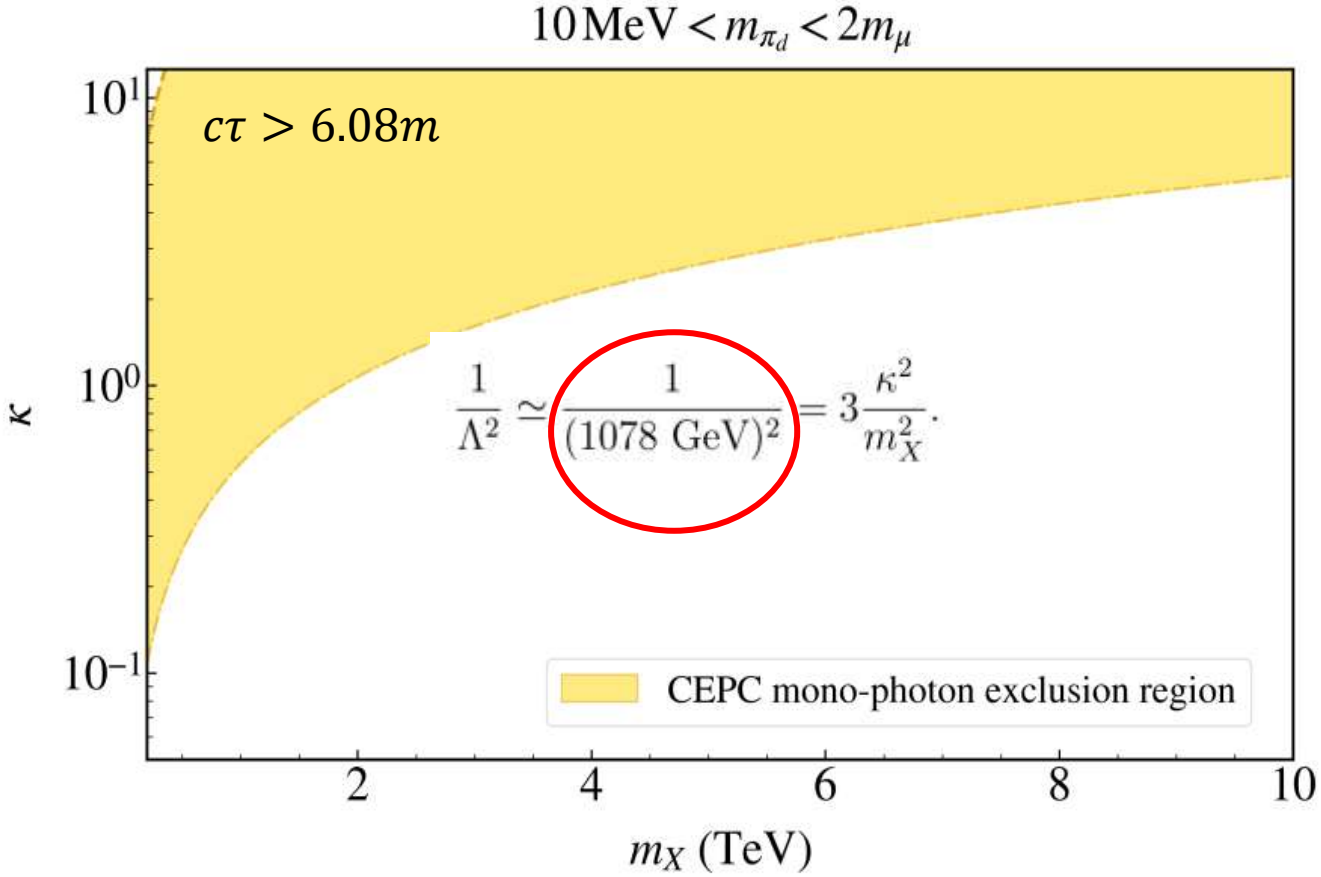


The mono-photon signature

$H-mode$: $\sqrt{s}=240\ GeV$
$L=5.6\ ab^{-1}$

$$\mathcal{L}=\frac{1}{\Lambda_t^2}\bar{