Heavy neutrinos at NA62

based on JHEP 1807 (2018) 105

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XXVII International Workshop on Deep Inelastic Scattering and Related Subjects

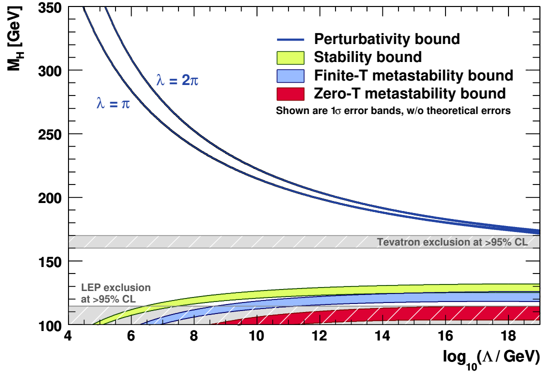
Disclaimer

- I am not an experimentalist.
- I do not speak on behalf of the NA62 collaboration.
- Nonetheless, we have published estimates on heavy neutrinos at NA62.
- One member of our collaboration is an experimentalist at NA62.

Hierarchy problem

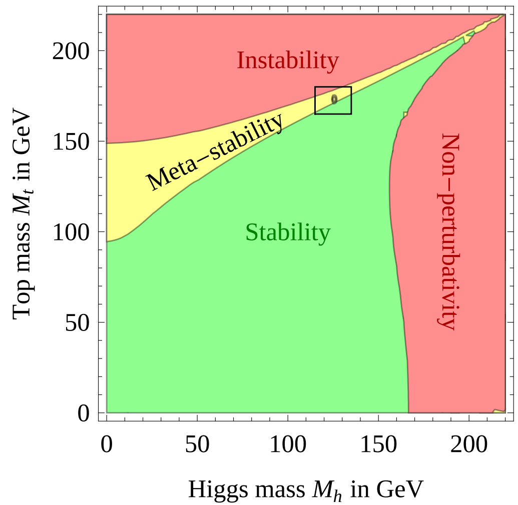
Higgs mass [Ellis et al. 2009]

Only in a small window of m_h can the SM be extended to the M_P



Higgs-top conspiracy [Degrassi et al. 2012]

Their mass values happen to put us into a meta-stable vacuum



The SM is technically natural up to M_P

Hierarchy problem

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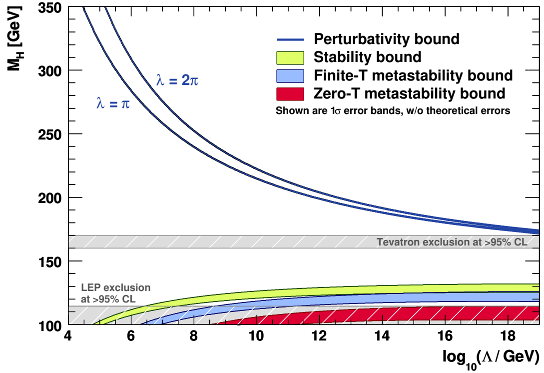
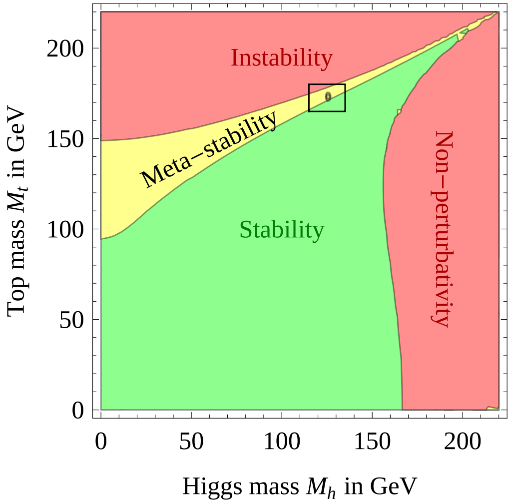


New Physics

- Heavy NP easily destabilizes the Higgs mass
- NP at the electroweak scales circumvents this problem
- must be coupled feebly enough to have evaded detection

Higgs-top conspiracy [Degrassi et al. 2012]

Their mass values happen to put us into a meta-stable vacuum



The SM is technically natural up to M_P

Relatively light and feebly coupled NP

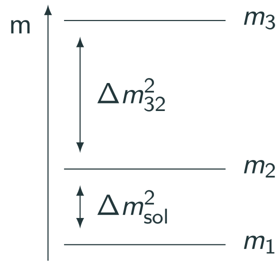
leads to long lived particles

Neutrino masses

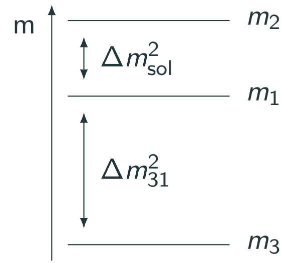
Masses differences

- There are two measured mass differences for potentially three light neutrino masses m_1, m_2, m_3
- one neutrino may still be massless $m_{\text{lightest}} = 0$
- The smaller "solar" mass difference is given by $\Delta m^2_{\text{sol}} = m^2_2 - m^2_1$

Normal ordering



Inverted ordering



Parameter

Variables	Normal Ordering	Inverted Ordering
m^2_1	m^2_{lightest}	$m^2_{\text{lightest}} - \Delta m^2_{32} - \Delta m^2_{\text{sol}}$
m^2_2	$m^2_{\text{lightest}} + \Delta m^2_{\text{sol}}$	$m^2_{\text{lightest}} - \Delta m^2_{32}$
m^2_3	$m^2_{\text{lightest}} + \Delta m^2_{31}$	m^2_{lightest}
larger Δm^2	$\Delta m^2_{31} = m^2_3 - m^2_1$	$\Delta m^2_{32} = m^2_3 - m^2_2$

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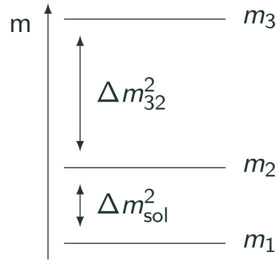
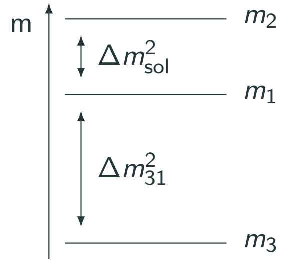


