FASER/T2K実験における軽い新粒子探索

(Search for light new particles at FASER/T2K)

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(Miyazaki U.)

based on

"*Dark Photon from light scalar boson decay at FASER*", JHEP03 (2021) 072
"*New Constraint on Dark Photon at T2K off-axis near detector*", JHEP11 (2023) 056

in collaboration with

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Tomoya Iizawa (Oxford U.), Hidetoshi Otono (Kyushu U.)
Yosuke Takubo (KEK)

Seminar @ Tokyo Univ. of Science, 28th, May 2024

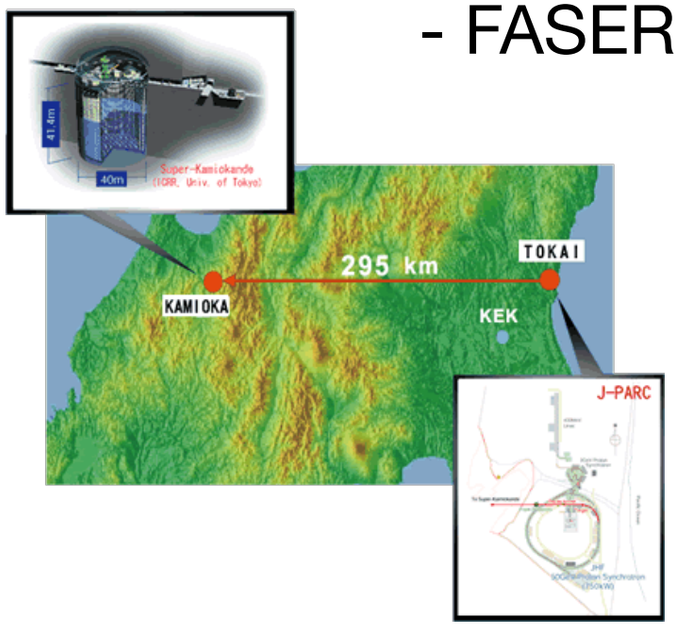
今日の話

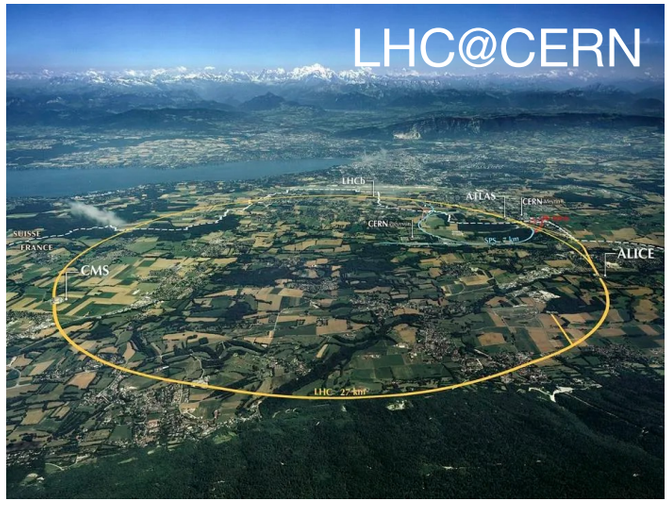
⭐ 暗黒光子をFASER実験とT2K実験でどこまで探せるか？

- キーワード
  - 暗黒光子 (Dark Photon)
  - 暗黒ヒッグス (Dark Higgs)
  - 自発的対称性の破れ
  - FASER実験, T2K実験

暗黒セクター

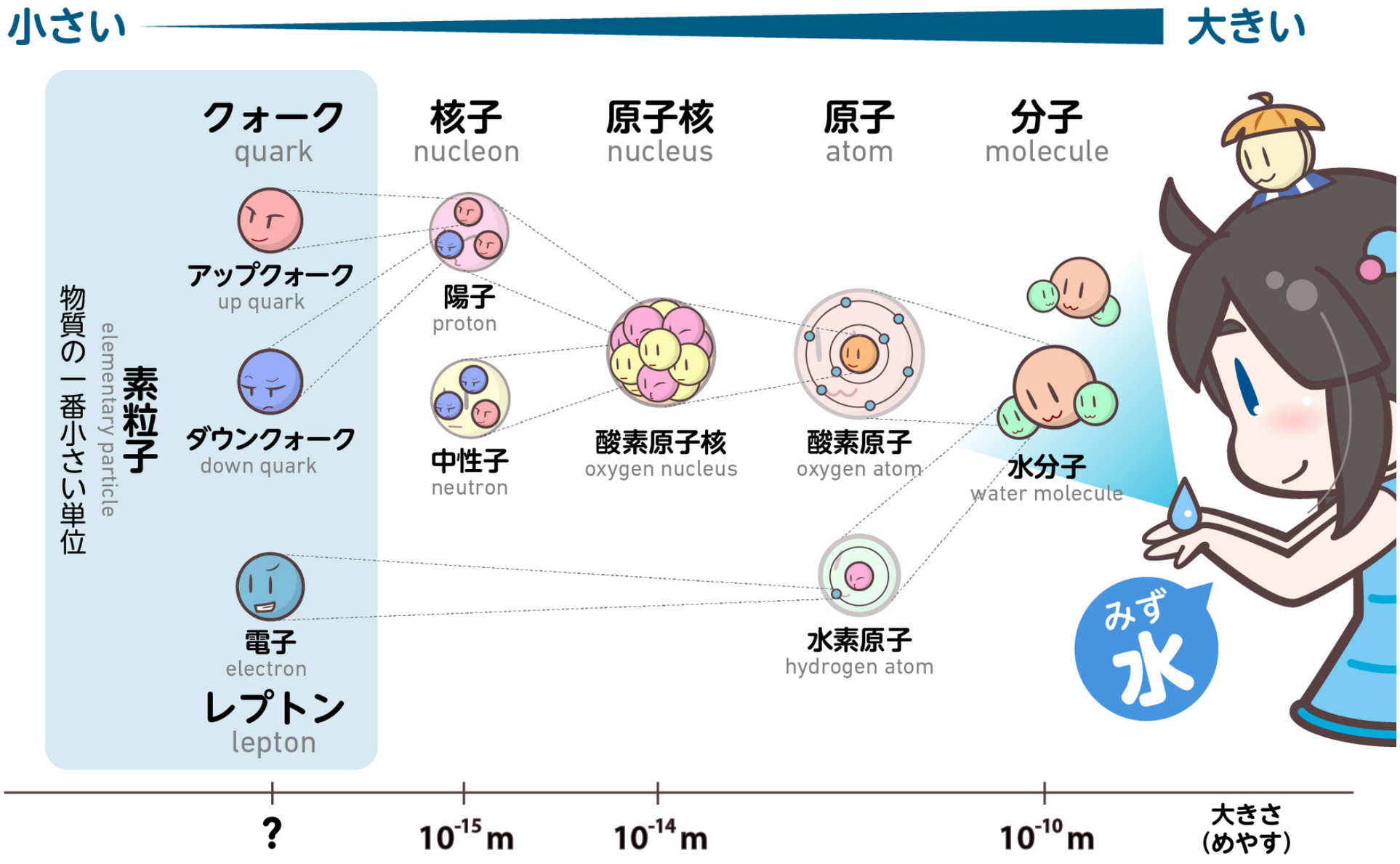
暗黒物質 (Dark Matter)





0. Fast review of
Standard Model and Higgs mechanism

Elementary particle

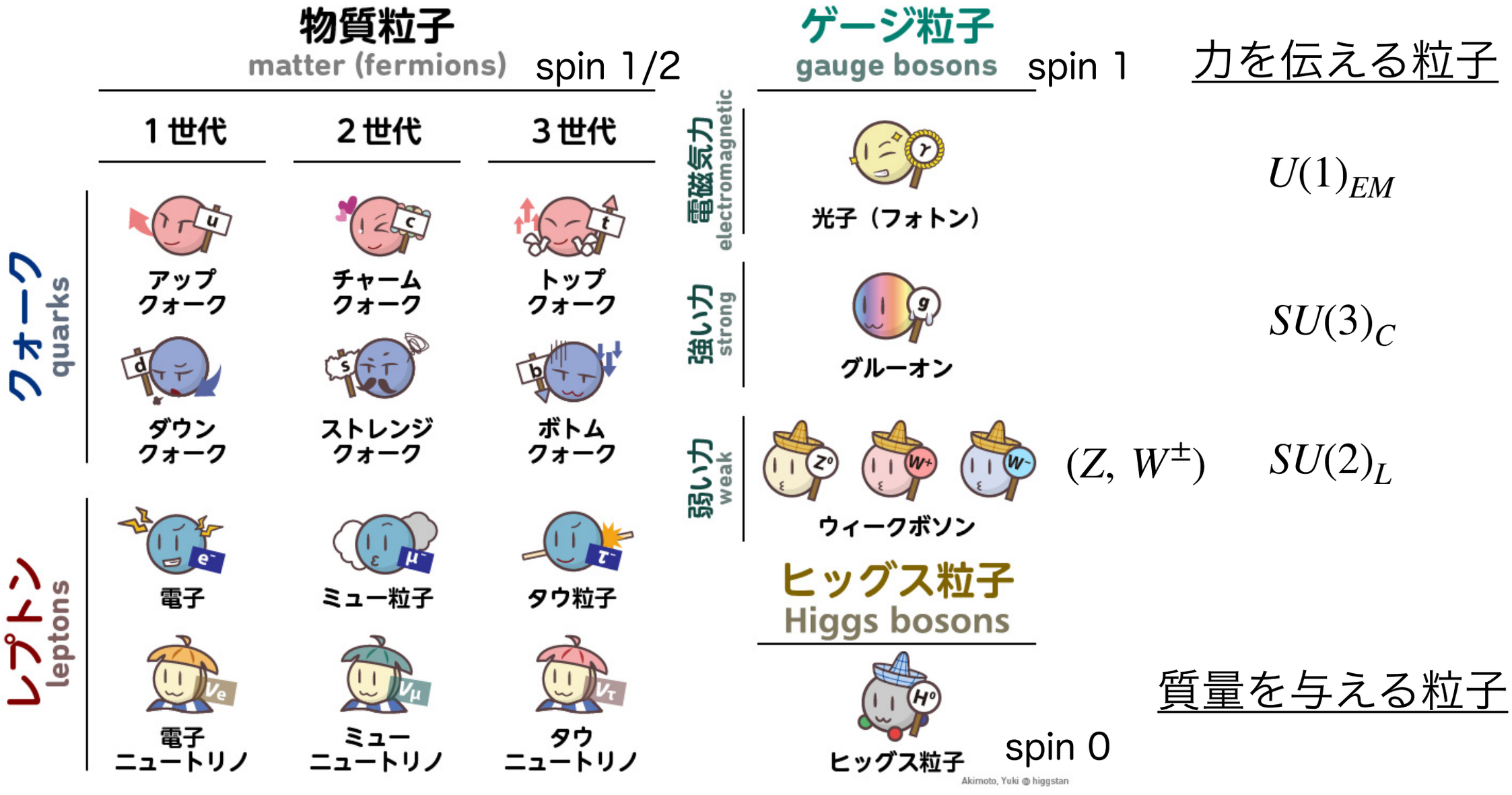


物質の最小単位

higgstan.com

Standard model

（力＝相互作用）



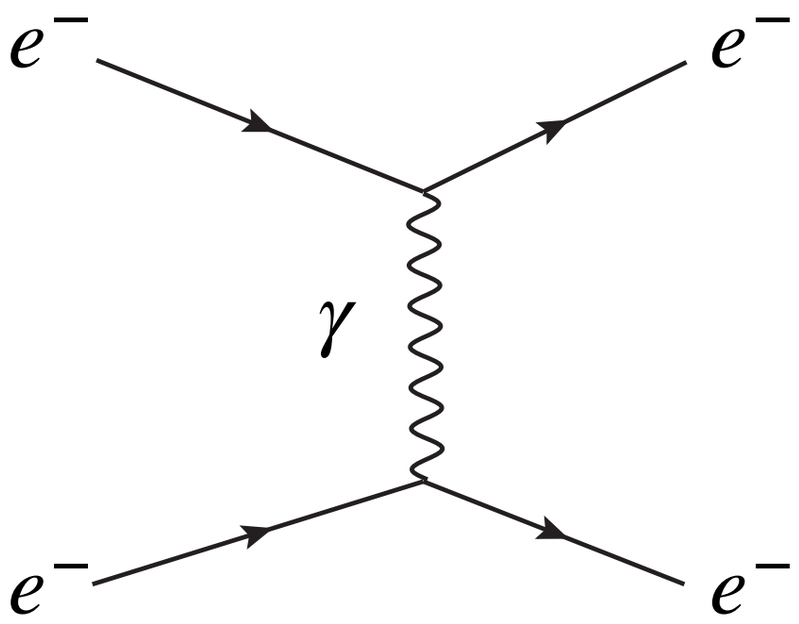
higgstan.com

Photon

higgstan.com

- 電磁波の量子
- 電磁気力を伝える仮想量子

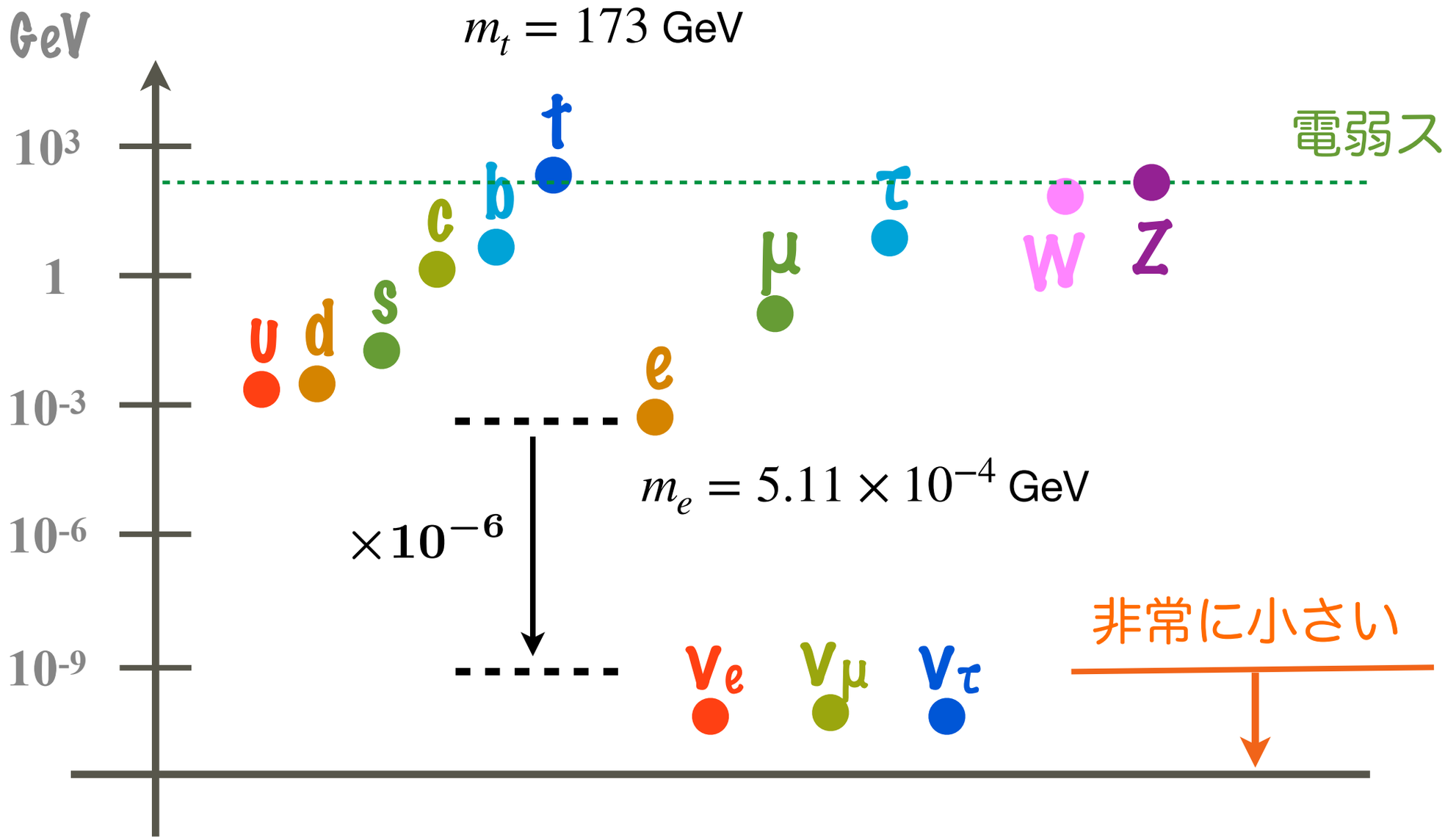
ファインマン
ダイアグラム



Mass spectrum

1GeV = 10^9eV

1MeV = 10^6eV



質量ゼロ

- 光子 (Photon)
- グルーオン (Gluon)

Higgs mechanism

F. Englert &P.Higgs,
Nobel prize in physics in 2013

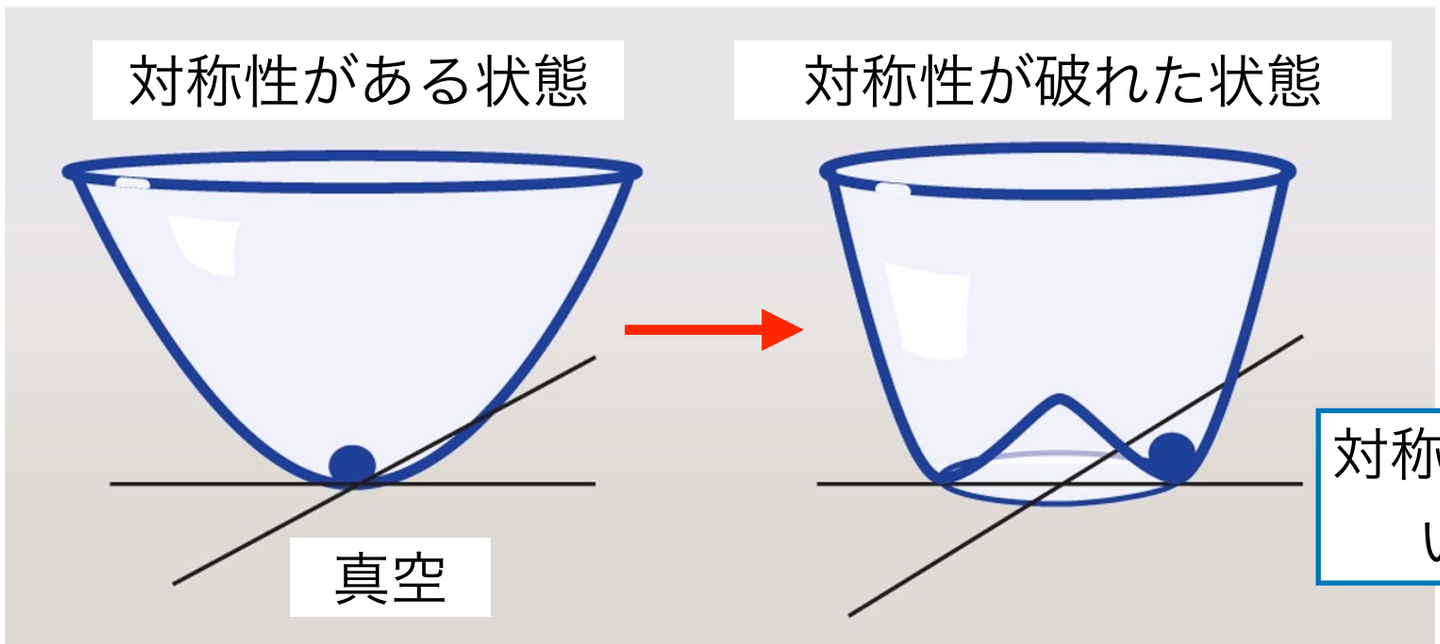
- 素粒子が質量を持つことは対称性によって禁止
- 特にWとZボソンの質量は大問題

