Detection of Neutral Long-lived Particles from Accelerator-based Experiments

Xabier Marcano

(on behalf of Marta Losada)

Laboratoire de Physique Théorique d'Orsay

xabier.marcano@th.u-psud.fr

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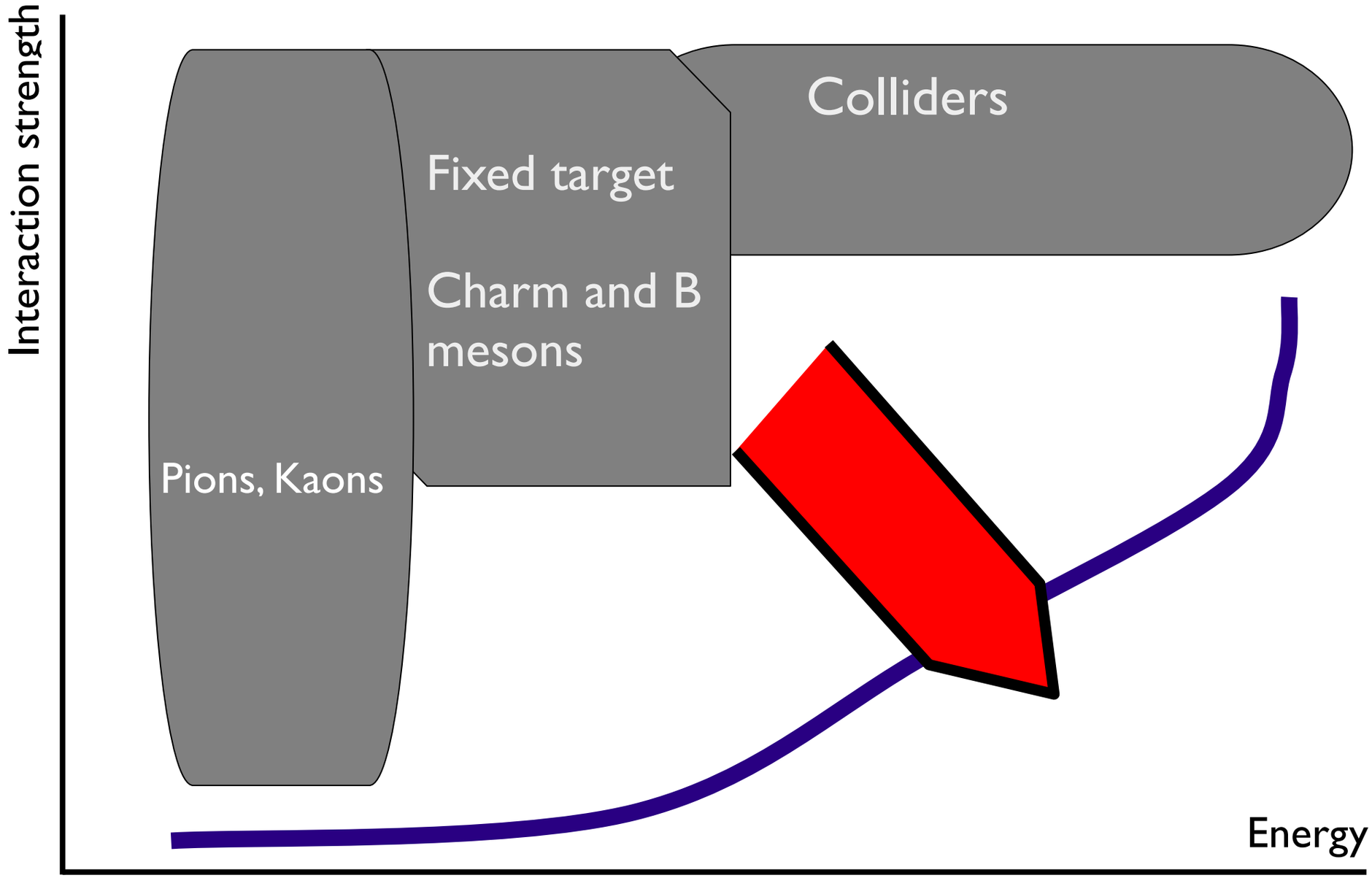
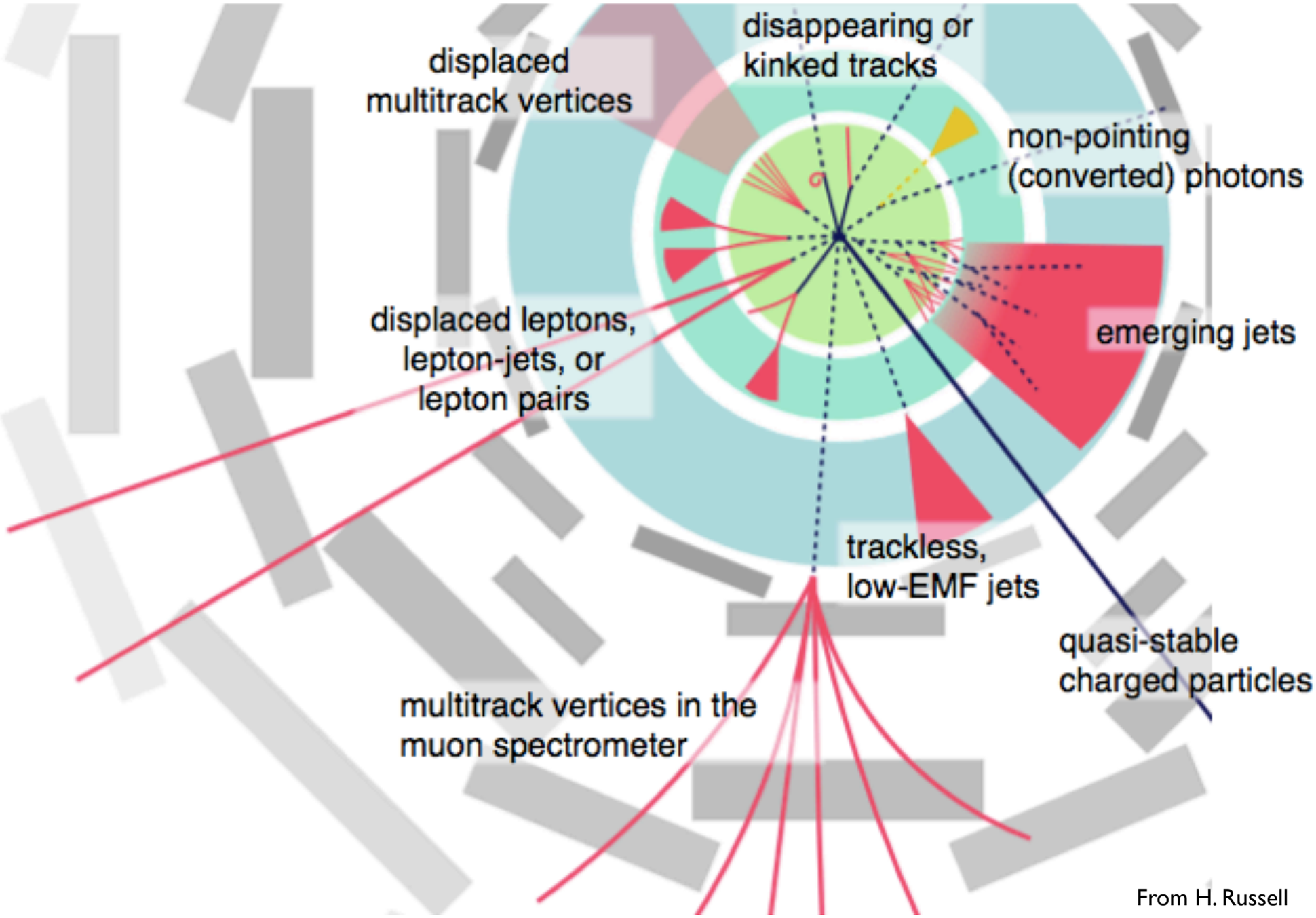
What is the NP scale?

Which experiment can probe where?



- Energy ranges that have been covered by accelerator experiments seem to imply the NP is weakly coupled.
- Search for very weakly coupled NP, and in particular for new long lived particles.

Colliders: LLP decay modes and signatures



From H. Russell

Intermediate lifetimes

LLP LHC White paper.

Some significant LHC LLP analysis

See R. Rosten and A. Soffer's talks at LLP WKSP May

Search	arXiv
Disp (& prompt) heavy neutral leptons	1905.09787
Displaced hadronic (CalRatio) jets	**1902.03094**
Heavy charged LLPs	**1902.01636**
Displaced vertex + displaced muon	CONF-2019-006
Multi-charged LLPs	1812.03673
Muon vertex	1811.07370
Z + Displaced hadronic (CalRatio) jet	1811.02542

ATLAS

Search	arXiv
Delayed Jets	**EXO-19-001**
Disappearing Tracks	**SUS-19-005**
Displaced Jets	1811.07991

CMS

Also LHCb and Belle have done searches and can provide new interesting results with upgrades.

Basic ingredients

- Decay rate/total width of the LLPs
  - ➡ Mass of LLP
  - ➡ Interaction strength

- Experimental design
  - ➡ Production mechanism
  - ➡ Detector geometry (location, size…)

- Decay length: $L = \frac{p}{M} c\tau$

$$N_{\text{events}} = \mathscr{L} \int d\sigma(\text{SM} \to \text{LPP}) \times BR(\text{LPP} \to \text{SM}) \times P_N(L) \times \varepsilon_{\text{geo}}$$

Main challenges

New objects not suitable to standard defs and algorithms

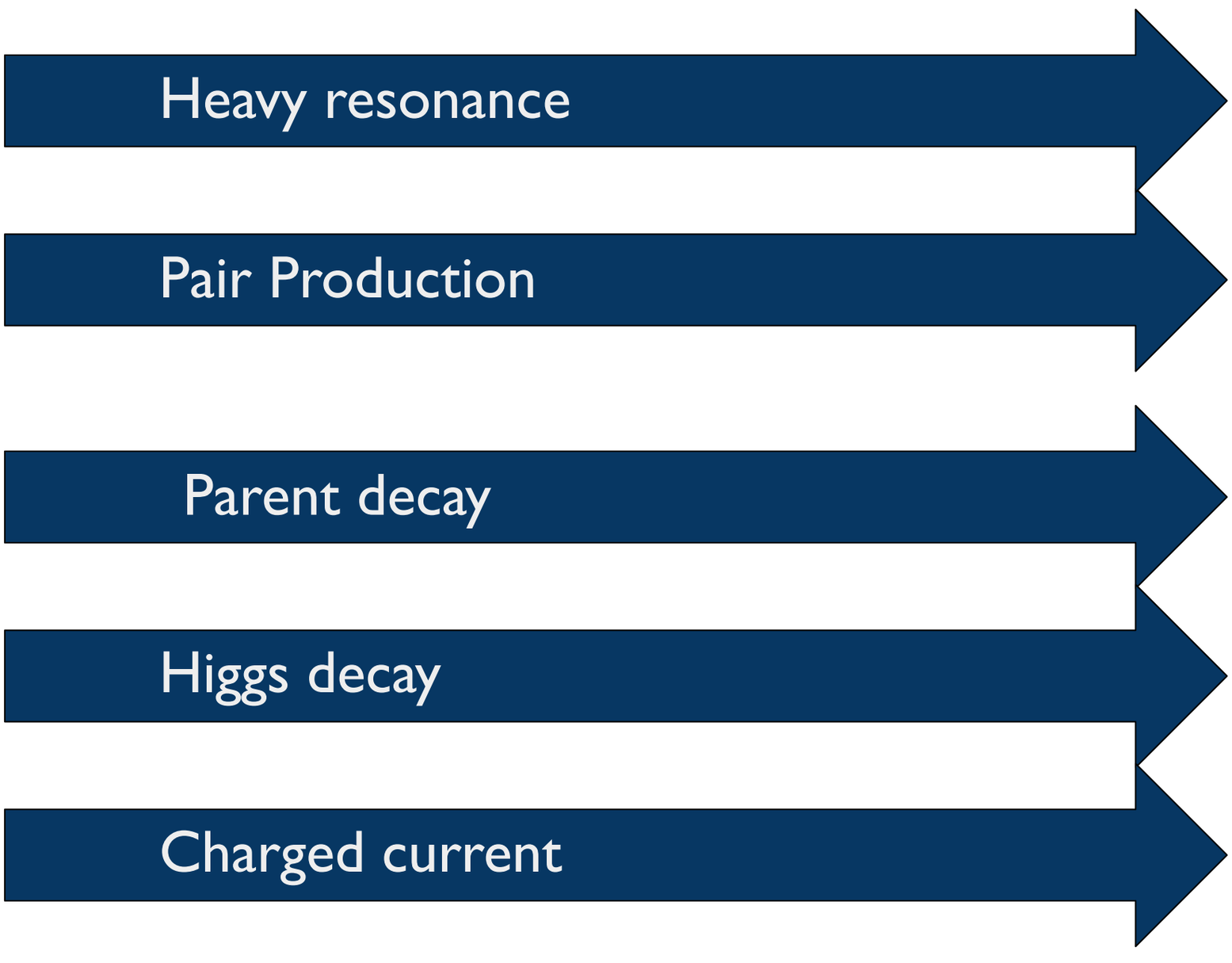
Unconventional backgrounds

requiring more data-driven techniques

Examples:

long lived particles in SM
hadronic detector interactions
particles from outside of collision
algorithmically induced fakes

Colliders: LLP Production



LLP LHC White paper.

