HERBI DREINER AND THE LONG-LIVED SEARCH FOR LONG-LIVED PARTICLES

Jordy de Vries
University of Amsterdam & Nikhef

TIME-LINE

- Compared to most here, I've only known Herbi for a relatively short time
- From 2013-2015 I was a postdoc at the FZ-Julich/HISKP in Bonn in the group of Ulf
- I worked on boundary of hadronic/nuclear and particle physics (electric dipole moments, hadronic parity violation)

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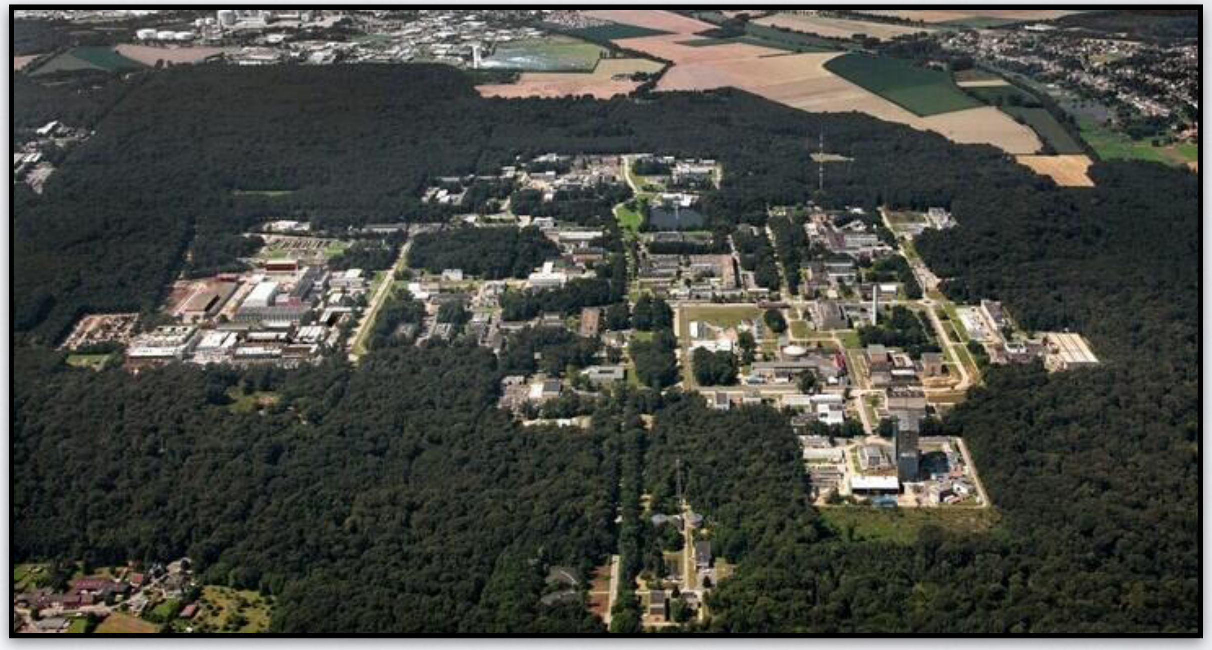
FORSCHUNGSZENTRUM



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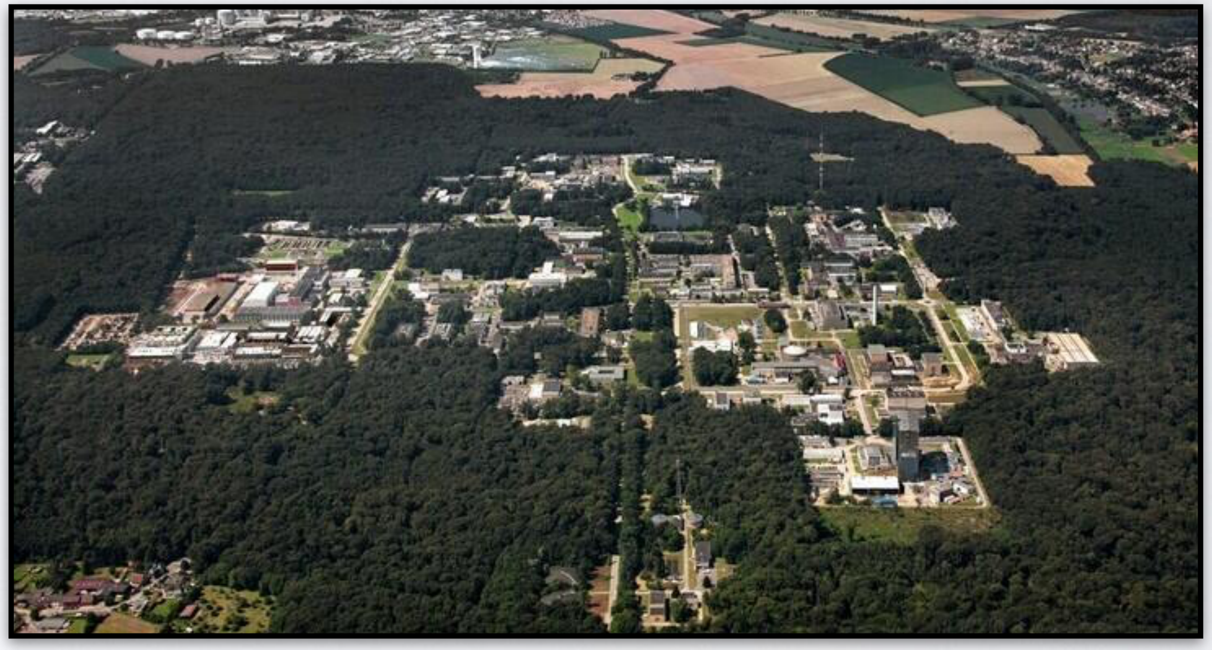

- I TA’ed for ‘Theoretischen Mechanik I‘ taught by Christoph Hanhart and Herbi (I supervised the TA’s and made the problem sets and solutions).
- Kinda **scared** of Herbi in the beginning…

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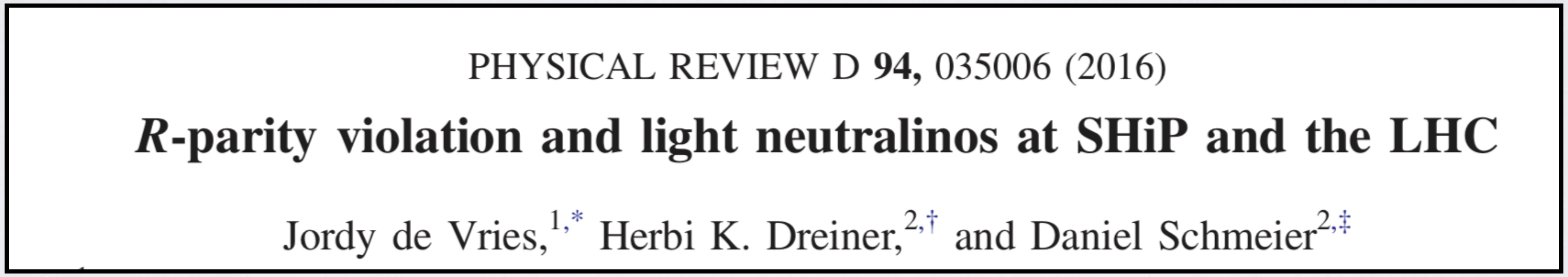
- Wanted to work more on particle physics -> started working on Higgs physics and Standard Model EFT but all with remote collaborators

- Reached out to Herbi to ask if we could collaborate on something



PHYSICAL REVIEW D **94,** 035006 (2016)

_R_-parity violation and light neutralinos at SHiP and the LHC

Jordy de Vries,[1,*] Herbi K. Dreiner,[2,†] and Daniel Schmeier[2,‡]

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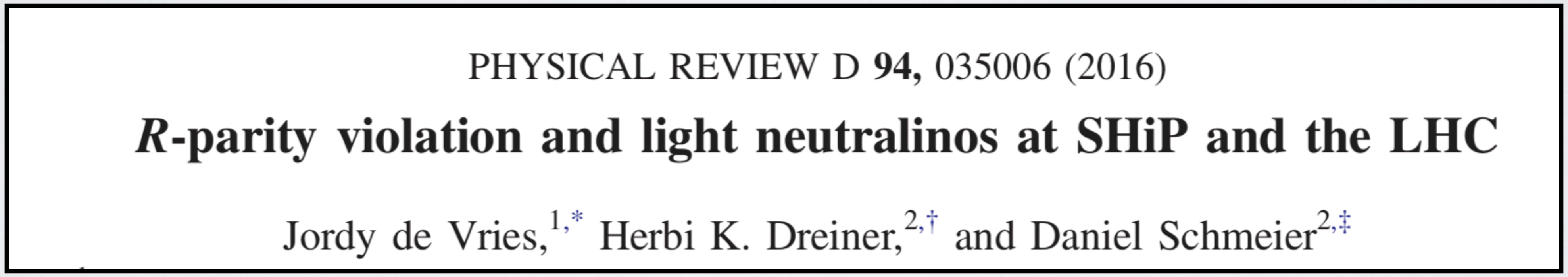

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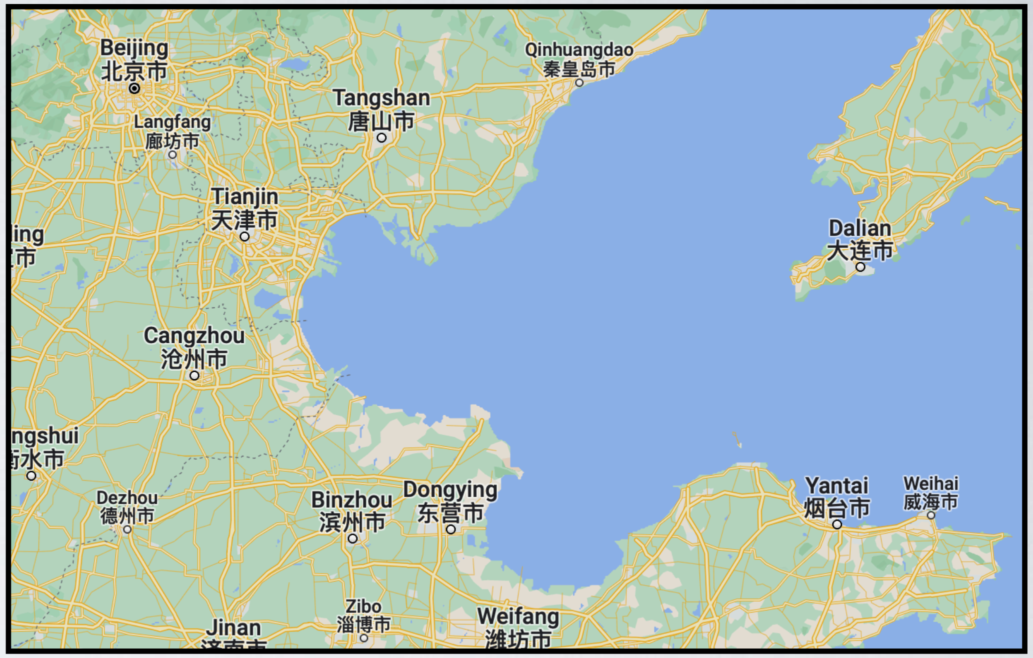
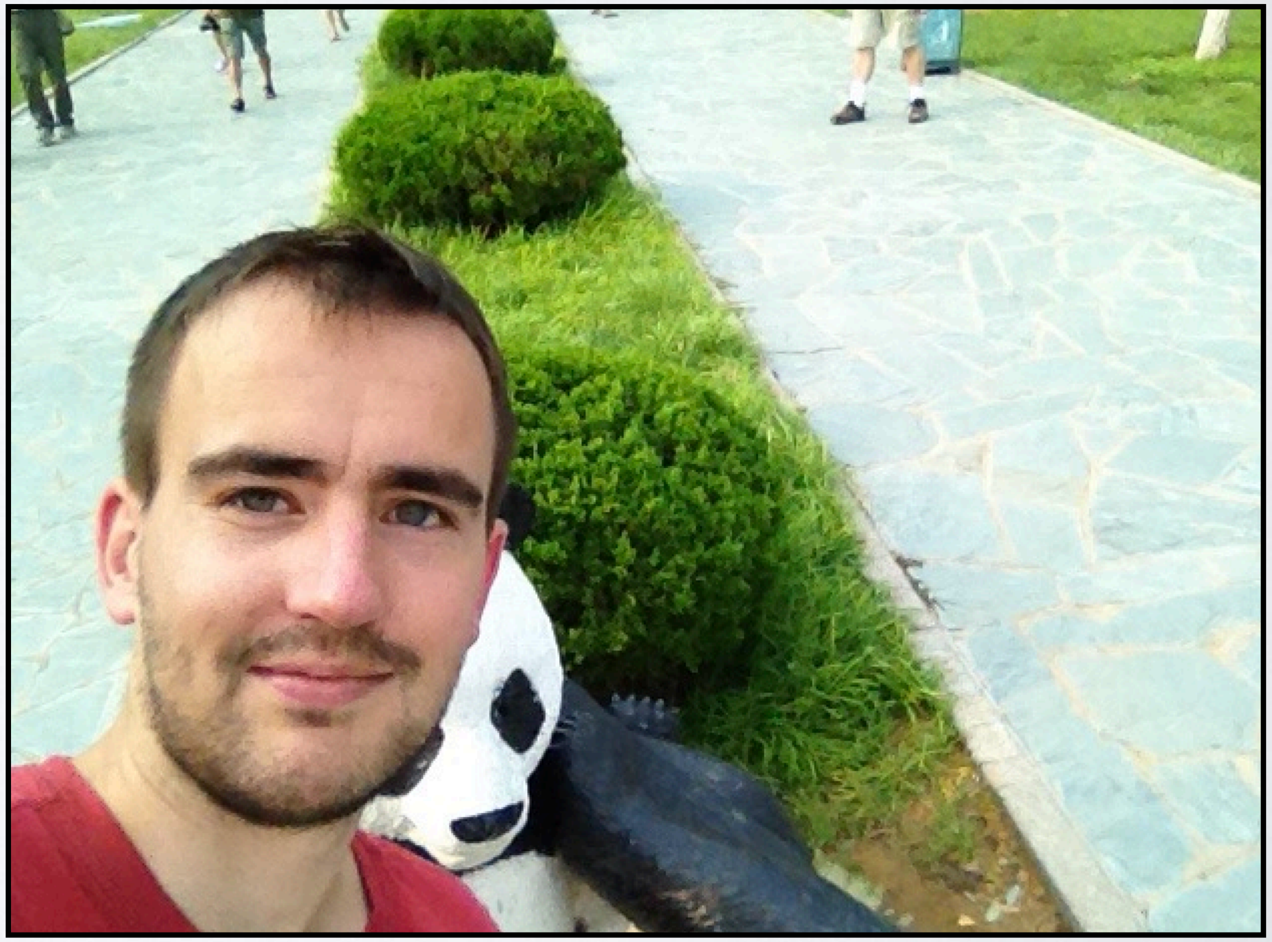
- Kinda interesting since I knew next-to-nothing about SUSY, RPV, nor SHiP ….
- This work is closely connected to our current efforts which I'll talk about here
- We've been collaborating since (also through Herbi's excellent students)
- I almost worked in Herbi's goup by accepting his postdoc offer but then deciding to go to Nikhef in Amsterdam once I got a fellowship in 2016. Sorry….