自発的対称性の破れなら問題を回避できる

- Brout-Englert-Higgs mechanism
  - ヒッグス場の真空凝縮＝相転移
  - ヒッグス場の凝縮によって対称性が破れる

冷たい窓に凝縮する水滴

ヒッグスのポテンシャルエネルギー



Higgs mechanism

memo

$$\langle H \rangle = \langle 0 | H | 0 \rangle$$

- ヒッグス場が真空凝縮すると

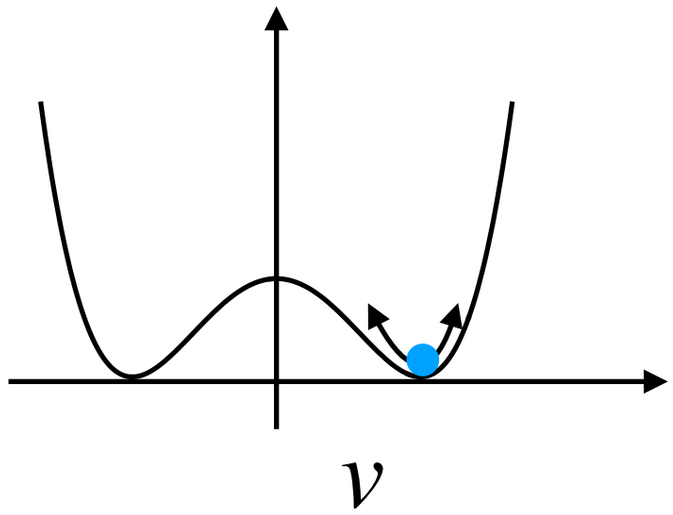
$$\langle H \rangle = 0 \longrightarrow \langle H \rangle = v \ (\neq 0)$$

v : 真空期待値

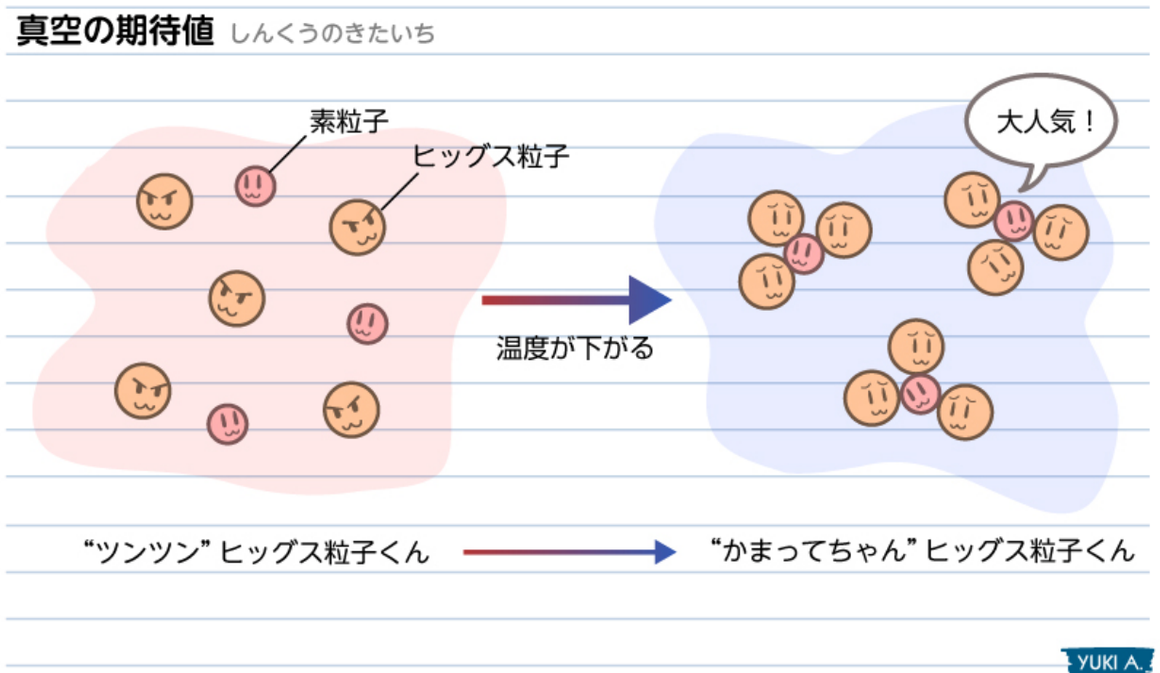
対称性がある真空　　対称性が破れた真空

- ヒッグス粒子は真空周りの励起

$$H = \frac{1}{\sqrt{2}}(v+h)$$



- 質量はヒッグス場の真空期待値から得られる



Gauge boson mass

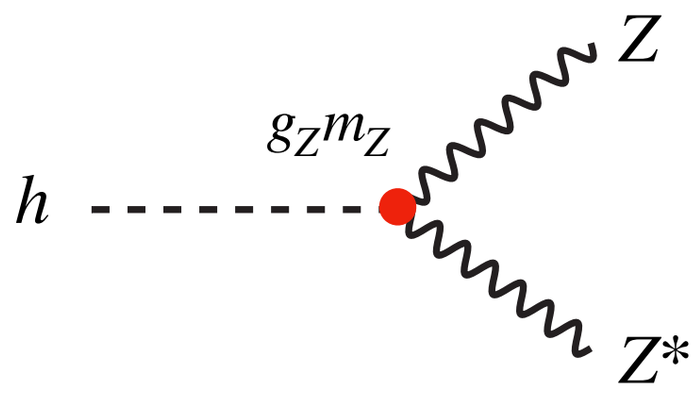
- ゲージ粒子(Z boson)の質量

$$\mathscr{L} = g_Z^2 H^\dagger H Z^\mu Z_\mu \xrightarrow[H=\frac{v+h}{\sqrt{2}}]{} \underline{\frac{1}{2} m_Z^2 Z^\mu Z_\mu} + \underline{\frac{1}{2} g_Z m_Z h Z^\mu Z_\mu} + \frac{1}{8} g_Z^2 h^2 Z^\mu Z_\mu$$

Z boson mass : $m_Z = \frac{1}{2} g_Z v$

- ヒッグス(h)-Z-Z 相互作用
  - 自発的対称性の破れによる
    質量獲得の証拠

- ヒッグス粒子が2つのゲージ粒子に崩壊



Fermion mass

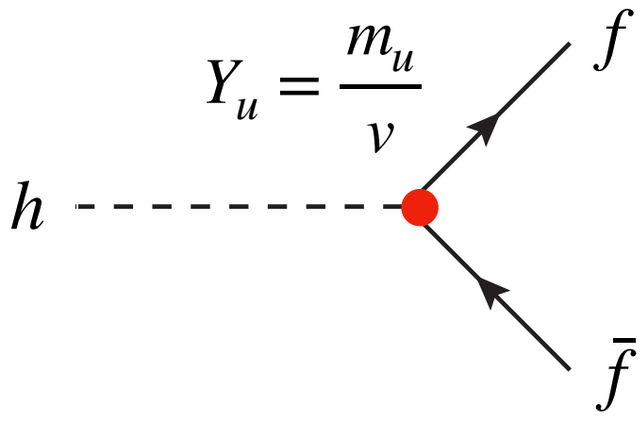
- クォーク & レプトンの質量

$$\mathscr{L} = Y_u \overline{u_L} \tilde{H} u_R + h.c. \longrightarrow \underline{m_u(\overline{u_L}u_R + \overline{u_R}u_L)} + \frac{Y_u}{\sqrt{2}}\overline{u_L}u_R h + h.c.$$

$$H = \frac{v+h}{\sqrt{2}}$$

u quark mass : $m_u = \frac{Y_u}{\sqrt{2}} v$

- *h-f-f* 相互作用
  - ヒッグス粒子が2つのフェルミオンに崩壊



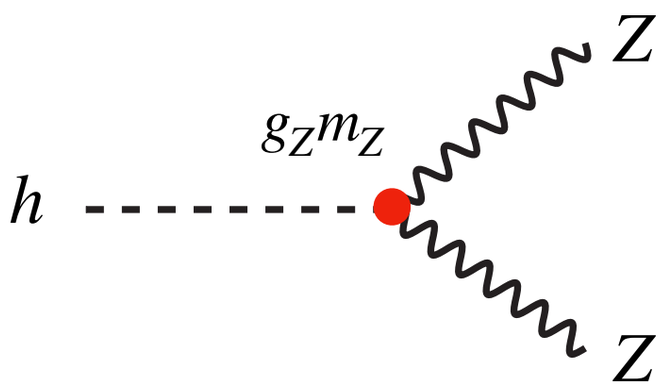
まとめ

- 光子 (フォトン, Photon) は電磁気力を伝えるゲージ粒子

  電荷を持っている粒子と相互作用（反応）する

- ヒッグス (Higgs) は対称性を破って素粒子に質量を与える

- ヒッグス機構によって対称性が破れた証拠



Outline

1. Introduction

2. Dark Photon with Dark Higgs

3. FASER and T2K sensitivity

4. Summary

1. Introduction

ここからスライドが英語になります
（単語が分からない場合はいつでも聞いてください）

Introduction

SM = Standard Model

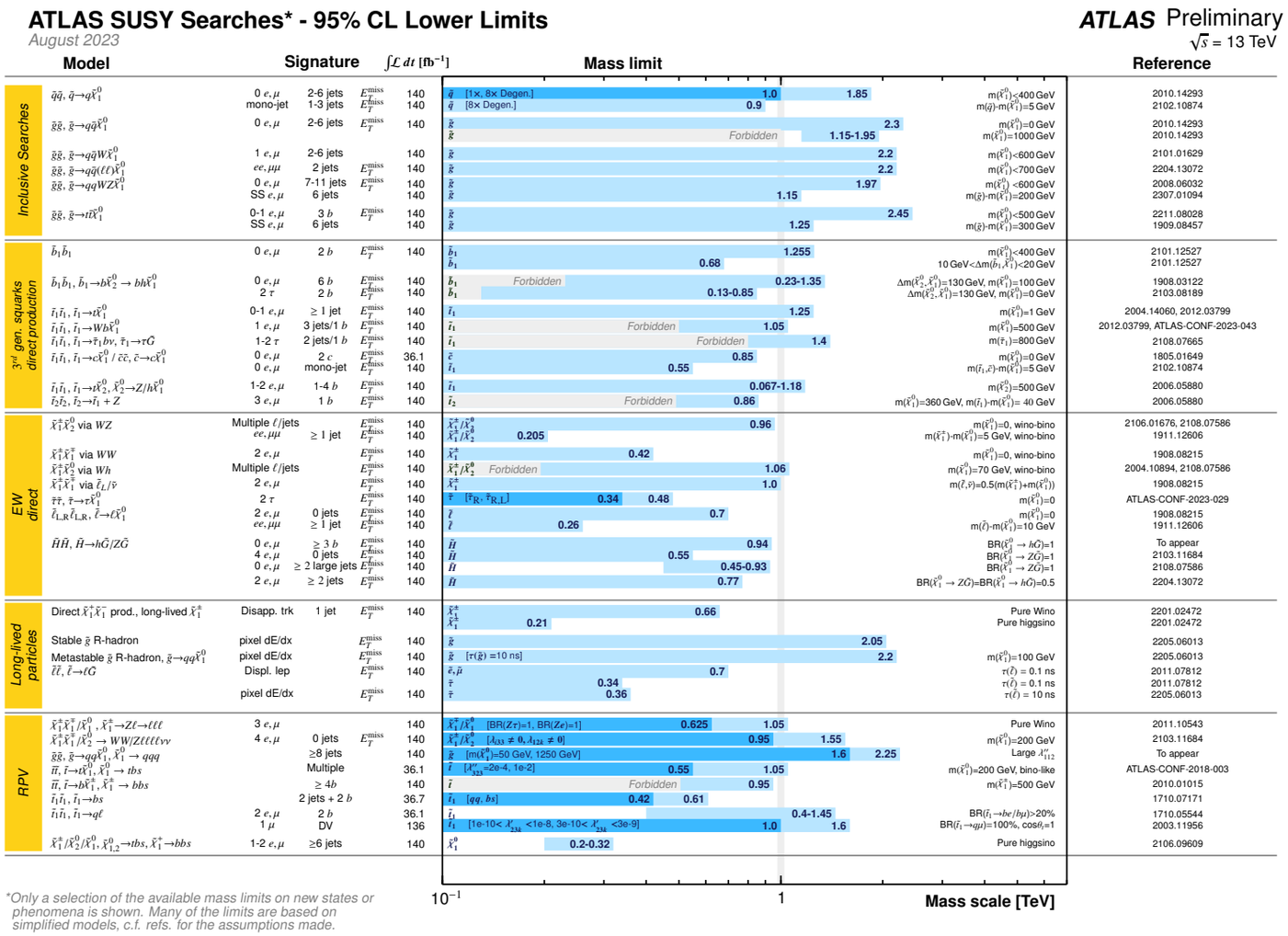
- The standard model has been explaining almost all experimental results
- There are problems that the SM cannot address
  - Phenomenology side:
    - Neutrino mass and mixing (Lepton Flavor Violation)
    - Baryon asymmetry of the Universe
    - Dark Matter/Dark Energy
    - Anomalous magnetic moment 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…

Introduction

New Physics Beyond the SM (BSM) must solve these problems

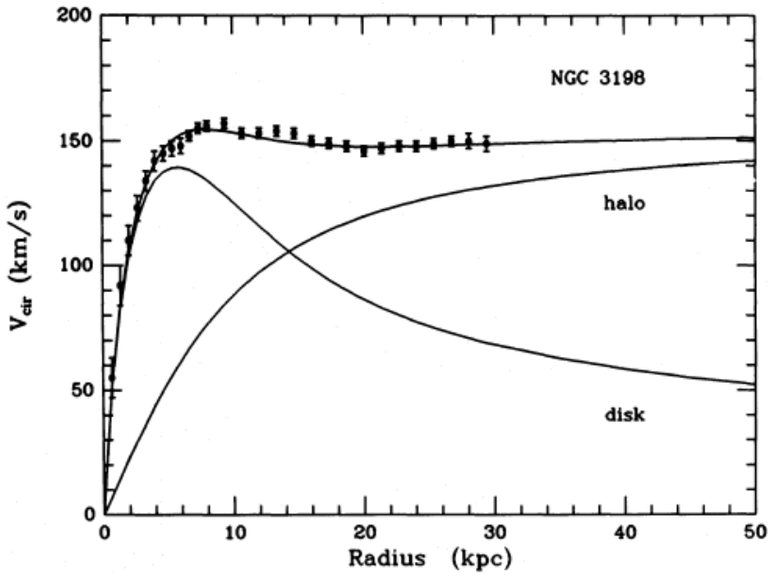
SUSY, extra dim. technicolor …

But no convincing signatures of BSM have been seen yet…

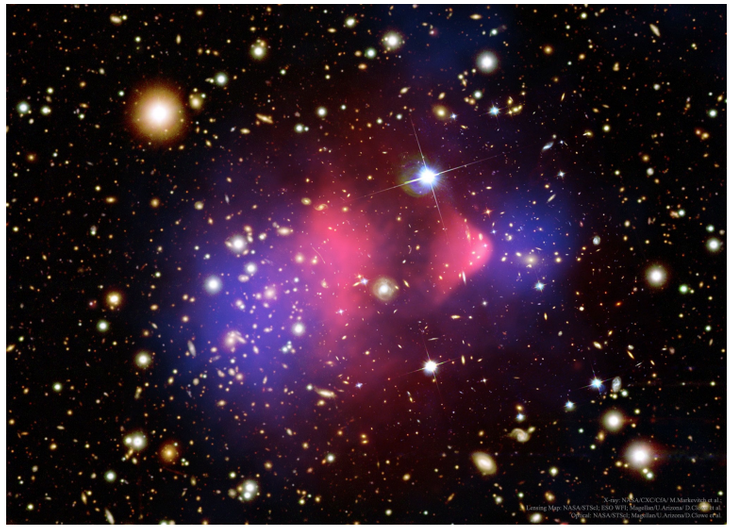


Dark Matter

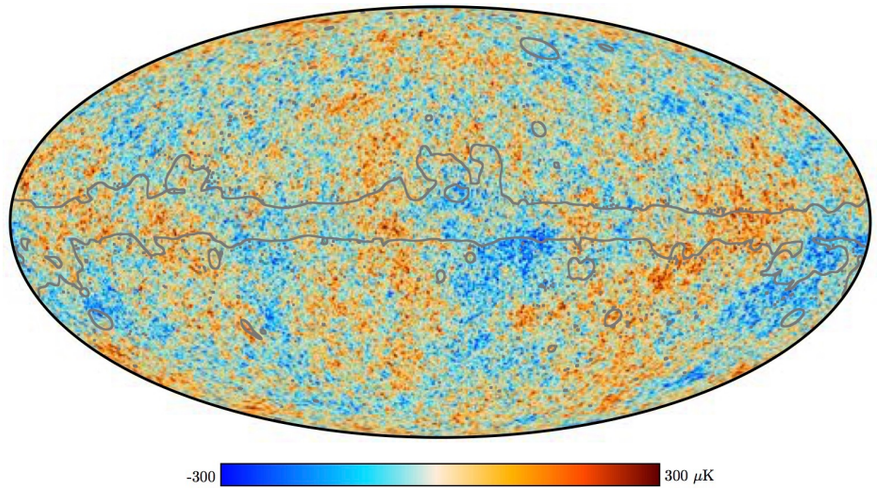
Rotation curves of galaxies



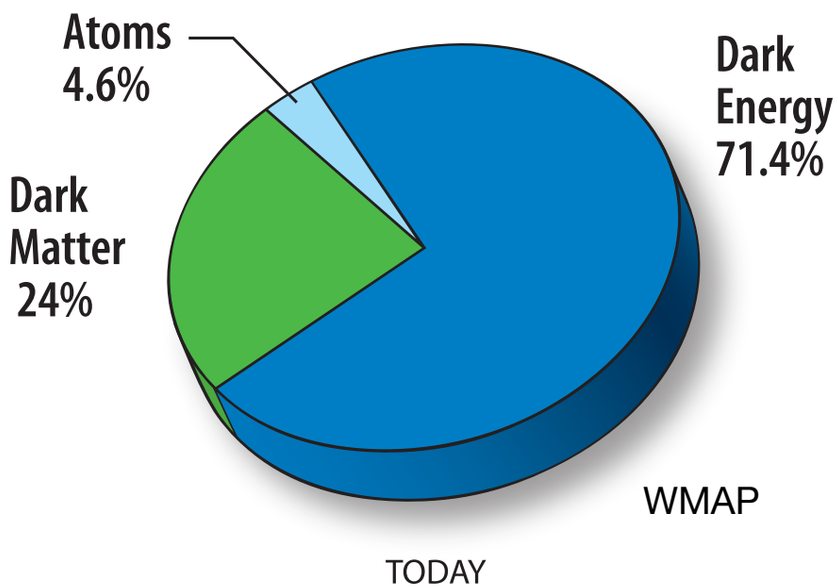
The bullet cluster



Cosmic microwave background



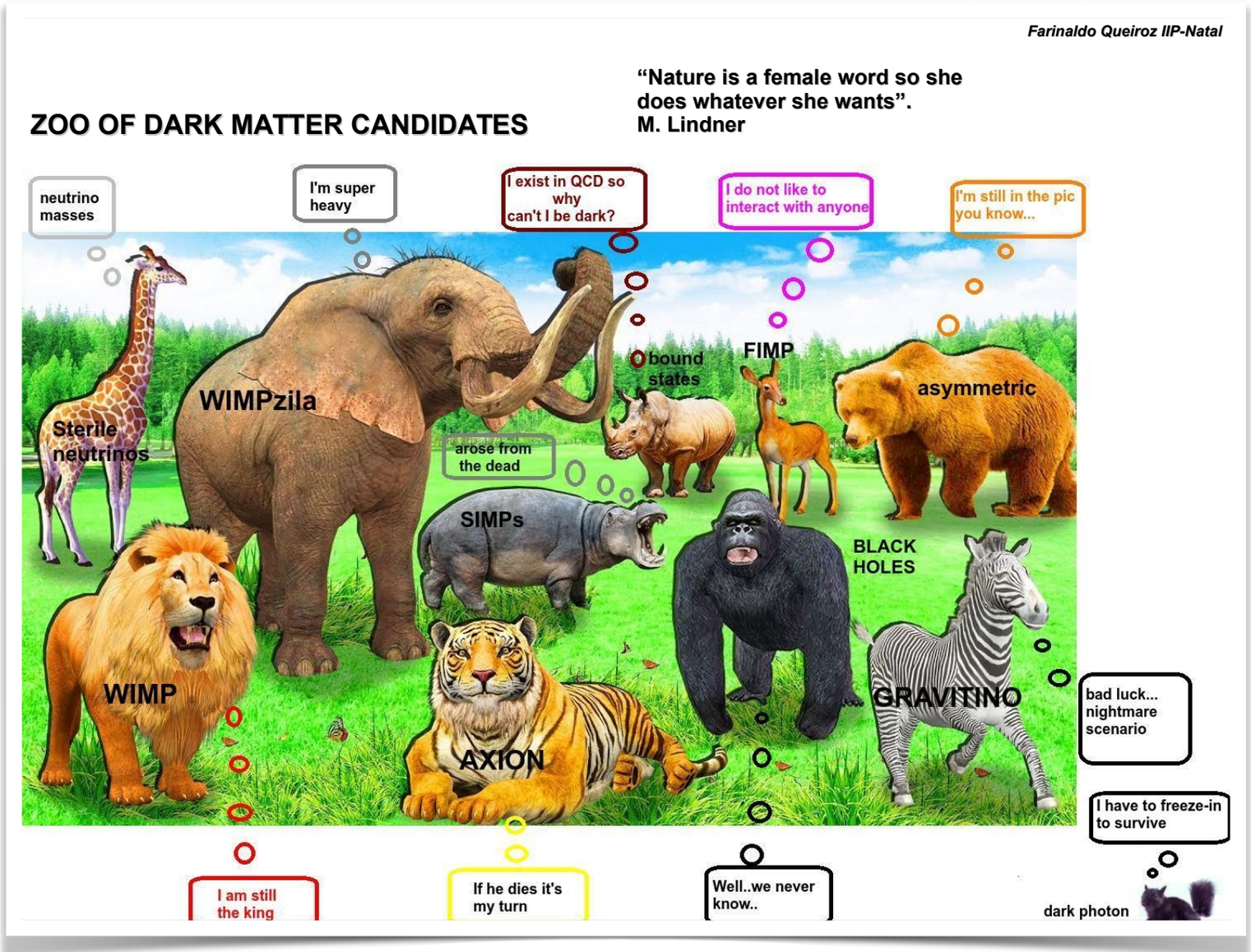
- The DM occupies 24% of the total energy density of the Universe.
- The ordinary matter is just 4.6%.



