neutrino physics benchmarks for colliders

JOSÉ W F VALLE

LISHEP 2023
International School on High Energy Physics

ASTROPARTICLES
Astroparticles and High Energy Physics Group

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VNIVERSITAT DE VALÈNCIA
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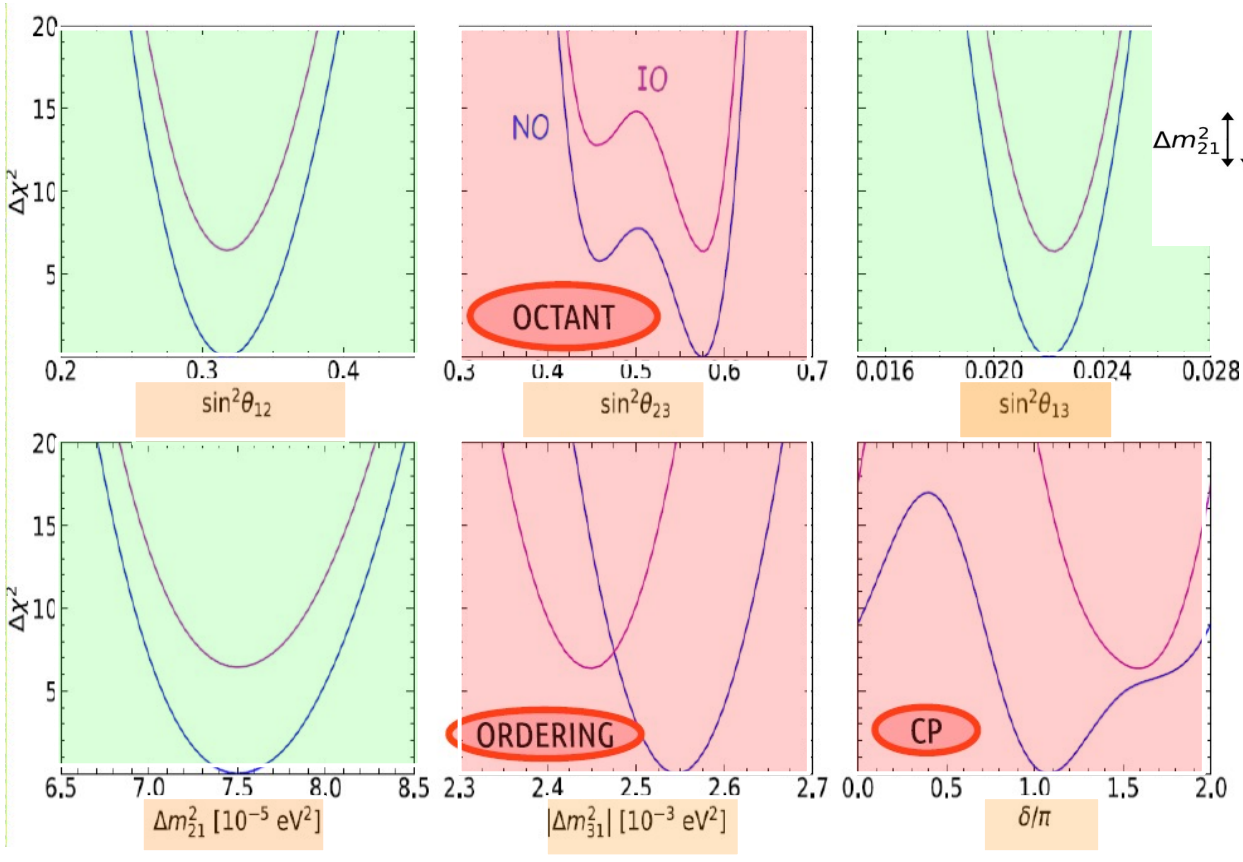
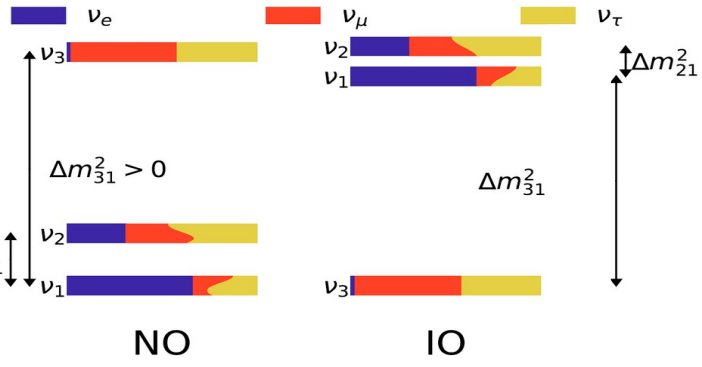
neutrino oscillations