PANDA'S

- We took a trip to China together in 2015 (Weihai)
- With a memorable visit to see Chinese panda's





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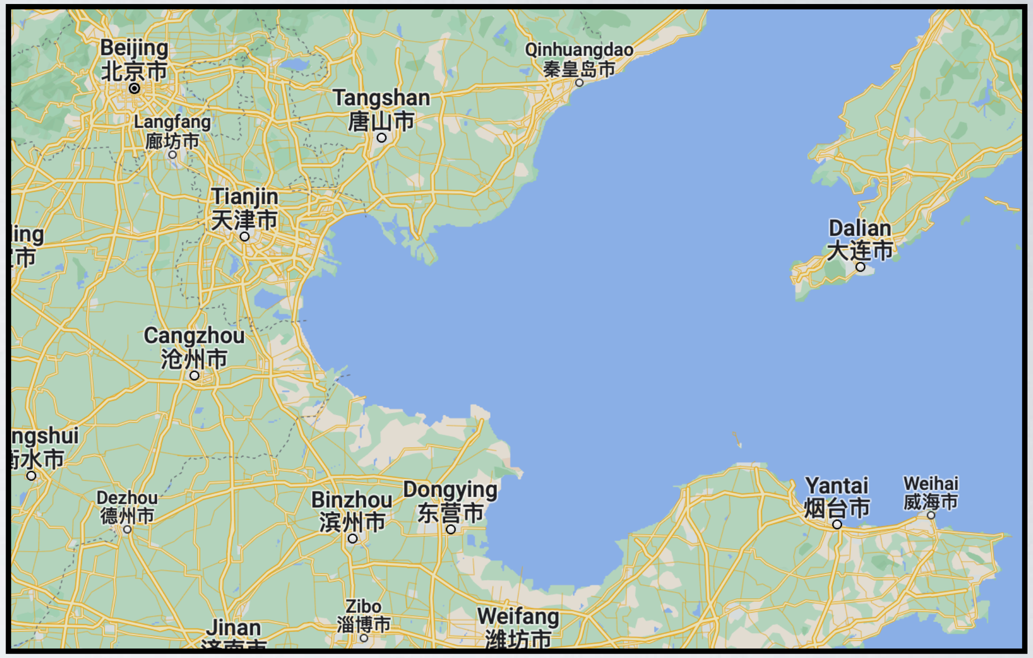

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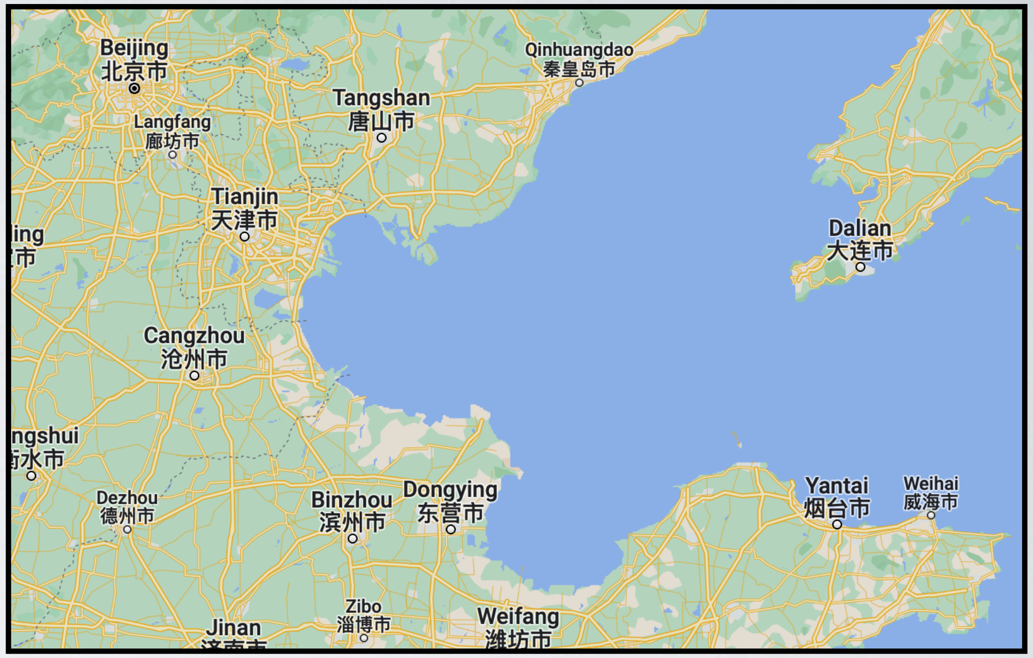

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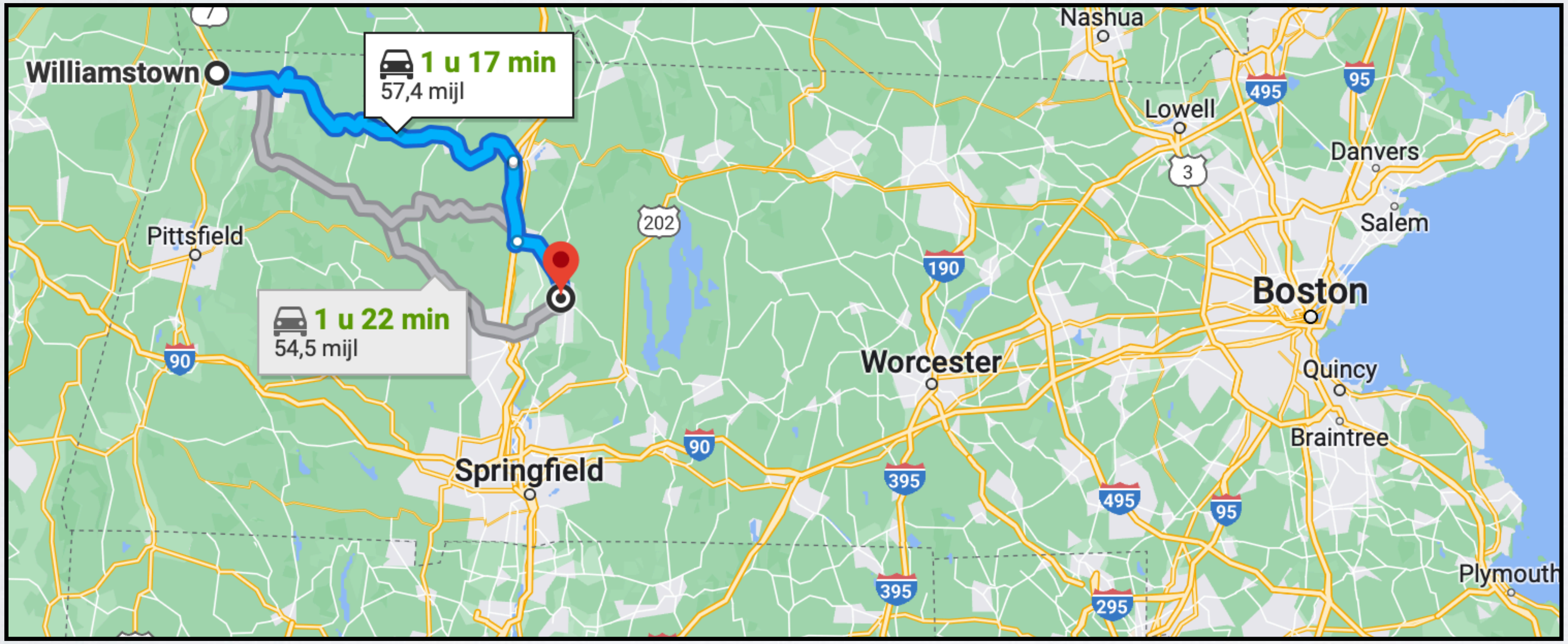

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The puzzle of the neutrino mass

- Neutrinos are formally massless in the SM → **but neutrino oscillations** ….
- Easy fix: Insert gauge-singlet right-handed neutrino υ_R (or several)

$$\mathscr{L} = -\, y_\nu \, \bar{L}\tilde{H}\nu_R \qquad\qquad y_\nu \sim 10^{-12} \to m_\nu \sim 0.1\,\mathrm{eV}$$

- Nothing really wrong with this…. I can stop the talk now….

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- Nothing really wrong with this…. **But nothing forbids a Majorana Mass term**

$$\mathscr{L} = -\, y_\nu \, \bar{L}\tilde{H}\nu_R - M_R \, \nu_R^T C \nu_R$$

'Everything that is not forbidden is compulsary'

- M_R is not connected to electroweak scale: **could be a completely new scale**
- **Does this term exist in nature? How can we find out ?**
- Note: this is not the only way to generate neutrino masses !

The puzzle of the neutrino mass

$$\mathscr{L} = - y_\nu \, \bar{L}\tilde{H}\nu_R - M_R \, \nu_R^T C \nu_R$$

Minkowski ‘77

- 1+1 case: diagonalization leads to **Majorana mass eigenstates**

$$\mathscr{L} = - \frac{1}{2} \left(\bar{\nu}_L \, \bar{\nu}_R^c \right) \begin{pmatrix} 0 & v y_\nu \\ v y_\nu & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} \quad \to - \frac{1}{2} \left(\bar{\nu}_1 \, \bar{\nu}_2 \right) \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad \nu_i^c = \nu_i$$

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- If M_R is significantly larger (>> eV) than active neutrino masses: **see-saw mechanism**

$$m_1 \simeq \left| \frac{y_\nu^2 v^2}{m_R} \right| \qquad m_2 \simeq m_R \qquad \begin{aligned} \nu_1 &\simeq \nu_L + \nu_L^c - \theta\nu_R^c - \theta^* \nu_R \\ \nu_2 &\simeq \nu_R + \nu_R^c + \theta\nu_L^c + \theta^* \nu_L \end{aligned} \qquad |\theta| \simeq \sqrt{\frac{m_1}{m_2}}$$

- Much **larger mixing angles are possible** in 3+n models (linear or inverse seesaw)
- n must be 2 or larger to get 2 nonzero active neutrino masses

Attractive mass ranges

- **See-saw (variants) can work for essentially any right-handed scale**

eV keV MeV GeV TeV ….. 10^{15} GeV M_R ?

- If Yukawa coupling order 1 then $m_1 \simeq \left|\frac{v^2}{m_R}\right| \to m_R \simeq 10^{15}\,\mathrm{GeV}$
- Thermal leptogenesis possible $m_R \geq 10^{9}\,\mathrm{GeV}$ Davidson Ibarra '02

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- But also leptogenesis possible with TeV sterile neutrinos! Pilaftsis ’97, Akhmedov et al ’98
- And even in the MeV-GeV range See e.g. Shaposhnikov et al (many works) Drewes et al ‘21
- KeV sterile neutrino could be Dark Matter (but getting more difficult) and essentially decoupled from neutrino mass generation Dodelson, Widrow ’97 Shaposhnikov et al ‘05
- eV sterile neutrinos potentially related to short base-line anomalies
- **Clear motivation to look for a broad range of sterile neutrino masses**

