neutrino oscillations and the prospects for new physics

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February, 2024

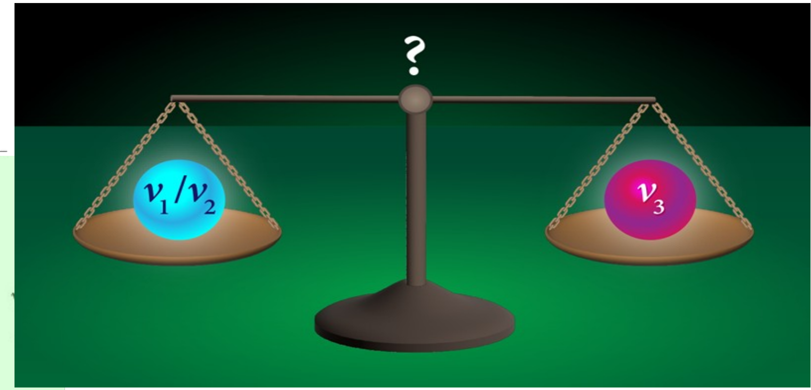
ASTROPARTICLES
Astroparticles and High Energy Physics Group

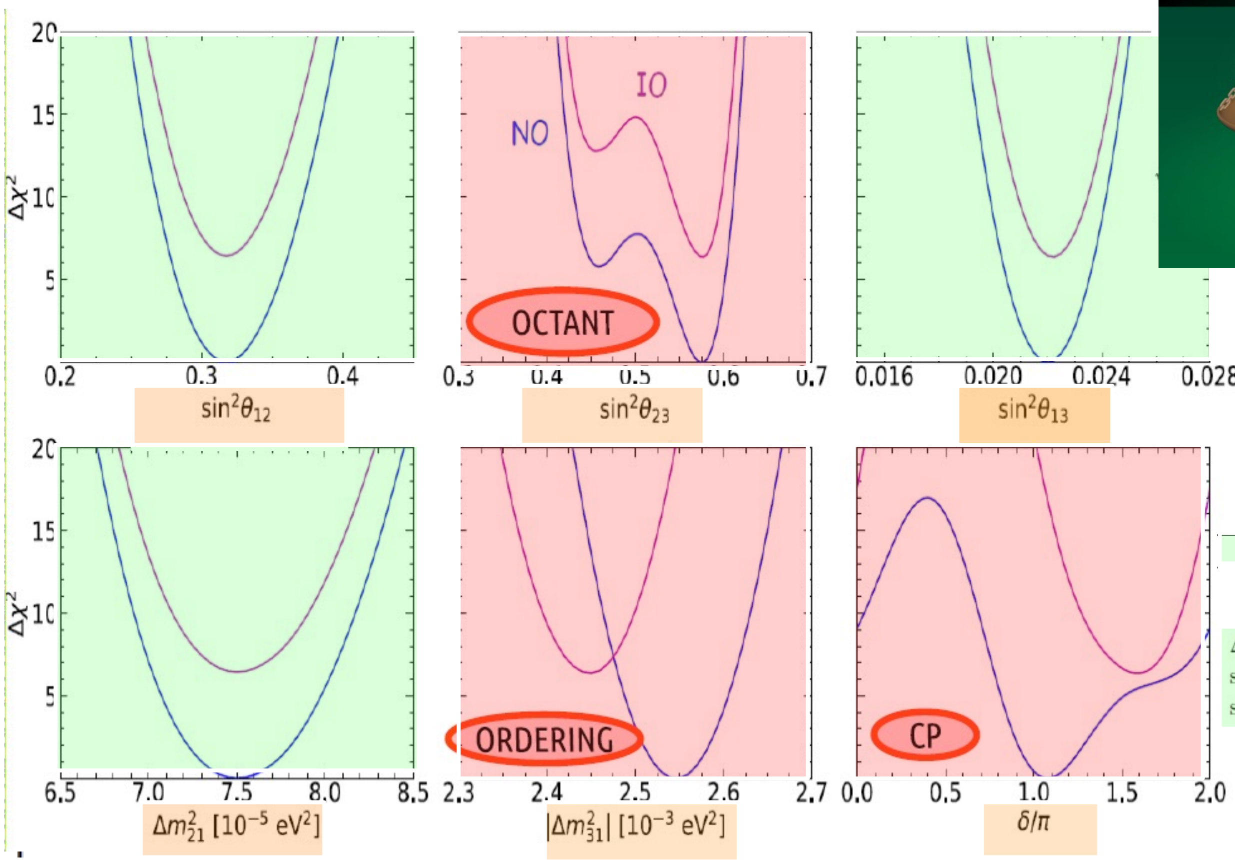
IFIC Institut de Física Corpuscular
Vniversitat de València
CSIC Consejo Superior de Investigaciones Científicas
Gobierno de España
Ministerio de Ciencia e Innovación
Generalitat Valenciana
Conselleria de Educación, Universidades y Empleo

3-neutrino oscillation status

PF de Salas et al JHEP02(2021)071

https://zenodo.org/record 4593330#.YFoBVWNKjIo





	PDG2020	Relative Uncertainty (1σ)
Δm^2_{21}	$(7.53\pm0.18)\times10^{-5}$ eV^2	2.4%
$\sin^2\theta_{12}$	0.307 ± 0.013	4.2%
$\sin^2\theta_{13}$	0.0218 ± 0.0007	3.2%

$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$ (2.8% precision)

Lisi's talk

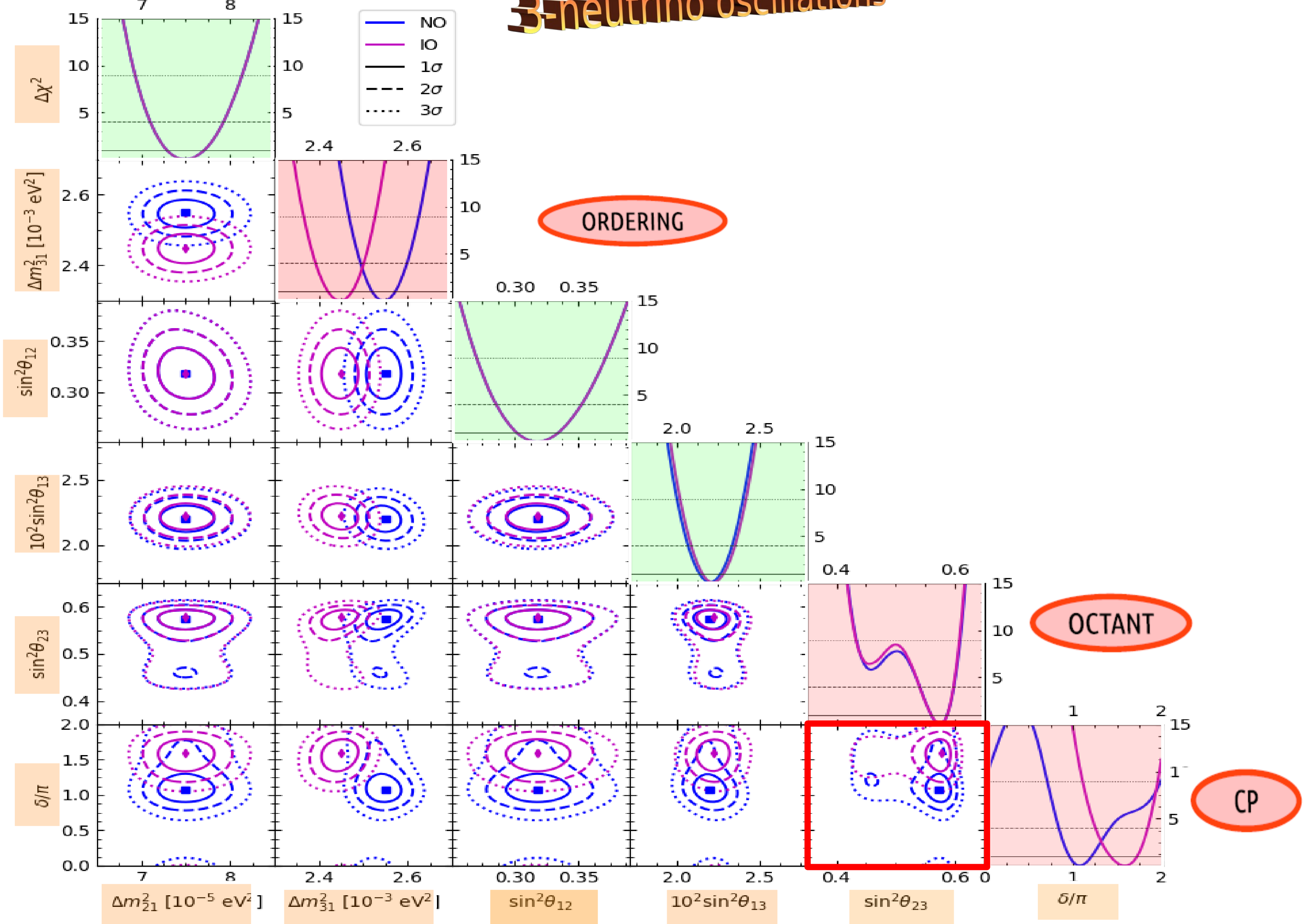
@jwvalle2

3-neutrino oscillations

PF de Salas et al JHEP02(2021)071

https://globalfit.astroparticles.es/

https://zenodo.org/record 4593330#.YFoBVWNKjIo



Agreement with NuFit and Bari groups

@jwvalle3

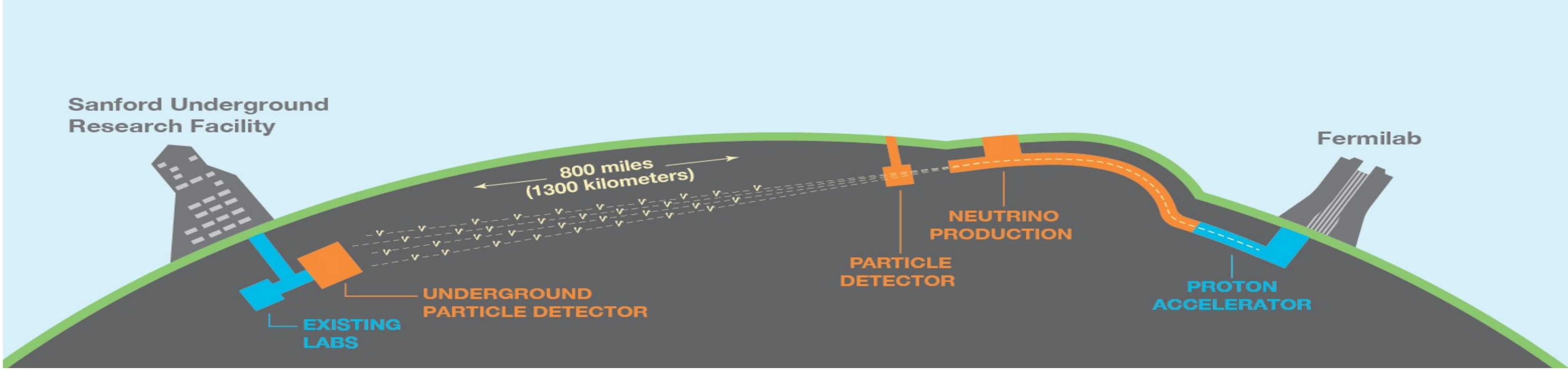
CPV

CPV review, e.g. Nunokawa, Parke, Valle Prog.Part.Nucl.Phys. 60 (2008) 338

PhysRevLett117(2016)061804
New J.Phys. 19 (2017) 9, 093005
PhysRevD97 (2018) 095026

