Abstract

Neutrino physics is a broad and diverse field, both experimentally and theoretically. As the standard oscillation picture begins to settle we are moving into an era where precise tests of the neutrino picture can be made. In this talk I will discuss the present and future status of many theoretical probes and a broad range of experiments spanning twenty orders of magnitude in neutrino energy. In particular, I will highlight the strongly interconnected nature of new physics studies in the neutrino sector.

Beyond the Standard Model physics with accelerator neutrino experiments

Peter B. Denton

APS April 2020

April 19, 2020

White Paper on New Opportunities at the Next-Generation Neutrino Experiments (Part 1: BSM Neutrino Physics and Dark Matter)

C.A. Argüelles, A.J. Aurisano, B. Batell, J. Berger, M. Bishai, T. Boschi, N. Byrnes, A. Chatterjee, A. Chodos, T. Coan, Y. Cui, A. de Gouvêa, P.B. Denton, A. De Roeck, W. Flanagan, R.P. Gandrajula, A. Hatzikoutelis, M. Hostert, B. Jones, B.J. Kayser, K.J. Kelly, D. Kim, J. Kopp, A. Kubik, K. Lang, I. Lepetic, P. Machado, C.A Moura, F. Olness, J.C. Park, S. Pascoli, S. Prakash, L. Rogers, I. Safa, A. Schneider, K. Scholberg, S. Shin, I.M. Shoemaker, G. Sinev, B. Smithers, A. Sousa, Y. Sui, V. Takhistov, J. Thomas, J. Todd, Y.-D. Tsai, Y.-T. Tsai, D. Vanegas Forero, J. Yu, C. Zhang

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With the advent of a new generation of neutrino experiments which leverage high-intensity neutrino beams for precision measurements, it is timely to explore physics topics beyond the standard neutrino-related physics. Given that the realm of beyond the standard model (BSM) physics has been mostly sought at high-energy regimes at colliders, such as the LHC at CERN, the exploration of BSM physics in neutrino experiments will enable complementary measurements at the energy regimes that balance that of the LHC. This is in concert with new ideas for high-intensity beams for fixed target and beam-dump experiments world-wide, e.g., those at CERN. The combination of the high intensity proton beam facilities and massive detectors for precision neutrino oscillation parameter measurements and for CP violation phase measurements will help make BSM physics reachable even in low energy regimes in accelerator based experiments. Large mass detectors with highly precise tracking and energy measurements, excellent timing resolution, and low energy thresholds will enable searches for BSM phenomena from cosmogenic origin, as well. Therefore, it is conceivable that BSM topics in the next generation neutrino experiments could be the dominant physics topics in the foreseeable future, as the precision of the neutrino oscillation parameter and CPV measurements continues to improve. In this spirit, this white paper provides a review of the current landscape of BSM theory in neutrino experiments in two selected areas of the BSM topics - dark matter and neutrino related BSM - and summarizes the current results from existing neutrino experiments to set benchmarks for both theory and experiment. This paper then provides a review of upcoming neutrino experiments throughout the next 10 - 15 year time scale and their capabilities to set the foundation for potential reach in BSM physics in the two aforementioned themes.

1907.08311

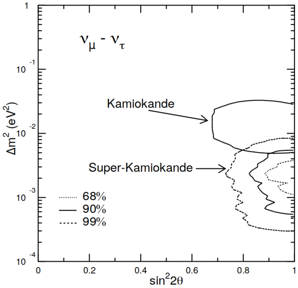
Why Neutrinos Are Awesome

1. 7+ new parameters
   - Oscillations $\to 6$
   - Mass scale $\to 1+$
2. Mass generation mechanism
3. Nature of neutrinos
4. Poorly measured $\Rightarrow$ great place to look for new physics
5. Resolve anomalies
6. Role of neutrinos in the early universe
7. Extreme particle physics production
8. High degree of interconnectivity

Discovery of Oscillations

Super-KamiokaNDE

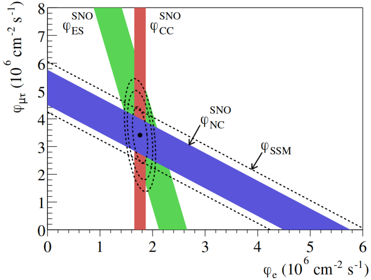
$P(\nu_\mu \to \nu_\mu)$ $\Delta m^2 \sim 10^{-3}$ eV^2



SK hep-ex/9807003

SNO

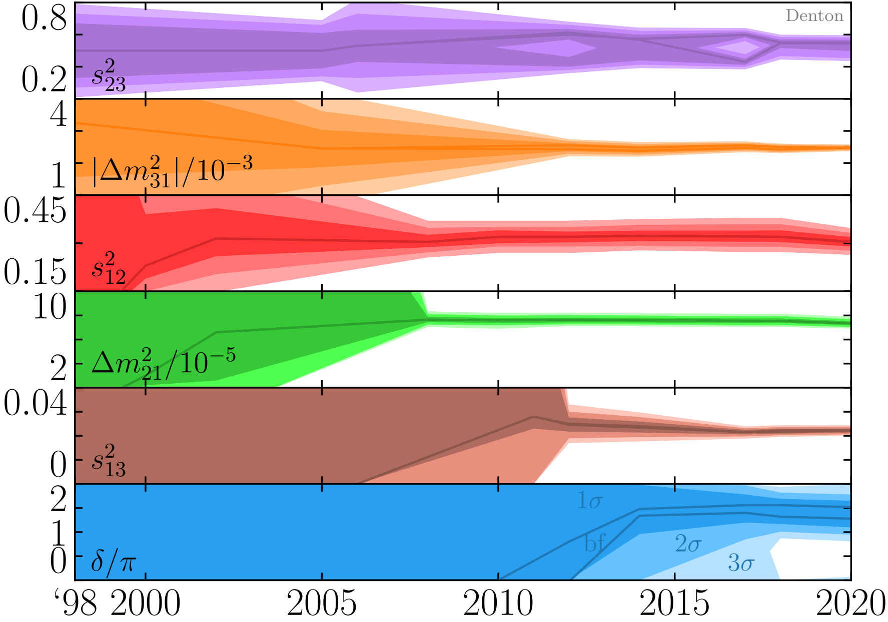
$P(\nu_e \to \nu_e)$ $\Delta m^2 \sim 10^{-5}$ eV^2



