Connecting energy, intensity
and
cosmic frontiers through neutrinos

CEPC Workshop
13 – 18 AUGUST,2023
Fudan University, China

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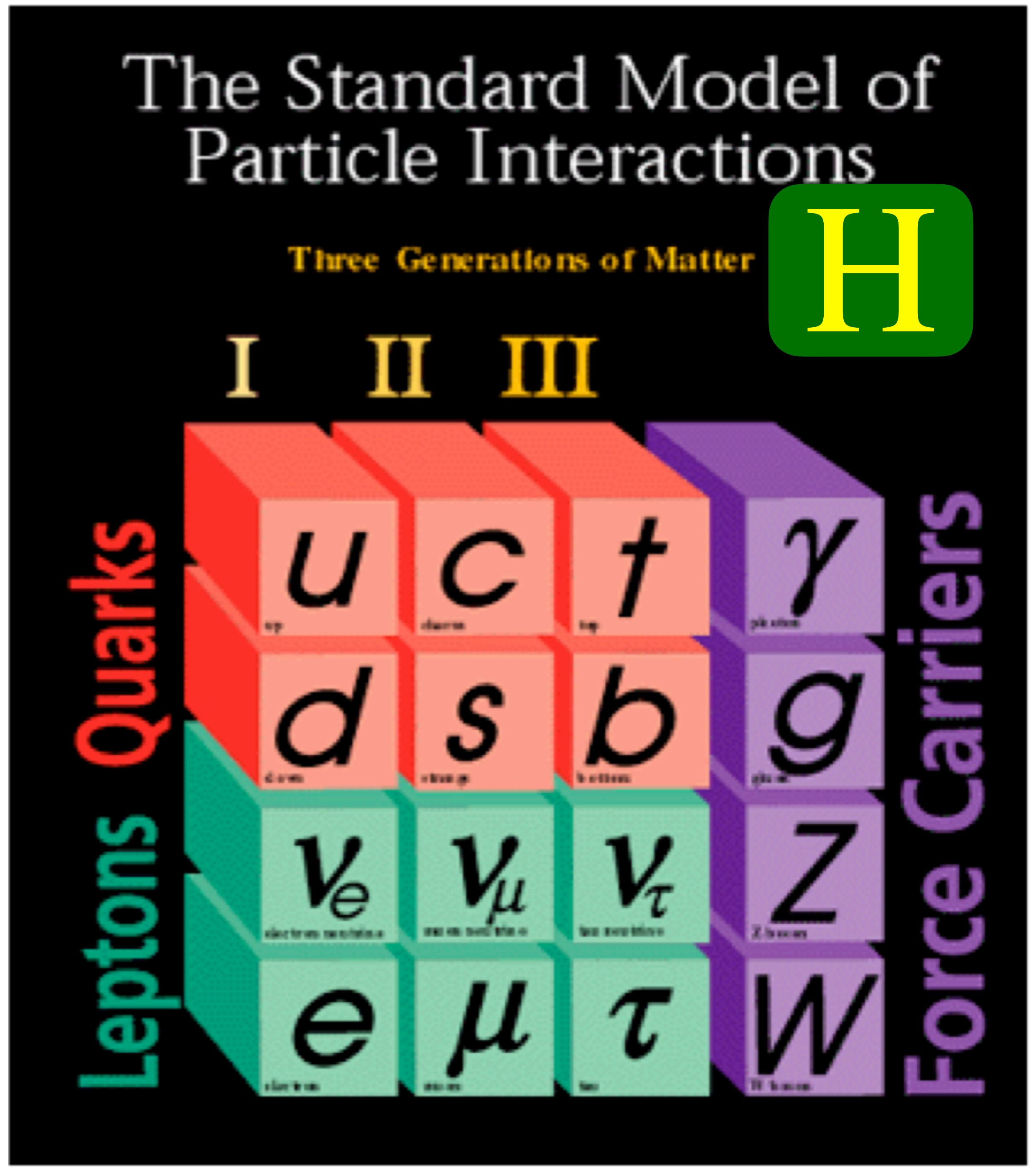
Introduction



Over the decades experiments
have found each
and every missing pieces

Verified the facts that
they belong to this family

Finally at the Large Hadron collider
Higgs has been observed
→ Its properties must be verified

Strongly established with interesting shortcomings

Few of the very interesting anomalies :

Tiny neutrino mass and flavor mixings

Relic abundance of dark matter . . .

SM can not explain them

Birth of a new idea : generation of neutrino mass

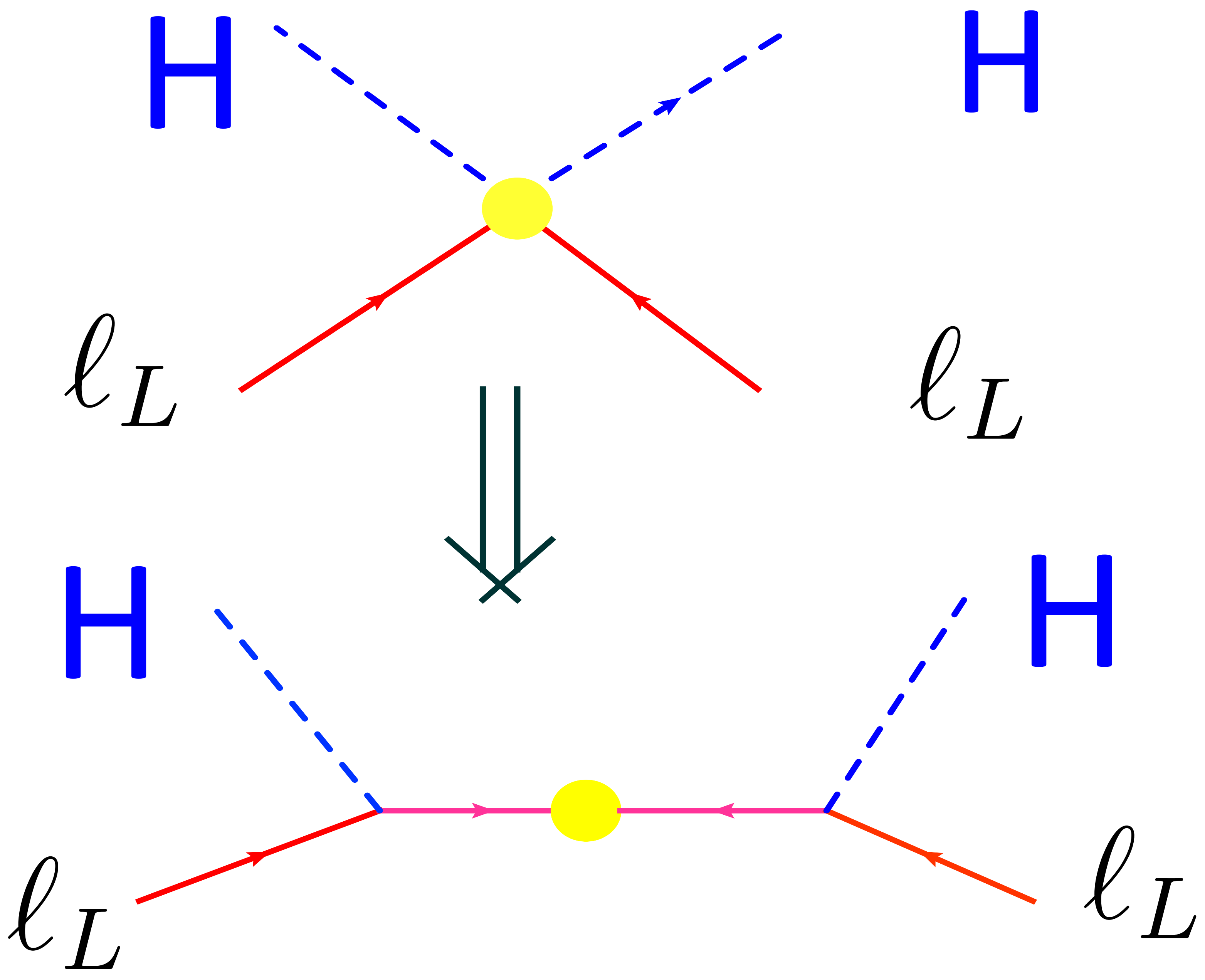
Weinberg Operator in SM (d=5), PRL 43, 1566(1979)

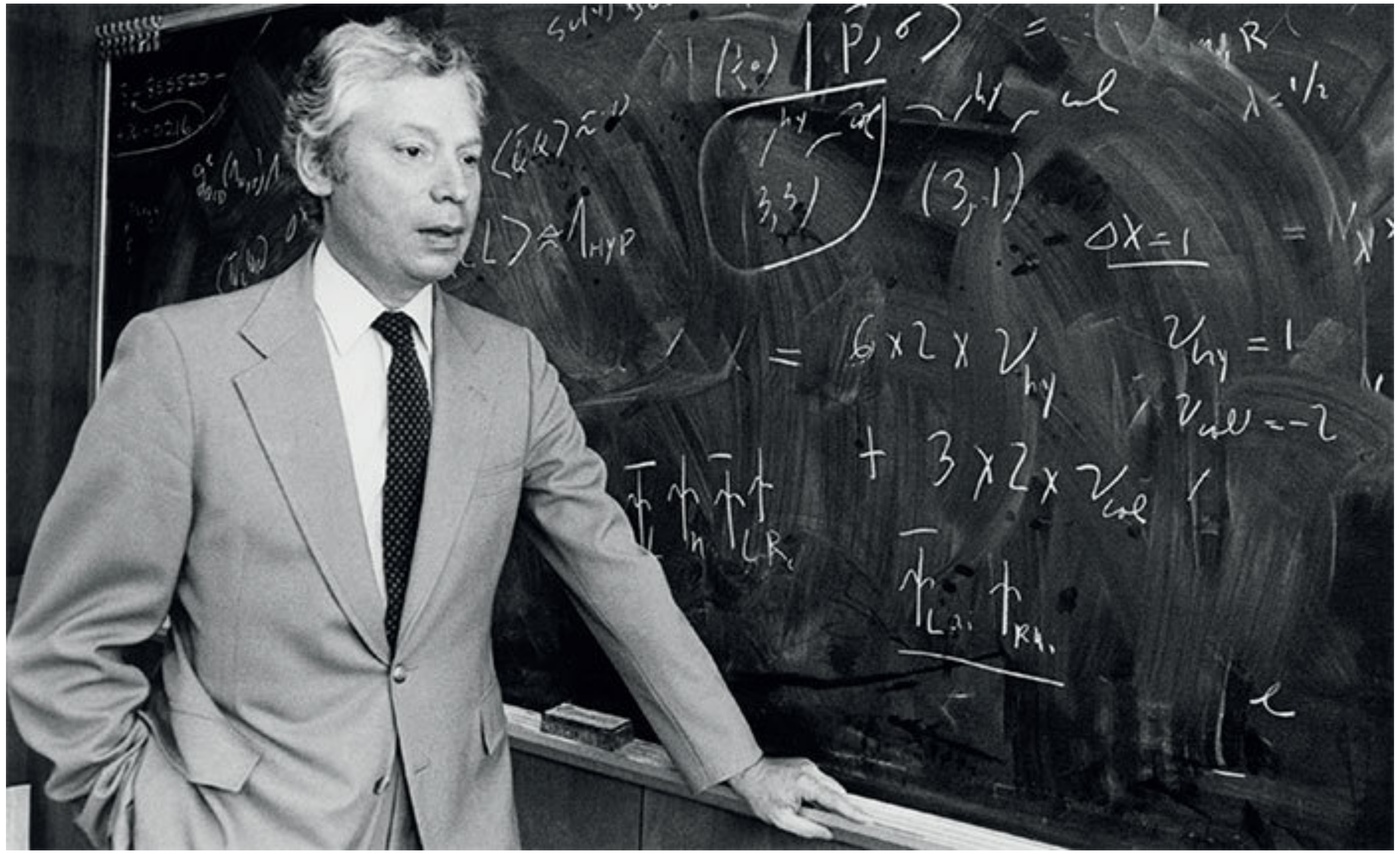
$$\frac{\overline{\ell_L} H \overline{\ell_L^c}^T H}{M}$$

within the Standard Model

Steven Weinberg : 1933 – 2021

The dimension 5 operator can be realized in the following ways





Majorana mass term is generated by the breaking of the lepton numbers by 2 units.

Scenarios

Neutrino mass

Tree level

SM + Particles

Gauge extension

Singlet, triplet fermions
Triplet scalars

Left – right
general U(1)

Seesaw, inverse seesaw I, II, III

Quantum level

I, II, III . . .

Higher dimensional operators

Neutrino conncetion

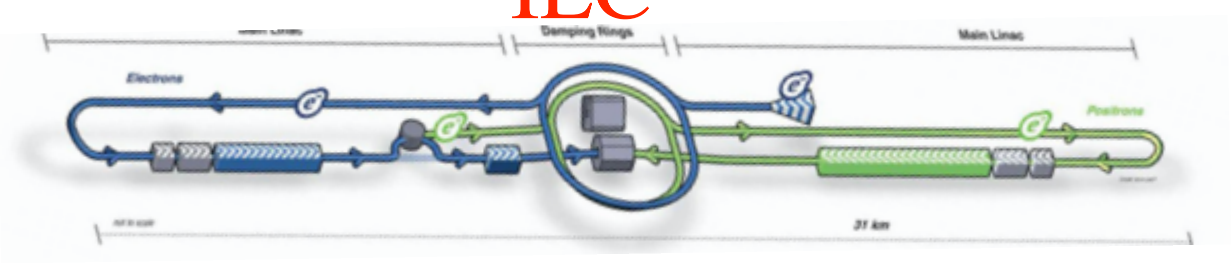
Energy frontier : Scientists build partcile acclerators to explore high energy scale to explore new phenomena after the subatomic collisions.

Intensity frontier : Highly intense beams from accelerators are used to to investigate the ultra rare processes of nature.

