Neutrino from muons from the GeV to the TeV and beyond

31 July 2025

Physics At The Highest Energies With Colliders
GGI

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HIDDeν Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Horizon2020

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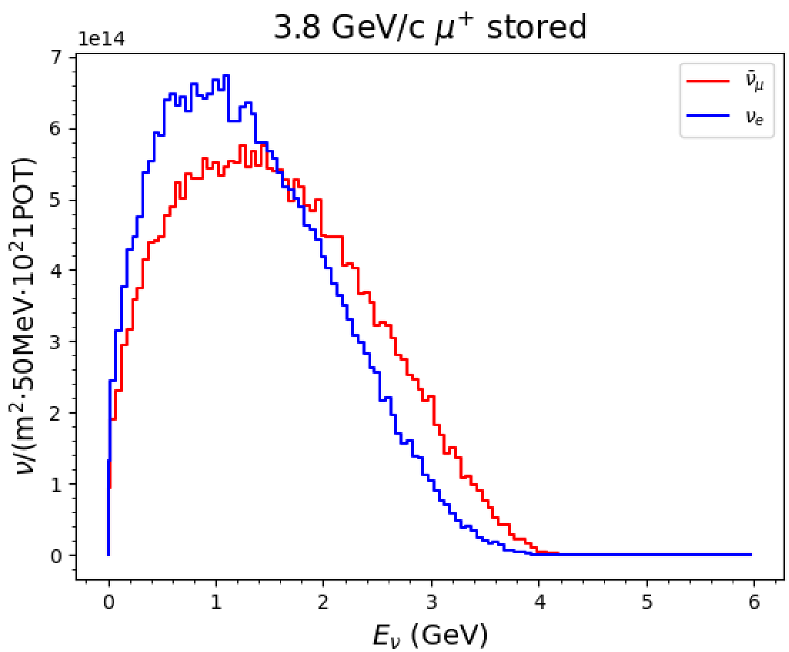
Neutrinos from muons

a.k.a. nuSTORM, nu factory, HEnu from muon collider.

A controlled beam of muons will lead to a precisely known flux of muon and electron (anti-)neutrinos that can be used to search for neutrino and BSM.

Neutrino flux in nuSTORM.

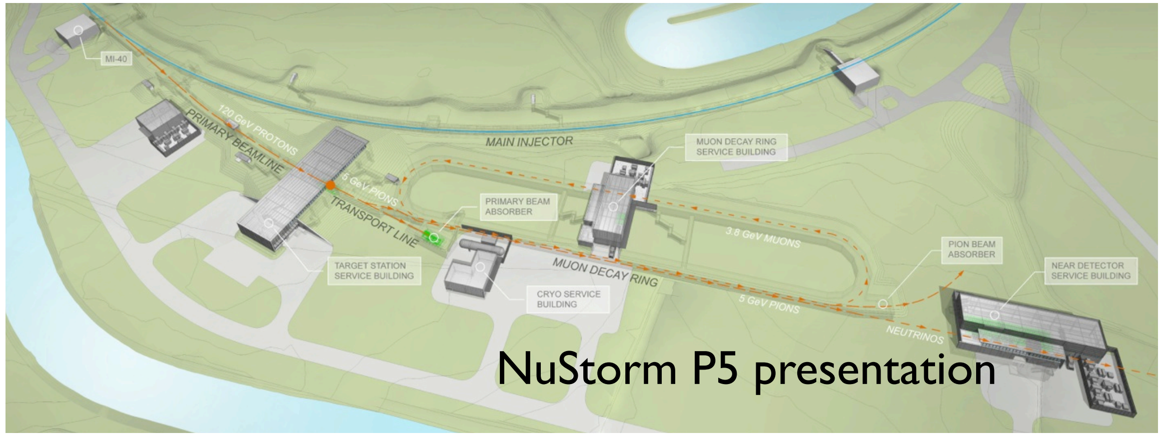


ESPP abstract n. 200.

A magnetised detector is useful in order to discriminate between leptons and anti leptons and identify the neutrino flavour detected.

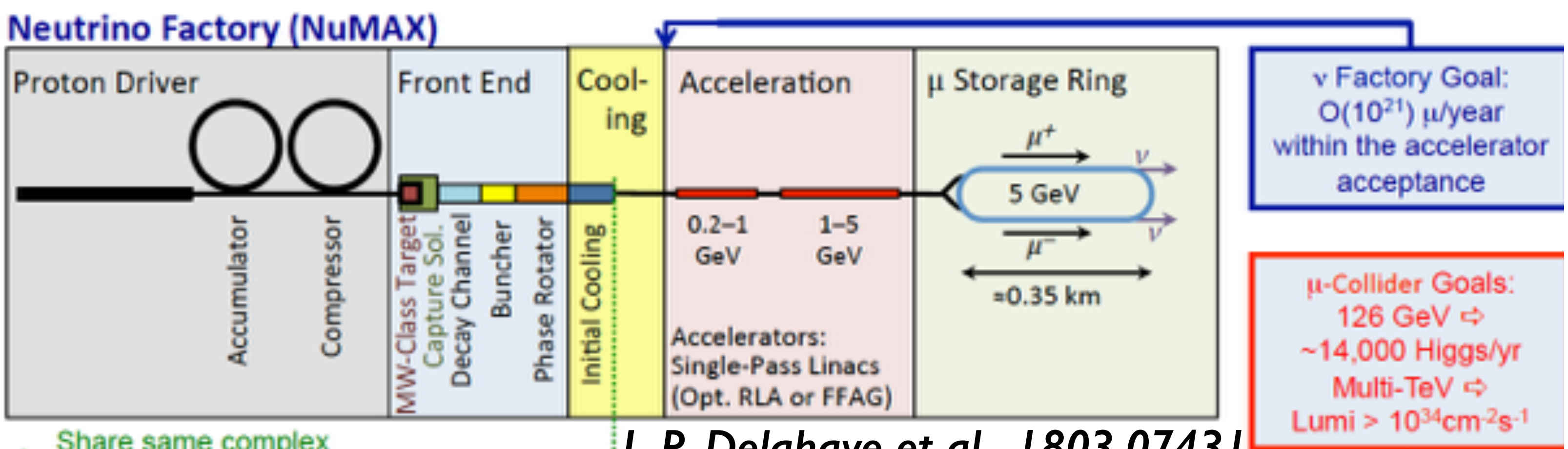
nuSTORM

E~1-6 GeV, decay ring ~100 m, M_{det}~100 ton, L~ few 100 m



Neutrino factory and LENF

E~ few GeV, decay ring ~1000 m, M_{det}~few x 10 kton, L~ 1300 km



J.-P. Delahaye et al., 1803.07431

HE neutrinos from muon decays?

Neutrino physics

Current status of neutrino parameters: the era of very precise neutrino physics

IC24 with SK atmospheric data

	Normal Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.435 \to 0.585$
$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	$41.3 \to 49.9$
$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.02030 \to 0.02388$
$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	$8.19 \to 8.89$
$\delta_{\rm CP}/^\circ$	212^{+26}_{-41}	$124 \to 364$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \to +2.578$

- 2 mass squared differences
- 3 sizable mixing angles (one not too well known)
- mild hints of CPV (not robust)
- mild indications in favour of NO (?)

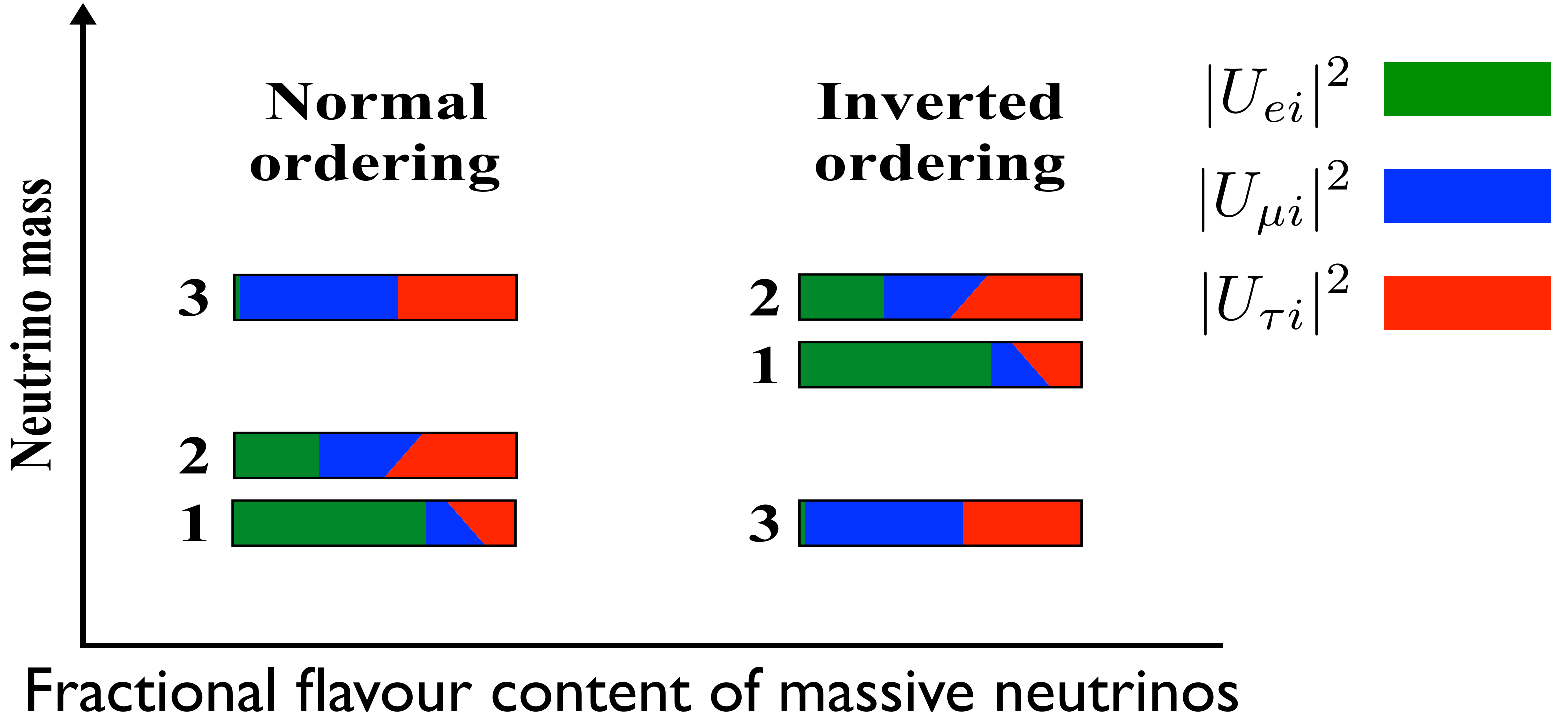
http://www.nu-fit.org/

NuFit 6.0, JHEP 12 (2024), See also Capozzi et al., de Salas et al.

The past 20 years have seen a remarkable progress in determining neutrino properties! How about the next 20?

Neutrino masses

$\Delta m^2_{21} \ll \Delta m^2_{31}$ implies at least 3 massive neutrinos.



$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m_{\rm min} + \Delta m^2_{21}}$$
$$m_3 = \sqrt{m_{\rm min} + \Delta m^2_{31}}$$

$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m_{\rm min} + |\Delta m^2_{32}| - \Delta m^2_{21}}$$
$$m_2 = \sqrt{m_{\rm min} + |\Delta m^2_{32}|}$$

Measuring the masses requires:

- the mass scale: $m_{\rm min}$
- the MO: very mild preference for NO.

Leptonic Mixing and CP-violation

The Pontecorvo-Maki-Nakagawa-Sakata matrix

$$\nu_i = U^\dagger \nu_\alpha \longrightarrow \mathcal{L}_{CC} = \frac{g}{\sqrt{2}} (\bar{e}_L, \bar{\mu}_L, \bar{\tau}_L) \gamma^\mu U_{\rm osc} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix} W_\mu$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

CPV?

- Mixings very different from quark sector.
- Possibly, large leptonic CPV.
  CPV is a fundamental question, possibly related to the origin of the baryon asymmetry and to the origin of the flavour structure.

What do we still need to know in 2025?

1. **What is the nature of neutrinos?**

2. **What are the values of the masses?** Absolute scale and the ordering.

3. **Is there CP-violation?**

4. **What are the precise values of mixing angles?**

5. **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Non-unitarity? Other effects?

Very exciting experimental programme.

Phenomenology questions for the future

1. What is the nature of neutrinos?

2. What are the values of the masses? Absolute scale and the ordering.

Neutrino oscillation experiments

3. Is there leptonic CP-violation?

4. What are the precise values of mixing parameters?

Requires also precise knowledge of cross sections.

5. Is the standard picture correct? Are there NSI? Sterile neutrinos? Other effects?

Very exciting experimental programme.

Neutrino oscillations

Let's assume that at t=0 a muon neutrino is produced

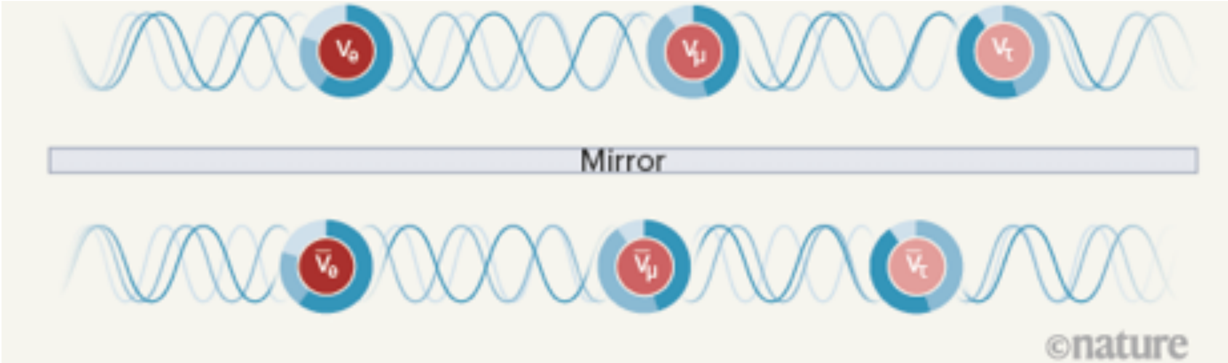
$$|\nu, t=0\rangle = |\nu_\mu\rangle = \sum_i U_{\mu i} |\nu_i\rangle$$

The time-evolution is given by the solution of the Schroedinger equation with free Hamiltonian:

$$|\nu, t\rangle = \sum_i U_{\mu i} e^{-iE_i t} |\nu_i\rangle$$

At detection, projecting over the flavour state :

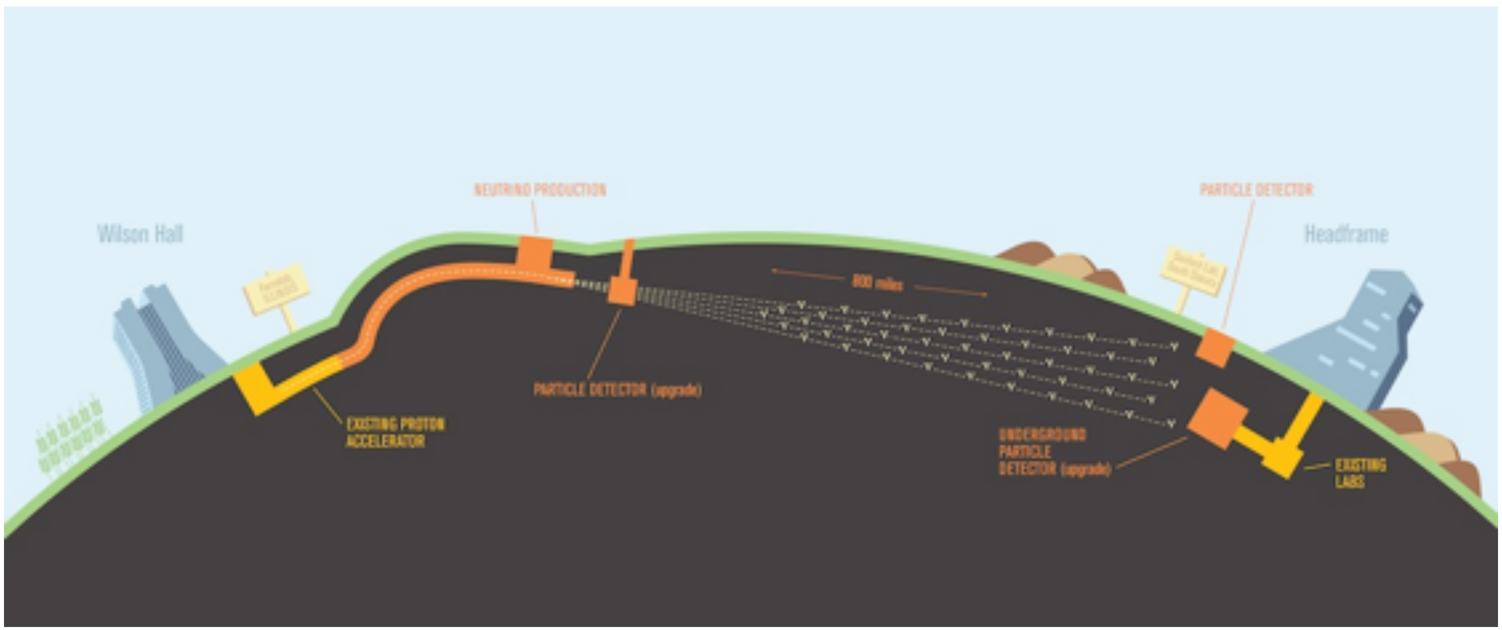
$$P(\nu_\alpha \to \nu_\beta) \quad = \quad \left| \sum_i U_{\alpha 1} U^*_{\beta 1} e^{-i\frac{\Delta m^2_{i1}}{2E} L} \right|^2 \overset{2\nu}{=} \sin^2 2\theta \;\; \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$



Nature, SP and J. Turner, News and views, 15 April 2020

Long-baseline neutrino oscillations

- LBL experiments search for neutrino oscillations, for neutrinos that are produced at an accelerator complex and travel 100s Km before scattering in large detectors.