SNO nucl-ex/0204008

Oscillations $\Rightarrow v_\nu < c$

Three distinct masses


Denton
0.8
0.2
s_{23}^2
4
1
$|\Delta m_{31}^2|/10^{-3}$
0.45
0.15
s_{12}^2
10
2
$\Delta m_{21}^2/10^{-5}$
0.04
0
s_{13}^2
2
1
0
δ/π
1σ
bf
2σ
3σ
‘98
2000
2005
2010
2015
2020

Mass Generation

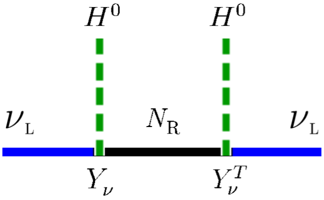
Dirac

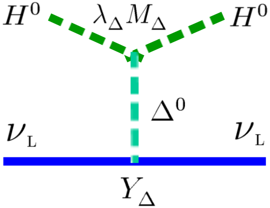
$$\mathcal{L} \supset -\bar{\ell}_L Y_\ell H E_R - \bar{\ell}_L Y_\nu \tilde{H} N_R + h.c.$$

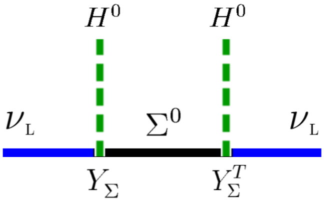
Impose $B-L$

$y_\nu / y_e \lesssim 10^{-6}$

Seesaw







M_ν: $\quad -\frac{1}{2} Y_\nu \frac{v^2}{M_R} Y_\nu^T \qquad \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta} \qquad -\frac{1}{2} Y_\Sigma \frac{v^2}{M_\Sigma} Y_\Sigma^T$

Inverse

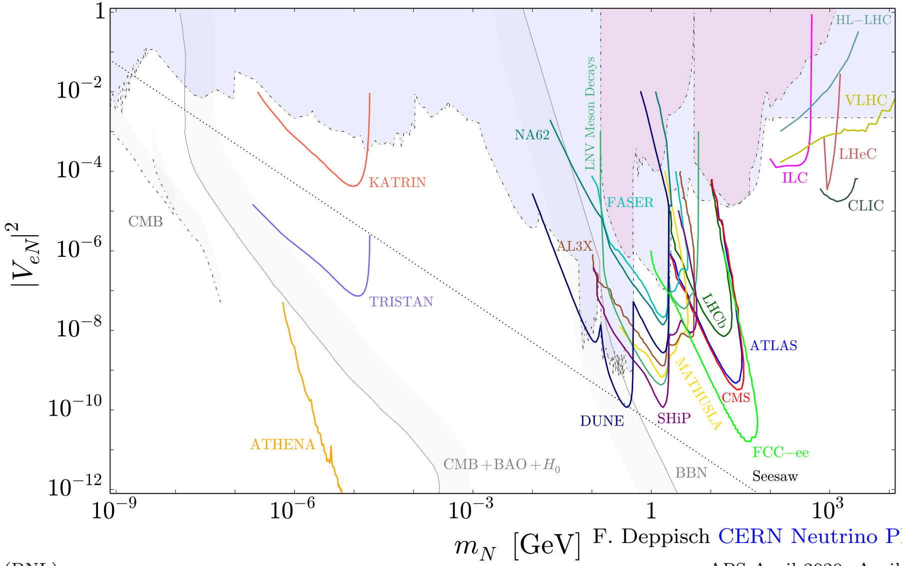
$$M_\nu : \; M_D \frac{1}{M_S^T} \mu \frac{1}{M_S} M_D^T$$

H. Fritzsch, M. Gell-Mann, P. Minkowski PLB 1975
P. Minkowski PLB 1977
W. Konetschny, W. Kummer PLB 1977
D. Wyler, L. Wolfenstein NPB 1983
R. Foot, H. Lew, X. He, G. Joshi ZPC 1989

New Neutrino Physics

1. **Sterile neutrinos**
2. Neutrino Non-Standard Interactions (NSI)
3. Neutrino decay
4. Unitarity violation
5. Intensity frontier (beam dump)
6. Synergies

Sterile Neutrinos: Where are they Hiding?



F. Deppisch CERN Neutrino Platform ’19

Sterile Neutrinos: the eV puzzle

Experimental evidence for $m_4 \sim 1$ eV:

- LSND + MiniBooNE: 3.8 σ + 4.7 σ

LSND hep-ex/0104049

MiniBooNE 1805.12028

- Reactor Antineutrino Anomaly: 3 σ

G. Mention, et al. 1101.2755

Daya Bay 1704.01082

A. Hayes, E. McCutchan, A. Sonzogni, et al. 1707.07728

- Gallium anomaly: 3 σ

C. Giunti, M. Laveder 1006.3244

2.3 σ: J. Kostensalo, et al. 1906.10980

- NEOS, DANSS, Neutrino-4: $\sim 3\ \sigma$, 2.8 σ, 2.8 σ

NEOS Neutrino, '18

DANSS Neutrino, '18

Neutrino-4 1809.10561

Sterile Neutrinos: eV Constraints

Experimental constraints from:

- IceCube 1605.01990
- MINOS/MINOS+ 1710.06488
- Super-K 1410.2008
- KARMEN hep-ex/0203021
- CDHS PLB 134, 281 (1984)
- Daya Bay, MINOS, Bugey-3 1607.01177
- OPERA 1303.3953
- ICARUS 1209.0122
- NOvA 1706.04592
- PROSPECT 1806.02784

