Heavy Neutral Leptons

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Long-Lived Particles and the Third Generation

Low scale seesaw (type I)

[Minkowski 1977; Mohapatra et al. 1980]

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 $\quad$ M_{ij} Majorana mass

Electroweak symmetry breaking

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

Seesaw mechanism

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

produces tiny masses for the left handed neutrinos

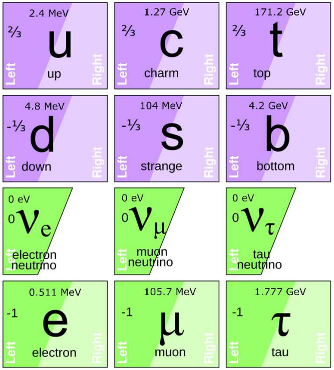
Small mixing into mass eigenstates

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

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

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

νMSM

[Asaka et al. 2005; Shaposhnikov 2007]

SM is symmetric under $B-L$

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 $\nu_{Ri} + \nu^c_{Rj}$

$B-L$ 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 $\mathcal{O}(\text{keV})$ dark matter candidate

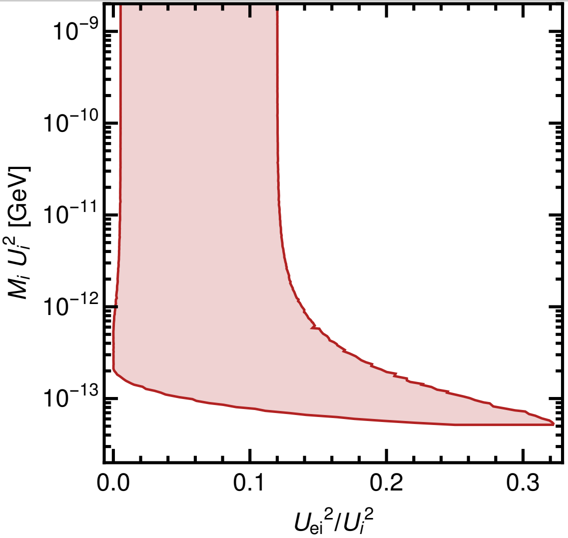
Yukawa coupling

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

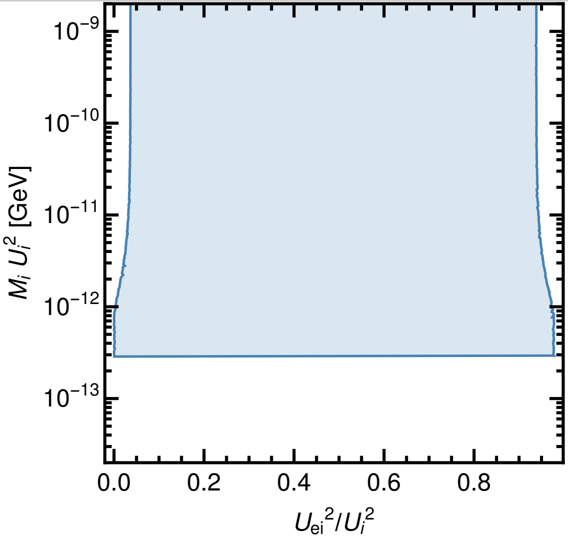
- pseudo Dirac pair with coupling $\mathcal{O}(y)$
- Dark matter candidate with coupling $\mathcal{O}(\epsilon')$

Applicability of the $B - L$ symmetric limit

Normal ordering



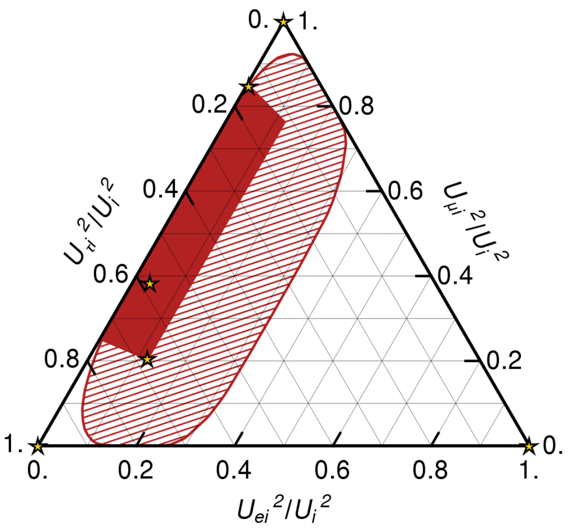
Inverted ordering



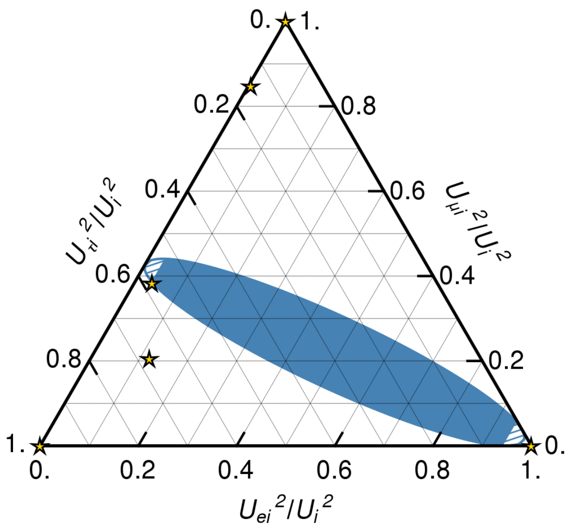
- In the symmetric limit U_{ei}^2/U_i^2 is independent of $M_i U_i^2$
- which holds for $U_i^2 > 10^{-11}$ GeV$/M_i$.

Mixing patterns allowed by neutrino oscillation (two active flavours)

Normal ordering



Inverted ordering

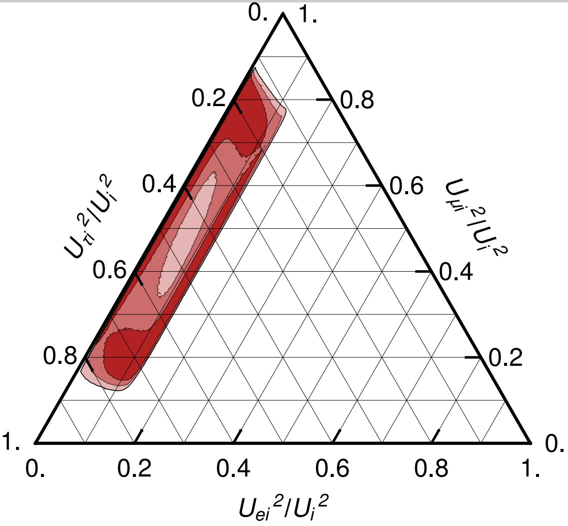


The ratio U_a^2/U_2 is independent of other heavy neutrino parameter

- coloured regions are allowed by Neutrino oscillation data
- hashed regions are not $B-L$ symmetric
- At the moment only $B-L$ symmetric couplings are experimentally relevant

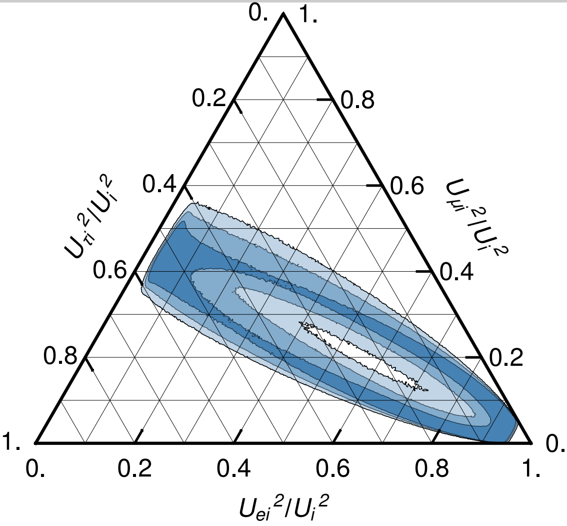
Probability contours for U_{ai}^2 (two active flavours)

Normal Ordering



Flat prior on α

Inverted Ordering



Flat prior on α

Coloured areas consistent

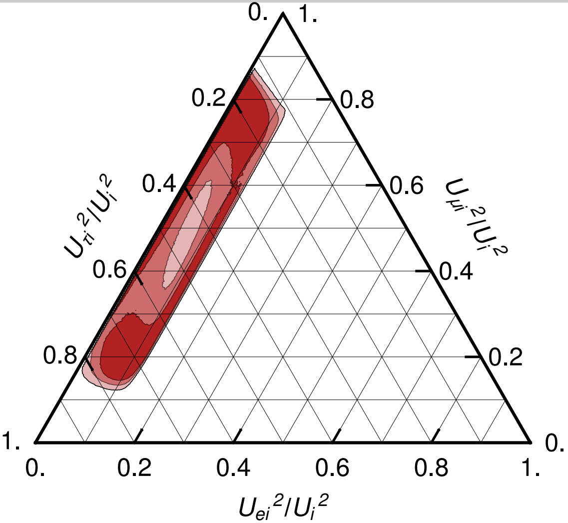
with neutrino oscillation data at 1, 2, and 3 σ