DUNE 2008.12769
Hyper-K
ESSnuSB

Expected CP discovery Sensitivity: standard 3-nu vs Unitarity violation



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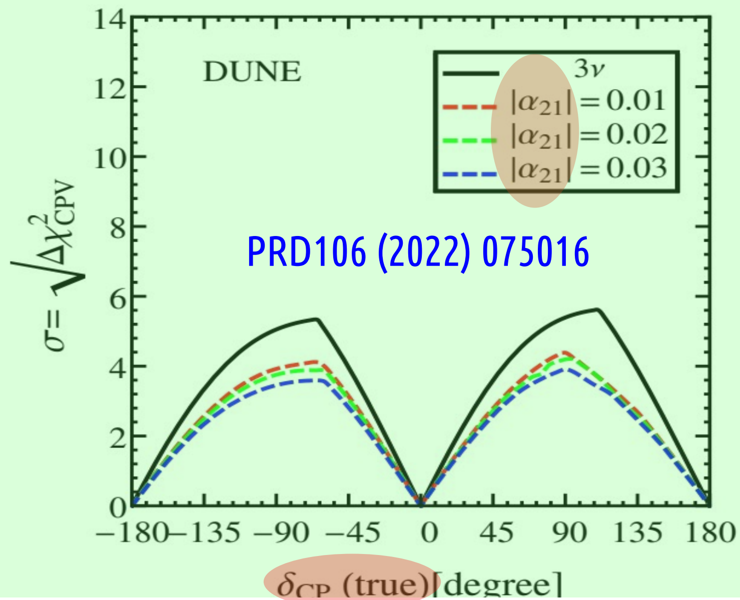

PRD106 (2022) 075016

PhysRevLett117(2016)061804

New J.Phys. 19 (2017) 9, 093005

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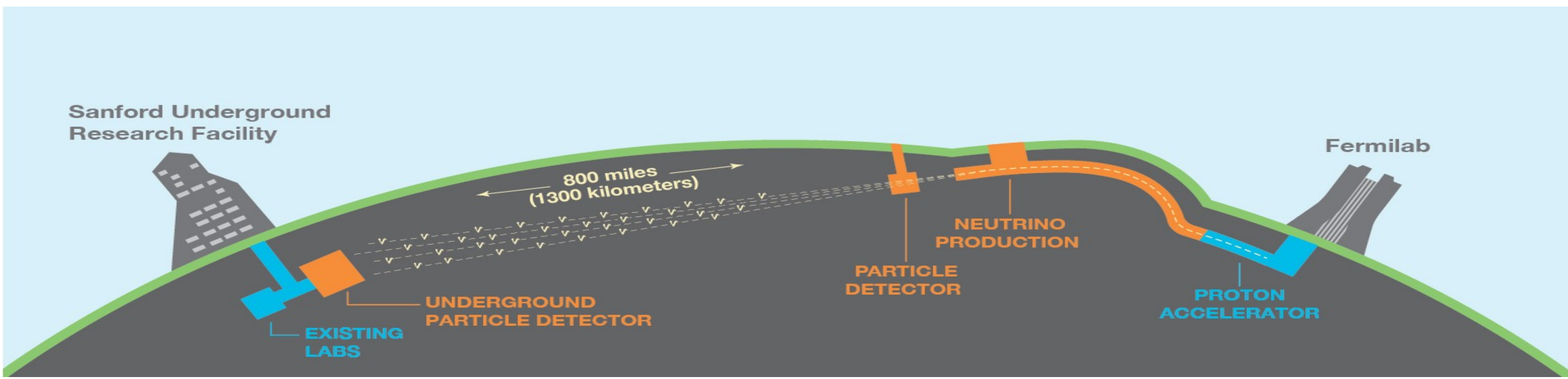

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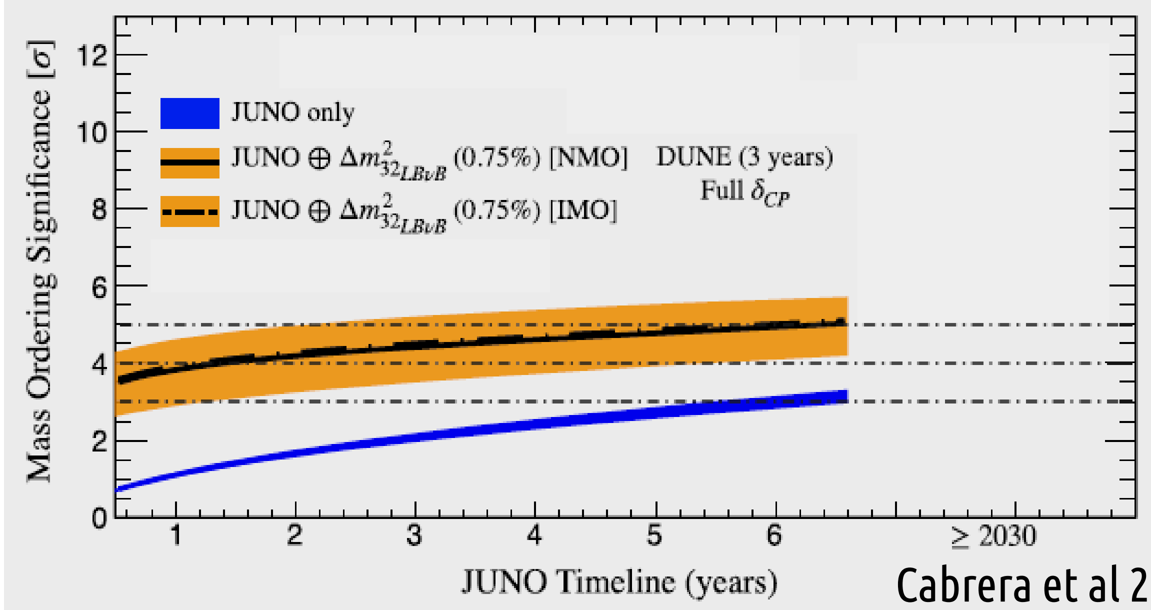
mass ordering

Synergy of **JUNO** with

long-baseline neutrino beams

NovA and **T2K**

DUNE and **Hyper-K**



Cabrera et al 2008.11280

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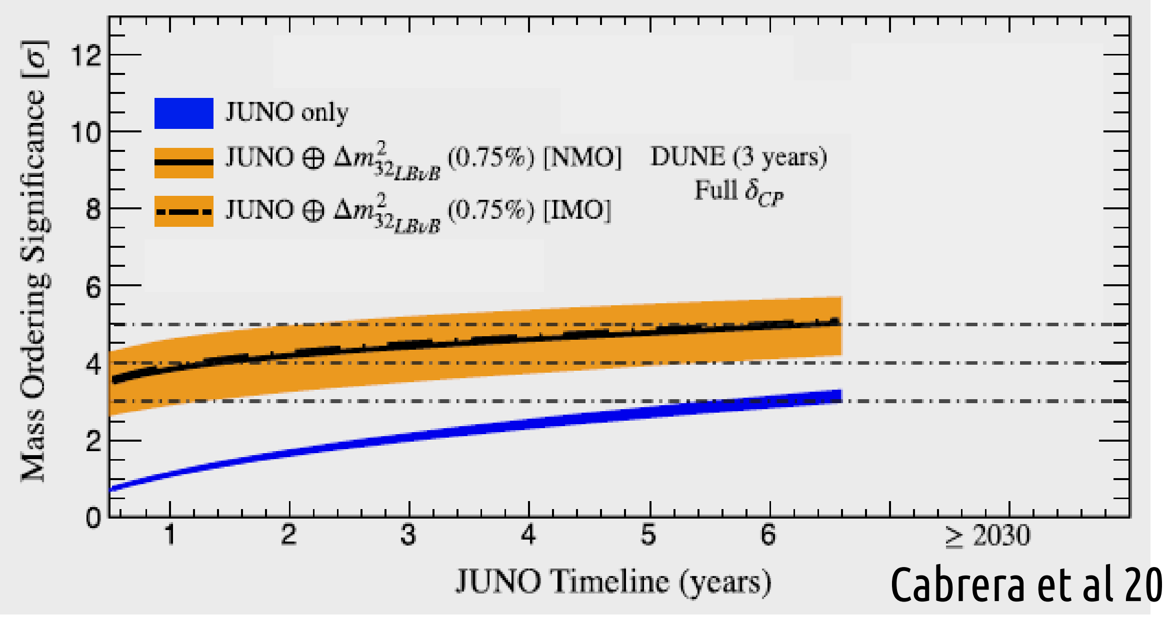
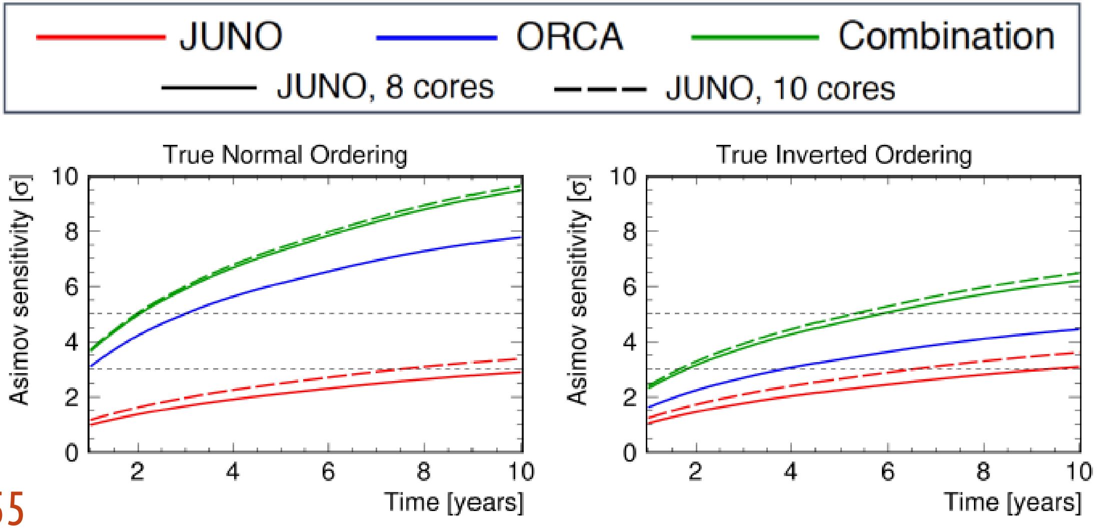


Cabrera et al 2008.11280

Synergy with neutrino telescopes

KM3NET/ORCA



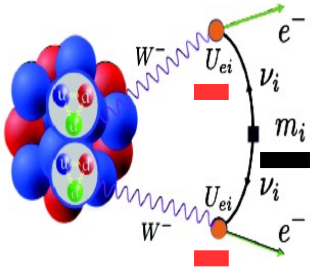
S. Aiello et al JHEP03(2022)055

Figure 7. NMO sensitivity as a function of time for only JUNO (red), only ORCA (blue), and the combination of JUNO and ORCA (green), considering 2 (solid) or 4 (dashed) Taishan NPP reactors, corresponding respectively to 8 or 10 reactor cores at 53 km from JUNO.