  ⋮

$3 + N$ doesn't help

J. Kopp, et al. 1303.3011

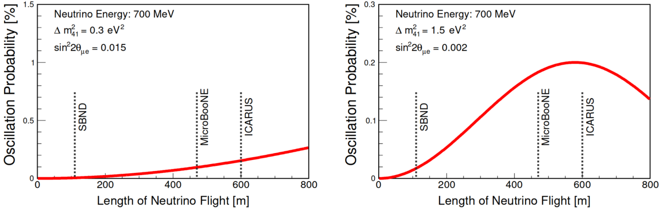
Cosmology needs to be accommodated

Short Baseline Neutrino Program

1. Leverage LAr to discriminate photons from electrons

μB 1910.02166

2. L is easier to measure than E



P. Machado, O. Palamara, D. Schmitz 1903.04608

3. Test bed for LAr technology

Distance is Easier Than Energy

Oscillations depend on L/E:

Distance

1. Easy to measure
(accelerator, atm $\to \cos\theta_z$)
2. Hard to vary in accelerator

Energy

1. Broad-band beams
2. Cross sections are hard
3. Fluxes are hard

All sterile evidence is measured at a single distance

All sterile constraints are measured at multiple distances

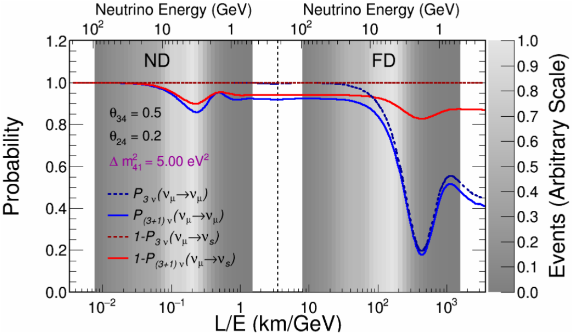
Sterile in a Long-Baseline Experiment

Appearance guarantees disappearance:

$$P_{\mu e} \simeq 4|U_{e4}|^2|U_{\mu4}|^2\sin^2(\Delta_{41})$$

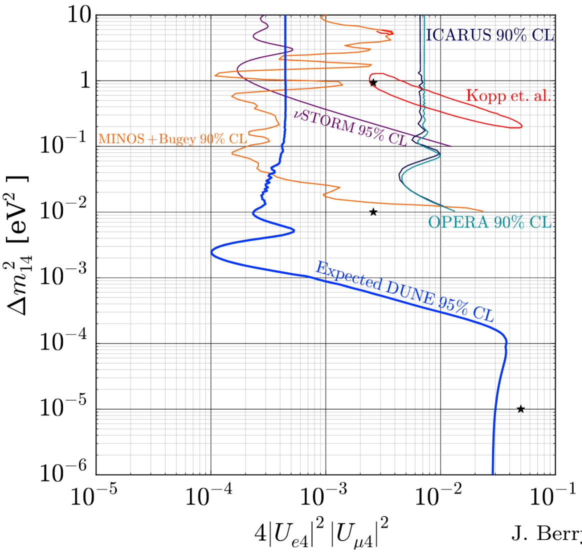
$$P_{\alpha\alpha} \simeq 1 - 4|U_{\alpha4}|^2(1-|U_{\alpha4}|^2)\sin^2(\Delta_{41})$$

$$\Delta_{ij} = \Delta m^2_{ij}L/4E$$



MINOS+

Sterile Now and in the Future



J. Berryman, et al. 1507.03986

New Neutrino Physics

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Neutrino Non-Standard Interactions

Generalized framework
connects oscillations to scattering

$$\mathcal{L}_{\rm NC,NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha\beta}^{f,P} (\bar\nu_\alpha \gamma^\mu P_L \nu_\beta)(\bar f \gamma_\mu P f)$$

$P \in \{P_L, P_R\}$, $f \in \{e, u, d\}$, NC & CC, SPVAT

L. Wolfenstein PRD 1978

M. Lindner, W. Rodejohann, X-J. Xu 1612.04150

135 parameters!

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

B. Dev, PBD, et al. 1907.00991

Neutrino Non-Standard Interactions: UV Completion

Simplified model Lagrangian:

$$\mathscr{L}_{\rm NSI} = g_\nu Z'_\mu \bar\nu \gamma^\mu \nu + g_f Z'_\mu \bar f \gamma^\mu f$$

which gives a potential

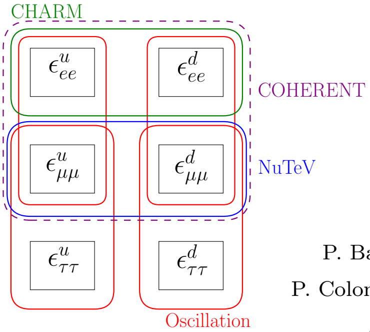
$$V_{\rm NSI} \propto \frac{g_\nu g_f}{q^2 + m_{Z'}^2}$$

Models with large NSIs consistent with CLFV:

Y. Farzan, I. Shoemaker 1512.09147 Y. Farzan, J. Heeck 1607.07616 D. Forero and W. Huang 1608.04719
K. Babu, A. Friedland, P. Machado, I. Mocioiu 1705.01822 PBD, Y. Farzan, I. Shoemaker 1804.03660
U. Dey, N. Nath, S. Sadhukhan 1804.05808 Y. Farzan 1912.09408

NSIs: Oscillation - Scattering Synergy

	Oscillations	**Scattering**
Mediator mass	Nearly any	$M_{Z'} \gtrsim \sqrt{Q^2}$
Degeneracies	LMA-Dark Diagonal	Direct probe
ν_τ sector	Can probe	Need ν_τ's

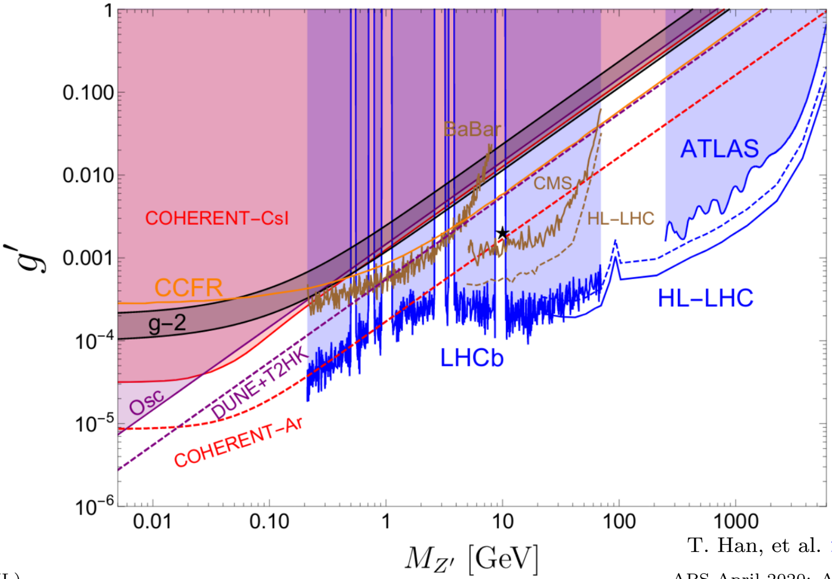


LMA-Dark:

P. Bakhti, Y. Farzan 1403.0744

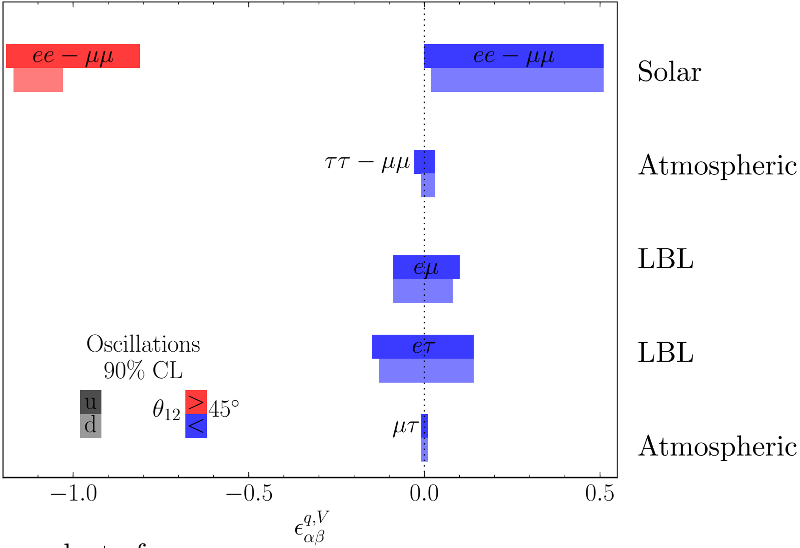
P. Coloma, T. Schwetz 1604.05772

Neutrino Non-Standard Interactions: Scattering



T. Han, et al. 1910.03272

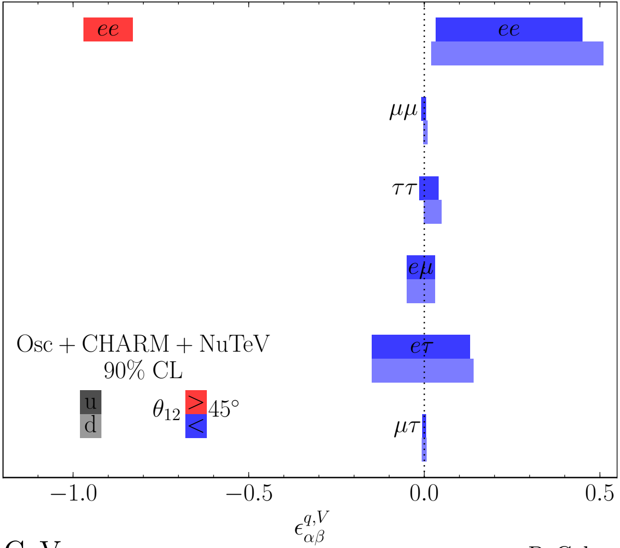
NSI Global Fit: Oscillations



Oscillations are independent of $m_{Z'}$

P. Coloma, PBD, et al. 1701.04828

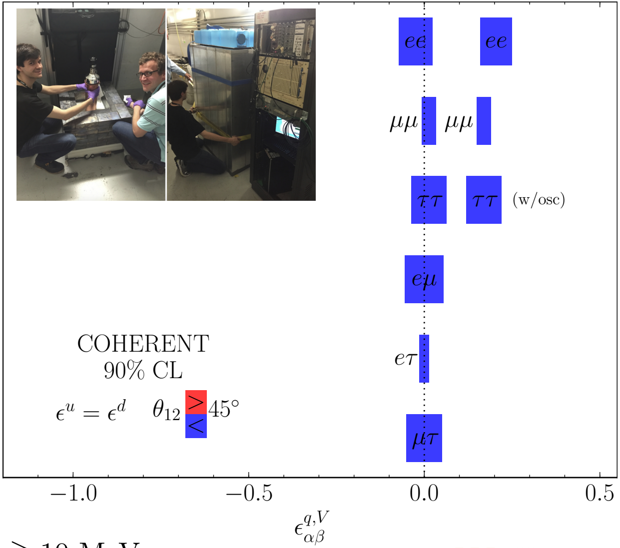
Heavy NSI Global Fit: CHARM & NuTeV



Heavy $\Rightarrow m_{Z'} \gtrsim 1$ GeV.

P. Coloma, PBD, et al. 1701.04828

NSI Constraints: COHERENT

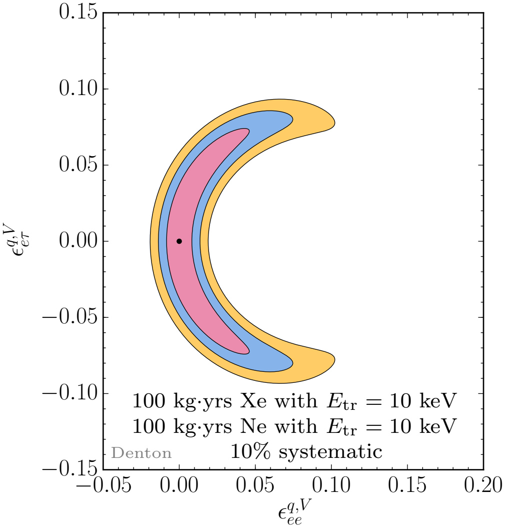


Valid down to $m_{Z'} \gtrsim 10$ MeV

PBD, Y. Farzan, I. Shoemaker 1804.03660

Looking to the COHERENT Future

Interference of different materials is powerful



$$\epsilon_{ee,\rm deg}^{q,V} = \frac{1}{3}\frac{Y_n - (1 - 4\sin^2\theta_W)}{Y_n + 1}$$

$$Y_n \in [1, 1.43]$$

$$\epsilon_{ee,\rm deg}^{q,V} \in [0.15, 0.18]$$

$Y_n = N_n/N_p$

Solar upturn?