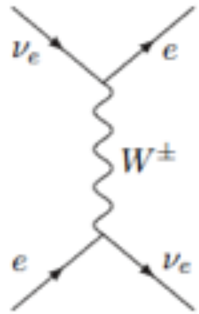


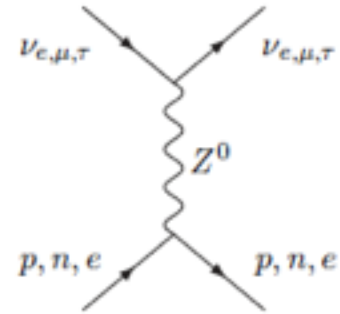
Credit: Symmetry magazine

- When neutrinos travel through a medium, they interact with the background of e, p and n.

The background is CP and CPT violating, and the resulting oscillations are as well.

- Neutrinos undergo forward elastic scattering via CC and NC interactions.

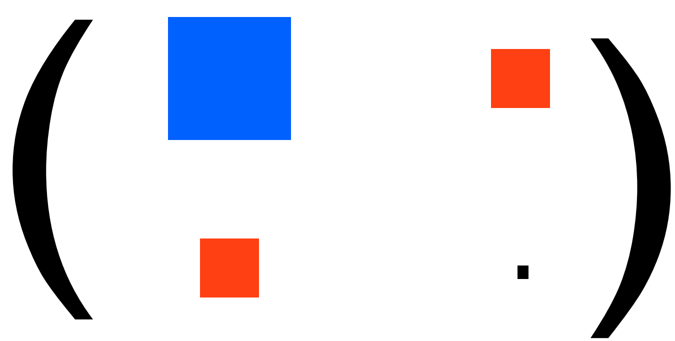




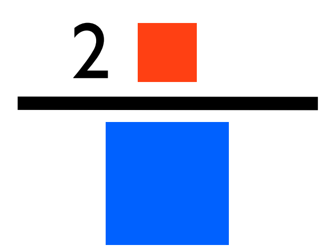
- Matter effects are described by a potential V in the effective Hamiltonian which determines the time evolution.

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos(2\theta) + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin(2\theta) \\ \frac{\Delta m^2}{4E}\sin(2\theta) & \frac{\Delta m^2}{4E}\cos(2\theta)\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Effective Hamiltonian



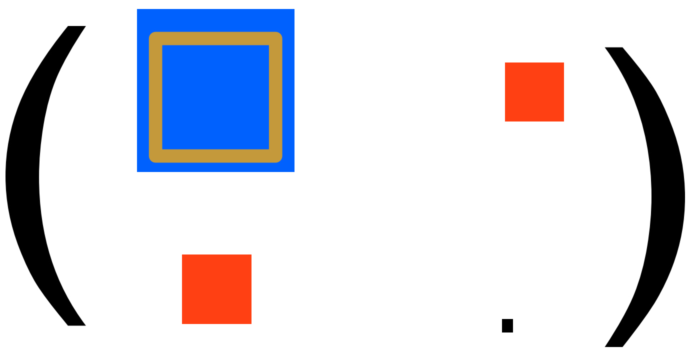
$\tan 2\theta \sim$



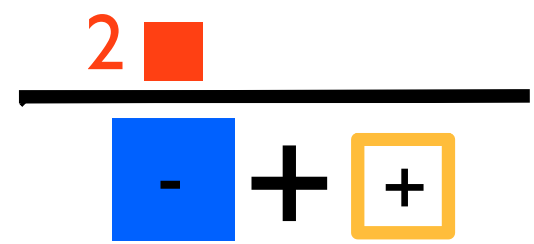
In long baseline experiments

 $-\frac{\Delta m^2}{2E}\cos(2\theta)$ $\quad \nu \quad +\sqrt{2}G_F N_e \quad \bar{\nu} \quad -\sqrt{2}G_F N_e$

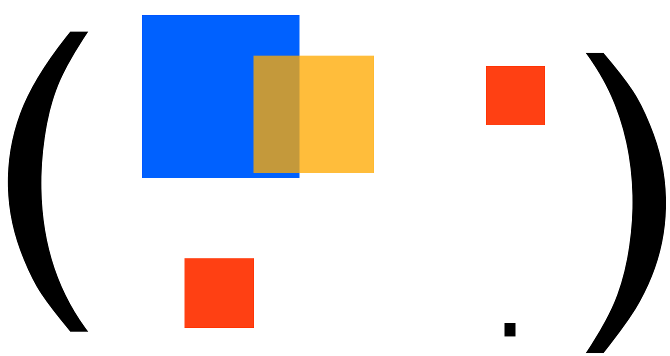
For neutrinos



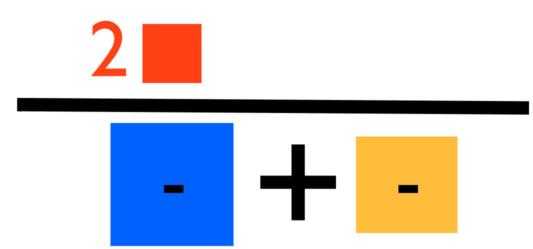
$\Delta m^2 > 0$ enhancement

$\tan 2\theta^M \sim$ 

For antineutrinos



$\Delta m^2 > 0$ suppression

$\tan 2\theta^M \sim$ 

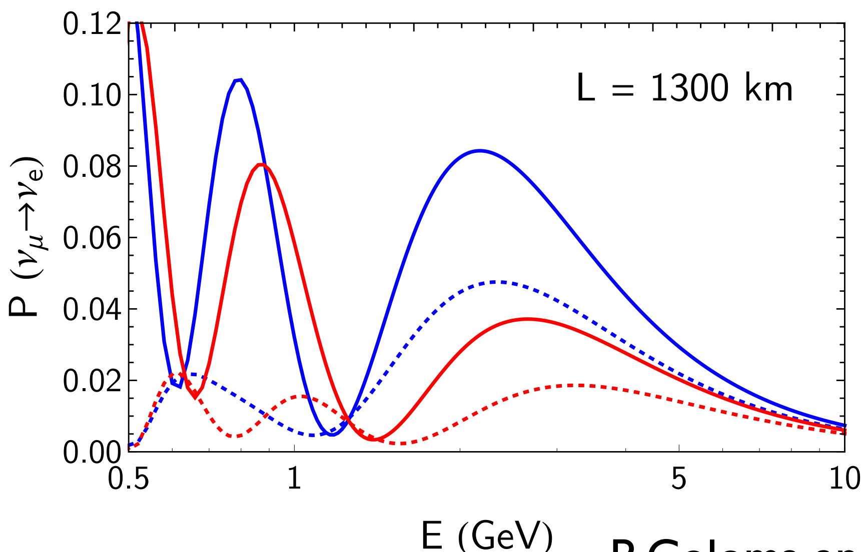
The 3-neutrino probability can be approximated as

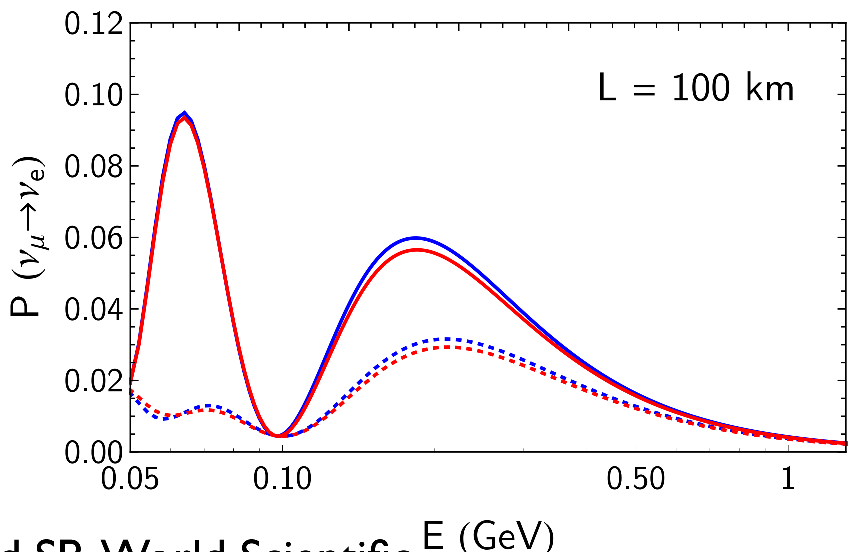
A. Cervera et al., hep-ph/0002108;
K. Asano, H. Minakata, 1103.4387;
S. K. Agarwalla et al., 1302.6773;
P. Denton, S. Parke and X. Zhang, 1907.02534…

$$P_{\mu e} \simeq 4c_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta_{31}L}{4E}$$
$$+\sin 2\theta_{12} \sin 2\theta_{23} s_{13} \frac{\Delta_{21}L}{2E} \sin \frac{(1-r_A)\Delta_{31}L}{4E} \cos\left(\delta - \frac{\Delta_{31}L}{4E}\right)$$
$$+s_{23}^2 \sin^2 2\theta_{12} \frac{\Delta_{21}^2 L^2}{16E^2} - 4c_{23}^2 s_{13}^4 \sin^2 \frac{(1-r_A)\Delta_{31}L}{4E}$$

with

$$\Delta_{31} \equiv \Delta m_{31}^2/(2E_\nu)$$
$$r_A \simeq \frac{\sqrt{2}G_F N_e}{\Delta m_{31}^2/(2E_\nu)}$$





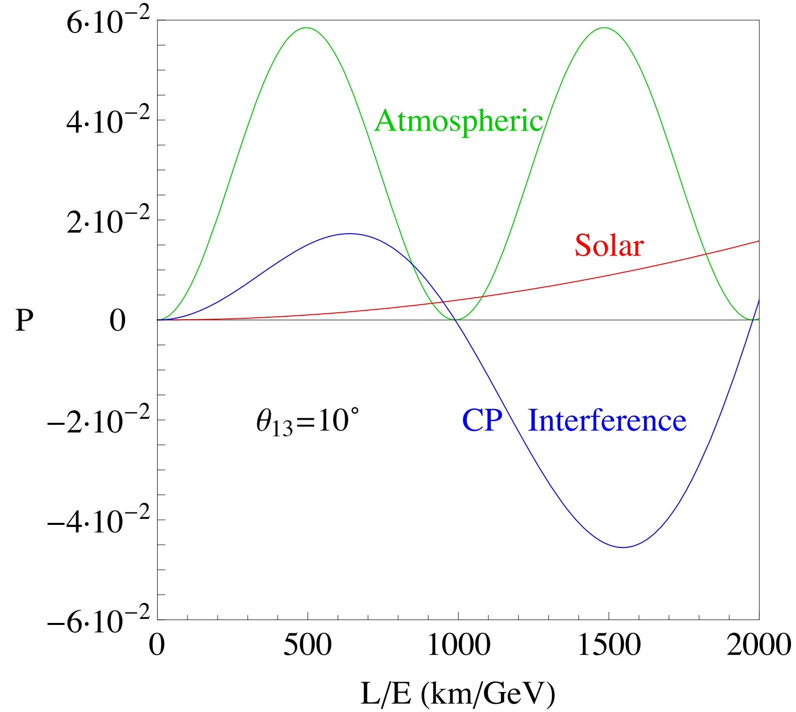
P. Coloma and SP, World Scientific

Long-baseline neutrino oscillations and leptonic CP violation

$$P_{\mu e} \simeq 4c_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta_{31}L}{4E}$$
$$+ \sin 2\theta_{12} \sin 2\theta_{23} s_{13} \frac{\Delta_{21}L}{2E} \sin \frac{(1-r_A)\Delta_{31}L}{4E} \cos\left(\delta - \frac{\Delta_{31}L}{4E}\right)$$
$$+ s_{23}^2 \sin^2 2\theta_{12} \frac{\Delta_{21}^2 L^2}{16E^2} - 4c_{23}^2 s_{13}^4 \sin^2 \frac{(1-r_A)\Delta_{31}L}{4E}$$

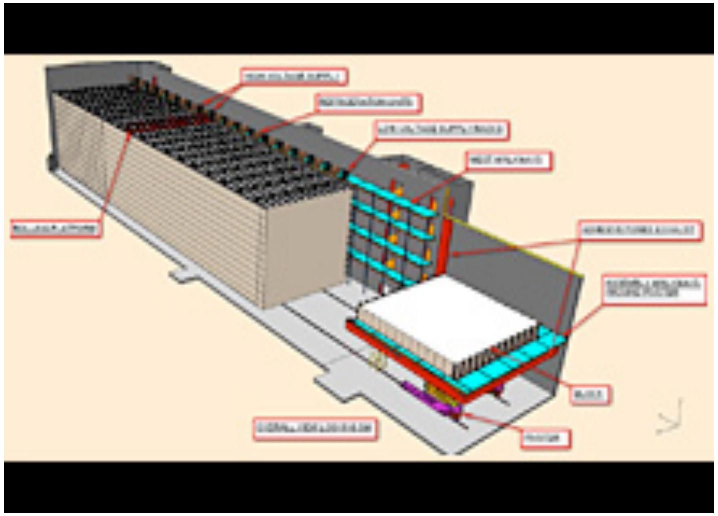
A. Cervera et al., hep-ph/0002108; K. Asano, H. Minakata, 1103.4387; S. K. Agarwalla et al., 1302.6773...

- The determination of CPV and of the mass ordering are entangled.
- Matter effects increase with energy and distance.
- CPV effects more pronounced at low energy.



P. Coloma, E. Fernandez-Martinez, JHEP1204

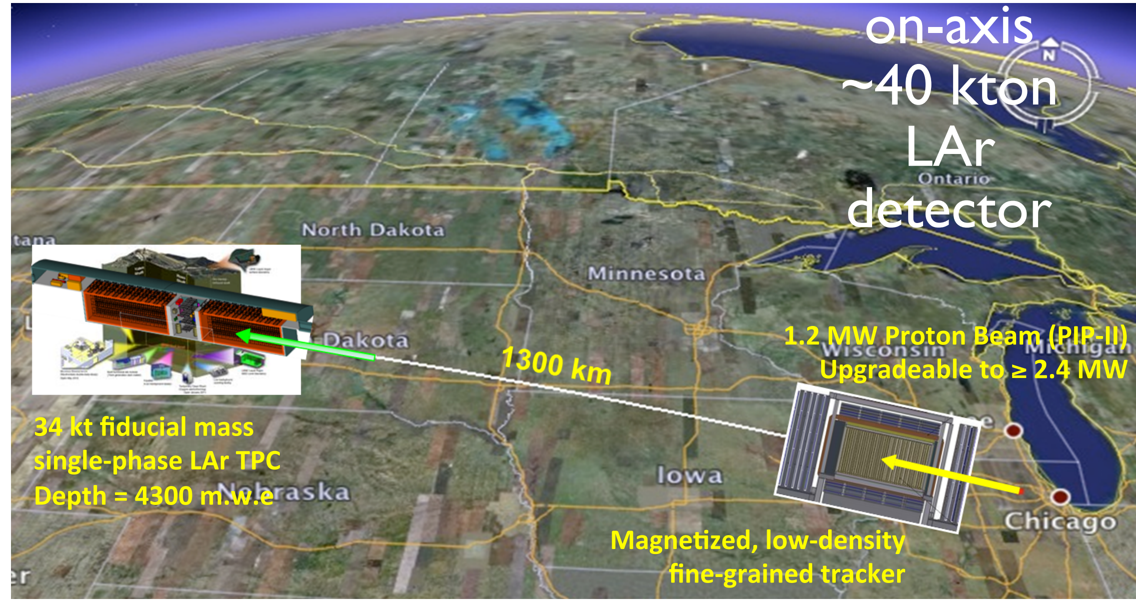
Present/Future LBL exp

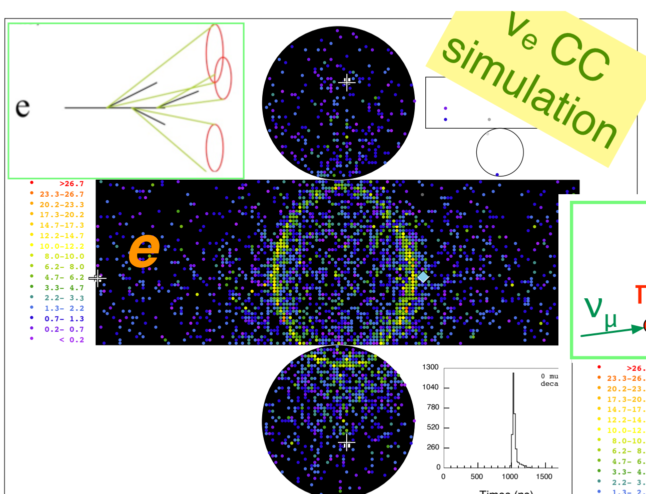


NOvA: 810 km off-axis
~14 kton plastic scintillator detector

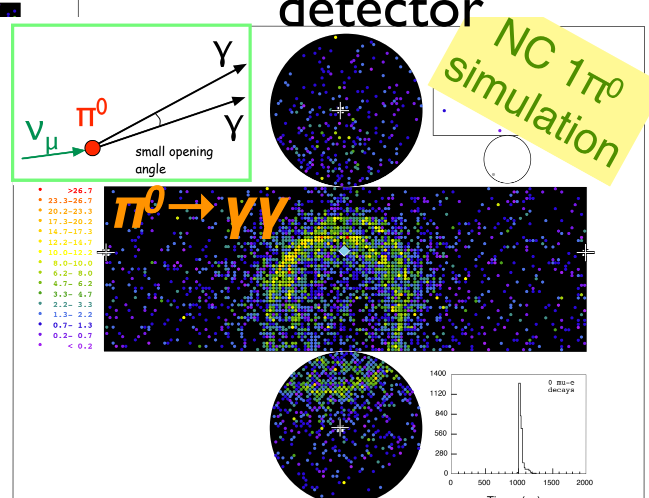
T2K: 295 km off-axis
~22.5 kton WC detector

