Dark Sector with Light Mediators

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Aso workshop on PPC 2023 @ Aso, Kumamoto on 14th November 2023

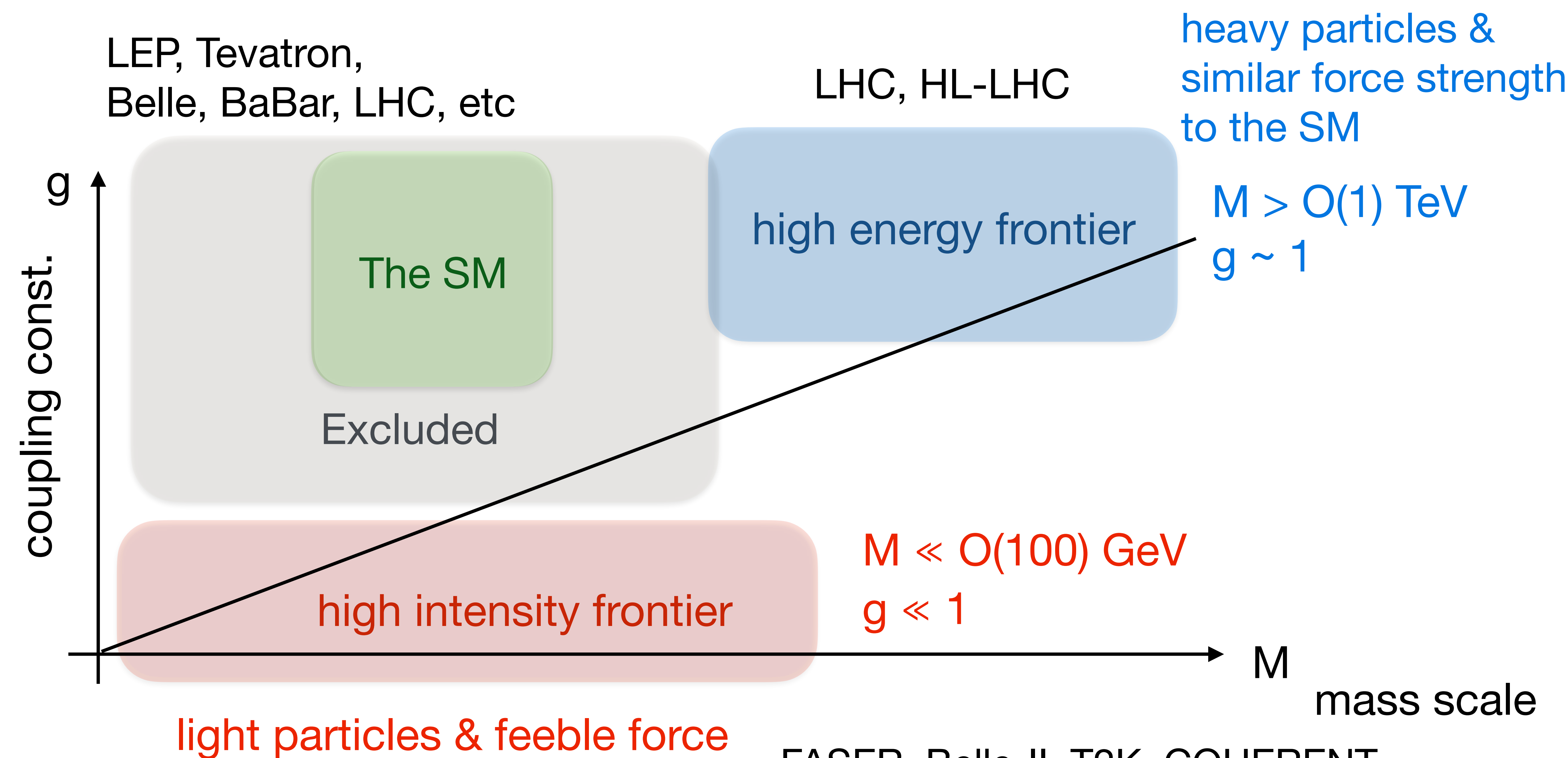
- Interested in physics regarding *light and feebly interacting particles*
  - IceCube gap and muon g-2 in $L_\mu - L_\tau$ model at Belle-II
  - Dark photon/B-L via dark higgs @ FASER and T2K
  - Lepton flavor violating decays @ FASER

    Araki san's talk
  - Inelastic dark matter @ FASER
  - Atomki anomaly

- Other possible new physics and also possibilities at other experiments
  - Axion-Like-Particles (incl. LFV)
  - Dark mesons (e.g. dark chiral symmetry breaking)
  - On-going experiments : Belle-II, FASER, T2K
  - Future/Planned : ILC beam dump, FACET, SHiP, DUNE etc.

- Let's discuss together when you are interested in

Light & feebly int.



FASER, Belle-II, T2K, COHERENT,
NA64, NA62,
CODEX-b, FACET, MATHUSLA,
SHiP, $NA64_\mu$, DUNE, ILC, APEX,
MESA,VEPP3, Mu3e, etc…

New Physics Scale

- Naively, new light particles suggest **low scale new physics**.

  It could be as low as and/or slightly above new particle masses.

- Such particles can be signatures of **high scale new physics**.

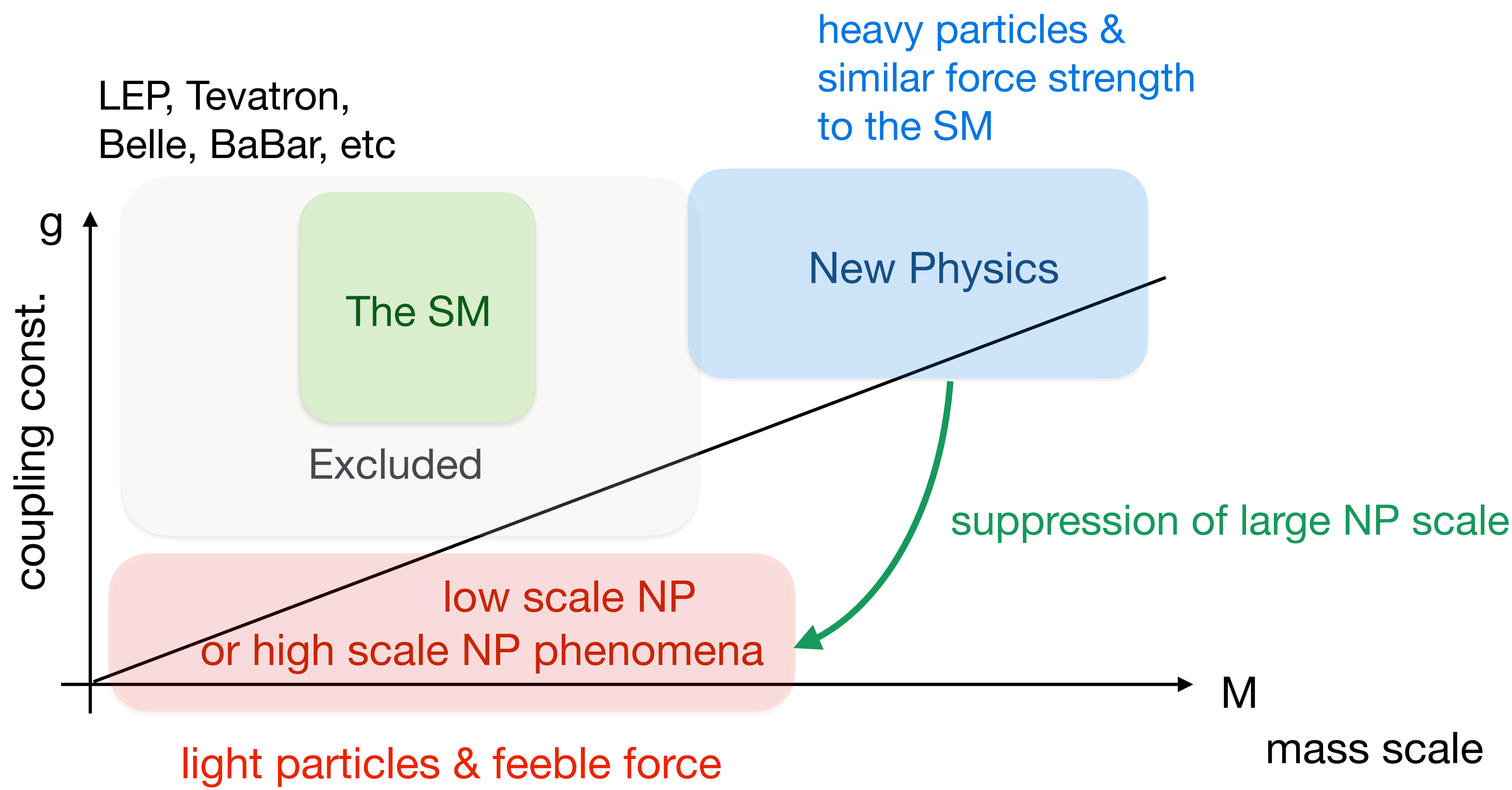
  e.g.
  - Gravity is very much weak (and graviton is massless), even though it is the Planck scale physics.
  - Neutrino masses are tiny, which could originate from EW Dirac and super-heavy Majorana masses (seesaw).
  - Axion mass and coupling are O(1) meV and O(10^{-12}) /GeV for the breaking scale of PQ symmetry, $f_A \sim 10^9$ GeV.

e.g. dark photon
  - Suppose a new gauge boson of $U(1)_D$, with mass *O*(100) MeV and the coupling *O*(10^{-4}).

