HPNP2025

The 7th International Workshop on
"Higgs as a Probe of New Physics 2025"

Prospects on the minimal 5D U(1) Lμ-Lτ : Power of DUNE near detector

Kenji Nishiwaki

(केंजी निशिवाकि ← Kenđi Nishiwaki ←
니시와키 겐지← केंजी निशिवाकि← 西脇 健二)

Based on works with Dibyendu Chakraborty, Arindam Chatterjee and Ayushi Kaushik,

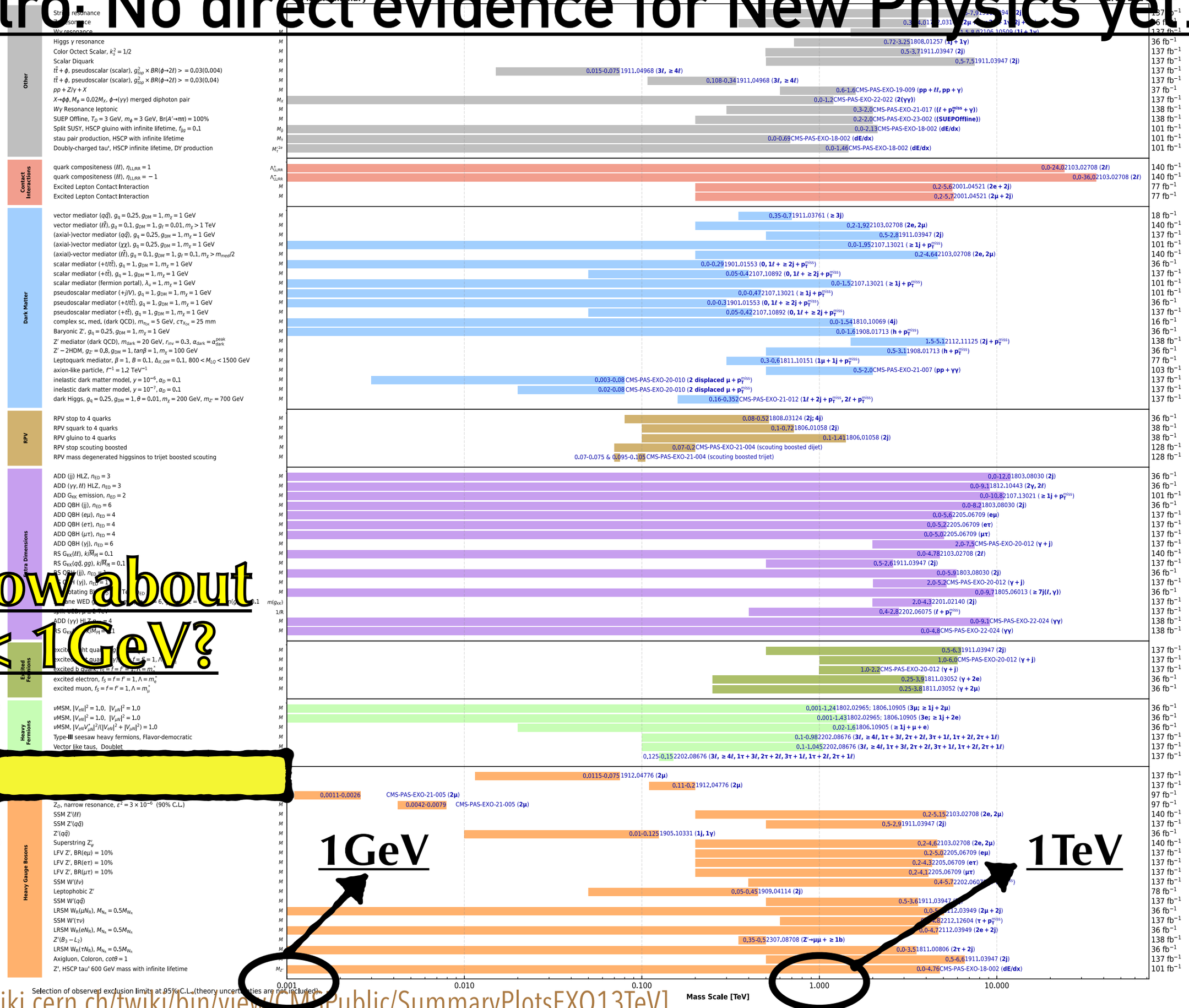
Phys. Rev. D110 (2024) 9, 095030 [arXiv:2407.20615]

SHIV NADAR
INSTITUTION OF EMINENCE DEEMED TO BE UNIVERSITY
DELHI NCR

Talk @ HPNP2025, 13 June 2025 [Fri]

大阪大学
THE UNIVERSITY OF OSAKA

Intro. No direct evidence for New Physics yet...



How about ≤1GeV?

1GeV

1TeV

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

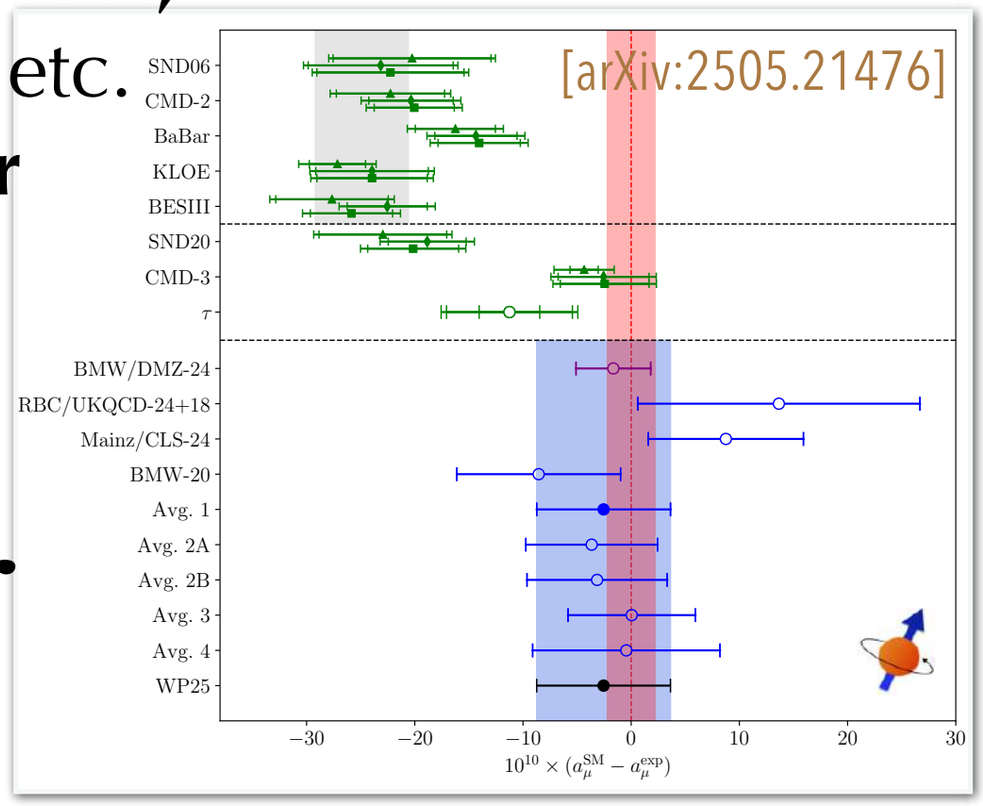
[https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV]

Intro: Very weakly coupled Sub-GeV BSM

→ typically <~ 10^{-4} - 10^{-3}

[Motivation]

- **Less explored,** sensitive to many leptonic/hadronic processes.
- **Connection to the early stage of the Universe;**
  Neutrino N_{eff}, Big Bang Nucleosynthesis, etc.
- **Mediator for Sub-GeV WIMP dark matter**
- ~~Addressing muon (g-2) anomaly (?)~~

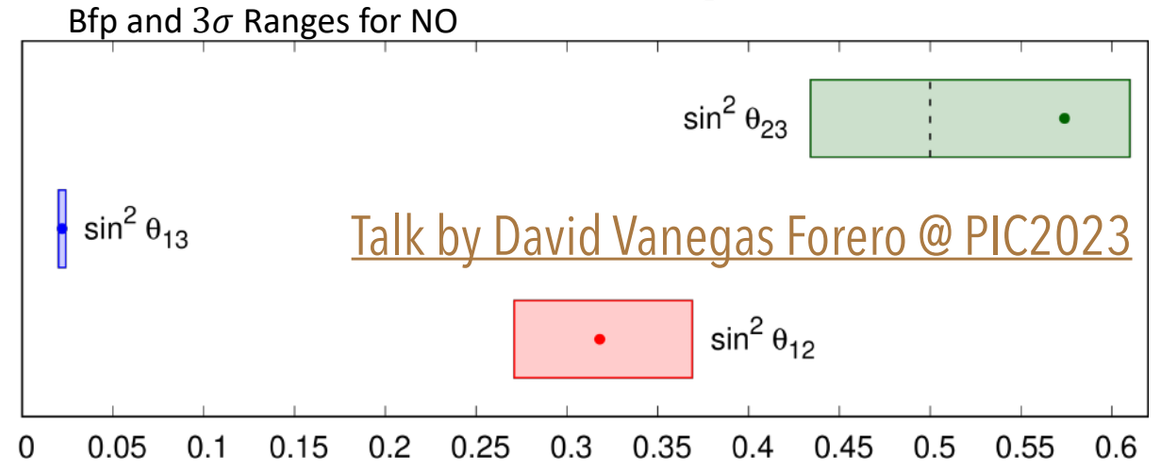


[Bosonic Candidates]

- Pesudoscalar: axion-like particle:
  new global symmetry.
- **Vector: new gauge boson:**
  new gauge symmetry ⇐ our focus.

Intro: Something in the lepton sectors?

- **Great experimental updates** are associated with the **lepton sector**.
  ⇒ We will focus on it.

