Searches for right-handed neutrinos at accelerators

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DESY Theory Workshop — Quantum field theory meets gravity

Low scale seesaw (type I)

[Minkowski 1977; Asaka et al. 2005]

Three right handed neutrinos

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

y_{ai} Yukawa coupling $\qquad$ M_{ij} Majorana mass

EWSB

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

SM is $B - L$ symmetric

small M_{ij} minimizes breaking

Seesaw mechanism

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

produces tiny masses for the left handed neutrinos

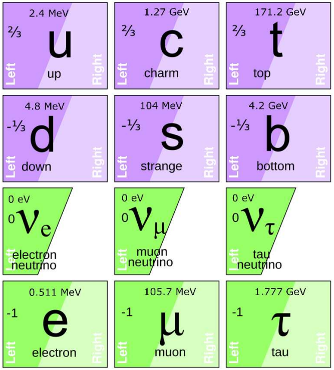
Small mixing into mass eigenstates

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

Coupling of N_i to the SM

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

Complements SM fields



νMSM may explain

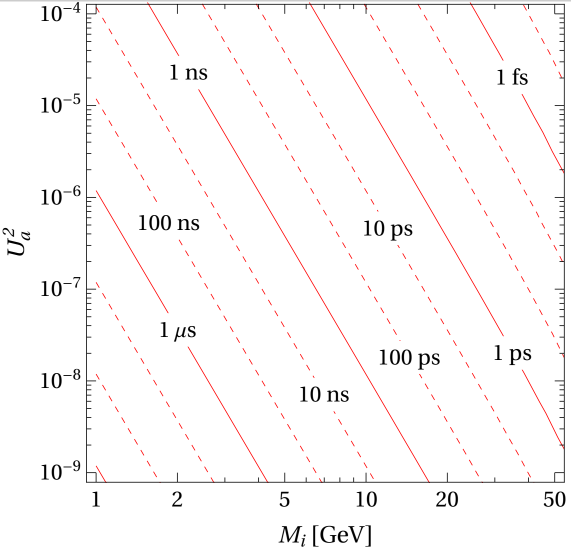
- Neutrino oscillation
- Neutrino masses
- Leptogenesis
- Dark matter

Abbreviation

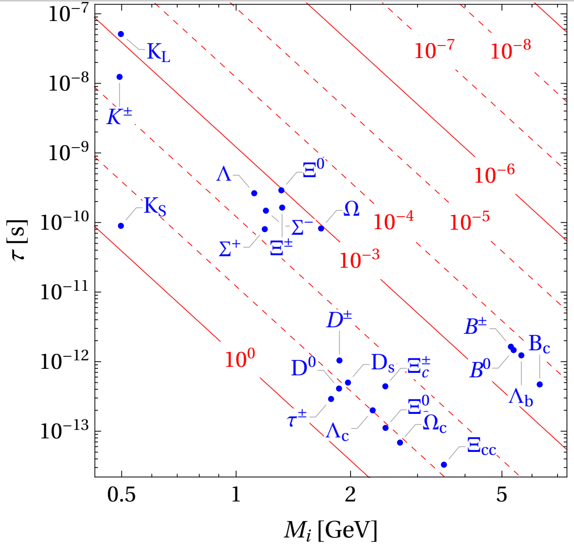
$$U^2_a = \sum_i U^2_{ai} \;, \quad U^2_{ai} = |\theta_{ai}|^2$$

