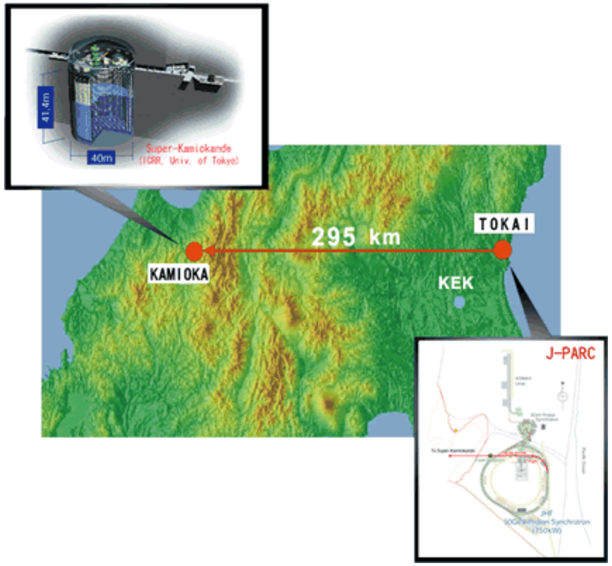
Hint for low scale seesaw from colliders

Hiroyuki Ishida (NCTS)

@New Physics with Displaced Vertices, NCTS, 2018/06/21

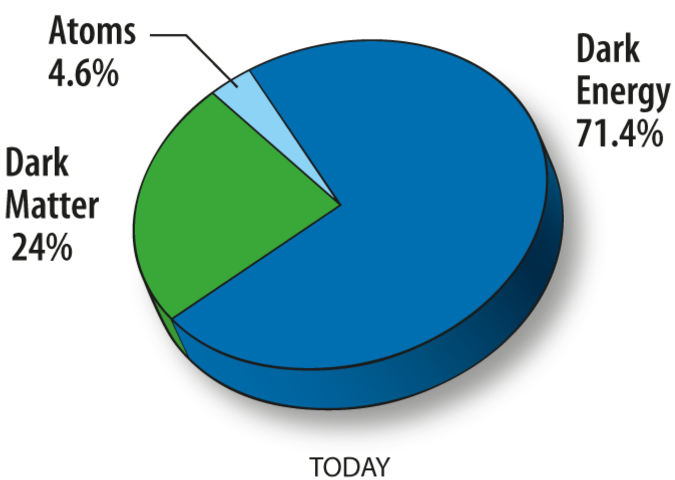
Introduction

- Hints for new physics



Taken from T2K web cite
http://t2k-experiment.org/ja/

-Neutrinos are massive



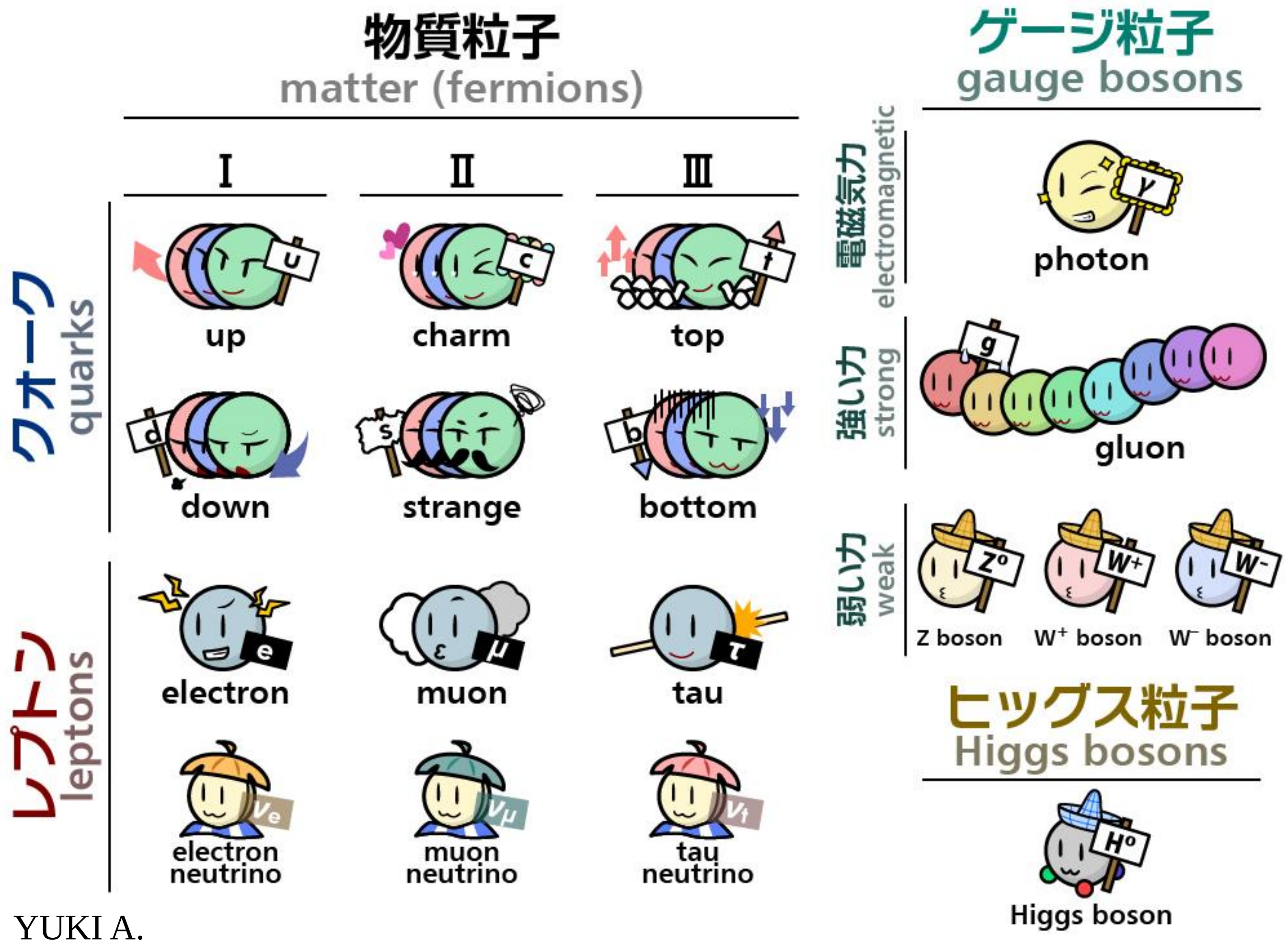
Taken from NASA web cite
https://wmap.gsfc.nasa.gov/universe/uni_matter.html

-Dark matter is there

-Matter anti-matter asymmetry needs to be created

Introduction

- Missing particles in the Standard Model



YUKI A.

Introduction

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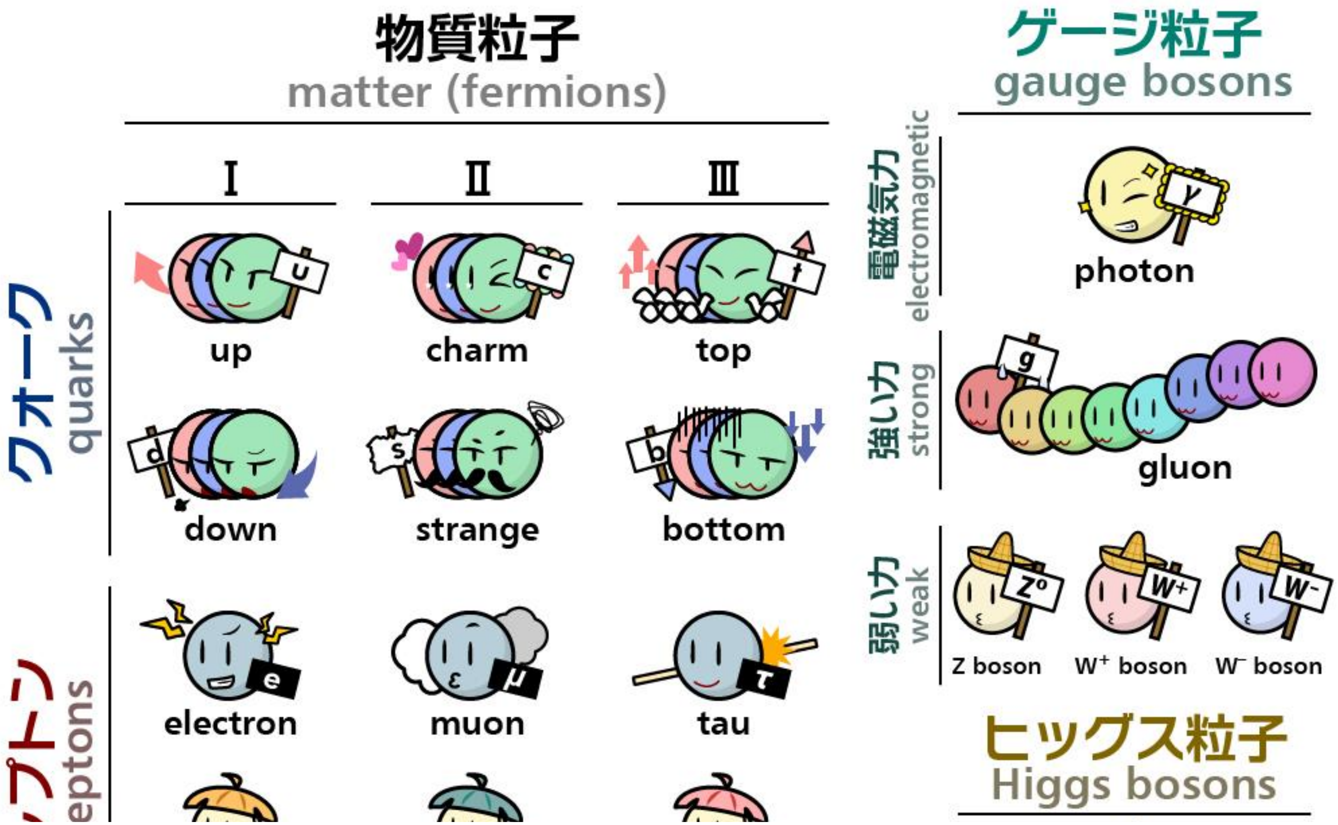
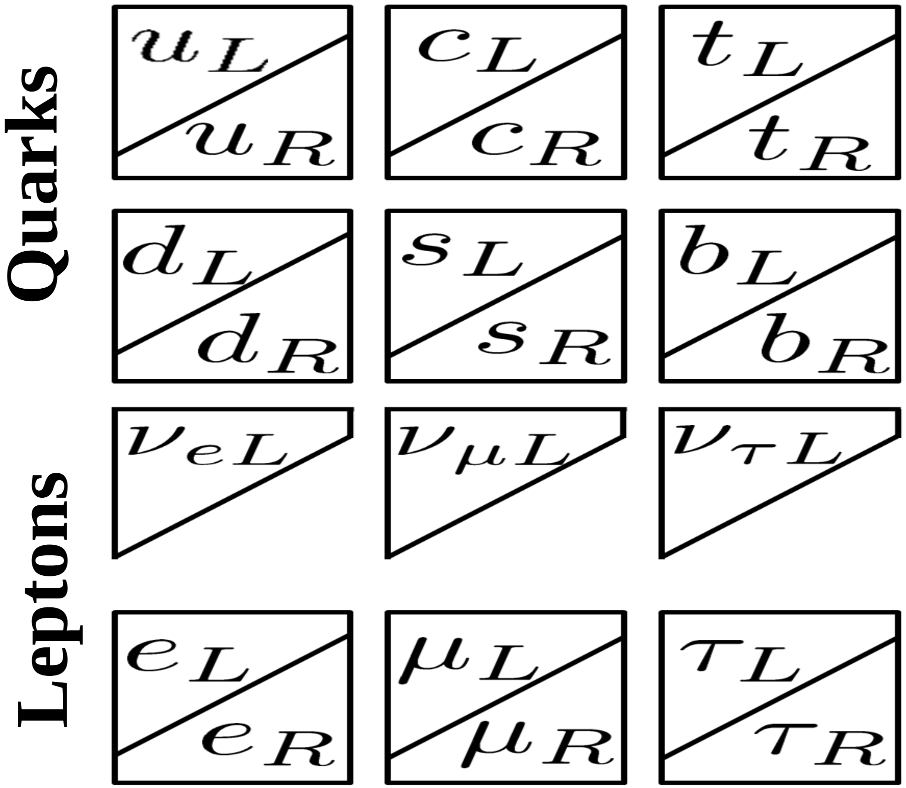


All the particles have been observed
and the SM looks to be completed

Introduction

- Missing particles in the Standard Model



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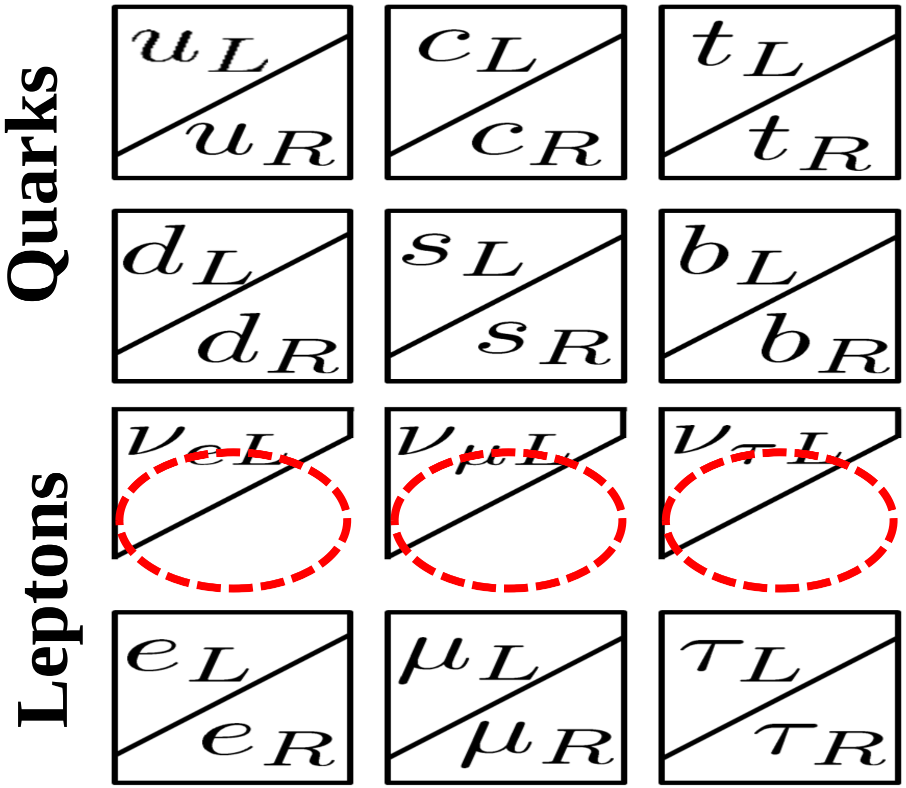