Unknown Majorana phase α

correspond to the circular structure

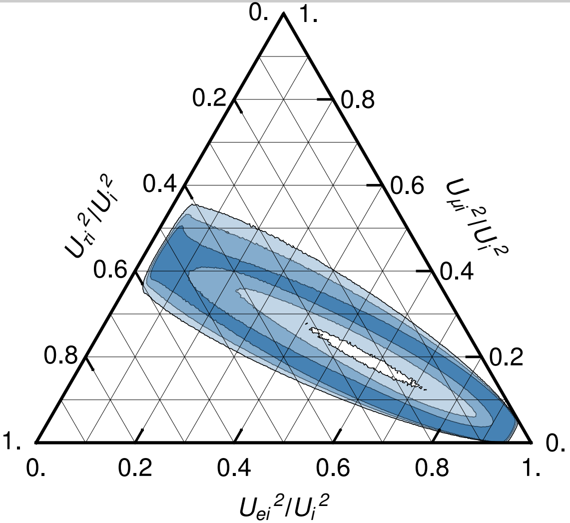
Probability contours for U_{ai}^2 (two active flavours)

Normal Ordering



Flat prior on $\sin(\alpha/2+\delta)$

Inverted Ordering



Flat prior on $\sin(\alpha/2)$

Coloured areas consistent

with neutrino oscillation data at 1, 2, and 3 σ

Unknown Majorana phase α

correspond to the circular structure

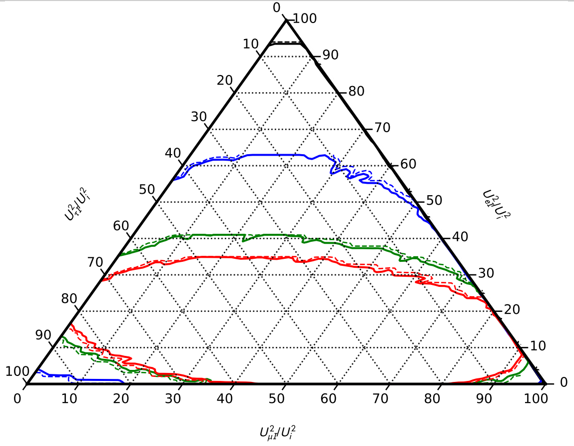
Probability contours are

stable against change of prior on Majorana phase α

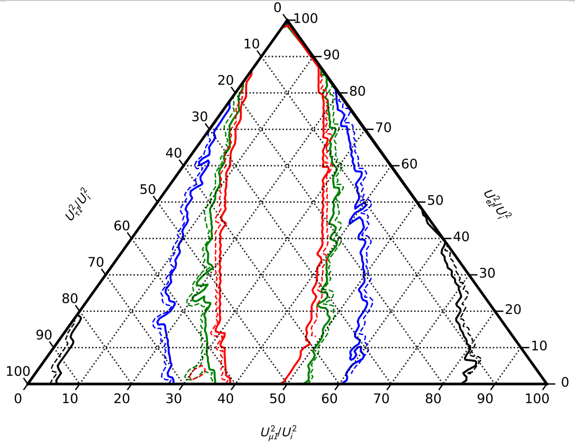
Probability contours for U^2_{ai} (three active flavours)

[Chrzaszcz et al. 2019]

Normal Ordering



Inverted Ordering



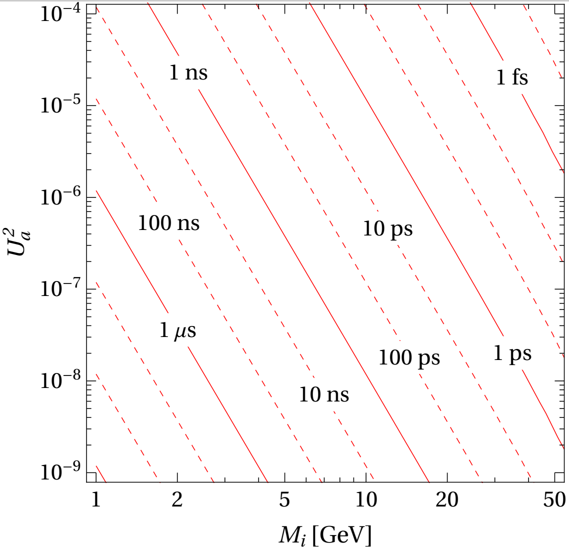
Contours depend on

$m_{\nu_0} < 0.01$, 0.1, 1, $10\,\mathrm{meV}$ for 1 and $2\,\sigma$

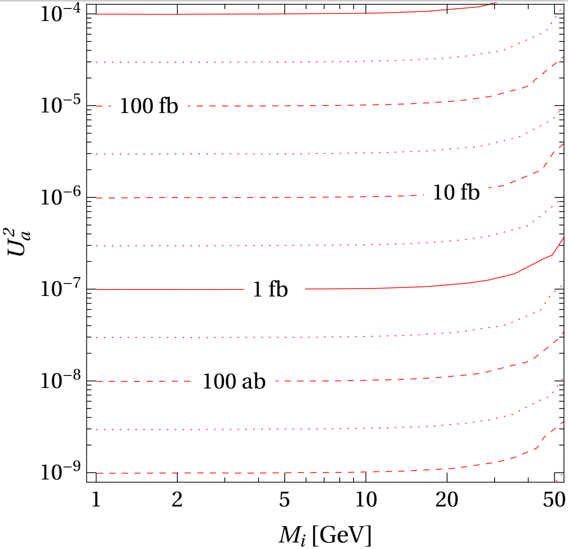
The non-minimal case is considerably less predictive

Properties

Lifetime



Production crosssection at the LHC

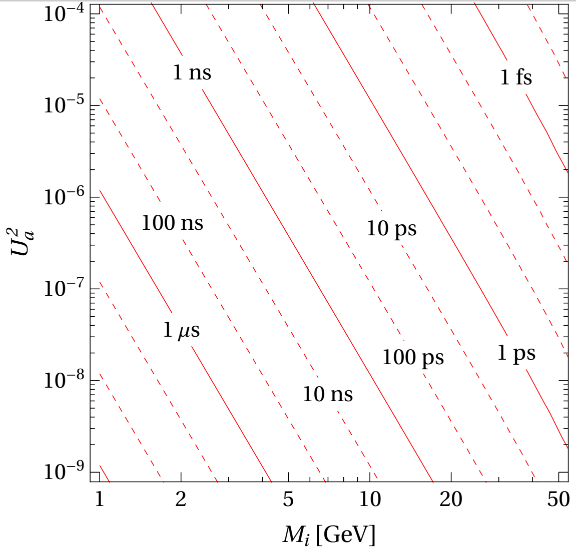


Decay width for $M \gg 5\,\mathrm{GeV}$

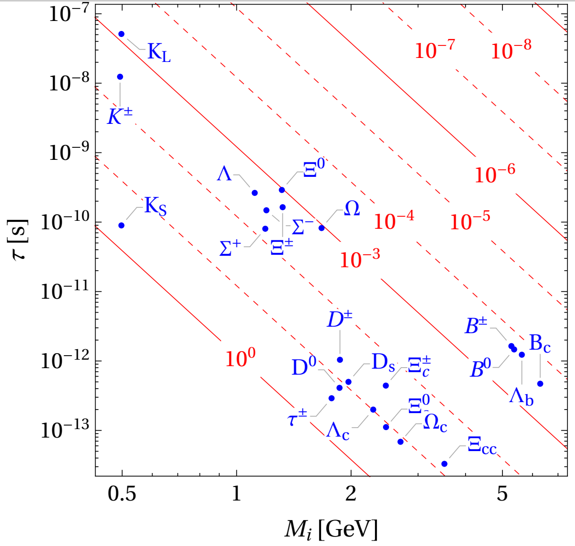
$$\Gamma_N \simeq 11.9 \times \frac{G_F^2}{96\pi^3} U_a^2 M^5 \ ,$$