Cosmic frontier : Astrophysicists use the cosmos as the laboratory to investigate the fundamental laws of physics from a complementary point of view of particle accelerator.

Future Circular Collider – hh/ee/eP

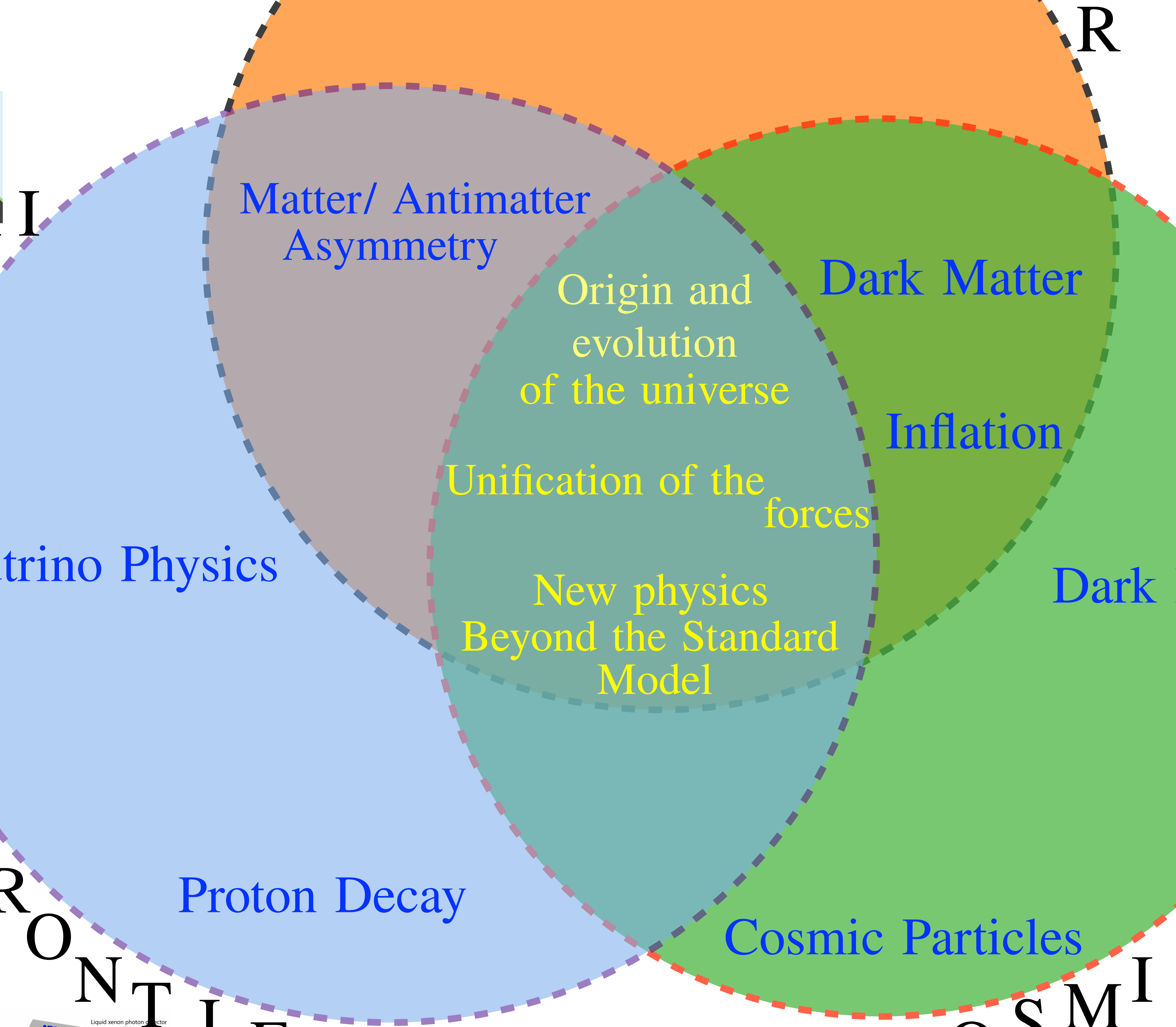
ILC



ENERGY FRONTIER

INTENSITY FRONTIER

COSMIC FRONTIER



Origin of mass

Matter/ Antimatter Asymmetry

Dark Matter

Origin and evolution of the universe

Inflation

Unification of the forces

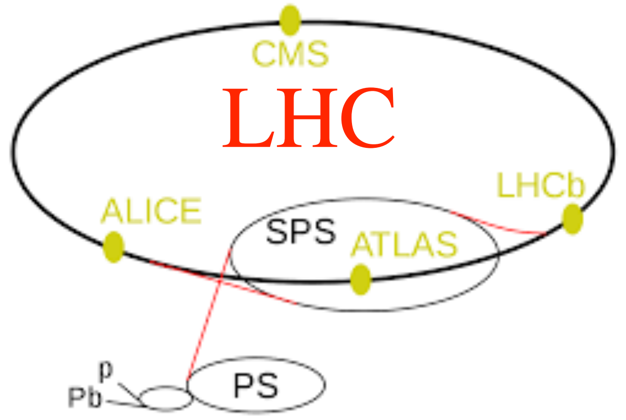
Neutrino Physics

Dark Energy

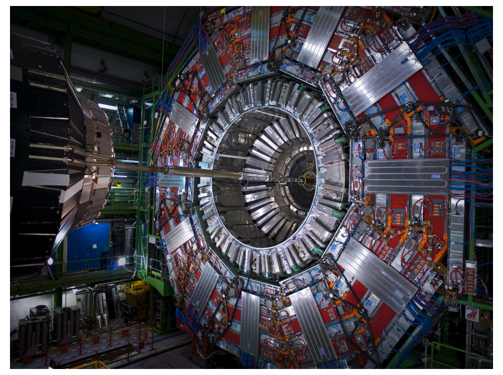
New physics Beyond the Standard Model

Proton Decay

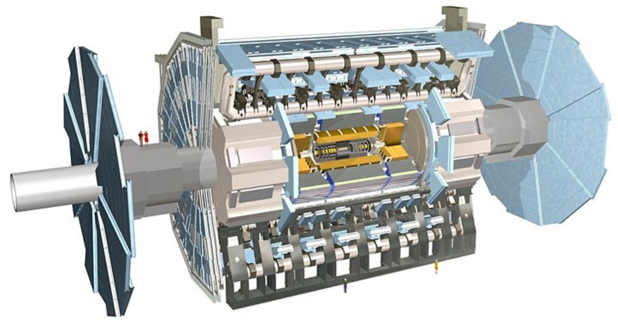
Cosmic Particles



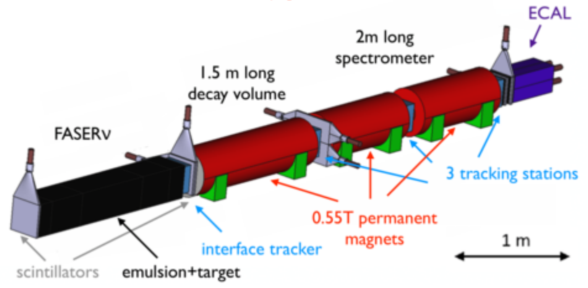
CMS



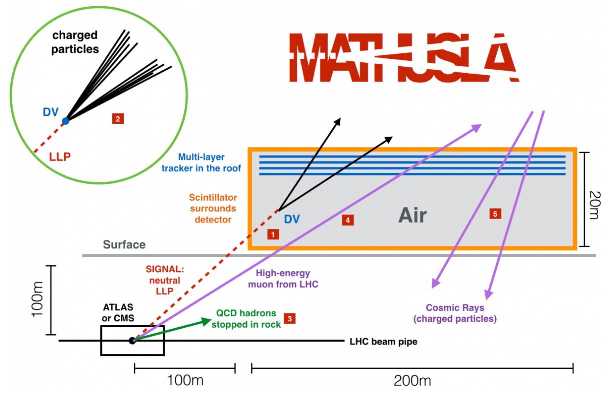
ATLAS



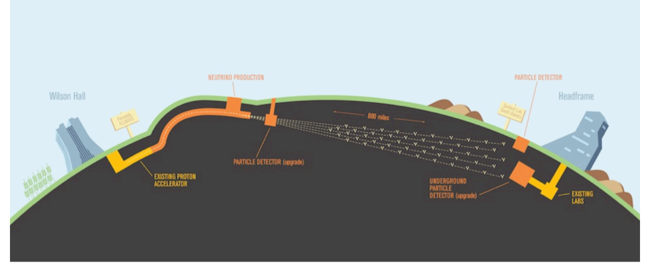
FASER



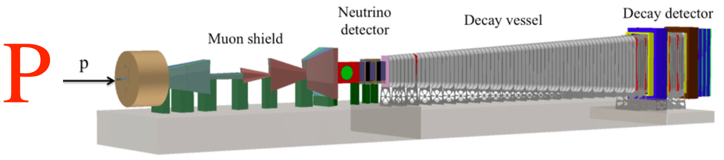
MATHUSLA



DUNE

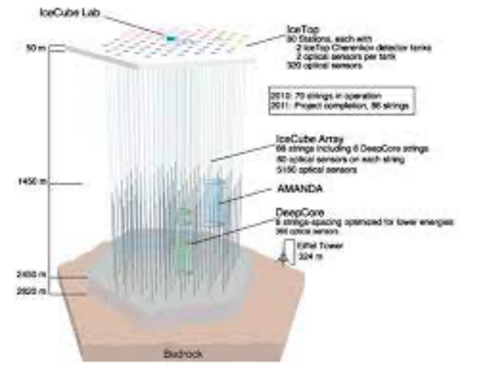


SHiP

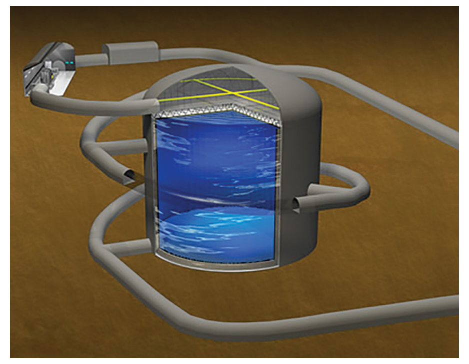


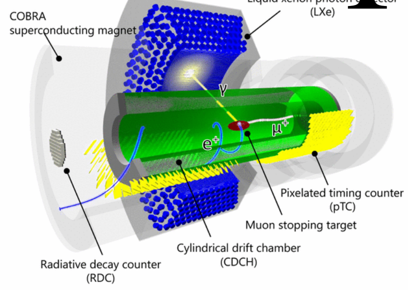
NA62

IecCube/PINGU



Hyper – K



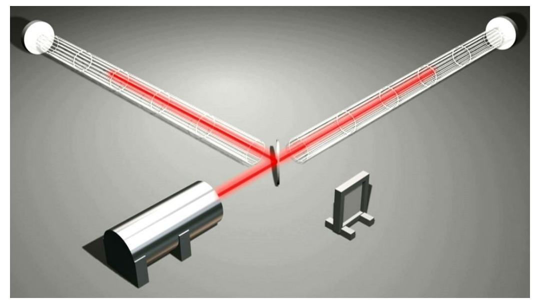


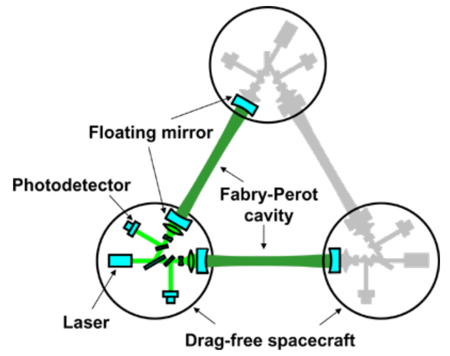
LFV(MEG, BaBaR)

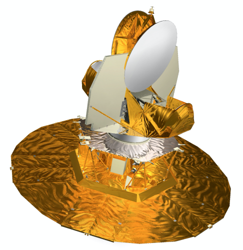
Ground based telescopes

Interferometers

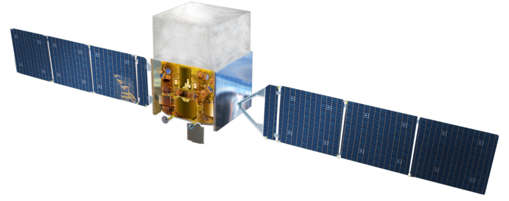
LIGO/ DECIGO







CMB/WMAP



Space Telescopes (FermiLAT)

Particle content

Dobrescu, Fox; Cox, Han, Yanagida; AD, Okada, Raut;
Chiang, Cottin, AD, Mandal; AD, Takahashi, Oda, Okada AD, Dev, Okada

	SU(3)$_c$	SU(2)$_L$	U(1)$_Y$			$U(1)_X$
q_L^i	**3**	**2**	$+1/6$	x_q	$=$	$\frac{1}{6}x_H + \frac{1}{3}x_\Phi$
u_R^i	**3**	**1**	$+2/3$	x_u	$=$	$\frac{2}{3}x_H + \frac{1}{3}x_\Phi$
d_R^i	**3**	**1**	$-1/3$	x_d	$=$	$-\frac{1}{3}x_H + \frac{1}{3}x_\Phi$
ℓ_L^i	**1**	**2**	$-1/2$	x_ℓ	$=$	$-\frac{1}{2}x_H - x_\Phi$
e_R^i	**1**	**1**	-1	x_e	$=$	$-x_H - x_\Phi$
H	**1**	**2**	$+1/2$	x'_H	$=$	$\frac{1}{2}x_H$
N_R^i	**1**	**1**	0	x_ν	$=$	$-x_\Phi$
Φ	**1**	**1**	0	x'_Φ	$=$	$2x_\Phi$

3 generations of SM singlet right handed neutrinos (anomaly free)

Charges before the anomaly cancellations

Charges after Imposing the anomaly cancellations

$$m_{Z'} = 2\, g_X v_\Phi$$

x_H, x_Φ will appear the coupling with Z'