\chi}\ell\bar{\ell}\chi$$





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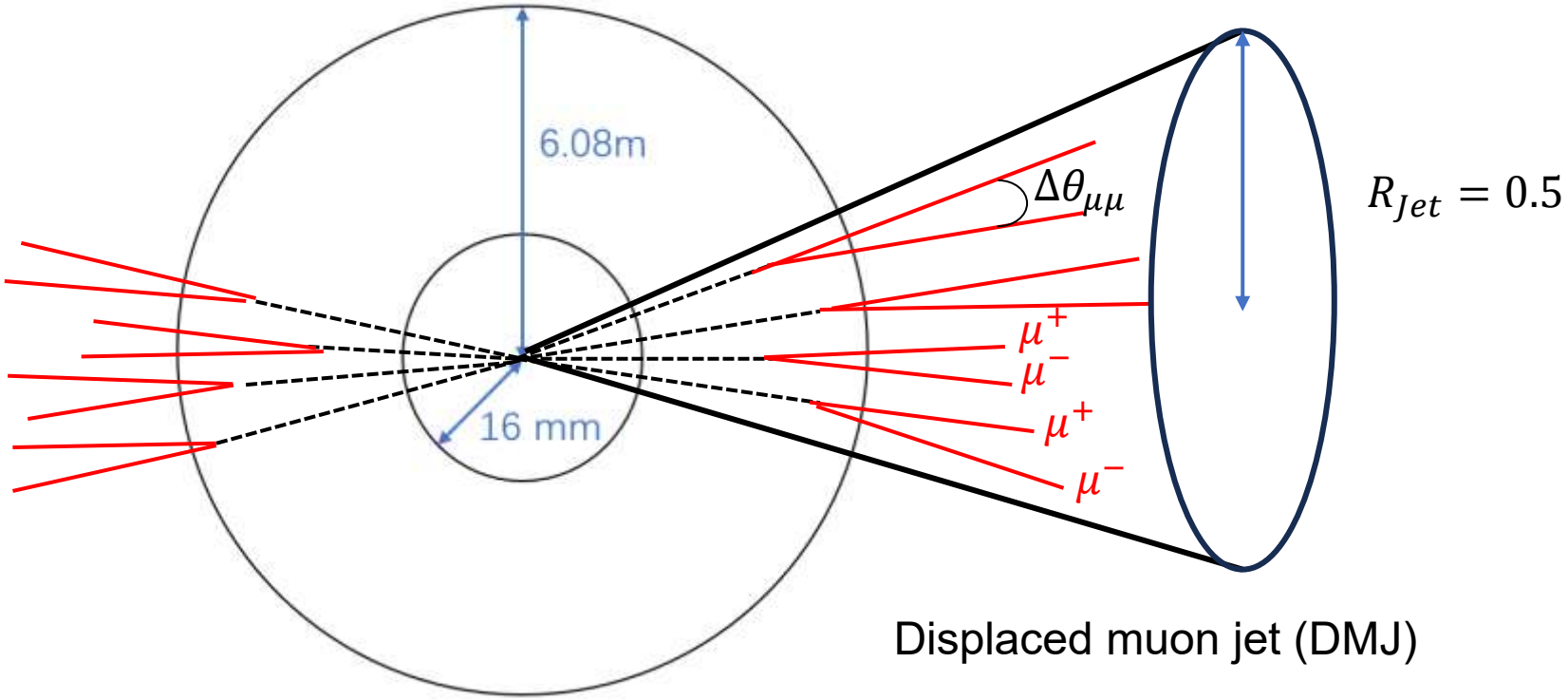
The displaced muon jet signature