Properties

Lifetime



SM particles vs. coupling strength U^2



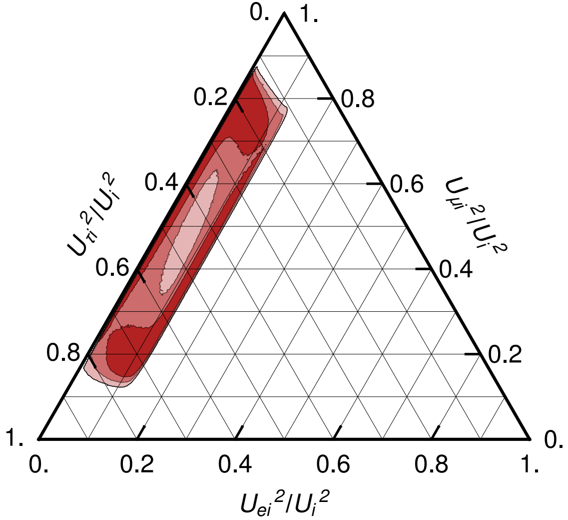
Decay width for $M \gg 5\,\mathrm{GeV}$

$$\Gamma_N \simeq 11.9 \times \frac{G_F^2}{96\pi^3} U_a^2 M^5 \ ,$$

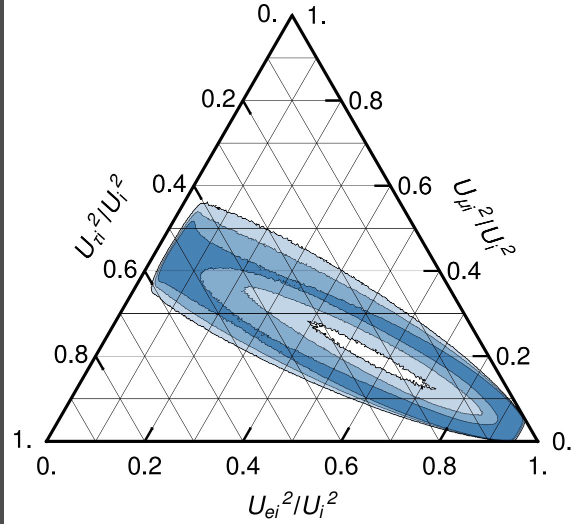
Probability contours for U_{ai}^2 (2 active flavours)

The ratio U_a^2/U_2 is independent of other heavy neutrino parameter

Normal Ordering



Inverted Ordering



Coloured areas consistent with

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

Unknown Majorana phase

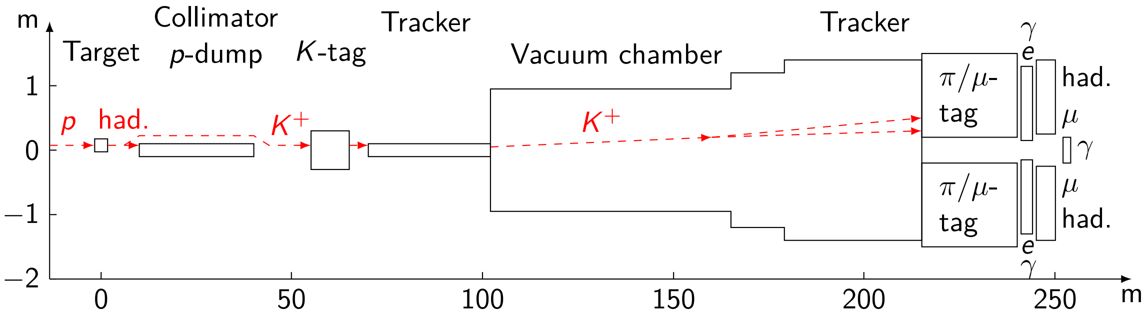
correspond to the circular structure

NA62

NA62

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

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



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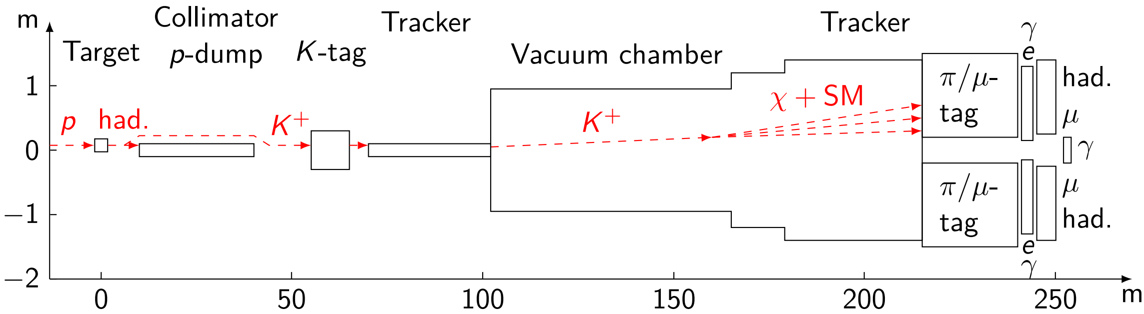