    The breaking scale of $U(1)_D$ is estimated as

$$v_\phi = \frac{M}{g'} = \mathcal{O}(1)\ \mathrm{TeV}$$

New Physics Scale



high intensity frontier covers

Both low scale and high scale new physics

LLP search experiments

Experiments to search for light and feebly interacting particles

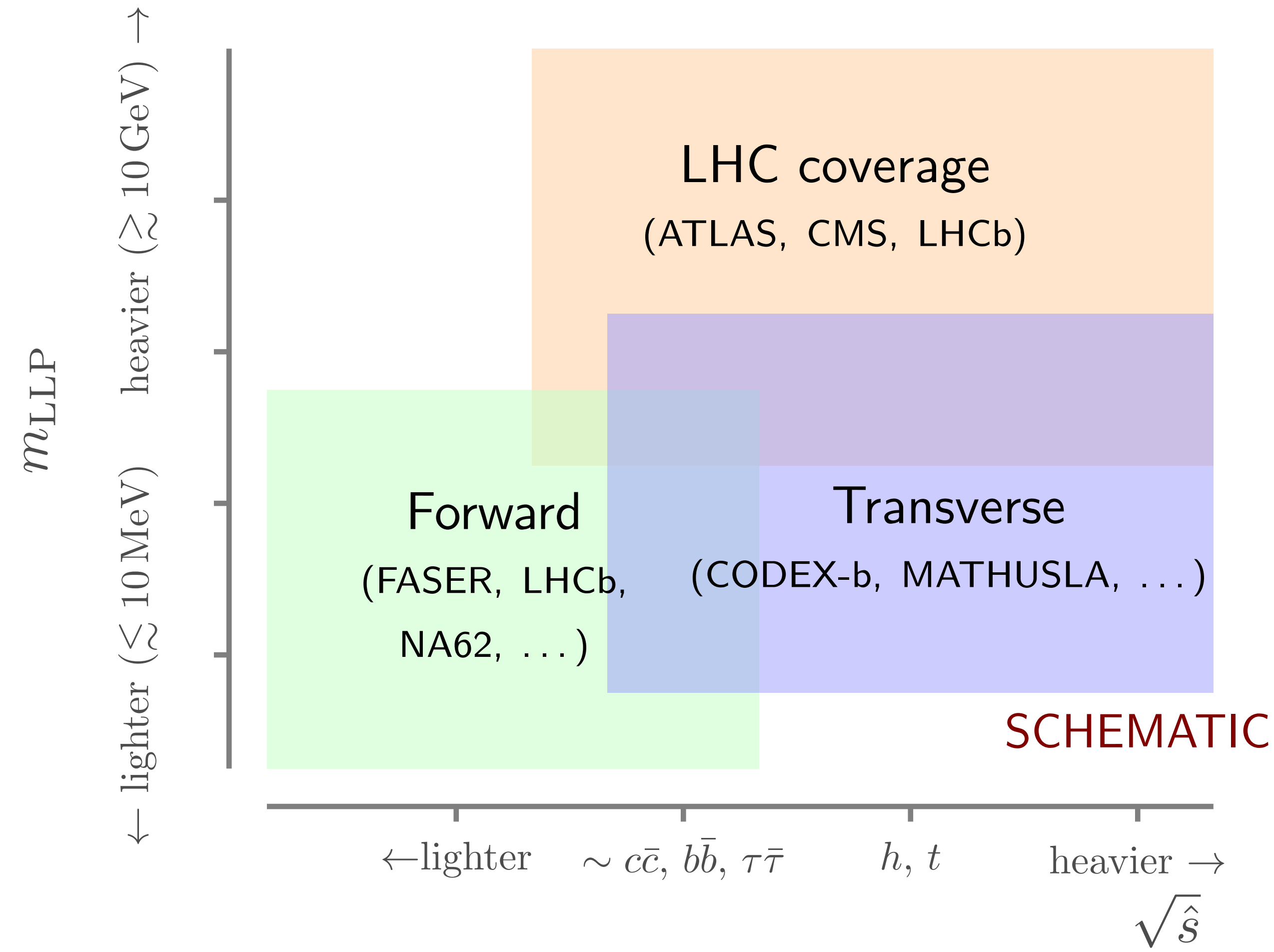
LHC

- 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

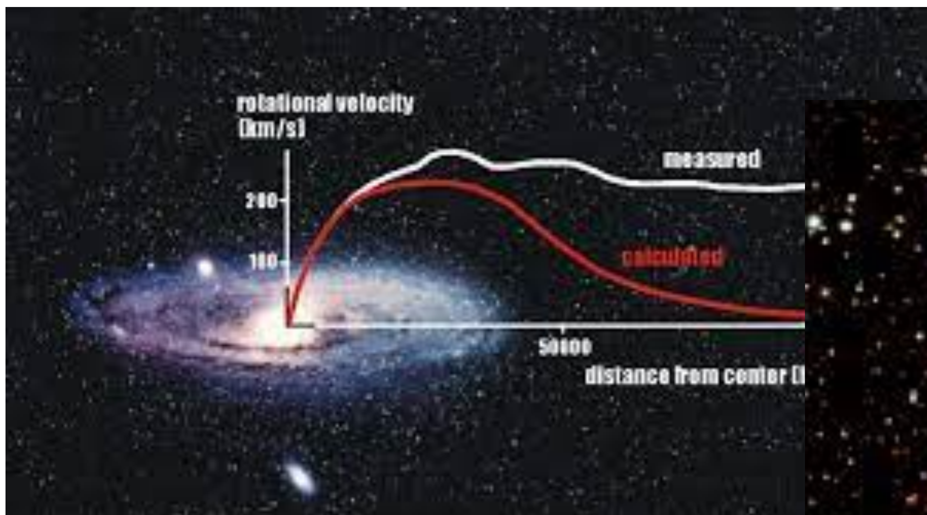


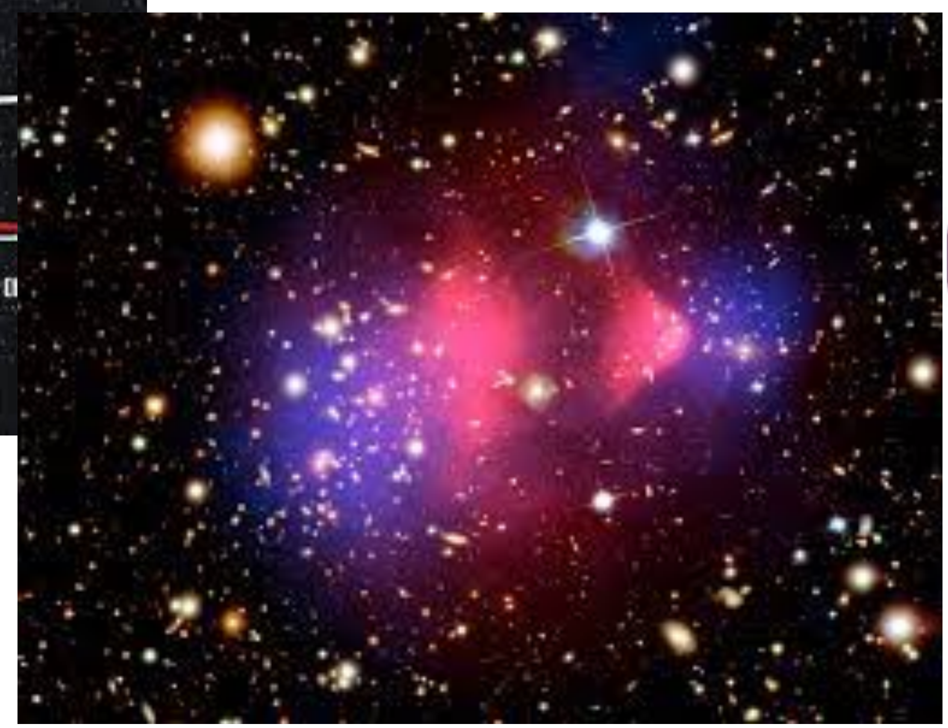
Good time to consider light and feebly int. physics

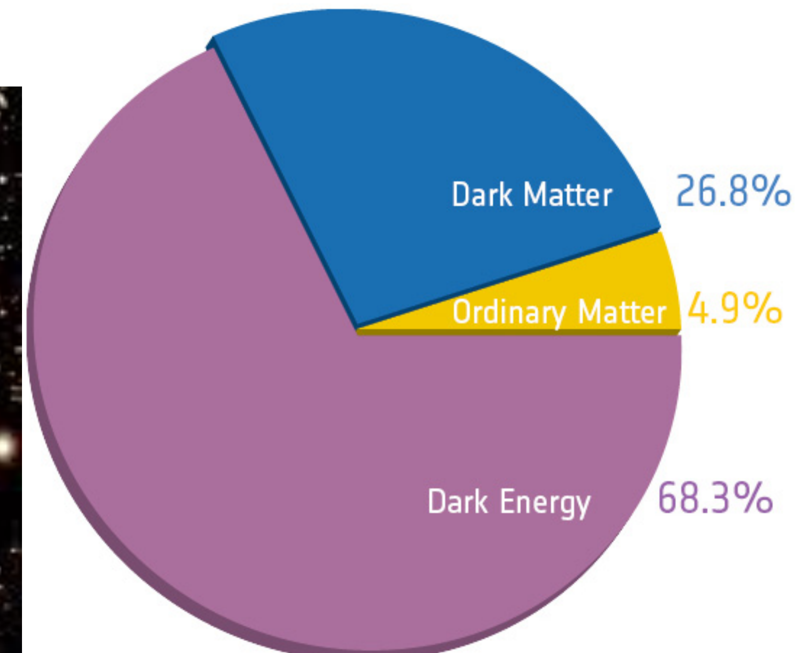
Main Motivation

Dark Matter

- One of the major open questions in particle physics and cosmology



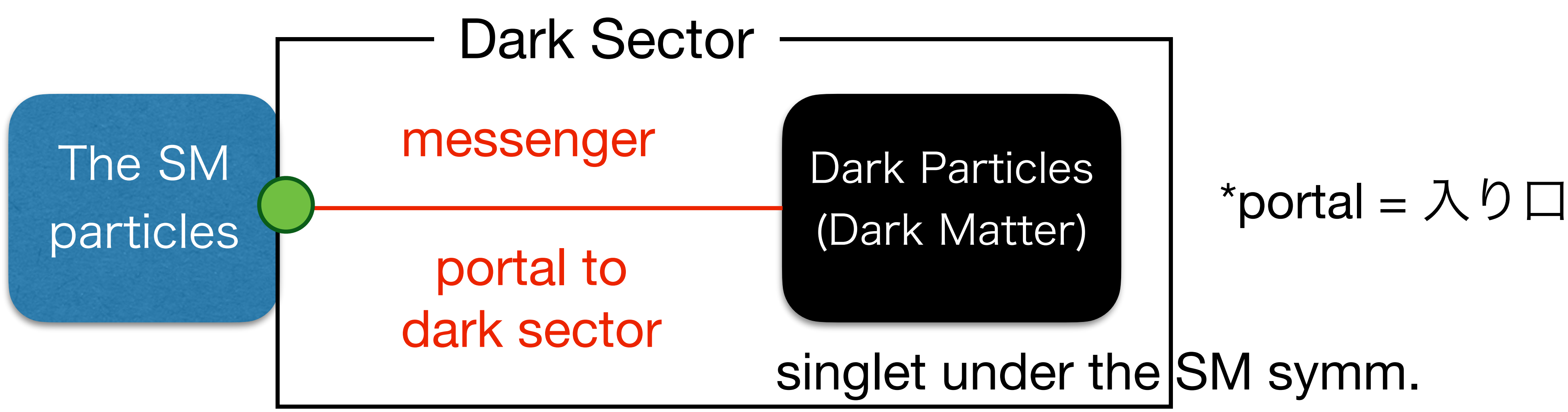




- No candidates in the Standard Model (SM) particle content
- New neutral massive particle weakly coupled to the matter

Dark Sector

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



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

Dark Sector

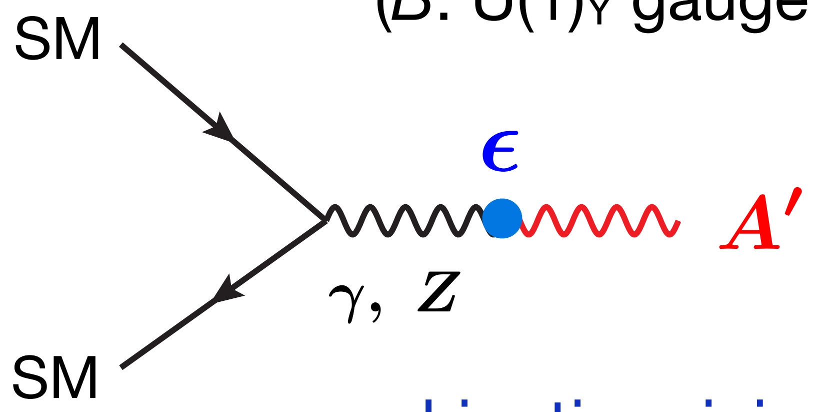
- "Dark Particles" are model(problem)-dependent.
- "Portal-SM Interactions" are rather model-independent.