Inverted ordering



Best fit values from the NuFIT 3.1 release by the ν-fit collaboration

Variables	Normal Ordering	Inverted Ordering
(smaller) Δm^2_{sol}	7.40×10^{-5} eV^2	7.40×10^{-5} eV^2
larger Δm^2	2.515×10^{-3} eV^2	-2.483×10^{-3} eV^2
$\sin^2\theta_{12}$	0.307	0.307
$\sin^2\theta_{13}$	0.02195	0.02212
$\sin^2\theta_{23}$	0.565	0.572

Heavy Neutrinos

Low scale seesaw (type I) [Minkowski 1977; Mohapatra et al. 1980; Yanagida 1980; Schechter et al. 1980]

Three right handed neutrinos

$$\mathcal{L}_{\nu_R} = -\frac{1}{2}\overline{\nu^c_{R}}_i M_{ij} \nu_{Rj} - y_{ai} \bar{\ell}_a \varepsilon \phi \nu_{Ri} + \text{h.c.}$$

M_{ij} Majorana mass;
y_{ai} Yukawa coupling

Electroweak symmetry breaking

Dirac mass: $m_{ai} = v y_{ai}$

Seesaw mechanism

$$m_\nu = -m_{ai} M^{-1}_{ij} m^T_{bj} = -\theta_{ai} M_{ij} \theta^T_{bj} \ , \quad \theta_{ai} = m_{aj} M^{-1}_{ij} \ ,$$

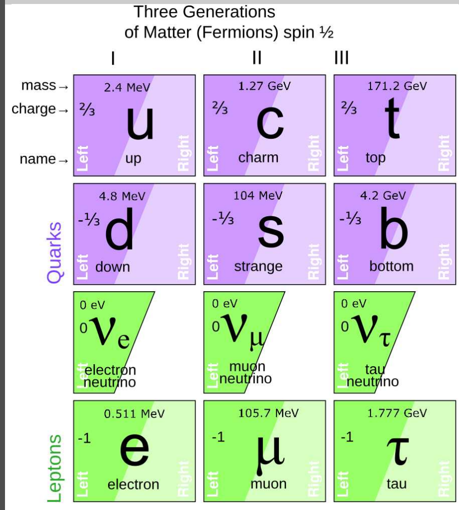
produces tiny masses for the left handed neutrinos

Small mixing into mass eigenstates

$$\nu \simeq U^\dagger_\nu (\nu_L - \theta \nu^c_R) \ , \qquad N \simeq \nu_R + \theta^T \nu^c_L \ ,$$

the PNMS matrix U_ν diagonalises the m_ν

The neutrino is special



May explain

- Neutrino oscillation data
- Neutrino masses
- Baryogenesis via Leptogenesis
- Dark matter

Three right handed neutrinos

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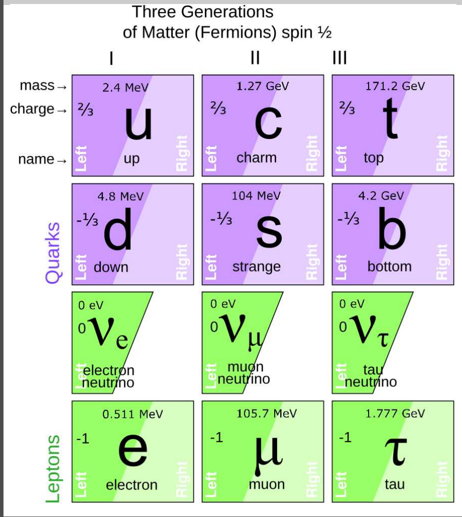

Coupling of N_i to the SM

$$\mathcal{L} \supset -\frac{m_W}{v} \overline{N} \theta^*_a \gamma^\mu e_{La} W^+_\mu - \frac{m_Z}{\sqrt{2} v} \overline{N} \theta^*_a \gamma^\mu \nu_{La} Z_\mu - \frac{M}{v} \theta_a h \overline{\nu_L}_\alpha N + \text{h.c.} \ .$$

νMSM

SM is symmetric under $U(1)_{B-L}$

Majorana mass M_{ij} breaks this symmetry

The $B - L$ symmetry is restored

- in the limit of $M_{ij} \to 0$
- if ν_{Ri} form pseudo Dirac pairs $\nu_{Ri} + \nu_{Rj}^c$

νMSM

[Asaka et al. 2005; Shaposhnikov 2007]

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$B-L$ violating parameter

ϵ, ϵ', μ, μ' are small

Mass matrix

$$M_{ij} = M \begin{pmatrix} 1-\mu & 0 & 0 \\ 0 & 1+\mu & 0 \\ 0 & 0 & \mu' \end{pmatrix}$$

- Almost mass degenerate pseudo dirac pair
- lighter $\mathcal{O}(\mathrm{keV})$ dark matter candidate

Yukawa coupling

$$y_{ai} = \begin{pmatrix} y_e + \epsilon_e & i(y_e - \epsilon_e) & \epsilon'_e \\ y_\mu + \epsilon_\mu & i(y_\mu - \epsilon_\mu) & \epsilon'_\mu \\ y_\tau + \epsilon_\tau & i(y_\tau - \epsilon_\tau) & \epsilon'_\tau \end{pmatrix}$$

- pseudo Dirac pair with coupling $\mathcal{O}(y)$
- Dark matter candidate with coupling $\mathcal{O}(\epsilon')$

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Abbreviation

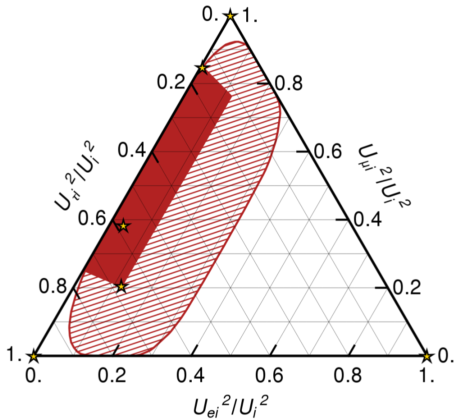
$$U^2 = \sum_a U_a^2 \,, \quad U_a^2 = \sum_i U_{ai}^2 \,, \quad U_{ai}^2 = |\theta_{ai}|^2 \,,$$

The ratio U_a^2/U_2

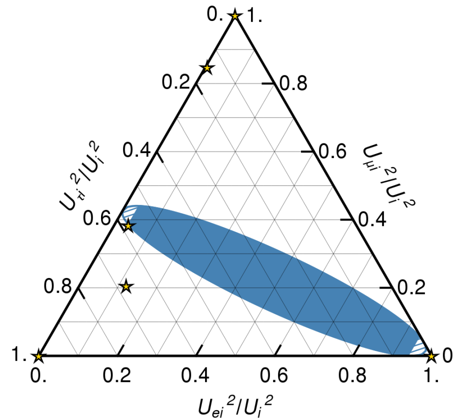
becomes independent of other heavy neutrino parameter