Hidden sectors at NA62

- 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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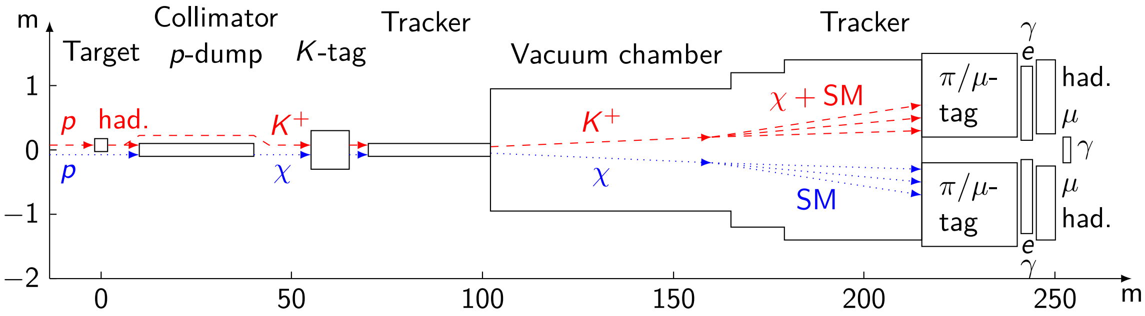


Hidden sectors at NA62

- 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 Dump mode

Simulation

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

Run 3 (2021–2023)

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

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

$$n_N \simeq 2N_{\mathrm{POT}} \left(\chi_c f_D \, \mathrm{BR} \left(D \to XN \right) + \chi_b f_B \, \mathrm{BR} \left(B \to XN \right) \right) \ ,$$

χ production cross section

f production fractions of mesons

Number of reconstructed events

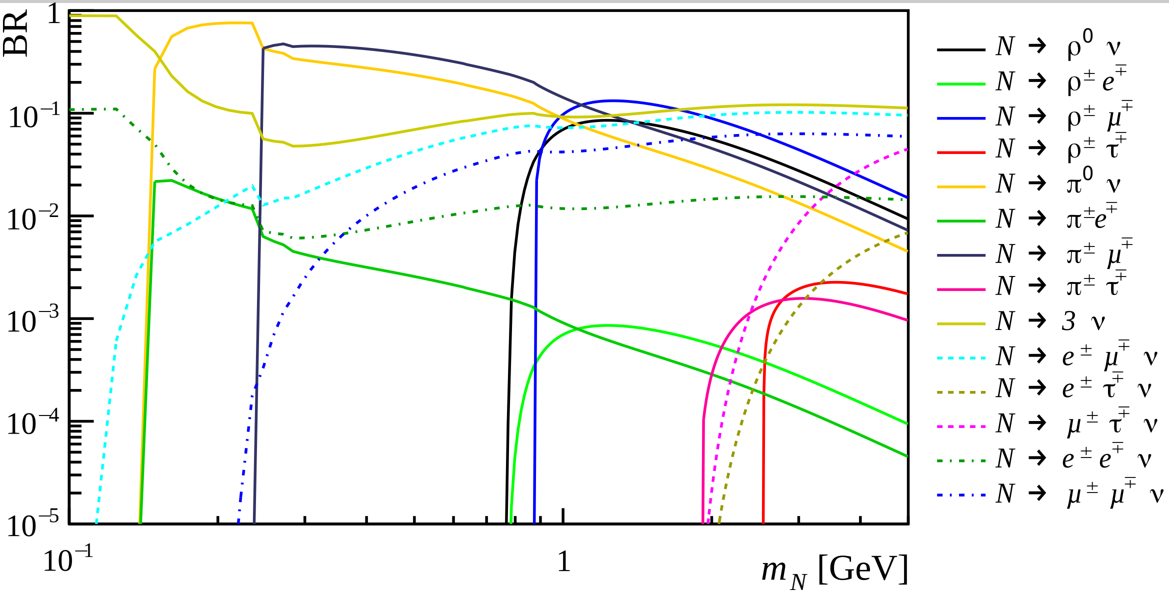
$$N_{\mathrm{obs}} = n_N \sum_{f,\, f'=e,\, \mu,\, \tau,\, \pi,\, K} \mathrm{BR} \left(N_i \to f^+ f'^- X \right) \mathcal{A}_i \left(f^+ f'^- X,\ M_i,\, U^2_{e,\, \mu,\, \tau} \right) \varepsilon \left(f^+ f'^- X,\ M_i \right) \ ,$$