Attractive mass ranges

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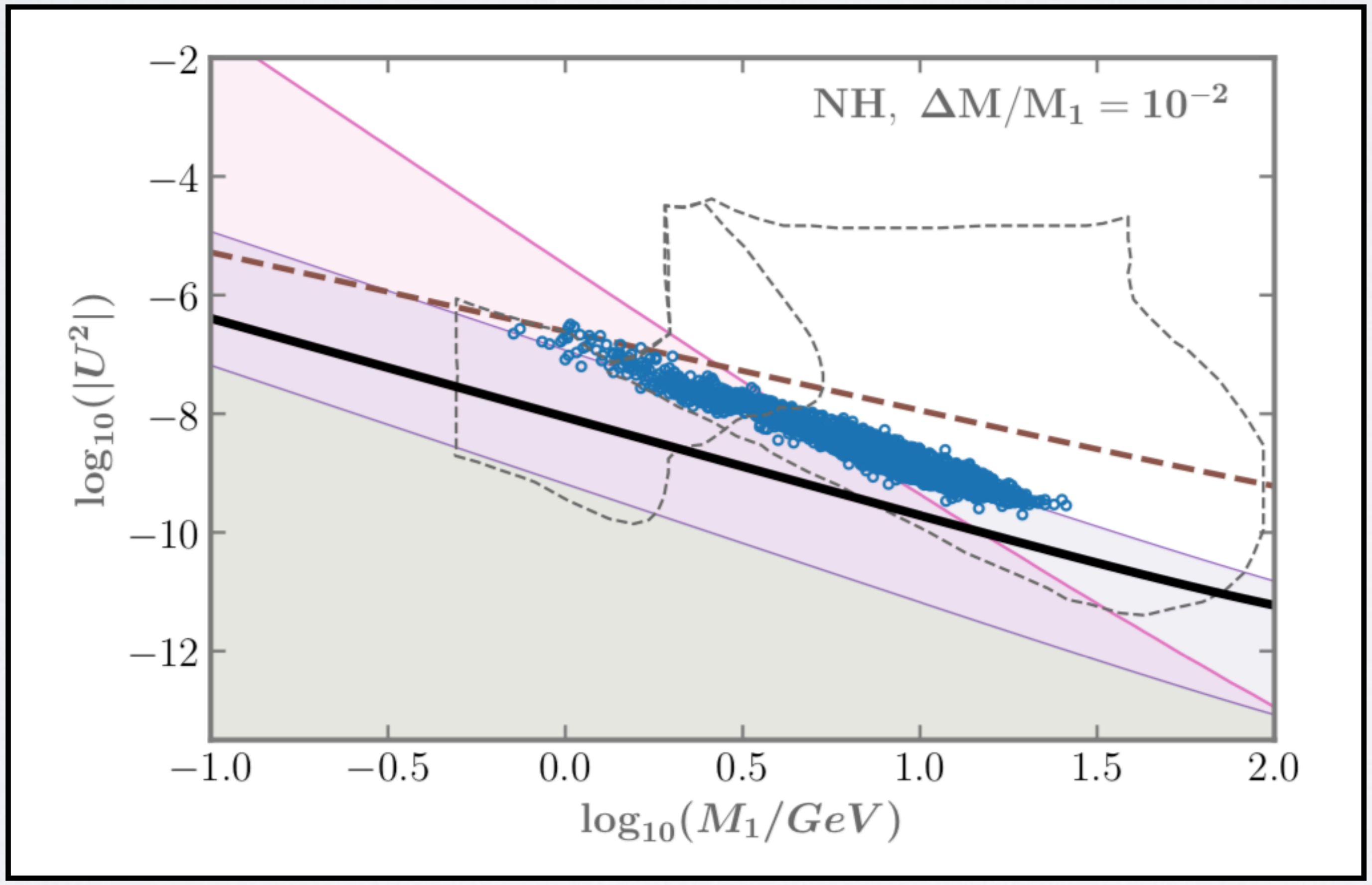
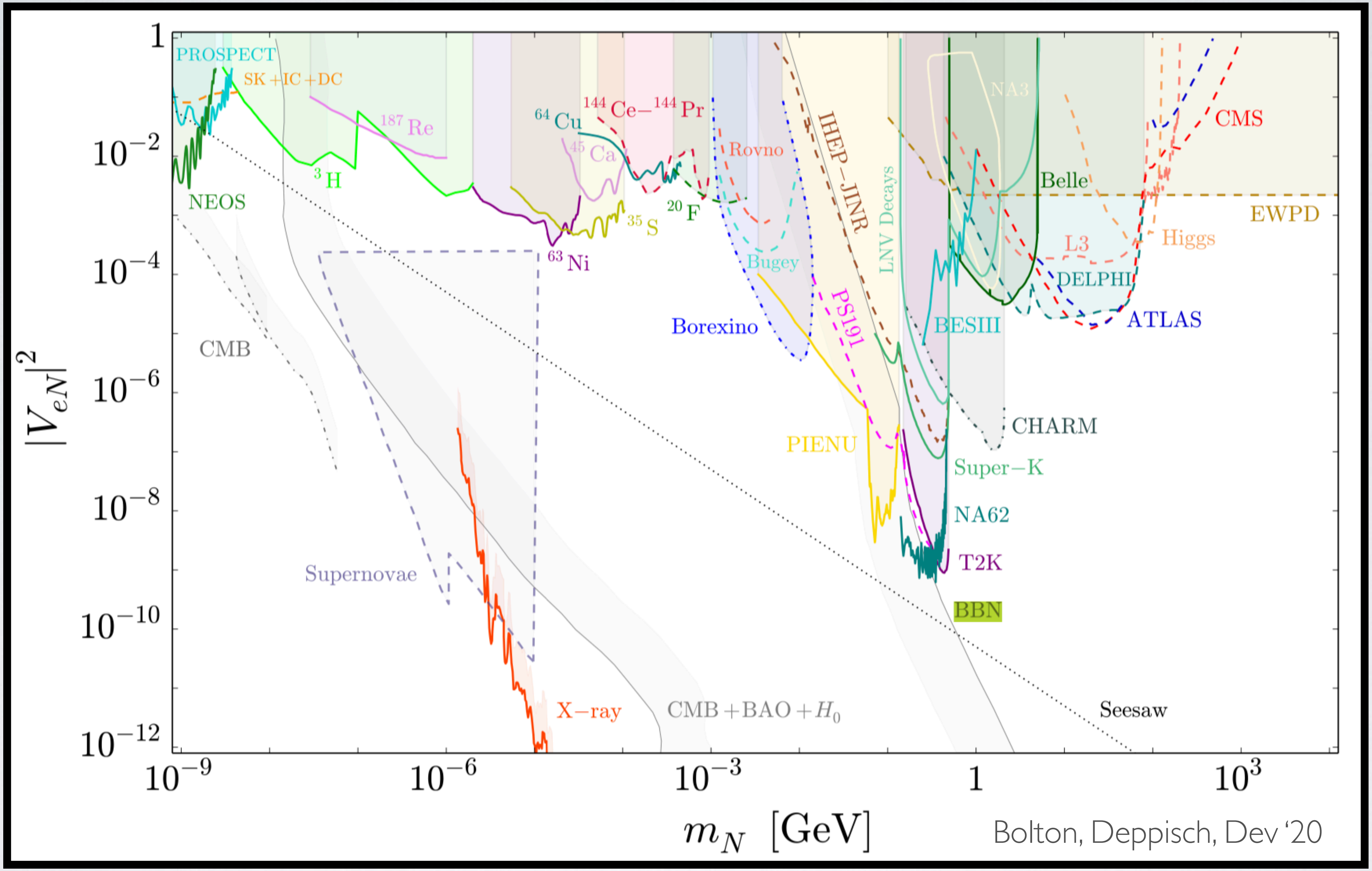
eV keV MeV GeV TeV ….. 10^{15} GeV → **M_R ?**



Hernandez, Lopez-Pavon, Rius, Sandner '22

A zoo of searches !

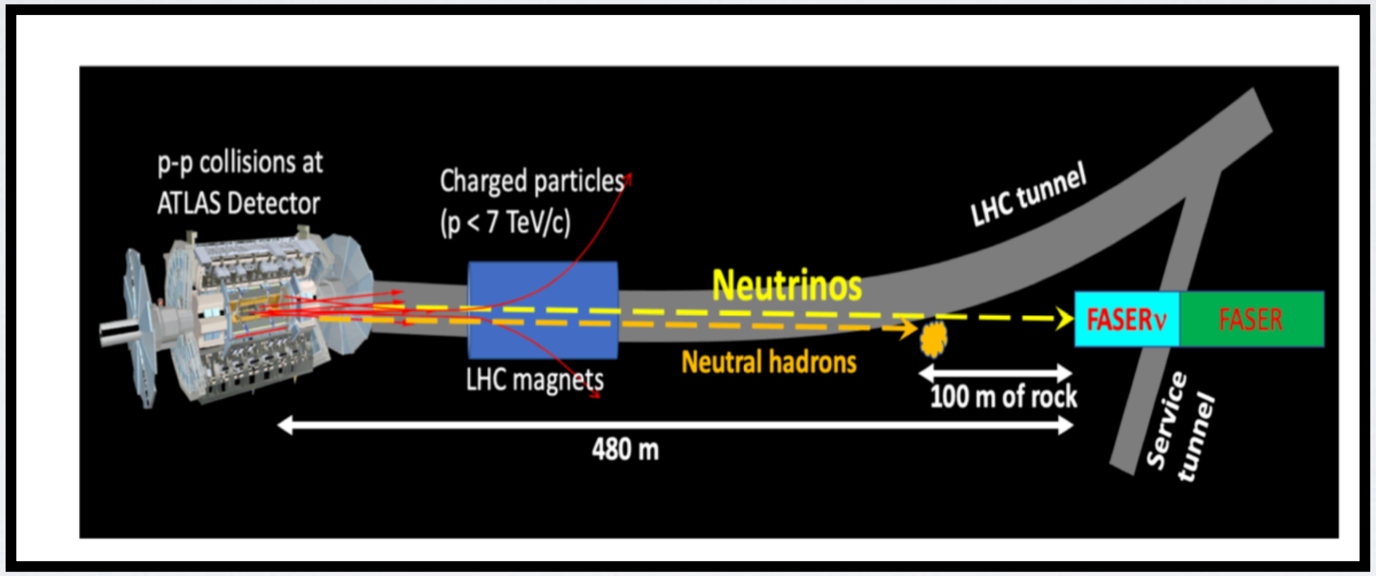


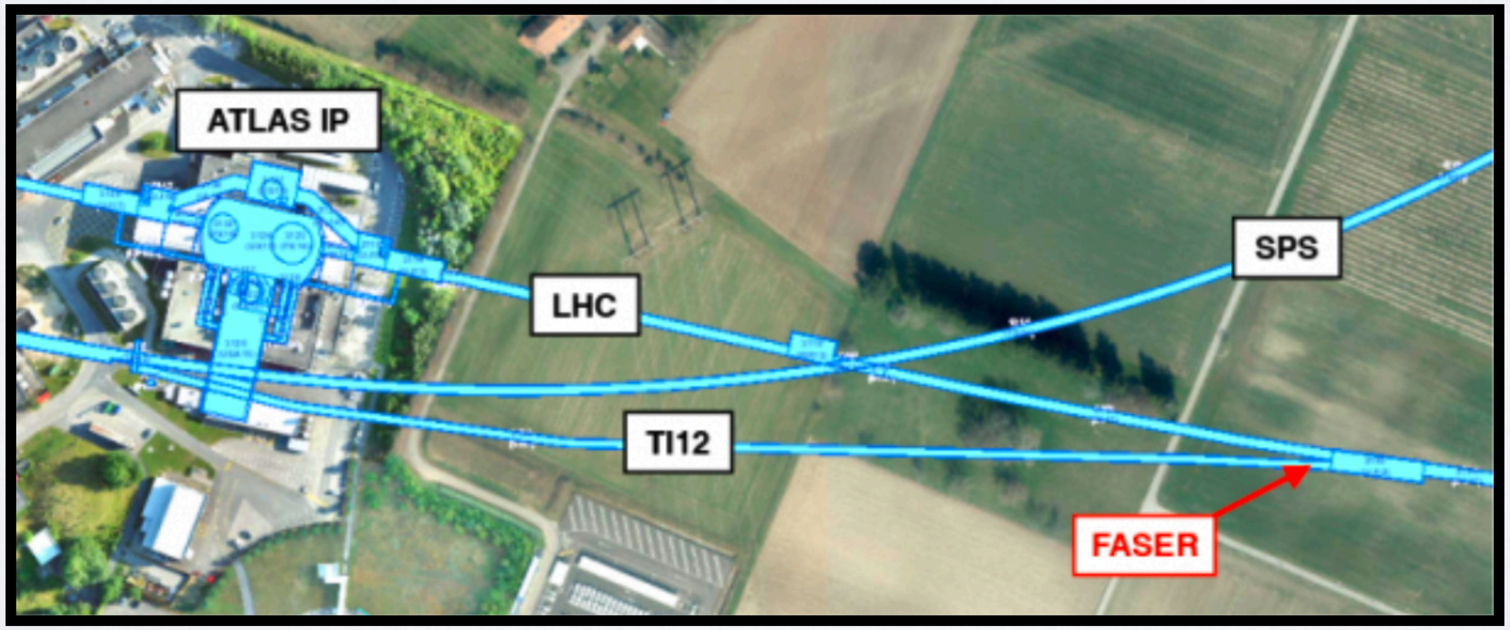
Bolton, Deppisch, Dev ‘20

- Beta decay, beam dumps, colliders, EWPD, …….
- Cosmological constraints (e.g. BBN and CMB)

Interesting prospects at LHC and DUNE etc

- **Current limits will improve significantly with new experiments**
- A renewed focus on searches for long-lived particles (LLP) (such as sterile neutrinos)