DUNE: 1300 km
on-axis
~40 kton
LAr
detector

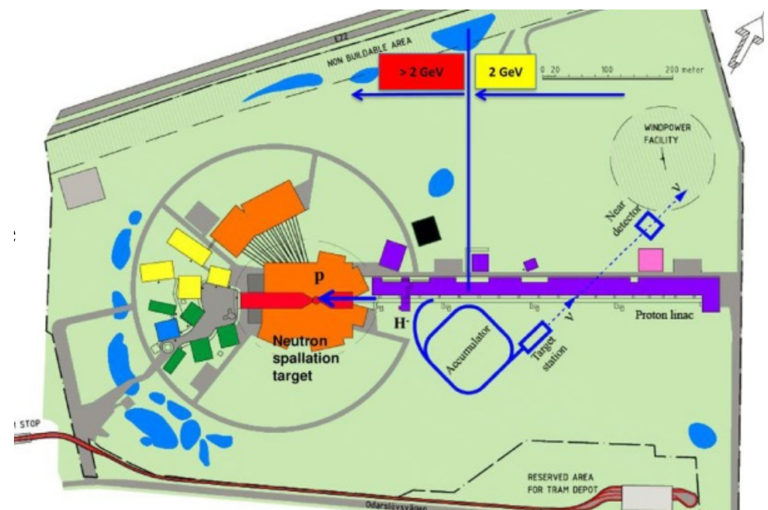




T2HK: 295 km
off-axis
~1 Mton WC
detector

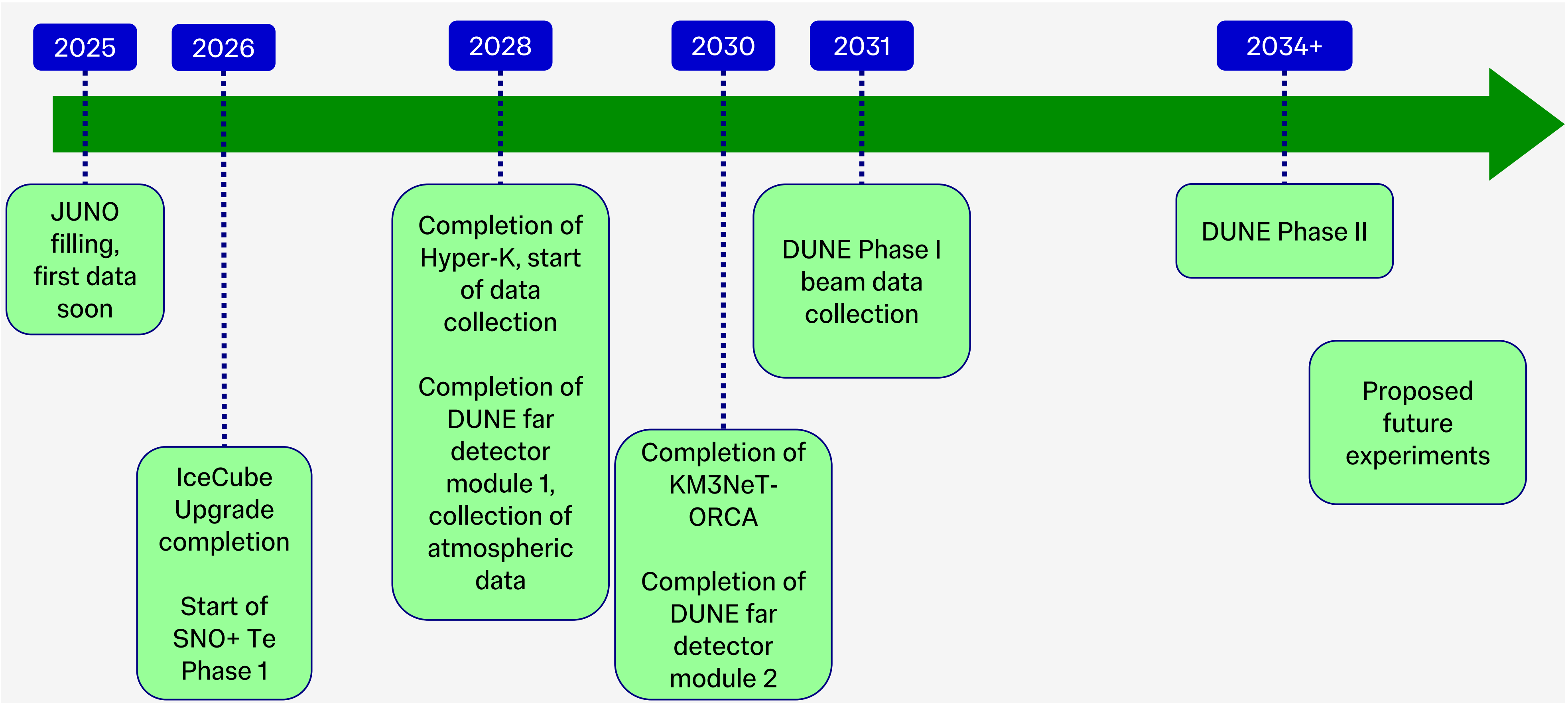


M. Shiozawa, for
T2HK coll., NuPhys
2014



~1 BEuros for the neutrino facility including detector

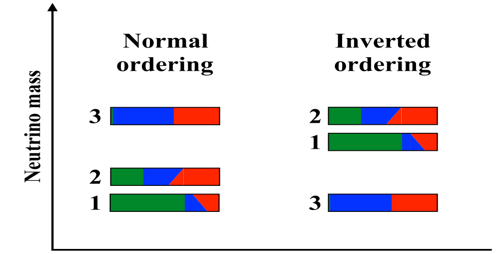
***ESSnuSB**: 300-500 km*
~0.5 Mton WC detector
second osc. maximum



M. Scott, talk at ESPP '25

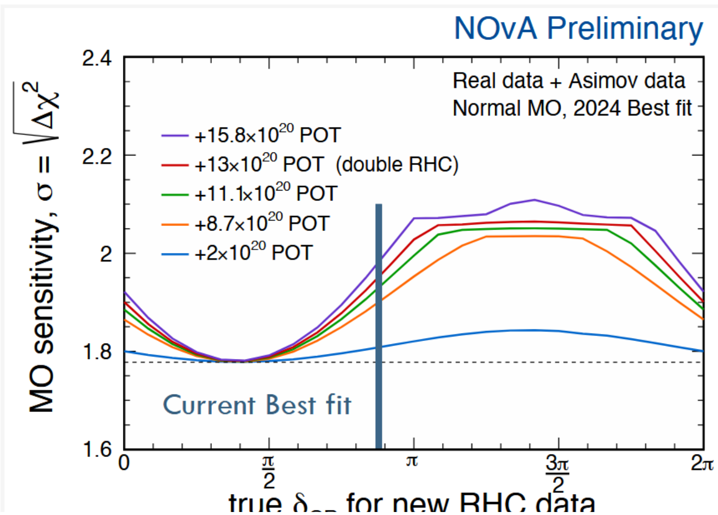
Question 1: neutrino mass ordering

Mass ordering sensitivity

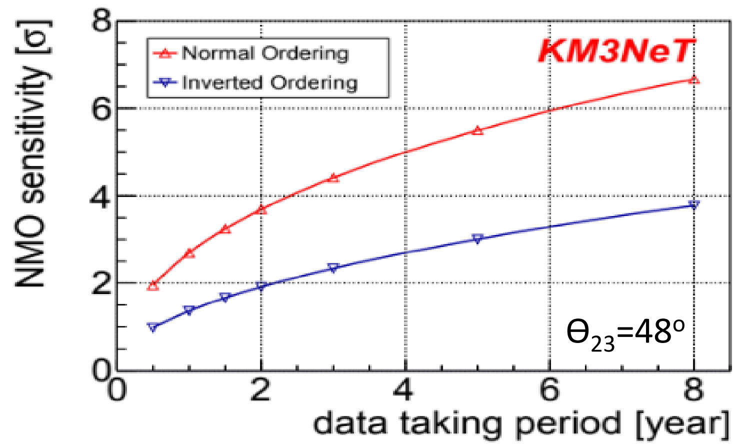


The current situation is still rather uncertain.

We know we will know the ordering by 2035ish.