B – L case

$\mathrm{x_H} = 0,\ \mathrm{x_\Phi} = 1$

$U(1)_X$ breaking

$$\mathcal{L}_Y \supset -\sum_{i,j=1}^{3} Y_D^{ij}\overline{\ell_L^i}HN_R^j - \frac{1}{2}\sum_{i=k}^{3} Y_N^k \Phi \overline{N_R^{k\,c}} N_R^k + \text{h.c.},$$

$$\boxed{m_D^{ij} = \frac{Y_D^{ij}}{\sqrt{2}}v_h}$$

$$\boxed{m_{N^i} = \frac{Y_N^i}{\sqrt{2}}v_\Phi}$$

$$m_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \quad m_\nu \simeq -M_D M_N^{-1} M_D^T$$

Seesaw mechnism

Z' interactions

Interaction between the quarks and Z' $$\mathcal{L}^q = -g'(\overline{q}\gamma_\mu q^q_{x_L} P_L q + \overline{q}\gamma_\mu q^q_{x_R} P_R q)Z'_\mu$$

Interaction between the leptons and Z' $$\mathcal{L}^\ell = -g'(\overline{\ell}\gamma_\mu q^\ell_{x_L} P_L \ell + \overline{e}\gamma_\mu q^\ell_{x_R} P_R e)Z'_\mu$$

$q^f_{x_L} \neq q^f_{x_R}$ affects the phenomenology

Partial decay width

Charged fermions $$\Gamma(Z' \to 2f) = N_c \frac{M_{Z'}}{24\pi} \left(g^f_L\left[g', x_H, x_\Phi\right]^2 + g^f_R\left[g', x_H, x_\Phi\right]^2 \right)$$

light neutrinos $$\Gamma(Z' \to 2\nu) = \frac{M_{Z'}}{24\pi}\, g^\nu_L\left[g', x_H, x_\Phi\right]^2$$

heavy neutrinos $$\Gamma(Z' \to 2N) = \frac{M_{Z'}}{24\pi}\, g^N_R\left[g', x_\Phi\right]^2 \left(1 - 4\frac{m_N^2}{M_{Z'}^2}\right)^{\frac{3}{2}}$$

Production modes of the RHNs at the colliders : pp, e^-e^+, e^-p

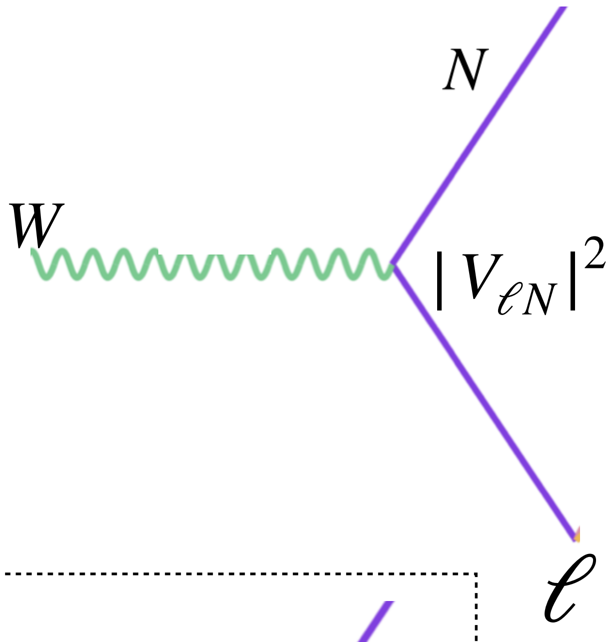
Flavor eigenstate can be expressed in terms of the mass eigenstate

$$\nu_\ell \simeq U_{\ell m}\nu_m + V_{\ell n}N_n$$

PMNS matrix

$M_D M_N^{-1}$

(1)



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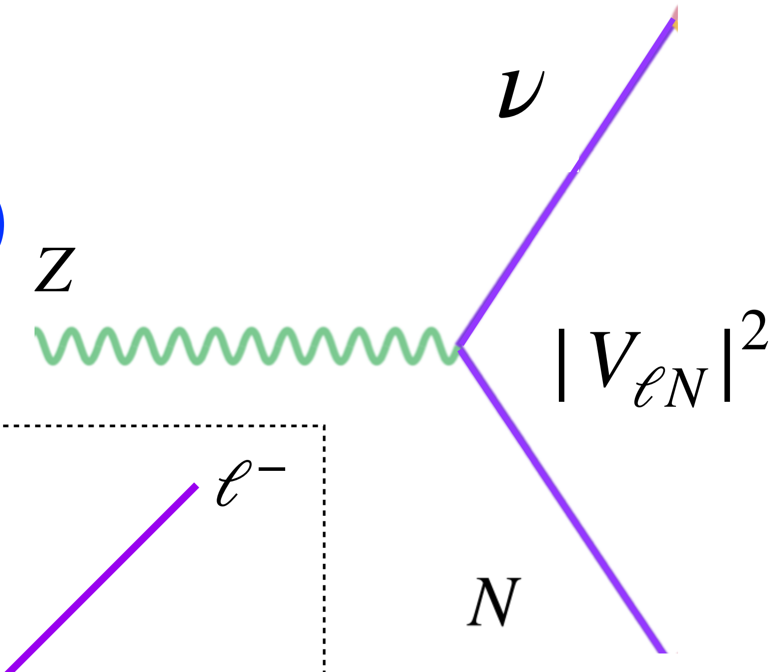
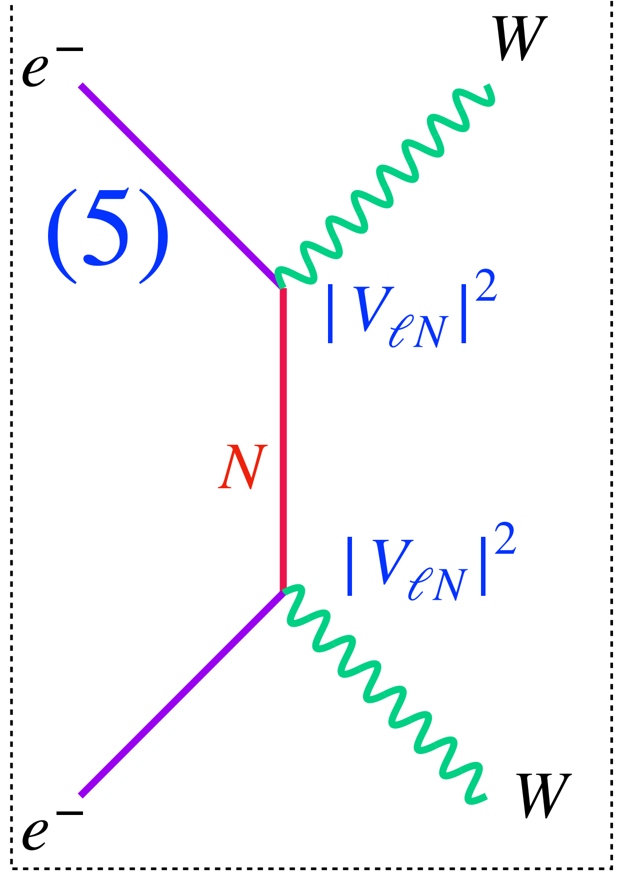
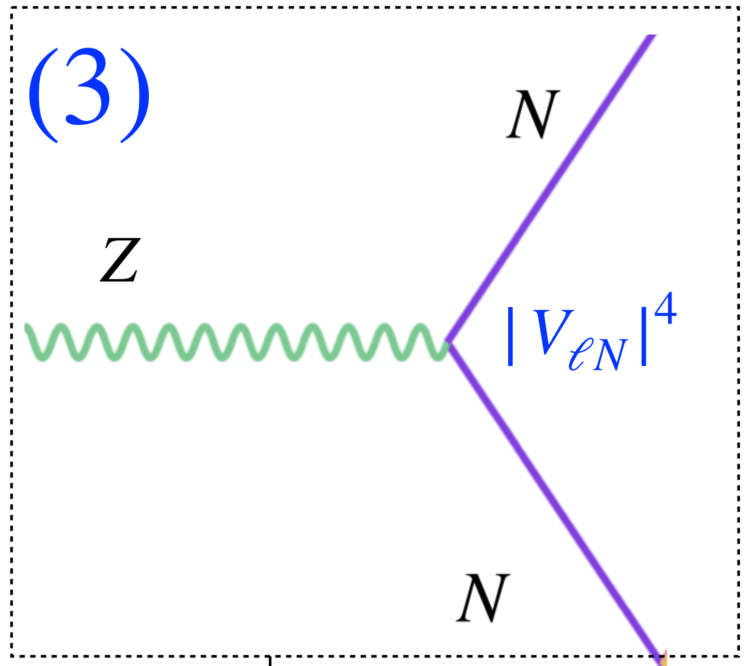


possible to produce
@lepton collider, however,
$|V_{eN}|^4$ suppressed

(5)

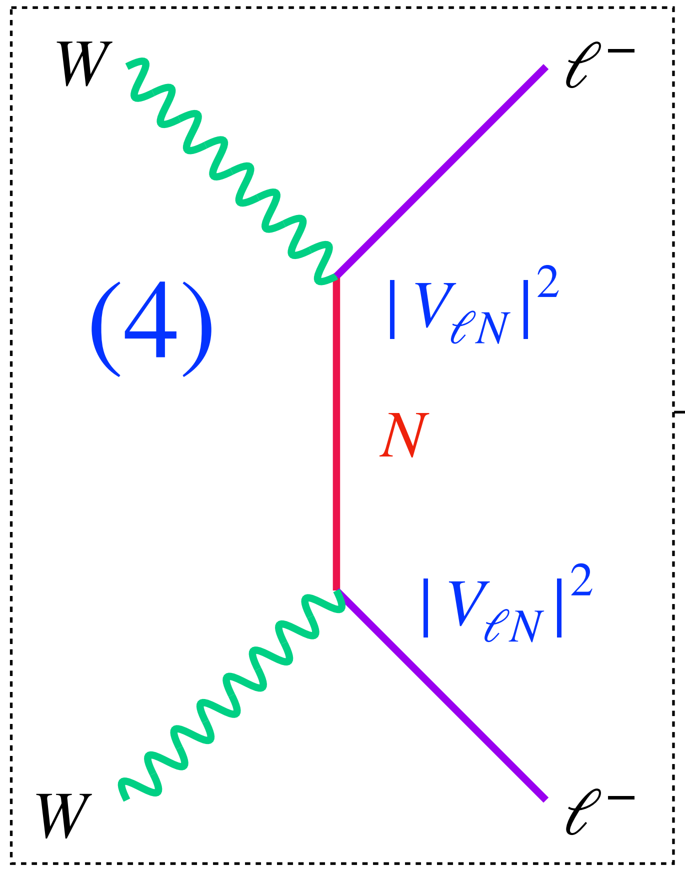


(3)



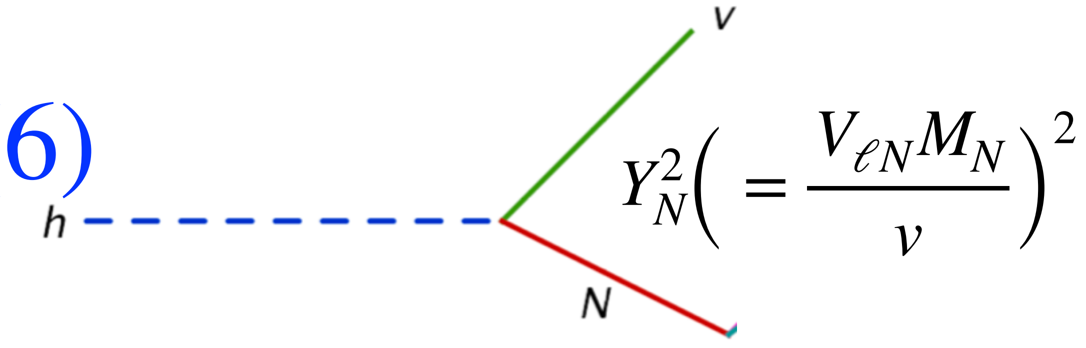
possible to produce
@LHC, however,
$|V_{\ell N}|^4$ suppressed

(4)

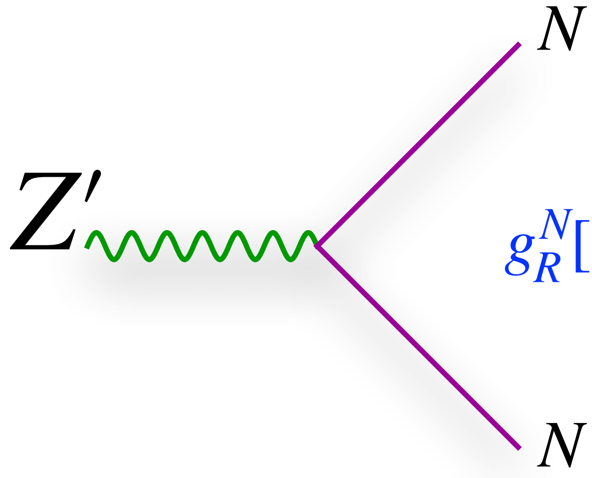


possible to produce
@LHC, however,
$|V_{\ell N}|^4$ suppressed

(6)



Direct interaction of the RHNs



$g_R^N[g_x, x_H] = \big(0\ x_H + (-1)\big) g_x$

We consider $x_\Phi = 1$

Properties of the model and phenomenology

New particles Z' boson Heavy Majorana Neutrino(RHN)

$U(1)_X$ Higgs boson

Phenomenology Z' boson production and decay

Z' boson mediated processes Heavy neutrino production

$U(1)_X$Higgs phenoemenology : Vacuum Stability

BSM scalar production, decay into RHN pair

Dark Matter Collider phenomenology

Dev, Pilaftsis; Iso, Okada, Orikasa
Orikasa, Okada, Yamada; Dev, Mohapatra, Zhang

Leptogenesis and many more

Z' boson production and heavy neutrino phenomenology

$\nu - \mathcal{N}$, $\nu -$ e, $\mathrm{e}^-\mathrm{e}^+$ scattering; proton, electron beam dump and dark photon search

