Experimental searches for Heavy Neutral Leptons

Gaia Lanfranchi
CERN & INFN

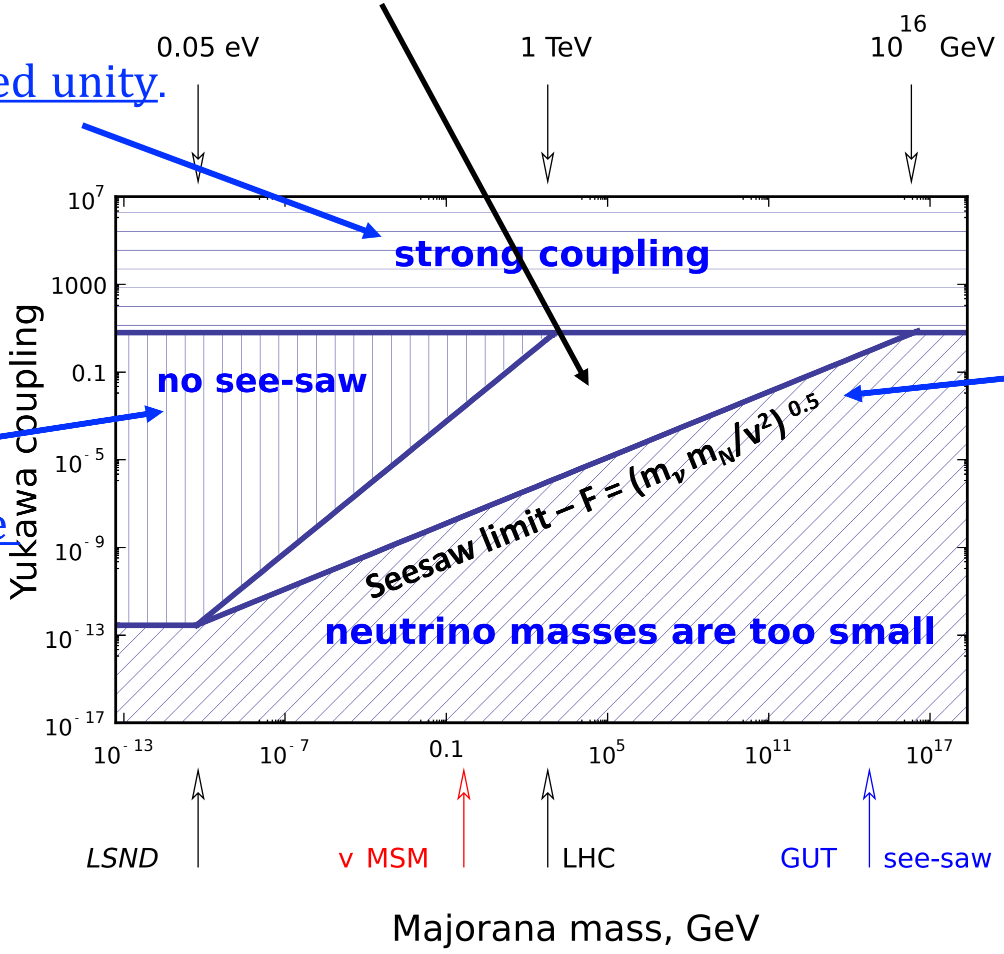
CERN Neutrino Cross-Talk seminar - 22 November 2019

Can HNLs be the origin of the neutrino masses and oscillations?

$SU(2)xU(1)_L$ singlet Right Handed Neutrinos responsible of the neutrinos' mass generation can have any coupling/mass in the white area, assuming an approximate $U(1)_L$ global symmetry

One or few of the Yukawas exceed unity.

-> perturbative treatment is not valid.



Seesaw line:

Below this line neutrino masses cannot be explained.

Dirac neutrino masses exceed the Majorana masses of the HNLs.

(In this domain HNLs interact with the neutrinos too strongly and would lead to visible effects in different neutrino experiments, would modify the invisible width of Z, etc.)

Couplings, masses, and number of HNLs are unknown:

N = 2 if m(active lightest) = 0;

N = 3 if m(active lightest)>0

Can HNLs be the origin of the neutrino masses and oscillations?

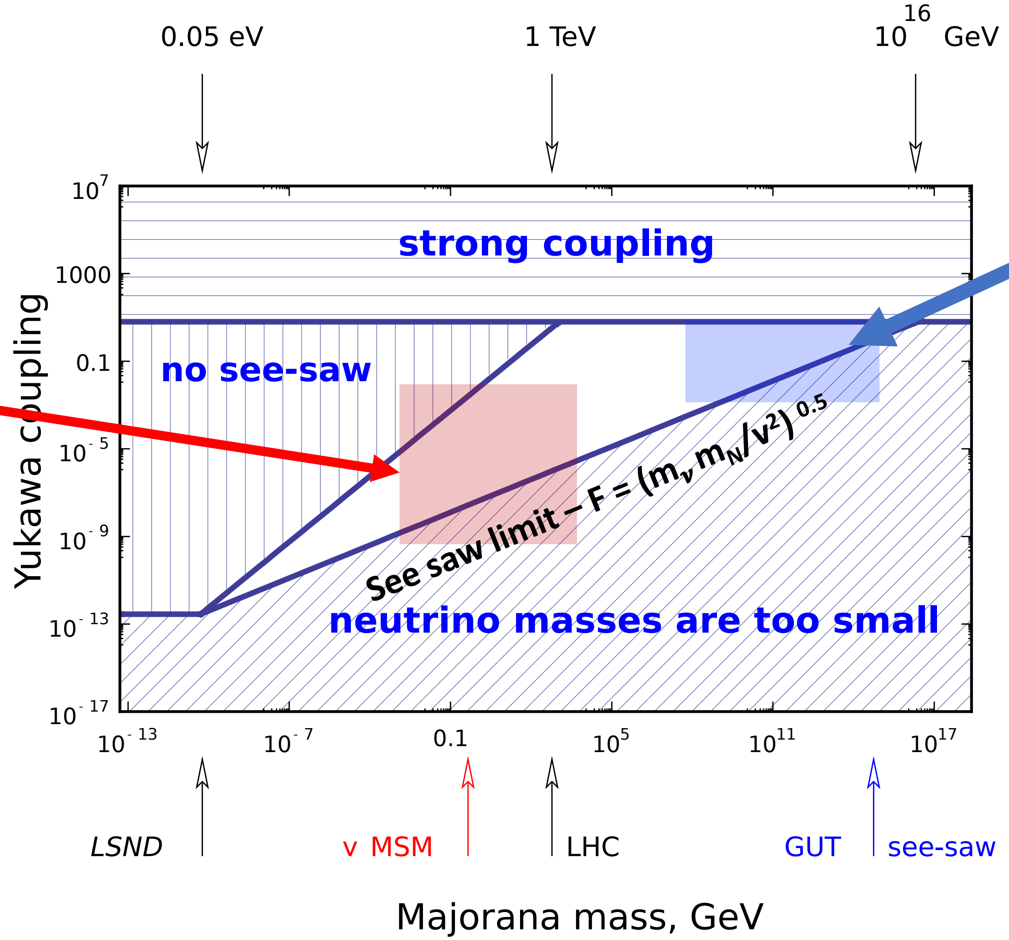
SU(2)xU(1)$_L$ singlet Right Handed Neutrinos responsible of the neutrinos' mass generation can have any coupling/mass in the white area, assuming an approximate U(1)$_L$ global symmetry

Shaposhnikov 0605047
Kersten,Smirnov: 0705.3221

Alternative choice:
EW "see-saw" type I
(νMSM)

It is "natural" to assume that the masses of the RH neutrinos are below/around the EW scale

NB: Masses at the EW scale and Yukawa ~ 10^{-12}-10^{-6} could be a consequence of a "symmetry-protected" scenario.



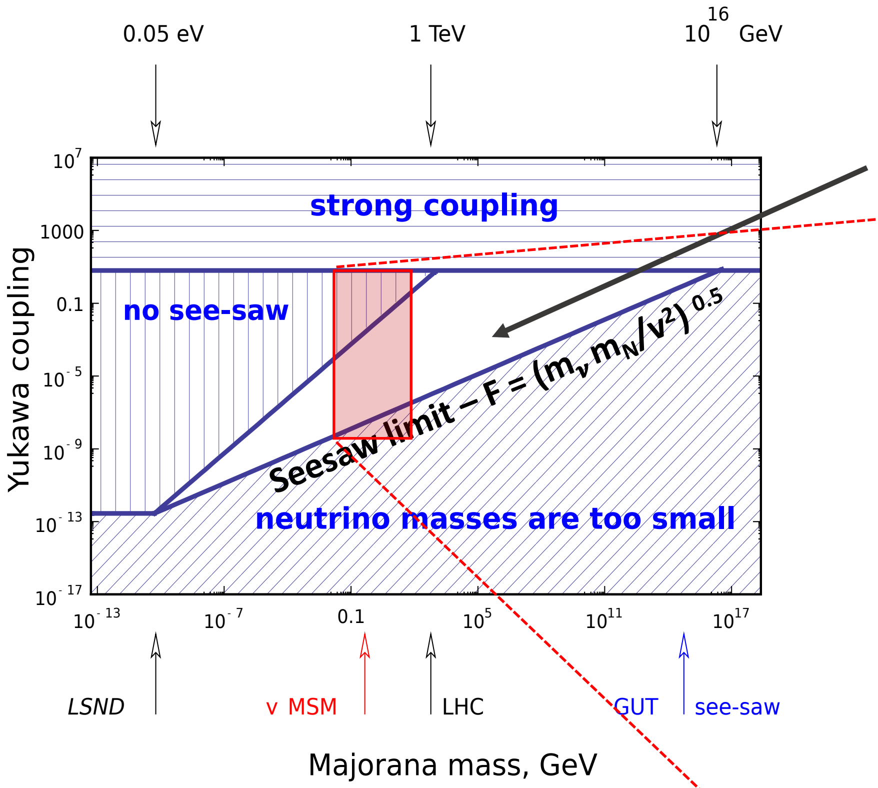
Standard choice:
GUT see-saw

It "natural" to assume that Yukawa couplings of the RH neutrinos are similar to the top Yukawa, o(1).

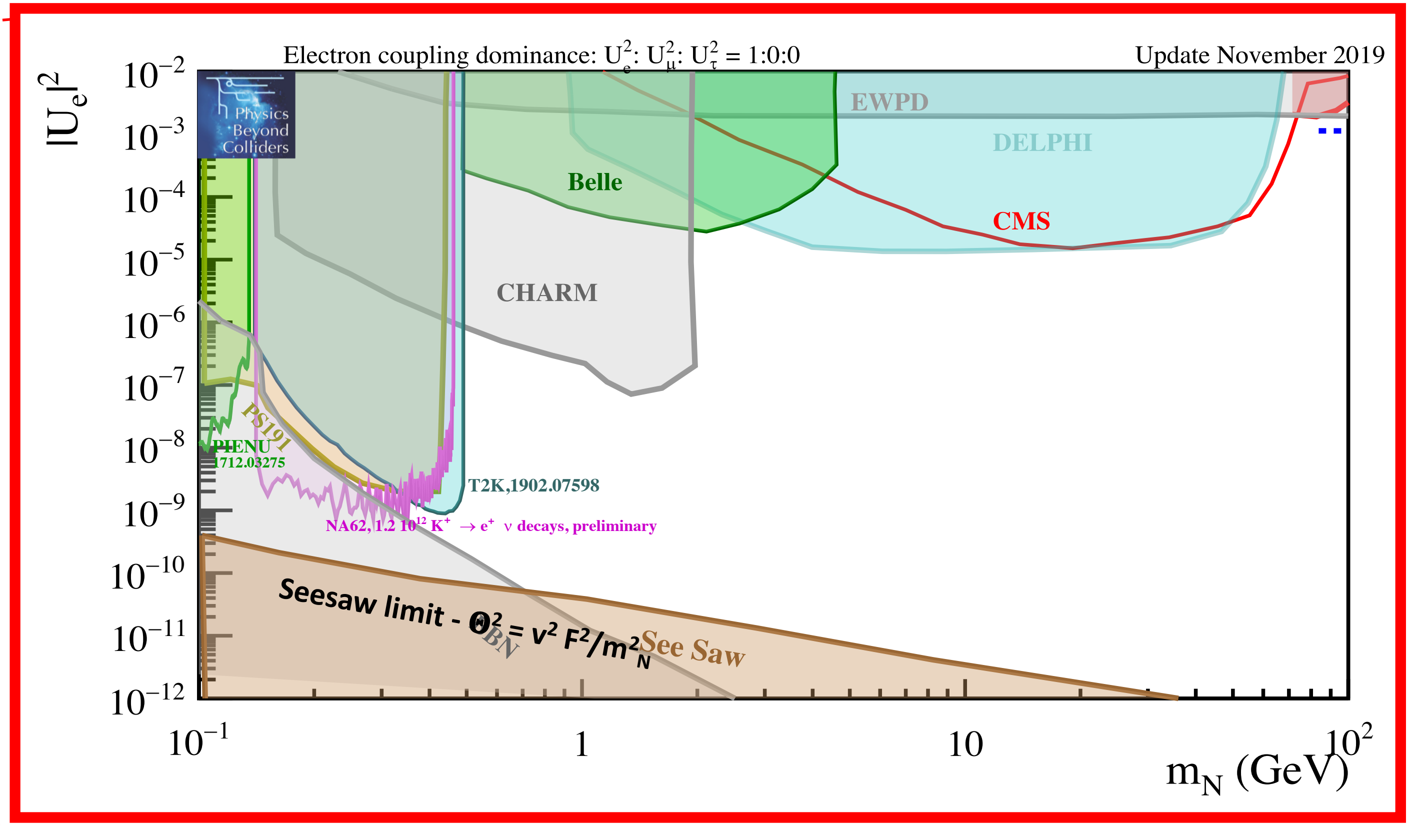
$$M_N \simeq \frac{F^2 v^2}{m_{atm}} \simeq 6 \times 10^{14}\ \mathrm{GeV}$$

Large spectrum of possible masses. Here we focus on the 0.1-100 GeV range.

HNLs experimental searches: current status



Updated status of HNL searches for electron-coupling dominance



For m_N= 2 GeV , $U^2 \sim 10^{-8}$

→ Yukawa coupling ~ 10^{-6}

(like the electron…)

Can we infer any information about HNLs from active neutrinos?

What do we know about HNLs couplings to active neutrinos?

Very little: in fact with 3 HNLs we introduce 18 new parameters that can easily accommodate any PMNS pattern. But, in presence of additional terms, the PMNS matrix could become not unitary:

Leptonic mixing matrix for 3 active neutrinos and 2 RHN in the limit of exact symmetry
(3 active neutrinos massless and 2 heavy neutrinos with degenerate mass values)

PMNS matrix

$$U = \begin{pmatrix} \mathcal{N}_{e1} & \mathcal{N}_{e2} & \mathcal{N}_{e3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{\mu 1} & \mathcal{N}_{\mu 2} & \mathcal{N}_{\mu 3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{\tau 1} & \mathcal{N}_{\tau 2} & \mathcal{N}_{\tau 3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau & \frac{1}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{\mathrm{i}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & \frac{-\mathrm{i}}{\sqrt{2}}(1-\frac{1}{2}\theta^2) & \frac{1}{\sqrt{2}}(1-\frac{1}{2}\theta^2) \end{pmatrix}$$

The leptonic mixing matrix U is unitary up to second order in theta:
→ The PMNS matrix becomes the non-unitary 3x3 submatrix N

See Stefan's talk

The mixing of the active and sterile neutrinos can be quantified by the mixing angles:

$$\theta_\alpha = \frac{y^*_{\nu_\alpha}}{\sqrt{2}}\frac{v_{\mathrm{EW}}}{M}\,, \qquad |\theta|^2 := \sum_\alpha |\theta_\alpha|^2$$

HNL-active neutrino mixing angles and PMNS non unitarity

Current knowledge of the active neutrino mixing angles is still very poor with respect to e.g. CKM elements:

CKM

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

$$J = (3.18 \pm 0.15) \times 10^{-5}$$

PMNS

3σ

NuFIT 3.2 (2018)

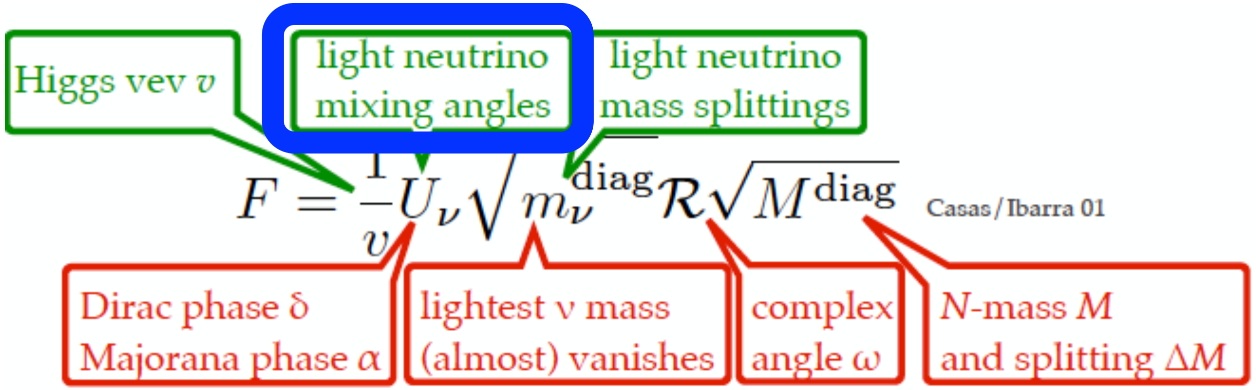
$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$

$$J \simeq 0.033 \sin \delta$$

Precision might be key not only to to discriminate different models and identify a clear pattern but also to shed light on the possible PMNS non-unitarity effects.

HNL-active neutrino mixing angles and PMNS non unitarity

The present status of neutrino oscillation experiments allows to do some quantitative analysis.
One can use the statistical information about the light neutrino parameters gathered
in various neutrino oscillation experiments to obtain a **probability distribution for the U^2_a/U^2**.



Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\rm diag}}\,\mathcal{R}\sqrt{M^{\rm diag}}$$

Casas/Ibarra 01

Dirac phase δ
Majorana phase α

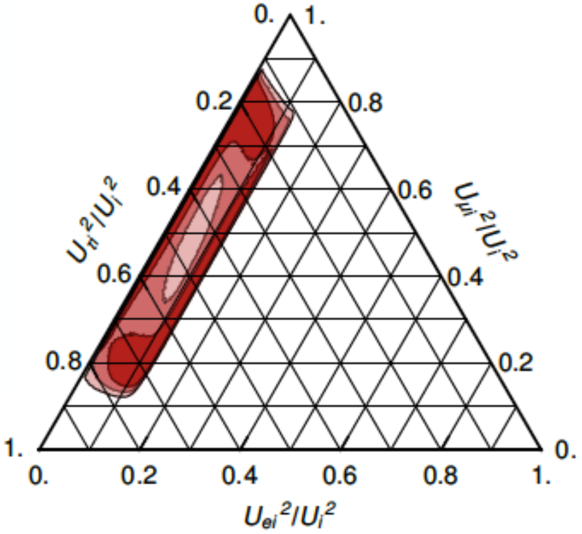
lightest ν mass (almost) vanishes

complex angle ω

N-mass *M* and splitting Δ*M*

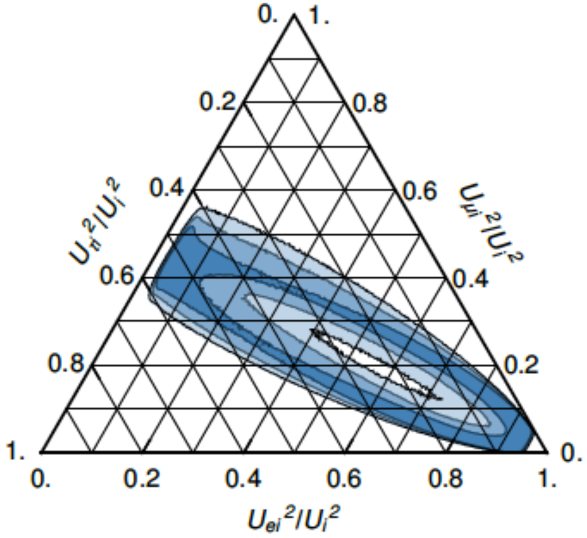
In case of one generation the seesaw formula holds:
$U^2 = v^2F^2/m_N^2$

Normal Mass Ordering



(c) Flat prior on α, using NuFIT 3.2 data.

Inverted Mass Ordering



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M. Drewes et al., 1801.04207

We cannot know absolute values of couplings to the three active neutrino generations but we can constrain the ratios.

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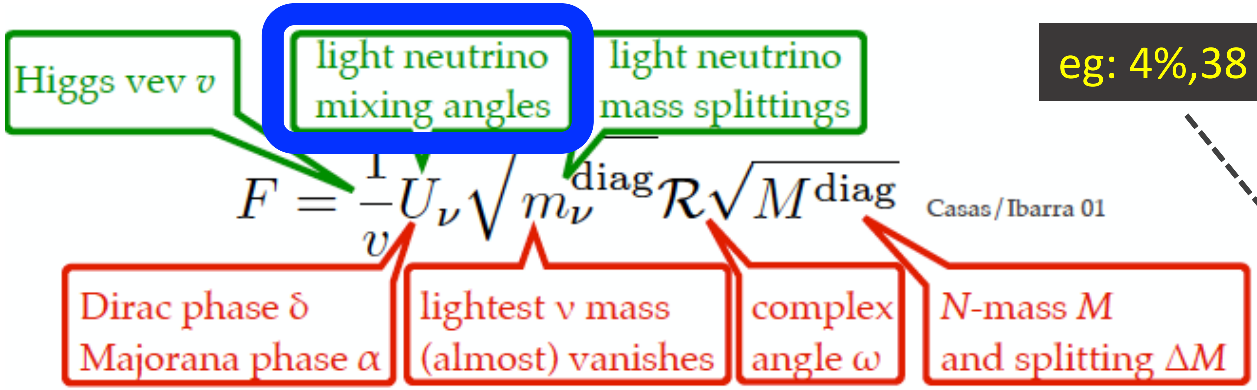


$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\text{diag}}}\, \mathcal{R} \sqrt{M^{\text{diag}}}$$

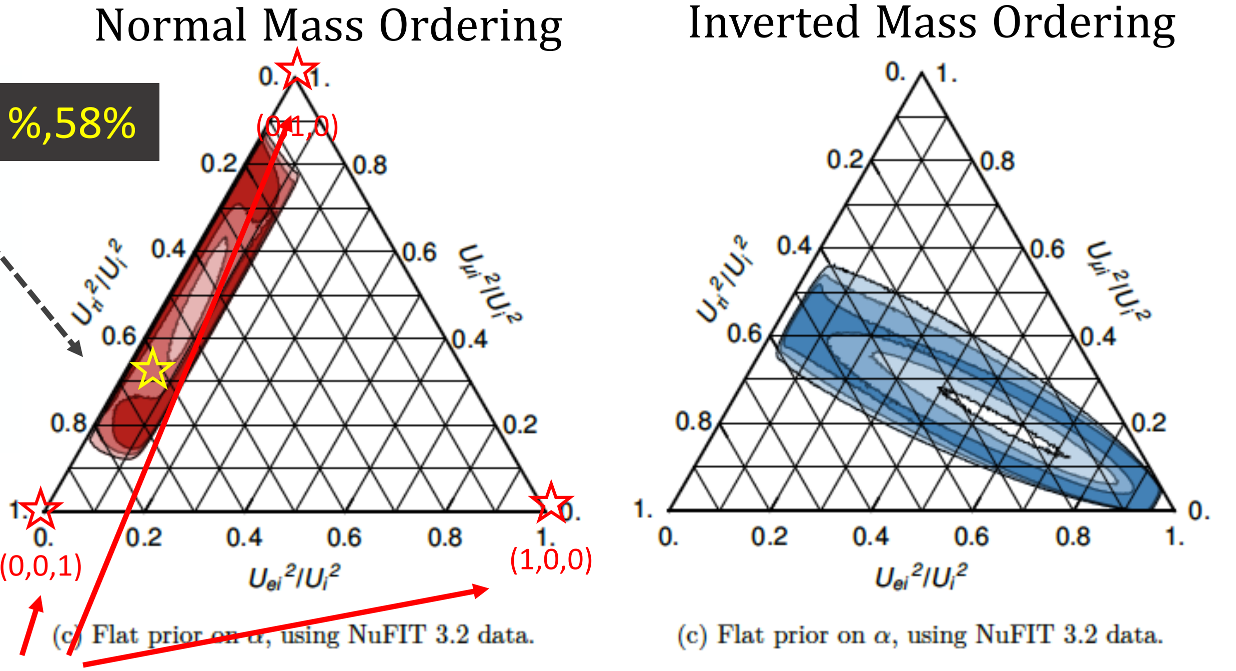
Casas/Ibarra 01

In case of one generation the seesaw formula holds:
$U^2 = v^2F^2/m_N^2$

eg: 4%,38 %,58%

Normal Mass Ordering

Inverted Mass Ordering



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Single flavor dominance (very conservative)

M. Drewes et al., 1801.04207

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HNL-active neutrino mixing angles and δ_{CP}

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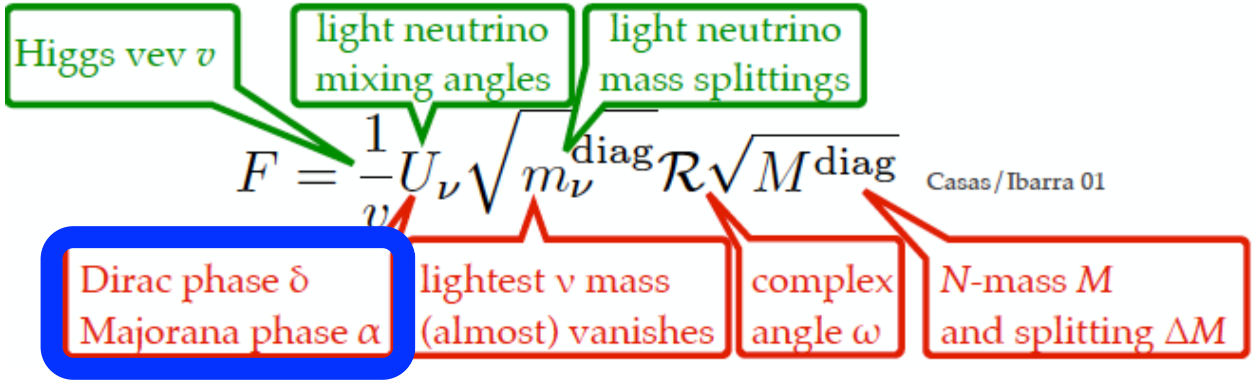
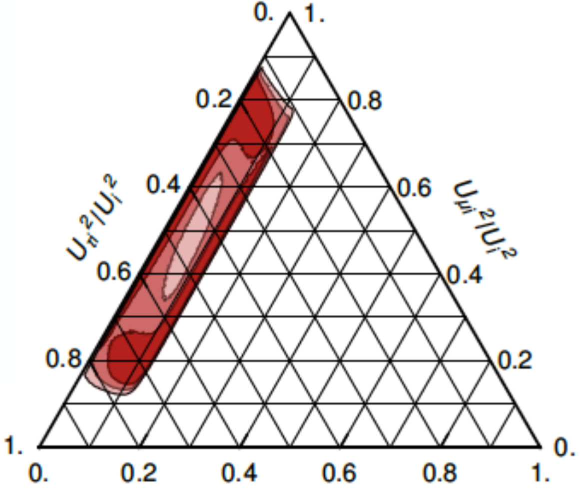


$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\text{diag}}} \mathcal{R} \sqrt{M^{\text{diag}}}$$

Casas / Ibarra 01

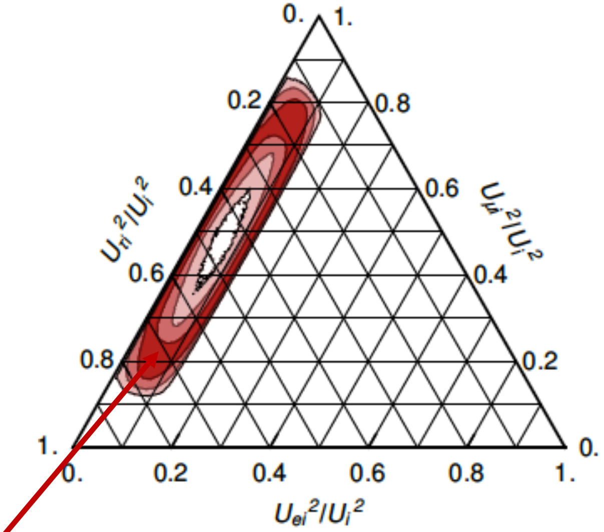
In case of one generation you have the seesaw formula:
$U^2 = v^2 F^2 / m_N^2$

without δ_{CP}



(c) Flat prior on α, using NuFIT 3.2 data.

with δ_{CP} = -π/2 +- π/9

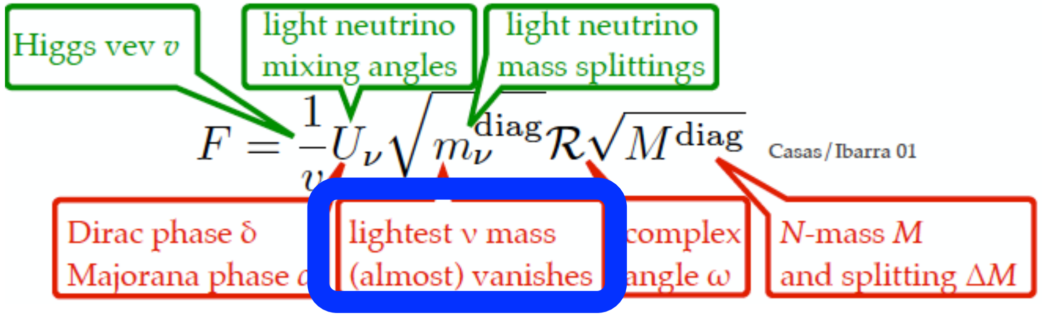


(b) Using the NuFIT 3.2 data

M. Drewes et al., 1801.04207

Inclusion of knowledge of δ_{CP} does not change dramatically the situation

HNLs mixing parameters: lower limit from lightest active neutrino



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Dirac phase δ
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lightest ν mass
(almost) vanishes