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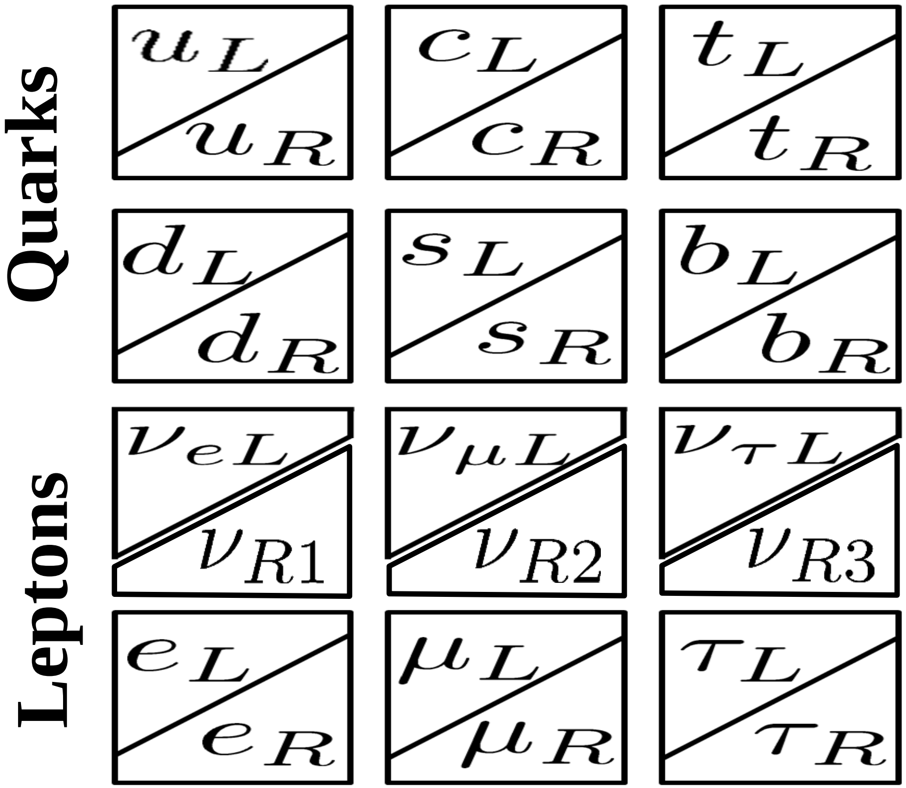

Adding RH neutrinos looks natural!

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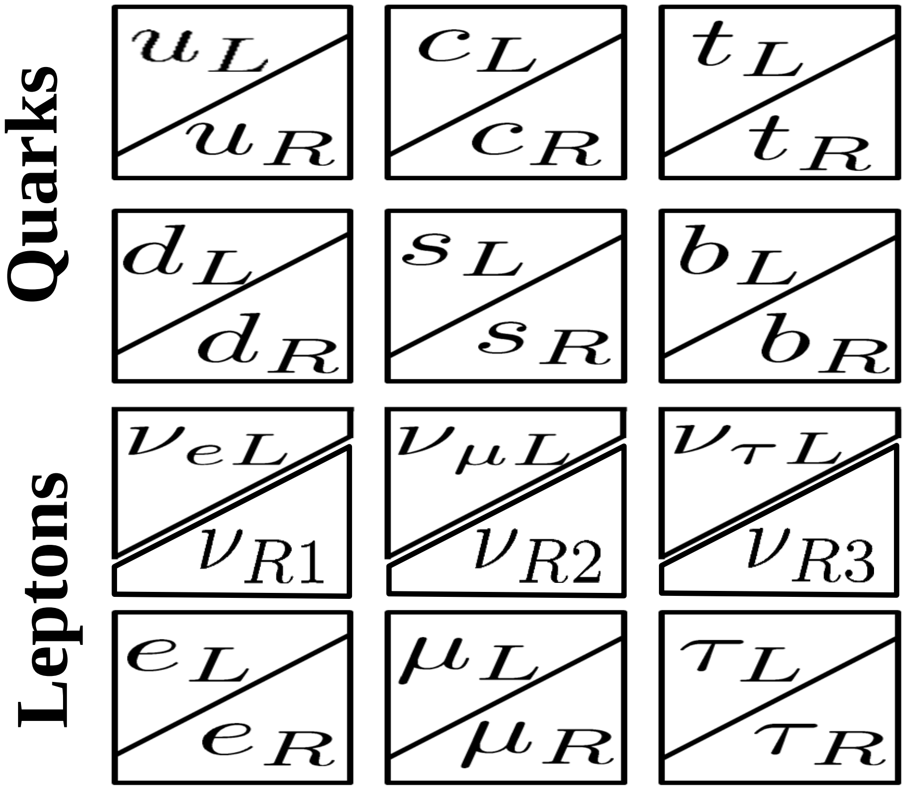

Adding RH neutrinos looks natural!

How many RH neutrinos are necessary?

Introduction

- What we know from oscillation experiments

-Flavor mixing angles

NuFIT 3.2 (2018)

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$

$$V_{\rm CKM} = \begin{pmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{pmatrix}$$

[PDG]

Larger mixing than quark sector

-Mass squared difference

$$\Delta m^2_{21} = 7.4 \times 10^{-5} \mathrm{eV}^2 \qquad \Delta m^2_{31} = 2.494 \times 10^{-3} \mathrm{eV}^2$$

[NuFIT3.2 (2018)]

-(Dirac CP violating phase) $\delta \sim -\pi/2$

Introduction

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[NuFIT3.2 (2018)]

At least, two mass scales are required!

Introduction

[Minkowski (1977);Yanagida(1979);Gell-Mann,Ramond,Slansky (1979); Glashow (1980);Mohapatra,Senjanovic(1980)]

- Usual way to obtain neutrino masses (type-I seesaw)

-Adding RH neutrinos

$$\mathcal{L}_{\nu mass} = F_{\alpha I}\bar{L}_{\alpha}H\nu_{RI} + \text{h.c.} + \frac{M_M}{2}\overline{\nu^c_{RI}}\nu_{RI}\,.$$

*Dirac masses : $F_{\alpha I}\langle H\rangle$ *Majorana masses : M_M

-Tiny neutrino masses can be realized by hierarchy

$$\hat{M} = \begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} \xrightarrow[M_D \ll M_M]{\text{diagonalization}} \begin{pmatrix} M_\nu & 0 \\ 0 & M_M \end{pmatrix}$$

where $M_\nu \simeq -M_D M_M^{-1} M_D^T$

($I = 2$ is needed at least)

Introduction

- Physical states of neutrinos

  *Active neutrinos : $\nu_i = U^\dagger_{\mathrm{MNS}} \nu_{L\alpha} - U^\dagger_{\mathrm{MNS}} \Theta \nu^C_{RI}$

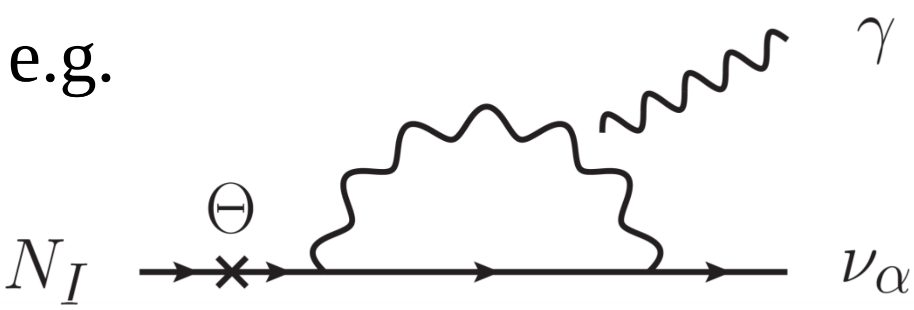
  *Heavy neutral leptons (HNL) : $N^C_I = \nu^C_{RI} + \Theta^\dagger \nu_{L\alpha}$

Note: sometimes it's called as sterile neutrinos but this is NOT MiniBooNE sterile neutrino!

- Important parameter : $\Theta \equiv M_D / M_M \quad \left(|\Theta|^2 = M_\nu / M_M \right)$

  HNL can have gauge interaction through this mixing

e.g.



Introduction

- Required Majorana scale to realize seesaw

$$\frac{F^2 v_{\rm EW}^2}{M_M} \simeq 0.1 \text{ eV}$$

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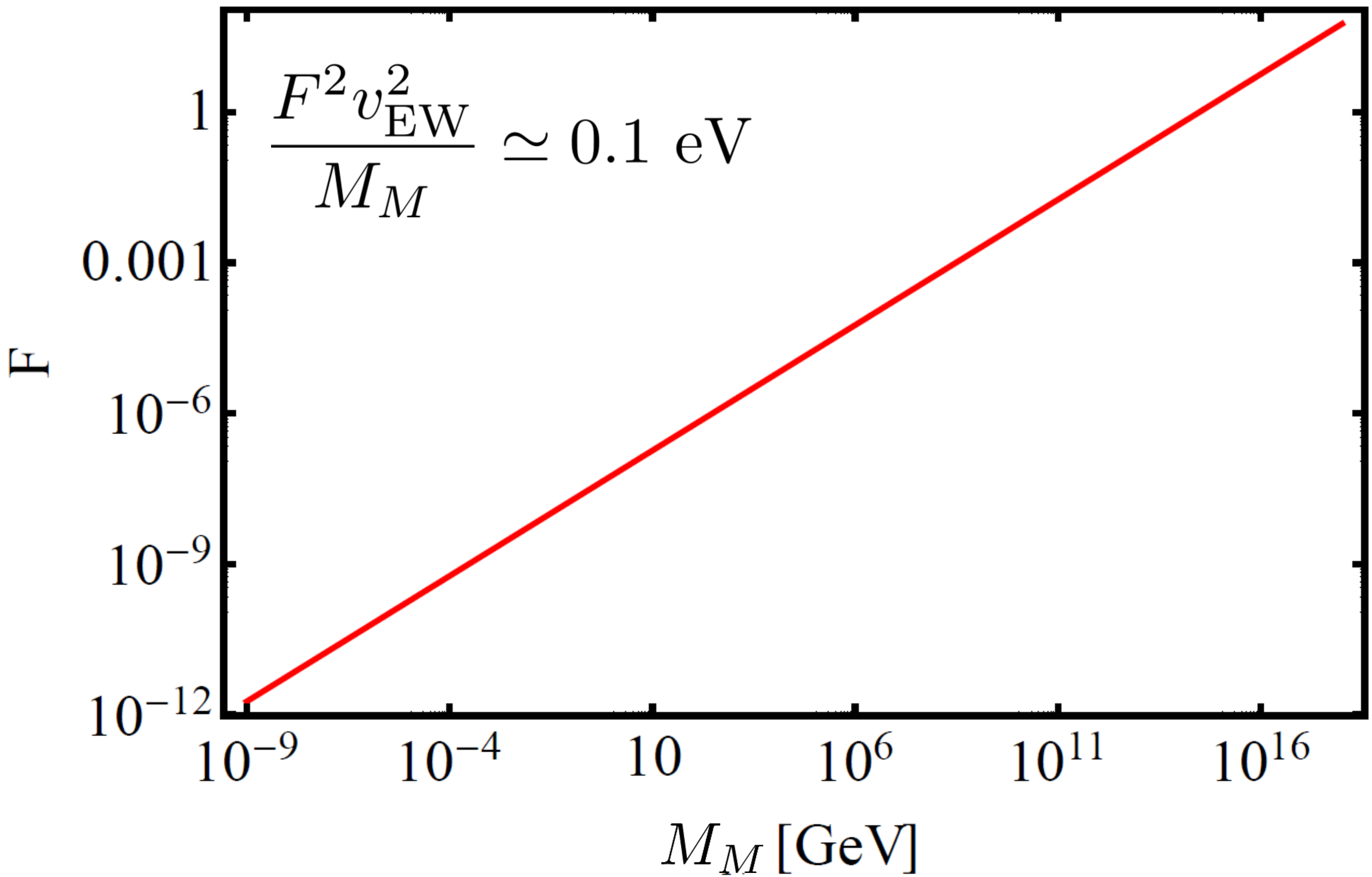