P. Vahle, NOvA, PAC '24

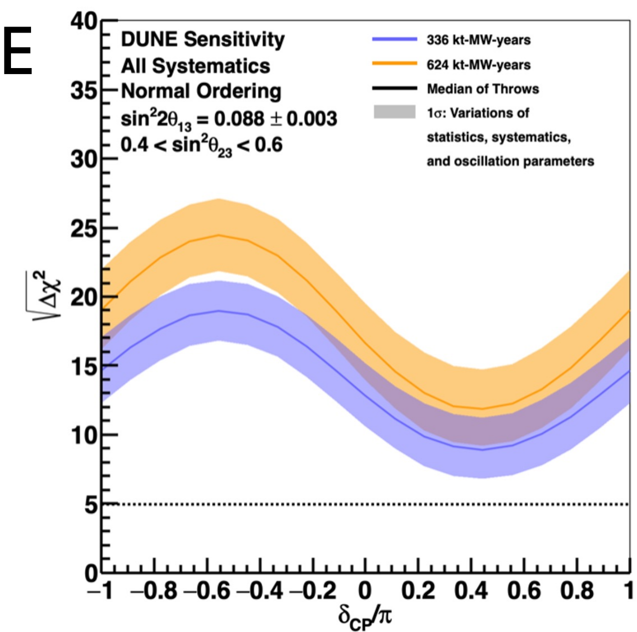


SK, HK, IceCube

A. Heijboer's talk at Neutrino 2022

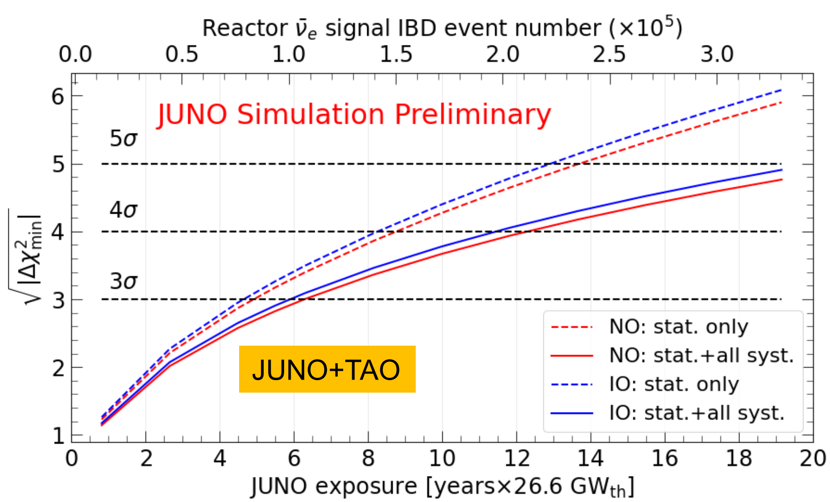
DUNE Coll., 2006.16043

DUNE

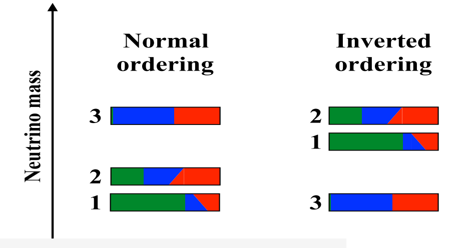


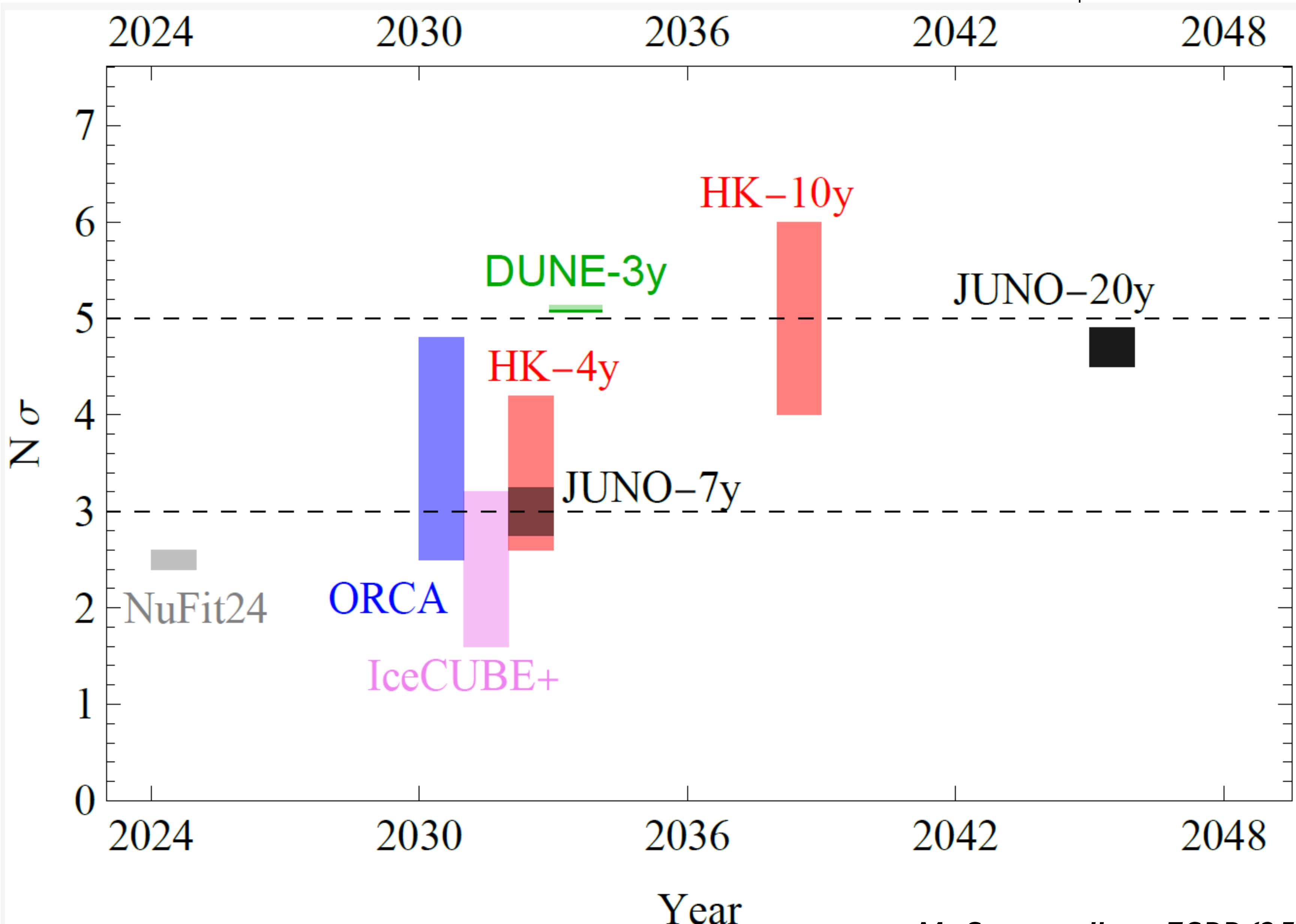
JUNO

J. Zhao's talk at Neutrino 2022



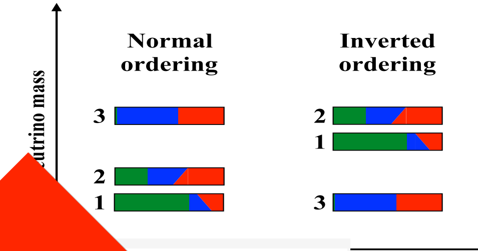
Mass ordering sensitivity

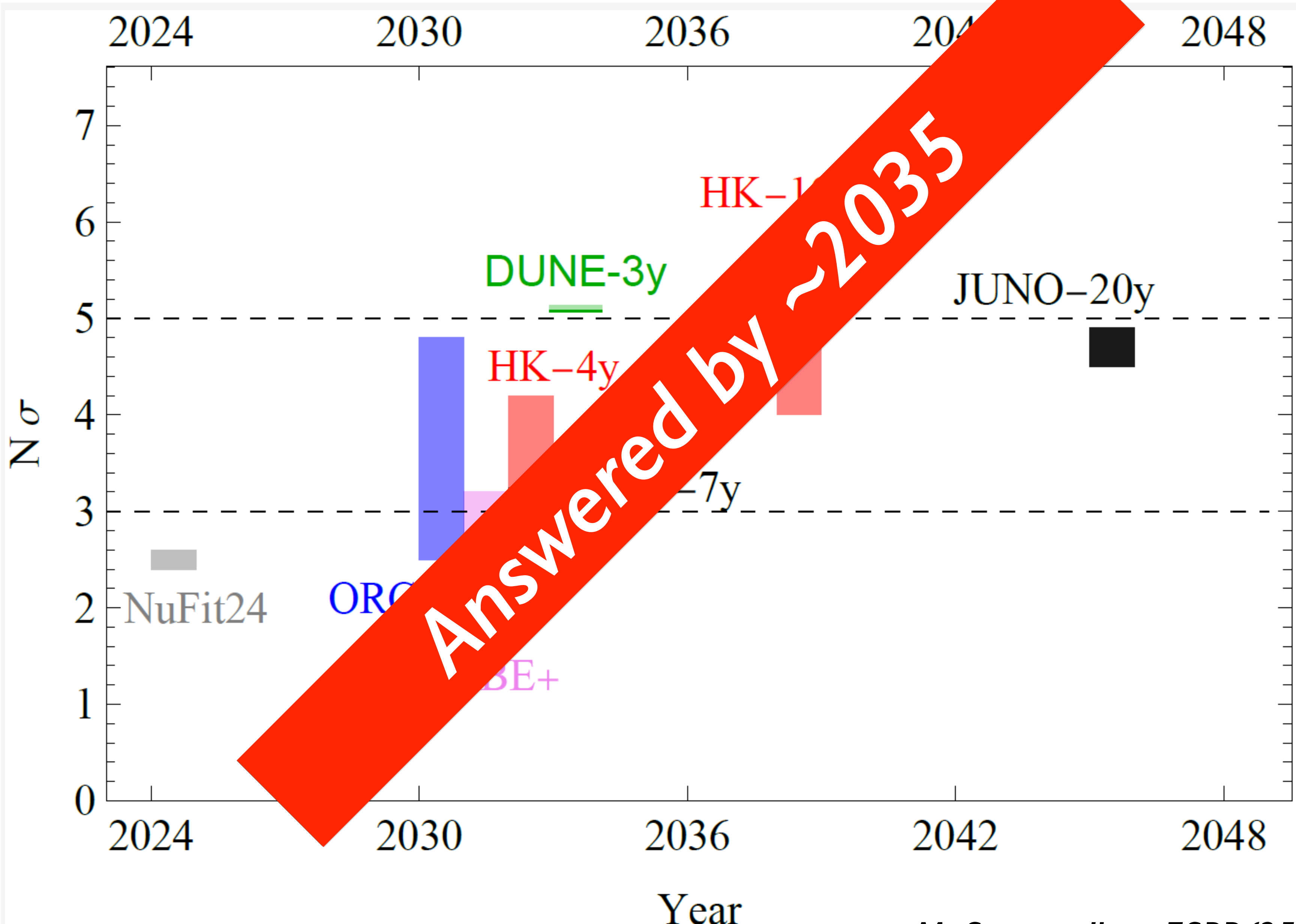




M. Scott, talk at ESPP '25

Mass ordering sensitivity





M. Scott, talk at ESPP '25

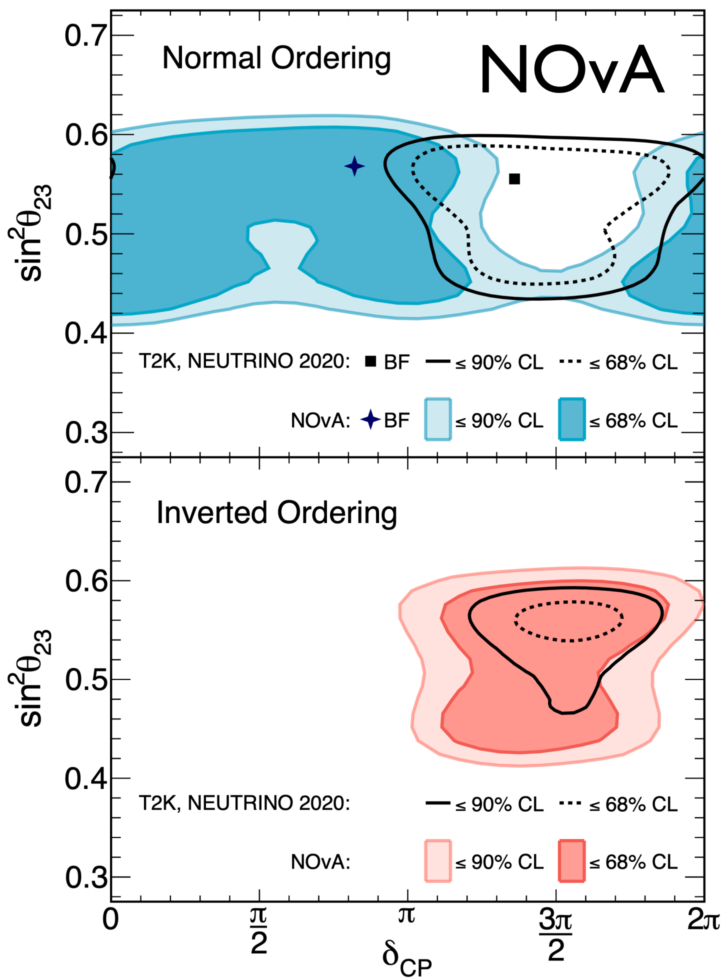
Question 2:
Leptonic CP violation

CPV sensitivity

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

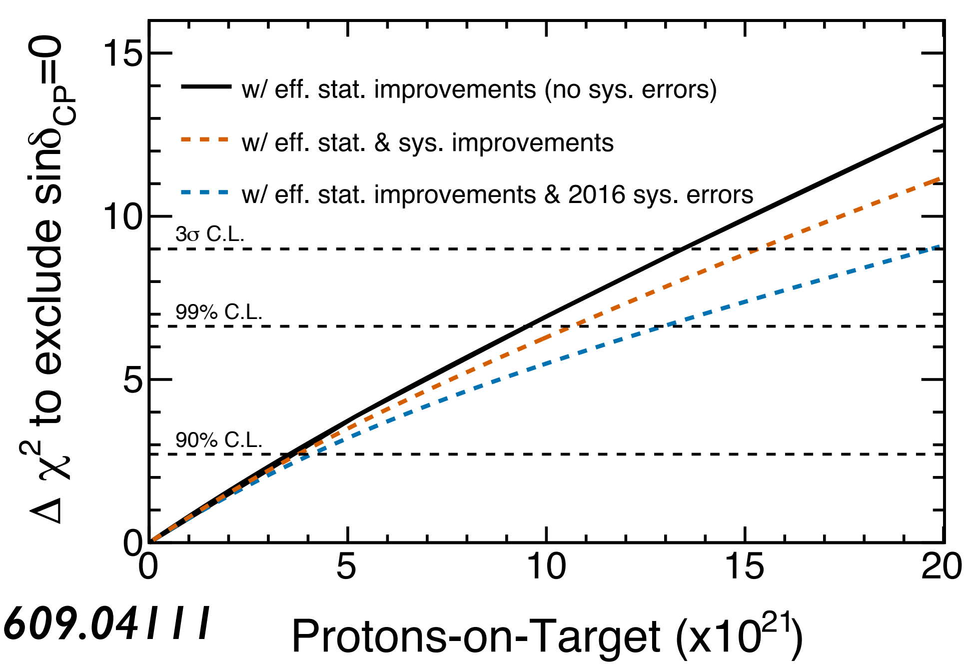
Hints of leptonic CPV?
Situation remains unclear.
Expect very soon T2K-NOvA joint analysis.

2020 data set: https://arxiv.org/abs/2108.08219



J. Hartnell's talk at Neutrino 2022

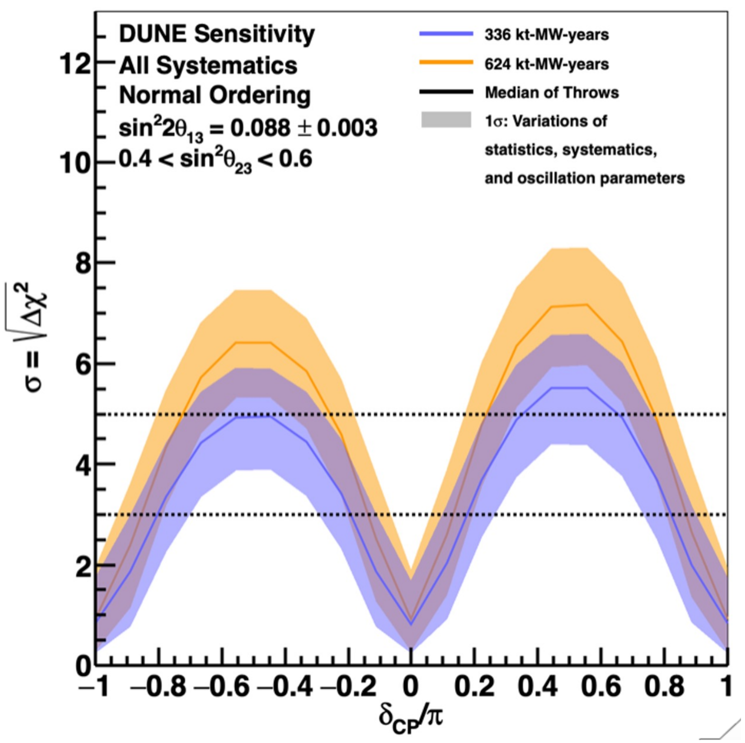
T2K phase 2 extension aims at reaching 1.3 MW in the next few years (20x10^21pot).



T2K, 1609.04111

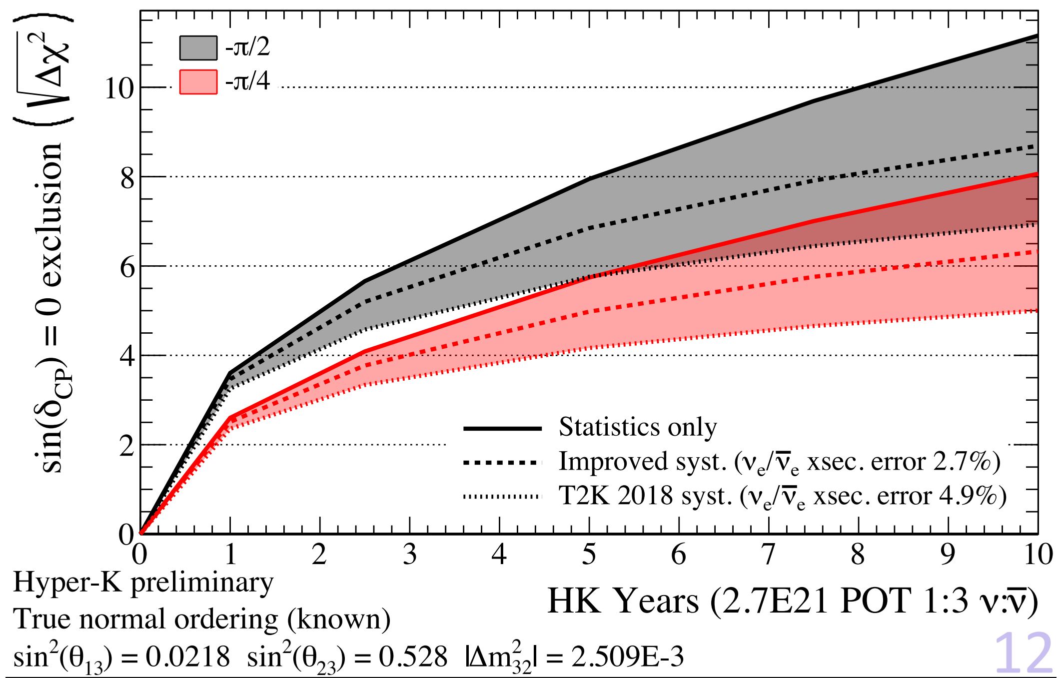
DUNE and T2HK will get to 5 sigma for a large range of values of delta by 2040 (possibly 2035??). Whether we discover it or not depends on the true delta.

DUNE



DUNE Coll., 2006.16043

T2HK



J. Wilson's talk at Neutrino 2022

The knowledge of systematic errors is a limiting factor in the physics reach. The key uncertainty relates to the neutrino scattering cross sections.

nuSTORM would allow a precise determination of the relevant cross sections with strong impact on DUNE and T2HK sensitivity.

	nuSTORM
$\sigma\ \nu_e/\nu_\mu$	+
$\sigma\ \overline{\nu}/\nu$	+
E_ν	−
Readiness	+
Muon collider R&D	+

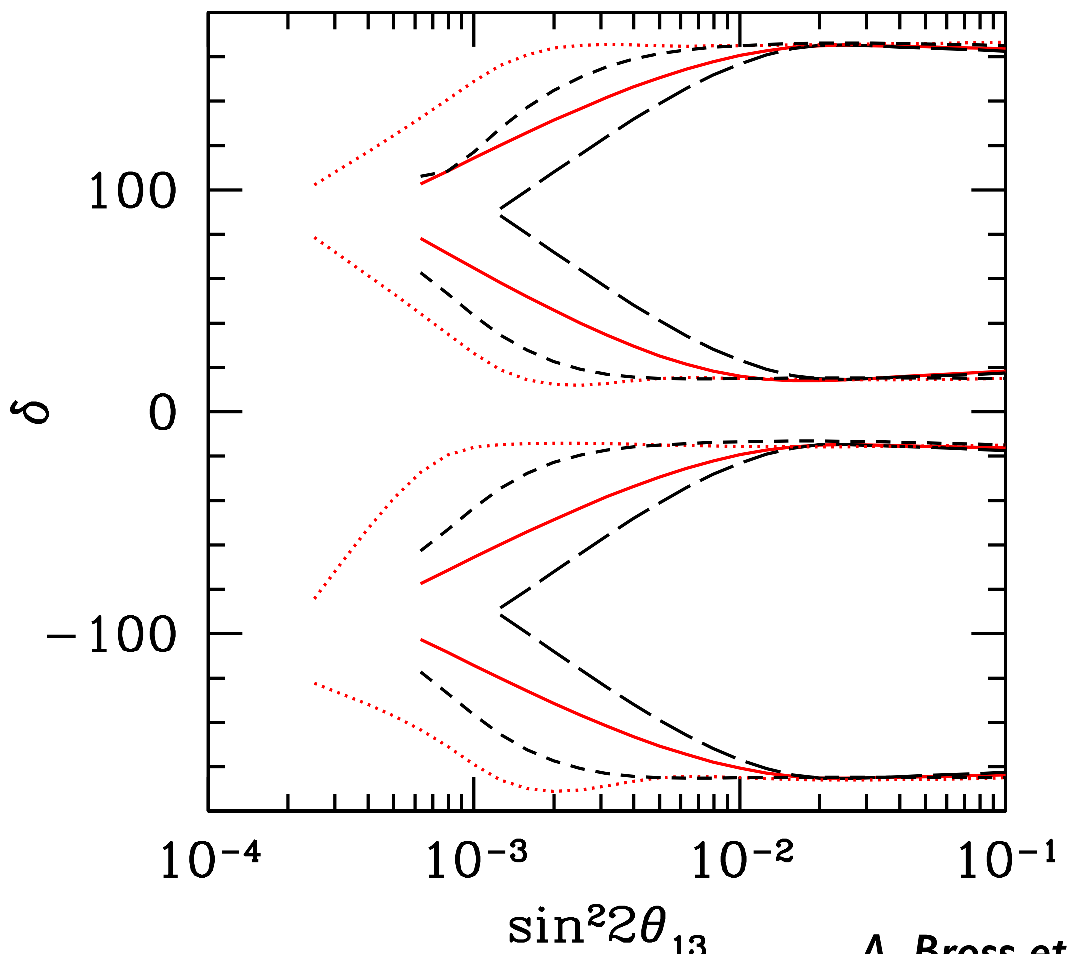
Scott's talk at ESPP '25

These are limiting systematic for HK CPV discovery and precision.

The reconstruction of neutrino energy plays a key role in DUNE CPV sensitivity.

Scenario 1: no leptonic CPV discovery

If the delta phase is too close to 0, pi, DUNE and T2HK will not be able to discover leptonic CPV.



It is essential to pursue this measurement with a more sensitive experiment: neutrino factory.