Portals

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

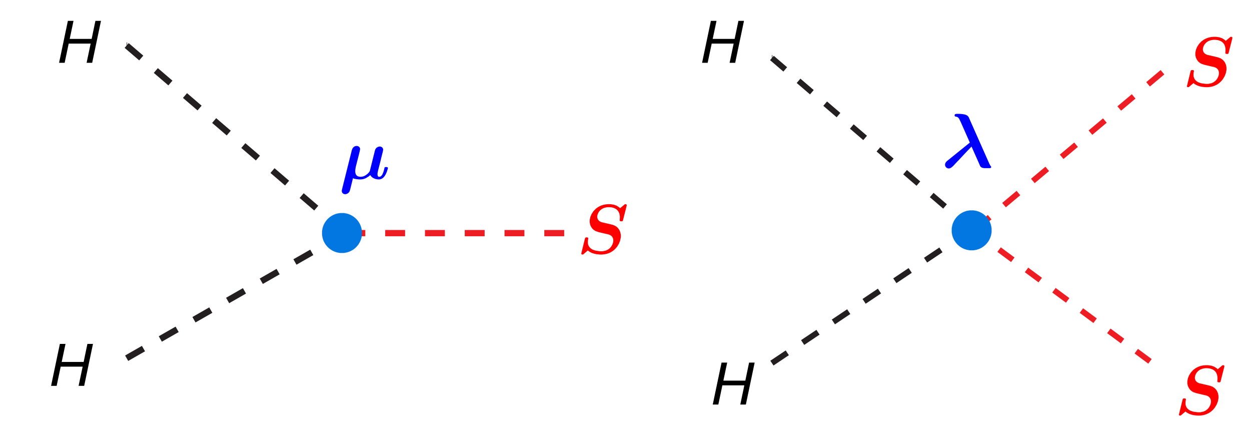
- Vector Portal : $\epsilon B_{\mu\nu} A'^{\mu\nu}$

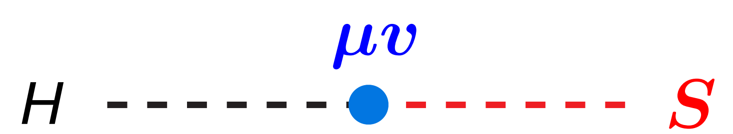
(*B*: $U(1)_Y$ gauge boson)



gauge kinetic mixing

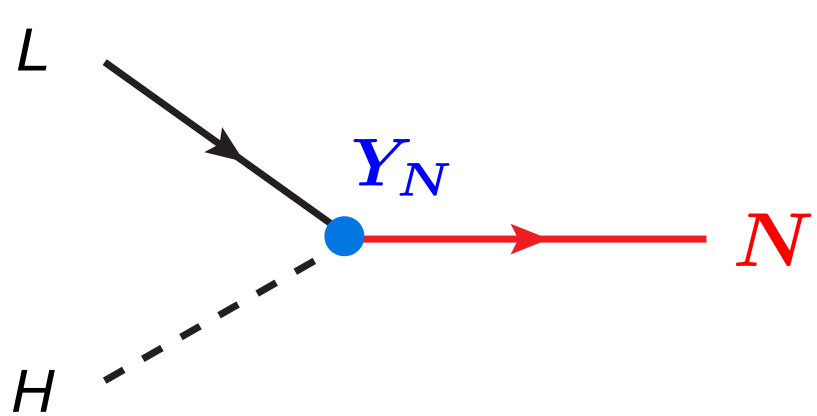
- Scalar Portal : $(\mu S + \lambda' S^2)|H|^2$





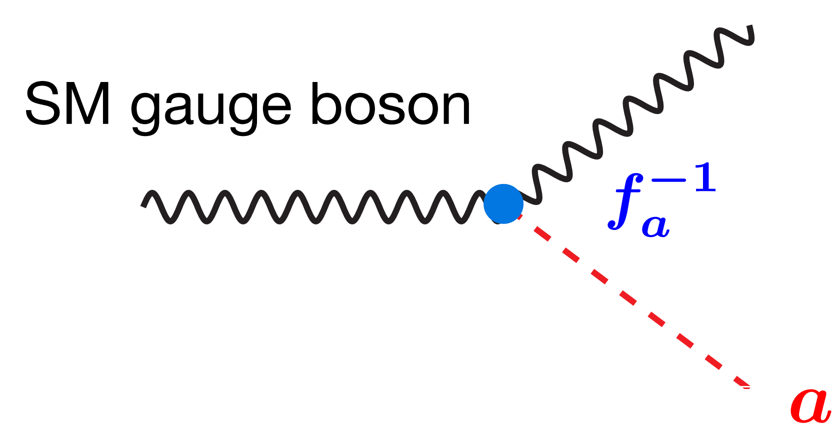
scalar mixing

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



right-handed neutrino

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

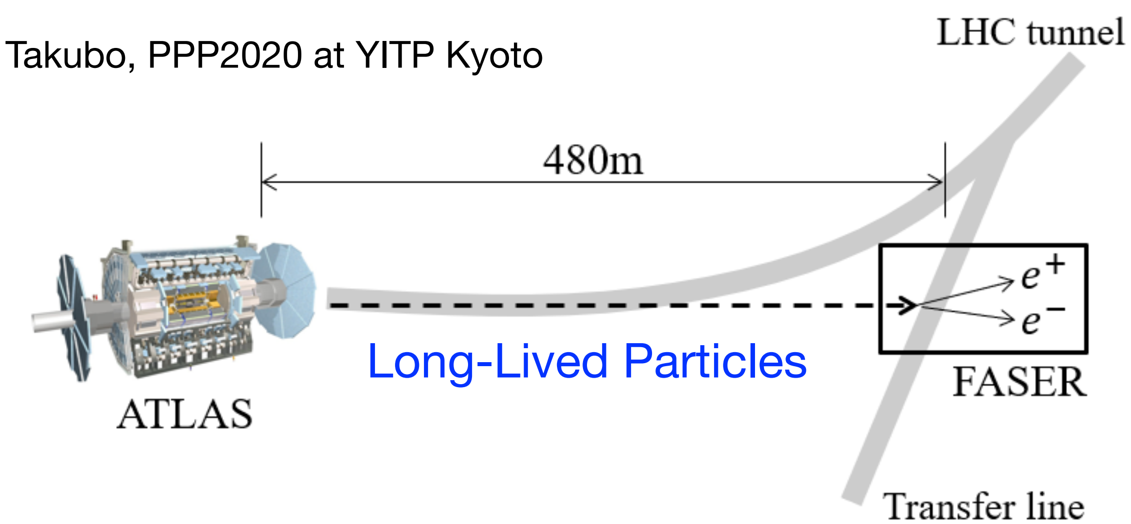


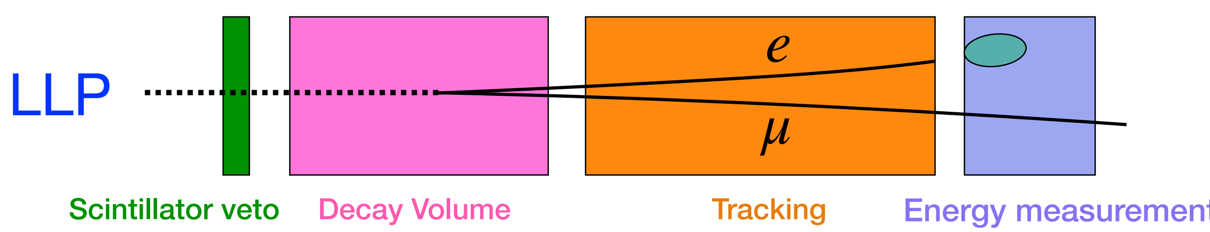
FASER experiment

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

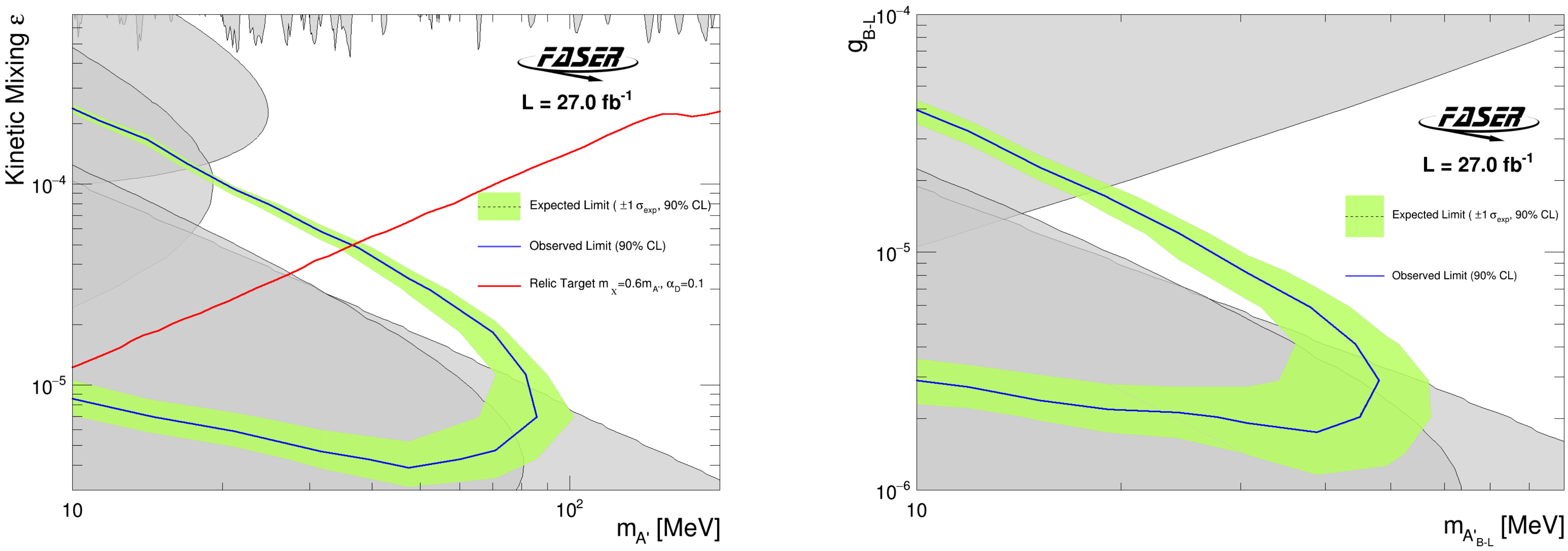




- Decays of LLP will be identified.
  - separation of e and μ with opposite charges.
  - two tracks with the same momentum, originated from the same vertex.
  - half of energy deposit compared to the total energy of two tracks.