@jwvalle5

neutrinoless doublebeta decay

$$\left|\sum_j U_{ej}^2 m_j\right| = |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{2i\phi_{12}} + s_{13}^2 m_3 e^{2i\phi_{13}}|$$



Original symmetrical parametrization

Schechter & JV PRD22 (1980) 2227

Rodejohann, JV Phys.Rev. D84 (2011) 073011

Versus PDG phase convention

KamLAND-Zen 2203.02139 GERDA 2009.06079

C Adams et al 2212.11099

Agostini et al. Science 365 (2019) 1445

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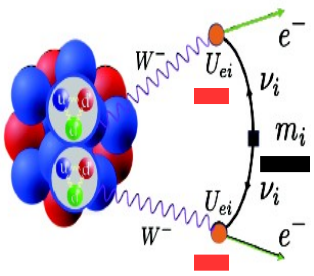

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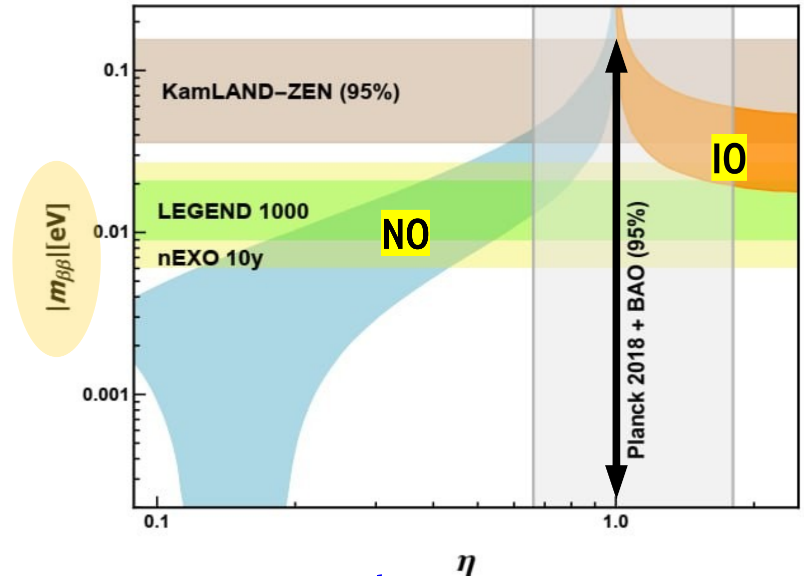
Nearly degenerate



Lattanzi et al JHEP 10 (2020) 213

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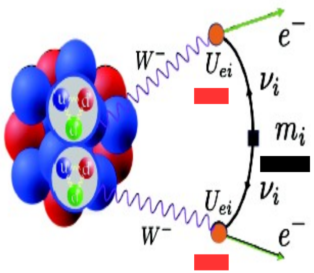

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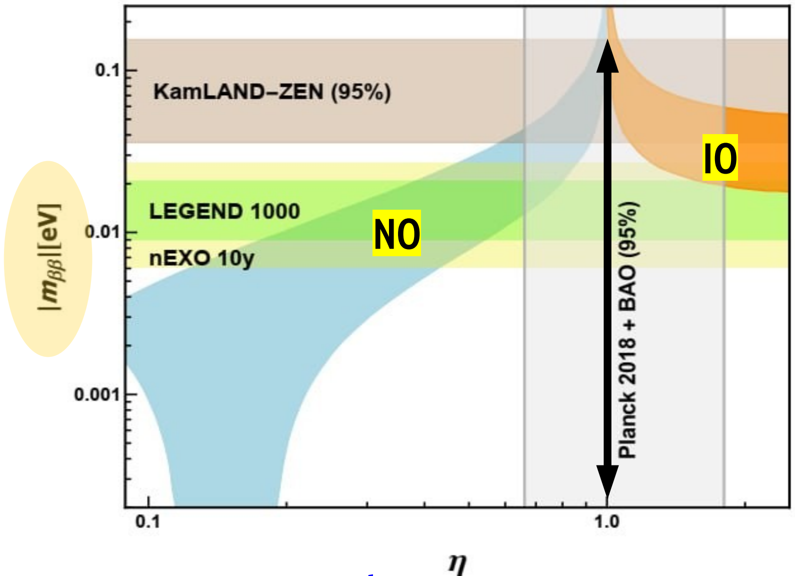
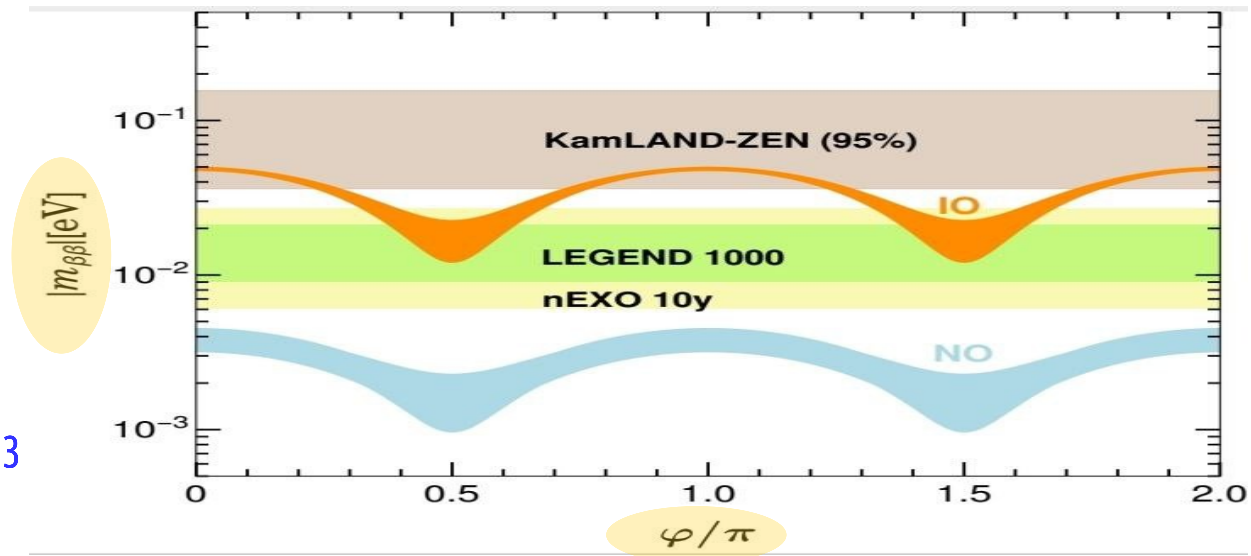


Lattanzi et al JHEP 10 (2020) 213

Nearly degenerate

- **One-massless neutrino**



majorana phase

Reig et al Phys.Lett. B790 (2019)303
Barreiros, Felipe & Joaquim JHEP (2019) 223
Mandal et al PLB789 (2019) 132
Avila et al Eur.Phys.J.C 80 (2020) 10, 908

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- **3-massive case**

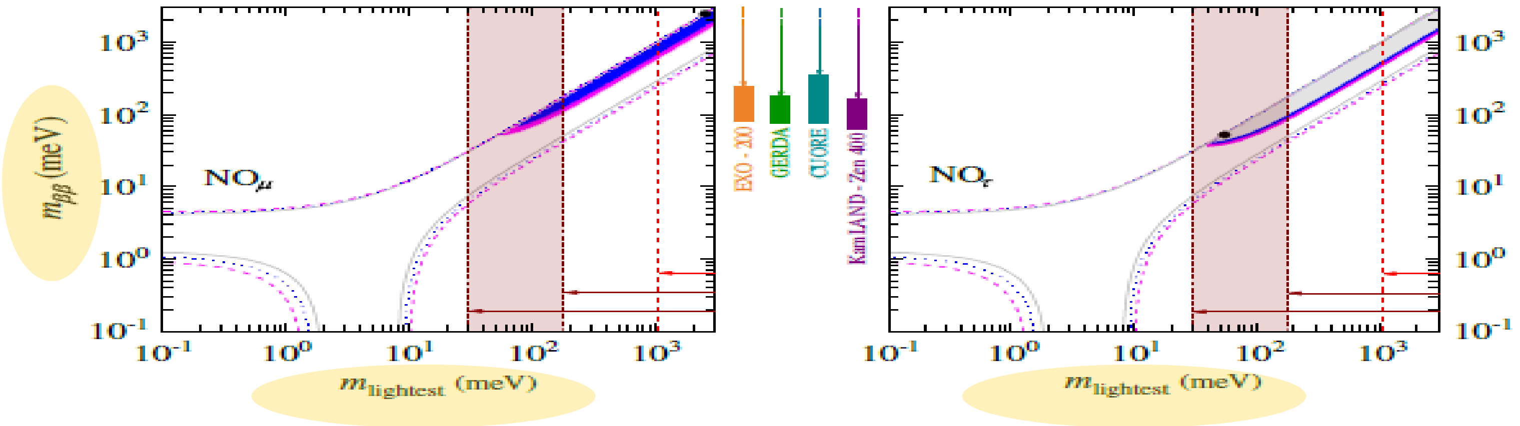
Lower bounds from oscil. legacy + family symmetries

Dorame et al PhysRevD86(2012)056001

Dorame et al Nucl.Phys.B861 (2012) 259-270

King et al Phys.Lett. B724 (2013) 68-72 etc

From Barreiros et al JHEP04(2021)249



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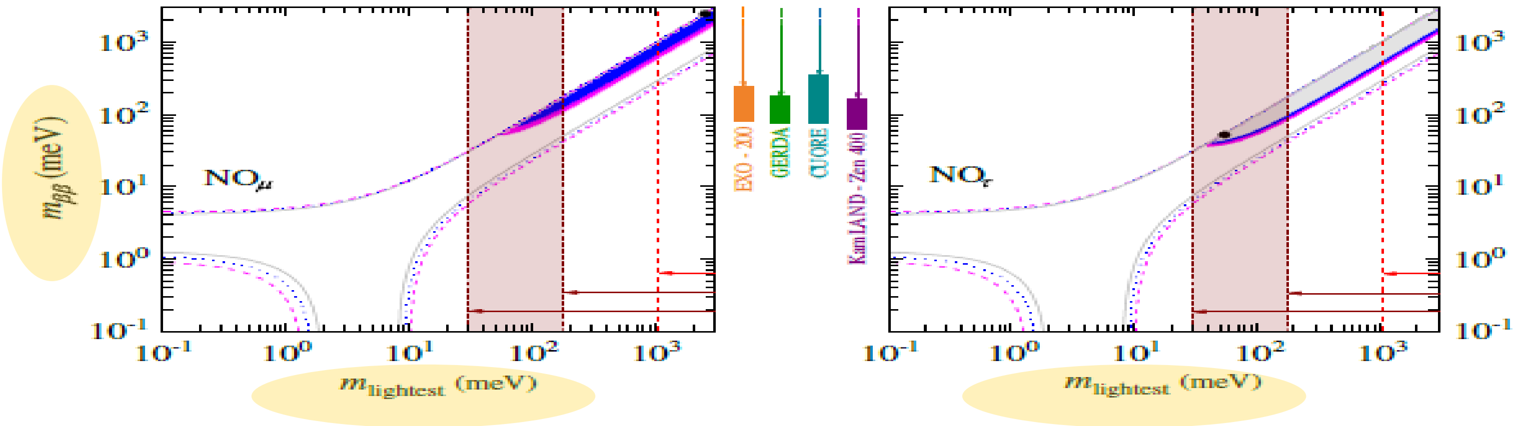
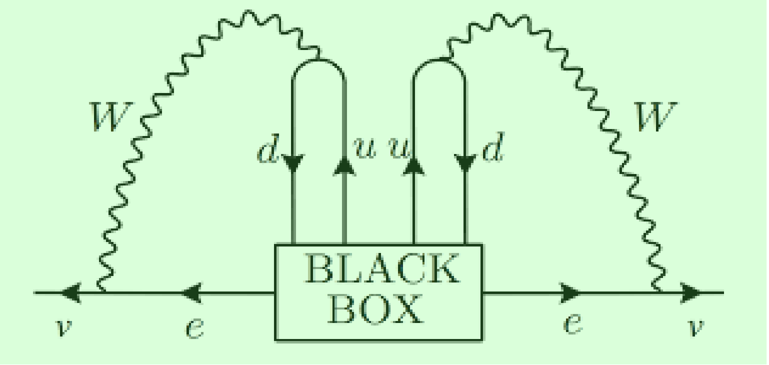


Significance

Schechter, Valle Phys.Rev.D25 (1982) 2951

Duerr, Lindner, Merle JHEP06(2011)091

B.J.P. Jones 2108.09364 (TASI 2020)