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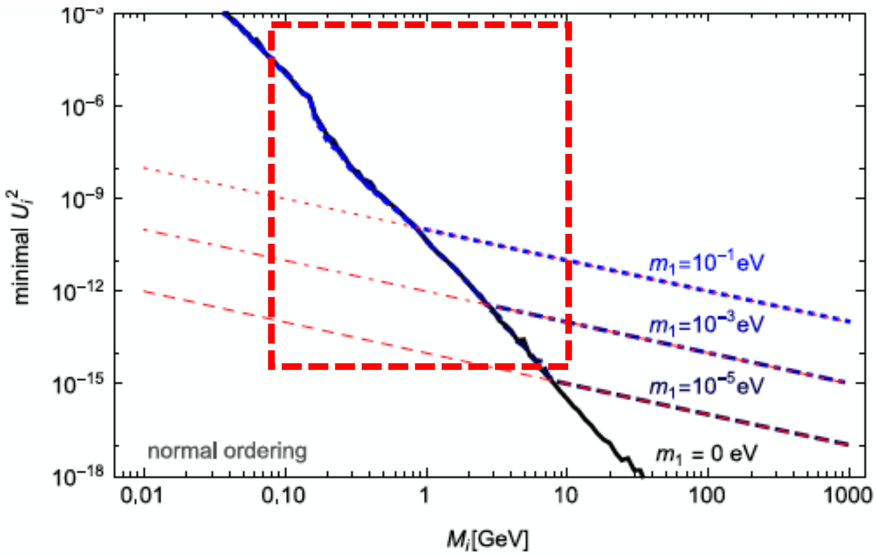
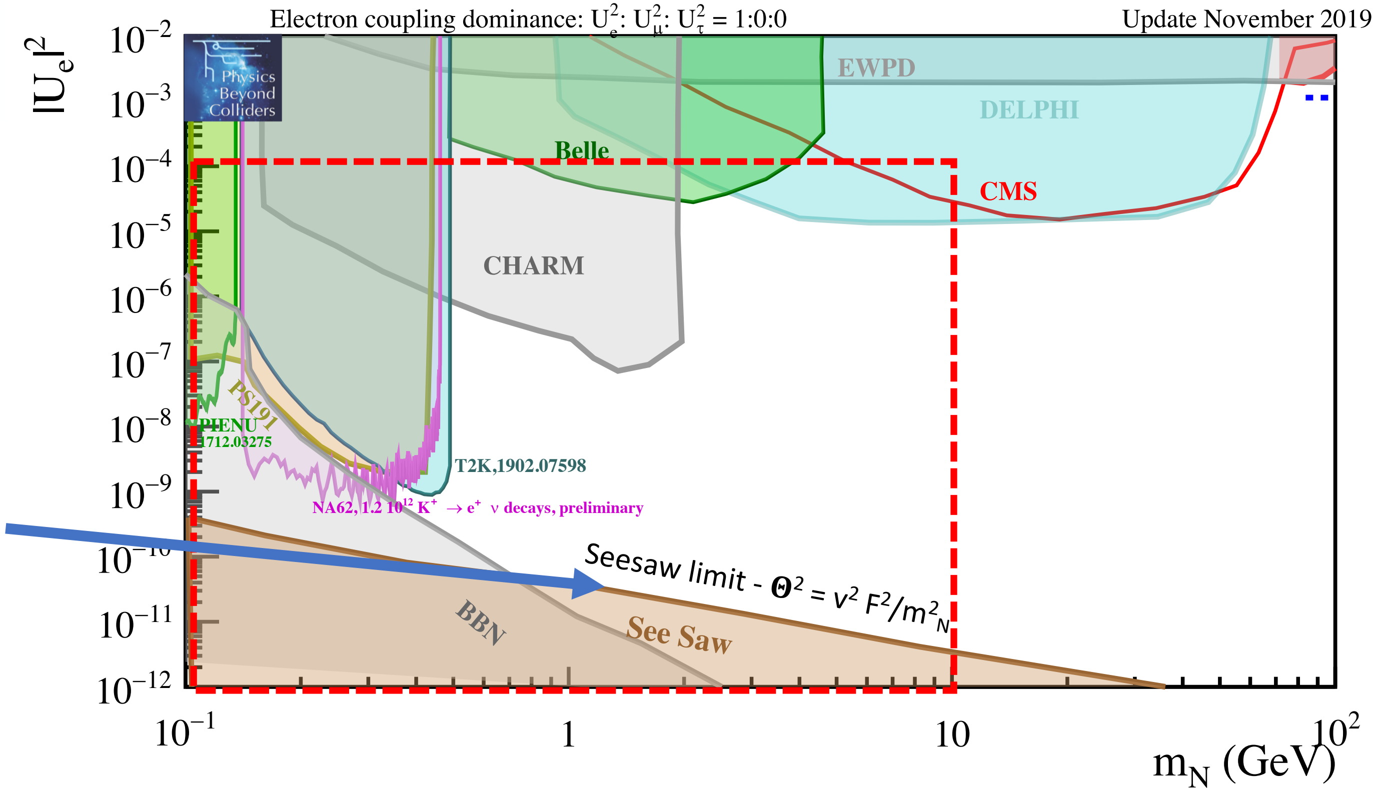
N-mass M
and splitting ΔM



M. Drewes et al., 1904.11959



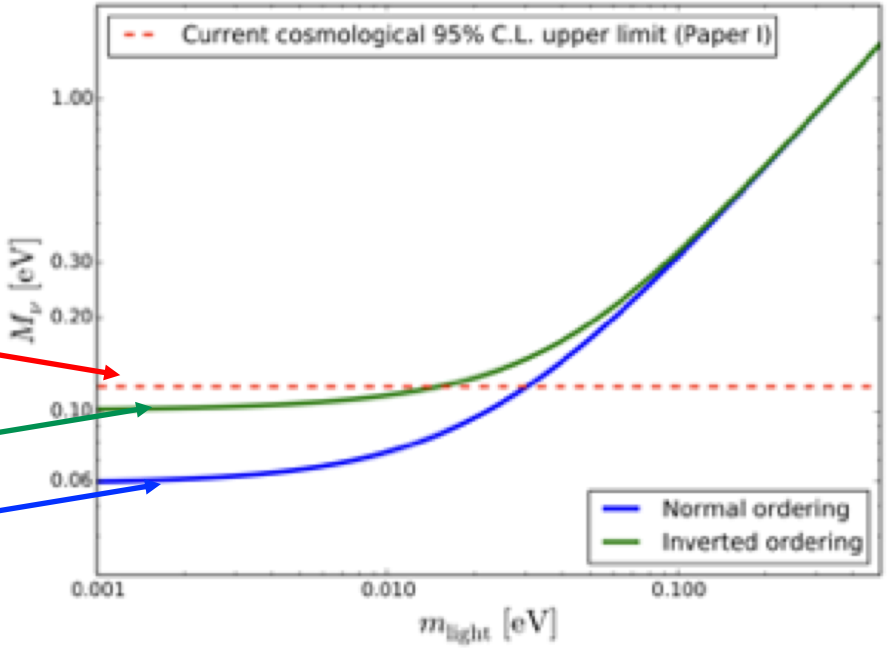
Seesaw limit - $\Theta^2 = v^2 F^2/m_N^2$

Lower boundary depends on the mass of the lightest active neutrino

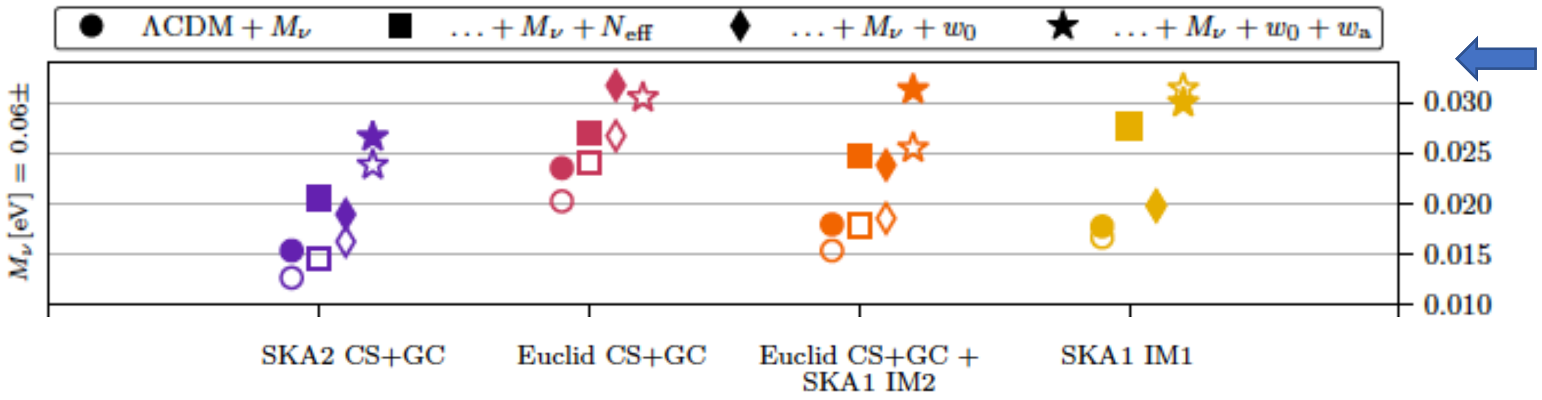
Current knowledge on the absolute active neutrino masses

Current cosmological limits on the sum of neutrino masses is between 0.12 ‾ 0.14 eV, (depending on what dataset you use).

From oscillations we know that
$\sum m_\nu$ >= 0.10 eV for Inverted Ordering
$\sum m_\nu$ >= 0.06 eV for Normal Ordering.



Sprenger et al., 1801.08331



New data from Euclid and Square Km Array (SKA) will be able to bring the cosmological limit down to $\sum m_\nu$ <= 0.06 ± 0.02 eV and shed light on the value of the mass of the lightest neutrino
(and the seesaw limit of HNLs…)

HNLs and Big Bang Nucleo-synthesis

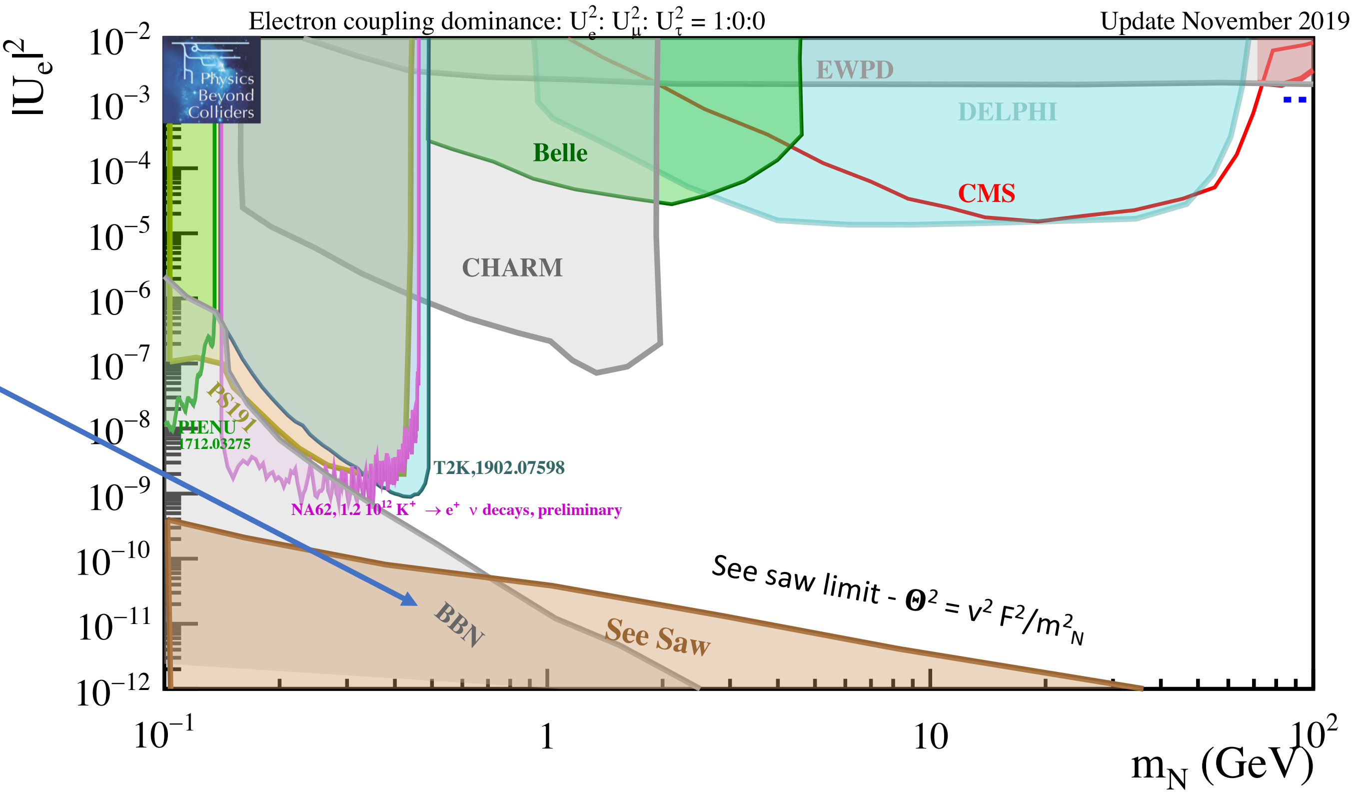
<u>Big Bang Nucleosynthesis (BBN):</u>

to avoid tension with the observed abundance of light elements in the intergalactic medium, HNLs should be enough short-lived that their decays do not disturb the primordial nucleosynthesis and the measured density of light elements (eg. ^{4}He).

NB:

any feebly-interacting particle should decay before 0.1 sec (< BBN) or after 300,000 years (eg. Dark Matter) in order to not perturb BBN and CMB expectations

- see Hufnagel et al, arXiv:1808.09324.



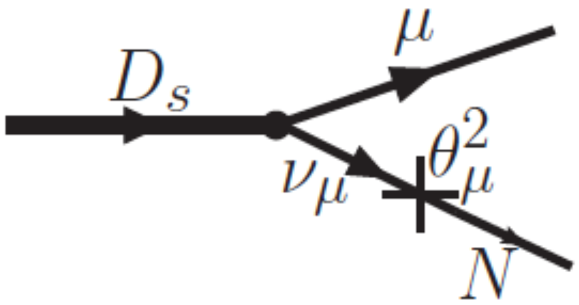
How can we directly search for HNLs?

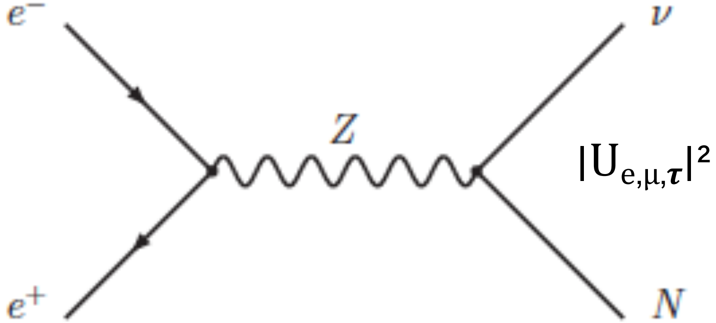
HNL production modes

(and corresponding experimental facilities)

If the HNLs exist, they would be produced in every process containing active neutrinos with a branching fraction proportional to the mixing parameters $|U_{e,\mu,\tau}|^2$.

K decays ⟶ kaon and neutrino experiments;
D,B decays ⟶ B-factories, LHCb and beam-dump
W decays ⟶ LHC and future pp, ep colliders
Z decay ⟶ LEP and future e+ e- colliders

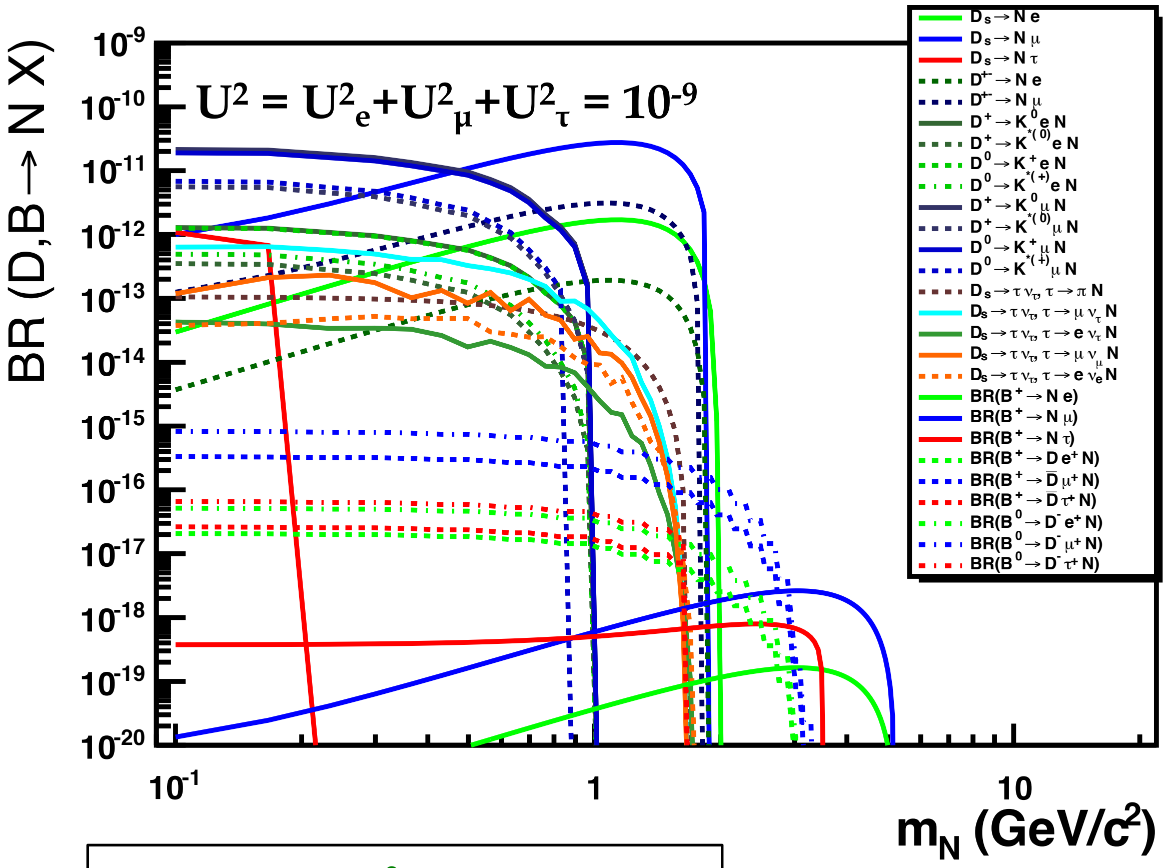




HNL production modes via D and B decays

HNLs can be produced in decays where a neutrino is replaced by a N (kinetic mixing, U²);

$U^2_e:U^2_\mu:U^2_\tau = 1:16:3.8$
Normal hierarchy of active neutrino masses



Green-ish: U^2_e dominated
Blue-ish: U^2_μ dominated
Red-ish : U^2_τ dominated

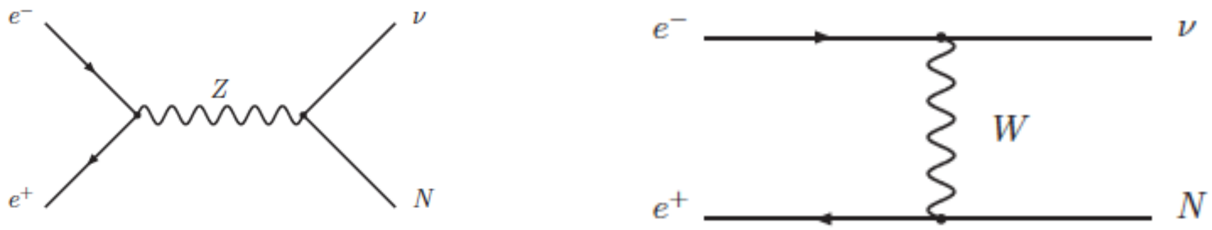
Production via D, B decays

- $D \to K \ell N$
- $D_s \to \ell N$
- $D_s \to \tau \nu_\tau$ followed by $\tau \to \mu \nu N$ or $\tau \to \pi N$
- $B \to \ell N$
- $B \to D \ell N$
- $B_s \to D_s \ell N$

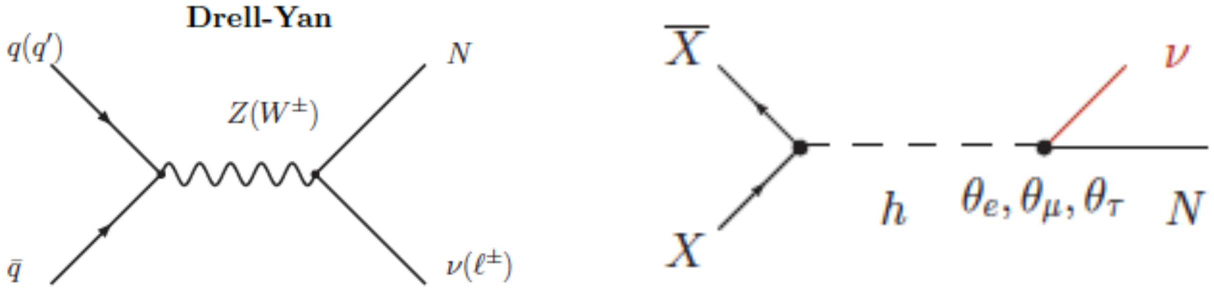
Similar production processes for K decays

HNL production modes at ee, pp, ep colliders:

ee colliders: Z in s-channel (dominant at the Z pole), W in t-channel (for higher energies)

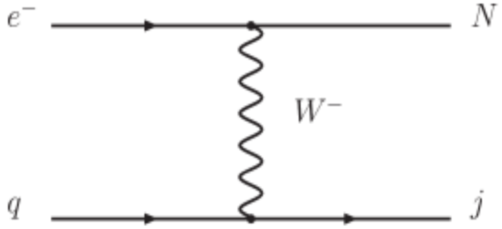


pp colliders: Drell-Yan processes (dominant), Higgs boson decays, gauge boson fusion (eg: W γ)

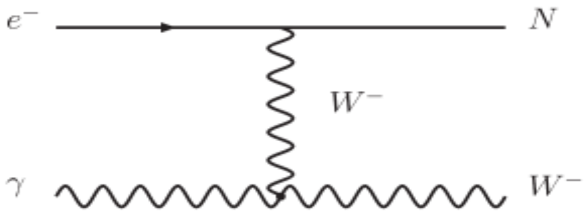


ep colliders: W in t-channel and W γ boson fusion

See Stefan's talk



production channel: $\mathbf{W_t}^{(q)}$



production channel: $\mathbf{W_t}^{(\gamma)}$

HNL production modes

✓ Production processes and related experimental facilities:

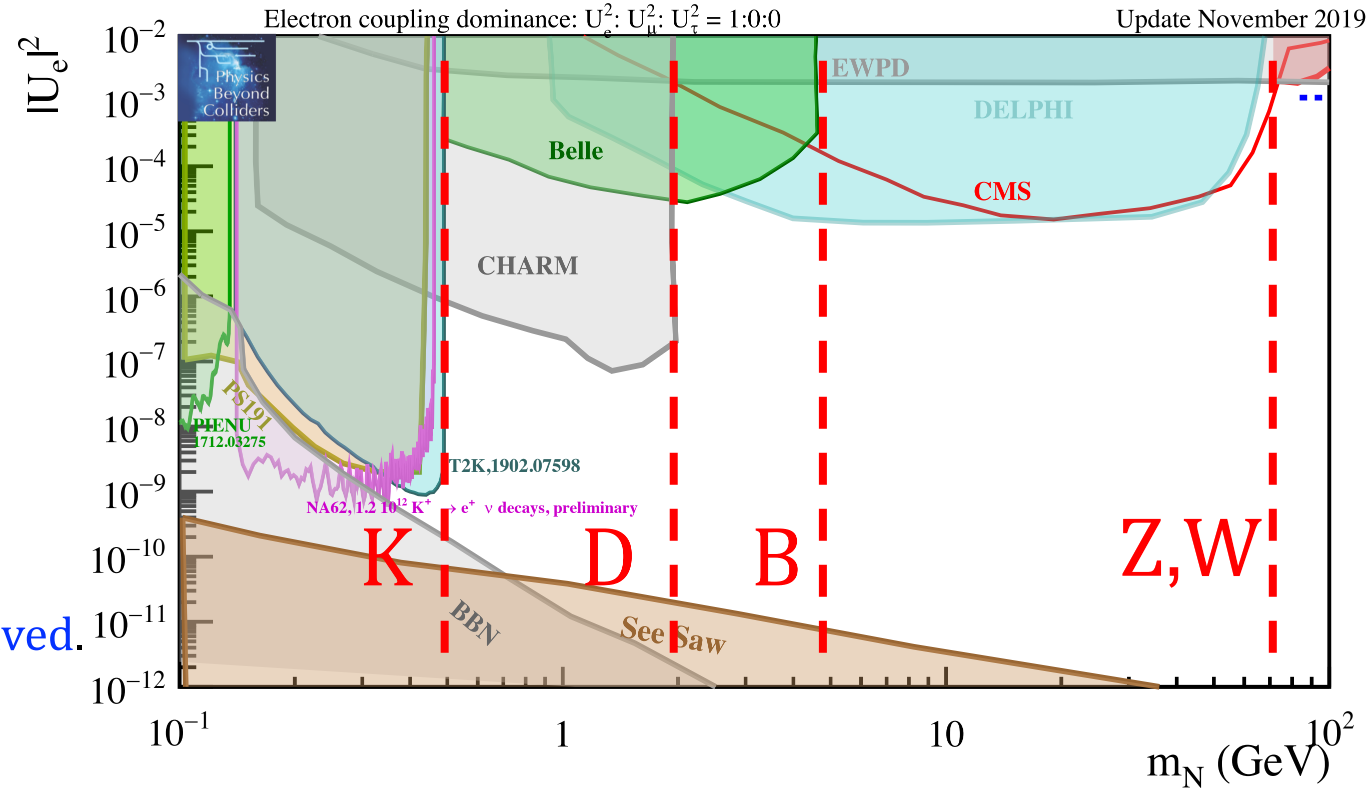
K decays ⟶ kaon and neutrino experiments;
D,B decays ⟶ B-factories, LHCb and beam-dump
W decays ⟶ LHC and future pp, ep colliders
Z decay ⟶ LEP and future e+ e- colliders

✓ The decay rate is proportional to the mass to the fifth power:

$$\Gamma_{N\to\text{weak}} \propto |U_{\alpha I}|^2\, G_F^2\, M_I^5$$

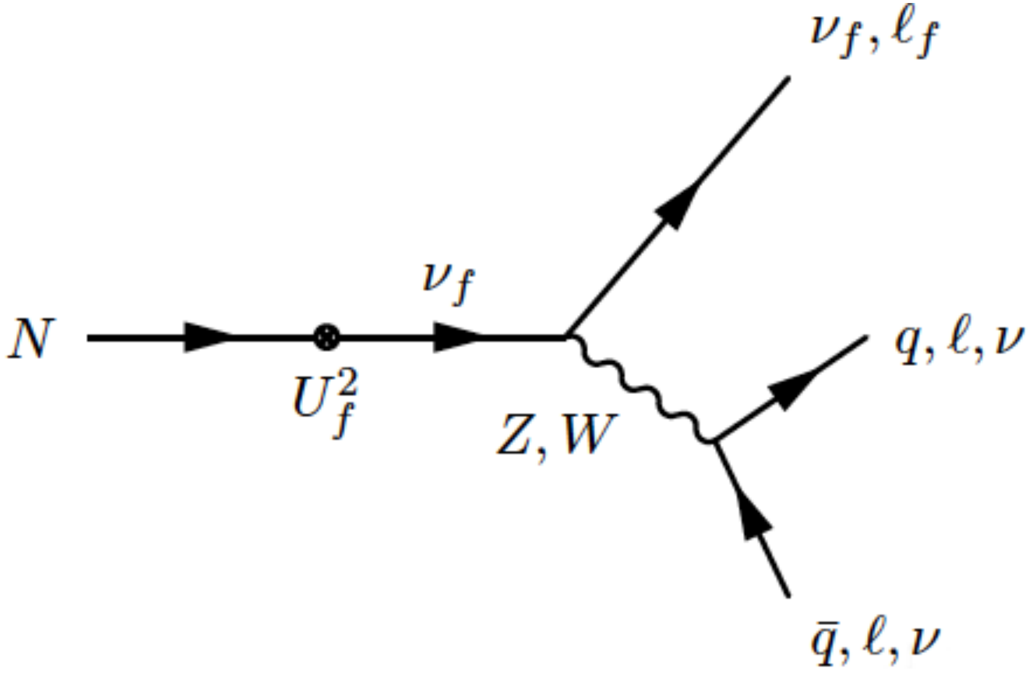
Hence: the more HLN is massive the more is short-lived.

Thresholds set by the production process.