$\mathcal{A}_l$ geometrical acceptance

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

Branching Fractions

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

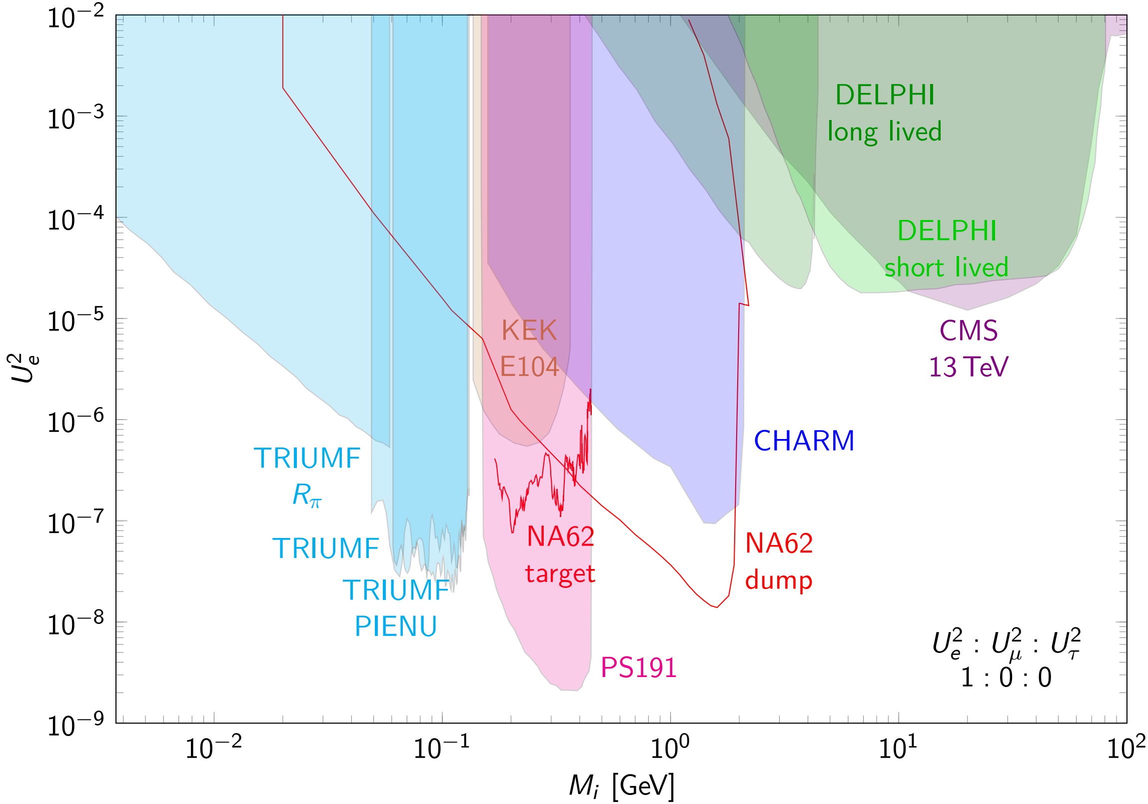


The dominant modes are

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

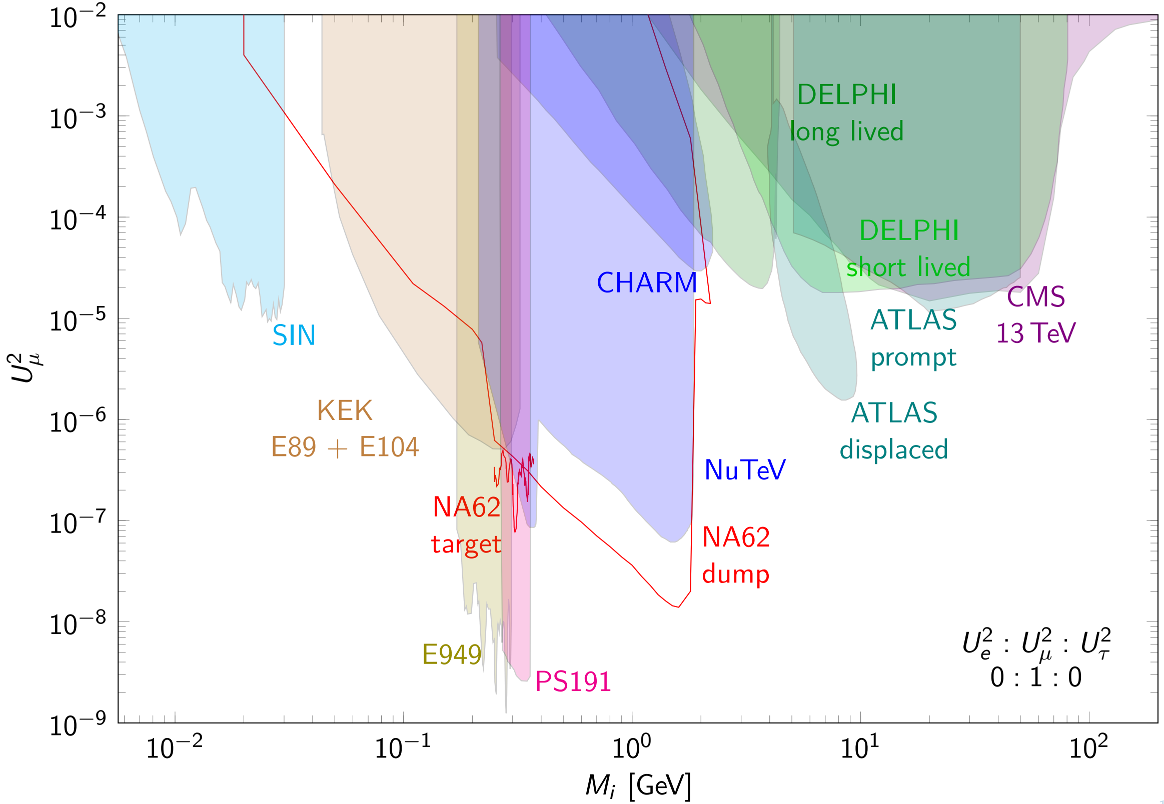
The detector is able to reconstruct all final states having two charged tracks

