

# Searches for Right-handed Neutrinos at Accelerator-based Experiments

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## Three right handed neutrinos

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

$y_{ai}$  Yukawa coupling

$M_{ij}$  Majorana mass

## Electroweak symmetry breaking

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

## Seesaw mechanism

$$m_\nu = -m_{ai} M_{ij}^{-1} m_{bj}^T = -\theta_{ai} M_{ij} \theta_{bj}^T, \quad \theta_{ai} = m_{aj} M_{ij}^{-1}$$

produces tiny masses for the left handed neutrinos

## Small mixing into mass eigenstates

$$\nu \simeq U_\nu^\dagger (\nu_L - \theta \nu_R^c), \quad N \simeq \nu_R + \theta^T \nu_L^c$$

## Coupling of $N_i$ to the SM

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

## Complements SM fields

2.4 MeV $\frac{2}{3}$ Left <b>u</b> up Right	1.27 GeV $\frac{2}{3}$ Left <b>c</b> charm Right	171.2 GeV $\frac{2}{3}$ Left <b>t</b> top Right
4.8 MeV $-\frac{1}{3}$ Left <b>d</b> down Right	104 MeV $-\frac{1}{3}$ Left <b>s</b> strange Right	4.2 GeV $-\frac{1}{3}$ Left <b>b</b> bottom Right
0 eV 0 Left <b><math>\nu_e</math></b> electron neutrino Right	0 eV 0 Left <b><math>\nu_\mu</math></b> muon neutrino Right	0 eV 0 Left <b><math>\nu_\tau</math></b> tau neutrino Right
0.511 MeV -1 Left <b>e</b> electron Right	105.7 MeV -1 Left <b><math>\mu</math></b> muon Right	1.777 GeV -1 Left <b><math>\tau</math></b> tau Right

## $\nu$ MSM may explain

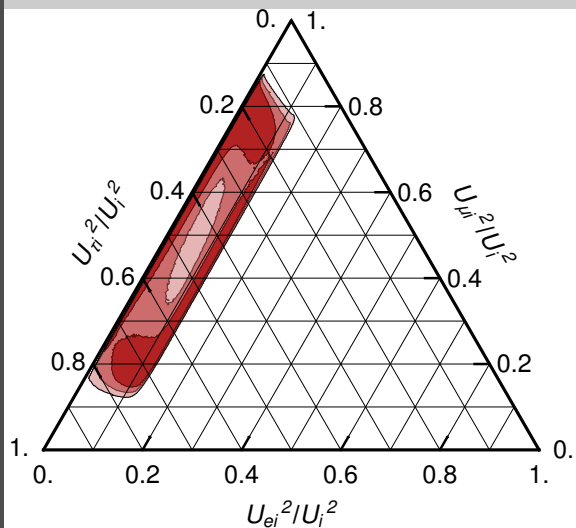
- ▶ Neutrino oscillation
- ▶ Neutrino masses
- ▶ Leptogenesis
- ▶ Dark matter