For $2m_\mu < m_{\pi d} < 2m_\tau$: π_d decay in the detector and produce plenty of displaced muons



Displaced muon jet (DMJ)

Signal events :events with at least **2** DMJs

background free!

$$N_S = L * \sigma * \epsilon = 3$$

DMJ definition:

select muons:

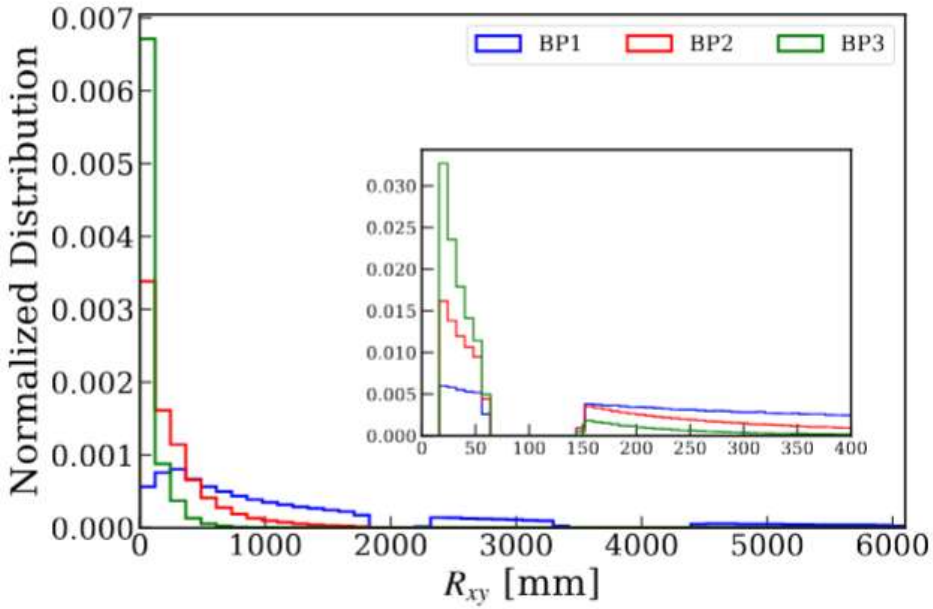
1. pT (μ) > 1 GeV and $|\eta_\mu| < 3.0$
2. $\Delta\theta > 0.02$ rad
3. mother particle (π_d) decays in the detector region

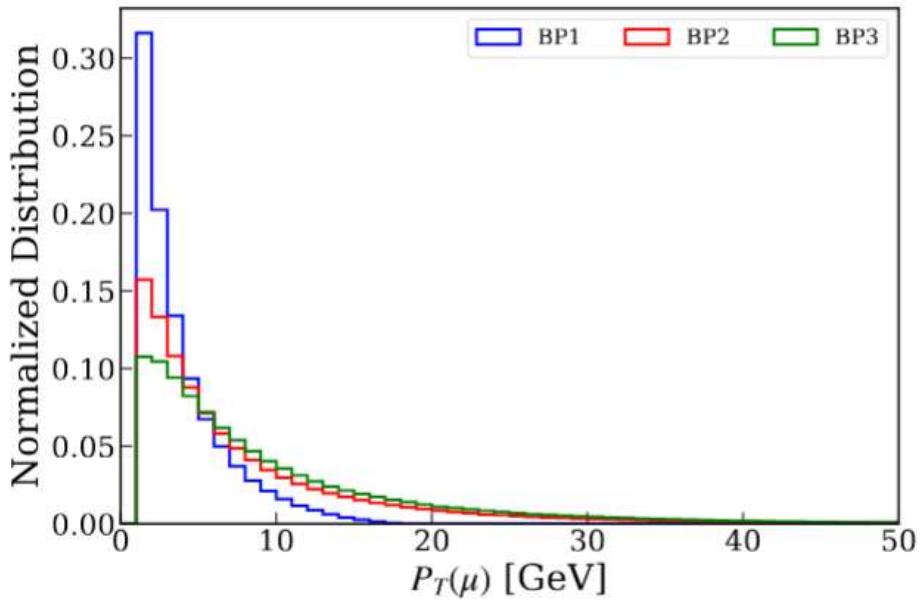
clusting:

FASTJET
anti-kt algorithm
$R_{Jet} = 0.5$

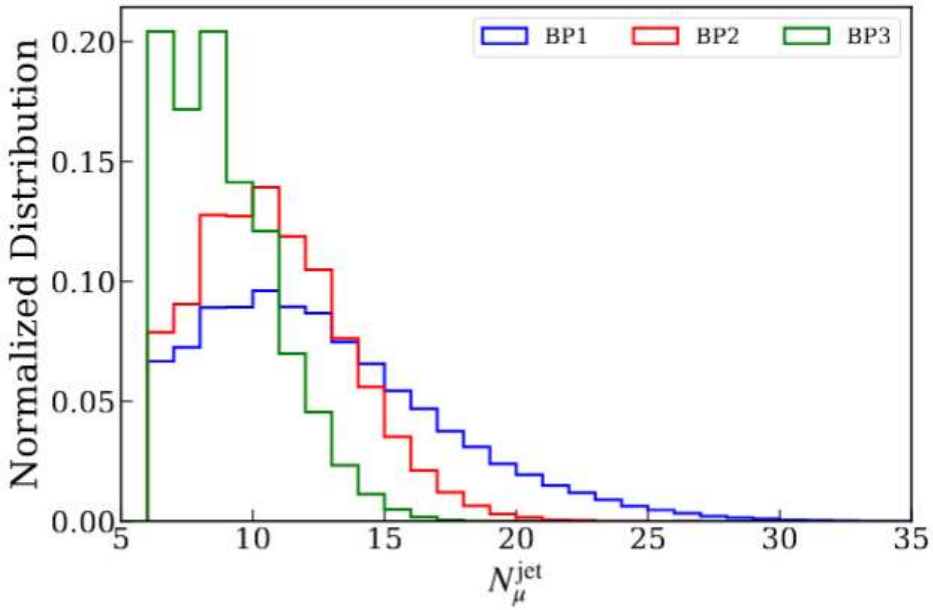
A jet with more than **6** muons is defined as a DMJ.

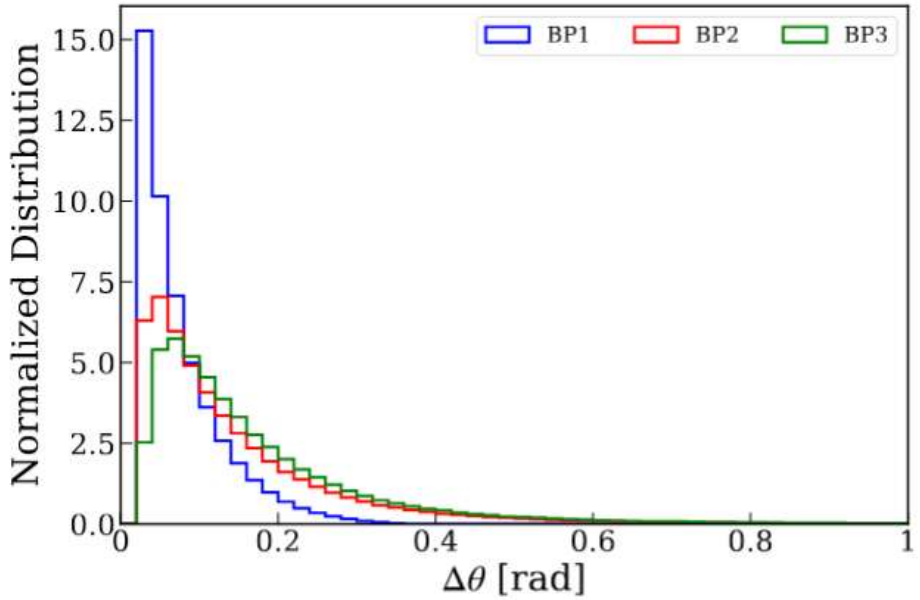
Distribution of observable kinematic variables