NSI Degeneracies in LBL Parameters

- Mass ordering $\Leftrightarrow$ $\epsilon_{ee} - \epsilon_{\mu\mu}$
- θ_{23} $\Leftrightarrow$ $\epsilon_{e\mu}$, $\epsilon_{e\tau}$
- δ $\Leftrightarrow$ $\epsilon_{e\mu}$, $\phi_{e\mu}$, $\epsilon_{e\tau}$, $\phi_{e\tau}$
- θ_{13} $\Leftrightarrow$ $\epsilon_{e\mu}$, $\epsilon_{e\tau}$

P. Coloma, et al. 1105.5936
Z. Rahman, A. Dasgupta, R. Adhikari 1503.03248
P. Coloma 1511.06357
S. Agarwalla, S. Chatterjee, A. Palazzo 1607.01745
J. Hyde 1806.09221

Can be lifted with different matter potentials and 1$^{\text{st}}$ and 2$^{\text{nd}}$ max

1. DUNE
2. T2HK(K)
3. ESSnuSB

New Neutrino Physics

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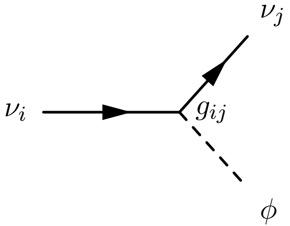
Neutrino Decay

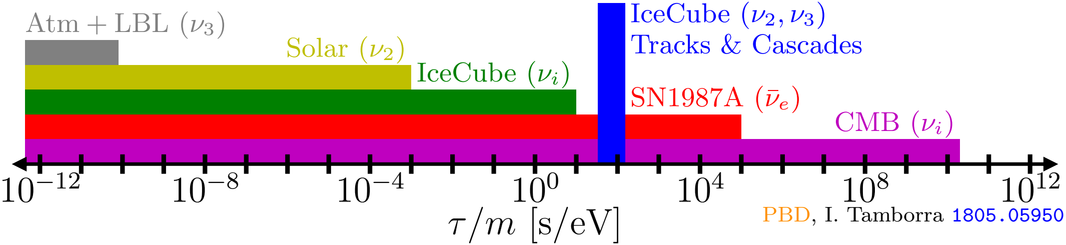
$$\mathcal{L} \supset g_{ij}\bar{\nu}_j\nu_i\phi + h_{ij}\bar{\nu}_j i\gamma_5\nu_i\phi + \text{h.c.}$$



Y. Chikashige, R. Mohapatra, R. Peccei, PLB 1981

Final states can be:

- **Invisible**: ν_R, $\bar{\nu}_L$
- **Visible**: ν_L, $\bar{\nu}_R$



PBD, I. Tamborra 1805.05950

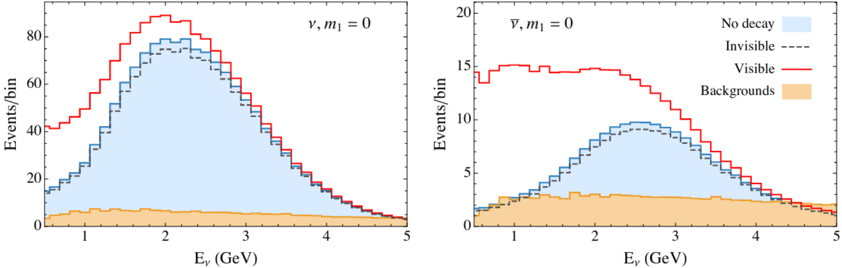
Visible Decay

Depletion:

$$\frac{\Delta m^2 L}{2E} \to \frac{\Delta m^2 L}{2E} - \frac{i}{2}\Gamma L$$

Regeneration:

$$\text{Complicated, integral over initial spectrum}$$



The $\nu_\mu \to \nu_e$ channel for $\nu_3 \to \nu_1$ decay P. Coloma, O. Peres 1705.03599

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Unitarity Violation

Our measured 3×3 matrix is a submatrix of a larger unitary matrix,

$$U = \begin{pmatrix} U_{3\times3} & & \\ & & \\ & & \end{pmatrix}$$

$$\sum_{i=1}^{3} |U_{\alpha i}|^2 = 1 \qquad \sum_{\alpha\in\{e,\mu,\tau\}} |U_{\alpha i}|^2 = 1$$

Unitarity Violation

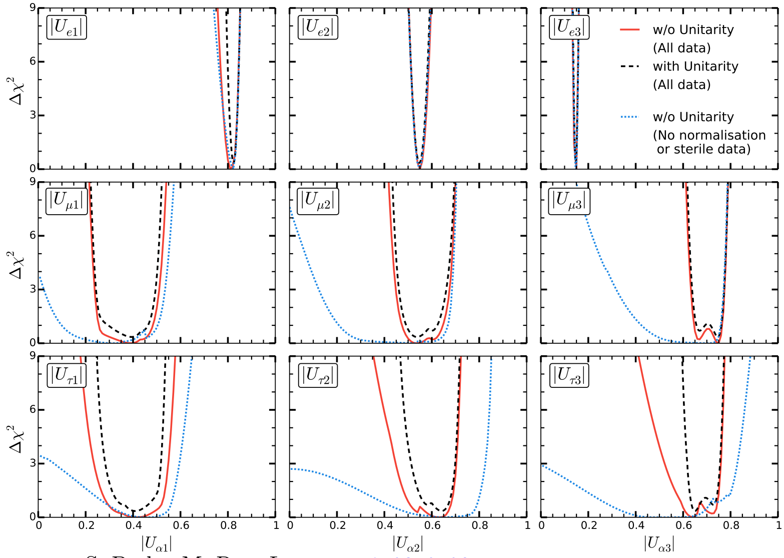
Our measured 3×3 matrix is a submatrix of a larger unitary matrix,