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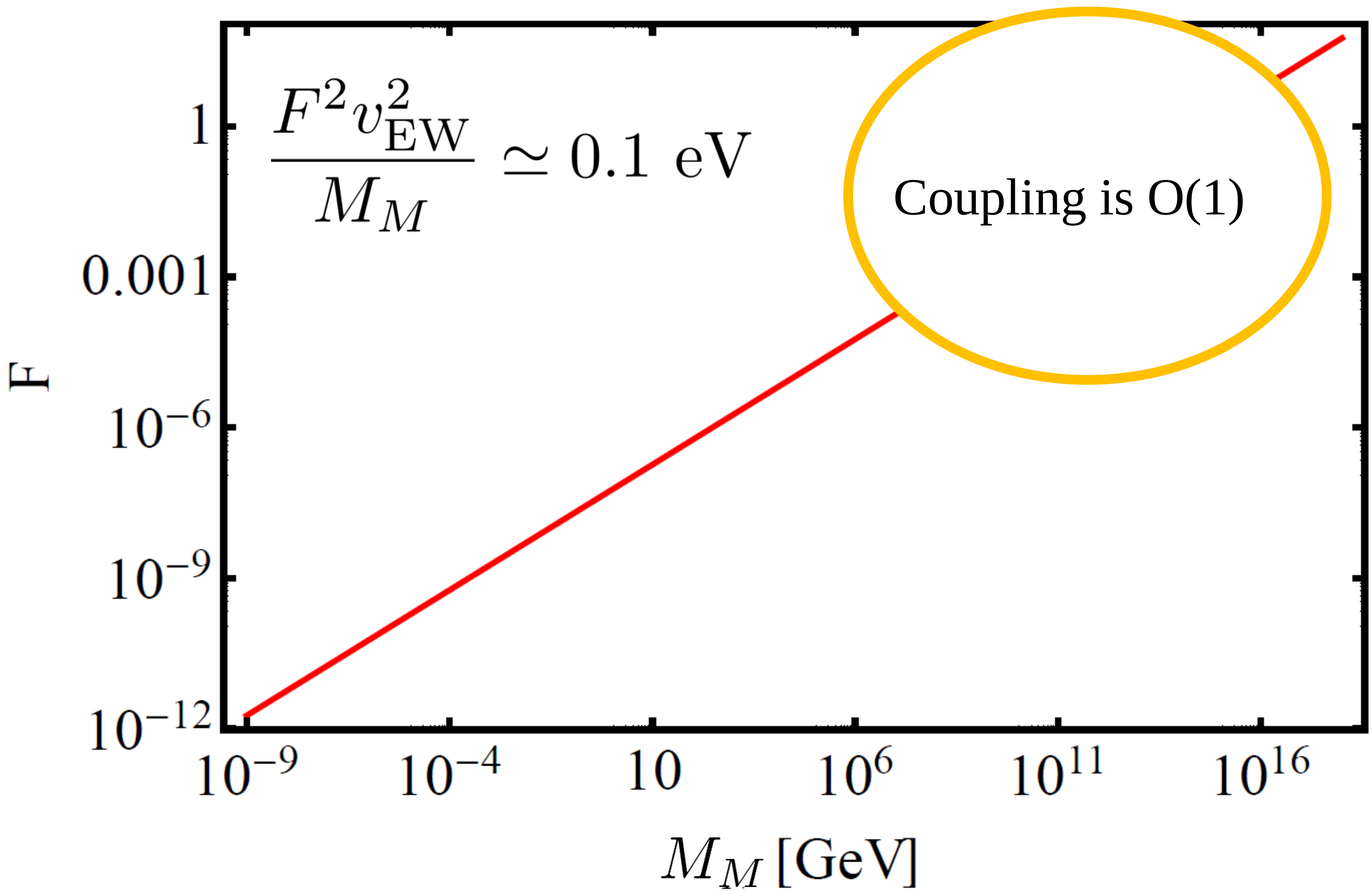

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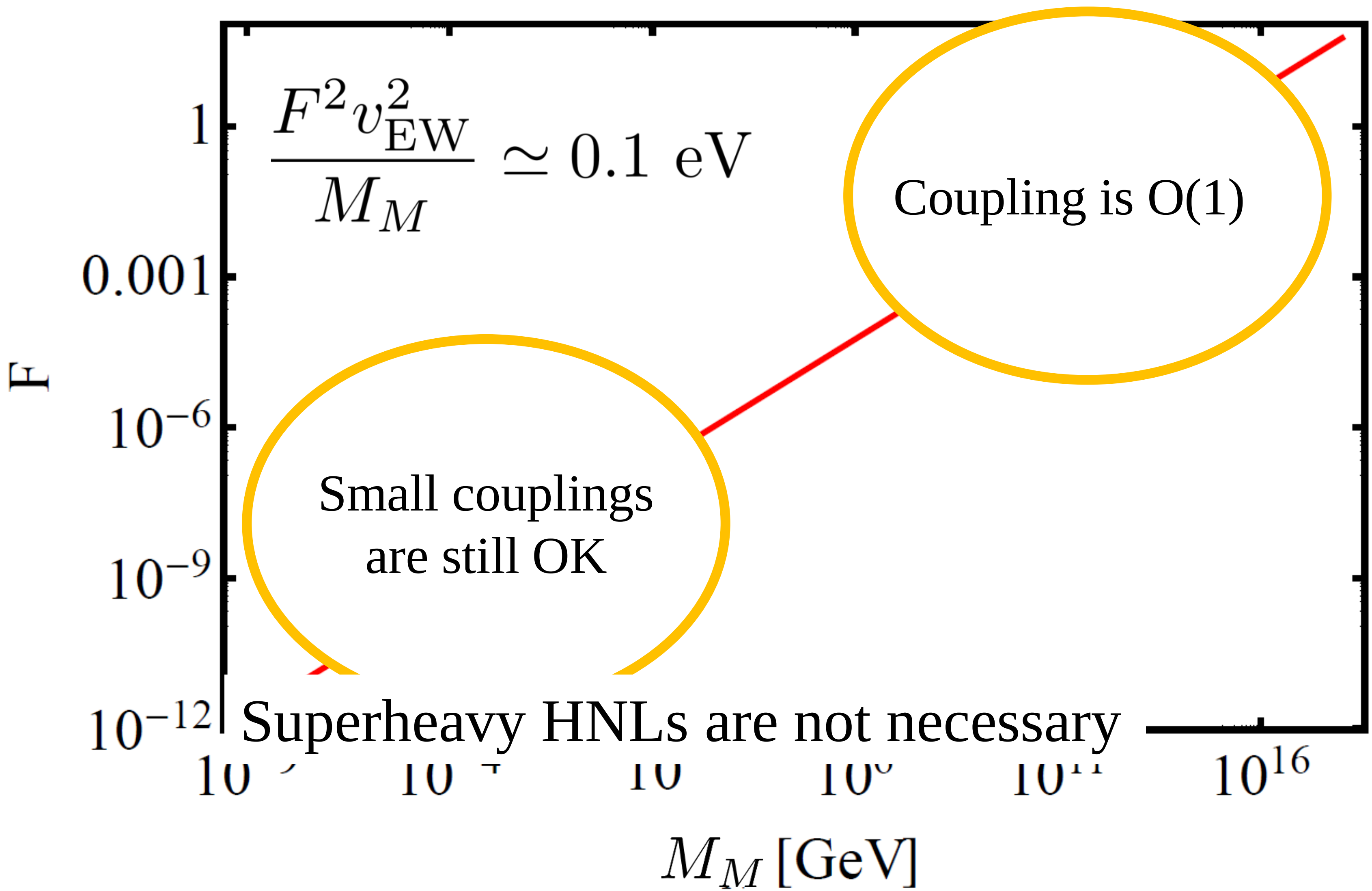

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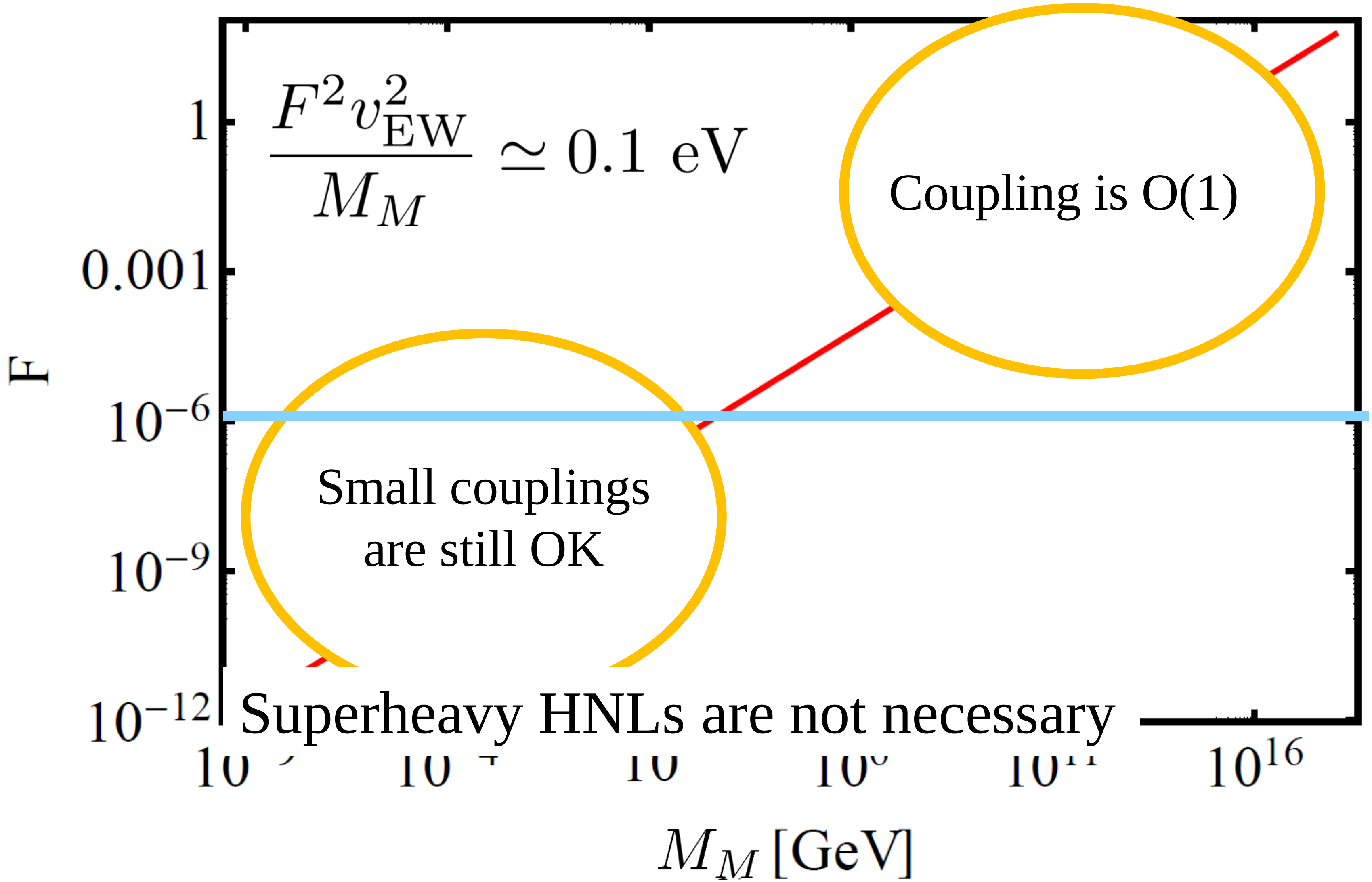

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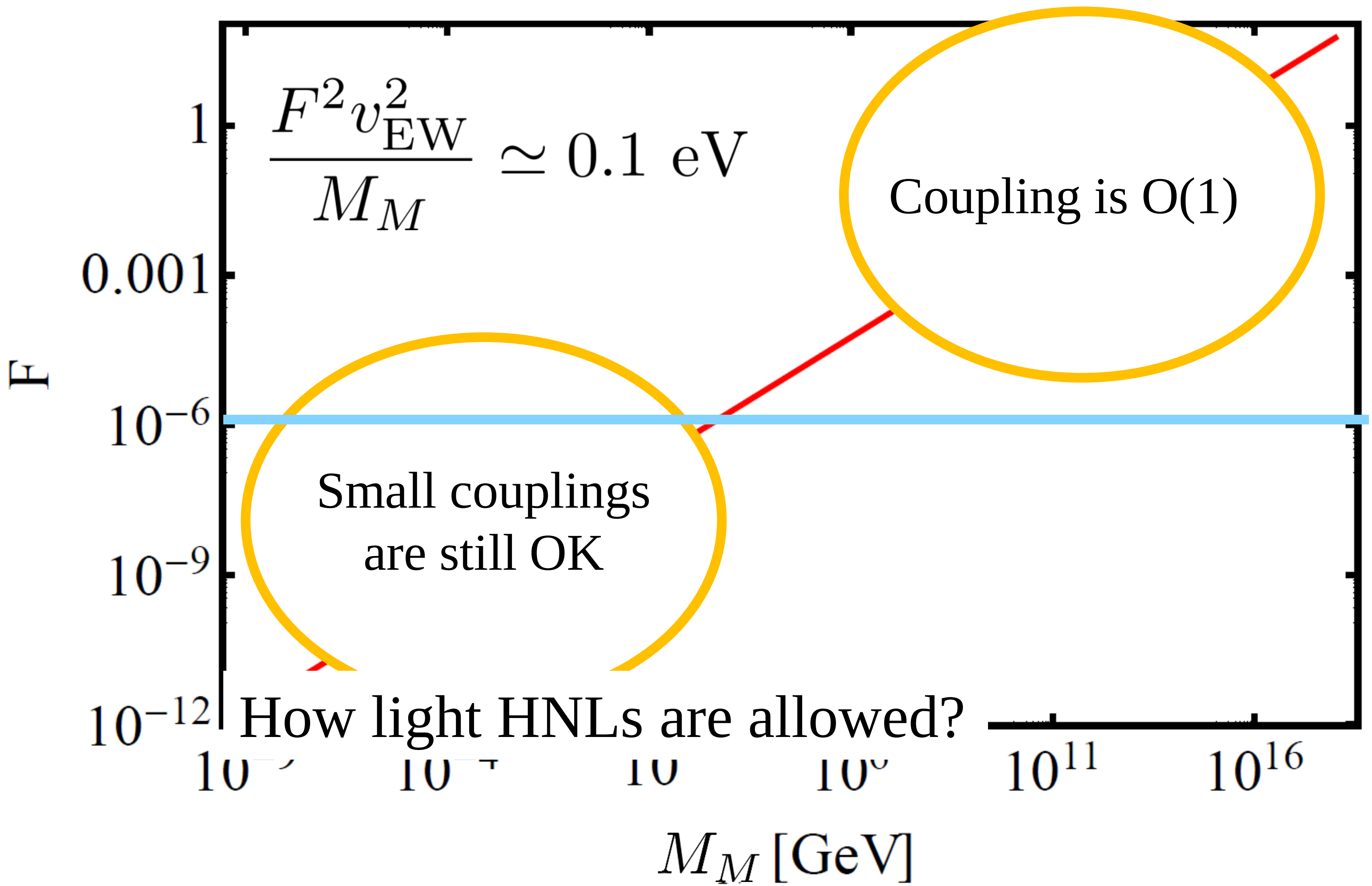


How light HNLs are allowed?