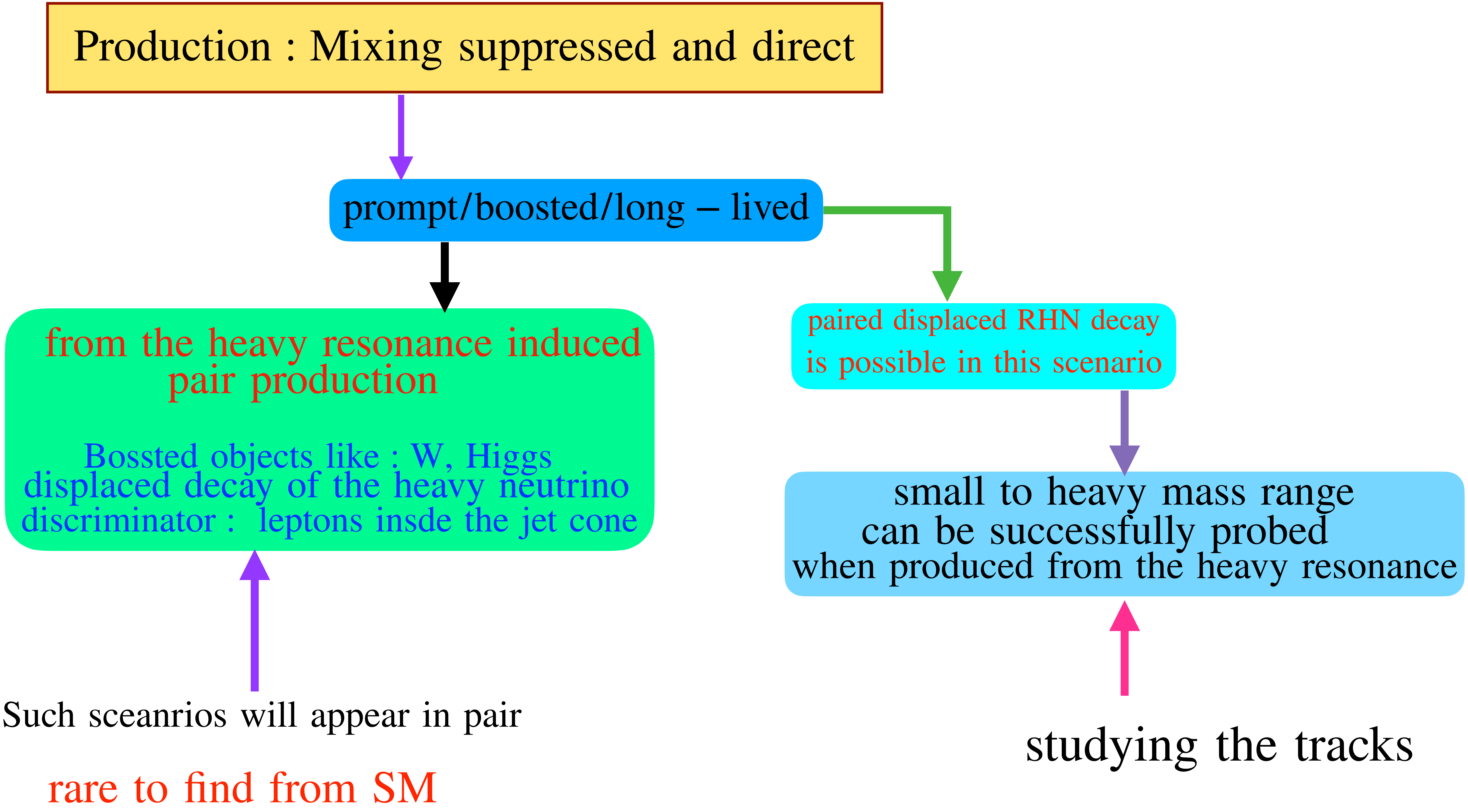
2307.09737

Fermionic pair production form the Z' : $\mathcal{A}_{\text{FB, LR, FB}-\text{LR}}$

Bhabha scattering

2104.10902

Heavy neutrino searches at different coliders



Production : Mixing suppressed and direct

prompt/boosted/long – lived

from the heavy resonance induced
pair production

Bossted objects like : W, Higgs
displaced decay of the heavy neutrino
discriminator : leptons insde the jet cone

Such sceanrios will appear in pair

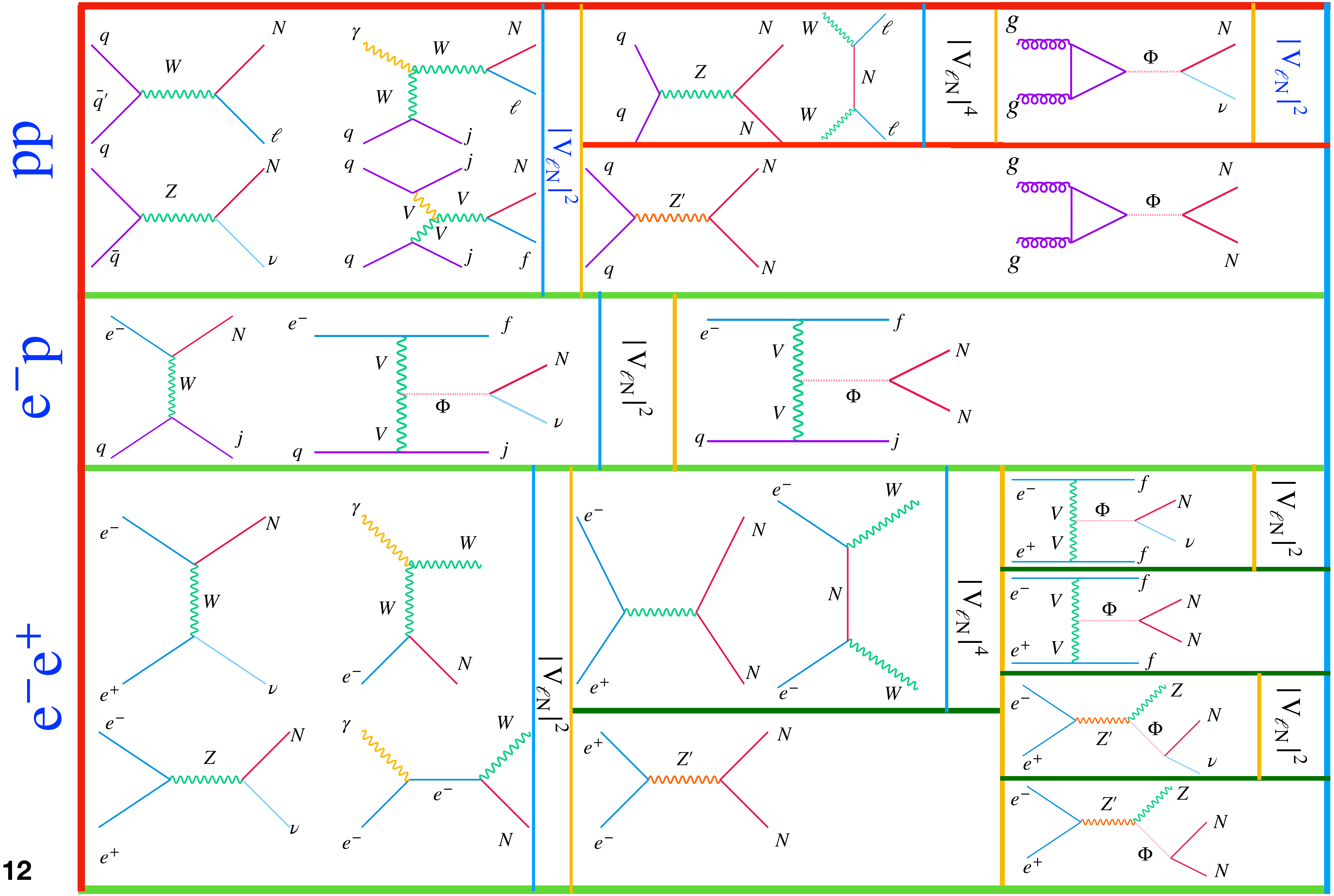
rare to find from SM

paired displaced RHN decay
is possible in this scenario

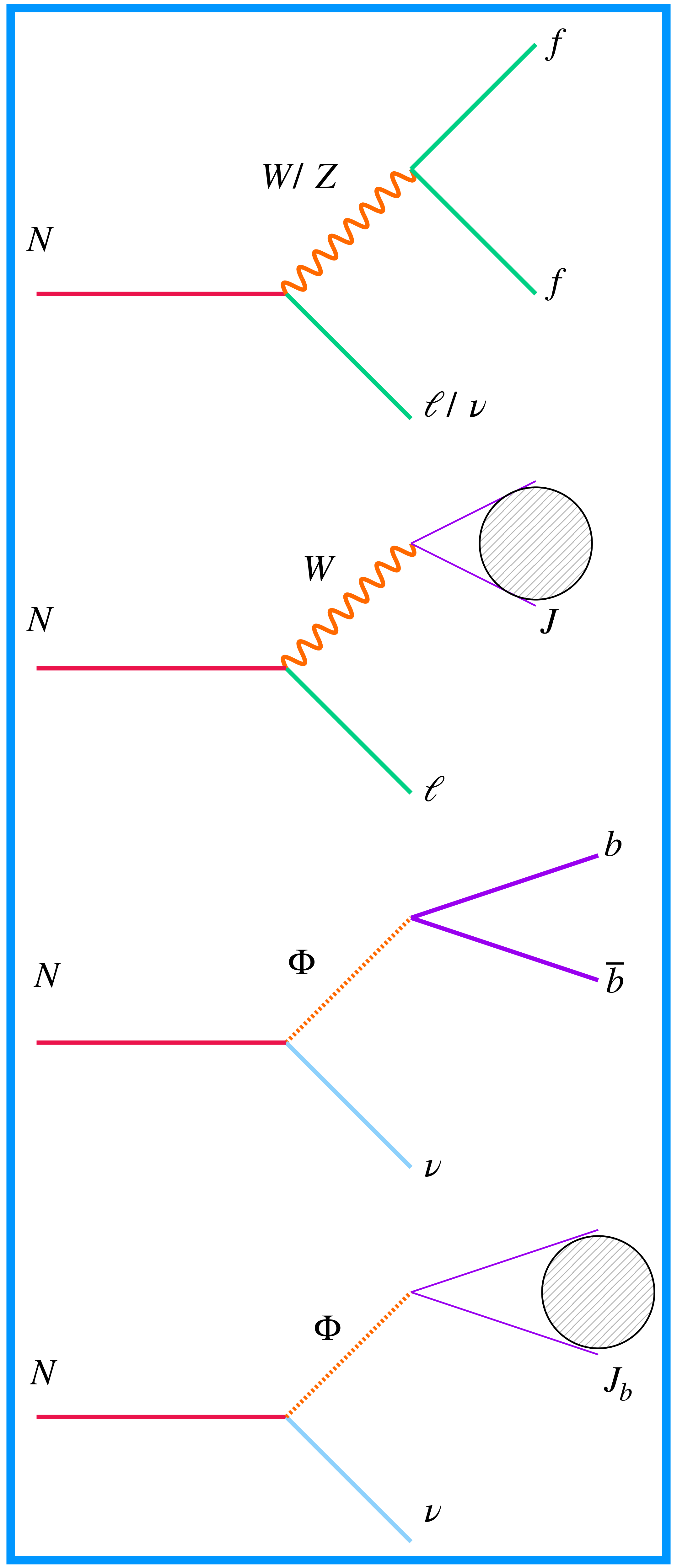
small to heavy mass range
can be successfully probed
when produced from the heavy resonance