Properties

Lifetime



SM background vs. coupling strength U^2



Decay width for $M \gg 5$ GeV

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NA62

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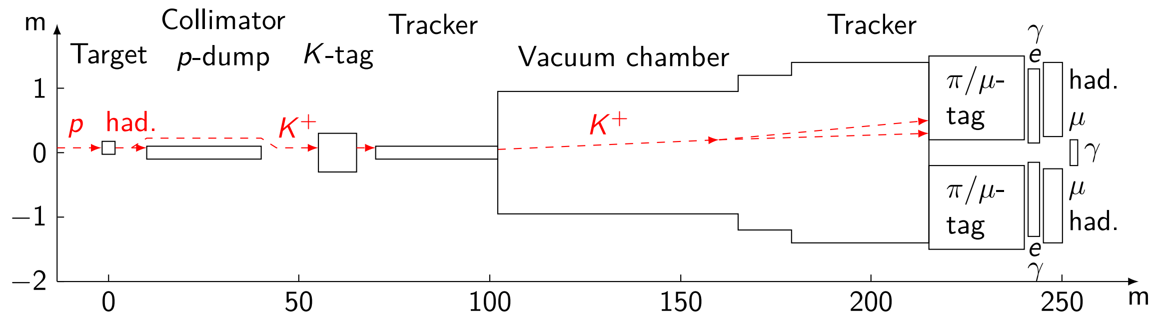
Fixed target experiment in the North Area using the CERN SPS with the goal to

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



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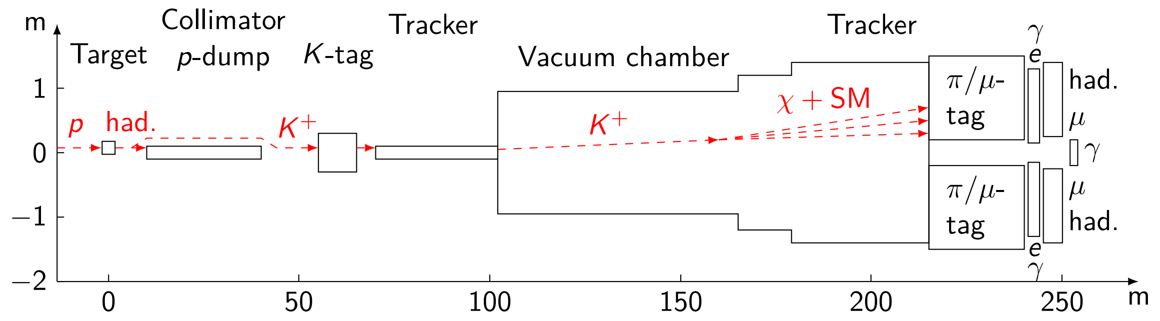

Hidden sectors at NA62

- 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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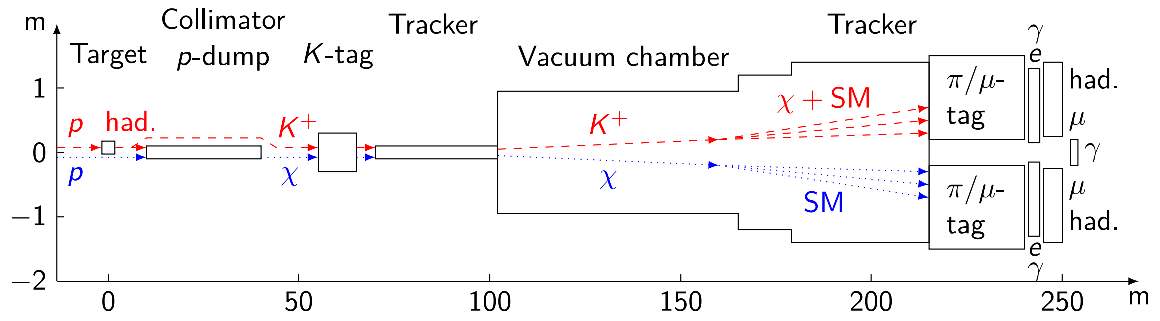


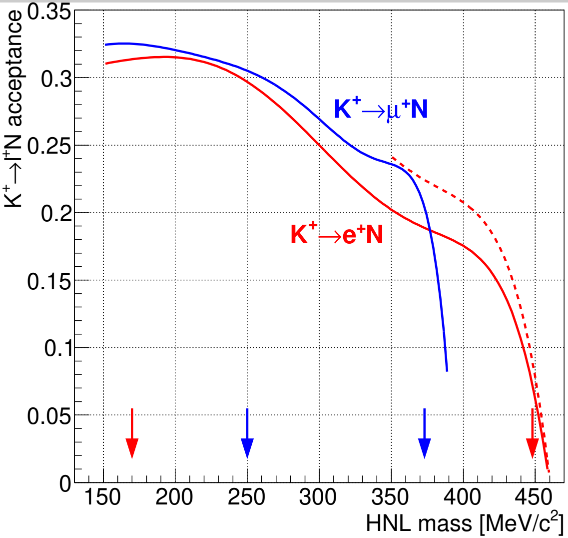
Hidden sectors at NA62

- 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

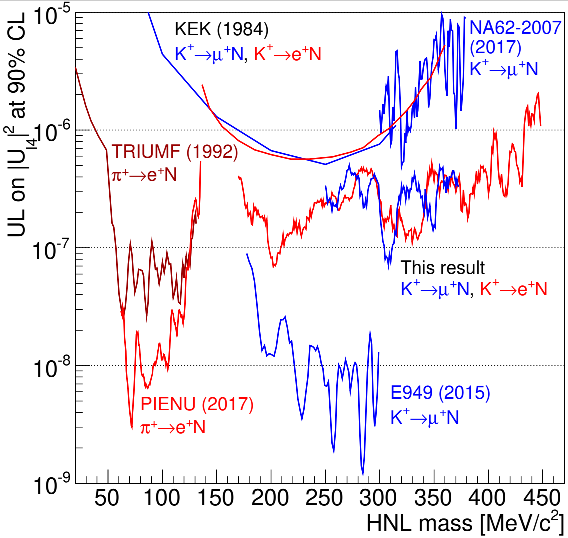
Heavy Neutrinos in the Target mode

[NA62 2017]

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



Result

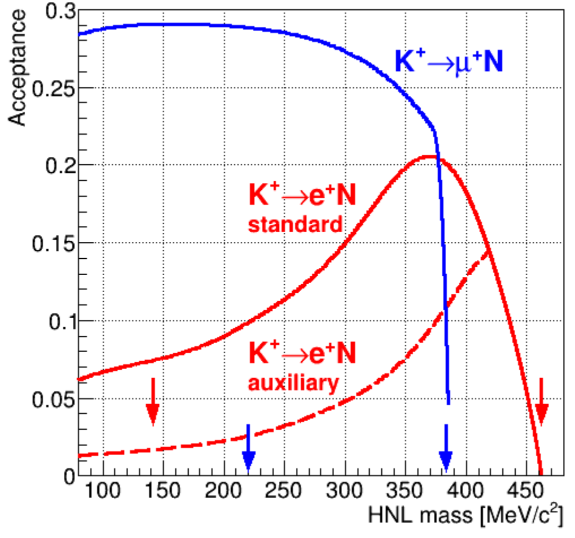


5 days of operation in 2015

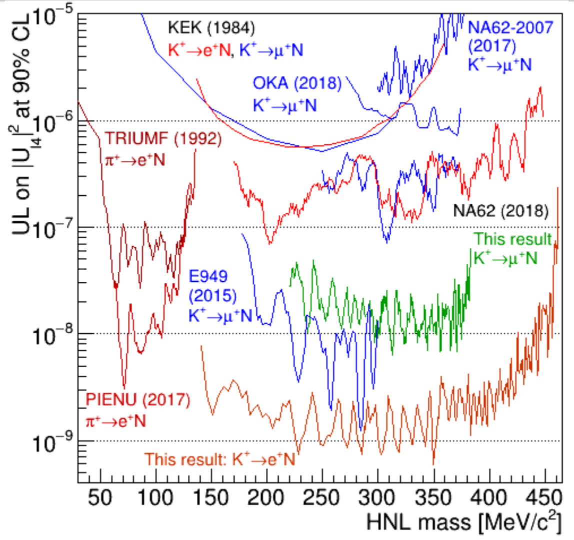
Heavy Neutrinos in the Target mode

[NA62 2019]

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



Result



New preliminary result (2016–2017 data)