pure U_e^2



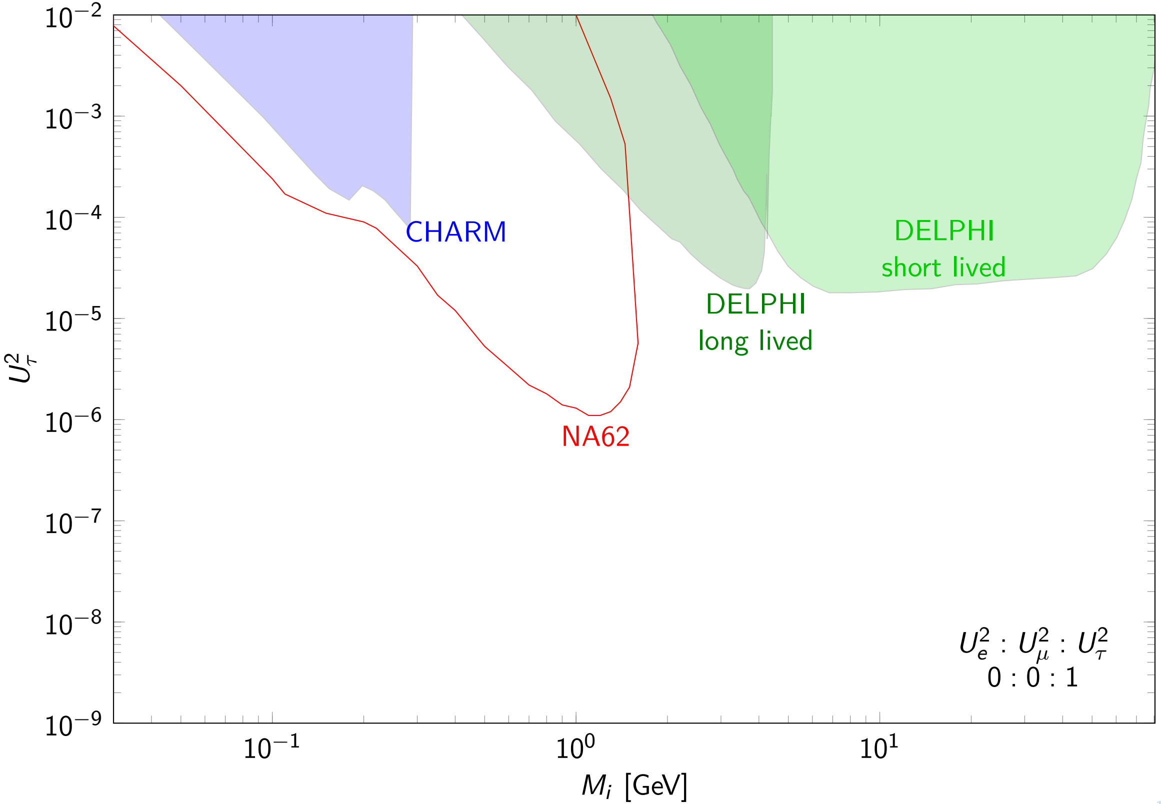
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
U_e^2
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
M_i [GeV]
DELPHI long lived
DELPHI short lived
CMS 13 TeV
KEK E104
CHARM
TRIUMF R_π
TRIUMF
TRIUMF PIENU
NA62 target
NA62 dump
PS191
$U_e^2 : U_\mu^2 : U_\tau^2$
1 : 0 : 0