studying the tracks

Production processes

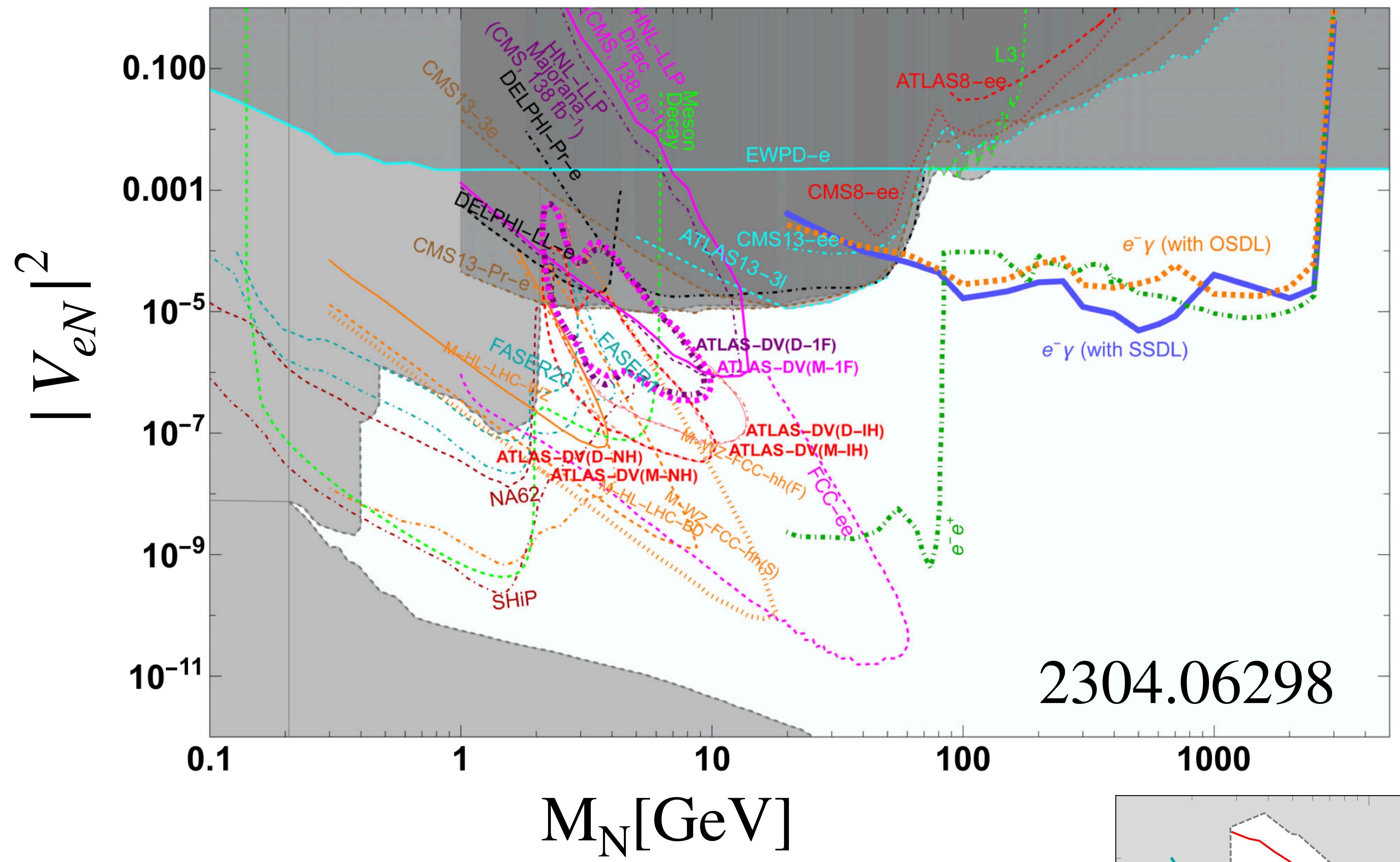


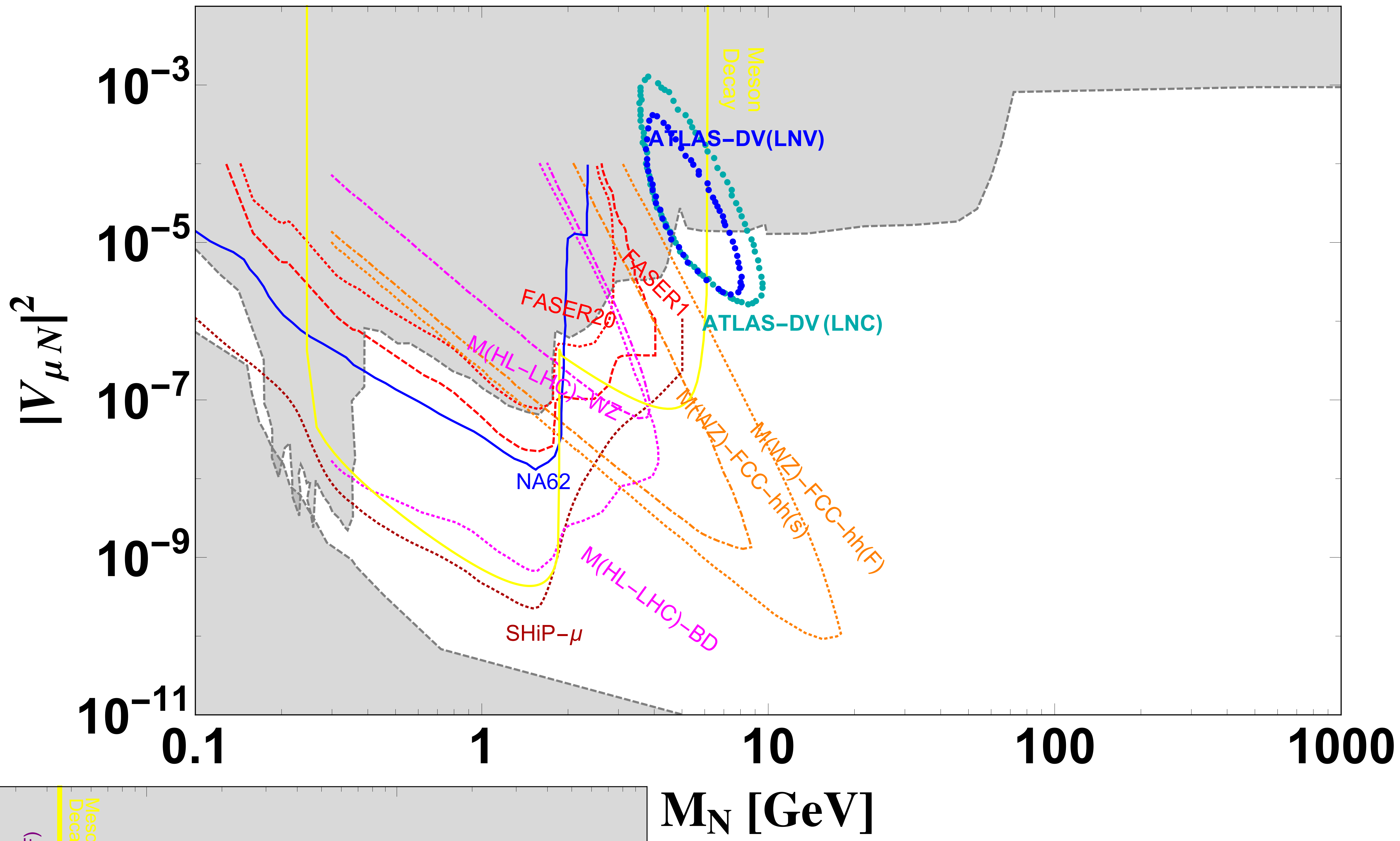
Decay

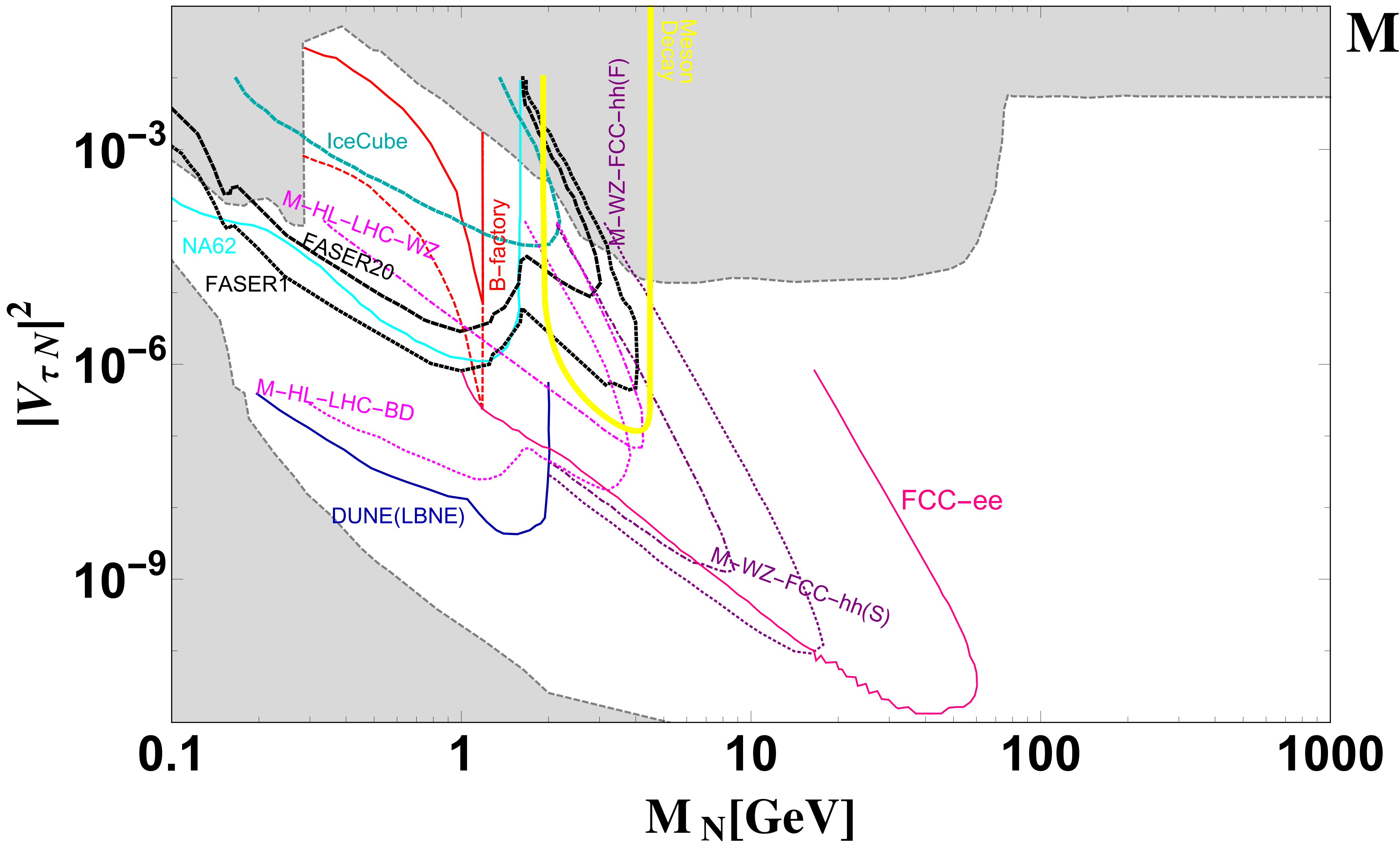


Existing and prospective bounds on the mixings

1502.06541 1805.00070 1908.09562

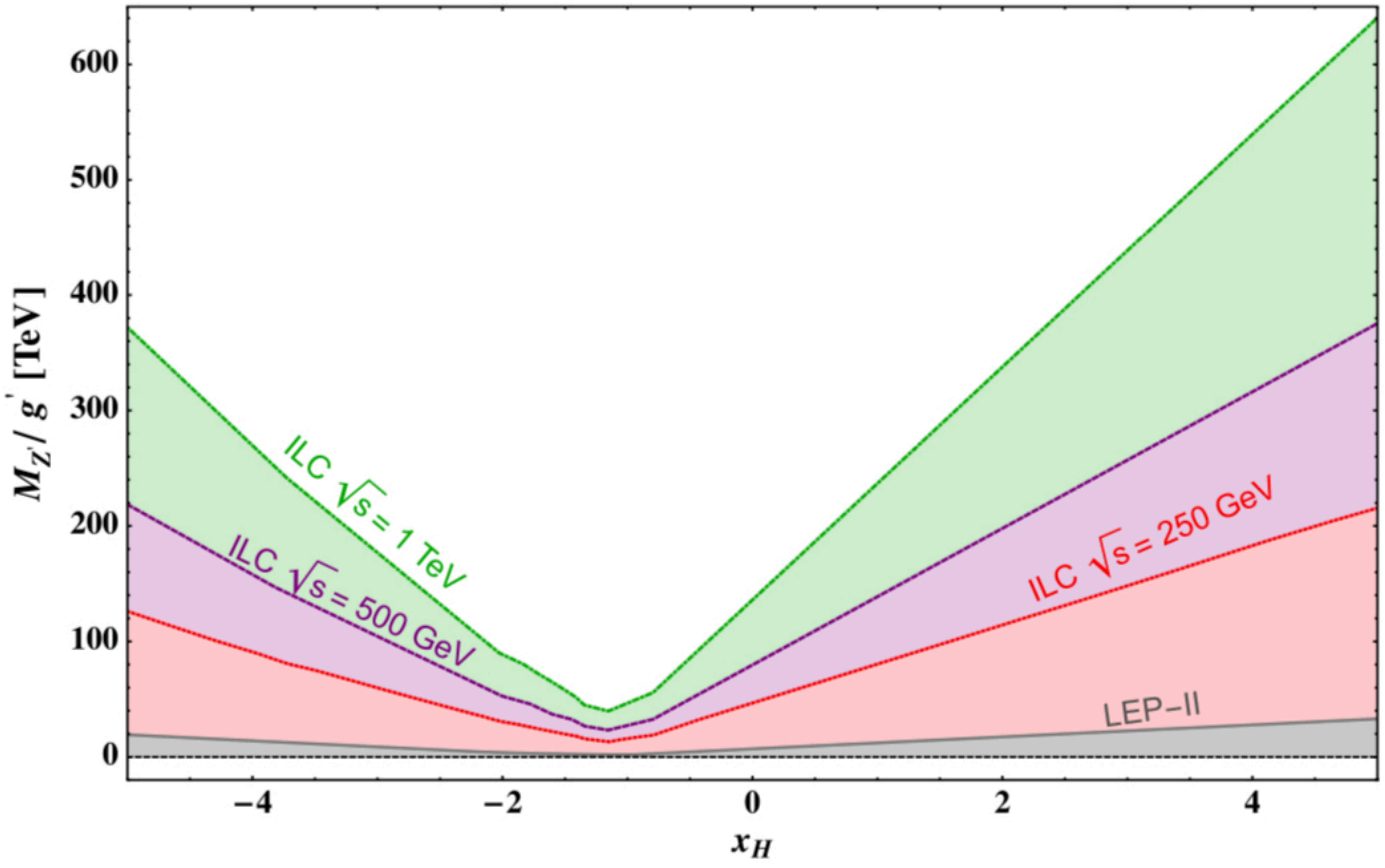






Limits on the model parameters

Considering the limit $M_{Z'} >> \sqrt{s}$ and appling effective theory we find the limits on $\frac{M_{Z'}}{g'}$ using LEP – II (1302.3415) and (prospective) ILC (1908.11299) :



$$\frac{\pm 4\pi}{(1+\delta_{ef})(\Lambda^{f\pm}_{AB})^2}(\bar{e}\gamma_\mu P_A e)(\bar{f}\gamma_\mu P_B f)$$

Z' exchange matrix element for our process

$$\frac{(g')^2}{{M_{Z'}}^2 - s}[\bar{e}\gamma_\mu(x_\ell{}' P_L + x_e{}' P_R)e][\bar{f}\gamma_\mu(x_{f_L} P_L + x_{f_R} P_R)f]$$

Matching the above equations we obtain

$$\boxed{M^2_{Z'} - s \geq \frac{g'^2}{4\pi}|x_{e_A} x_{f_B}|(\Lambda^{f\pm}_{AB})^2}$$