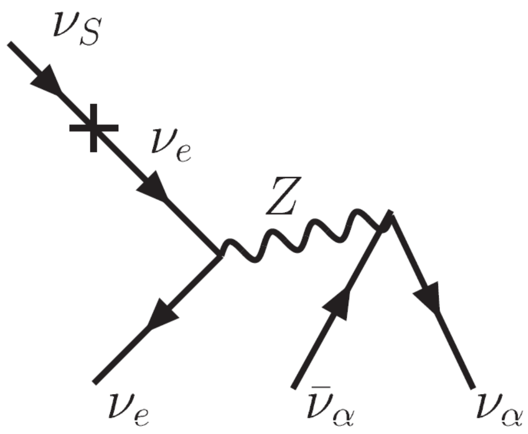
Introduction

- Once HNLs contribute active ν masses via seesaw

$$|\Theta|^2 = M_\nu / M_M$$

-Constraint on lifetime [Ruchayskiy and Ivashko (2012)]

$$M_M < m_\pi \simeq 140\ \mathrm{MeV}$$



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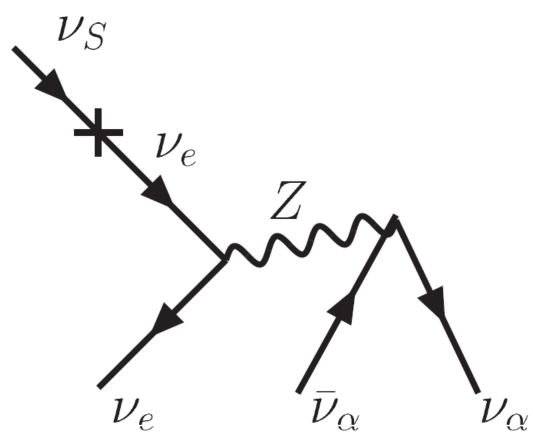


$|\Theta|^2$ ↑ lifetime ↓

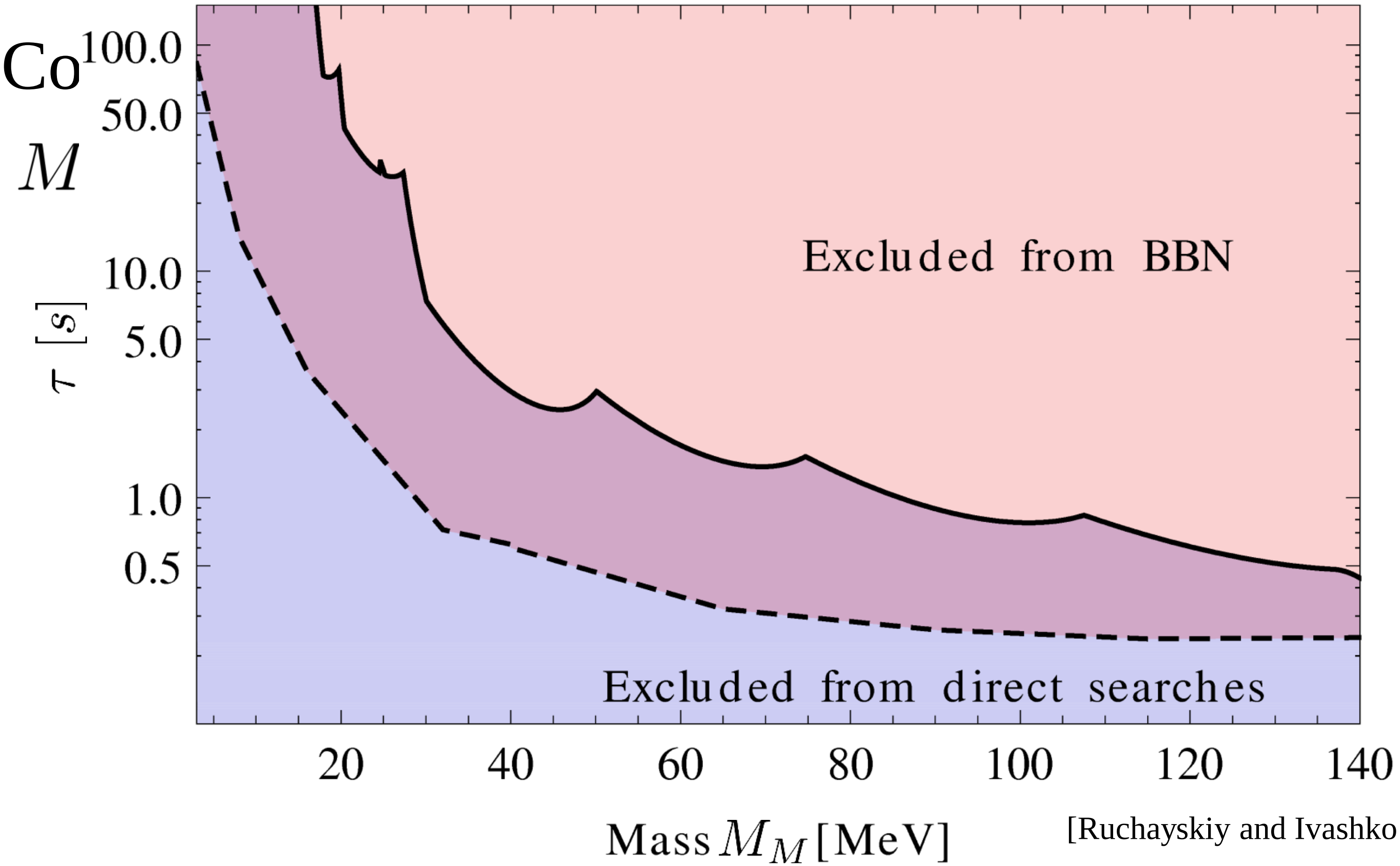
detectability ↑

Introduction

- Once HNLs contribute active ν masses via seesaw

$$|\Theta|^2 = M_\nu / M_M$$

-Co



[Ruchayskiy and Ivashko (2012)]

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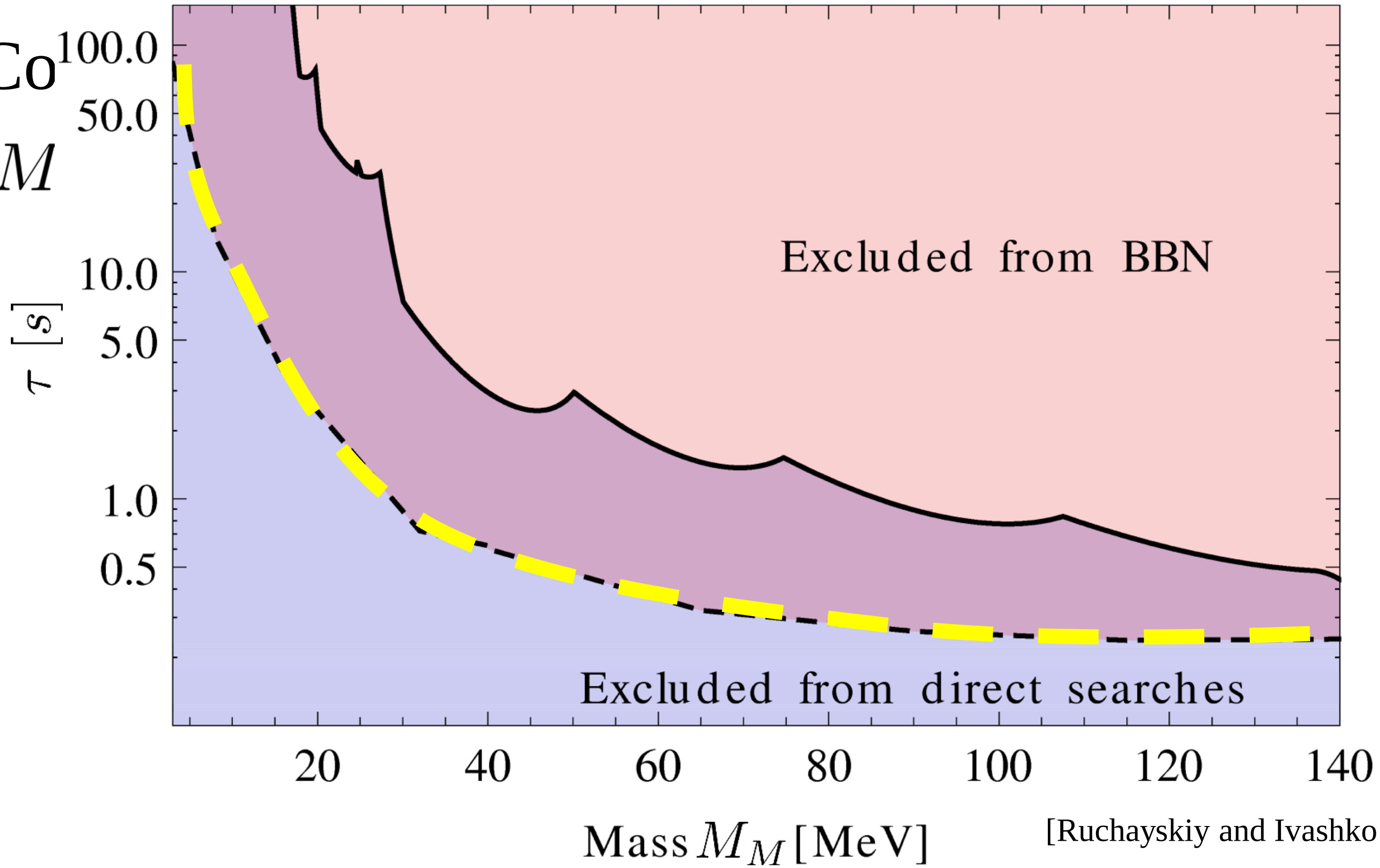

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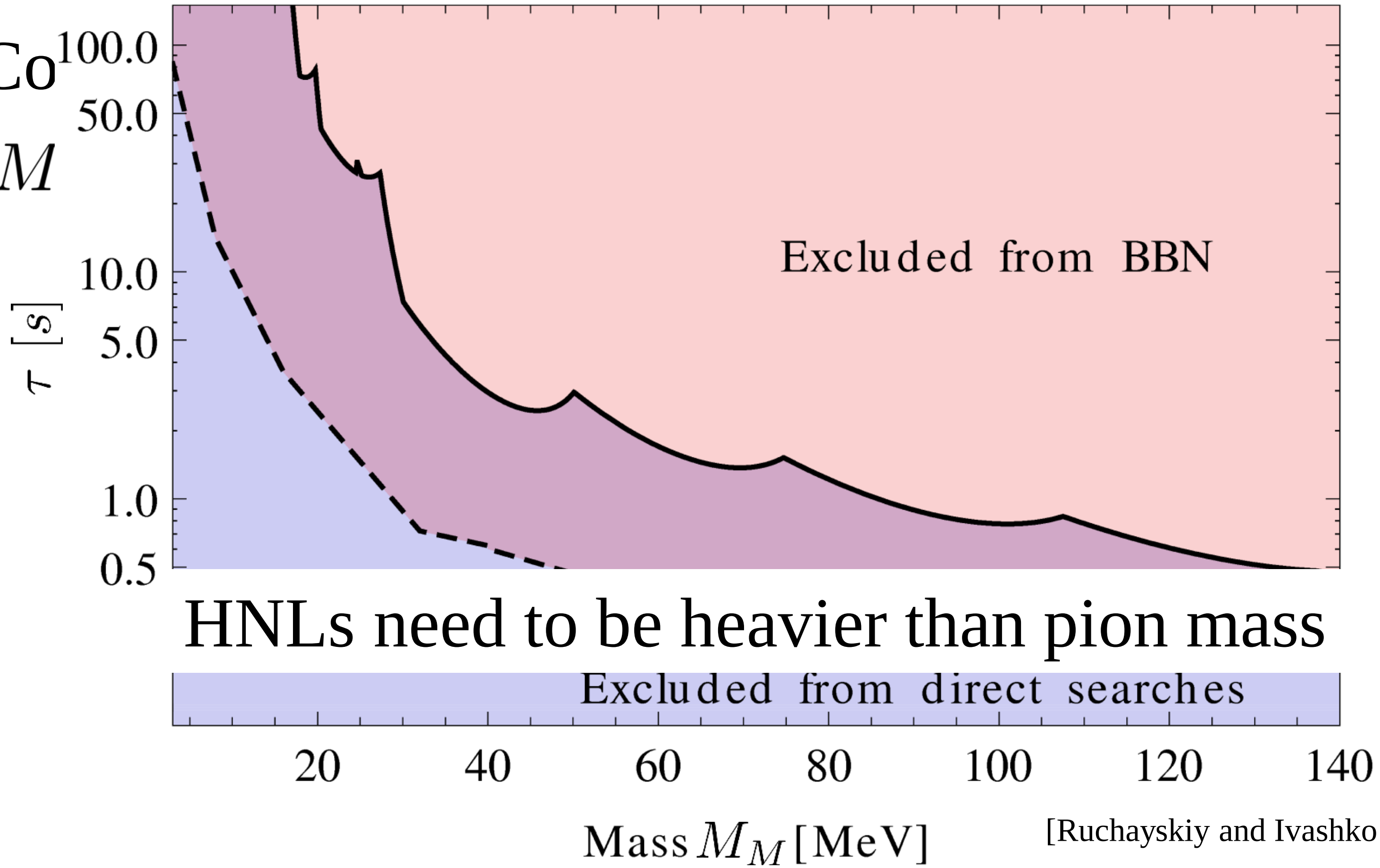

HNLs need to be heavier than pion mass

[Ruchayskiy and Ivashko (2012)]

Introduction

- Testability of HNL

Center mass energy of LHC: 10^4 GeV

Direct production is impossible when $M_M \sim 10^{15}$ GeV

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Direct production is impossible
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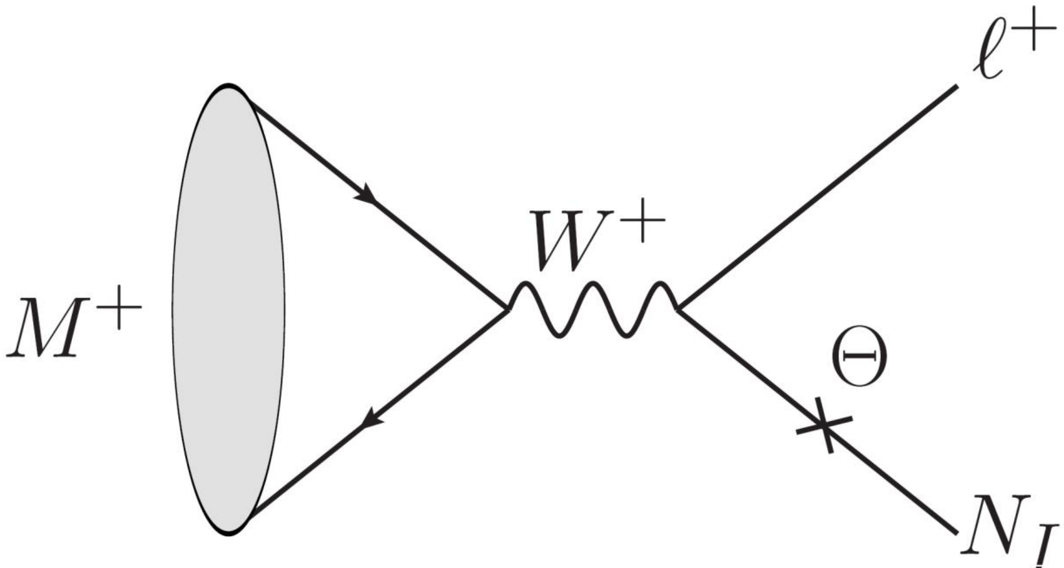
If $M_M < M_{\rm meson}$



