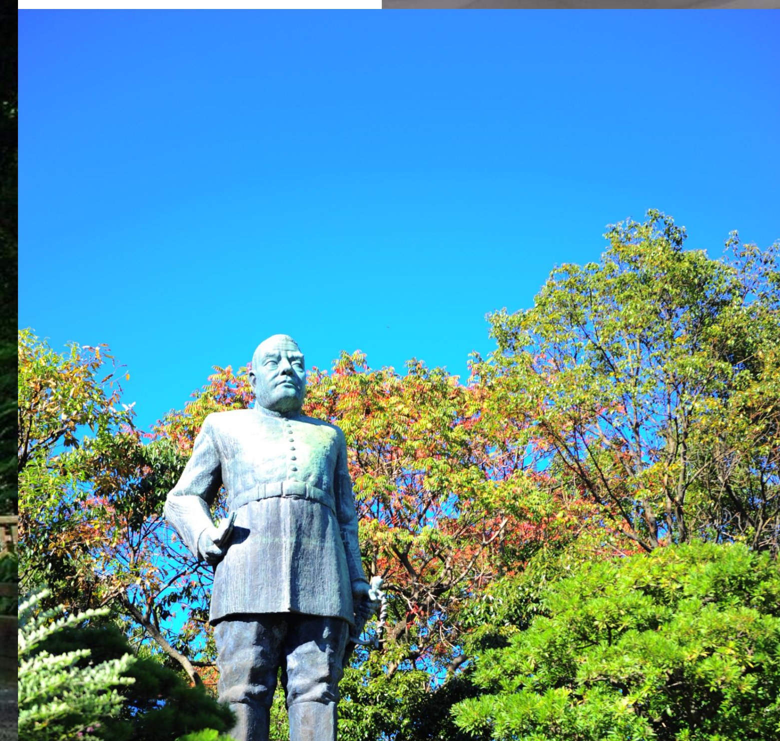
Welcome to

Kagoshima workshop on Particles, Fields and Strings 2023



Kagoshima workshop on Particles, Fields and Strings 2023

趣旨

★ 世話人がじっくり話を聞きたい人を招待

★ 少人数でゆったりとざっくばらんに物理を議論したい

★ 幅広いトピック（レプトン系、弦の現象論、高次元、量子論、場の理論、宇宙論、暗黒物質）の問題に関してみんなで議論しよう

2/19	title	speaker	
chair: H. Otsuka			
15:00–15:45	Search for lepton flavor violation from dark sector	Takashi Shimomura	(Miyazaki U. & Kyushu U.)
15:45–16:30	ミューオニウム-反ミューオニウム転換で探るレプトンフレーバー混合	Yuichi Uesaka	(Kyushu Sangyo U.)
16:30–16:45	break		
chair: S. Eijima			
16:45–17:30	レプトン数の時間発展とマヨラナタイプ位相	Yusuke Shimizu	(Hiroshima U.)
17:30–17:40	鹿児島情報	Soma Onoda	(Kyushu U.)

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2/20	title	speaker	
chair: O. Seto			
9:00-9:45	Sterile neutrinos and non-standard interactions of neutrinos	Osamu Yasuda	(Tokyo Metropolitan U.)
9:45-10:30	Leptogenesis in gauged U(1)_{L_mu-L_tau} model	Shintaro Eijima	(ICRR, U. Tokyo)
10:30-11:00	break		
chair: H. Suzuki			
11:00-11:45	Modular symmetry in the string EFT	Hajime Otsuka	(Kyushu U.)
11:45-12:30	Flux compactification and the hierarchy problem	Nobuhito Maru	(NITEP/Osaka Metropolitan U.)
12:30-14:00	Lunch		
chair: O. Yasuda			
14:00-14:45	素粒子実験における弱測定の応用について： B中間子を用いたCP非保存測定を例に	Yosuke Takubo	(KEK)
14:45-15:30	Gradient flow exact renormalization group	Hiroshi Suzuki	(Kyushu U.)
15:30-16:00	break		
chair: K. Nagao			
16:00-16:20	Machine Learning Exploration of Quark and Lepton Flavor Structures	Satsuki Nishimura	(Kyushu U.)
16:20-16:40	フレーバー構造で探る暗黒物質	Coh Miyao	(Kyushu U.)
16:40-17:00	Fractional topological charge in lattice Abelian gauge theory	Motokazu Abe	(Kyushu U.)

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2/21	title	speaker	
chair: N. Maru			
9:00–9:45	Tensions in cosmology and its implications for new physics	Tomo Takahashi	(Saga U.)
9:45–10:30	Early cosmology with ultra-relativistic bubble wall expansion	Wen Yin	(Tohoku U.)
10:30–11:00	break		
chair: T. Takahashi			
11:00–11:45	Probing axions with the measurements of photon's birefringence	Ippei Obata	(IPMU, U. Tokyo)
11:45–12:30	原始揺らぎの量子性は観測できるか？	Sugumi Kanno	(Kyushu U.)
12:30–14:00	Lunch		
14:00–16:00	Free discussion		

2/22			
chair: K. Tsumura			
9:00–9:45	What can we learn from the direction of dark matter?	Keiko Nagao	(Okayama U. of Science)
9:45–10:30	Lepton flavor violation and DM constraints in a radiative seesaw model	Osamu Seto	(Hokkaido U.)
10:30–11:00	Break		
chair: T. Shimomura			
11:00–11:45	Link soliton in model with U(1)_{B-L} and U(1)_{PQ} symmetries	Yu Hamada	(KEK)
11:45–12:30	The origin of pseudo-Nambu-Goldstone Dark Matter	Koji Tsumura	(Kyushu U.)

Miyazaki workshop in 2020

Welcome to

Miyazaki Workshop on Particle Physics and Cosmology 2020

この研究会の目的はさまざま分野から研究者を集め、素粒子物理と宇宙物理の重要な問題に対する最新の結果やアイディアを議論することである。
参加者全員が議論に参加できるように、基本的な知識から最新の成果までを話して頂く。

Invited Speakers

- Yugo Abe (National Institute of Technology, Miyakonojo College)
- Tetsutaro Higaki (Keio University)
- Koji Ishiwata (Kanazawa University)
- Keisuke Izumi (Nagoya University)
- Tatsuo Kobayashi (Hokkaido University)
- Nobuhito Maru (Osaka City University)
- Takaaki Nomura (Korea Institute for Advanced Study)
- Toshifumi Noumi (Kobe University)
- Kin-ya Oda (Osaka University)
- Ken-ichi Okumura (Kyushu University)
- Yutaka Ookouchi (Kyushu University)
- Joe Sato (Saitama University)
- Osamu Seto (Hokkaido University)
- Takashi Shimomura (Miyazaki University)
- Yutaro Shoji (KMI, Nagoya University)
- Michihisa Takeuchi (KMI, Nagoya University)
- Masahide Yamaguchi (Tokyo Institute of Technology)

Miyazaki workshop in 2020

- ★ どの様な感じで話すのかは講演者にお任せ
- ★ 「何が問題で何をしたいと考えているのか」
- ★ トークの最中でもたくさん質問が出て議論も非常に盛り上がった
  (ただし半分以上の人が最後まで話しきれなかった)
- ★ 共同研究につながった

今回も

- ★ どのような感じで話すのかは講演者にお任せ
- ★ 質問はいつでもOK。時間配分は講演者にお任せ
- ★ ただし時間厳守でお願いします
- ★ 時間が来たらいったん纏めるか途中で終わってください
- ★ 続きは休み時間、お昼・晩ごはん、free discussion timeに個別で。

よろしくお願いします

Search for Lepton Flavor Violation at FASER

Takashi Shimomura
(Miyazaki U. & Kyushu U.)

based on

"Search for lepton flavor violating decay at FASER", JHEP01 (2023)
"Electron beam dump constraints on light bosons with LFV coupling", JHEP11 (2021)
"Dark photon from light scalar boson decays at FASER", JHEP06 (2021)

in collaboration with

Takeshi Araki (Ohu U.), Kento Asai (ICRR, Tokyo U.)
Hidetoshi Otono (Kyushu U.), Yosuke Takubo (KEK)

February 19th, 2023 @ Kagoshima workshop, particles, fields and strings 2023

Introduction

The Standard Model has been explaining almost all of experiments so far.

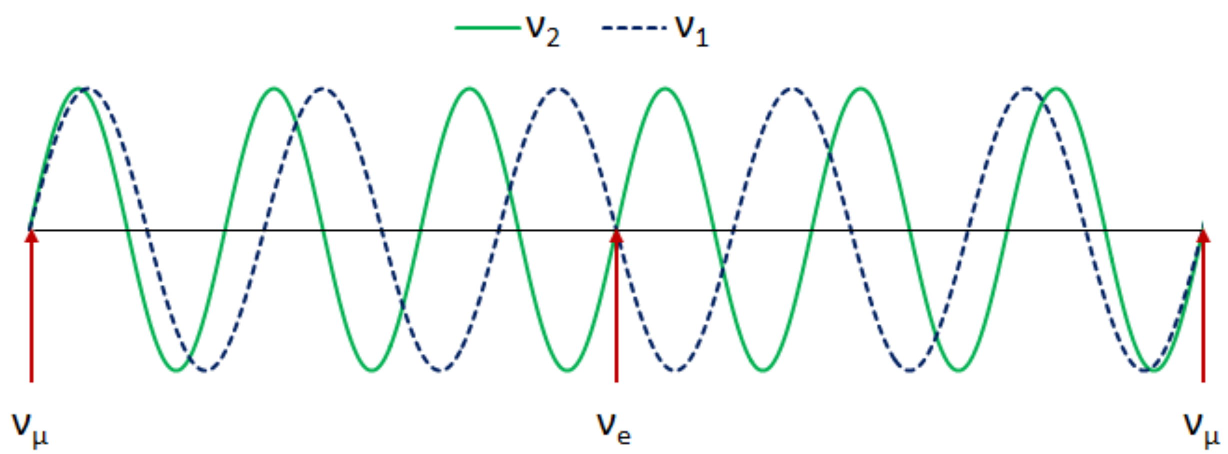
However, there exist problems that can not be answered by the SM,

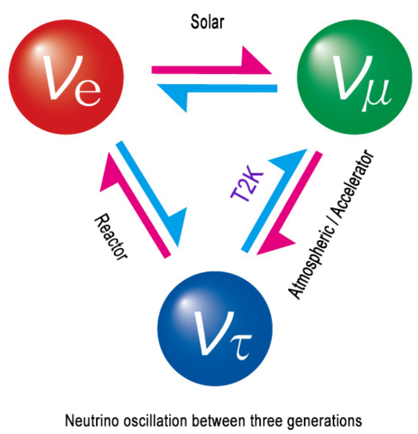
- Phenomenology side:
    - Neutrino mass and mixing/Lepton Flavor Violation
    - Baryon asymmetry of the Universe
    - Dark matter/Dark Energy
    - Anomalous magnetic moment of the muon (electron?)
    - Strong-CP problem
    - etc…

- Theoretical side:
    - Number of generations
    - Origin of forces (gauge symmetry), including gravity
    - Hierarchy from the Planck/GUT scale to the EW scale
    - etc…

Lepton Flavor Violation

- Neutrino oscillation showed that lepton flavor is not conserved in neutral lepton sector.

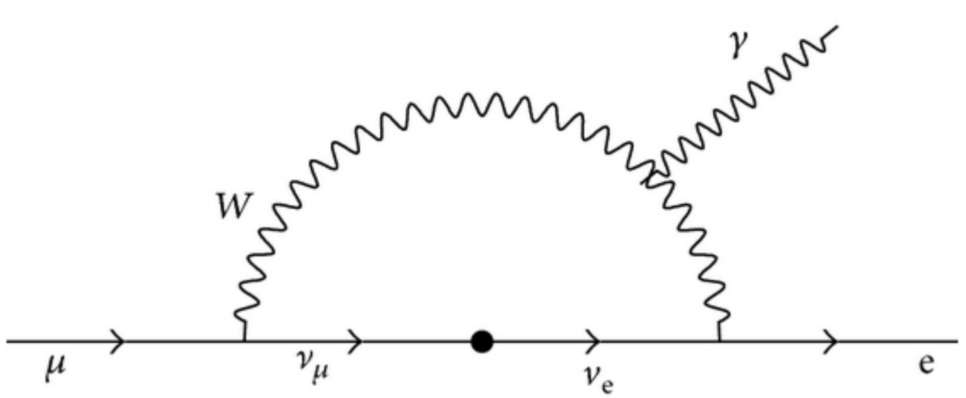




- Lepton Flavor Violation (LFV) can occur in charged lepton sector (CLFV).
  - CLFV can be induced from ν mixing

$$\mathrm{Br}(\mu \to e\gamma) \sim \mathcal{O}(10^{-54})$$

  - No symmetries forbid CLFV.



Sizable CLFV is a clear signature of the BSM

Lepton Flavor Violation

Constraints on CLFV

Calibbi and Signorelli, Riv.Nuovo Cim. 41 (2018)

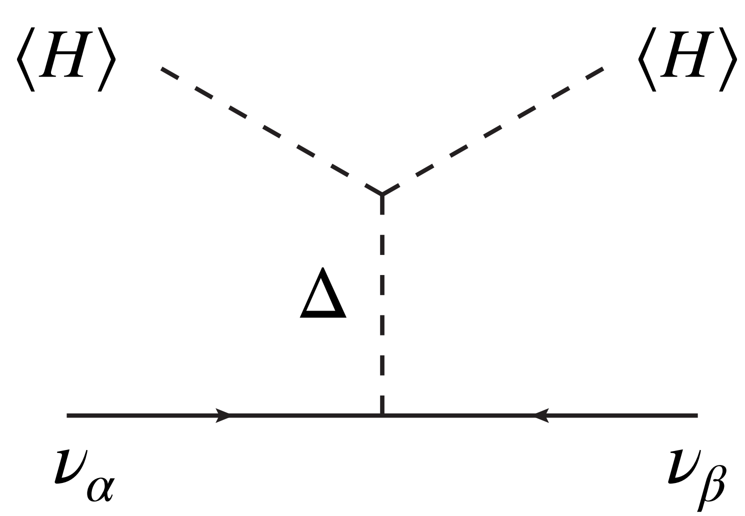
Reaction	Present limit	C.L.	Experiment	Year	Reference
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	90%	MEG at PSI	2016	[49]
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	90%	SINDRUM	1988	[50]
$\mu^-\text{Ti} \to e^-\text{Ti}\,^{(a)}$	$< 6.1 \times 10^{-13}$	90%	SINDRUM II	1998	[51]
$\mu^-\text{Pb} \to e^-\text{Pb}\,^{(a)}$	$< 4.6 \times 10^{-11}$	90%	SINDRUM II	1996	[52]
$\mu^-\text{Au} \to e^-\text{Au}\,^{(a)}$	$< 7.0 \times 10^{-13}$	90%	SINDRUM II	2006	[54]
$\mu^-\text{Ti} \to e^+\text{Ca}^*\,^{(a)}$	$< 3.6 \times 10^{-11}$	90%	SINDRUM II	1998	[53]
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$	90%	SINDRUM	1999	[55]
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	90%	BaBar	2010	[56]
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	90%	BaBar	2010	[56]
$\tau \to eee$	$< 2.7 \times 10^{-8}$	90%	Belle	2010	[57]
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	90%	Belle	2010	[57]

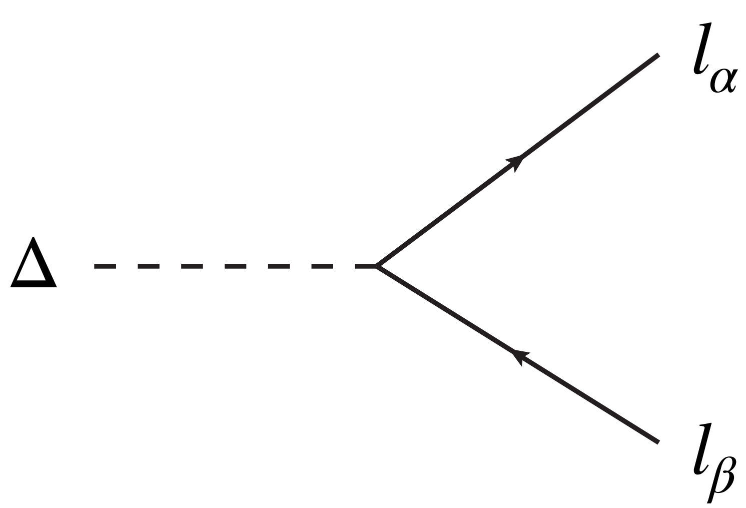
CLFV is much suppressed/weak.