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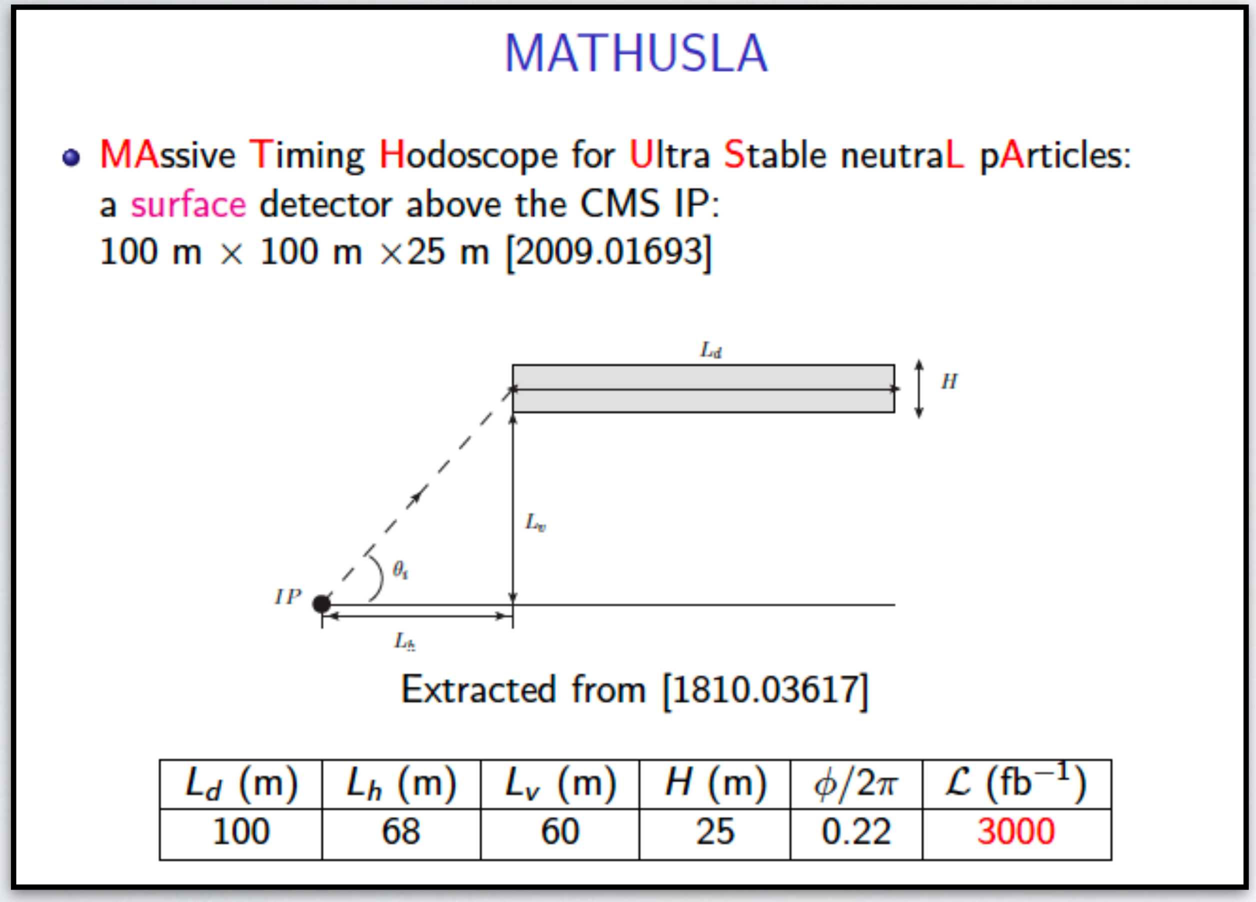
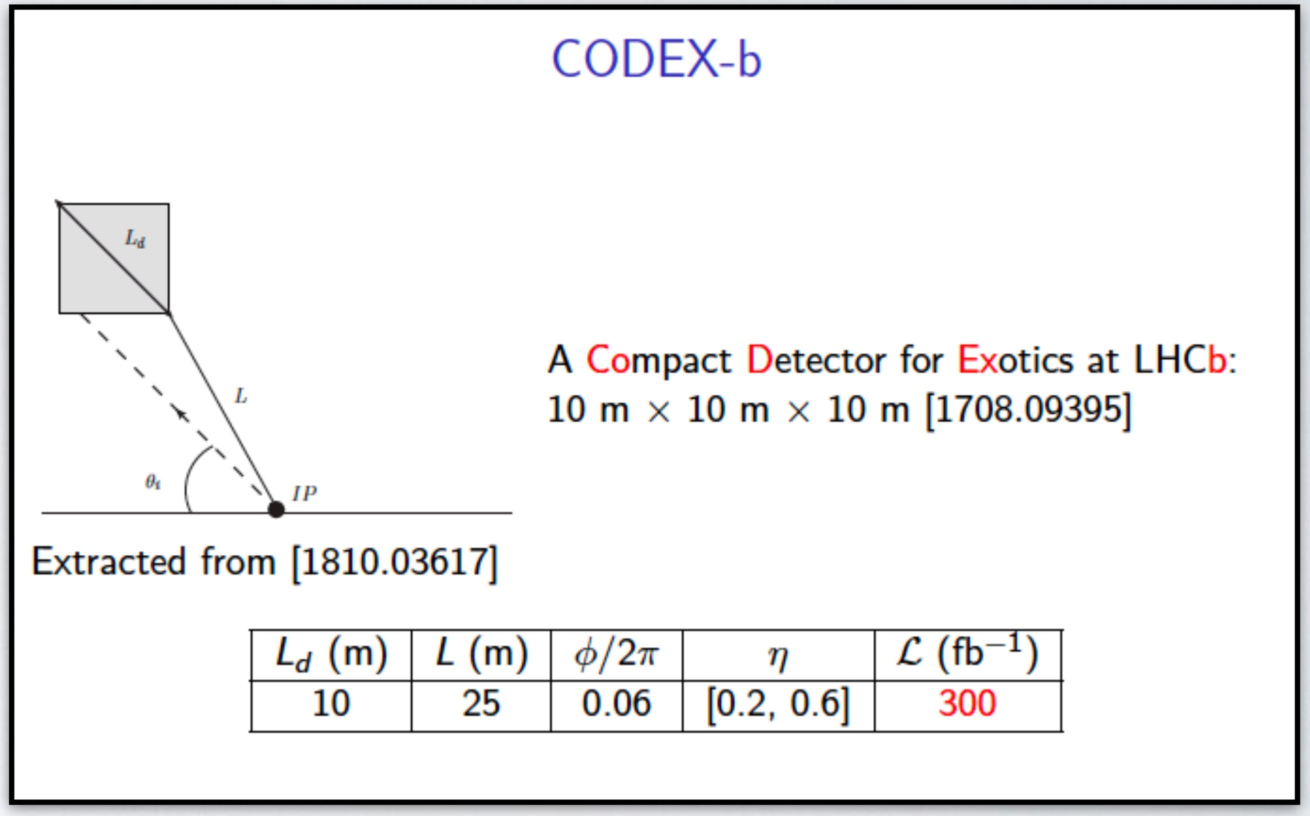


MATHUSLA

- MAssive Timing Hodoscope for Ultra Stable neutraL pArticles: a surface detector above the CMS IP: 100 m × 100 m ×25 m [2009.01693]

Extracted from [1810.03617]

L_d (m)	L_h (m)	L_v (m)	H (m)	$\phi/2\pi$	$\mathcal{L}$ (fb^{-1})
100	68	60	25	0.22	3000



CODEX-b

A Compact Detector for Exotics at LHCb: 10 m × 10 m × 10 m [1708.09395]

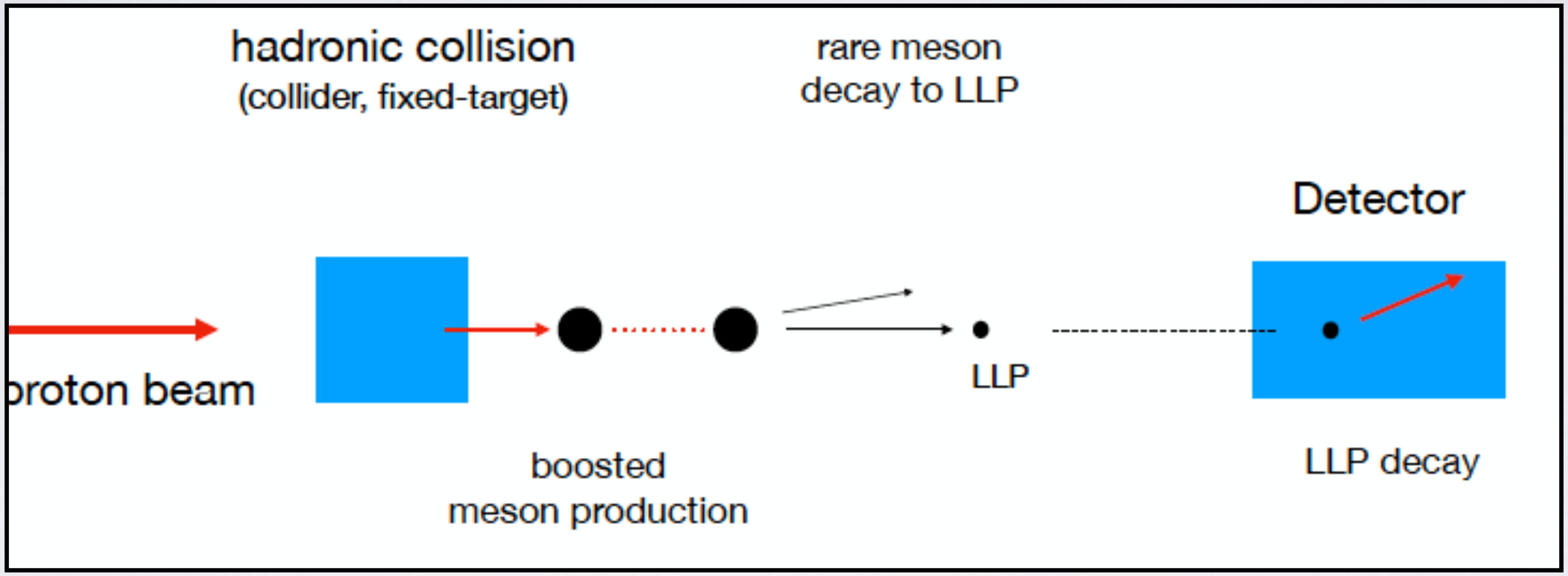
Extracted from [1810.03617]

L_d (m)	L (m)	$\phi/2\pi$	η	$\mathcal{L}$ (fb^{-1})
10	25	0.06	[0.2, 0.6]	300

- **+ ANUBIS, MoEDAL-MAPP 1&2, AL3X , DUNE, …… etc**

Basic idea

- Focus on finding sterile neutrinos in mass range < B-meson mass
- B, D, K mesons copiously produced in experiments and can produce GeV sterile neutrinos



I stole this beautiful illustration from Herbi. It shows his artistic side.

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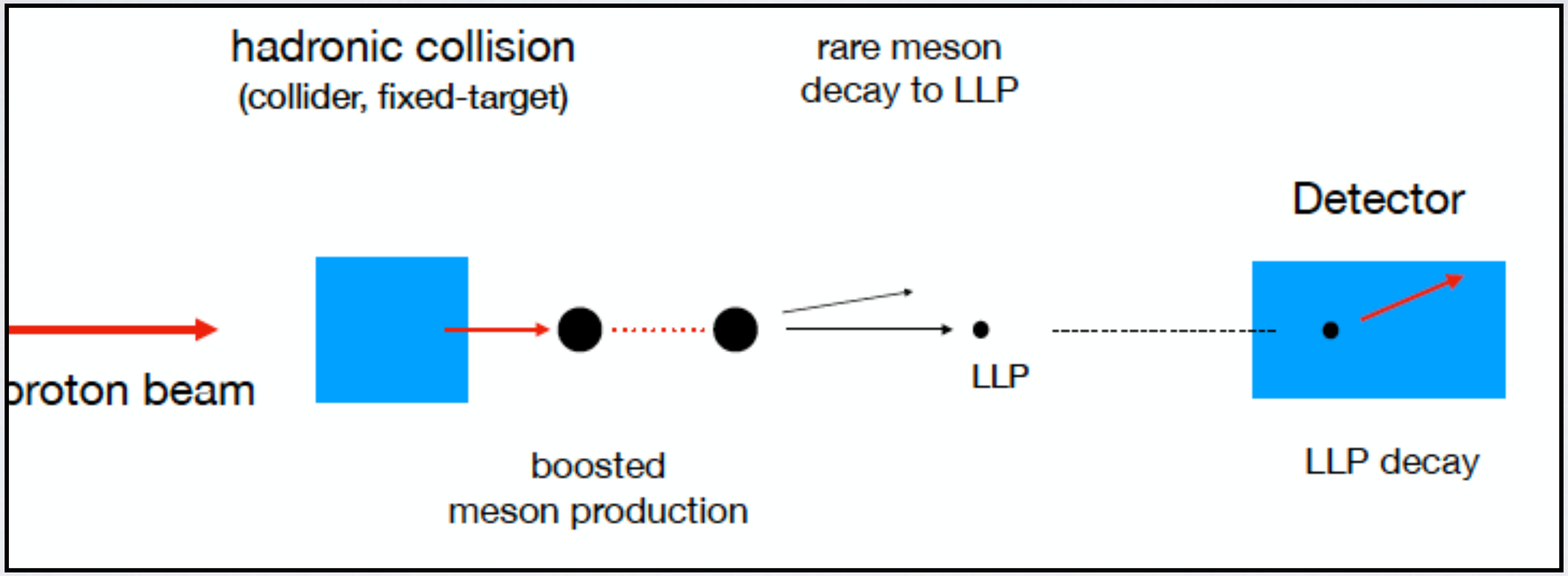

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- Different experiments sensitive to different lifetimes depending on distance of the detector

- Backgrounds from long-lived hadrons, muons, cosmic rays etc
- All detectors are 10-500 m away from IP —> space to install veto and shielding segments
- Directional cuts for cosmic ray background

- We will look at 3-event isocurves (assume no background)

Theoretical framework

- In mass basis, charged weak currents couple to ‘sterile’ states as well.

$$\mathscr{L} \sim U_{e4}\, \bar{e}_L \gamma^\mu \nu_4\, W_\mu$$

- Interactions suppressed by small mixing angles $U_{e4} \sim \sqrt{\frac{m_\nu}{m_4}}$ (but could be larger)

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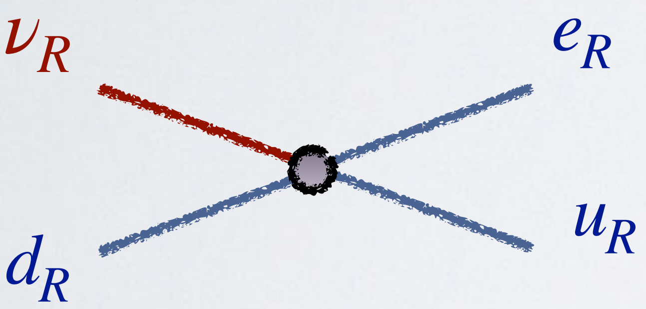
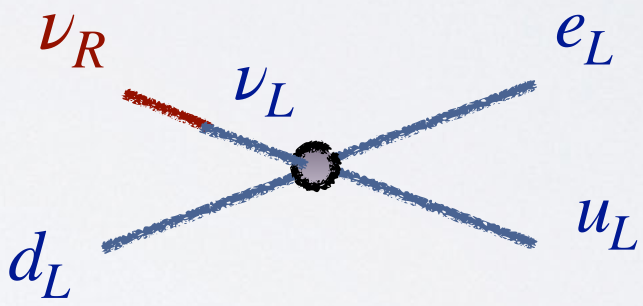
- **Right-handed neutrinos could only appear sterile at low energies**
- Example: left-right symmetry: right-handed neutrinos are charged under SU(2)$_R$



$$\sim \left(\frac{1}{M_{W_R}}\right)^2$$



$$\sim \left(\frac{1}{M_{W_L}}\right)^2 \sqrt{\frac{m_\nu}{m_4}}$$

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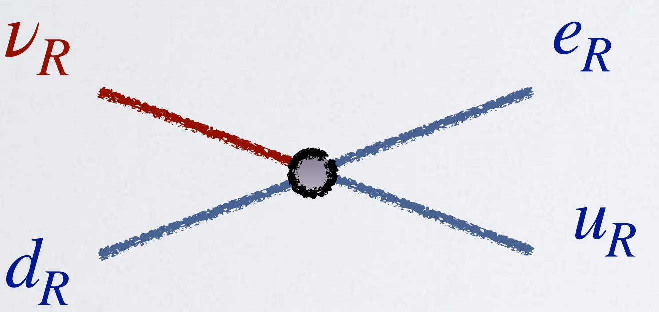