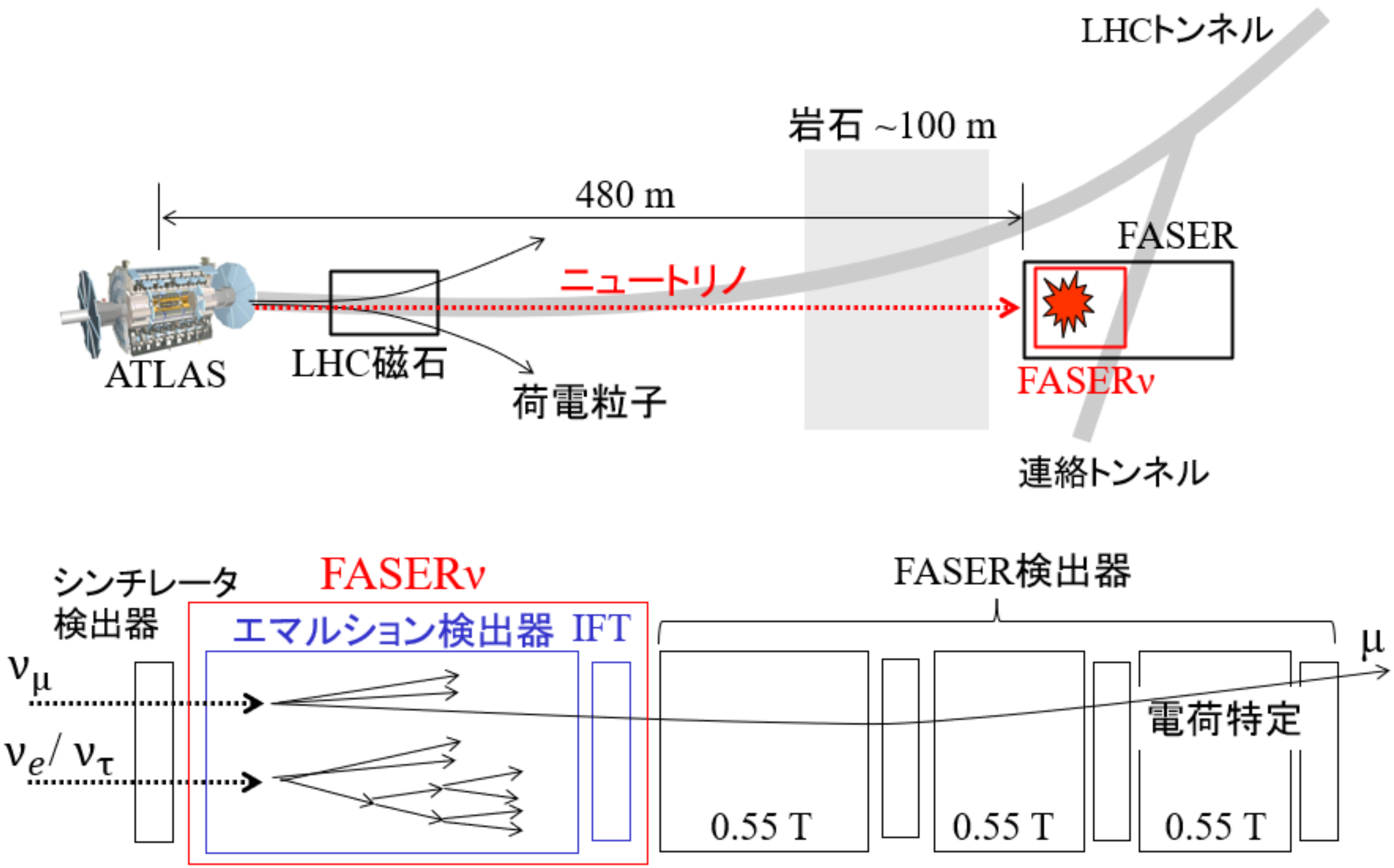
Dark Photon @FASER

First results on dark photon and B-L gauge boson



FASERν experiment

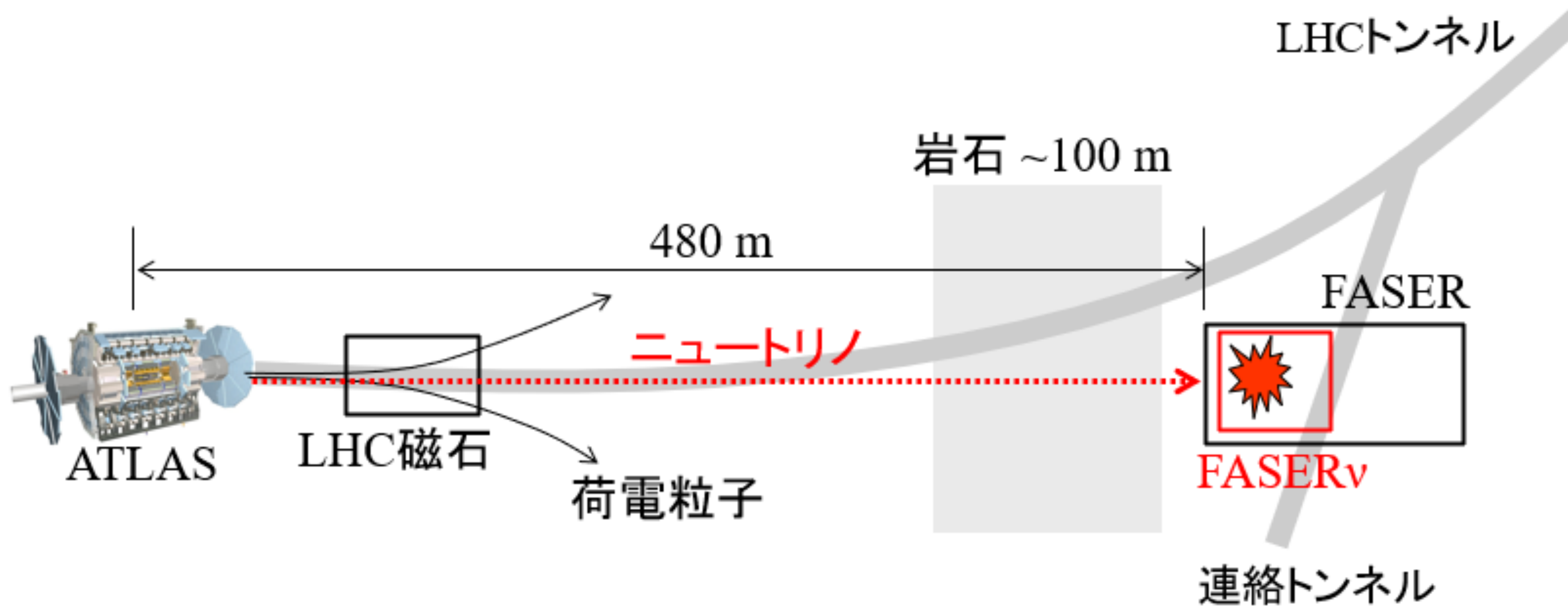
FASER JAPAN HP

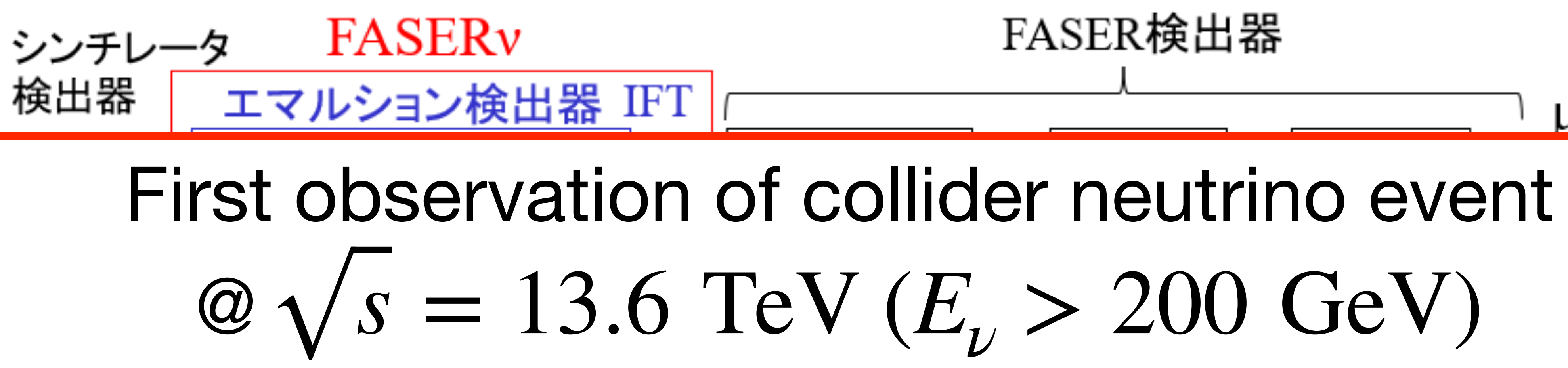


LHC加速器におけるFASERν検出器の配置(上)とニュートリノの検出原理(下)。IFTはインターフェース飛跡検出器を表している。ν_e, ν_μ, ν_τ, μは電子ニュートリノ、ミューニュートリノ、タウニュートリノ、ミューオンを示している。

FASERν experiment

FASER JAPAN HP





First observation of collider neutrino event

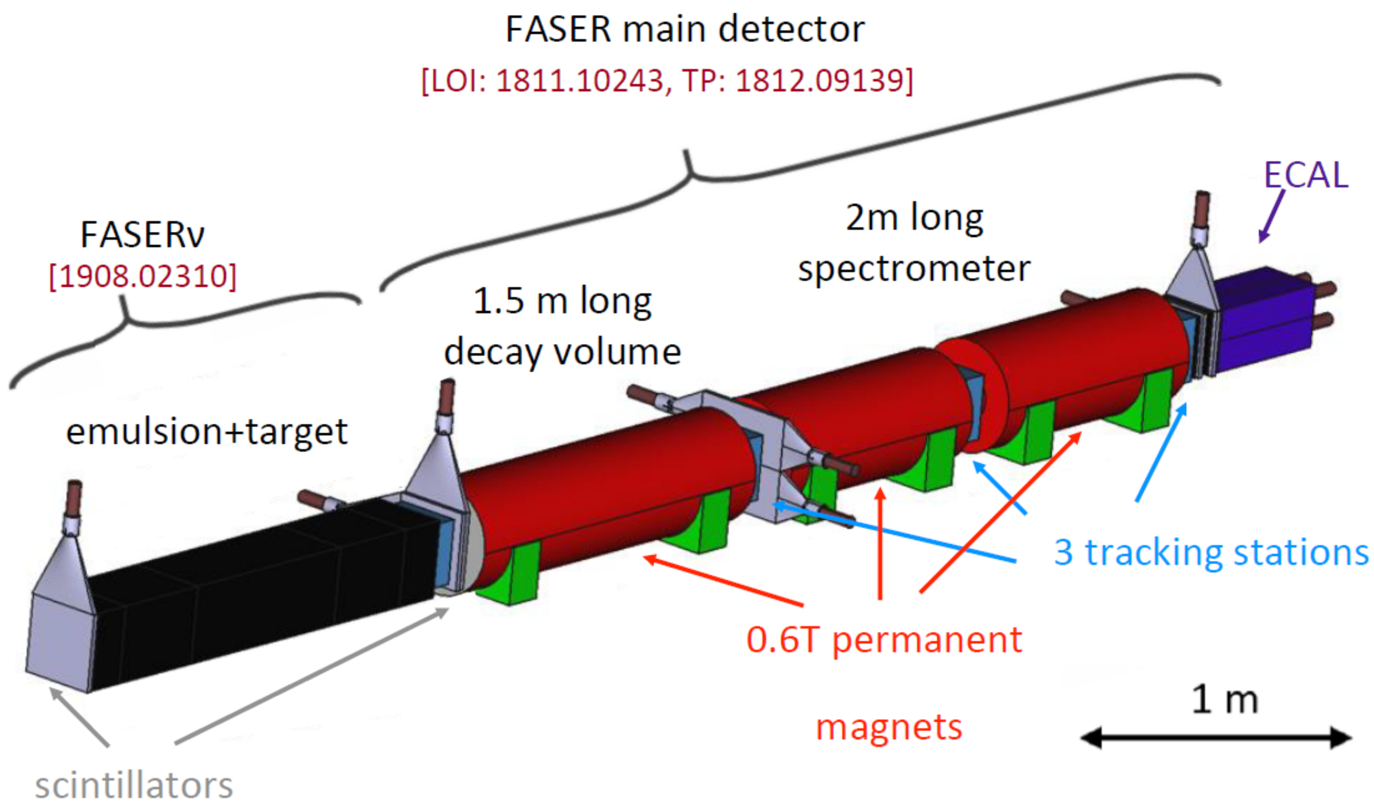
@ $\sqrt{s} = 13.6$ TeV ($E_\nu > 200$ GeV)

LHC加速器におけるFASERν検出器の配置(上)とニュートリノの検出原理(下)。IFTはインターフェース飛跡検出器を表している。ν_e, ν_μ, ν_τ, μは電子ニュートリノ、ミューニュートリノ、タウニュートリノ、ミューオンを示している。

