

Search for long lived neutral leptons at the LHC

LHCにおける長寿命中性レプトンの探索

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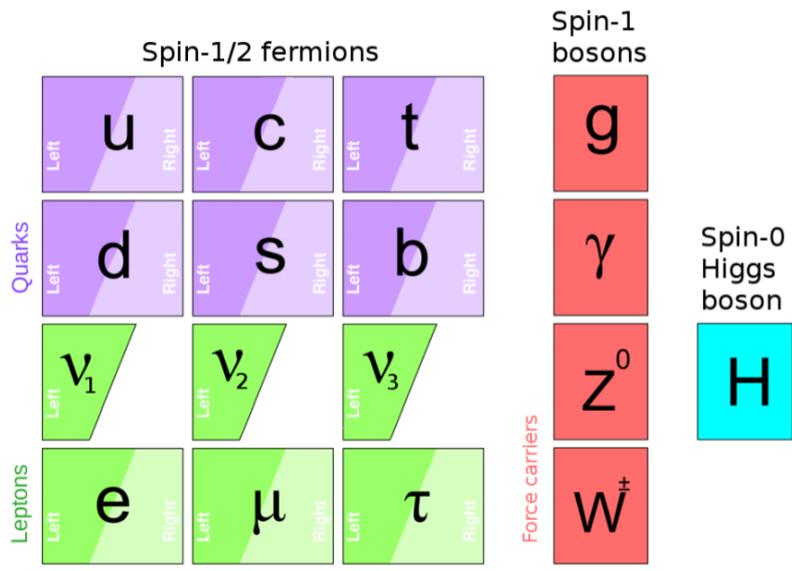
Exploration of Particle Physics and Cosmology
with Neutrinos Workshop 2019

Iga, Mie, Japan

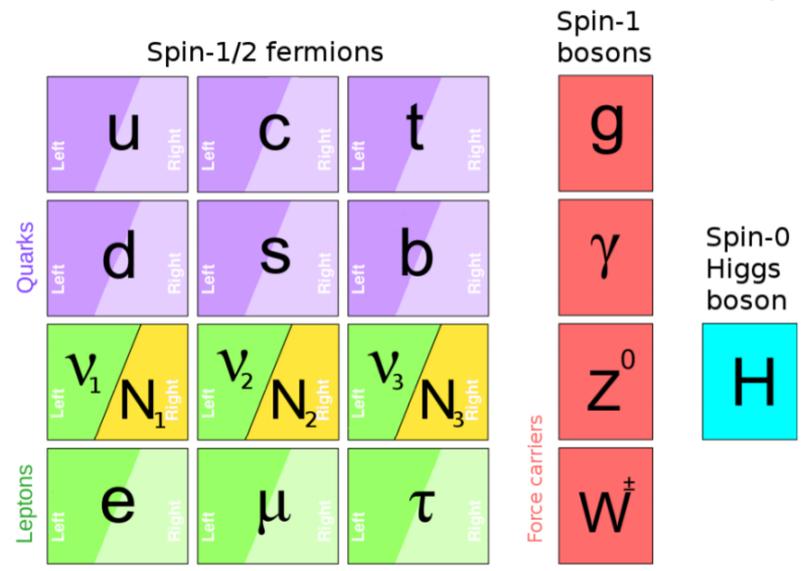
3/13 Neutrino Minimal Standard Model

- Neutrino masses Please see Eijima-san's presentation on Wednesday
- Asymmetry between matter and anti-matter
- Dark matter
- Models with addition of three right-handed neutrinos to the Standard Model can explain the big three questions.
 - [arXiv:hep-ph/0505013](https://arxiv.org/abs/hep-ph/0505013)

Standard Model (SM)



Neutrino Minimal Standard Model (ν MSM)

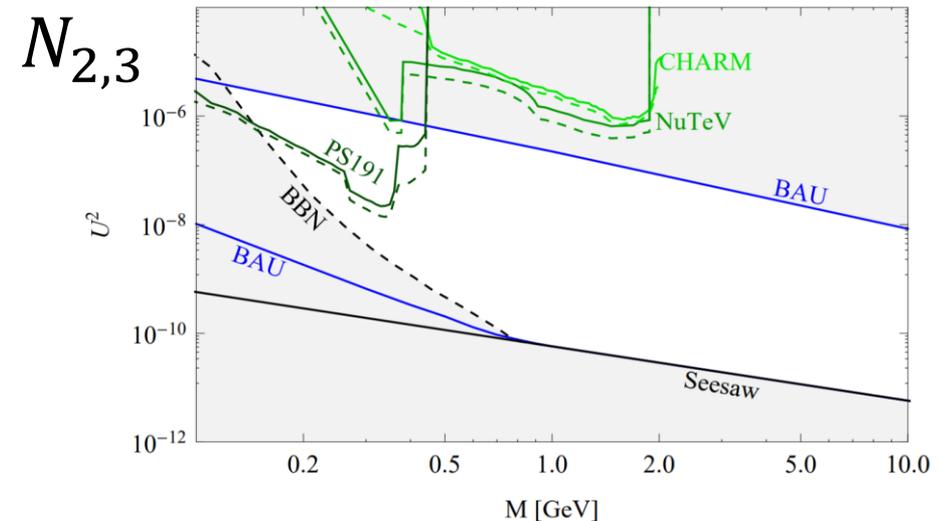
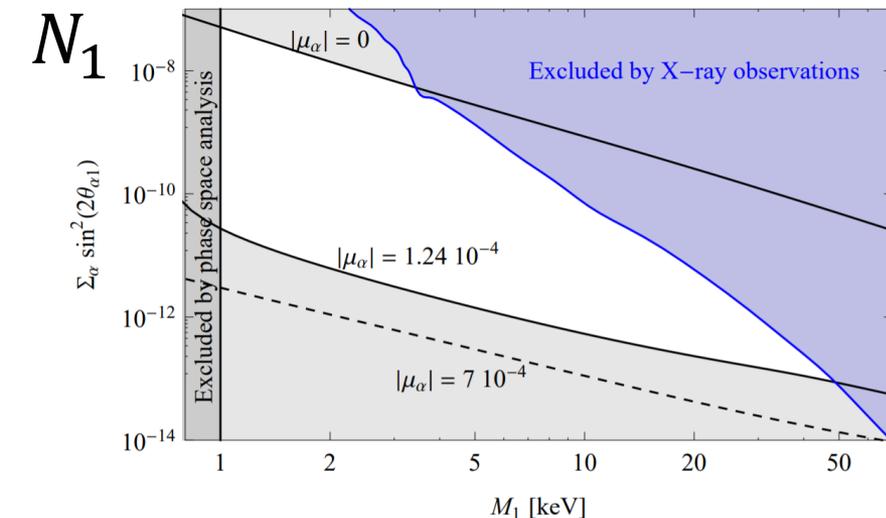