Lepton Flavor Violation

- LFV will be induced through the generation of neutrino mass.

  Many mechanisms
  - Dirac neutrino (via Higgs mechanism)
  - Seesaw mechanism (type-I, II, III, inverse, linear, etc)
  - Two Higgs doublet models (type-I, II, X(leptophilic), Y)
  - Radiative seesaw (too many variants)
  - Flavor symmetry (gauged $L_\alpha - L_\beta$)





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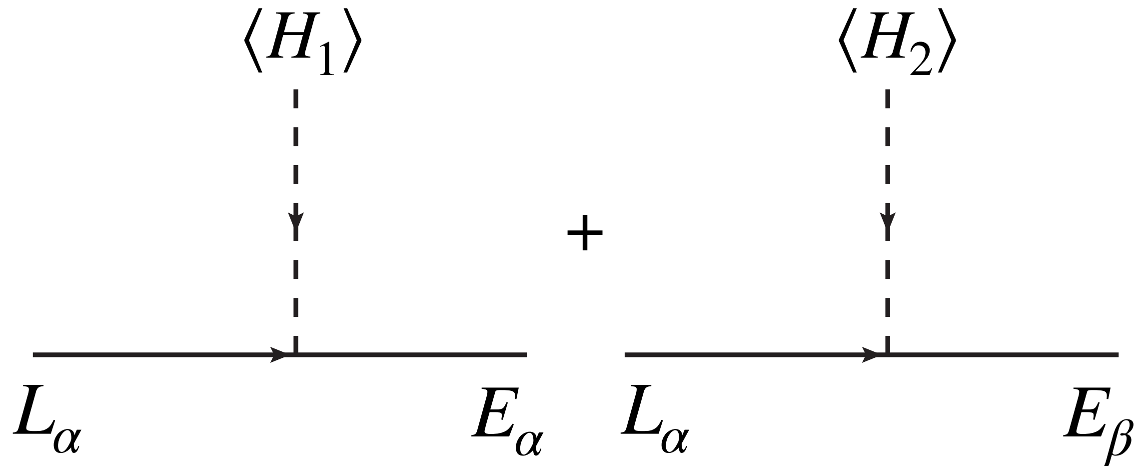

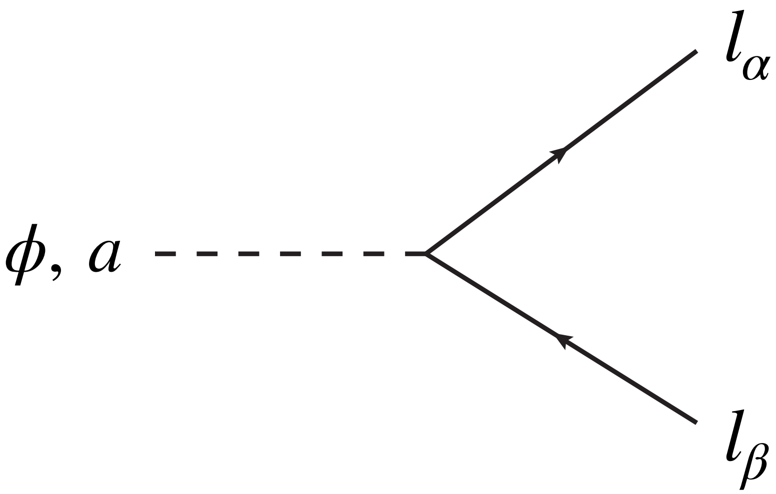

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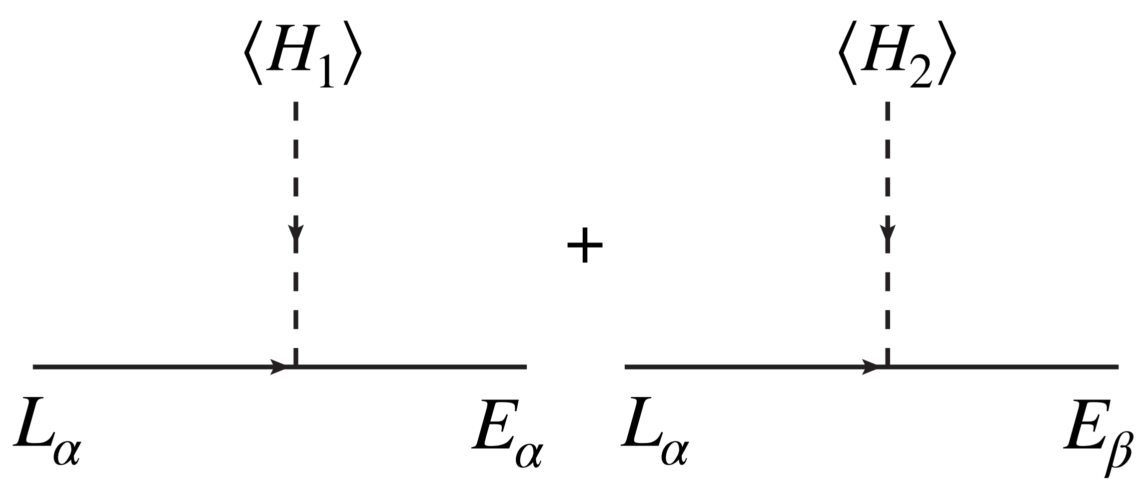

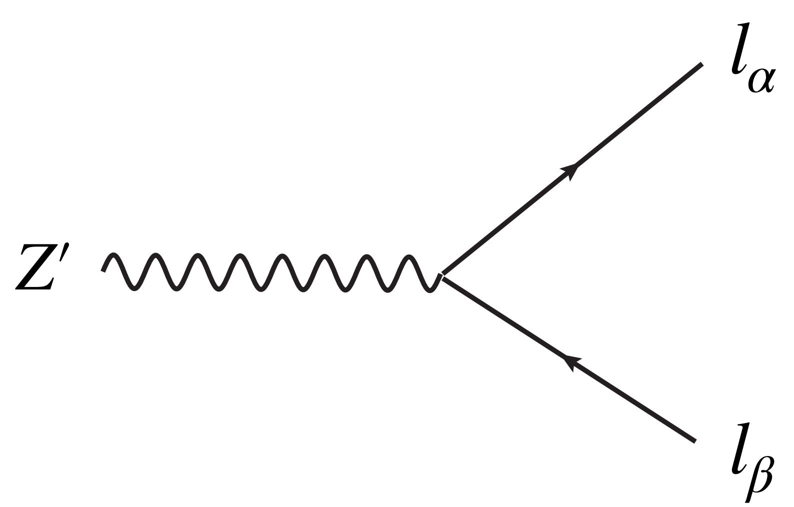

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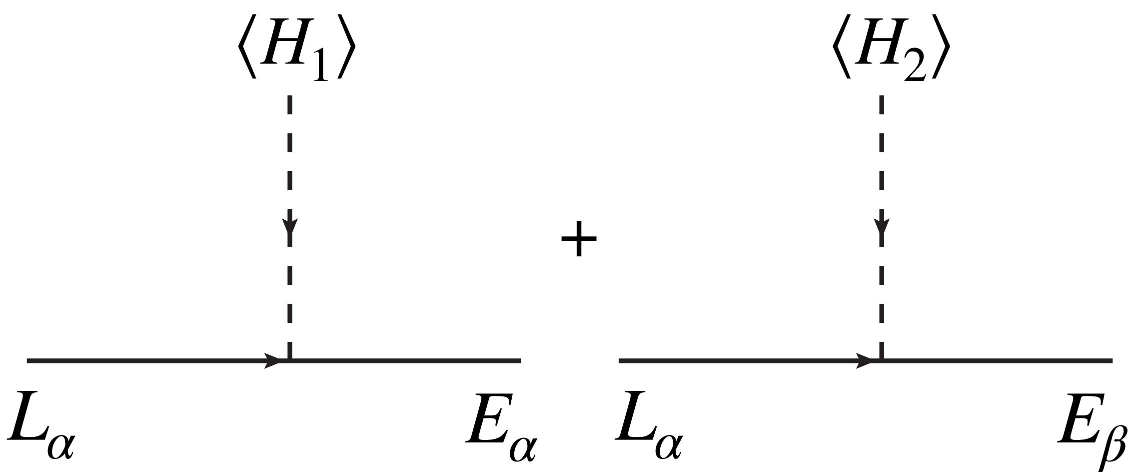

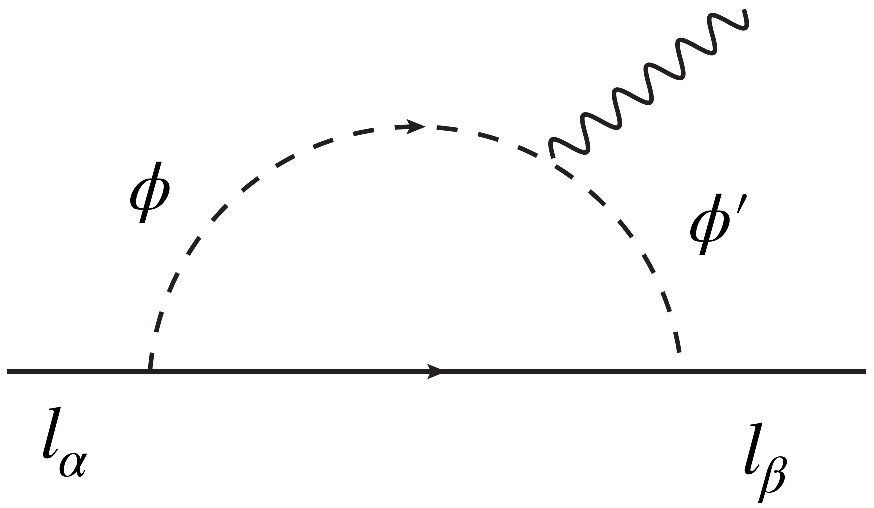

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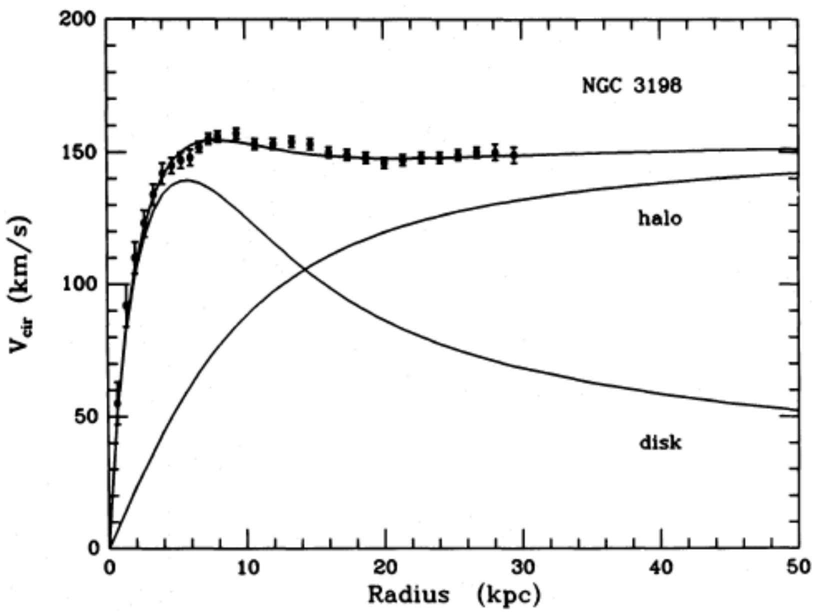
Interaction types of LFV depend on mechanisms/models,

- Scalar int. (multi-higgs)
- Pseudo-Scalar int. (multi-higgs)
- Vector int. (flavored gauge symmetry)
- Dipole int. (flavored gauged symmetry)

Dark Matter

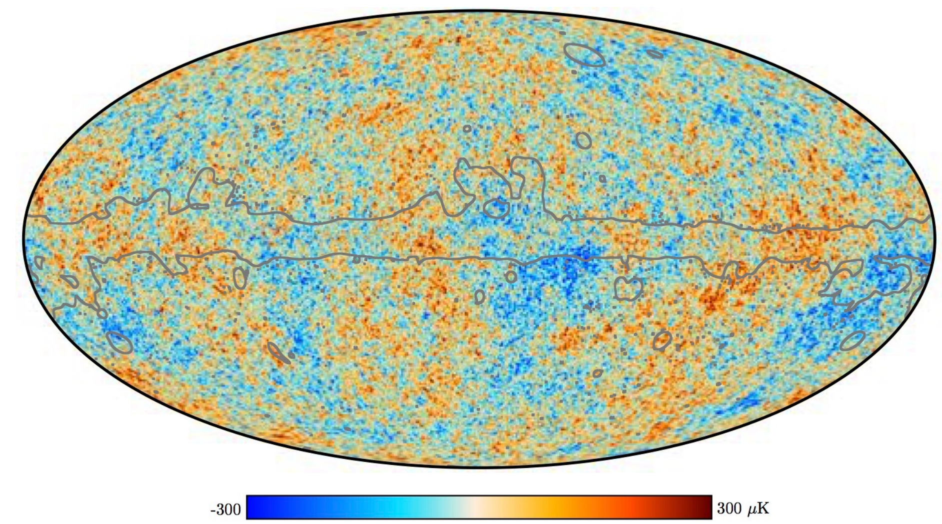
The existence of dark matter (DM) has been well established through gravitational effects.