Dark Matter Candidates

- There are many candidates, via thermal or non-thermal productions
  - Weakly Interacting Massive Particles (WIMPs)
  - Axion or Axion-Like-Particles (ALPs)
  - Sterile neutrinos
  - pNG particles
  - Dark Photon
  - Gravitino
  - etc…

None of them have been found yet



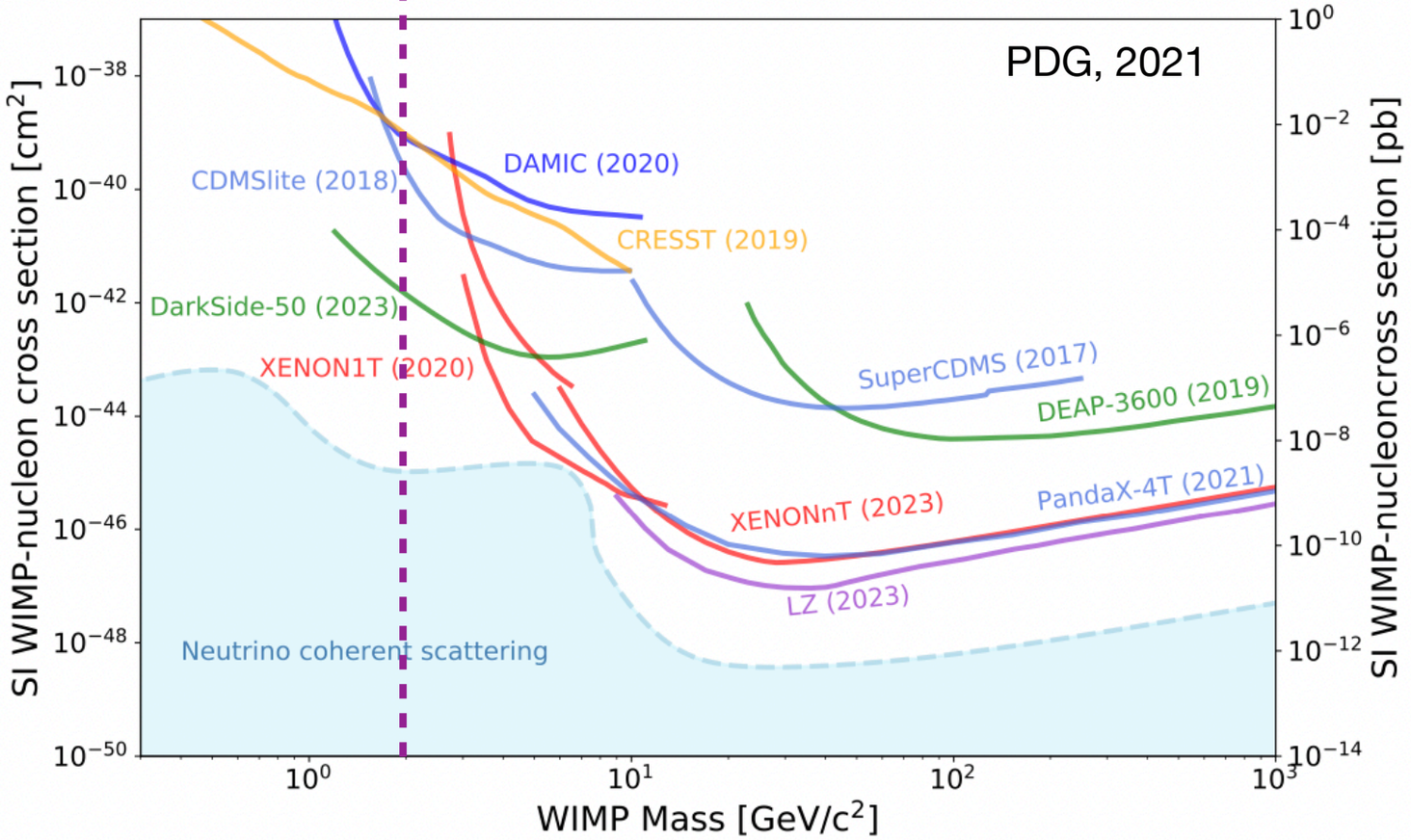
taken from F. Queiroz slide

Light DM

Lee-Weinberg bound

Light DM ← → WIMPs

(WIMP=Weakly Interacting Massive Particle)



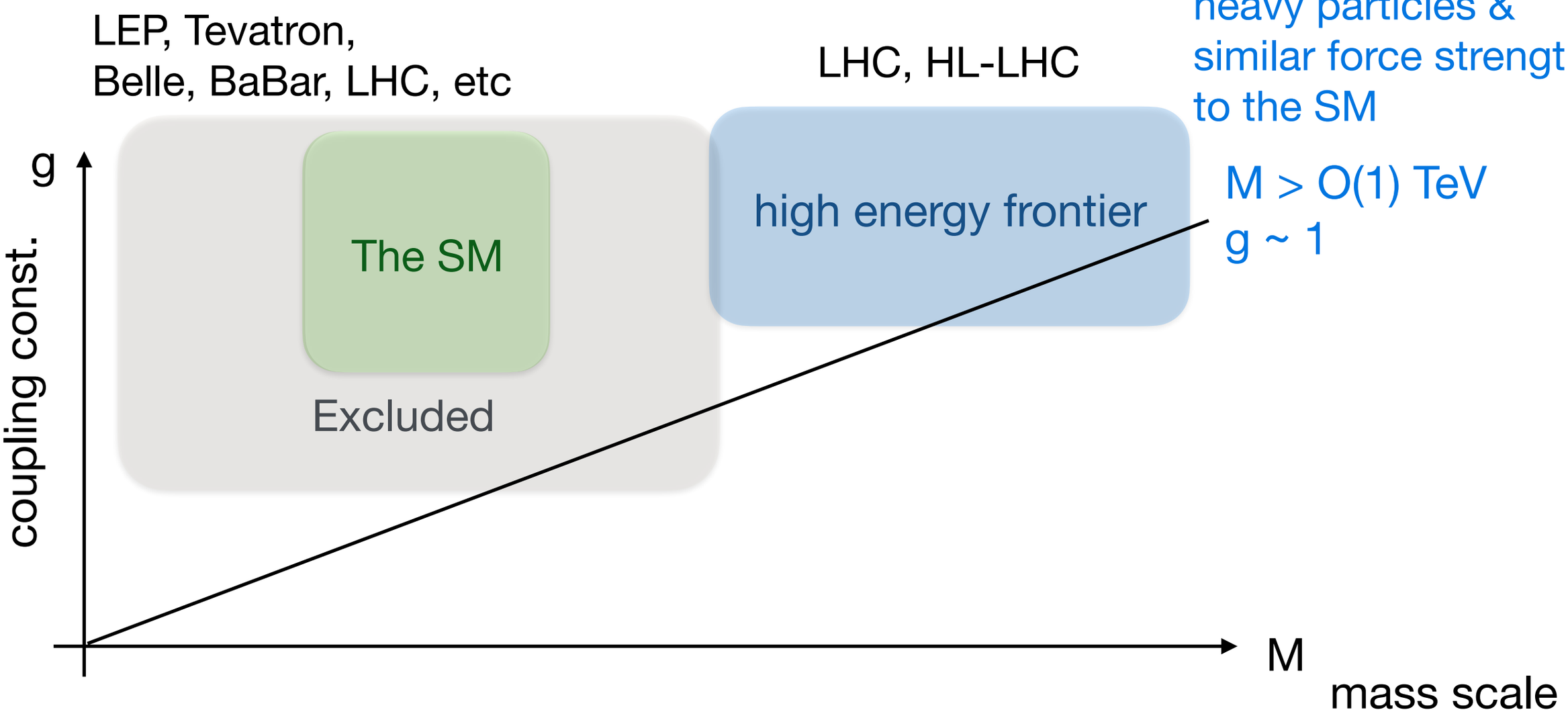
- Lee-Weinberg bound : When the DM annihilates through the weak int., its mass must be > 2 GeV to avoid overproduction.

Lee and Weinberg, PRL 39 (1977)

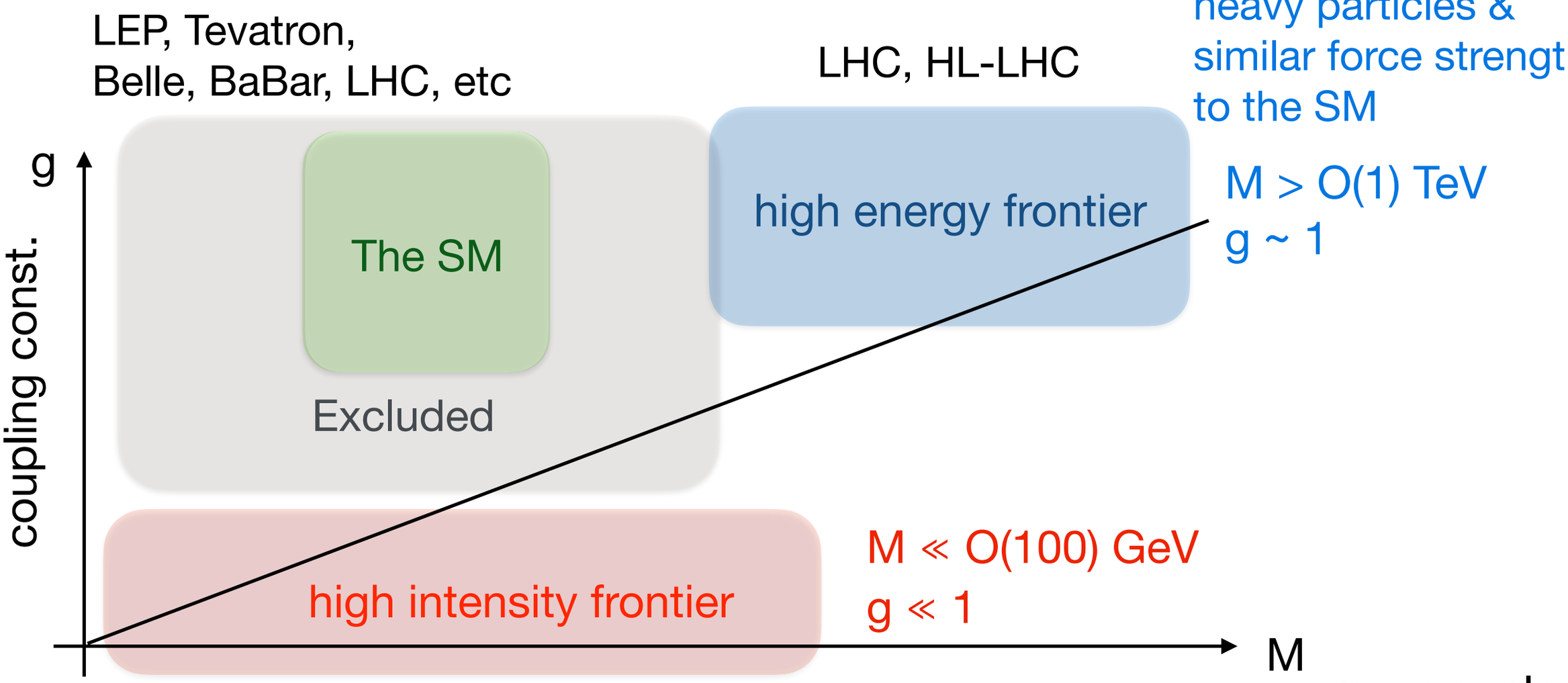
- Introducing a new light force mediator, the DM can annihilate efficiently. Then, the DM can be lighter than 2 GeV.

Boem and Fayet,
Pospelov, et al

Light Mediator



Light Mediator



light particles & feeble force

FASER, Belle-II, SHiP, COHERENT,
NA64μ, ILC, DUNE, APEX,
MESA,VEPP3, Mu3e, T2K, etc…

Dark Sector

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

(*portal = gate)

- No direct interactions exist between the SM and dark particles.
- Portal particle connects two sectors.

Dark Sector

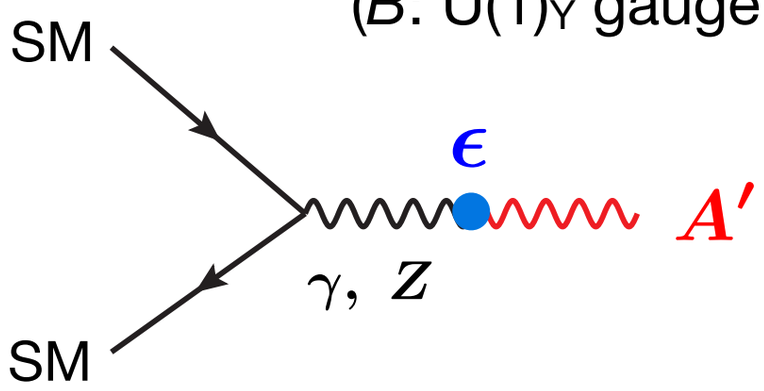
- "Dark Particles" are model(problem)-dependent.
- "Portal-SM Interactions" are rather model-independent.

(constrained by symmetry & spin)

Portals

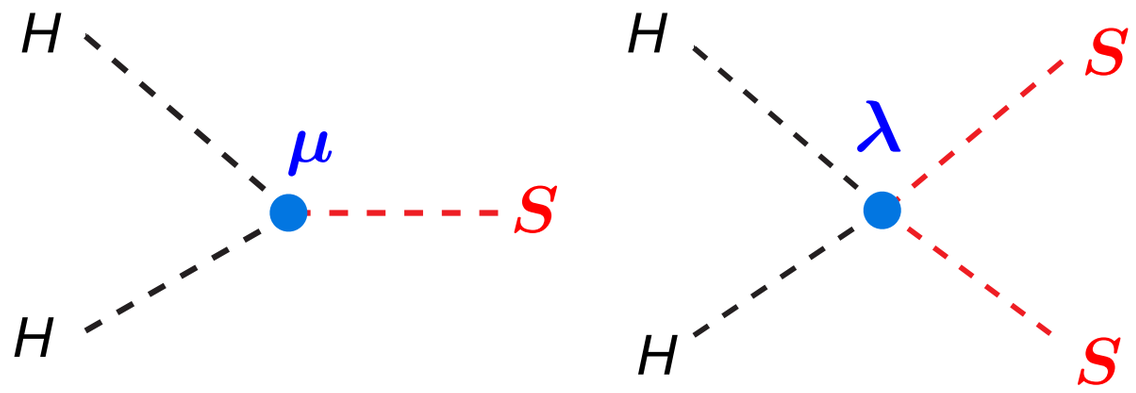
- Vector Portal : $\epsilon B_{\mu\nu} A'^{\mu\nu}$

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



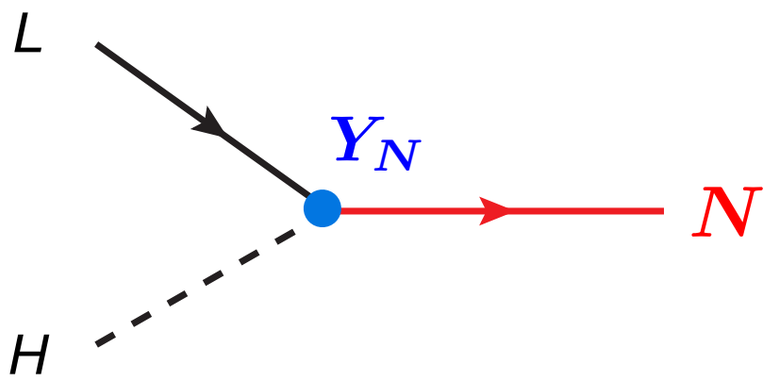
Dark photon/extra Z'

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



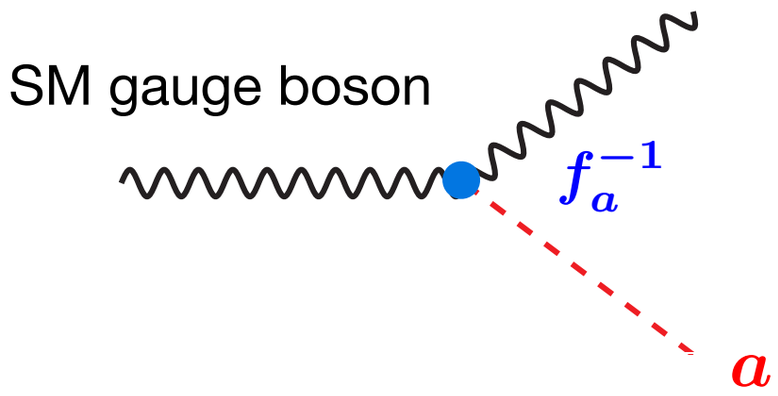
Dark Higgs

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



right-handed neutrino

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



Pseudoscalar/ALPs

Dark photon & Dark Higgs

- Dark photon and dark Higgs are benchmark models of the portals.
- Both portals have been studied separately.
  - Dark photon is the gauge boson of dark symmetry.
    → mixes with the EM photon
  - Dark Higgs breaks dark symmetry spontaneously.
    → mixes with the SM Higgs
- Mechanism of dark photon mass generation
  - Mass of dark photon is given by hand in minimal model (some literatures)
  - Some mechanism is required for realistic model
    - Stuckelberg mechanism (connection to string theory?)
    - Spontaneous symmetry breaking (Higgs mechanism)

      → Dark photon model with dark Higgs

Dark sector search

- Dark sector could accommodate new physics such as
  - Dark matter
  - Neutrino mass/mixing
  - Baryon asymmetry of the Universe
  - Strong CP problem

For review, Feng et al. J.Phys.G 50 (2023)

- Experiments are running now, and planned for near future.
  - FASER, FASER2
  - Belle-II, NA64
  - T2K, DUNE
  - FACET, Codex-b, MATHULSA, etc

We are in good era to study dark sector physics

Purpose

In this talk, I will discuss the following two studies

- Dark photon model with dark Higgs
  - Dark Higgs contribution to dark photon production
  - Sensitivity to dark photon search at the FASER experiment

    "*Dark Photon from light scalar boson decay at FASER*", JHEP03 (2021) 072

- Sensitivity to dark photon search at T2K experiment
  - First study of dark photon sensitivity at T2K
  - Constraint from present results
  - Future sensitivity at upgraded T2K

    "*New Constraint on Dark Photon at T2K off-axis near detector*", JHEP11 (2023) 056

2. Dark Photon with Dark Higgs

Dark photon model

- Introduce a dark symmetry $U(1)_{dark}$ to the SM
  - The SM particles are singlet under $U(1)_{dark}$.
  - Dark photon A' can have kinetic mixing term.
  - Dark Higgs Φ is introduced to break $U(1)_{dark}$.