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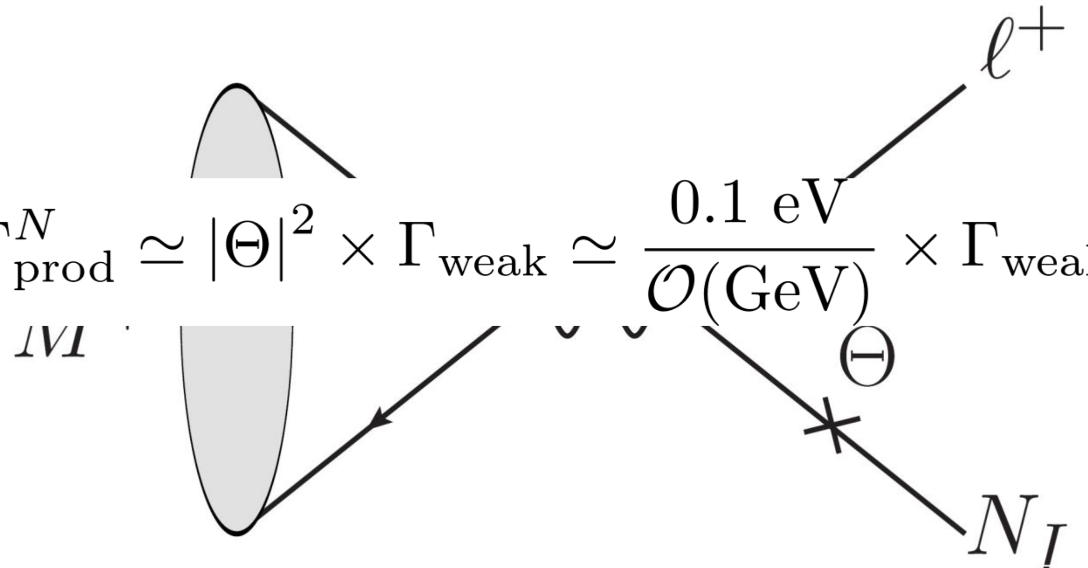

$$\Gamma^N_{\text{prod}} \simeq |\Theta|^2 \times \Gamma_{\text{weak}} \simeq \frac{0.1\ \text{eV}}{\mathcal{O}(\text{GeV})} \times \Gamma_{\text{weak}}$$

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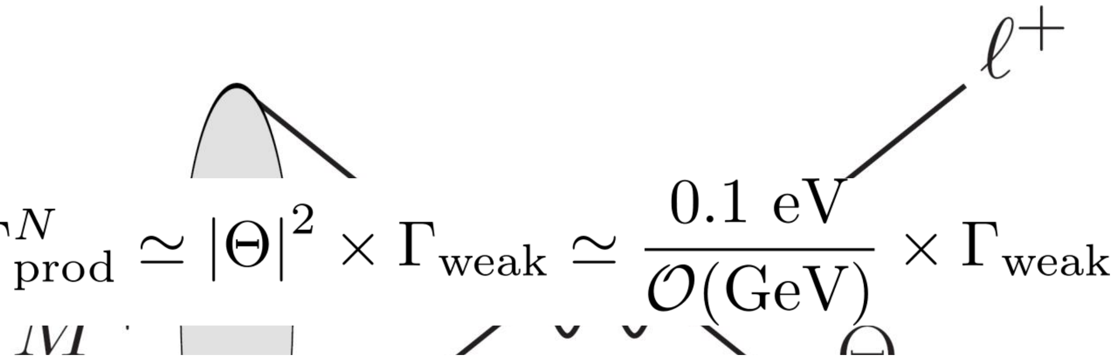

$$\Gamma^N_{\rm prod} \simeq |\Theta|^2 \times \Gamma_{\rm weak} \simeq \frac{0.1\ {\rm eV}}{\mathcal{O}({\rm GeV})} \times \Gamma_{\rm weak}$$

Hints of low scale seesaw can be got by
high intensity experiments!!

Contents

- Today, I would like to focus on…

*LNV B decay at future collider

[Asaka and H.I. (2016)]

*LNV B decay at future B experiments

[Cvetič and Kim (2017)]

*Displaced vertices search at future LHCb

[Antusch, Cazzato, and Fischer (2017)]

*Displaced vertices search at LHC

[Giovanna, Helo, and Hirsch, arXiv:1806.05191]

Contents

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In further discussions,
Majorana mass and mixing angle are considered
as independent parameters

Excuse for assumption

- Generic feature of Yukawa coupling [Casas, Ibarra(2001)]

$$F_{\alpha I} = \frac{i}{\langle H \rangle} U D_\nu^{\frac{1}{2}} \Omega D_N^{\frac{1}{2}}$$

* $D_N^{\frac{1}{2}} = \mathrm{diag}\left(\sqrt{M_2}\,, \sqrt{M_3}\right)$
* $D_\nu^{\frac{1}{2}} = \mathrm{diag}\left(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}\right)$
* $U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12}-s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12}-s_{23}s_{13}s_{12}e^{i\delta} & s_{13}c_{13} \\ s_{23}s_{12}-c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12}-c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\eta} & \\ & & 1 \end{pmatrix}$
* $\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \end{pmatrix}$ for N.H. $\Omega = \begin{pmatrix} \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \\ 0 & 0 \end{pmatrix}$ for I.H.

ω is arbitrary complex, $\xi = \pm 1$

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Independent of seesaw relation!

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$$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \cos\mathrm{Re}\omega & -\sin\mathrm{Re}\omega \\ 0 & \xi\sin\mathrm{Re}\omega & \xi\cos\mathrm{Re}\omega \end{pmatrix} \begin{pmatrix} 0 & 0 \\ \cosh\mathrm{Im}\omega & -i\sinh\mathrm{Im}\omega \\ i\sinh\mathrm{Im}\omega & \cosh\mathrm{Im}\omega \end{pmatrix}$$

Imaginary part can determine
the magnitude of Yukawa coupling

Because,
$$\sinh\mathrm{Im}\omega = \frac{1}{2}\left(\exp\left[\mathrm{Im}\omega\right] - \exp\left[-\mathrm{Im}\omega\right]\right)$$
$$\cosh\mathrm{Im}\omega = \frac{1}{2}\left(\exp\left[\mathrm{Im}\omega\right] + \exp\left[-\mathrm{Im}\omega\right]\right)$$

Enhancement of Yukawa coupling (mixing angle)
can be realized by Imω!

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$$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \cos\mathrm{Re}\omega & -\sin\mathrm{Re}\omega \\ 0 & \xi\sin\mathrm{Re}\omega & \xi\cos\mathrm{Re}\omega \end{pmatrix} \begin{pmatrix} 0 & 0 \\ \cosh\mathrm{Im}\omega & -i\sinh\mathrm{Im}\omega \\ i\sinh\mathrm{Im}\omega & \cosh\mathrm{Im}\omega \end{pmatrix}$$

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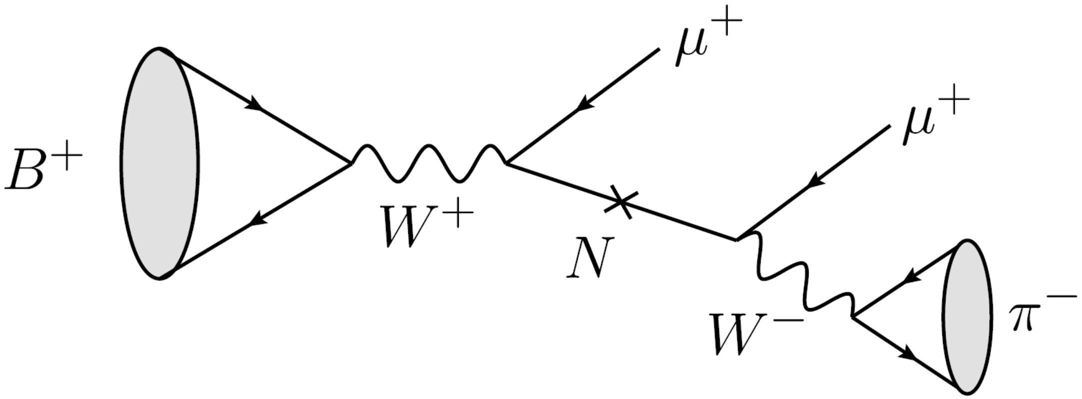
Just for simplicity,
we analyze the extended SM by “a” RHν

LNV B decay at future collider

[Asaka and H.I. (2016)]

LNV B decay at future collider [Asaka and H.I. (2016)]

- Focusing process



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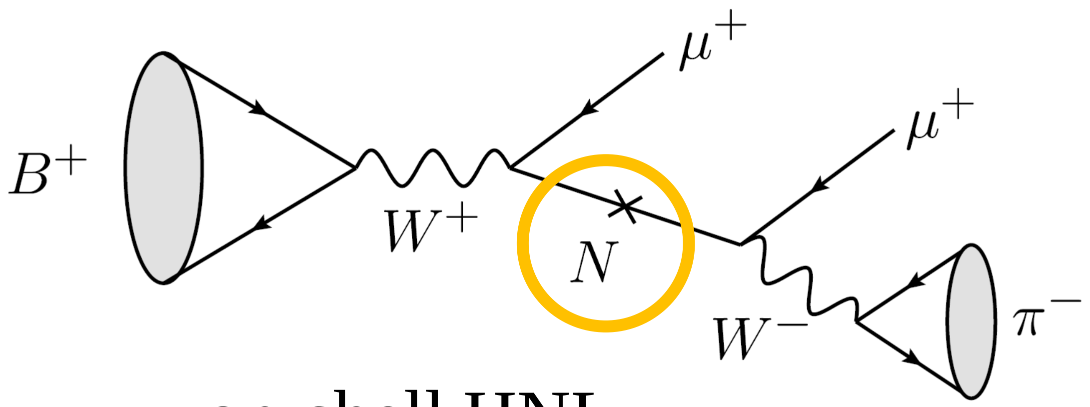

on-shell HNL

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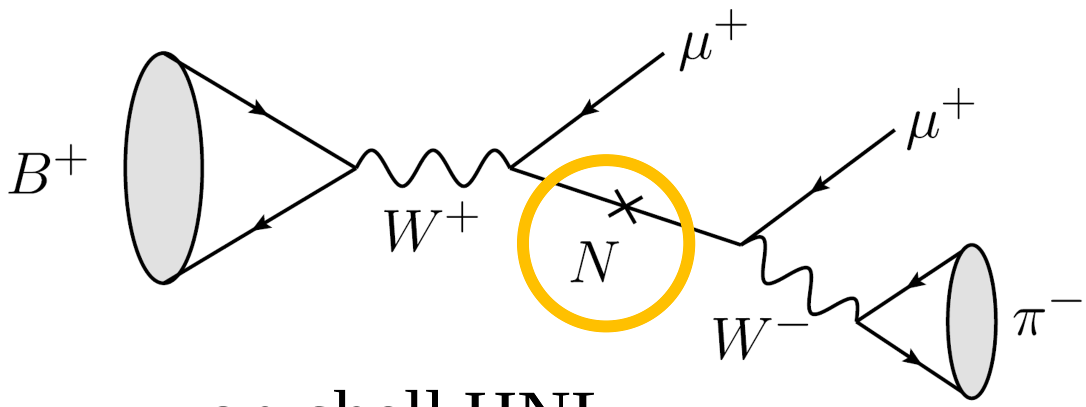

on-shell HNL

*Considerable mass range

$$m_\pi - m_\mu < M_M < m_B - m_\mu$$

$$(m_B \simeq 5.38 \text{ GeV})$$

*Assumption

$$\Theta_\mu \neq 0 \text{ and } \Theta_e\,, \Theta_\tau = 0$$

LNV B decay at future collider [Asaka and H.I. (2016)]

- Focusing future collider: Belle II and FCC-ee@Z-pole

-Difference

*Process

$\Upsilon(4S)$

↳ $B^+ \to \mu^+ + N \to \mu^+ + \mu^+ + \pi^-$ @Belle II

LNV B decay at future collider [Asaka and H.I. (2016)]

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$\Upsilon(4S)$

$\hookrightarrow B^+ \to \mu^+ + N \to \mu^+ + \mu^+ + \pi^-$ @Belle II

given by experiment ($N_B = 5 \times 10^{10}$ with $50\ \mathrm{ab}^{-1}$)

LNV B decay at future collider [Asaka and H.I. (2016)]

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*Process

$\Upsilon(4S)$ Effective detector length: $\ell_{\rm det} = 1.5 \text{ m}$

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Z

$B^+ \to \mu^+ + N \to \mu^+ + \mu^+ + \pi^-$ @FCC-ee

$\left(N_{B^+} = N_Z \times {\rm Br}(Z \to b\bar{b}) \times f_u\right)$

LNV B decay at future collider [Asaka and H.I. (2016)]

- Focusing future collider: Belle II and FCC-ee@Z-pole

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Z

$B^+ \to \mu^+ + N \to \mu^+ + \mu^+ + \pi^-$ @FCC-ee

$(N_{B^+} = N_Z \times {\rm Br}(Z \to b\bar{b}) \times f_u)$

given by experiment fraction of B^+ from $\bar{b}$

LNV B decay at future collider [Asaka and H.I. (2016)]

- Focusing future collider: Belle II and FCC-ee@Z-pole

  -Difference

  *Process

$\Upsilon(4S)$ Effective detector length: $\ell_{\rm det} = 1.5$ m

$B^+ \to \mu^+ + N \to \mu^+ + \mu^+ + \pi^-$ @Belle II

given by experiment ($N_B = 5 \times 10^{10}$ with 50 ab^{-1})