## Abbreviation

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

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

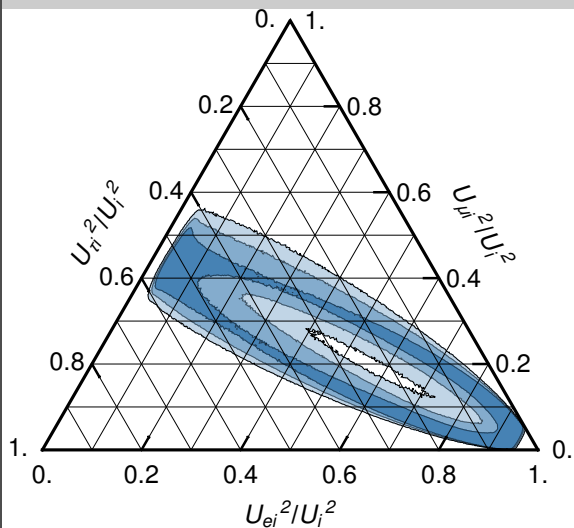
## Normal Ordering



Coloured areas consistent

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

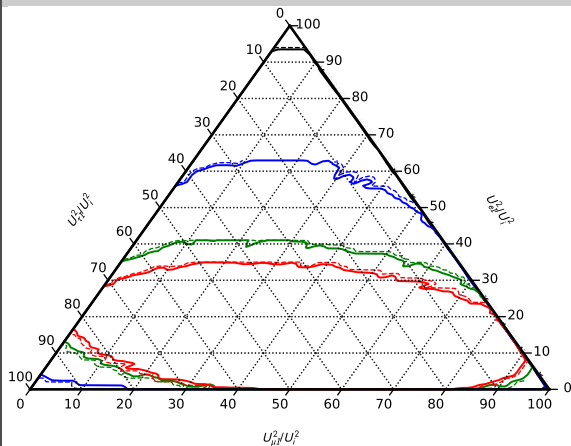
## Inverted Ordering



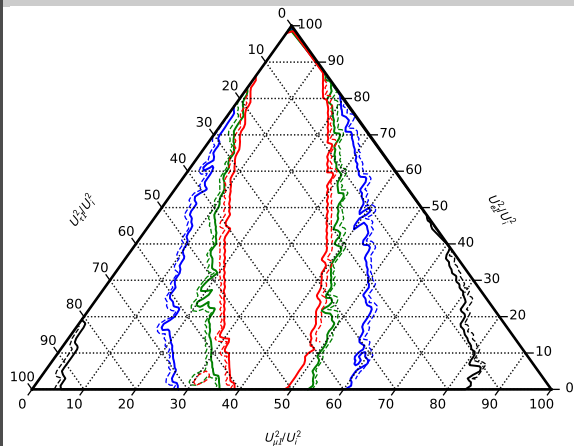
Unknown Majorana phase  $\alpha$

correspond to the circular structure

## Normal Ordering



## Inverted Ordering



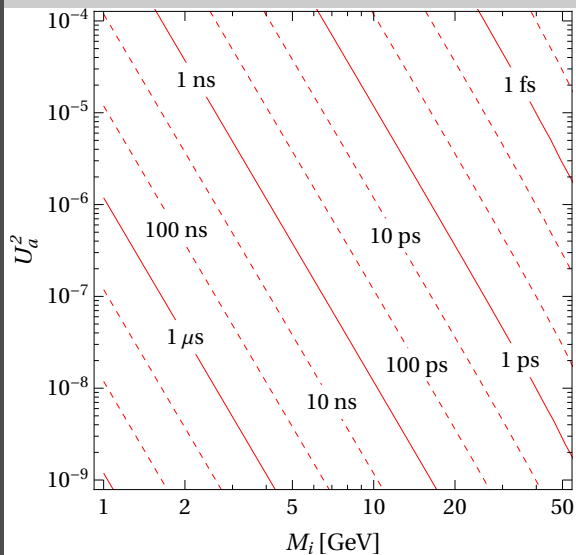
Contours depend on

$m_{\nu 0} < 0.01, 0.1, 1, 10$  meV for 1 and 2  $\sigma$

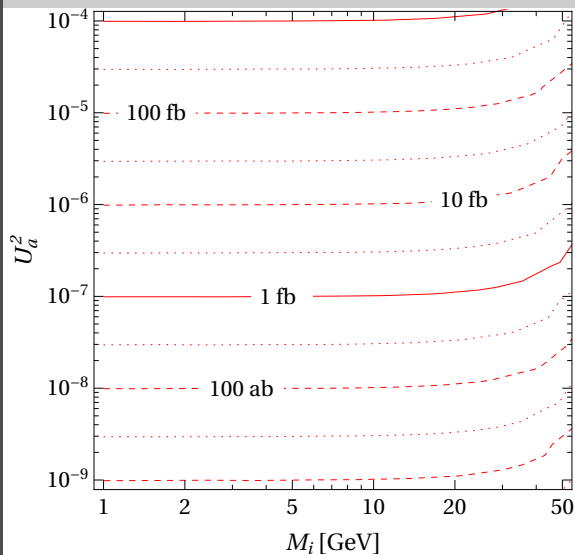
The non-minimal case is considerably less predictive

# Properties

## Lifetime



## Production crosssection at the LHC

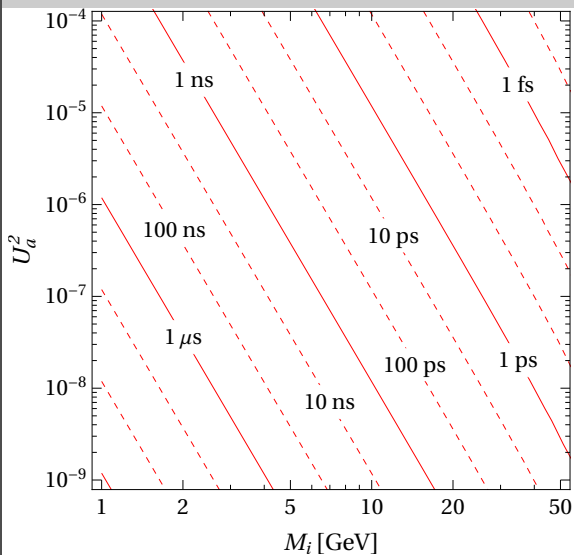


Decay width for  $M \gg 5$  GeV

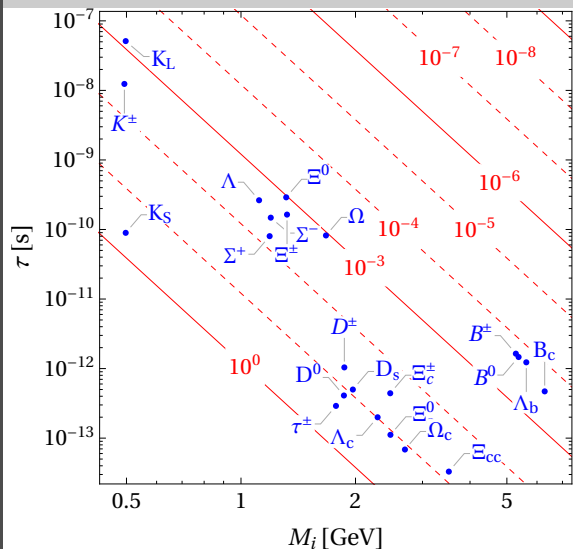
$$\Gamma_N \simeq 11.9 \times \frac{G_F^2}{96\pi^3} U_a^2 M^5,$$

# Properties

## Lifetime



## SM background vs. coupling strength $U^2$



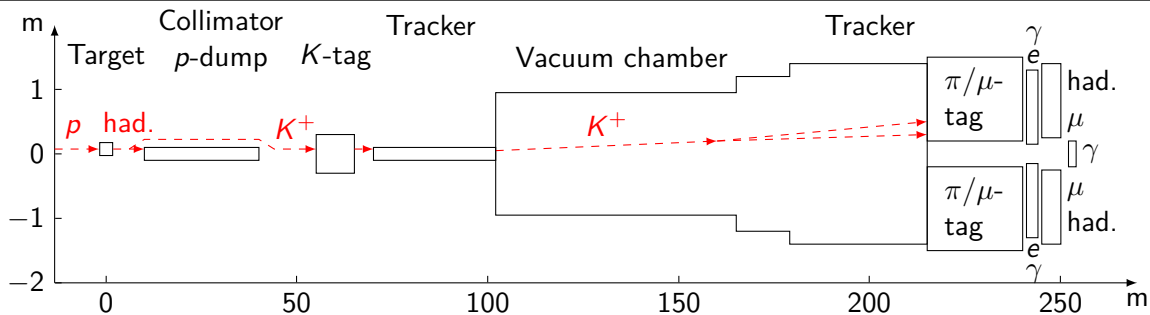
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NA62