HNL decay modes

Once produced, they can then decay again to SM particles through mixing (U^2) with a SM neutrino. This (now massive) neutrino can decay to a large amount of final states through emission of a Z^0 or W boson (NC or CC currents):



Decay channels

$N \to H^0 \nu$, with $H^0 = \pi^0, \rho^0, \eta, \eta'$

$N \to H^{\pm} \ell^{\mp}$, with $H = \pi, \rho$

$N \to 3\nu$

$N \to \ell_i^{\pm} \ell_j^{\mp} \nu_j$

$N \to \nu_i \ell_j^{\pm} \ell_j^{\mp}$

HNL decay modes

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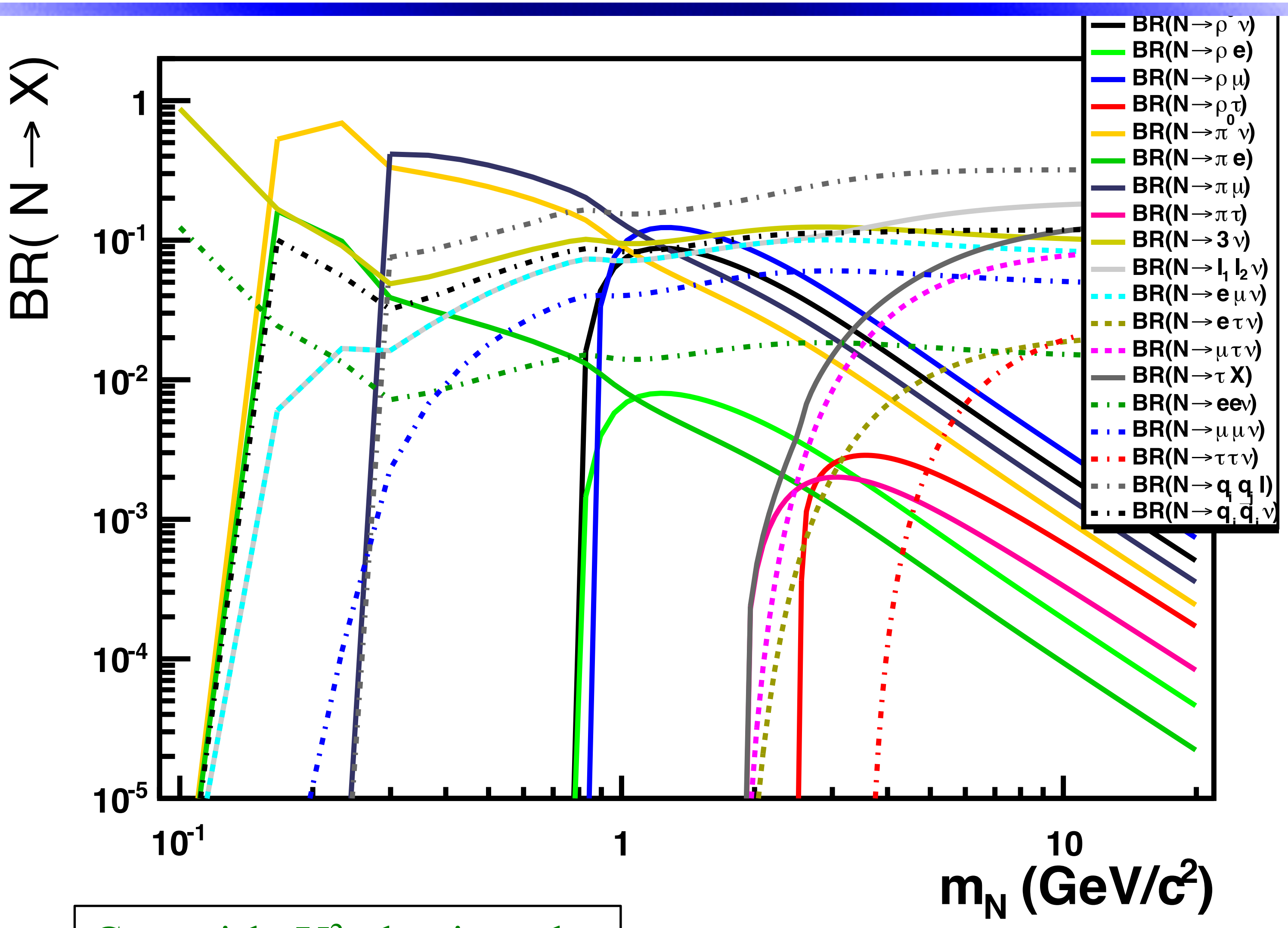
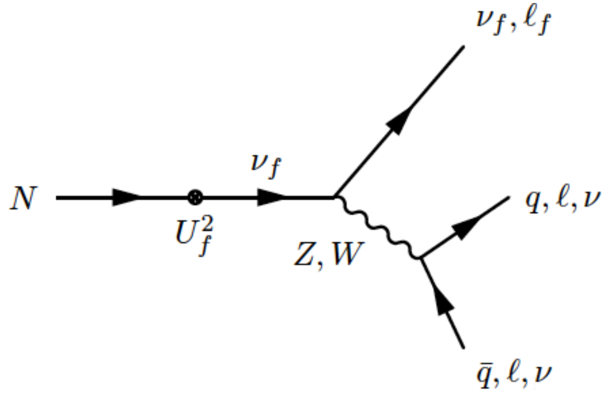
Normal hierarchy of active neutrino masses





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$N \to 3\nu$

$N \to \ell_i^\pm \ell_j^\mp \nu_j$

$N \to \nu_i \ell_j^\pm \ell_j^\mp$

Green-ish: U^2_e dominated

Blue-ish: U^2_μ dominated

Red-ish : U^2_τ dominated

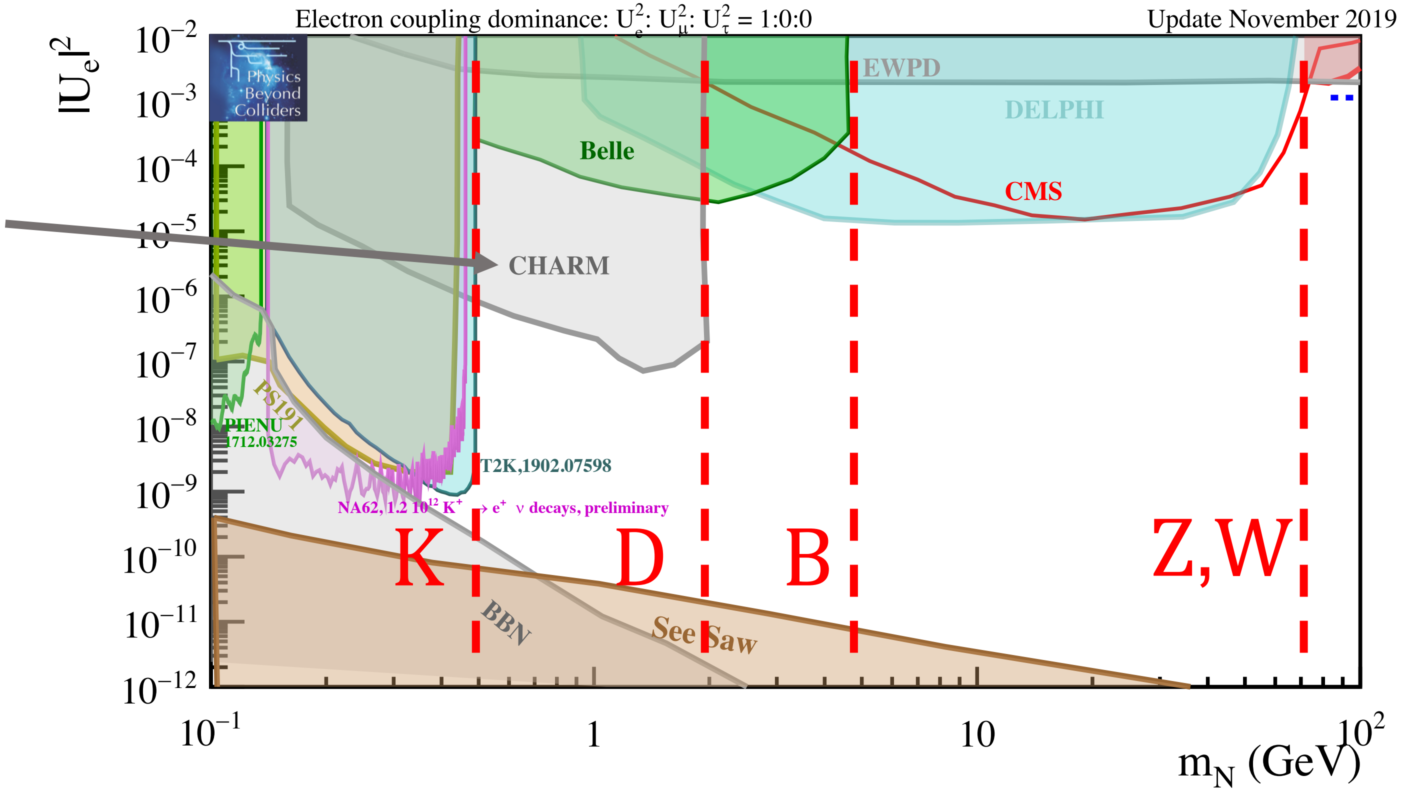
HNL experimental searches:
the past, the present and the future

HNL searches - the past (1986-2013)

1986: CHARM @ CERN

Phys. Lett. 166B (1986) 473

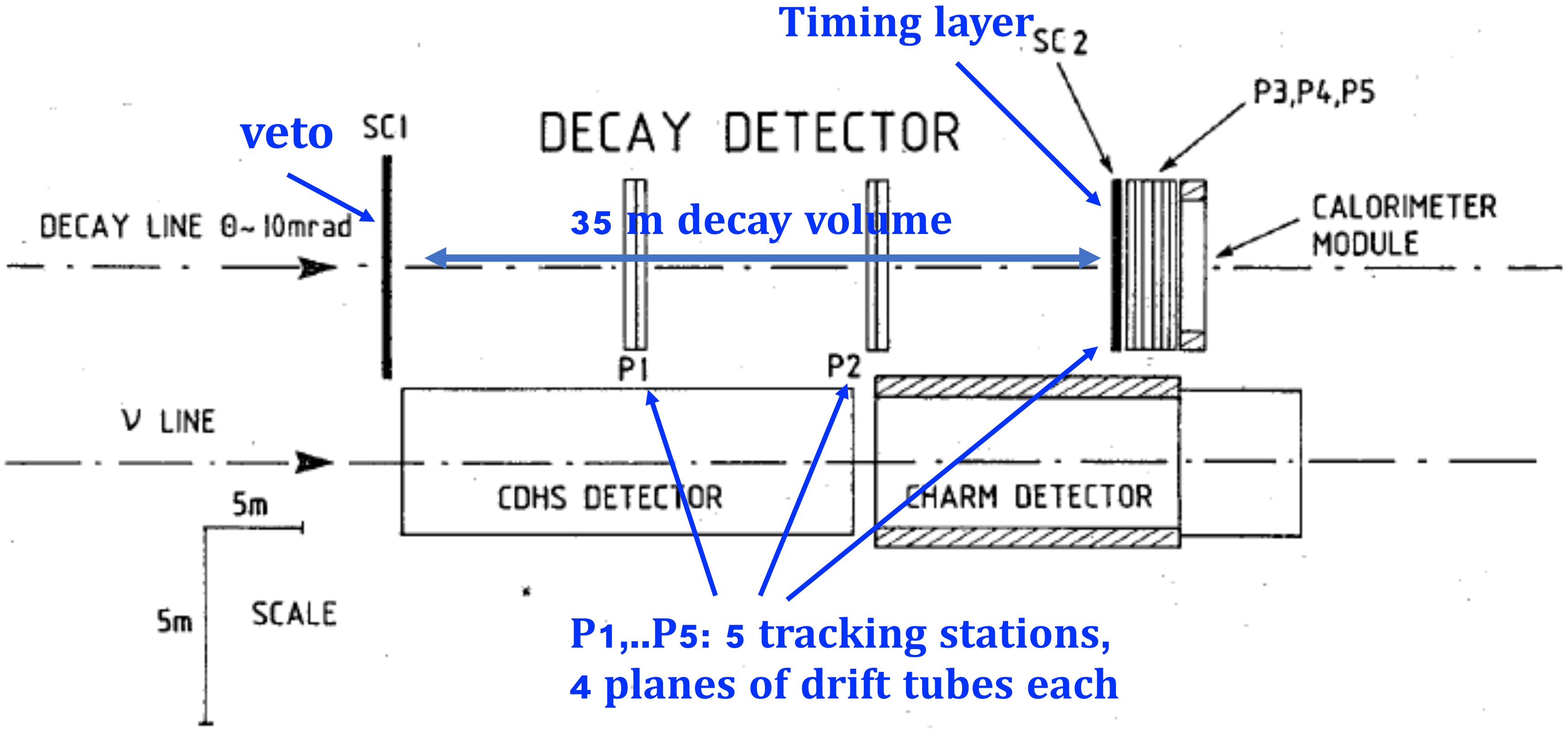
Dump of o($2 \cdot 10^{18}$) 400 GeV protons on a thick Cu beam dump; look for visible decays with electrons in the final state in the 35 m long decay volume with a spectrometer of 3 × 3 m² cross section.



Search for HNLs at the SPS in the '80

Phys. Lett. 166B (1986) 473
(signed by Ferroni & U. Amaldi).

Proton beam impinging on **Cu-based dump** 480 m upstream of the decay volume



Timing layer

veto

35 m decay volume

P1,..P5: 5 tracking stations,
4 planes of drift tubes each

CHARM result still dominates the sensitivity for U^2_e up to the D meson mass (after > 30 years)

HNL searches - the past (1986-2013)

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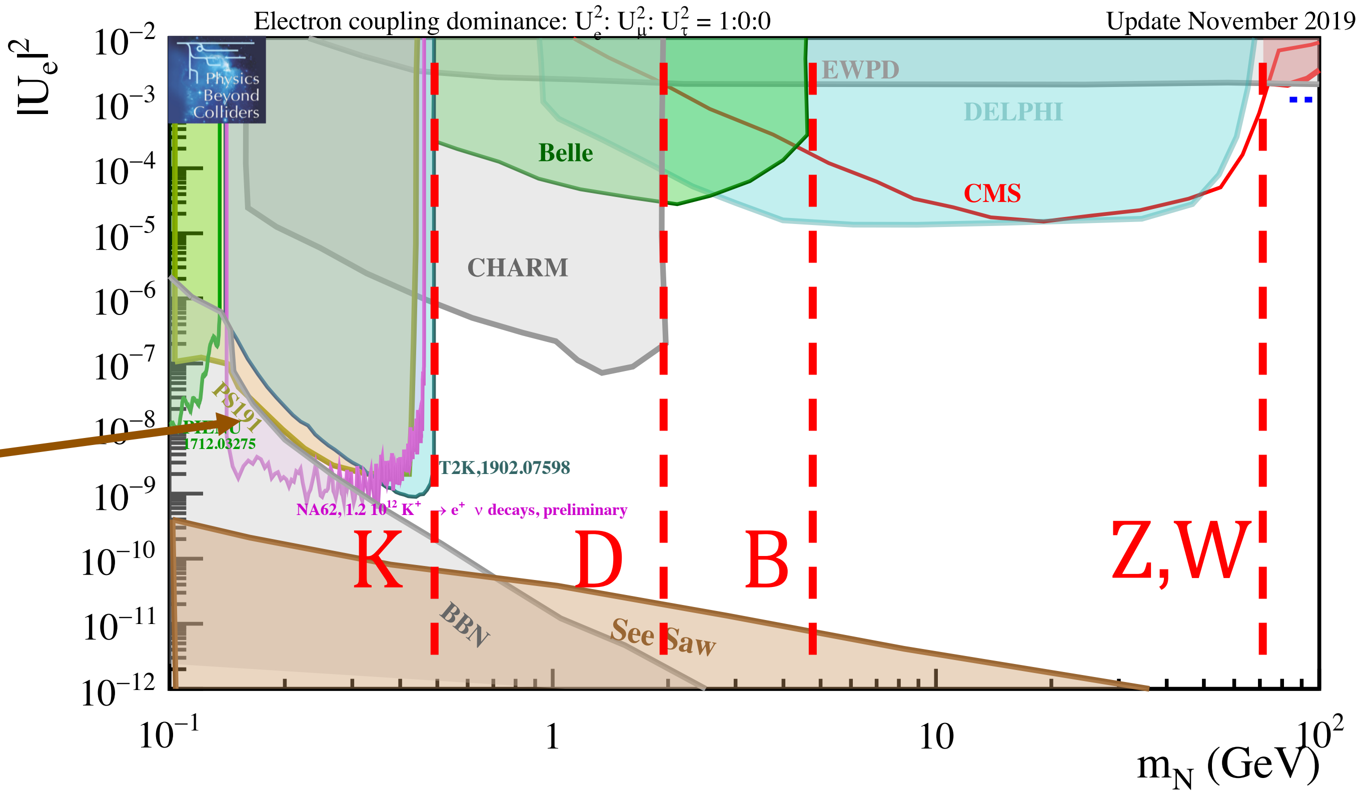
1988: PS191 @ CERN

Phys. Lett. B203 (1988) 332

specifically designed to search for neutrino decays in a low-energy neutrino beam. Made of 10 m long nearly empty decay volume instrumented by flash chambers, calorimeter and scintillator hodoscope. → **Dominated the mass range below the kaon mass until 6 months ago**.



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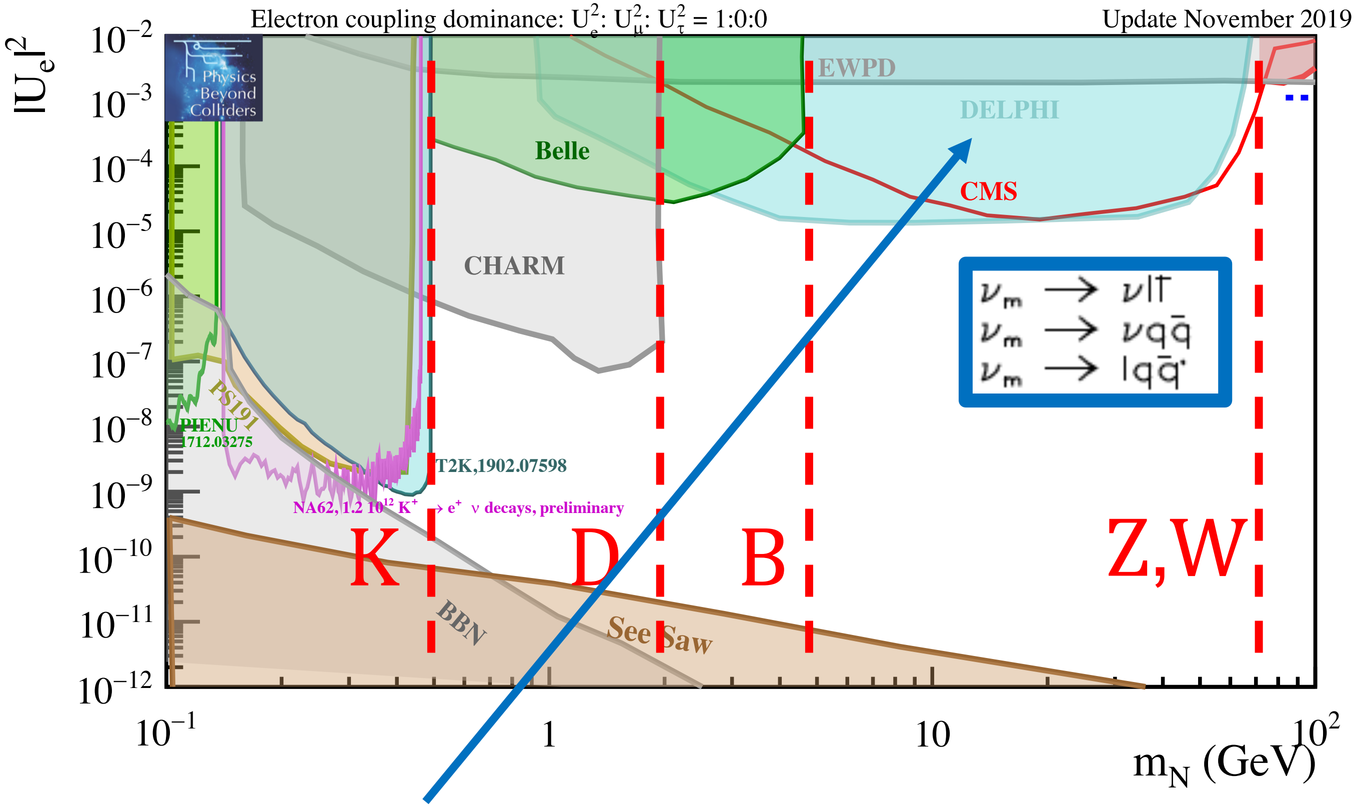

1997: LEP data dominated by DELPHI:
3.3 × 10⁶ hadronic Z⁰ decays at LEP1 ($Z \longrightarrow \nu N$);
Prompt and displaced decays. Z. Phys. C74 (1997) 57.

HNL searches - the past (1986-2013)

2013 Belle @ KEK: 772 M of BB pairs, leptonic and semileptonic B mesons decays, B ⟶ X l N, where l = e, μ and X = K (*), D(*), (ρ,π, η, etc.) or nothing; range of masses between K and B masses. *Phys. Rev. D87 (2013) 071102*.

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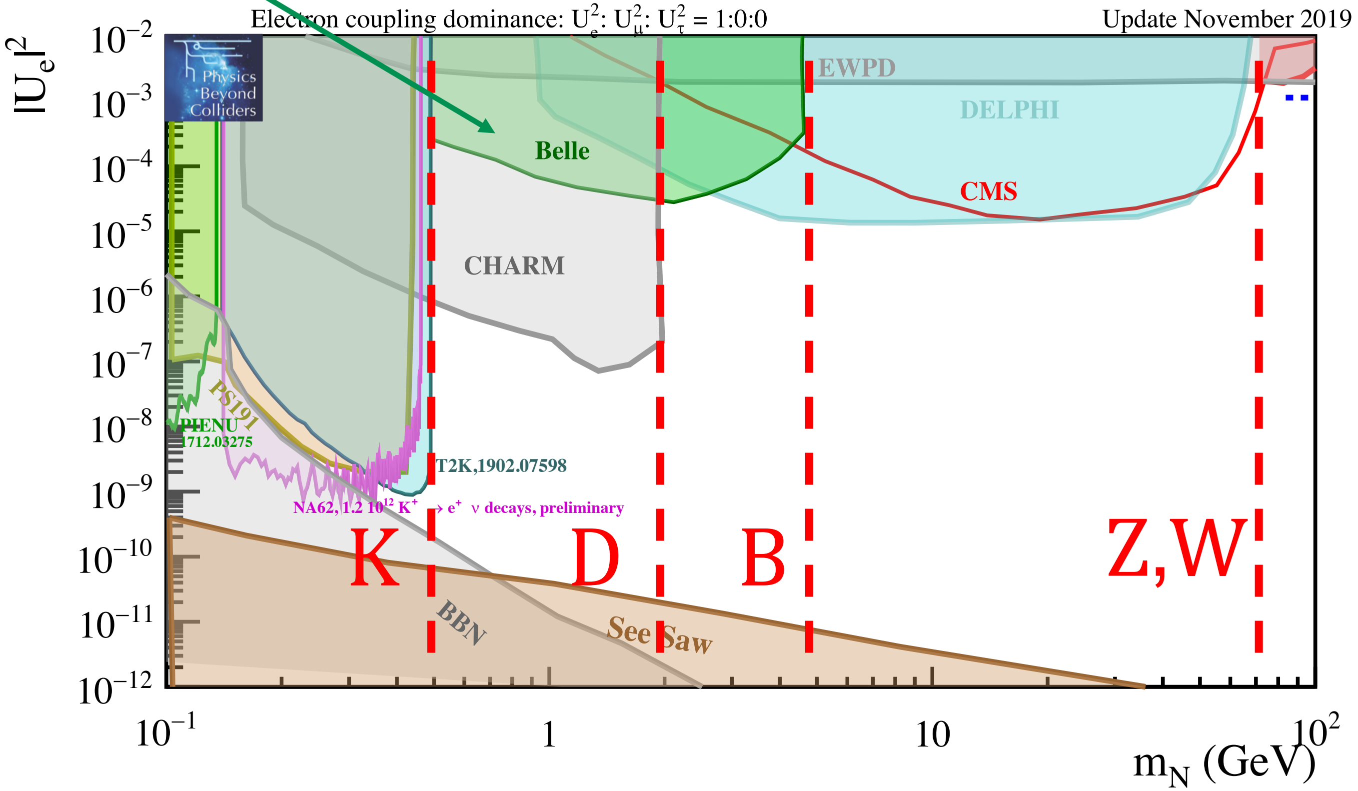
Phys. Lett. B203 (1988) 332

specifically designed to search for neutrino decays in a low-energy neutrino beam. Made of 10 m long nearly empty decay volume instrumented by flash chambers, calorimeter and scintillator hodoscope. → **Dominated the mass range below the kaon mass until 6 months ago**.



1997: LEP data dominated by DELPHI:

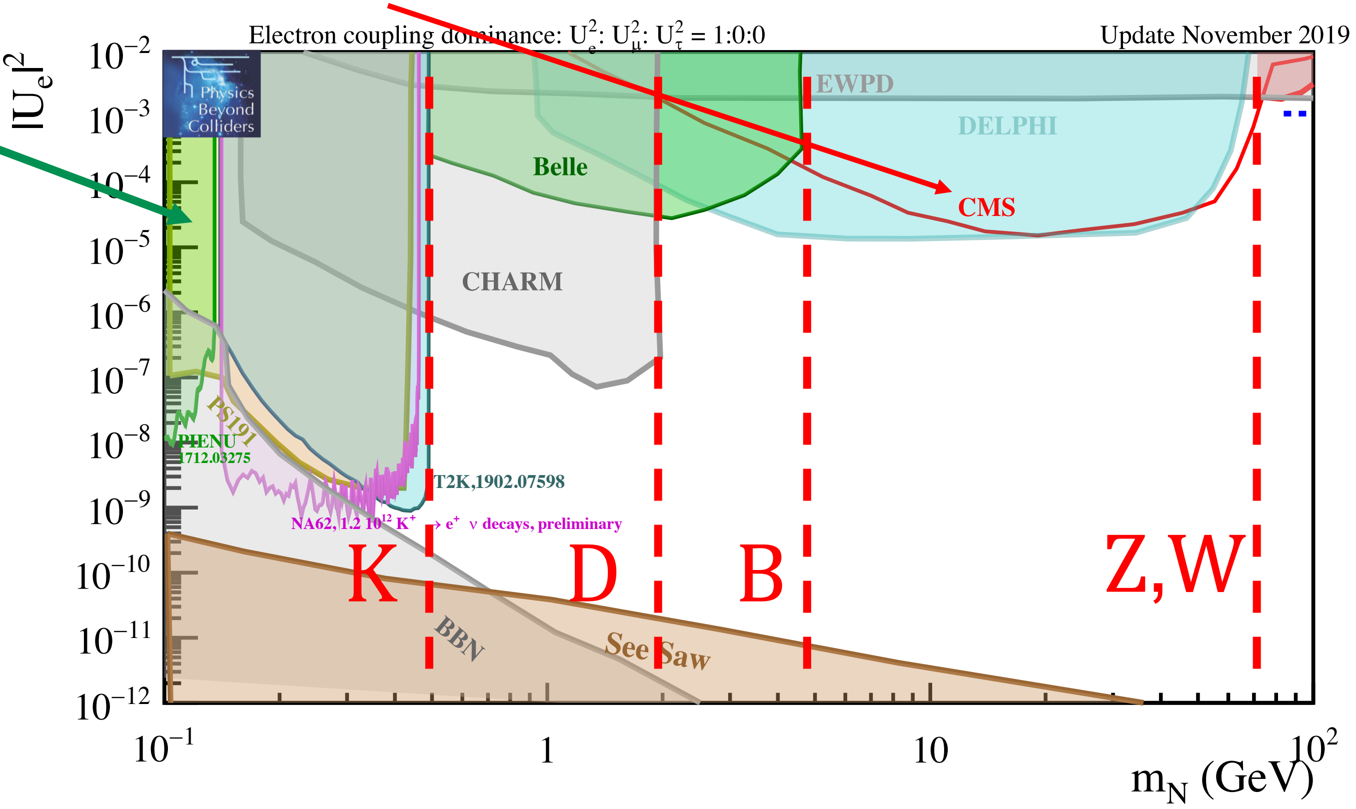
3.3×10^6 hadronic Z^0 decays at LEP1

Z. Phys. C74 (1997) 57.

HNL searches - the present (2018-2019)

2018: CMS: trilepton search, any combination of electrons/muons, prompt decays only, LNV or LNC , (N-> W l, W -> l' nu) 13 TeV, 35 fb^{-1}. 1802.02965 (not much better than DELPHI)

2018: PIENU @ TRIUMF M13 beamline,
10^7 $\pi^+ \longrightarrow e^+ \nu$ decays, p = 75 MeV
(4 years of data taking).
Phys.Rev. D97 (2018) no.7, 072012