	Q	u	d	L	e_R	H	Φ
$SU(3)_C$	**3**	**3**	**3**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**1**
$U(1)_Y$	1/6	2/3	−1/3	-1/2	−1	1/2	0
$U(1)_{\rm dark}$	0	0	0	0	0	0	1

Lagrangian

$$\mathscr{L} = \mathscr{L}_{\rm SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{\epsilon}{2}A'^{\mu\nu}B_{\mu\nu} + \mathscr{L}_{DH}$$

$$\mathscr{L}_{DH} = |D_\mu \Phi|^2 - V_{DH}, \quad (D_\mu = \partial_\mu - ig'A'_\mu)$$

$$V_{\rm DH} = -\mu_D^2 \Phi^\dagger\Phi + \frac{\lambda_D}{4}(\Phi^\dagger\Phi)^2 + \frac{\lambda'}{2}(H^\dagger H)(\Phi^\dagger\Phi)$$

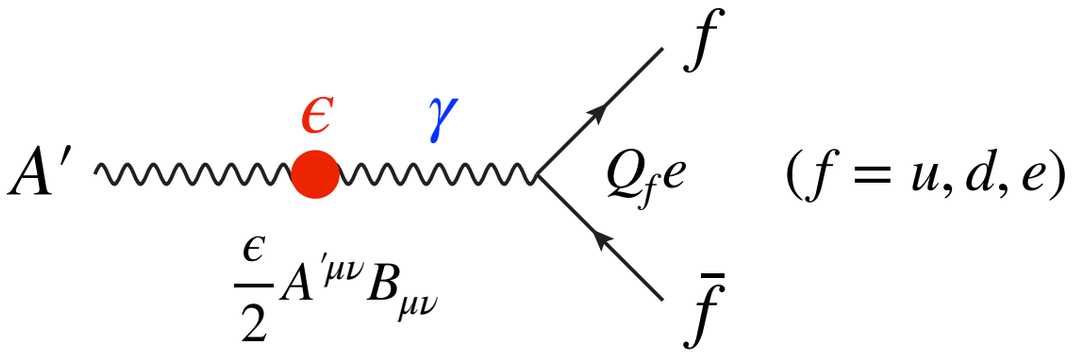
where ϵ : kinetic mixing parameter

B : U(1) hypercharge gauge boson (⊃ EM photon)

Dark photon interaction

- Due to the kinetic mixing, A' can mix with the EM photon
- A' interacts with charged particles through the EM current

$$\mathscr{L}_{int} = \epsilon e J^{\mu}_{EM} A'_{\mu}$$



- Dark photon can decay into charged leptons & hadrons.

Decay width

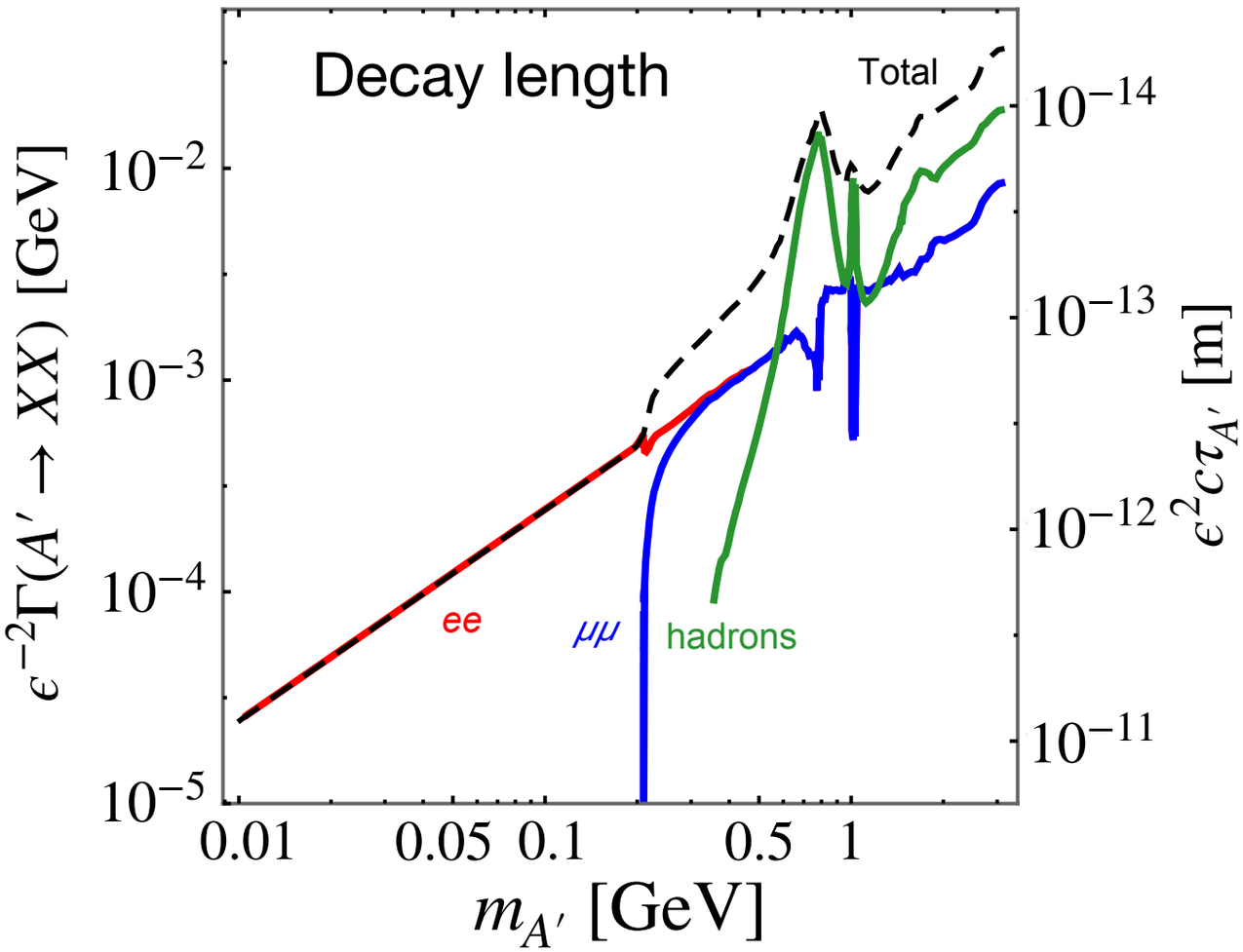
$$\Gamma(A' \to \ell\bar{\ell}) = \frac{\epsilon^2 e^2 m_{A'}}{12\pi}\left(1 + \frac{2m_\ell^2}{m_{A'}^2}\right)\beta_{A'}(l) \qquad \left(\beta_{A'}(l) = \sqrt{1 - 4m_l^2/m_{A'}^2}\right)$$

$$\Gamma(A' \to \text{had.}) = \Gamma(A' \to \mu\bar{\mu})\ R(m_{A'}^2)$$

where $R(s) = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$

Dark photon decay length

minimal model (w/o dark higgs)



For $\epsilon = 10^{-7}$

$$c\tau_{A'} = 100 \text{ m} \text{ @ } m_{A'} = 0.1\text{GeV}$$

cf: muon

$$c\tau_{\mu} = 220 \text{ m}$$

Dark photon mass

Mass generation mechanism

- Spontaneous symmetry breaking is one of the natural mechanisms.
  - Dark Higgs boson Φ must be introduced as the origin of A' mass
  - $U(1)_{\text{dark}}$ is broken by dark Higgs vev.

Dark Higgs kinetic term

$$|D_\mu \Phi|^2 \supset g'^2 \Phi^\dagger \Phi A'_\mu A'^\mu \xrightarrow[\Phi = (v_\phi + \phi)/\sqrt{2}]{\text{U(1)}_{\text{dark}}\ \text{br.}} \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu + g' m_{A'} \phi A'_\mu A'^\mu + \cdots$$

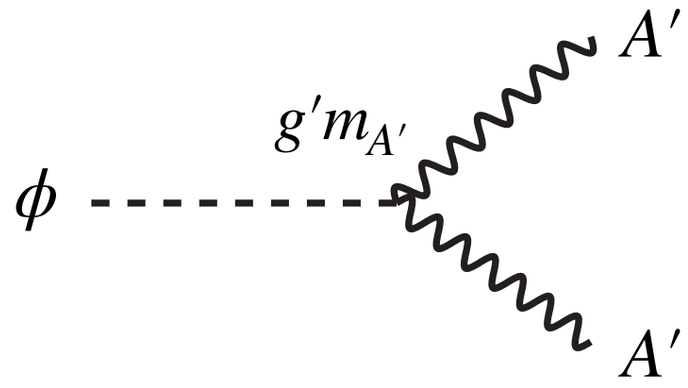
$$(m_{A'} = g' v_\phi)$$

The $\phi A' A'$ interaction is

Direct consequence of the mass generation.

Dark Higgs decay into $A'A'$

- Dark higgs can decay into two dark photons



Decay width of $\phi \to A'A'$

- Controlled by g'
- Enhanced when $m_{A'} \ll m_\phi$ due to longitudinal component

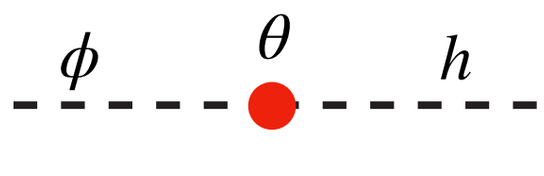
$$\Gamma(\phi \to A'A') = \frac{g'^2}{8\pi}\frac{m_{A'}^2}{m_\phi}\beta_\phi(A')\left[2+\frac{m_\phi^4}{4m_{A'}^4}\left(1-2\frac{m_{A'}^2}{m_\phi^2}\right)\right]$$

$$\simeq \frac{g'^2}{32\pi}\frac{m_\phi^2}{m_{A'}^2}m_\phi \qquad \text{where } \beta_\phi(A') = \sqrt{1-4m_{A'}^2/m_\phi^2}$$

Dark higgs interaction

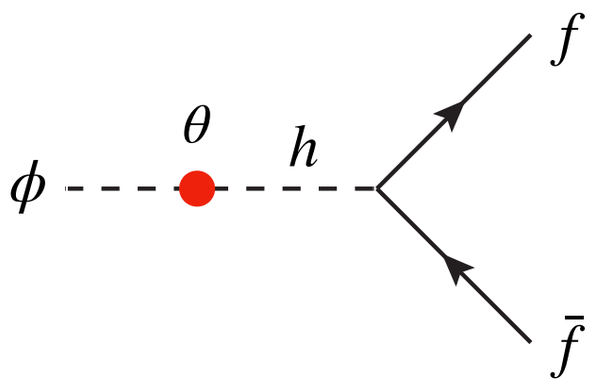
- Dark higgs can mix with the SM higgs after the symmetry breaking

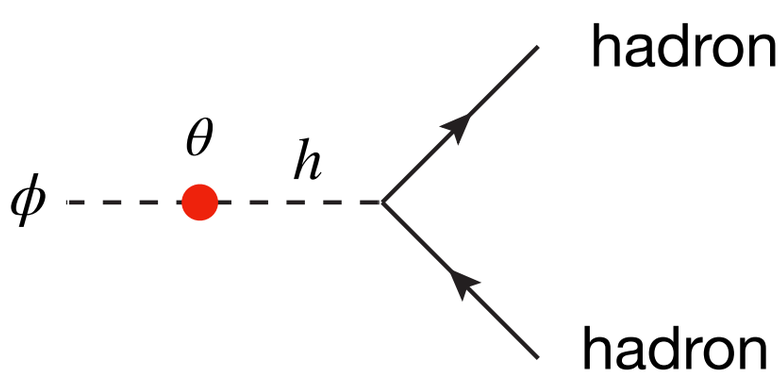
$$V_{\mathrm{DH}} \supset \frac{\lambda'}{2}(H^\dagger H)(\Phi^\dagger \Phi) \longrightarrow \left(\frac{\lambda'}{4} v v_\phi\right) h\phi$$



$$\theta \simeq \frac{v m_{A'}}{4 m_h^2} \frac{\lambda'}{g'}$$

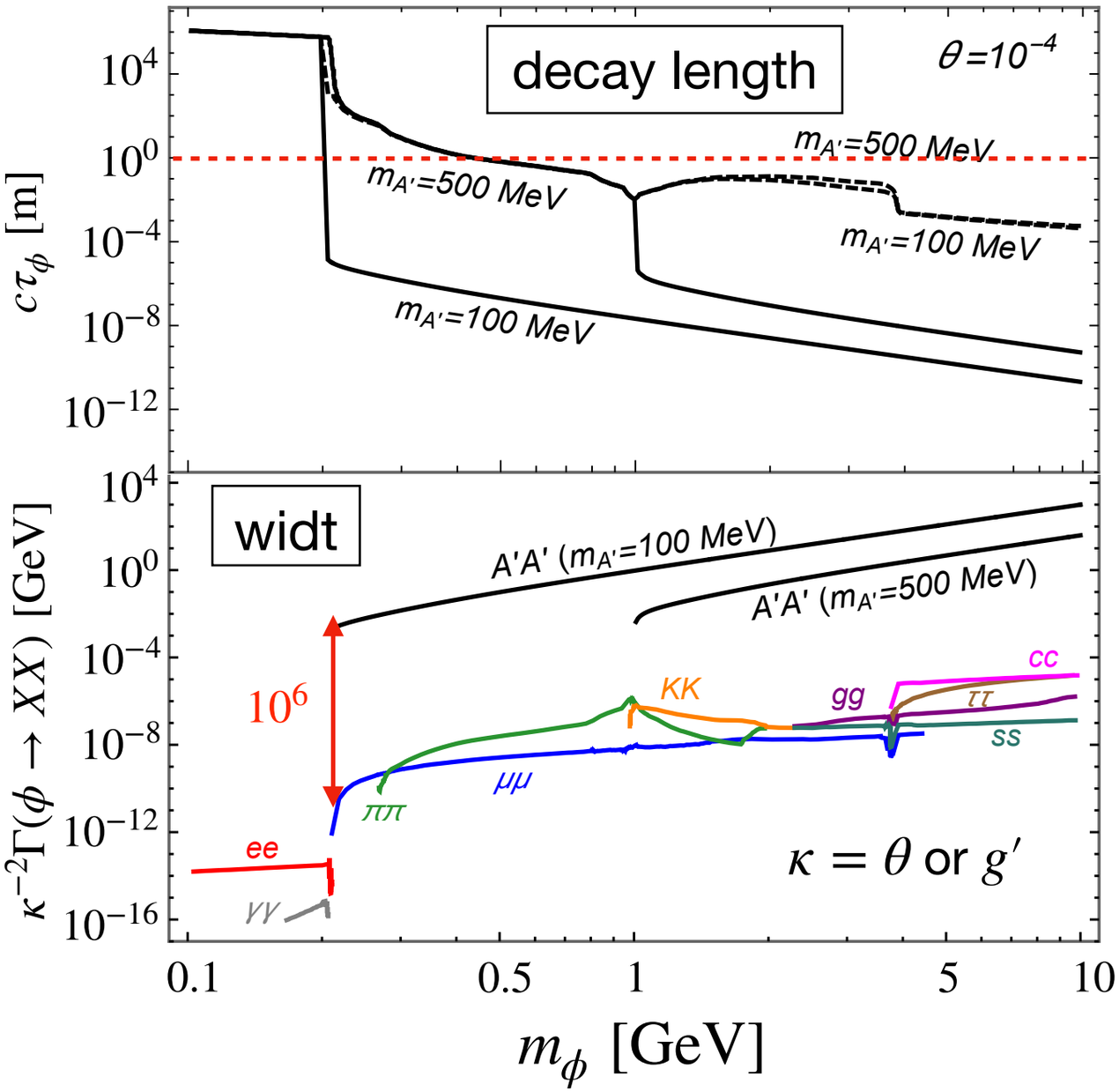
- Dark higgs can decay into the SM particles through the mixing





Decay width : $\Gamma(\phi \to \mathrm{SM}) = \theta^2 \Gamma(h \to \mathrm{SM})(m_\phi) \propto \theta^2 m_\phi$

ϕ decay with



Solid for $g' = 10^{-4}$

Dashed for $g' = 10^{-8}$

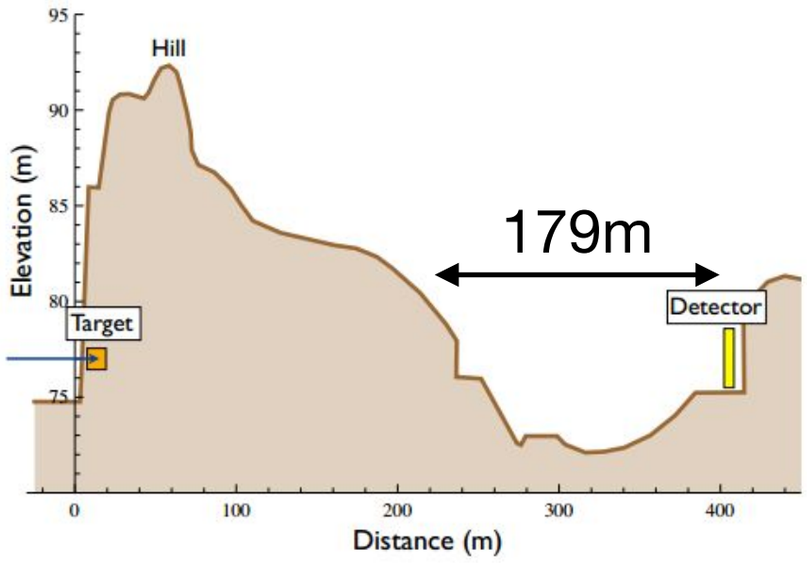
- ϕ dominantly decays into $A'A'$
- Long-lived for small g'

→ possible new source and carrier of A'

Production of dark photon

- Dark photon production :
  - Proton/electron bremsstrahlung ($p \to p + A'$, $e \to e + A'$)
  - Rare meson decays ($\pi \to \gamma A'$, $\eta \to \gamma A'$, $\eta' \to \gamma A'$)
  - Drell-Yang, QCD processes ($q\bar{q} \to A'$)