4/13 Right-handed neutrinos in ν MSM

- Also known as Heavy Neutral Leptons (HNLs).
- N_1 : Dark matter
 - $1 \text{ keV} < M_1 < 50 \text{ keV}$
- N_2, N_3 : Sources of matter-antimatter asymmetry and neutrino masses by Seesaw mechanism
 - $0.1 \text{ GeV} < M_2, M_3 < 80 \text{ GeV}$
 - **Reach of accelerator experiments**
- Mixing with left-handed neutrinos
- [arXiv:1208.4607 \[hep-ph\]](https://arxiv.org/abs/1208.4607)

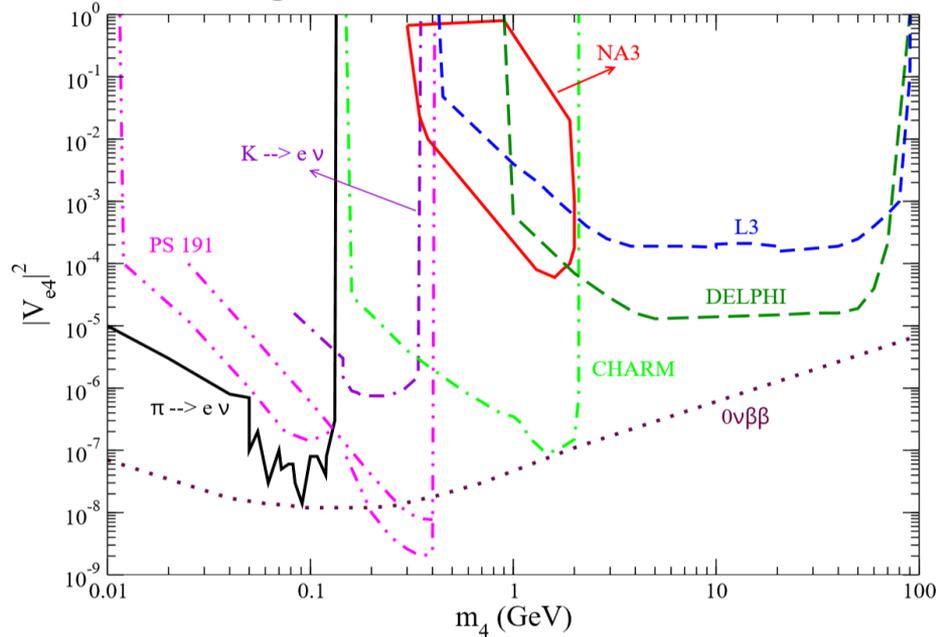
$$\tau_N = (4 \cdot 10^{-12} \text{ s}) |U|^{-2} (m_N / 1 \text{ GeV})^{-5.19}$$
$$m_N \sim 10 \text{ GeV}, |U|^2 \sim 10^{-5} \rightarrow c\tau_N \sim 1 \text{ mm}$$

\rightarrow long lived neutral leptons

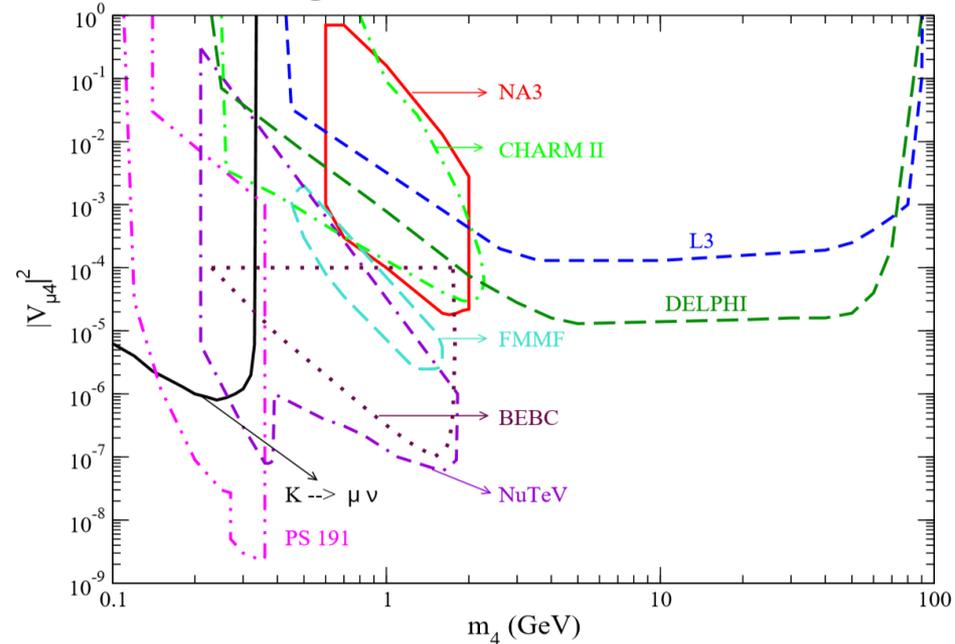


- Limits on right handed neutrino mass m_4 and mixing $|V_{\ell 4}|^2$
- [arXiv:0901.3589 \[hep-ph\]](https://arxiv.org/abs/0901.3589)
- DELPHI results ([Z. Phys. C74 \(1997\) 57-71](https://doi.org/10.1007/s00381-000-0057-1)) give the best limits for $m_4 > 2$ GeV.