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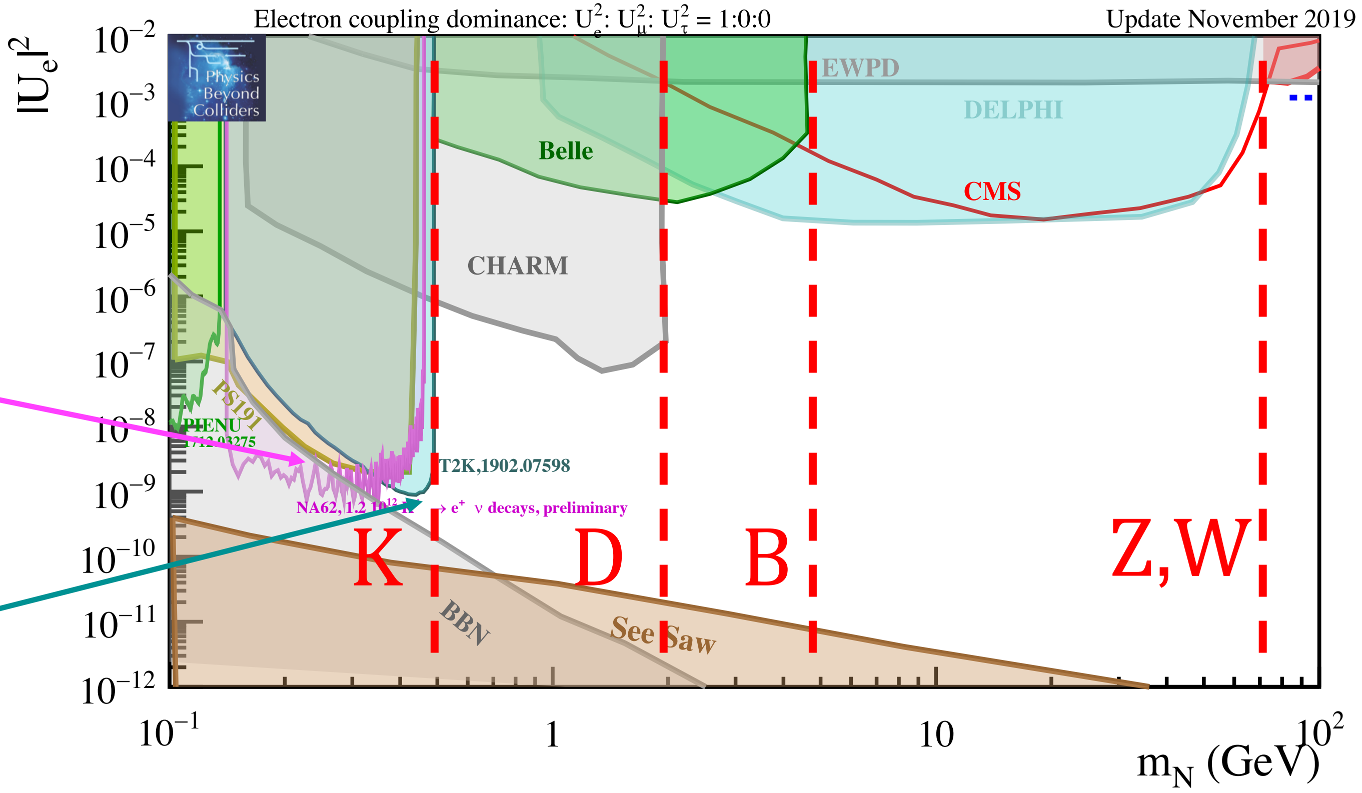
(4 years of data taking).
Phys.Rev. D97 (2018) no.7, 072012

2019: NA62 in kaon mode, preliminary
1.2×10^{12} K^+ decays in FV (30% of 2016-2018 dataset)
[Goudzovski, KAON2019]

2019: T2K, off-axis ND280,
2010-2017 dataset,
(12.34×10^{20} pot (ν-mode) and 6.3 10^{12} pot (anti-ν mode))
Phys.Rev. D100 (2019) no.5, 052006, arXiv:1902.07598

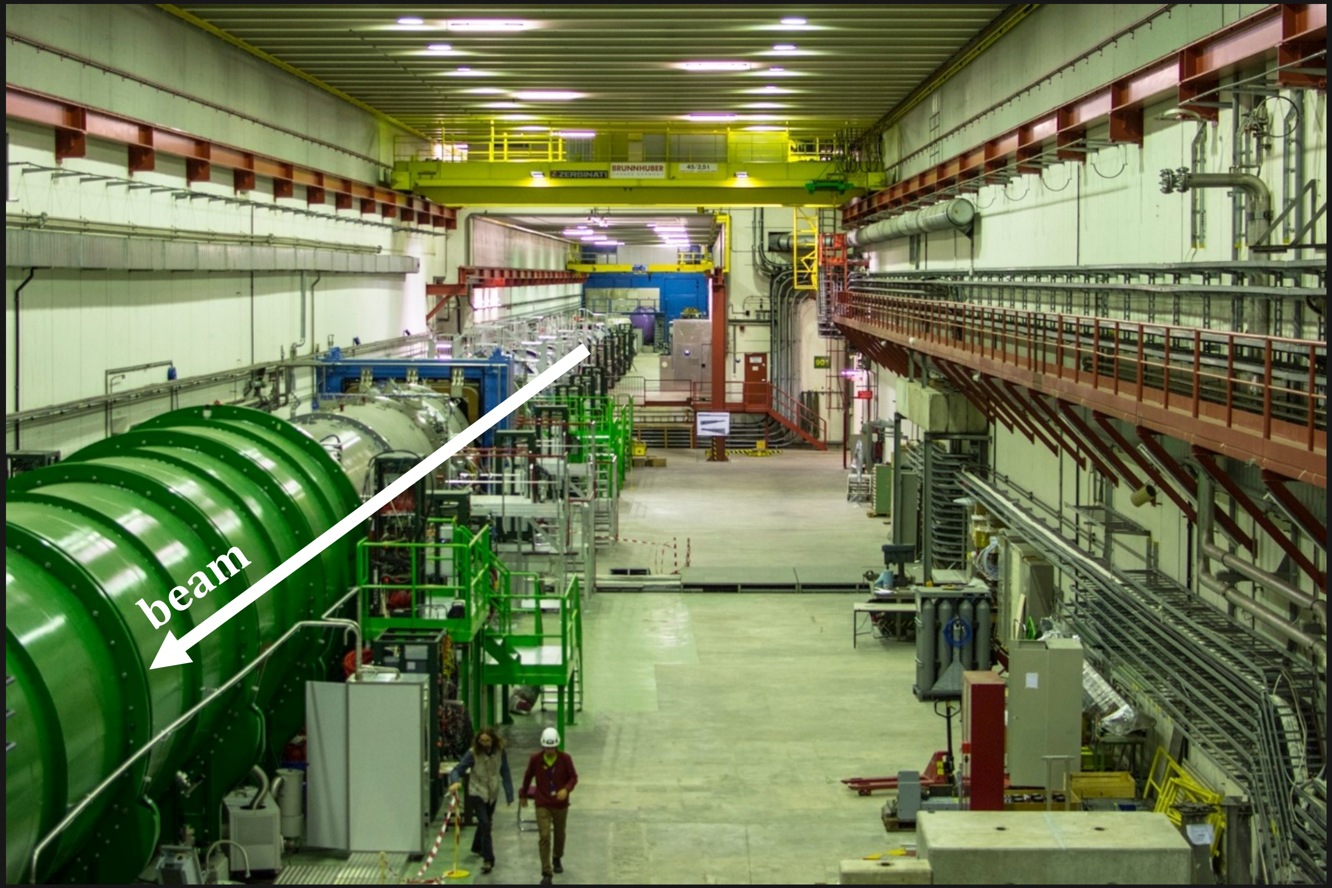


NA62 and T2K pushed the 90% CL exclusion limit down to the BBN boundary. Beautiful results.

The NA62 experiment @ K12 in EHN3

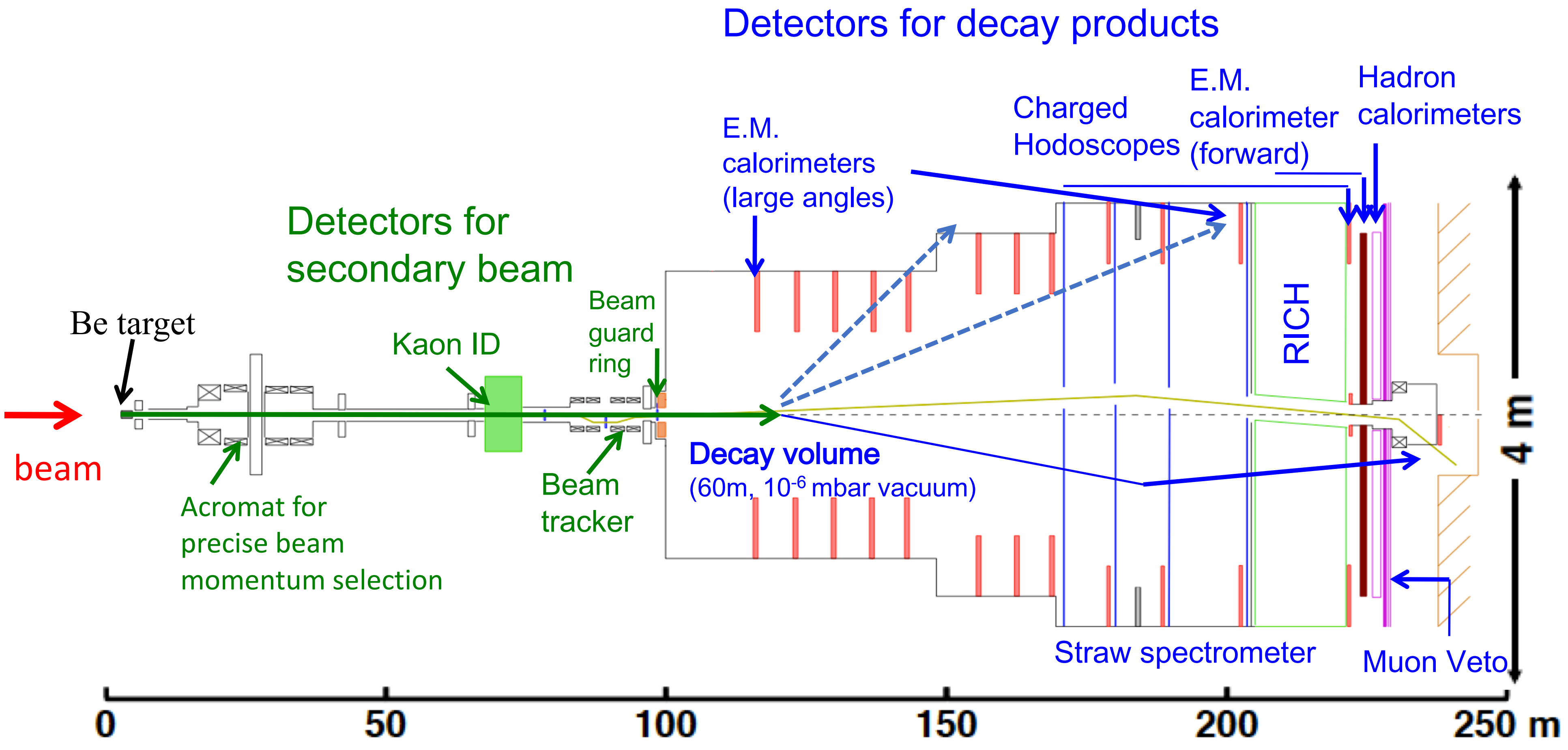
(the "Kaon Factory")

https://na62.web.cern.ch/



NA62 currently running in K12. Main goal: measure the BR($K^+ \longrightarrow \pi^+ \nu \bar{\nu}$) with 10% accuracy.

The NA62 experiment - layout



Physics run 2016 (30 days, ~1.3×10^{12} ppp): 2×10^{11} useful K^+ decays.

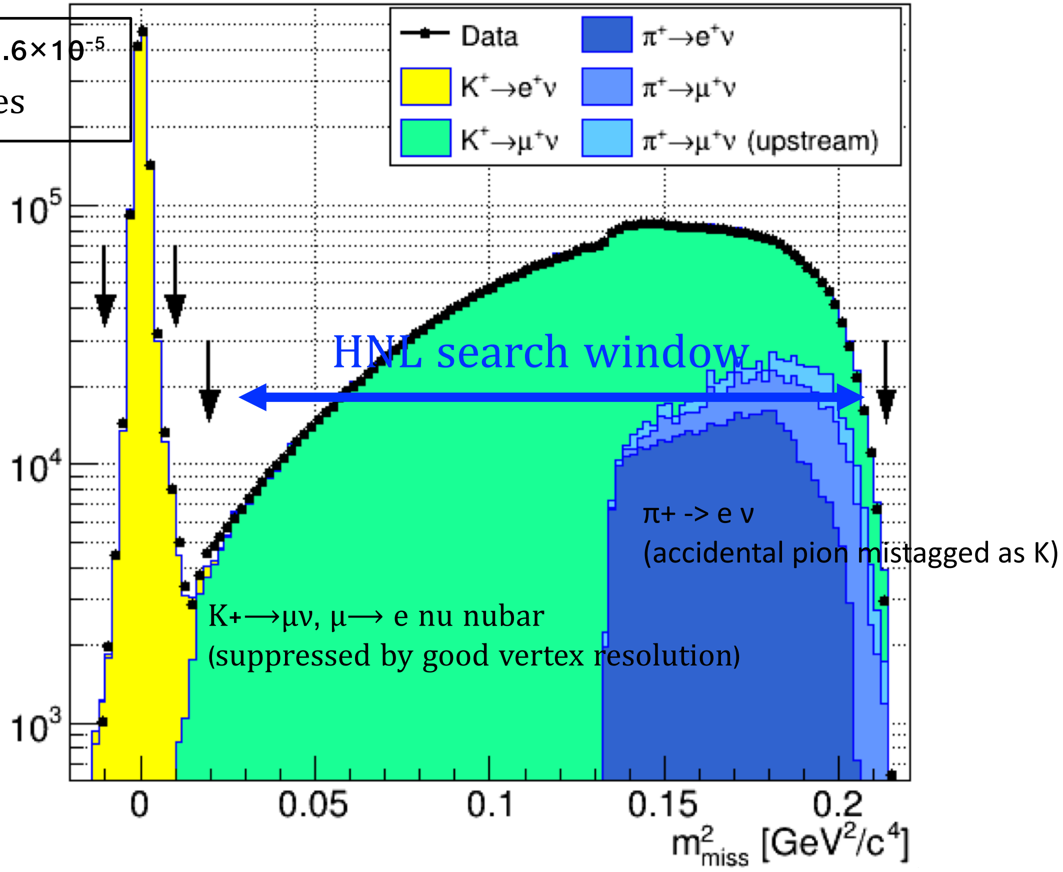
Physics run 2017 (161 days, ~2.0×10^{12} ppp): 2×10^{12} useful K^+ decays.

Physics run 2018 (217 days, ~2.3×10^{12} ppp): 4×10^{12} useful K^+ decays.

NA62 in kaon mode

HNL search in $K^+ \longrightarrow e^+ N$ and $K^+ \longrightarrow \mu^+ N$ decays: bump hunting over continuous background spectrum

K+->e+nu, BR=1.6×10⁻⁵
1.19M candidates



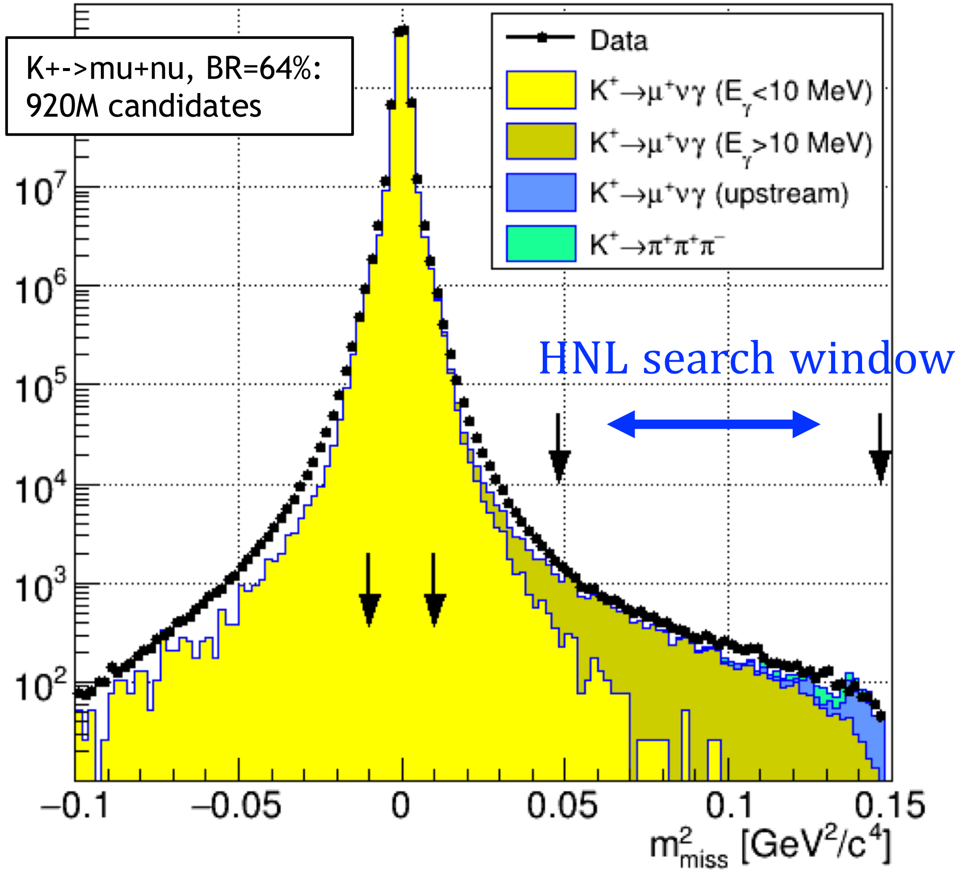
HNL search window

π+ -> e ν
(accidental pion mistagged as K)

K+⟶μν, μ⟶ e nu nubar
(suppressed by good vertex resolution)

squared missing mass: $(P_K-P_e)^2$

K+->mu+nu, BR=64%:
920M candidates



HNL search window

squared missing mass: $(P_K-P_\mu)^2$

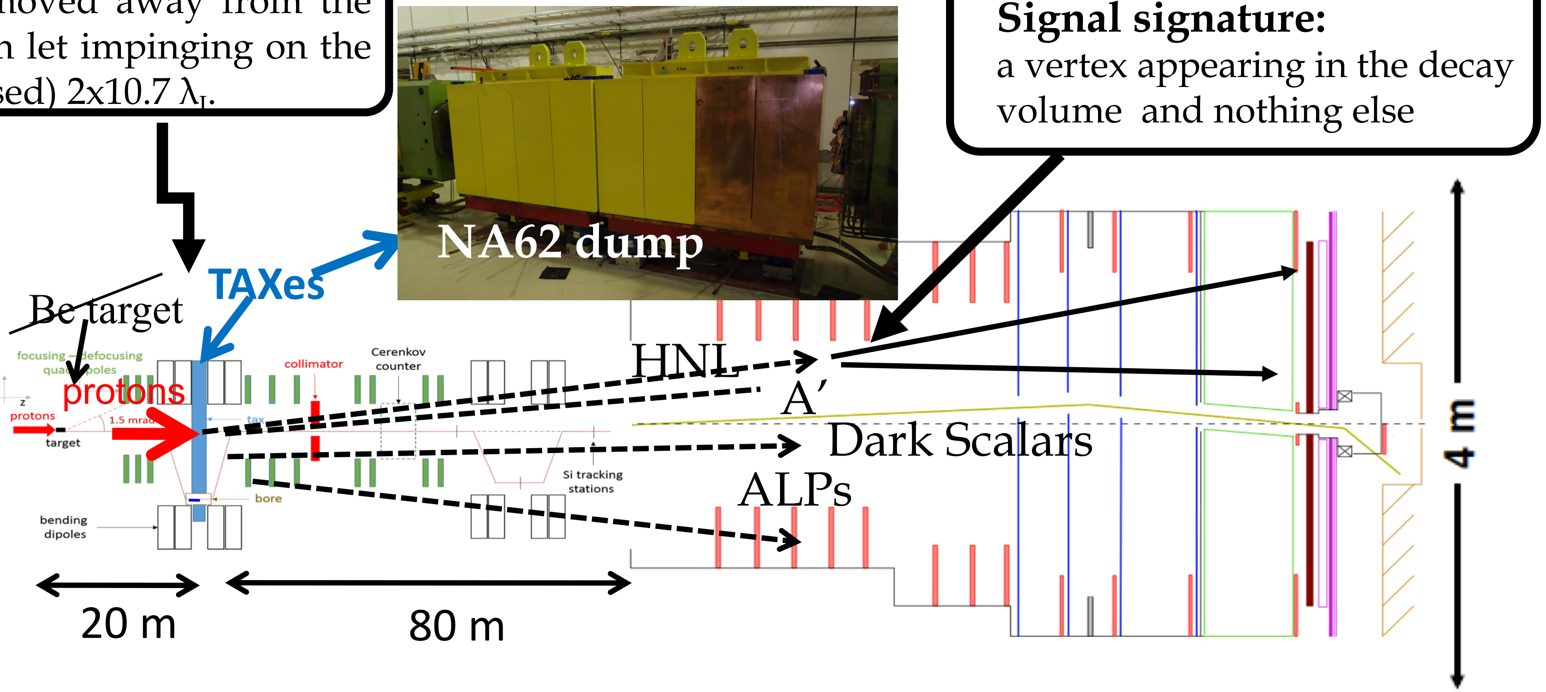
Searches are background dominated - progress will be slow

NA62 in dump mode

Dump mode allows NA62 to search for Hidden States above the K^+ mass.
Switch between kaon and dump mode possible within minutes.
~3x10^{16} pot collected in dump mode in 2016-2018 (~50 integrated hours of data taking)

Be target can be moved away from the beam and the beam let impinging on the collimators (Cu-based) 2x10.7 λ_I.

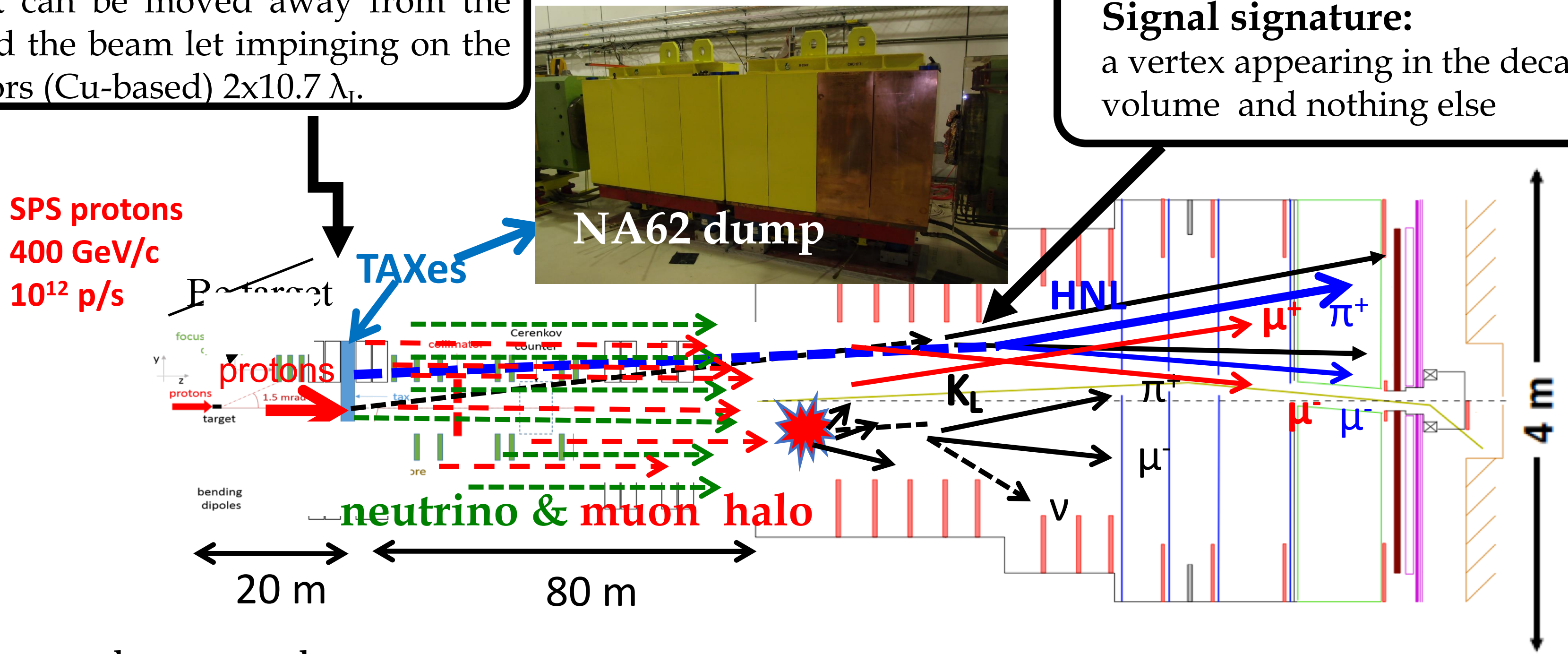
Signal signature:
a vertex appearing in the decay volume and nothing else



NA62 intends to collect 10^{18} POT in dump mode before LS3 (e.g.: by 2024-2025)
This corresponds to 3-4 months of dedicated data taking at 100% (or slightly more) beam intensity.

NA62 in dump mode

Dump mode allows NA62 to search for Hidden States above the K⁺ mass.
Switch between kaon and dump mode possible within minutes.
~3x10¹⁶ pot collected in dump mode in 2016-2018 (~50 integrated hours of data taking)



Be target can be moved away from the beam and the beam let impinging on the collimators (Cu-based) 2x10.7 λ_I.

Signal signature:
a vertex appearing in the decay volume and nothing else

Two types of background expected:

1) muon combinatorial background:

⟶ mostly out-of-time tracks, not pointing backwards to the target; main detector to reject it: tracker and charged hodoscopes

2) neutrino and muon inelastic interactions with the detector material, namely with the decay vessel;

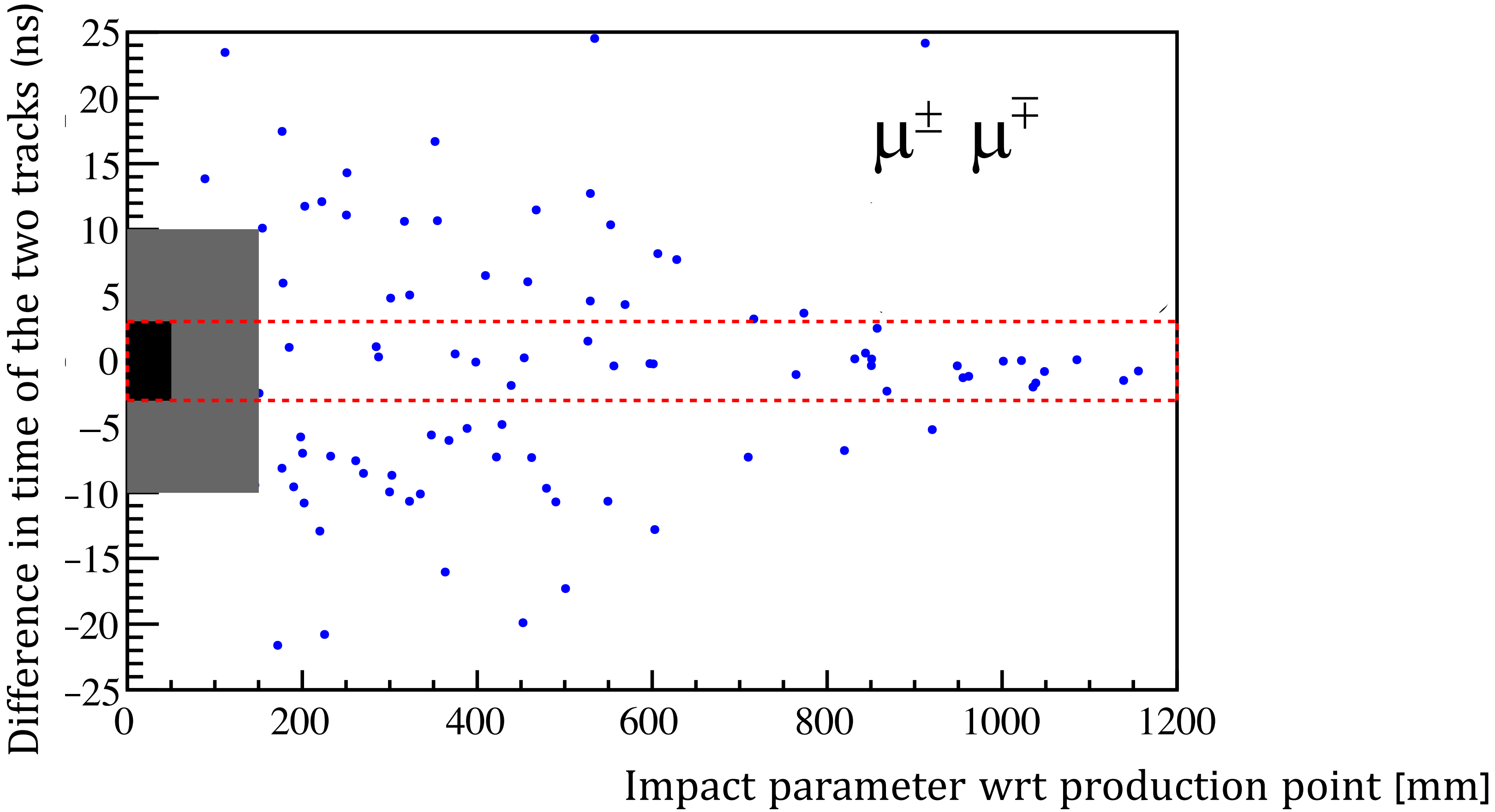
→ mostly in-time tracks, not pointing backwards to the target; main detectors to reject it: tracker for pointing & VETOes.