PF de Salas et al JHEP02(2021)071

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

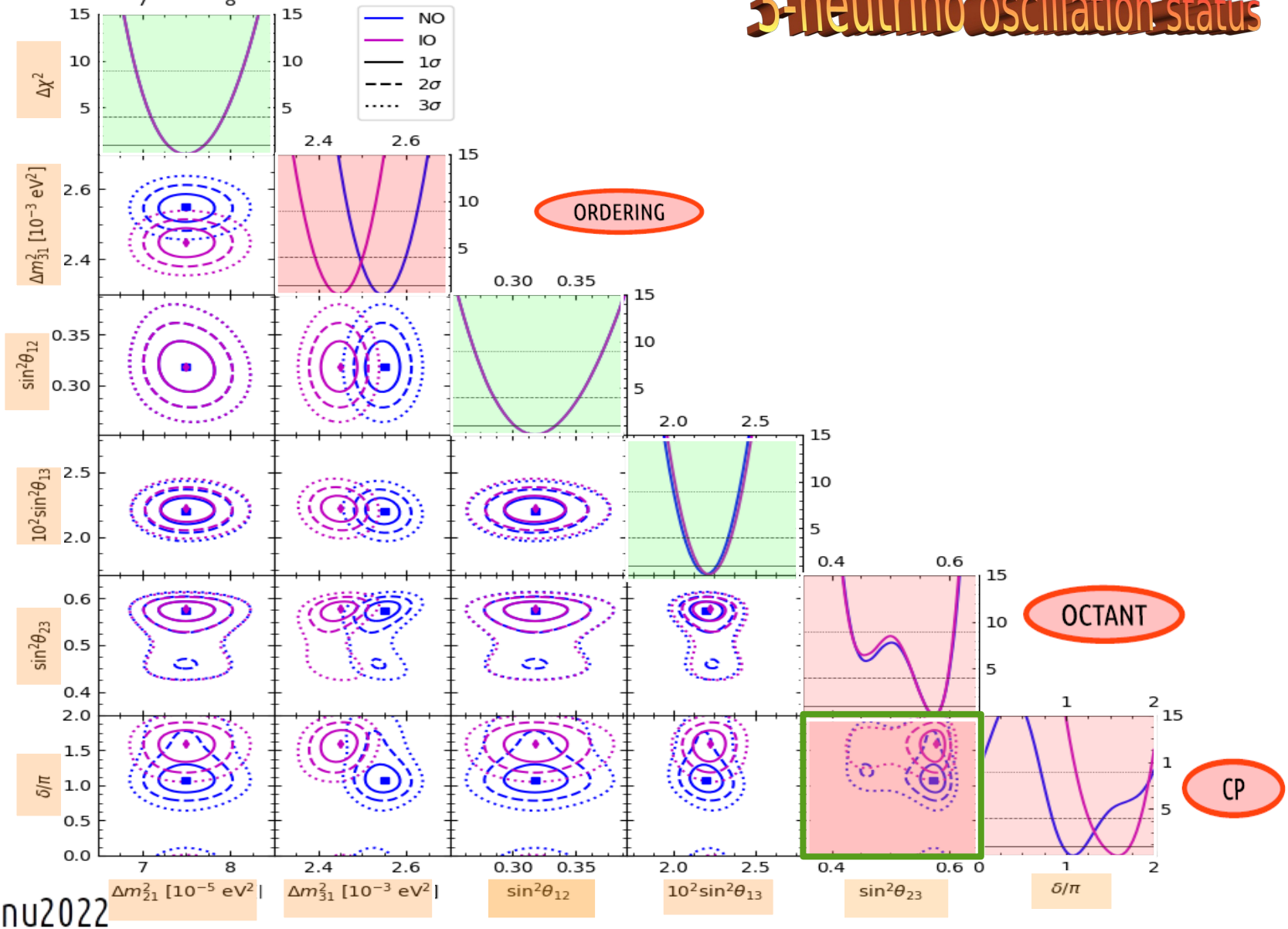




Similar results from Bari and NuFit groups

@jwvalle2

3-neutrino oscillation status



PF de Salas et al JHEP02(2021)071

https://globalfit.astroparticles.es/

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

Updates from nu2022

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

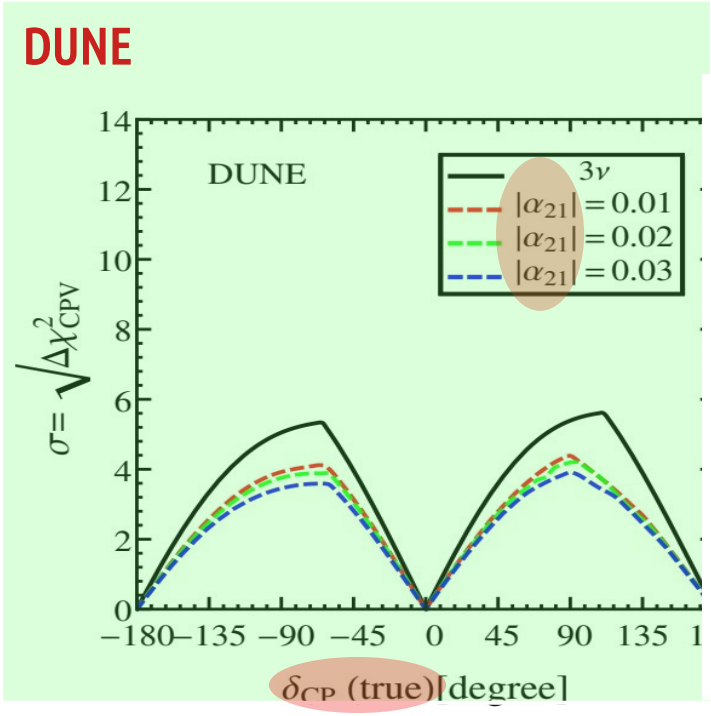
@jwvalle3

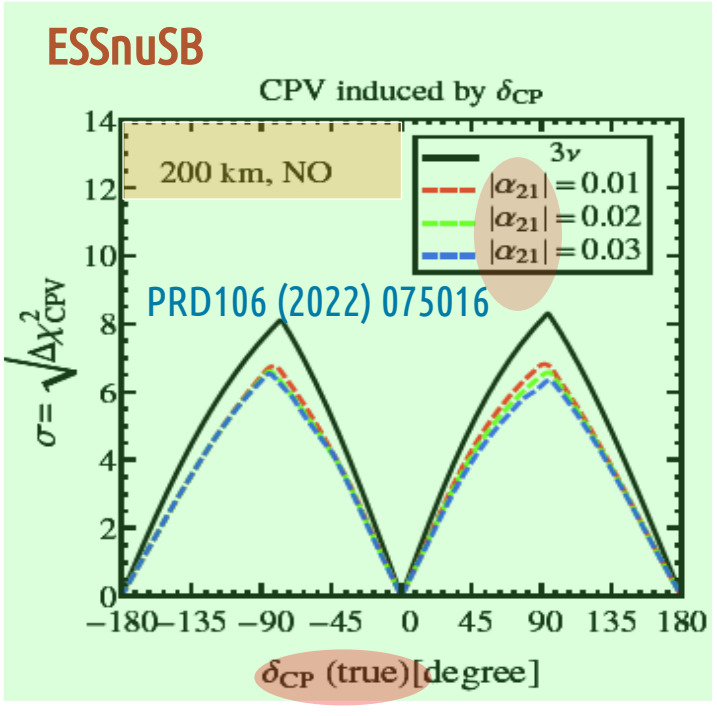
CPV

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

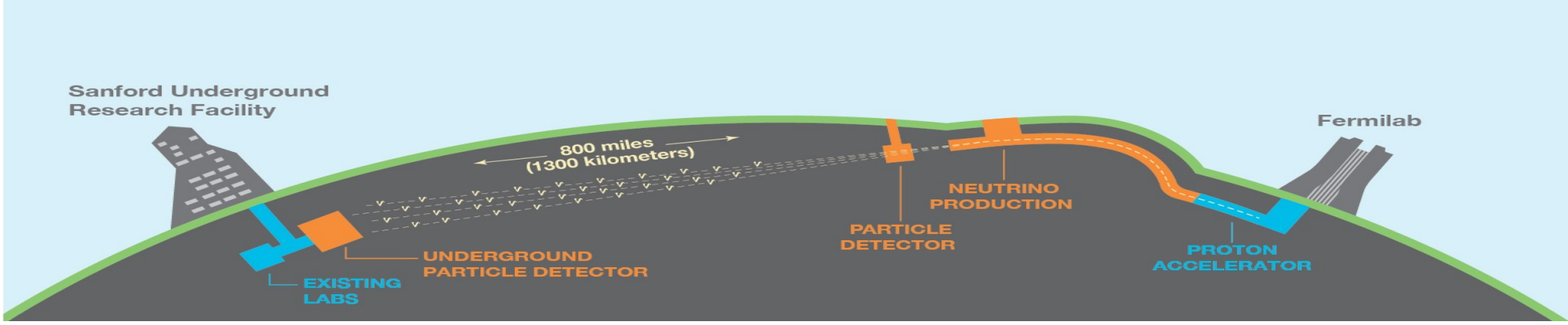
2008.12769

DUNE
Hyper-K





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



CPV reviews Nunokawa, Parke, Valle Prog.Part.Nucl.Phys. 60 (2008) 338
Branco, Felipe, Joaquim, Rev.Mod.Phys. 84 (2012) 515

@jwvalle4

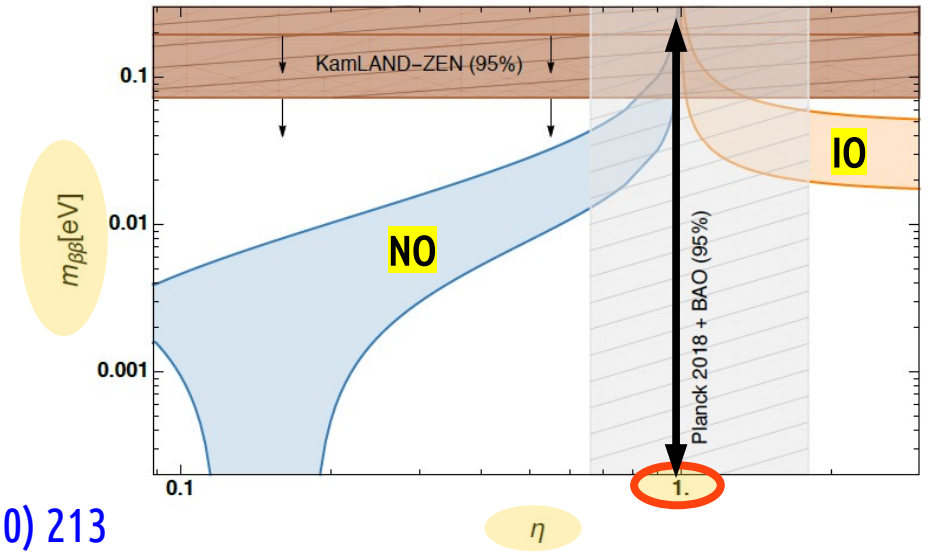
neutrinoless doublebeta decay

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

Schechter & JV PRD22 (1980) 2227
Rodejohann, JV Phys.Rev. D84 (2011) 073011

Nearly degenerate

Lattanzi et al JHEP 10 (2020) 213



degeneracy parameter

neutrinoless doublebeta decay

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

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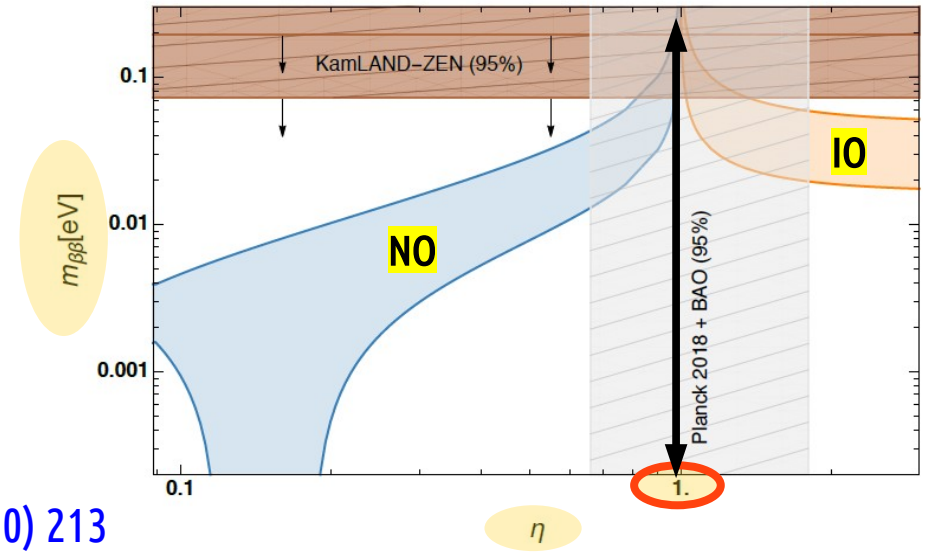
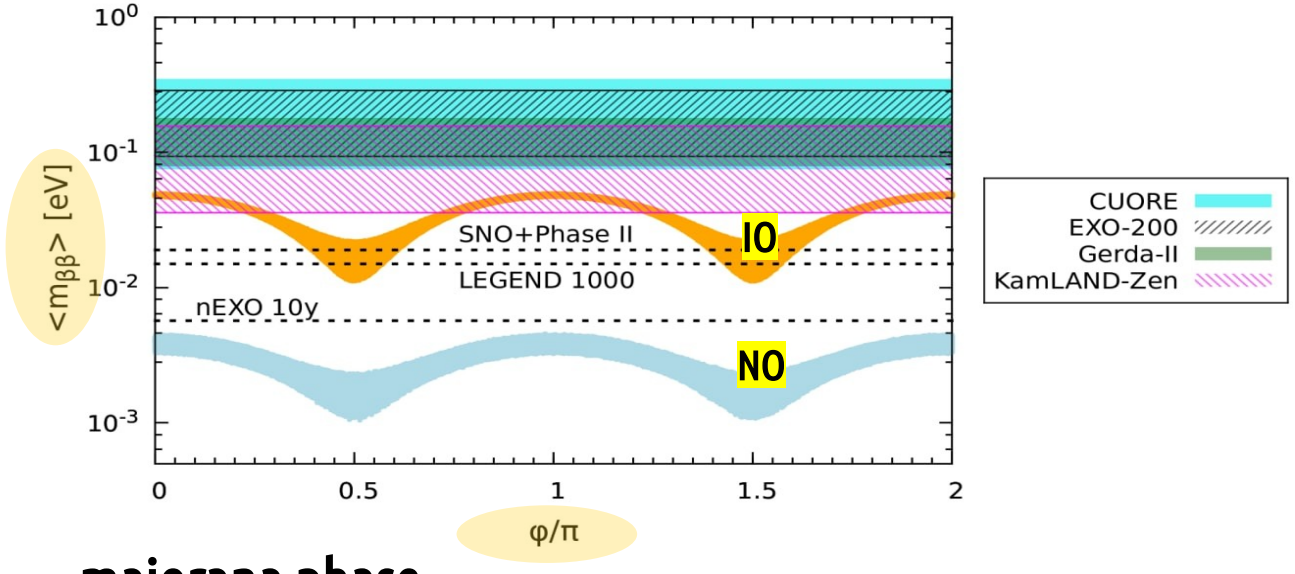