Mixing with electron neutrino

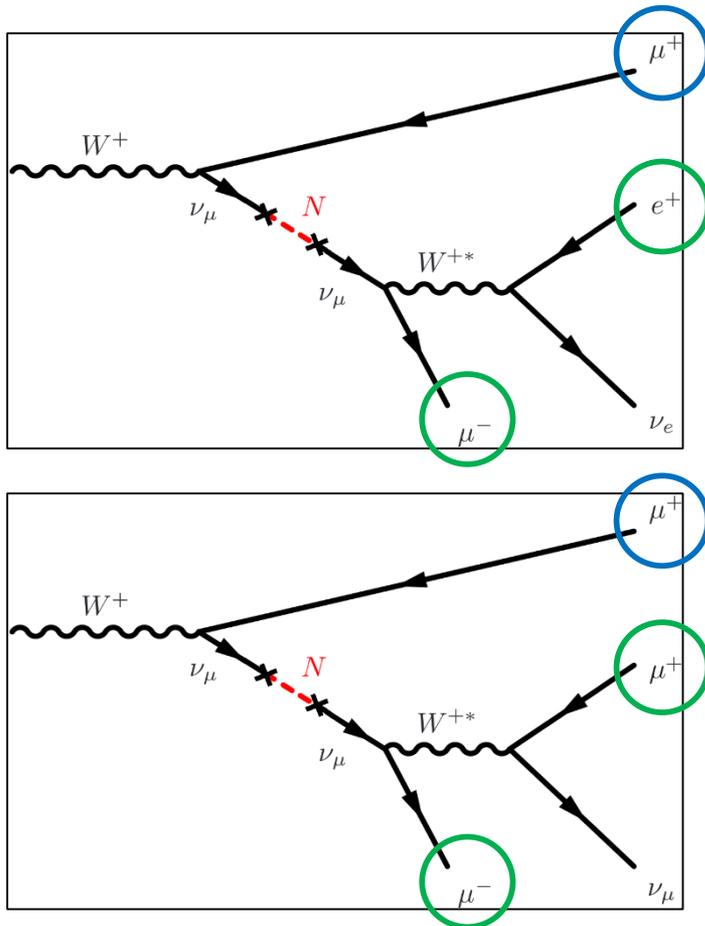


Mixing with muon neutrino

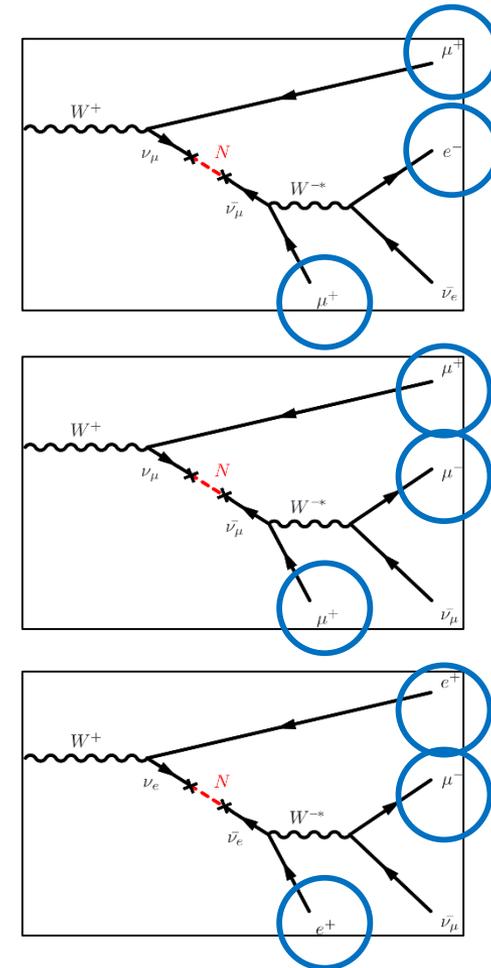


- [arXiv:1905.09787 \[hep-ex\]](https://arxiv.org/abs/1905.09787), [EXOT-2017-26](https://arxiv.org/abs/1702.02368)

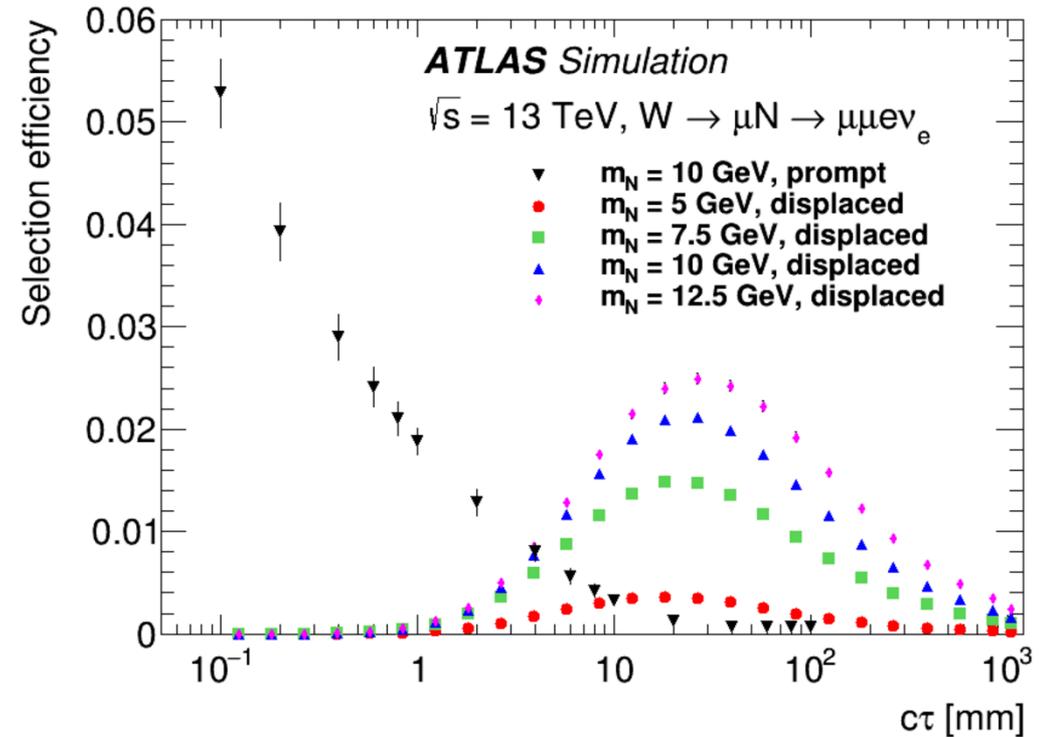
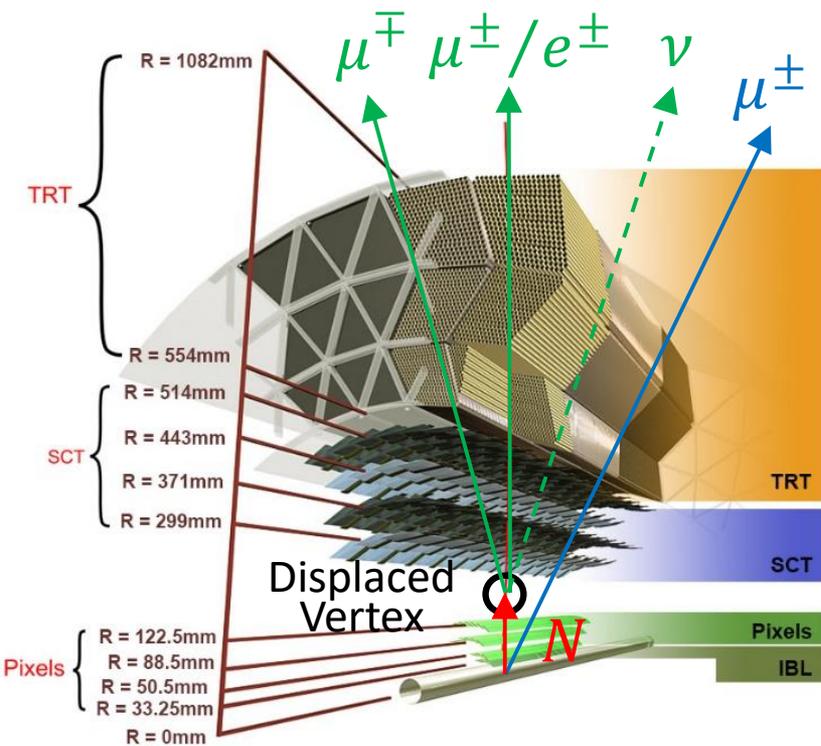
Displaced signature not assuming lepton number violation