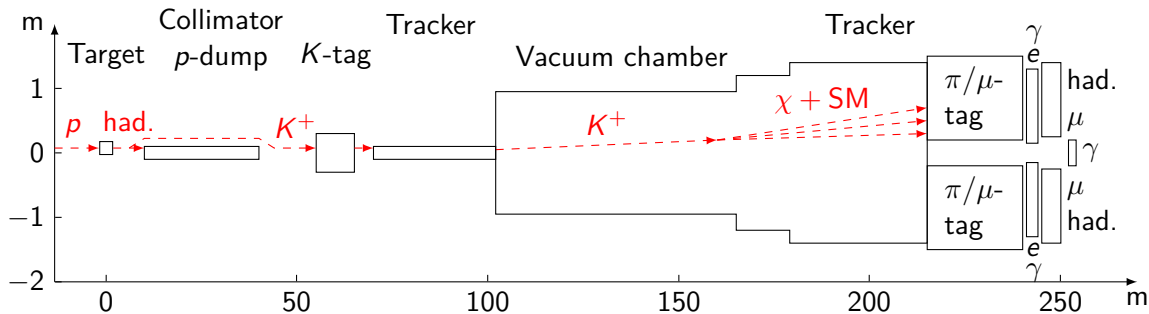
Fixed target experiment in the North Area using the CERN SPS with the goal to

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



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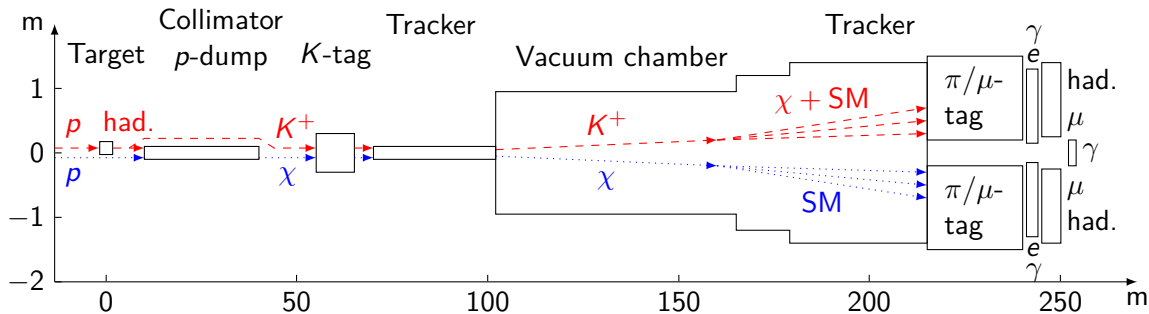


Hidden sectors at NA62

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

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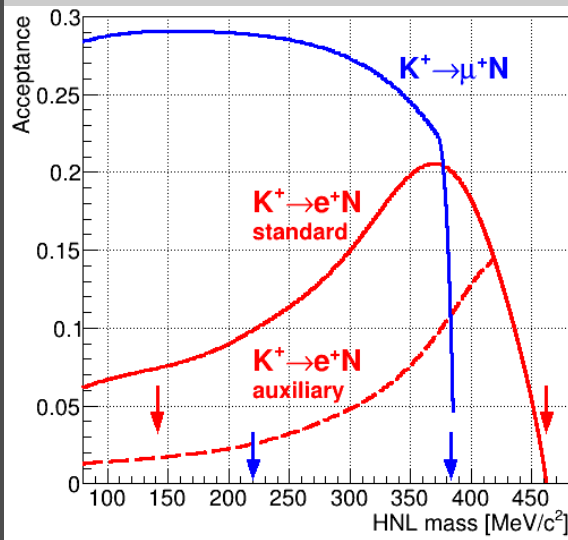
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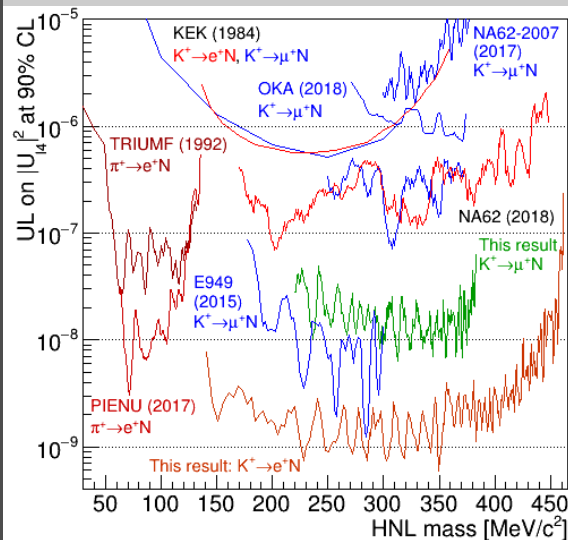
Hidden sectors at NA62

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

## Acceptance of $K^+ \rightarrow \ell^+ N$



## Result



$K^+ \rightarrow \mu^+ N$  5 days of operation in 2015

$K^+ \rightarrow e^+ N$  5 days of operation in 2015

$K^+ \rightarrow \mu^+ N$  (2016–2017 data)

$K^+ \rightarrow e^+ N$  (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  $2 \times 10^{15}$   $D^-$  and  $10^{11}$   $B^-$ -mesons