Rotation curves of galaxies

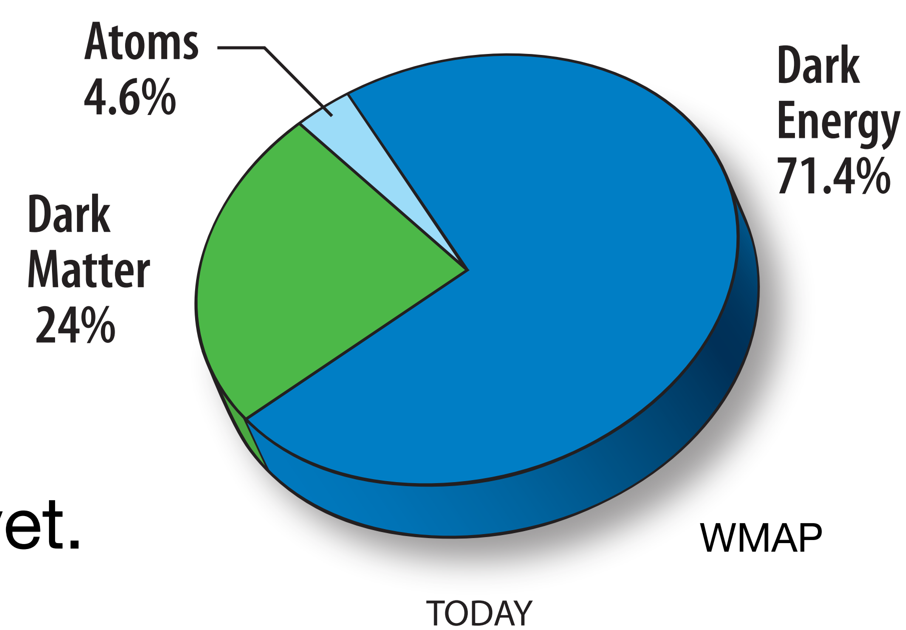


The bullet cluster

Cosmic microwave background



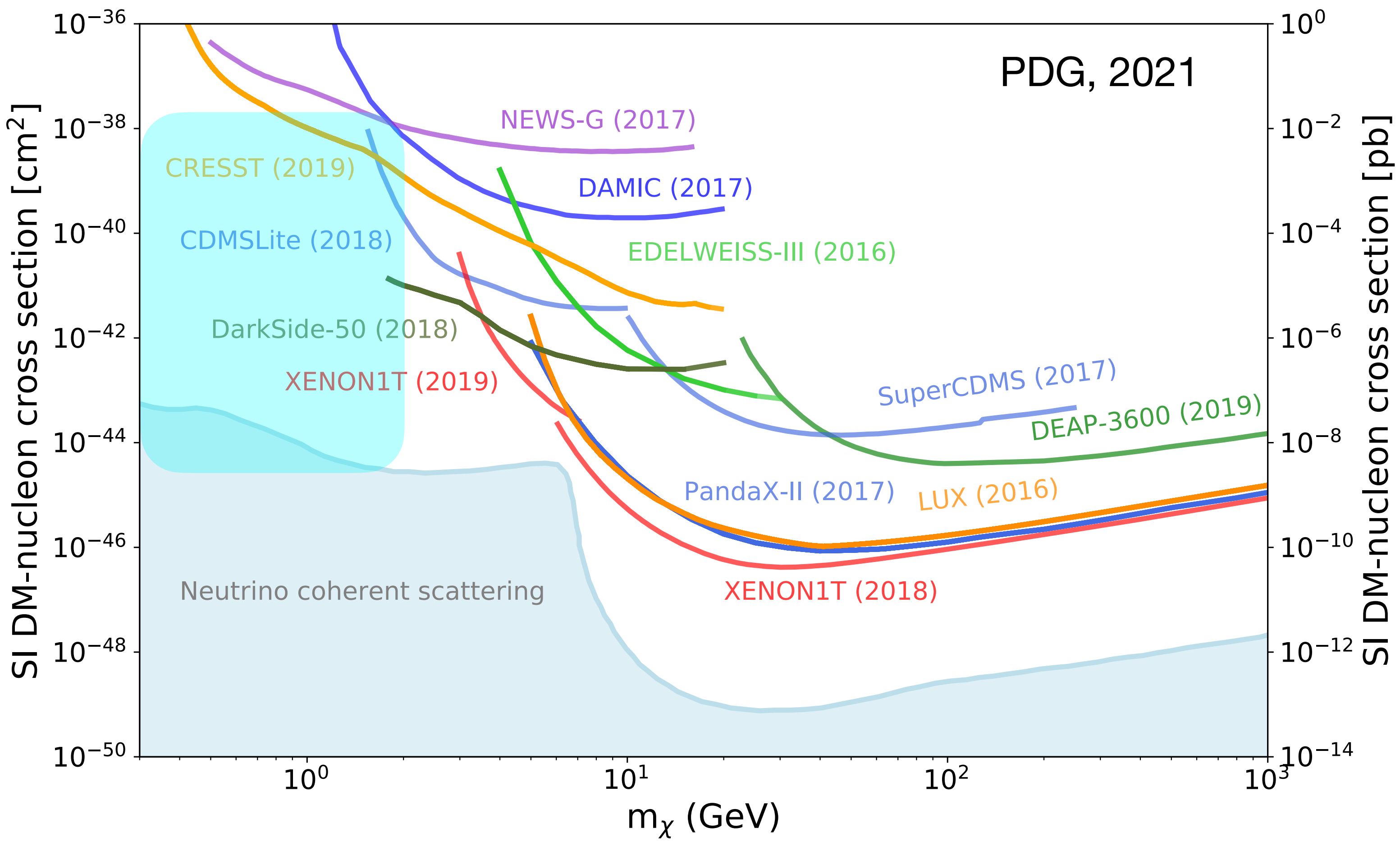
- The DM occupies 24% of the total energy density of the Universe.
- The ordinary matter is just 4.6%.
- The DM has not been directly observed yet.



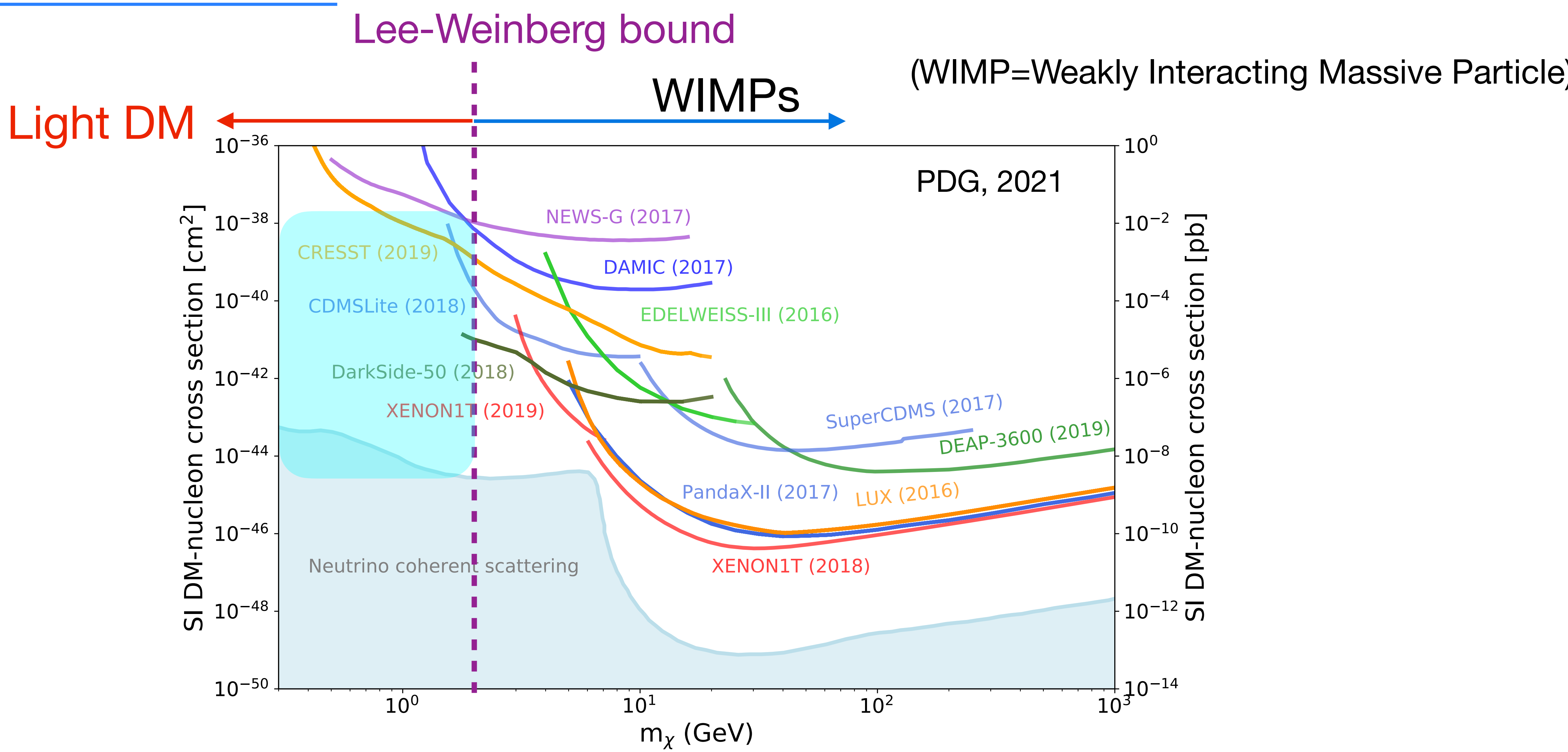
DM candidates

- Dark matter should be massive, electrically/color neutral and stable or long-lived particles.
- There are many candidates, via thermal or non-thermal productions.
    - Weakly Interacting Massive Particles (WIMPs)
    - Axion or Axion-Like-Particles (ALPs)
    - Pseudo-Nambu-Goldstone particles
    - Sterile neutrinos
    - Dark Photon
    - Gravitino

DM constraints



Light Mediator

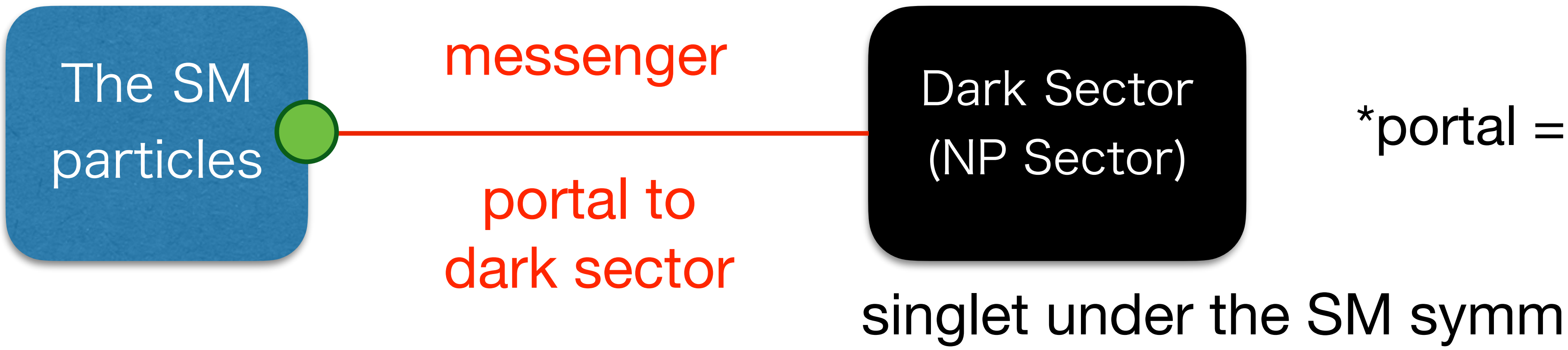


- When the DM annihilates through the weak int, its mass must be > 2 GeV to avoid overproduction. Lee and Weinberg, PRL 39 (1977)

- Introducing a new light force mediator, the DM can annihilate efficiently. Then, the DM can be lighter than 2 GeV. Boem and Fayet, Pospelov, et al

Dark Sector Model

Non-observation of BSM leads to the idea of ***"dark sector (NP sector)"*,** **which almost decouples from the SM sector.**



*portal = 入り口

- No direct interactions exist between the SM and dark particles.
- Messenger particle (portal) connects two sectors.

Dark Sector

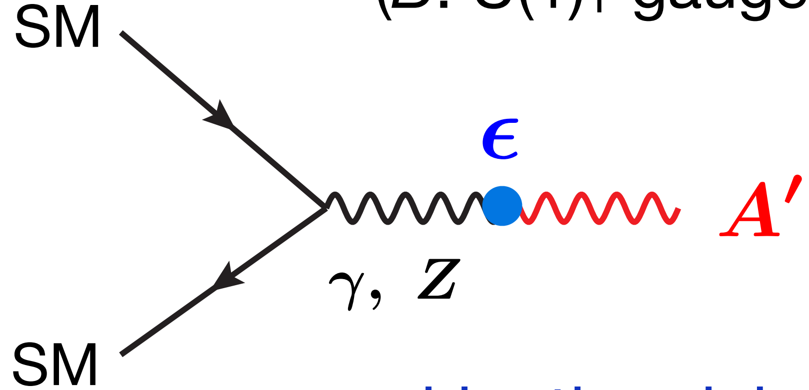
- "Dark Particles" are model(problem)-dependent.
- "Portal-SM Interactions" are rather model-independent.

Portals

There are **4 possible portals** invariant under the SM symmetries,

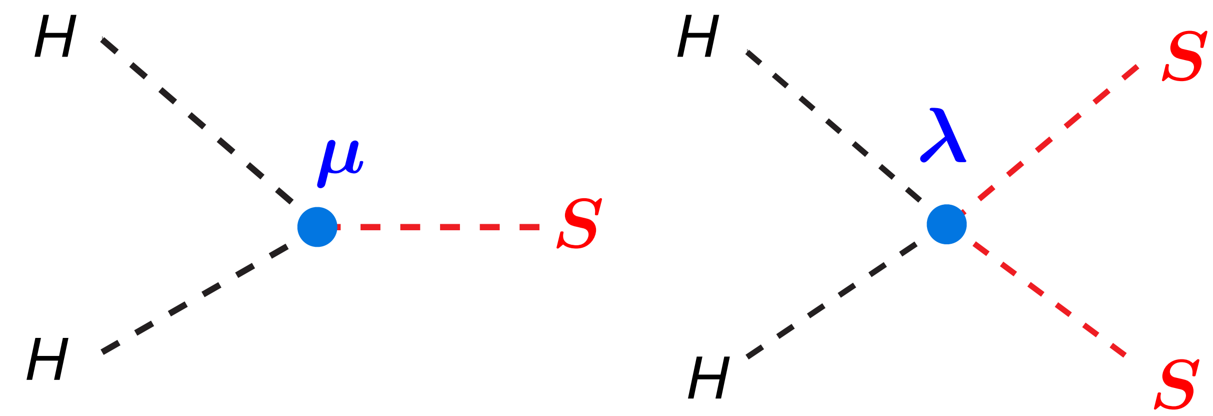
- Vector Portal : $\epsilon B_{\mu\nu} A'^{\mu\nu}$