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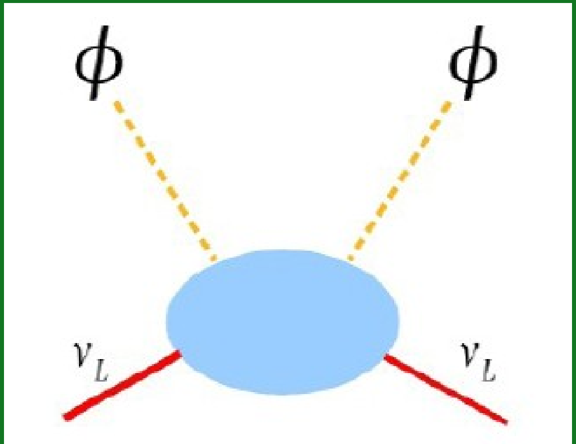
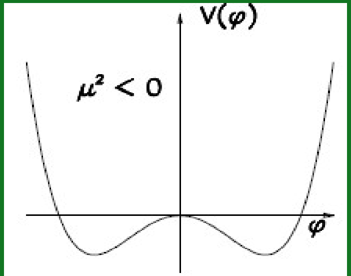
Origin of neutrino mass



Origin of neutrino mass

stability

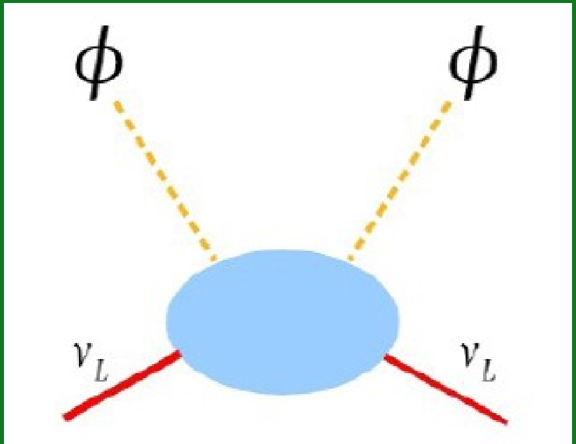


SEESAW dynamics

$$v_3 v_1 \sim {v_2}^2$$

Mandal et al PRD101 (2020) 115030

JHEP03(2021)212 & JHEP07(2021) 029



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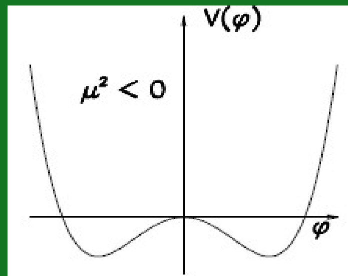

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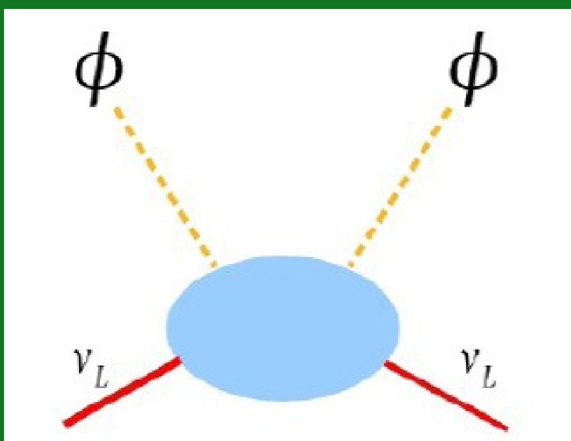
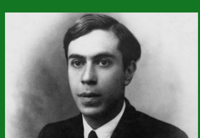
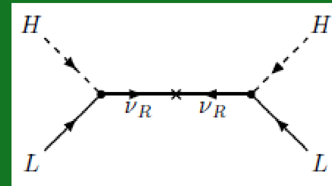


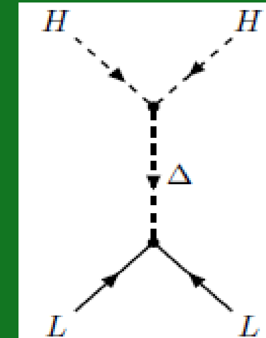




TYPE I (III)

Minkowski 77
Gellman Ramond Slansky 80
Glashow, Yanagida 79
Mohapatra Senjanovic 80
Lazarides Shafi Weterrich 81
Schechter-Valle 80 & 82

TYPE II



Schechter-Valle 80 & 82

Miranda et al
PLB829 (2022) 137110
PRD105 (2022) 095020

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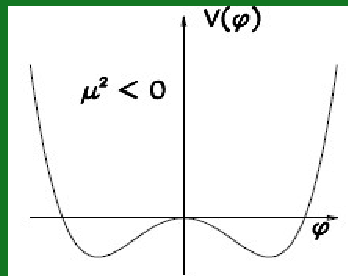

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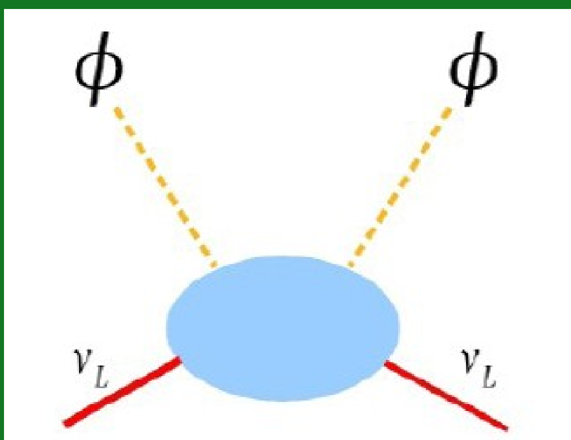

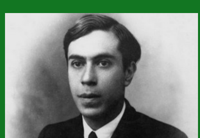

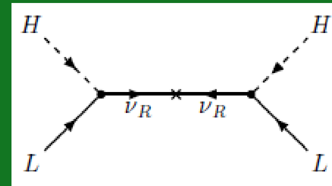

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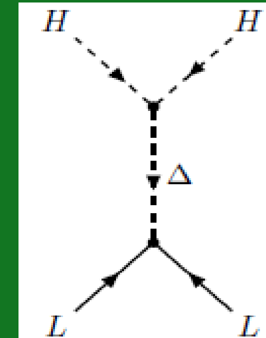

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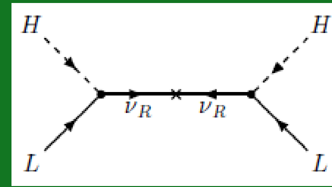
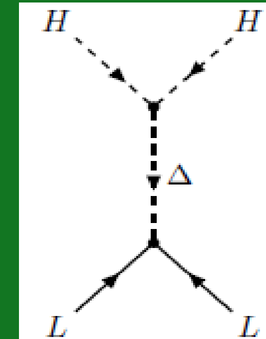
L-R seesaw # of Rs = # Ls (3,3)

SM seesaw any # of singlets (3,m)

Origin of neutrino mass





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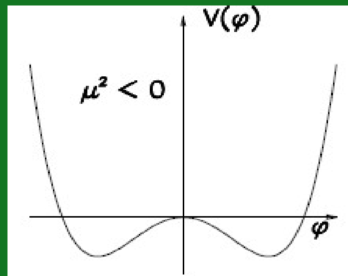

Mandal et al PRD101 (2020) 115030

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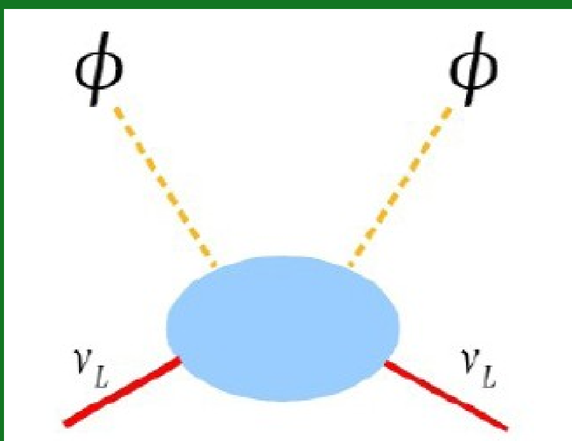
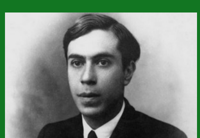


- **MISSING PARTNER**

(3,2) min viable type1 seesaw
(3,1) scoto-seesaw template

$m_{\beta\beta}$



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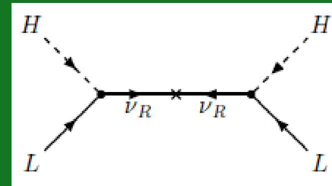

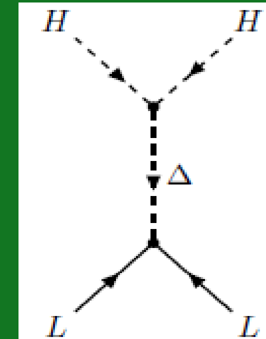

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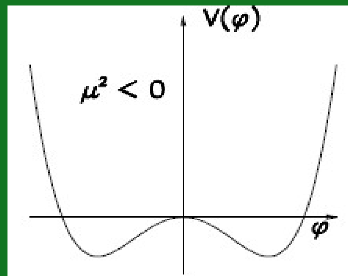

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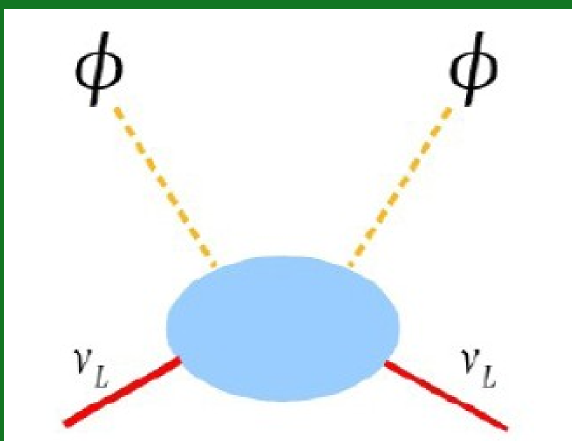
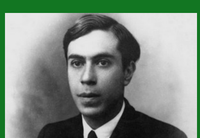
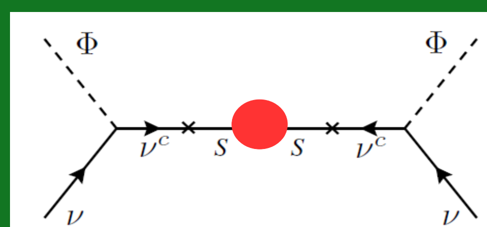


- **MISSING PARTNER** **(3,2)** min viable type1 seesaw
  (3,1) **scoto-seesaw** template

$m_{\beta\beta}$

- **LOW-SCALE Type1 SEESAW (3,6) ISS & LSS**





Mohapatra,Valle 86
Akhmedov et al Phys.Rev.D53 (1996) 2752
PhysLettB368 (1996) 270
Malinsky et al PhysRevLett95(2005)161801

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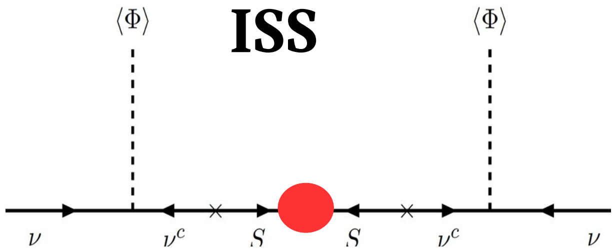

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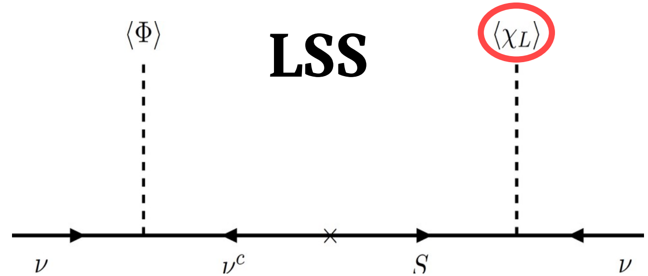