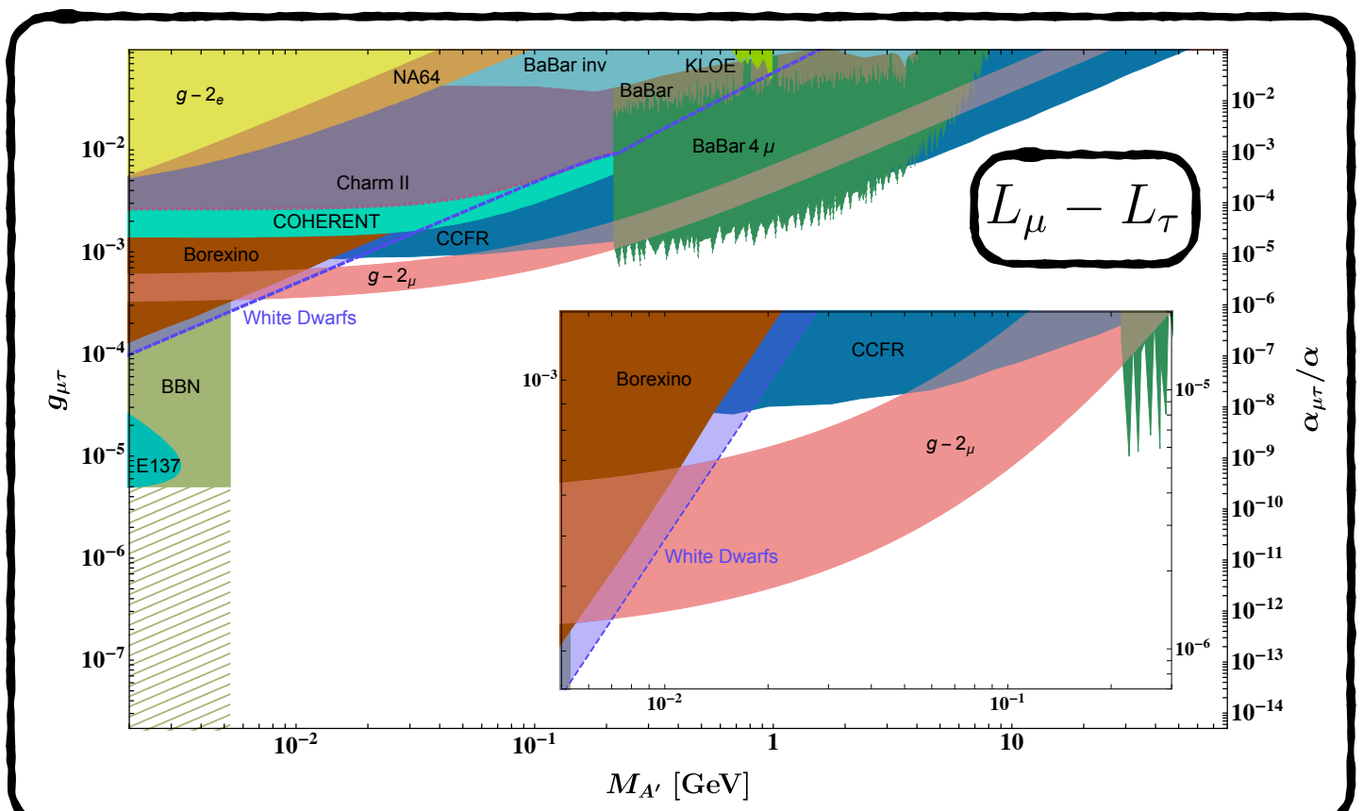


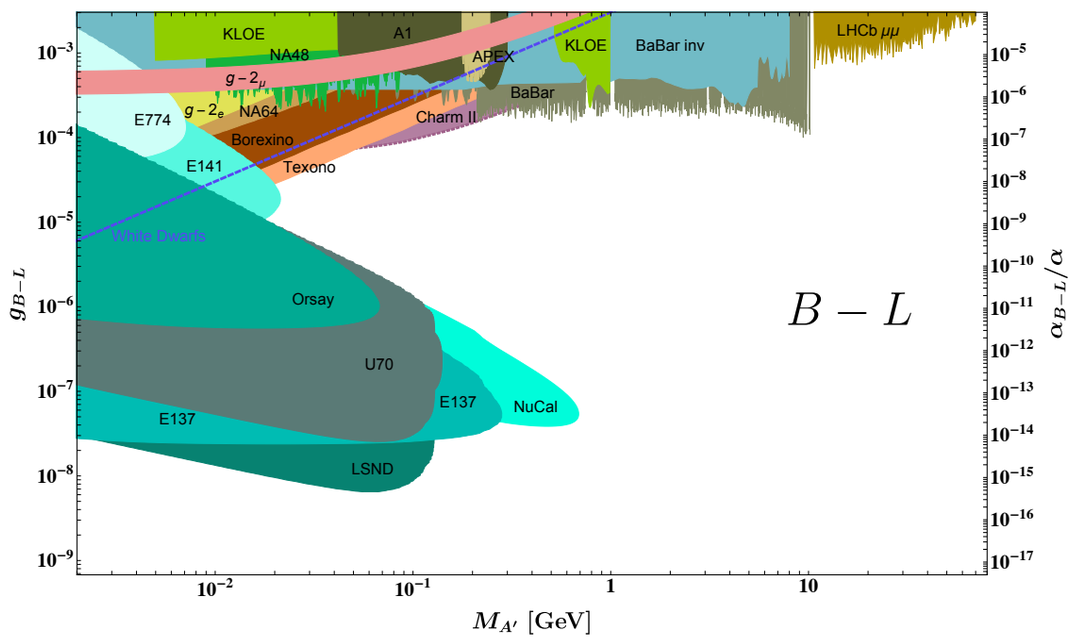
- A good candidate:
  L_μ-L_τ gauge interaction.

[R.Foot, Mod. Phys. Lett. A6 (1991) 527]
[X.G.He et al., Phys. Rev. D43 (1991) 22]
[X.G.He et al., Phys. Rev. D44 (1991) 2118]
[R.Foot et al., Phys. Rev. D50 (1994) 4571]

anomaly free

Gauge Group	(Q_L^i, u_R^i, d_R^i)	(L_L^e, e_R)	(L_L^μ, μ_R)	(L_L^τ, τ_R)	ϕ_h
$U(1)_{L_\mu - L_\tau}$	0	0	1	-1	0





[M.Bauer et al., 1803.05466]

Intro: Something in the lepton sectors?

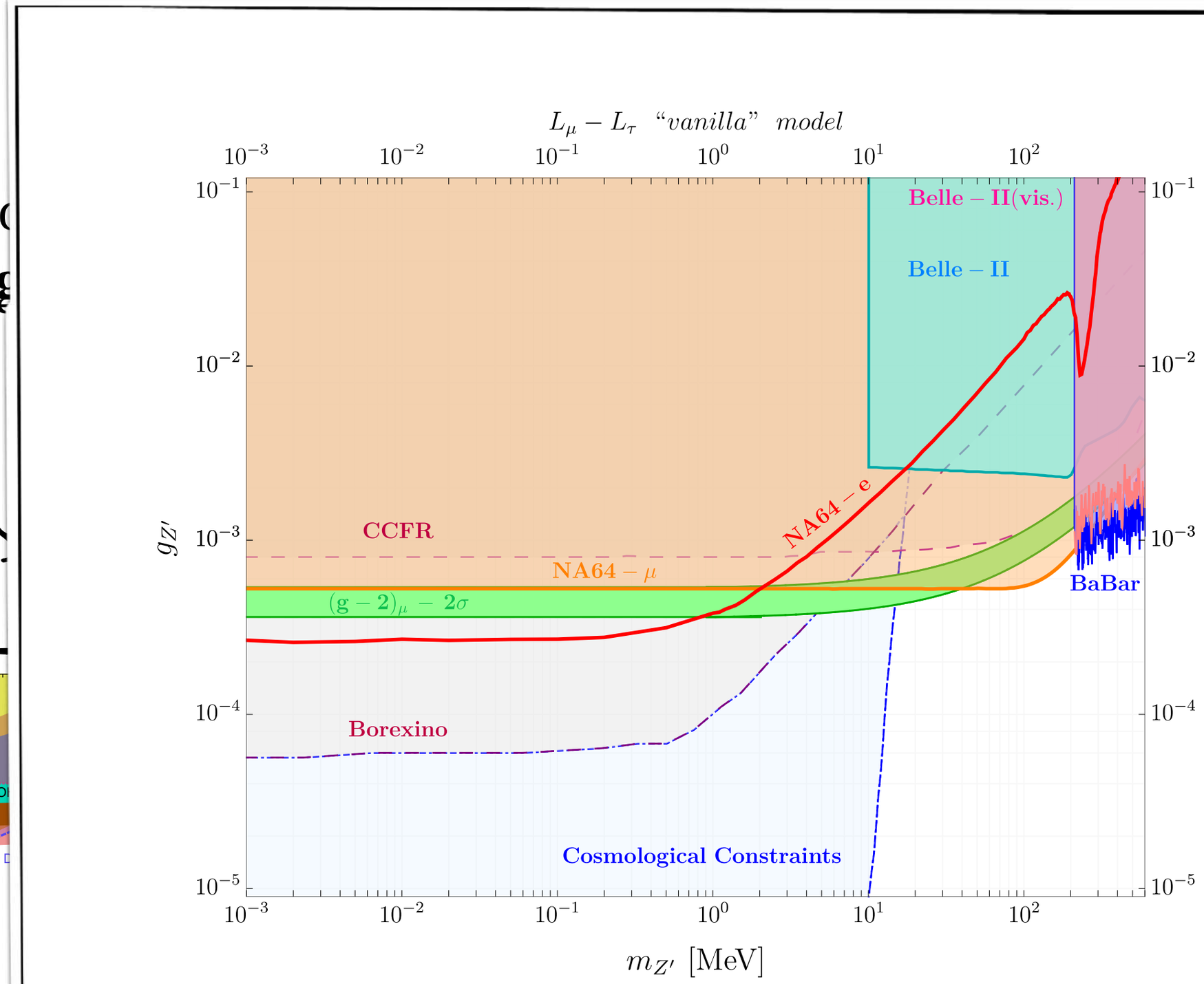
- **Great** …ctor.

  ⇒ We …

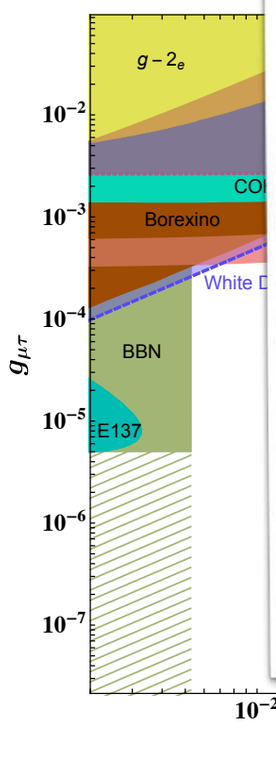
- A gooc…

L_μ-L_τ g…

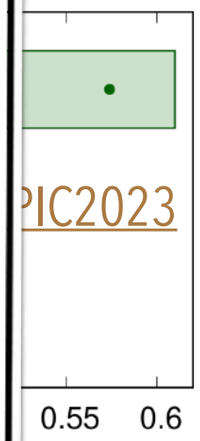
anomaly free

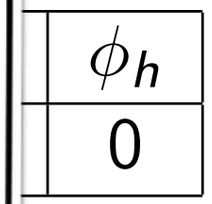


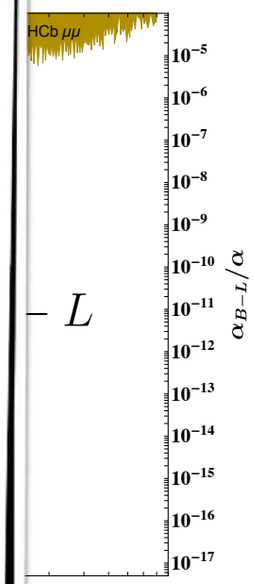
[Yu. M. Andreev et al.., 2404.06982]



[M.Bauer et al., 1803.05466]