Indicates a large VEV scale can be probed from LEP – II to ILC1000 via ILC250 and ILC500

Shows limits on $M_{Z'}$ vs g' for LEP – II, ILC250, ILC500 and ILC1000

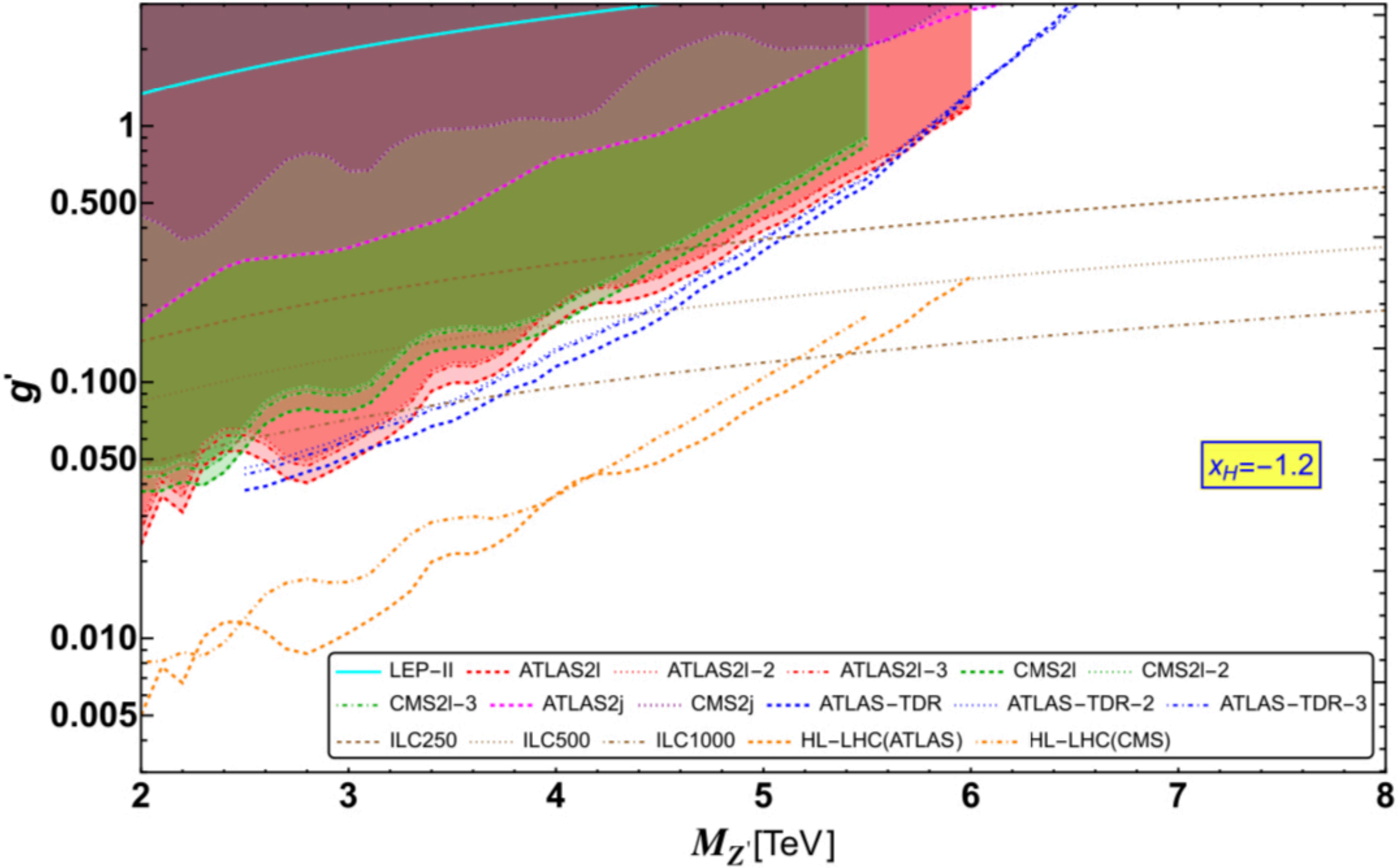
Limits on $M_{Z'}$ and g' can also be obtained from dilepton and dijet searches at the LHC

$$\boxed{g' = \sqrt{g^2_{\text{Model}}\left(\frac{\sigma^{\text{Obs.}}_{\text{ATLAS}}}{\sigma_{\text{Model}}}\right)}}$$

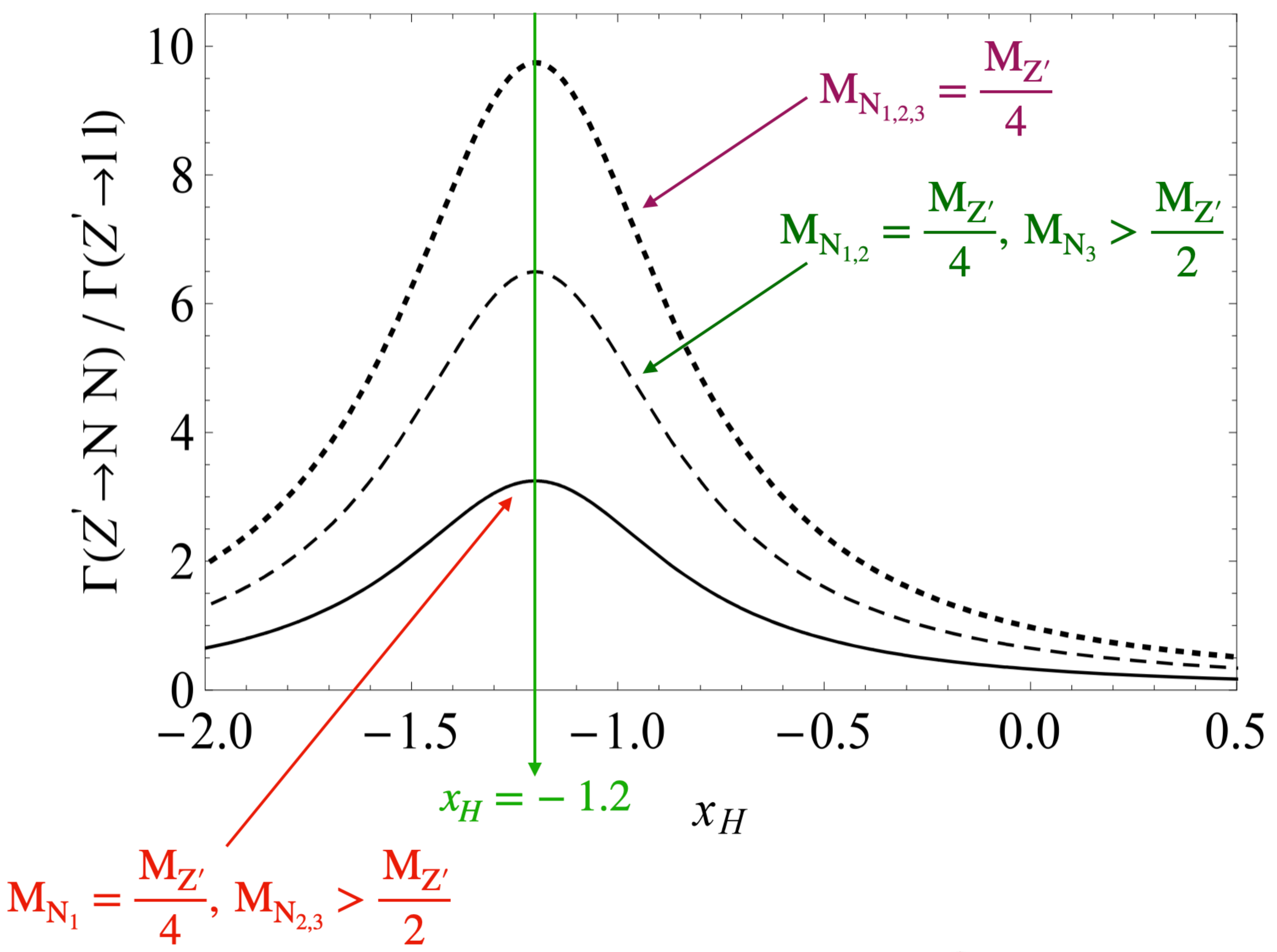
Limits on $U(1)_X$ coupling as a function of $M_{Z'}$

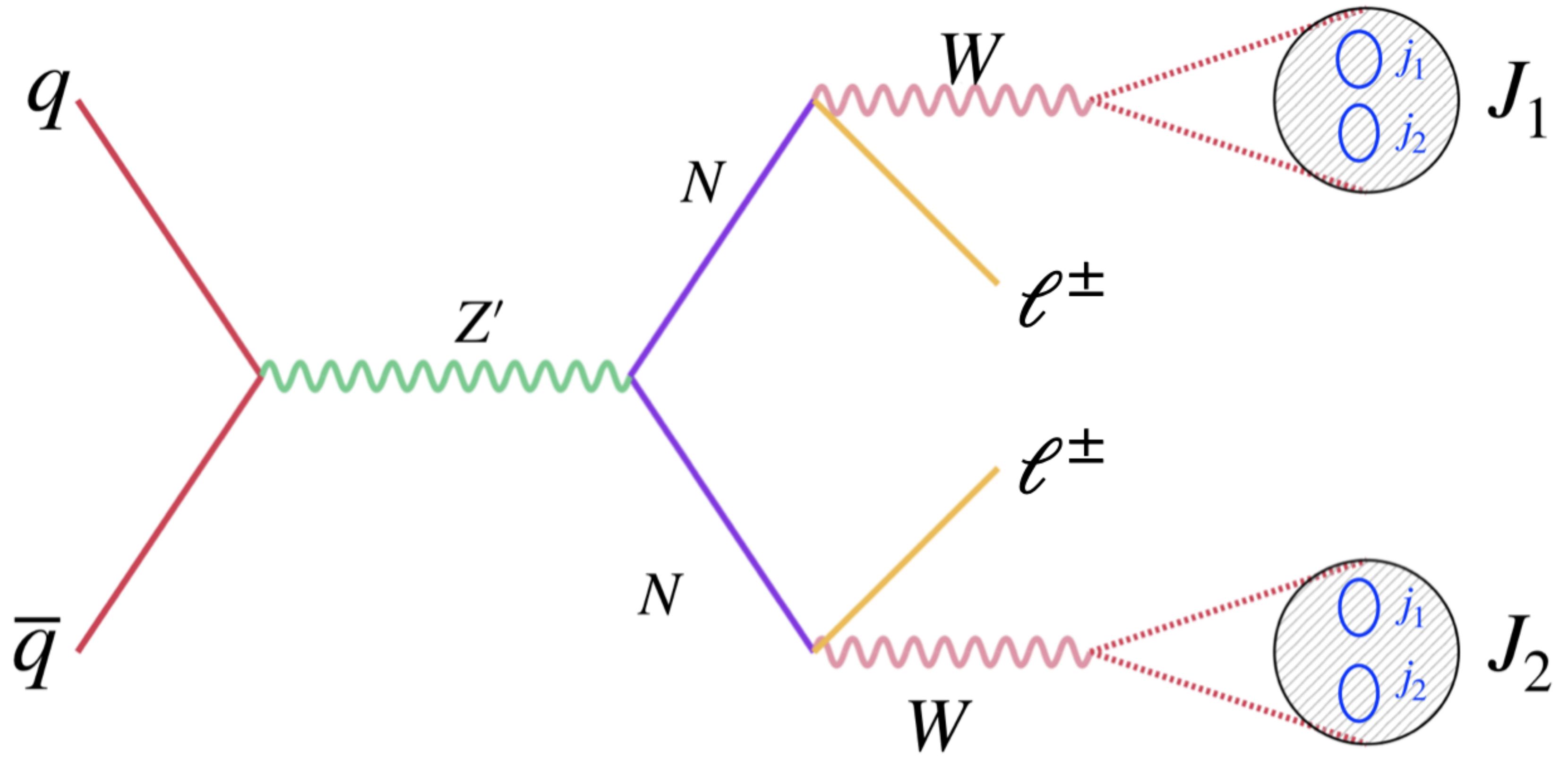
2202.13358

Comparing LHC(2ℓ, 2j from CMS, ATLAS), LEP – II data and prospective ILC bounds



Pair production of RHN from Z'