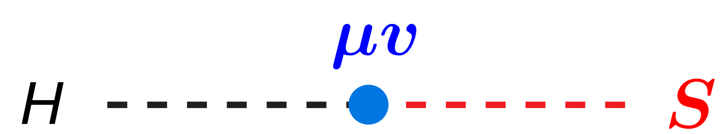
(*B*: $U(1)_Y$ gauge boson)



gauge kinetic mixing

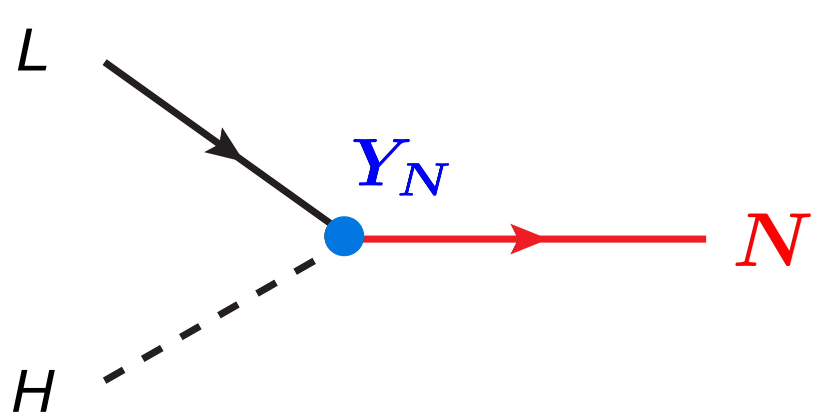
- Scalar Portal : $(\mu S + \lambda' S^2)|H|^2$





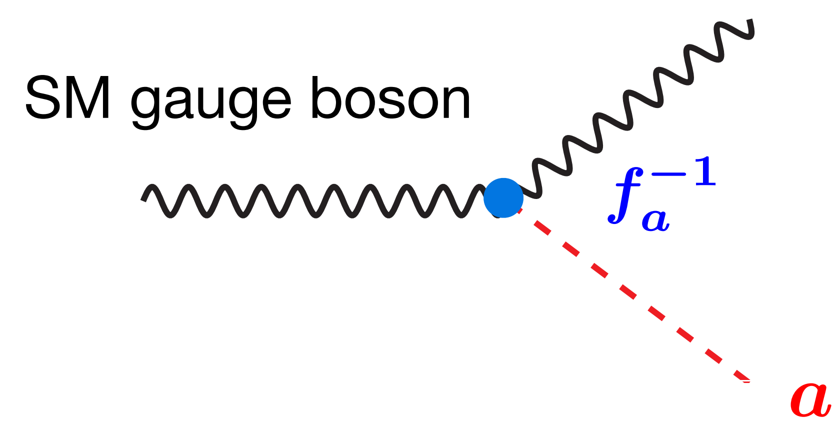
scalar mixing

- Fermion Portal : $Y_N \overline{L} H N$

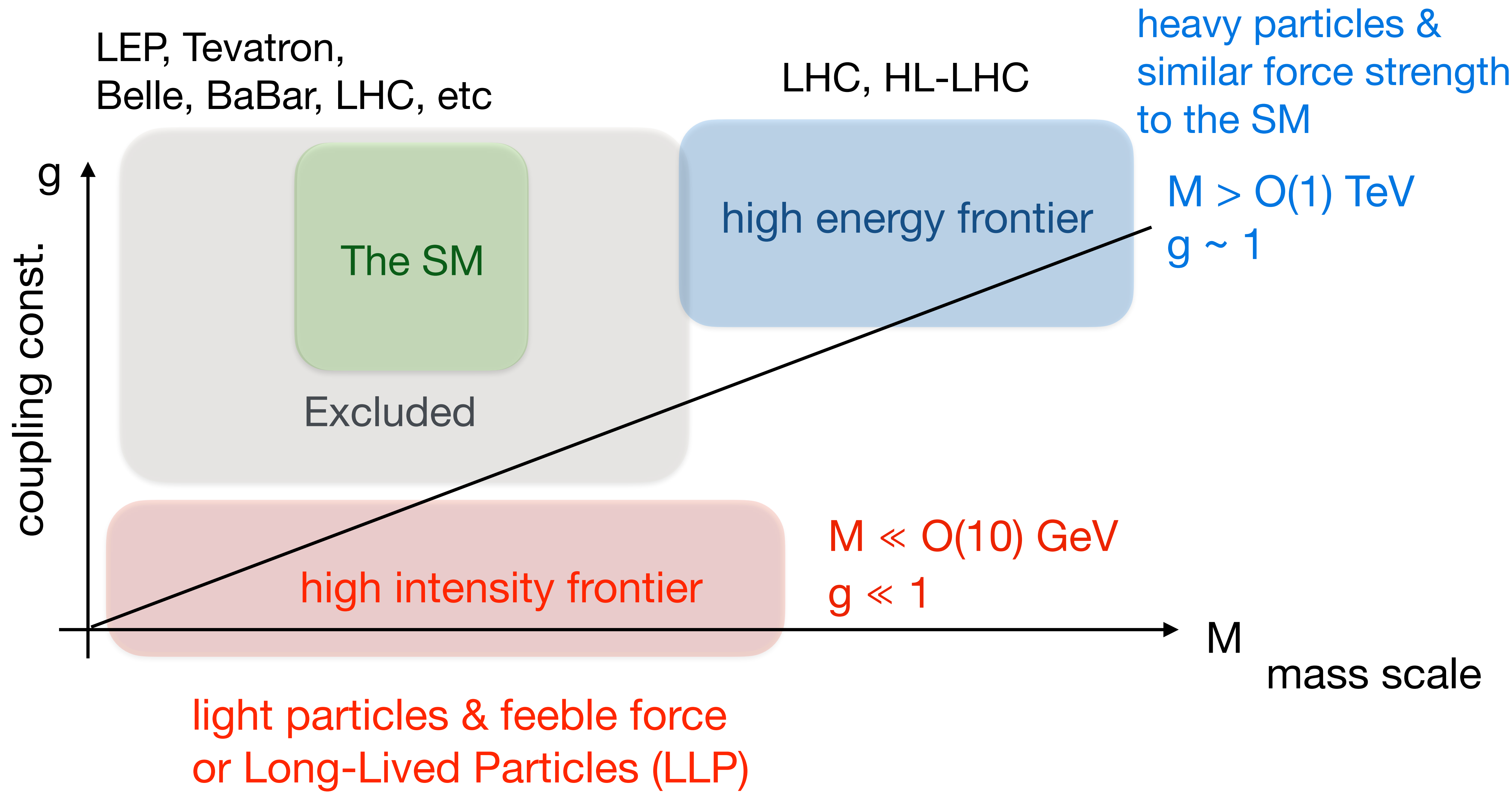


right-handed neutrino

- Axion Portal : $\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$



Energy Scale



Introduction

Experiments to search for light and feebly interacting particles

LHC

- FASER (dark photon/higgs, etc)

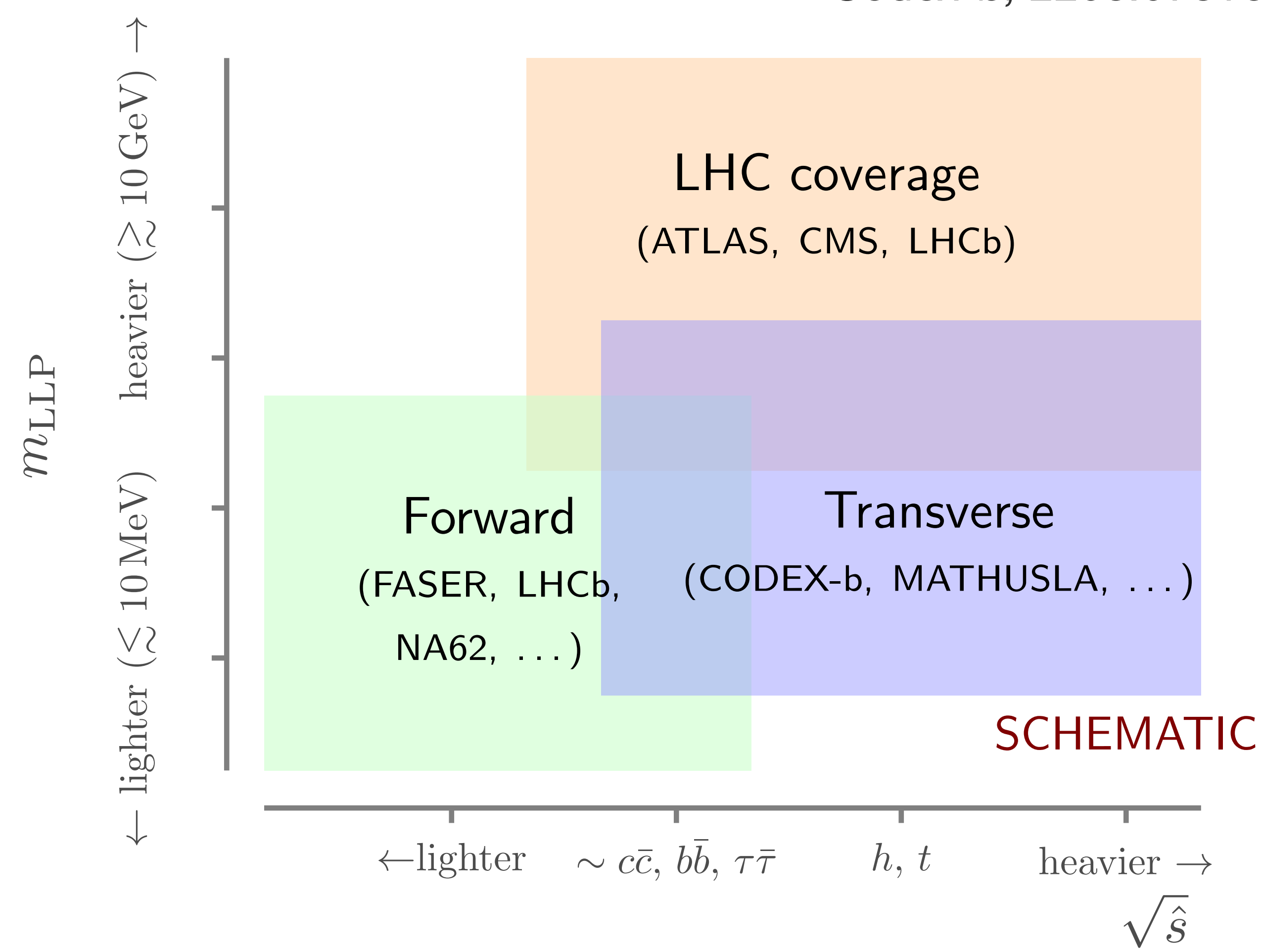
- CODEX-b
- MATHUSLA
- FACET

Collider

- Belle-II (dark photon)
- NA62 (heavy neutral lepton)
- NA64 (dark photon)

- SHiP (hidden particles)
- DUNE (heavy neutral lepton, trident)