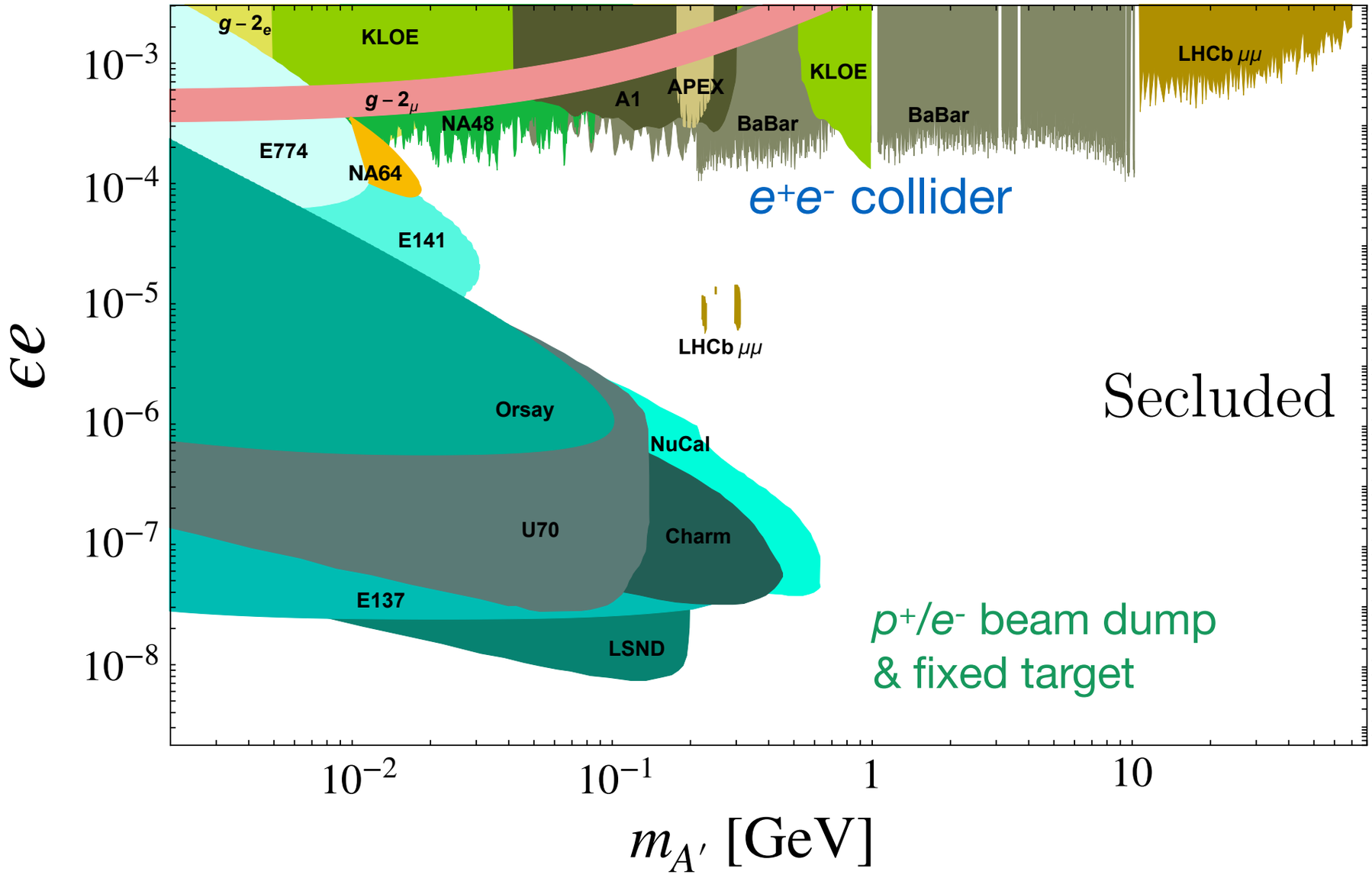
- Dark photon search experiments :
  - Fixed target/beam dump experiment (CHARM, NuCal, E141, NA64)
  - Electron-Positron collider (BaBar, Belle, KLOE)
  - Hadron collider (LHC)



ex) E137 experiment at SLAC

- Electron beam dump
- 179m to the detector
- 25m long decay volume

Present status of dark photon



cf:

- Strong int.
  $g_3 = 1$
- Weak int.
  $g_2 = 0.6$
  $g_2 = 0.3$
- EM int.
  $e = 0.3$

"Hunting all the hidden photon"
Bauer, et al, JHEP07 (2018)

Production of dark higgs

- Dark higgs production :
  - ~~Proton/Electron bremsstrahlung~~ Negligible due to tiny Yukawa
  - Rare meson decays ($B \to K\phi, K \to \pi\phi$)
  - Gluon fusion, Associated process ($gg \to \phi, e^+e^- \to Z\phi$)

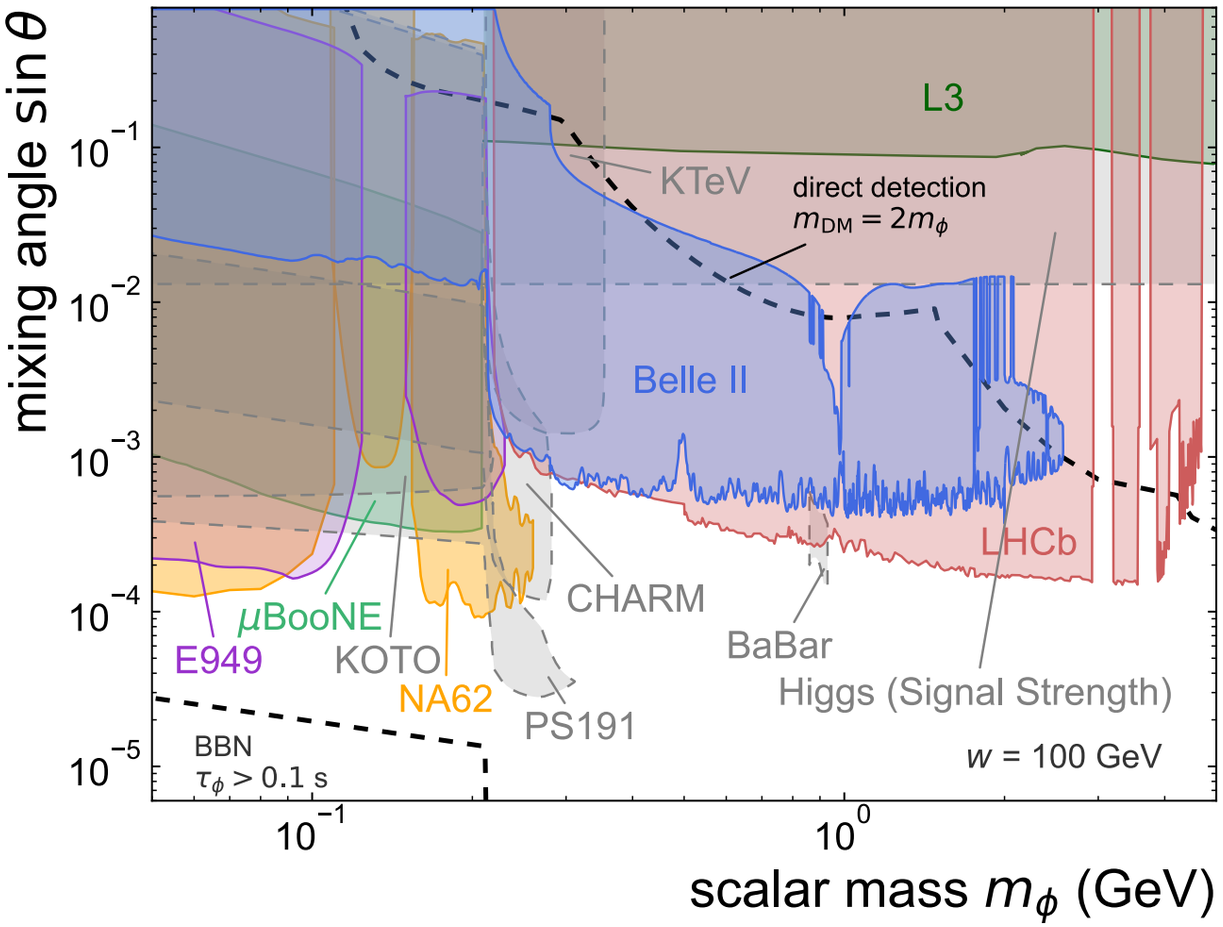
- Dark higgs search experiments :
  - Electron-Positron collider (Belle-II)
  - Proton beam dump (CHARM, PS191, NA62)
  - Hadron collider (LHCb)

Present status of dark higgs

"Dark higgs boson at Forward Search experiment"
Feng et al. PRD(2018)

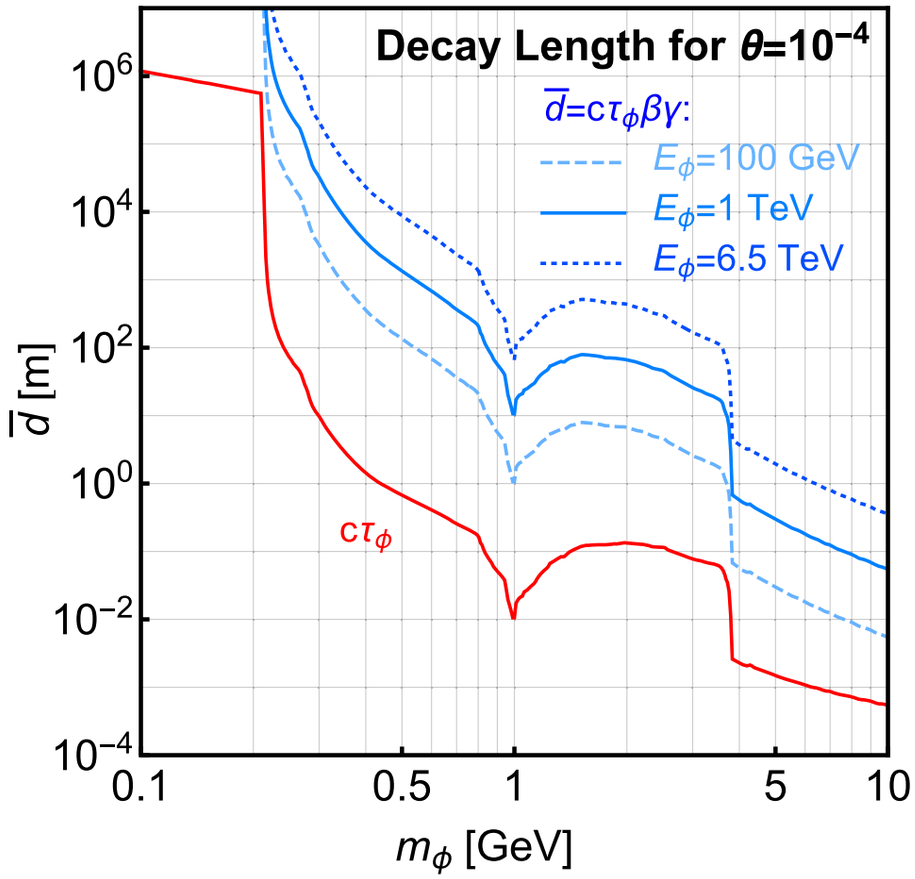
Dark Higgs

$$\mathscr{L}_{int} = \theta \frac{m_f}{v} \bar{f} \phi f$$



"Dark higgs boson at colliders"
Ferber et al. Prog. Part. Nucl. Phys. (2024)

Decay length



For $\theta = 10^{-4}$

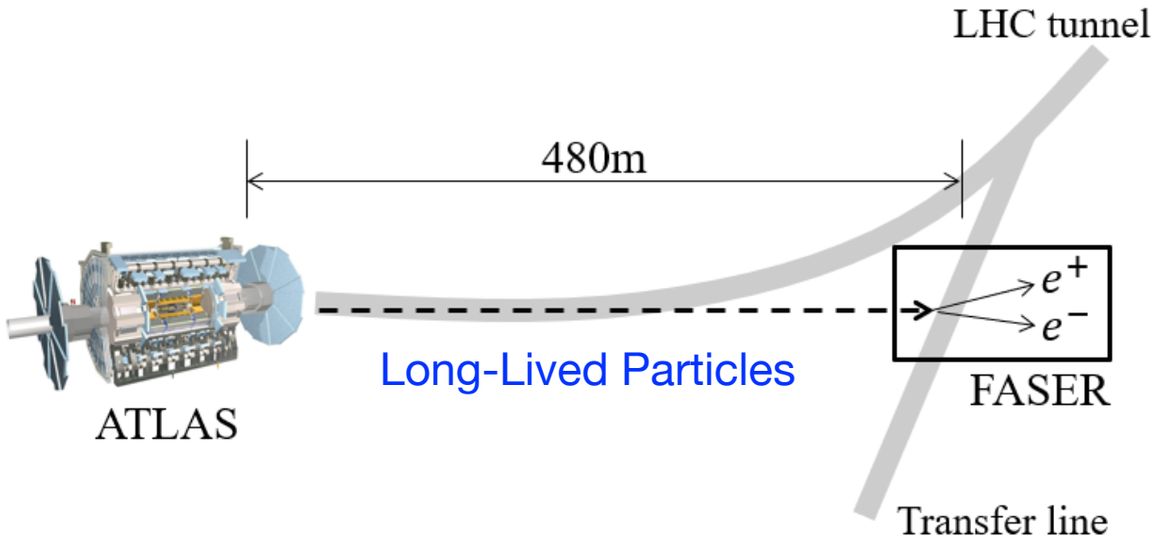
$$c\tau_\phi = 10^{-2}\text{m} \;@\; m_\phi = 1\text{GeV}$$

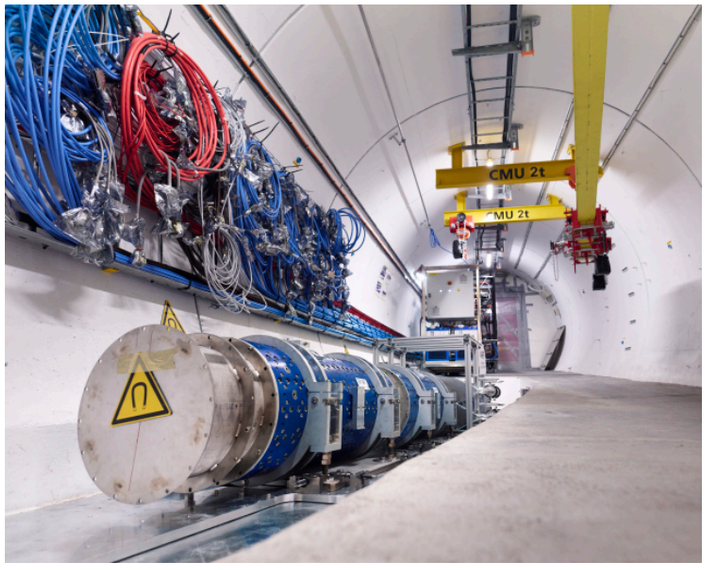
4. FASER and T2K sensitivity

FASER experiment

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

- ForwArd Search ExpeRiment (FASER) at LHC, from 2022 to 2025
- Search for long-lived new particles produced at ATLAS interaction point.
- Detector placed 480m downstream from the interaction point.

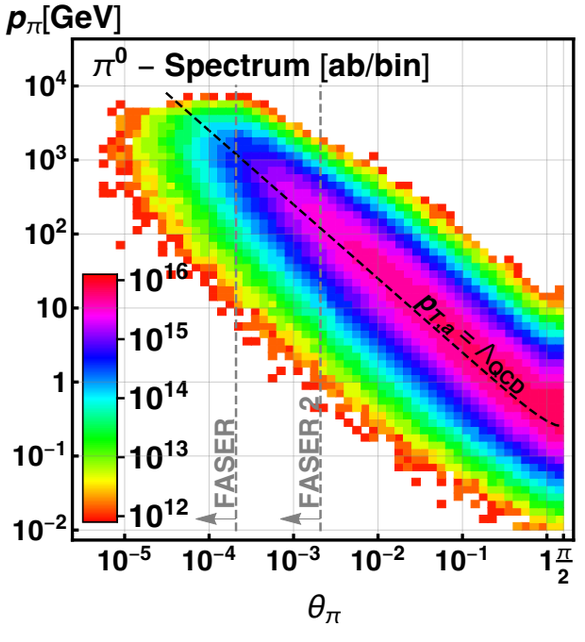




- Inelastic pp scattering produces collimated and energetic particles in forward direction

$$10^{17}\pi^0,\ 10^{16}\eta,\ 10^{15}D,\ 10^{13}B$$

within 1mrad of beam (Run3)



Pion distribution

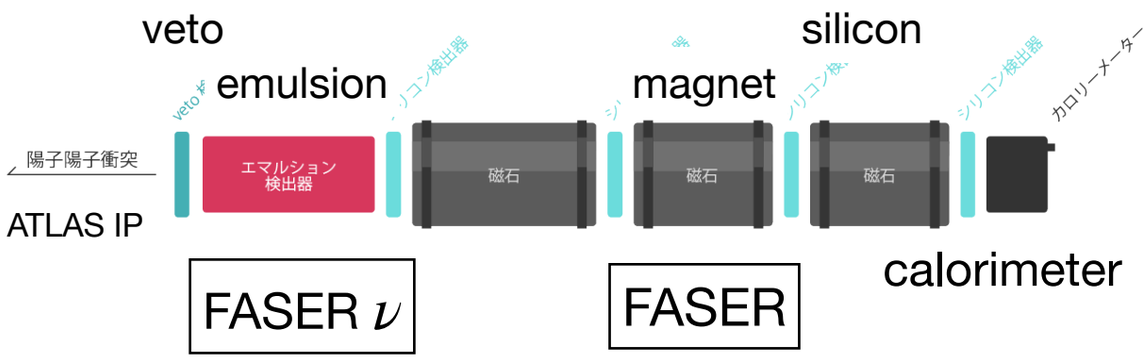
angle to beam direction

FASER Detector

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

	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

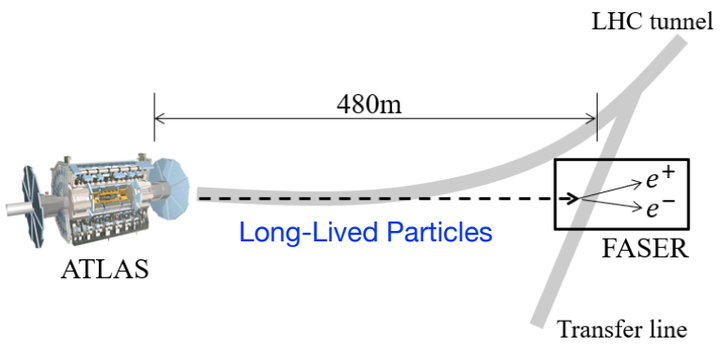
FASER : LHC run3, FASER2 : LH-LHC



- Upgrade to FASER2 has been proposed

Very low background (almost BG free)

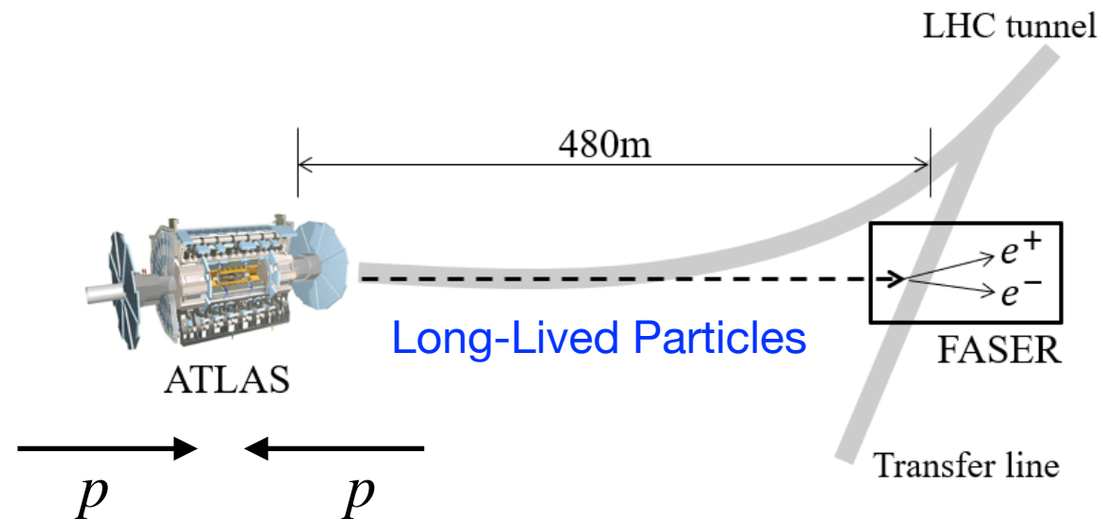
- 100m underground
- shielded by ~100m of rock and concrete
- Possible main BG is neutrino interaction
  ~ 0.0045 events for 0.15 ab^{-1}