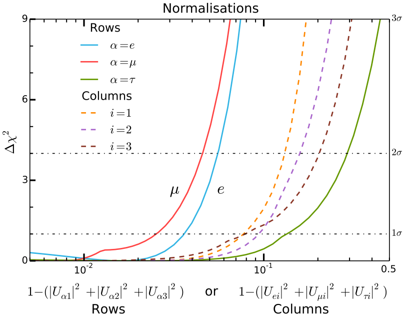
$$U = \begin{pmatrix} & & & \cdots \\ & U_{3\times 3} & & \cdots \\ & & & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

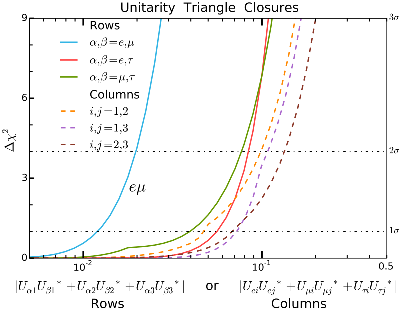
$$\sum_{i=1}^{3} |U_{\alpha i}|^2 \leq 1 \qquad \sum_{\alpha \in \{e,\mu,\tau\}} |U_{\alpha i}|^2 \leq 1$$

Triangles no longer close

Unitarity Constraints







S. Parke, M. Ross-Lonergan 1508.05095

Unitarity Violation Framework

Parameterize this:

$$N = \left[1 - \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix}\right] U$$

$$H = \frac{1}{2E}\left[\begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} + N^\dagger \begin{pmatrix} V_{NC} + V_{CC} & & \\ & V_{NC} & \\ & & V_{NC} \end{pmatrix} N\right]$$

Unitarity Violation Framework

Parameterize this:

$$N = \left[1 - \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix}\right] U$$

$$H = \frac{1}{2E}\left[\begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} + N^\dagger \begin{pmatrix} V_{NC} + V_{CC} & & \\ & V_{NC} & \\ & & V_{NC} \end{pmatrix} N\right]$$

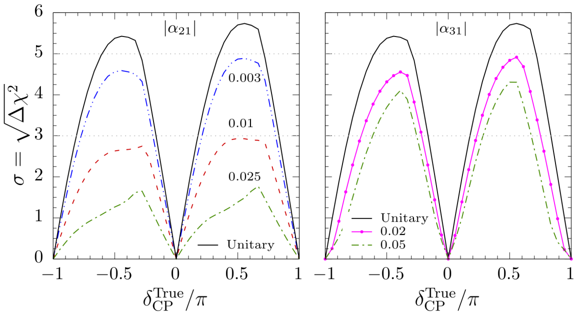
Mapping between UV↔NSI↔Sterile

$$\epsilon_{ee} = -\alpha_{11} \qquad \epsilon_{\mu\mu} = \alpha_{22} \qquad \epsilon_{\tau\tau} = \alpha_{33}$$

$$\epsilon_{e\mu} = \frac{1}{2}\alpha^*_{21} \qquad \epsilon_{e\tau} = \frac{1}{2}\alpha^*_{31} \qquad \epsilon_{\mu\tau} = \frac{1}{2}\alpha^*_{32}$$

M. Blennow, et al. 1609.08637

Unitarity Violation At DUNE



F. Escrihuela, et al. 1612.07377

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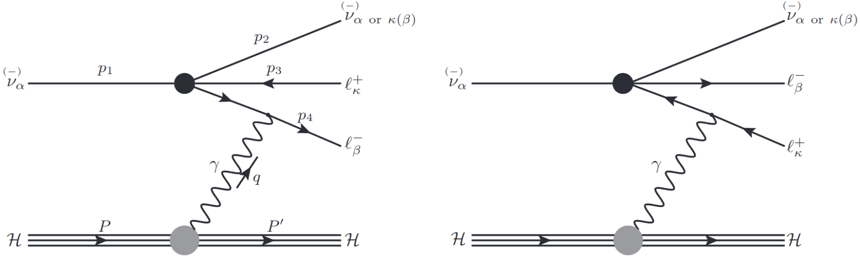
Tridents



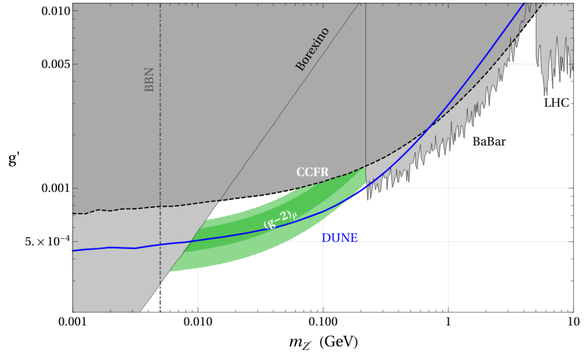
To date ~ 100 $\mu^+\mu^-$ detected

DUNE will detect $\mathcal{O}(10^3)$ events: $e\mu$, ee, and $\mu\mu$

P. Ballett, et al. 1807.10973

Tridents with New Physics

$L_\mu - L_\tau$ model sensitivity



3 + 3 years of DUNE ND trident measurements

W. Altmannshofer, et al. 1902.06765

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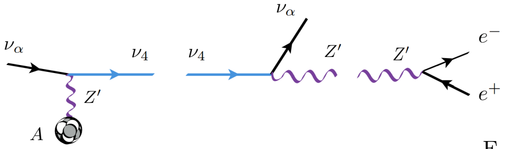
LSND/MiniBooNE Sterile+NSI Explanations

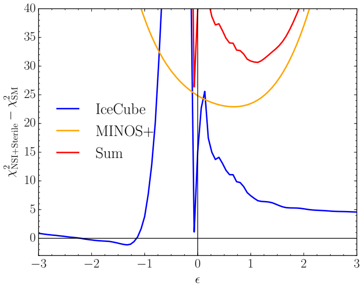
Upscatter to unstable ν_s which promptly decays via Z'