pure U_μ^2



SIN
KEK
E89 + E104
NA62
target
E949
PS191
CHARM
NuTeV
NA62
dump
DELPHI
long lived
DELPHI
short lived
ATLAS
prompt
ATLAS
displaced
CMS
13 TeV
$U_e^2 : U_\mu^2 : U_\tau^2$
0 : 1 : 0
U_μ^2
M_i [GeV]

pure U_τ^2

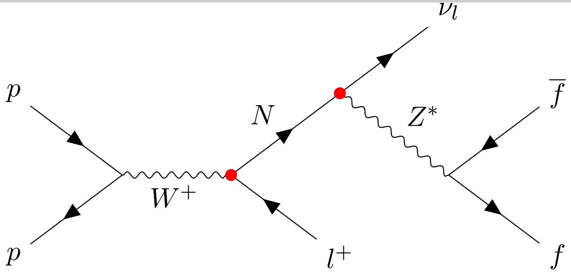


CHARM
DELPHI
short lived
DELPHI
long lived
NA62
$U_e^2 : U_\mu^2 : U_\tau^2$
0 : 0 : 1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
U_τ^2
10^{-1}
10^{0}
10^{1}
M_i [GeV]

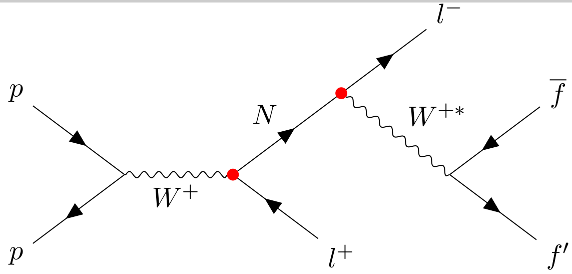
LHC

Signature

Z-decay



W-decay



Search strategy

- trigger on first lepton
- search for secondary vertex

Muon chamber [Bobrovskyi et al. 2011; CMS 2015]

- muon chamber reaches farther than tracker
- long lived particles can be search for using only muon chambers

Displaced vertex reconstruction

- at least 2 tracks
- invariant mass of 5 GeV (in order to suppress nuclear interactions backgrounds)
- particles must transverse at least half of the tracker
- or the complete muon chamber

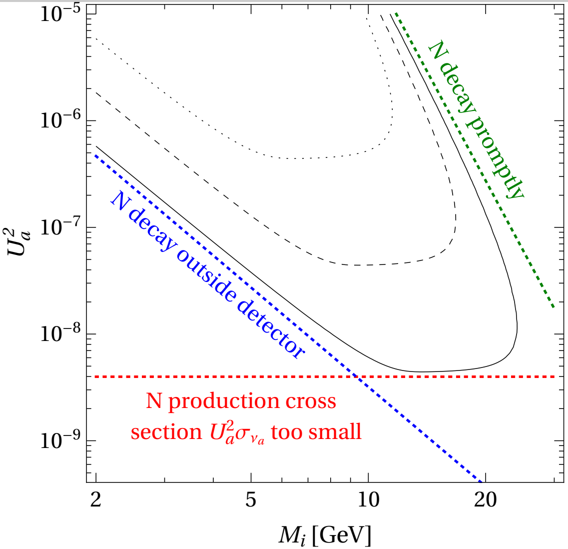
Expectations

Simplified model

$$N_d \sim L_{\text{int}} \sigma_\nu U^2 \left(e^{-l_0/\lambda_N} - e^{-l_1/\lambda_N} \right) f_{\text{cut}} \ ,$$

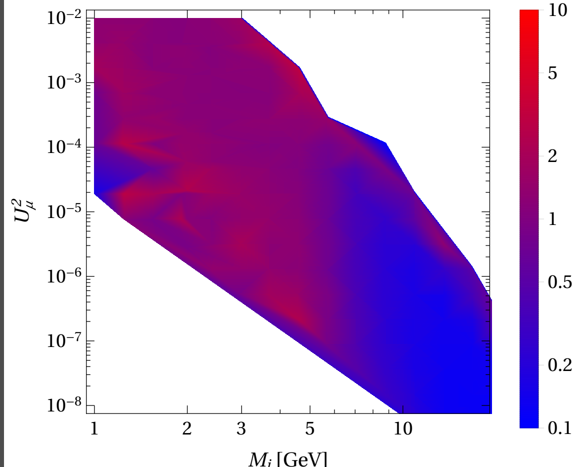
l_0 minimal displacement $\quad$ l_1 detector length $\quad$ $\lambda_N = \frac{\beta\gamma}{\Gamma_N}$ decay length