Z Effective detector length: $\ell_{\rm det} = 2$ m

$B^+ \to \mu^+ + N \to \mu^+ + \mu^+ + \pi^-$ @FCC-ee

$(N_{B^+} = N_Z \times \mathrm{Br}(Z \to b\bar{b}) \times f_u)$

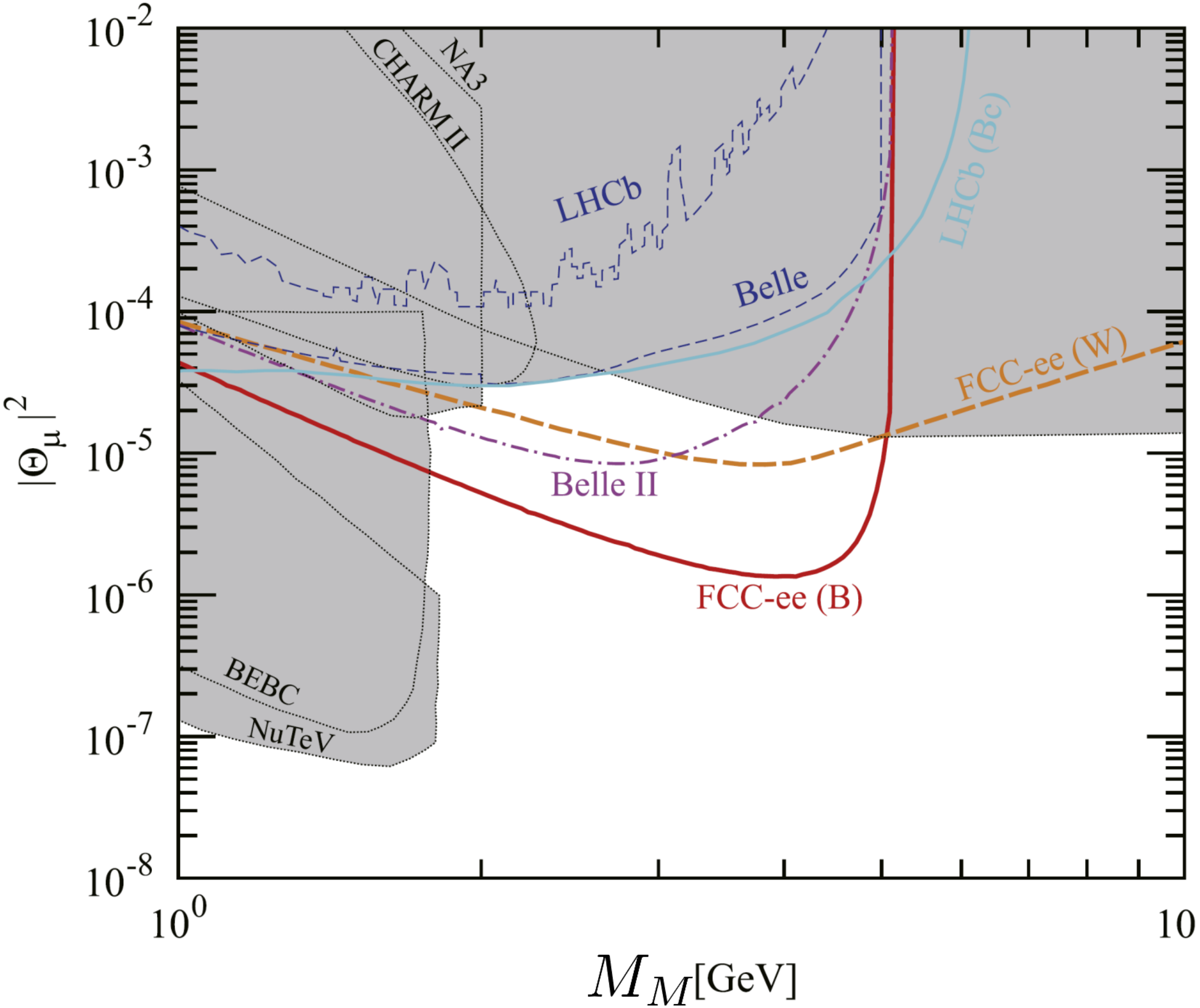
($N_B = 6.2 \times 10^{-2} N_Z$ with $N_Z = 10^{13}$)

LNV B decay at future collider [Asaka and H.I. (2016)]

- Result

LNV B decay at future collider [Asaka and H.I. (2016)]

• Res

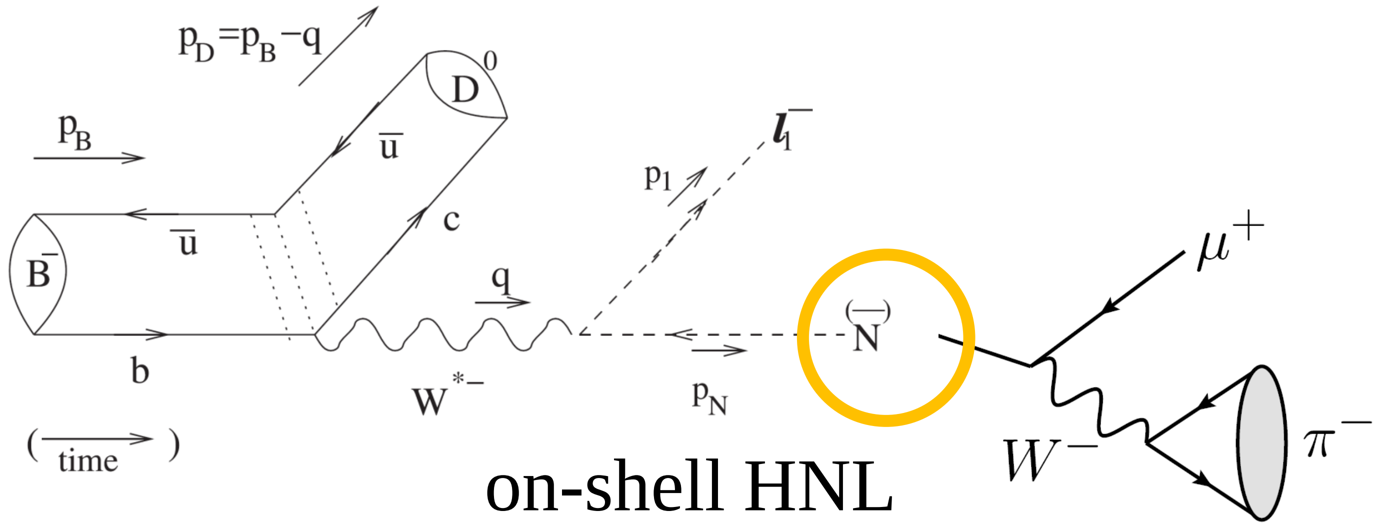


LNV B decay at future B experiments

[Cvetič and Kim (2017)]

LNV B decay at future B experiments [Cvetič and Kim (2017)]

- Focusing process (in addition to $B^+ \to \mu^+\mu^+\pi^-$)



*Considerable mass range

$$m_\pi - m_\mu < M_M < m_B - m_\mu \text{ or}$$

$$m_\pi - m_\mu < M_M < m_B - m_D^{(*)} - m_\mu$$

*Assumption $(m_D \simeq 1.87 \text{ GeV}, m_D^* \simeq 2.01 \text{ GeV})$

$$\Theta_\mu \neq 0 \text{ and } \Theta_e, \Theta_\tau = 0$$

LNV B decay at future B experiments [Cvetič and Kim (2017)]

- Focusing experiments: Belle II and LHCb

-Difference

*Process

$\Upsilon(4S)$

↳ $B^+ \to$ interested processes @Belle II

given by experiment ($N_B = 5 \times 10^{10}$ with $50\ \mathrm{ab}^{-1}$)

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given by experiment ($N_B = 4.8 \times 10^{12}$ with private communication)

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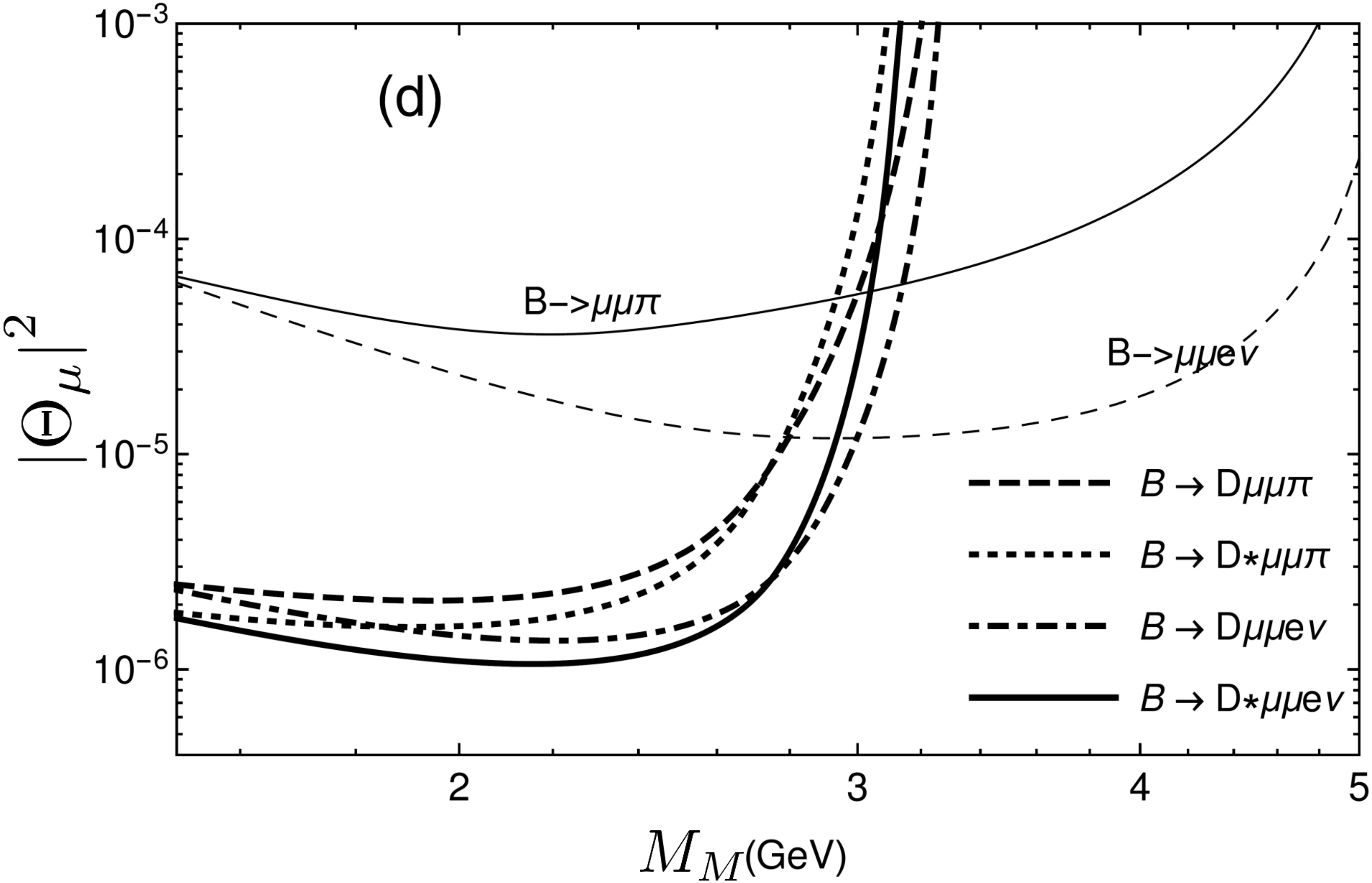
Effective detector length: $\ell_{\rm det} = 2.3 \text{ m}$

$B^+ \to$ interested processes @LHCb

given by experiment ($N_B = 4.8 \times 10^{12}$ with private communication)

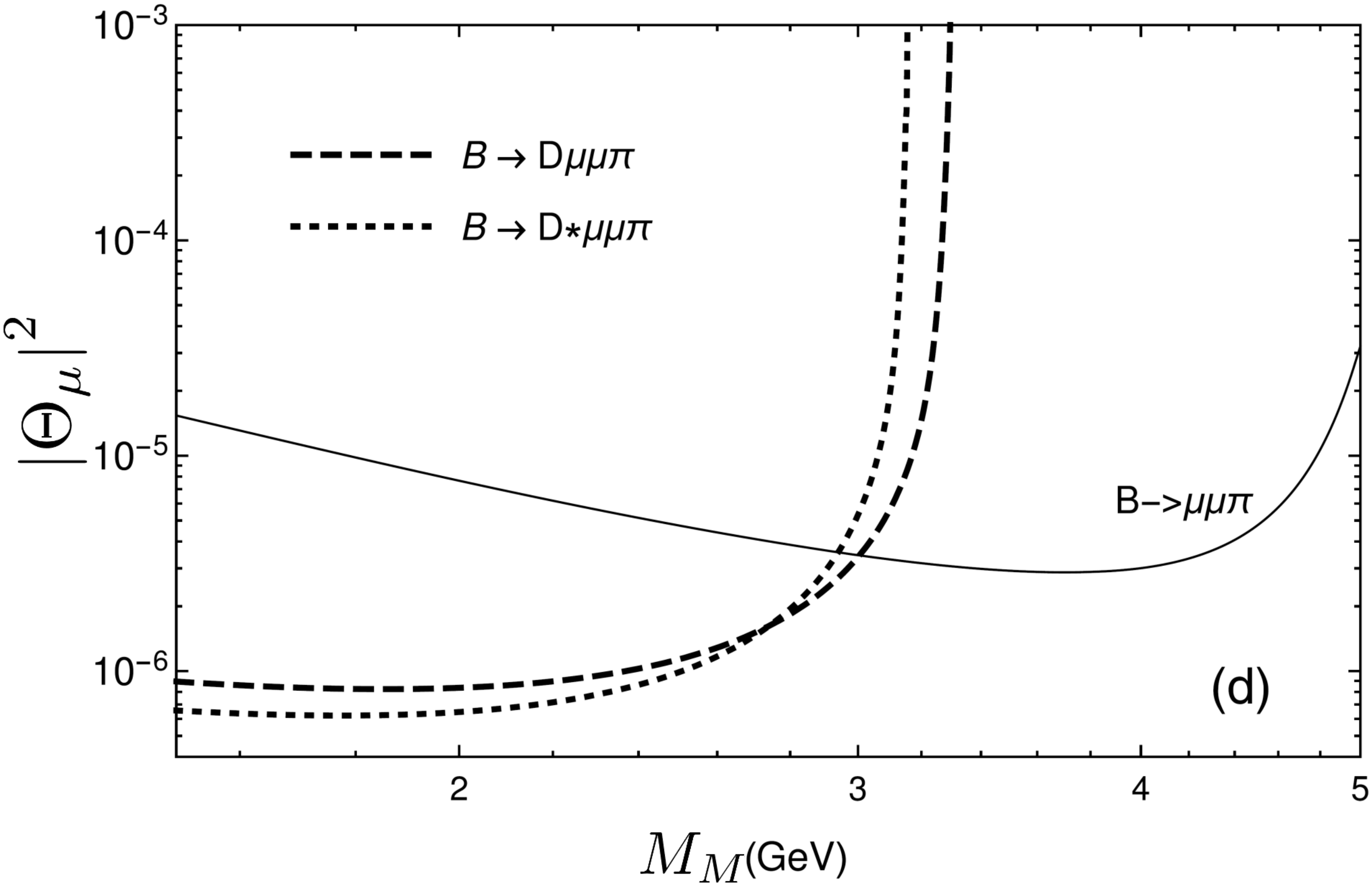
LNV B decay at future B experiments [Cvetič and Kim (2017)]