Combinatorial μ+μ- background

An example of how the μ+μ- background looks like in a dump experiment

Signal region

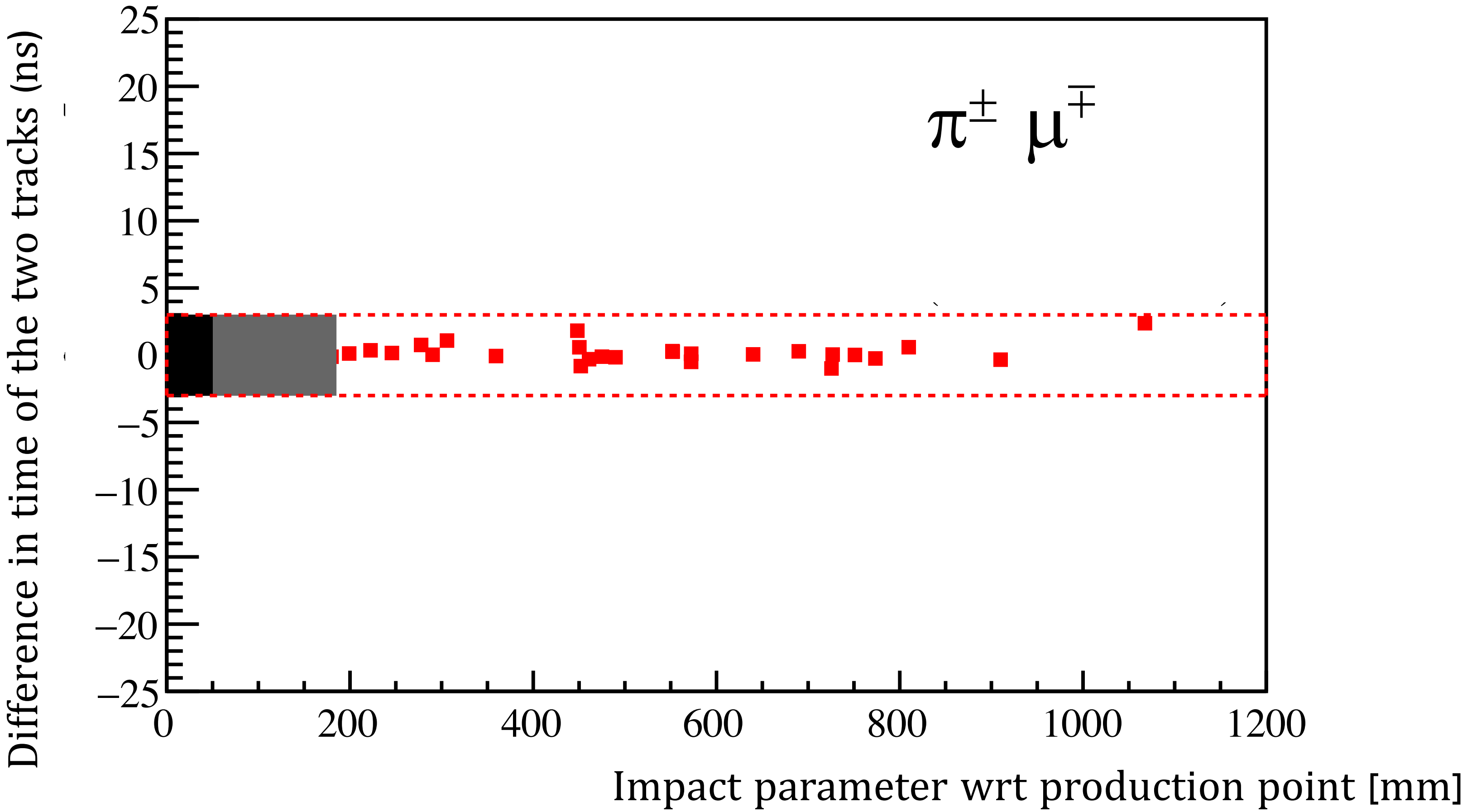
Bkg control region



Dimuon background is dominated by combinatorial background.
hence it is intrinsically made of out-of-time events with sparse IP values.

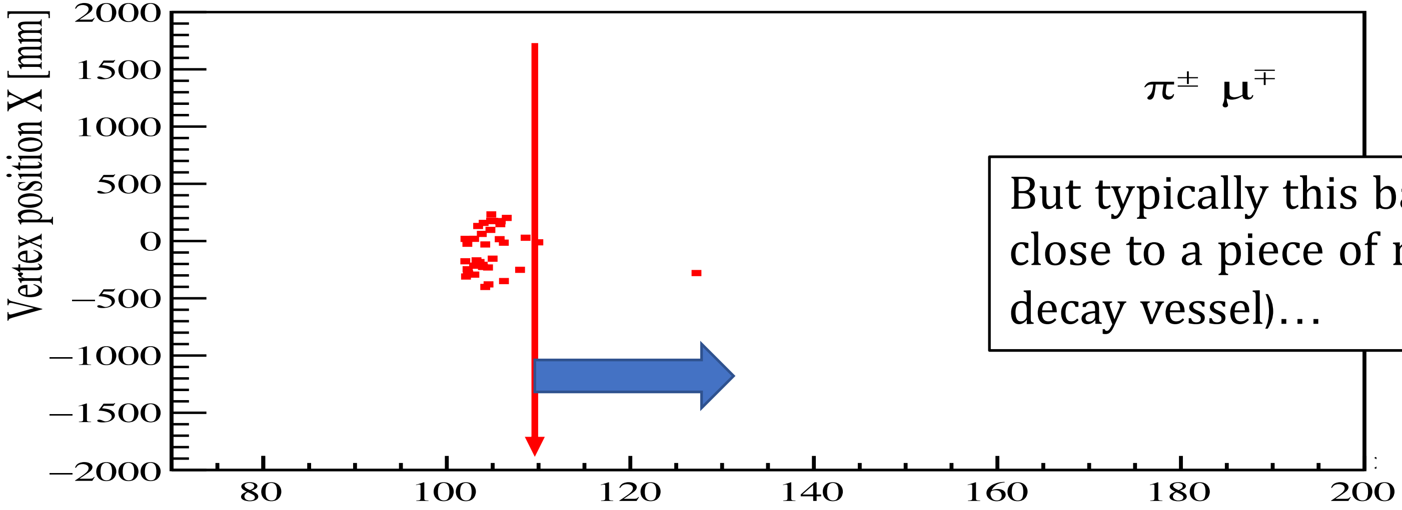
muon/neutrino inelastic interactions: **$\pi^{\pm}\mu^{\mp}$** background

An example of how the π+μ- background looks like in a generic dump experiment

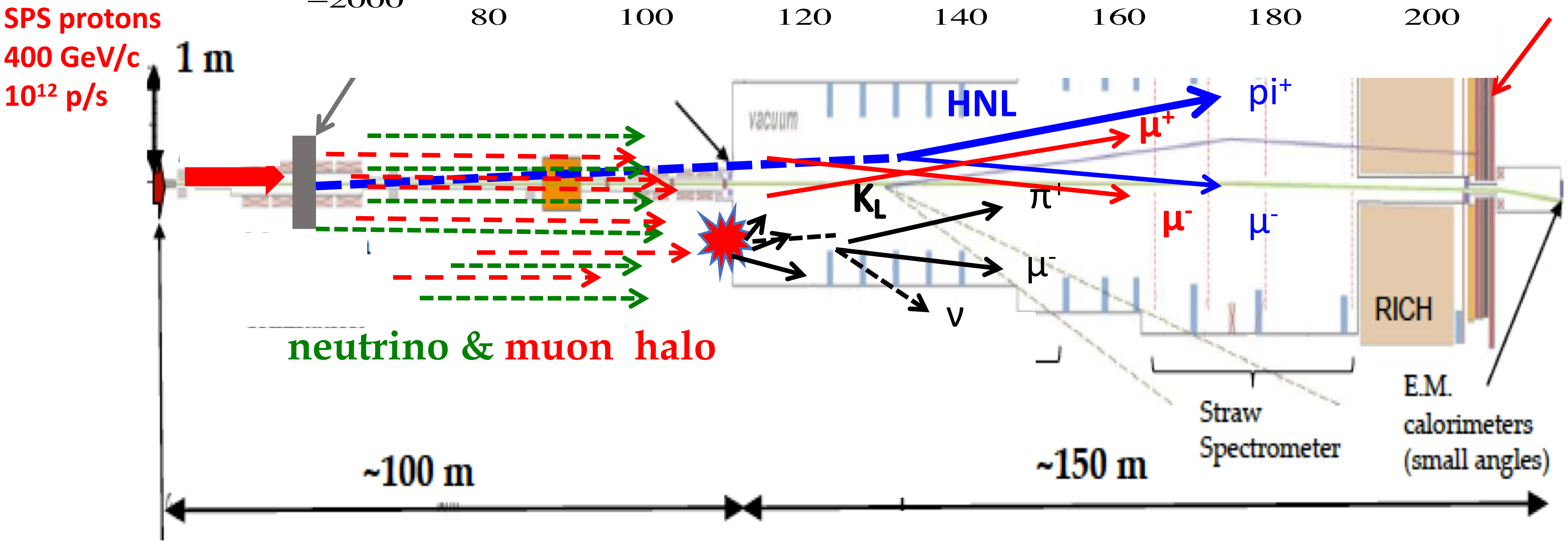


π+μ- background is dominated by inelastic interactions,
hence it is intrinsically made of in-time events with whatever IP.

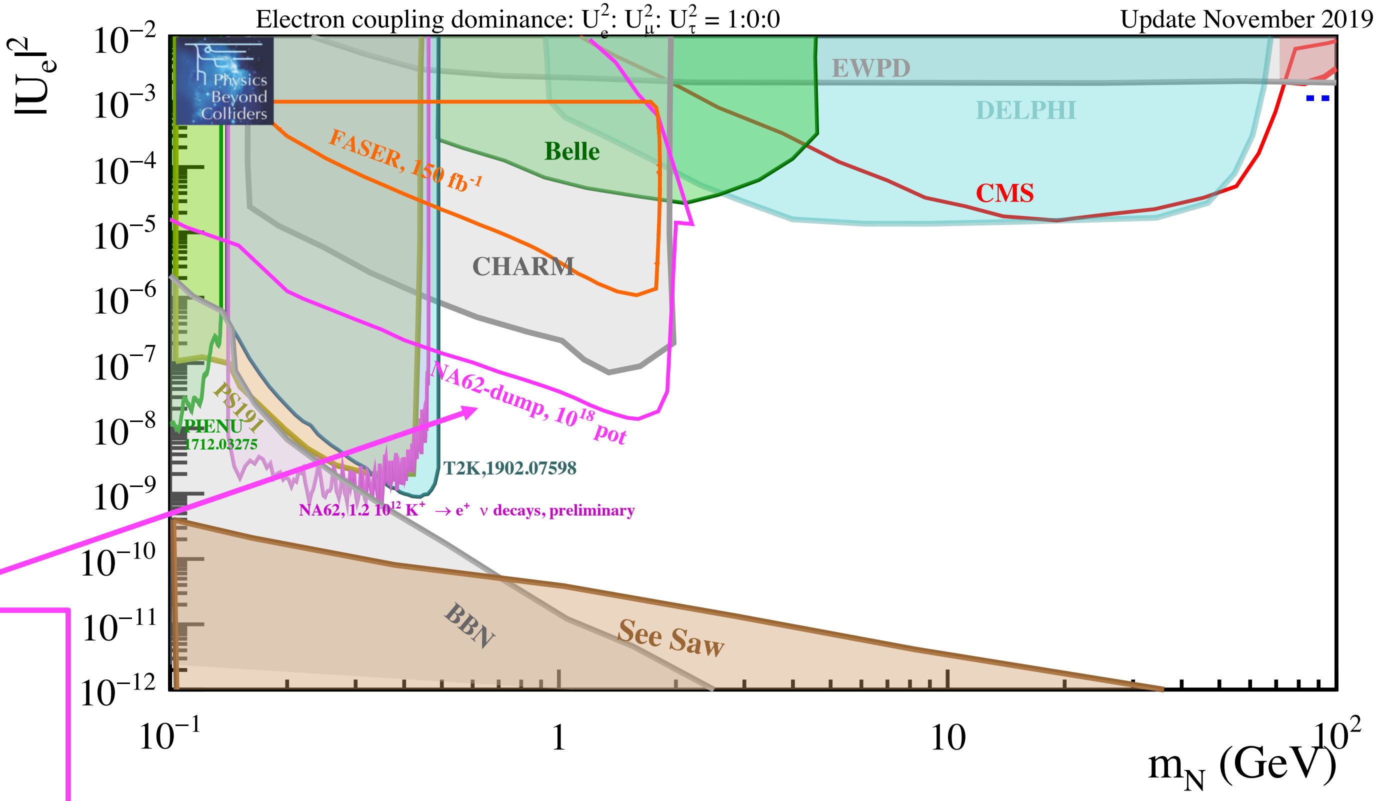
muon/neutrino inelastic interactions: $\pi^{\pm}\mu^{\mp}$ background



But typically this background is concentrated close to a piece of material (eg: endcap of the decay vessel)…



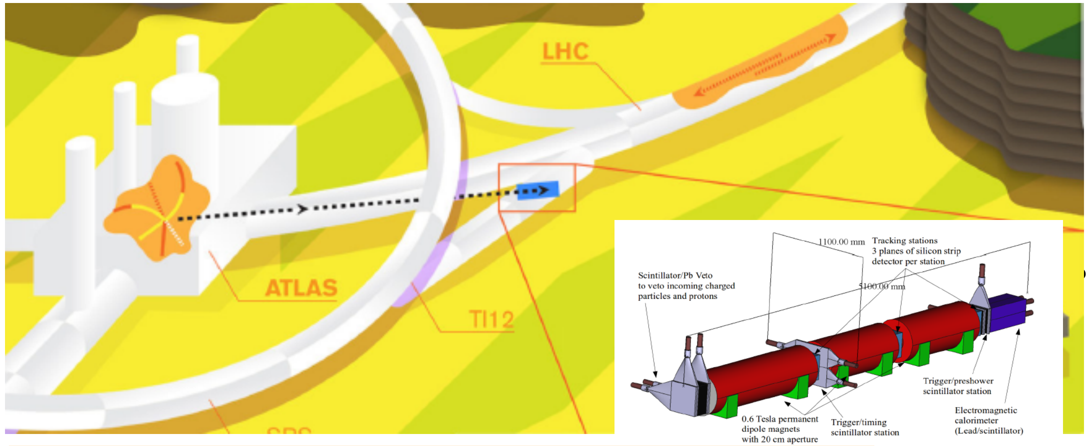
HNL searches: the short-term future (2021-2024)



NA62-dump:

Addendum CERN-SPSC-2019-039 submitted to the SPSC in October: 2-3 months in Run 3 to collect ~10^{18} pot in dump mode and go beyond the K mass.

HNL searches: the short-term future (2021-2024)



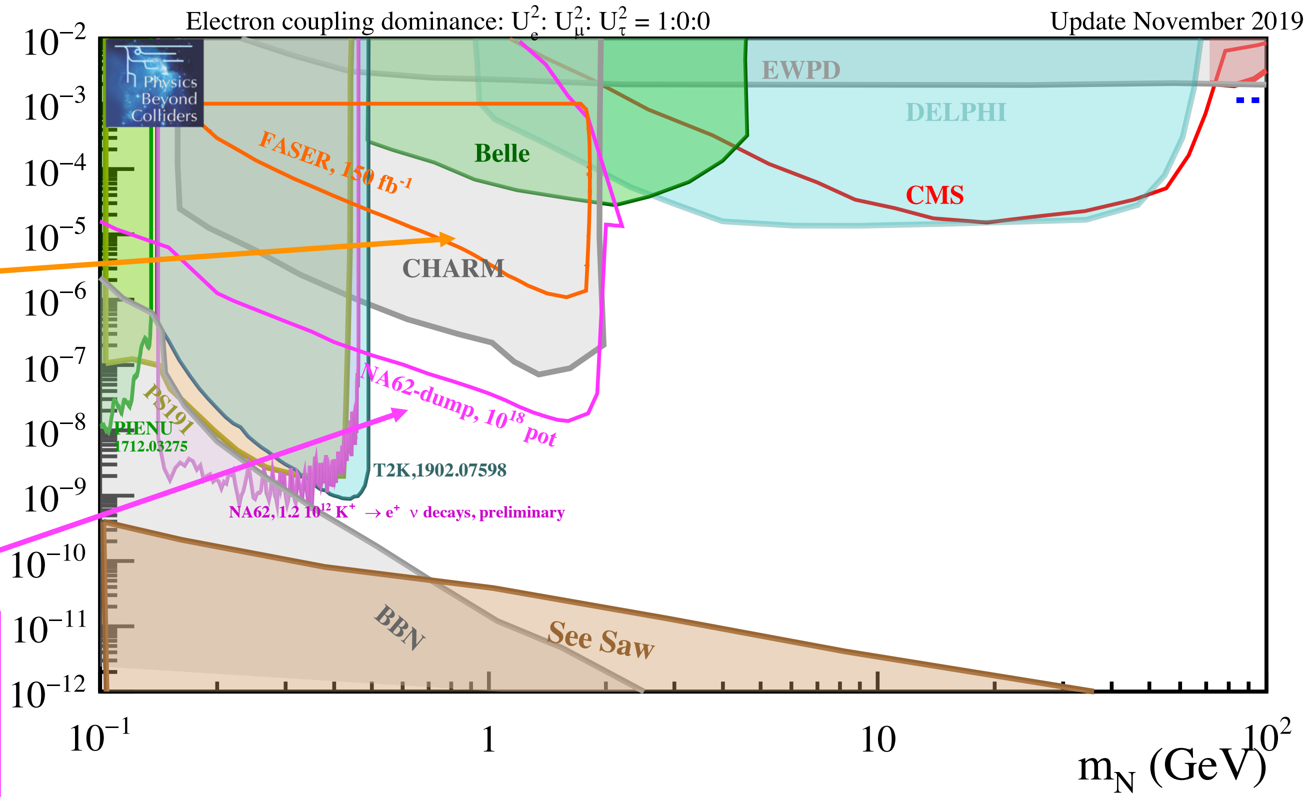
FASER, 1811.10243

10 cm radius, 1.5 m long

approved by the CERN Research Board

In March 2019 and being installed now

@ TI12, 480 m downstream of ATLAS IP.



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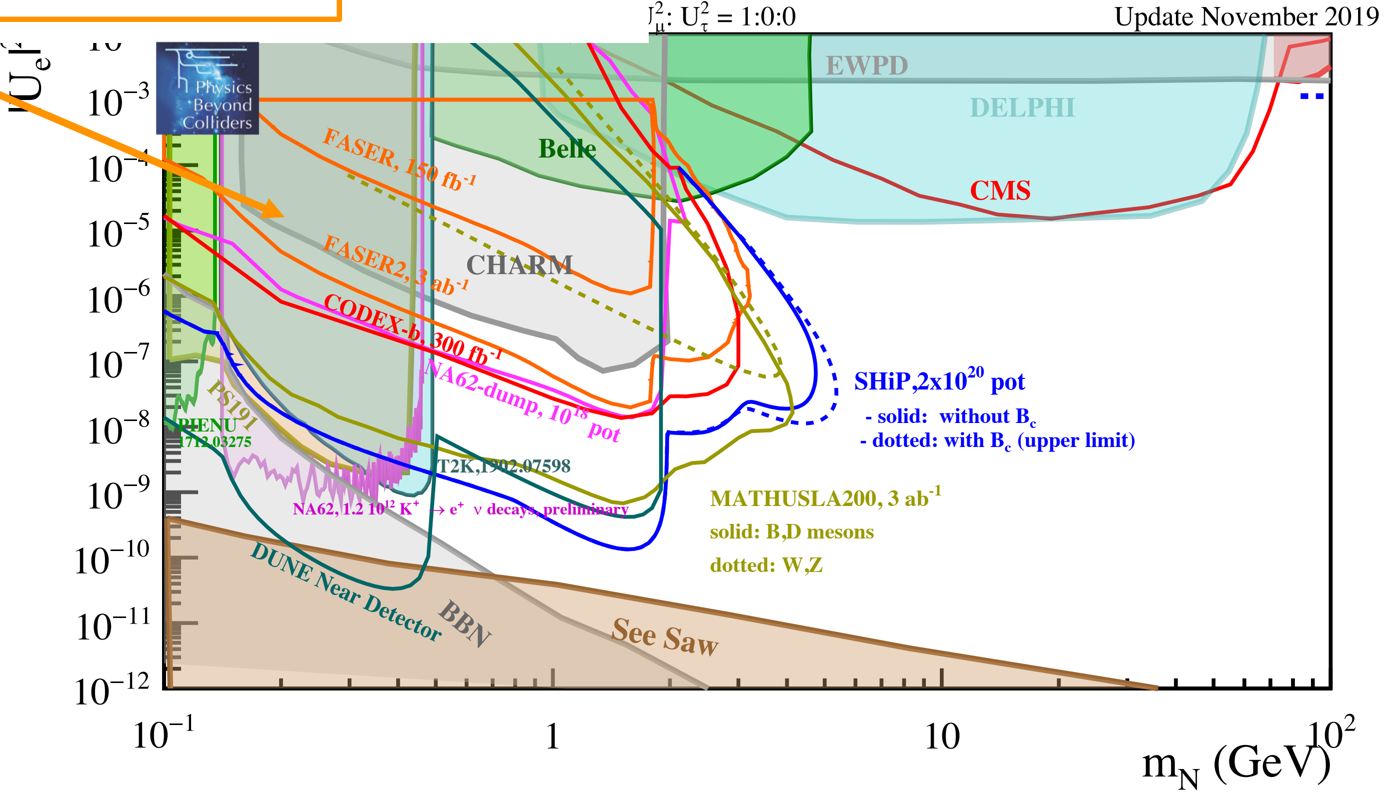
HNL experimental searches

the medium-term future (10-15 years)

HNL searches: the medium-term future (2028++)

<u>FASER2: </u>upgrade of FASER detector
R = 1 m, length = 5 m
Aim to collect 3 ab⁻¹ in HL-LHC era.

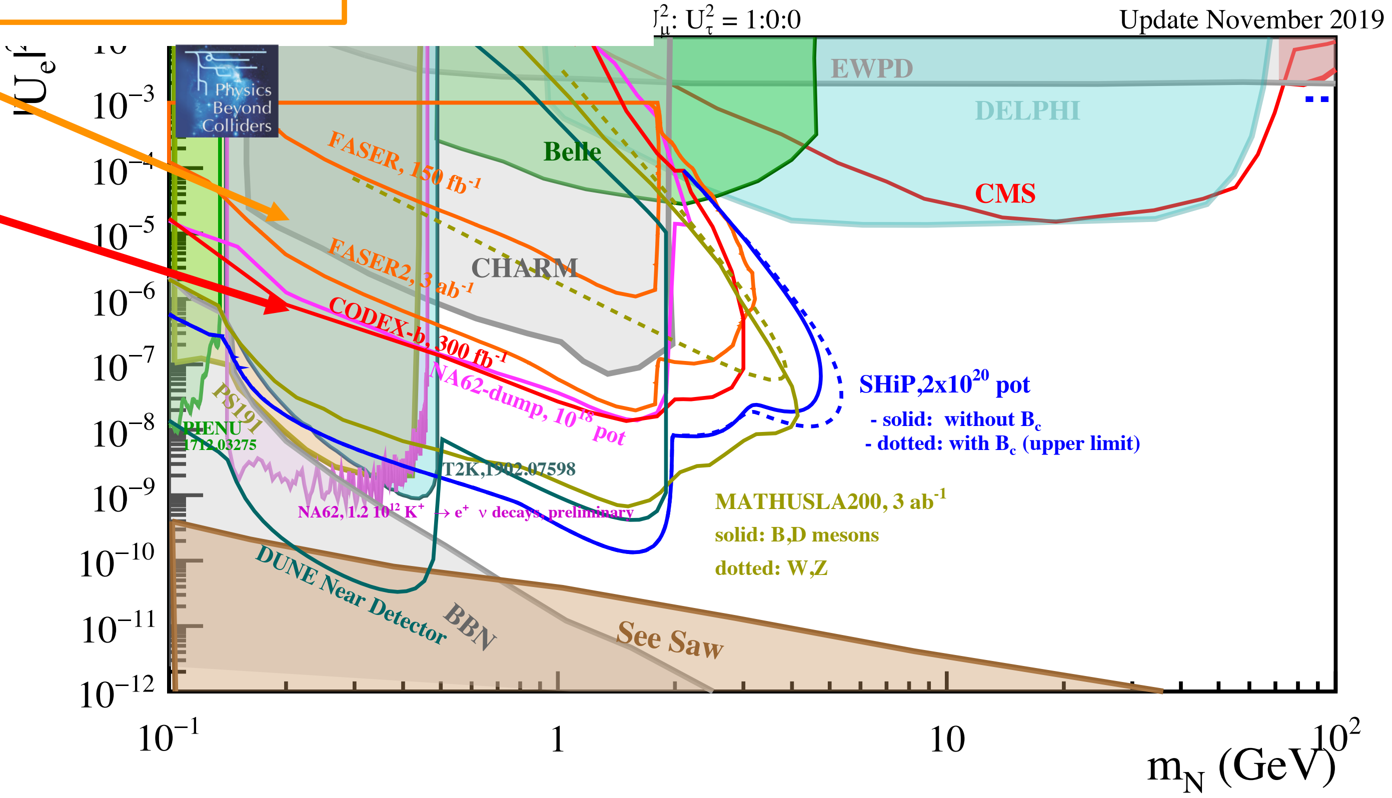


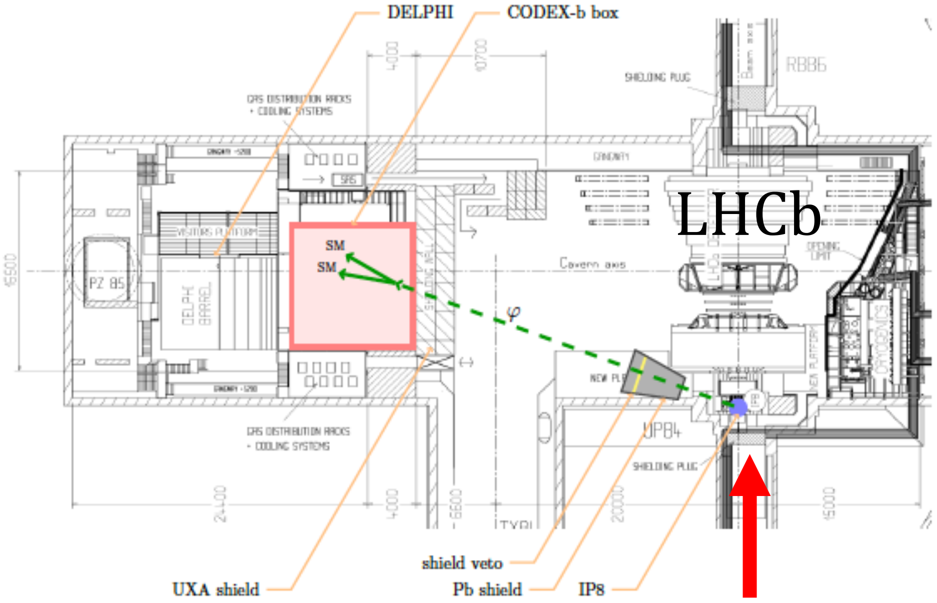
HNL searches: the medium-term future (2028++)

FASER2: upgrade of FASER detector
R = 1 m, length = 5 m
Aim to collect 3 ab⁻¹ in HL-LHC era.

CODEX-b: 1708.09395, 1911.00481

- UXA hall, 25 m away from LHCb IP
- 300 fb-1 in Run 5
- 10x10x10 m³ RPC-based detector.

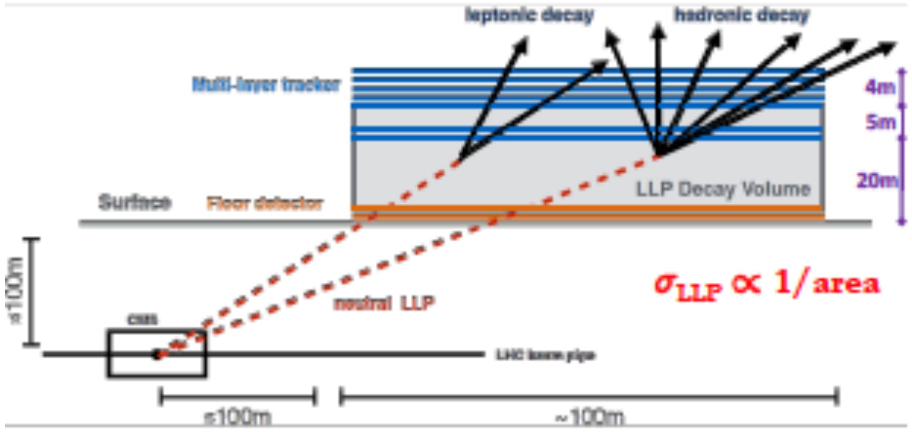


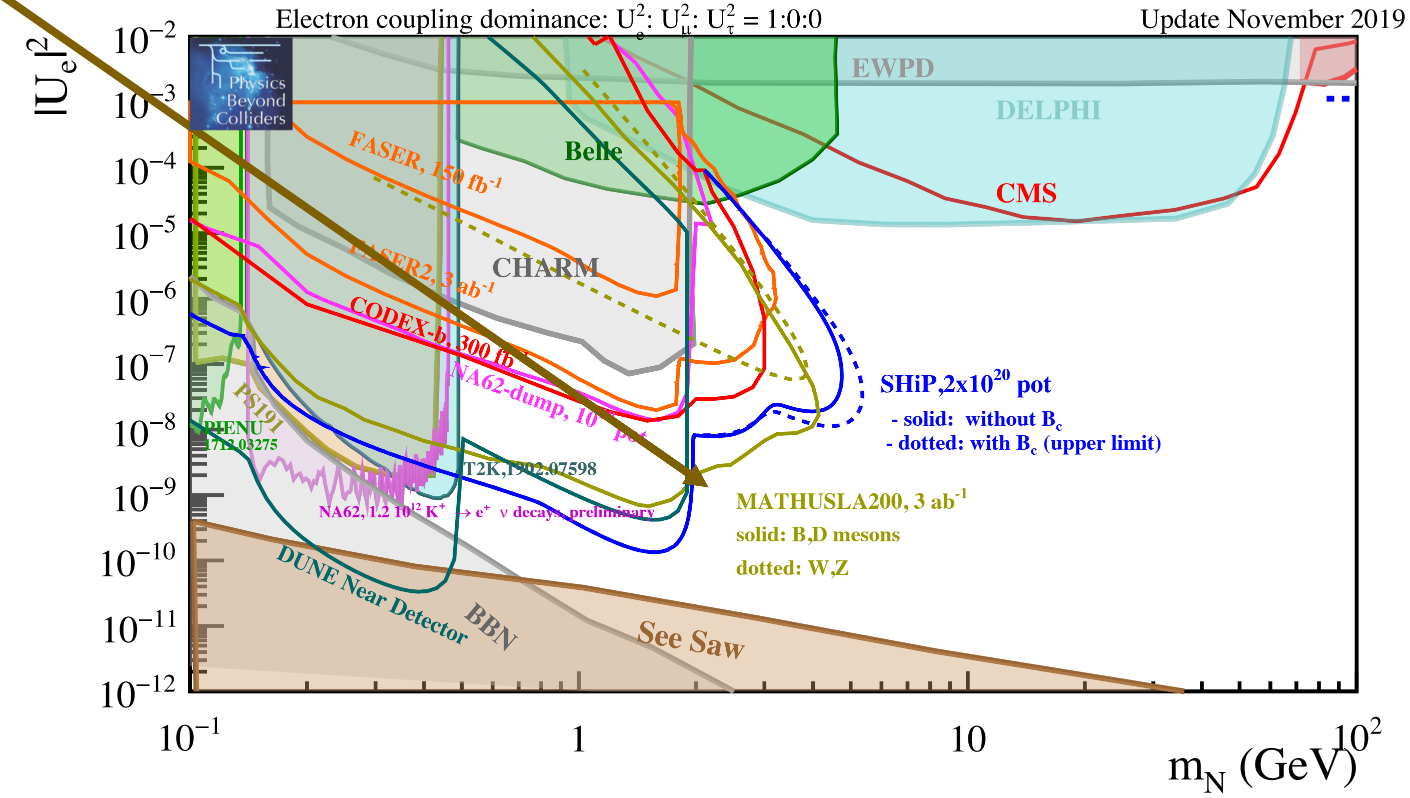


A lot of creativity in proposing the use of unexpected sites….