degeneracy parameter

One-massless neutrino

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

C Adams et al 2212.11099
Agostini et al. Science 365 (2019) 1445



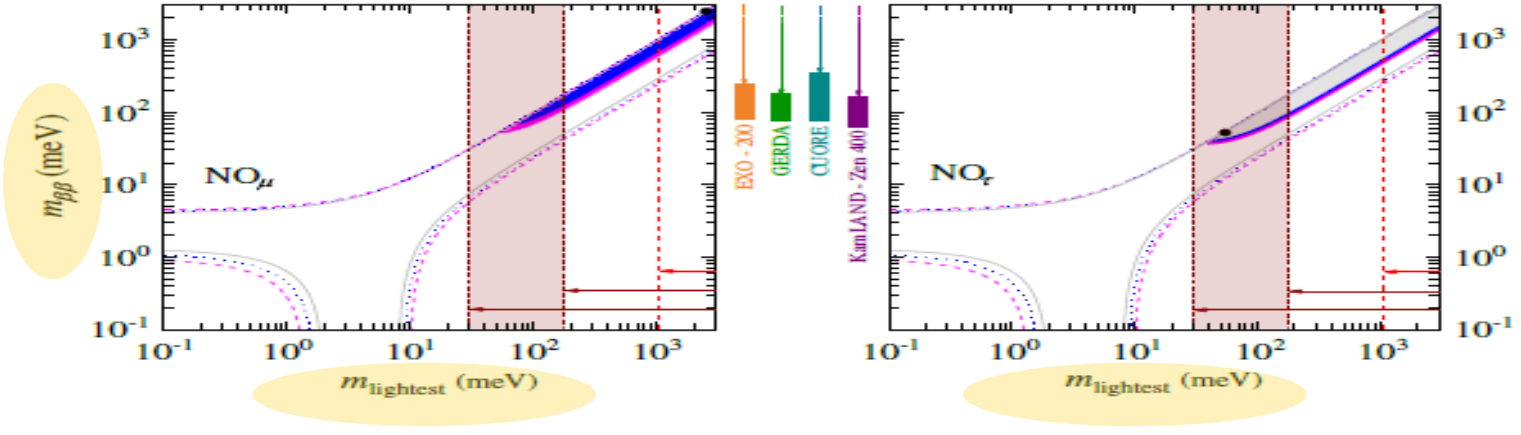
majorana phase

- **3-massive case**

Lower bounds from family symmetries

Dorame et al PhysRevD86(2012)056001
Dorame et al Nucl.Phys.B 861 (2012) 259-270
King et al Phys.Lett. B 724 (2013) 68-72 etc

From Barreiros et al JHEP04(2021)249



3-massive case

Lower bounds from family symmetries

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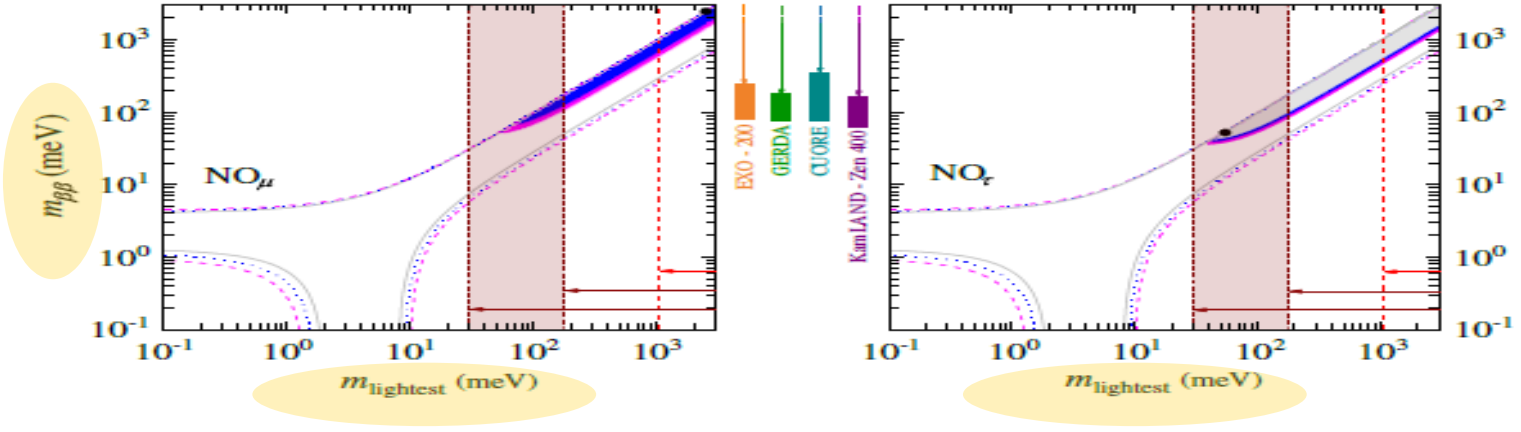
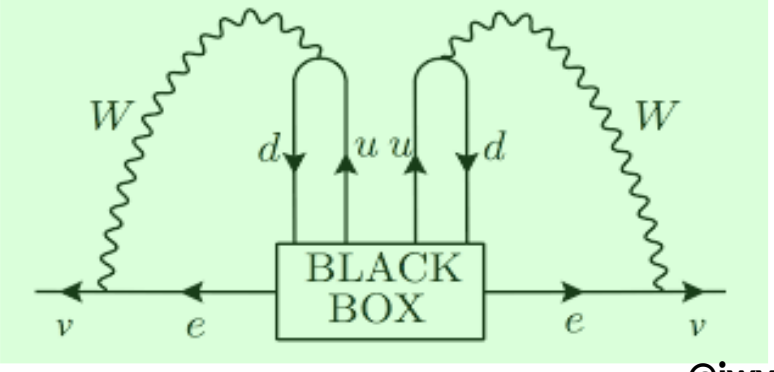
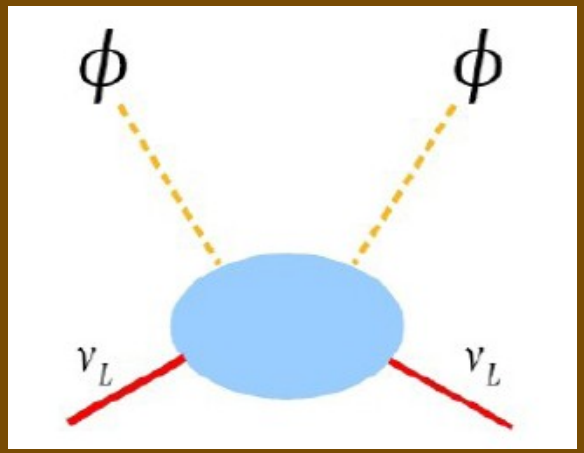


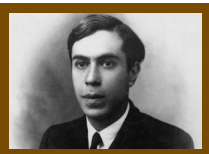
Significance

Schechter, Valle PhysRev D25 (1982) 2951
Duerr, Lindner, Merle JHEP06(2011)091
B.J.P. Jones 2108.09364 (TASI 2020)