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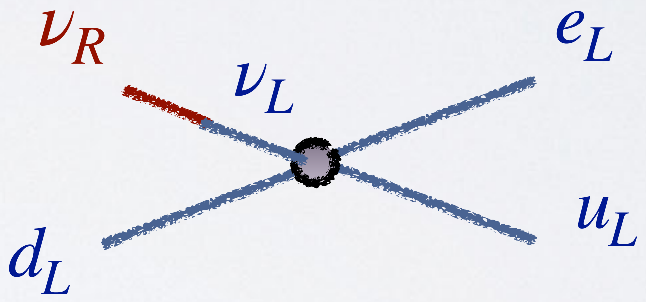


$$\sim \left(\frac{1}{M_{W_L}}\right)^2 \sqrt{\frac{m_\nu}{m_4}}$$

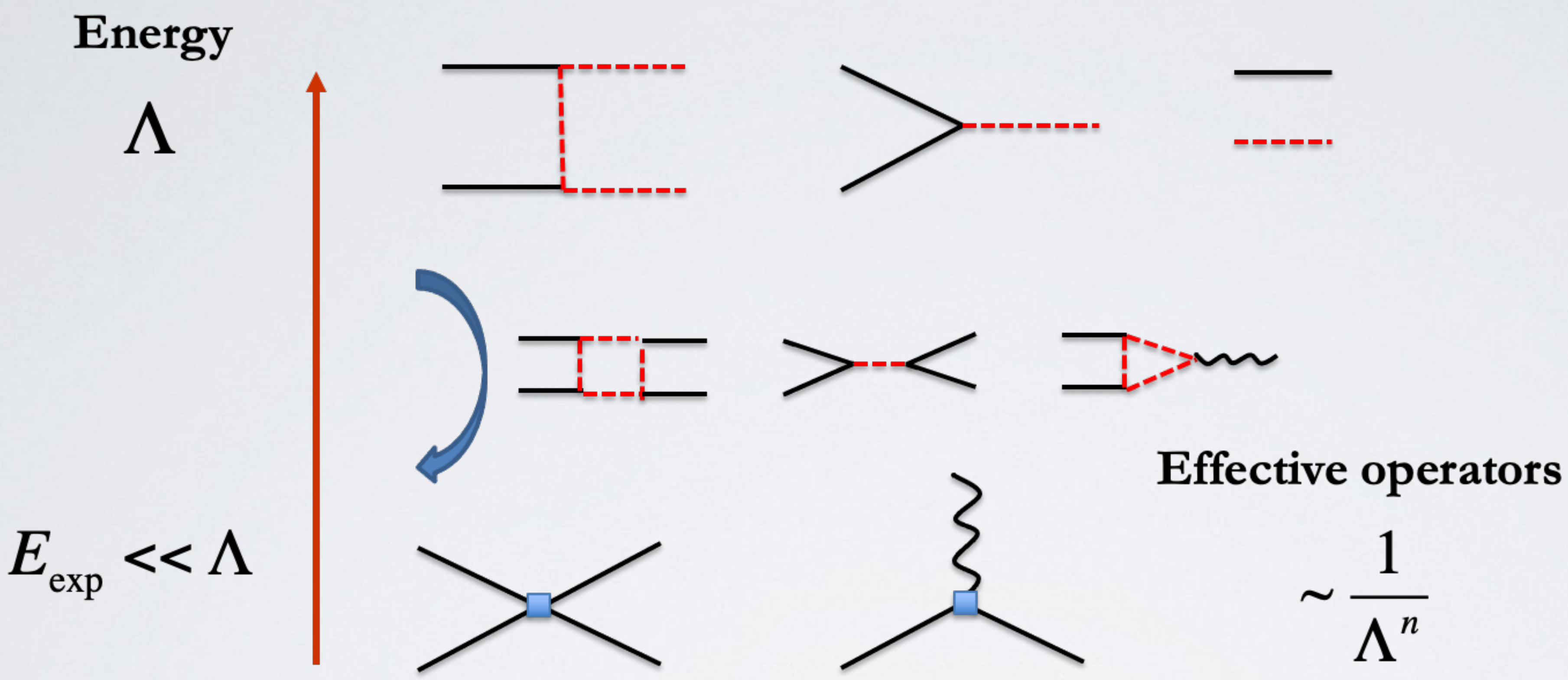
- For GeV sterile states, non-standard interactions relevant up to

$$M_{W_R} \sim M_{W_L} \left(\frac{m_4}{m_\nu}\right)^{1/4} \sim 50\,\mathrm{TeV}$$

- This also happens in for instance Leptoquark scenarios and can be used in solutions to anomalies such as muon g-2 or flavor anomalies (not today)

Effective field theory

- Assume that non-standard interactions from decoupled sector



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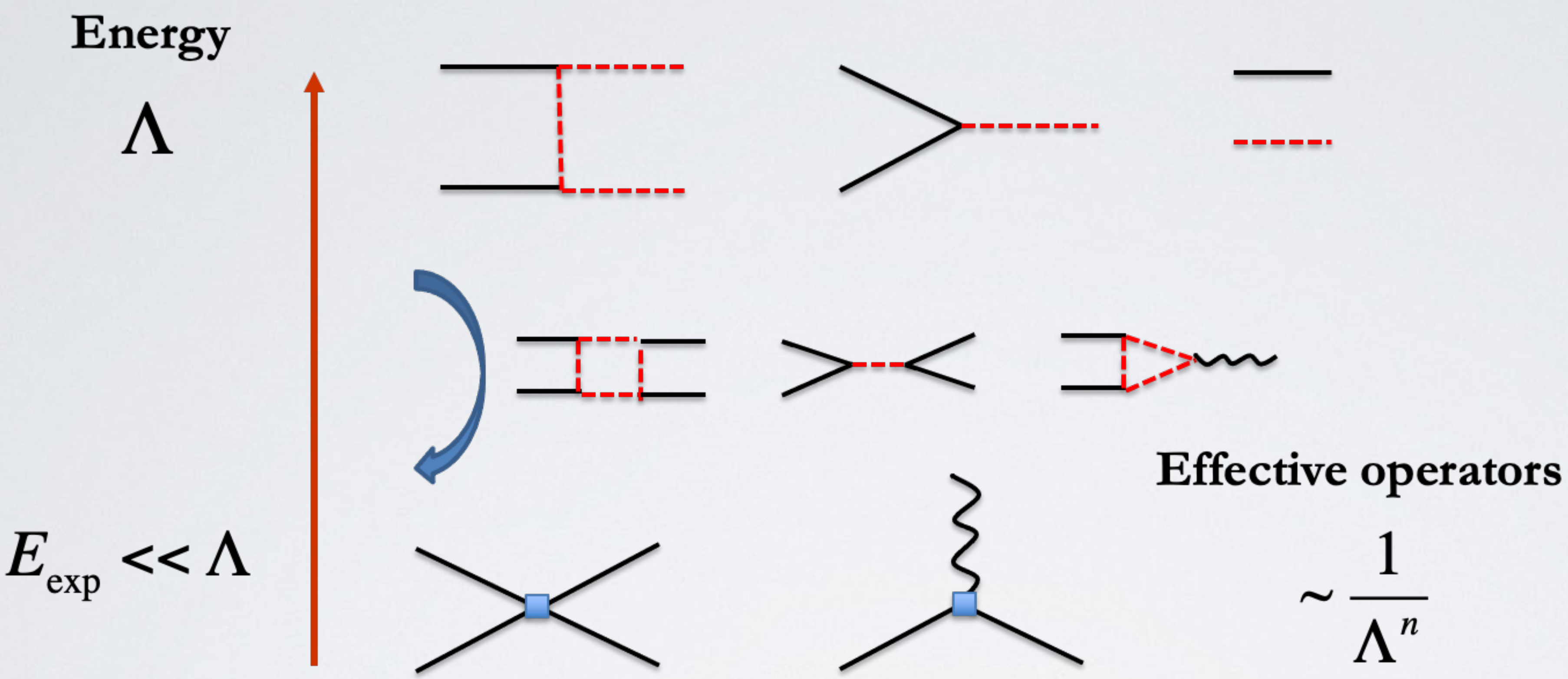


Energy

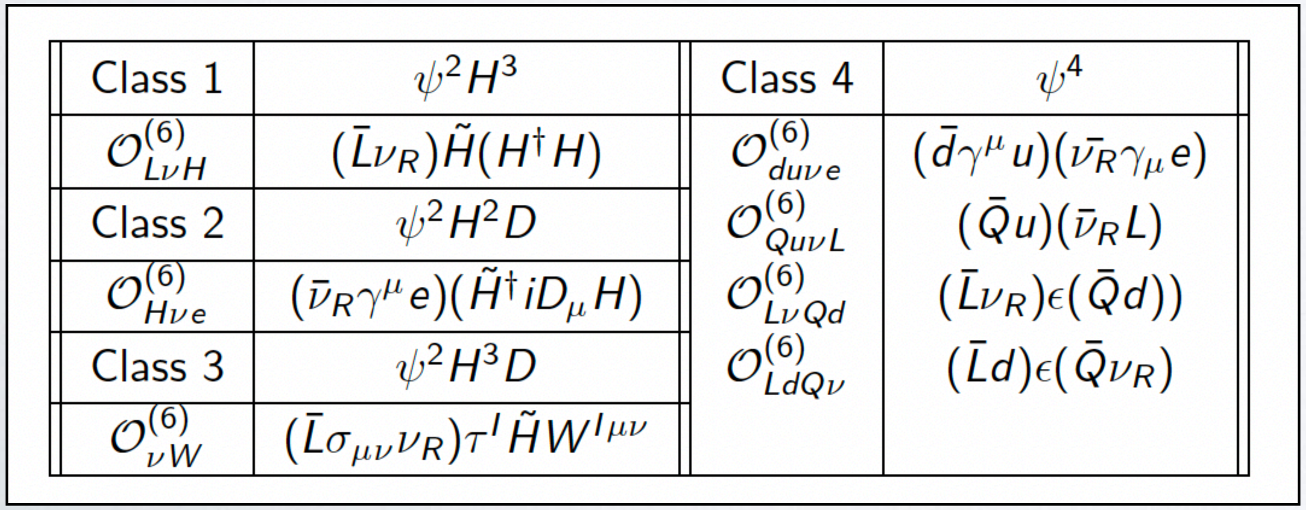
Λ

$E_{\text{exp}} << \Lambda$

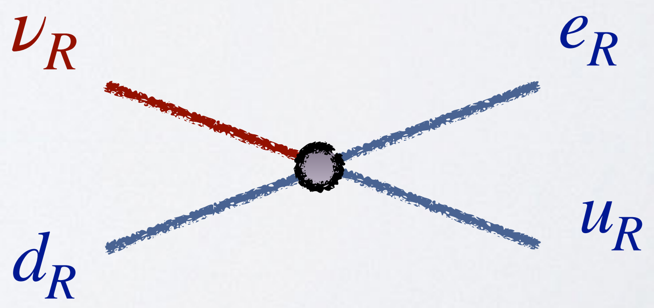
Effective operators

$\sim \frac{1}{\Lambda^n}$

- Extend Standard Model EFT to include right-handed singlets: **nu**SMEFT



Class 1	$\psi^2 H^3$	Class 4	ψ^4
$\mathcal{O}^{(6)}_{L\nu H}$	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}^{(6)}_{du\nu e}$ $\mathcal{O}^{(6)}_{Qu\nu L}$ $\mathcal{O}^{(6)}_{L\nu Qd}$ $\mathcal{O}^{(6)}_{LdQ\nu}$	$(\bar{d}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu e)$ $(\bar{Q}u)(\bar{\nu}_R L)$ $(\bar{L}\nu_R)\epsilon(\bar{Q}d))$ $(\bar{L}d)\epsilon(\bar{Q}\nu_R)$
Class 2	$\psi^2 H^2 D$		
$\mathcal{O}^{(6)}_{H\nu e}$	$(\bar{\nu}_R\gamma^\mu e)(\tilde{H}^\dagger iD_\mu H)$		
Class 3	$\psi^2 H^3 D$		
$\mathcal{O}^{(6)}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I\tilde{H}W^{I\mu\nu}$		



$\sim \frac{1}{\Lambda^2}$

Effective field theory

- We are interested in low-energy decays of mesons and GeV neutrinos
- Evolve operators down and **match** nuSMEFT → nuLEFT
- After rotating to the neutrino mass basis

$$
\begin{aligned}
\mathcal{L}^{(6,7)}_{\rm mass} \;=\; \frac{2G_F}{\sqrt{2}}\Big\{ & \bar{u}_L\gamma^\mu d_L\left[\bar{e}_L\gamma_\mu C^{(6)}_{\rm VLL}\,\nu + \bar{e}_R\gamma_\mu C^{(6)}_{\rm VLR}\,\nu\right] + \bar{u}_R\gamma^\mu d_R\,\bar{e}_R\,\gamma_\mu C^{(6)}_{\rm VRR} \\
& \bar{u}_L d_R\,\bar{e}_L\,C^{(6)}_{\rm SRR}\nu + \bar{u}_R d_L\,\bar{e}_L\,C^{(6)}_{\rm SLR}\nu + \bar{u}_L\sigma^{\mu\nu}d_R\,\bar{e}_L\sigma_{\mu\nu}\,C^{(6)}_{\rm TRR}\nu \\
& +\frac{1}{v}\bar{u}_L\gamma^\mu d_L\,\bar{e}_L\,C^{(7)}_{\rm VLR}\,i\overleftrightarrow{D}_\mu\nu\Big\} + {\rm h.c.}\,,
\end{aligned}
$$