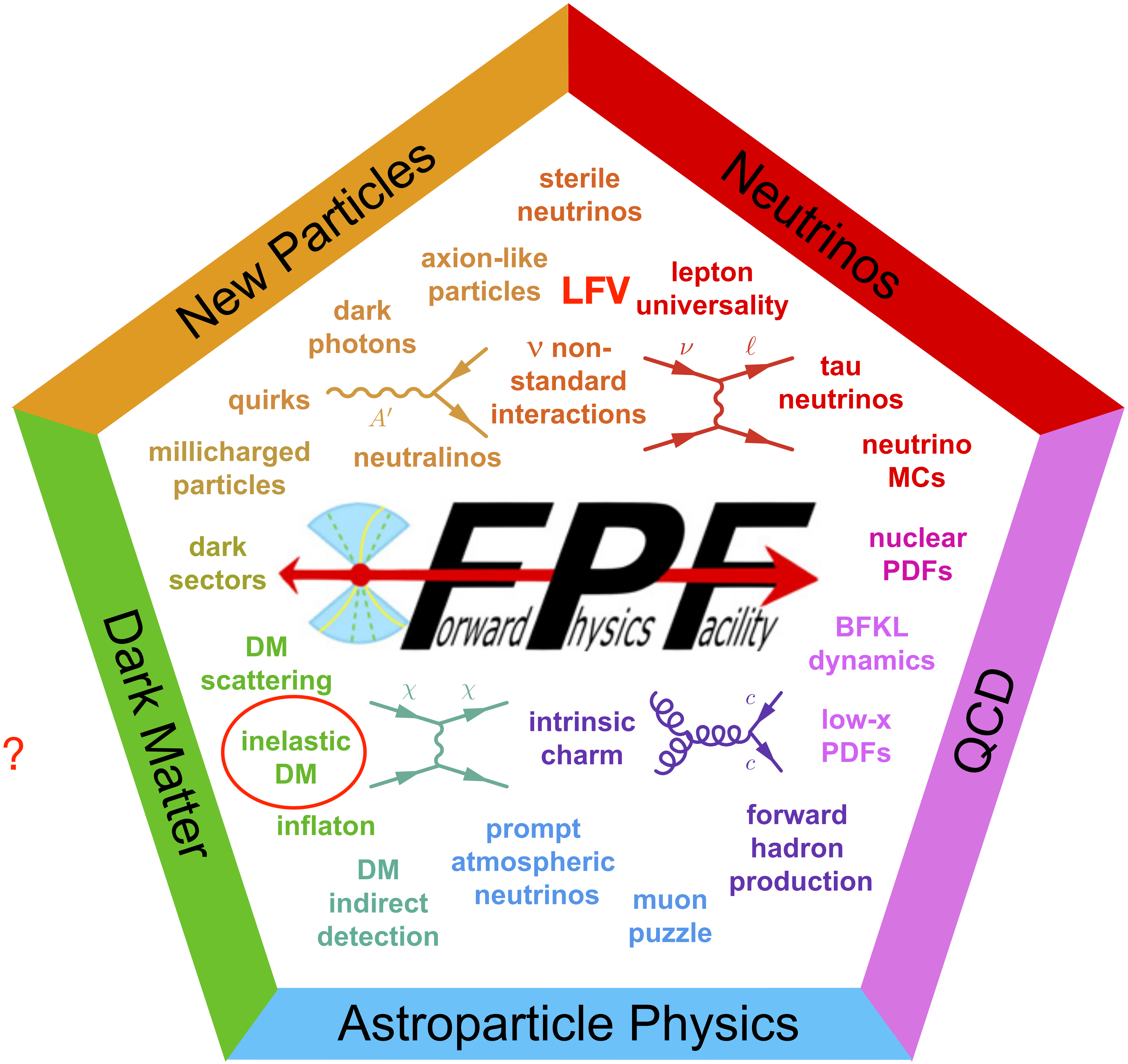
FASER2 detector

- 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)	$\mathcal{L}$ (ab^{-1})
FASER	478.5	480	0.1	0.15
FASER 2	475	480	1.0	3.0



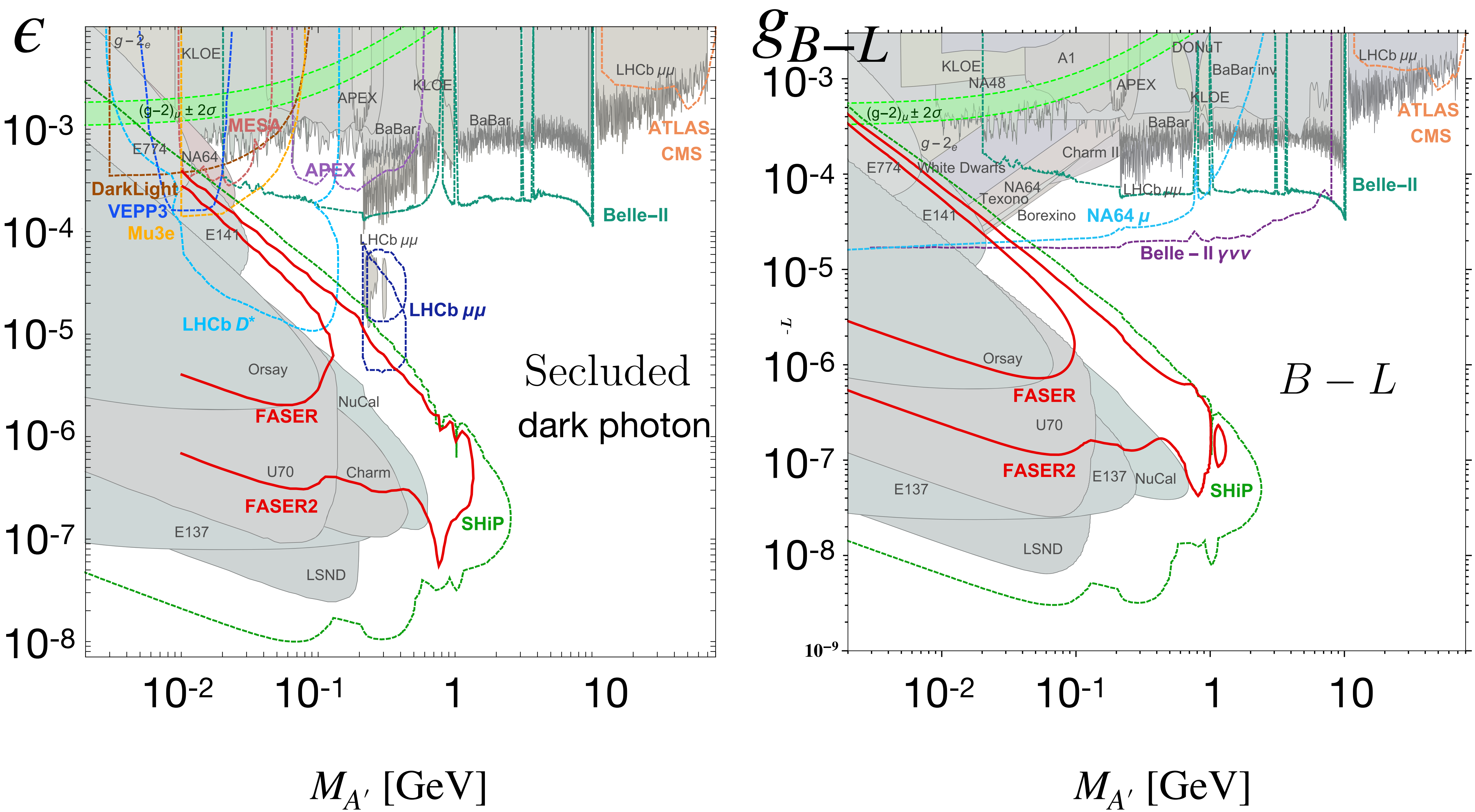
Forward Physics Facilities



Hidden QCD?