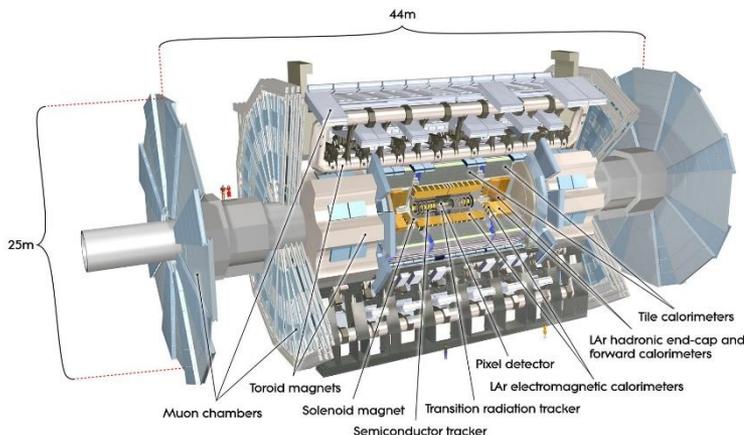
Prompt signature assuming lepton number violation



Latest ATLAS search (2)

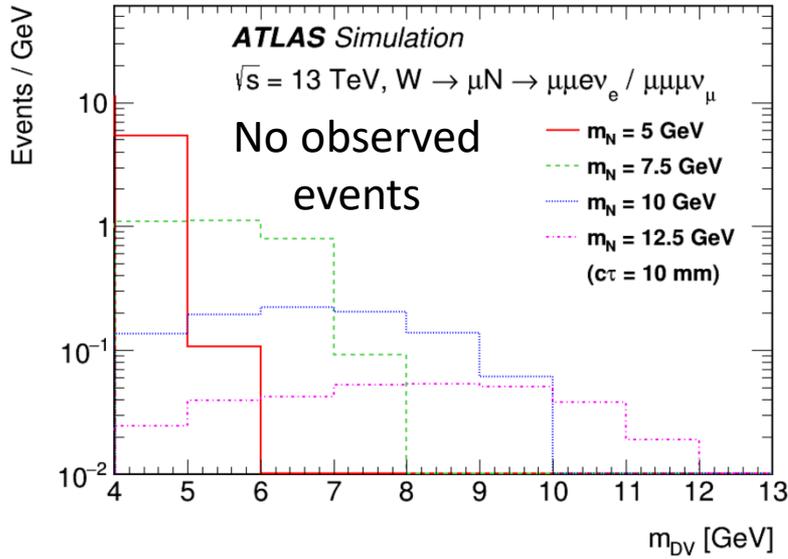


- Large mixing \rightarrow short lifetime and large branching fraction
 - Prompt signature is better.
- Small mixing \rightarrow long lifetime and small branching fraction
 - Displaced signature is better.
 - Limited by ATLAS detector volumes.

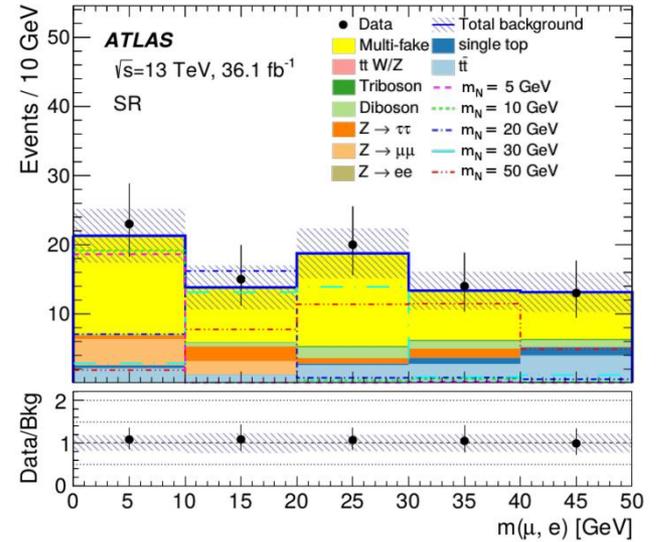


Latest ATLAS search (3)