Origin of neutrino mass



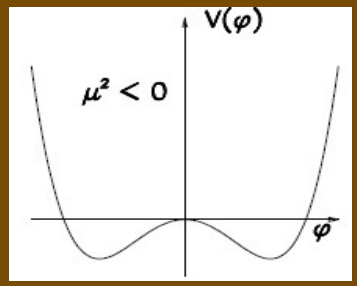


Origin of neutrino mass

stability

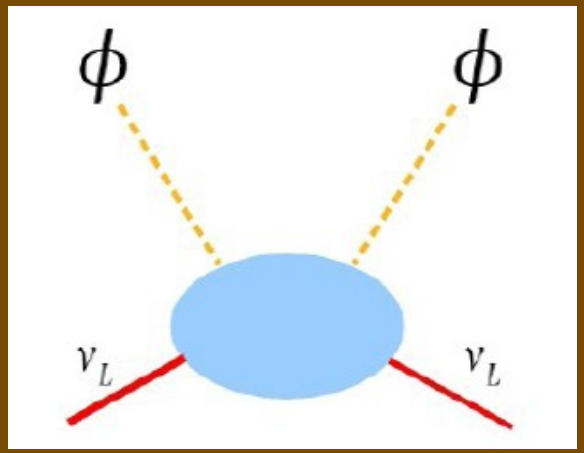
SEESAW dynamics

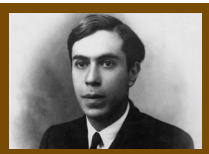
$$v_3 v_1 \sim v_2{}^2$$



Mandal et al Phys.Rev.D 101 (2020) 115030

JHEP03(2021)212 & JHEP07(2021) 029



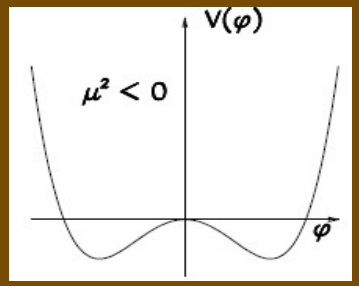


Origin of neutrino mass

stability

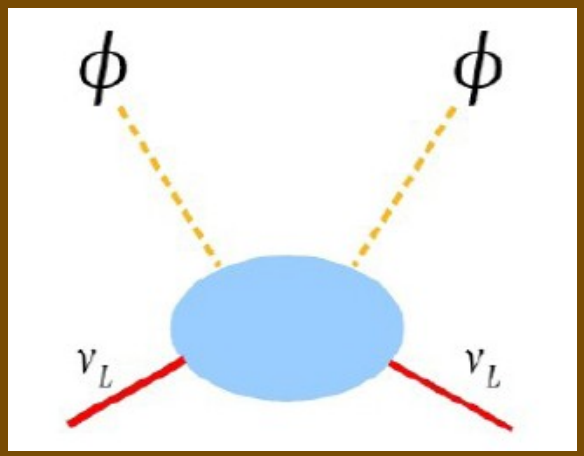
SEESAW dynamics

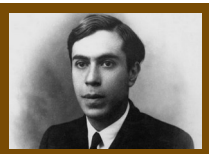
$$v_3 v_1 \sim v_2^{\,2}$$

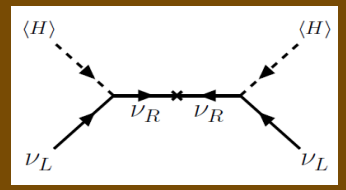


Mandal et al Phys.Rev.D 101 (2020) 115030

JHEP03(2021)212 & JHEP07(2021) 029

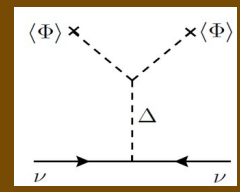






TYPE I

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

L-R seesaw # of Rs = # Ls

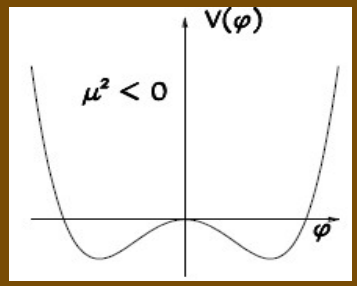
SM seesaw # of singlets arbitrary

Origin of neutrino mass

stability

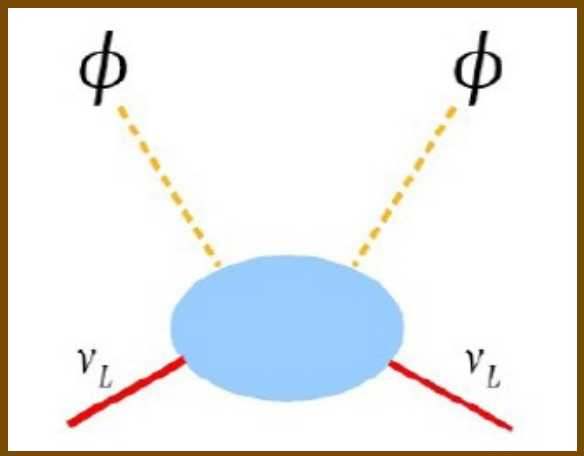
SEESAW dynamics

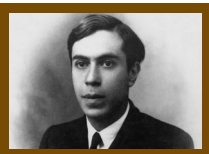
$$v_3 v_1 \sim v_2{}^2$$

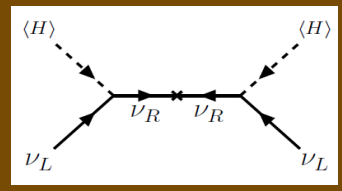


Mandal et al Phys.Rev.D 101 (2020) 115030

JHEP03(2021)212 & JHEP07(2021) 029







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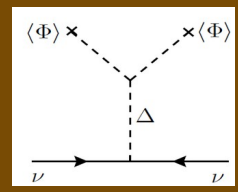


TYPE II

Schechter-Valle 80 & 82

L-R seesaw # of Rs = # Ls

SM seesaw # of singlets arbitrary

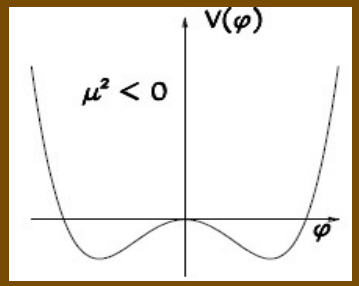
- **MISSING PARTNER**

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

$m_{\beta\beta}$

Origin of neutrino mass

stability

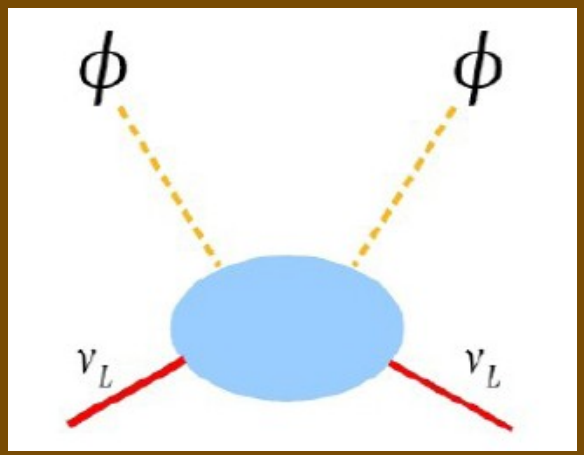


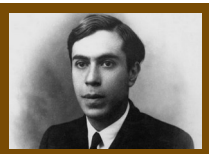
SEESAW dynamics

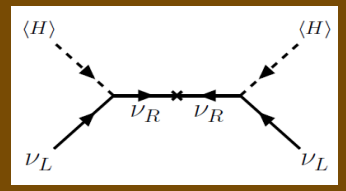
$$v_3 v_1 \sim v_2{}^2$$

Mandal et al Phys.Rev.D 101 (2020) 115030

JHEP03(2021)212 & JHEP07(2021) 029







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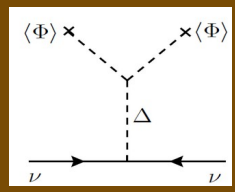


TYPE II

Schechter-Valle 80 & 82

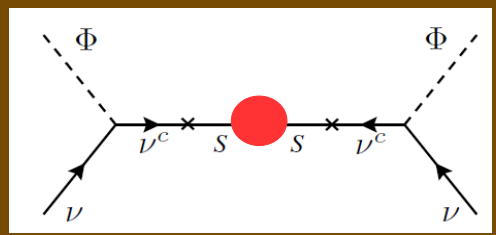
L-R seesaw # of Rs = # Ls

SM seesaw # of singlets arbitrary

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

$m_{\beta\beta}$

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



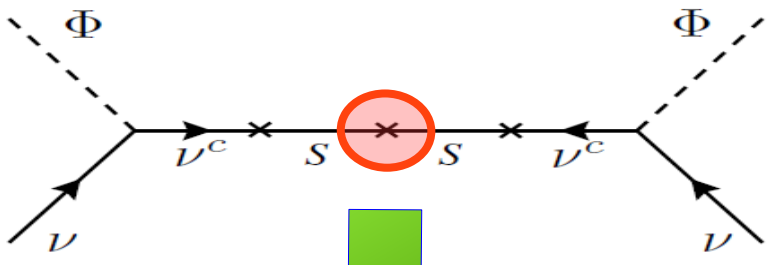
Mohapatra,Valle 86

Akhmedov et al Phys.Rev.D53 (1996) 2752
PhysLettB368 (1996) 270

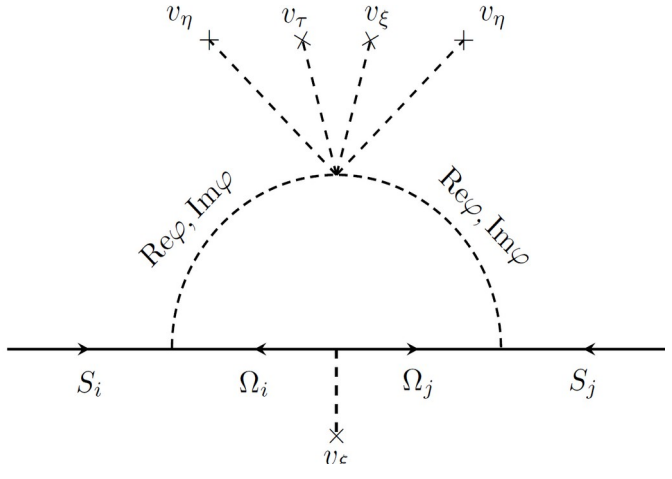
Malinsky et al PhysRevLett95(2005)161801