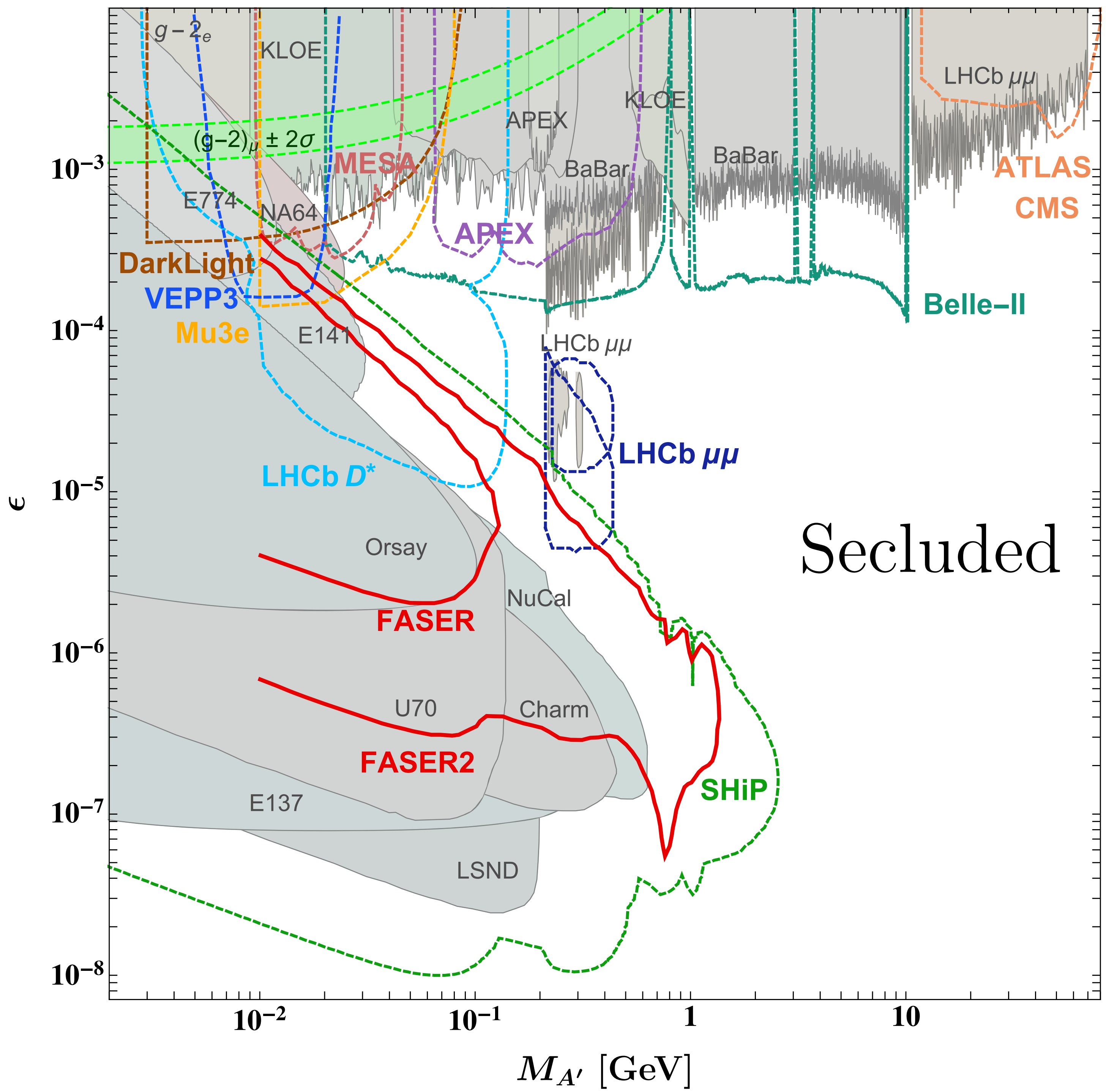
Codex-b, 2203.07316



Good time to consider light and feebly int. physics

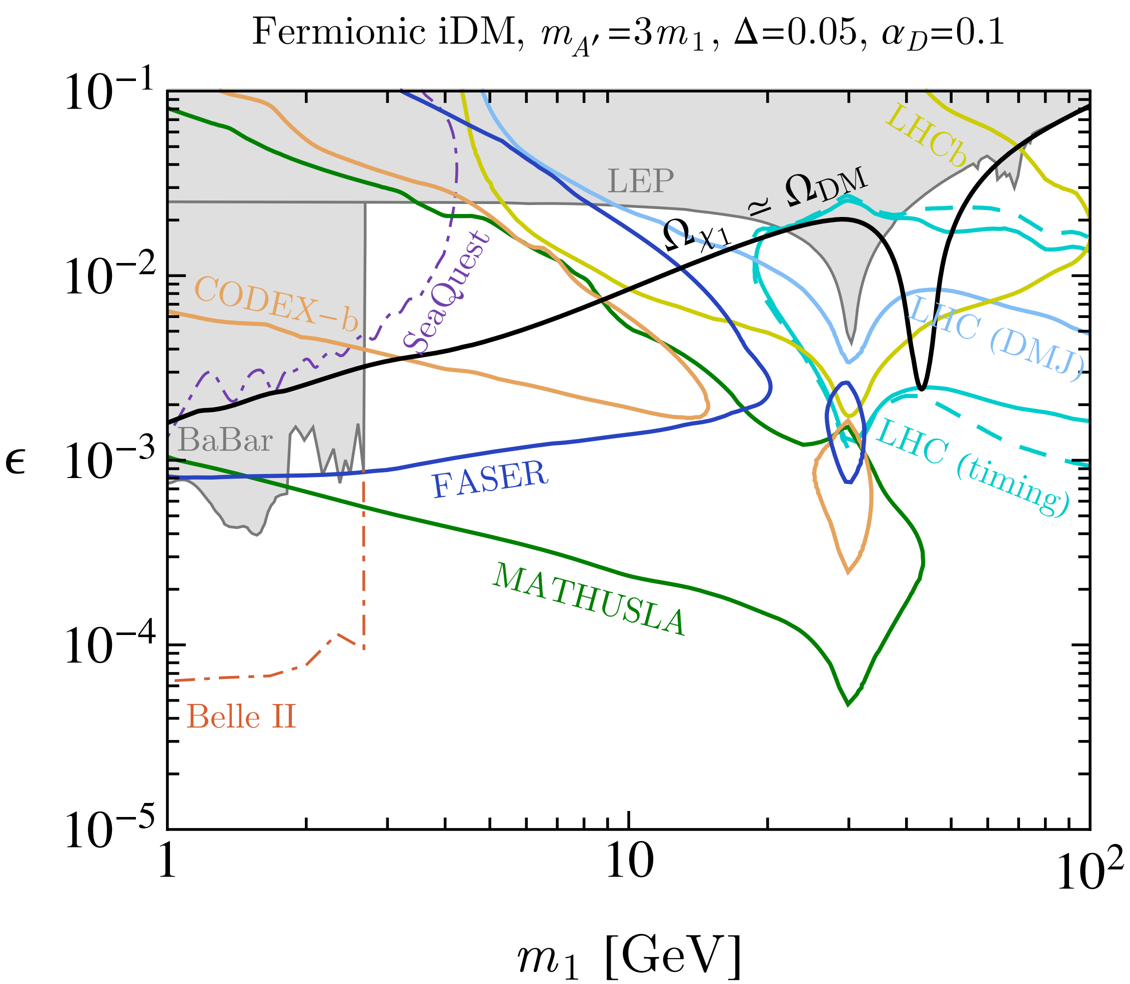
Vector Portals

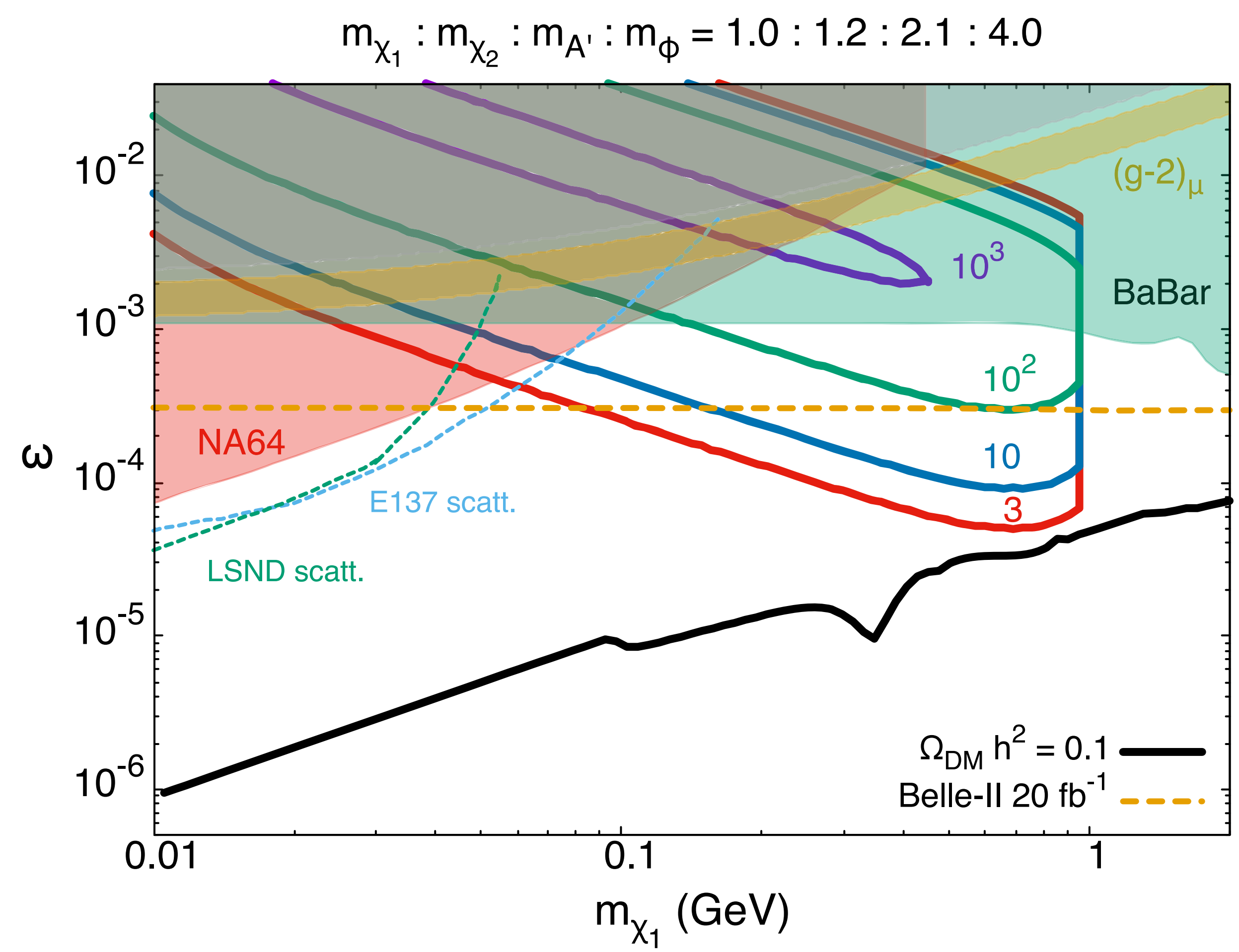
- Dark photon (vector portal)



Vector Portals

- Inelastic dark matter via vector mediator (portal)





What I want to do

- Feebly interacting particles or dark sectors appeared in low (light) scale are motivated by dark matter.
- High intensity experiments to search for BSM are running and proposed.

I want to study

- What mechanisms/models can be incorporated in dark sector?
  (origin of dark particles & neutrino mass)
- How small are CLFVs in such models?
  (typical patterns from symmetry?)

When you are interested in, let's discuss and collaborate!

What I want to do

Before building models,

- Is it possible to search for CLFV at experiments like FASER?
- If possible, how small can CLFV be?

Todays talk

- Show the sensitivity plot to CLFV coupling at FASER2
- Assuming some underlying model
- Focusing on the production from scalar bosons which generate masses and flavor violations.

Contents

1. Introduction
2. Interaction Lagrangians
3. FASER experiment
4. Production of light bosons
5. Sensitivity region
6. Summary

2. Interaction Lagrangian

Interaction Lagrangians

CLFV only in *e*-*μ* sector

The FASER detector will identify *e* and μ but be difficult for τ.

Four types of CLFV interactions

Scalar boson : Scalar(ϕ)- and Pseudoscalar(a)- type

Leptophilic Higgs doublet: $\mathcal{L} = y_{\alpha\beta}\bar{l}_\alpha \phi l_\beta + h.c.$

$\downarrow \; l_\alpha = V_{\alpha i} l_i$

Yukawa type CLFV int. $\mathcal{L} = V^\dagger y_{\alpha\beta} V \bar{l}_i \phi l_j + h.c.$

Vector boson : Vector(Z')- and Dipole(A')-type

$L_\mu - L_\tau$ gauge symmetry: $\mathcal{L} = g_{Z'} Z'_\mu \bar{l}_i \gamma^\mu V^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} V l_j$

U(1) dark photon model: No tree-level but loop-induced CLFV couplings to the SM particles

Scalar-type int.

$$\mathcal{L}_{\rm scalar} = \frac{\theta_{h\phi}}{v} \sum \underbrace{m_f \overline{f} \phi f}_{\text{CLFC int.}} + \underbrace{(y_{e\mu} \overline{e_L} \phi \mu_R + y_{\mu e} \overline{\mu_L} \phi e_R + \text{h.c.})}_{\text{CLFV int.}}$$

$\theta_{h\phi}$: mixing with the SM higgs

m_f : mass of the SM fermions

$y_{e\mu,\mu e}$: CLFV coupling

Pseudoscalar-type int.

$$\mathcal{L}_{\rm pseudoscalar} = \frac{\partial_\rho a}{\Lambda} \Big(\sum \underbrace{c_{ff} \overline{f} \gamma^\rho \gamma_5 f}_{\text{CLFC int.}} + \underbrace{c_{e\mu} \overline{e} \gamma^\rho \gamma_5 \mu + c^*_{e\mu} \overline{\mu} \gamma^\rho \gamma_5 e}_{\text{CLFV int.}} \Big)$$

Λ : a cutoff scale

c_{ff} : CLFC coupling

$c_{e\mu}$: CLFV coupling

Vector-type int.

$$\mathcal{L}_{\rm vector} = g_{Z'} Z'_\rho (\underbrace{s^2\ \bar{e}\gamma^\rho e + c^2\ \bar{\mu}\gamma^\rho \mu}_{\text{CLFC int.}} + \underbrace{sc\ \bar{\mu}\gamma^\rho e + sc\ \bar{e}\gamma^\rho \mu)}_{\text{CLFV int.}}$$

$$+ g_{Z'} Z'_\rho (-\bar{\tau}\gamma^\rho \tau + \overline{\nu_\mu}\gamma^\rho \nu_\mu - \overline{\nu_\tau}\gamma^\rho \nu_\tau)$$

$g_{Z'}$: gauge coupling

$s = \sin\theta,\ c = \cos\theta$

θ : LFV mixing

Dipole-type int.

$$\mathcal{L}_{\rm dipole} = \frac{1}{2} \sum_{\ell = e,\mu,\tau} \underbrace{\mu_\ell \bar{\ell} \sigma^{\rho\sigma} \ell A'_{\rho\sigma}}_{\text{CLFC int.}} + \frac{\mu'}{2} \underbrace{(\bar{\mu}\sigma^{\rho\sigma} e + \bar{e}\sigma^{\rho\sigma}\mu) A'_{\rho\sigma}}_{\text{CLFV int.}}$$

μ_l : CLFC dipole coupling

μ' : CLFV dipole coupling

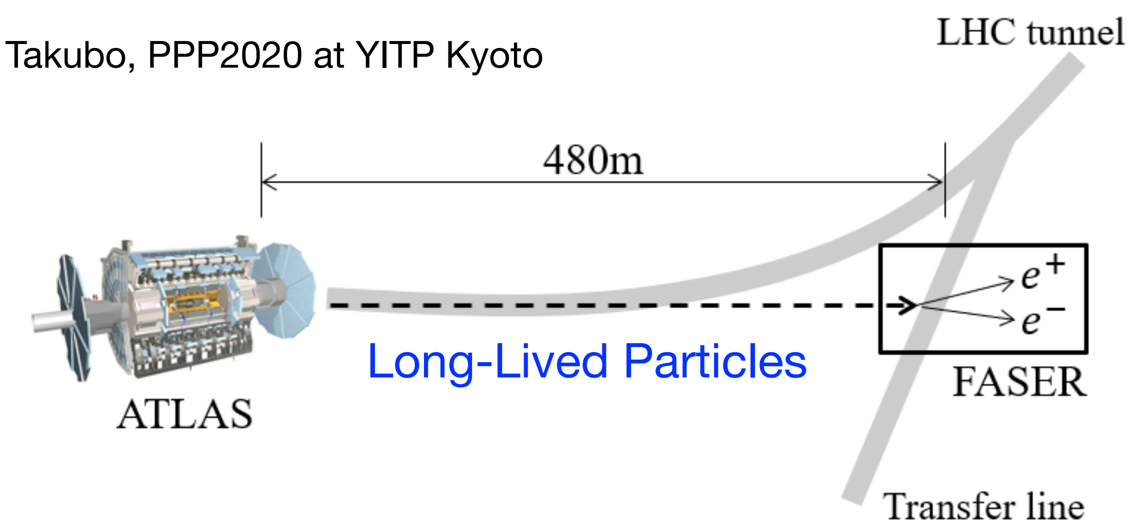
3. FASER experiment

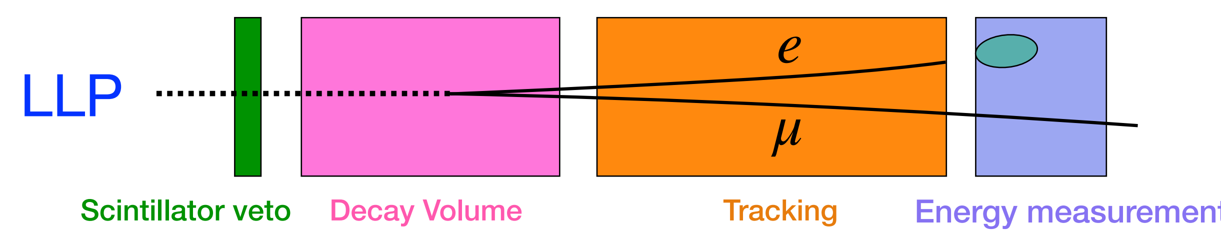
FASER experiment

Feng, Galon, Kling, Trojanowski, PRD97 (2018)
"The FPF at HL-LHC", arXiv:2203.05090

- ForwArd Search ExpeRiment (FASER) at LHC, starting from 2022.
- Detector is placed 480m downstream from the ATLAS interaction point.
- Search for long lived particles such as dark photon, dark Higgs, Axion-like particle, etc.