Allowed range of U_a^2/U^2

Normal Ordering



Inverted Ordering



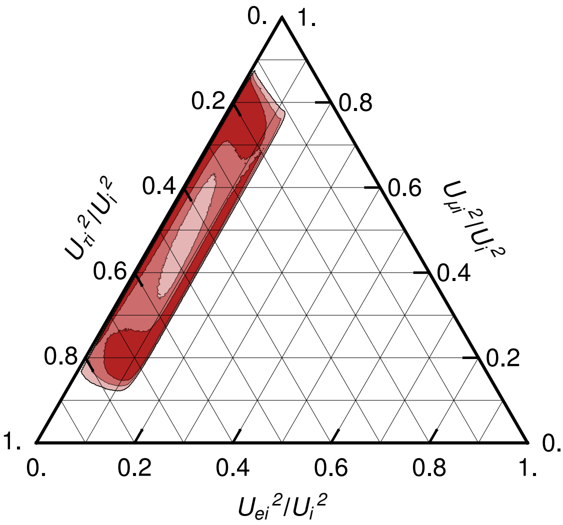
- for arbitrary parameter choices (hashed region)
- in the symmetric limit (filled region).
- The stars mark our benchmark scenarios.

Benchmark scenarios U_a^2/U^2 in %

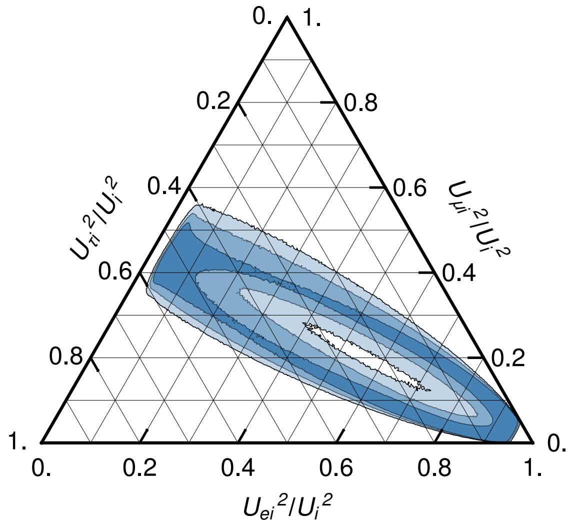
	U_{ei}^2	:	$U_{\mu i}^2$	:	$U_{\tau i}^2$
A	0.530	:	84.7	:	14.7
B	12.0	:	20.5	:	67.5
C	3.65	:	38.3	:	58.0
D	100	:	0	:	0
E	0	:	100	:	0
F	0	:	0	:	100

Probability contours for the heavy neutrino couplings

Normal Ordering



Inverted Ordering



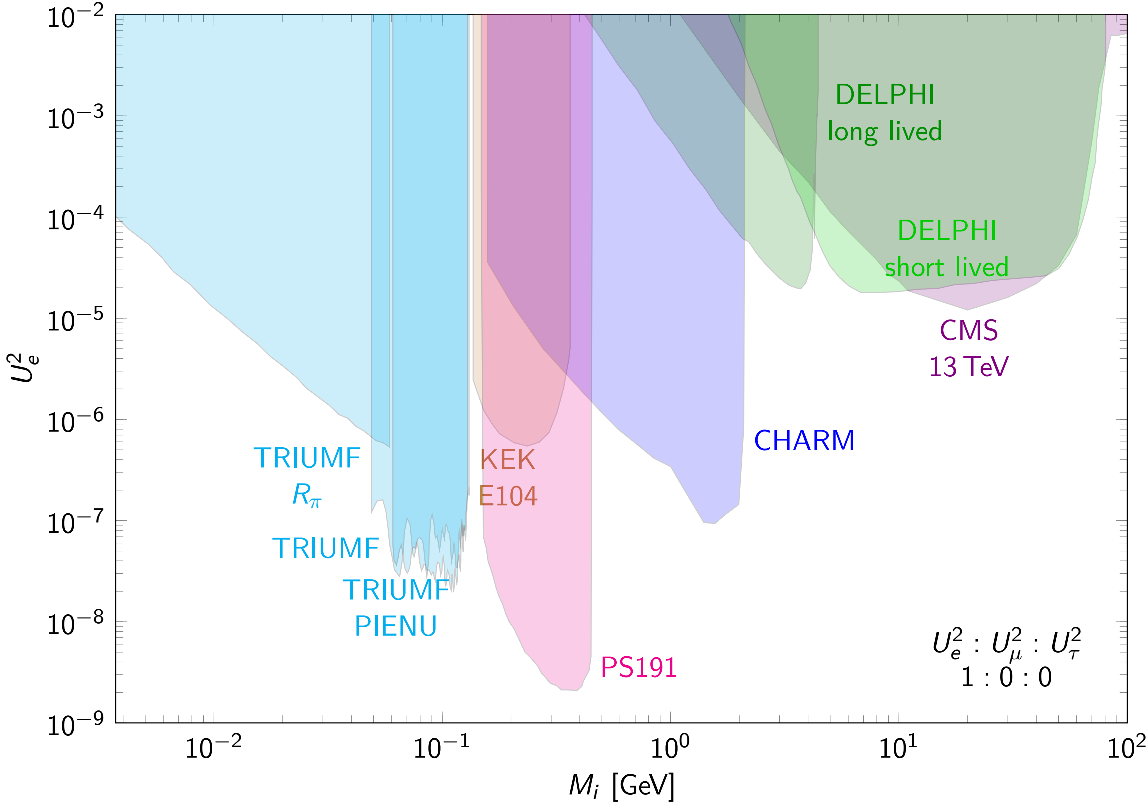
Coloured areas

consistent with neutrino oscillation data at $1\,\sigma$, $2\,\sigma$, $3\,\sigma$