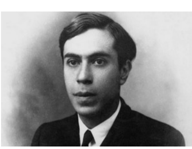

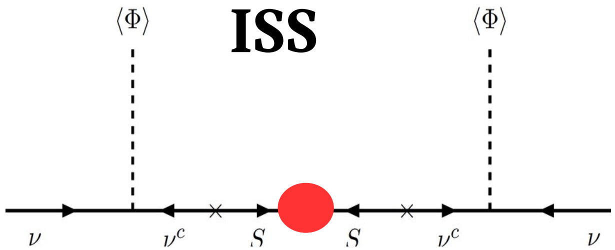

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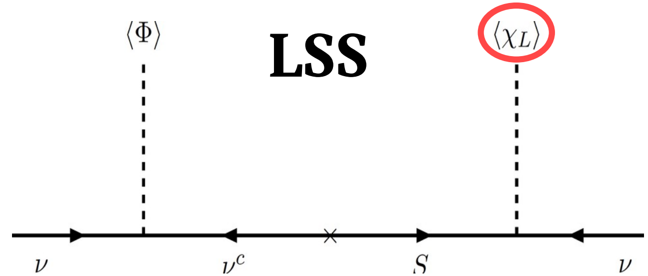
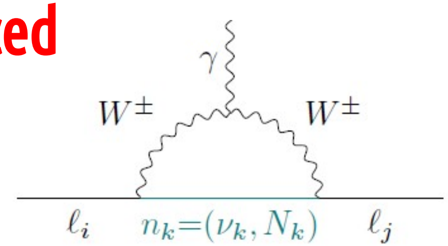
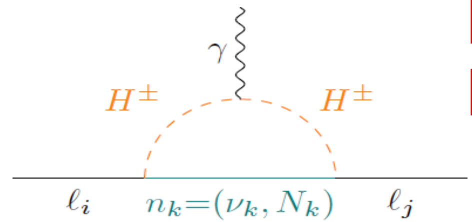


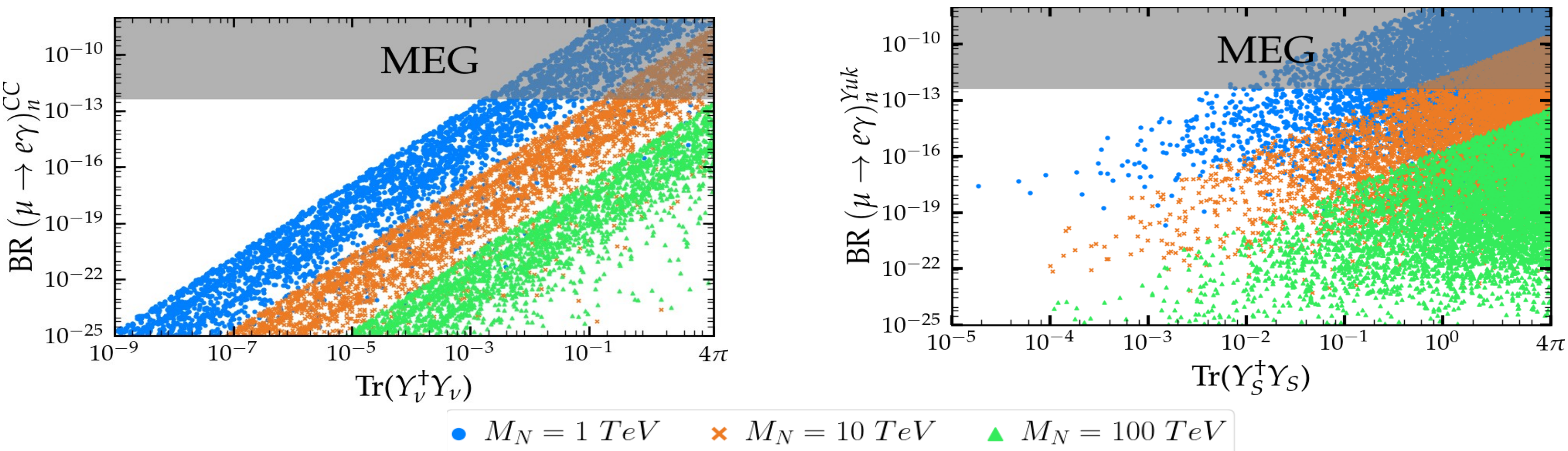
CC-induced cLFV

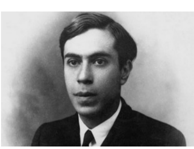


Batra et al
JHEP 07 (2023) 221

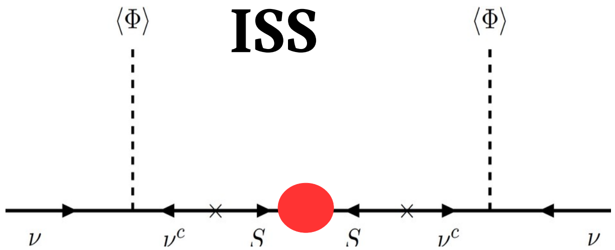


Leptophilic Higgs cLFV

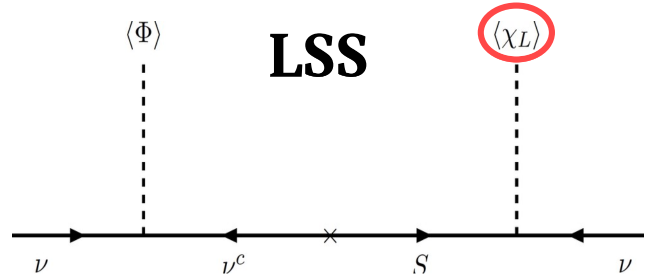




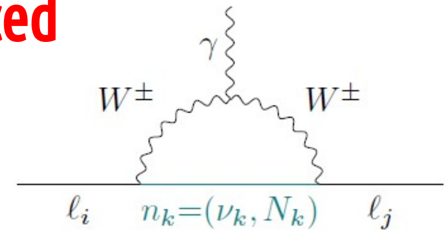
@jwvalle9



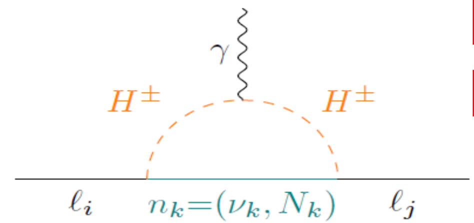
(3,6)



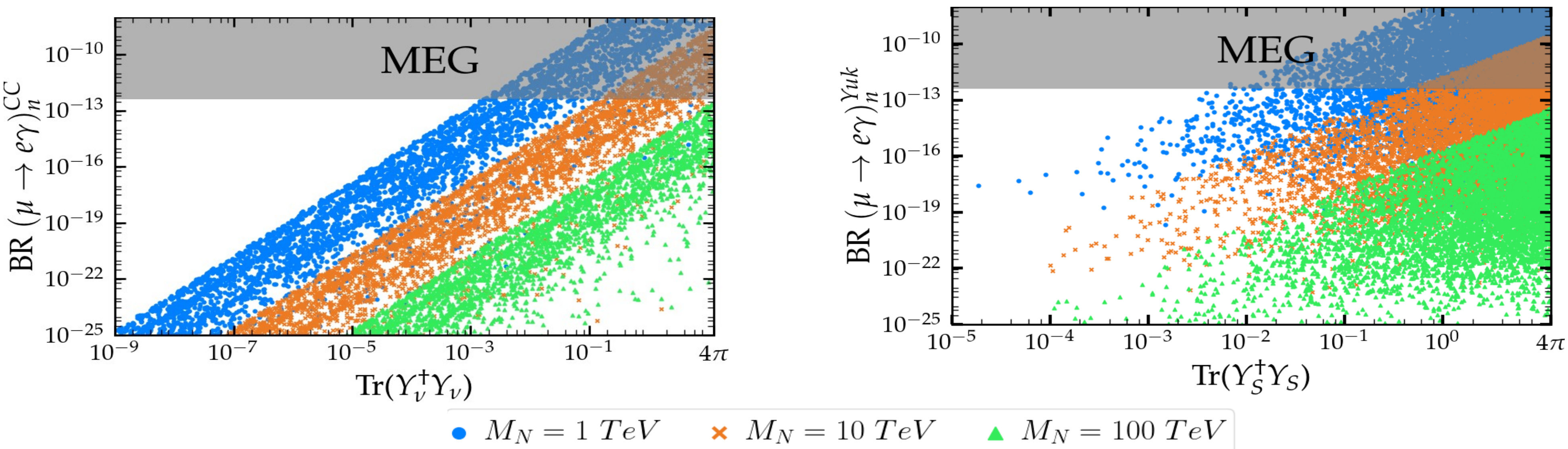
CC-induced cLFV

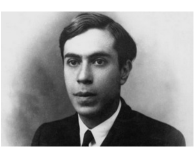


Batra et al
JHEP 07 (2023) 221



Leptophilic Higgs cLFV



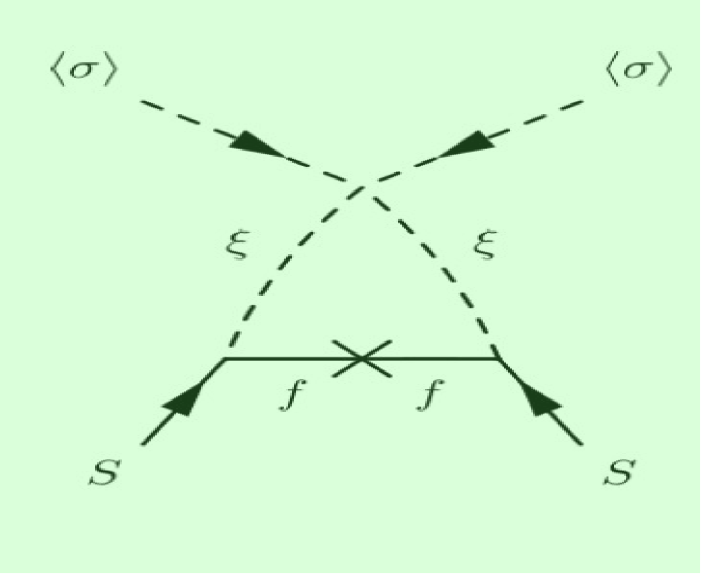


cLFV even in massless neutrino limit Bernabeu et al B187 (1987) 303-308

@jwvalle9


DARK MATTER
PROTON
PHOTON
e-
NEUTRINO
MUON
NEUTRON
QUARK
VISIBLE MATTER
DARK ELECTRONS
e
e
DARK NEUTRON
NEUTRALINO
GRAVITINO
AXION
AXION
Wimp

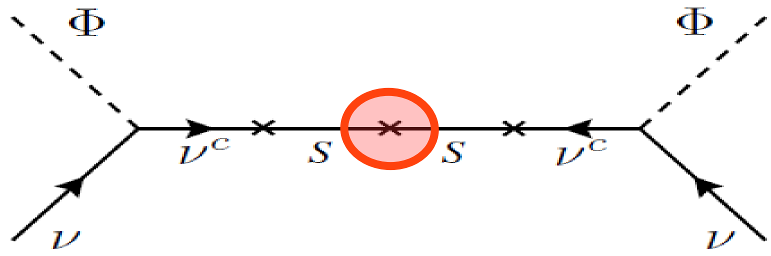
is dark matter the radiative seed of neutrino mass?



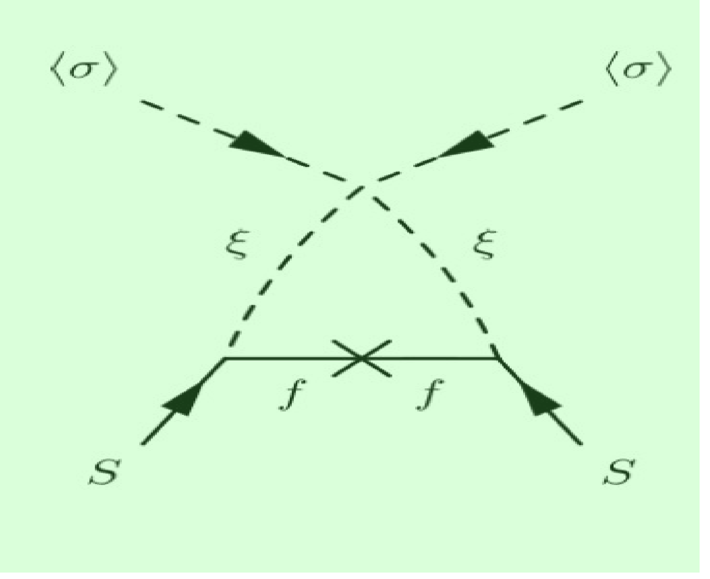
Mandal et al Phys.Lett.B821 (2021) 136609

double protection in low scale seesaw

(3,6)



is dark matter the radiative seed of neutrino mass?