- These are all charged currents (neutral currents included but not shown)
- The neutrinos are now described by 3+n mass eigenstates ν
- In minimal model, production of '4th' neutrino through $C^{(6)}_{VLL} \sim G_F V_{ud} U_{e4}$

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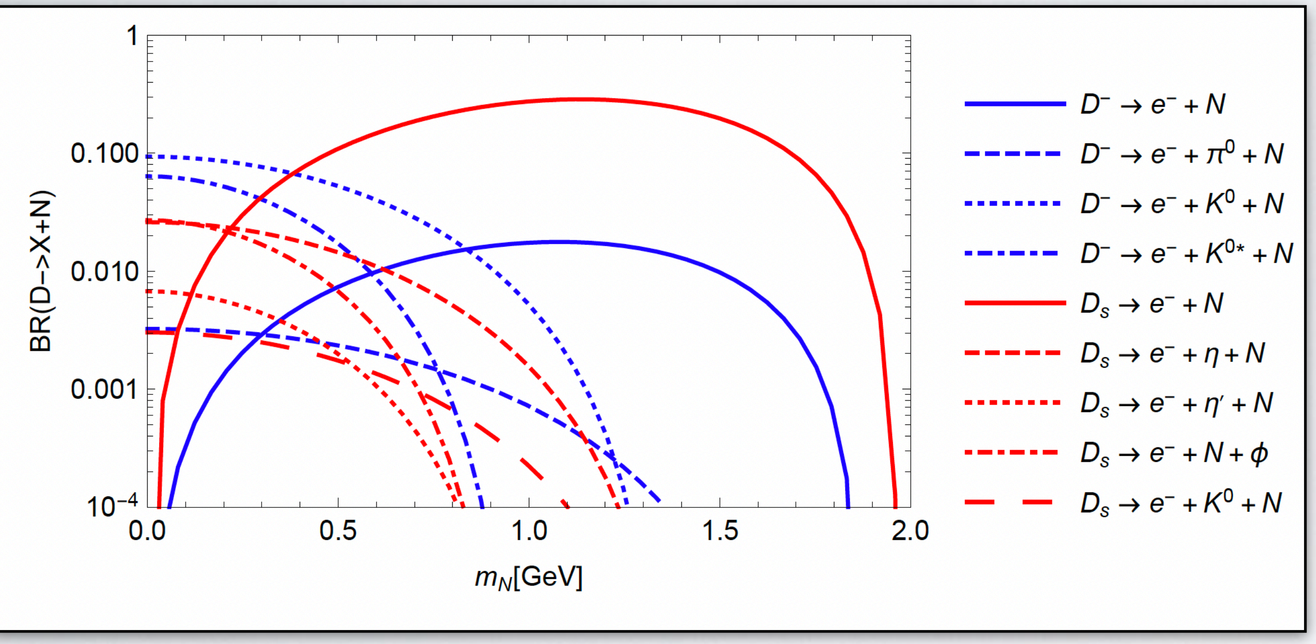
- Other operators induced by higher-dim operators and scale as $\sim v^2/\Lambda^2$
- Left-right models: $C^{(6)}_{VLR}, C^{(6)}_{VRR}$ Leptoquarks: $C^{(6)}_{SRR}, C^{(6)}_{SLR}, C^{(6)}_{TRR}$
- Can also be used to describe light neutralinos (interpret nu as neutralino)

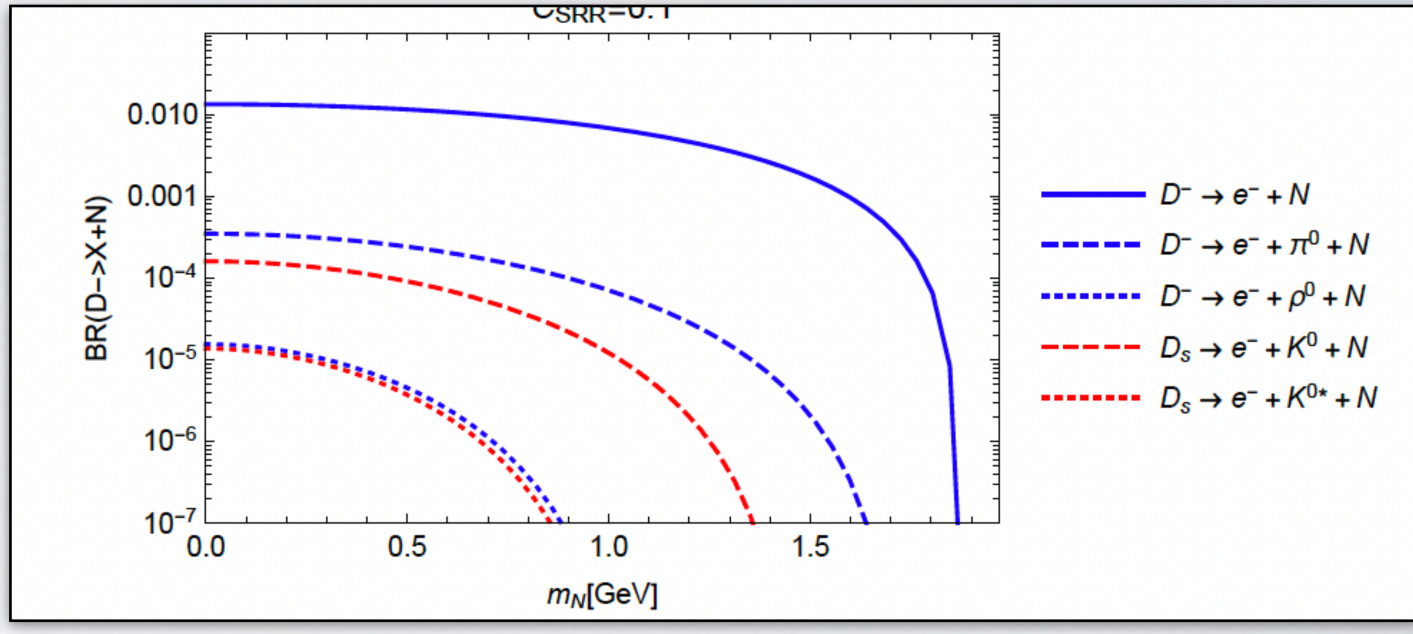
D. Dercks et al '15, Julian Guenther et al, in prep

Production of sterile states

- We focus on production through meson decays (by far dominant for M ~ GeV)
- In minimal scenarios (only vector currents), 2-body decays helicity suppressed



$U_{e4} = 1$

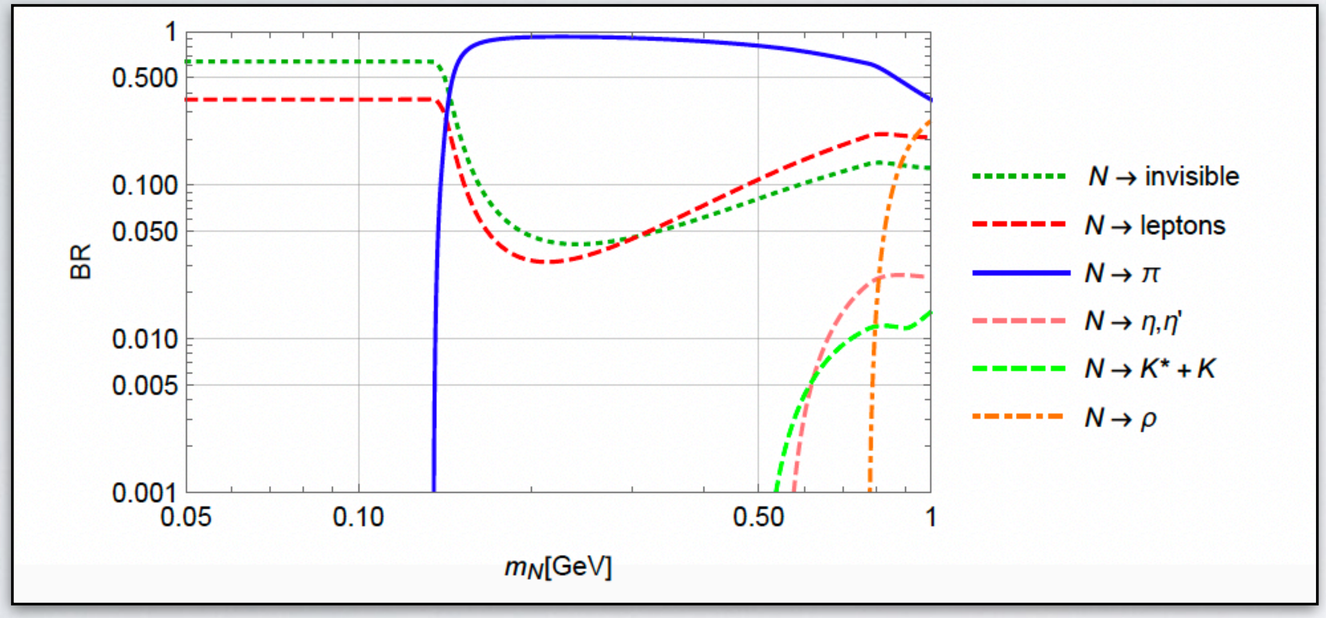


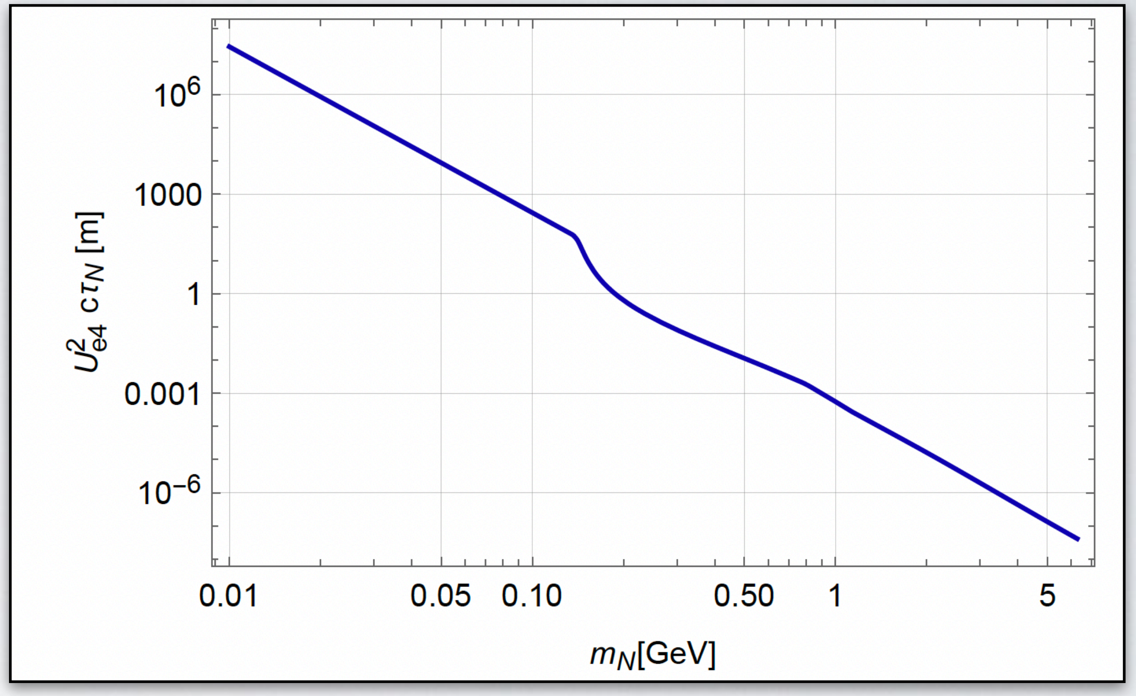
$C_{SRR} = 0.1$

- Similar plots for B mesons
- Hadronic input are D and B meson decay constants and form factors
- Known well for Vector currents, but less known for BSM currents. Some uncertainties.