@jwvalle7

doubly protected inverse seesaw

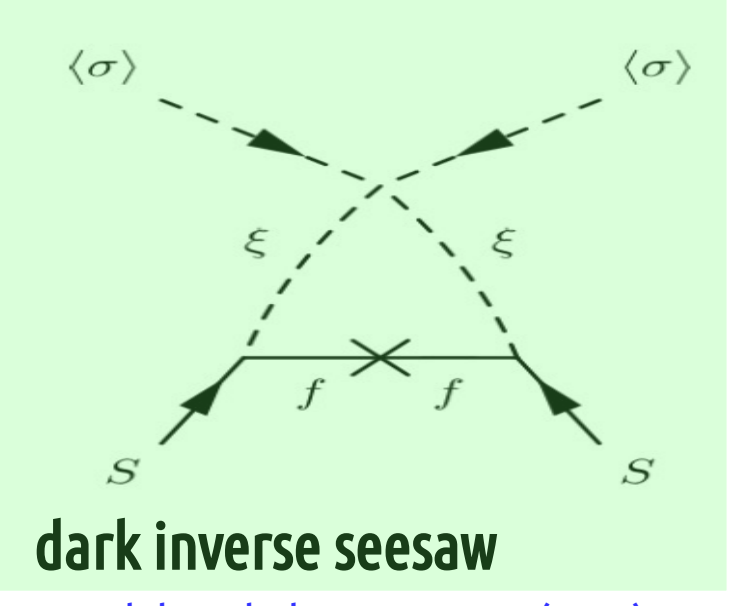


radiative
inverse seesaw



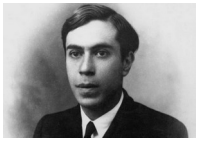
L-R scheme

:Cárcamo Hernández et al JHEP 1902 (2019) 065



dark inverse seesaw

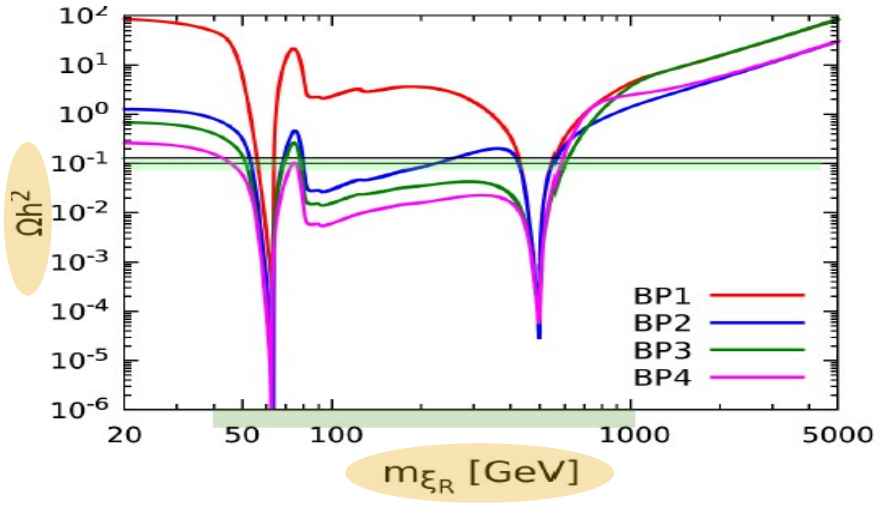
Mandal et al Phys.Lett.B821 (2021) 136609



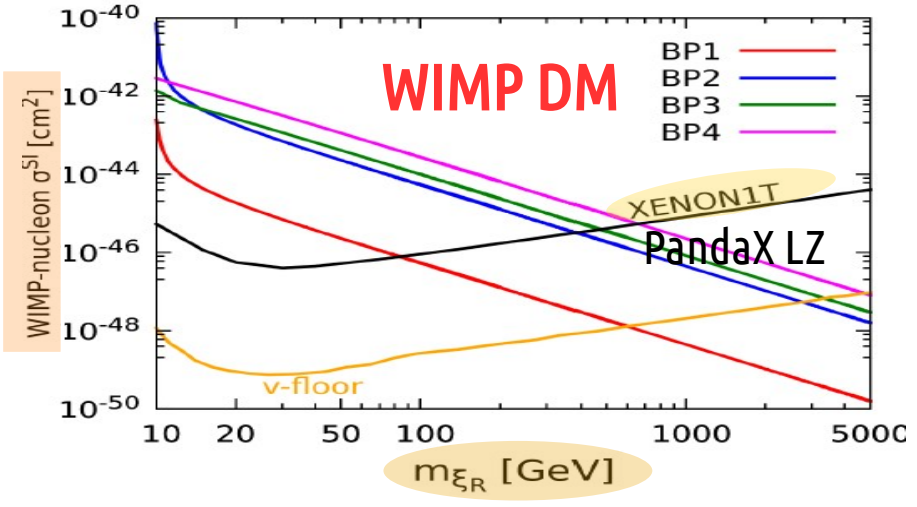
dark inverse typeI seesaw mechanism

LambdaCDM

Phys.Lett.B821 (2021) 136609

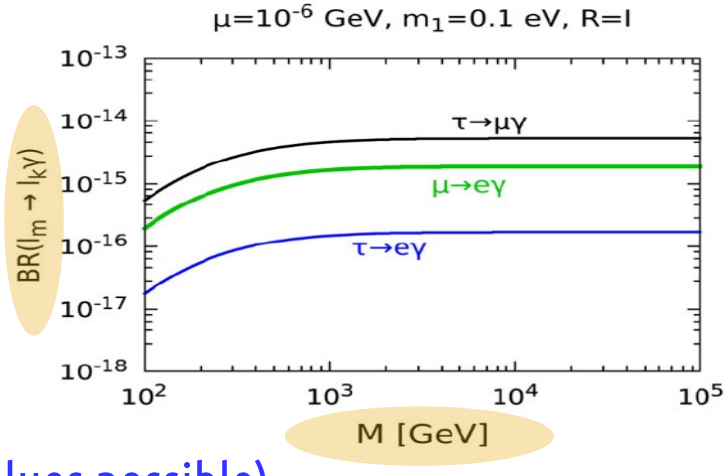


Xenon1T PhysRevLett.121.111302
PandaX Lux-Zepellin



large cLFV from inverse type I seesaw

Mandal et al
Phys.Lett.B 821 (2021) 136609



(larger values possible)

@jwvalle9

linear seesaw & CDF II W mass anomaly

$$m_W^{\rm CDF} = 80.4335 \pm 0.0094 \ {\rm GeV}$$
$$m_W^{\rm SM} = 80.354 \pm 0.007 \ {\rm GeV}$$

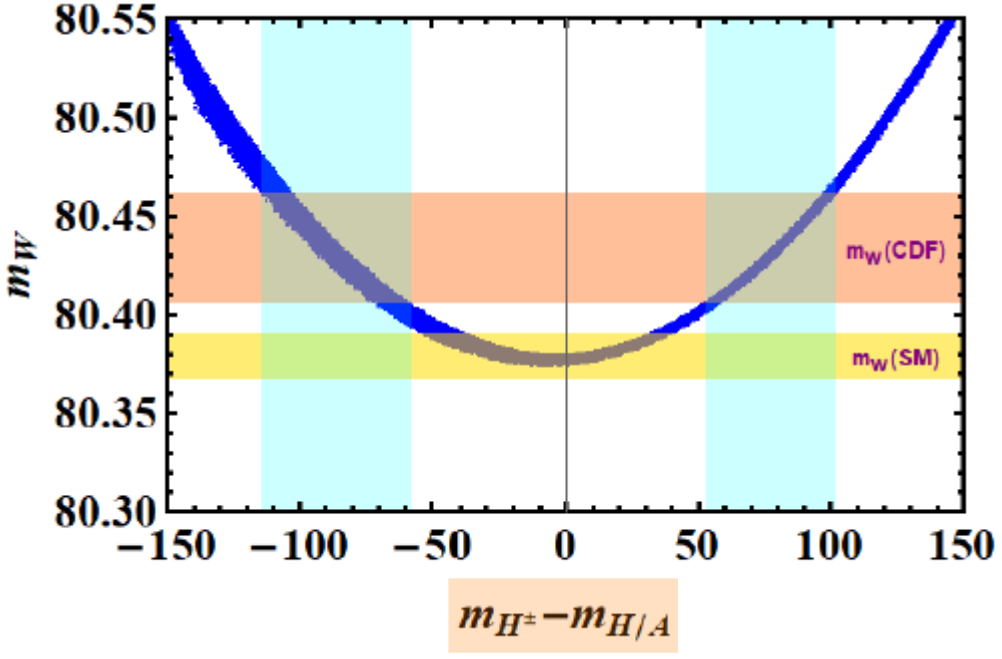
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & M_L \\ m_D^T & 0 & M_R \\ M_L^T & M_R^T & 0 \end{pmatrix}$$

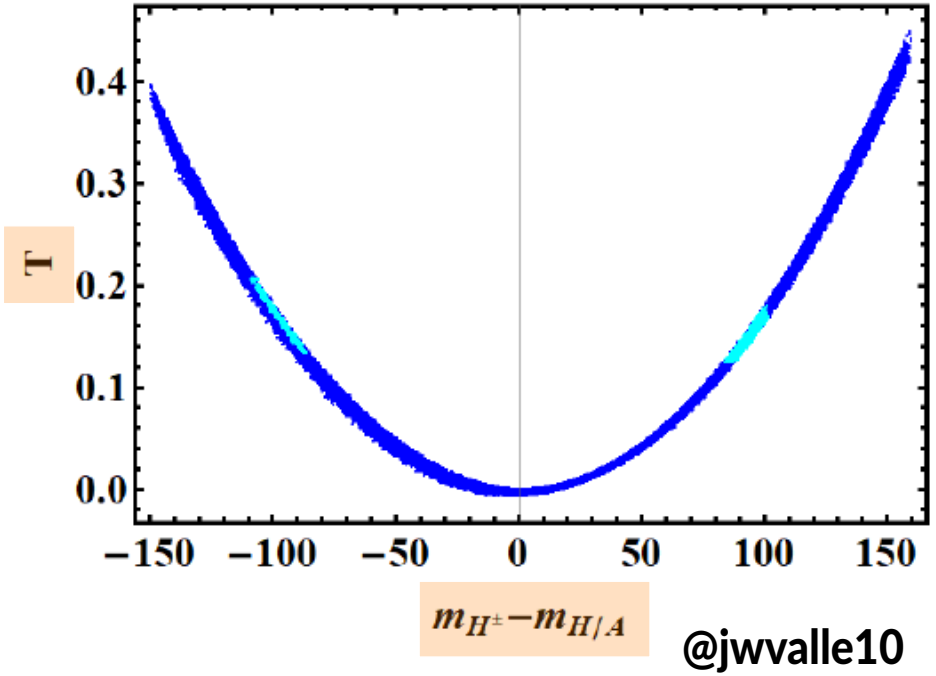
$$m_W^2 = m_W^2|_{\rm SM} \left(1 + \frac{s_W^2}{c_W^2 - s_W^2} \Delta r|_{\rm NP}\right)$$

$$\frac{\alpha}{s_W^2}\left(-\frac{1}{2} S + c_W^2 T + \frac{c_W^2 - s_W^2}{4 s_W^2} U\right)$$