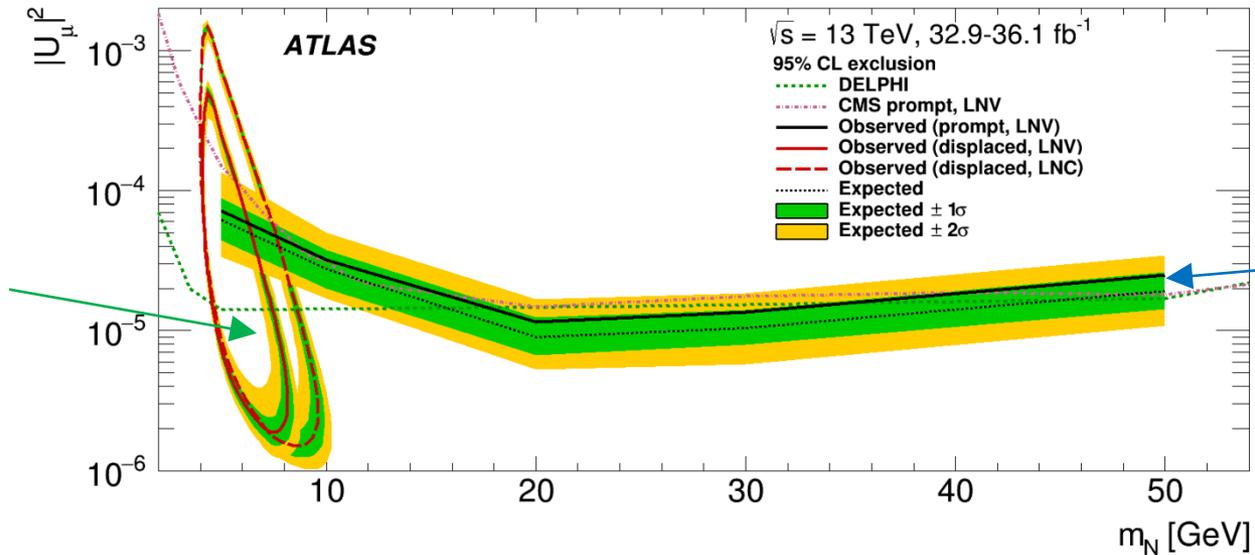
Displaced signature



Prompt signature



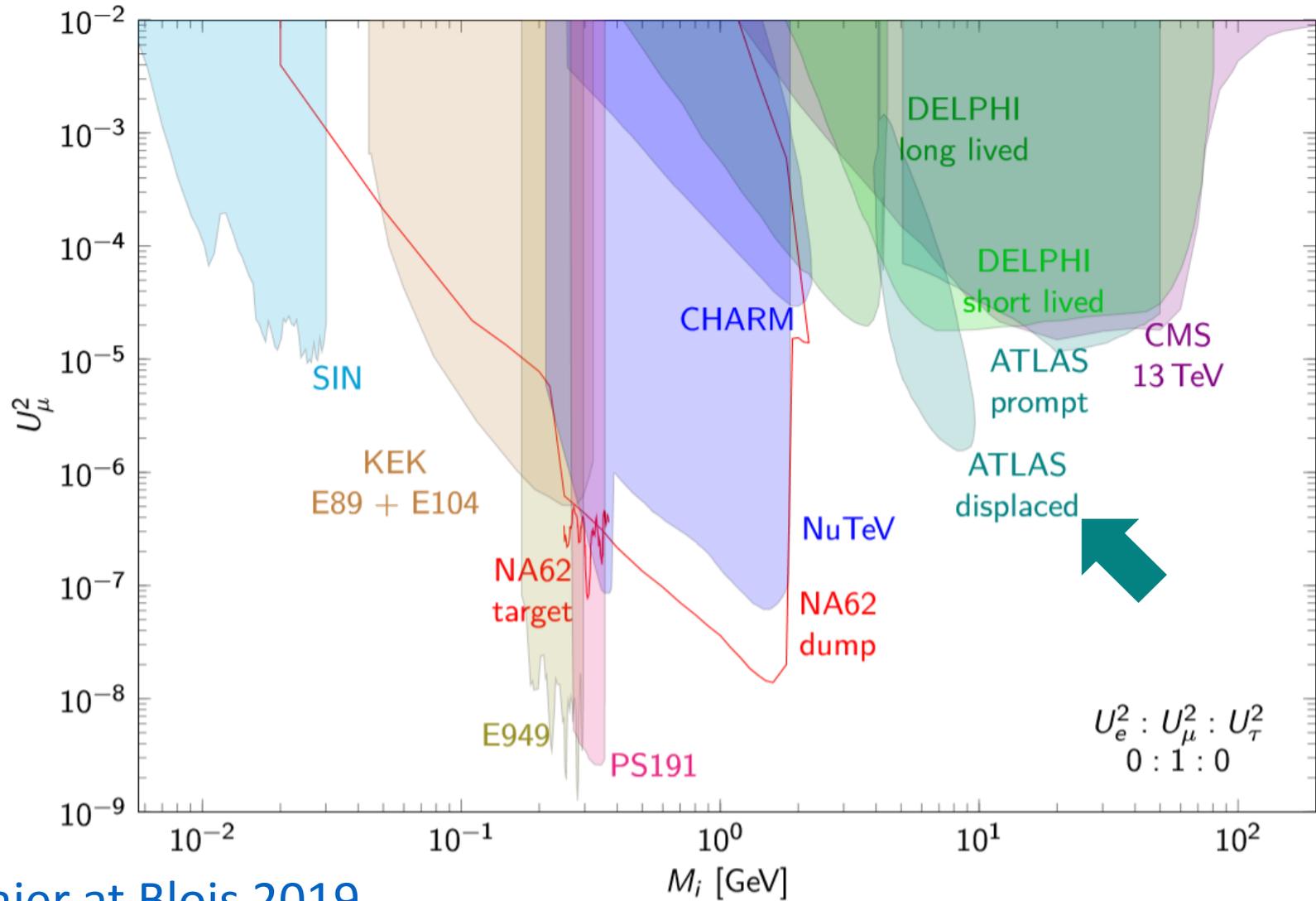
Displaced signature



Prompt signature

Compilation of latest results

pure U_μ^2



11/13 Possible improvements of displaced signature (1)

- More integrated luminosity.
 - 32.9 fb^{-1} (only 2016) $\rightarrow 140 \text{ fb}^{-1}$ (2015-2018)

- Use prompt electrons as well.

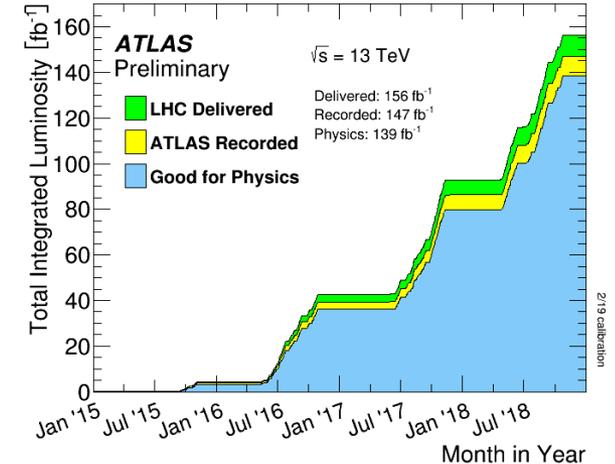
- $W^\pm \rightarrow \mu^\pm \mu^\mp \ell^\pm \nu_\ell$
- $W^\pm \rightarrow e^\pm e^\mp \ell^\pm \nu_\ell$

- Tracking dedicated to this analysis

- A displaced vertex with two leptons with opposite signs
- Since background is limited, we can relax selection criteria to increase efficiency and sensitivity.