LLP-typology

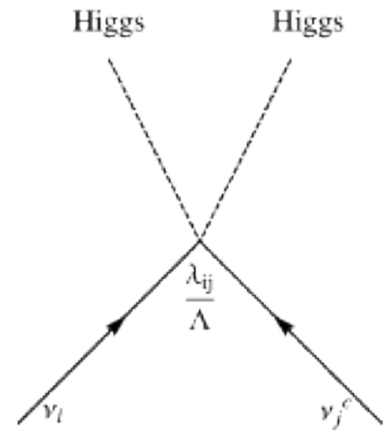
01	SUSY-like	• neutralinos, sleptons
02	Dark matter portal	• LDMs
03	Higgs portal	• dark scalar, dark photon
04	Gauge portal	• dark photon
05	Neutrino portal	heavy neutral lepton
06	ALPs	axion

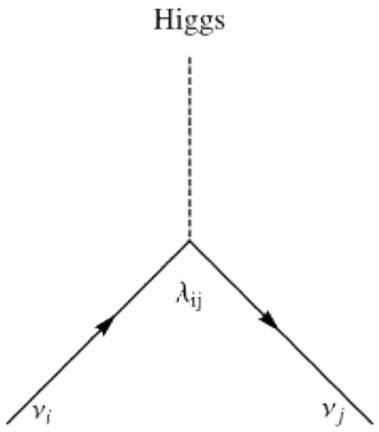
Why Heavy Neutral Leptons ?

Minimal neutrino mass models

$$-\mathcal{L}_{\text{Dirac}} = \bar{\nu}_L m_\nu \nu_R + h.c. \;\leftrightarrow \bar{L}\tilde{\Phi}\lambda\nu_R + h.c.$$

$$m_\nu \sim \lambda \frac{v^2}{\Lambda}$$





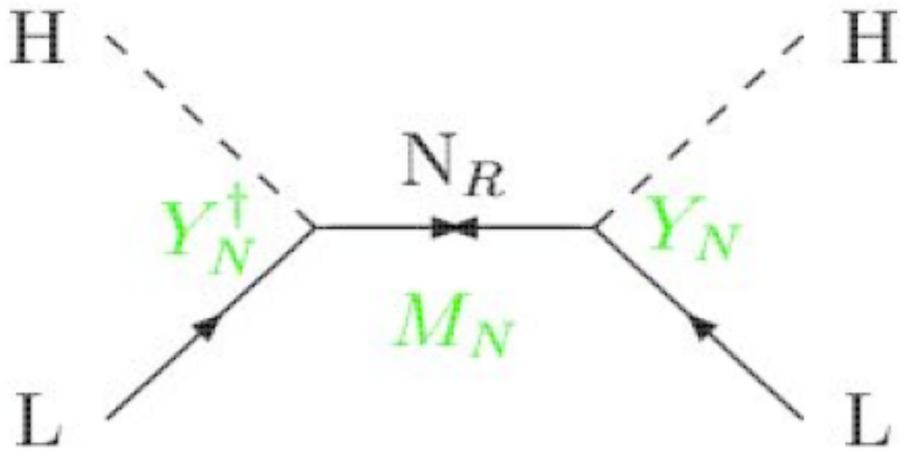
$$m_\nu \sim \lambda v$$

$$-\mathcal{L}_{\text{Majorana}} = \bar{\nu}_L m_\nu \nu_L^c + h.c. \;\leftrightarrow \bar{L}\tilde{\Phi}\ \alpha\ \tilde{\Phi} L^c + h.c.$$

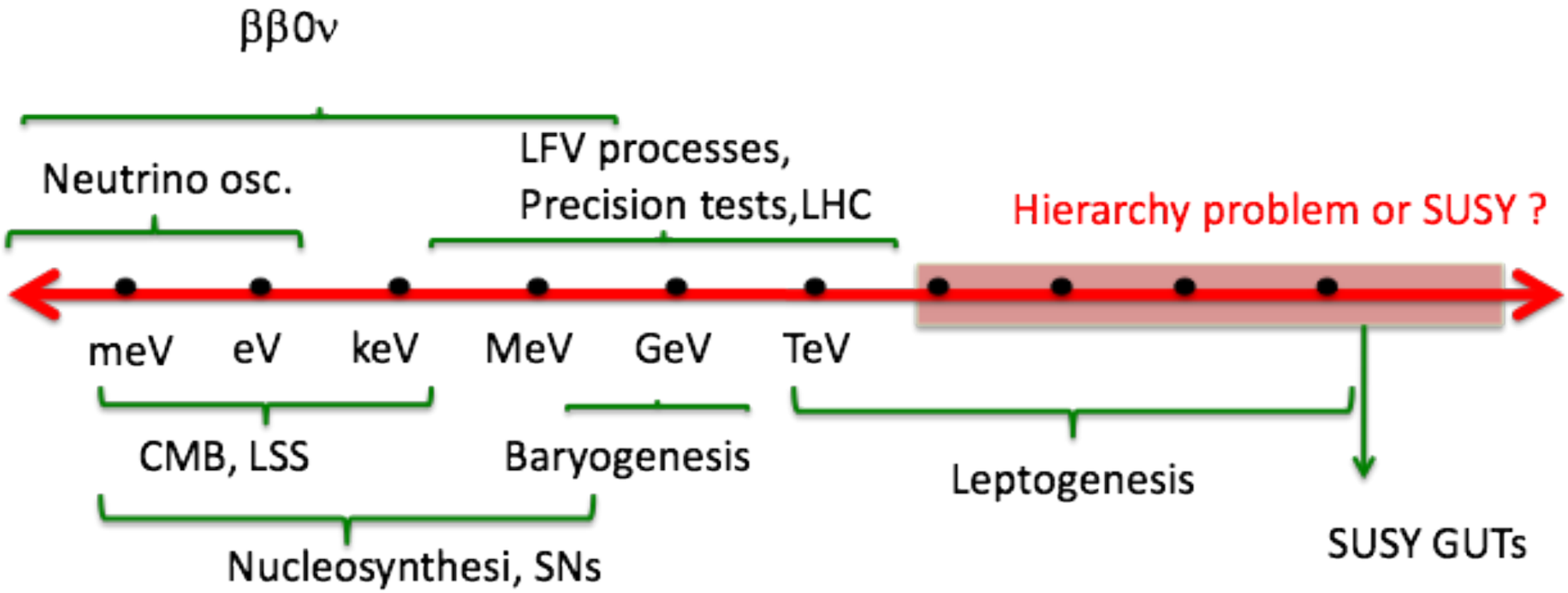
Seesaw Mechanism

$$\mathcal{L} = \mathcal{L}_{SM} - \sum^{n_R} \bar{l}_L^\alpha Y^{\alpha i} \tilde{\Phi} \nu_R^i - \sum^{n_R} \frac{1}{2} \bar{\nu}_R^{ic} M_N^{ij} \nu_R^j + h.c.$$

$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$



Physics from HNLs
Can we get to identify the NP scale?



Light Sterile Neutrinos White Paper, Abazajian et al arXiv: 1204.5379 and refs. therein