Sterile Neutrino decays

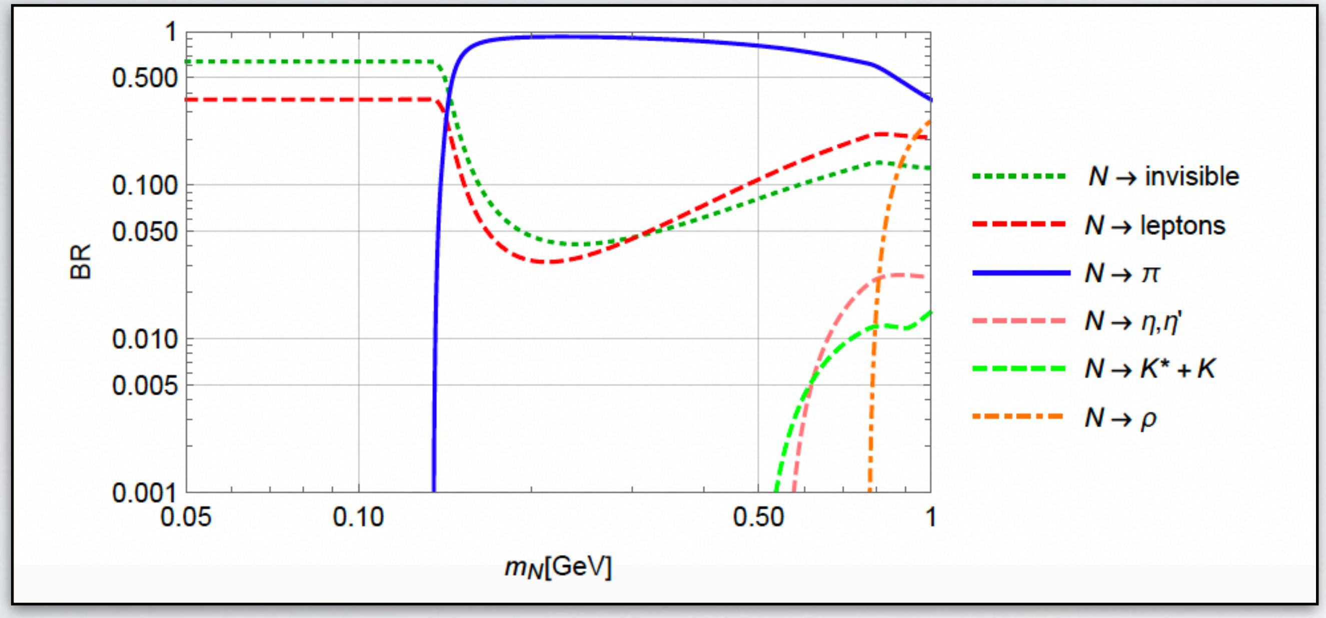
- Two-body decays to meson + lepton, and (semi-)leptonic three-body decays
- Computation from same Lagrangian: focus on final states with 2 charged particles

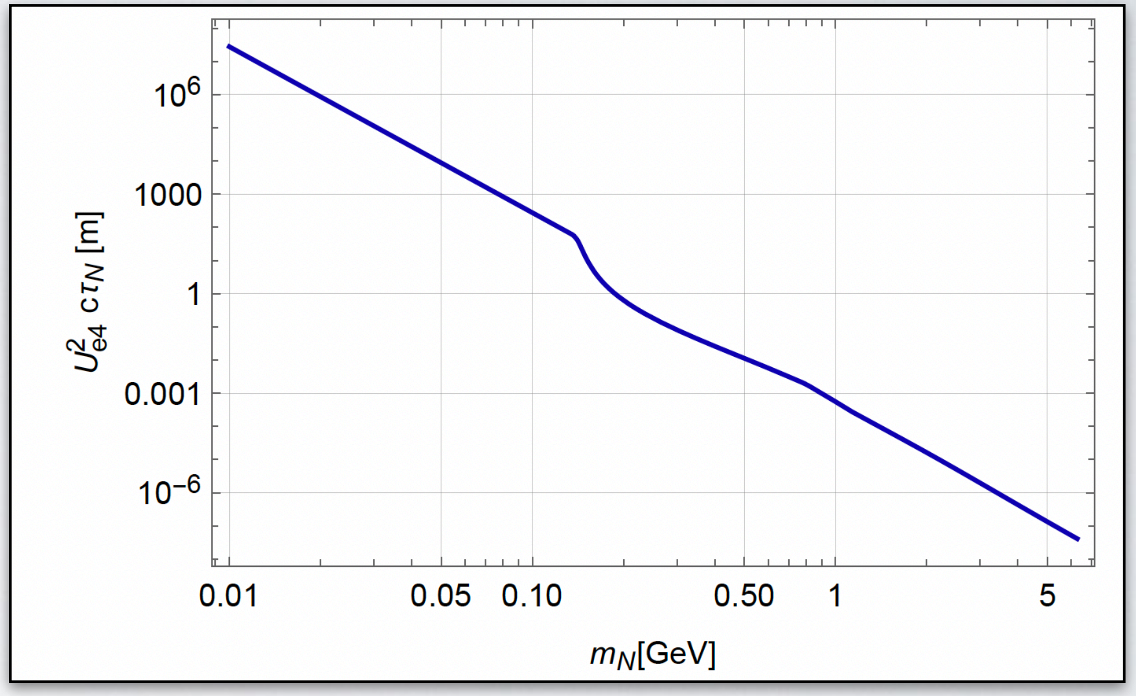




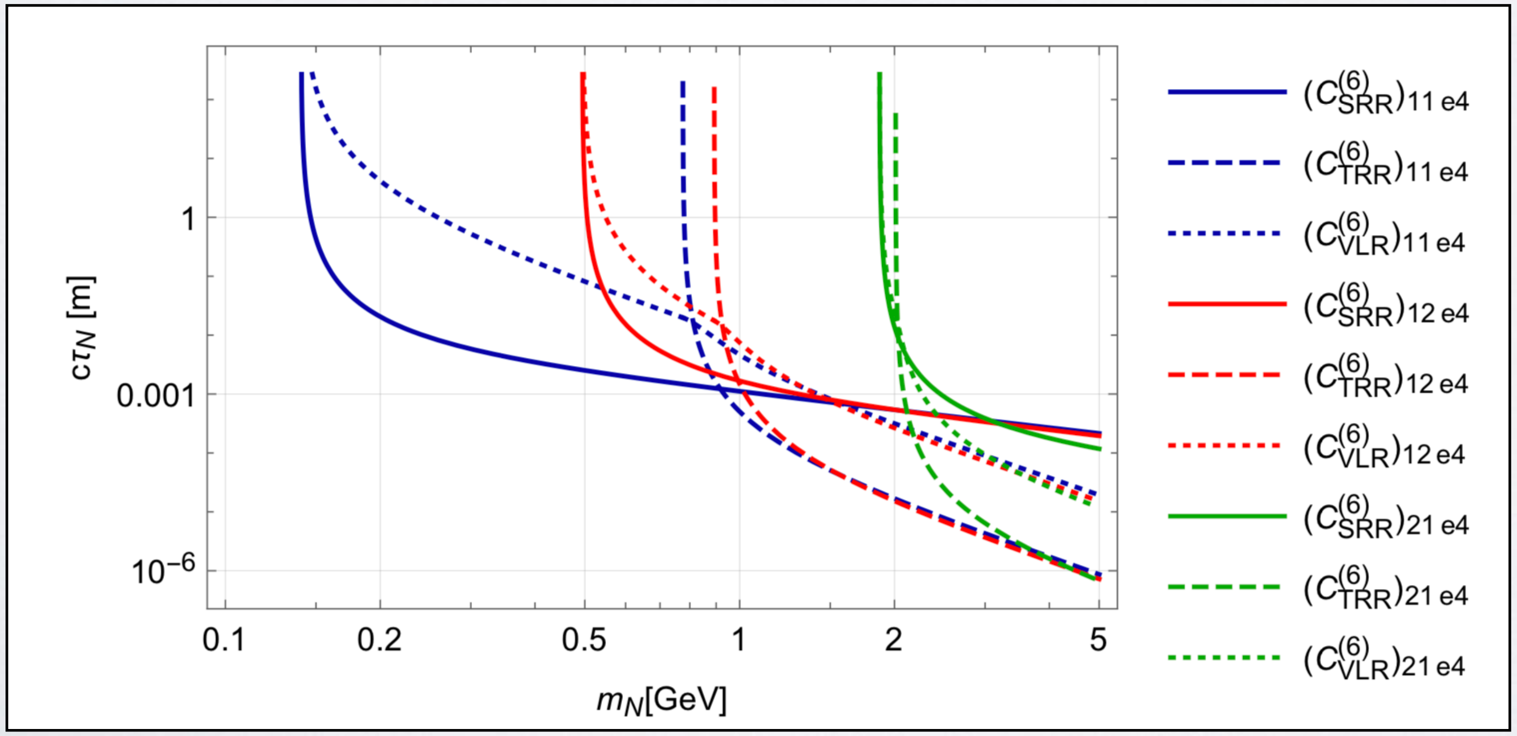
Sterile Neutrino decays

- Two-body decays to meson + lepton, and (semi-)leptonic three-body decays
- Computation from same Lagrangian: focus on final states with 2 charged particles





- Similar for higher-dimensional operators, but long-lived above meson threshold



$C_i = 1$

Simulations

- Compute meson production at experiments with Pythia 8 (Simulation started by Daniel)

$$\boxed{N_N^{\text{prod}} \quad = \quad \sum N_{M_i} \cdot \text{Br}(M_i \to N + X)}$$

- Simulate around 10^6 events and rescale to total number of producers mesons with 3 ab^{-1}

$$\begin{aligned} &N_{D^\pm}^{\text{HL-LHC}} = 2.04 \times 10^{16}, \quad N_{D^0}^{\text{HL-LHC}} = 3.89 \times 10^{16}, \quad N_{D_s}^{\text{HL-LHC}} = 6.62 \times 10^{15}, \\ &N_{B^\pm}^{\text{HL-LHC}} = 1.46 \times 10^{15}, \quad N_{B^0}^{\text{HL-LHC}} = 1.46 \times 10^{15}, \quad N_{B_s}^{\text{HL-LHC}} = 2.53 \times 10^{14}. \end{aligned}$$

- For each proposed experiment then determine Probability of decay in detector

- For now, not a detector simulations and just use whole volume

$$\boxed{N_N^{\text{dec}} \quad = \quad N_N^{\text{prod}} \cdot \langle P[N \text{ in f.v.}] \rangle \cdot \text{Br}(N \to \text{signal})}$$

Intermediate quiz

In a visit to Utrecht, Herbi almost got himself killed in a very Dutch way. **But how ?**

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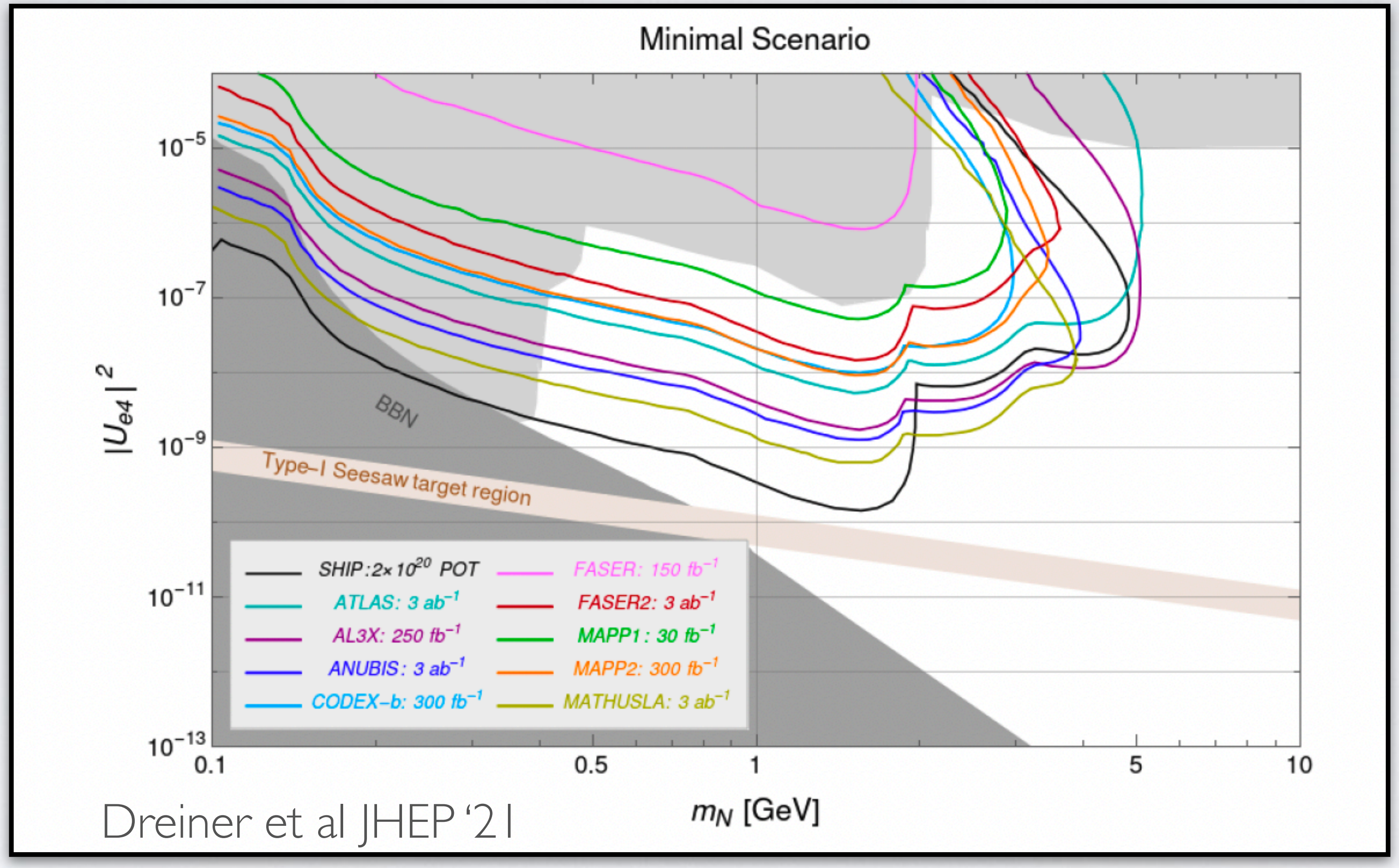
C. He got overrun by a Dutch cyclist (and then yelled at)

Back to Physics

- All ingredients to determine parameter space with 3 visible decays in detector

Minimal scenarios

- **Current limits will improve significantly with new experiments**



Dreiner et al JHEP ‘21

See also many other works: Bondarenko et al, Shaposhnikov et al, Drewes et al, Pascoli et al

- Proposed experiments can come pretty close to naive seesaw band
- Very good tests of low-scale leptogenesis scenarios
- Our results are not reliable for masses below kaon threshold