- Backgrounds

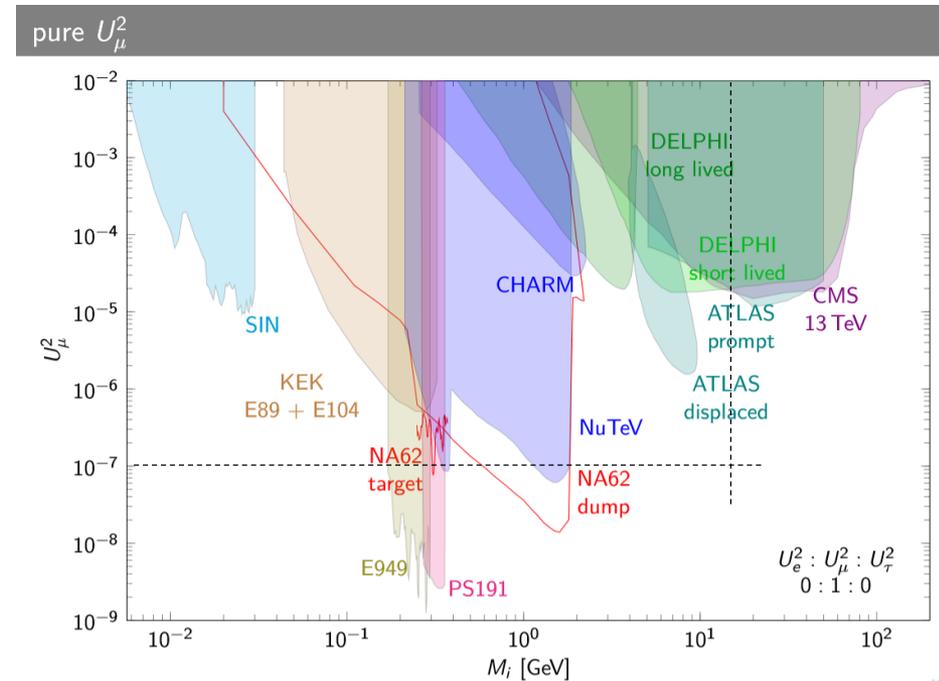
- Random track crossing
 \rightarrow (a modified) ABCD method
- Hadron interaction
- Meta stable particles
- Cosmic ray muons



Num. of leptons	Same sign	Opposite sign
2	$N(1 - \epsilon_{OS})\epsilon_\ell^2$	$N\epsilon_{OS}\epsilon_\ell^2$
1	$2N(1 - \epsilon_{OS})\epsilon_\ell(1 - \epsilon_\ell)$	$2N\epsilon_{OS}\epsilon_\ell(1 - \epsilon_\ell)$
0	$N(1 - \epsilon_{OS})(1 - \epsilon_\ell)^2$	$N\epsilon_{OS}(1 - \epsilon_\ell)^2$

12/13 Possible improvements of displaced signature (2)

- Use of transverse mass m_T
 - A prompt lepton + two displaced leptons + missing E_T (displaced neutrino)
 - Jacobian peak of W boson for background rejection
- Systematics evaluation
 - Tracking and vertexing
 - $K_S^0 \rightarrow \pi^+ \pi^-$
 - $B^\pm \rightarrow K^\pm J/\psi (\rightarrow \mu^+ \mu^-)$
 - Displaced electrons
 - $\gamma \rightarrow e^+ e^-$
 - Displaced muons
 - Cosmic ray muons

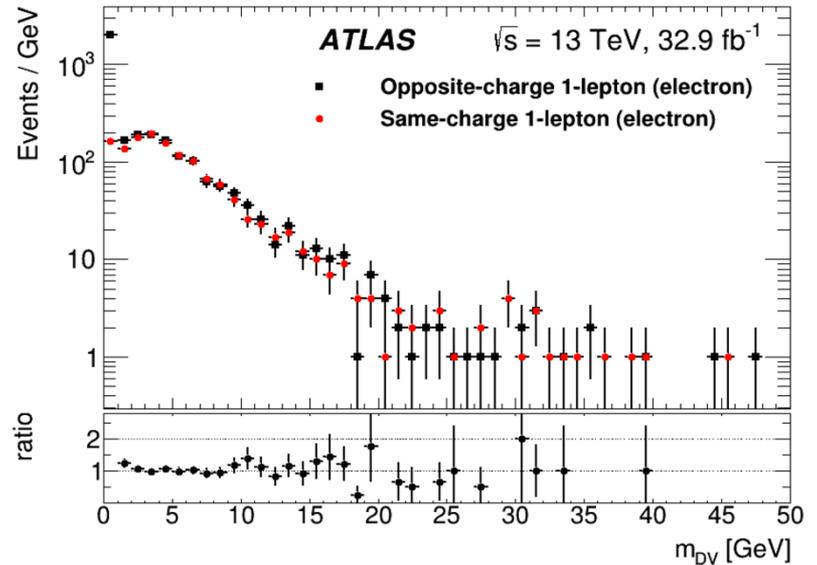
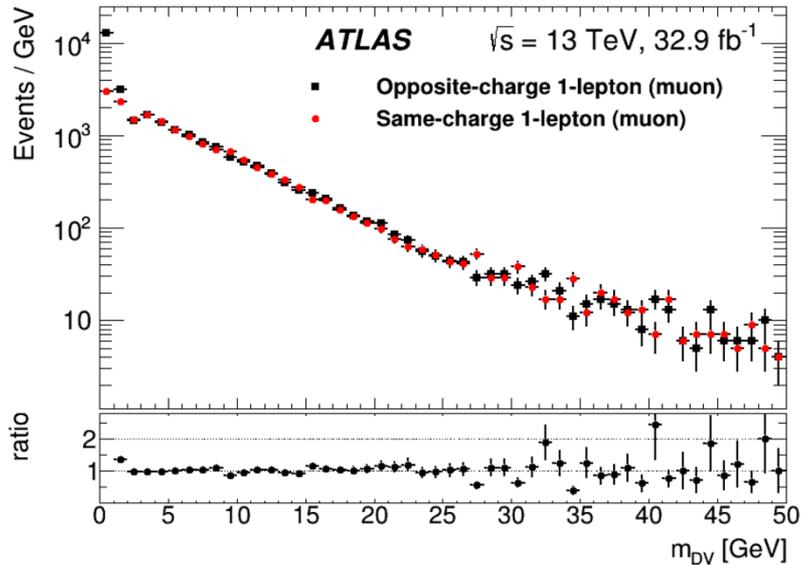
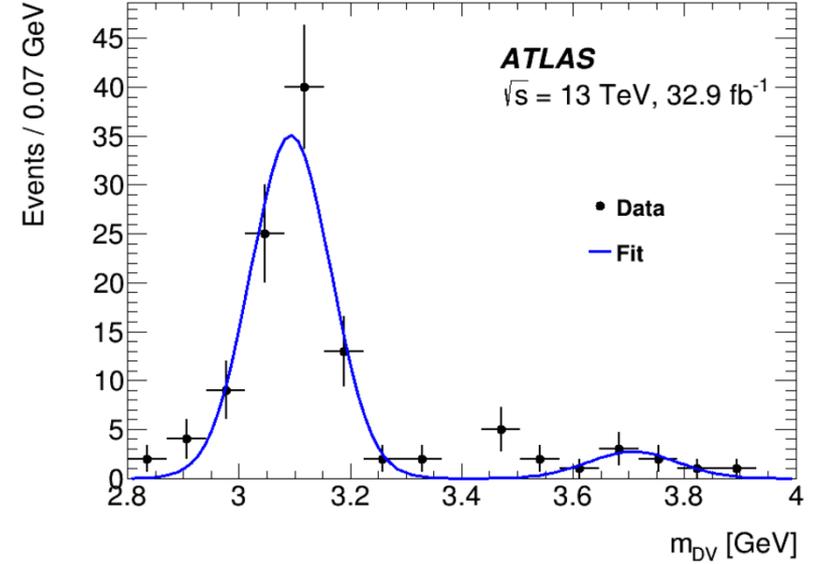
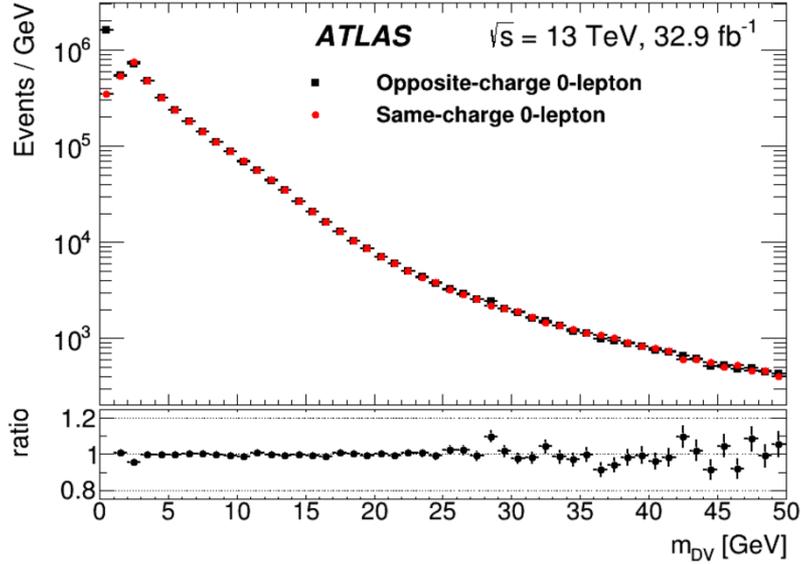