The basics for HNL in SM + N

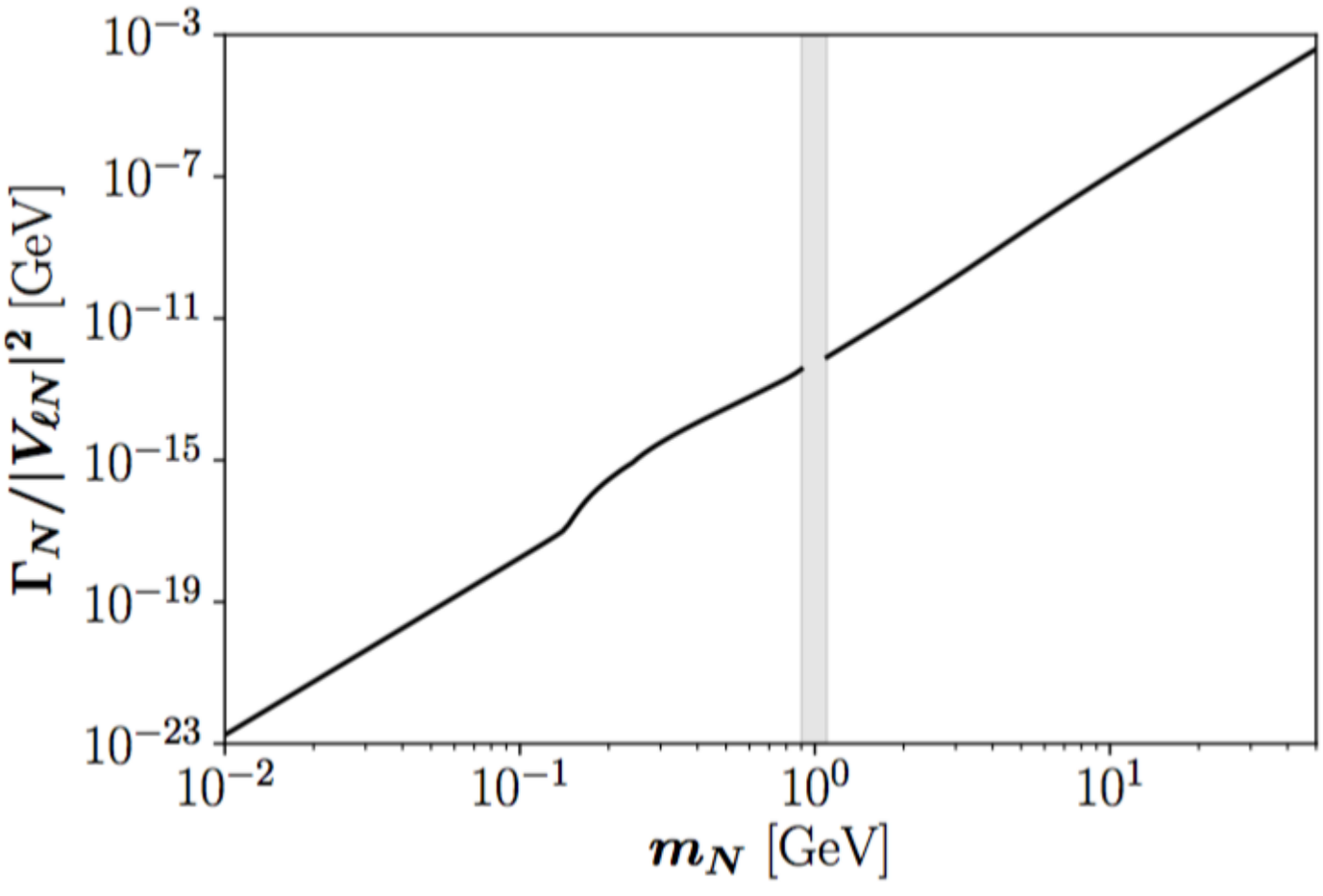
Width

$$\Gamma_N \propto G_F^2 \, m_N^5 \sum_{\ell = e,\mu,\tau} |V_{\ell N}|^2$$

Production

Decay

Length



The basics for HNL in SM + N

Width

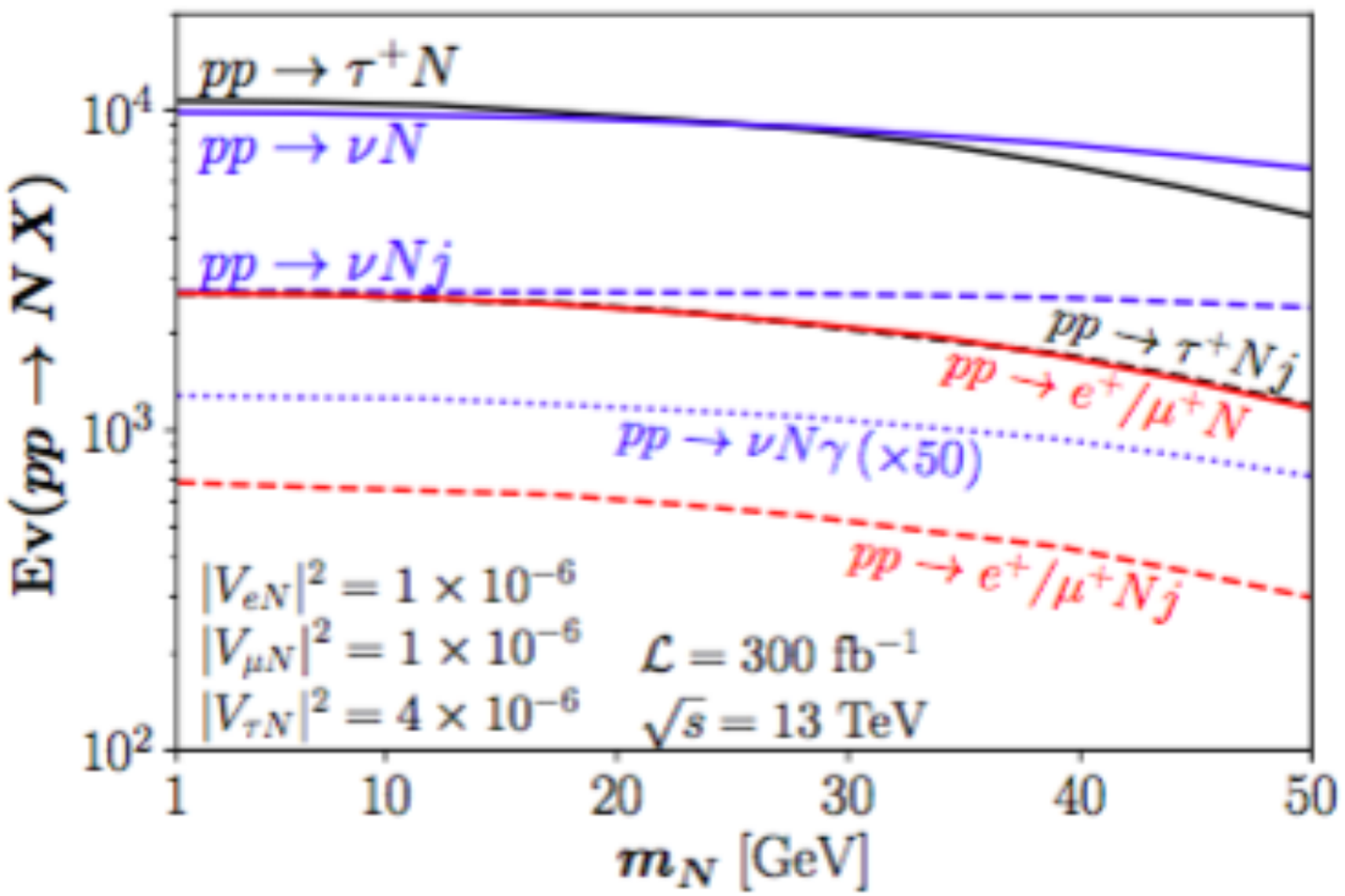
$$\mathrm{BR}_{W^\pm \to \ell^\pm N} \propto |V_{\ell N}|^2$$

$$\mathrm{BR}_{Z \to \nu N} \propto \sum_\ell |V_{\ell N}|^2, \quad \mathrm{BR}_{H \to \nu N} \propto \left(\frac{m_N}{m_W}\right)^2 \sum_\ell |V_{\ell N}|^2$$

Production

Decay

Length

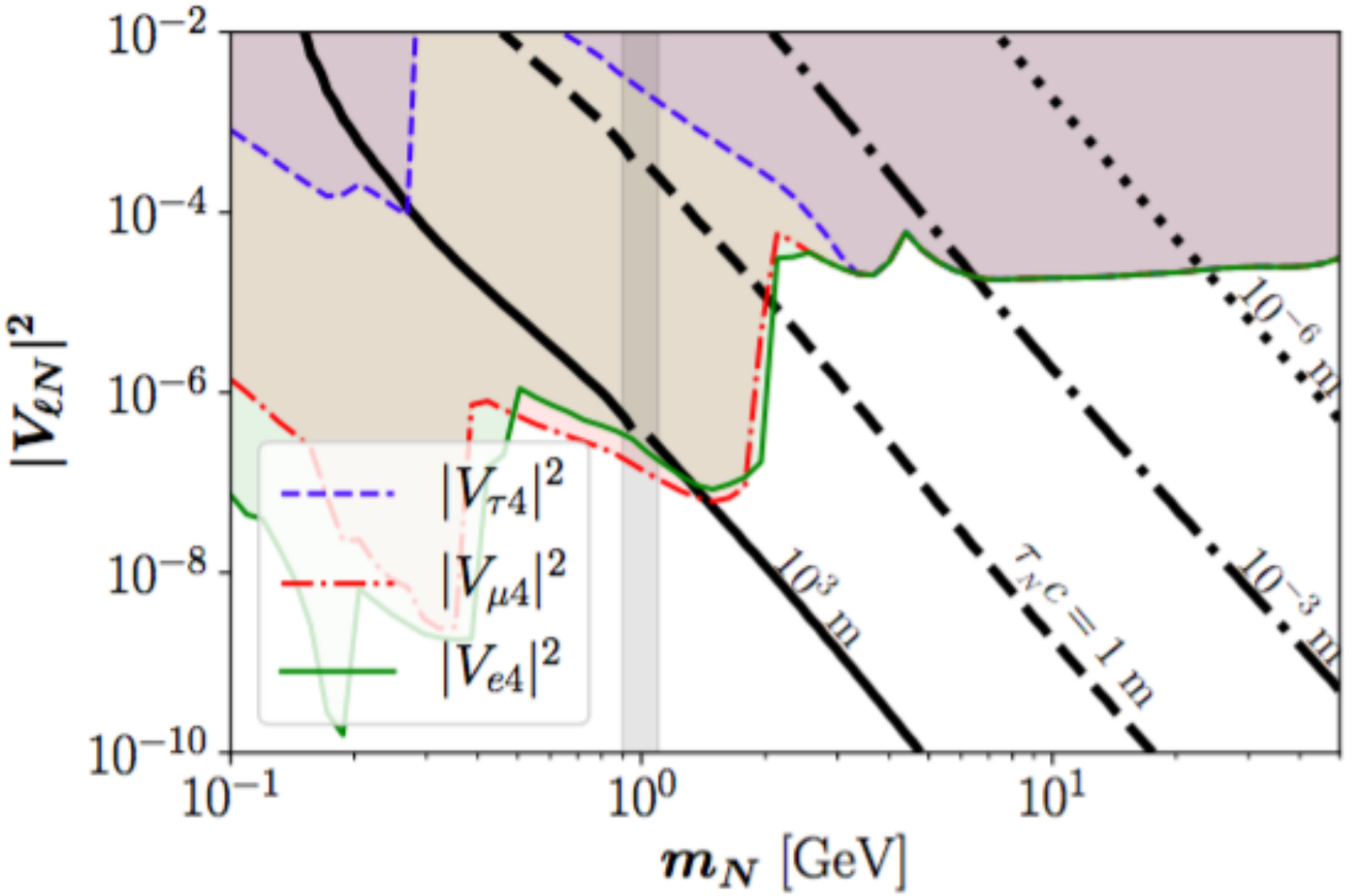


The basics for HNL in SM + N

Width

Production

Decay Length



The basics for HNL in SM + N

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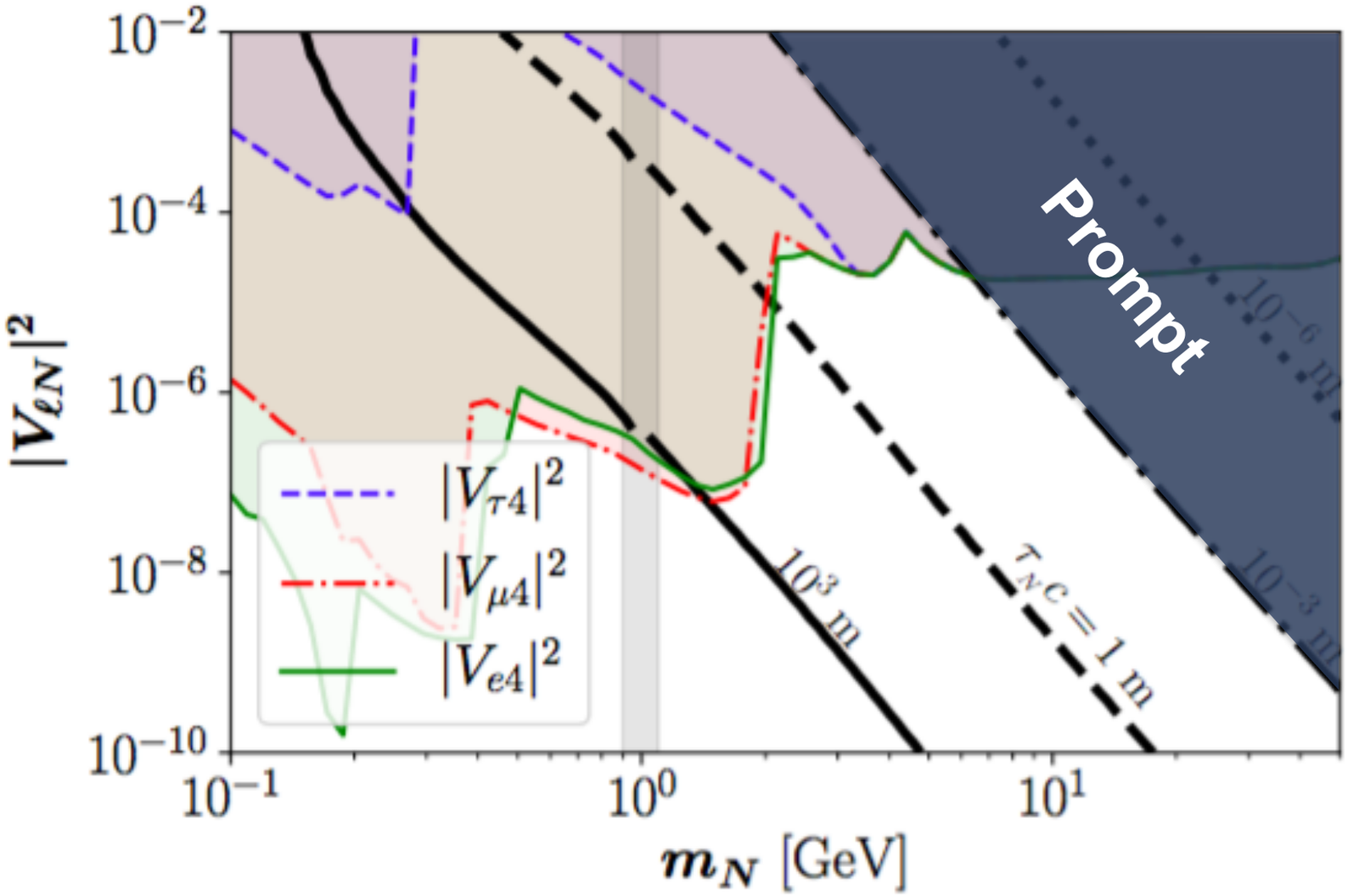
Production