The Majorana phase is unknown

and correspond to the circular structure in the plots

pure U_e^2



DELPHI
long lived
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CHARM
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$U_e^2 : U_\mu^2 : U_\tau^2$
1 : 0 : 0
U_e^2
M_i [GeV]
10^{-2}
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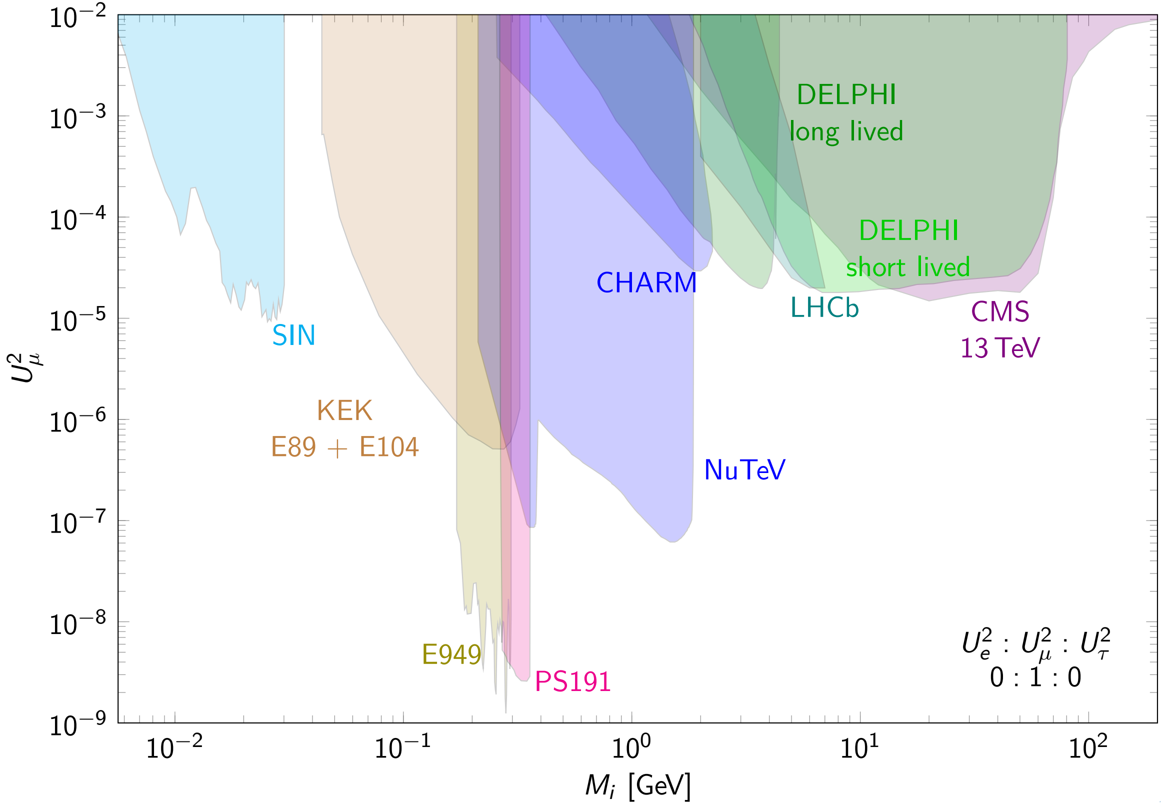
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

pure U_μ^2



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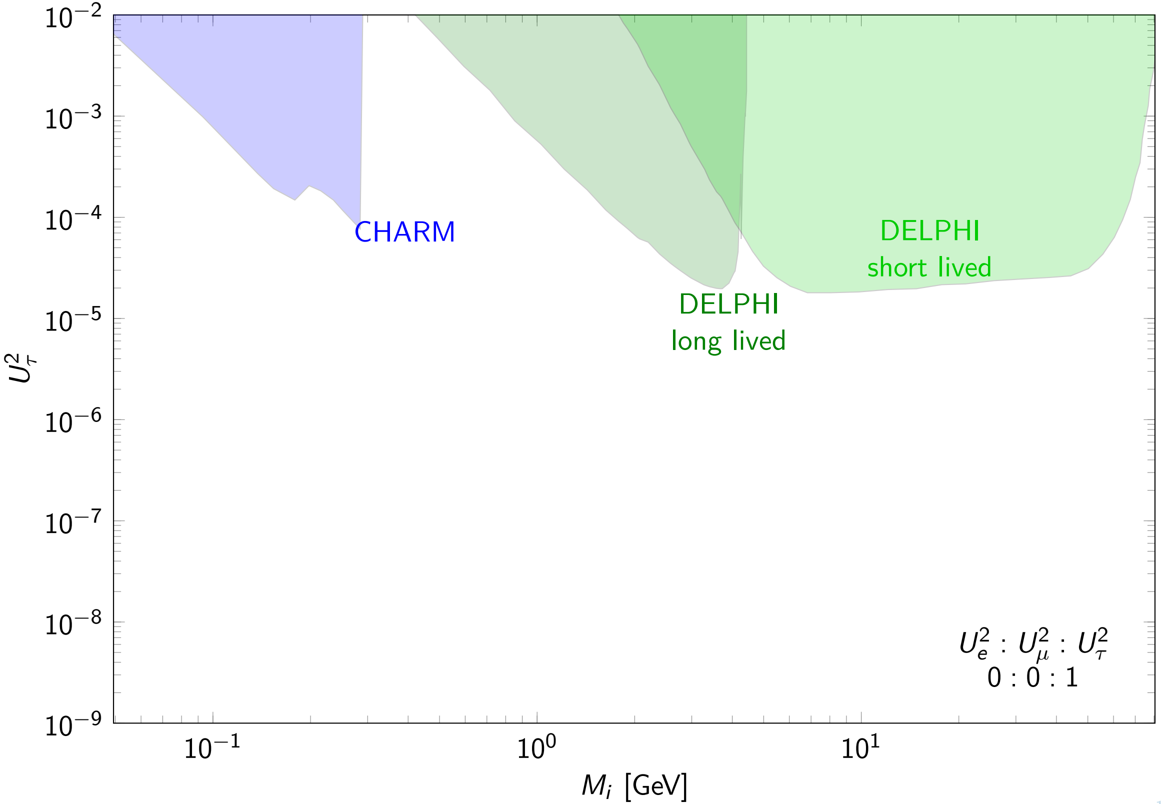
10^{2}
M_i [GeV]
DELPHI
long lived
DELPHI
short lived
CHARM
SIN
LHCb
CMS
13 TeV
KEK
E89 + E104
NuTeV
E949
PS191
$U_e^2 : U_\mu^2 : U_\tau^2$
0 : 1 : 0