E. Bertuzzo, et al. 1807.09877

C. Argüelles, M. Hostert, Y. Tsai 1812.08768

$m_4 \sim 1$ eV with ϵ_{ss}



J. Liao, D. Marfatia 1602.08766

PBD, Y. Farzan, I. Shoemaker 1811.01310

Didn't Discuss

Not enough time,

1. Decoherence
2. LIV, CPT
3. Large extra dimensions
4. ν - dark sector connections
5. Dark sector searches

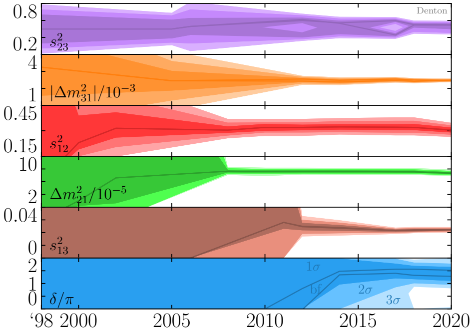
Key Points

- Oscillation parameters becoming measured
- Accelerator neutrinos probe a broad range of BSM models
- Sterile hints will be resolved “soon”
- Interesting to look at 2+ BSM models at once

Thanks!

Backups

References



SK hep-ex/9807003

M. Gonzalez-Garcia, et al. hep-ph/0009350

M. Maltoni, et al. hep-ph/0207227

SK hep-ex/0501064

SK hep-ex/0604011

T. Schwetz, M. Tortola, J. Valle 0808.2016

M. Gonzalez-Garcia, M. Maltoni, J. Salvado 1001.4524

T2K 1106.2822

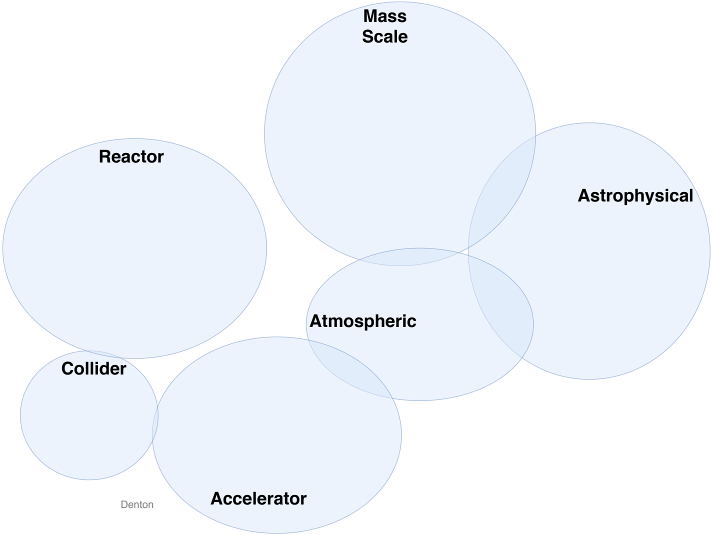
D. Forero, M. Tortola, J. Valle 1205.4018