Decay Length

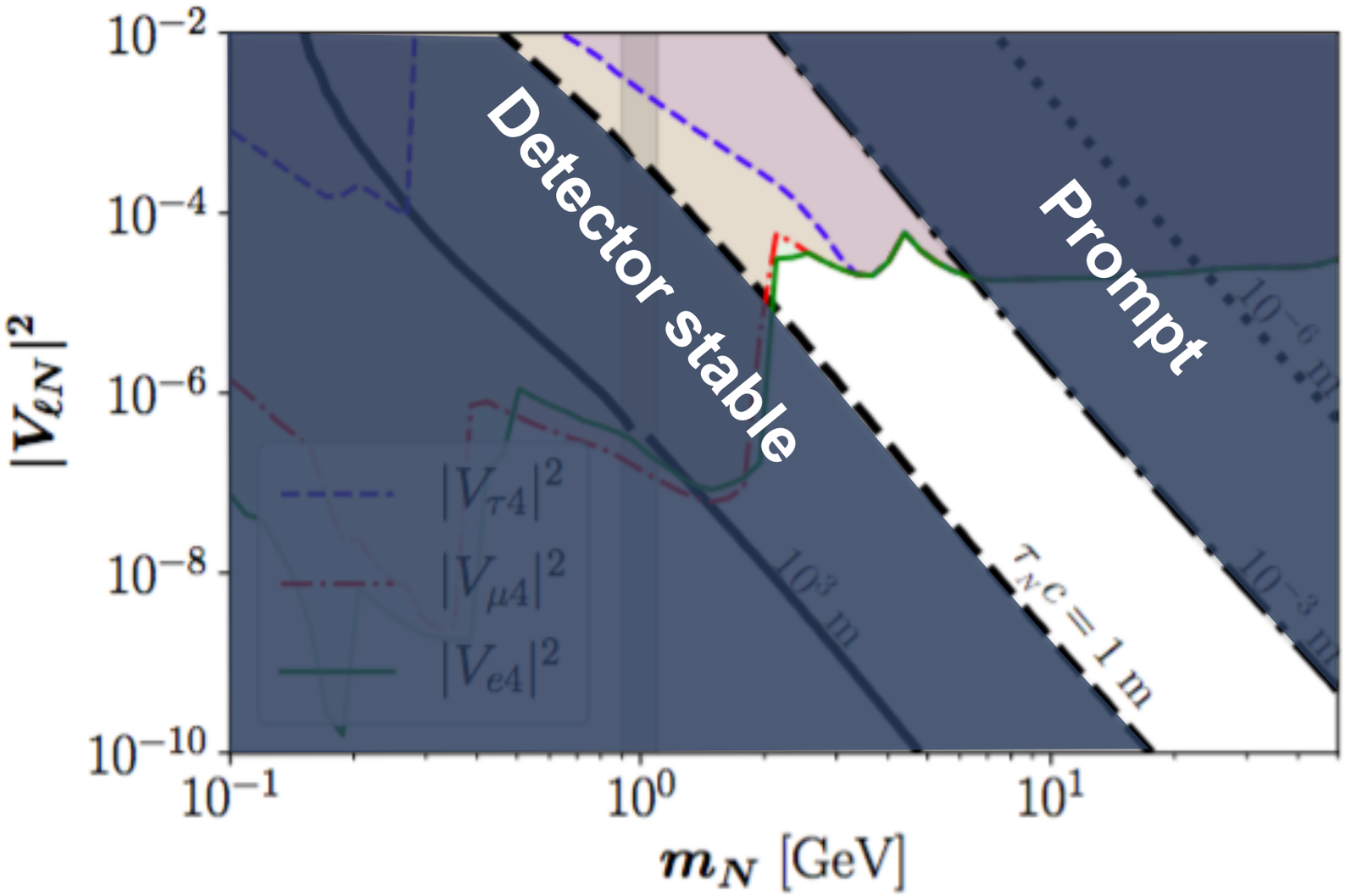


The basics for HNL in SM + N

Width

Production

Decay Length



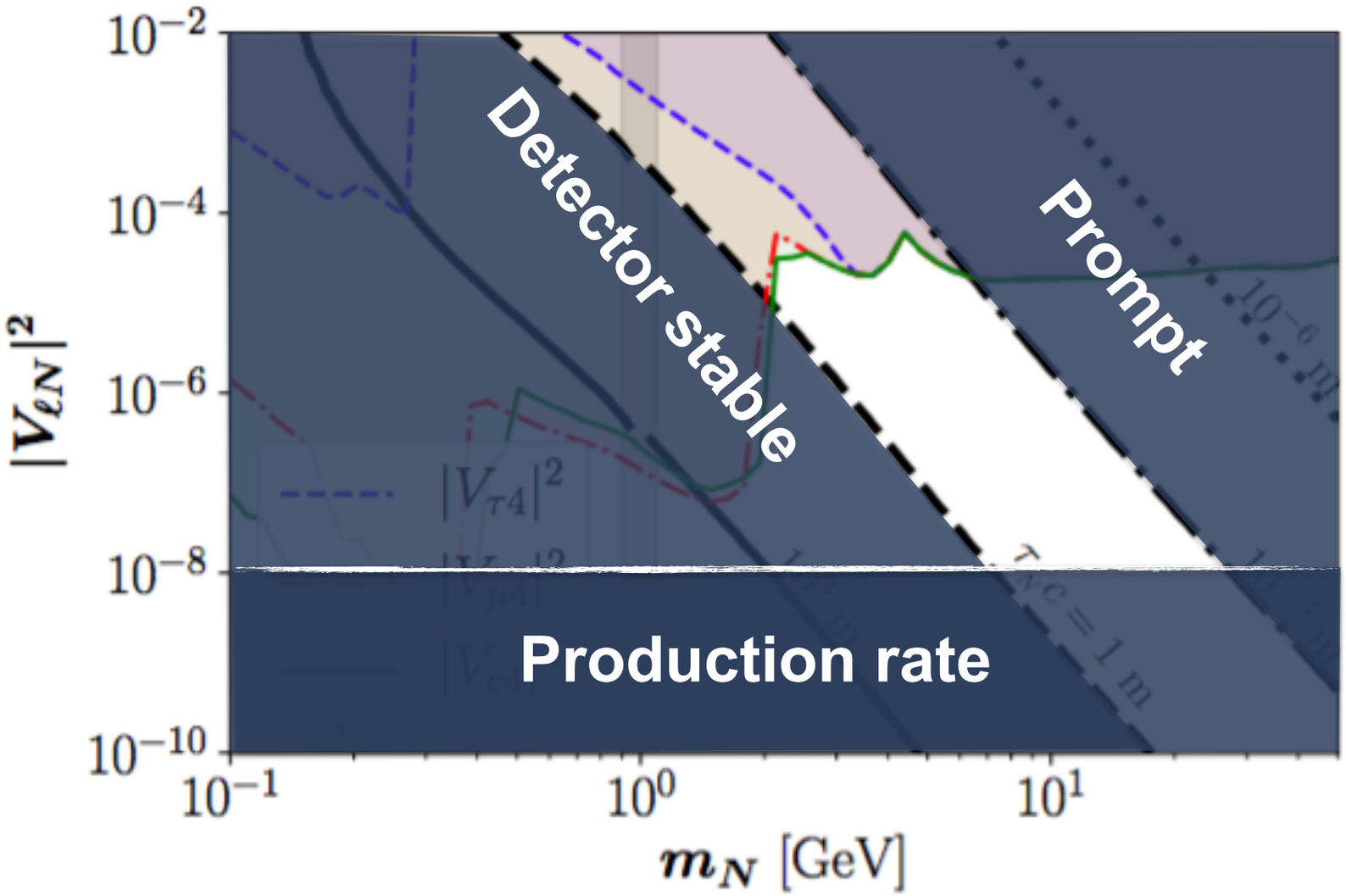
The basics for HNL in SM + N

Width

Production

Decay

Length



The basics for HNL in SM + N

Width