pure U_τ^2



CHARM
DELPHI
short lived
DELPHI
long lived
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0 : 0 : 1
U_τ^2
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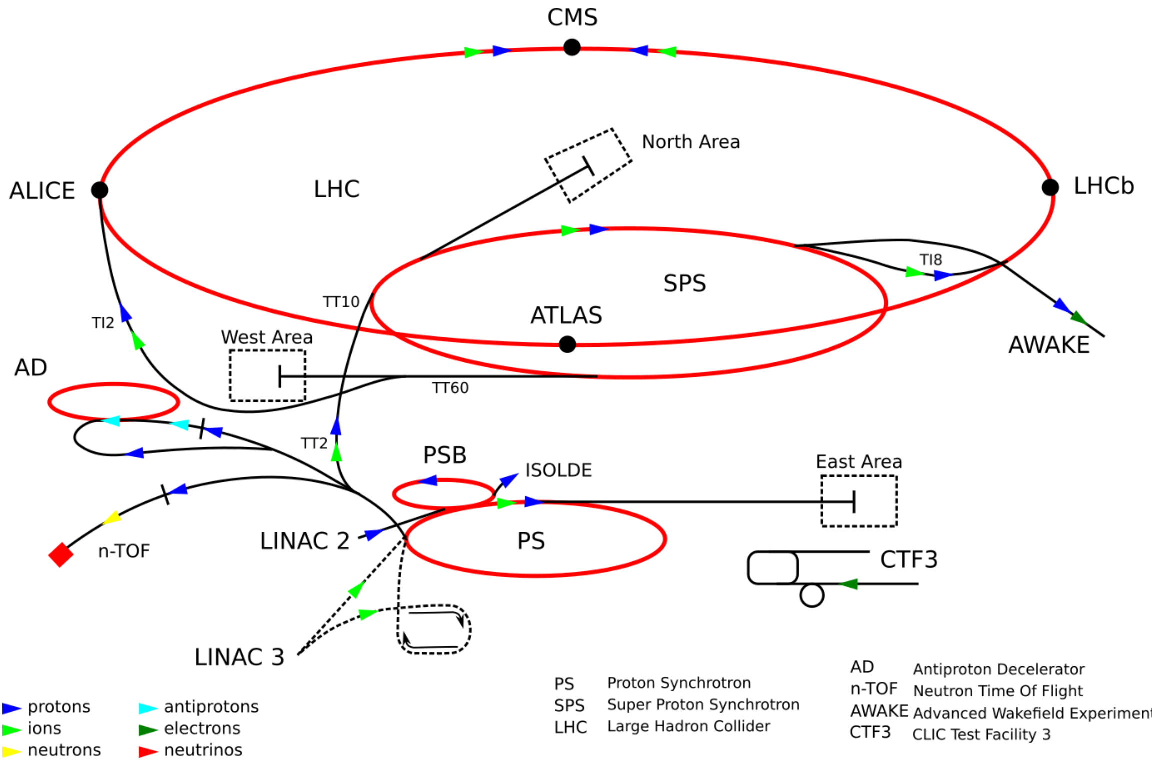
NA62

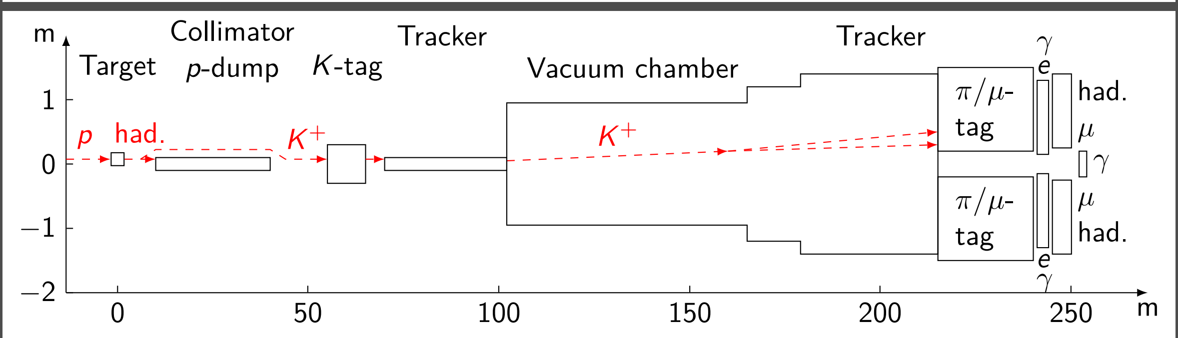
SPS and North Area at CERN



NA62

Fixed target experiment in the North Area using the CERN SPS with the goal to

- measure the very rare kaon decay $K^+ \to \pi^+ \nu \bar{\nu}$
- extract a $10\,\%$ measurement of the CKM parameter $|V_{td}|$



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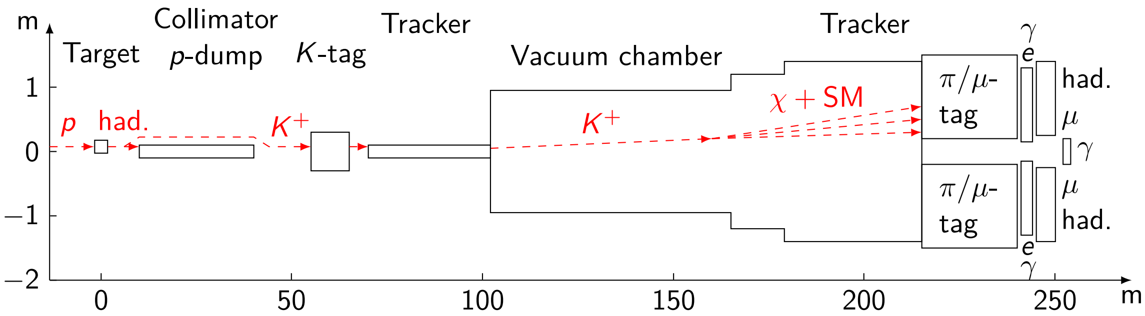

Hidden sectors at NA62

- it can also be used to search for hidden new physics χ such as a heavy neutrino
- Target mode
- only K^+ induced processes