HNL searches: the medium-term future (2028++)

MATHUSLA: 200x200 (or 100x100) m² on top of CMS
20 m of decay volume, 1 veto layer, 5 tracking planes;
3 ab^{-1} in the HL-LHC era [1606.06298, 1806.07396, CERN-LHCC-2018-025]





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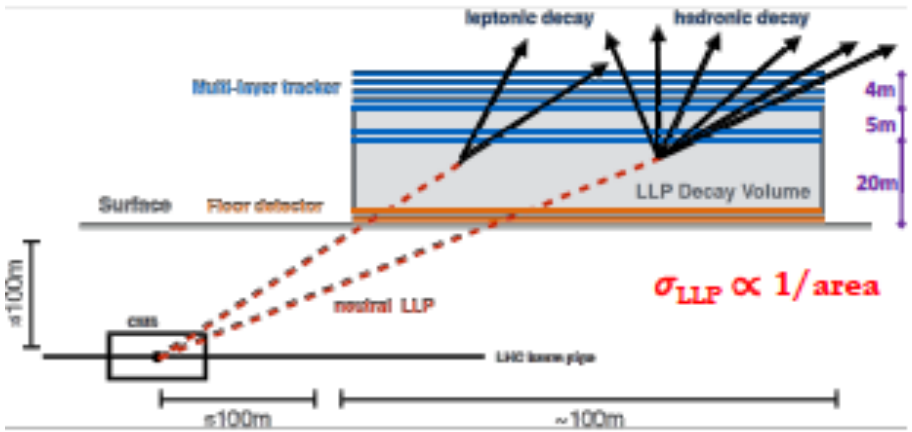
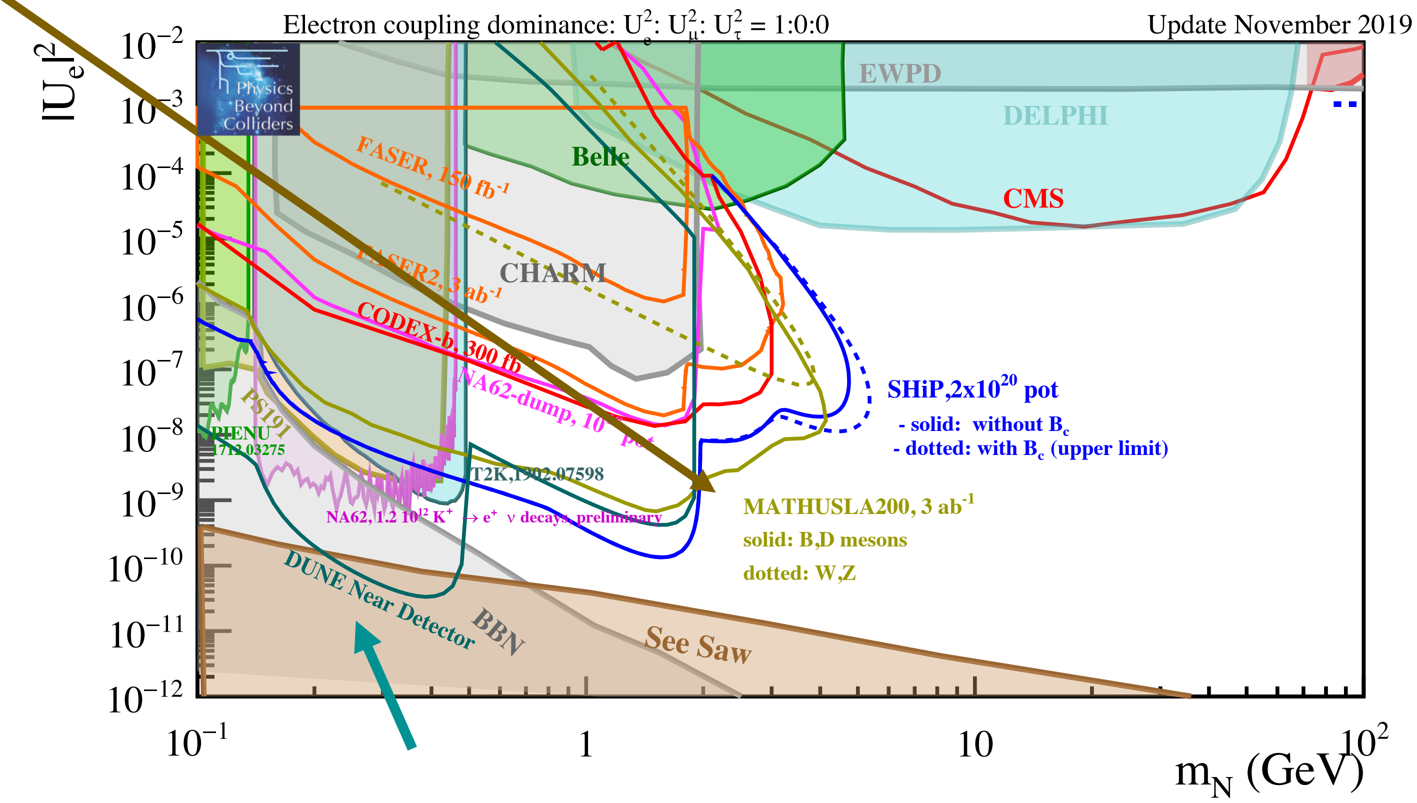
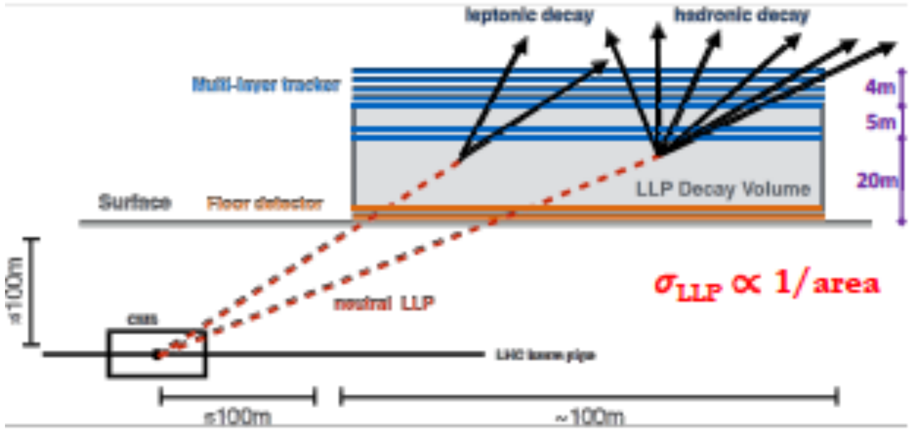


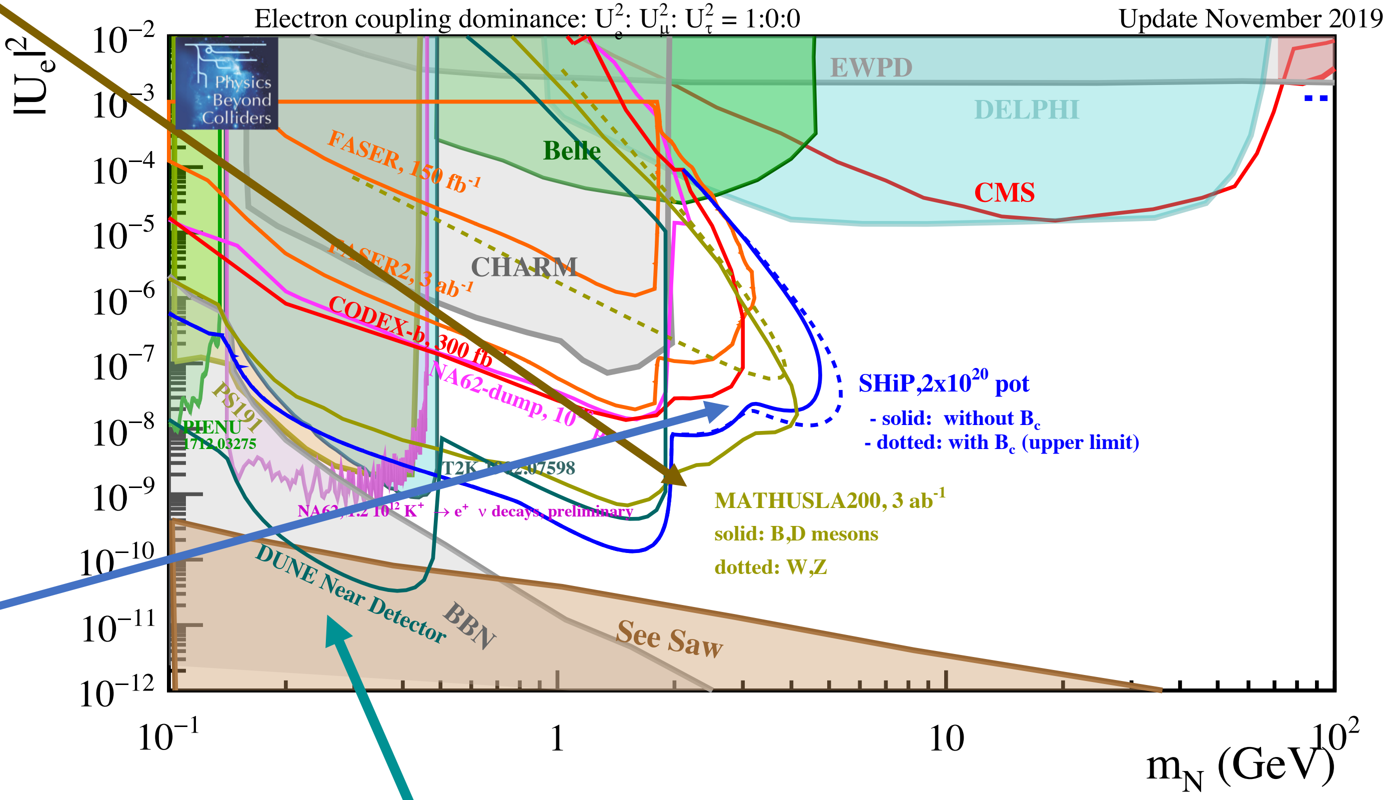


DUNE (preliminary): 12 years of data taking, 2x10^{22} pot collected; K and D produced in a graphite target

HNL searches: the medium-term future (2030++)

MATHUSLA: 200x200 (or 100x100) m² on top of CMS
20 m of decay volume, 1 veto layer, 5 tracking planes;
3 ab^{-1} in the HL-LHC era [1606.06298, 1806.07396, CERN-LHCC-2018-025]





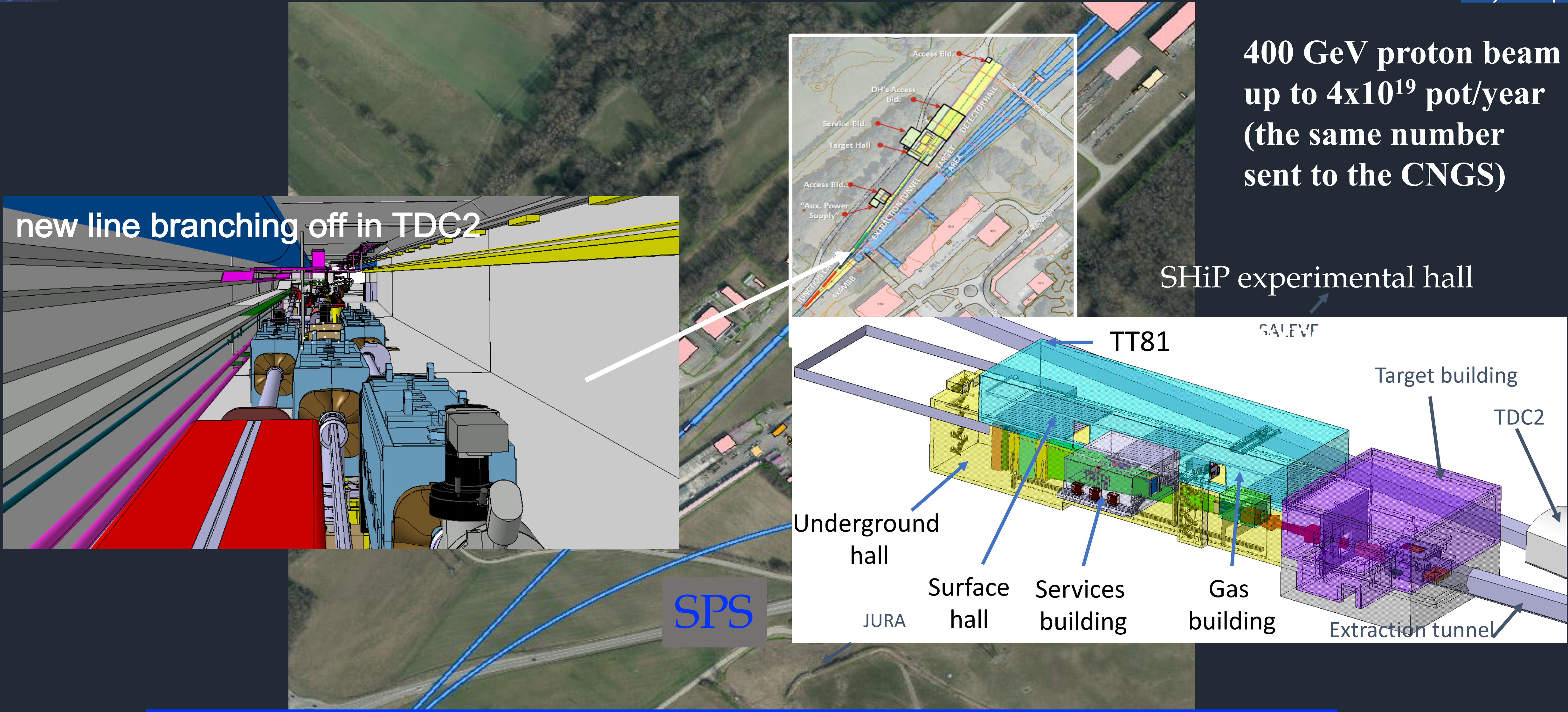
SHiP @ BDF: 5 years of data taking, $2\text{x}10^{20}$ pot **will dominate the searches between K and B masses:**

- SHiP Technical Proposal: [arXiv:1504.04956]
- The SHIP Physics Case: arXiv: 1504.04955
- SHiP Progress Report: CERN-SPSC-2019-010
- SHiP Comprehensive Design Study in preparation

DUNE (preliminary): 12 years of data taking, $2\text{x}10^{22}$ pot collected

The Beam Dump Facility (BDF) in the North Area

400 GeV proton beam up to 4×10^{19} pot/year (the same number sent to the CNGS)



Brand new high-intensity proton beam proposed in the North Area

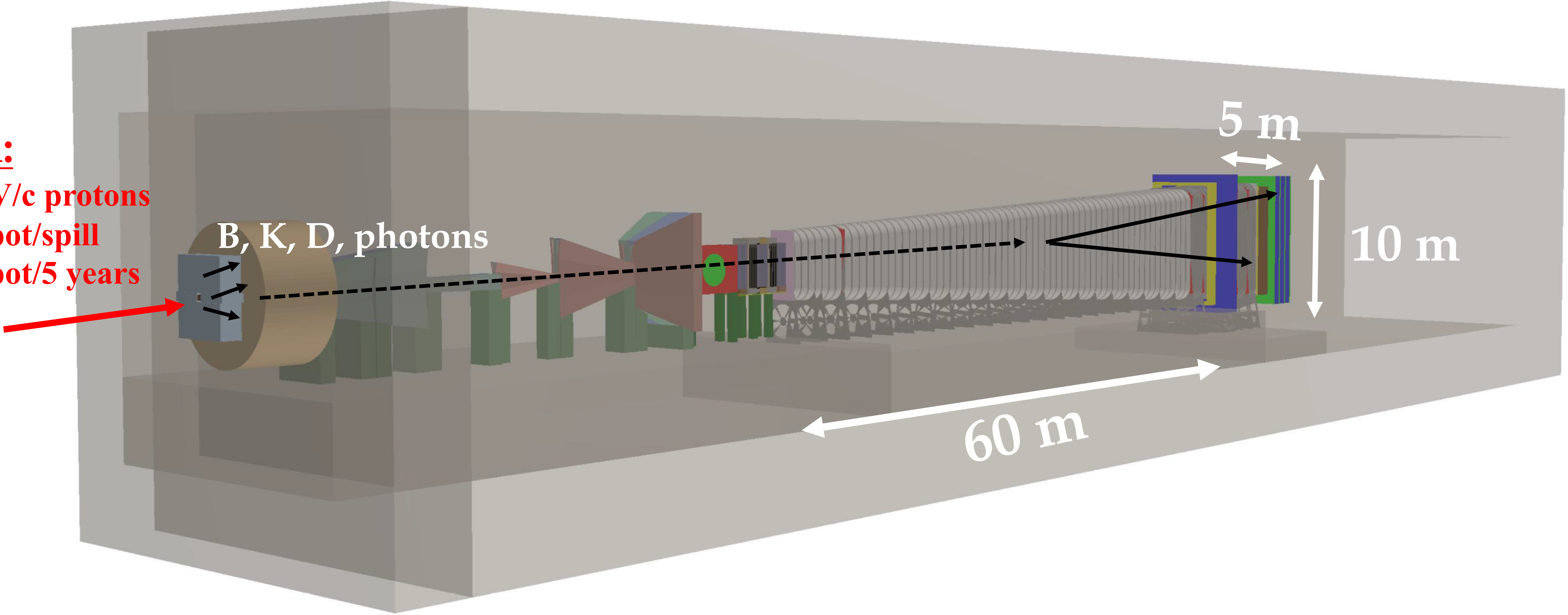
SHiP @ BDF

Beam:

400 GeV/c protons

$4\mathrm{x}10^{13}$ pot/spill

$2\mathrm{x}10^{20}$ pot/5 years



- ✓ Hidden particles have very feeble couplings, hence they are (very) long-lived:
  - The 60m-long, in-vacuum decay volume allows SHiP to be sensitive to extremely low couplings (long lifetimes);
- ✓ Hidden particles from D and B decays have large p_T:
  - SHiP large geometrical acceptance maximizes detection of decay products.

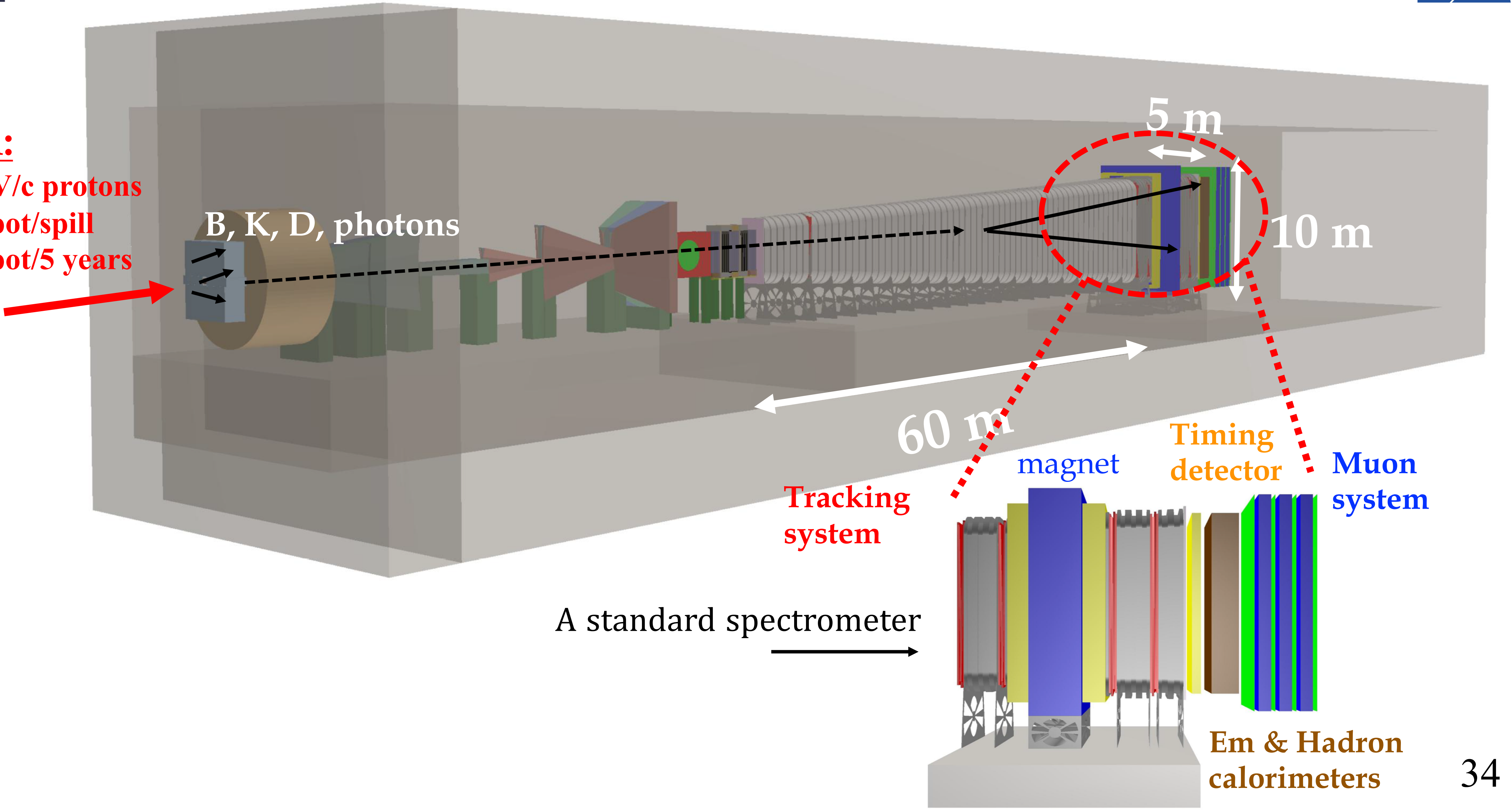
SHiP @ BDF: Hidden Sector Spectrometer

Beam:

400 GeV/c protons

4×10^{13} pot/spill

2×10^{20} pot/5 years

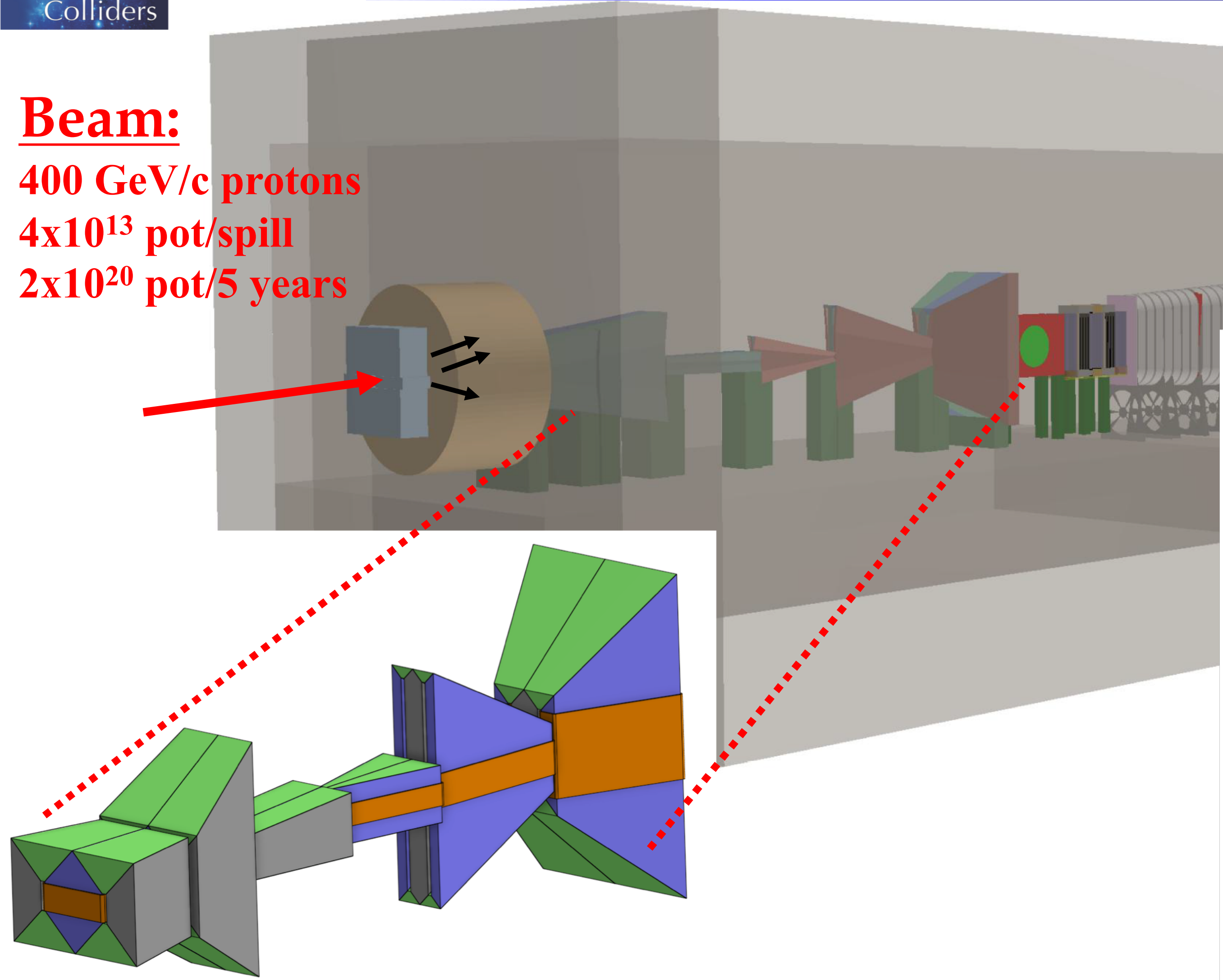


A standard spectrometer

SHiP @ BDF: Active Muon Shield

Beam:

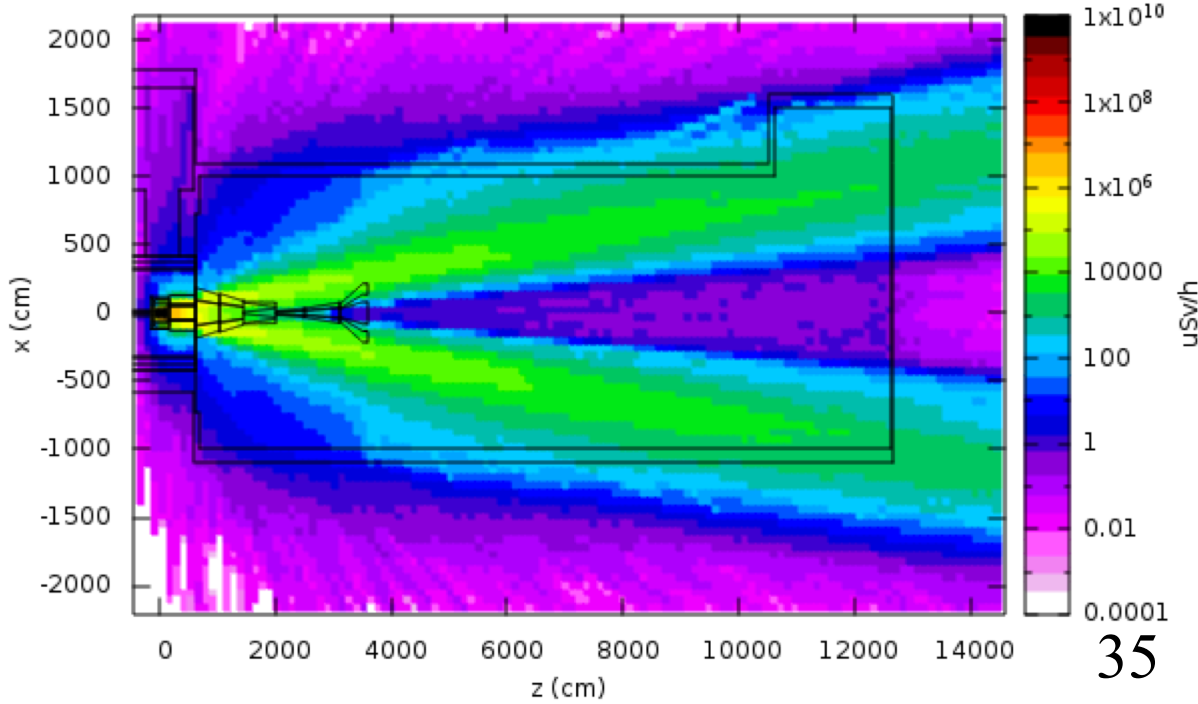
400 GeV/c protons
4×10^{13} pot/spill
2×10^{20} pot/5 years