- I naively expect limits will be $m_N < 15$ GeV and $|V_{\ell N}|^2 > 10^{-7}$.

Summary

- Neutrino Minimal Standard Model (ν MSM) can explain neutrino masses, asymmetry between matter and anti-matter, dark matter.
- Right-handed neutrinos of ν MSM have long lifetimes.
- Searches of right-handed neutrinos of ν MSM are high profile.
- LHC experiments have a unique opportunity to search right-handed neutrinos (N_2 and N_3) with $m_N > 5$ GeV.
- Latest ATLAS search set the best limit around $m_N \sim 8$ GeV.
 - [arXiv:1905.09787 \[hep-ex\]](https://arxiv.org/abs/1905.09787)
- We should be able to largely improve the limit (or discover signals) with more statistics and tuned analysis.

$^{15/13}$ Displace vertex mass distributions



Background estimation

Table 6: Observed number of events in the control and validation regions used for evaluating the backgrounds in the displaced HNL signature, including all sources of background except for single cosmic-ray muons reconstructed as back-to-back muons and metastable particles. Transfer factors to translate the number of 0-lepton DVs to 2-lepton DVs are obtained using a same-charge DV control sample. Validation is performed using 1-lepton DVs. The number of events in the signal and validation regions is also indicated.

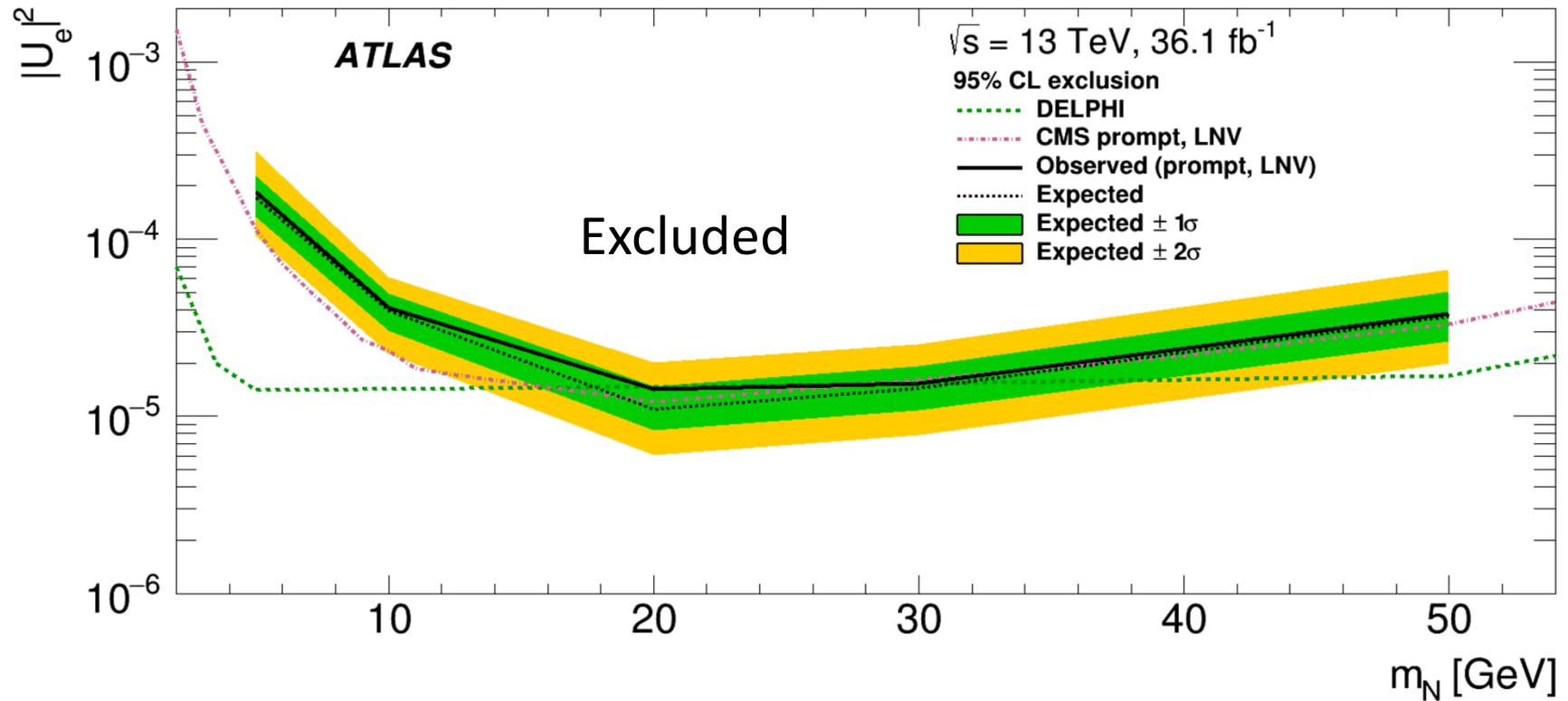
Leptons in DV	Same-charge DV	Opposite-charge DV	Opposite-charge DV estimated
2	0	0 (signal region)	< 2.3 at 90% CL
1 (μ)	83	89	82.4 \pm 9.0
1 (e)	28	35	27.8 \pm 5.3
0	169254	168037	