- Three 0.57T dipole magnets
  → e, μ, π separation
  (difficult for τ)
- Tracking spectrometer
  → identify decay vertex with
  $\mathcal{O}(10-100)\mu$m resolution
- EM calorimeter
  → 100% energy deposit for e
  small amount for μ

Production processes

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

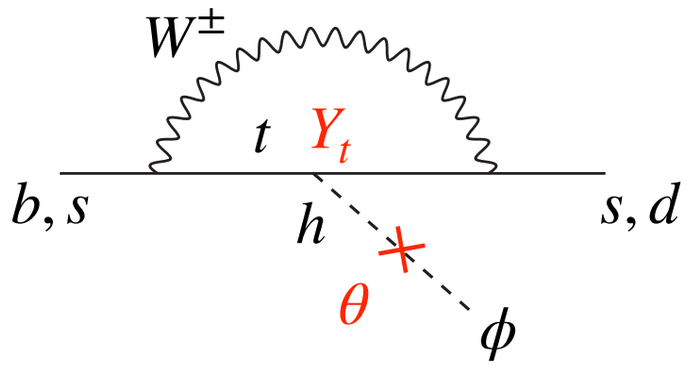


- Proton-Proton collision with $\sqrt{s} = 14$ TeV.
- Production of dark photon and dark Higgs
  - Proton bremsstrahlung, $p \to p + A'$
  - Meson decays $(B,\ K,\ D, \eta') \to \phi, \quad (\eta, \pi) \to A'$
  - Drell-Yang, QCD processes
  - Dark Higgs decays, dominantly $\phi \to A' + A'$

Meson decay into ϕ

- FCNC decays of meson
  - ex) $B \to K_s\phi, \quad K \to \pi\phi$

    Top loop gives large contribution



$$\longrightarrow \quad \mathscr{L}_{bs\phi} = \frac{3\sqrt{2}G_F m_b m_t^2 V_{ts}^* V_{tb}}{16\pi^2 v}\theta^2 \overline{s_L} b_R \phi + h.c.$$

- Branching ratio

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

$$\mathrm{Br}(K_L \to \pi^0\phi) = 7.0 \times 10^{-3} x_{K,\phi}\theta^2$$

$$\mathrm{Br}(K^{\pm} \to \pi^{\pm}\phi) = 2.0 \times 10^{-3} x_{K,\phi}\theta^2$$

meson mass (GeV)

($x_{i,\phi}$, $f_{i,\phi}$: kinematical factor)

5.3

1.0 $\quad \mathrm{Br}(\eta' \to \eta\phi) = 7.2 \times 10^{-5} x_{\eta,\phi}\theta^2$

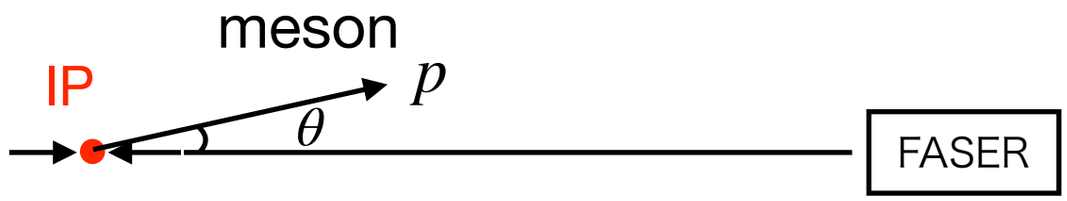
0.5 $\quad \mathrm{Br}(\eta \to \pi^0\phi) = 1.9 \times 10^{-6} x_{\eta,\phi}\theta^2$

$\quad \mathrm{Br}(K_S \to \pi^0\phi) = 2.2 \times 10^{-6} x_{K,\phi}\theta^2$

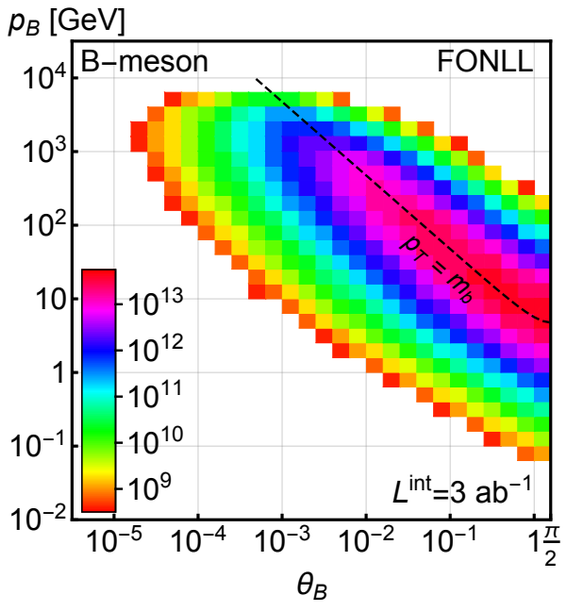
0.14 $\quad \mathrm{Br}(\pi^{\pm} \to e\nu\phi) = 1.9 \times 10^{-9} f_{\pi,\phi}\theta^2$

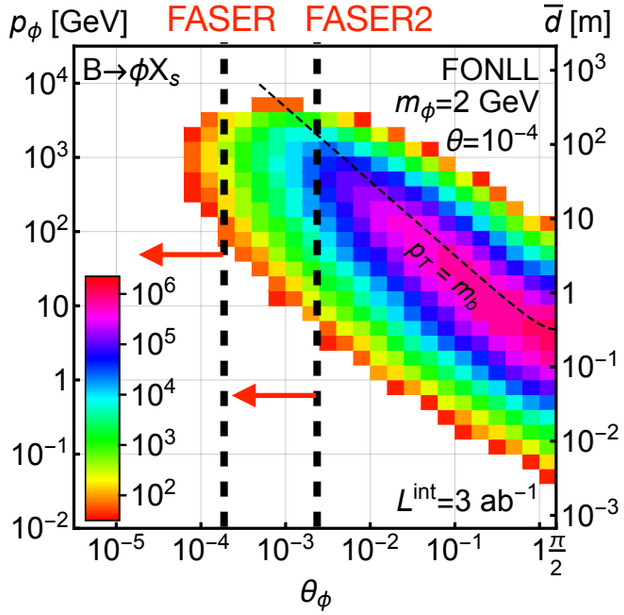
Dark Higgs from meson decay

- Mesons produced at LHC



B meson





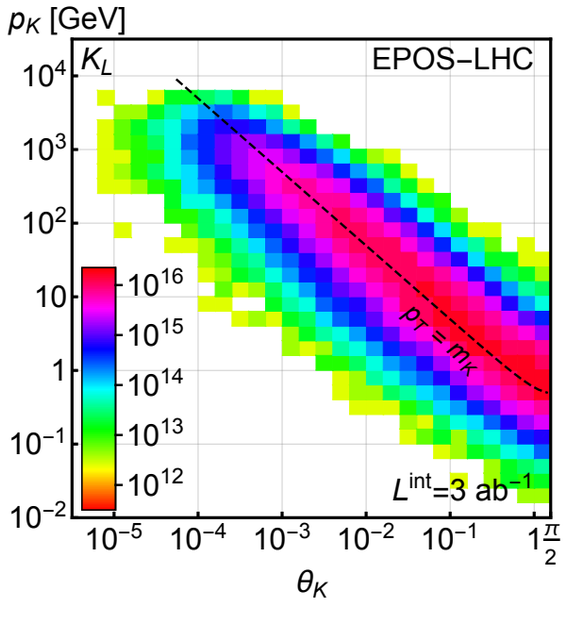
Number of ϕ

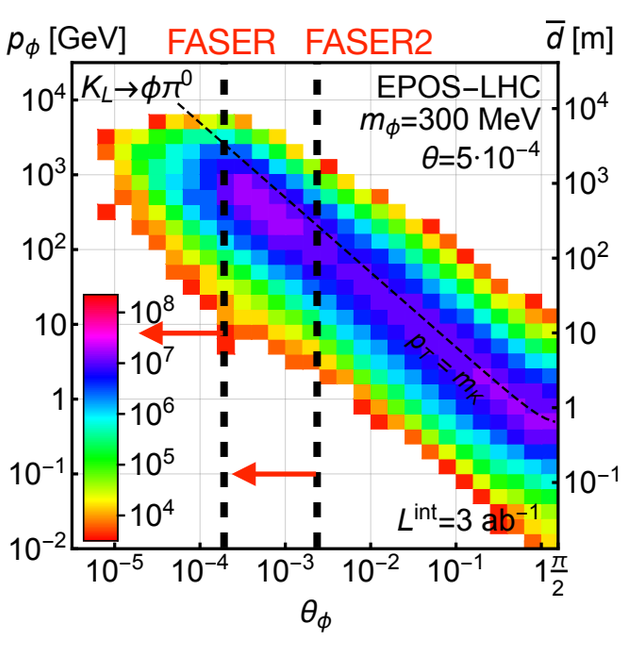
From *B* decay

$N_\phi \simeq 10^6 - 10^7$

Dominant process

K_L meson



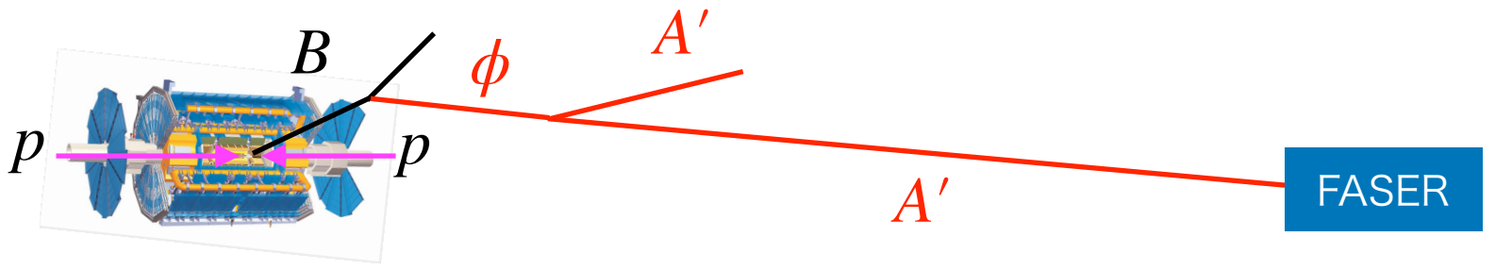


From *K* decay

$N_\phi \simeq 10^6 - 10^7$

Not important due to the long life of K

Number of Events



- Expected number of events

$$N_{A'} = L \int dp_B d\theta_B \frac{d\sigma_{pp\to B}}{dp_B d\theta_B} \mathrm{Br}(B \to X_s \phi) \mathrm{Br}(\phi \to A'_1 A'_2) \sum_{j=1,2} P^{\mathrm{det}}_{A'_j}(\mathbf{p}_{A'}, \mathbf{p}_\phi)$$

cross section of B production	Decay of B into ϕ	Decay of ϕ into $A'A'$	Decay probability inside the detector

L : Luminosity

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

FASER : LHC run3, FASER2 : LH-LHC

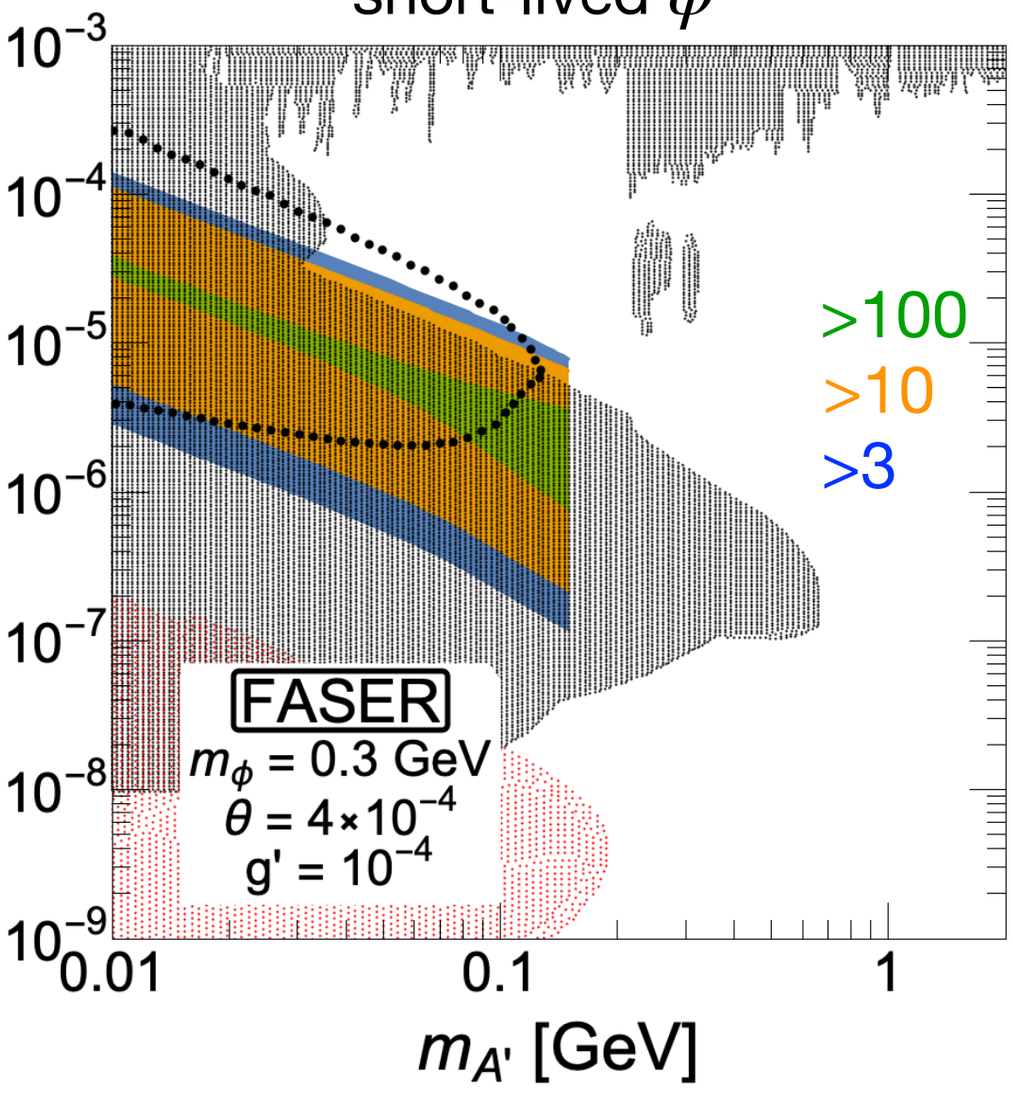
FASER sensitivity

"Dark photon from light sclara decays at FASER"

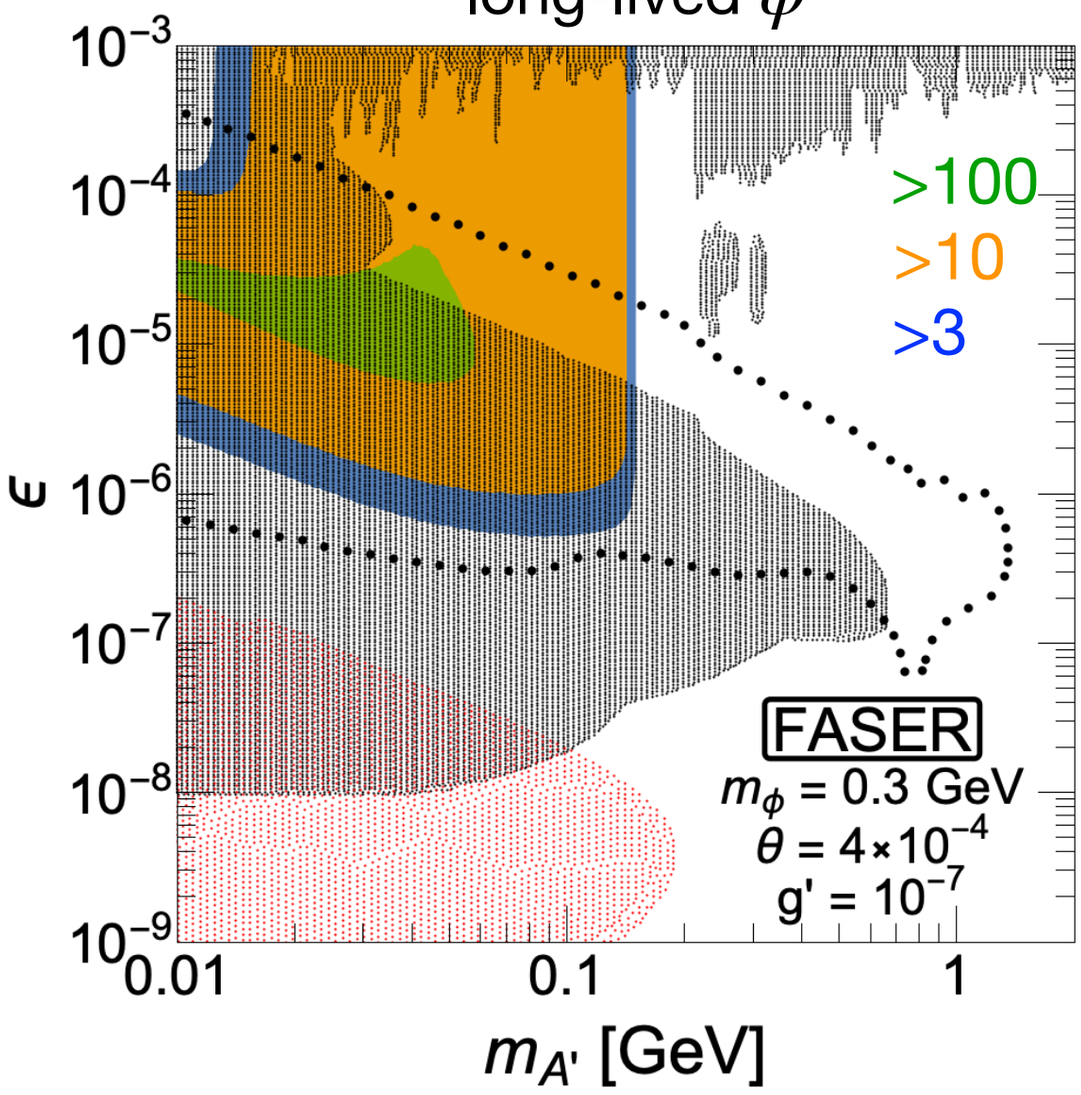
[Araki, Asai, Otono, TS, Takubo, 2008.12765]