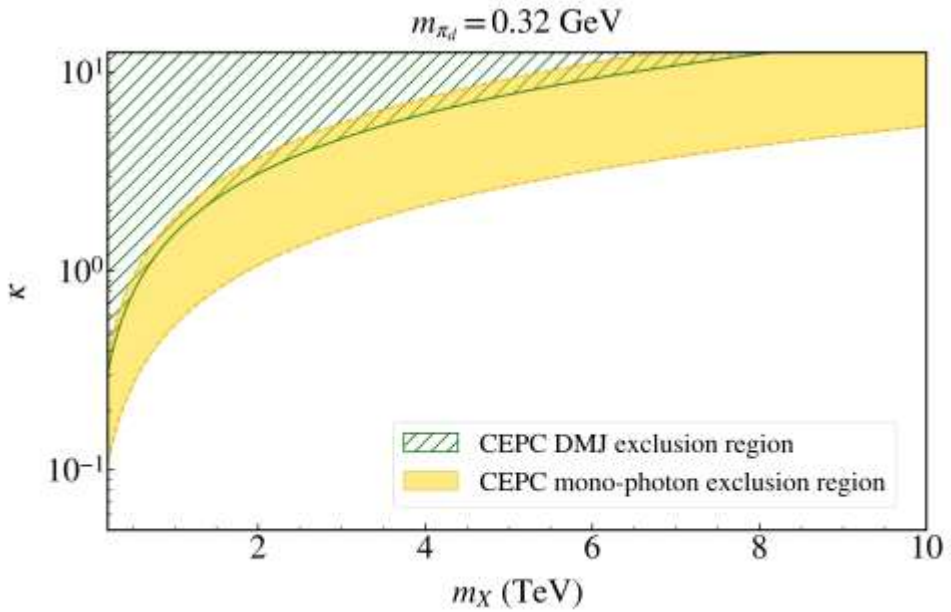


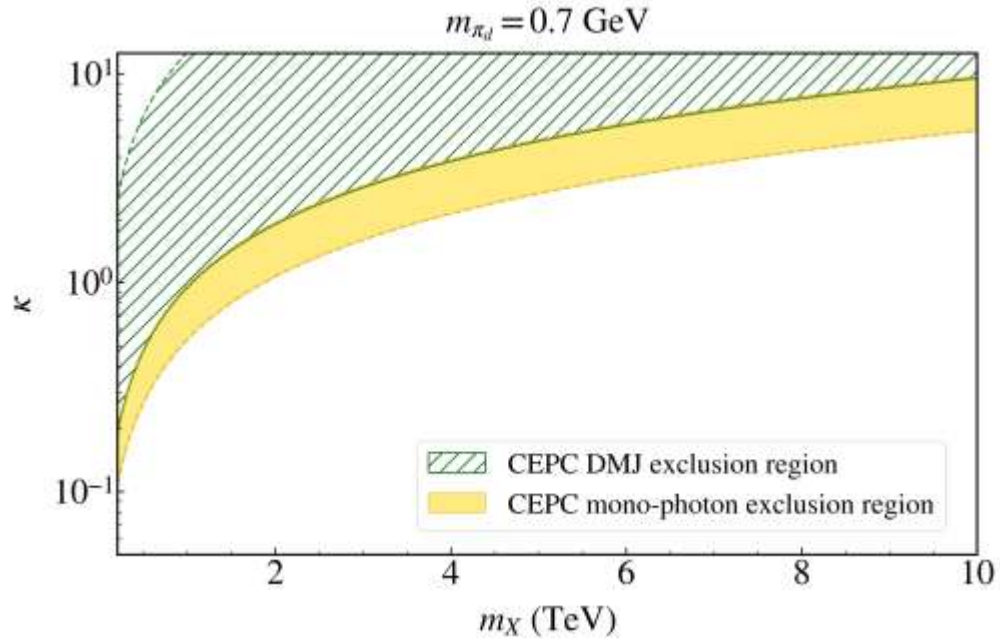
BP1: $m_{\pi d} = 0.32\ GeV$
BP2: $m_{\pi d} = 0.7\ GeV$
BP3 : $m_{\pi d} = 1.0\ GeV$