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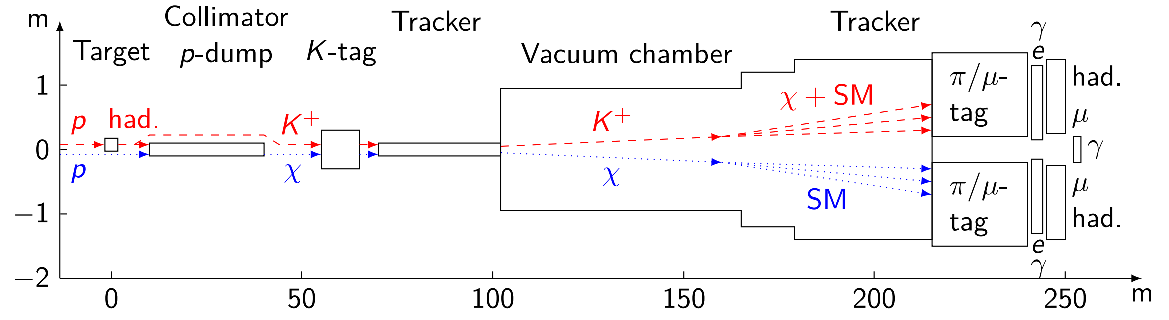
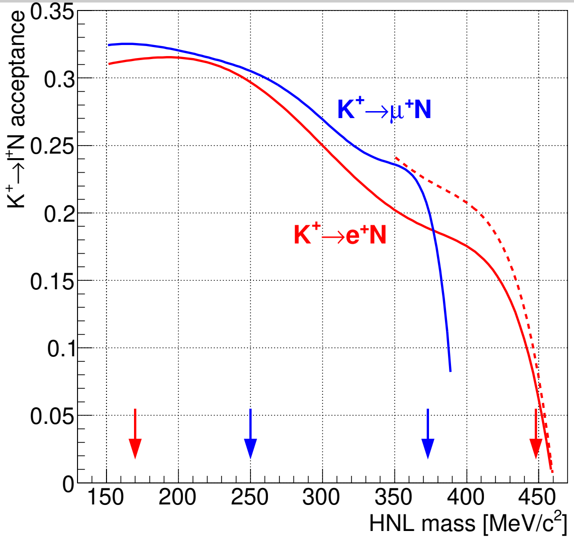


Hidden sectors at NA62

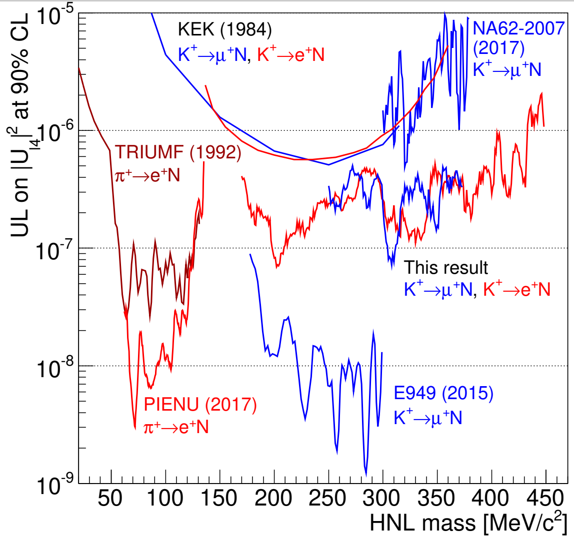
- it can also be used to search for hidden new physics χ such as a heavy neutrino
- Target mode
- only K^+ induced processes
- Dump mode
- D- and B-meson induced processes dominate

Heavy Neutrinos in the Target mode

Acceptance of $K^+ \to \ell^+ N$



Result



5 days of operation in 2015

Heavy Neutrinos in the Dump mode

Simulation

- Toy Monte Carlo of the dump mode
- Zero background assumption

Run 3 (2021–2023)

- 10^{18} proton on target (POT)
- corresponds to about 80 days of data taking

Production of heavy neutrinos via 2×10^{15} D- and 10^{11} B-mesons

$$n_N \simeq 2N_{\mathrm{POT}} \left(\chi_c \sum_{D_j = D^+,\, D^0,\, D_s} f_{D_j} \, \mathrm{BR}\left(D_j \to XN_i\right) + \chi_b \sum_{B_k = B^+,\, B^0,\, B_s} f_{B_k} \, \mathrm{BR}\left(B_K \to XN_i\right) \right) ,$$

χ production cross section normalization

f production fractions of mesons

Number of reconstructed events

$$N_{\mathrm{obs}} = n_N \sum_{f,\, f' = e,\, \mu,\, \tau,\, \pi,\, K} \mathrm{BR}\left(N_i \to f^+ f'^- X\right) \mathcal{A}_i \left(f^+ f'^- X,\ M_i,\ U^2_{e,\, \mu,\, \tau}\right) \varepsilon \left(f^+ f'^- X,\ M_i\right) ,$$

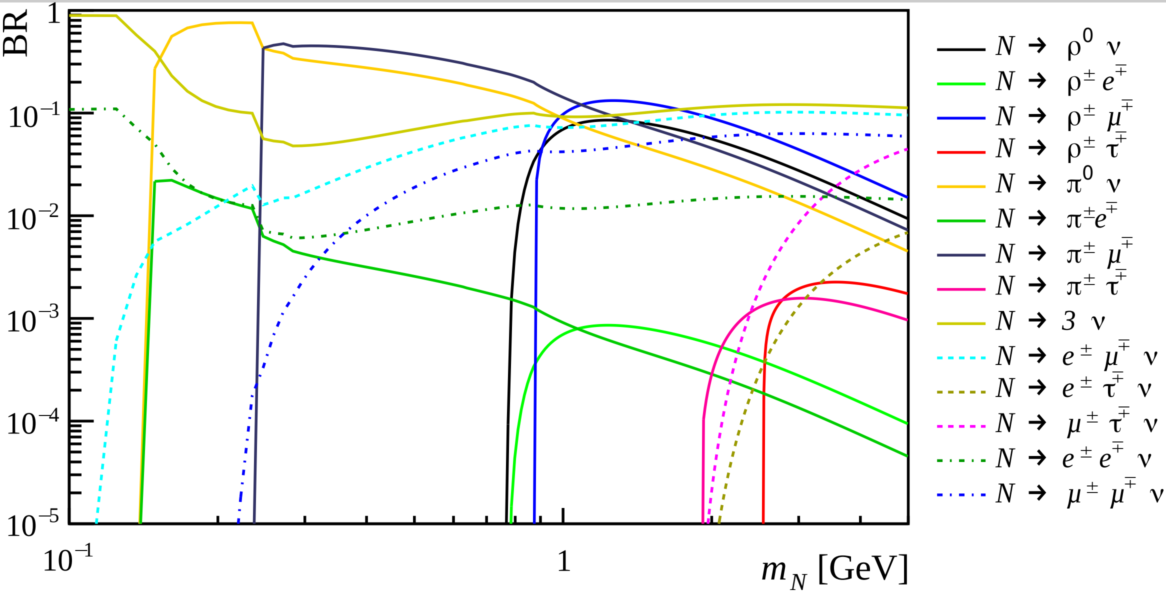
$\mathcal{A}_l$ geometrical acceptance

ε efficiency (trigger, reconstruction, selection); assumed to be 100 %!