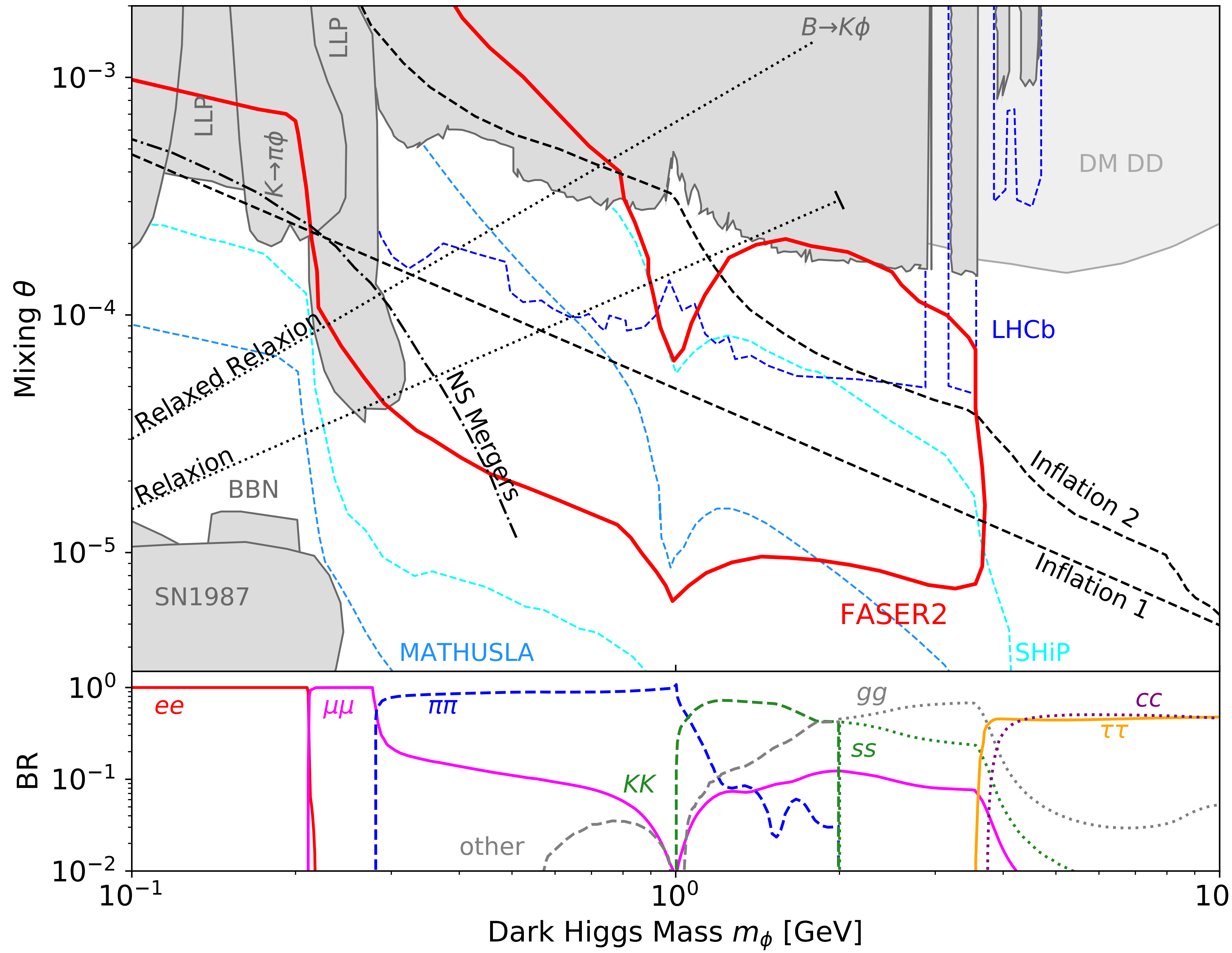
Vector Boson

Produced via $\pi, \eta, \eta' \to \gamma A'$ and $p \to p + A'$



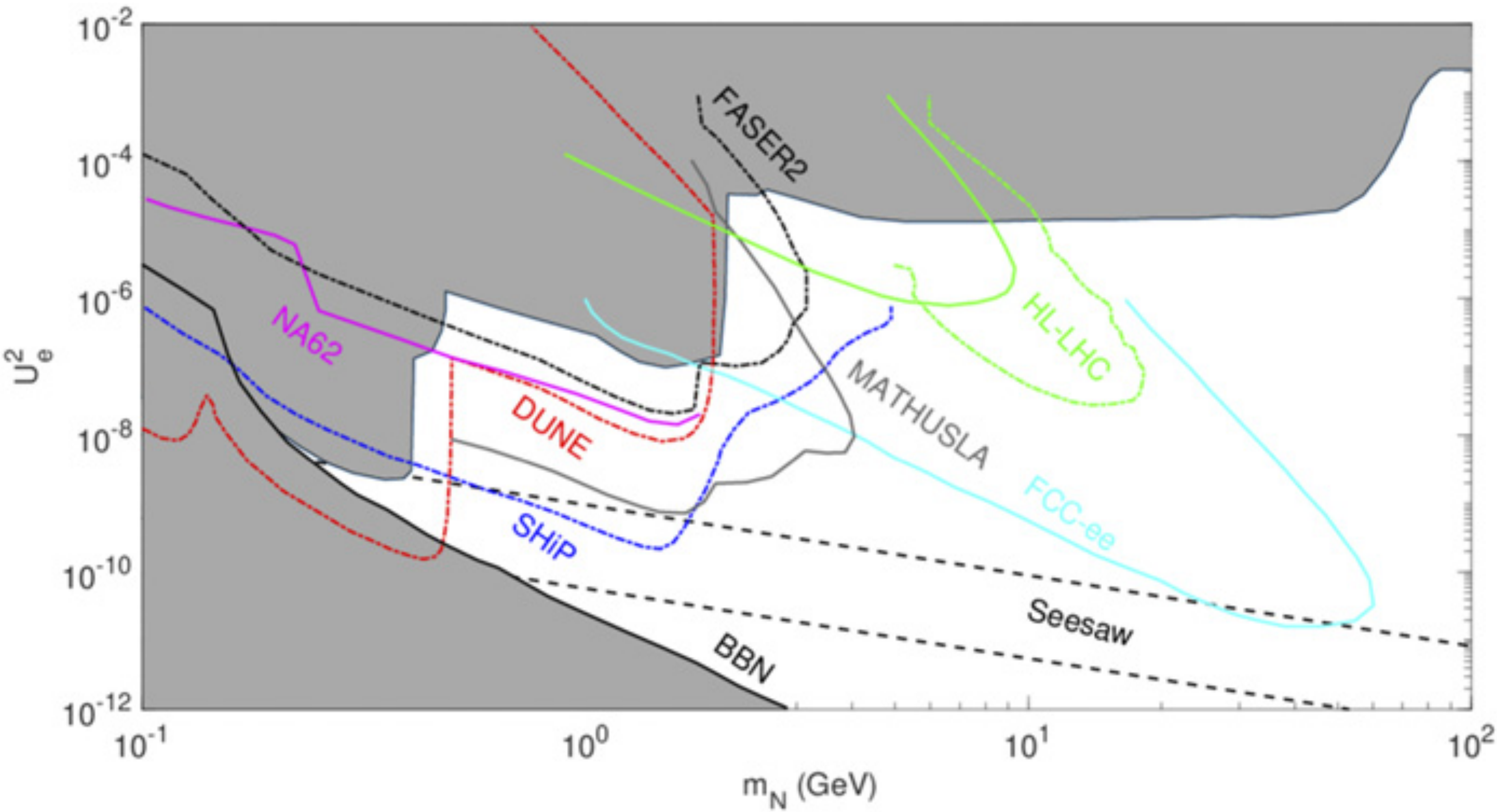
Scalar Boson

Produced via $K \to \pi + \phi$, $B \to K + \phi$

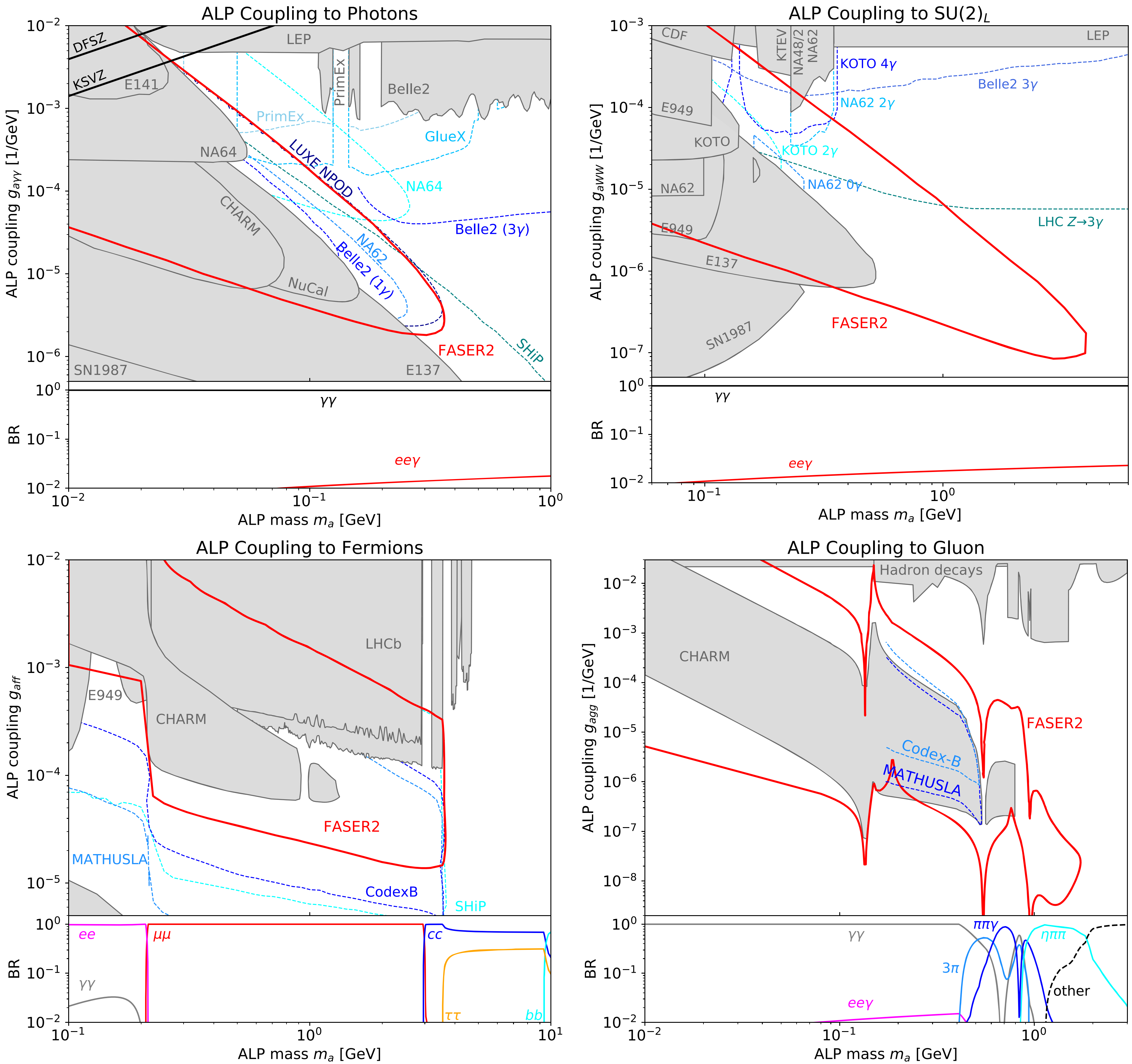


Heavy Neutral Lepton

Produced via meson decays



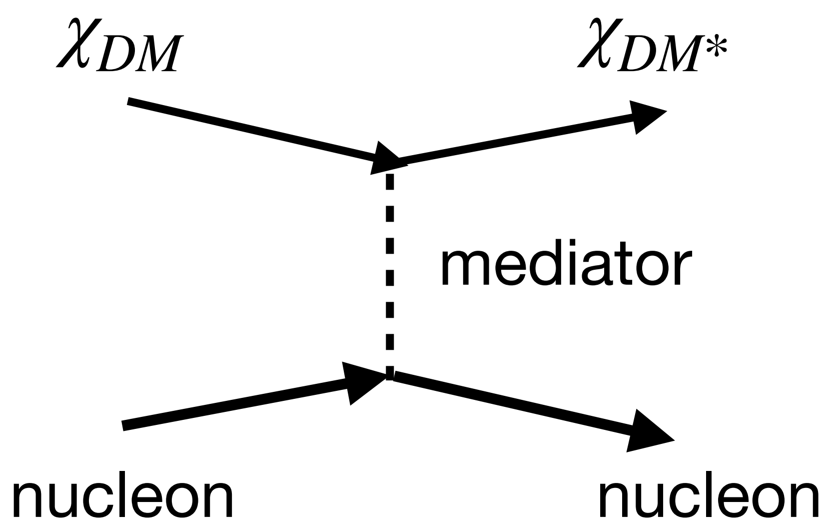
ALPs

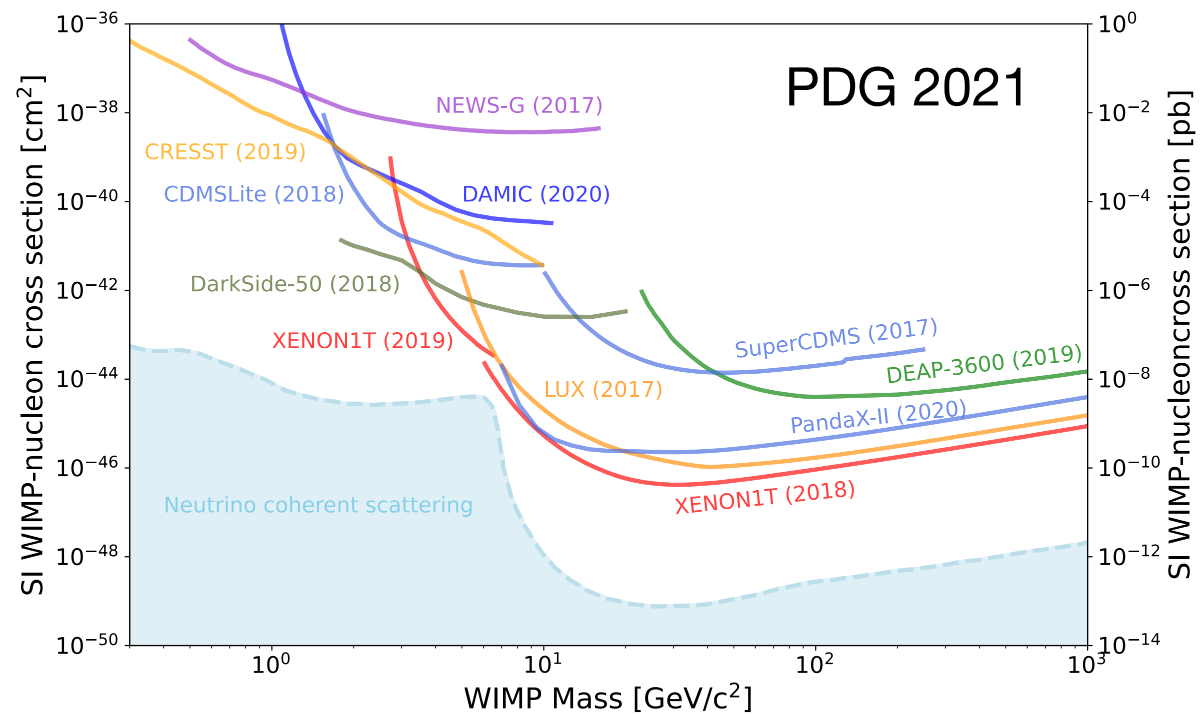

ALP Coupling to Photons
DFSZ
KSVZ
LEP
E141
PrimEx
Belle2
GlueX
NA64
LUXE NPOD
CHARM
NA62
Belle2 (1γ)
Belle2 (3γ)
NuCal
SHiP
FASER2
SN1987
E137
γγ
eeγ
ALP coupling $g_{a\gamma\gamma}$ [1/GeV]
BR
ALP mass m_a [GeV]
ALP Coupling to SU(2)$_L$
CDF
KTEV
NA48/2
NA62
KOTO 4γ
Belle2 3γ
NA62 2γ
E949
KOTO
KOTO 2γ
NA62 0γ
LHC Z→3γ
E137
SN1987
ALP coupling g_{aWW} [1/GeV]
ALP Coupling to Fermions
LHCb
E949
CHARM
MATHUSLA
CodexB
SHiP
ee
μμ
cc
ττ
bb
ALP coupling g_{aff}
ALP Coupling to Gluon
Hadron decays
Codex-B
MATHUSLA
ππγ
ηππ
3π
other
ALP coupling g_{agg} [1/GeV]

Inelastic DM

- Inelastic Dark Matter (iDM) is a compelling candidate for sub-GeV thermal DM.