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

$\chi$  production cross section

$f$  production fractions of mesons

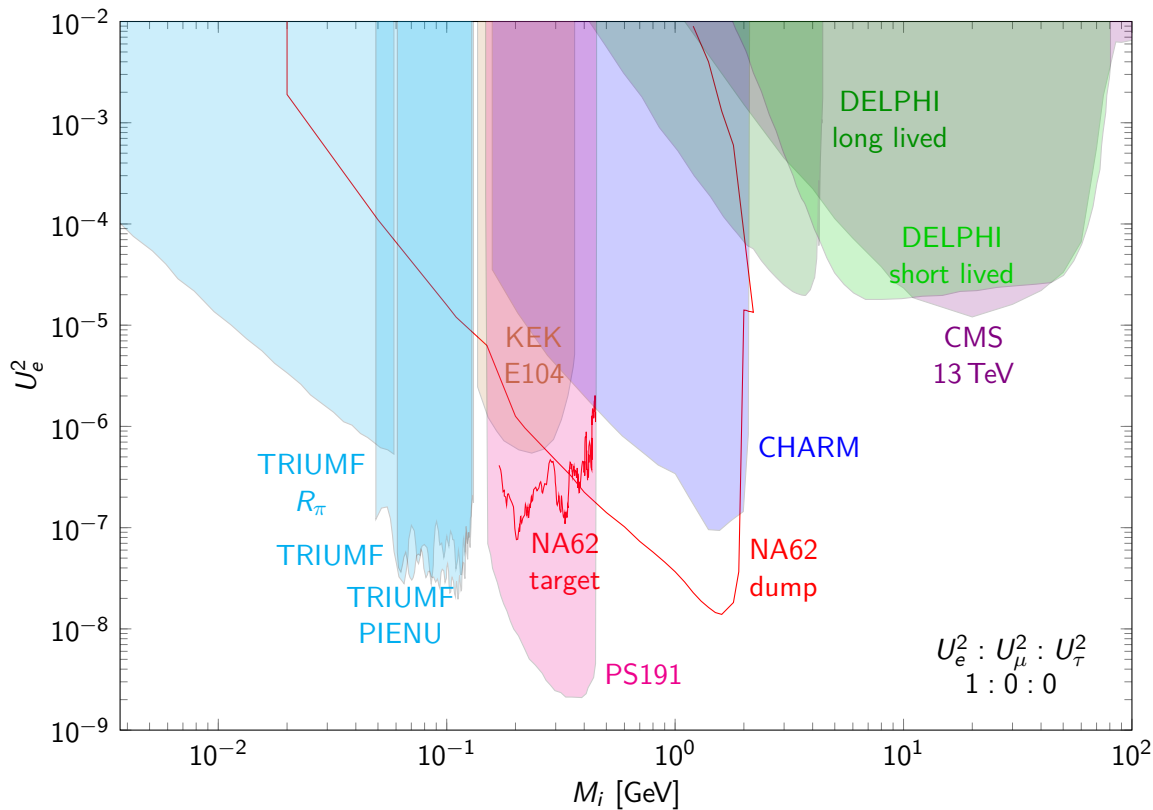
## Number of reconstructed events

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

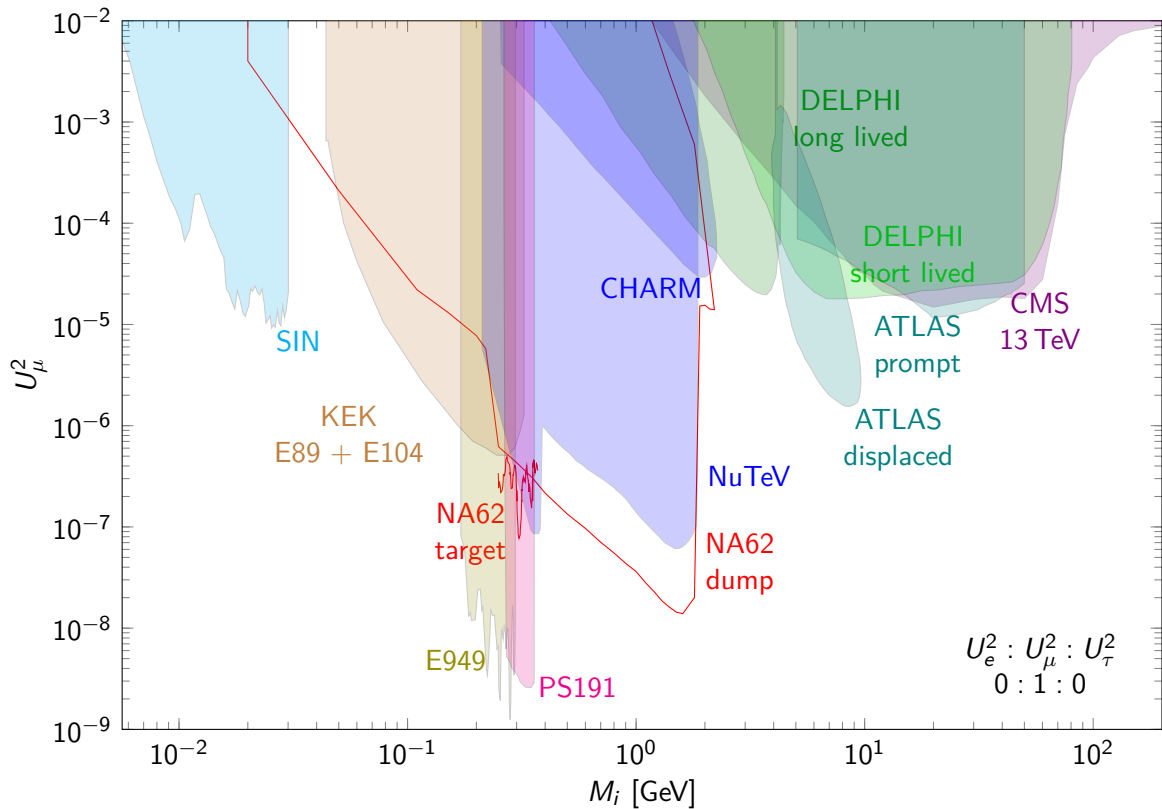
$\mathcal{A}_i$  geometrical acceptance

$\varepsilon$  efficiency assumed to be 100 %!  
(trigger, reconstruction, selection)