A. Bross et al., 0709.3889

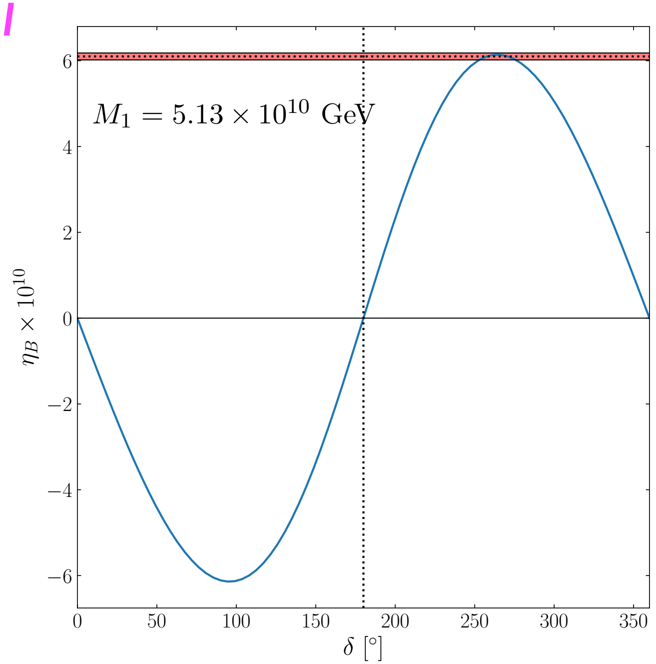
- CP violation is a key aspect of the SM and it is important to establish if it concerns also the leptonic sector.
- CPV is related to the origin of the leptonic mixing structure.
- The delta phase can explain the baryon asymmetry of the Universe but only if it is sufficiently CP-violating.

For high E see-saw type I

$$|\sin\theta_{13}\,\sin\delta| \gtrsim 0.09$$

SP, Petcov, Riotto, hep-ph/0609125

Generically, if $\delta < 25^o - 35^o$ and similarly around 180^o, delta cannot be responsible for the baryon asymmetry in high E see-saw type I.



K. Moffat et al., 1809.08251

Question:
Precision measurement of oscillation parameters

Scenario 2: leptonic CPV discovered

If discovered, the key physics goal will be the precise measurement of the oscillation parameters.

- The values of the mixing angles seem to indicate an underlying symmetry: $\theta_{23} \sim 45^o$, θ_{13} not too far from 0.

	2012 NuFIT 1.0	2014 NuFIT 2.0	2016 NuFIT 3.0	2018 NuFIT 4.0	2021 NuFIT 5.1
θ_{12}	15%	14%	14%	14%	14%
θ_{13}	30%	15%	11%	8.9%	9.0%
θ_{23}	43%	32%	32%	27%	27%
Δm^2_{21}	14%	14%	14%	16%	16%
$\lvert\Delta m^2_{3\ell}\rvert$	17%	11%	9%	7.8%	6.7% [6.5%]
δ_{CP}	100%	100%	100%	100% [92%]	100% [83%]
$\Delta\chi^2_{\text{IO-NO}}$	±0.5	−0.97	+0.83	+4.7 [+9.3]	+2.6 [+7.0]

w/o [w] SK atm data

Gonzalez-Garcia et al., 2111.03086

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

JUNO Coll., 2204.13249

Typically, there are relations between masses, mixing angles and CPV phase.

E.g. the so-called sumrules:

$$\sin\theta_{23} - \frac{1}{\sqrt{2}} = \sin\theta_{13}\cos\delta$$

$$\cos\delta = \frac{t_{23}s_{12}^2 + s_{13}^2 c_{12}^2/t_{23} - s_{12}^{\nu 2}(t_{23} + s_{13}^2/t_{23})}{\sin 2\theta_{12} s_{13}}$$

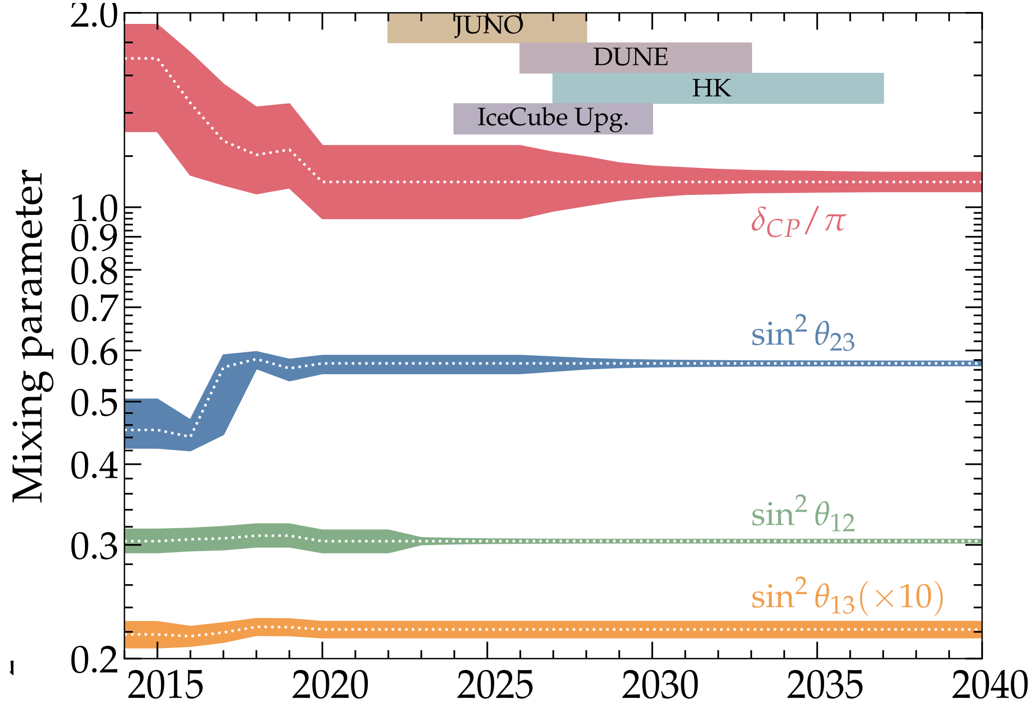
Ballet et al., Girardi et al.

Needed:

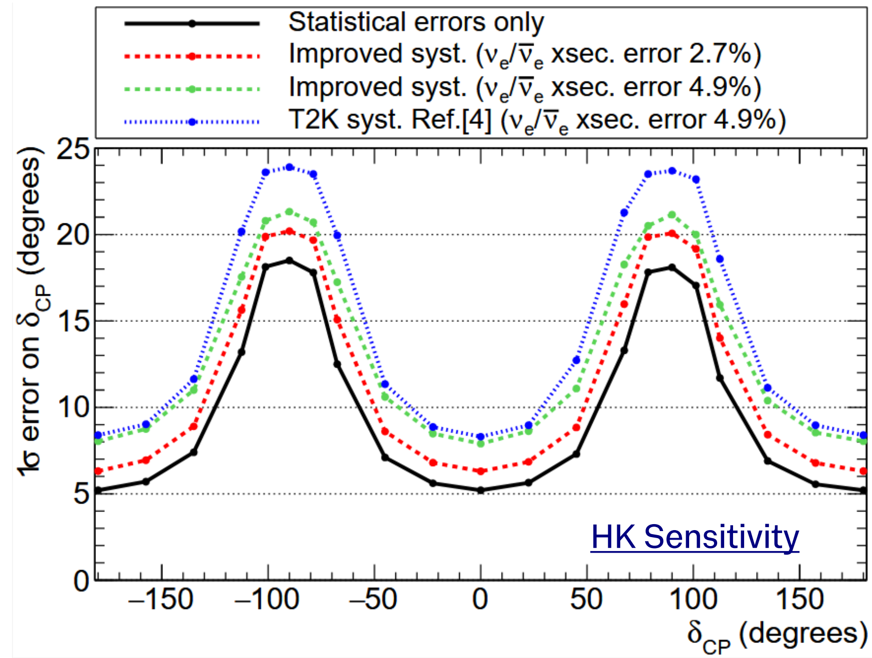
- A precise measurements of the oscillation parameters (including the delta phase).
- Mass ordering and neutrino mass spectrum.

Reference		Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
Anarchy Model:					
dGM	[18]	Either			≥ 0.011 @ 2σ
$L_e - L_\mu - L_\tau$ Models:					
BM	[35]	Inverted			0.00029
BCM	[36]	Inverted			0.00063
GMN1	[37]	Inverted		≥ 0.52	≤ 0.01
GL	[38]	Inverted			0
PR	[39]	Inverted		≤ 0.58	≥ 0.007
S_3 and S_4 Models:					
CFM	[40]	Normal			0.00006 - 0.001
HLM	[41]	Normal	1.0	0.43	0.0044
		Normal	1.0	0.44	0.0034
KMM	[42]	Inverted	1.0		0.000012
MN	[43]	Normal			0.0024
MNY	[44]	Normal			0.000004 - 0.000036
MPR	[45]	Normal			0.006 - 0.01
RS	[46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
		Normal	$\theta_{23} \leq 45°$		0
TY	[47]	Inverted	0.93	0.43	0.0025
T	[48]	Normal			0.0016 - 0.0036
A_4 Tetrahedral Models:					
ABGMP	[49]	Normal	0.997 - 1.0	0.365 - 0.438	0.00069 - 0.0037
AKKL	[50]	Normal			0.006 - 0.04
Ma	[51]	Normal	1.0	0.45	0
SO(3) Models:					
M	[52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:					
CPP	[53]	Normal			0.007 - 0.008
		Inverted			≥ 0.00005
		Inverted			≥ 0.032
WY	[54]	Either			0.0006 - 0.003
		Either			0.002 - 0.02
		Either			0.02 - 0.15

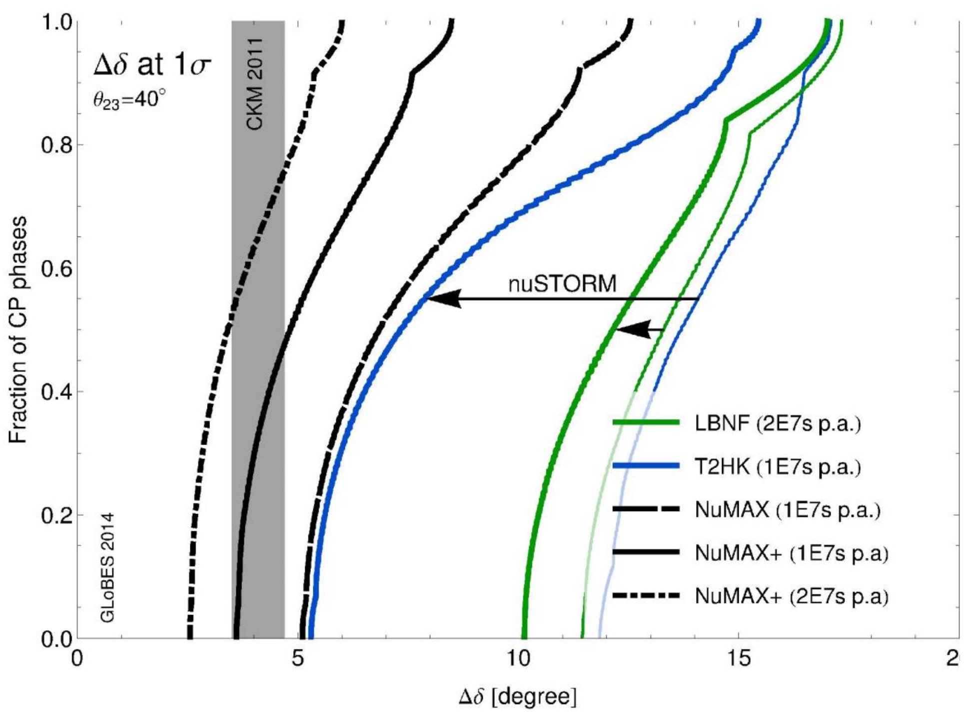
Albright, Chen, PRD 74 (2006)



N. Song et al., 2012.12893



T2HK coll.



A neutrino factory would be able to increase the precision on delta very significantly.

J.-P. Delahaye et al., 1803.07431

Phenomenology questions for the future

1. What is the nature of neutrinos?

2. What are the values of the masses? Absolute scale and the ordering.

3. Is there leptonic CP-violation?

4. What are the precise values of mixing parameters?

5. Is the standard picture correct? Are there NSI? Sterile neutrinos? Other effects?

Neutrino from muons

Very exciting experimental programme.

Question: Beyond 3-neutrino mixing

Is the standard 3-neutrino picture correct?

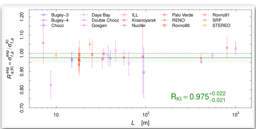
Neutrinos are the least known of the SM fermions and could provide a privileged window on new physics BSM.

With great precision of neutrino properties, the search for beyond 3-nu mixing becomes very compelling:

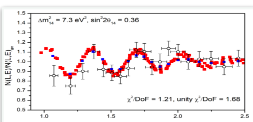
Neutrino 2002: 5 talks mainly on sterile neutrinos
Neutrino 2012: 4 talks mainly on sterile neutrinos
Neutrino 2022: 10 talks with many new results and theory developments
Neutrino 2032: ?????

- Non standard interactions, non-unitarity.
- Dark sector connection (with dark photons, FIPs, DM)
- Exotic properties: decays, decoherence, CPT and Lorentz violation…

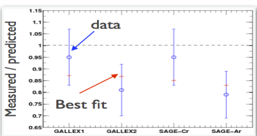
- Sterile neutrinos: Current hints for eV sterile neutrinos (LSND, MiniBooNE, BEST?) have not yet been confirmed or disproven. SBL oscillation experiments (SBN, reactor neutrino exp, BEST…) are testing them and will provide a definitive (???) answer by the end of this decade.



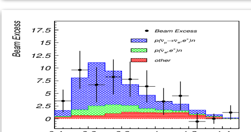
reactor flux anomaly
resolved with new input data
to flux calculation ✓



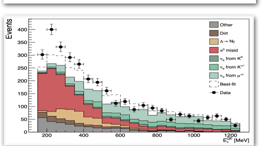
reactor spectra
is there really an anomaly? ?



gallium anomaly
unresolved, recently reinforced ?

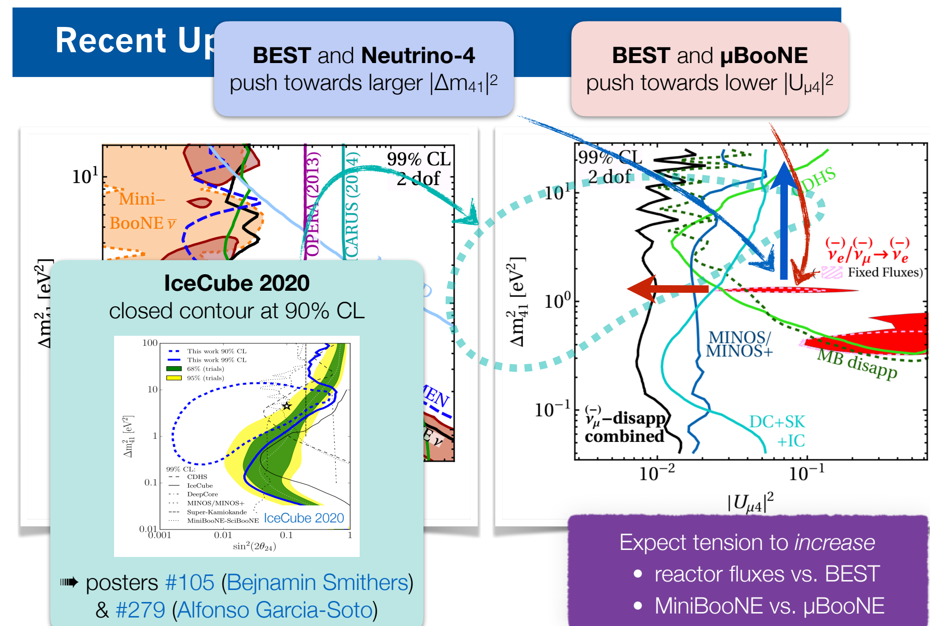


LSND
unresolved ?