Phys.Lett.B 834 (2022) 137408

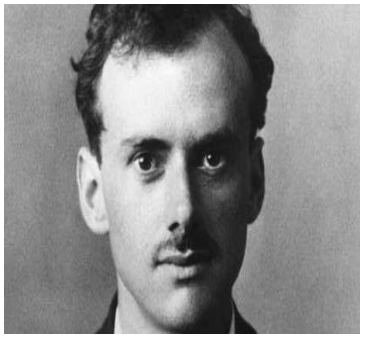
all 1sigma, except for CDF band, which is 3

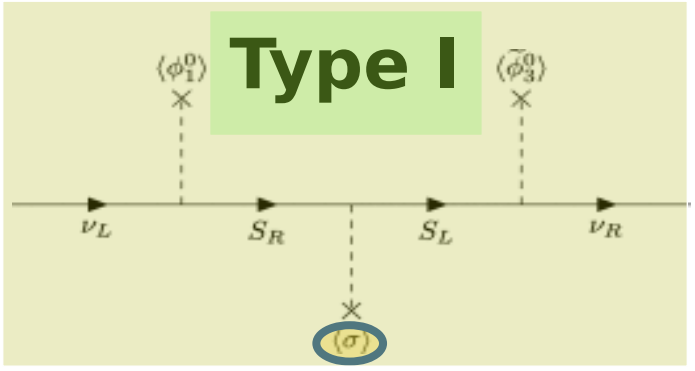


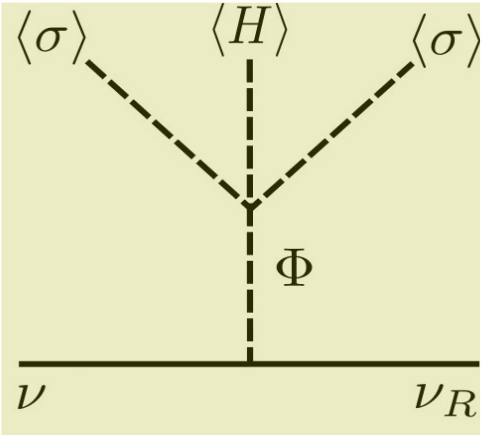


@jwvalle10

seesawing a la



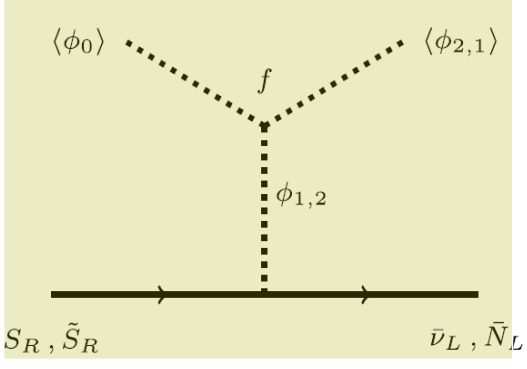




Type II

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



Phys.Lett. B761 (2016) 431-436

Phys.Lett. B767 (2017) 209-213

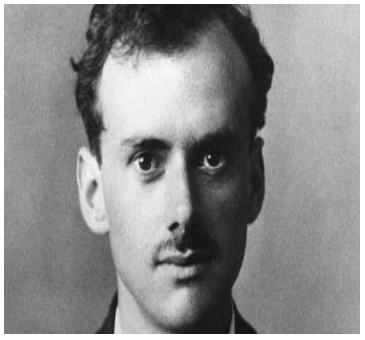
Phys.Rev. D98 (2018) 035009

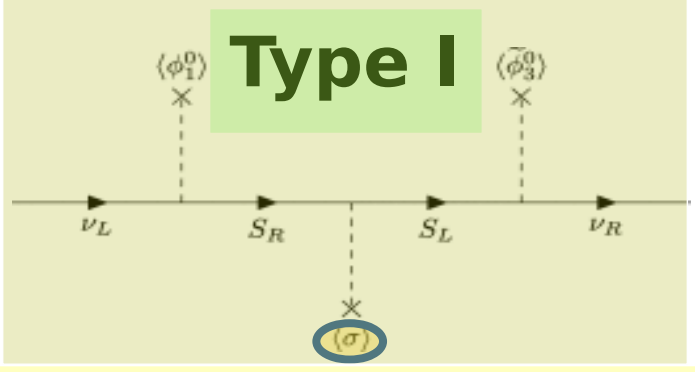
Phys.Lett. B781 (2018) 122-128

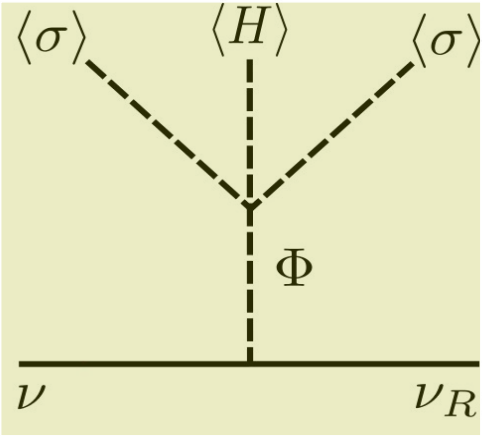
Addazi et al Phys.Lett. B759 (2016) 471-478

Phys.Lett. B755 (2016) 363-366

seesawing a la







Type II

symmetry protecting small neutrino mass

+ Diracness

Peccei-Quinn symmetry

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

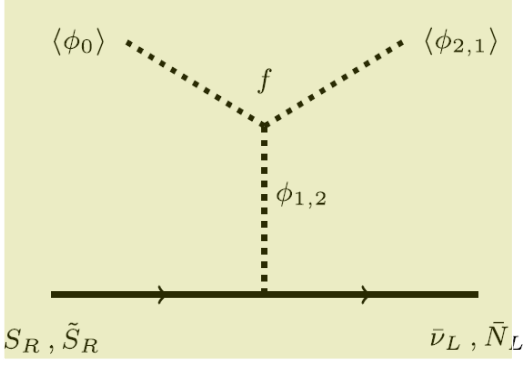
w ← SU3L

v_σ ← PQ

Phys.Lett.B 810 (2020) 135829

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



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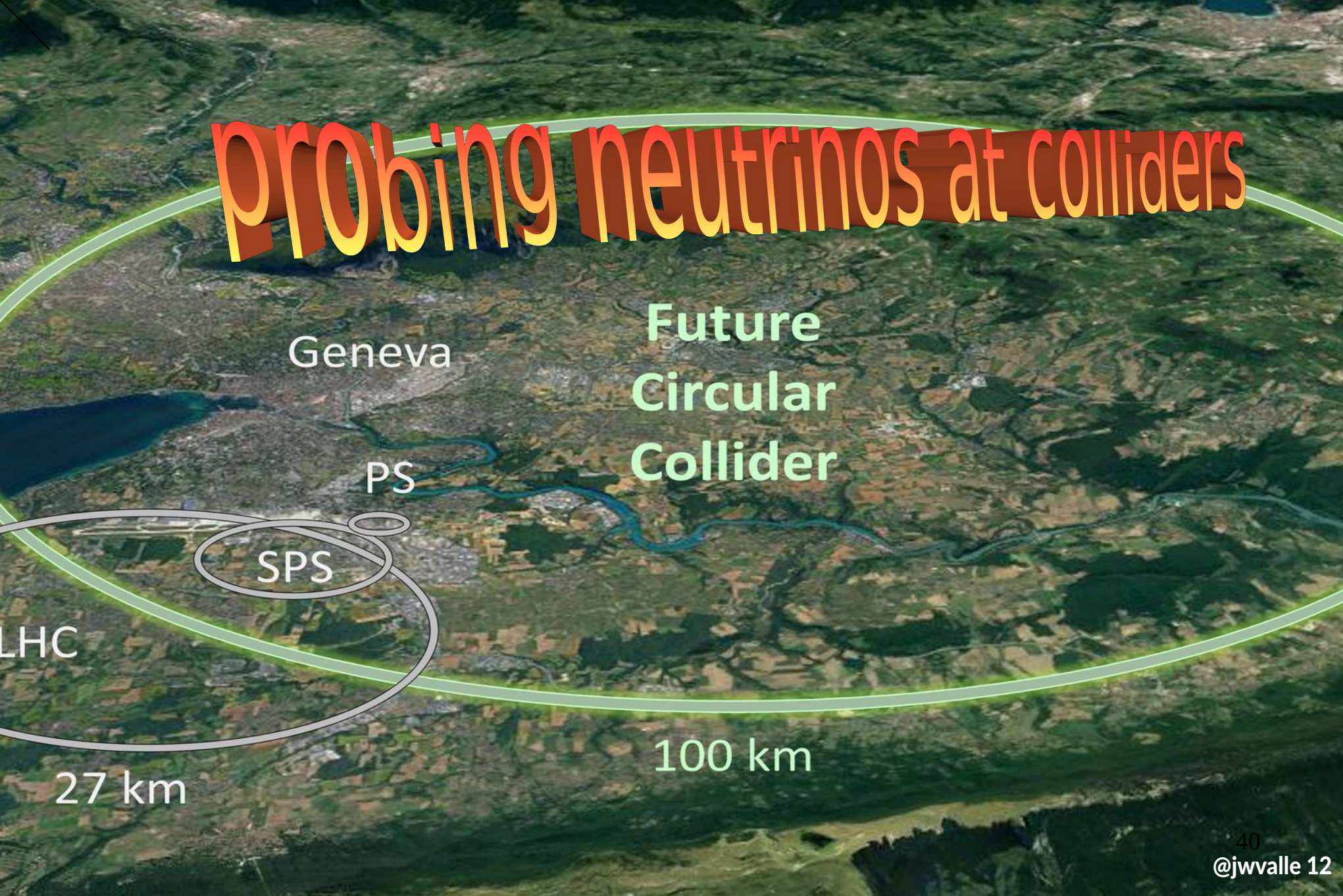
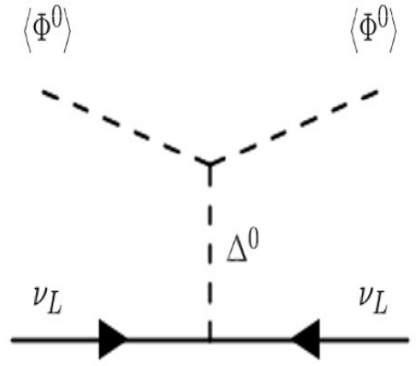

probing neutrinos at colliders
Future
Circular
Collider
Geneva
PS
SPS
LHC
100 km
27 km

simplest seesaw

current oscillation data can reconstruct triplet seesaw so that it can be tested at high-energies