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Decay

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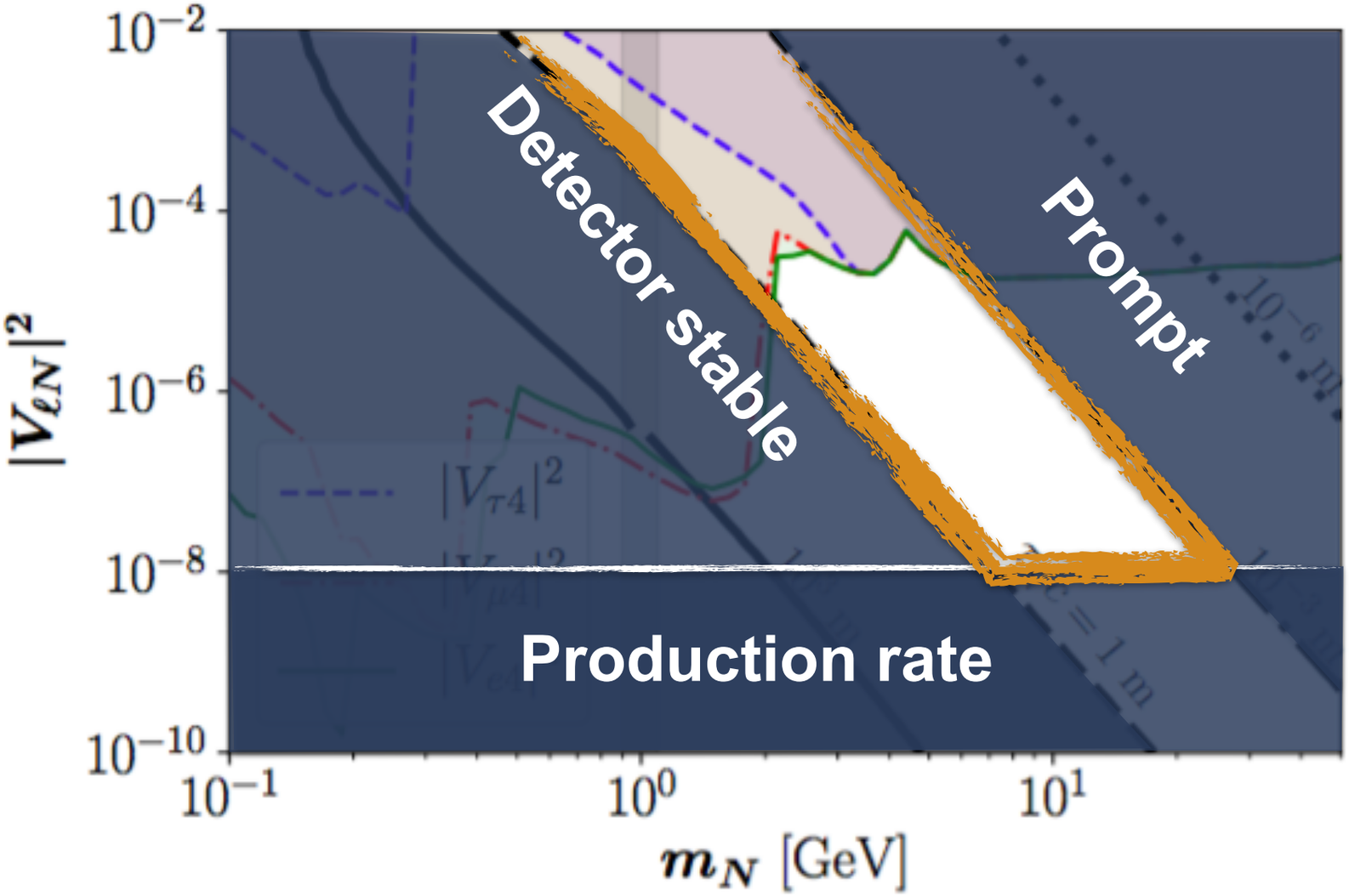
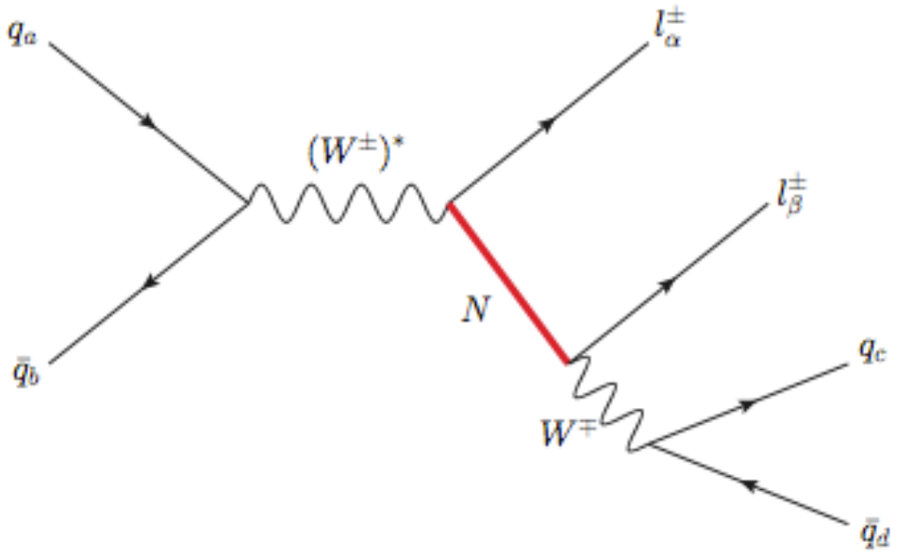
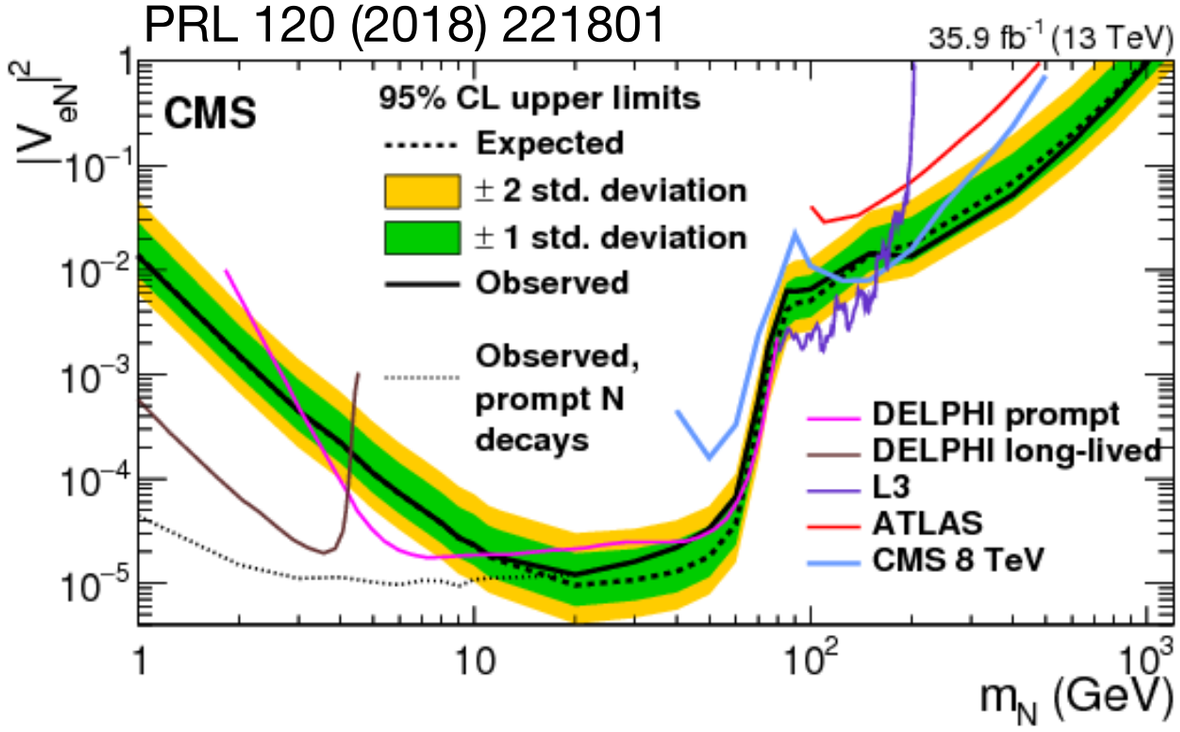
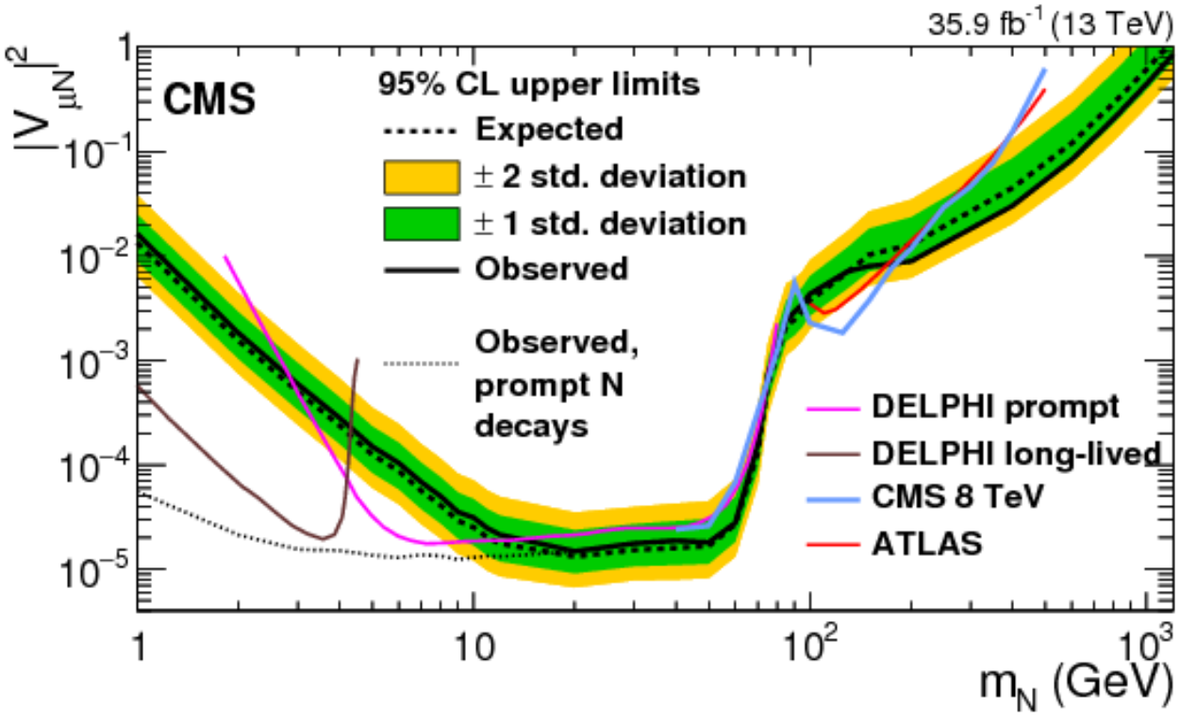