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

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

χ production cross section

f production fractions of mesons

Number of reconstructed events

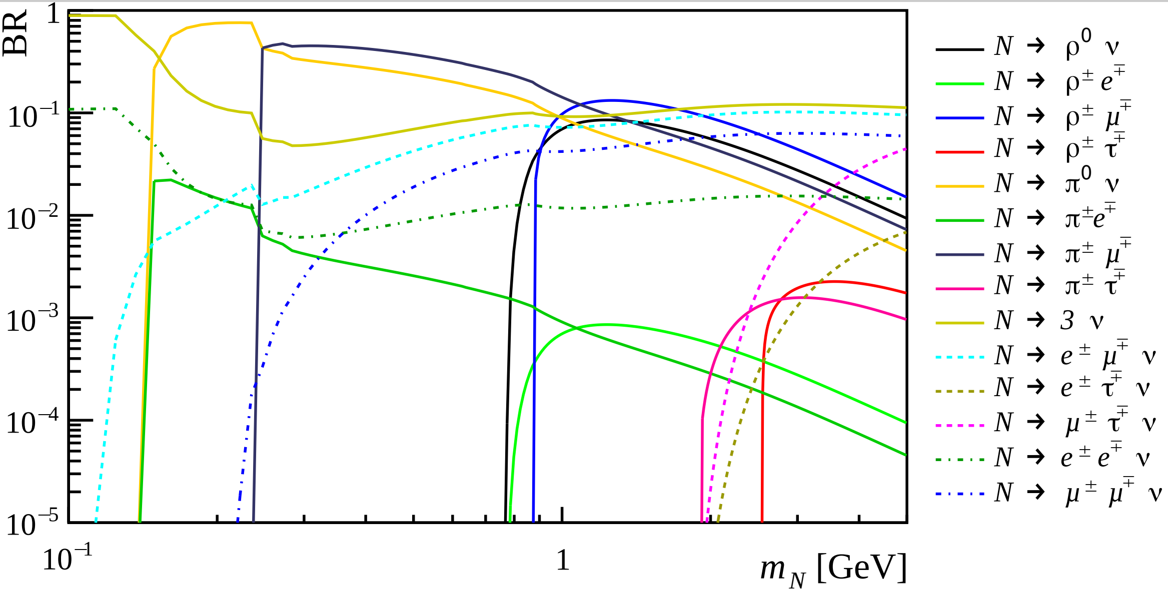
$$N_{\text{obs}} = n_N \sum_{f,\, f'=e,\, \mu,\, \tau,\, \pi,\, K} \text{BR}\left(N_i \to f^+ f'^- X\right) \mathcal{A}_i \left(f^+ f'^- X,\ M_i,\, U^2_{e,\, \mu,\, \tau}\right) \varepsilon \left(f^+ f'^- X,\ M_i\right) \ ,$$

$\mathcal{A}_I$ geometrical acceptance

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

Branching Fractions

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

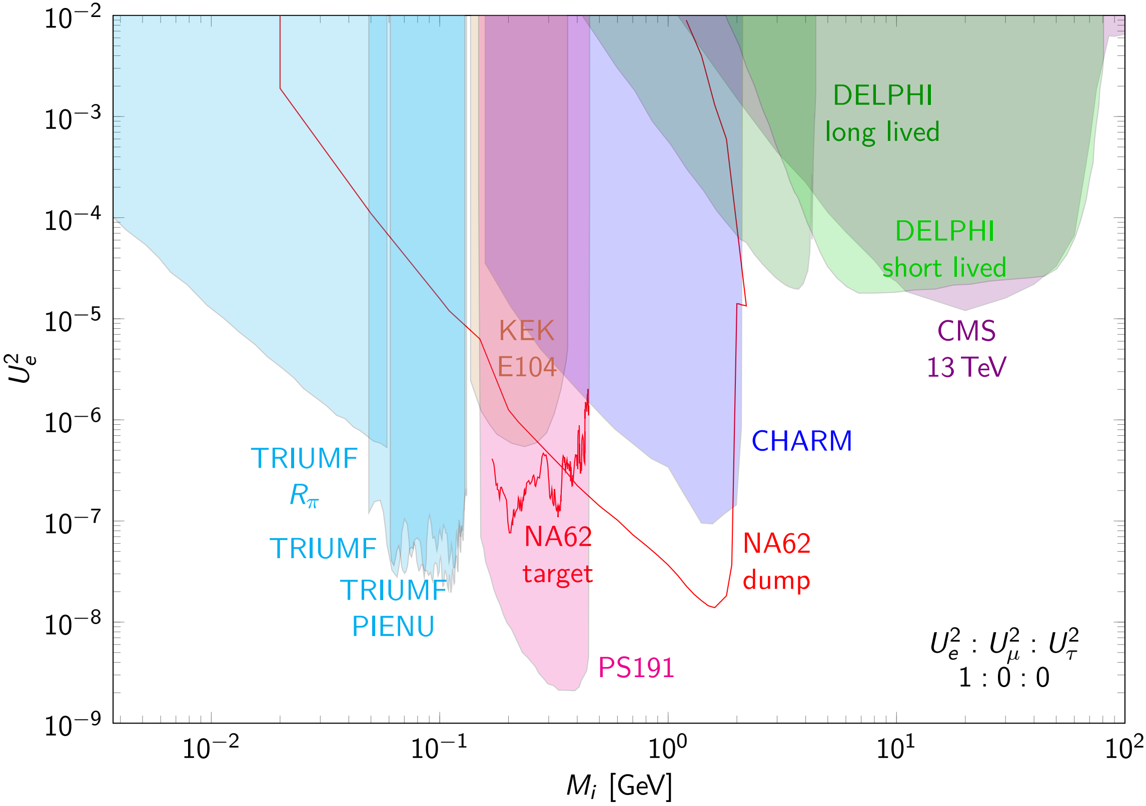


The dominant modes are

$$N_i \to 3\nu,\ \pi^0\nu,\ \pi^\pm\ell^\mp,\ \rho^0\nu,\ \rho^\pm l,\ \ell^+\ell^-\nu \qquad \text{where} \qquad \ell = e,\ \mu,\ \tau$$

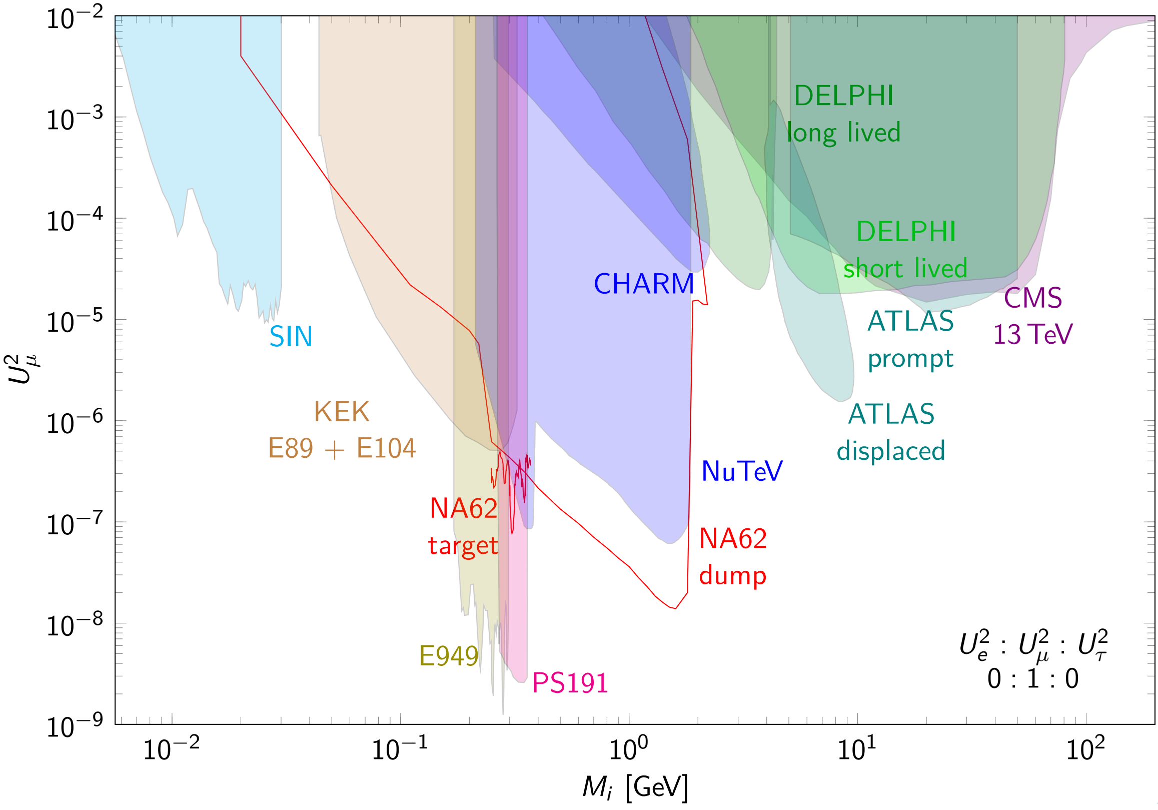
The detector is able to reconstruct all final states having two charged tracks