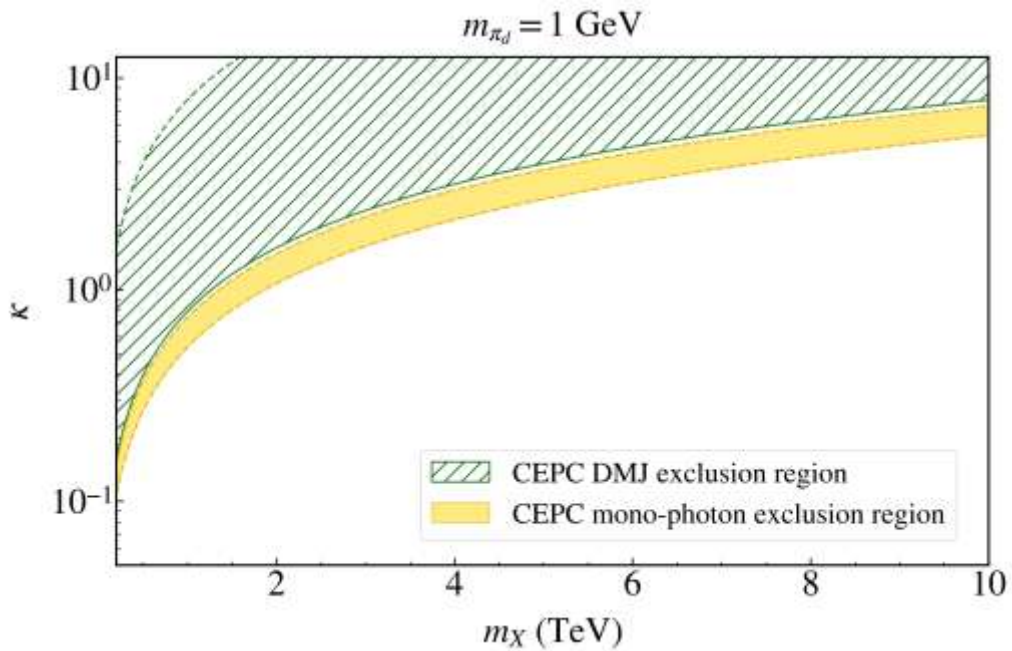




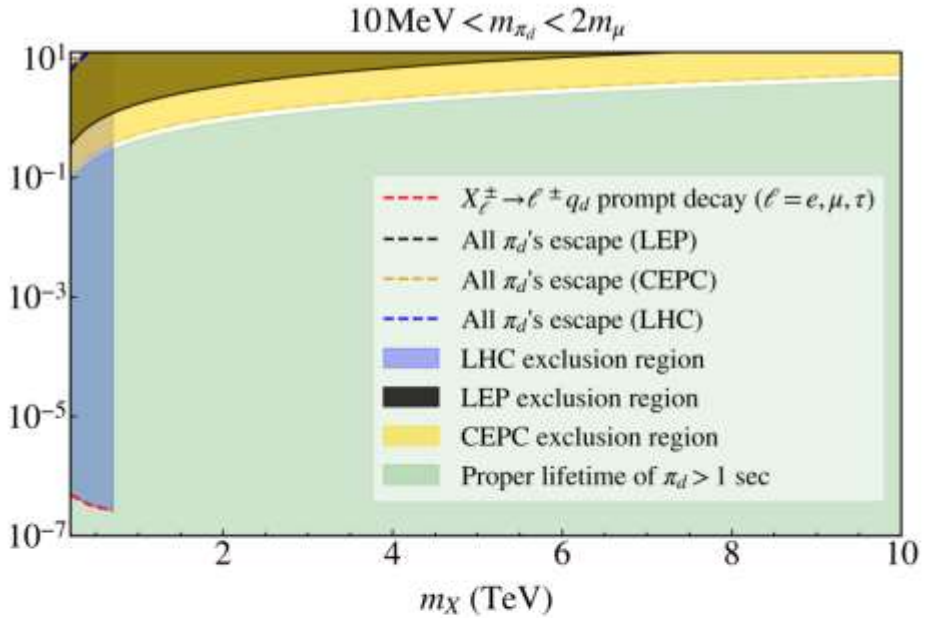
Results for 3 BPs in $2m_\mu < m_{\pi d} < 2m_\tau$