ATLAS, CMS searches
Type I Seesaw

PRL 120 (2018) 221801



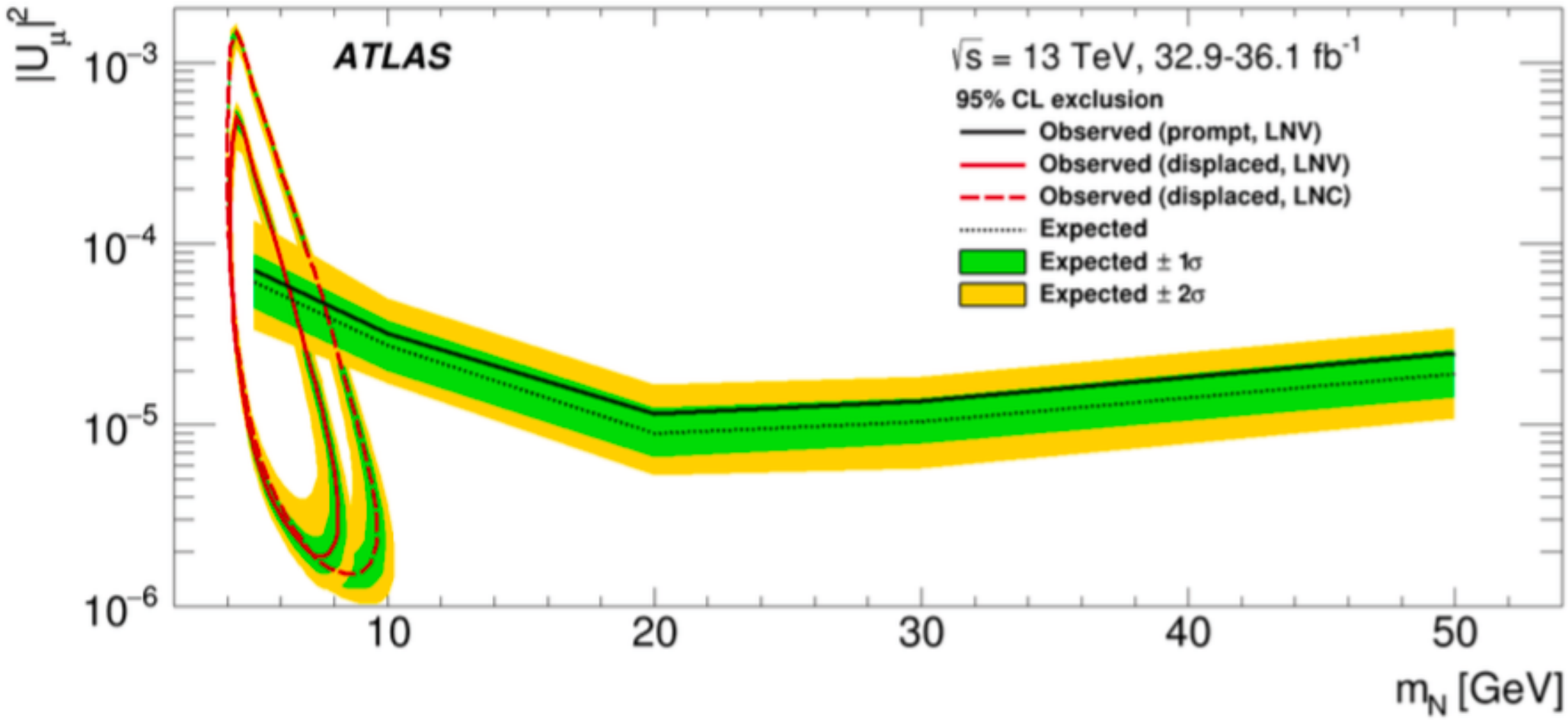


$M_N < M_W$

ATLAS DV

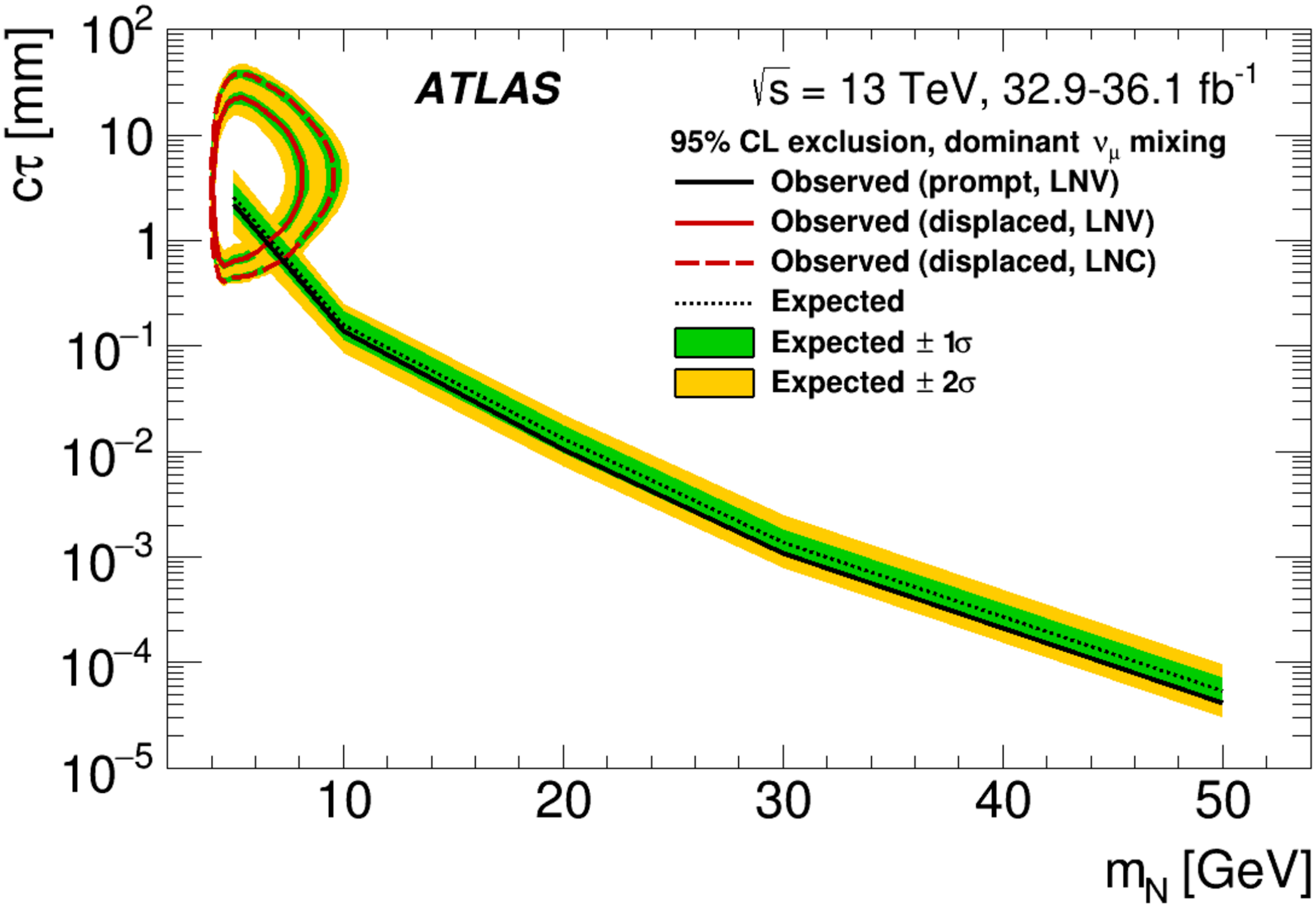
NEW

1905.09787



$W \rightarrow N\mu$

ATLAS DV


ATLAS
√s = 13 TeV, 32.9-36.1 fb-1
95% CL exclusion, dominant νμ mixing
Observed (prompt, LNV)
Observed (displaced, LNV)
Observed (displaced, LNC)
Expected
Expected ± 1σ
Expected ± 2σ
cτ [mm]
10^2
10
1
10^−1
10^−2
10^−3
10^−4
10^−5
10
20
30
40
50
m_N [GeV]

Beyond simplified assumptions

Higgs decays

Gago, Jones ,Hernández, Losada, Moreno [1505.05880]

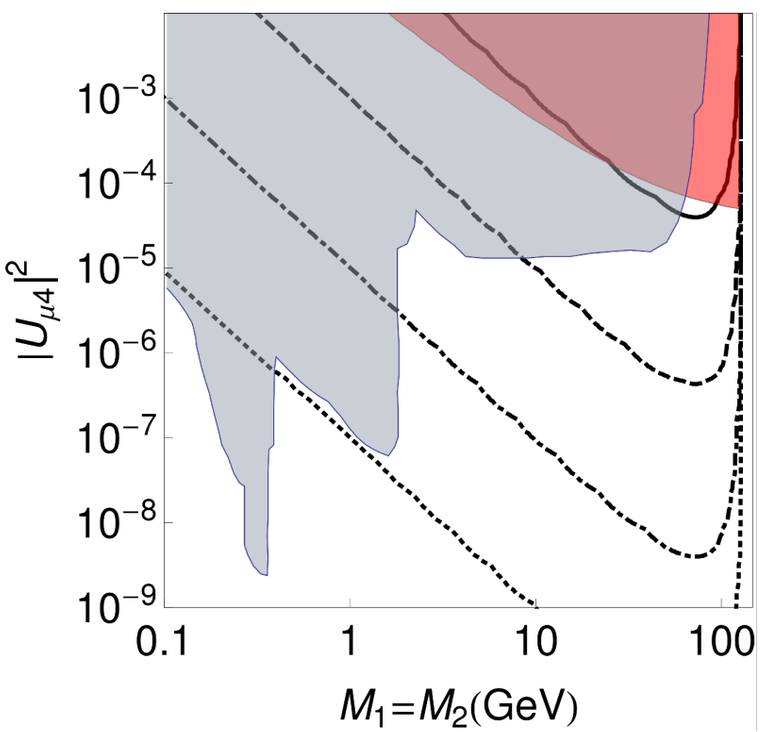
For L = 3000 fb^{-1}

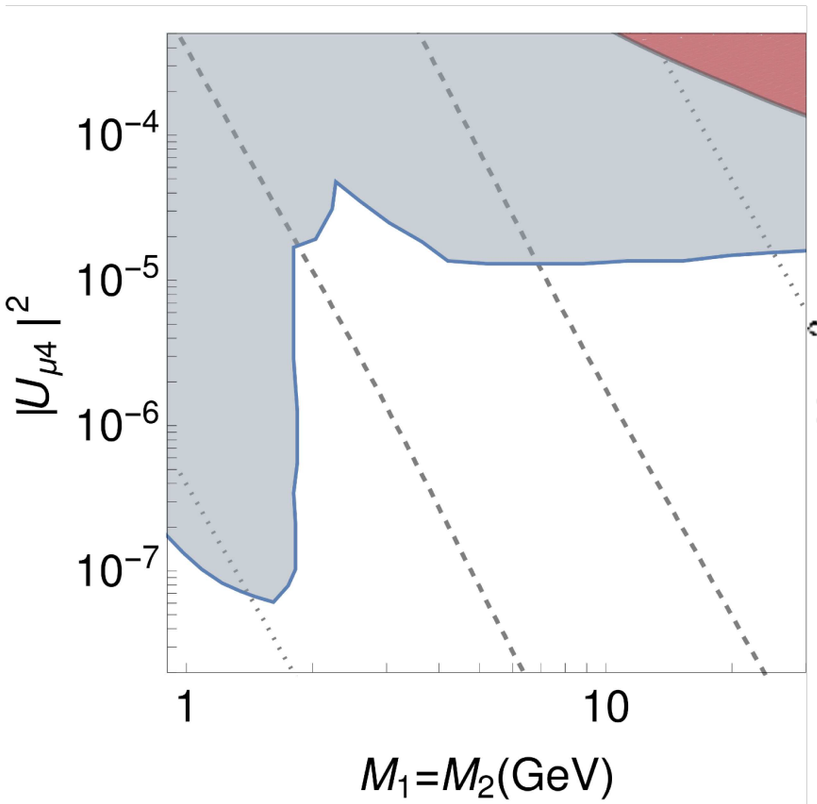
≋ 10^{11} W will be produced

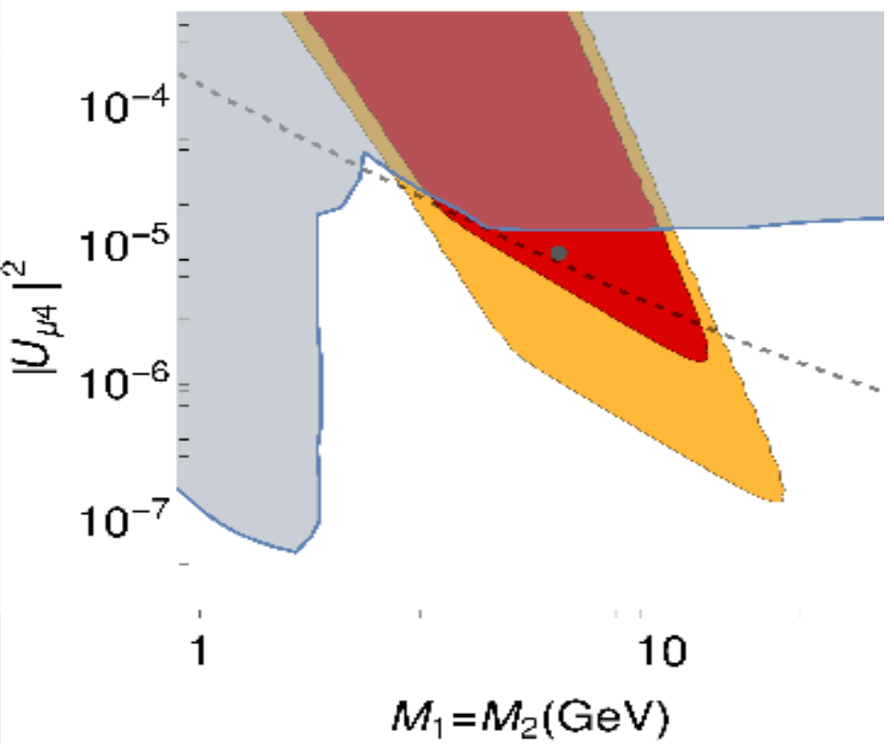
≋ 10^{8} H will be produced

250 events with 300 fb^{-1} w/o cuts

Directly test seesaw :
From Higgs production and decay explore heavy neutrinos with large lifetimes, which lead to a displaced vertex with leptonic and semi-leptonic decays