Intro: A sketch of a 5D extension

Dark Matter

Standard Model Particles

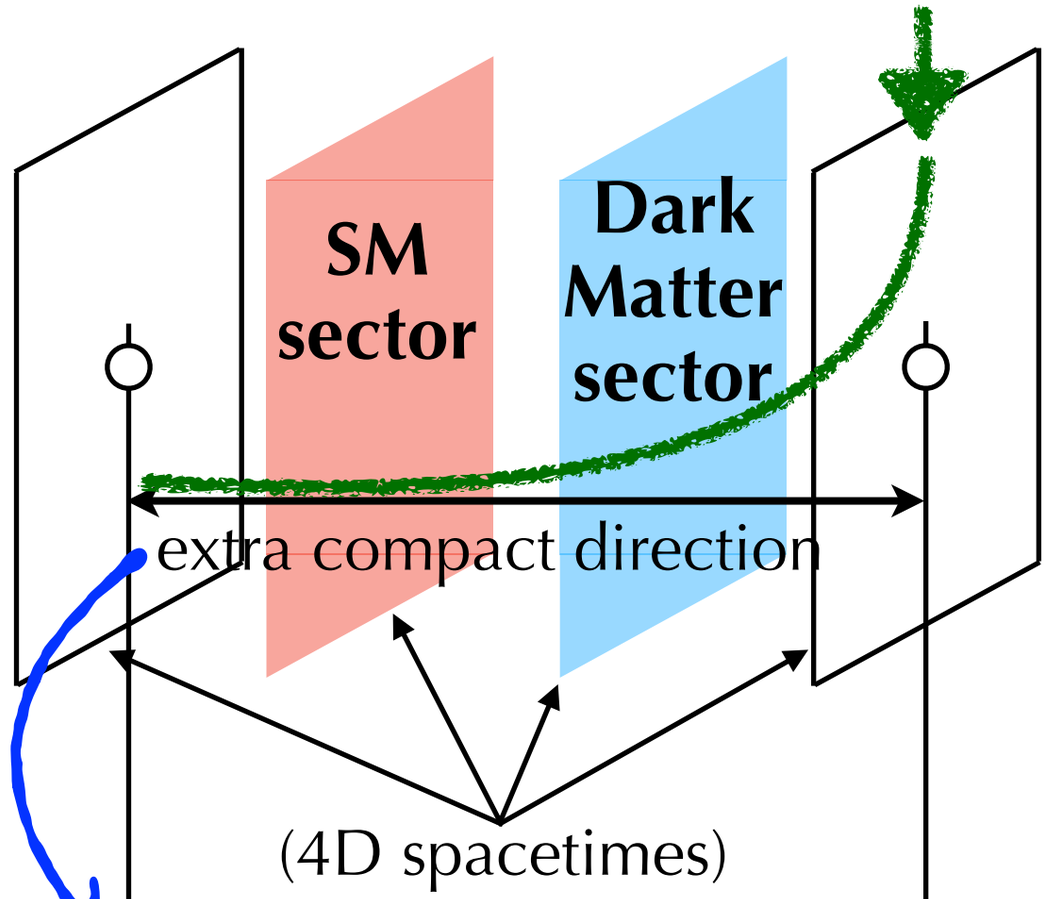
Right-hand Neutrinos

Force Mediator

SM Higgs scalar

An ordinary 4D scenario

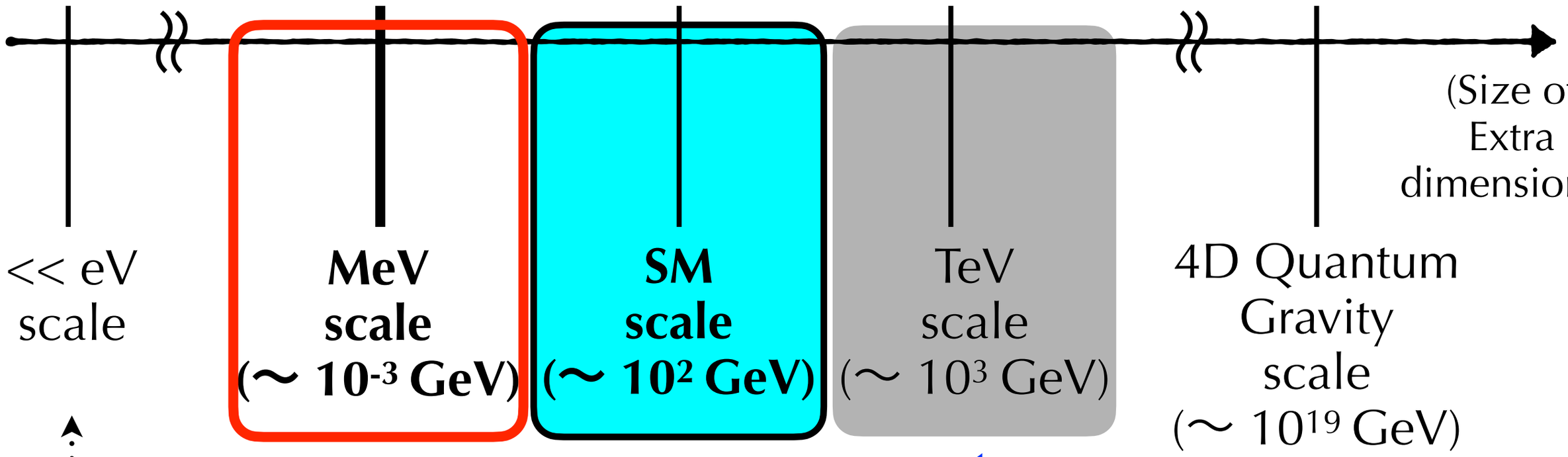
A 5D right-hand neutrino can naturally have a tiny overlap with the SM sector (⇒ a tiny coupling).



Multiple Mediators (4D gauge bosons)

A simple 5D extension

Intro: Size of (Extra dimension)$^{-1}$



Small couplings
⇒ Consistent with experiments

⇒ Uncharted interesting domain!

(Gravitational)

⇒ Simple extensions were disfavoured by the LHC.

no sizable communication (due to the large separation)

Table of Contents

1. Introduction: Why do we consider 5D MeV-scale U(1) L_μ-L_τ? [5 pages]

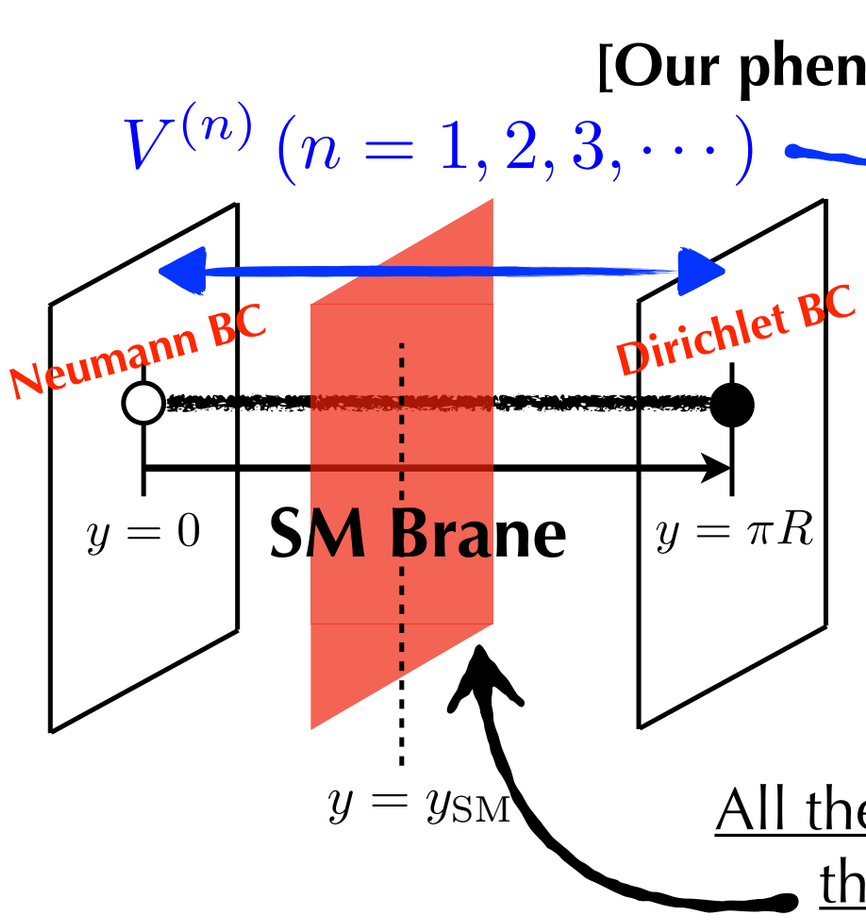
NEXT

2. νe channel in vanilla 5D U(1) L_μ-L_τ [4+1 pages]
   → many experiments → No neutrino/DM extension
3. Results for the flat case [3 pages]

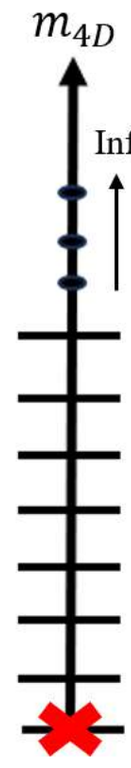
4D → 5D U(1)-(L_μ-L_τ) interaction

- To consider a simple generalisation, 4D → **5D** U(1)-(L_μ-L_τ), looks vaild:
  - ✓ **Multiple** gauge bosons contribute to physics.

[Our phenomenological Setup]



Fourier-series expansion



[5D U(1)-(L_μ-L_τ) gauge boson living in the full (4+1) spacetime]

⇔

[Infinite number of 4D gauge bosons, called Kaluza-Klein particles]

All the SM particles are confined within the (3+1)-subspacetime (brane).

Twisted BCs → No massless mode

Effective 4D Lagrangian includes kinetic mixings

[T.G.Rizzo, 1801.08525]
[K.L.McDonald, D.E.Morrissey, 1002.3361, 1010.5999]

- **Gauge-boson free part (in gauge-eigenbasis):**

[U(1)-(L_μ-L_τ)]$_{n=1,2,3,...}$ — kinetic mixings — (nth) KK mass — 5D U(1) L_μ-L_τ

$$\mathcal{L}_{\rm eff}^{(V\text{-free})} = \sum_n \left\{ -\frac{1}{4}\widehat{V}^{(n)}_{\mu\nu}\widehat{V}^{(n)\mu\nu} + \frac{\epsilon_n}{2c_W}\widehat{V}^{(n)}_{\mu\nu}\widehat{B}^{\mu\nu} + \frac{1}{2}M_n^2\widehat{V}^{(n)}_{\mu}\widehat{V}^{(n)\mu} \right\}$$

$$- \frac{1}{4}\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu} - \frac{1}{4}W^3_{\mu\nu}W^{3\mu\nu} + \frac{1}{2}\left(\frac{vg_2W^3_\mu + vg_1\widehat{B}_\mu}{2}\right)^2$$

SM part

$U(1)_Y$ — $SU(2)_L$ — via Higgs mechanism

- **Mass eigenbasis:**

Z-boson — photon — nth-U(1)-(L_μ-L_τ)

$$\widehat{B}_\mu = s_W Z_\mu + c_W A_\mu + \sum_n \left[\frac{\epsilon_n}{c_W} + s_W t_W \frac{\epsilon_n m^2_{Z,0}}{M_n^2 - m^2_{Z,0}}\right] V^{(n)}_\mu + \mathcal{O}\left(\epsilon_n^2\right),$$

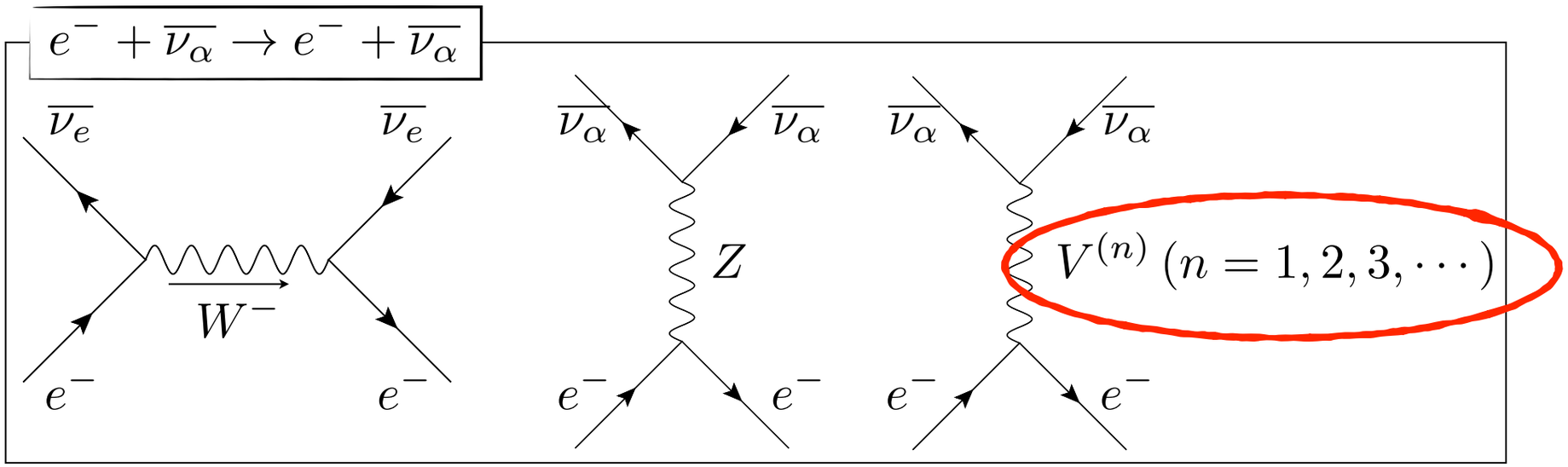
$$W^3_\mu = c_W Z_\mu - s_W A_\mu + c_W t_W \sum_n \frac{\epsilon_n m^2_{Z,0}}{M_n^2 - m^2_{Z,0}} V^{(n)}_\mu + \mathcal{O}\left(\epsilon_n^2\right),$$

$$\widehat{V}^{(n)}_\mu = \widetilde{V}^{(n)}_\mu = V^{(n)}_\mu - t_W \frac{\epsilon_n m^2_{Z,0}}{M_n^2 - m^2_{Z,0}} Z_\mu + \mathcal{O}\left(\epsilon_n^2\right).$$

Through kinetic mixings, KK U(1)-(L_μ-L_τ) bosons couple with electrons.