Schechter & JV PRD22 (1980) 2227
PRD25 (1982) 774



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

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

Miranda et al PLB 829 (2022) 137110

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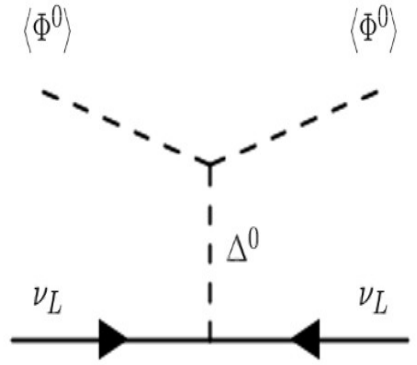
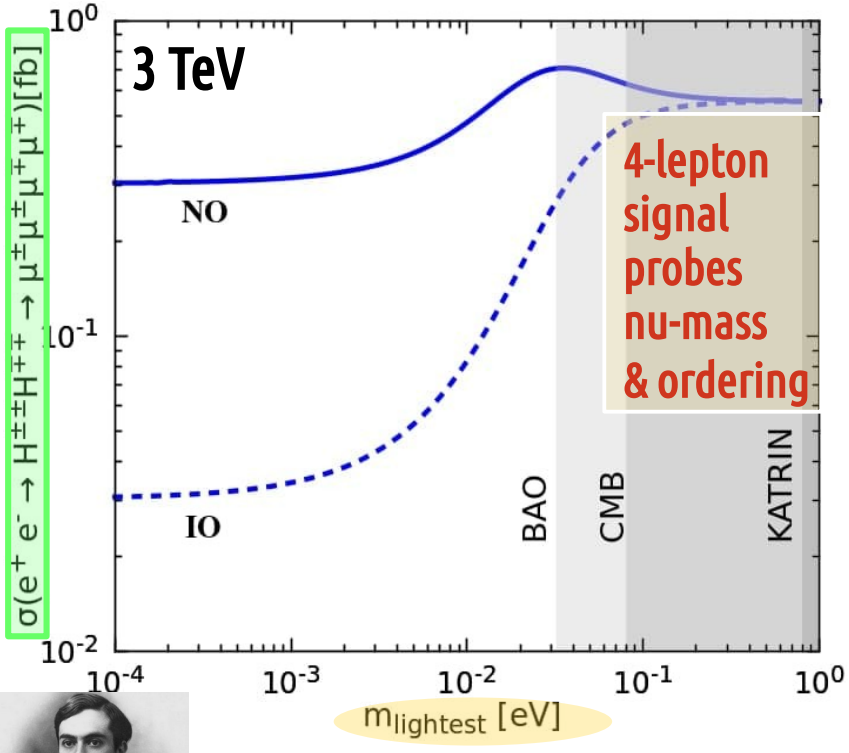


seesaw mediator produced in @ e+e- / pp collisions

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

Miranda et al PLB 829 (2022) 137110



simplest seesaw

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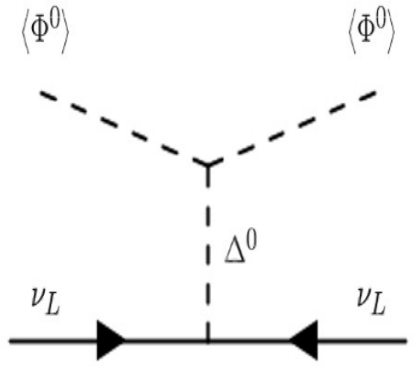

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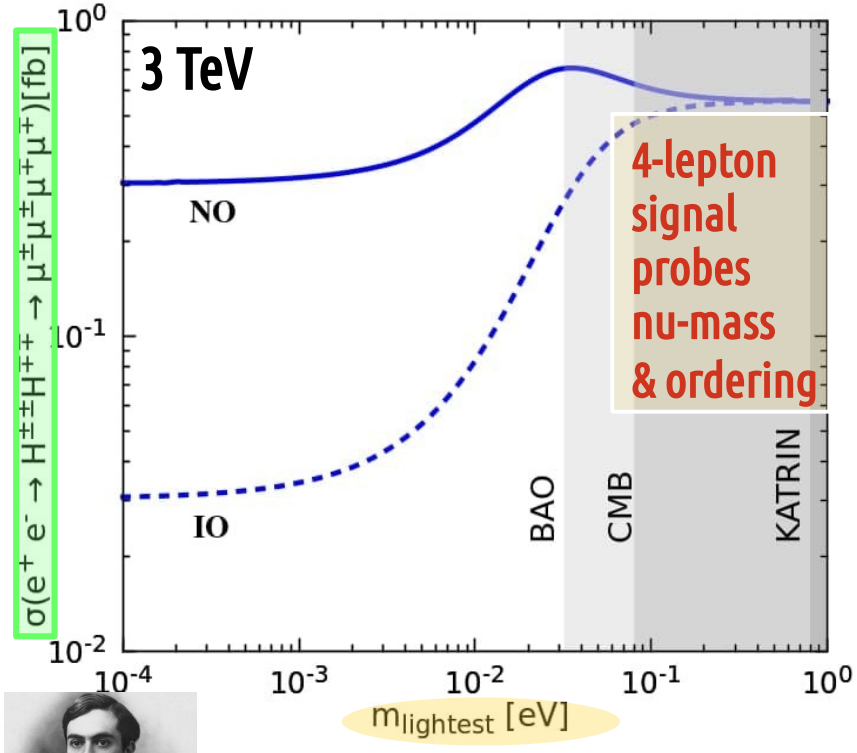
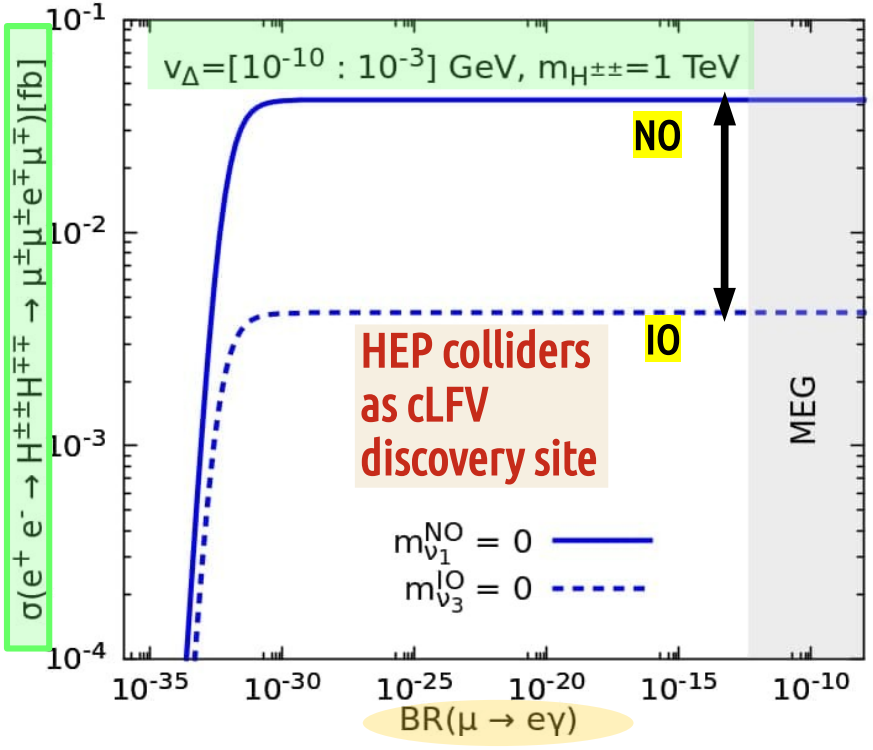
Miranda et al Phys.Rev.D105 (2022) 095020

Miranda et al PLB 829 (2022) 137110



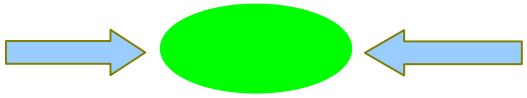


PROBING NEUTRINO PROPERTIES AT COLLIDERS

LSP from cascade squark & gluino decays

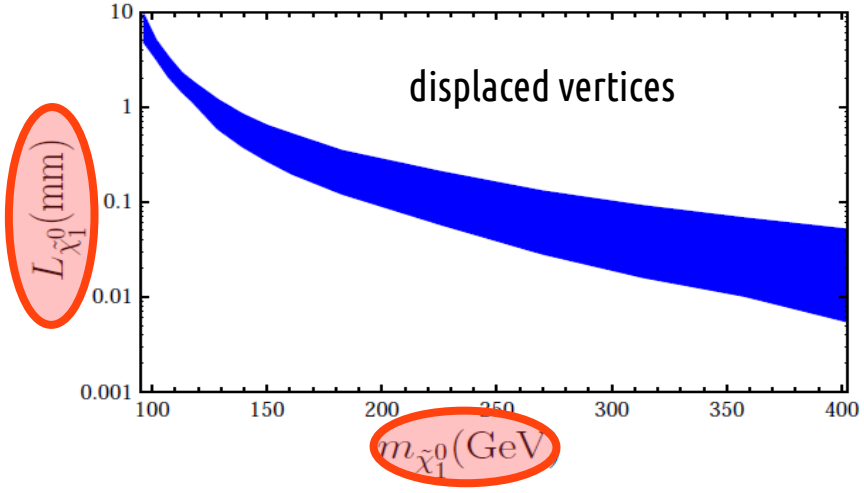
De Campos et al
Phys.Rev. D86 (2012) 075001