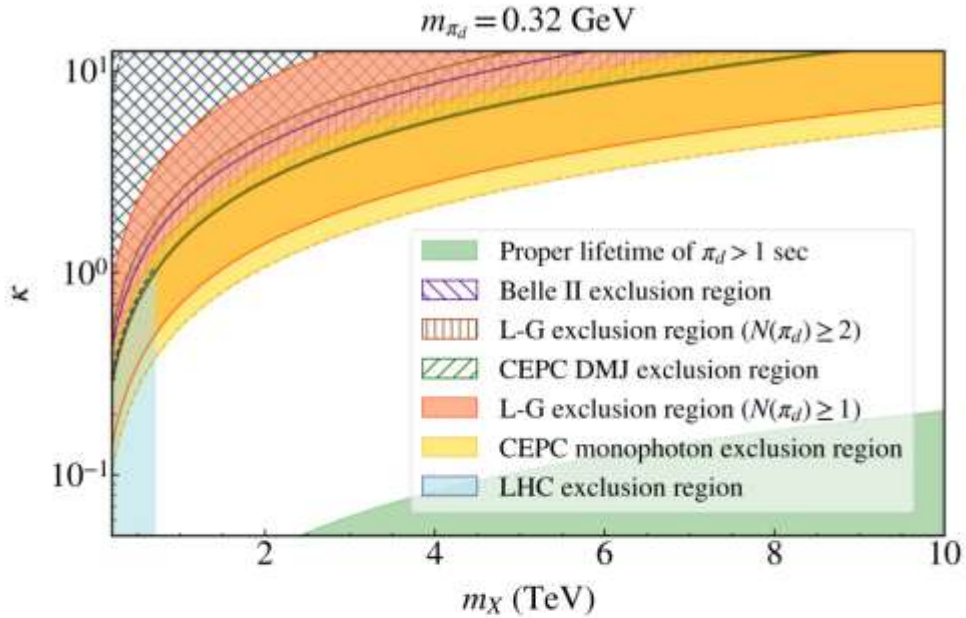


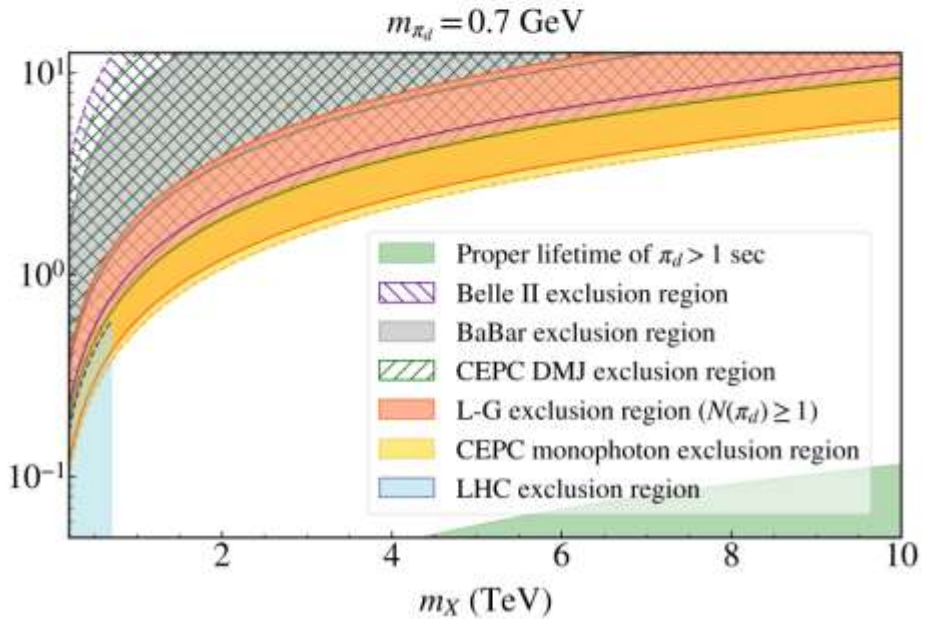


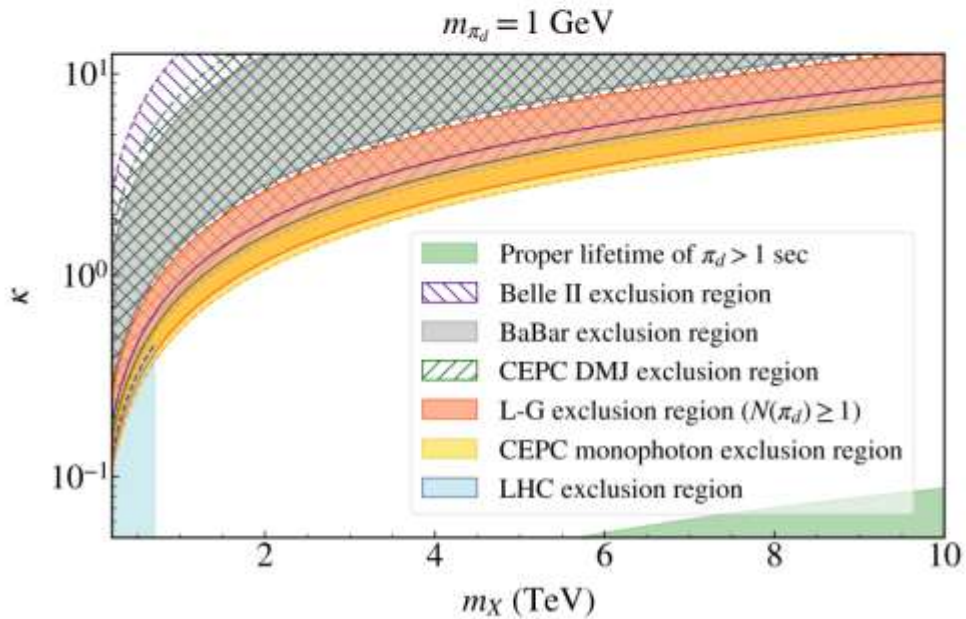


Results and Discussion









Summary and Outlook

- We concentrate on H-factory **CEPC** studies, using the mono-photon search for invisible final states and the displaced muon jet strategy for displaced signals. The two approaches are complementary and can exclude large-κ regions for mediator masses up to 10 TeV.

- We compare the exclusion reaches of **CEPC**, **LHC**, **LEP**, **BaBar**, **Belle II**, and the **Gazelle** (far detector), showing complementarity among different experiments.

- **Future research directions:**

① Probing mediator production via the Drell–Yan process at the **Muon Collider**.
② Developing dedicated strategies to maintain sensitivity for $m_{\pi_d} > 2m_{\tau}$.

Thank you
for your attention