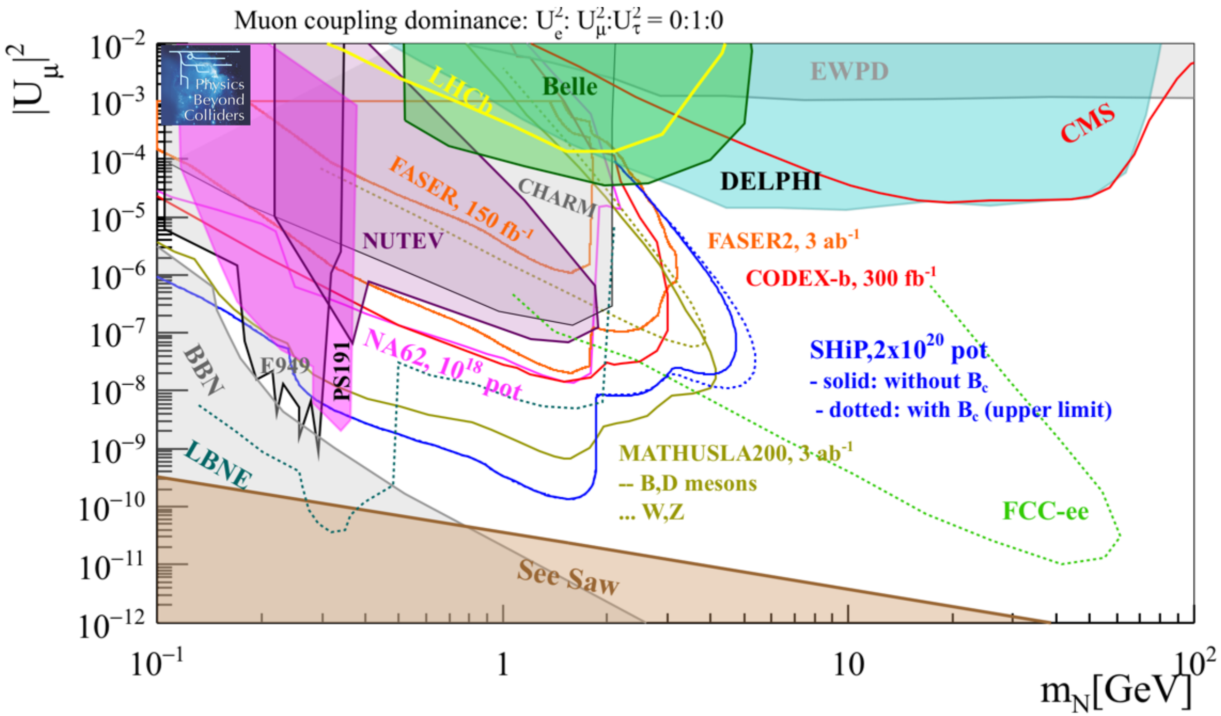
Active Muon Shield:

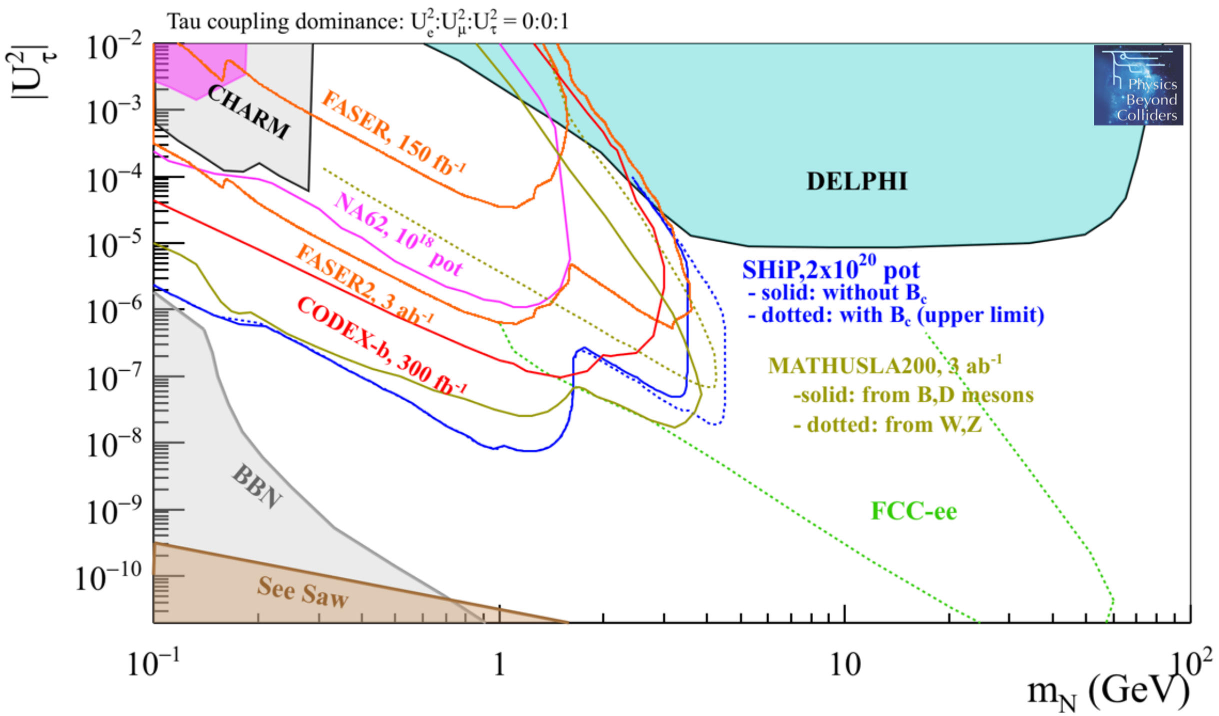
40 m long, 1400 tons of magnets,
sweeps out muons emerging from the target.

Prompt dose rate muons



HNL searches: couplings with second and third generations





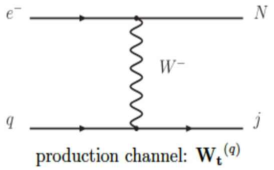
HNL experimental searches:
the very far future (20-30++ years)

HNL experimental searches: the very far future

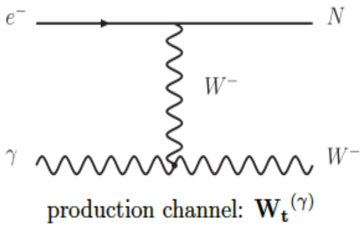
LHeC (1 ab^{-1}, 60 GeV e$^-$, 7 TeV p) and FCC-eh (3 ab^{-1}, 60 GeV e$^-$, 50 TeV p)

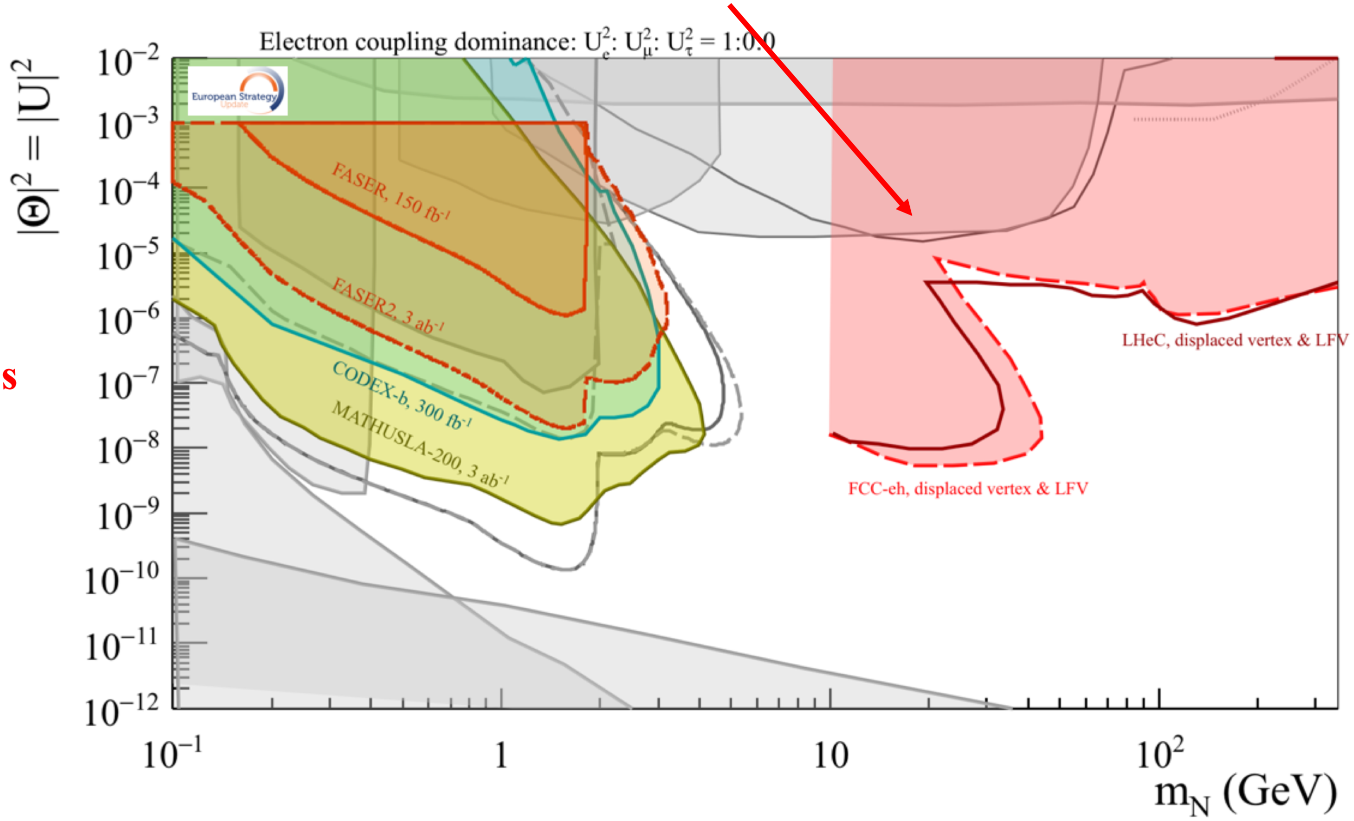
Production mechanisms at e p colliders:

T-channel W boson exchange



γ W boson fusion





Sources:

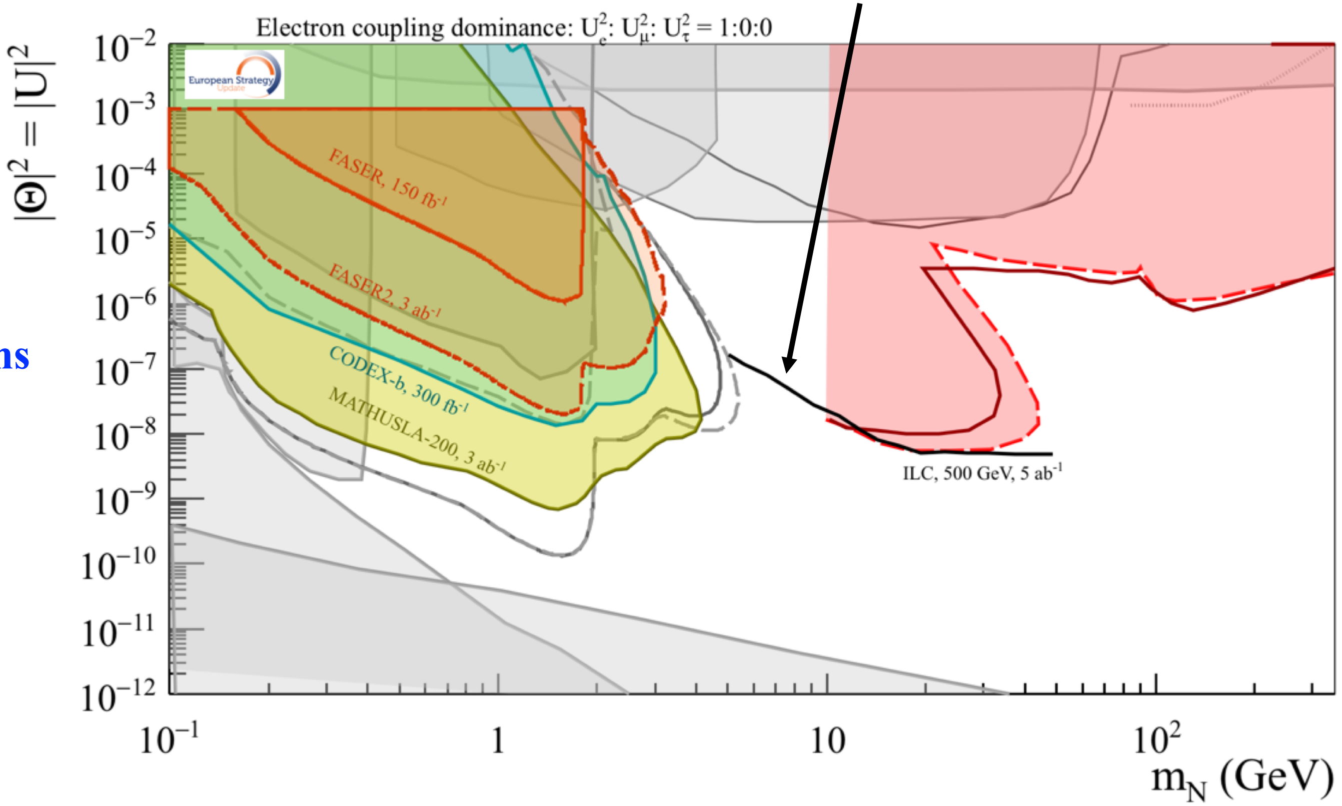
1. Submission #159 to ESPP “Exploring the Energy Frontier with Deep Inelastic Scattering at the LHC,”
2. FCC report, Vol.2 CERN-ACC-2018-0057

Both based on arXiv:1612.02728

LHeC and FCC-eh can explore low-coupling, high-mass (> 10 GeV) range.

HNL experimental searches: the very far future

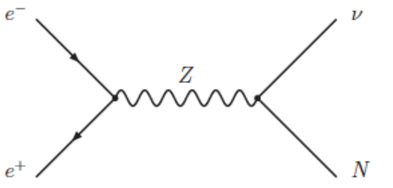
Prospects for ILC-500, 5 ab^{-1}



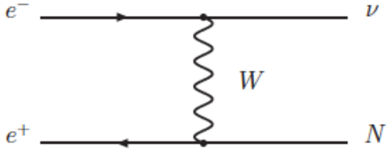
ILC can fill the gap between low-mass (< 5 GeV) and high-mass (> 10 GeV) regions

Source:
The ILC physics group (Peskin et al.)
Based on Antusch et al., 1710.03744

Production mechanisms at $e^+ e^-$ colliders:



production channel: $\mathbf{Z_s}$

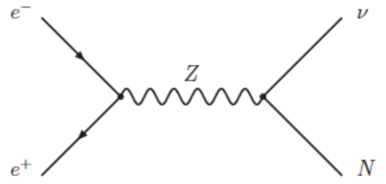


production channel: $\mathbf{W_t}$

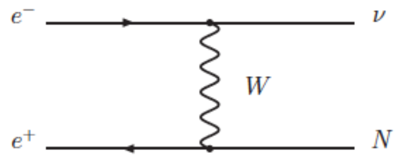
HNL experimental searches: the very far future

Prospects for CEPC: 10 ab^{-1} at the Z-pole and 5 ab^{-1} at 240 GeV.

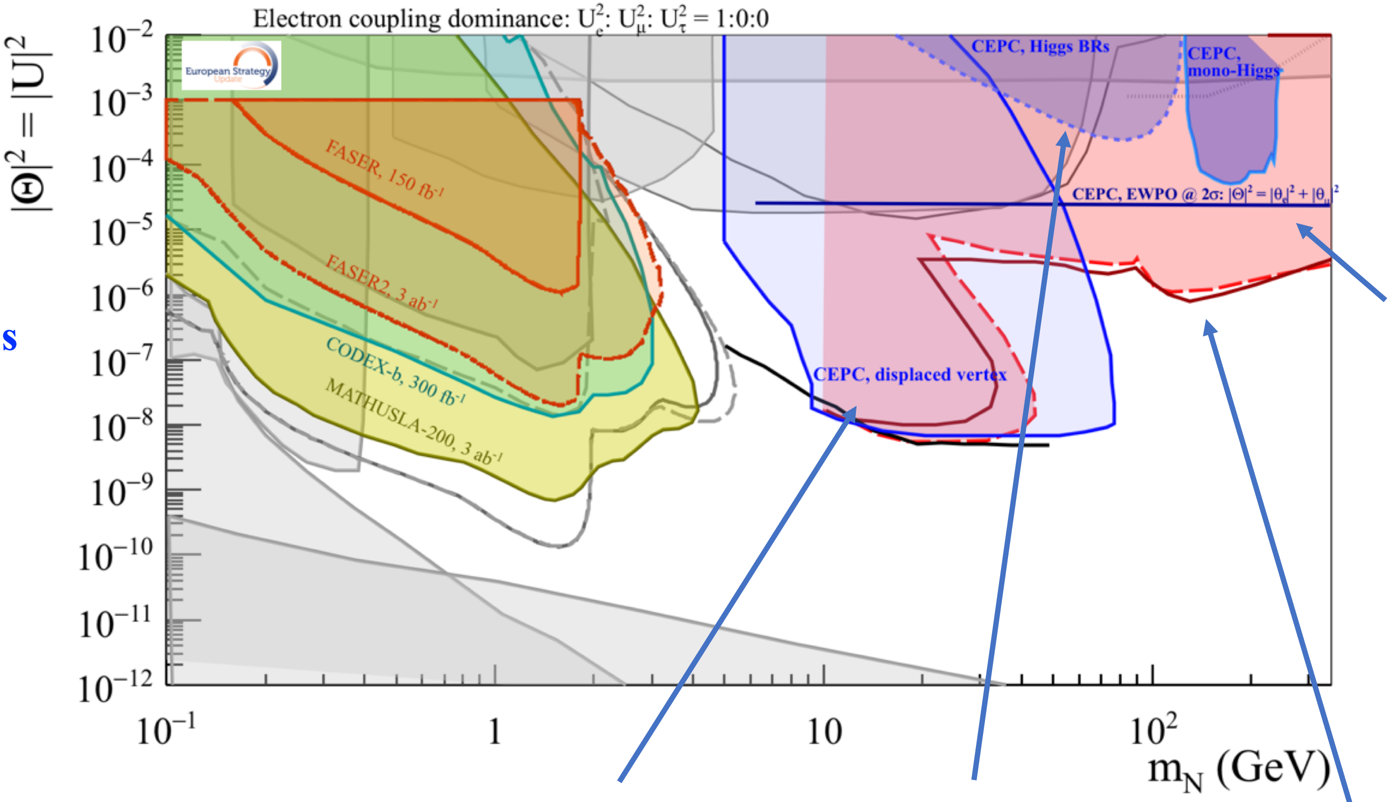
Production mechanisms at $e^+ e^-$ colliders:



production channel: $\mathbf{Z_s}$



production channel: $\mathbf{W_t}$



Source:
CEPC report, arXiv: 1811.10545
Based on arXiv:1612.02728

EWPO:

The PMNS matrix in presence of HNLs is not unitary. Modification of the theory prediction of precision observables. Present constraints include: EWPO, lepton universality, charged LFV, CKM unitarity.

$$\sigma_{\mu^- \to e^- \nu\bar{\nu}} = (\mathcal{N}\mathcal{N}^\dagger)_{ee} (\mathcal{N}\mathcal{N}^\dagger)_{\mu\mu} \cdot \sigma^{\rm SM}_{\mu^- \to e^- \nu\bar{\nu}}$$

$$G_F^2 \to G_\mu^2 = G_F^2 \cdot (\mathcal{N}\mathcal{N}^\dagger)_{ee} (\mathcal{N}\mathcal{N}^\dagger)_{\mu\mu}$$

Displaced vertex searches:

Several decay modes accessible

Higgs BR:

presence of HNL modifies the Higgs width and BRs. The more sensitive is the H⟶WW which constrains H⟶ν N (and Θ^2)

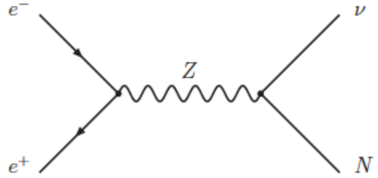
Mono-Higgs:

if m_N is above the Higgs mass, N ⟶ ν H , H ⟶ hadronically (dijet).

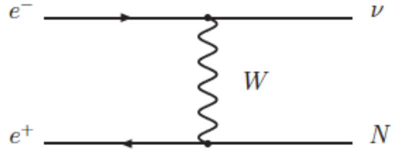
HNL experimental searches: the very far future

Prospects for FCC-ee : combination of data at the Z-pole (110 ab^{-1}), 2 m_W (7.5 ab^{-1}) and 240 GeV (5 ab^{-1}).

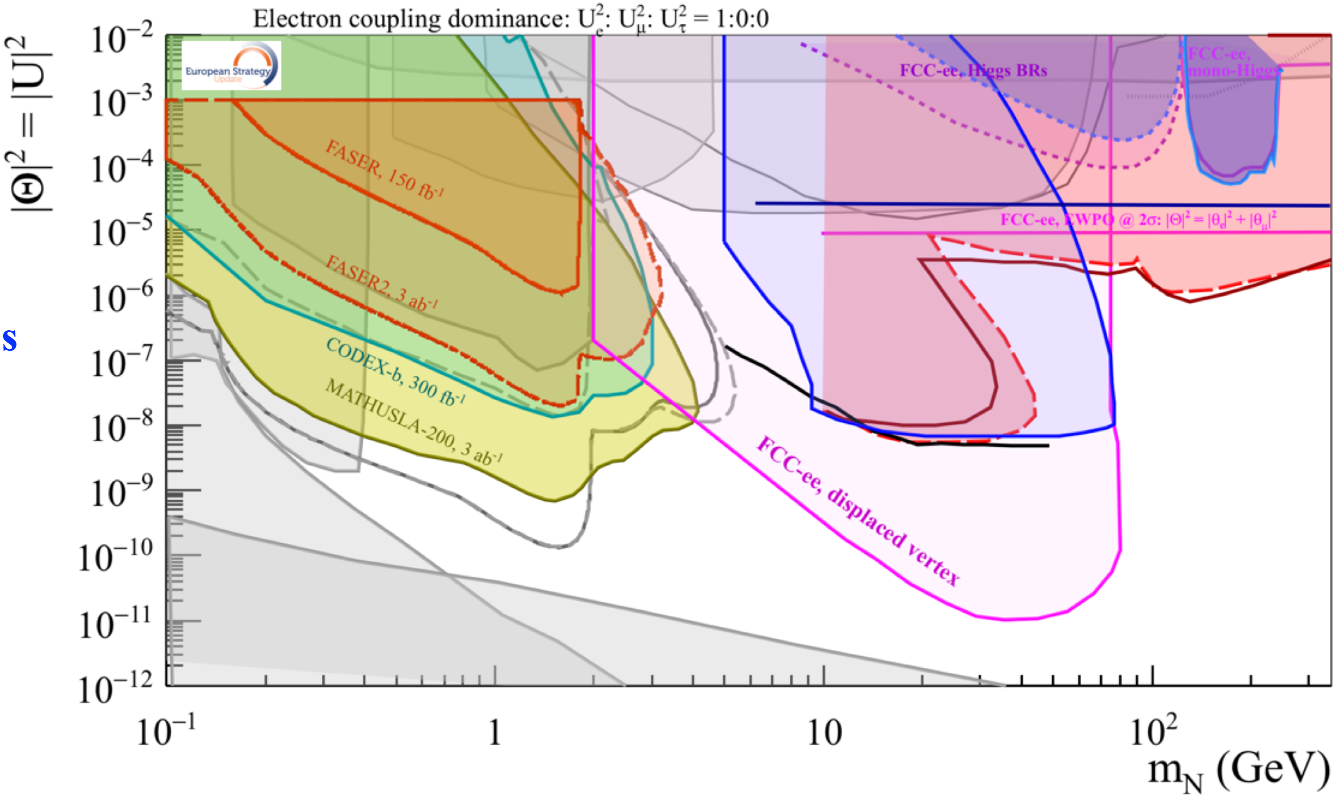
Production mechanisms at $e^+ e^-$ colliders:



production channel: Z_s



production channel: W_t

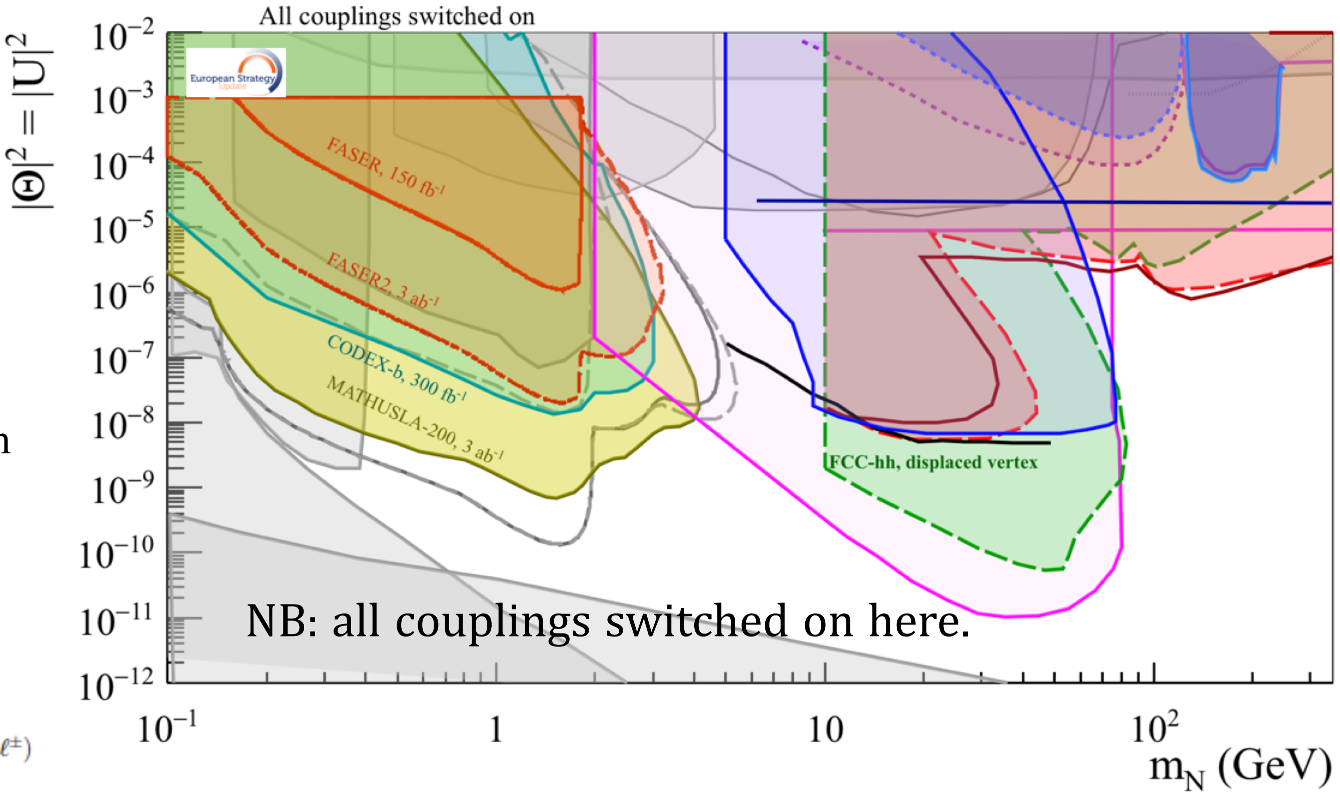


Source:
FCC report,
CERN-ACC-2018-0057
(based on Antusch et al., arXiv:1612.02728)

FCC-ee is highly competitive when running at the Z-pole

HNL experimental searches: the very far future

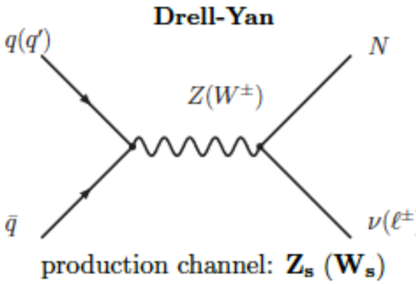
Prospects for FCC-hh: 100 TeV, 20 ab^{-1}



NB: all couplings switched on here.