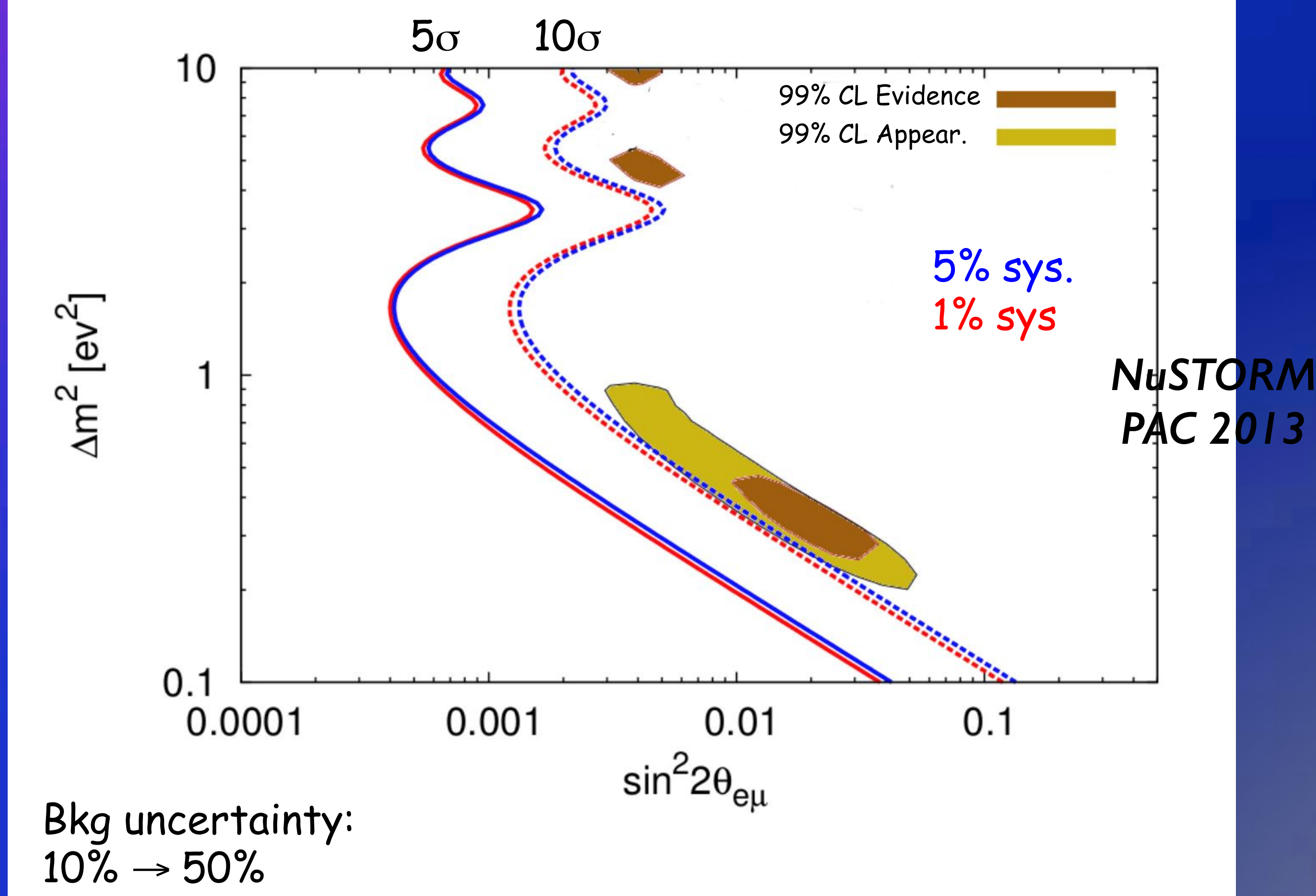
MiniBooNE
unresolved ?

See J. Kopp's talk at Neutrino 2022



The discovery of any signature beyond 3-neutrinos, would be game-changing for experiments and theory. Need to continue the search even for negative results.

NuSTORM would have intense neutrino beam with excellent knowledge of flux, composition.

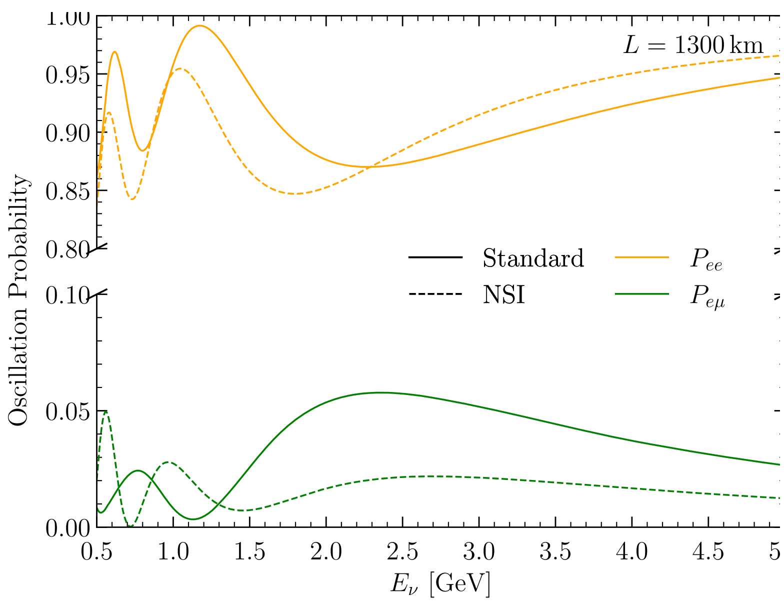


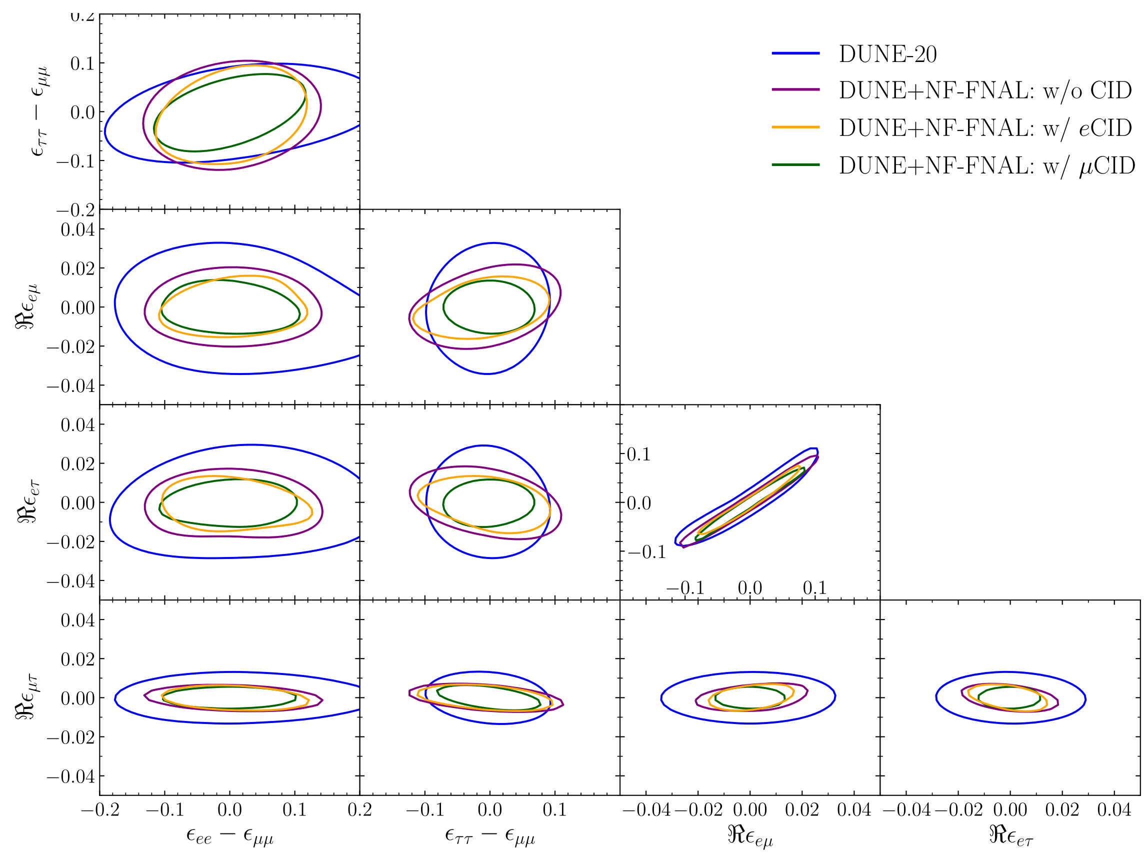
Global fit from: J. Kopp, P. A. N. Machado, M. Maltoni, and T. Schwetz, 392 JHEP 1305, 050 (2013)

NuSTORM would have excellent reach for sterile neutrinos.

Neutrino factory can search for

1. effects that appear at short distance: sterile neutrinos, NSIs, non-unitarity, CPT violation;
2. enhanced by long distances: NSIs in propagation.



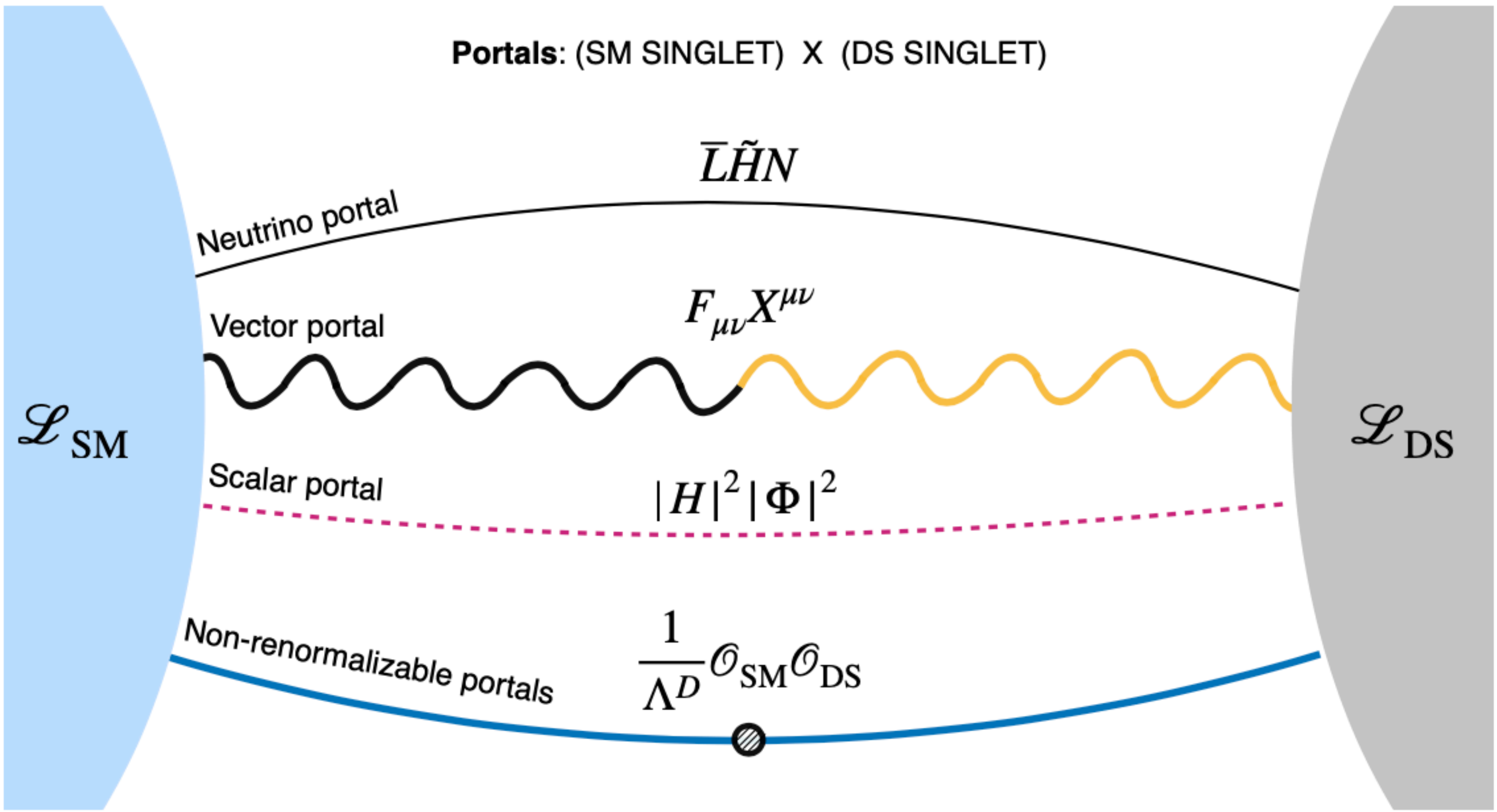


P. Denton, J. Gherlain, C.-F. Kong, NPB 1018 (2025)

BSM and Neutrino physics: the neutrino portal

Neutrino portal

New BSM can interact with SM via neutrino portal



EPSS abstract on Rich dark sectors, n. 250

After EW and U(1)' breaking, the active, sterile and dark neutrinos mix.

Neutrino masses Beyond SM

In the SM, neutrinos do not acquire mass and mixing.

Dirac Masses

If we introduce a right-handed neutrino, then an interaction with the Higgs boson emerges.

$$\mathcal{L} = -y_\nu \bar{L} \cdot \tilde{H} \nu_R + \text{h.c.} \longrightarrow m_D = y_\nu v = V m_{\text{diag}} U^\dagger$$

This term is SU(2) invariant and respects lepton number.

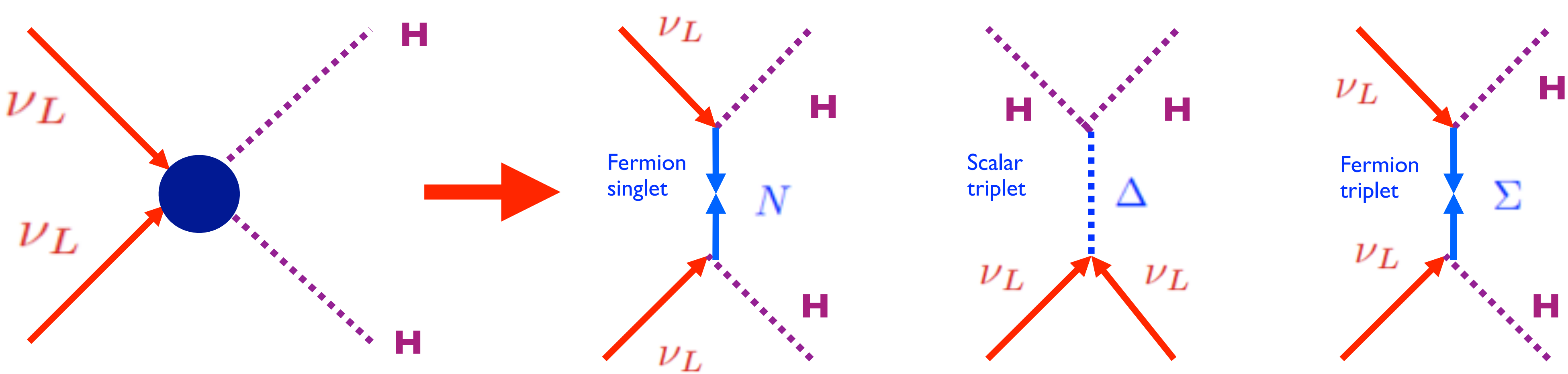
- why the coupling is so small??? $y_\nu \sim \frac{\sqrt{2} m_\nu}{v_H} \sim \frac{0.2 \text{ eV}}{200 \text{ GeV}} \sim 10^{-12}$
- why the leptonic mixing angles are large?
- why neutrino masses have at most a mild hierarchy?
- why no Majorana mass term for RH neutrinos? We need to impose L as a fundamental symmetry.

Majorana Masses

Introduce a Dimension 5 operator (or allow new scalar fields, e.g. a triplet):

$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M} = \frac{\lambda v_H^2}{M} \nu_L^T C^\dagger \nu_L$$

Weinberg operator, PRL 43



Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Ma, Mohapatra, Senjanovic, Magg, Wetterich, Lazarides, Shafi, Schecter, Valle, Hambye…

This term breaks lepton number and induces Majorana masses and Majorana neutrinos. It can be induced by a high energy theory (see-saw mechanism).

Neutrino masses BSM: "vanilla" see saw mechanism type I

Particle zoo

Symmetry magazine

- Introduce a right handed neutrino **N**
- It couples to the Higgs and has a Majorana mass

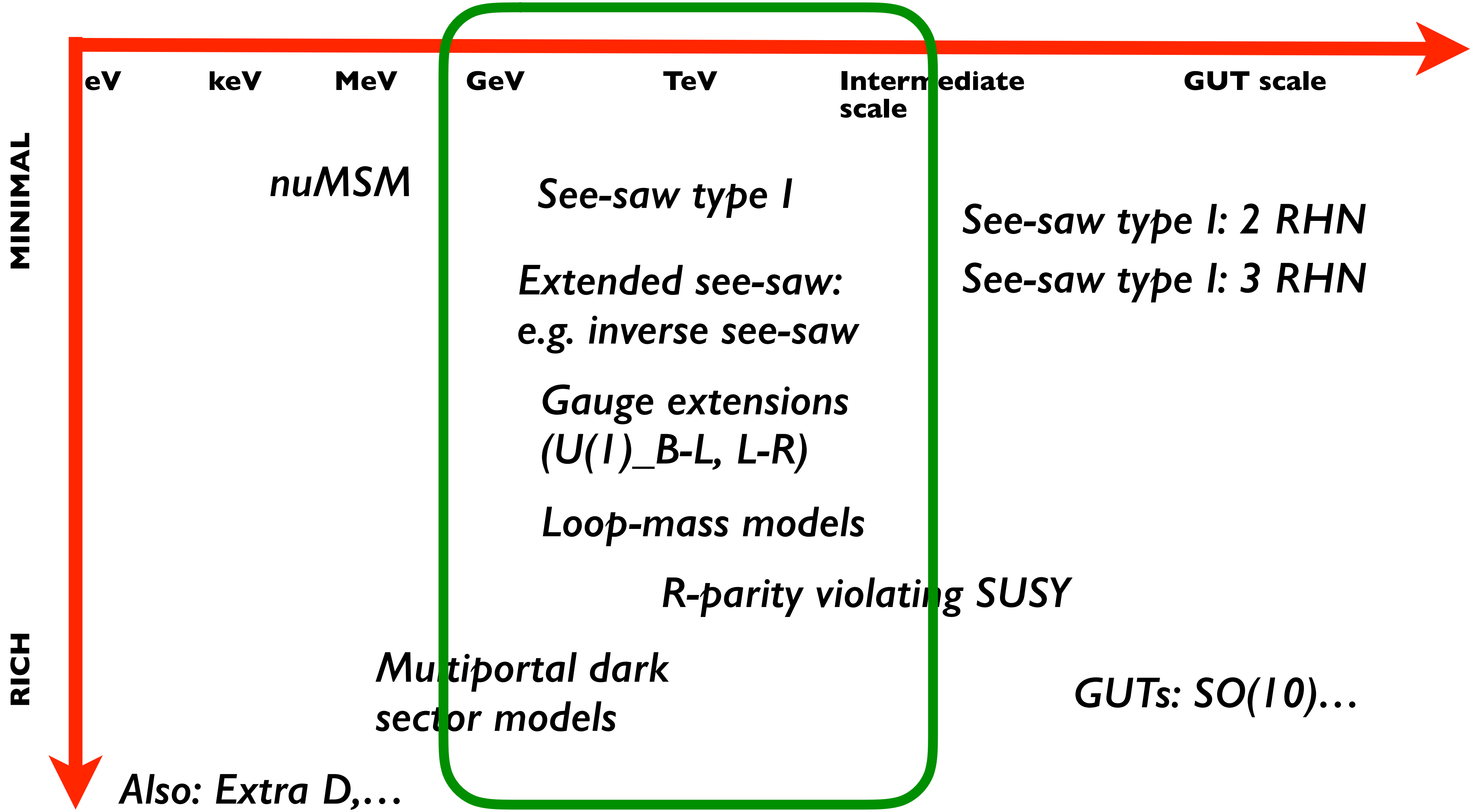
$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Rightarrow m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic

As a result, neutrinos can have naturally small masses and are Majorana particles.