pure U_e^2

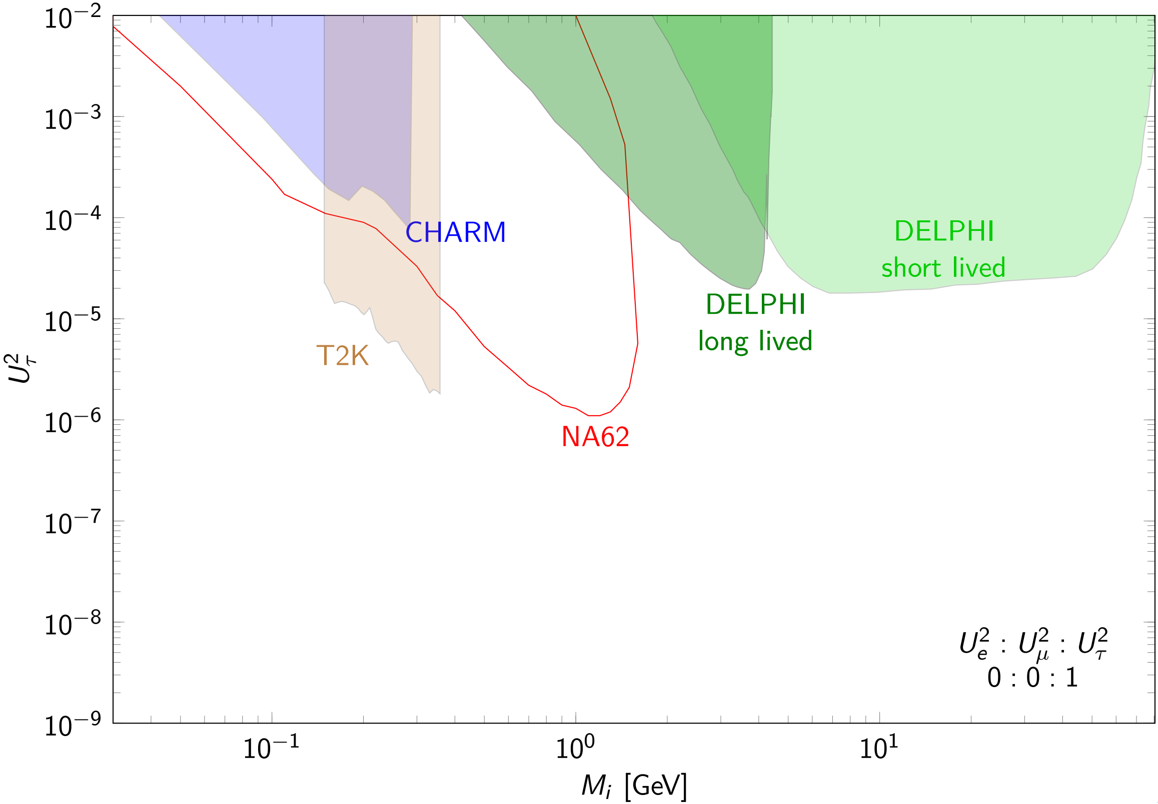


10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
U_e^2
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
M_i [GeV]
DELPHI long lived
DELPHI short lived
KEK E104
CMS 13 TeV
CHARM
TRIUMF R_π
TRIUMF
TRIUMF PIENU
NA62 target
NA62 dump
PS191
$U_e^2 : U_\mu^2 : U_\tau^2$
1 : 0 : 0

pure U_μ^2


10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
U_μ^2
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
M_i [GeV]
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

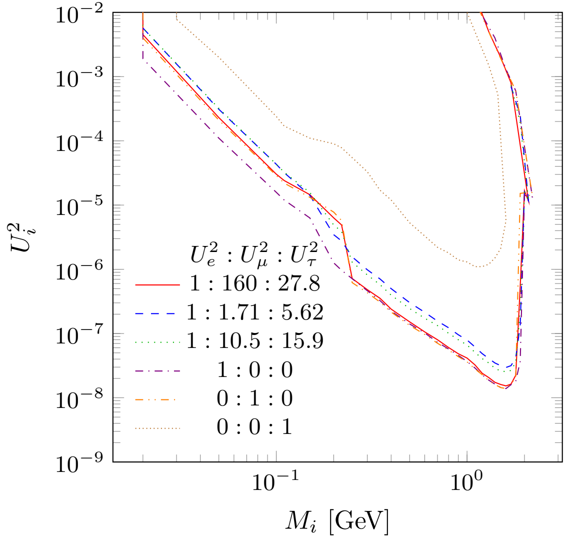
pure U_τ^2



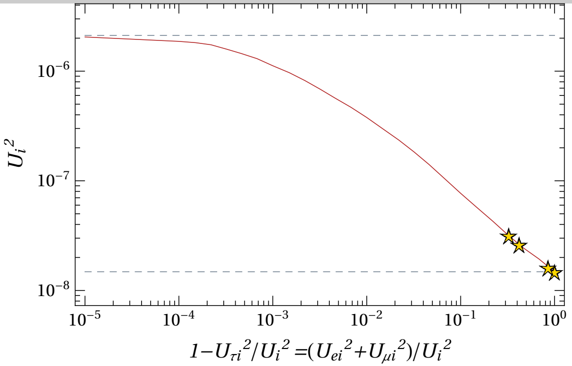
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
U_τ^2
10^{-1}
10^{0}
10^{1}
M_i [GeV]
CHARM
T2K
NA62
DELPHI
long lived
DELPHI
short lived
$U_e^2 : U_\mu^2 : U_\tau^2$
0 : 0 : 1

Realistic mixing patterns

Comparison between benchmark points



Sensitivity dependence on U_τ^2 / U^2



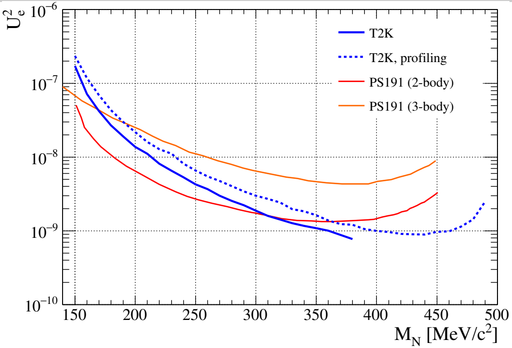
Take home message

The sensitivity of realistic mixing patterns is much better then the pure U_τ^2 case.

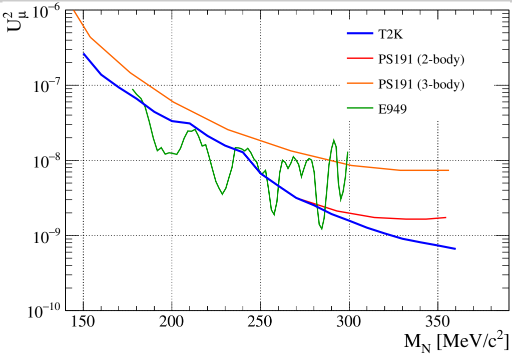
Tokai-to-Kamioka (T2K)

[T2K 2019]

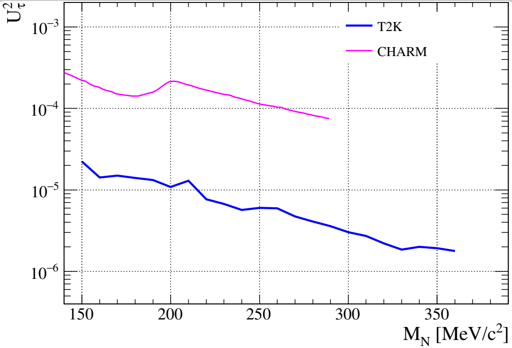
U_e^2



U_μ^2



U_τ^2



T2K

- long baseline neutrino experiment
- $K^\pm \to \ell^\pm N$ ($\ell = e, \mu$)

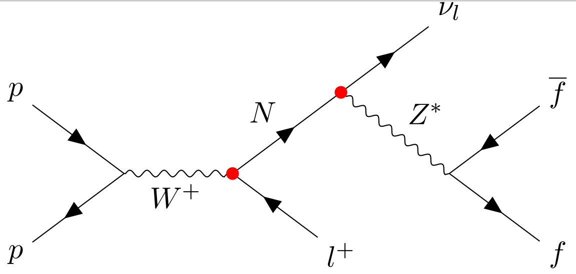
near detector ND280

- $N \to \ell^\pm \pi^\mp$ and $N \to \ell^\pm \ell^\mp \overset{(-)}{\nu}$
- Data taking: 2010–2017
- solid blue lines derived by marginalization over the other two flavours

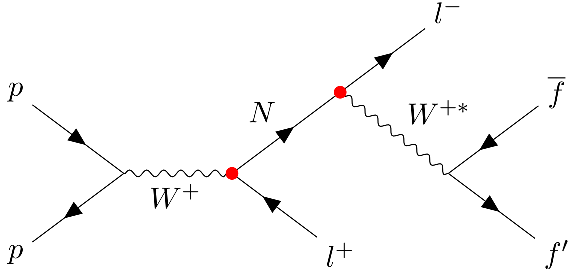
LHC

Signature

Z-decay



W-decay



Search strategy

- trigger on first lepton
- search for secondary vertex

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

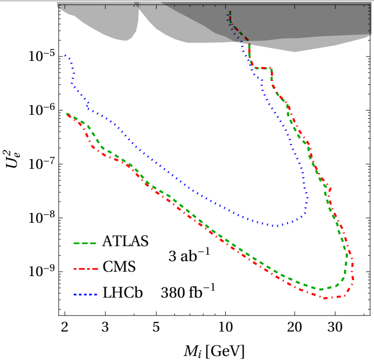
- muon chamber reaches farther than tracker
- long lived particles can be search for using only muon chambers