- Result-1 (Belle II sensitivity)



LNV B decay at future B experiments [Cvetič and Kim (2017)]

- Result-2 (LHCb sensitivity)



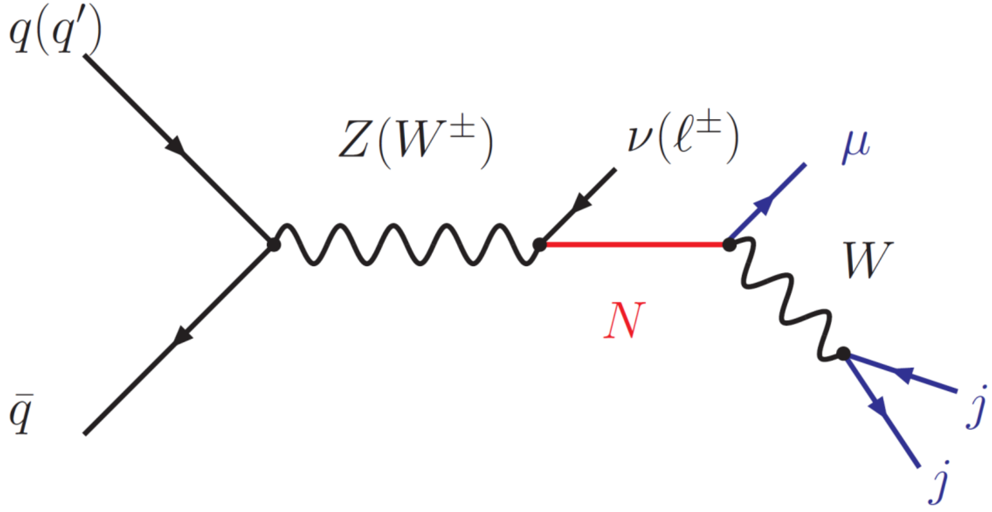
Displaced vertices search at future LHCb

[Antusch, Cazzato, and Fischer (2017)]

Displaced vertices search at future LHCb

[Antusch, Cazzato, and Fischer (2017)]

- Focusing process (NOT B decays!)



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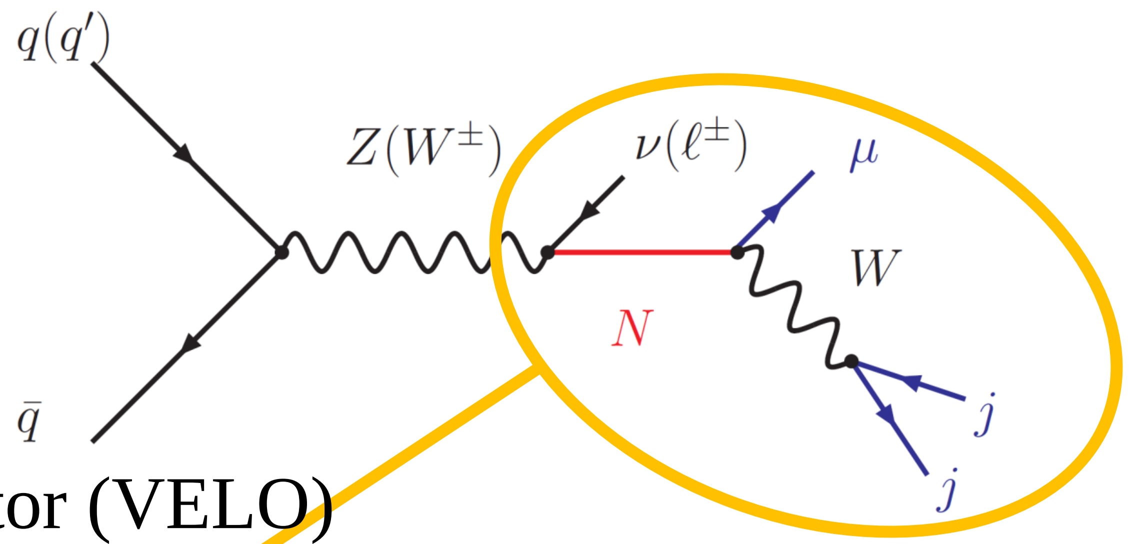
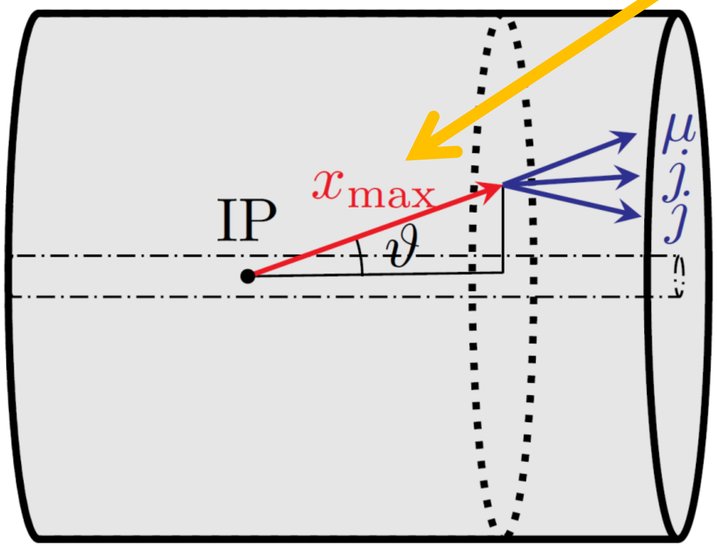


VErtex LOcator (VELO)



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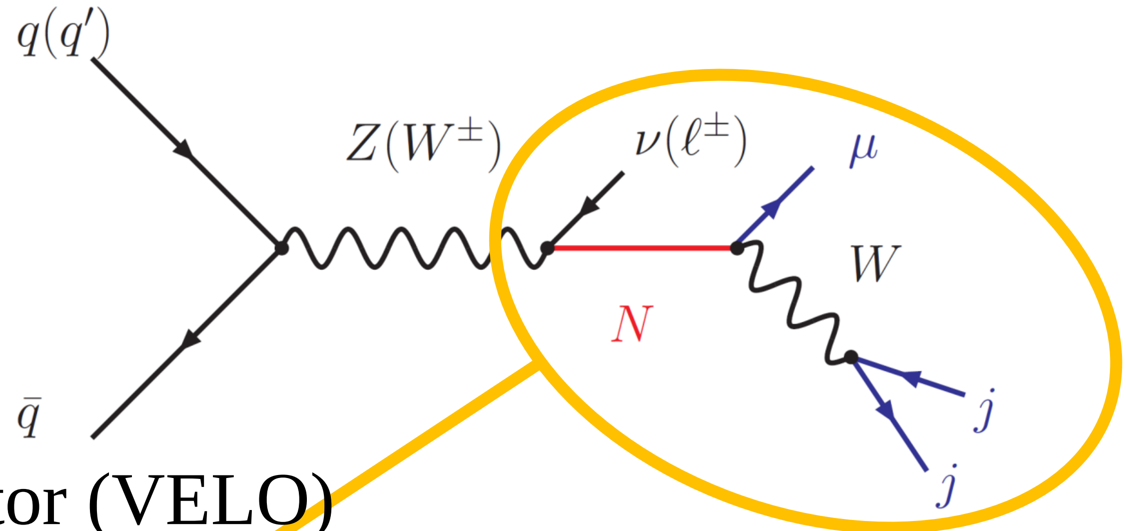

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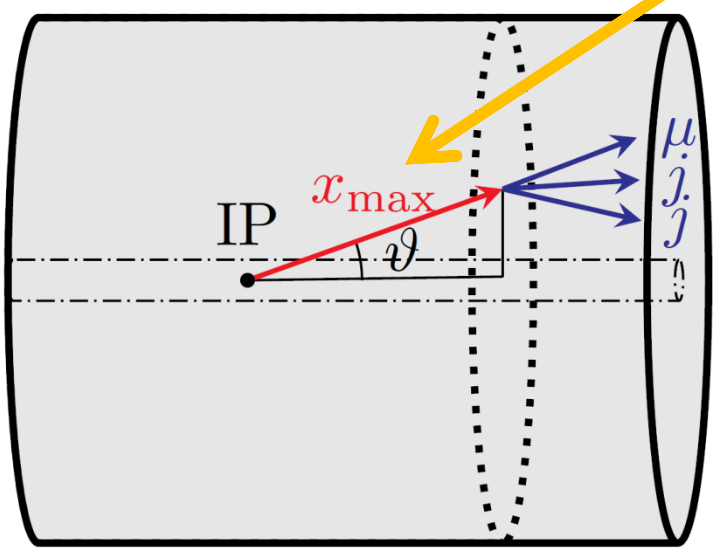

Maximal and minimal displacement

$$x_{\max}(\vartheta) = \begin{cases} \frac{z_{\max}}{\cos(\vartheta)} & \text{if } 0 \leq \vartheta \leq \arctan(r_{\max}/z_{\max}) \\ \frac{r_{\max}}{\sin(\vartheta)} & \text{if } \arctan(r_{\max}/z_{\max}) \leq \vartheta < \frac{\pi}{2} \end{cases}$$

$$x_{\min}(\vartheta) = \begin{cases} \frac{r_{\min}}{\sin(\vartheta)} & \text{if } \arctan(r_{\min}/z_{\max}) \leq \vartheta < \frac{\pi}{2} \\ \text{n.a.} & \text{otherwise} \end{cases}$$

(z :longitudinal, r :transverse)

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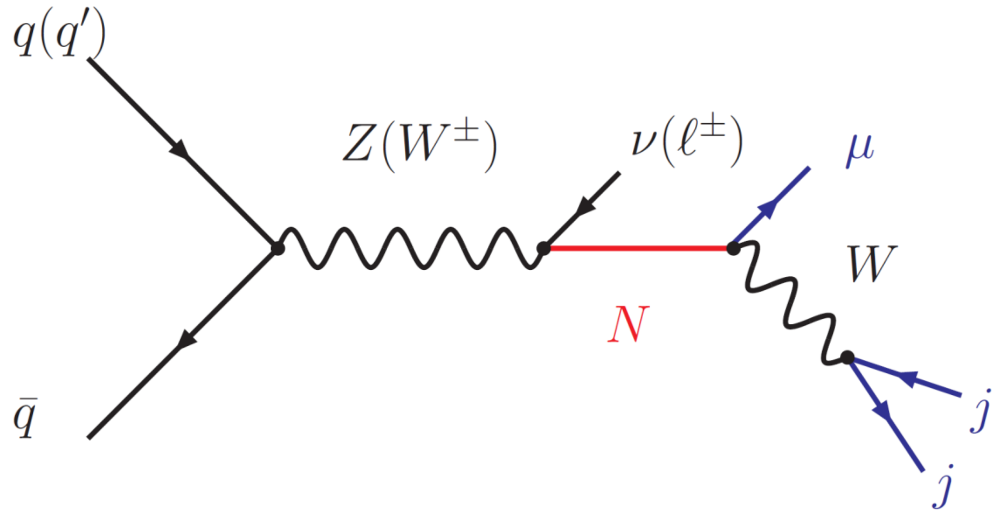
- Focusing process



*Considering mass range

$$4.5 \text{ GeV} < M_M < 25 \text{ GeV}$$

*Assumption

$$\Theta_\mu \neq 0 \text{ and } \Theta_e , \Theta_\tau = 0$$

Displaced vertices search at future LHCb

[Antusch, Cazzato, and Fischer (2017)]

- Constraints to see signal

-Event cuts

- $N(\mu) = 1$ and $N(j) > 0$
- $2 < \eta(f) < 5,\ f = \mu, j$
- $P_t(\mu) > 12$ GeV
- $M[\mu jj] > 4.5$ GeV

⇒ Reject all events from $M_M < 4.5$ GeV

and, $\vartheta[\mu jj] < 0.34$ due to geometric acceptance

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-Requirement to decay point of NHL