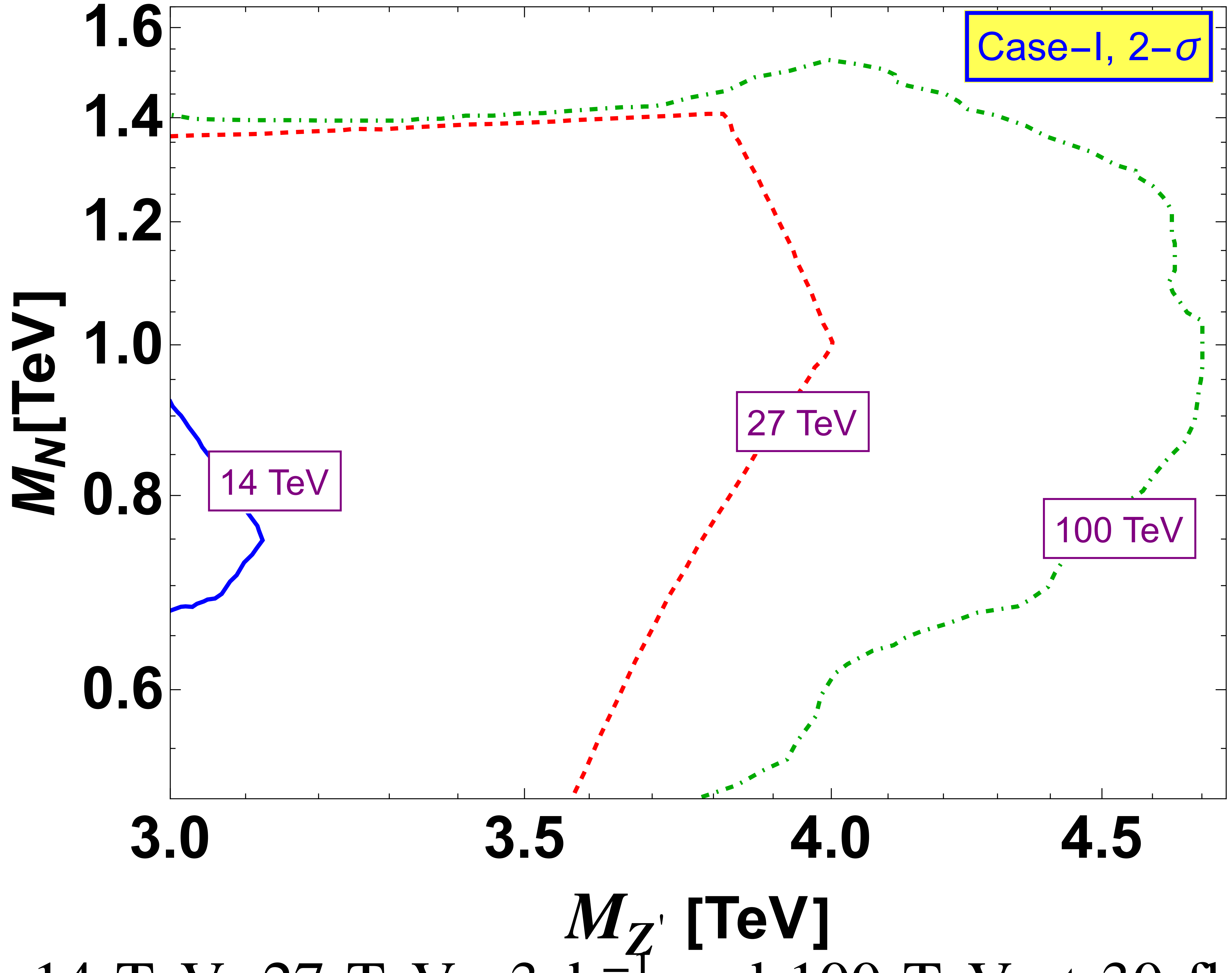


Cuts : $p_T^J > 100$ GeV, $p_T^{\ell_1,\ell_2} > 100$ GeV,

jet − mass window 15 GeV, b − veto

Backgorunds :

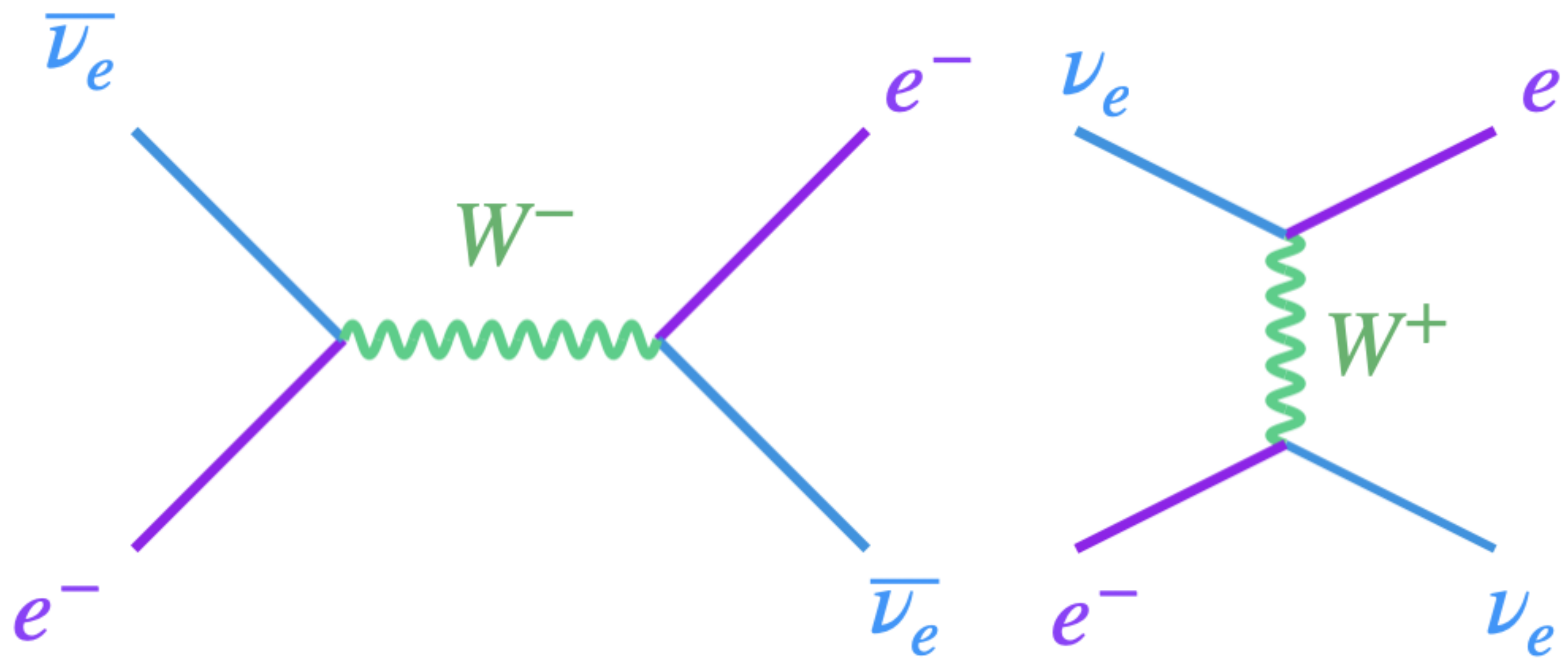
$W^\pm W^\pm jj,\ W^\pm Z jj,\ W^\pm W^\mp Z j,\ t\bar{t}W^\pm,\ t\bar{t}z$



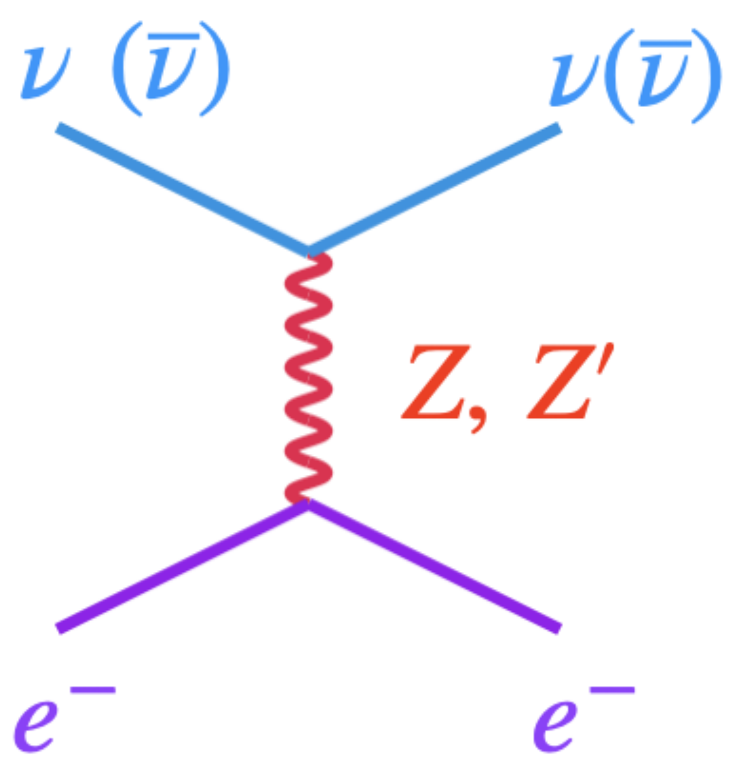
14 TeV, 27 TeV : 3ab^{-1} and 100 TeV at 30 fb^{-1}

Neutrino electron scattering

2111.08767



(1)



(2)

The interactions between charged leptons and Z′

	ℓ_{L_i}	e_{R_i}	N_{R_α}	H	Φ
SU(2)$_\text{L}$	**2**	**1**	**1**	**2**	**1**
U(1)$_\text{Y}$	$-1/2$	-1	0	$1/2$	0
U(1)$_X$	$-\frac{1}{2}x_H - x_\Phi$	$-x_H - x_\Phi$	$-x_\Phi$	$\frac{1}{2}x_H$	$2x_\Phi$

$$-\mathcal{L}_{\text{int}}^{\ell} = g_X(\overline{\ell_L}Q_X^{\ell}\gamma^\mu Z'_\mu \ell_L + \overline{\ell_R}Q_X^{e_R}\gamma^\mu Z'_\mu \ell_R)$$

SM : The interactions of the leptons with Z and W bosons

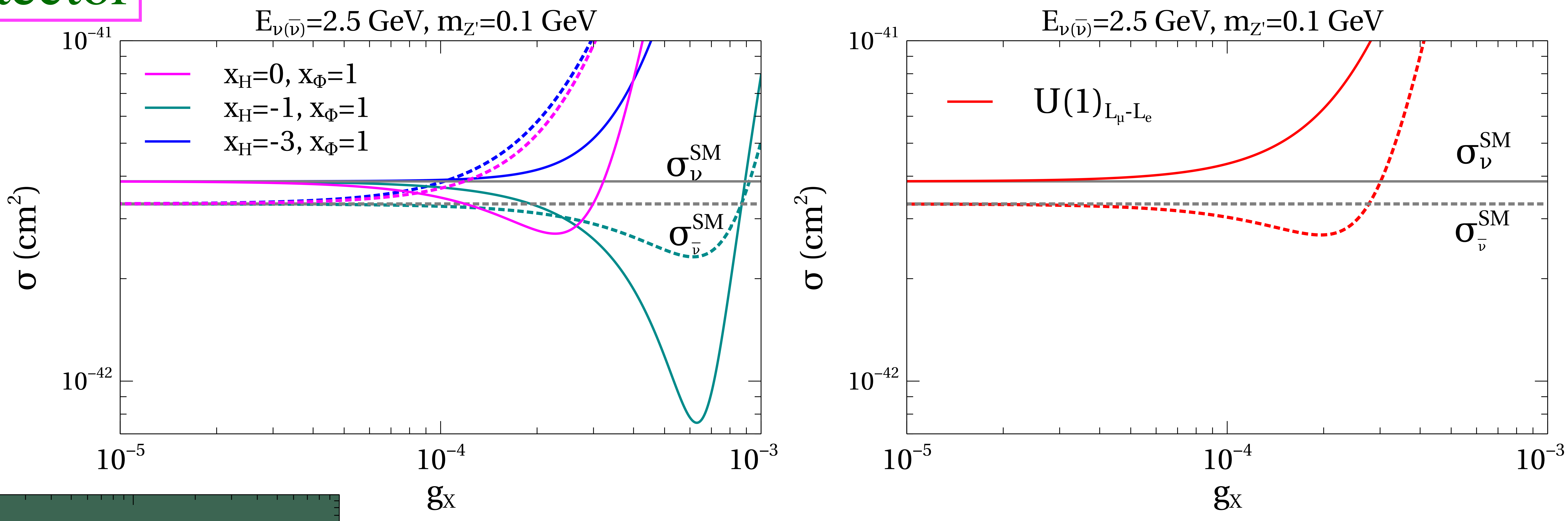
Scattering Process	a_1	a_2
$\nu_e e \to \nu_e e$	$\sin^2\theta_w + 1/2$	$\sin^2\theta_w$
$\bar{\nu}_e e \to \bar{\nu}_e e$	$\sin^2\theta_w$	$\sin^2\theta_w + 1/2$
$\nu_\beta e \to \nu_\beta e$	$\sin^2\theta_w - 1/2$	$\sin^2\theta_w$
$\bar{\nu}_\beta e \to \bar{\nu}_\beta e$	$\sin^2\theta_w$	$\sin^2\theta_w - 1/2$

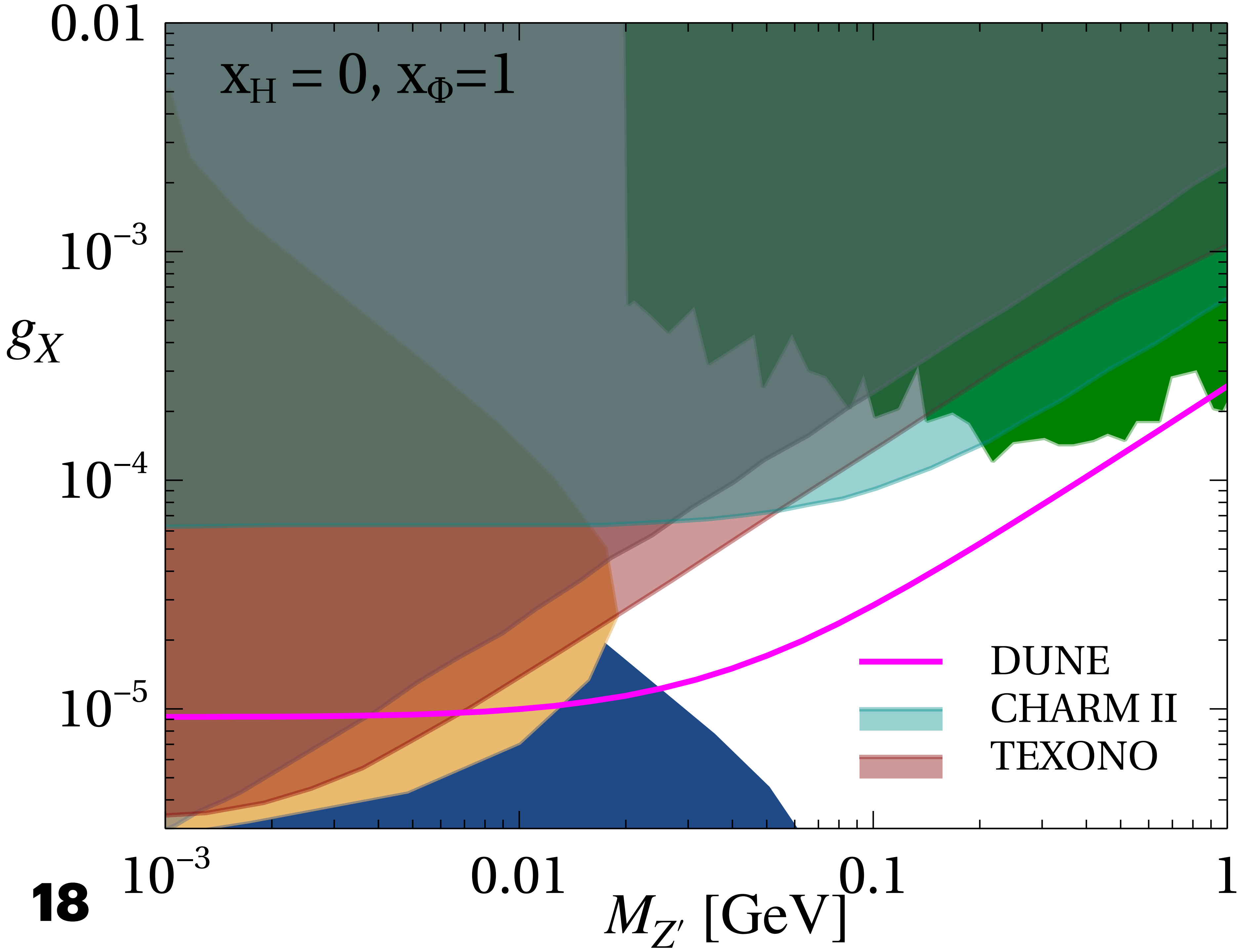
$$\frac{d\sigma(\nu e)}{dT} = \left.\frac{d\sigma(\nu e)}{dT}\right|_{\text{SM}} + \left.\frac{d\sigma(\nu e)}{dT}\right|_{\text{Z}'} + \left.\frac{d\sigma(\nu e)}{dT}\right|_{\text{int}}$$