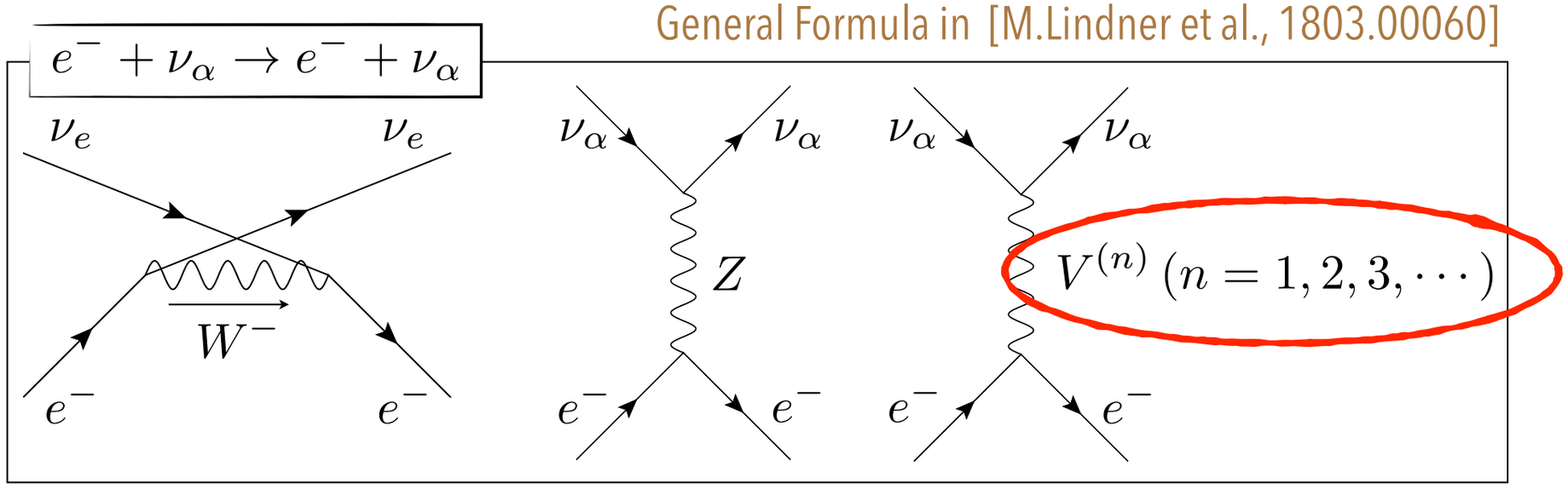
Elastic Neutrino-Electron Scattering (EvES)

- A powerful probe for **new particles** coupled with **ν_α (α=e,μ,τ)** and **e^-**.



via kinetic mixings

General Formula in [M.Lindner et al., 1803.00060]



[Previous Experiments]

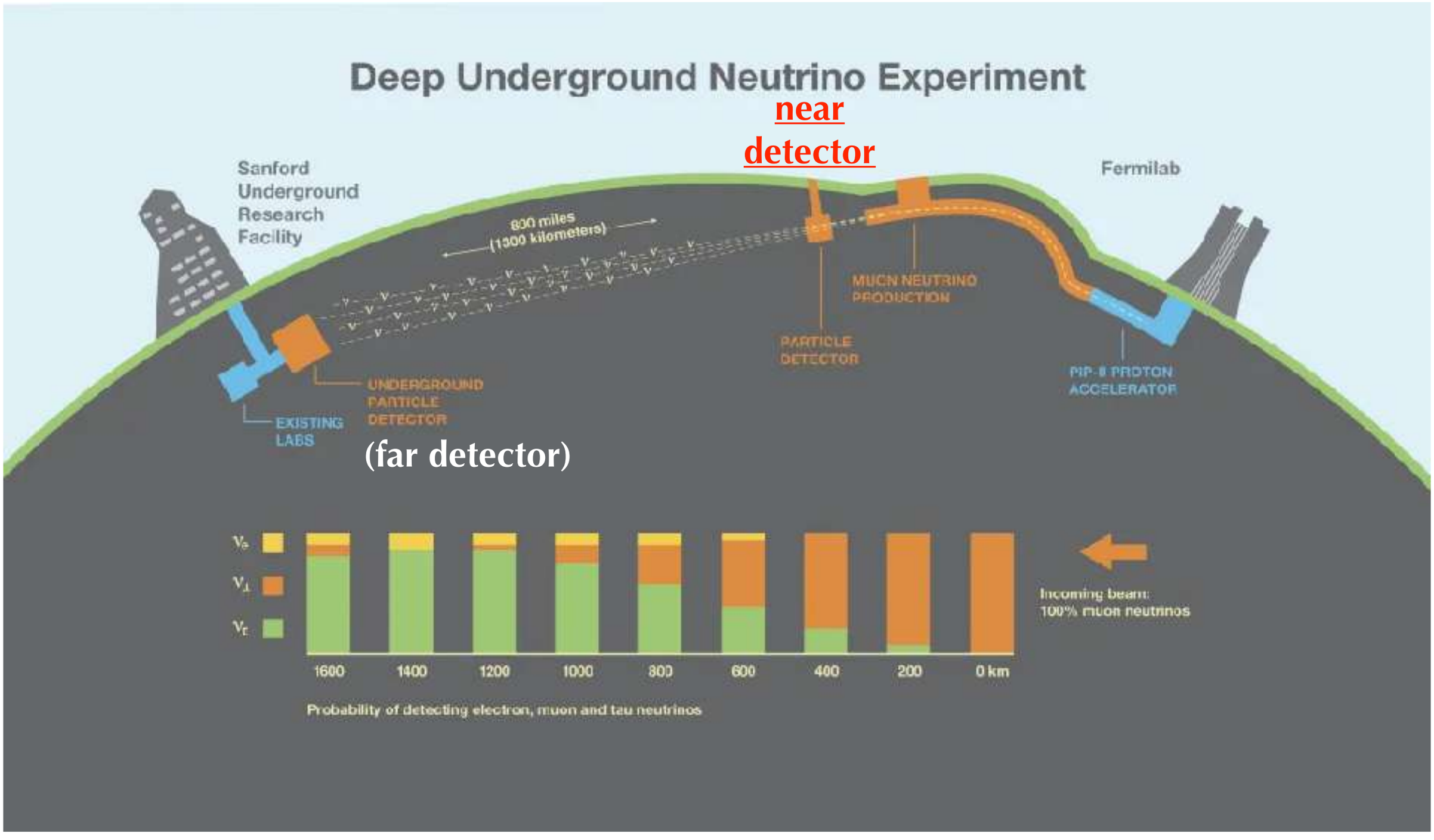
✓**Charm-II** (collider-ν, ν_μ, ν_μ*bar*)
✓**TEXONO** (reactor-ν, ν_e*bar*)
✓**Borexino** (Solar Neutrinos ⇔ ν_e, ν_μ, ν_τ)

✓GEMMA (ν_e*bar*) ← No strong discovery potential for MeV-scale intermediate new physics

EvES search in DUNE Near Detector

- The next-generation neutrino experiment is also beneficial for EvES.

[P.Bakhki, Y.Farzan, M.Rajaee, 1810.04441] + [some others]



[DUNE experiment]

DUNE Analysis (skippable)

[K.Chakraborty et al., 2111.08767] + [some others]

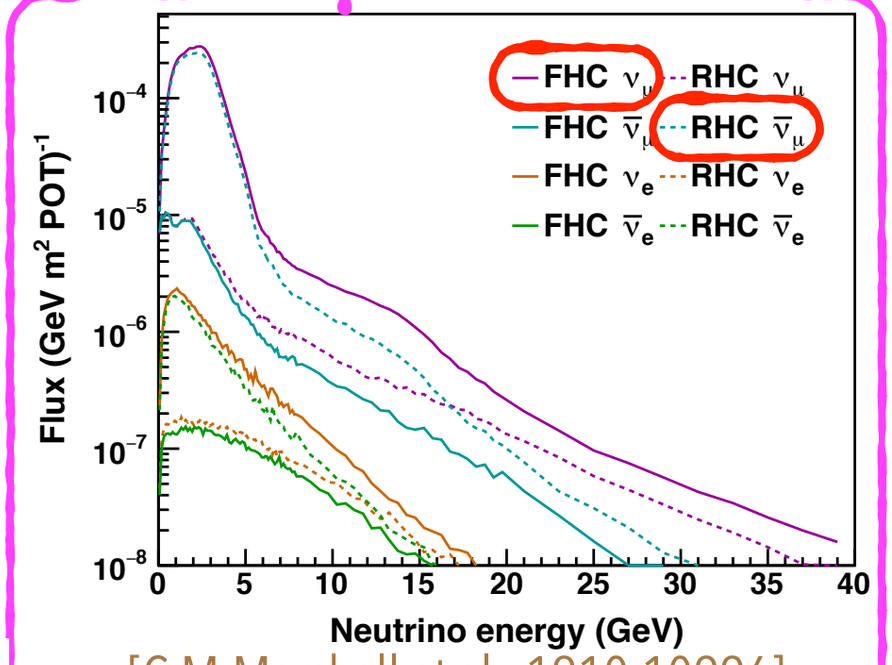
- (diff. event #): $\dfrac{dN^{\rm mode}}{d(E_e\theta_e^2)} = t_{\rm run}^{\rm mode} N_e N_{\rm POT} \sum_{X:e,\bar{e},\mu,\bar{\mu}} \int_{E_{\nu_X}^{\rm min}}^{E_{\nu_X}^{\rm max}} dE_\nu \dfrac{d\Phi_{\nu_X}^{\rm mode}(E_\nu)}{dE_\nu} \left[\dfrac{d\sigma_{e\nu_X}}{d(E_e\theta_e^2)}\right]$

"integrated luminosity"

neutrino fluxes

diff. cross section of $e\text{-}\nu_X \to e\text{-}\nu_X$ (our input)

The kinetic upper bound of $E_e(\theta_e)^2$: $2m_e$
⇒ Useful for reducing the background events.



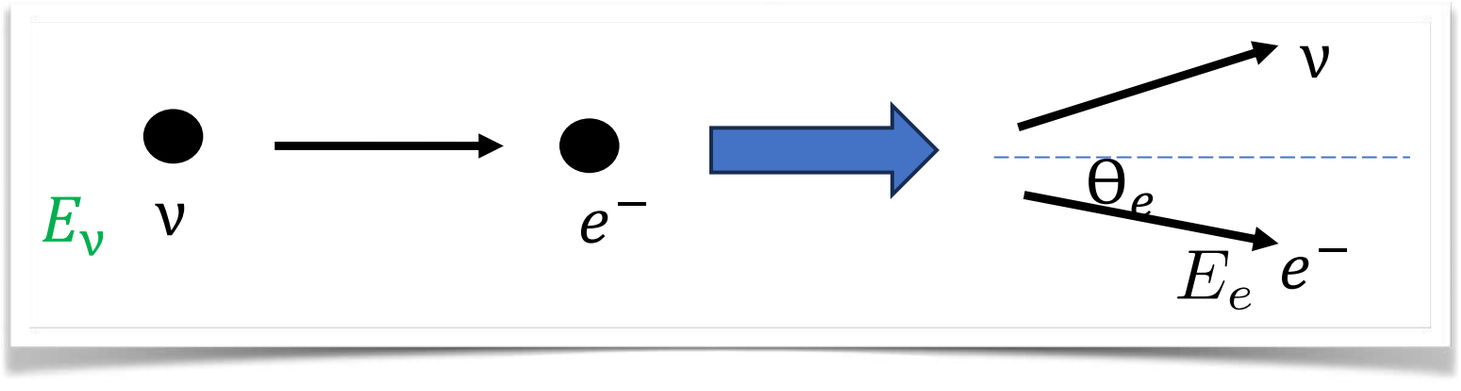
[C.M.Marshall et al., 1910.10996]

- (χ^2 form): $\chi^2_{\rm tot} := \chi^2_{\rm FHC} + \chi^2_{\rm RHC}$

$$\chi^2 := \min_{\alpha,\beta}\left[\sum_{i=1}^{4} \frac{\left(N_{\rm NP}^i - (1+\alpha)\,N_{\rm SM}^i - (1+\beta)\,N_{\rm BG}^i\right)^2}{N_{\rm NP}^i} + \frac{\alpha^2}{\sigma^2} + \frac{\beta^2}{\sigma^2}\right]$$

4-bin analysis (σ: 5%)

$[0,\ 0.5m_e]$, $[0.5m_e,\ m_e]$, $[m_e,\ 1.5m_e]$, and $[1.5m_e,\ 2m_e]$



[Background Events]

- ✓ CCQE: $\nu_e A \to e^- A'$
- ✓ π^0 misidenficiation ($\nu A \to \nu\pi^0 A$)

[A.de.Gouvea et al., 1912.06658]

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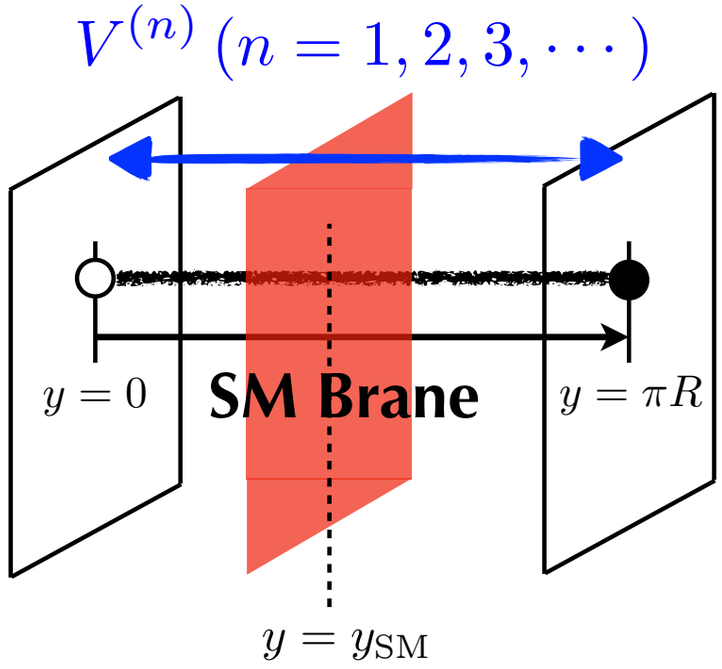
3. Results for the flat case [3 pages]