Mandal et al Phys.Lett.B821 (2021) 136609

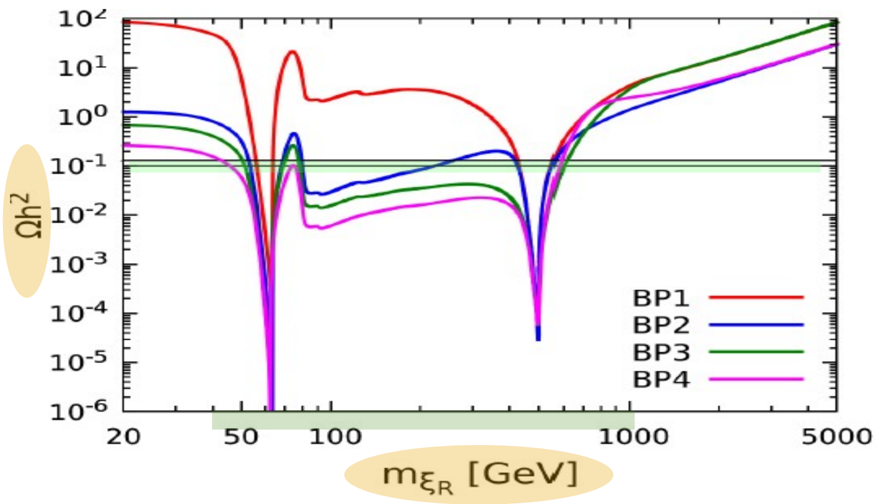
@jwvalle10

dark inverse seesaw

low-scale seesaw

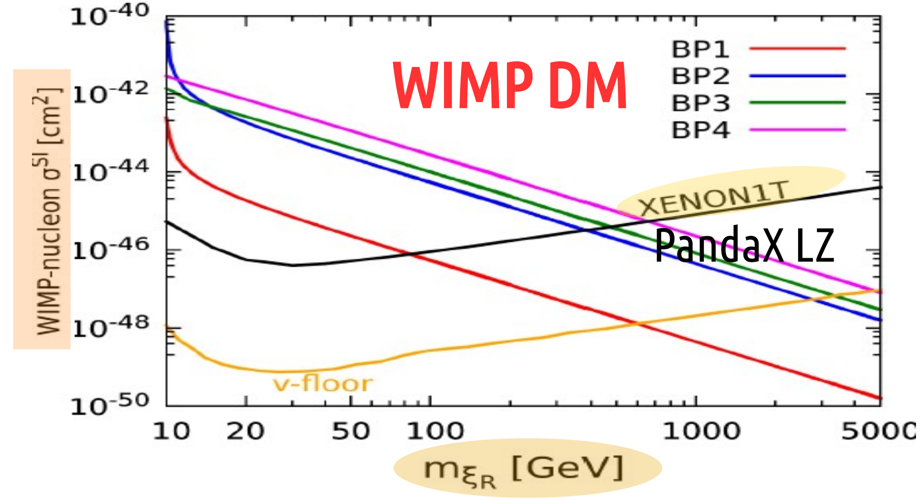
LambdaCDM

Phys.Lett.B821 (2021) 136609

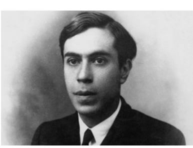


Xenon1T PhysRevLett.121.111302

PandaX Lux-Zepellin



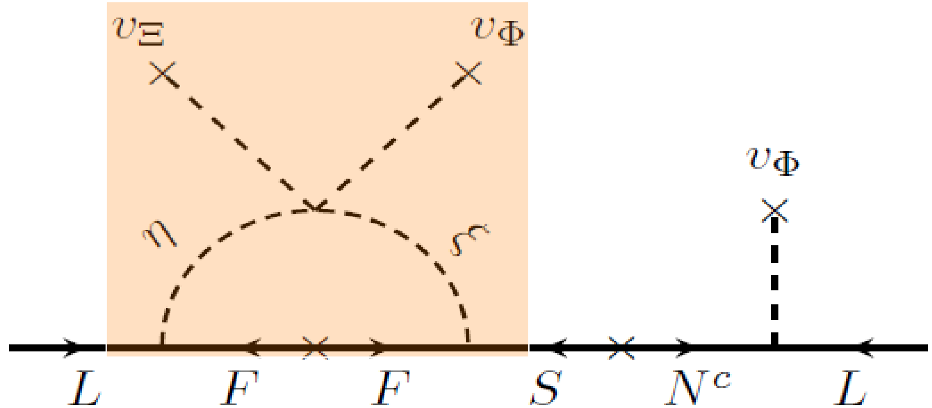
+ charged lepton flavor violation



@jwvalle11

low-scale seesaw — dark linear seesaw (3,6)

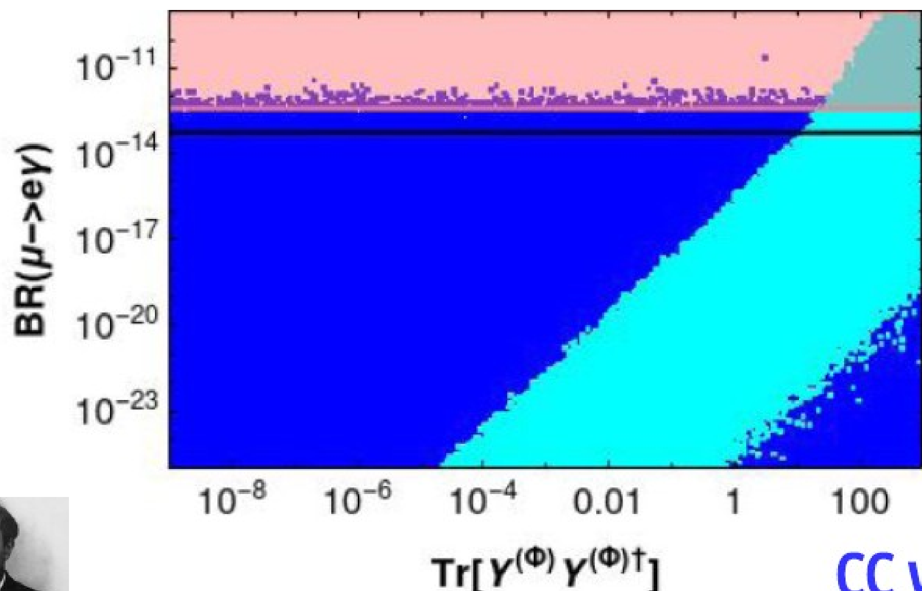
$$M_\nu = \begin{pmatrix} 0_{3\times3} & m_D & \varepsilon \\ m_D^T & 0_{3\times3} & M \\ \varepsilon^T & M & 0_{3\times3} \end{pmatrix}$$

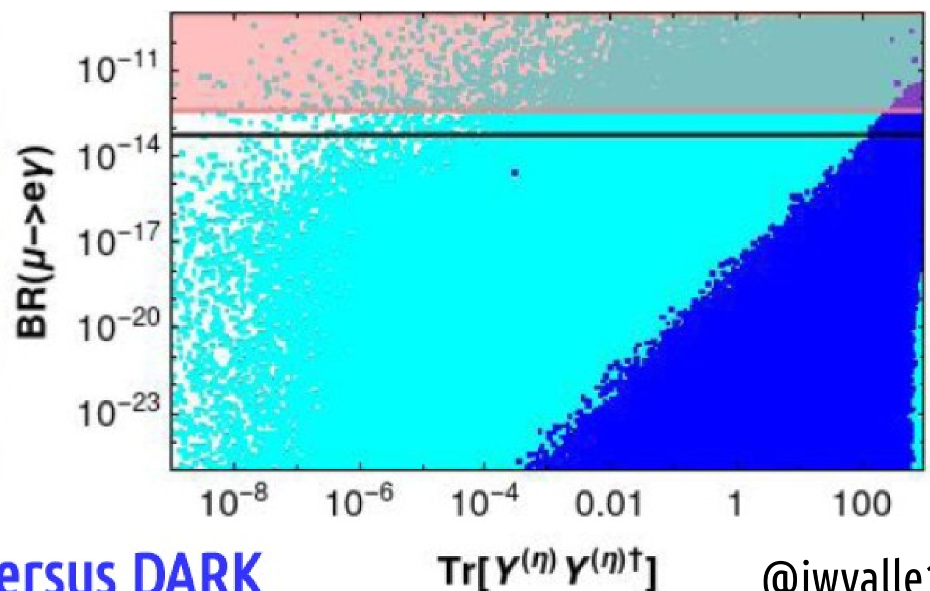


Carcamo, Vishnudath, J.V. JHEP 09 (2023) 046

$$m_{\rm light} = -\left[m_D M^{-1}\varepsilon^T + \varepsilon M^{-1} m_D^T\right]$$

(Also Batra, Camara, Joaquim, 2305.01687)