Light dark Higgs

short-lived ϕ



long-lived ϕ

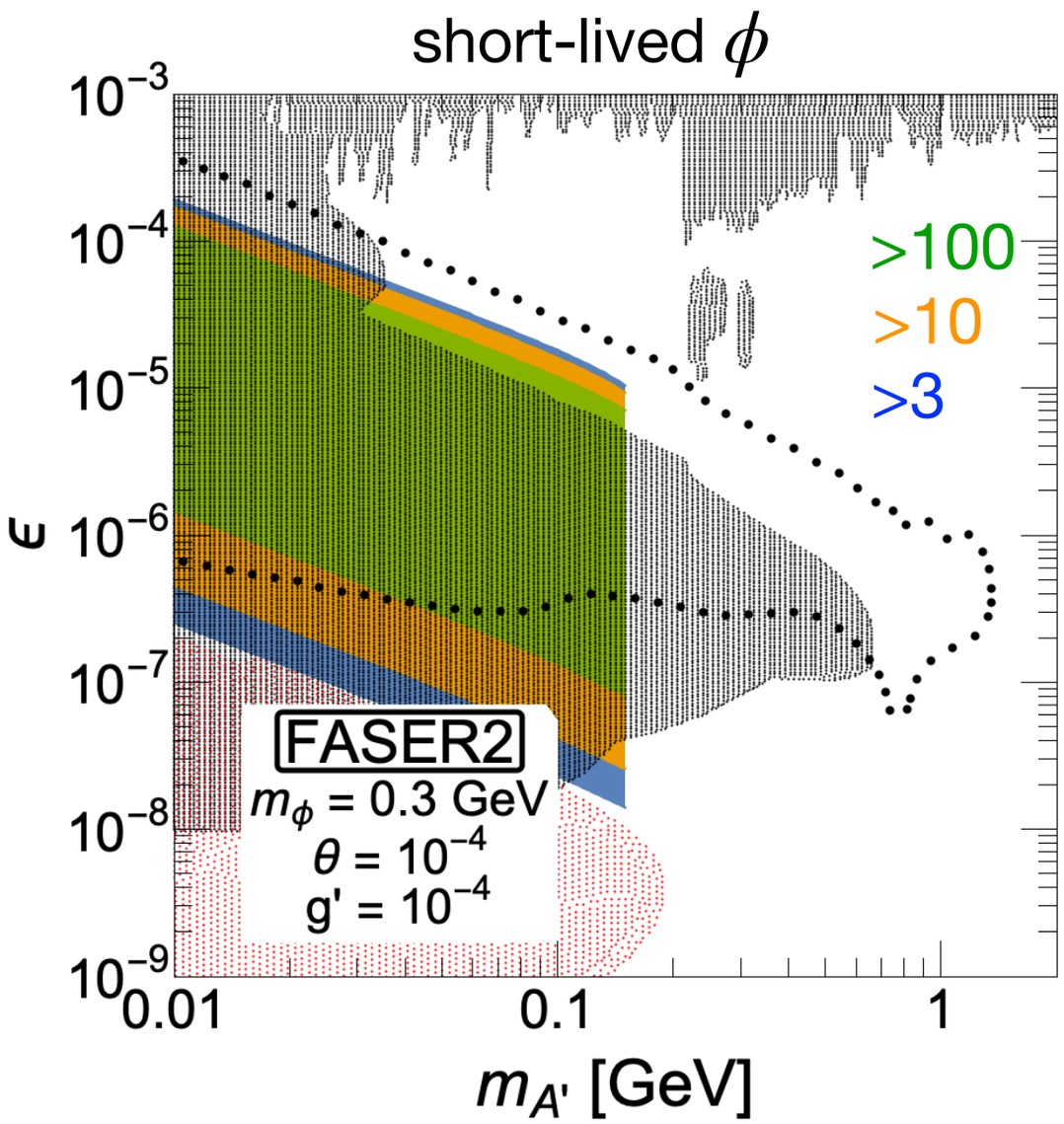


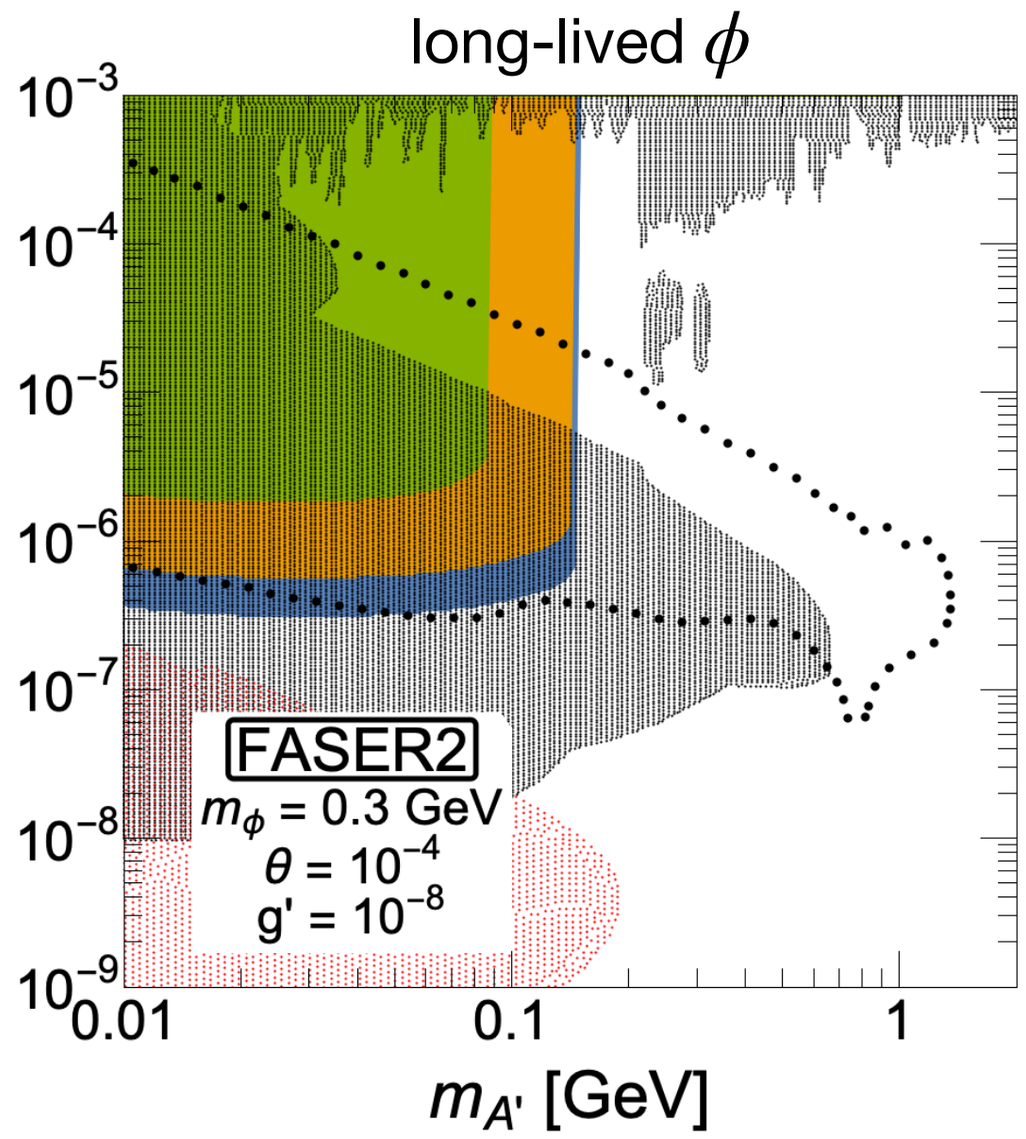
FASER 2 sensitivity

"Dark photon from light scalar decays at FASER"

[Araki, Asai, Otono, TS, Takubo, 2008.12765]

Light dark Higgs



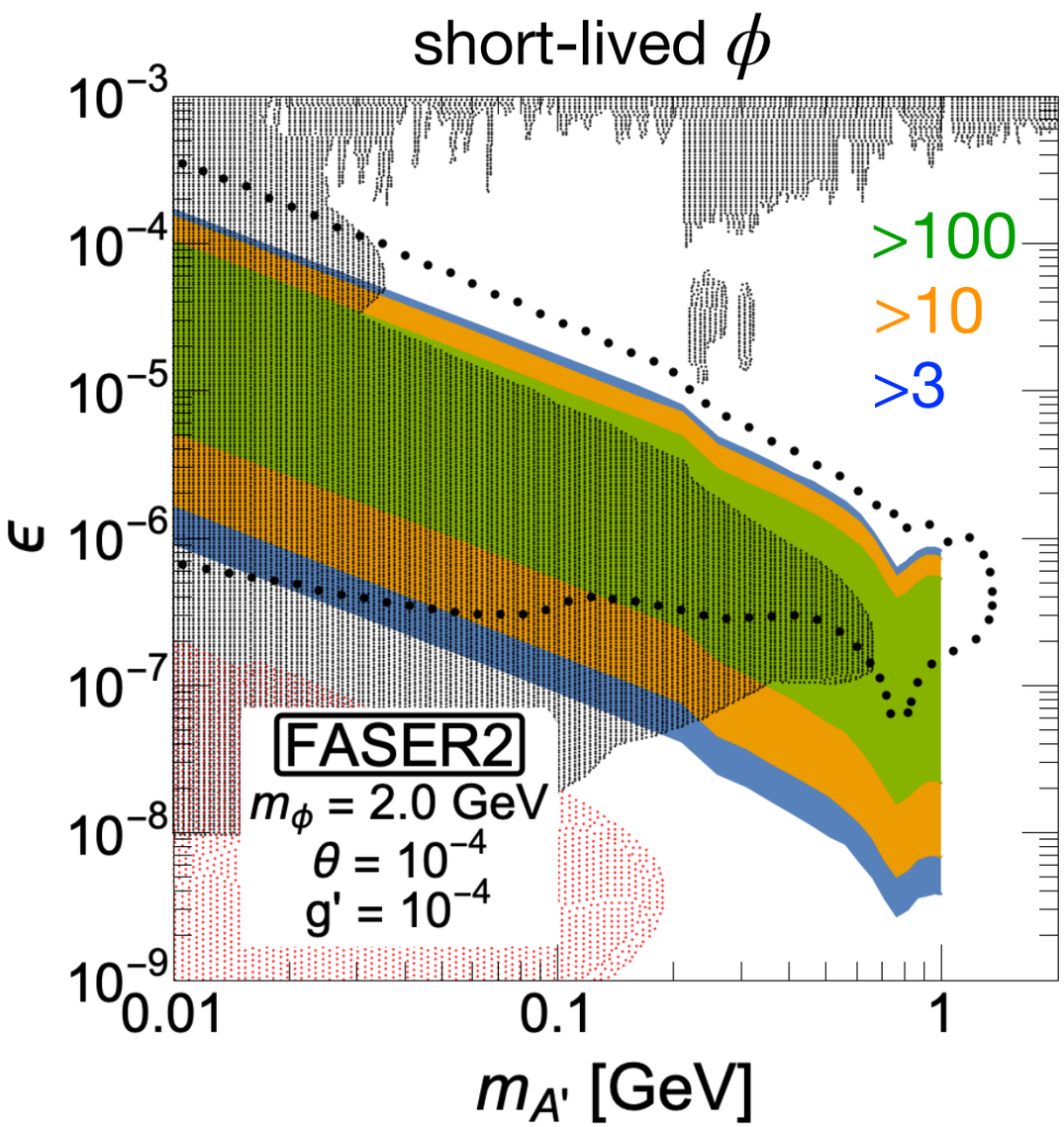


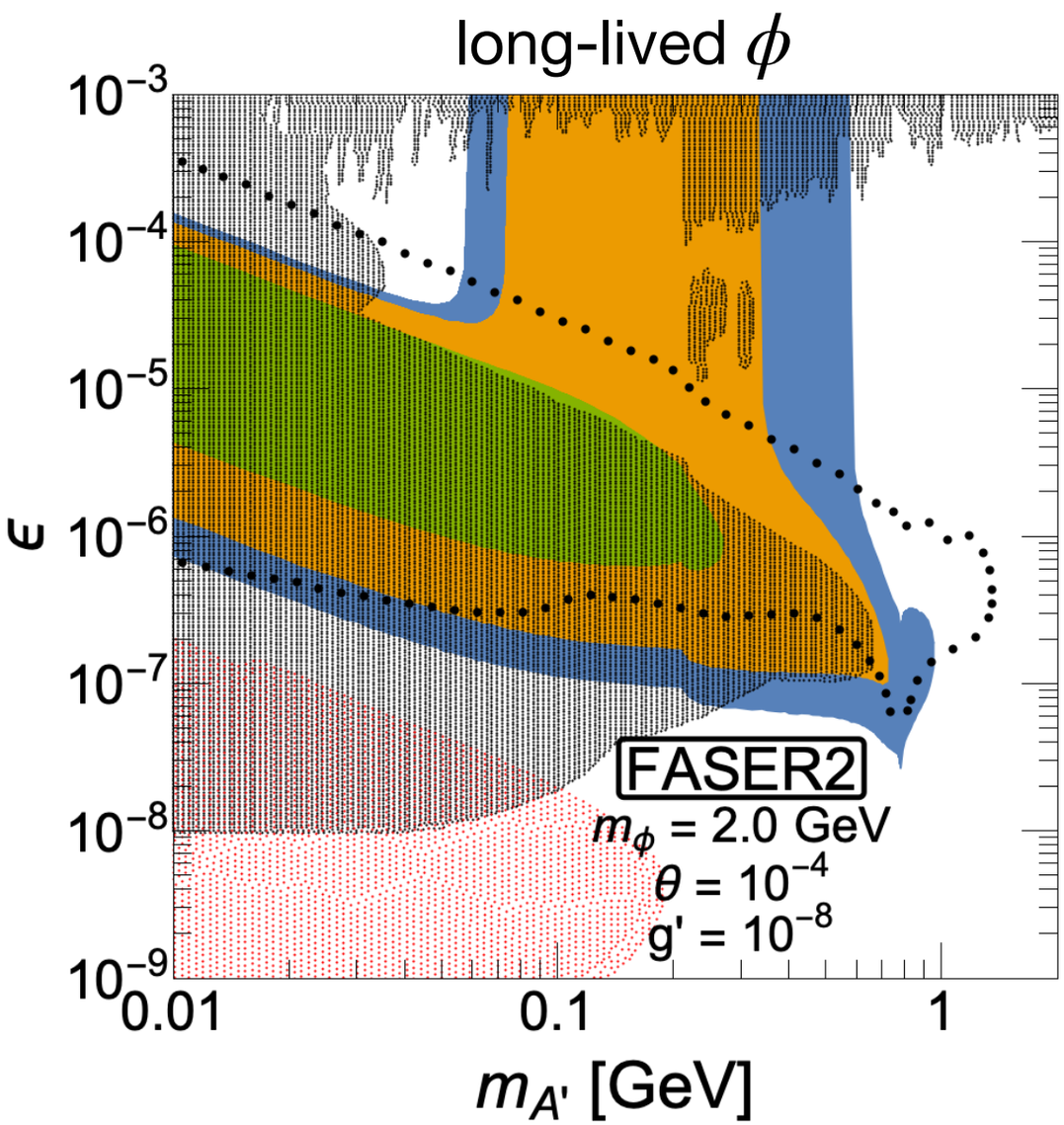
FASER 2 sensitivity

"Dark photon from light scalar decays at FASER"

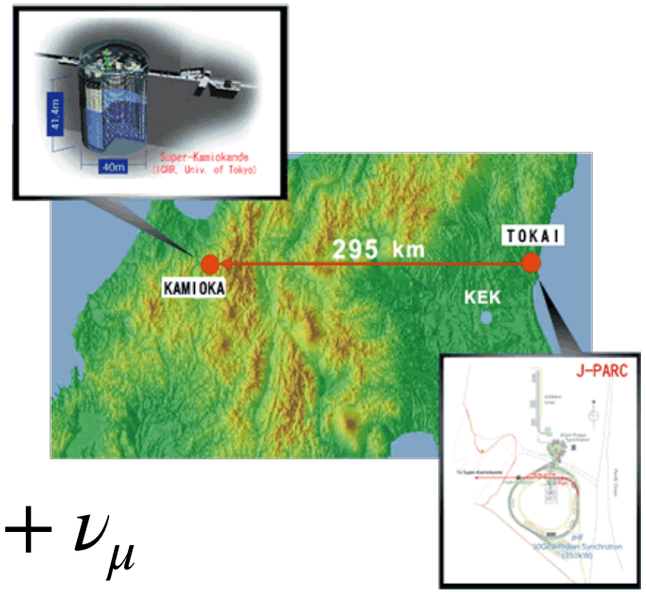
[Araki, Asai, Otono, TS, Takubo, 2008.12765]

Heavy dark Higgs

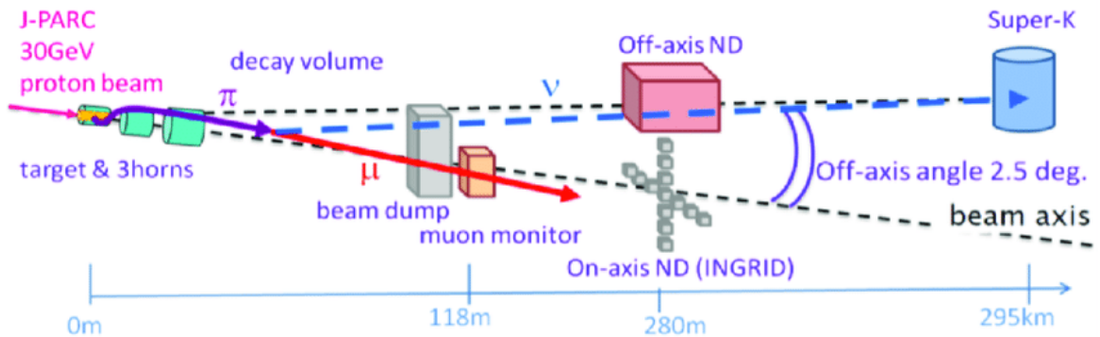




ND280 in T2K exp.

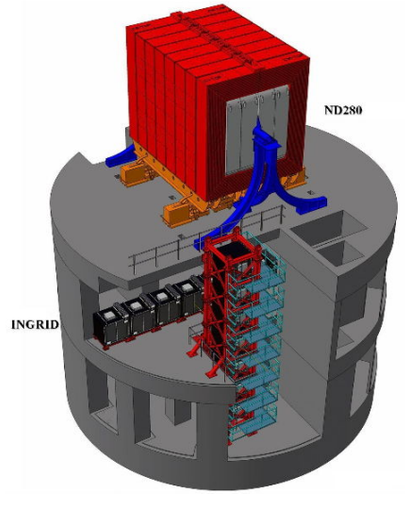


- Neutrino oscillation experiment, Tokai-To-Kamioka
- 30 GeV proton delivered to graphite target
- Neutrinos produced from charged pion decay $\pi \rightarrow \mu + \nu_\mu$



- Dear detector "ND280" at 280m from the target to measure the neutrino energy spectrum
  - 0.2T magnet is installed
  - (e, μ, π) can be measured
- Future upgrade to T2K-II and T2HK

width (m)	height (m)	depth (m)	θ_{ND} (deg)
2.4	2.4	5.8	2.0



proton on target : 3.8×10^{21} for T2K by 2021

1.0×10^{22} for T2K – II from 2023

3.7×10^{22} for T2HK after 2027

Production of A' at T2K

- Proton bremsstrahlung
  - Weizsacker-Williams approximation

$$\mathrm{d}N_{\mathrm{DP}}^{\mathrm{brems}} = N_{\mathrm{pot}} \, |F(m_{A'}^2)|^2 \, \mathrm{d}z \, \mathrm{d}p_{A',t}^2 \, \frac{\sigma_{pp}(s')}{\sigma_{pp}(s)} \, w(z, p_{A',t}^2) \, \Theta(\Lambda_{\mathrm{QCD}}^2 - q_{\mathrm{min}}^2)$$

mixing with vector mesons

pp inelastic cross section

splitting function

    - Form factor

Take into account the mixing with mesons

$$F(p_{A'}^2) = \sum_V \frac{f_V m_V^2}{m_V^2 - p_{A'}^2 - i m_V \Gamma_V} \qquad (V = \rho, \rho', \rho'', \omega, \omega', \omega'')$$

where

$$m_\rho = m_\omega = 0.77 \text{ GeV}, \; m'_\rho = m'_\omega = 1.25 \text{ GeV}, \; m''_\rho = m''_\omega = 1.45 \text{ GeV}$$