Valid Parameters

- 5D metric: $ds^2 = g_{MN}dx^M dx^N = e^{-2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$

  ✓ **A(y) = 0: *flat* extra dimension**

  ✓ ~~(A(y) = k*y: *warped* extra dimension)~~ skipped



- Effective parameters:

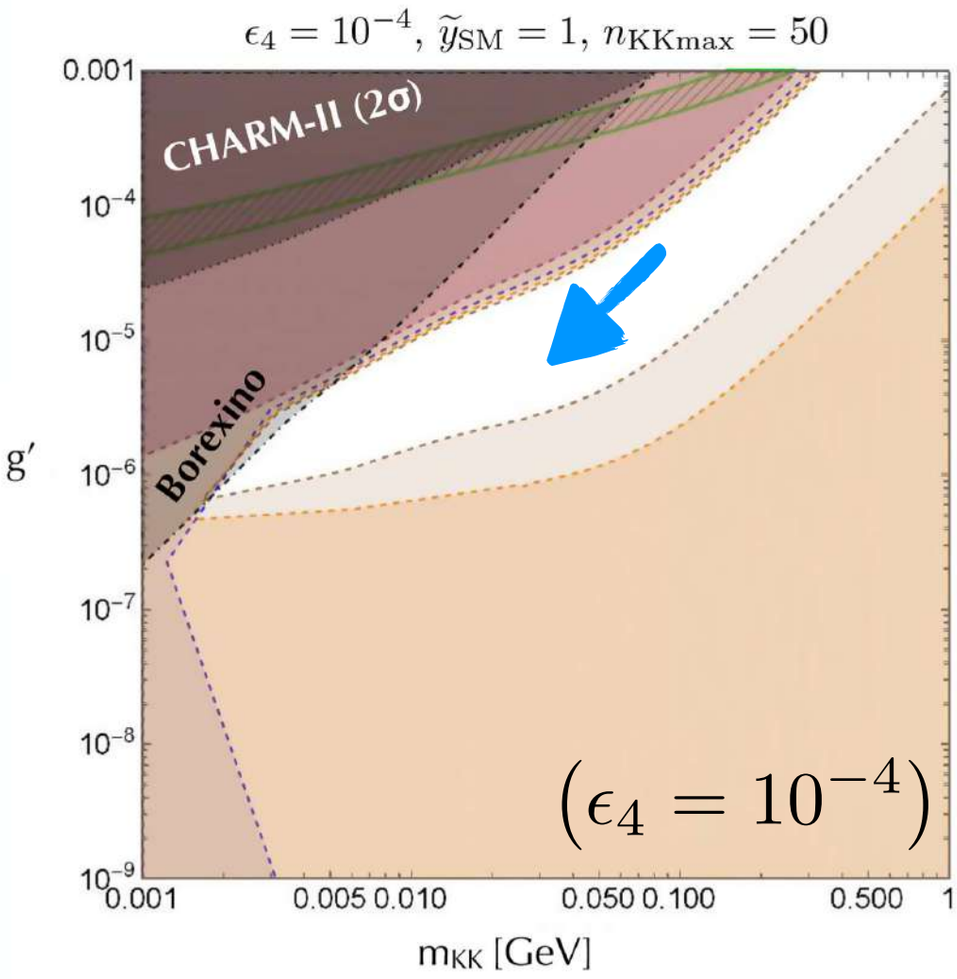
The mass of the lightest KK mode — **The position of the SM brane**

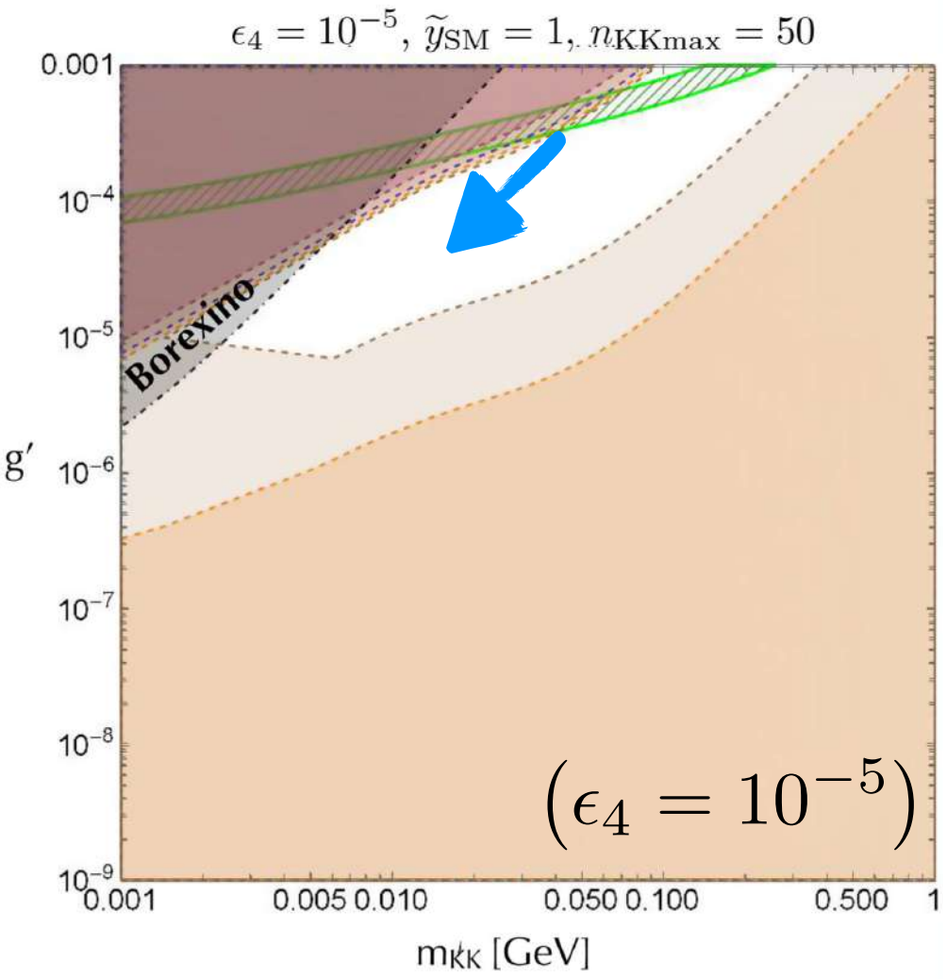
$$g', m_{\rm KK}, \epsilon_4, y_{\rm SM}, [k\ (\text{only in warped background})]$$

U(1)-(L_μ-L_τ) 4D gauge coupling — **Typical magnitude of the kinetic mixings** — ~~(The magnitude of "warping")~~ skipped

- We have checked that considering the **first 50 modes** in "Σ_n" (KK sum) is enough to maintain the convergence.
- The KK mass scales M_n are determined by the effective parameters.
  - ✦ For the flat case, $M_n = (n - 1/2)\ R^{-1}$ (n=1,2,3,…) [R: the radius of the compact ex-dim].

Result: flat, "larger" ϵ_4



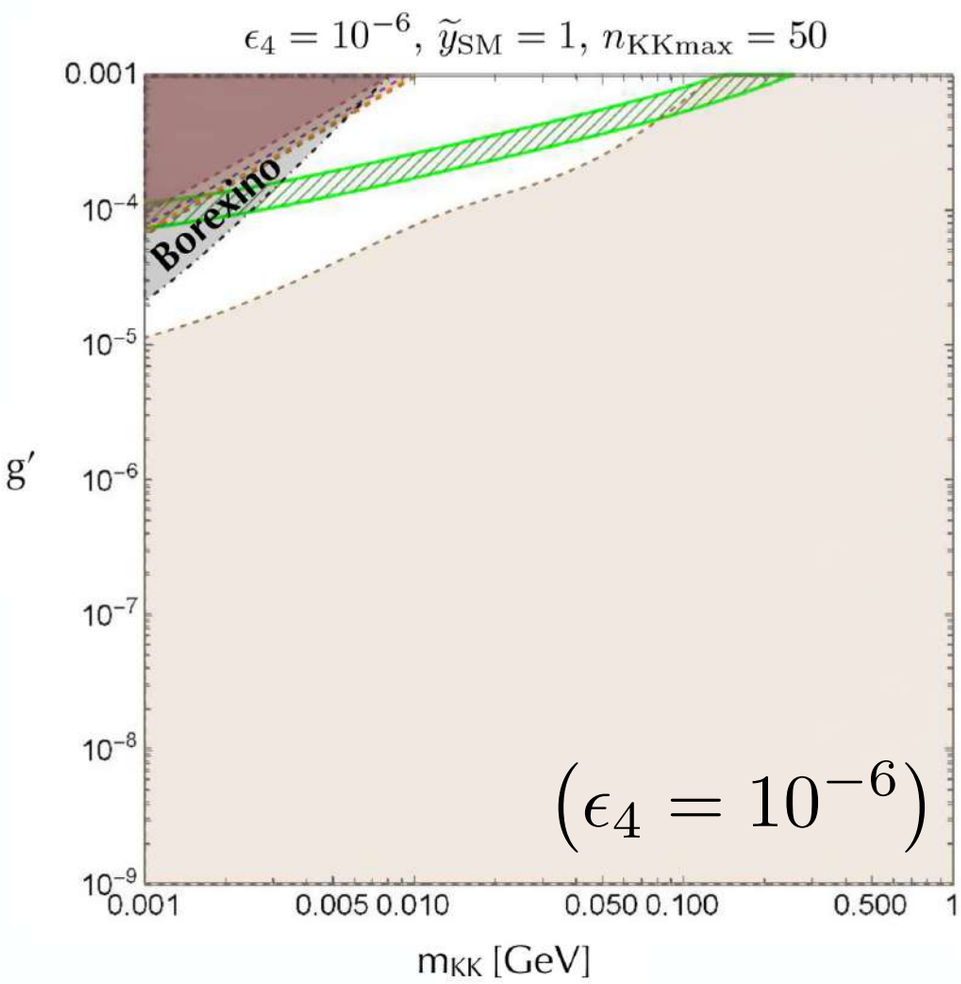


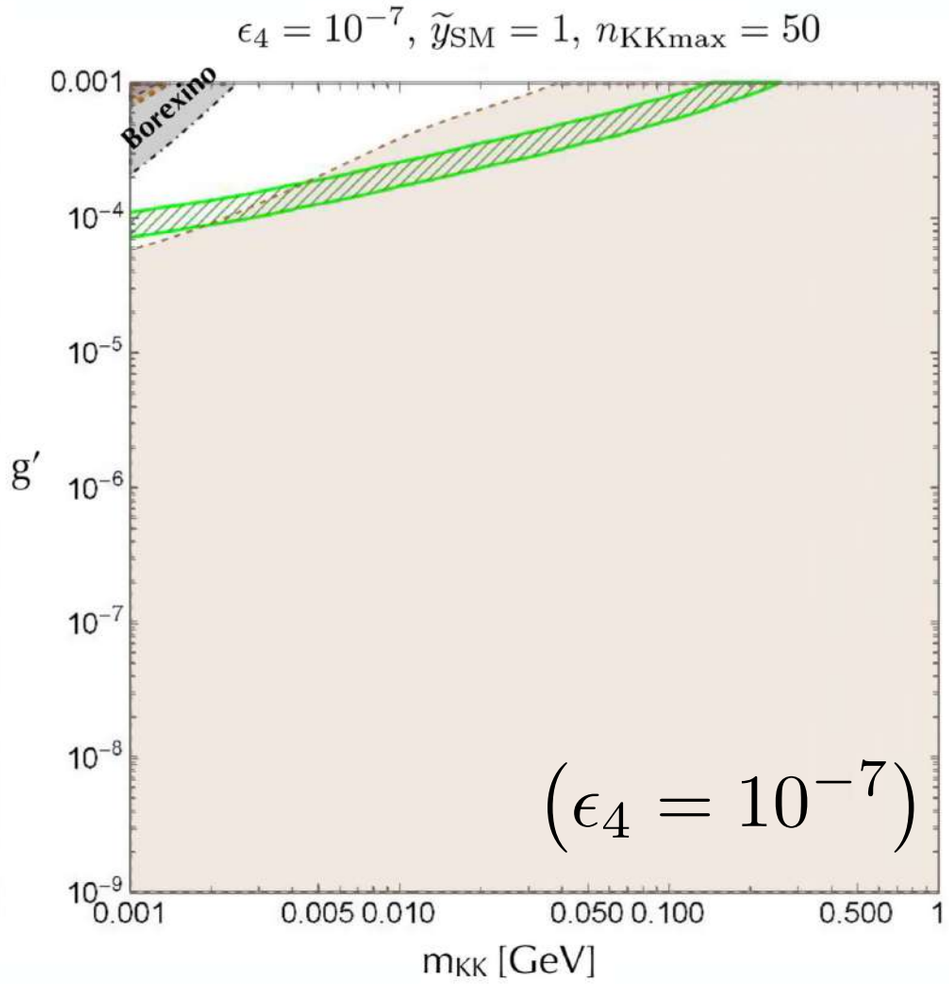
$(\widetilde{y}_{\rm SM} := y_{\rm SM}/R)$

disfavoured by arXiv:2505.21476
~~muon (g-2) [2σ favoured]~~
DUNE ND [7-year (2σ)]
DUNE ND [5-year (2σ)]
DUNE ND [3-year (2σ)]
DUNE ND [1-year (2σ)]

- **DUNE ND** has **a powerful potential** for investigating 5D U(1) L_μ-L_τ (**after a 5-year run** [= 2.5-year ν_μ-mode + 2.5-year $\nu_\mu$bar-mode]).
- No bound from TEXONO.
- **"Blindspot" is expected due to interference effects**.