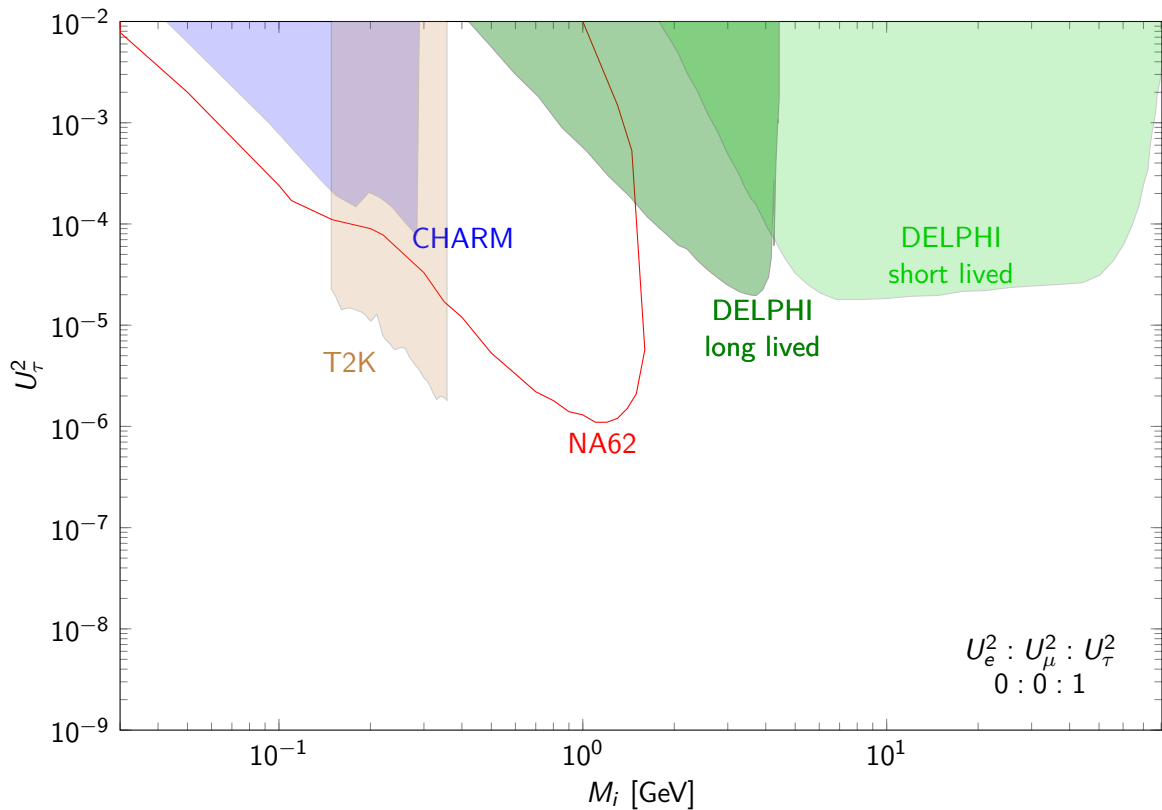
pure  $U_e^2$



pure  $U_\mu^2$

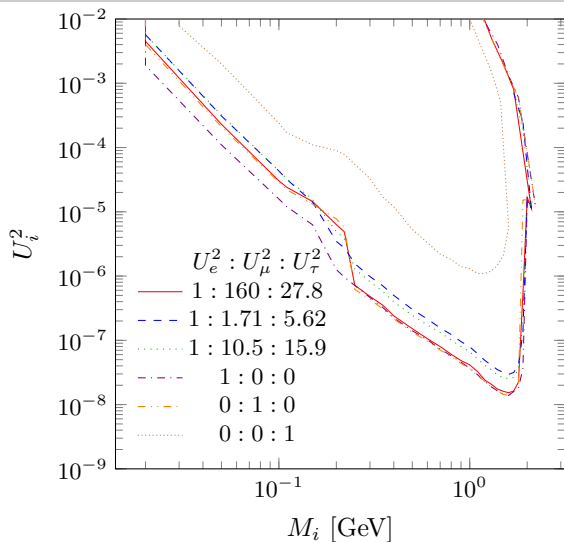


pure  $U_\tau^2$

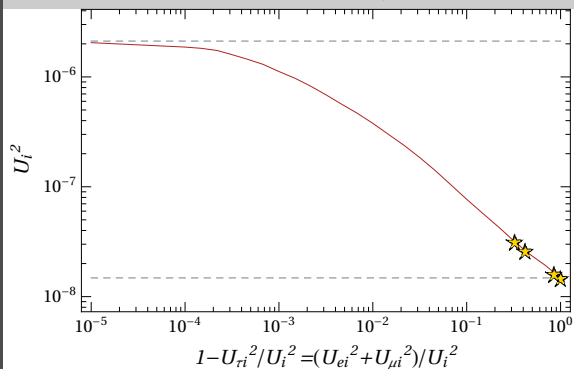


# Realistic mixing patterns

## Comparison between benchmark points



## Sensitivity dependence on $U_\tau^2/U^2$

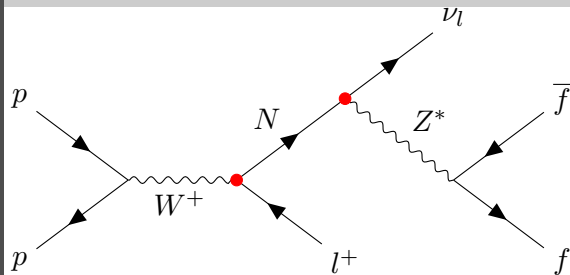


Take home message

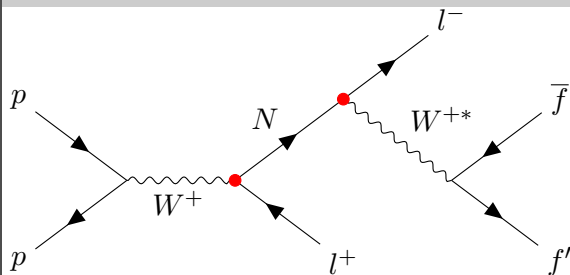
The sensitivity of realistic mixing patterns is much better than the pure  $U_\tau^2$  case.