Branching Fractions

[Gorbunov et al. 2007]

For scenario A: $U_{ie}^2 : U_{i\mu}^2 : U_{i\tau}^2 = 1 : 160 : 27.8$

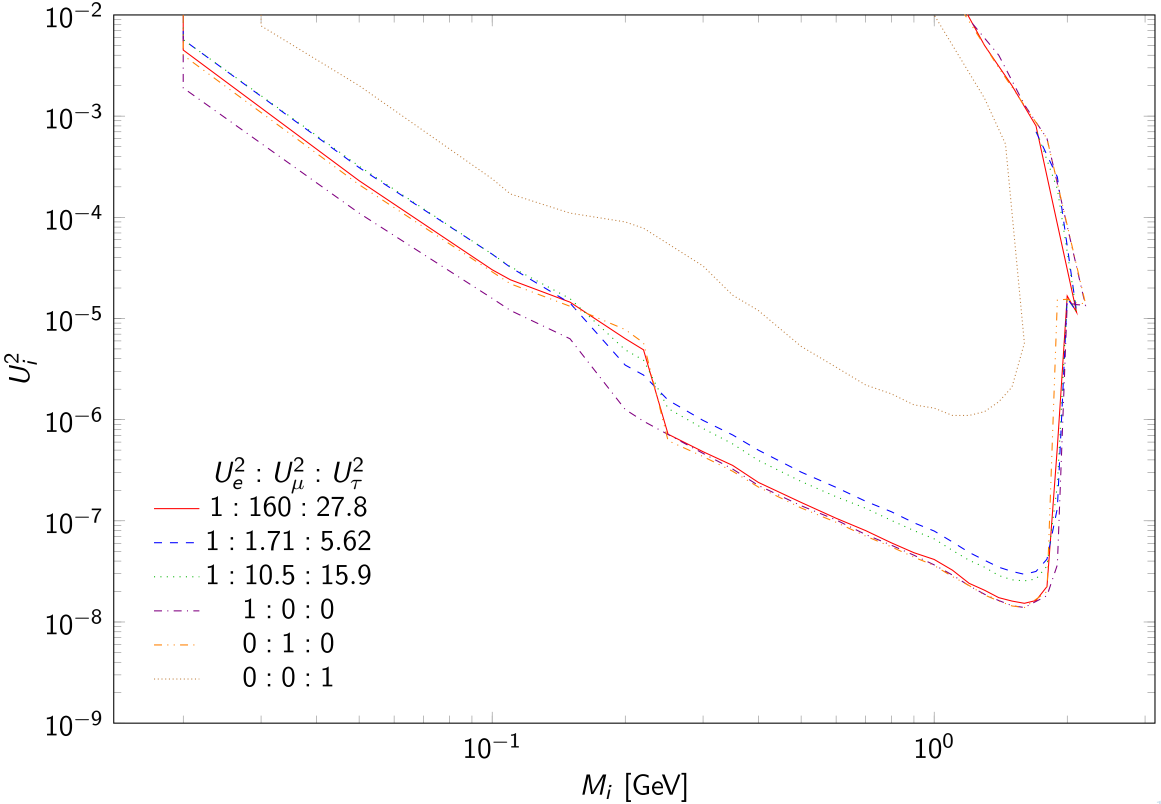


The dominant modes are

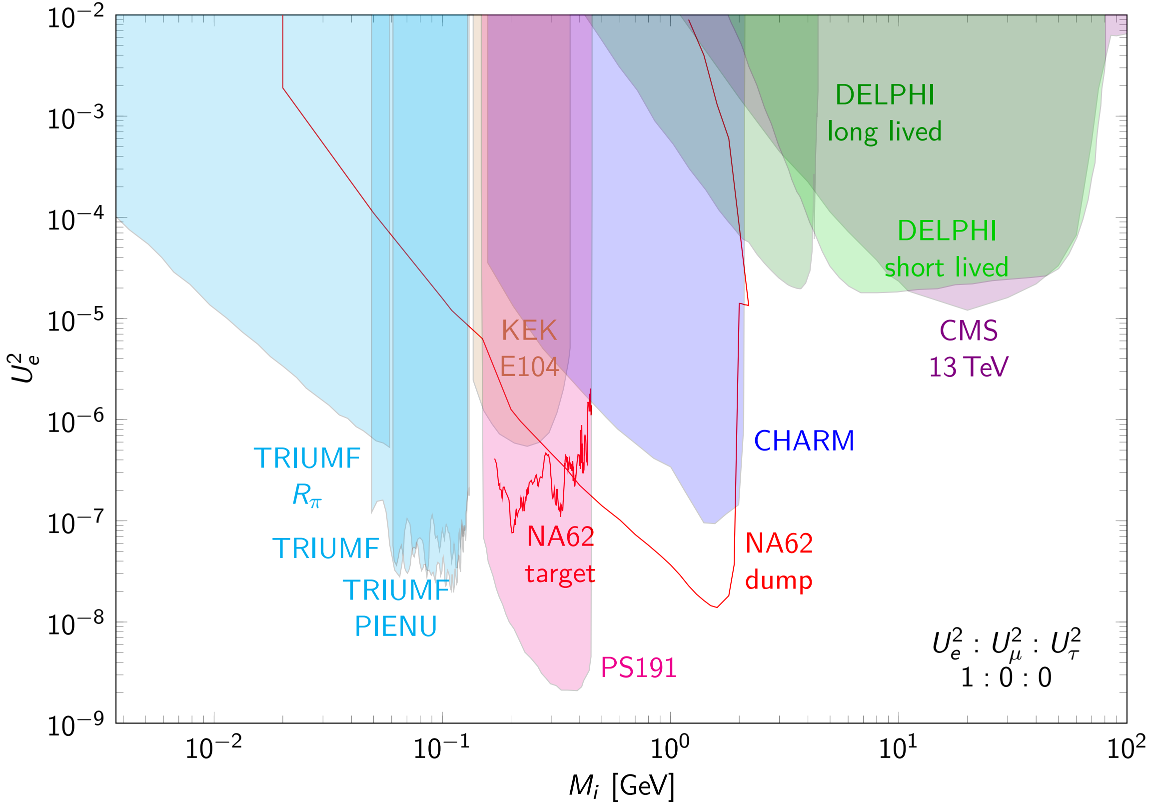
$$N_i \to 3\nu,\ \pi^0\nu,\ \pi^\pm\ell^\mp,\ \rho^0\nu,\ \rho^\pm l,\ \ell^+\ell^-\nu$$