Result: flat, "smaller" ϵ_4





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- ~~muon (g-2) [2σ favoured]~~
- DUNE ND [7-year (2σ)]
- DUNE ND [5-year (2σ)]
- DUNE ND [3-year (2σ)]
- DUNE ND [1-year (2σ)]

- Even for **smaller ε_4**, we can prove many areas in a **7-year** run.

Short Summary

- The minimal 5D extension of U(1)-(L_μ-L_τ) works well, the **DUNE near detector** will investigate **uncharted domains**.
- In EvES, the interference effects between SM and KK gauge bosons play a significant role. (⇒ **How to explore the blindspots?**)

Complementary searches for the coupling with the muon are important!

- **In Muon beam bump experiments** [D.Chakraborty, A.Chatterjee, A.Kaushik, K.N.; work in progress, appearing arXiv near future]
- **In TeV-scale Muon Collider** [D.Chakraborty, A.Chatterjee, A.Kaushik, K.N.; work in progress, appearing arXiv near future]

- Associated topics: Neutrino texture, lepton-portal DM, Hubble tension, and (gauged) Leptogenesis in 5D

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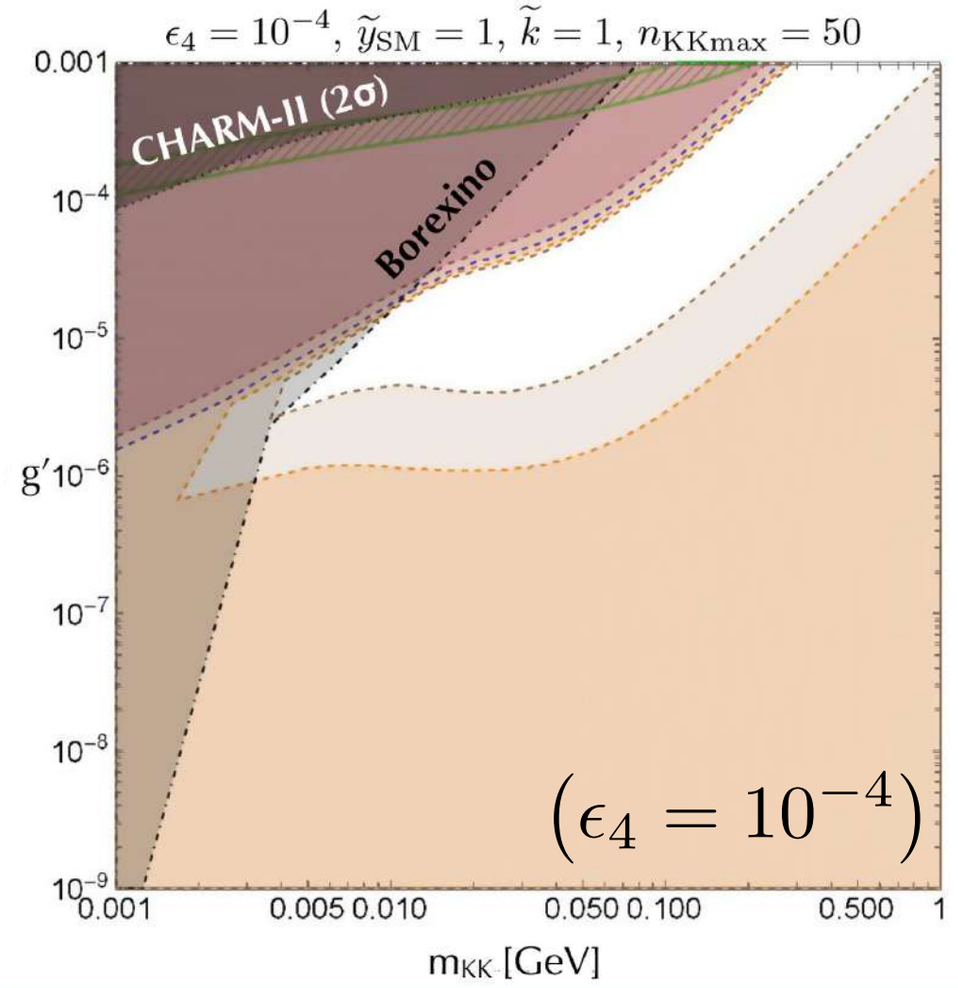
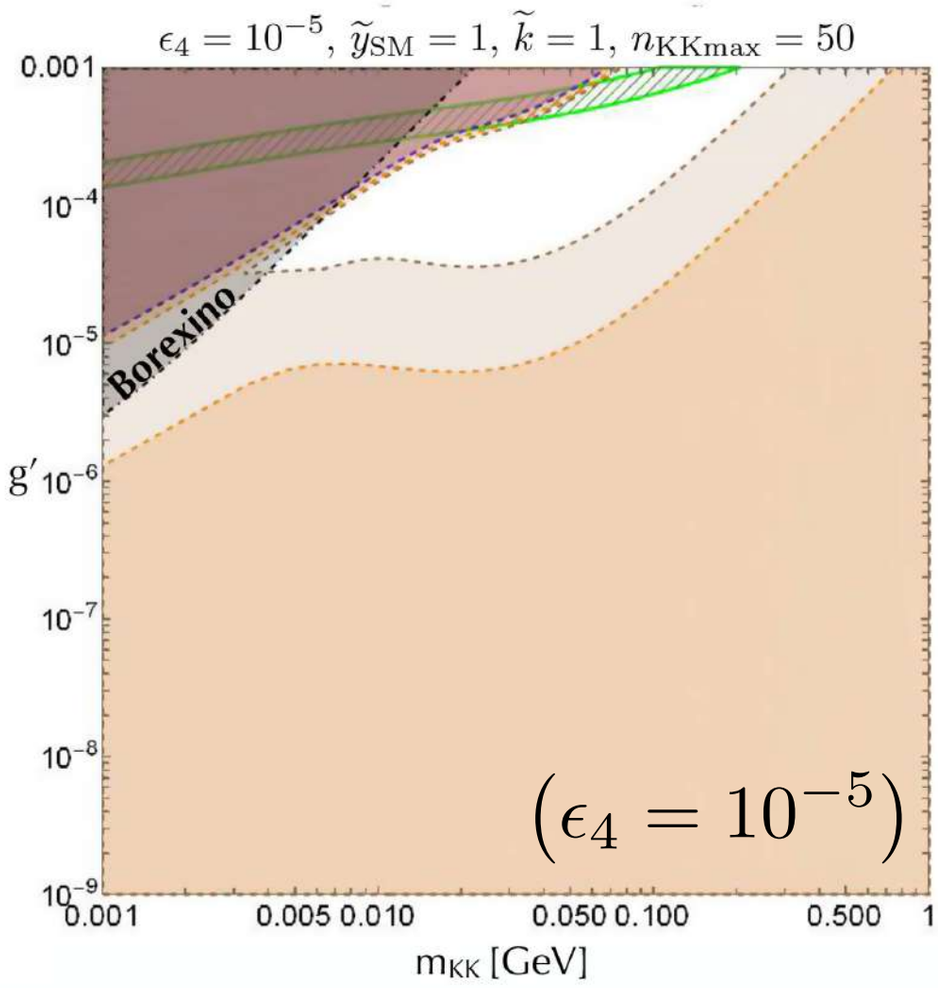
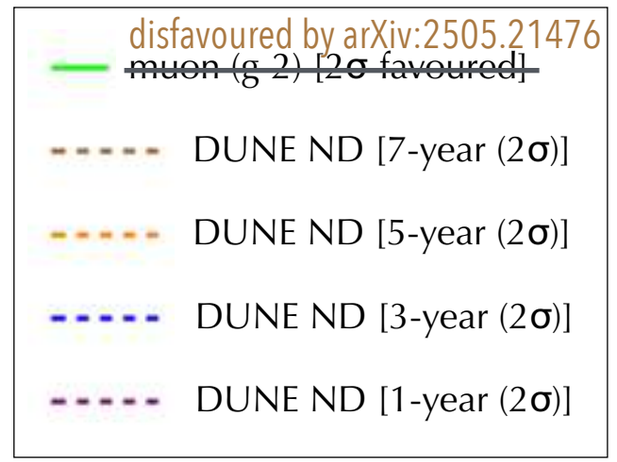
Backups