Takubo, PPP2020 at YITP Kyoto



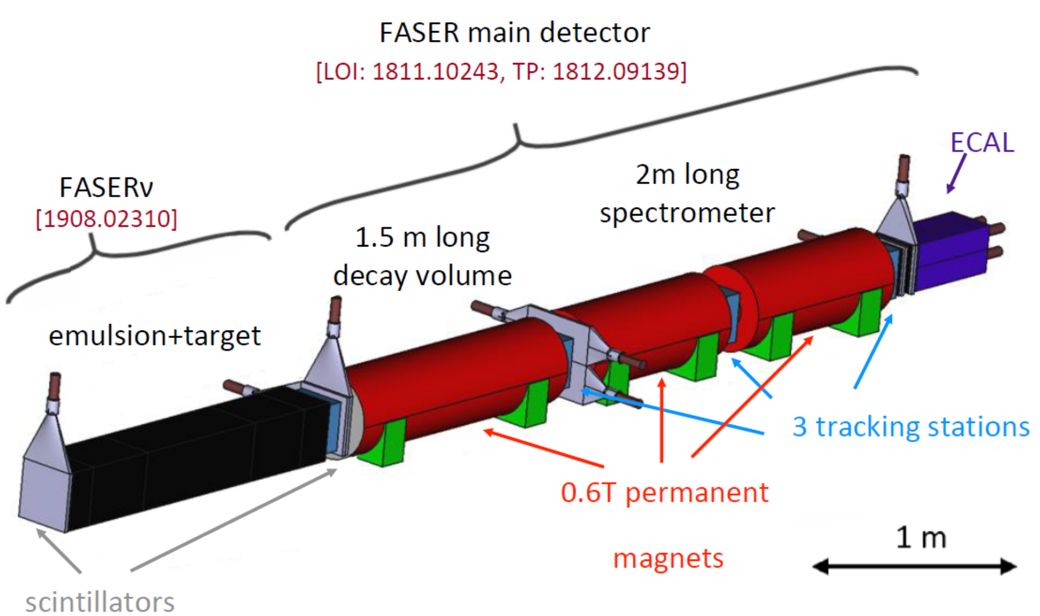


- CLFV decays of LLP will be identified.
  - separation of $e\mu$ with opposite charges.
  - two tracks with the same momentum, originated from the same vertex.
  - half of energy deposit compared to the total energy of two tracks.

FASER 2 detector

- Upgrade of the FASER detector is also planned at High-Luminosity LHC.
- The detector will be enlarged to increase statistics hundred times larger than FASER.

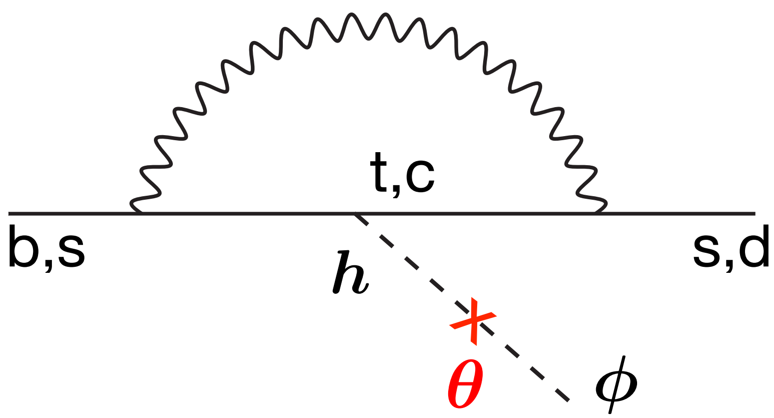
	length of decay volume		radius	integrated luminosity
	$L_{\rm min}$ (m)	$L_{\rm max}$ (m)	R (m)	$\mathcal{L}$ ($\rm ab^{-1}$)
FASER	478.5	480	0.1	0.15
FASER 2	475	480	1.0	3.0

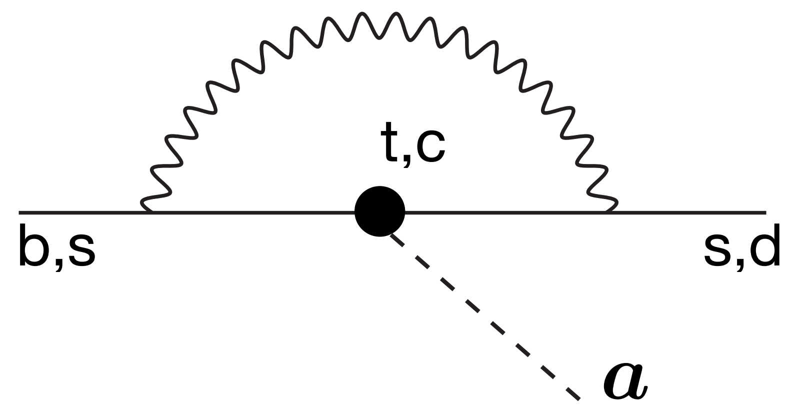


4. Production of light bosons

Production of scalar boson

- The scalar bosons ϕ can be produced from meson decays via the mixing with the SM Higgs boson.
- The pseudoscalar boson a also can be produced via the direct coupling.



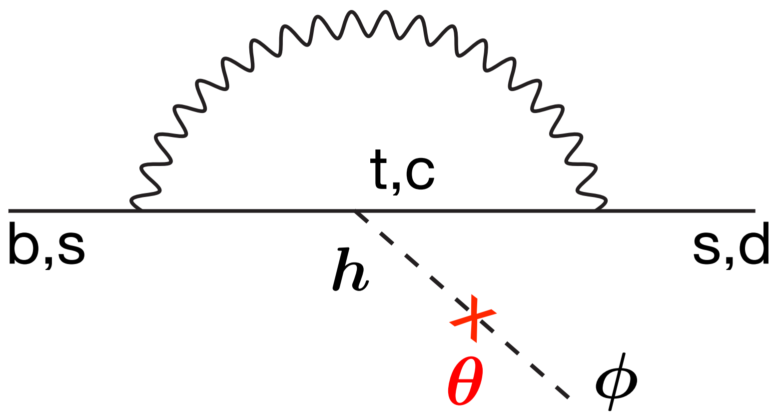


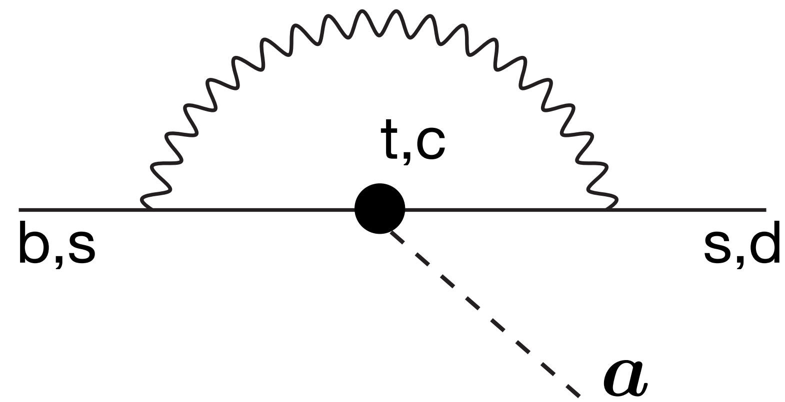
- Numbers of *B* and *K* meson are 10^{15} and 10^{17} for the HL-LHC case.
- The branching ratio Br($K \to \phi$) is 10^{-3} times smaller than Br($B \to \phi$).

B meson is a main source of the scalar boson

Production of scalar boson

- The scalar bosons ϕ can be produced from meson decays via the mixing with the SM Higgs boson.
- The pseudoscalar boson a also can be produced via the direct coupling.





Branching ratio of *B* decay

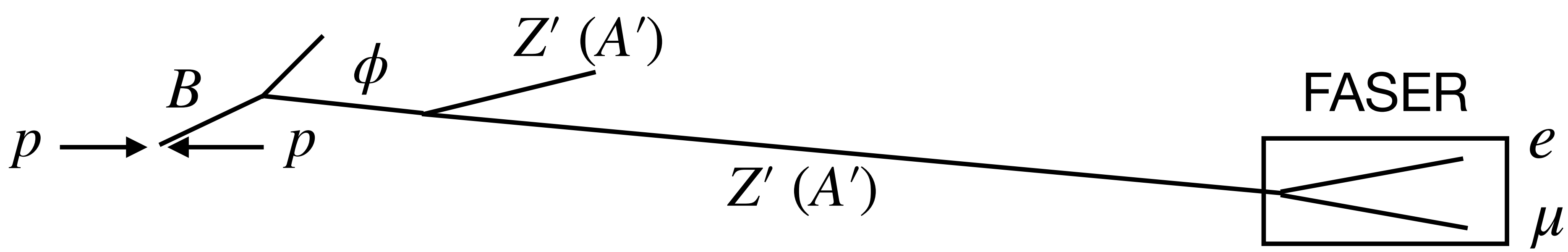
$$\mathrm{Br}(B \to X_s \phi) \simeq 5.7 \left(1 - \frac{m_\phi^2}{m_b^2}\right)^2 \theta_{h\phi}^2$$

$$\mathrm{Br}(B \to X_s a) \simeq \left[3.1 \left(1 - \frac{m_a^2}{m_B^2}\right) + 3.7 \left(1 - \frac{m_a^2}{m_B^2}\right)^3\right] \times \frac{4v^2 c_{tt}^2}{\Lambda^2}$$

Production of vector boson

- The vector bosons Z' and A' can not be produced from meson decays due to no direct couplings to quarks.
- Symmetry-breaking scalar bosons are expected to exist because the gauge bosons are massive.

The gauge boson can be produced through the decay of this scalar boson



Branching ratio of *B* decay

$$\Gamma(\phi \to GG) = \frac{g_G^2}{8\pi} \frac{m_G^2}{m_\phi} \left(2 + \frac{m_\phi^4}{4m_G^4} \left(1 - \frac{2m_G^2}{m_\phi^2} \right)^2 \right) \sqrt{1 - \frac{4m_G^2}{m_\phi^2}} \quad (G = Z',\, A')$$

The gauge bosons are dominantly produced due to longitudinal mode enhancement

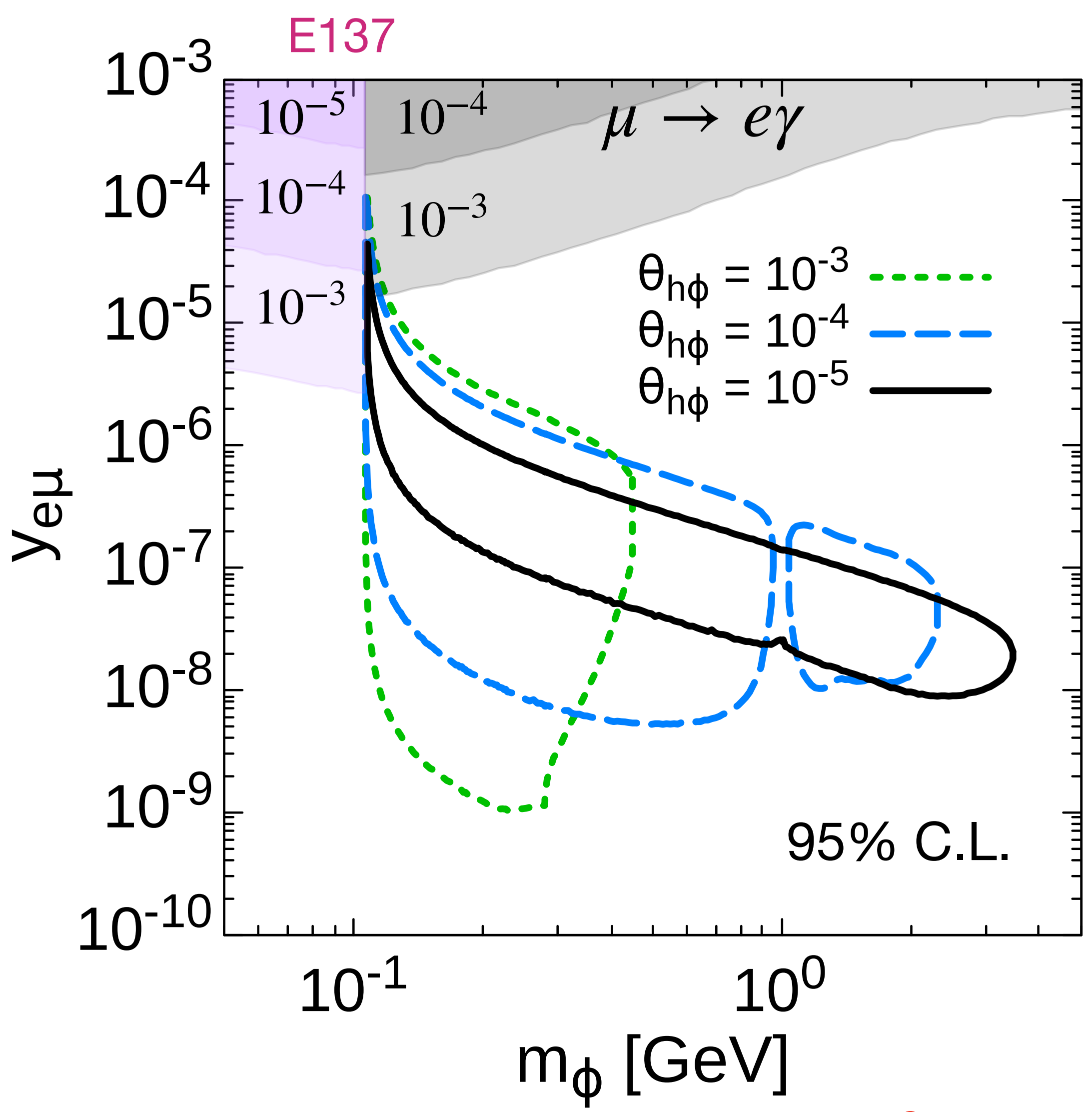
4. Sensitivity Region at FASER2

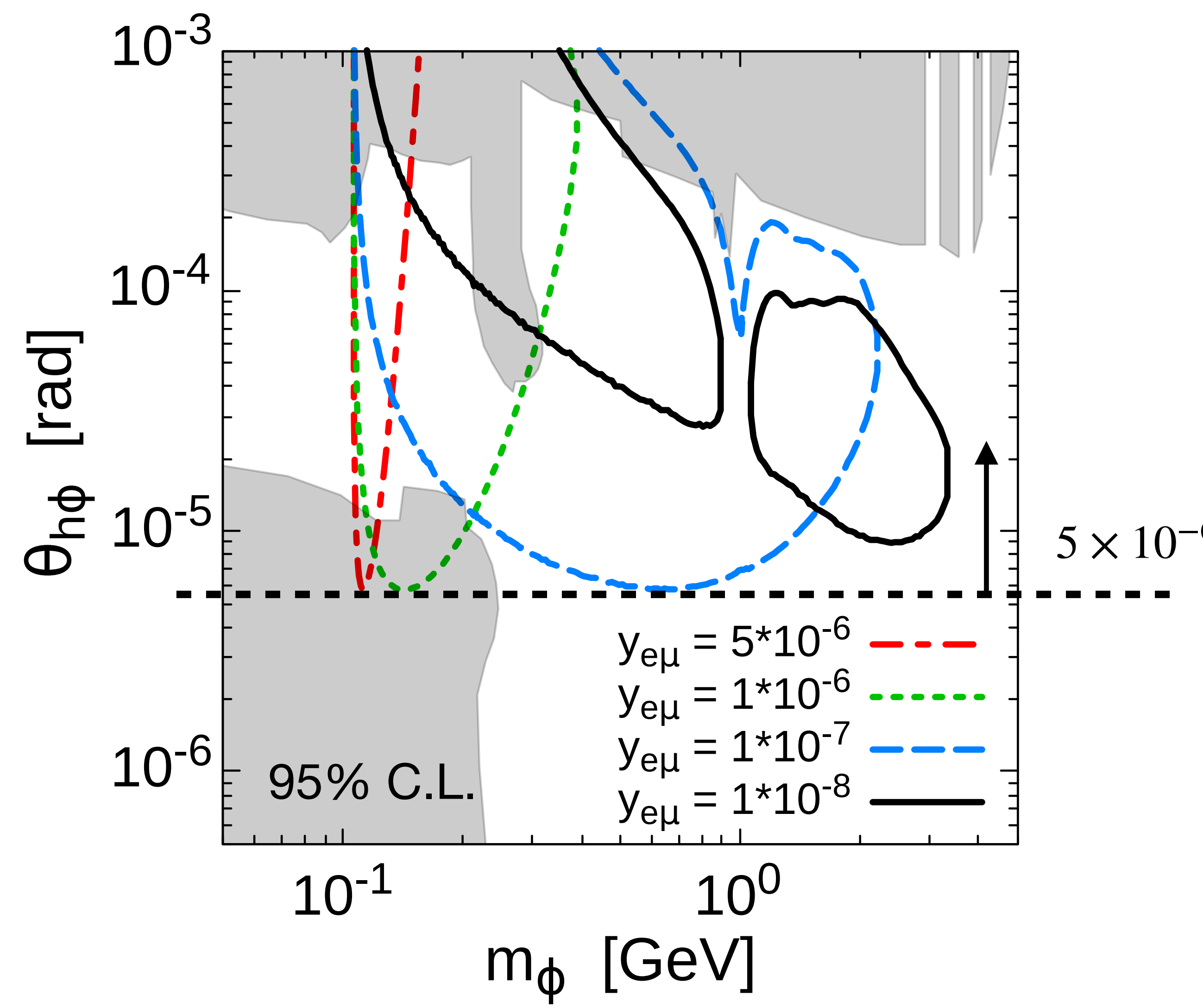
No 95% C.L. region were found for FASER due to the detector size and luminosity.