Brems. production is enhanced at resonance

Production of A' at T2K

- Meson decay
  - Dark Higgs contribution is negligible due to $\sqrt{s} = 7.75\ \mathrm{GeV}$
  - Light mesons $(X = \pi, \eta, \eta')$ are produced enough

$$\mathrm{BR}(X \to A'\gamma) = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_X^2}\right)^3 \mathrm{BR}(X \to \gamma\gamma)$$

with $\mathrm{BR}(\pi^0 \to \gamma\gamma) = 0.99,\ \mathrm{BR}(\eta \to \gamma\gamma) = 0.39,\ \mathrm{BR}(\eta' \to \gamma\gamma) = 0.023$

$$\mathrm{BR}(\eta' \to A'\rho) = \varepsilon^2 \frac{\left[(m_{A'}^2 - (m_{\eta'} + m_\rho)^2)(m_{A'}^2 - (m_{\eta'} - m_\rho)^2)\right]^{3/2}}{(m_{\eta'}^2 - m_\rho^2)^3} \mathrm{BR}(\eta' \to \gamma\rho)$$

with $\mathrm{BR}(\eta' \to \gamma\rho) = 0.30$

- For B-L model

$(\varepsilon e)^2$ is replaced by

g_{B-L}^2 for $\pi^0 \to A'\gamma$

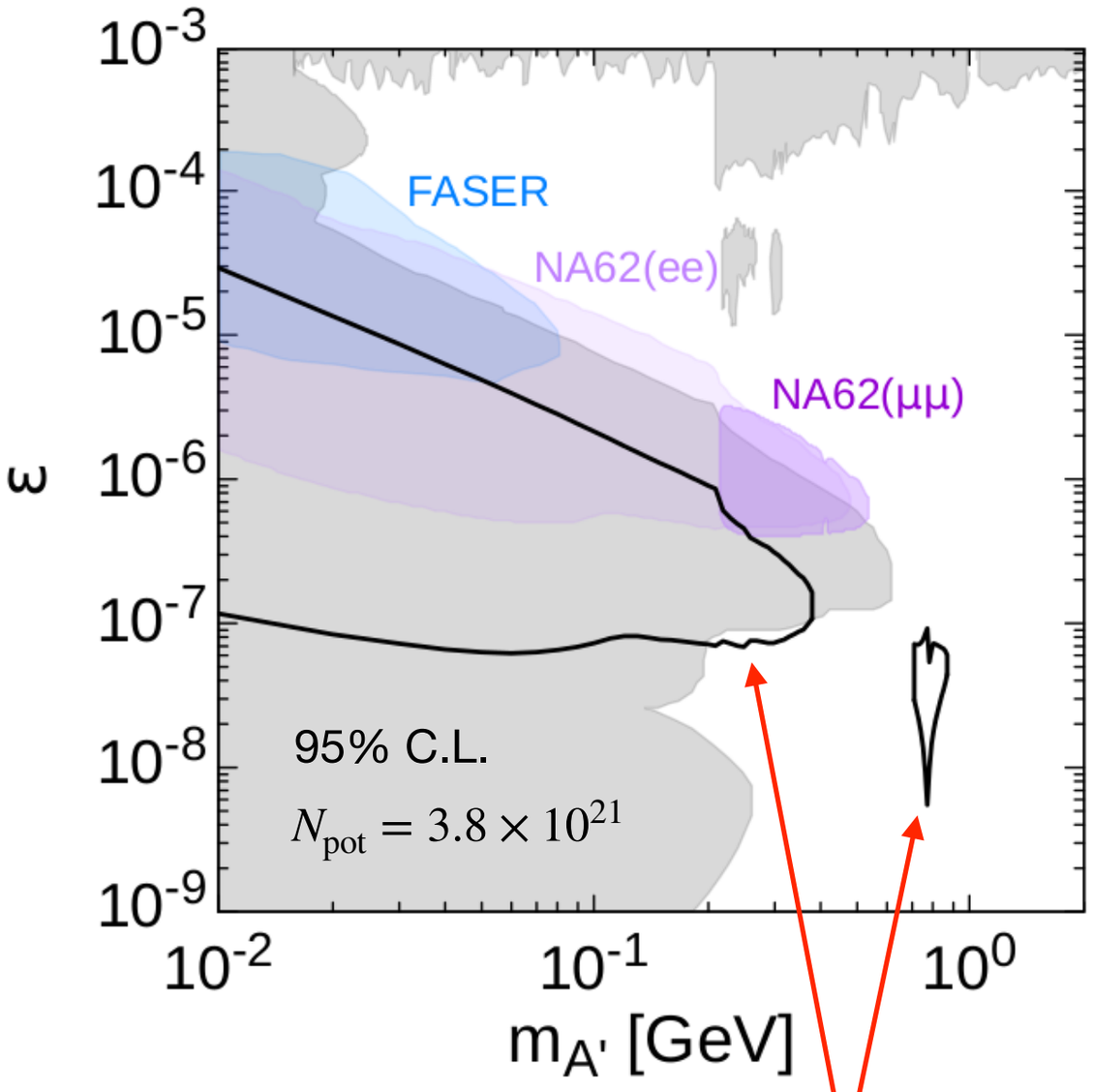
$g_{B-L}^2/4$ for $\eta \to A'\gamma$

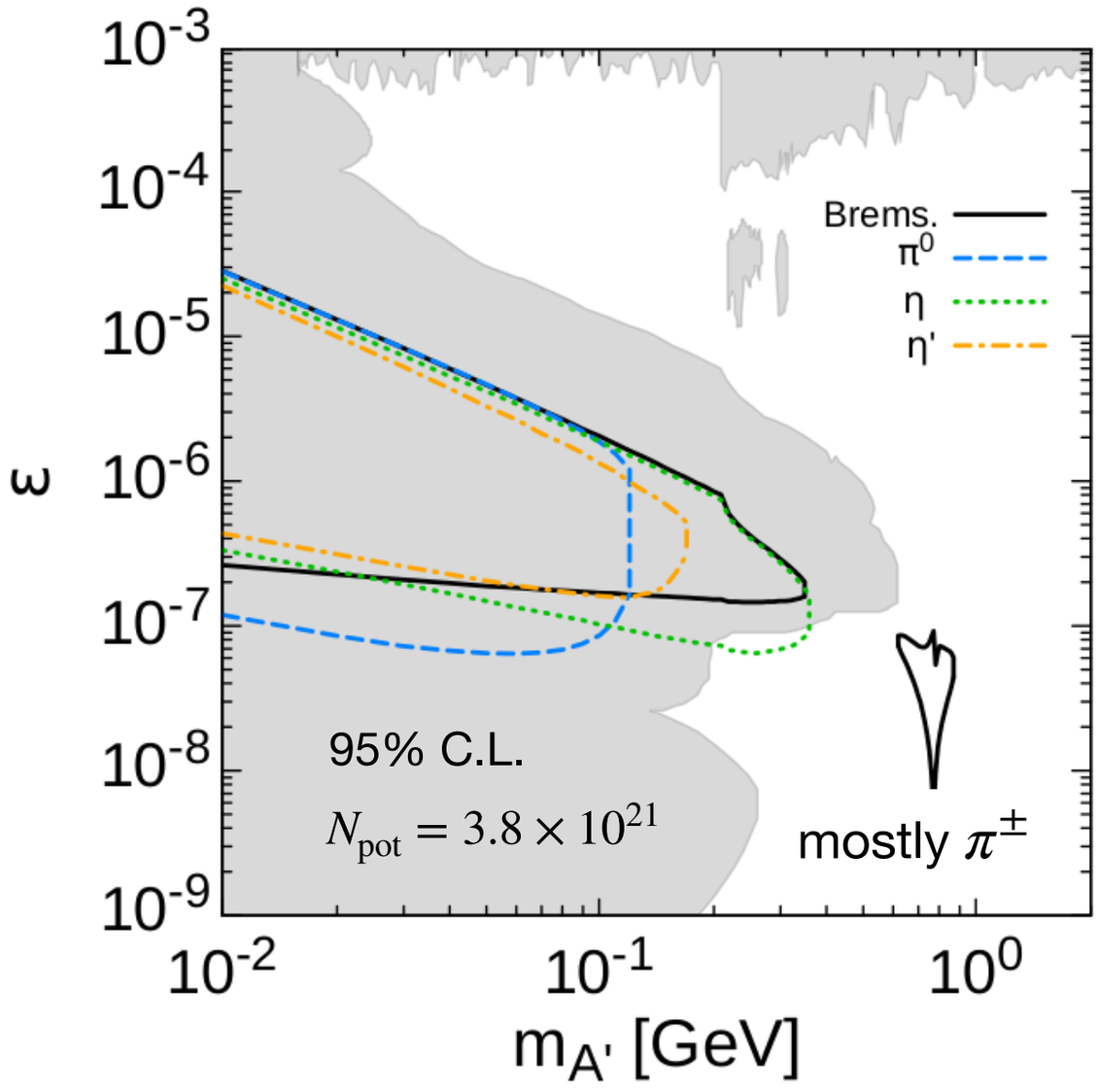
$\eta' \to A'\gamma$ is negligibly small

T2K exclusion region

"New Constraint on dark photon at T2K Off-Axis Near Detector"

[Araki, Asai, Iizawa, Otono, TS, Takubo, 2308.01565]

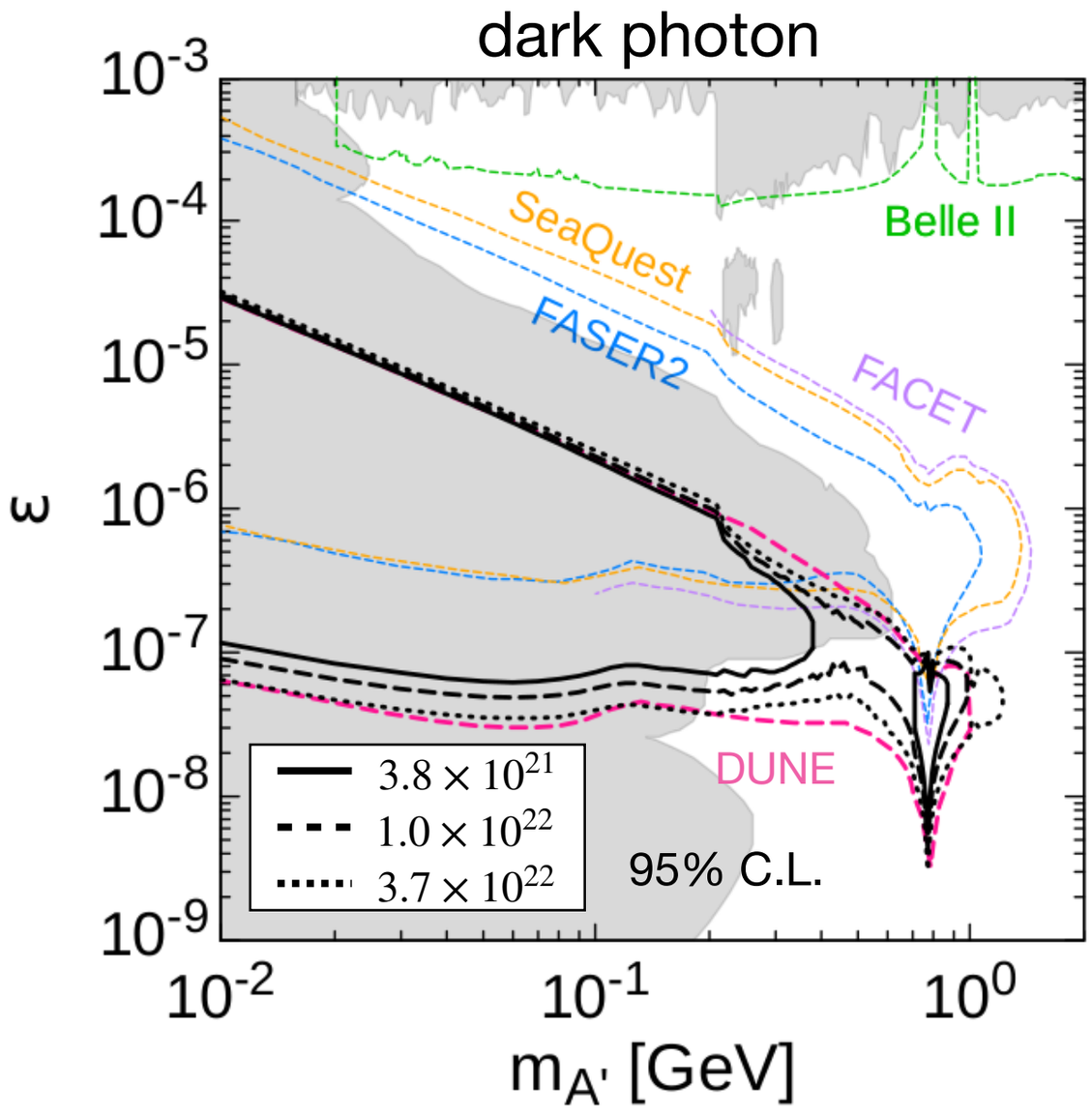


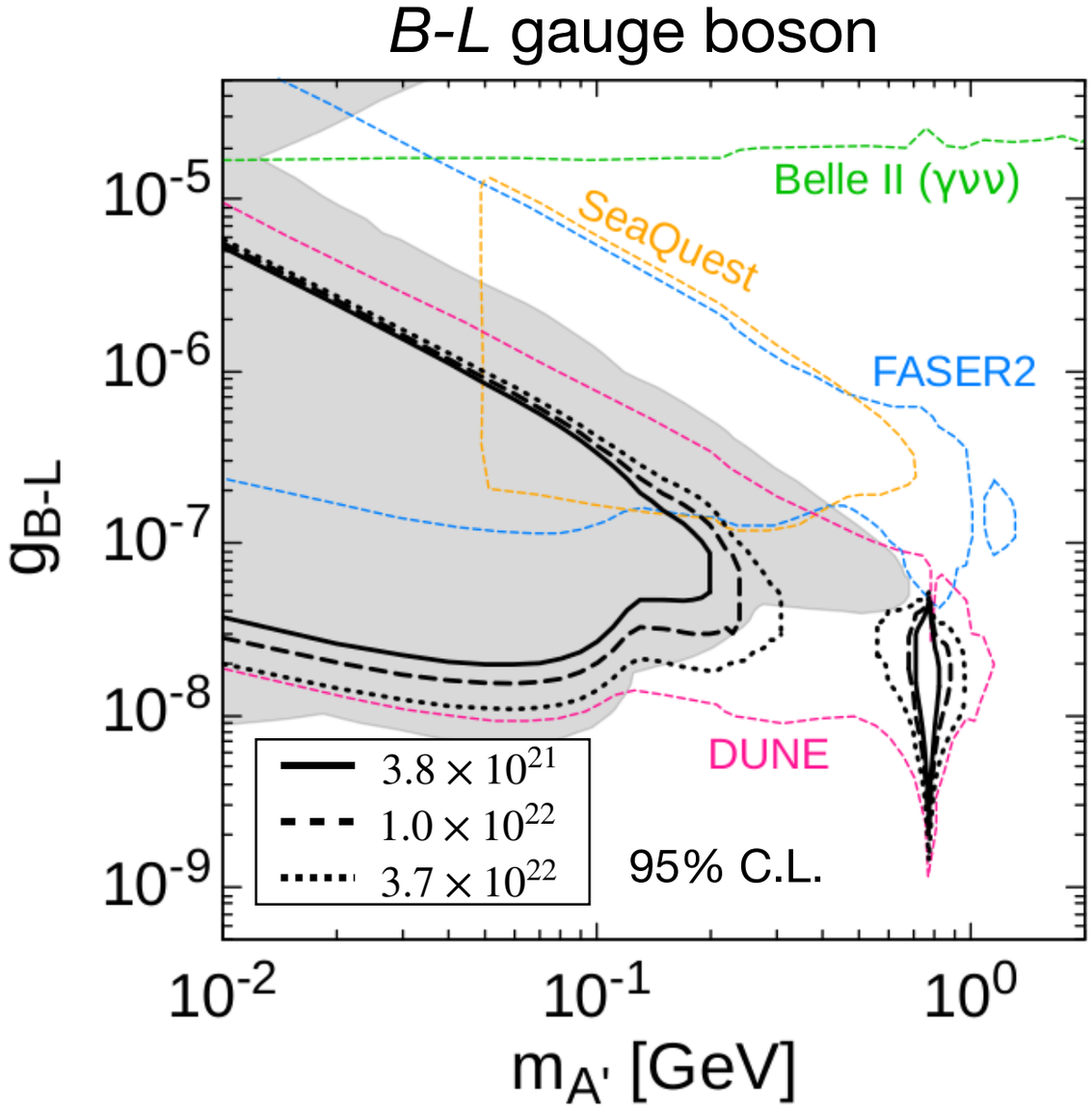


New excluded region by this work

Future T2K sensitivity

"New Constraint on dark photon at T2K Off-Axis Near Detector"
[Araki, Asai, Iizawa, Otono, TS, Takubo, 2308.01565]





5. Summary and Discussions

Summary

- We have studied the dark photon model with dark Higgs.
  - Dark Higgs can be a new source and carrier of dark photon
  - Dark photon from dark Higgs decay is significant at FASER
  - Search sensitivity is enlarged due to dark Higgs contribution
  - ND280 at T2K can be used for dark photon search
  - New constraints can be obtained by present data
  - Future upgrades will explore new parameter region

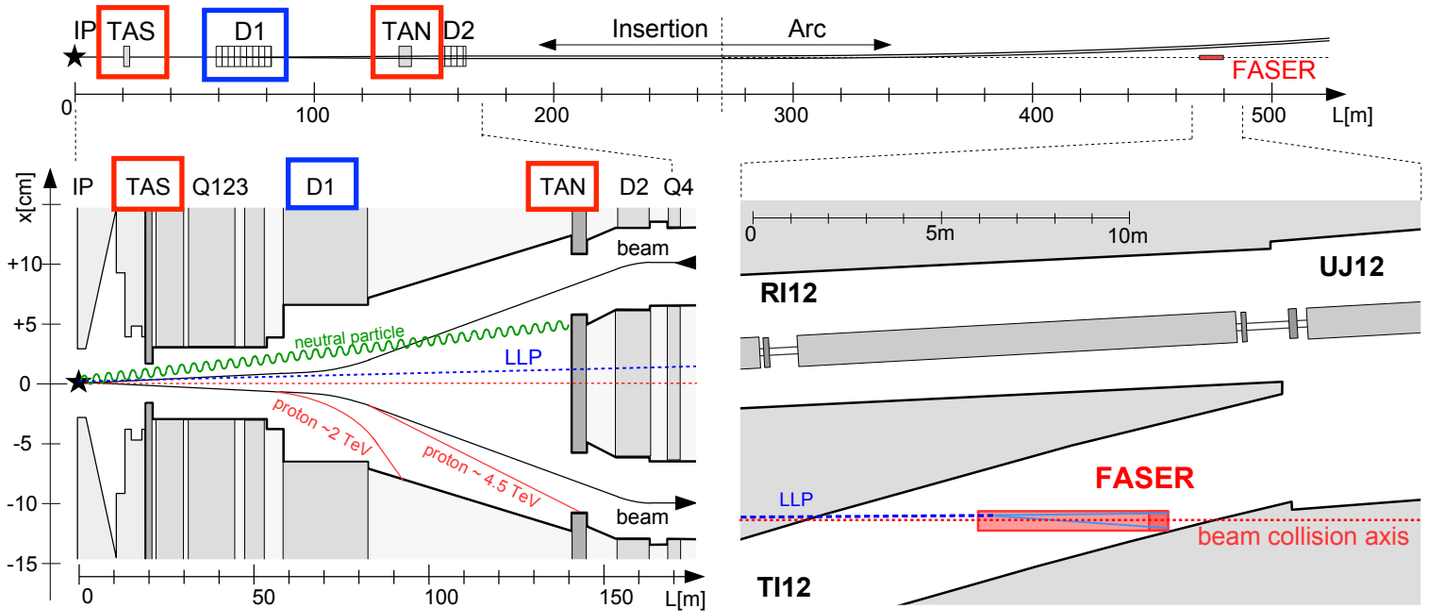
Discussion

- Why is the dark Higgs also light? Any reason?
- How results will chance if DM candidate exists?
- How about ALPs search at T2K?

Backup Slides

K mesons

- Neutral particle absorbers to protect magnets in the LHC tunnel



- K_L and $K^{\pm}$ are absorbed and deflected
  - TAS and TAN absorber placed at 20m and 140m downstream
  - $c\tau_{K_L} = 15.3\ \mathrm{m}$ and $\beta\gamma \sim 2000 @ p = 1\ \mathrm{TeV}$
  - D1 magnets placed at 60-80m
  - $c\tau_{K^{\pm}} = 3.7\ \mathrm{m}$ and $\beta\gamma \sim 2000 @ p = 1\ \mathrm{TeV}$

K meson contributions are much decreased