Neutrino mass models at the GeV-TeV scale



Two contrasting approaches can be taken:

Minimality: the fewest ingredients -> predictivity

Richness (theory-motivated): links, new signatures

What are TeV models?
and how to test them?

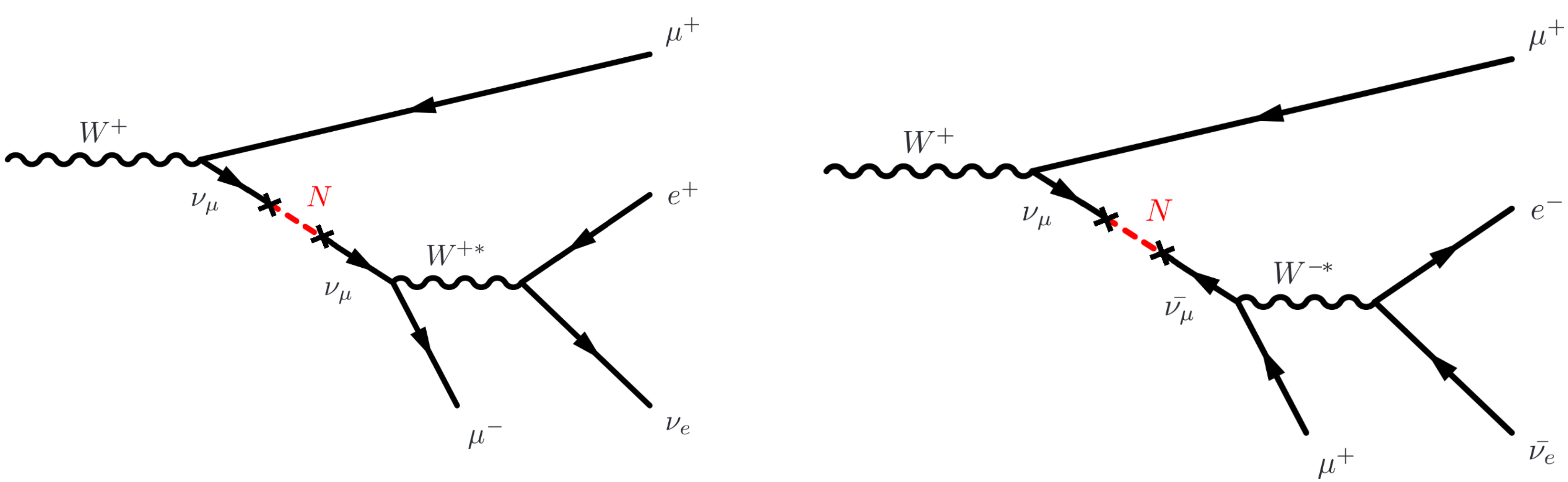
See-saw type I at colliders

In see-saw type I, HNLs are produced via mixing with neutrinos via W, Z or VBF. At 13 TeV:

$$\sigma(pp \to W) \cdot \mathcal{B}(W \to \ell N) = \sigma(pp \to W) \cdot \mathcal{B}(W \to \ell \nu) \cdot |U|^2 \left(1 - \frac{m_N^2}{m_W^2}\right)^2 \left(1 + \frac{m_N^2}{2m_W^2}\right)$$

Atre et al., 0901.3589, ATLAS, JHEP 10 (2019) 265

They subsequently decay via mixing as well.

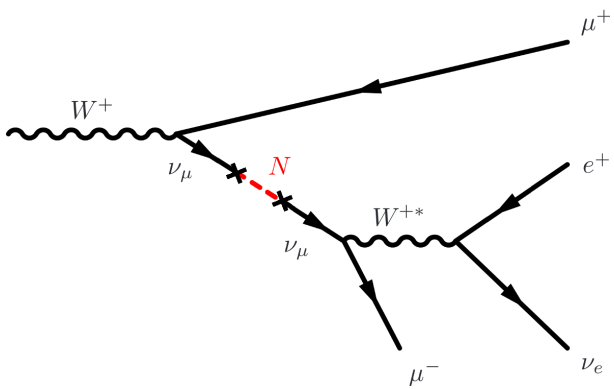


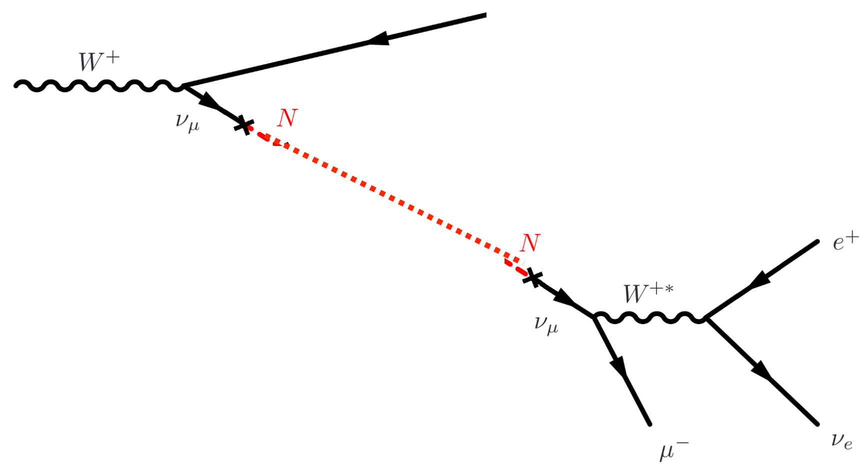
ATLAS Coll., JHEP 10 (2019) 265

The decay rate scales as (for $m_N < M_W$)

$$\Gamma \sim g^4 U^2 \frac{m_N^5}{m_W^4}$$

and the decay length can be short or >>mm.





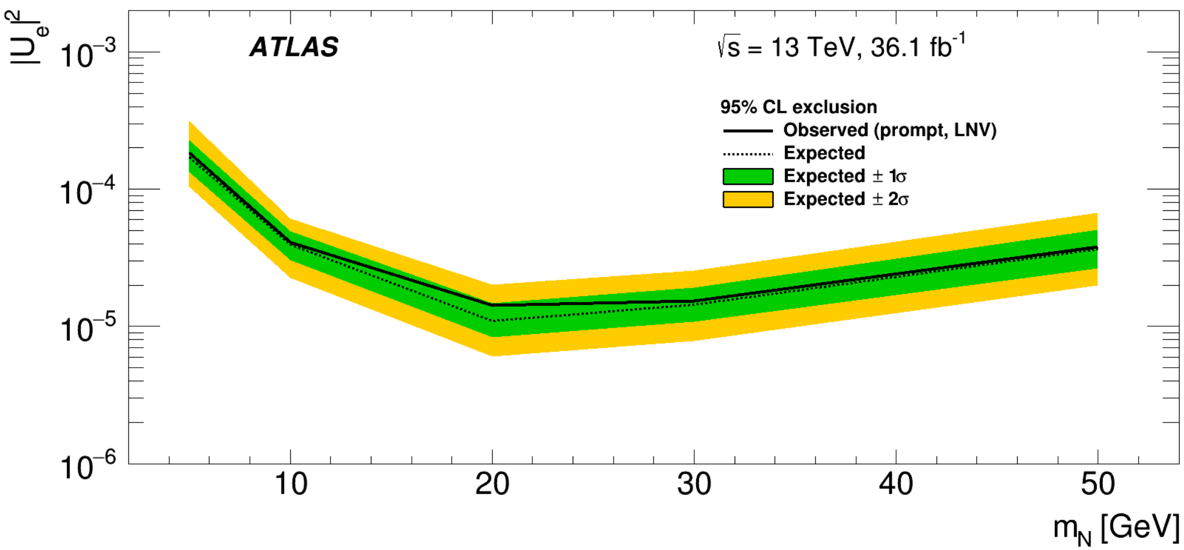
Two types of signatures:

Large mixing -> Prompt decays (multileptons, jets and missing energy….)

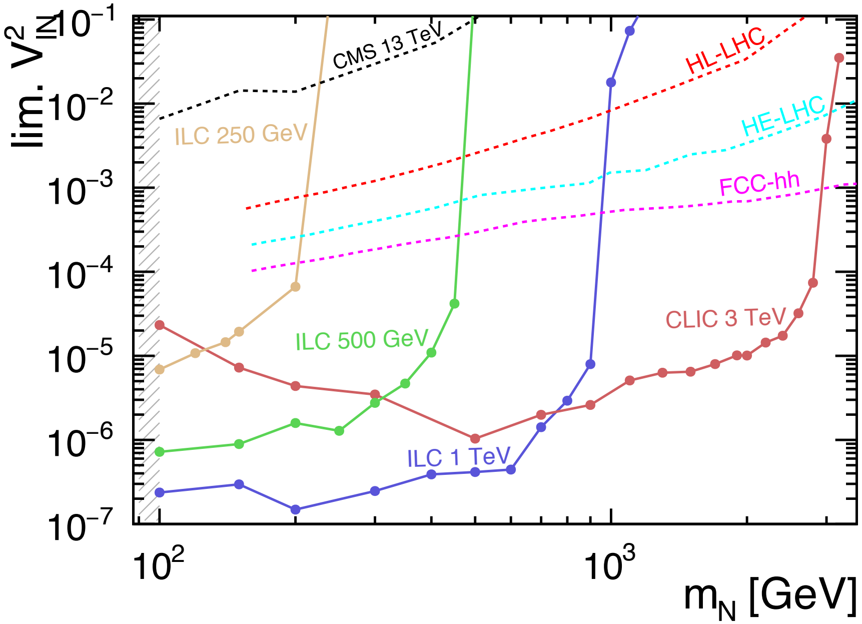
Small mixing -> Displaced vertices

Large mixing -> Prompt decays

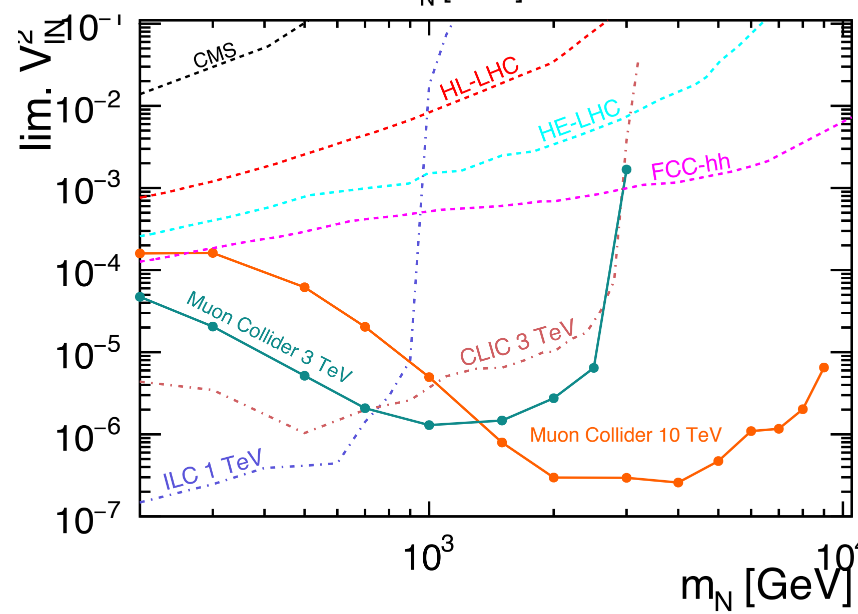
Search in ATLAS for HNL decays into tri-leptons at IP.



ATLAS Coll., JHEP 10 (2019) 265



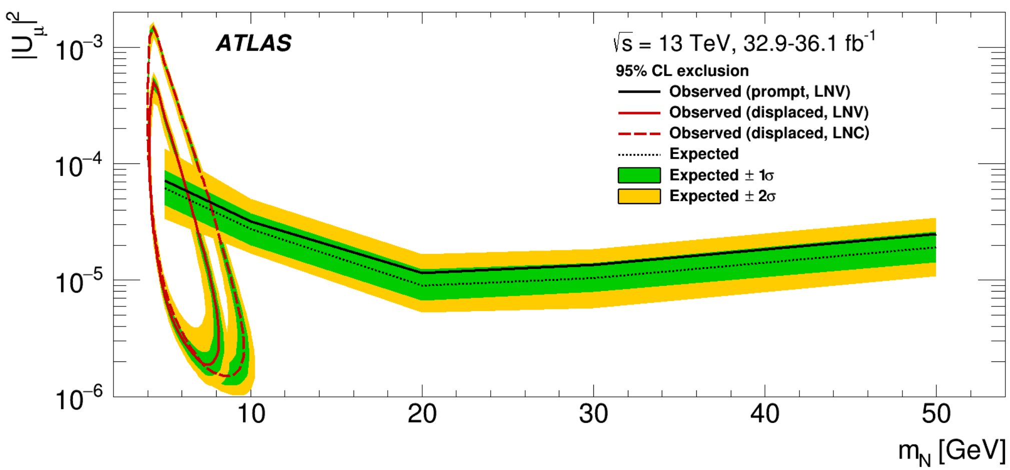
LHC analysis: [1812.08750], diff. assumption: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$



LHC analysis: [1812.08750], diff. assumption: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$

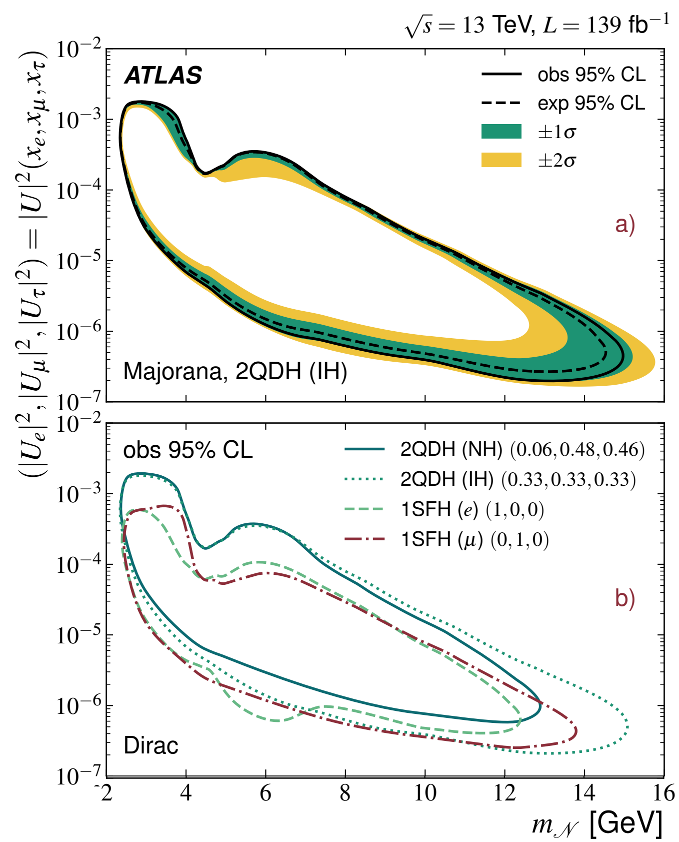
Displaced vertices

Search in ATLAS for HNLs assuming one prompt lepton and a DV with two leptons and missing E.



ATLAS Coll., 1905.09787

Usually one assumes one single flavour mixing but analysis are being now carried out for more realistic models.