Significances and major obstacles



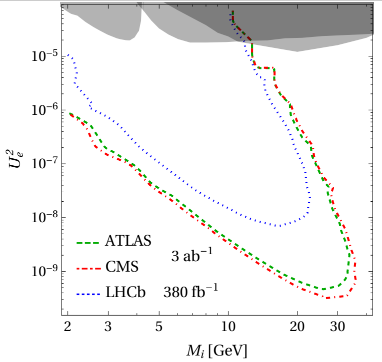
Deviation

of simplified model from full simulation

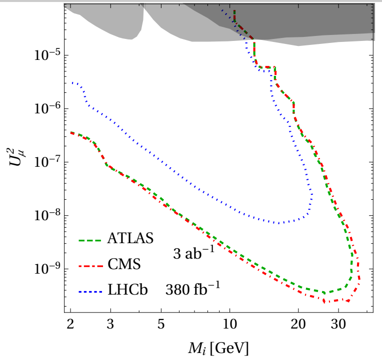


Maximal exclusion reach

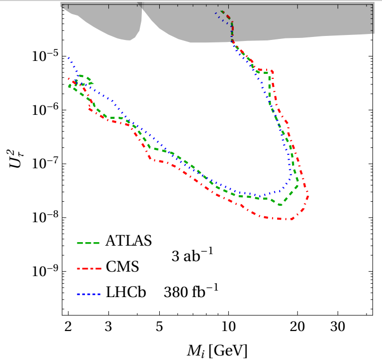
pure U_e^2



pure U_μ^2



pure U_τ^2



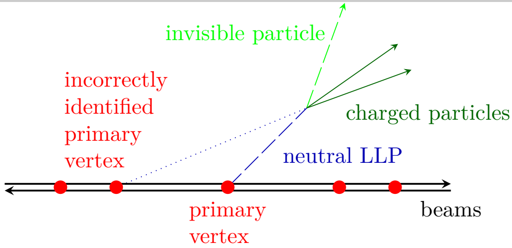
Heavy Ion Collisions

Properties of the heavy ions runs

Advantage

- No pile-up; single primary vertex
- Large nucleon multiplicity
  e.g. $A(\mathrm{Pb}) = 208$, $Z(\mathrm{Pb}) = 82$
- Number of parton level interactions per collision scales with A
  e.g. $\frac{\sigma_{\mathrm{PbPb}}}{\sigma_{pp}} \propto A^2 = 43 \times 10^3$

Single primary vertex



Better event reconstruction possible

Drawbacks

- There are a huge number of tracks near the interaction point which makes the search for prompt new physics extremely challenging
- The collision energy per nucleon is smaller. e.g. $\sqrt{s_{NN}} = 5.02\,TeV$ for Pb which is problematic for heavy new physics
- The instantaneous luminosity is lower for heavier ions
- The LHC has allocated much less time to heavy ions runs than to protons runs

Possible ways out

- Low luminosity allows for lower triggers
- Lighter ions allow for higher luminosity

The reason for the low luminosities are secondary beams [Jowett 2018]

For heavy ions there are additional contributions to the crosssection

[Meier et al. 2001]

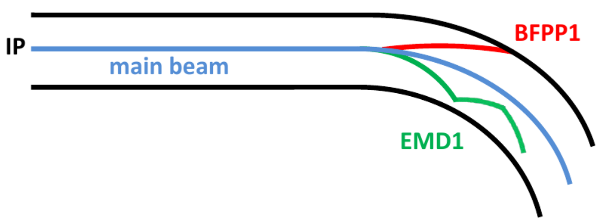
Bound-Free Pair Production (BFPP): $^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + e^{+}$

[Pshenichnov et al. 2001]

Electromagnetic Dissociation (EMD): $^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{207}\mathrm{Pb}^{82+} + n$

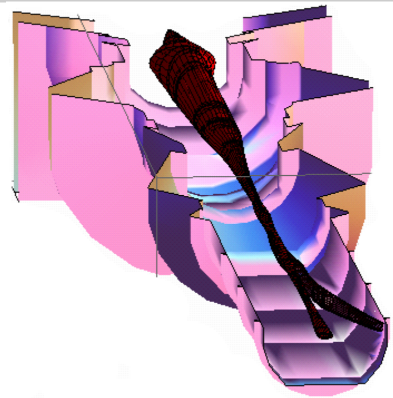
Leads to [Schaumann 2015]

- Larger cross section results in faster beam decay
- Secondary beams consisting of ions with different charge/mass ratio



Can accidentally quench the magnets

[Bruce et al. 2018]



Luminosity

[Benedikt et al. 2015]

The luminosity at one interaction point (IP) is

$L \propto N_b^2$ where N_b are number of ions per bunch

The initial bunch intensity [Jowett 2018]

for arbitrary ions is fitted to the information of the lead run

$$N_b\left({}^{A}_{Z}\mathrm{N}\right) = N_b\left({}^{208}_{82}\mathrm{Pb}\right)\left(\frac{Z}{82}\right)^{-p}$$

where $p = 1$ is a conservative assumption while $p = 1.9$ is a optimistic assumption.