LHC

## Z-decay



## W-decay



## Search strategy

- ▶ trigger on first lepton
- ▶ search for secondary vertex

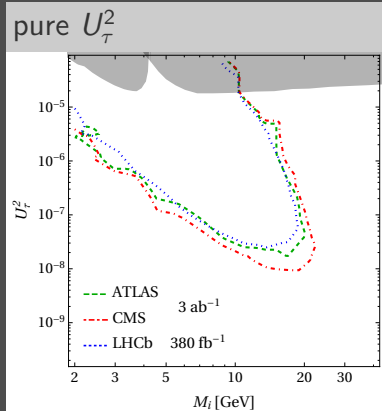
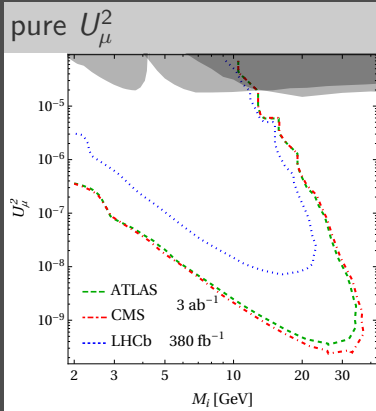
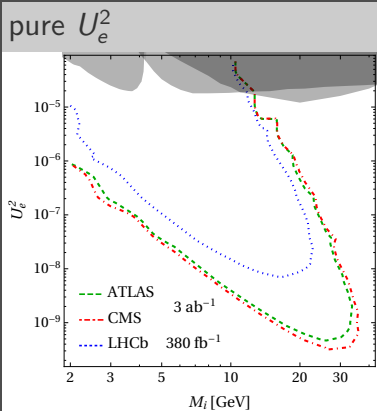
## Muon chamber [\[Bobrovskiy et al. 2011; CMS 2015\]](#)

- ▶ 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



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

[ATLAS 2017]

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

# Expectations

## Simplified model

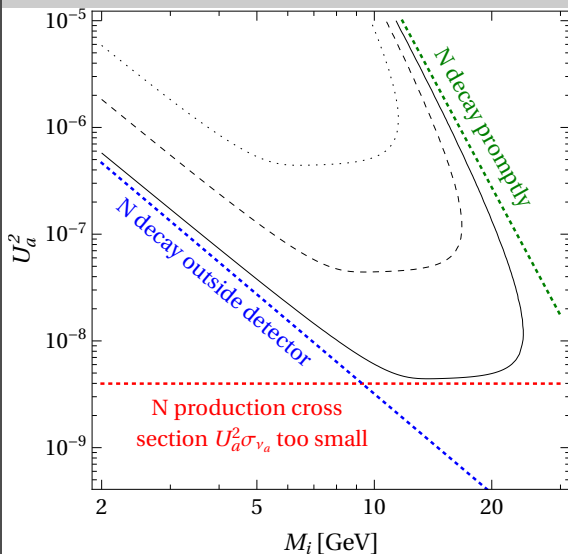
$$N_d \sim L_{\text{int}} \sigma_\nu U^2 \left( e^{-l_0/\lambda_N} - e^{-l_1/\lambda_N} \right) f_{\text{cut}} ,$$

$\lambda_N = \frac{\beta\gamma}{\Gamma_N}$  decay length

$l_0$  minimal displacement

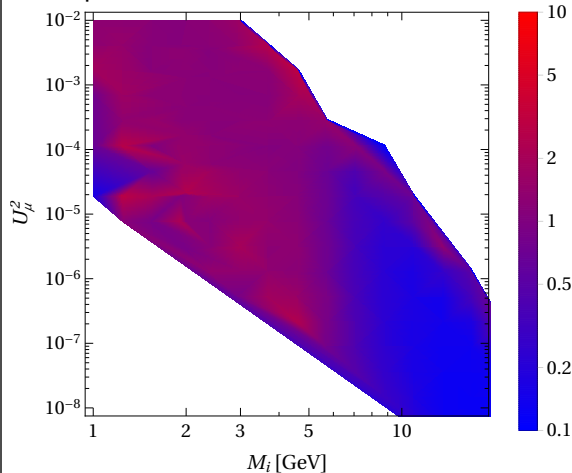
$l_1$  detector length

## Significances and major obstacles



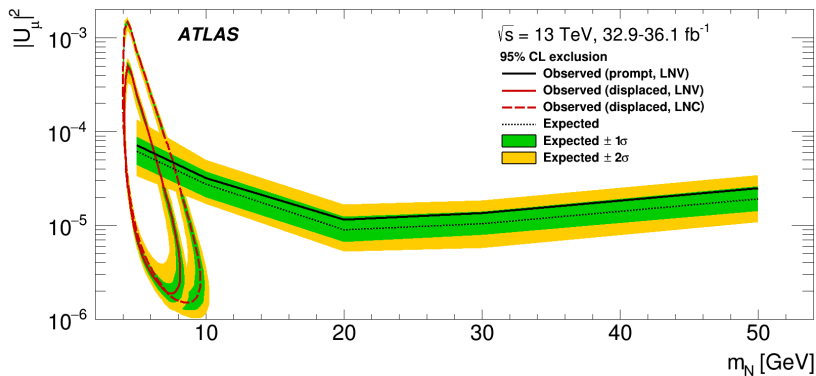
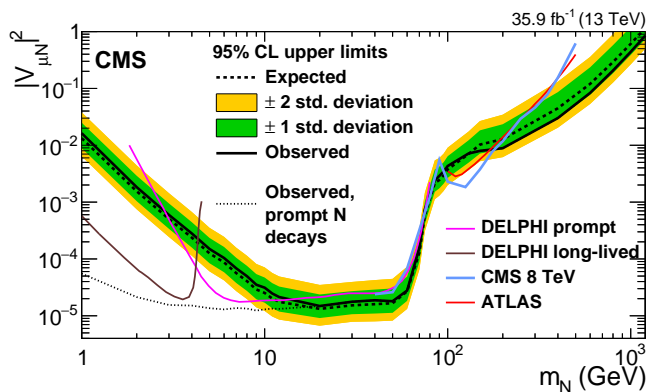
## Deviation