<u>Source</u>:
FCC report,
CERN-ACC-2018-0057
(based on Antusch et al.,
arXiv:1612.02728)

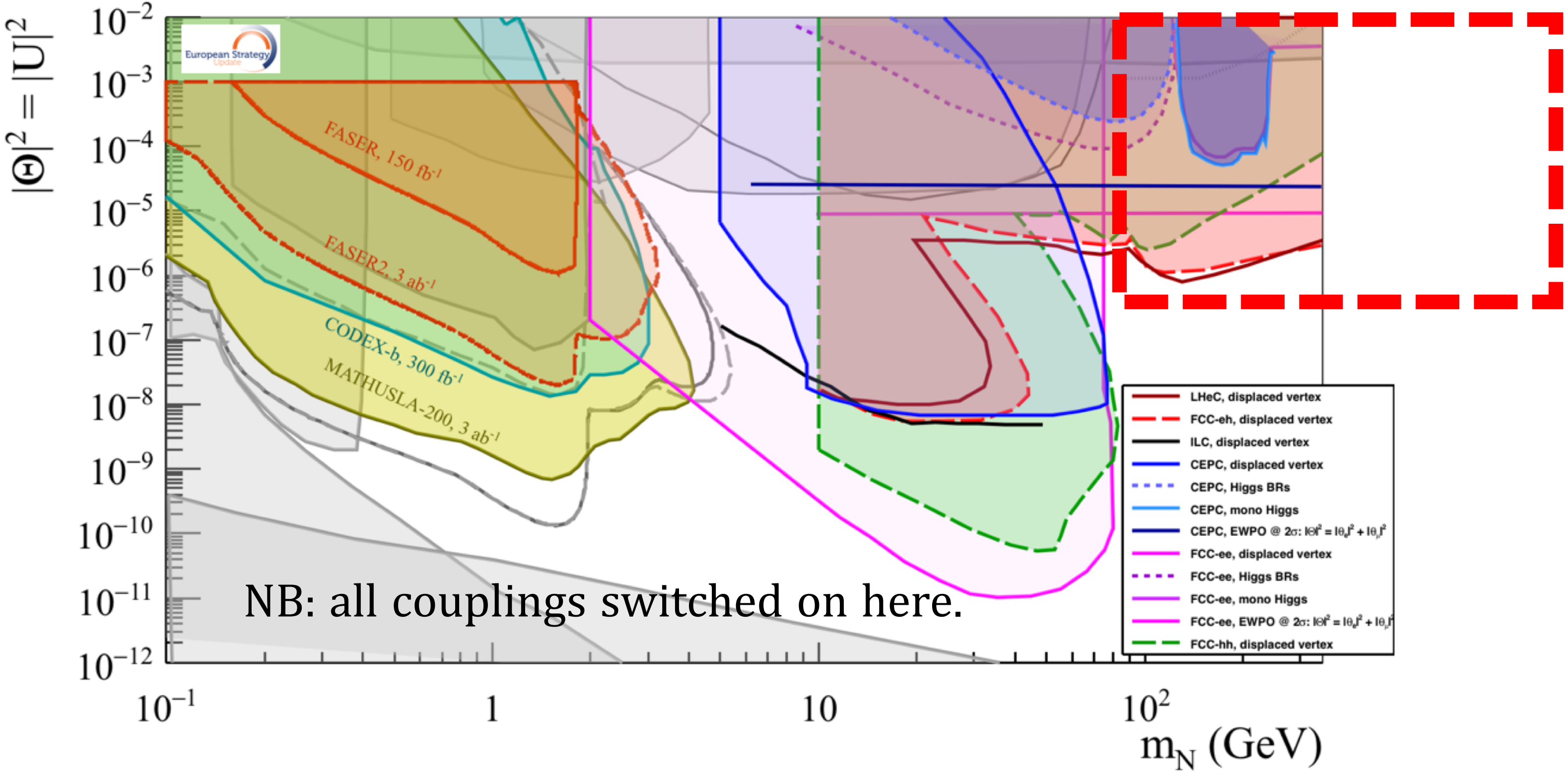
Production mechanism
at p p colliders:



FCC-hh cannot improve with respect to e+ e- colliders below the Z threshold
(but can improve at high masses, see later)

HNL experimental searches: the very far future

All together



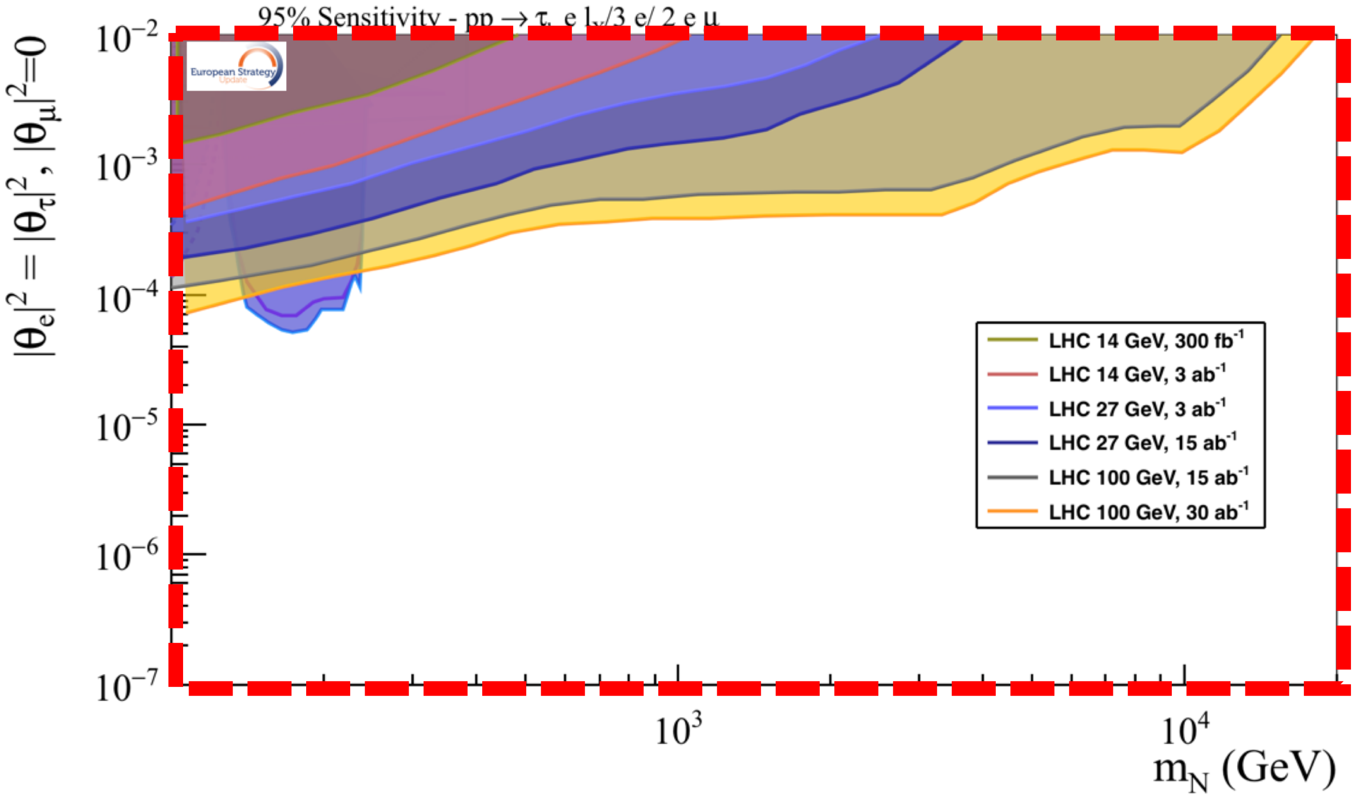
High mass range

NB: all couplings switched on here.

Nice complementarity between beam-dump and colliders' experiments

HNL experimental searches: the very far future

High mass range: LHC, HL-HC, HE-LHC, FCC-hh

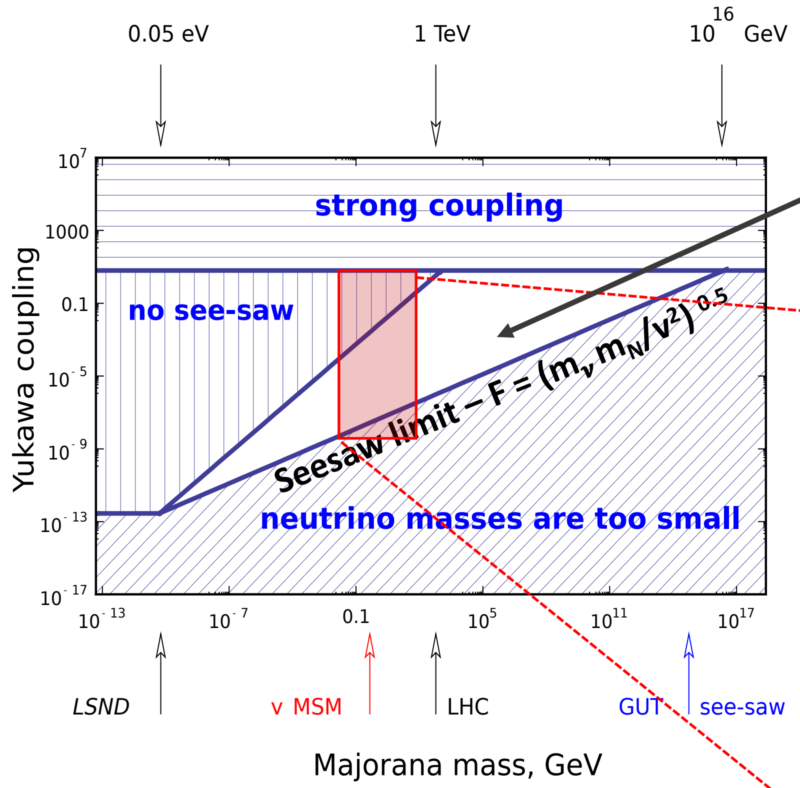


Source:

Beyond the Standard Model Physics at the HL-LHC and HE-LHC, arXiv:1812.07831

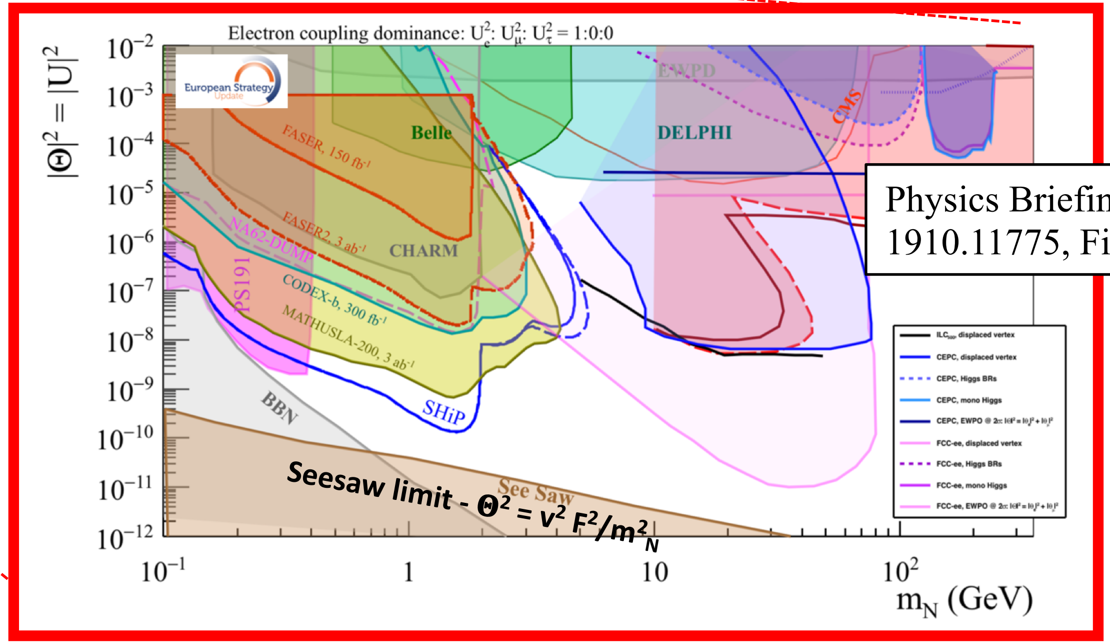
Hadron colliders can cover large-coupling in the high-mass range

HNL experimental searches: all together



Back to the initial plot:

SU(2)xU(1)$_L$ singlet Right Handed Neutrinos responsible of the neutrinos' mass generation can have any coupling/mass in the white area, assuming an approximate U(1)$_L$ global symmetry.



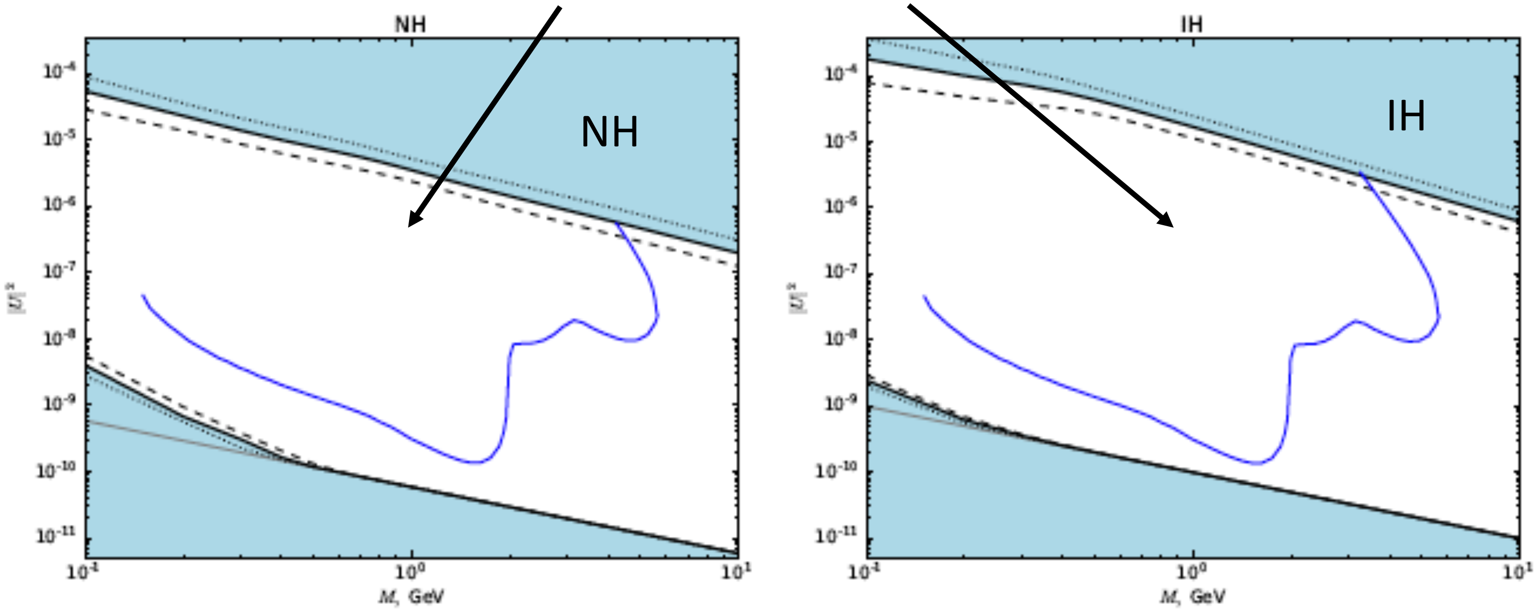
Physics Briefing Book,
1910.11775, Fig.8.19, p.138

With neutrino, beam dump, fixed-target, and future collider experiments we can explore (light) RHN in the mass range 0.1-90 GeV almost down to the see-saw limit.

Heavy Neutral Leptons: possible connection to leptogenesis

- ✓ **Initial idea:** Akhmedov, Rubakov, Smirnov 98
- ✓ **Formulation of kinetic theory and demonstration that NuMSM can explain neutrino masses, Dark matter and baryon asymmetry**: Asaka Shaposhnikov 05
- ✓ **Analysis of baryon asymmetry generation in the NuMSM:** Asaka, Shaposhnikov, Canetti, Frossard, Abada, Domcke, Lucente, Hernandez, Racker, Salvado, Drewes, Garbrech, Guetera, Klaric, Hambye, Eijima, Timiryasov, …

Regions compatible with leptogenesis



Eijima, Shaposhnikov, Timiryasov, 1808.10833

Region compatible with leptogenesis is accessible at accelerator-based experiments.

Conclusions

✓ HNLs could be a possible explanation of the origin of the neutrino masses and oscillations in a wide range of masses and couplings:

- Masses around (or below) the EW scale and very small Yukawa's are allowed within a symmetry-protected seesaw mechanism;
- For same values of masses and Yukawa couplings could also provide a valid mechanism of leptogenesis.

✓ Experimental searches of HNLs at or below the EW scale can be performed with a large variety of experimental facilities:

- neutrino, fixed-target, beam-dump, colliders, B-factories, future ee,ep, pp colliders, etc..

and are intimately connected to:

- active neutrino physics, astroparticle, and cosmology.

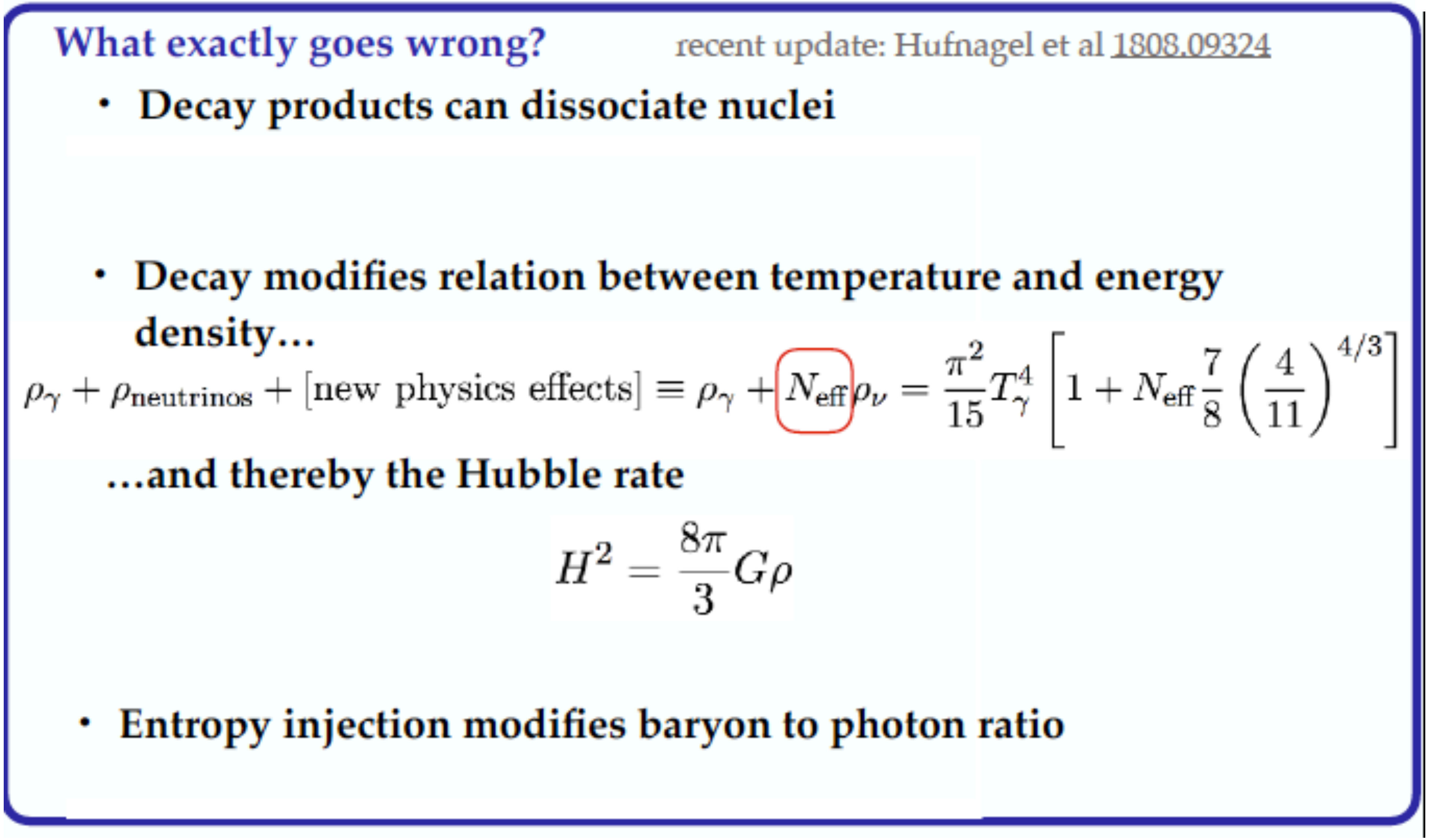
✓ The future of this (fascinating) field will be driven by:

- new astroparticle results (Euclid, SKA,..), active neutrino measurements (mixing angles and CP violating phase), $0\nu\beta\beta$ decays, beam-dump/neutrino experiments in the very-low (< 5 GeV) mass region and future e+ e- colliders in the Z,W masses region.

HNLs are a bright example of synergies and complementarities across very different communities, which is - in my opinion - the future of our field.

SPARES

Big Bang Nucleosynthesis



What exactly goes wrong? recent update: Hufnagel et al 1808.09324

- **Decay products can dissociate nuclei**

- **Decay modifies relation between temperature and energy density…**

$$\rho_\gamma + \rho_{\text{neutrinos}} + [\text{new physics effects}] \equiv \rho_\gamma + \boxed{N_{\text{eff}}}\rho_\nu = \frac{\pi^2}{15}T_\gamma^4\left[1 + N_{\text{eff}}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]$$

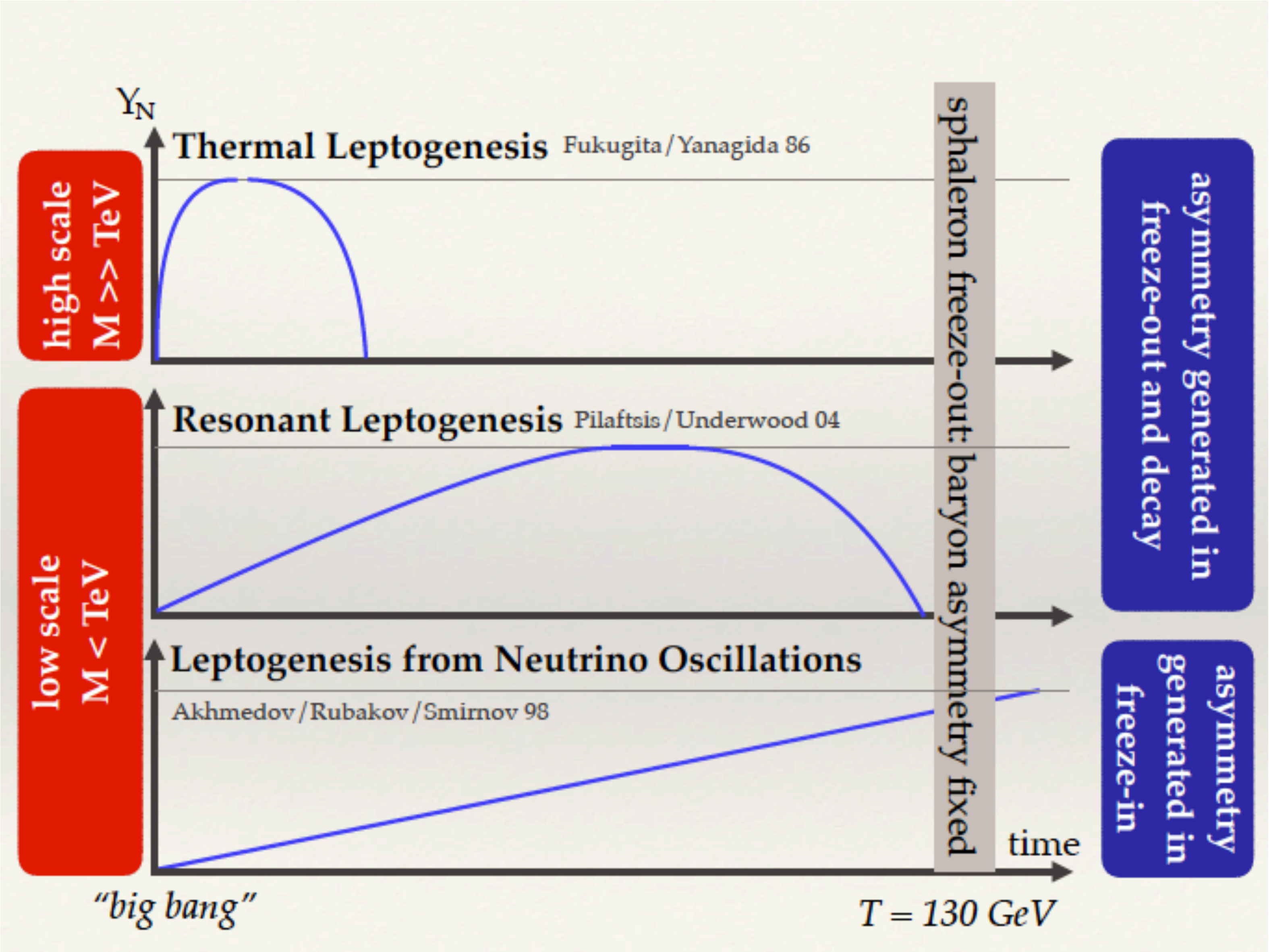
…and thereby the Hubble rate

$$H^2 = \frac{8\pi}{3}G\rho$$

- **Entropy injection modifies baryon to photon ratio**

Courtesy of M. Drewes

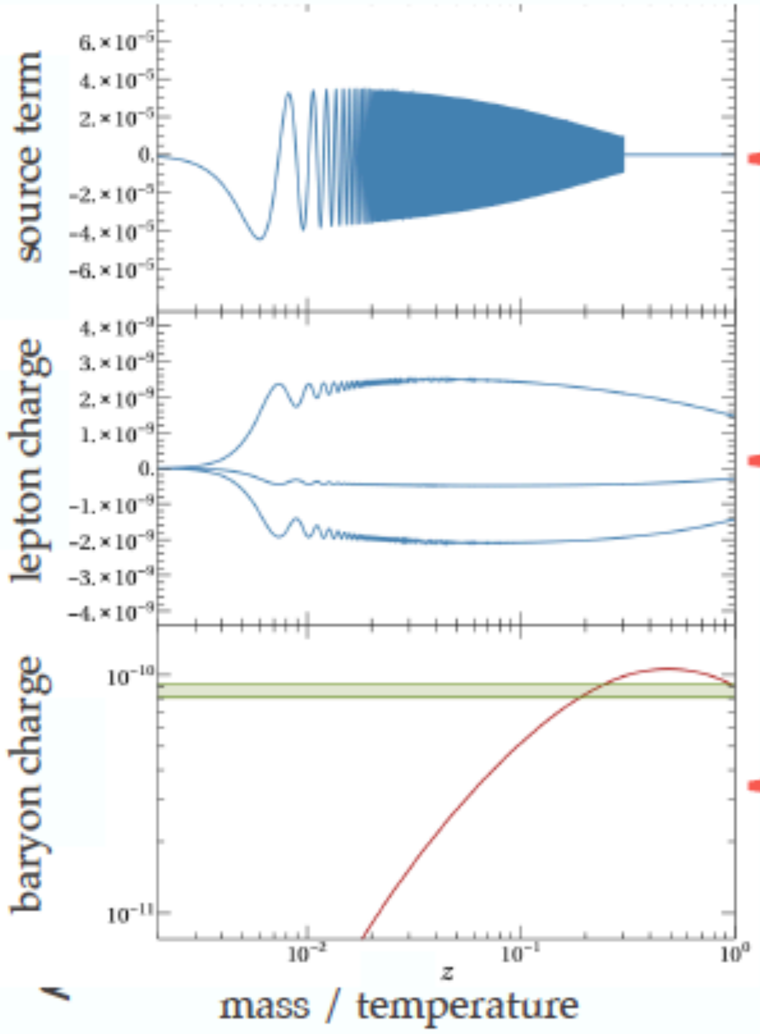
Heavy Neutral Leptons and Leptogenesis



Courtesy of M. Drewes

Heavy Neutral Leptons and Leptogenesis

Freeze-In Leptogenesis



Courtesy of M. Drewes

Heavy Neutrinos undergo CP violating oscillations during heat production.

This induces asymmetries in the SM lepton flavours.

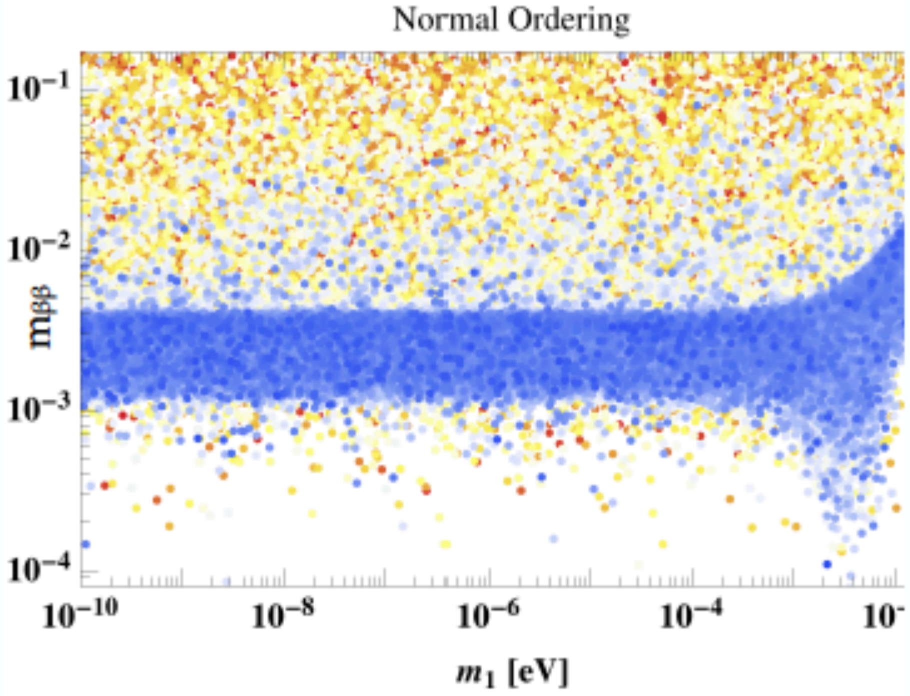
Sphalerons partly transfer the asymmetries into a baryon number.

The 0νββ Connection

Heavy neutrino exchange can dominate 0νββ…

…even in the leptogenesis region

⇒ additional probe of Reω !



Abada et al 1810.12463

Bezrukov 0505247

Blennow et al 1005.3240

Lopez Pavon et al 1209.5342

MaD / Eijima 1606.06221,

Hernandez et al 1606.06719,

Asaka et al 1606.06686

Abada et al 1810.12463

Courtesy of M. Drewes