Displaced vertex reconstruction

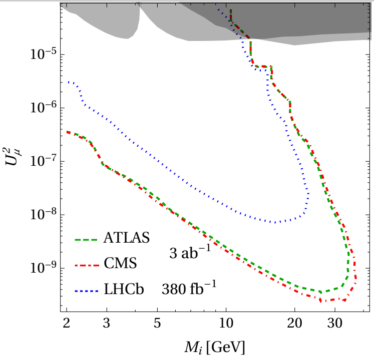
- at least 2 tracks
- invariant mass of 5 GeV (in order to suppress nuclear interactions backgrounds)
- particles must transverse at least half of the tracker
- or the complete muon chamber

Maximal exclusion reach

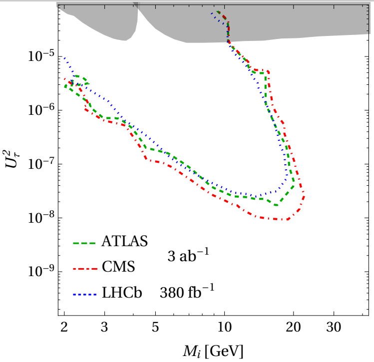
pure U_e^2



pure U_μ^2



pure U_τ^2



$p_T^{\min}$ of ATLAS single lepton and lepton pair triggers [ATLAS 2017]

	Single Lepton			Lepton Pair					
	e	μ	τ	e, e	e, μ	e, τ	μ, μ	μ, τ	τ, τ
$p_T^{\min}$ [GeV]	27	27	170	18, 18	8, 25 18, 15	30, 18	15, 15 23, 9	30, 15	40, 30

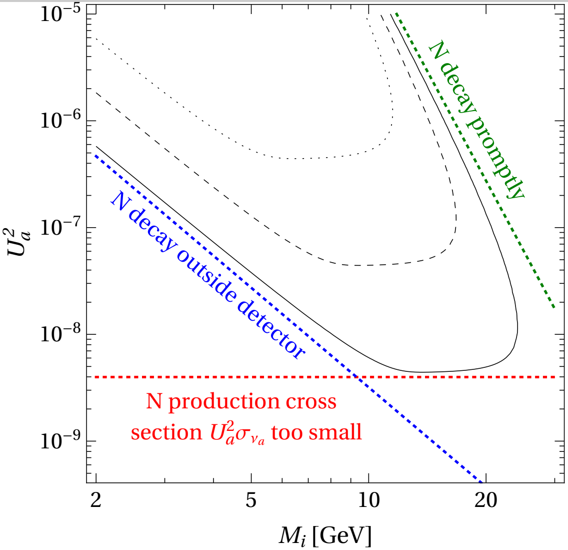
Expectations

Simplified model

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

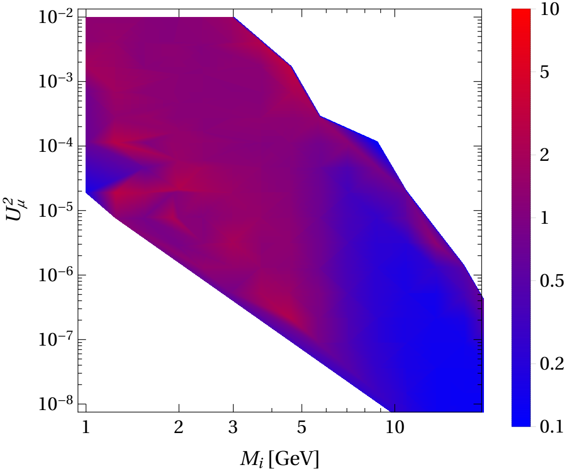
l_0 minimal displacement l_1 detector length $\lambda_N = \frac{\beta\gamma}{\Gamma_N}$ decay length

Significances and major obstacles



Deviation

of simplified model from full simulation



Displaced vertex searches at the LHC

M. Drewes and J. Hajer. “Heavy Neutrinos in displaced vertex searches at the LHC and HL-LHC”. arXiv: 1903.06100 [hep-ph]. №: CP3-19-11.

J. C. Helo, M. Hirsch, and S. Kovalenko. “Heavy neutrino searches at the LHC with displaced vertices”. *Phys. Rev.* D89. [Erratum: Phys. Rev. D93, no. 9, 099902(2016)], p. 073005. DOI: 10.1103/PhysRevD.89.073005,10.1103/PhysRevD.93.099902. arXiv: 1312.2900 [hep-ph].

E. Izaguirre and B. Shuve. “Multilepton and Lepton Jet Probes of Sub-Weak-Scale Right-Handed Neutrinos”. *Phys. Rev.* D91.9, p. 093010. DOI: 10.1103/PhysRevD.91.093010. arXiv: 1504.02470 [hep-ph].

A. M. Gago, P. Hernández, J. Jones-Pérez, M. Losada, and A. Moreno Briceño. “Probing the Type I Seesaw Mechanism with Displaced Vertices at the LHC”. *Eur. Phys. J.* C75.10, p. 470. DOI: 10.1140/epjc/s10052-015-3693-1. arXiv: 1505.05880 [hep-ph].

C. O. Dib and C. S. Kim. “Discovering sterile Neutrinos ligther than M_W at the LHC”. *Phys. Rev.* D92.9, p. 093009. DOI: 10.1103/PhysRevD.92.093009. arXiv: 1509.05981 [hep-ph].

G. Cottin, J. C. Helo, and M. Hirsch. “Displaced vertices as probes of sterile neutrino mixing at the LHC”. *Phys. Rev.* D98.3, p. 035012. DOI: 10.1103/PhysRevD.98.035012. arXiv: 1806.05191 [hep-ph]. №: IFIC/18-25, IFIC-18-25.

A. Abada, N. Bernal, M. Losada, and X. Marcano. “Inclusive Displaced Vertex Searches for Heavy Neutral Leptons at the LHC”. *JHEP* 01, p. 093. DOI: 10.1007/JHEP01(2019)093. arXiv: 1807.10024 [hep-ph]. №: LPT-ORSAY-18-79, PI/UAN-2018-631FT.

G. Cvetič, A. Das, and J. Zamora-Saá. “Probing heavy neutrino oscillations in rare W boson decays”. arXiv: 1805.00070 [hep-ph].

I. Boiarska et al. “Probing baryon asymmetry of the Universe at LHC and SHiP”. arXiv: 1902.04535 [hep-ph].

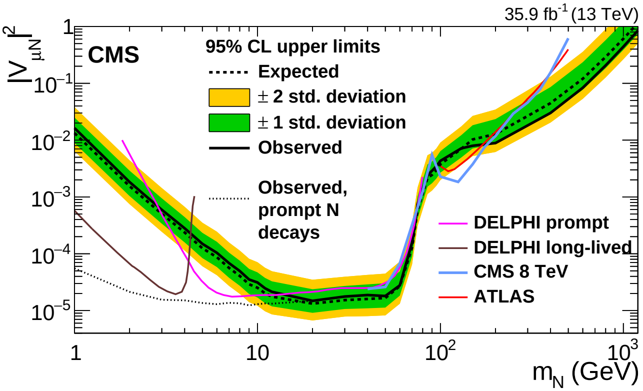
J. Liu, Z. Liu, L.-T. Wang, and X.-P. Wang. “Seeking for sterile neutrinos with displaced leptons at the LHC”. [JHEP07,159(2019)]. DOI: 10.1007/JHEP07(2019)159. arXiv: 1904.01020 [hep-ph]. №: EFI-19-6.

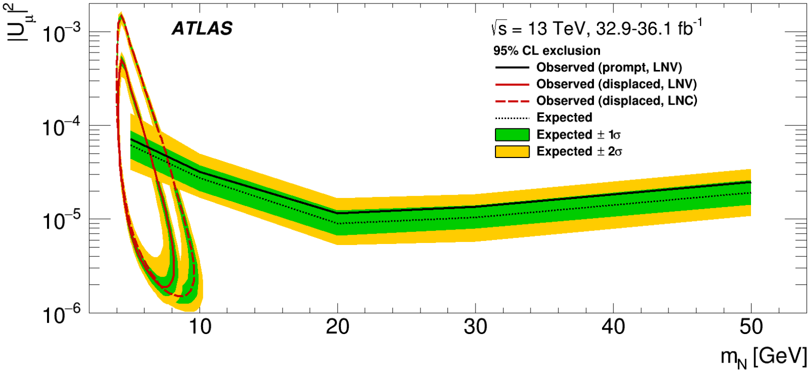
C. O. Dib, C. S. Kim, and S. Tapia Araya. “Search for light sterile neutrinos from $W^{\pm}$ decays at the LHC”. arXiv: 1903.04905 [hep-ph]. №: NCTS-PH/1801.