Scalar-type int.

$$\mathcal{L}_{\text{scalar}} = \frac{\theta_{h\phi}}{v} \sum m_f \overline{f} \phi f + (y_{e\mu} \overline{e_L} \phi \mu_R + y_{\mu e} \overline{\mu_L} \phi e_R + \text{h.c.})$$

($y_{e\mu} = y_{\mu e}$ and real)



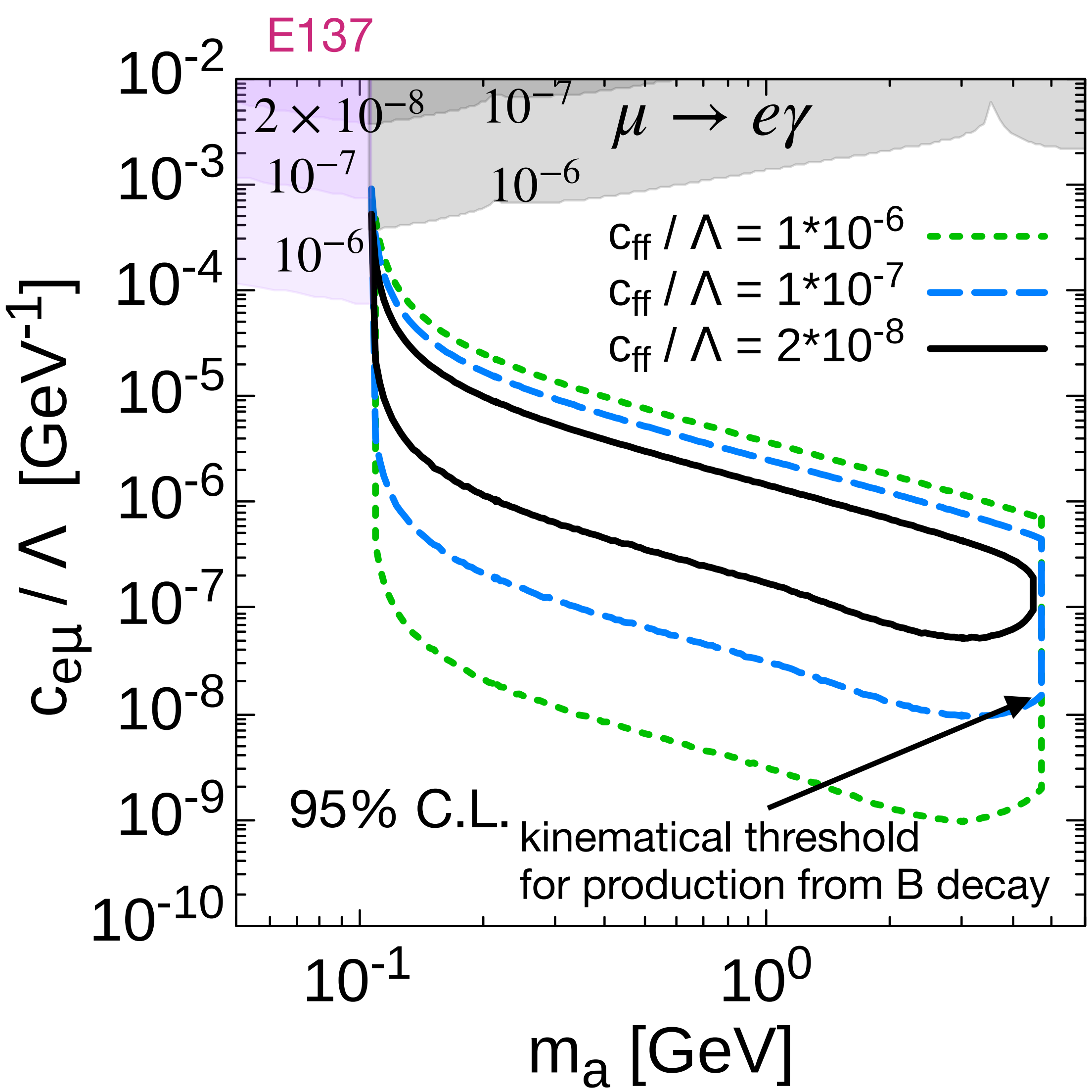


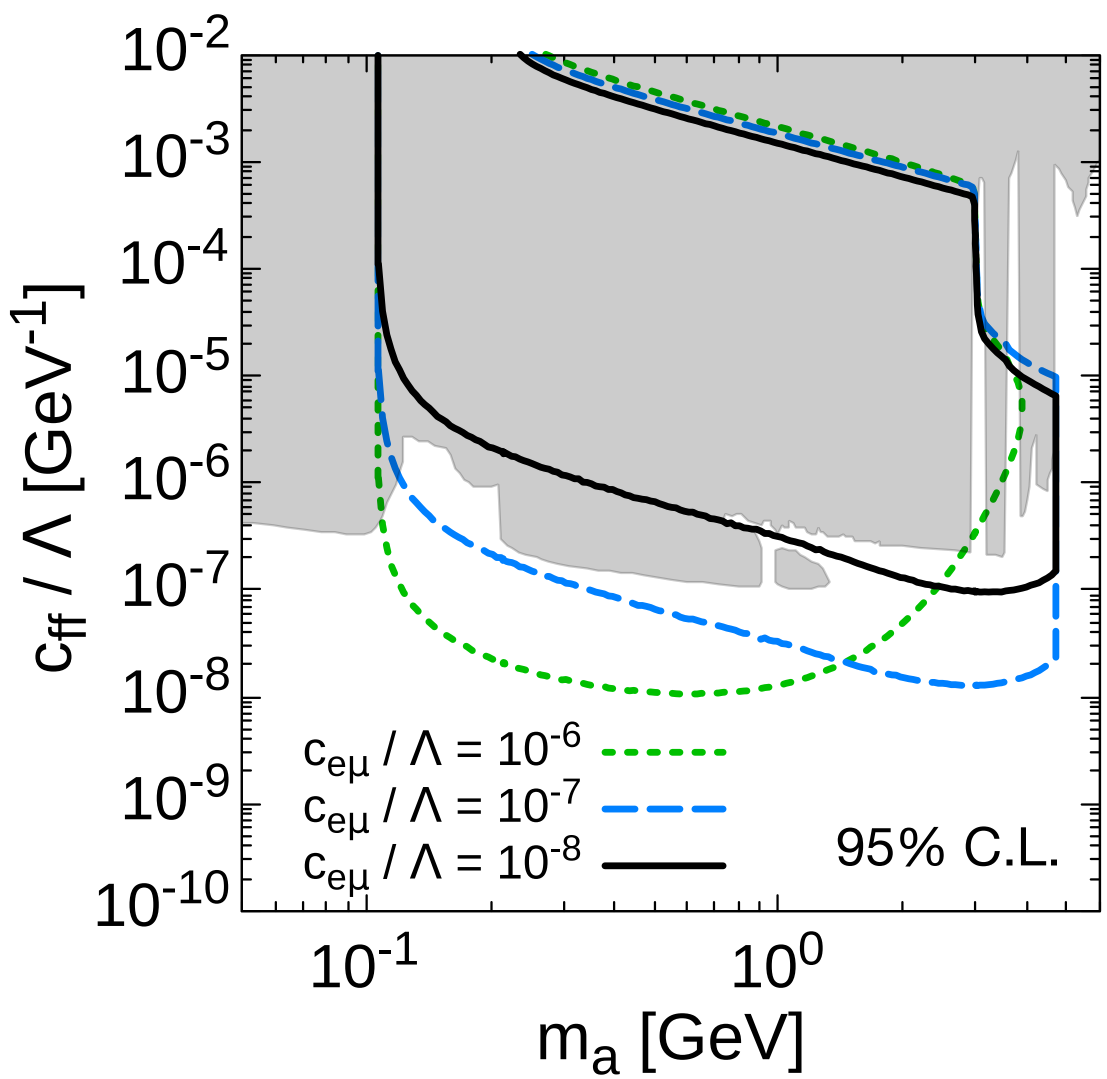
- total decay width $\propto \theta_{h\phi}^2$
- shorter-lived (decay into 2 mesons) in heavy mass region

Pseudoscalar-type int.

$$\mathcal{L}_{\text{pseudoscalar}} = \frac{\partial_\rho a}{\Lambda}\left(\sum c_{ff}\bar{f}\gamma^\rho\gamma_5 f + c_{e\mu}\bar{e}\gamma^\rho\gamma_5\mu + c^*_{e\mu}\bar{\mu}\gamma^\rho\gamma_5 e\right)$$

(c_{ff} is common)

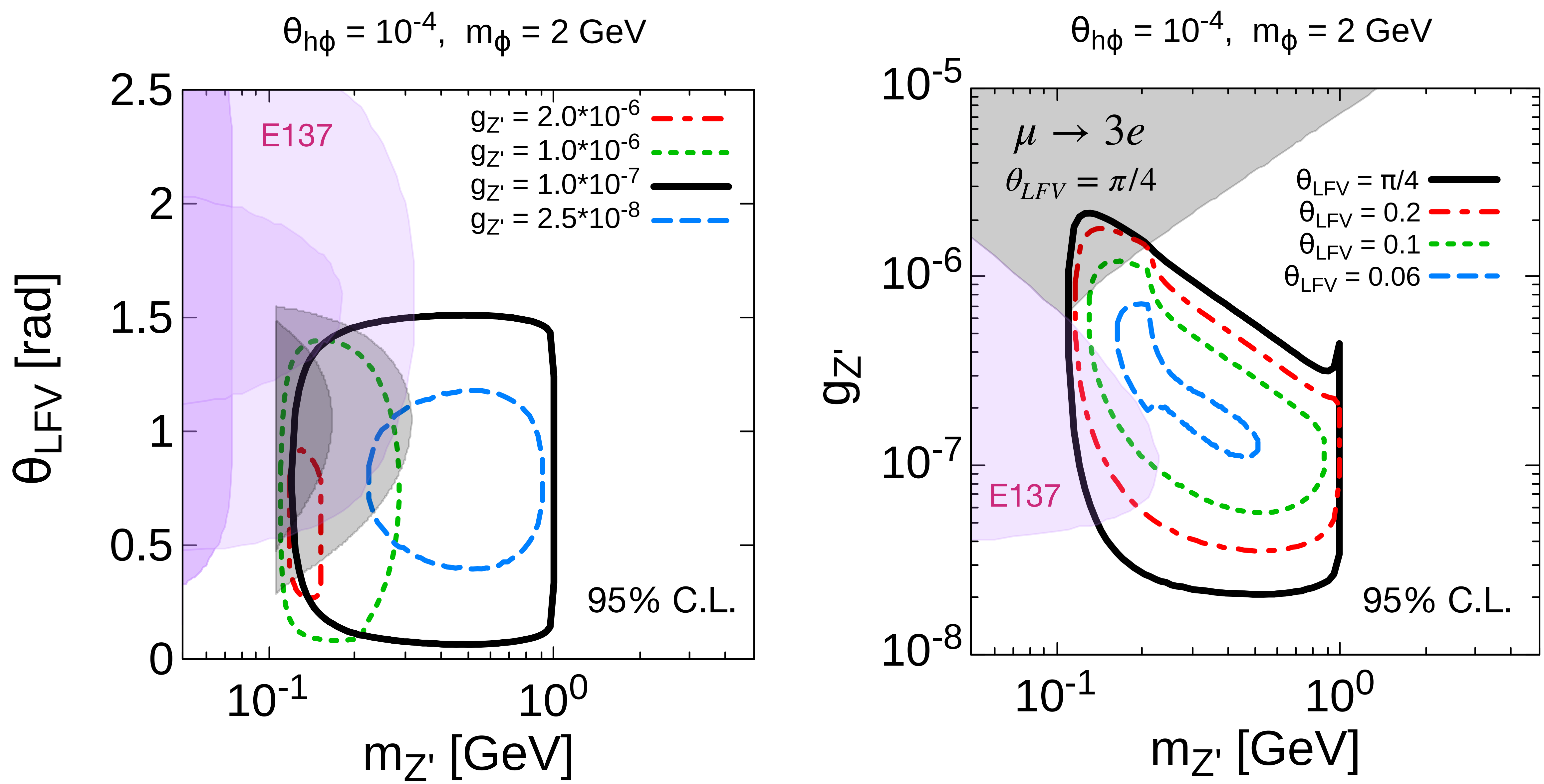




- longer-lived than scalar boson
  (decay into 2 mesons is forbidden)

Vector-type int.

$$\mathcal{L}_{\rm vector} = g_{Z'} Z'_\rho (s^2\ \bar{e}\gamma^\rho e + c^2\ \bar{\mu}\gamma^\rho \mu + sc\ \bar{\mu}\gamma^\rho e + sc\ \bar{e}\gamma^\rho \mu)$$
$$+ g_{Z'} Z'_\rho (-\bar{\tau}\gamma^\rho \tau + \overline{\nu_\mu}\gamma^\rho \nu_\mu - \overline{\nu_\tau}\gamma^\rho \nu_\tau)$$