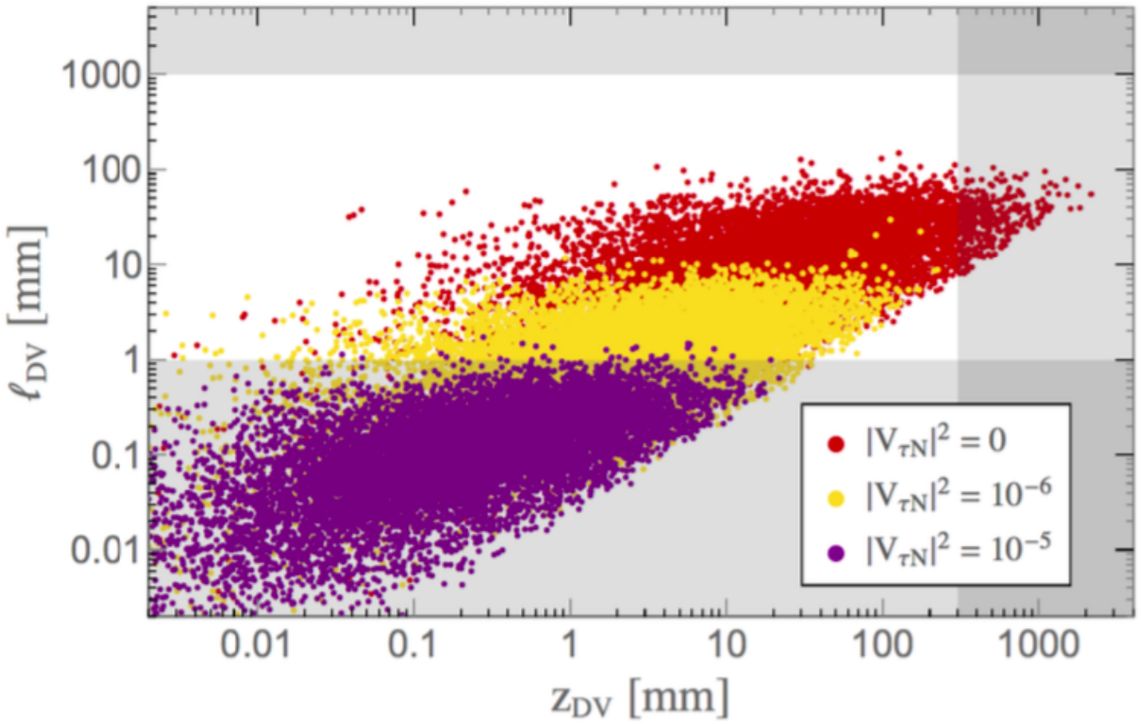


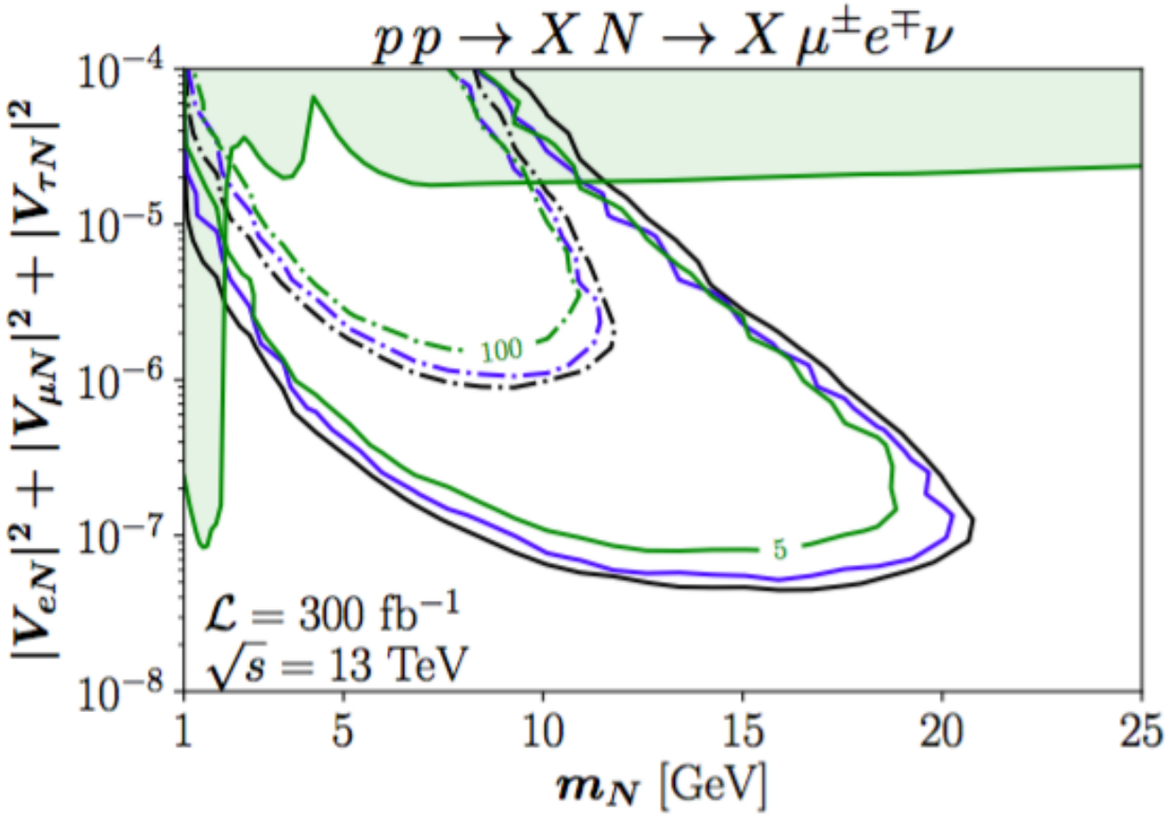




Flavour dependence/ Inclusive search

Abada, Bernal, Losada, Marcano [1807.10024]





Most analysis assume only one non-zero mixing angle

Typically favor triggering on prompt lepton

Many other models and analysis performed for HMLs, mostly assuming only one effective coupling.
See LLP LHC white Paper, PBC white paper, Sterile neutrinos white paper and refs. therein

Main issues:

triggering

reconstruction tracks, vertices

particle id

background understanding and estimation

Background from: cosmics, hadronic interactions, random track crossing, metastable hadrons

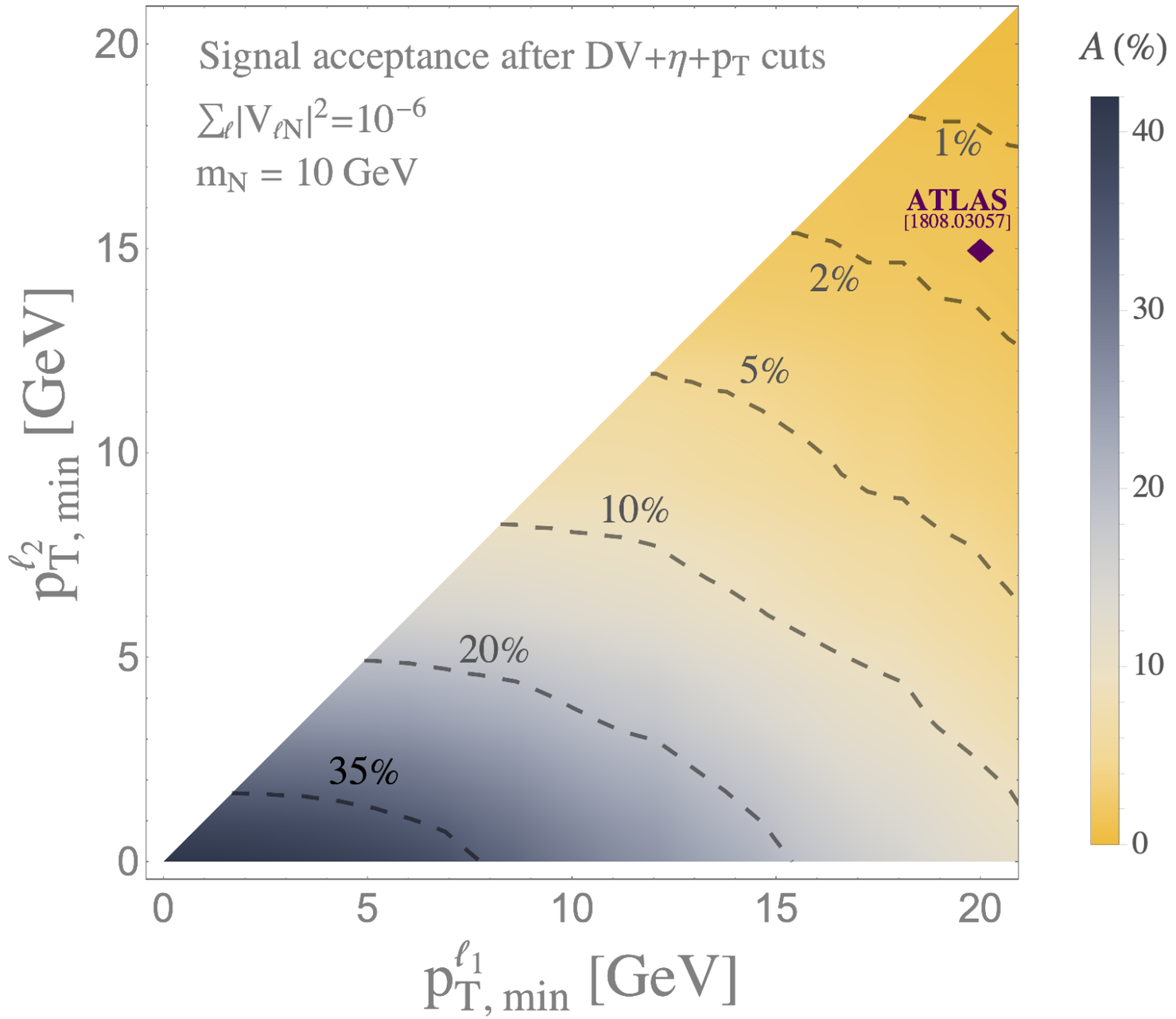
Implemented:

cosmic veto

ΔR cut

m_DV cut

p_T cuts on leptons

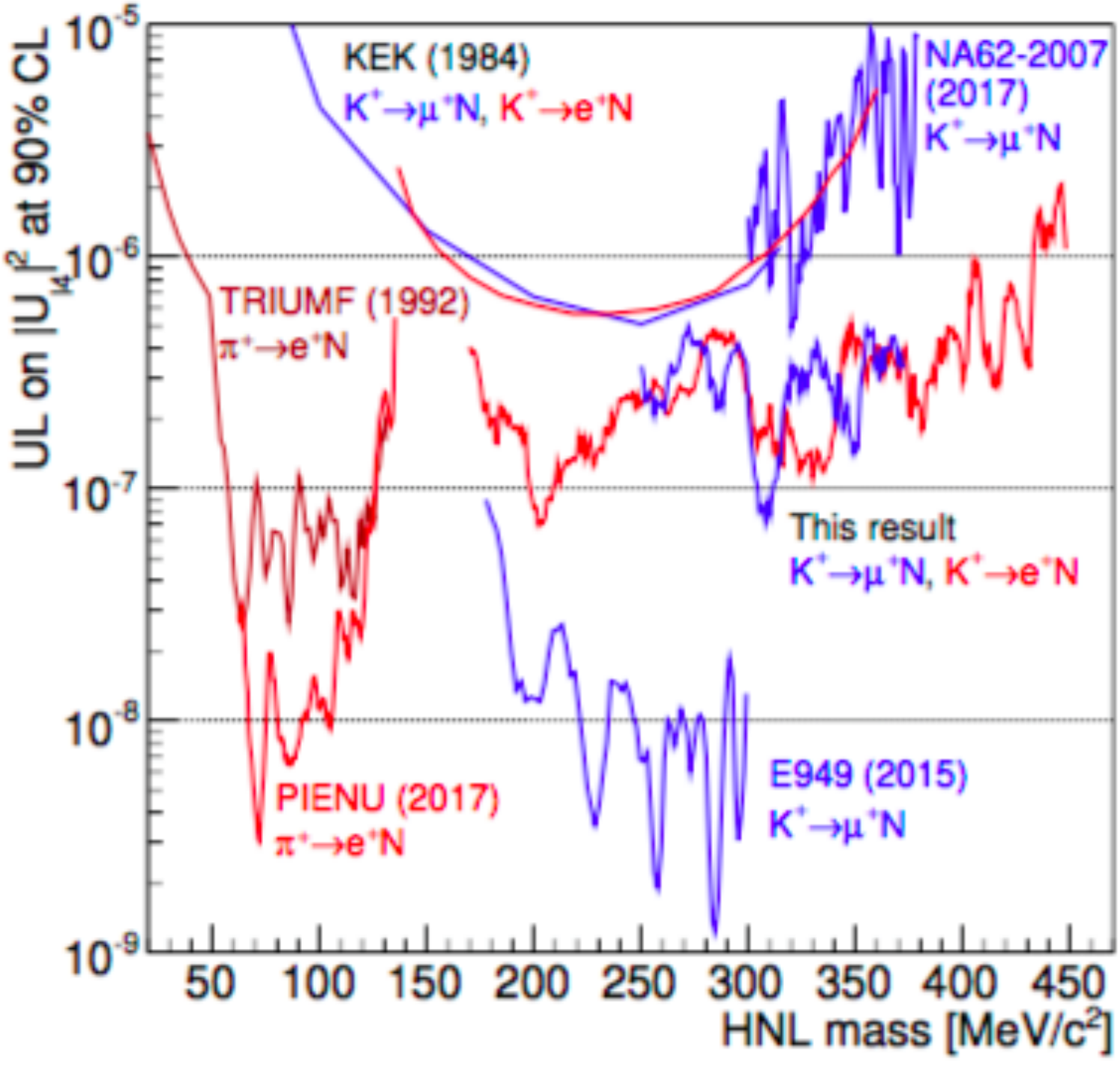


Beyond pp colliders

NA62

NEW

Update of HNL searches from K decays with NA48 and NA62

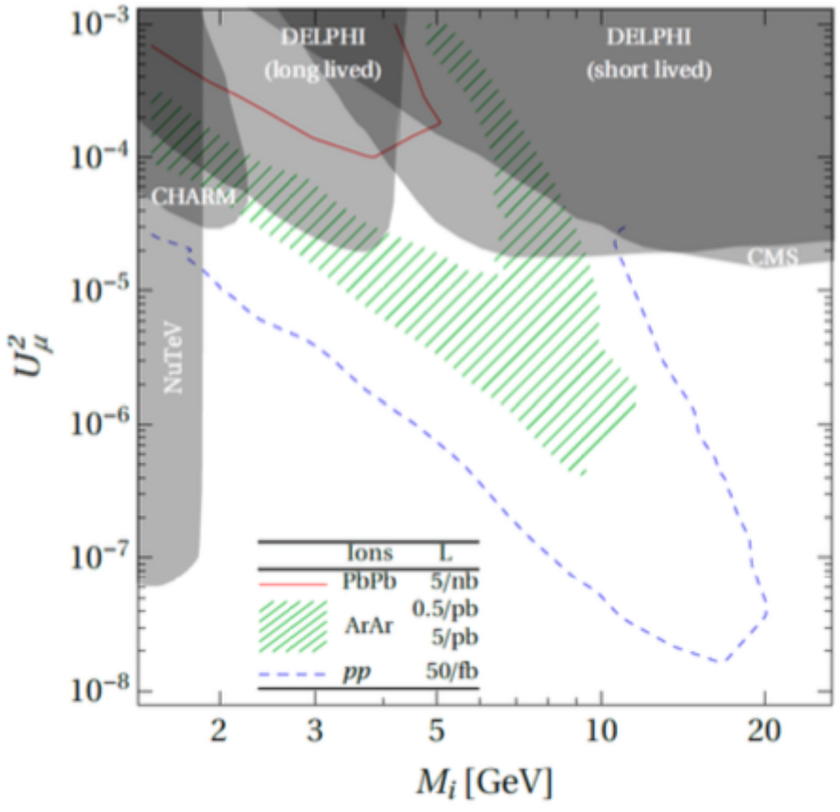


HNLs in Heavy Ion Collisions

Drewes et al

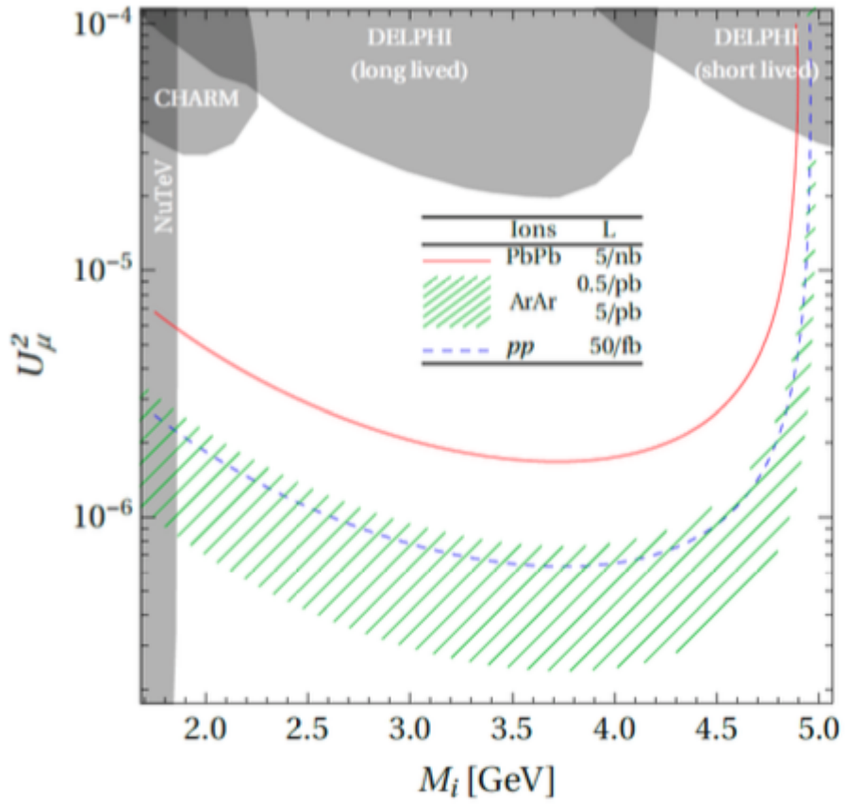
Trade off between luminosity and a optimal results with Ar

W decays



(a) Exclusion with $2\,\sigma$.

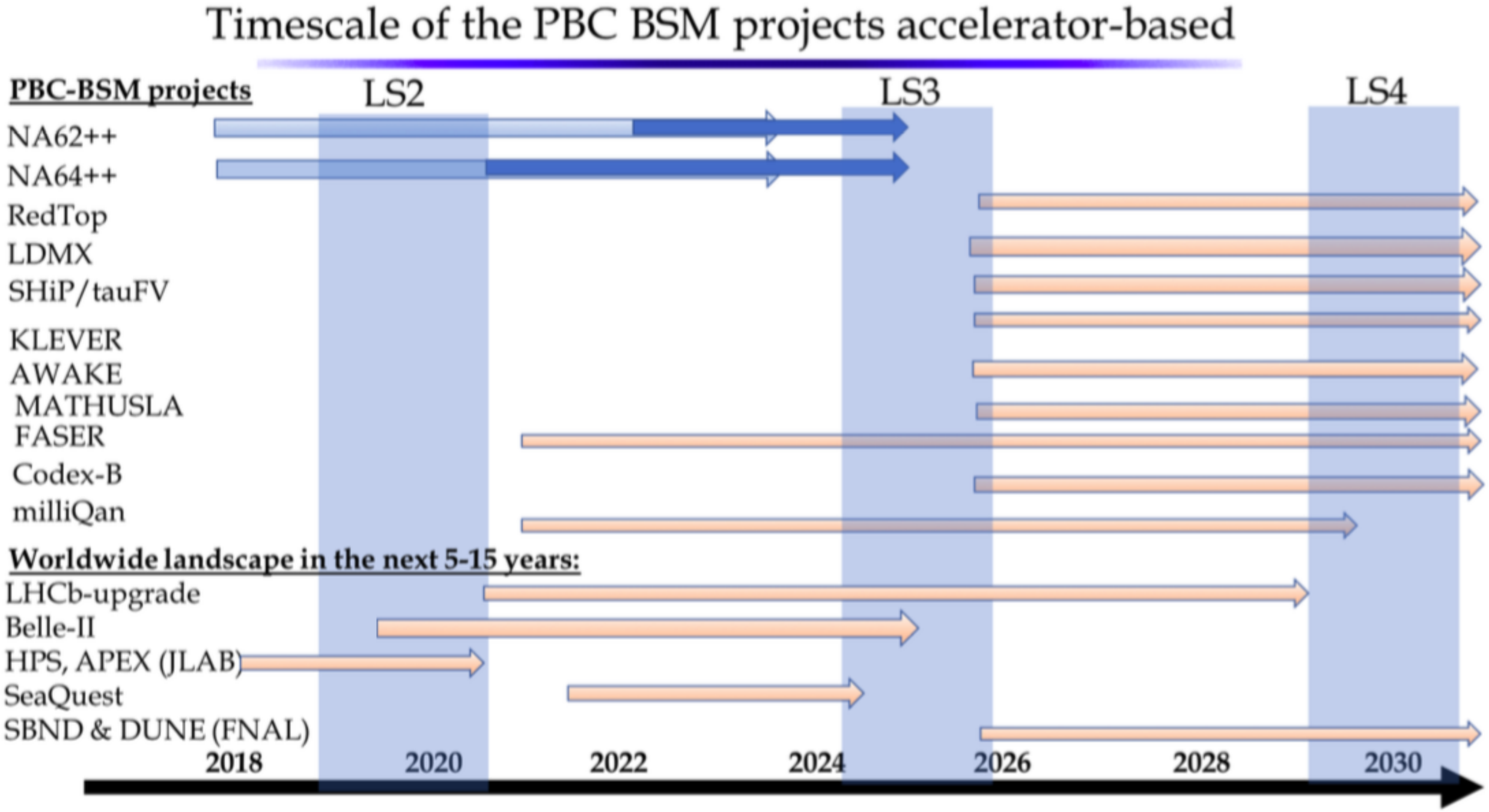
B meson decays



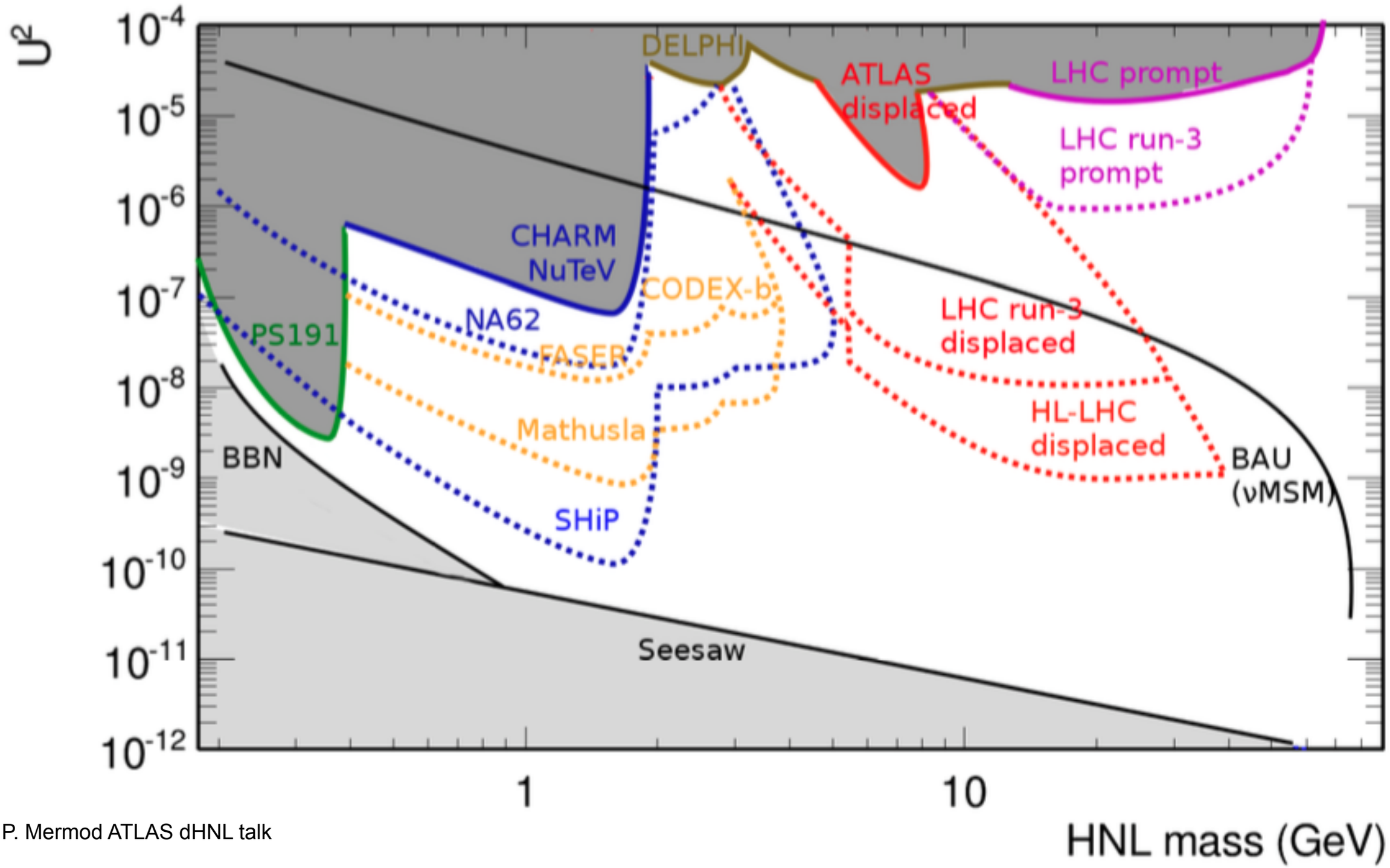
(a) Exclusion with $2\,\sigma$.

1901.09966

Future Experiments



Combined future results



P. Mermod ATLAS dHNL talk

Conclusions

Long-lived particles

- Challenging: dedicated searches are needed
- Exciting: explore what others can't explore

E.g. Heavy neutral leptons:

In the regimen MeV-GeV a clear and more complete picture of experiments (running or proposed) can further explore in depth the parameter space.

The next decade will provide further experimental results to pin down the properties of this kind of particles

Thank you

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