G. Cvetič, A. Das, S. Tapia, and J. Zamora-Saá. “Measuring the heavy neutrino oscillations in rare W boson decays at the Large Hadron Collider”. arXiv: 1905.03097 [hep-ph].

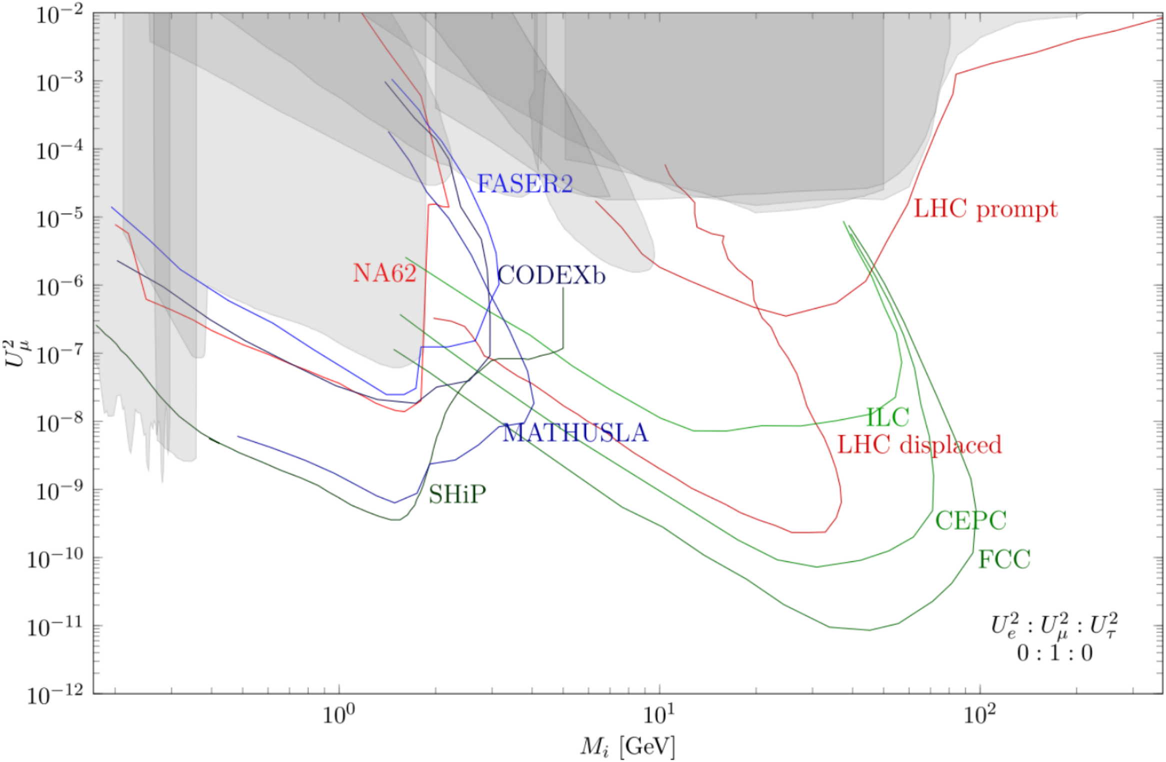
Prompt and displaced results for U_μ^2

[CMS 2018; ATLAS 2019]





Future


10^{-2}
10^{-3}
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10^{-12}
U_μ^2
10^0
10^1
10^2
M_i [GeV]
FASER2
LHC prompt
NA62
CODEXb
ILC
LHC displaced
MATHUSLA
SHiP
CEPC
FCC
$U_e^2 : U_\mu^2 : U_\tau^2$
$0 : 1 : 0$

Future detectors and colliders

S. Antusch, E. Cazzato, and O. Fischer. “Sterile neutrino searches at future e^-e^+, pp, and e^-p colliders”. *Int. J. Mod. Phys.* A32.14, p. 1750078. DOI: `10.1142/S0217751X17500786`. arXiv: `1612.02728 [hep-ph]`.

S. Antusch et al. “Probing Leptogenesis at Future Colliders”. *JHEP* 09, p. 124. DOI: `10.1007/JHEP09(2018)124`. arXiv: `1710.03744 [hep-ph]`. №: TUM-1160/18, CP3-17-48.

J. L. Feng, I. Galon, F. Kling, and S. Trojanowski. “ForwArd Search ExpeRiment at the LHC”. *Phys. Rev.* D97.3, p. 035001. DOI: `10.1103/PhysRevD.97.035001`. arXiv: `1708.09389 [hep-ph]`. №: UCI-TR-2017-08.

V. V. Gligorov, S. Knapen, M. Papucci, and D. J. Robinson. “Searching for Long-lived Particles: A Compact Detector for Exotics at LHCb”. *Phys. Rev.* D97.1, p. 015023. DOI: `10.1103/PhysRevD.97.015023`. arXiv: `1708.09395 [hep-ph]`.

D. Curtin et al. “Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case”. arXiv: `1806.07396 [hep-ph]`. №: FERMILAB-PUB-18-264-T.

SHiP. “A facility to Search for Hidden Particles (SHiP) at the CERN SPS”. arXiv: `1504.04956 [physics.ins-det]`. №: CERN-SPSC-2015-016, SPSC-P-350.

S. Alekhin et al. “A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case”. *Rept. Prog. Phys.* 79.12, p. 124201. DOI: `10.1088/0034-4885/79/12/124201`. arXiv: `1504.04855 [hep-ph]`. №: CERN-SPSC-2015-017, SPSC-P-350-ADD-1.

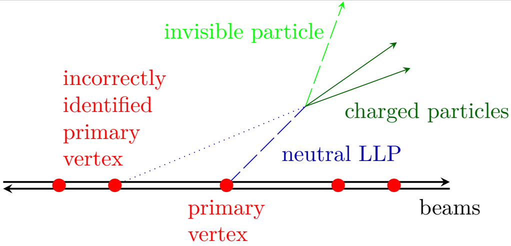
Heavy Ion Collisions

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): $^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + e^+$

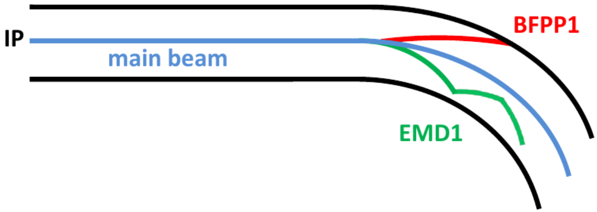
[Pshenichnov et al. 2001]

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

Leads to

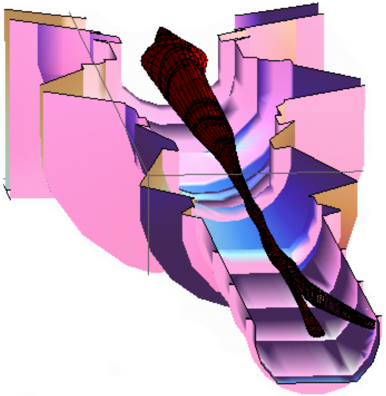
[Schaumann 2015]

- 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

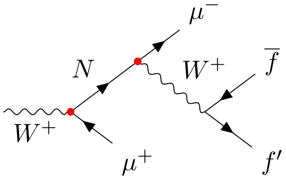
$$t_{\mathrm{opt}} = \tau_b\sqrt{\theta_{\mathrm{ta}}}\,, \qquad \text{with} \qquad \theta_{\mathrm{ta}} = \frac{t_{\mathrm{ta}}}{\tau_b}\,.$$

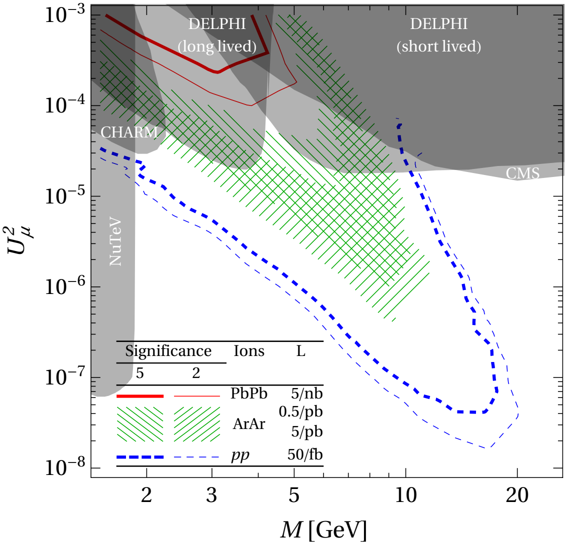
The average luminosity using the optimal run time is