The loss of number of ions per bunch N_b over time is given by

$$\frac{\mathrm{d}N_b}{\mathrm{d}t} = -\frac{N_b^2}{N_0\tau_b}\,, \qquad \tau_b = \frac{n_b}{\sigma_{\mathrm{tot}}\, n_{\mathrm{IP}}}\frac{N_0}{L_0}\,,$$

where n_{IP} is the number of interaction points.

For a given turnaround time t_{ta} between the physics runs

the integrated luminosity is maximised by

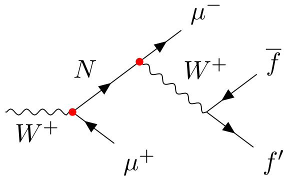
$$t_{\mathrm{opt}} = \tau_b\sqrt{\theta_{\mathrm{ta}}}\,, \qquad \text{with} \qquad \theta_{\mathrm{ta}} = \frac{t_{\mathrm{ta}}}{\tau_b}\,.$$

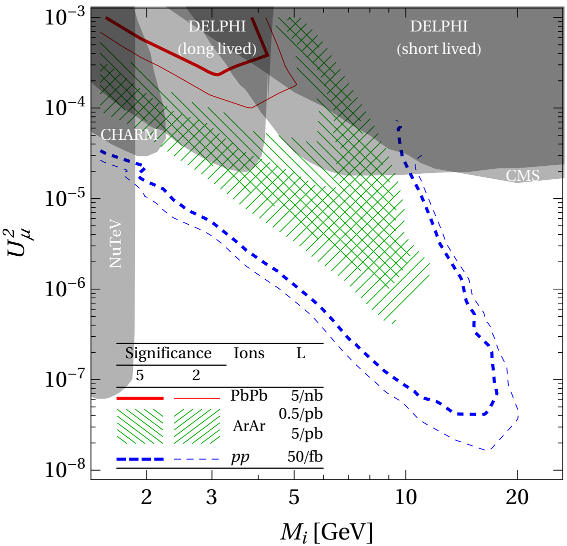
The average luminosity using the optimal run time is

$$L_{\mathrm{ave}}(t_{\mathrm{opt}}) = \frac{L_0}{\left(1+\sqrt{\theta_{\mathrm{ta}}}\right)^2}\,.$$

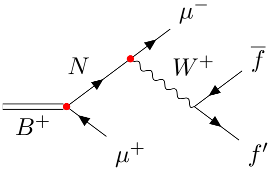
Heavy ion collisions

Full simulation of W production

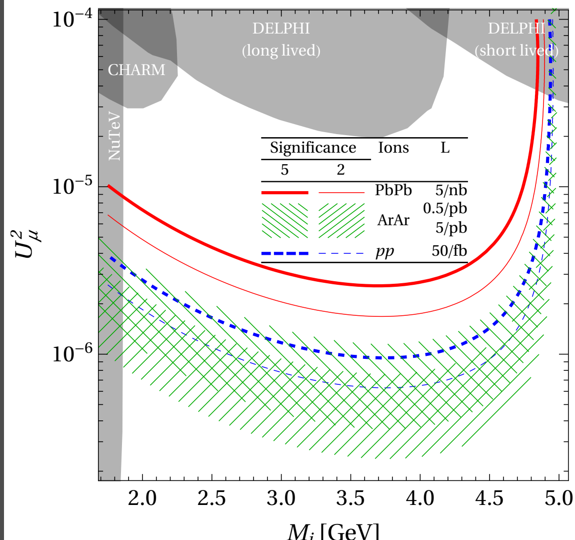




Simplified simulation of B production



Considerable lower trigger of $p_T > 3$ GeV for heavy ion collisions



Conclusion

- Heavy neutrinos constitute a minimal extension to the SM featuring long lived particles
- At the moment NA62 is the leading experiment able to search for right-handed neutrinos with masses between the K- and D-meson mass
- Displaced vertices are a promising signature to detect right-handed neutrinos at the LHC
- Heavy ion collisions provide a new environment to search for right-handed neutrinos

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