Smith & Weiner, PRD64 (2001), PRD72 (2005)



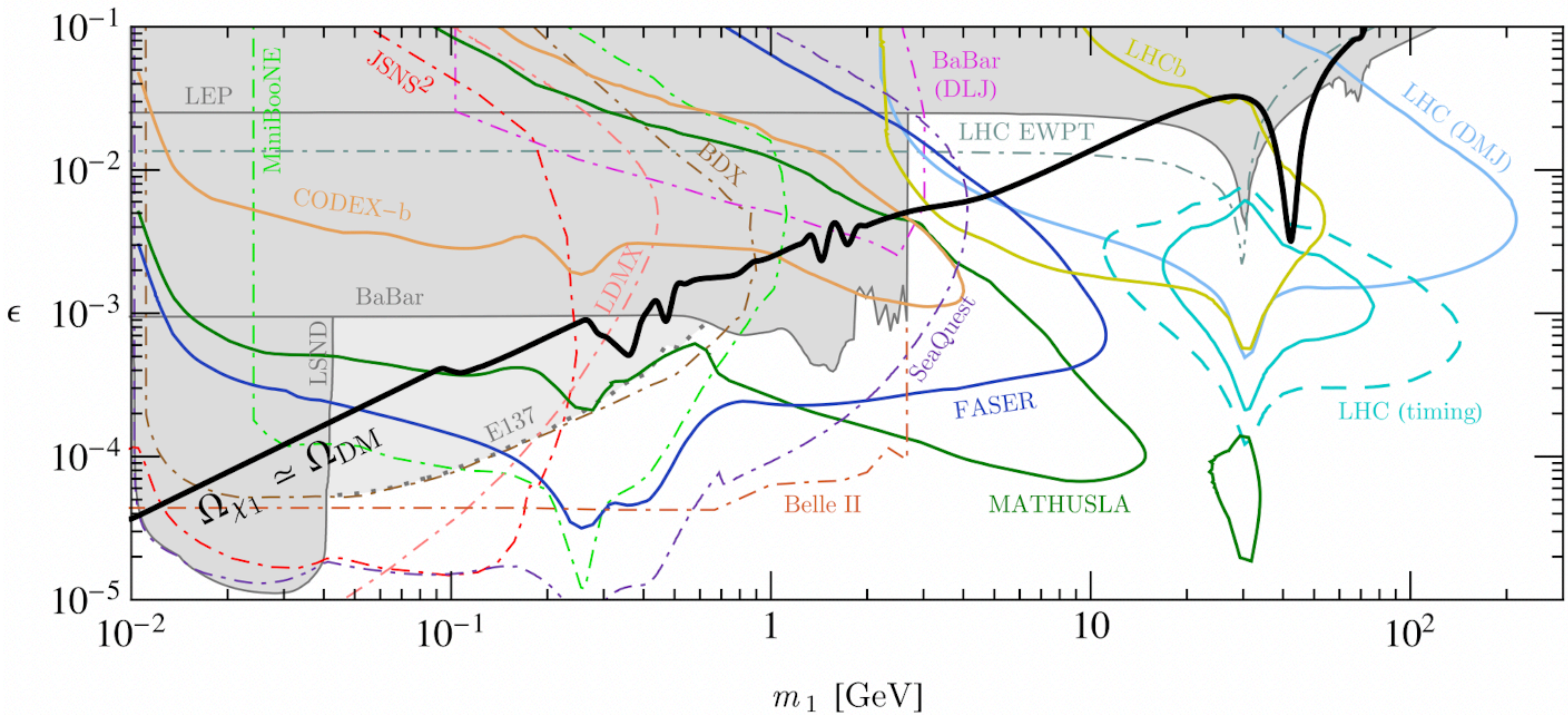


- DM inelastically scatters off nucleon to a heavier state DM*.

  → avoid the direct detection and CMB constraints

- DM and mediator can be lighter beyond the Lee-Weinberg bound.

Fermionic iDM, $m_{A'} = 3m_1$, Δ=0.1, α_D=0.1



Inelastic DM

Dark Photon with Dark Higgs Model

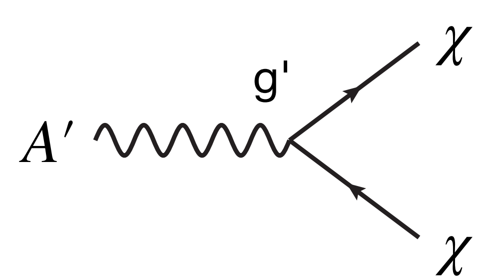
Dark Sector

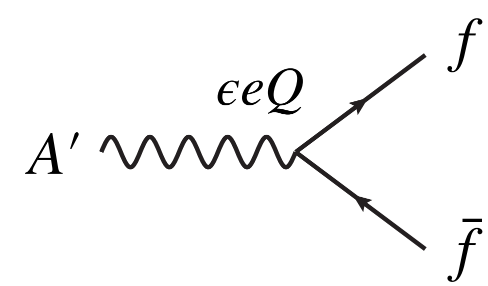
	Q	u_R	d_R	L	e_R	H	φ	χ	~~S~~
$SU(3)$	3	3	3	1	1	1		singlet	
$SU(2)_L$	2	1	1	2	1	2			
B_μ $U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$\frac{1}{2}$			
A'_μ $U(1)_X$	singlet						1	$\frac{1}{2}$	~~$\frac{1}{2}$~~

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM}^{\chi(S)} - \frac{1}{4}A'^{\mu\nu}A'_{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}A'^{\mu\nu} + (D^\mu\varphi)^*(D_\mu\varphi) - V,$$

- Mediator: A', φ
  - Dark Photon (vector portal)

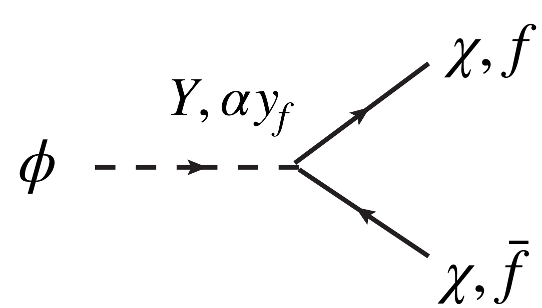
    Interact with the SM particles via kinetic mixing

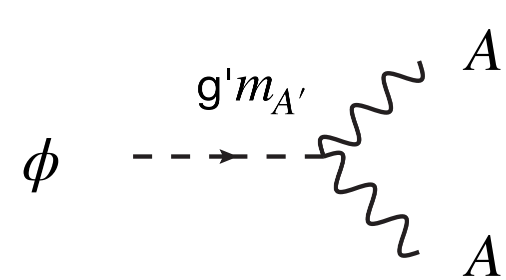




  - Dark Higgs (scalar portal)

    Interact with the SM particles via scalar mixing





Fermion iDM

- Mass term

$$\mathcal{L}_{M_\chi} = M_\chi(\bar{\chi}_L\chi_R + \bar{\chi}_R\chi_L) + \underline{\left(y_L\overline{\chi_L^c}\chi_L\varphi + y_R\overline{\chi_R^c}\chi_R\varphi + h.c.\right)}$$

mass splitting after SSB $\langle\varphi\rangle = \frac{v_\varphi}{\sqrt{2}}$

- Mass eigenvalues/states

$$m_{\chi_1,\chi_2} = \frac{1}{2}\sqrt{(m_L - m_R)^2 + 4M_\chi^2} \pm \underline{\frac{m_L + m_R}{2}}, \quad (m_{L(R)} \equiv \sqrt{2}y_{L(R)}v_\varphi)$$

For $M_\chi \gg m_L \simeq m_R$ ($\theta_\chi \simeq \pi/4$), small mass diff. is obtained

Mass eigenstates : χ_1, χ_2

$$\begin{pmatrix}\chi_1\\ \chi_2\end{pmatrix} = \begin{pmatrix}\cos\theta_\chi & -\sin\theta_\chi\\ \sin\theta_\chi & \cos\theta_\chi\end{pmatrix}\begin{pmatrix}\chi_L\\ \chi_R^c\end{pmatrix}, \quad \tan 2\theta_\chi = \frac{2M_\chi}{m_L - m_R}$$

- Inelastic int. in mass eigenstates

$$\mathcal{L}_{A'\mathrm{int}} = g' A'_\mu \left[\tilde{c}_\chi(\bar{\chi}_1\gamma^\mu\chi_1 - \bar{\chi}_2\gamma^\mu\chi_2) + \tilde{s}_\chi(\bar{\chi}_1\gamma^\mu\chi_2 + \bar{\chi}_2\gamma^\mu\chi_1)\right],$$

$$(\tilde{s}_\chi = \sin 2\theta_\chi, \tilde{c}_\chi = \cos 2\theta_\chi)$$

$$\mathcal{L}_{\phi\mathrm{int}} \supset \frac{1}{\sqrt{2}}(y_L - y_R)c_\alpha s_\chi c_\chi \phi(\overline{\chi_1^c}\chi_2 + \overline{\chi_1}\chi_2^c) + h.c.,$$

$$(s_\chi = \sin\theta_\chi, c_\chi = \cos\theta_\chi)$$

FASER experiment

Feng, Galon, Kling, Trojanowski, PRD97 (2018)
FASER collaboration, arXiv:1708.09389

- ForwArd Search ExpeRiment (FASER) at LHC, starting from 2022.
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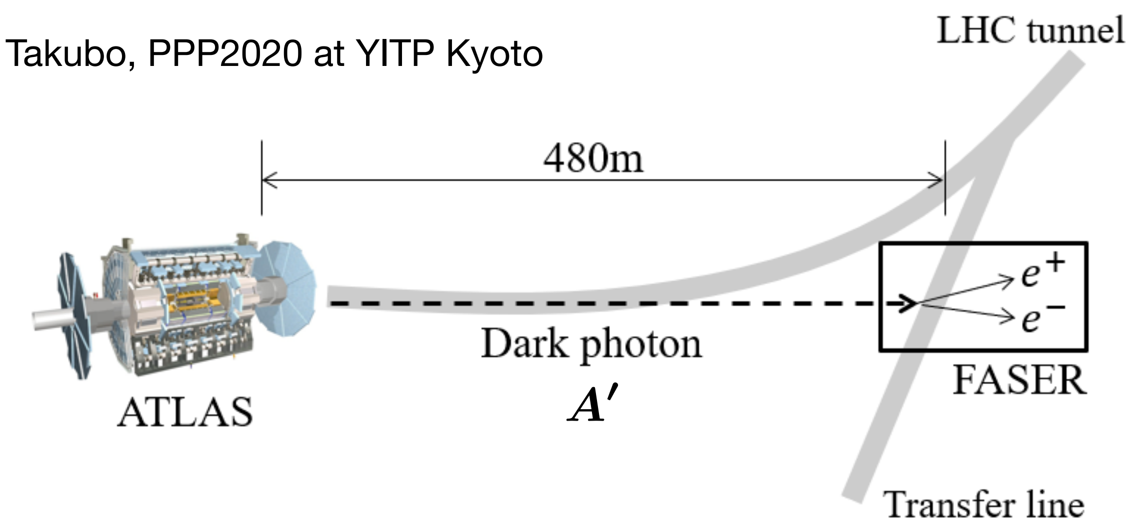

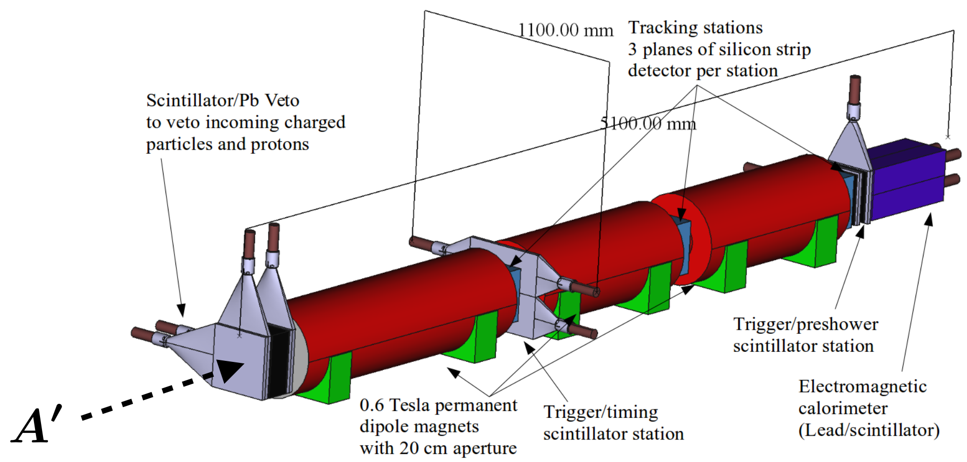

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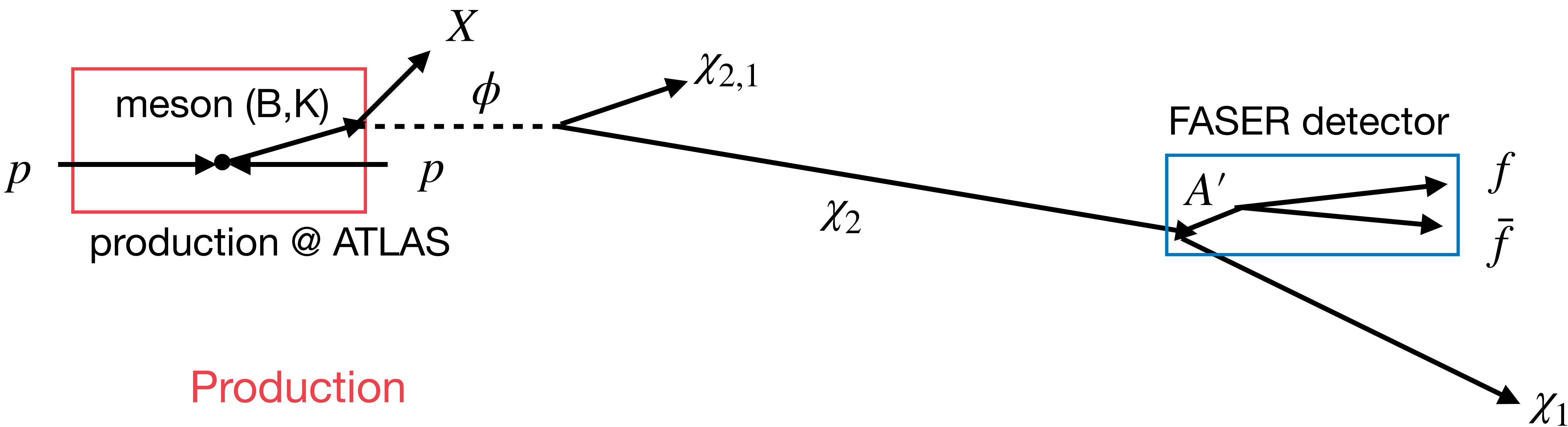
Signal at FASER