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

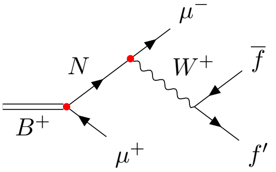
Heavy ion collisions

Full simulation of W production

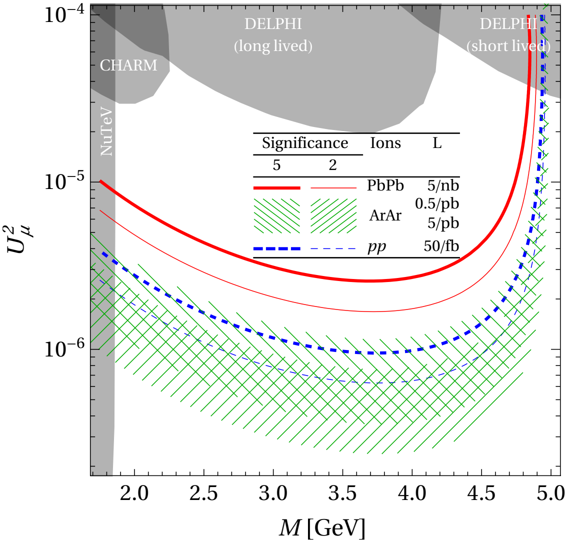




Simplified simulation of B production



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
- NA62 and the LHC experiments will be able to constrain U_τ^2 in τ final states
- Heavy ion collisions provide a new environment to search for right-handed neutrinos

References I

M. Drewes, J. Hajer, J. Klaric, and G. Lanfranchi. "NA62 sensitivity to heavy neutral leptons in the low scale seesaw model". *JHEP* 07, p. 105. DOI: `10.1007/JHEP07(2018)105`. arXiv: `1801.04207 [hep-ph]`.

M. Drewes, A. Giammanco, J. Hajer, M. Lucente, and O. Mattelaer. "A Heavy Metal Path to New Physics". arXiv: `1810.09400 [hep-ph]`. №: CP3-18-60.

M. Drewes and J. Hajer. "Heavy Neutrinos in displaced vertex searches at the LHC and HL-LHC". arXiv: `1903.06100 [hep-ph]`. №: CP3-19-11.

M. Drewes, A. Giammanco, J. Hajer, and M. Lucente. "Long Lived Particles Searches in Heavy Ion Collisions at the LHC". arXiv: `1905.09828 [hep-ph]`. №: CP3-19-26.

P. Minkowski. "$\mu \to e\gamma$ at a Rate of One Out of 10^9 Muon Decays?" *Phys. Lett.* 67B, pp. 421–428. DOI: `10.1016/0370-2693(77)90435-X`. №: PRINT-77-0182 (BERN).

R. N. Mohapatra and G. Senjanovic. "Neutrino Mass and Spontaneous Parity Violation". *Phys. Rev. Lett.* 44, p. 912. DOI: `10.1103/PhysRevLett.44.912`. №: MDDP-TR-80-060, MDDP-PP-80-105, CCNY-HEP-79-10.

T. Asaka and M. Shaposhnikov. "The νMSM, dark matter and baryon asymmetry of the universe". *Phys. Lett.* B620, pp. 17–26. DOI: `10.1016/j.physletb.2005.06.020`. arXiv: `hep-ph/0505013 [hep-ph]`.

M. Shaposhnikov. "A Possible symmetry of the νMSM". *Nucl. Phys.* B763, pp. 49–59. DOI: `10.1016/j.nuclphysb.2006.11.003`. arXiv: `hep-ph/0605047 [hep-ph]`. №: CERN-PH-TH-2006-079.

References II

M. Chrzaszcz et al. “A frequentist analysis of three right-handed neutrinos with GAMBIT”. arXiv: `1908.02302 [hep-ph]`.

NA62. “Search for heavy neutral lepton production in K^+ decays”. arXiv: `1712.00297 [hep-ex]`. №: CERN-EP-2017-311.

NA62. “Exotic searches at the NA62 experiment at CERN”. *International Conference on Kaon Physics 2019*. URL: `https://indico.cern.ch/event/769729/contributions/3511127`.

T2K. “Search for heavy neutrinos with the T2K near detector ND280”. *Phys. Rev.* D100.5, p. 052006. DOI: `10.1103/PhysRevD.100.052006`. arXiv: `1902.07598 [hep-ex]`.

S. Bobrovskyi, W. Buchmüller, J. Hajer, and J. Schmidt. “Quasi-stable neutralinos at the LHC”. *JHEP* 09, p. 119. DOI: `10.1007/JHEP09(2011)119`. arXiv: `1107.0926 [hep-ph]`. №: DESY-11-077.

CMS. “Search for long-lived particles that decay into final states containing two muons, reconstructed using only the CMS muon chambers”. №: CMS-PAS-EXO-14-012.

ATLAS. “Trigger Menu in 2016”. ATL-DAQ-PUB-2017-001. URL: `https://cds.cern.ch/record/2242069`.

CMS. “Search for heavy neutral leptons in events with three charged leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV”. *Phys. Rev. Lett.* 120.22, p. 221801. DOI: `10.1103/PhysRevLett.120.221801`. arXiv: `1802.02965 [hep-ex]`. №: CMS-EXO-17-012, CERN-EP-2018-006.

References III

ATLAS. “Search for heavy neutral leptons in decays of *W* bosons produced in 13 TeV *pp* collisions using prompt and displaced signatures with the ATLAS detector”. arXiv: `1905.09787 [hep-ex]`. №: CERN-EP-2019-071.

H. Meier, Z. Halabuka, K. Hencken, D. Trautmann, and G. Baur. “Bound free electron positron pair production in relativistic heavy ion collisions”. *Phys. Rev.* A63, p. 032713. DOI: `10.1103/PhysRevA.63.032713`. arXiv: `nucl-th/0008020 [nucl-th]`.

I. A. Pshenichnov, J. P. Bondorf, I. N. Mishustin, A. Ventura, and S. Masetti. “Mutual heavy ion dissociation in peripheral collisions at ultrarelativistic energies”. *Phys. Rev.* C64, p. 024903. DOI: `10.1103/PhysRevC.64.024903`. arXiv: `nucl-th/0101035 [nucl-th]`.

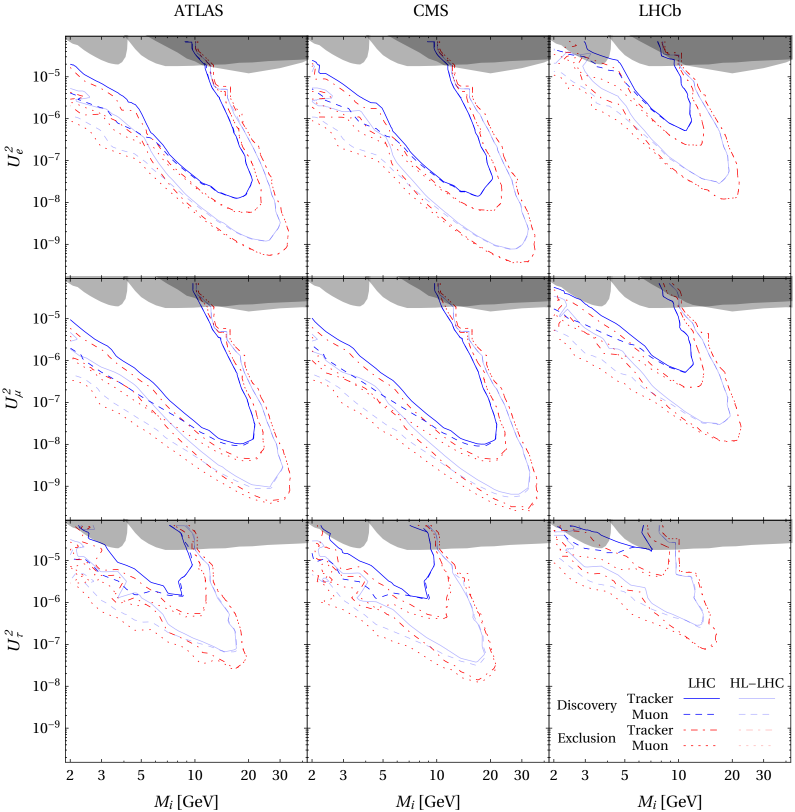
M. Schaumann. “Heavy-ion performance of the LHC and future colliders”. PhD thesis. Aachen, Germany: RWTH Aachen U. №: CERN-THESIS-2015-195, URN:NBN:DE:HBZ:82-RWTH-2015-050284.

R. Bruce, J. Jowett, and M. Schaumann. “Limitations for heavy-ion performance in the LHC”. URL: `https://agenda.irmp.ucl.ac.be/event/3186/contributions/3648`.

J. Jowett. “HL-LHC performance: Update for HE-LHC and light ions”. URL: `https://indico.cern.ch/event/686494/timetable`.

M. Benedikt, D. Schulte, and F. Zimmermann. “Optimizing integrated luminosity of future hadron colliders”. *Phys. Rev. ST Accel. Beams* 18, p. 101002. DOI: `10.1103/PhysRevSTAB.18.101002`.

Comparison of the exclusions reaches for the LHC experiments



Comparison for purely leptonic searches