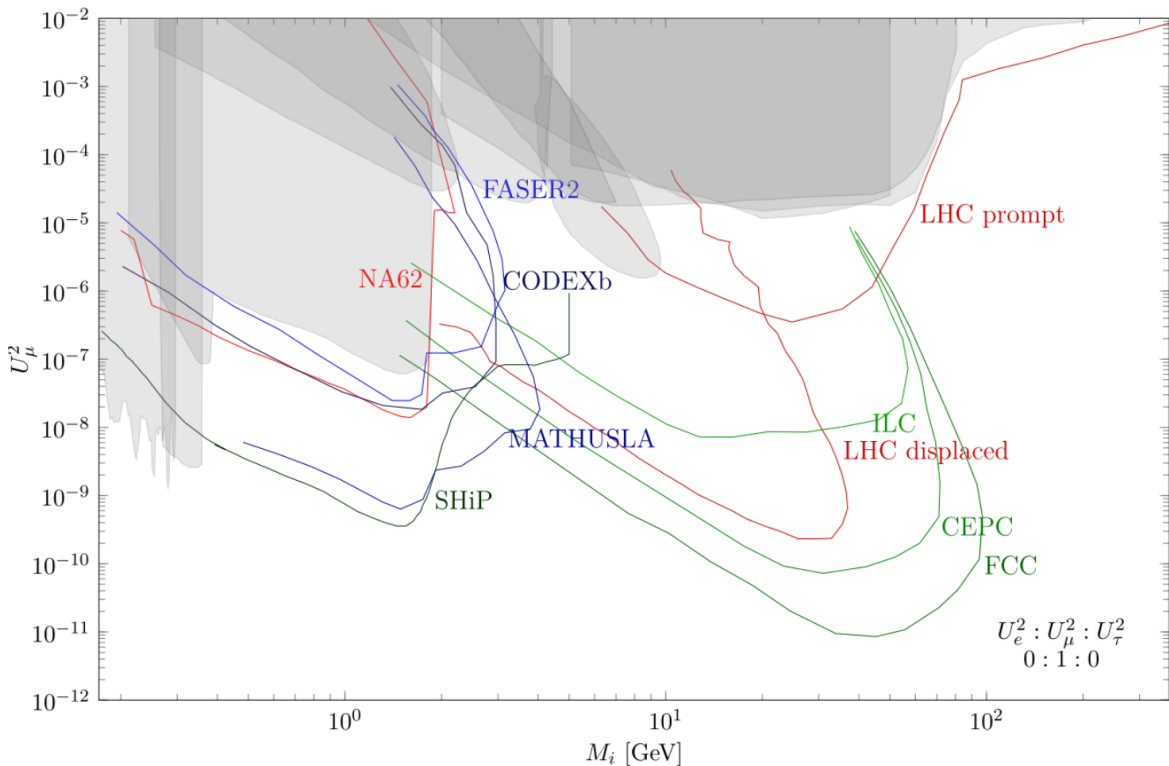
of simplified model from full simulation



# Displaced vertex searches at the LHC

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- J. C. Helo, M. Hirsch, and S. Kovalenko. “Heavy neutrino searches at the LHC with displaced vertices”. *Phys. Rev. D*89. [Erratum: *Phys. Rev. D*93, no. 9, 099902(2016)], p. 073005. doi: 10.1103/PhysRevD.89.073005, 10.1103/PhysRevD.93.099902. *arXiv*: 1312.2900 [hep-ph].
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- 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.
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- 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.

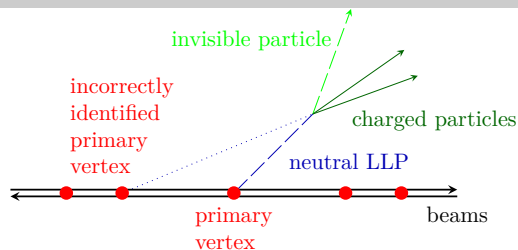
# Heavy Ion Collisions

# Properties of the heavy ions runs

## Advantage

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

## Single primary vertex



Better event reconstruction possible

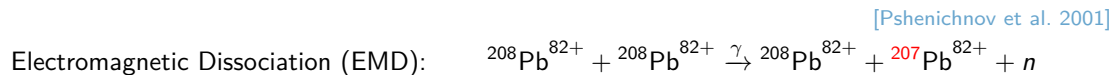
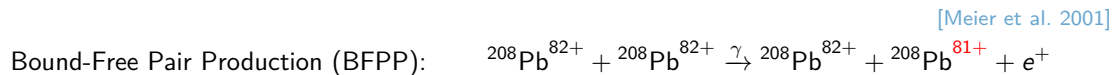
## Drawbacks

- ▶ 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.  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$  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

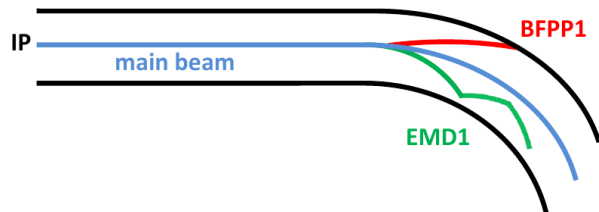
- ▶ Low luminosity allows for lower triggers
- ▶ Lighter ions allow for higher luminosity

For heavy ions there are additional contributions to the crosssection



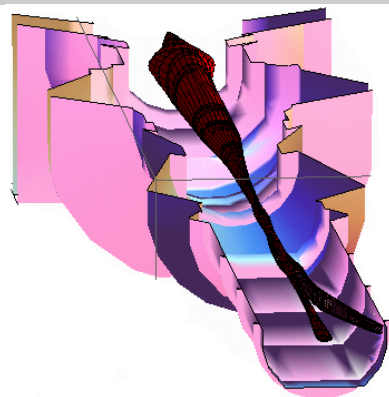
Leads to [Schaumann 2015]