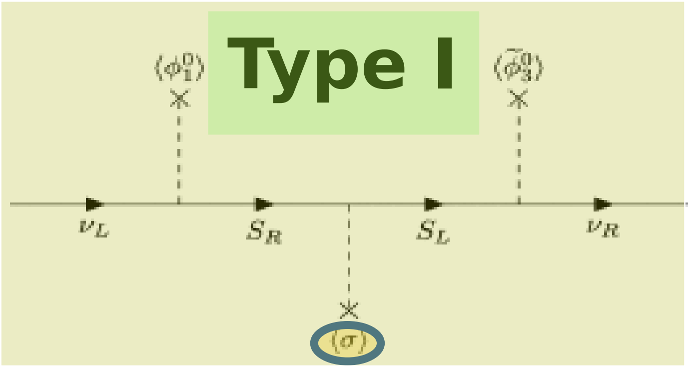


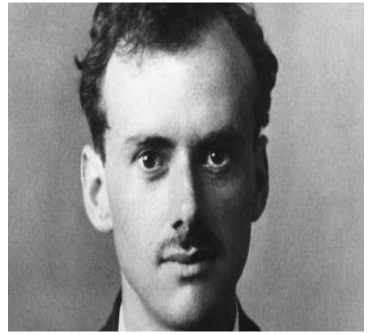


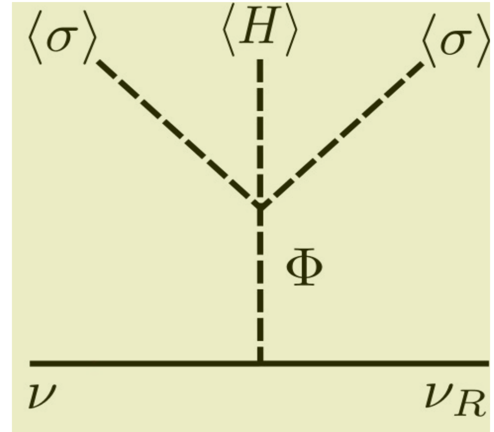
CC versus DARK

@jwvalle12

seesawing a la



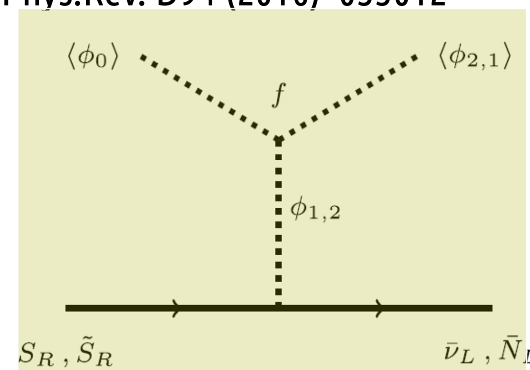




Type II

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



Phys.Lett. B761 (2016) 431-436

Phys.Lett. B767 (2017) 209-213

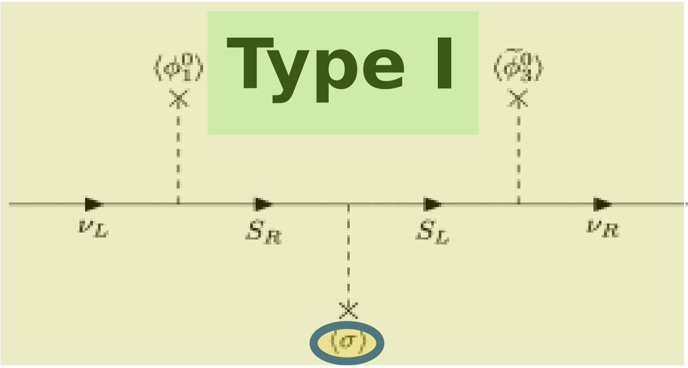
Phys.Rev. D98 (2018) 035009

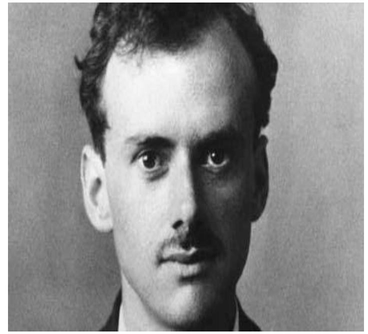
Phys.Lett. B781 (2018) 122-128

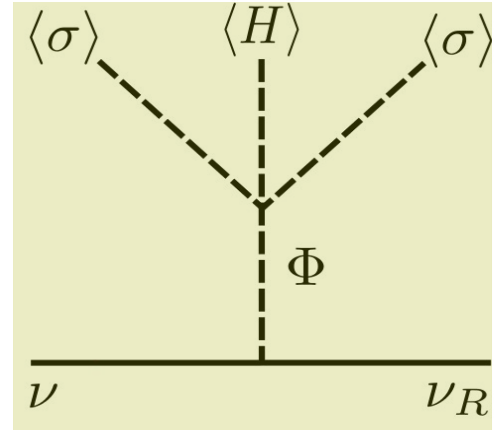
Addazi et al Phys.Lett. B759 (2016) 471-478

Phys.Lett. B755 (2016) 363-366

seesawing a la







Type II

Phys.Lett. B762 (2016) 162-165

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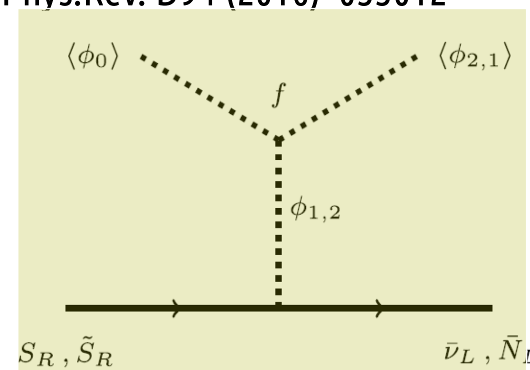


symmetry protecting small neutrino mass

+ Diracness

Peccei-Quinn symmetry

$$m_\nu^D \simeq \frac{y^{\nu_1}(y^S)^{-1}(y^{\nu_2})^T}{\sqrt{2}}\,\frac{v_W}{v_\sigma}.$$

SU3L (v_W)

PQ (v_σ)

Phys.Lett.B 810 (2020) 135829

Phys.Lett. B761 (2016) 431-436

Phys.Lett. B767 (2017) 209-213

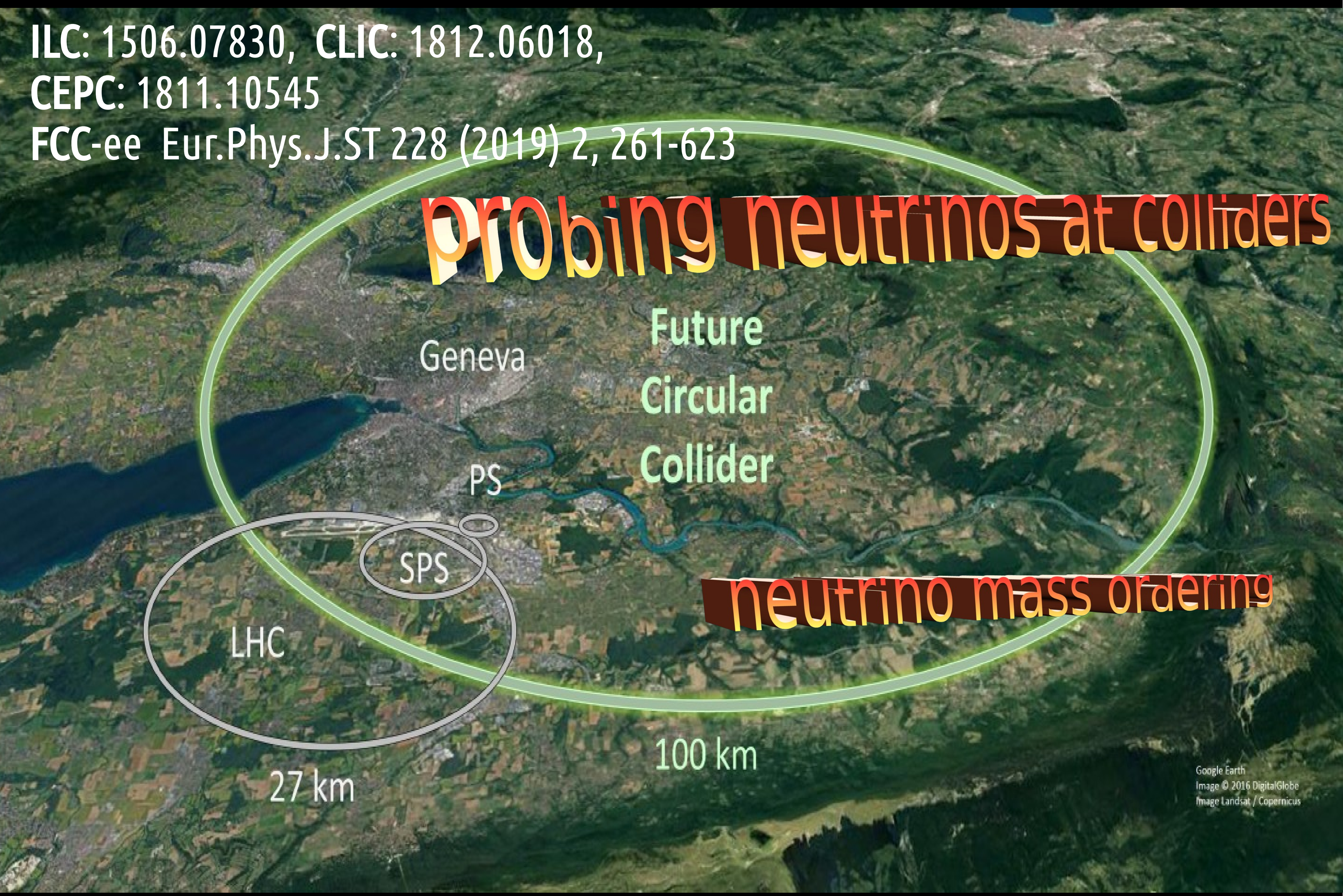
Phys.Rev. D98 (2018) 035009

Phys.Lett. B781 (2018) 122-128

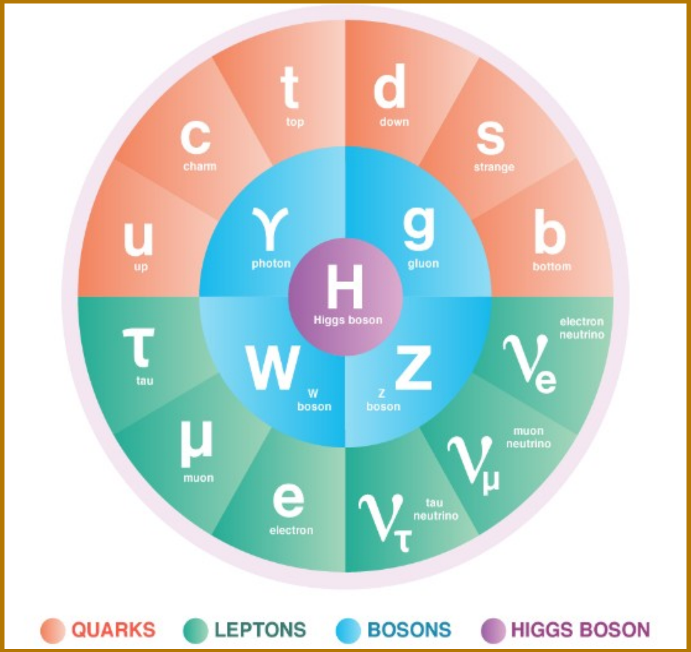
Addazi et al Phys.Lett. B759 (2016) 471-478

Phys.Lett. B755 (2016) 363-366

@jwvalle13


ILC: 1506.07830, CLIC: 1812.06018,
CEPC: 1811.10545
FCC-ee Eur.Phys.J.ST 228 (2019) 2, 261-623
probing neutrinos at colliders
Future
Circular
Collider
Geneva
PS
SPS
LHC
27 km
100 km
neutrino mass ordering
Google Earth
Image © 2016 DigitalGlobe
Image Landsat / Copernicus

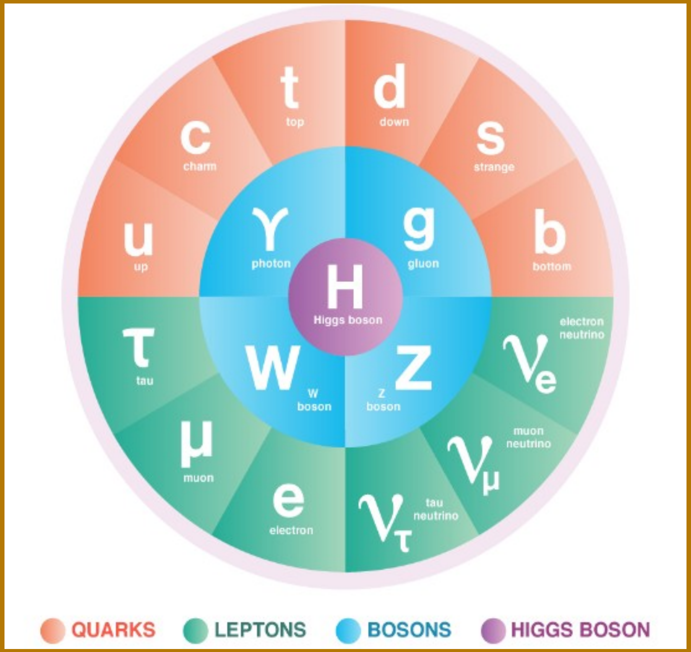
HIGGS DISCOVERY NOT THE LAST BRICK TO THE SM



Oscillation discovery brought

precision oscillation program,
CP, octant, ordering, NSI,unitarity,
0nuDBD, **CEvNS** ...

HIGGS DISCOVERY NOT THE LAST BRICK TO THE SM



Oscillation discovery brought

precision oscillation program,
CP, octant, ordering, NSI, unitarity,
0nuDBD, **CEvNS** …

DM may seed or mediate neutrino mass generation

neutrinos and **flavor**

neutrinos and strong CP problem

neutrinos and **unification**

neutrinos and SM anomalies

pheno imprints : collider probes of mass & ordering, cLFV, LNV ..