No. of leptons	Same charge	Opposite charge
2	B	A
1	B'	A'
0	D	C

$$A_{\text{est}} = B \cdot (C/D)$$

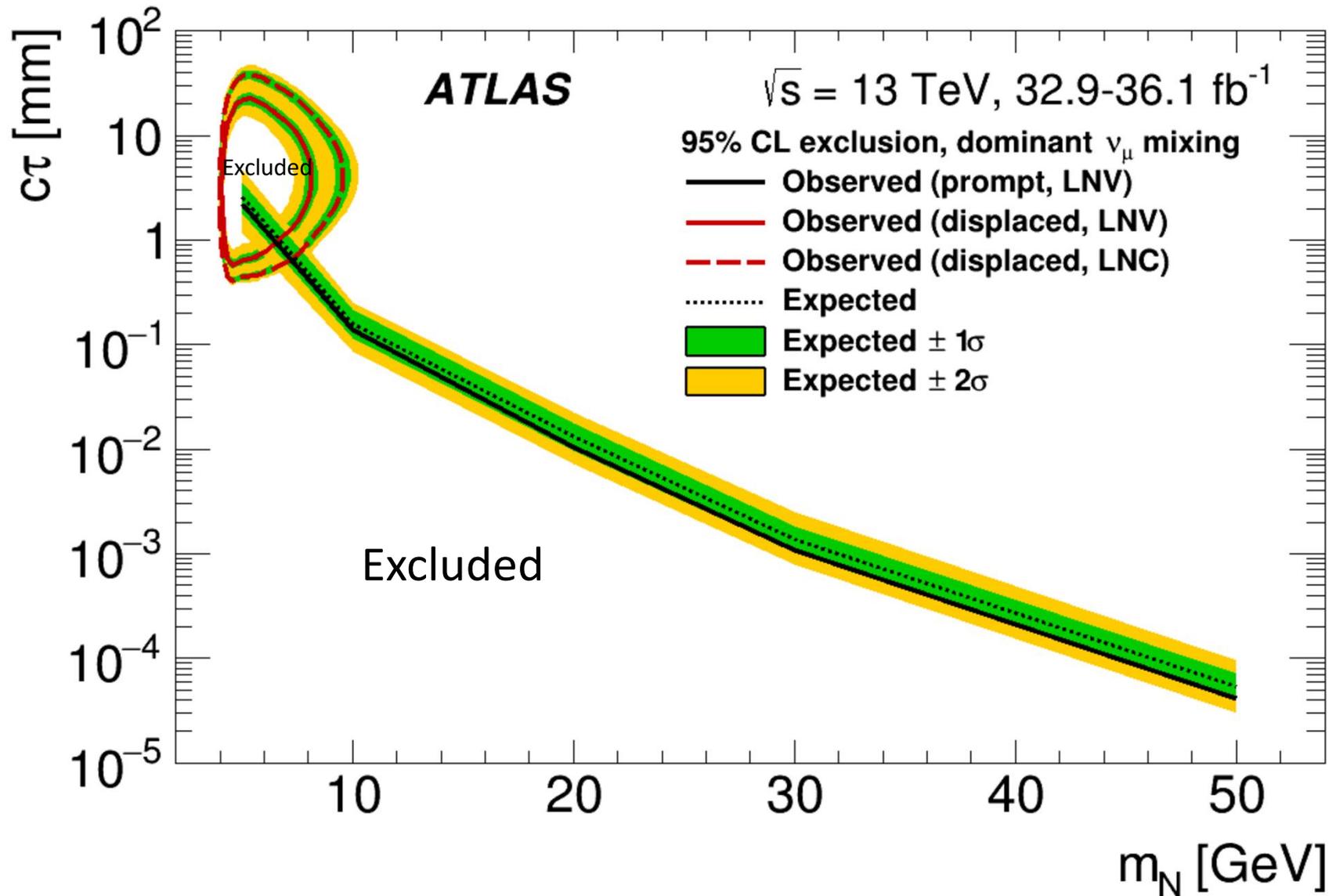
$$A'_{\text{est}} = B' \cdot (C/D)$$

Mixing with electron neutrino



- CMS : [arXiv:1802.02965](https://arxiv.org/abs/1802.02965) [hep-ex]

Mixing with muon neutrino



Relevant systematic uncertainties that can affect the signal efficiencies (with relative magnitude in between parentheses) include uncertainties in the efficiencies for the prompt-lepton reconstruction and identification (1%), displaced track and DV reconstruction (15%), displaced-lepton identification (5%), as well as uncertainties in the modelling of lepton kinematic distributions and individual decay branching ratios (10%), in the modelling of multiple pp interactions in the bunch crossing (10%), and due to MC statistical uncertainties (10%). To evaluate the dominant 15% uncertainty due to the modelling of displaced tracks and DV reconstruction, a sample of K_S^0 mesons is selected from two-pion vertices in the invariant mass window 488–508 MeV. The rate of K_S^0 reconstruction is parameterised as a function of the sum of the p_T of the two tracks ($\sum p_T$) and the radial distance (r_{DV}). In each window of $\sum p_T$ and r_{DV} , the efficiency is obtained by dividing the event yield by the expected exponentially falling distance distribution, and a weight is computed as the ratio between measured and simulated efficiencies. These weights are normalised to be equal to one at small radii and then used to reweight the DV efficiencies in the signal samples, and a relative difference of 15% is found as the maximum effect in the final selection efficiency. In addition, uncertainties in the W boson production cross section (3%) and the integrated luminosity (2.2%) are taken into account for the interpretation. The total systematic uncertainty, with all contributions added in quadrature, is 24%.