D. Forero, M. Tortola, J. Valle 1405.7540

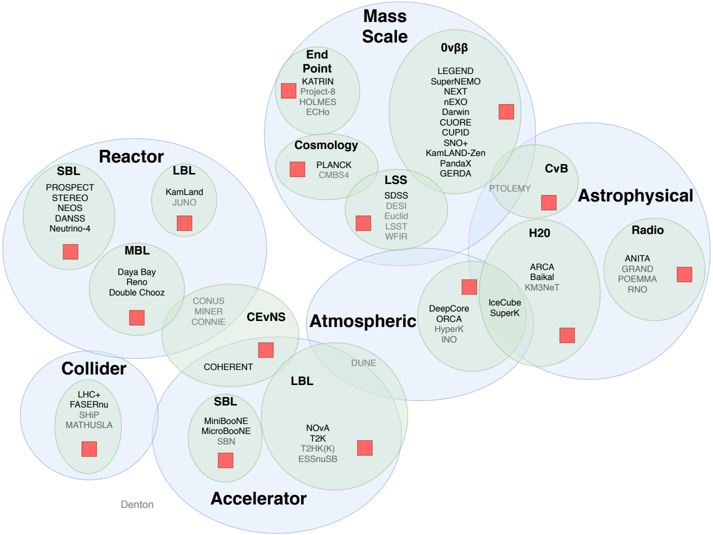
P. de Salas, et al. 1708.01186

F. Capozzi et al. 2003.08511

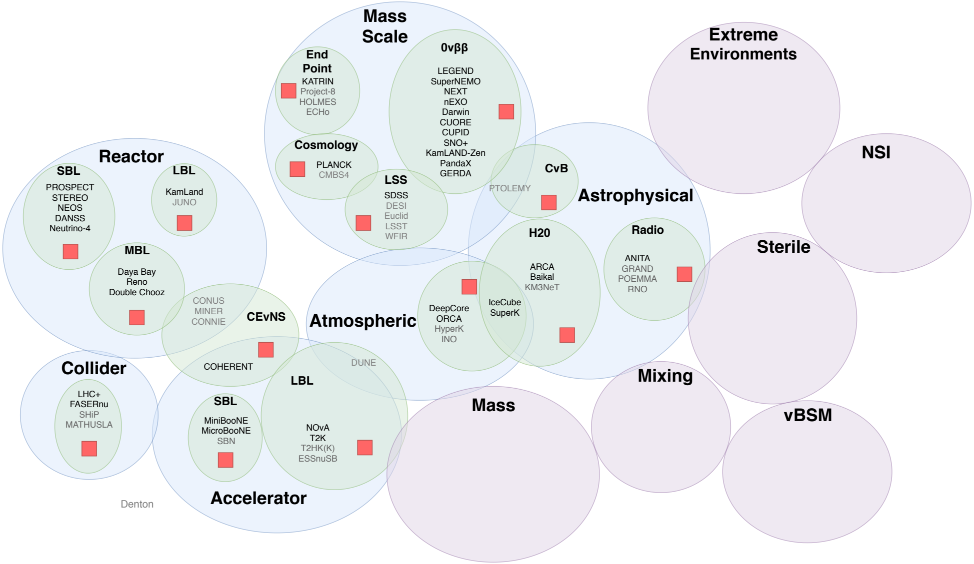
Experiments $\leftrightarrow$ Physics



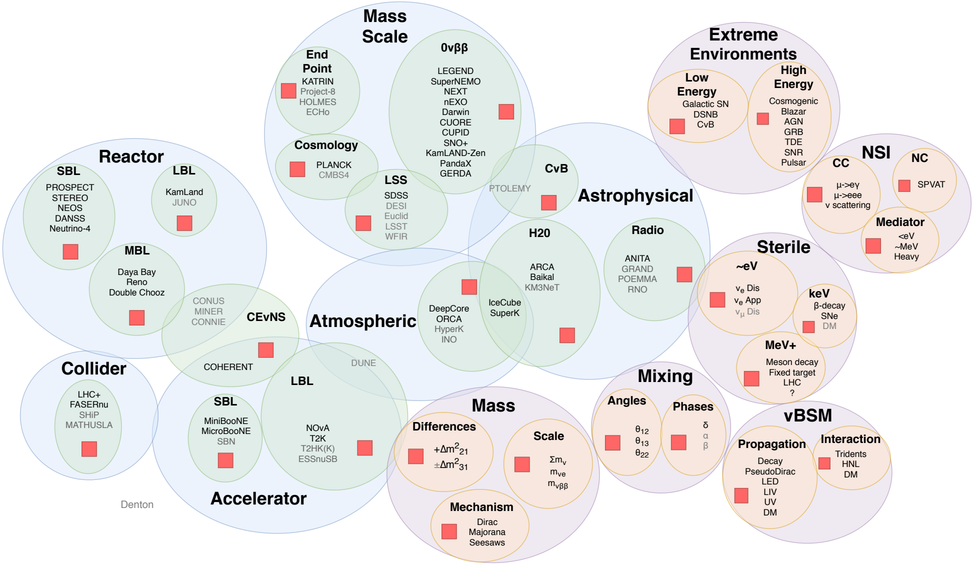
Experiments $\leftrightarrow$ Physics



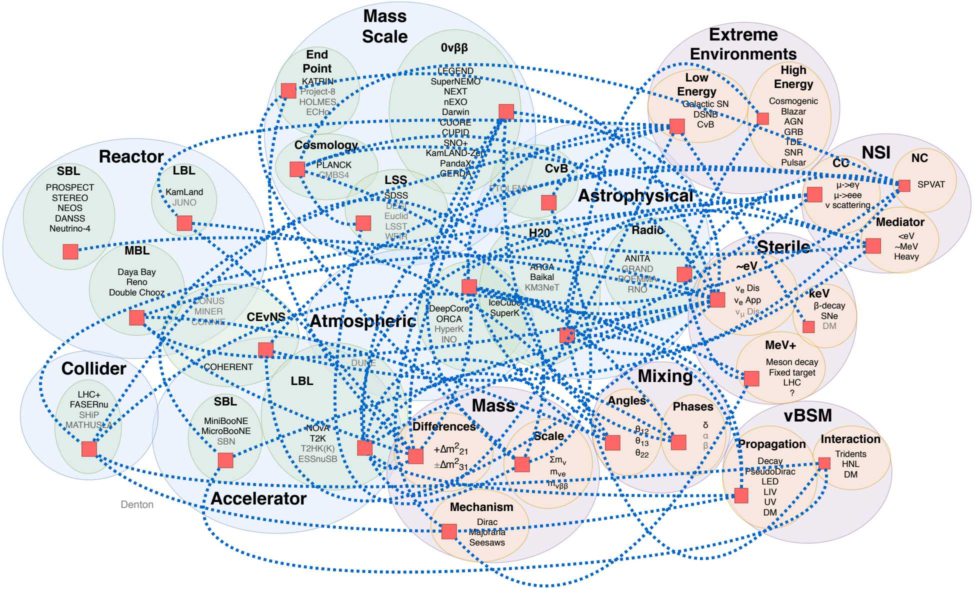
Experiments ↔ Physics



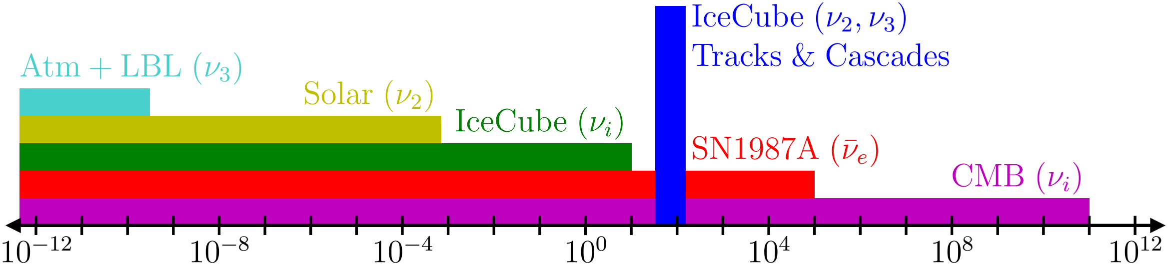
Experiments $\leftrightarrow$ Physics



Experiments $\leftrightarrow$ Physics



Invisible ν Decay Constraints and Evidence



The ν_μ spectrum is different than the ν_e, ν_τ at IceCube

IC 1607.08006

IC PoS ICRC2015 (2016) 1109

ν_2, ν_3-decay explains this, $> 3\ \sigma$

PBD, I. Tamborra 1805.05950

S. Hannestad, G. Raffelt hep-ph/0509278

Kamiokande-II, PRL 58 1490 (1987)

G. Pagliaroli, et al. 1506.02624

J. Berryman, A. de Gouvea, D. Hernandez 1411.0308

M. Gonzalez-Garcia and M. Maltoni 0802.3699

LSND, MiniBooNE Alternatives

CPT violation

H. Murayama, T. Yanagida hep-ph/0010178

G. Barenboim, L. Borissov, J. Lykken hep-ph/0212116

Dark Energy

D. Kaplan, A. Nelson, N. Weiner hep-ph/0401099

Extra dimensions

H. Pas, S. Pakvasa, T. Weiler hep-ph/0504096

Many non-sterile BSM explanations ruled out

J. Jordan, et al. 1810.07185