Result: warped, "larger" ϵ_4



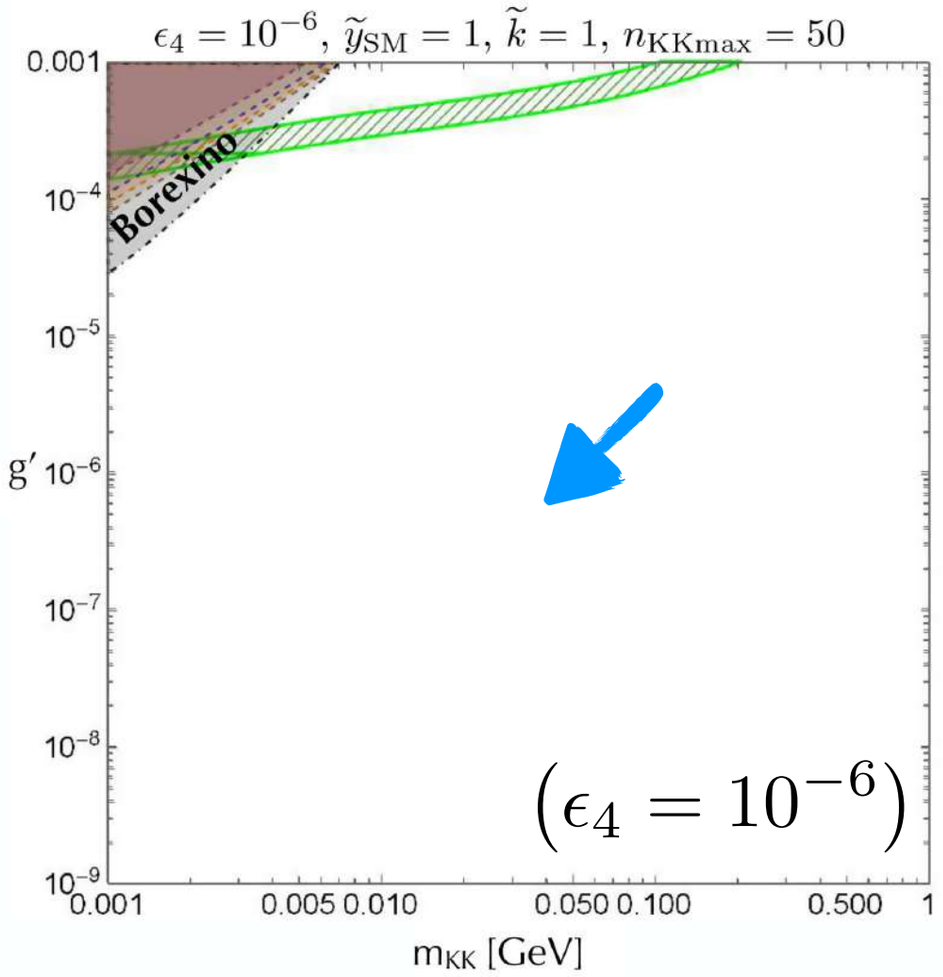


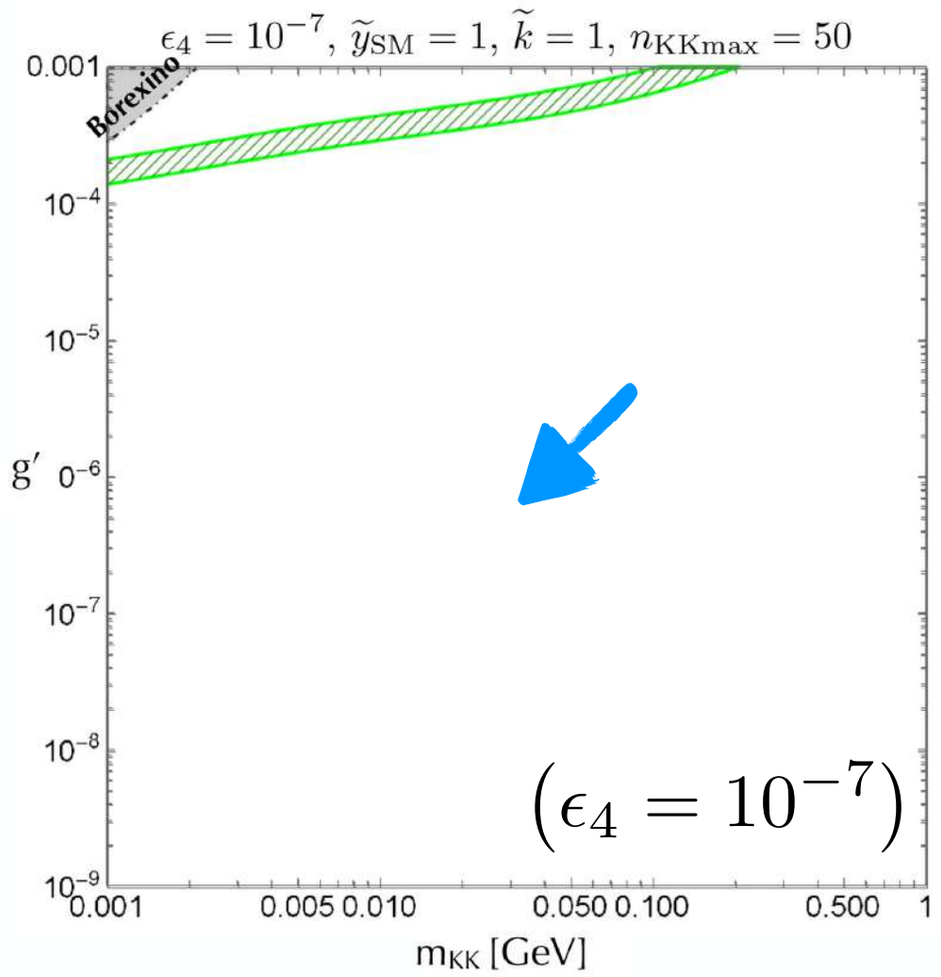
$(\widetilde{y}_{\rm SM} := y_{\rm SM}/R,\ \widetilde{k} := kR)$



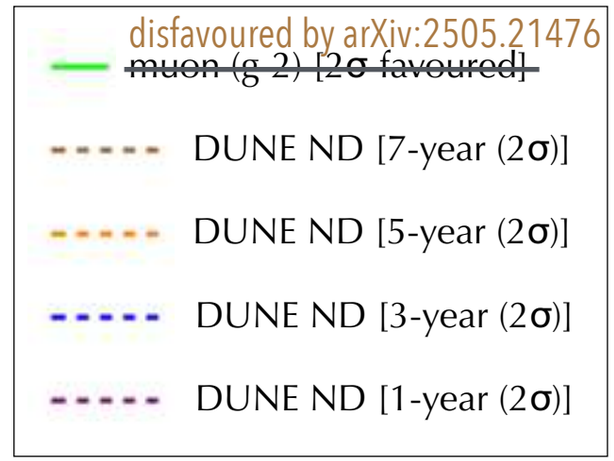
- The wavefunctions of KK gauge bosons are different from those in flat. So, we observe quite differences.

Result: warped, "smaller" ϵ_4



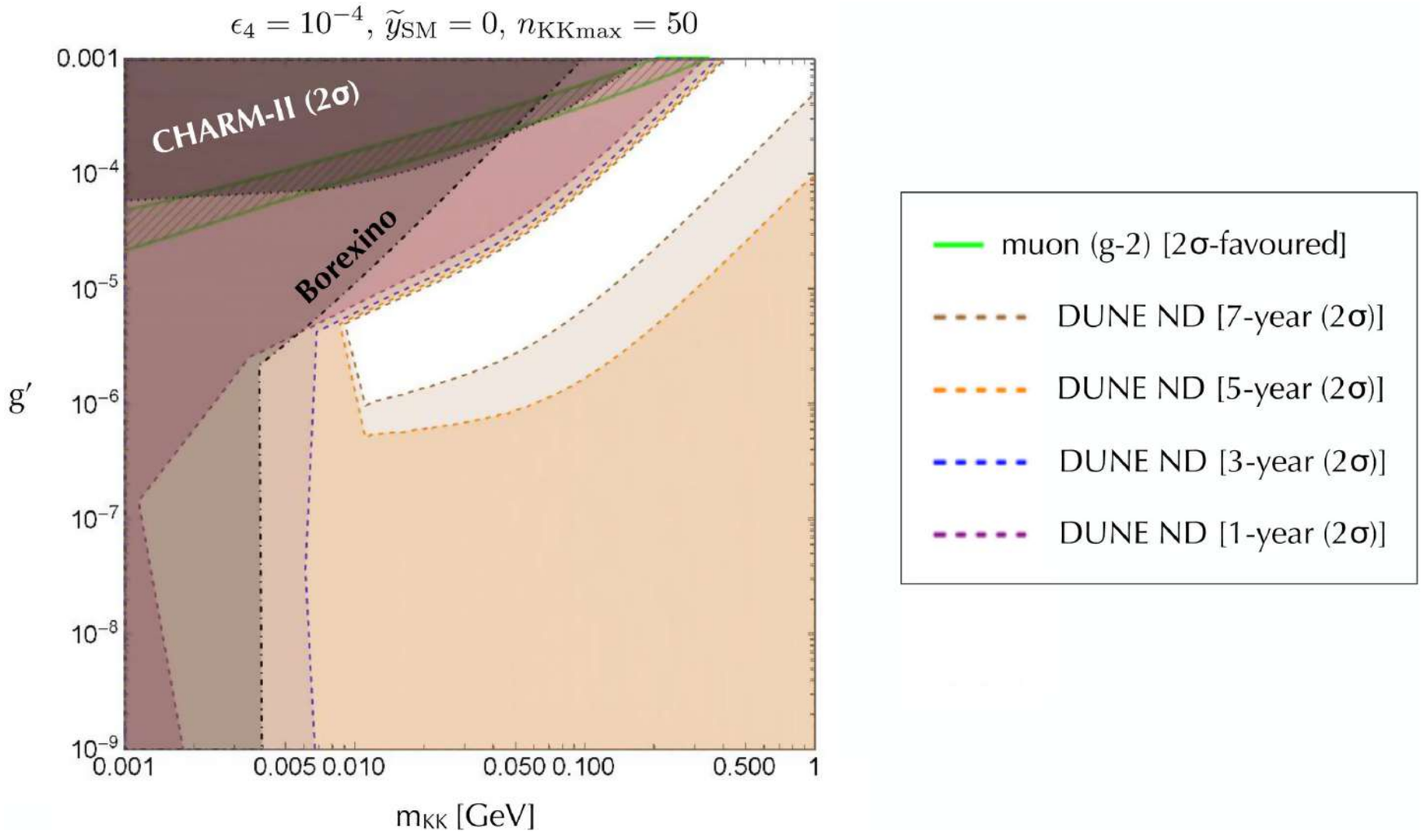


$(\widetilde{y}_{\rm SM} := y_{\rm SM}/R,\ \widetilde{k} := kR)$

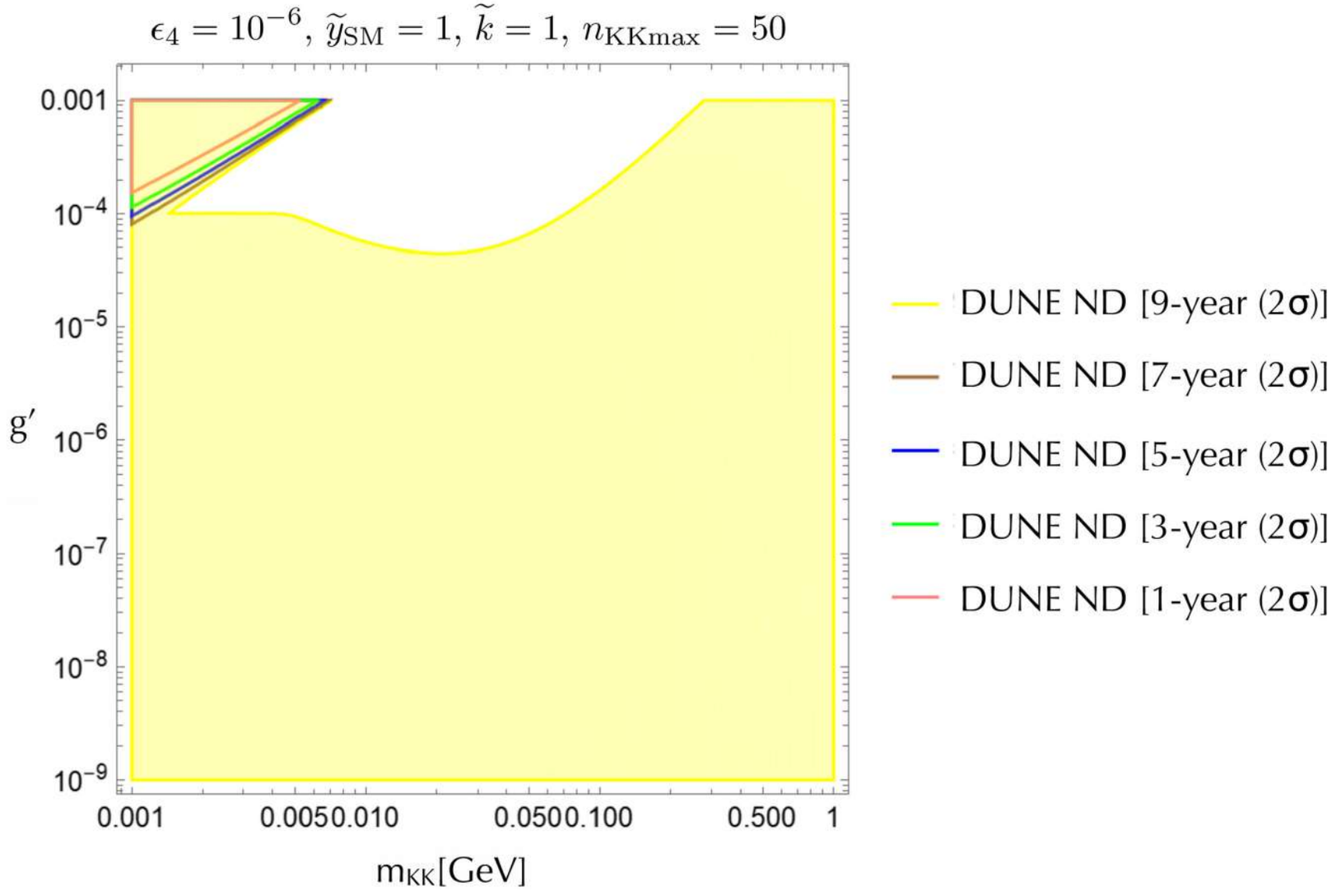


- In the warped case, **the blindspots are bigger**.
  So, we need more than 7 years to explore the parameter space.