*Decay inside the VELO $z_{\max} = 40$ cm

*Decay inside the volume $z_{\max} = 2$ m

Displaced vertices search at future LHCb

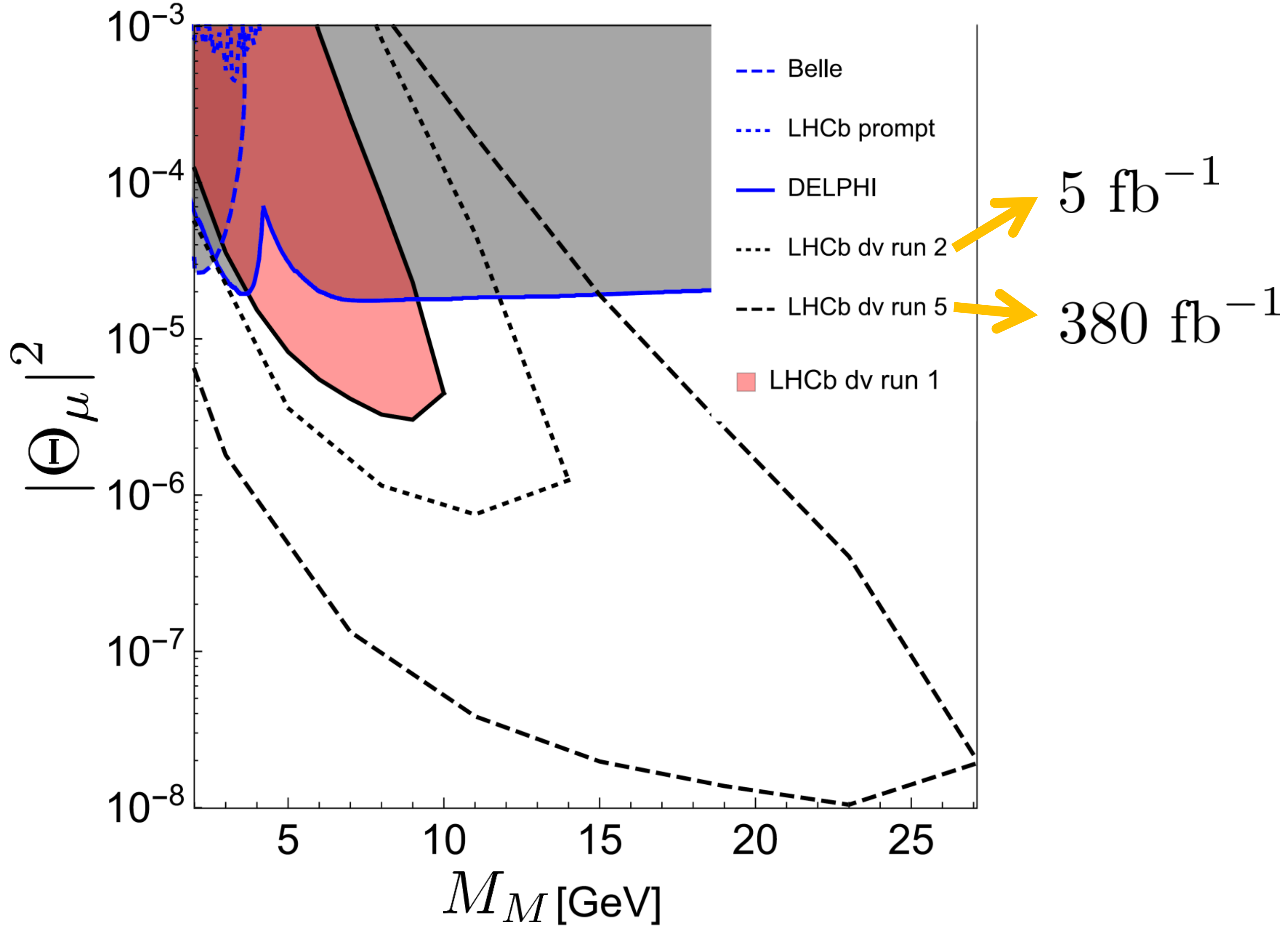
[Antusch, Cazzato, and Fischer (2017)]

- Future prospects

Displaced vertices search at future LHCb

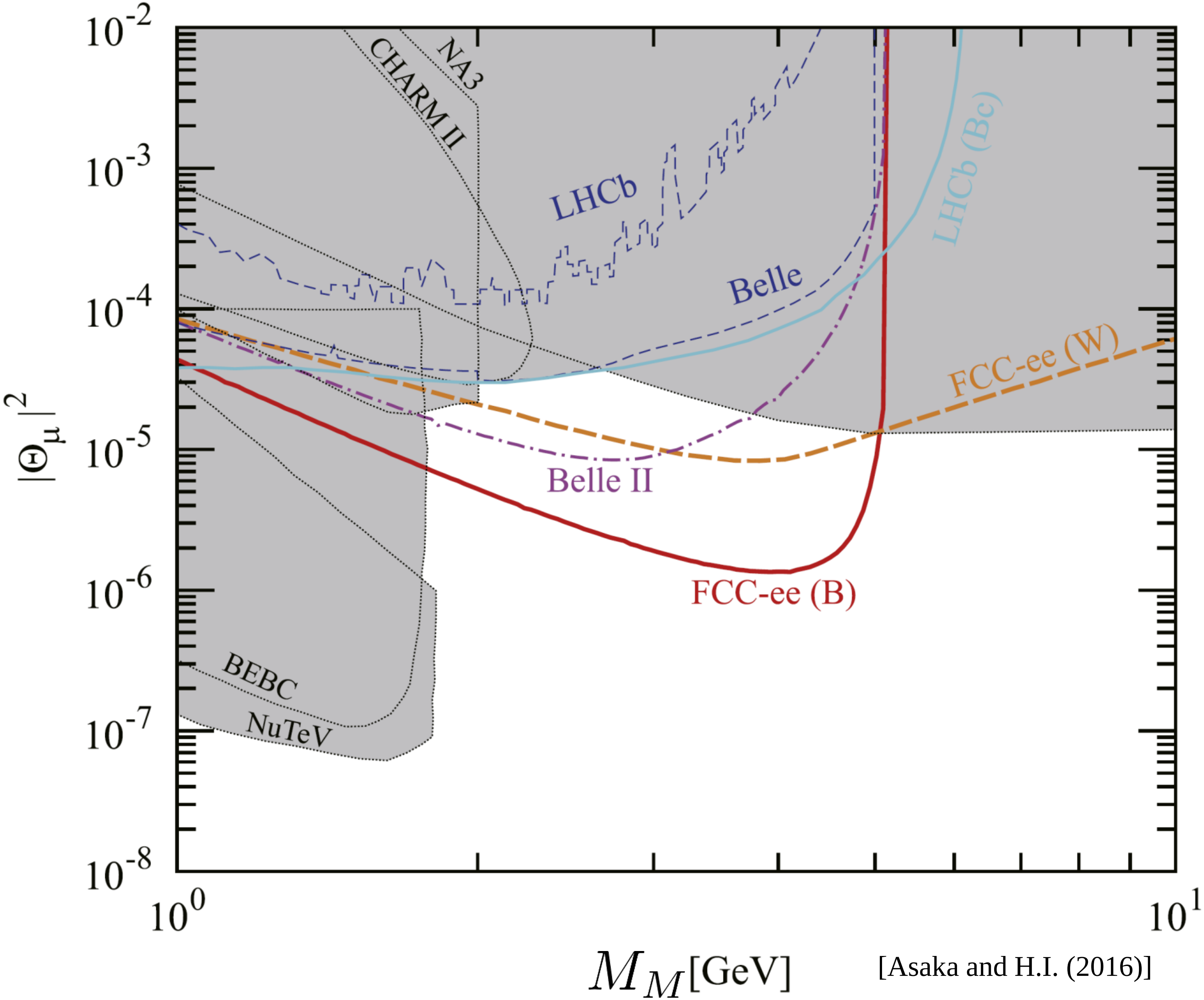
[Antusch, Cazzato, and Fischer (2017)]

- Future prospects



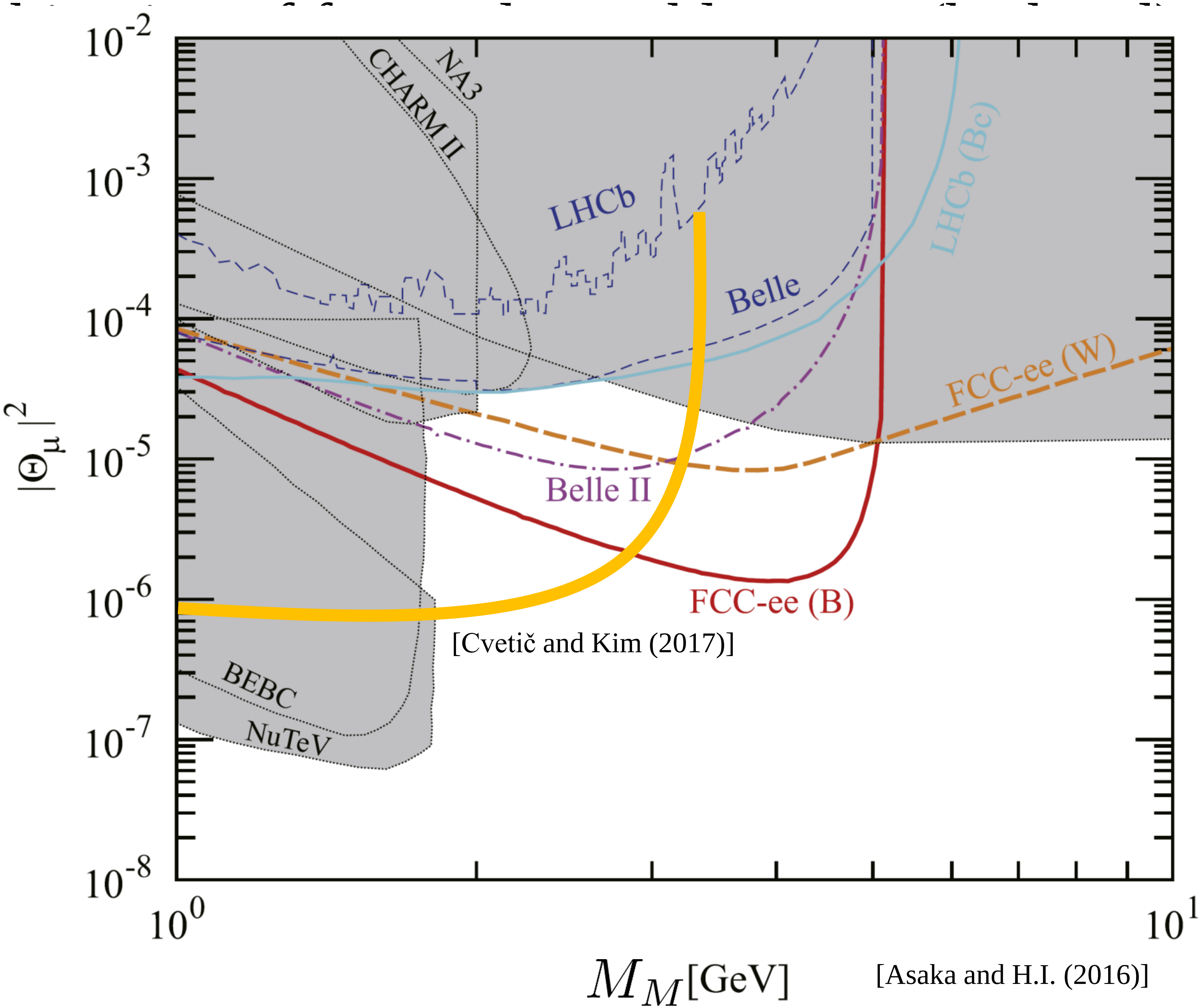
Combination of future detectable range (by hand)

Con



[Asaka and H.I. (2016)]

Con



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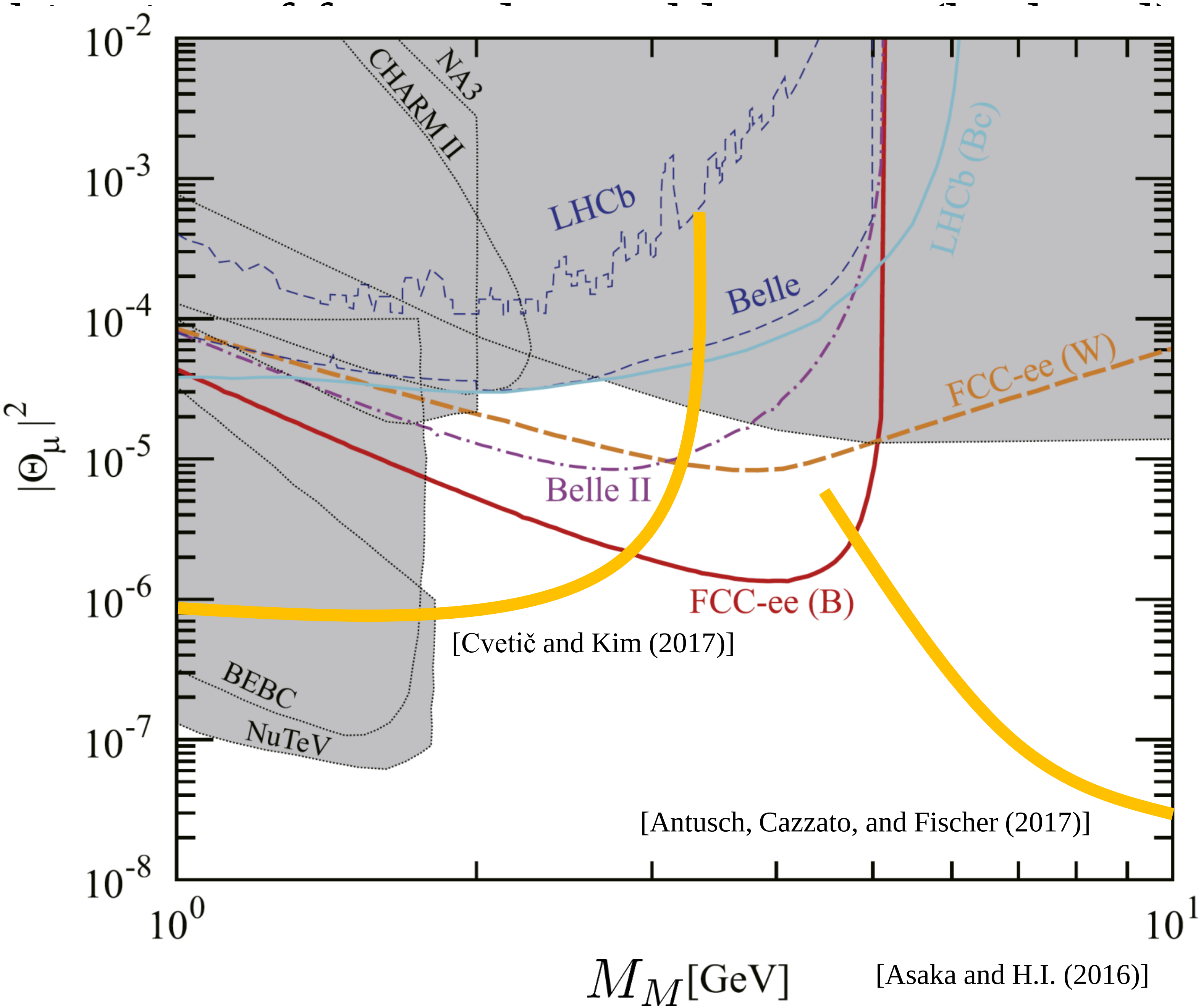

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- Low scale type-I seesaw

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Hope to find any hints for origin of neutrino mass
at (near) future colliders!!

Thank you
for your attention!