The detector is able to reconstruct all final states having two charged tracks

Results for NA62



pure U_e^2



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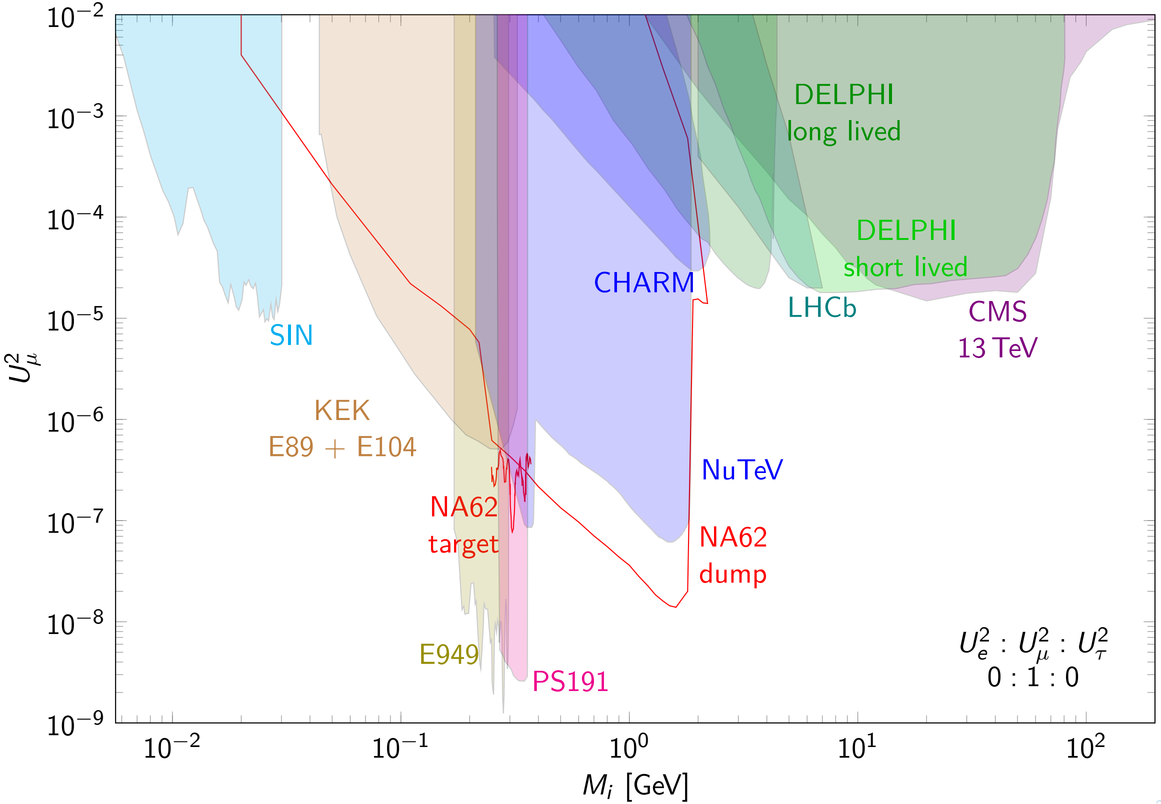
pure U_μ^2



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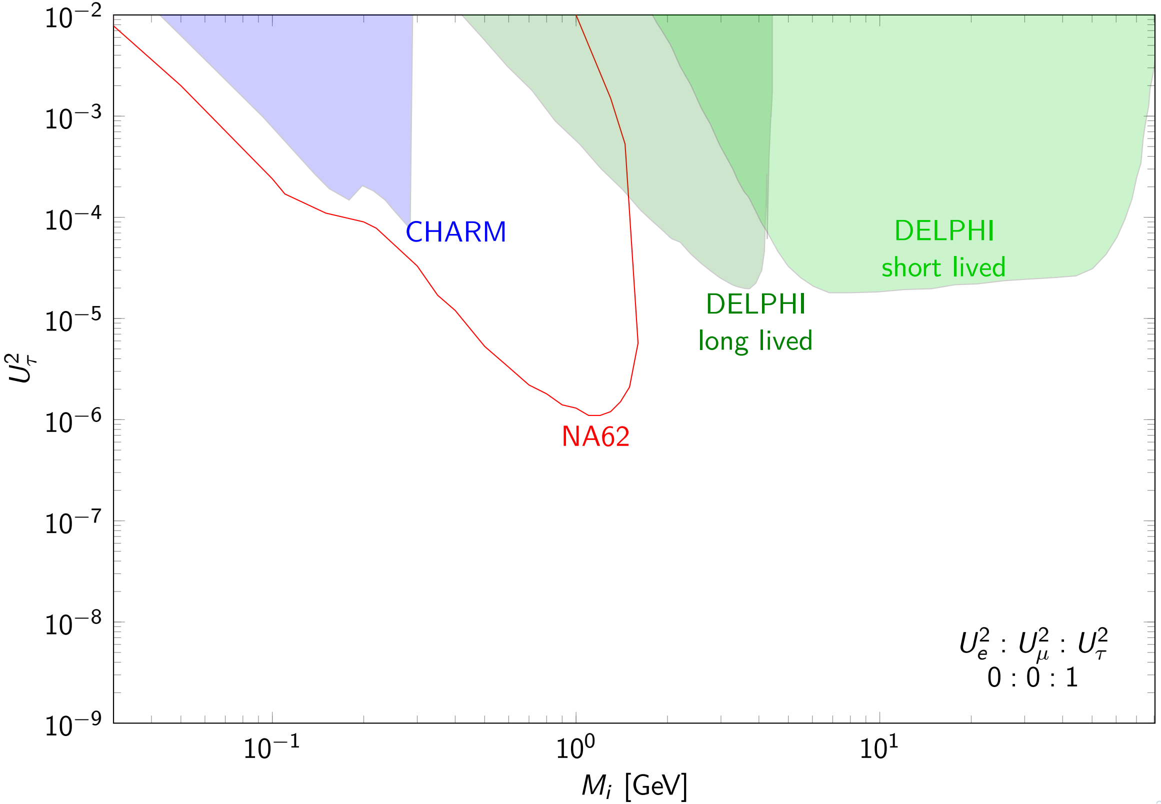
pure U_τ^2



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10^{-9}
10^{-1}
10^{0}
10^{1}

Conclusion

- Heavy neutrinos constitute a minimal extension to the SM
- They can easily have properties detectable at current or future experiments
- Fixed target experiments are a powerful tool to unveil hidden sectors
- Although not designed for this purpose NA62 is at the moment the leading experiment for masses between the Kaon and the D-meson mass (shown at the example of heavy neutrinos)
- There is an opportunity for fixed target experiments dedicated to new physics

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