Production

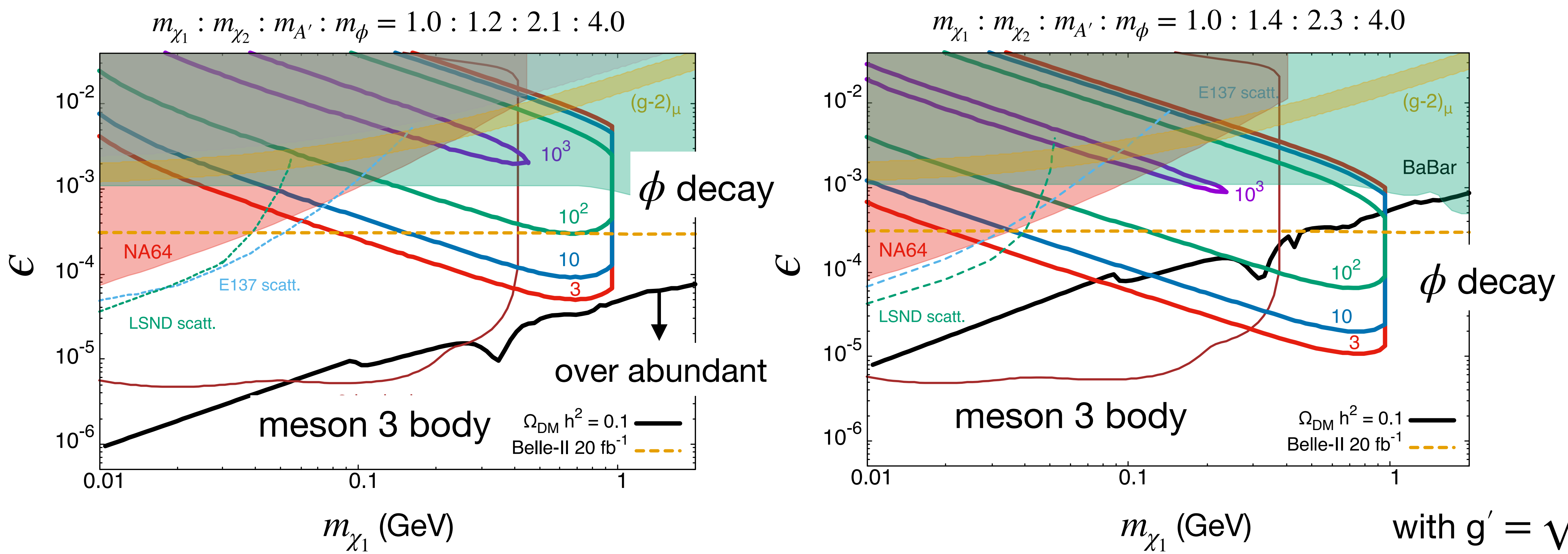
- ϕ produced from meson decays : $B, K \to \phi + X$
- χ_2 produced from ϕ decay : $\phi \to \chi_{2,1} + \chi_2$
- χ_2 produced from pseudo-scalar meson 3-body decays: $\pi^0, \eta, \eta' \to \gamma + A'^* \to \gamma + \chi_{1,2} + \chi_2$

Signal

- χ_2 decays into charged particles : $\chi_2 \to \chi_1 + A'^* \to \chi_1 + f + \bar{f}$

Sensitivity Plots for Fermion iDM (1)

Case 1: Decays of $A' \to \chi_1\chi_2$ and $\phi \to A'A'$ are forbidden



with $g' = \sqrt{4\pi}$, $\theta_\chi \simeq \pi/4$, $\alpha = 10^{-4}$

- production from ϕ decay (red, blue, green, purple)

  → $m_{\chi_1} \leq 1.0$ GeV & $\epsilon \geq 10^{-5}$

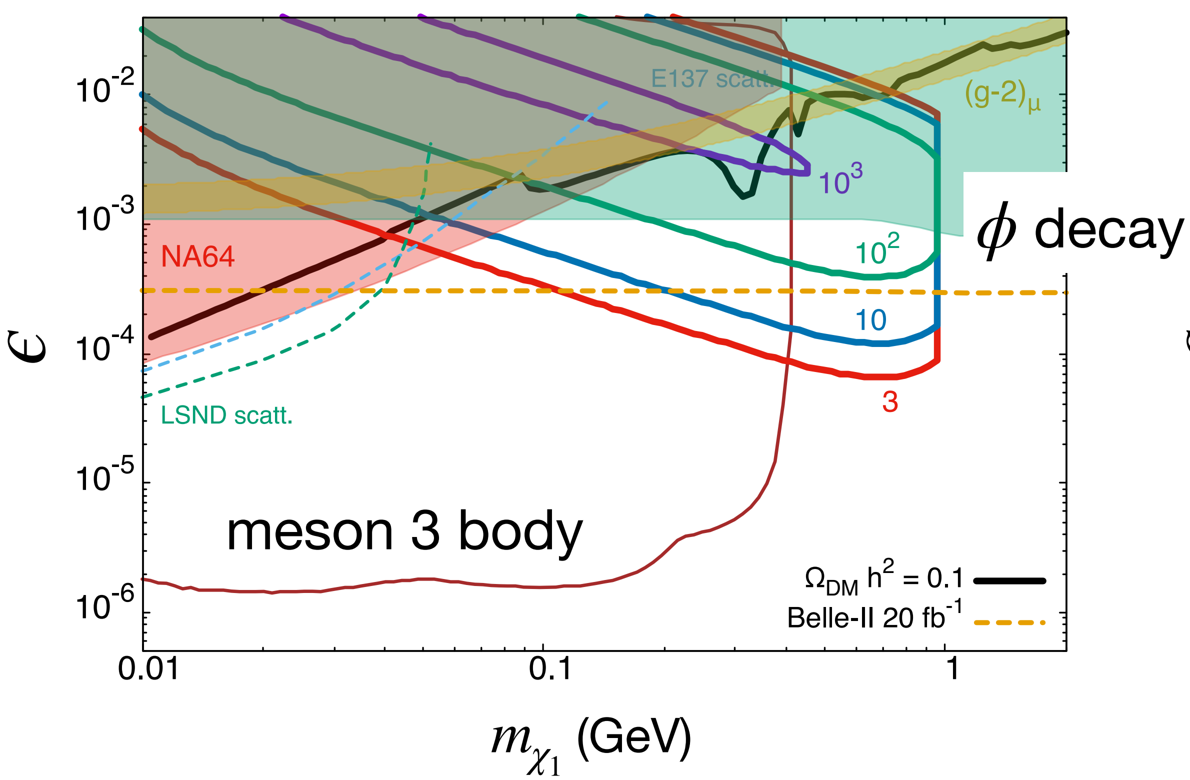
- production from meson 3-body decay (brown)

  → $m_{\chi_1} \leq 0.4$ GeV & $\epsilon \geq 10^{-6}$

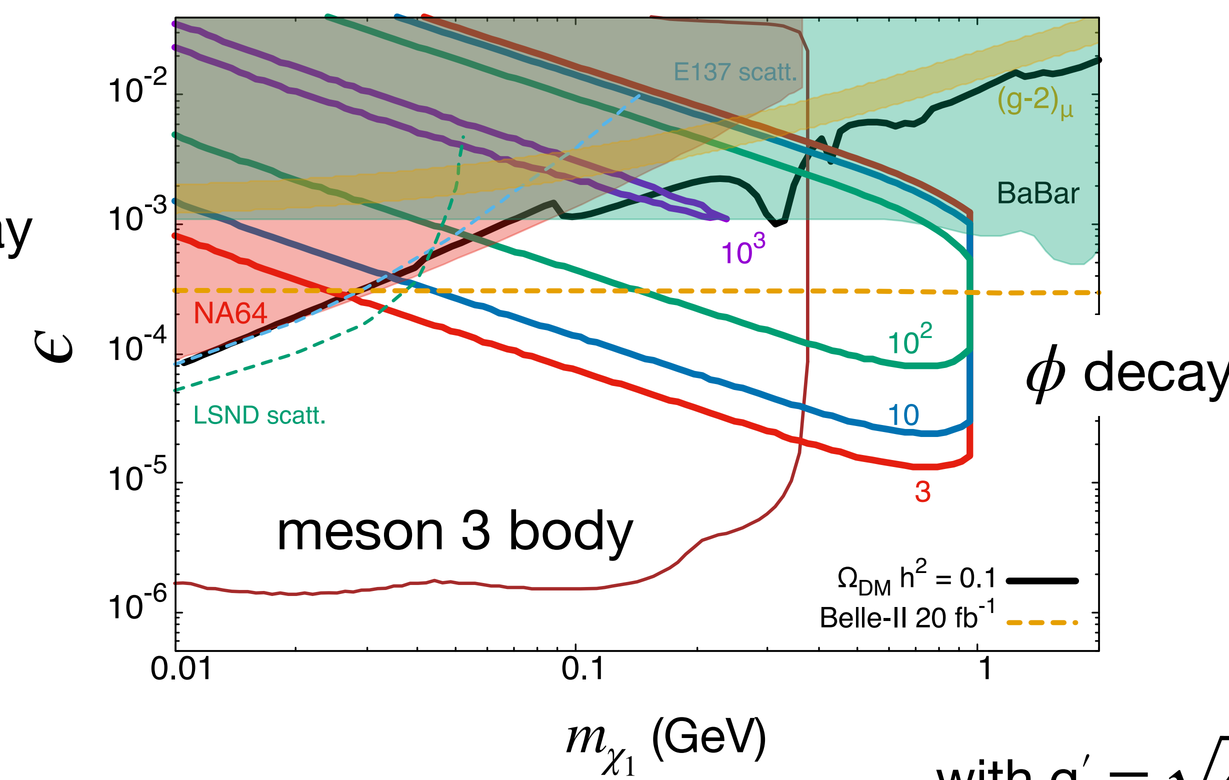
Sensitivity Plots for Fermion iDM (2)

Case 2: Only decay of $A' \to \chi_1 \chi_2$ is allowed

$m_{\chi_1} : m_{\chi_2} : m_{A'} : m_\phi = 1.0 : 1.2 : 2.4 : 4.0$



$m_{\chi_1} : m_{\chi_2} : m_{A'} : m_\phi = 1.0 : 1.4 : 2.55 : 4.0$



with $g' = \sqrt{4\pi}$,
$\theta_\chi \simeq \pi/4$
$\alpha = 10^{-4}$

- Dark matter abundance requires large ϵ

→ already excluded