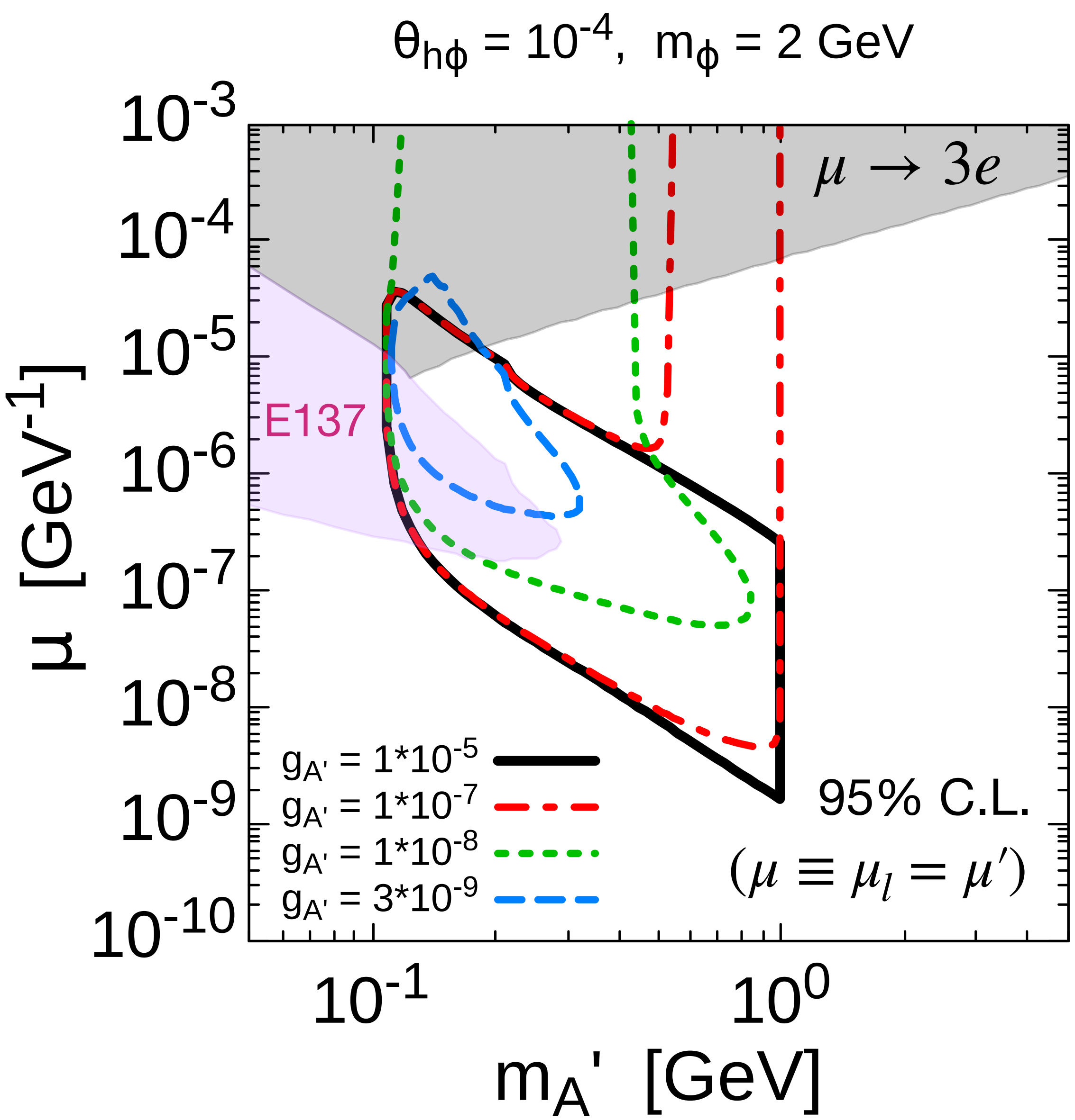


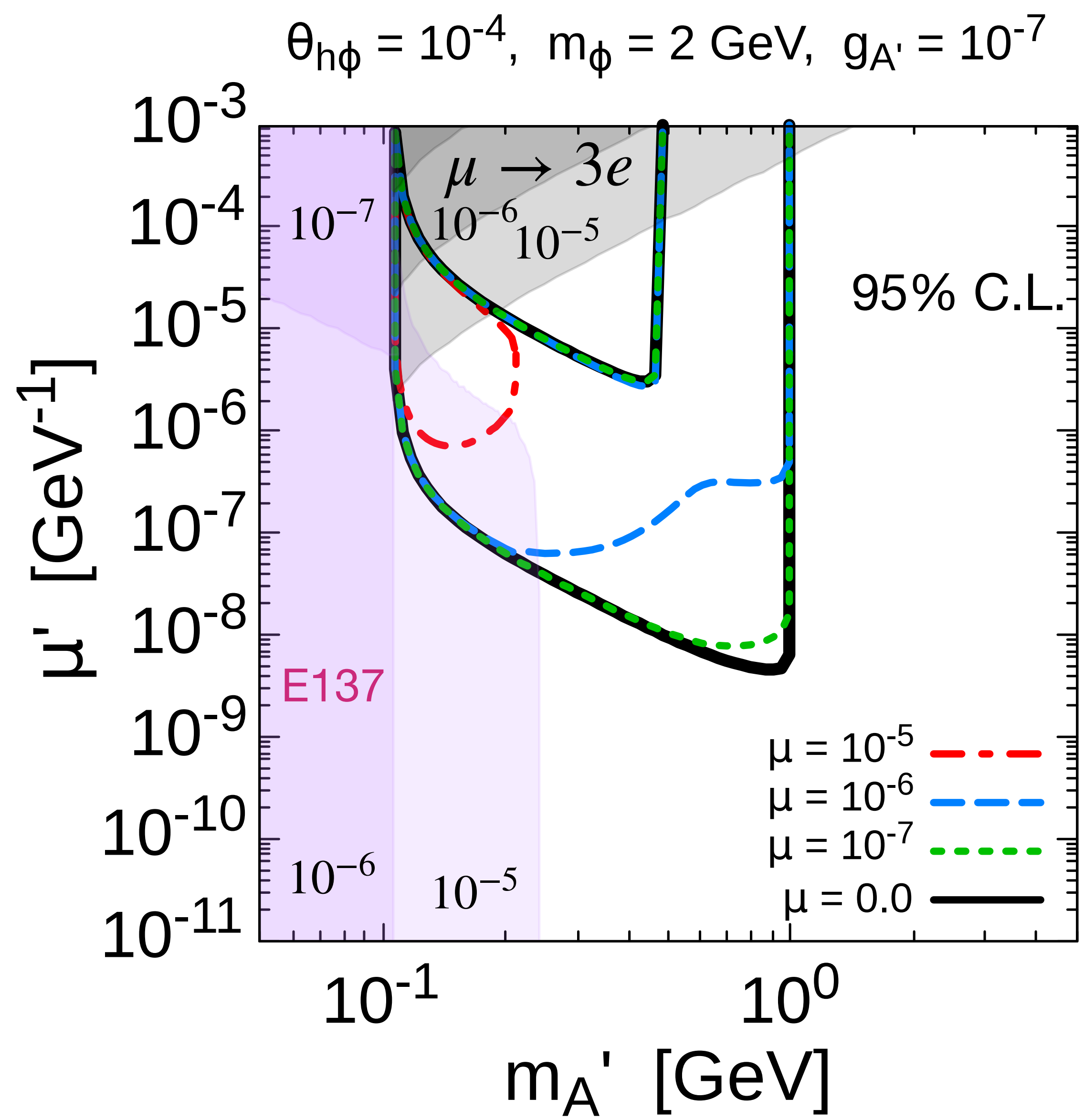
- decay length of ϕ and Z' $\propto g_{Z'}^2$

➡ $g_{Z'}$ is restricted

Dipole-type int.

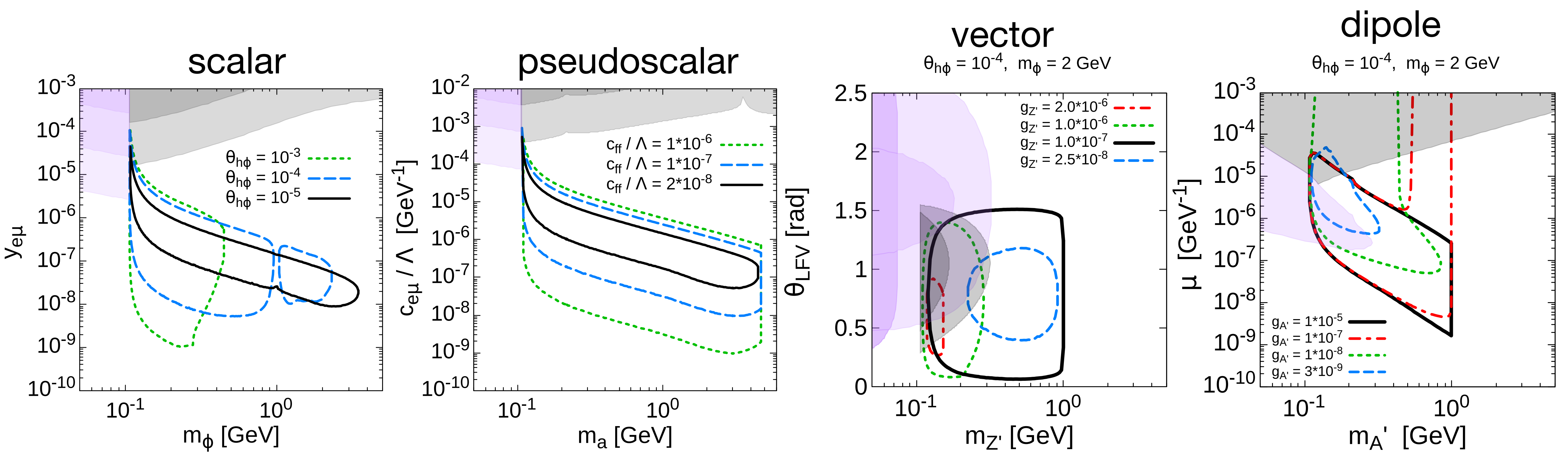
$$\mathcal{L}_{\text{dipole}} = \frac{1}{2} \sum_{\ell=e,\mu,\tau} \mu_\ell \bar{\ell} \sigma^{\rho\sigma} \ell A'_{\rho\sigma} + \frac{\mu'}{2} \left(\bar{\mu} \sigma^{\rho\sigma} e + \bar{e} \sigma^{\rho\sigma} \mu \right) A'_{\rho\sigma}$$





Summary

- We have studied the possibility of searching for CLFV decays of light bosons at FASER.
  - Scalar, Pseudoscalar, Vector and Dipole type interactions were considered.
  - The decay of the bosons into *eμ* was analyzed at FASER/FASER2.
  - FASER 2 is sensitive to small CLFV coupling unexplored yet.

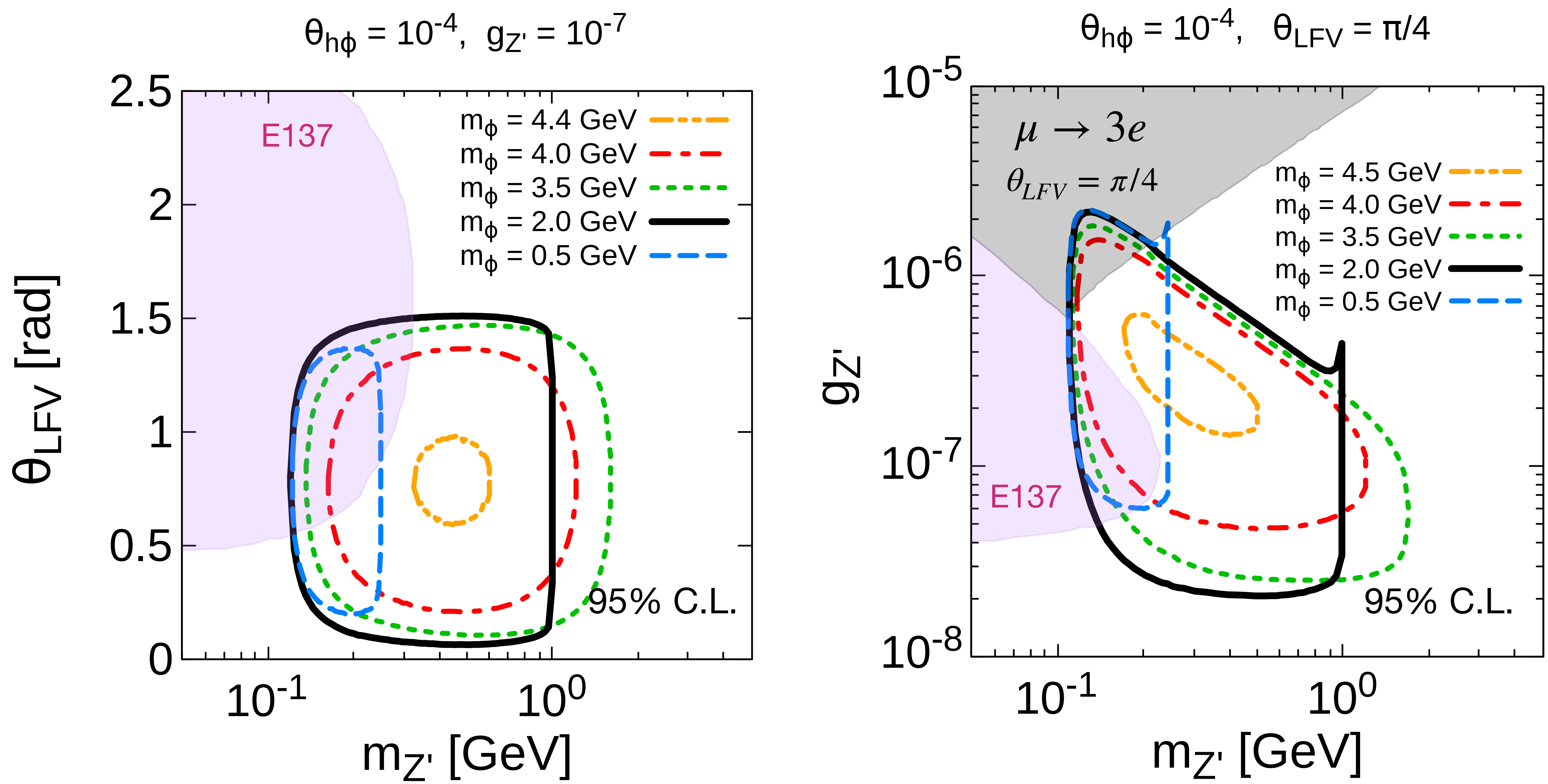


Thank you for your attention !

Back-Up Slides

Vector-type int.

$$\mathcal{L}_{\rm vector} = g_{Z'} Z'_\rho (s^2\ \overline{e}\gamma^\rho e + c^2\ \overline{\mu}\gamma^\rho \mu + sc\ \overline{\mu}\gamma^\rho e + sc\ \overline{e}\gamma^\rho \mu)$$
$$+ g_{Z'} Z'_\rho (-\overline{\tau}\gamma^\rho \tau + \overline{\nu_\mu}\gamma^\rho \nu_\mu - \overline{\nu_\tau}\gamma^\rho \nu_\tau)$$



- $\tau\tau$ channel open for $m_\phi > 3.5$ GeV

➡ # of Z' from *B* decay reduced

Dipole-type int.

$$\mathcal{L}_{\rm dipole} = \frac{1}{2}\sum_{\ell=e,\mu,\tau} \mu_\ell \bar{\ell}\sigma^{\rho\sigma}\ell A'_{\rho\sigma} + \frac{\mu'}{2}\left(\bar{\mu}\sigma^{\rho\sigma}e + \bar{e}\sigma^{\rho\sigma}\mu\right)A'_{\rho\sigma}$$