$$c_1 = -1/2 + 2\sin^2\theta_W,\ c_2 = -1/2$$

T : KE of out going electron

DUNE near detector





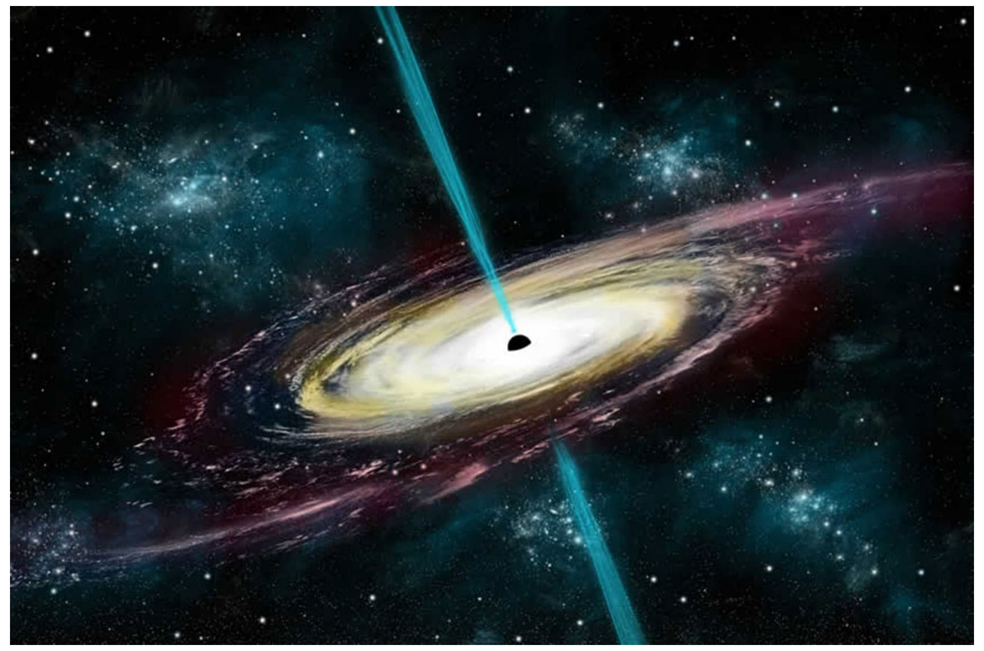
Total cross section of $\overset{(-)}{\nu_\mu} - e$ scattering for SM and U(1).

ν_μ : Solid, $\overline{\nu_\mu}$: Dashed

2111.08767 (DUNE), 2206.12676 (Beam dump)

Interesting propspects of neutrinos

with ShivaSankar et. al.
(will appear soon)



Neutrinos can be orginiated from the astrophysical sources

Galactic/ Extragalactic sources

Active galactic nuclei : A compact region at the center of the galaxy with high luminosity

Most luminous source of EM radiation. It has beeen observed in radiowaves and X – rays.

Gamma ray burst : Sudden intense flashes of the gamma rays

Highly energetic   Nature is unknown $(\nu\bar{\nu} \rightarrow e^{-}e^{+})$

Are the neutrinos emitted by these *distant* sources?   If emitted then how to study?

To study distant objects we need a telescope.

Basically we built it at the south pole of the earth and put it 1 km under the ground(ice) : IceCube detector.

Neutrios came the distant sources scattered with the electrons in the ice producing Cherenkov light.

In 2013, they detected few PeV neutrinos. In 2018, they observed energetic neutrinos.

In course of time they have measured high energy cosmic neutrinos between 100 TeV to 10 PeV from extra galactic sources and cosmic ray muons.

Neutrinos are charge neutral : no bending under the electromagnetic field.

So the neutrinos do not scatter and can be directly ➡ pointed back to the source.

Further interesting open aspects for the BSM physics

(1) What is the origin of Dark matter : Cobe, WPMAP, Planck : Relic : $\Omega h^2 \sim 0.12$

Possible solution : Standard Model singlet fermion(Dirac/Majorana), scalars being protected by some symmetryies.

Non baryonic, electric charge neutral, stable $\tau_{DM} > t_U$ Future experiment like LUX

(2) Matter Antimatter asymmetry : anti baryon number density $<<$ baryon number density

Fukugita, Yanagida Leptogenesis

Inclusion of the RHN can explain such scenario through leptogenesis.

RHN decay (out of equilibrium) in the early universe generates lepton asymmetry.

Sphaleron process lepton asymmetry → baryon asymmetry.

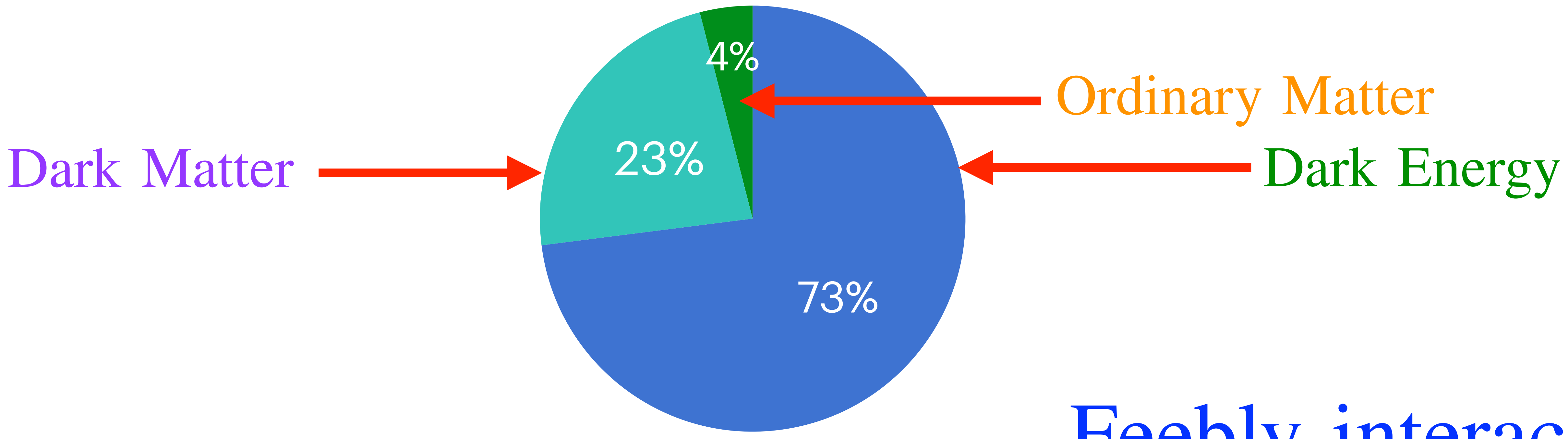
(3) Cosmological Inflation : Origin of primordial density fluctuations : scalar field as inflaton.

(4) Strong CP : SM gauge symmetry allows to add a CP violating term (θ) in $G^{\mu\nu}G_{\mu\nu}$

Strongly constrained from neutron EDM : Natural origin of smallness

Inclusion of the axion may solve this issue. Axion can be a DM candidate.

Dark matter and neutrinos



Weekly interacting

Such models can successfully fit a potential Dark matter candidate ($N_{1/3}$) adding discrete symmetry Z_2

Depending upon the model parameters

Relic

Direct search

Z' portal, Higgs portal

Mono – jet, mono – photon

LHC ILC

Feebly interacting

DM abundance is obtained by the annihilation and decay of the SM particles

DM yield increases with the increase in coupling

UV Freeze – in : DM produced by the SM particles mediated by portal

IR Freeze – in : DM interacts with visible sector via a renormalizable operator production dominates at low T

Z' mediated processes

RHN DM

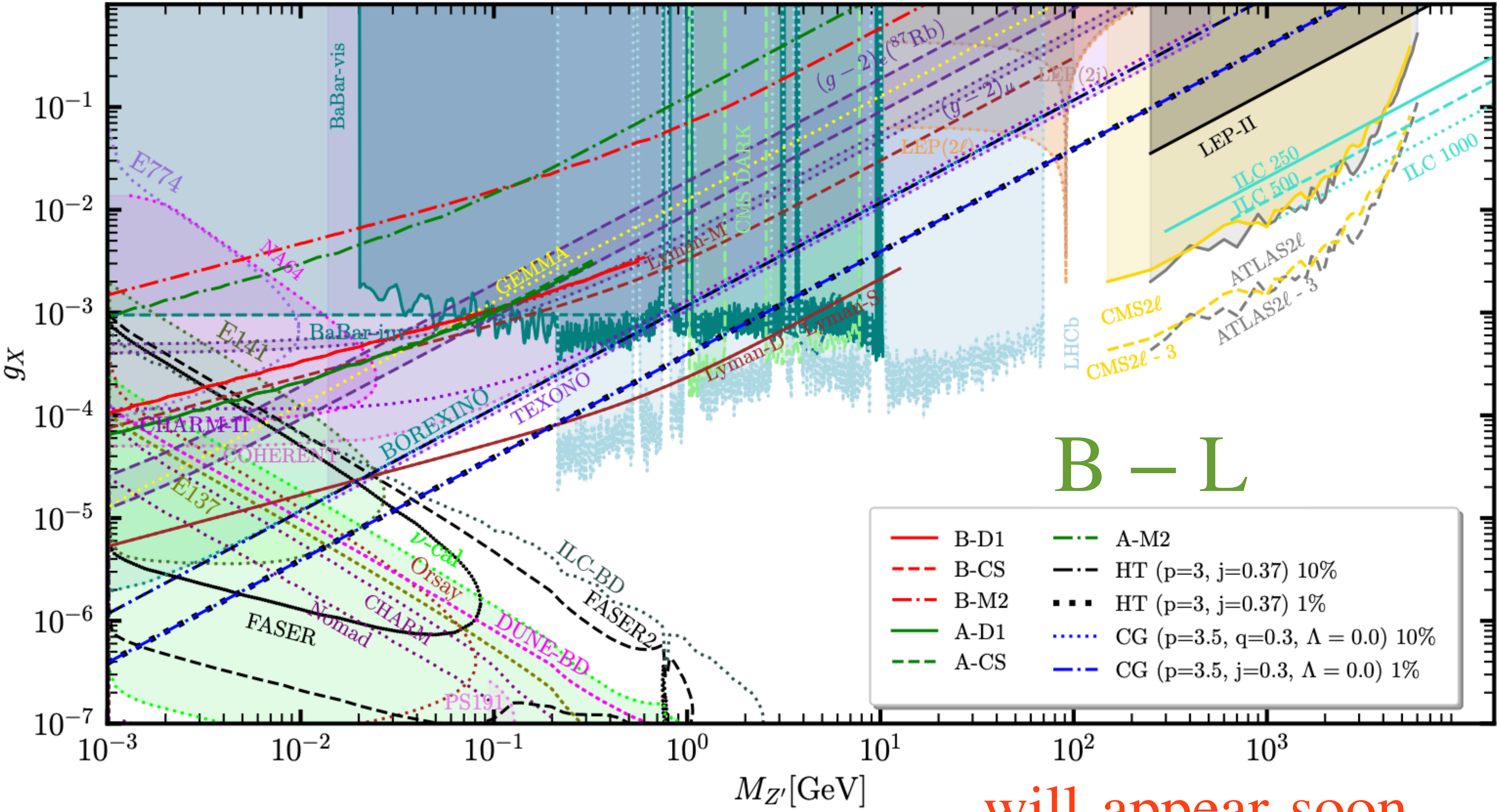
SM fermions annihilate into RHN DM through Z'

RHN DM in MeV scale
Z' in TeV scale

Pair produced from Z'

RHN DM decays into positrons to explain

511 keV INTEGRAL anomaly



B – L

will appear soon

Conclusions

We are looking for a scenario where which can explain a variety of beyond the SM sceanrios .

The proposal for the generation of the tiny neutrino mass, from the seesaw mechanism, under investigation at the energy frontier .

Mnay aspects can be addressed in these scenarios which could connect three interesting frontiers of physics

The motivations of these works is to find a new particle, a new force carrier as a part of the of the new physics search including various BSM aspects .