@jwvalle15

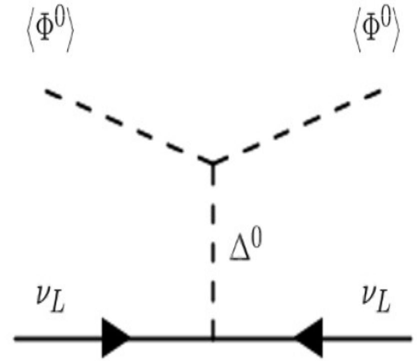
Back-ups

low-scale type-2

triplet seesaw

Schechter & JV PRD22 (1980) 2227

PRD25 (1982) 774



Can be reconstructed from data leading to high-energy tests

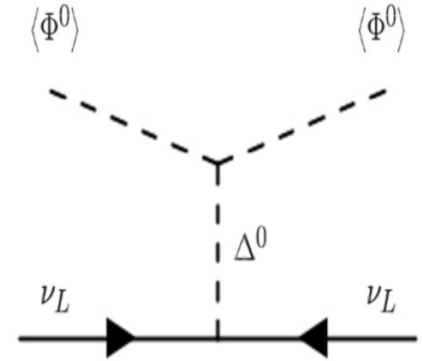
Miranda et al Phys.Rev.D105 (2022) 095020

seesaw mediator produced in @ e+e- / pp collisions

Miranda et al PLB 829 (2022) 137110

low-scale type-2

triplet seesaw

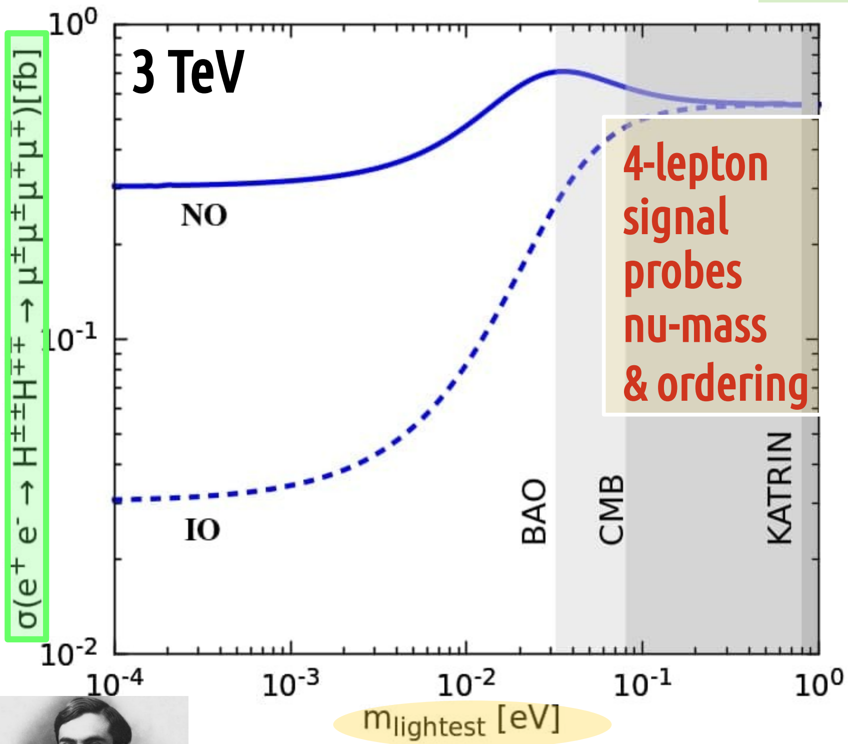


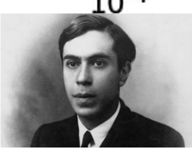
Can be reconstructed from data leading to high-energy tests

seesaw mediator produced in @ e+e- / pp collisions

Miranda et al Phys.Rev.D105 (2022) 095020

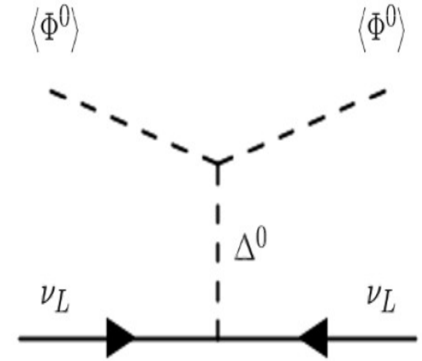
Miranda et al PLB 829 (2022) 137110





low-scale type-2

triplet seesaw



Can be reconstructed from data leading to high-energy tests

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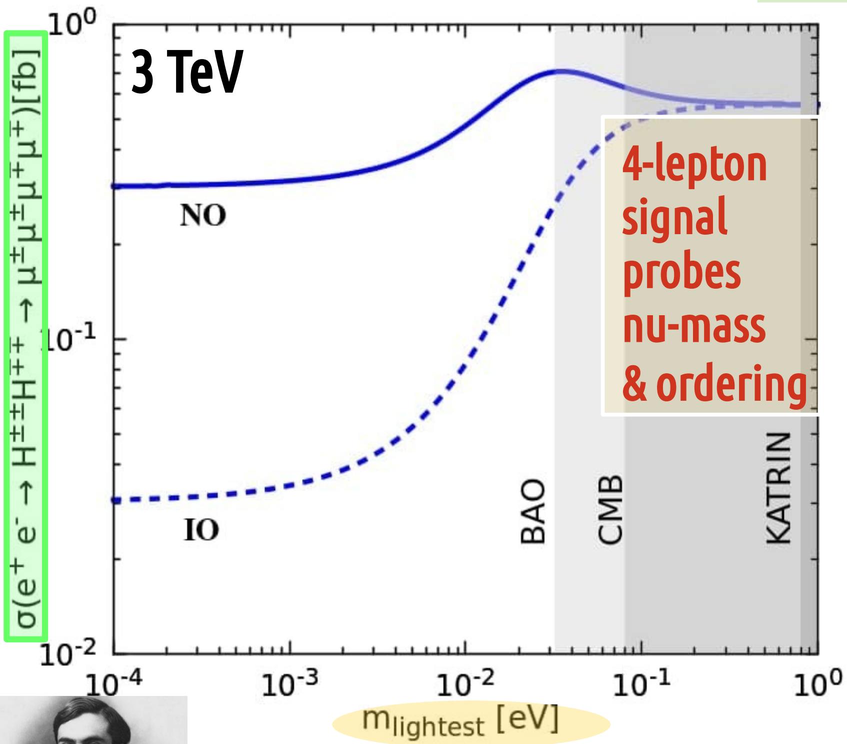
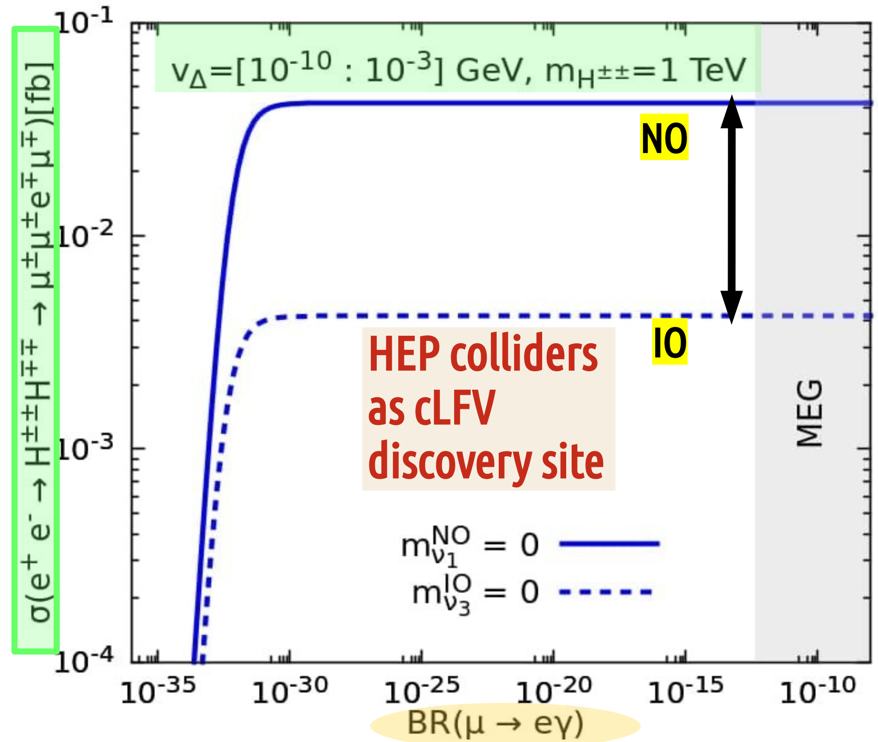
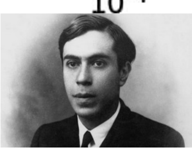
Miranda et al Phys.Rev.D105 (2022) 095020



Miranda et al PLB 829 (2022) 137110



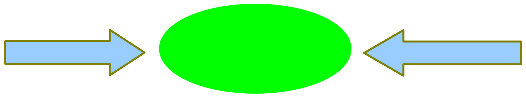


SUSY mediators

De Campos et al
Phys.Rev. D86 (2012) 075001

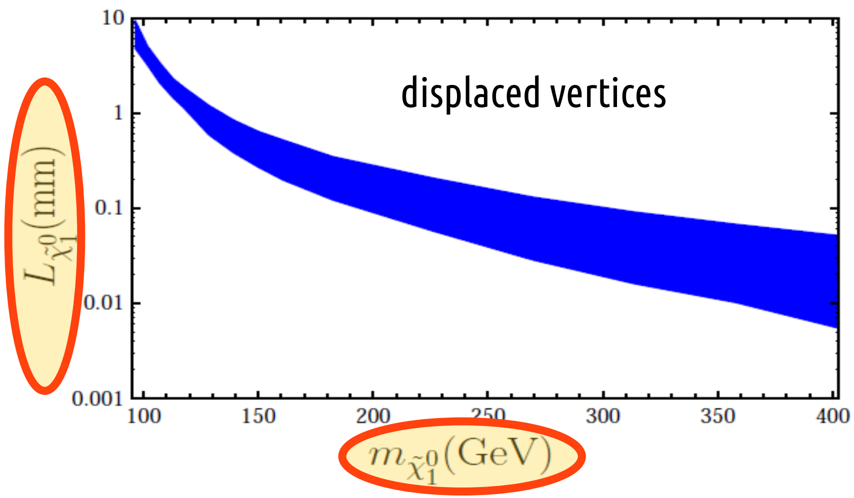
LSP from cascade squark & gluino decays

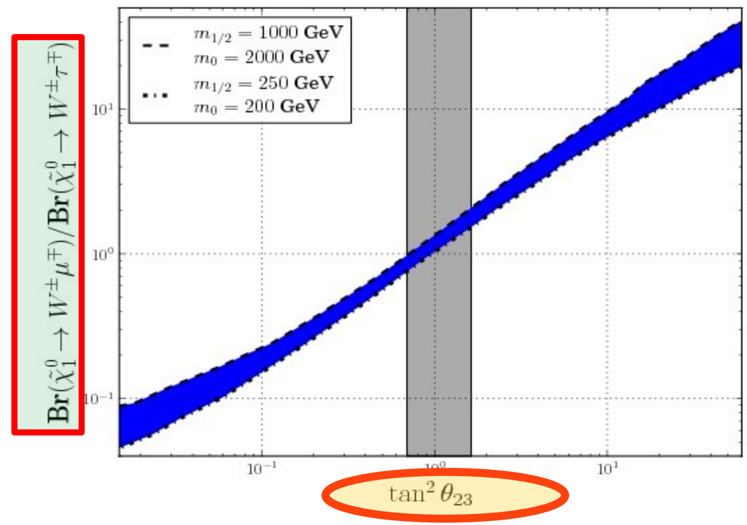
$$\tilde{\chi}_1^0 \to W^{\pm} l_i^{\mp} \qquad \tilde{\chi}_1^0 \to Z^0 \nu_i$$



Lightest neutralino decay correlates with atm angle

Lightest neutralino decay length





PROBING Theta atm @ LHC