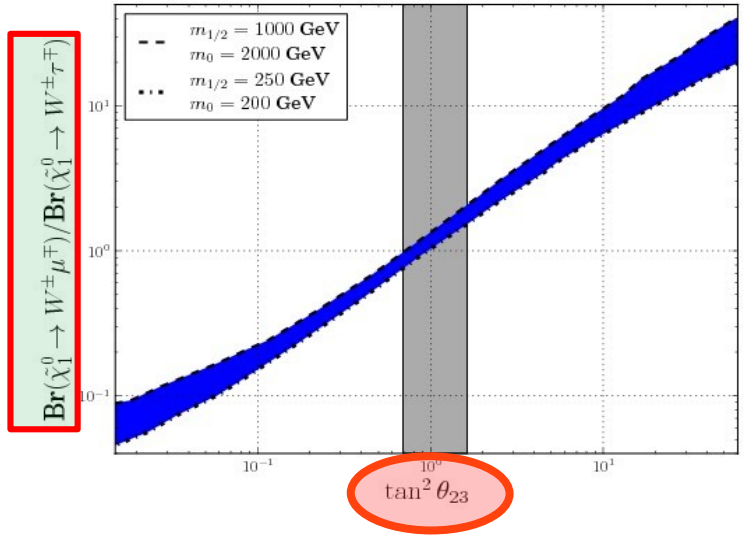
$$\tilde{\chi}_1^0 \to W^{\pm} l_i^{\mp} \qquad \tilde{\chi}_1^0 \to Z^0 \nu_i$$



Lightest neutralino decay correlates with atm angle

Lightest neutralino decay length

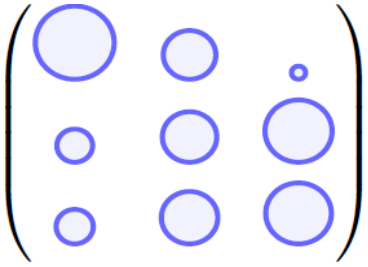




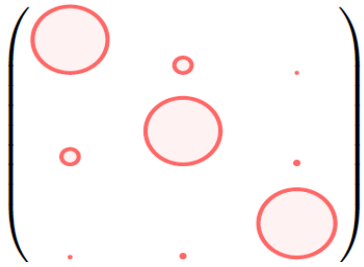
PROBING **Theta_atm** @ **LHC**

flavour legacy of oscillations

Q/L mixing pattern

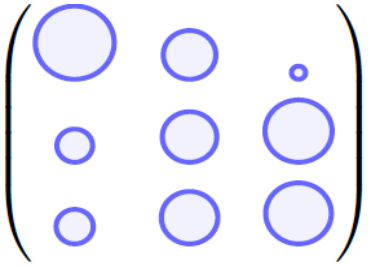


versus

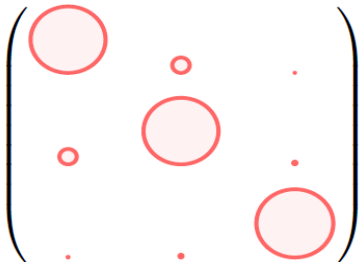


flavour legacy of oscillations

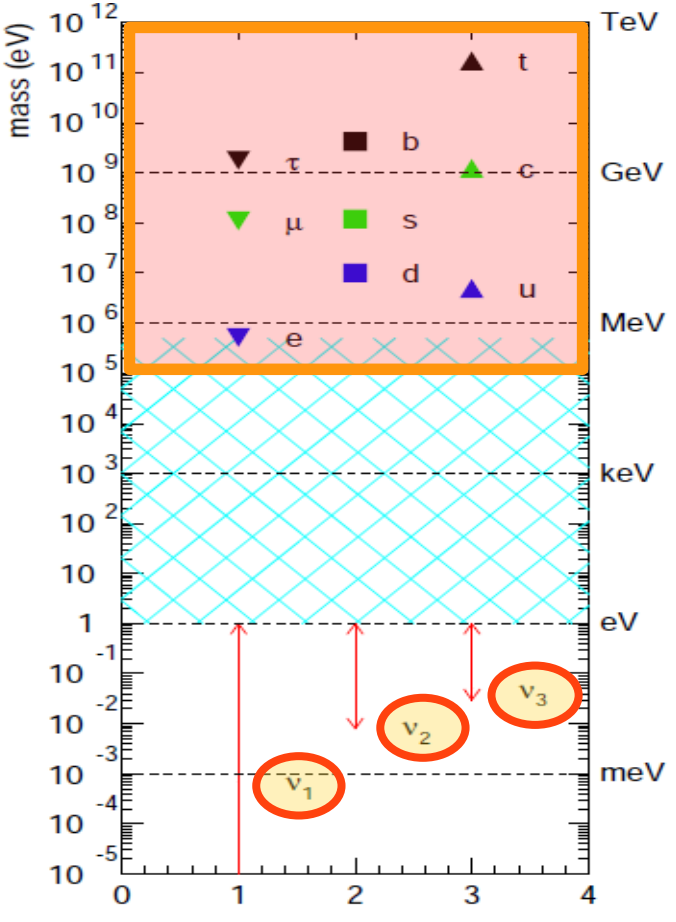
Q/L mixing pattern



versus

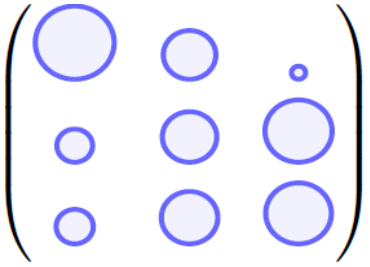


Q/L mass hierarchies

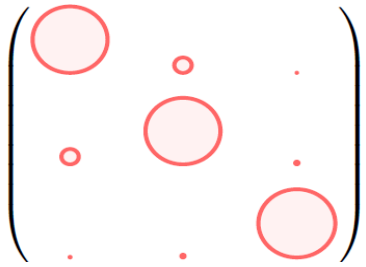


flavour legacy of oscillations

Q/L mixing pattern

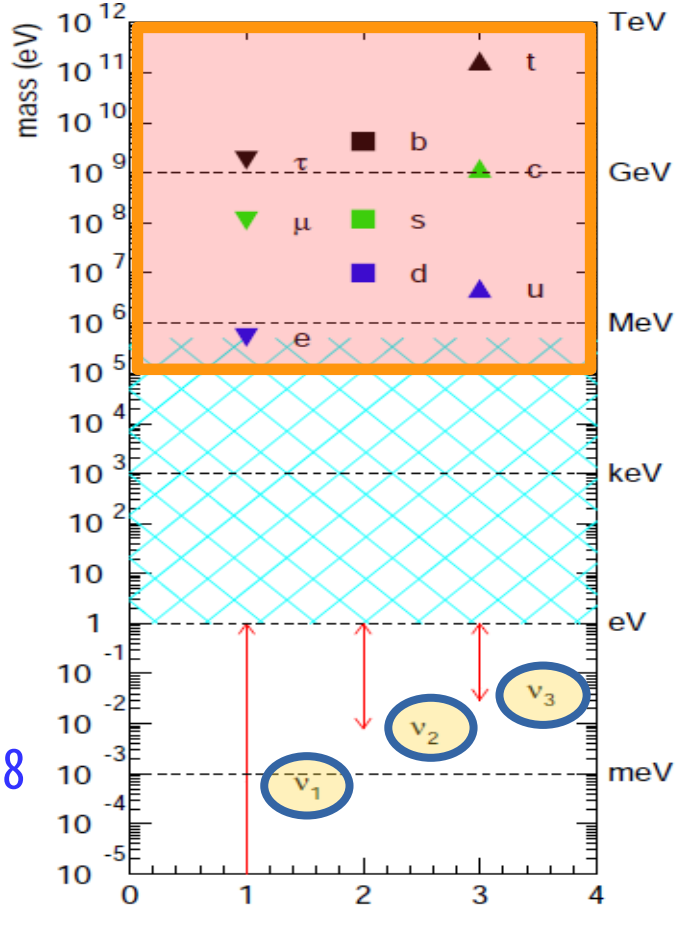


versus



Q/L mass hierarchies

$$\frac{m_\tau}{\sqrt{m_\mu m_e}} \approx \frac{m_b}{\sqrt{m_s m_d}}$$



Morisi et al Phys.Rev. D84 (2011) 036003
King et al Phys. Lett. B 724 (2013) 68
Morisi et al Phys.Rev. D88 (2013) 036001
Bonilla et al Phys.Lett. B742 (2015) 99
Reig, JV, Wilczek Phys.Rev. D98 (2018) 095008
De Anda et al Phys. Rev. D105 (2022) 055030

a more radical departure??

Higgs discovery is not the last brick !

Higgs discovery is not the last brick !

Oscillation discovery brought neutrinos to the spotlight

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

Higgs discovery is not the last brick !

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Collider imprints of neutrino completions:

cLFV signatures from seesaw mediators

neutrinos and flavor

neutrinos and dark matter

neutrinos and strong CP problem

neutrinos and unification

neutrinos and SM anomalies