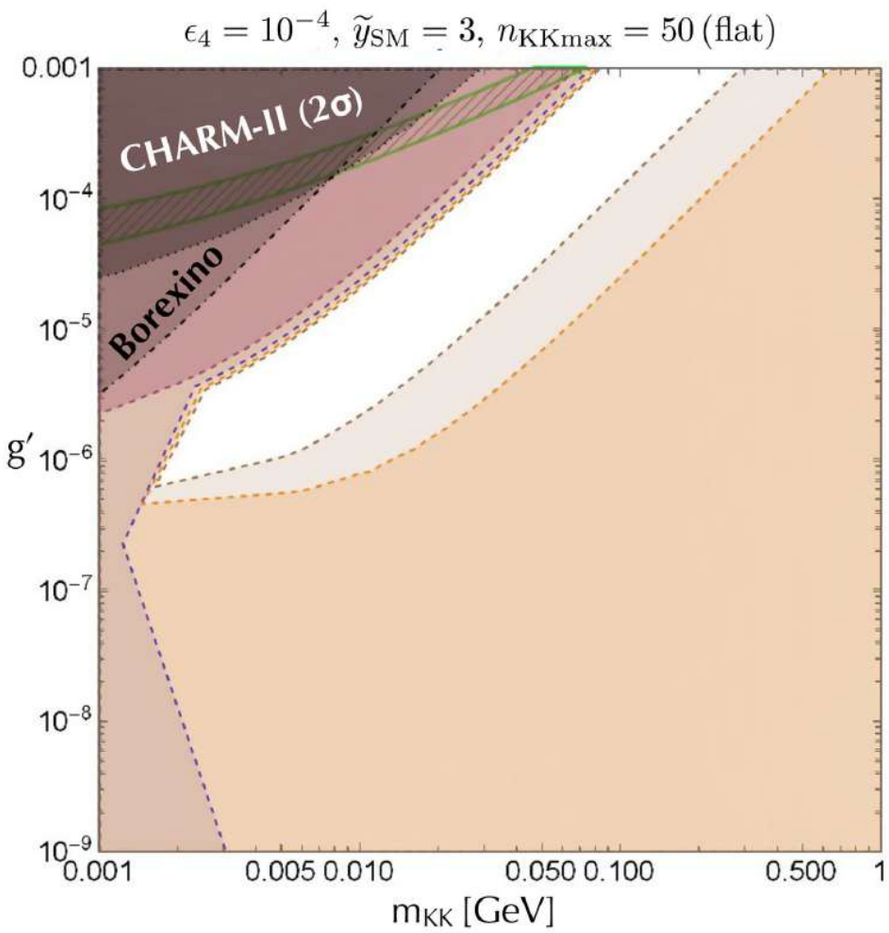
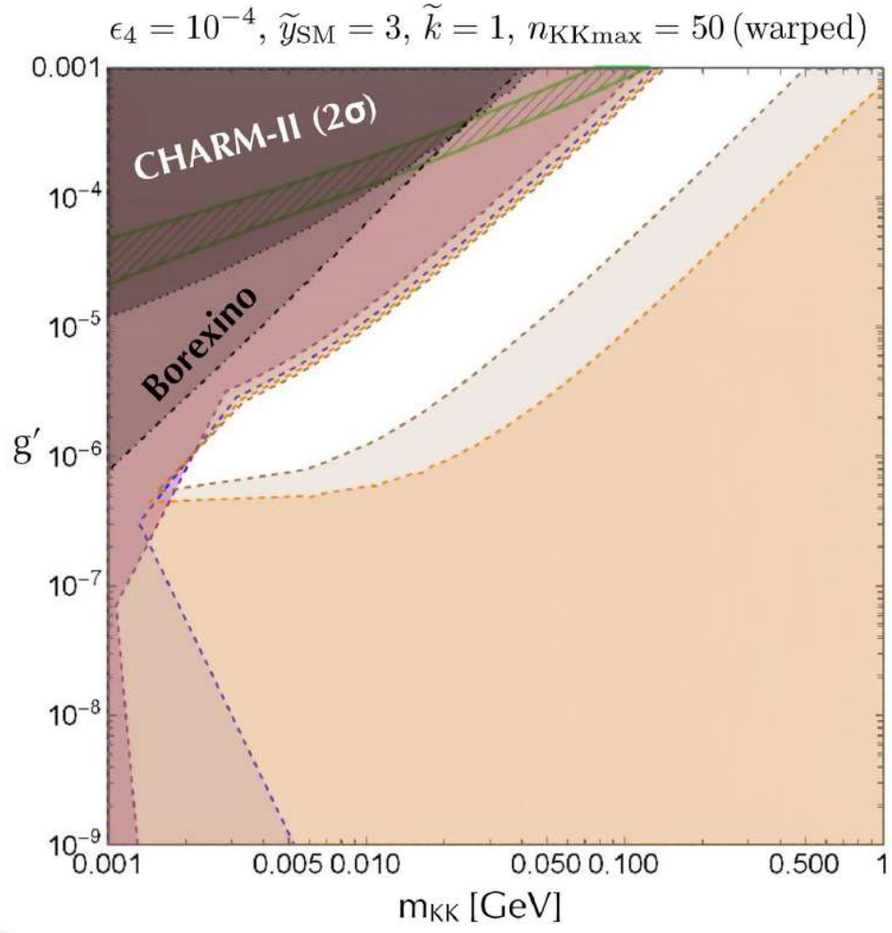
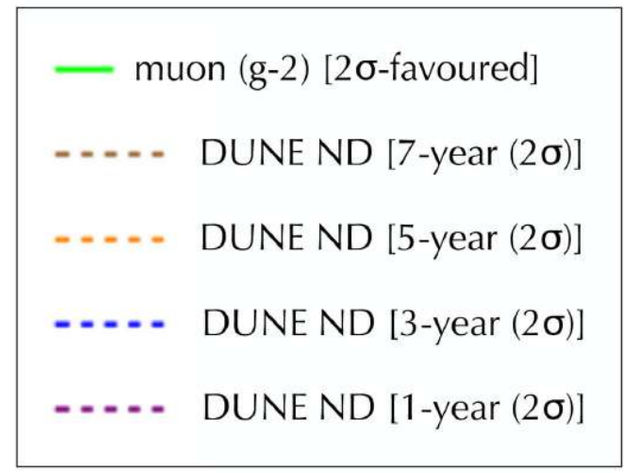
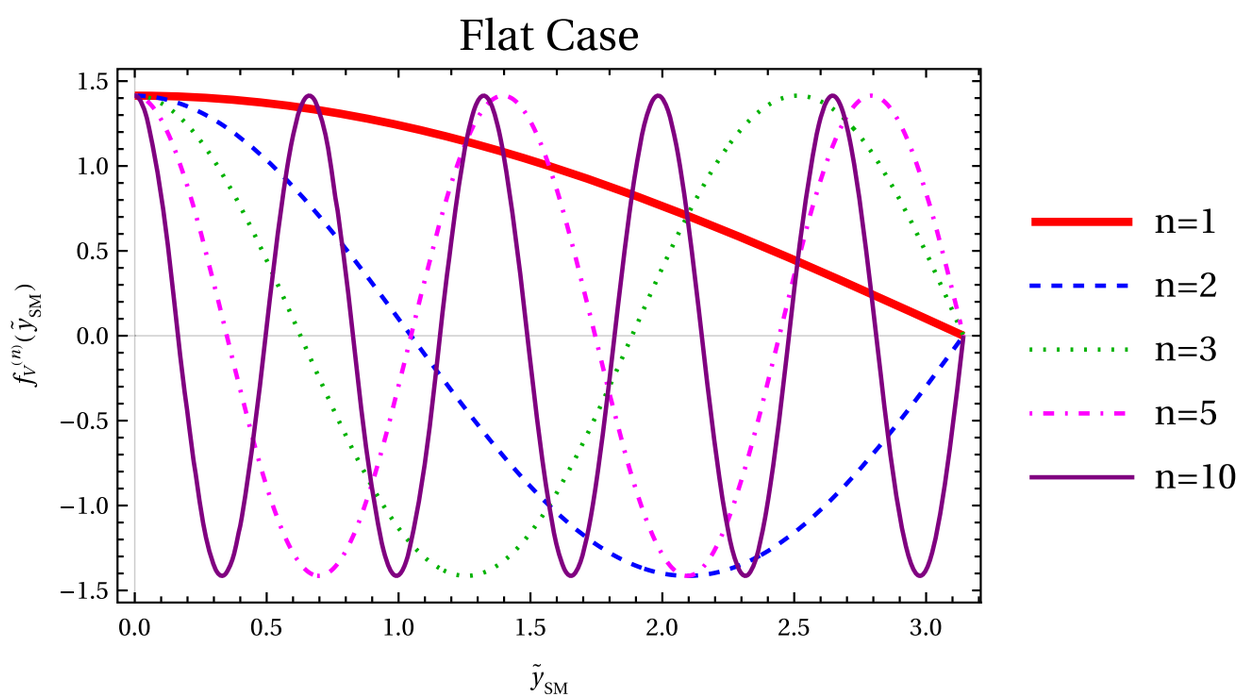
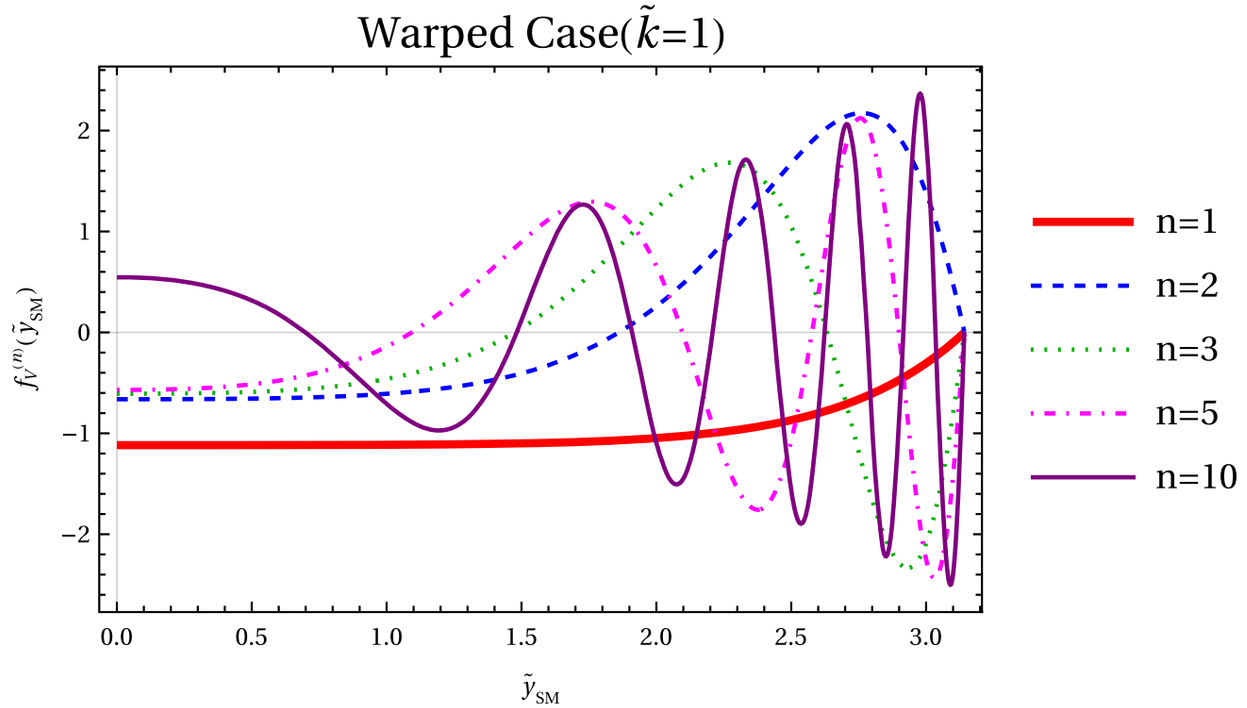
flat case


$\epsilon_4 = 10^{-4}$, $\widetilde{y}_{\rm SM} = 0$, $n_{\rm KKmax} = 50$
CHARM-II (2σ)
Borexino
g′
0.001
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0.001
0.005
0.010
0.050
0.100
0.500
1
m_{KK} [GeV]
muon (g-2) [2σ-favoured]
DUNE ND [7-year (2σ)]
DUNE ND [5-year (2σ)]
DUNE ND [3-year (2σ)]
DUNE ND [1-year (2σ)]

warped case


$\epsilon_4 = 10^{-6}$, $\widetilde{y}_{\rm SM} = 1$, $\widetilde{k} = 1$, $n_{\rm KKmax} = 50$
0.001
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
g′
0.001
0.005
0.010
0.050
0.100
0.500
1
m_{KK}[GeV]
DUNE ND [9-year (2σ)]
DUNE ND [7-year (2σ)]
DUNE ND [5-year (2σ)]
DUNE ND [3-year (2σ)]
DUNE ND [1-year (2σ)]

flat case



warped case