- ▶ 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]



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

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

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

$$\frac{dN_b}{dt} = -\frac{N_b^2}{N_0 \tau_b}, \quad \tau_b = \frac{n_b}{\sigma_{\text{tot}} n_{\text{IP}}} \frac{N_0}{L_0},$$

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

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

the integrated luminosity is maximised by

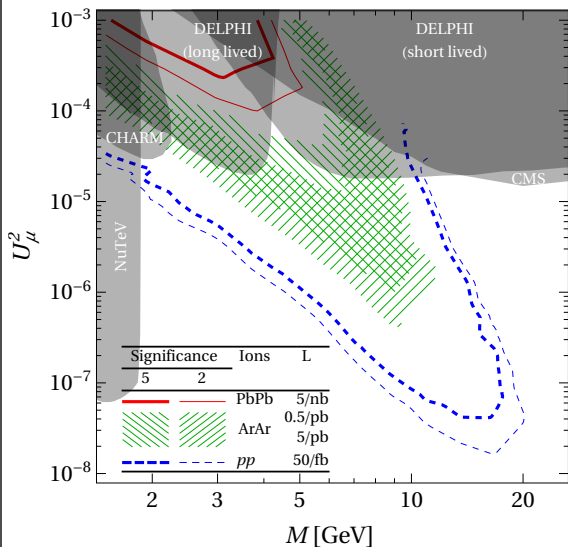
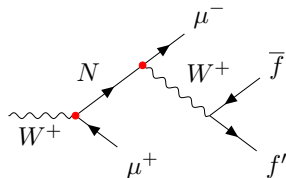
$$t_{\text{opt}} = \tau_b \sqrt{\theta_{\text{ta}}}, \quad \text{with} \quad \theta_{\text{ta}} = \frac{t_{\text{ta}}}{\tau_b}.$$

The average luminosity using the optimal run time is

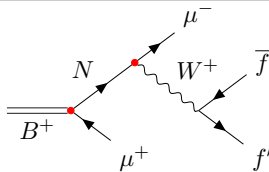
$$L_{\text{ave}}(t_{\text{opt}}) = \frac{L_0}{(1 + \sqrt{\theta_{\text{ta}}})^2}.$$

# Heavy ion collisions

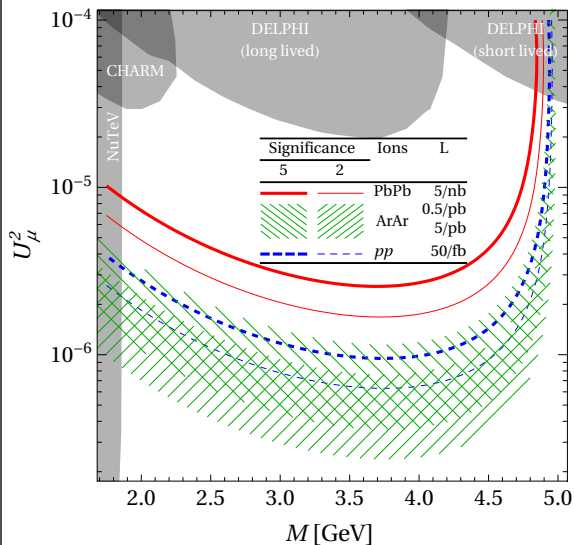
## Full simulation of $W$ production



## Simplified simulation of $B$ production



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

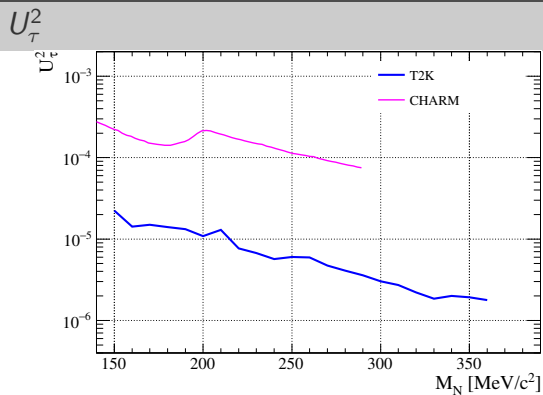
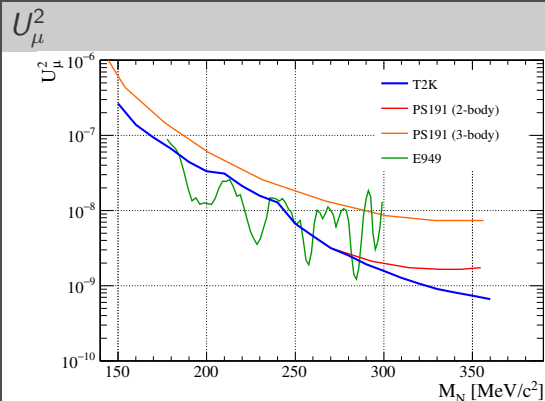
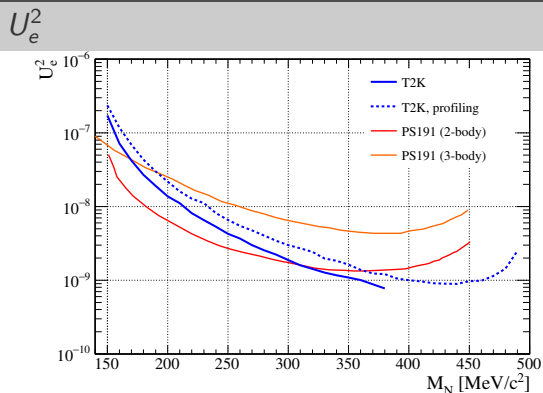


- ▶ Heavy neutrinos constitute a minimal extension to the SM featuring long lived particles
- ▶ At the moment NA62 is the leading experiment able to search for right-handed neutrinos with masses between the  $K^-$  and  $D$ -meson mass
- ▶ Displaced vertices are a promising signature to detect right-handed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

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## T2K

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

## near detector ND280

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