ATLAS Coll., PRL 2204.11988

Beyond minimal see-saw type I

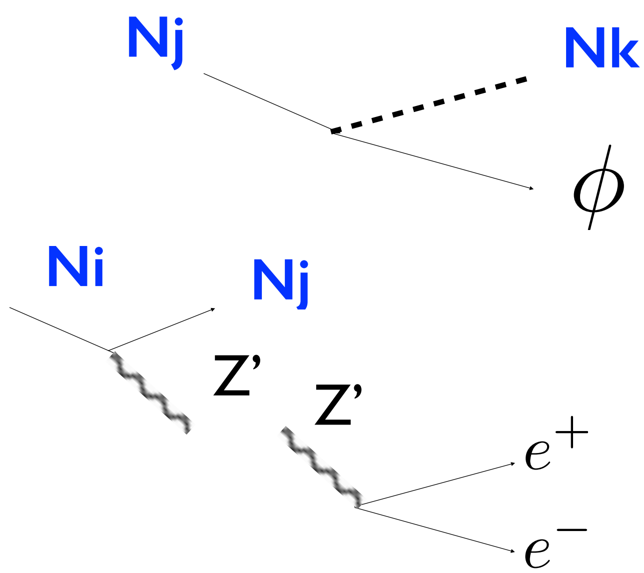
HNL can also interact with the SM via other channels. In see-saw type III, they are triplets of the SM.

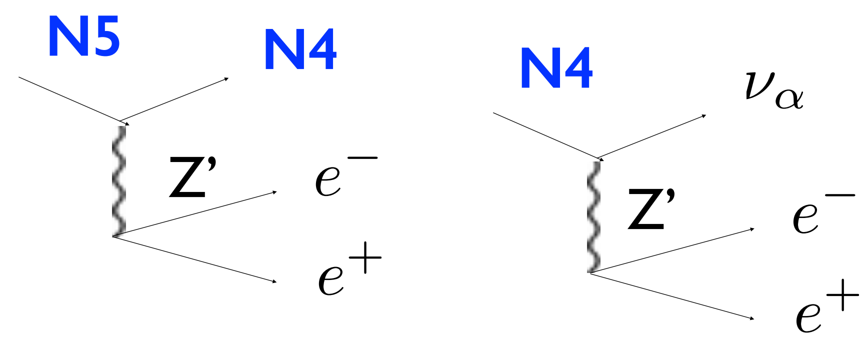
Gauge extensions of the SM at the TeV scale include:

- B-L: anomaly-free with Ns;
- combinations of Le, Lmu, Ltau, e.g. Lmu-Ltau;
- secluded U(1);
- L-R models: possible remnant of Pati-Salam, SO(10) models, they naturally embed NR.

HNL production is not suppressed by the mixing angle but can proceed via large gauge couplings if SM also charged (or via mixing, if not).

Decays can still be due to SM+mixing, or into dark sector particles (that can further decay) and SM, leading to faster decays.

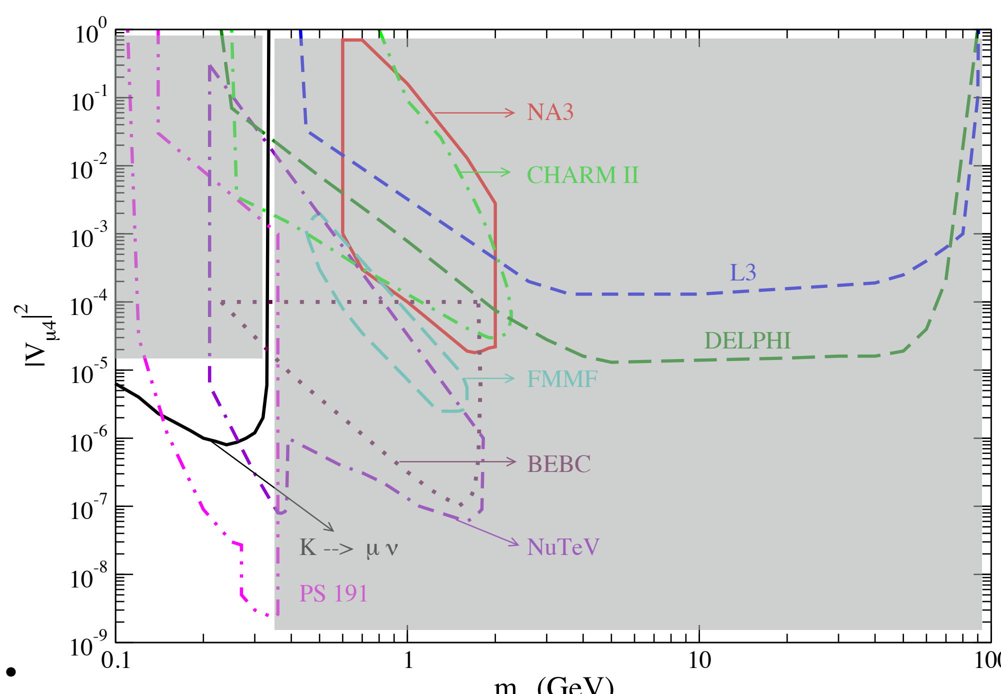




decay chains

Fast visible and invisible decays

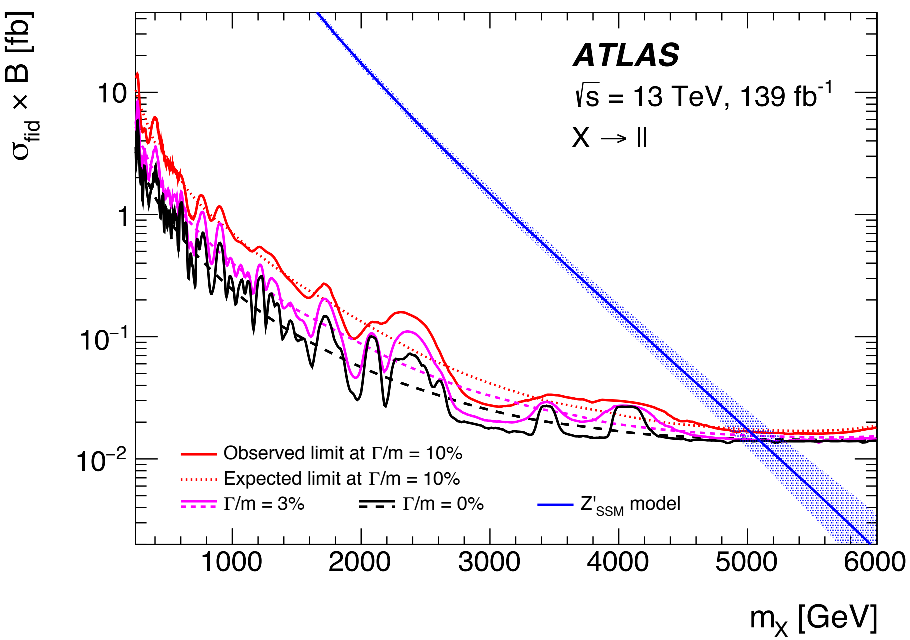
HNL decay bounds need to be reevaluated and they may not apply (e.g. beam dump experiments).



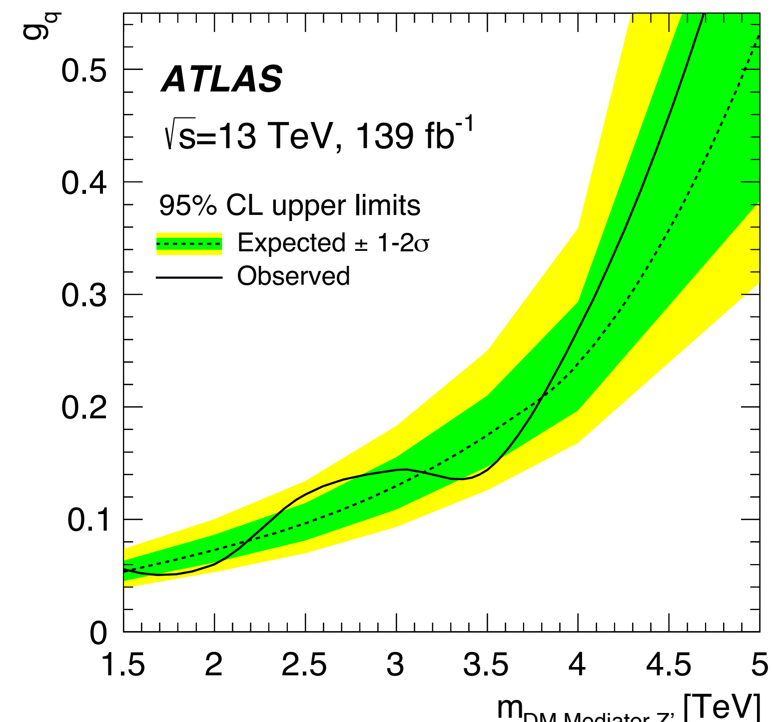
Adapted from Atre et al. 2009

B-L extensions

They contains a heavy Z' which couples with large couplings to HNLs. ATLAS, CMS, LHCb searches for dileptons, dijets and ditops. The decay Br depends on additional states present, e.g. DM, HNLs….

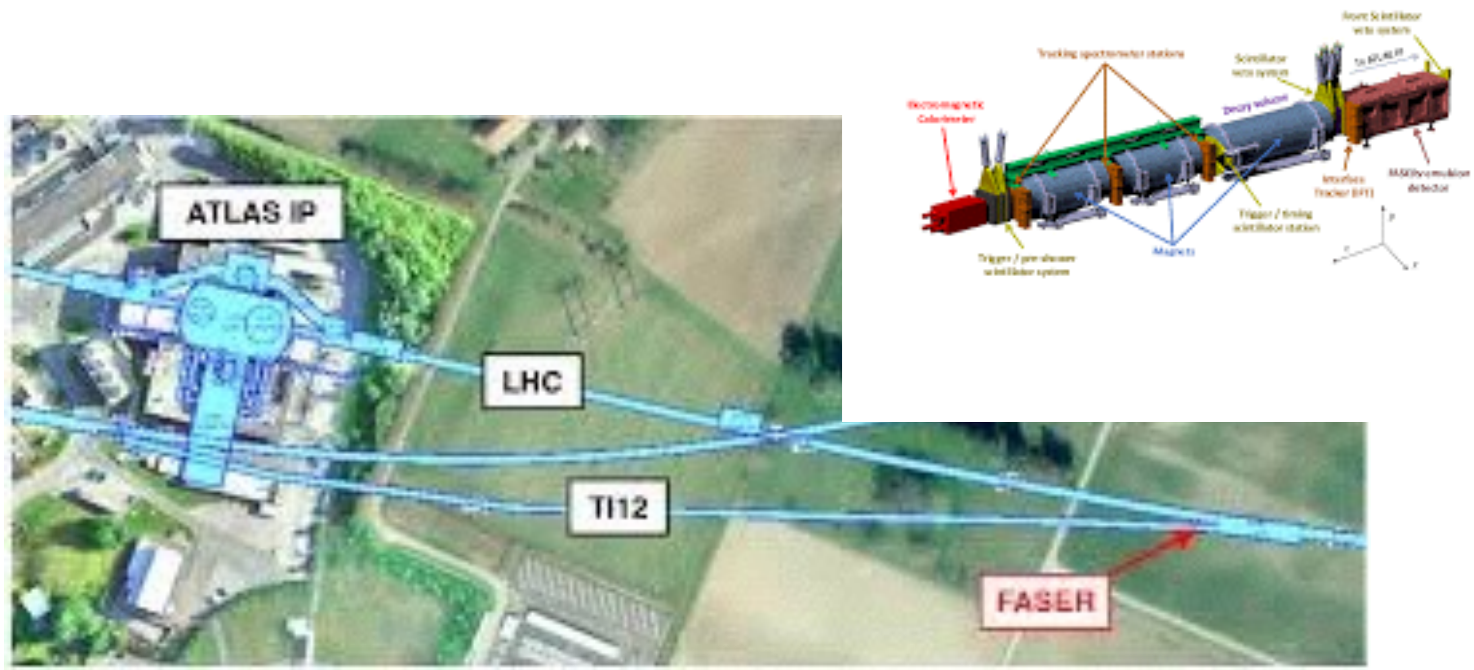


ATLAS Coll.,1903.06248



ATLAS Coll.,1910.08447

Many collider-based experiment has been proposed at the LHC: FASER, Mathusla, CODeX,… to search for new physics by looking at exotics produced 1. at the interaction point that decay/interact in the detector; 2. by scattering of neutrinos in the detector itself.

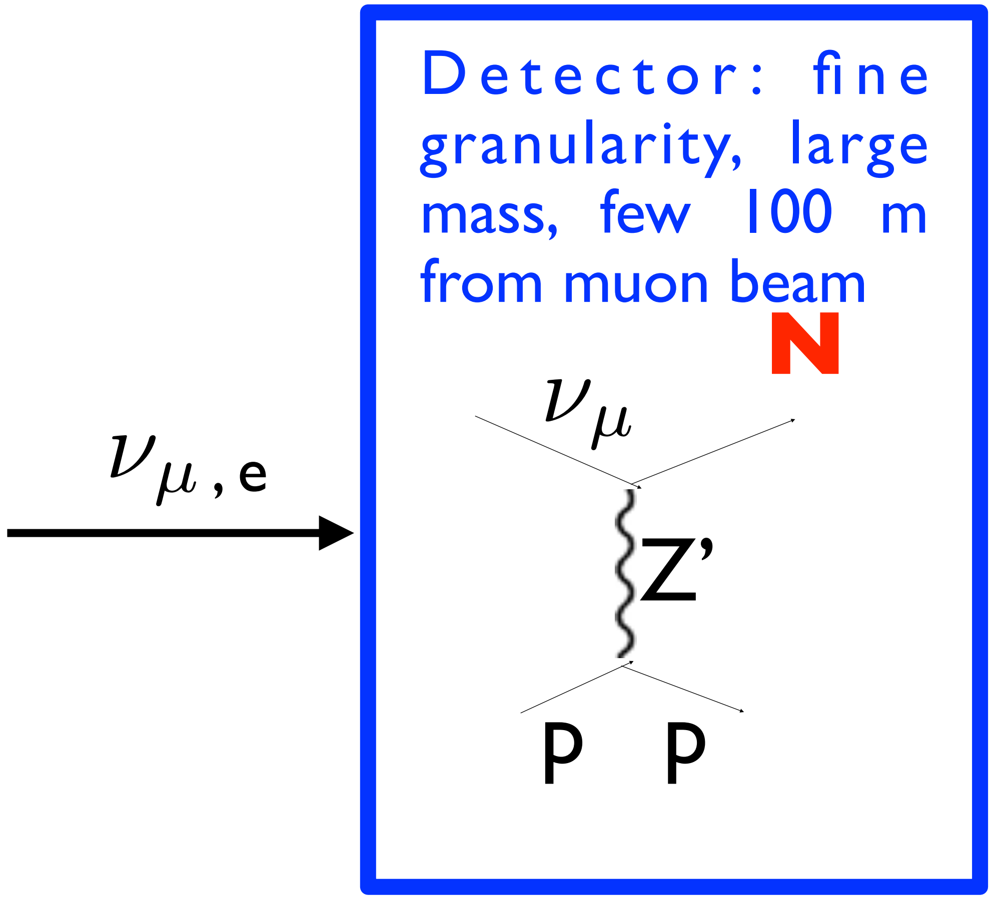


FASER exp, FASERnu

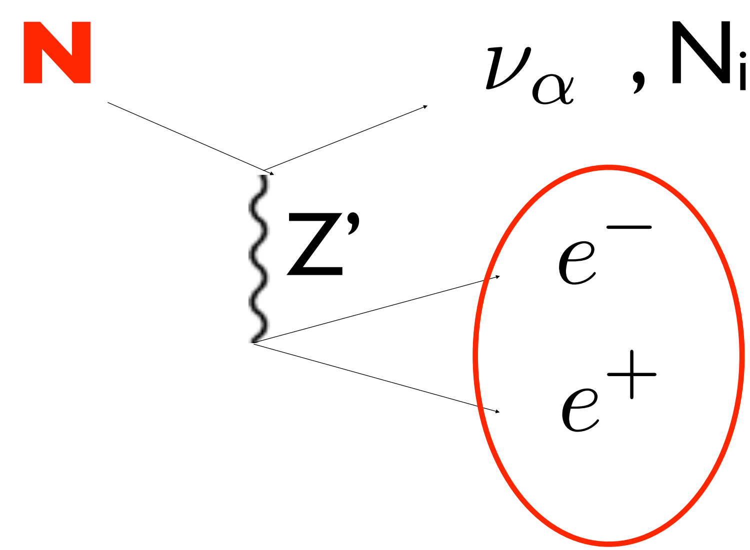
Can one do something similar at a muon collider? Advantages: exotics produced at the interaction point but also high energy neutrinos from muon decays.

New exp signatures

HE neutrinos from muon decays (in a straight line) -> Up-scattering of an HNL N (or other exotic) in the detector and its decay into ee (mumu) nu.



For MiniBooNE see P. Ballett, S. Pascoli, M. Ross-Lonergan, PRD 99 (2019). See also S. Gnineko, PRL 103 (2009), E. Bertuzzo et al., PRL 121 (2018).



This would allow to test dark sectors in the GeV mass range by looking at these dark particles.

Conclusions

Neutrinos are the most elusive and mysterious of the known particles.

Current status: precise knowledge of most of neutrino properties. Key questions open (nature, CPV) due to be answered in the next decade. Thriving experimental programme.

Neutrino masses is the only particle physics evidence BSM. What is their origin?

Link with colliders Neutrino mass models at the TeV scale assume new particles and interactions that may be tested in colliders. LNV is a key observable and directly linked with neutrino masses (and leptogenesis?).