Minimal scenarios

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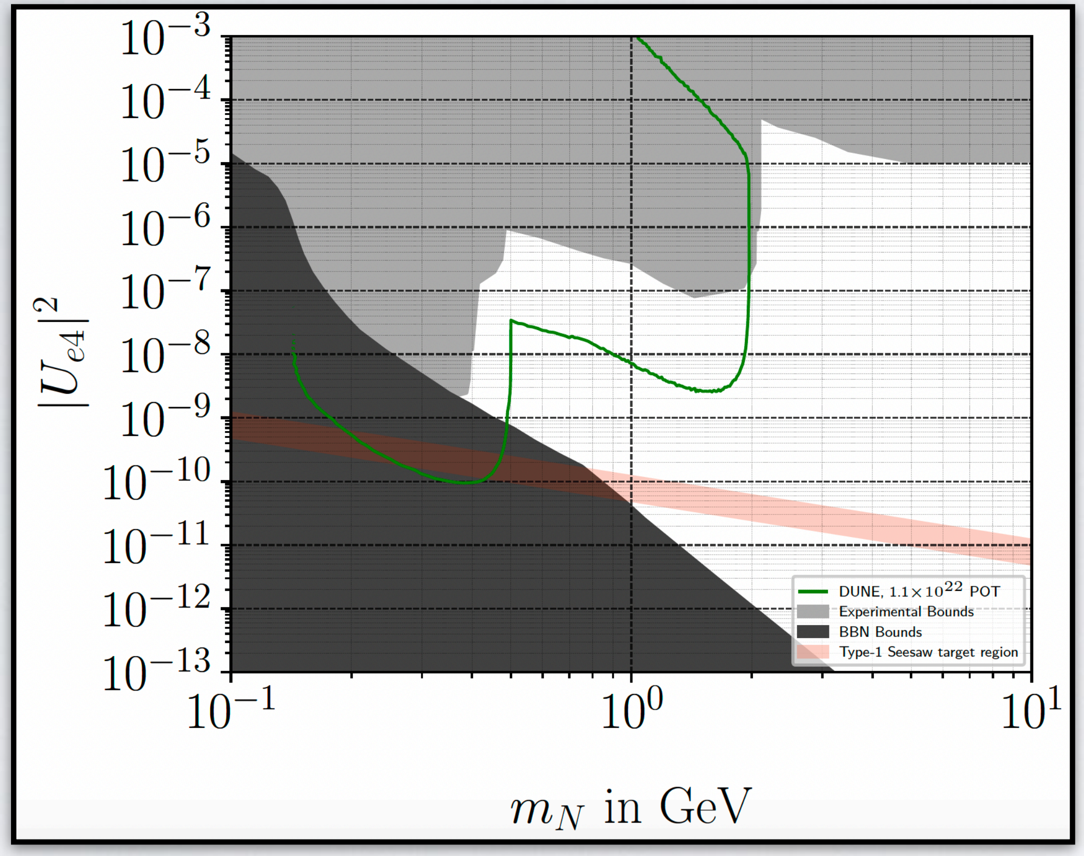
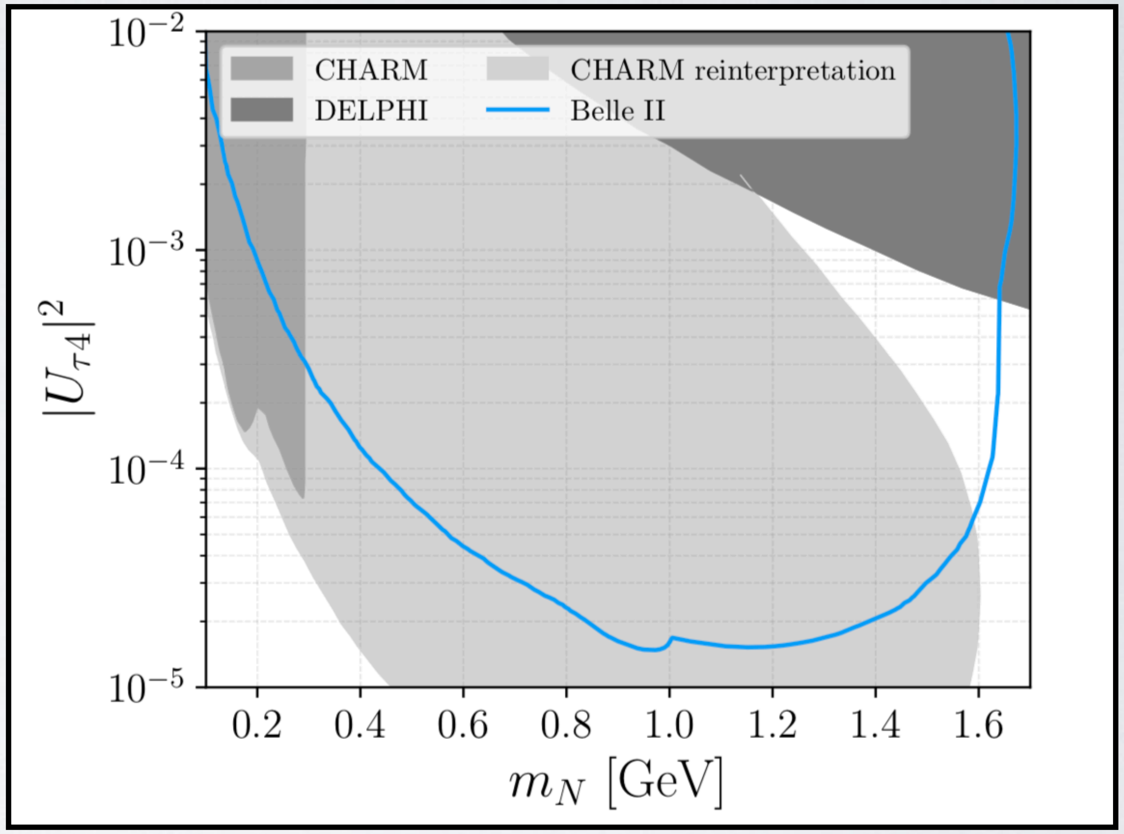


Dreiner et al, in prep



Dreiner et al, 2021

See also many other works: Bondarenko et al, Shaposhnikov et al, Drewes et al, Pascoli et al

Similar bounds from BECB as CHARM (Barouki et al)

- DUNE will be very sensitive for sterile masses below 2 GeV

- Belle-II sensitive to couplings to third-generation (marginally compared to CHARM/BECB)

Non-Minimal scenarios

- A bit hard to do a general study (many operators)
- We work with Benchmark scenarios where we turn on one '**production operator**' and one '**decay operator**'

- Example: a LeptoQuark (R2) inspired model

$$\boxed{\mathcal{L}_{\rm LQ} = -y^{RL}_{jk}\bar{d}_{Rj}\tilde{R}^a\epsilon^{ab}L^b_{Lk} + y^{\overline{LR}}_{il}\bar{Q}^a_{Li}\tilde{R}^a\nu_{Rl} + \mathrm{h.c.}}$$

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- Integrate out leptoquarks, match and run, and rotate to mass basis

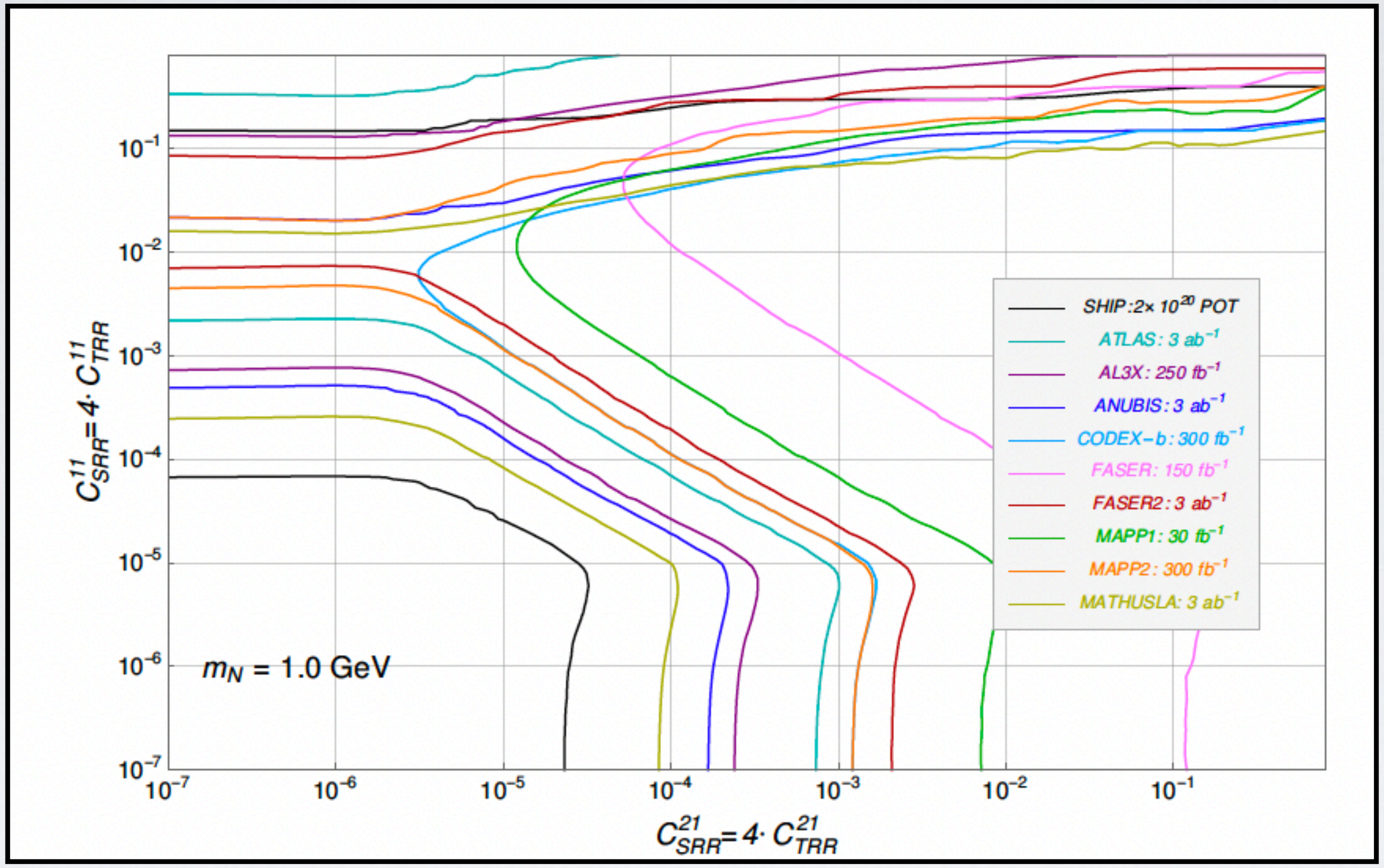
$$\left(C^{(6)}_{\rm VLL}\right)_{ije4} = -2V_{ij}U_{e4}$$

$$\left(C^{(6)}_{\rm SRR}\right)_{ije4} = 4\left(C^{(6)}_{\rm TRR}\right)_{ije4} = \left(\frac{v^2}{2}\frac{1}{m^2_{\rm LQ}}y^{\overline{LR}}_{i1}y^{RL*}_{je}\right)_{ije1} U^*_{44}$$

- Then pick flavor assignment and add minimal coupling

$$\boxed{U_{e4} \simeq \sqrt{\frac{m_\nu}{m_N}}, \qquad U_{44} = 1}$$

LeptoQuark inspired scenarios



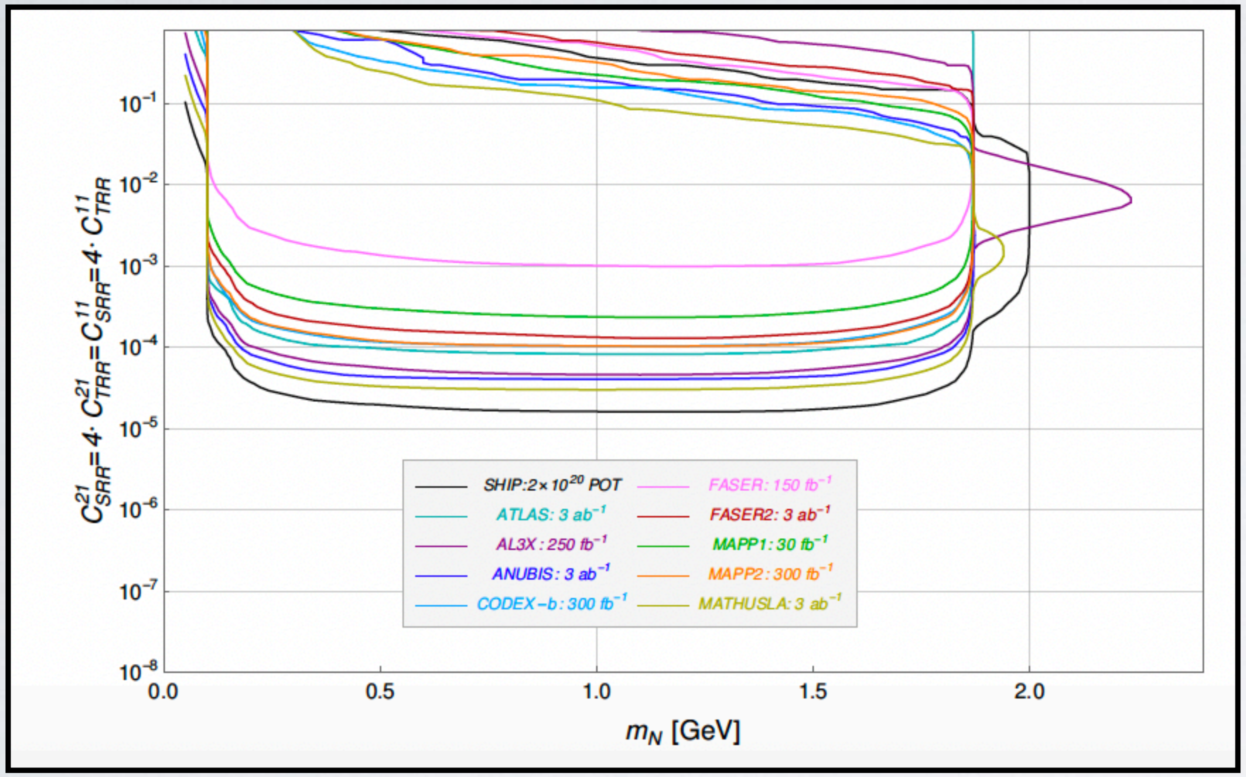
Decay coupling (N -> pi, rho + X)

Production coupling (D -> N + X)

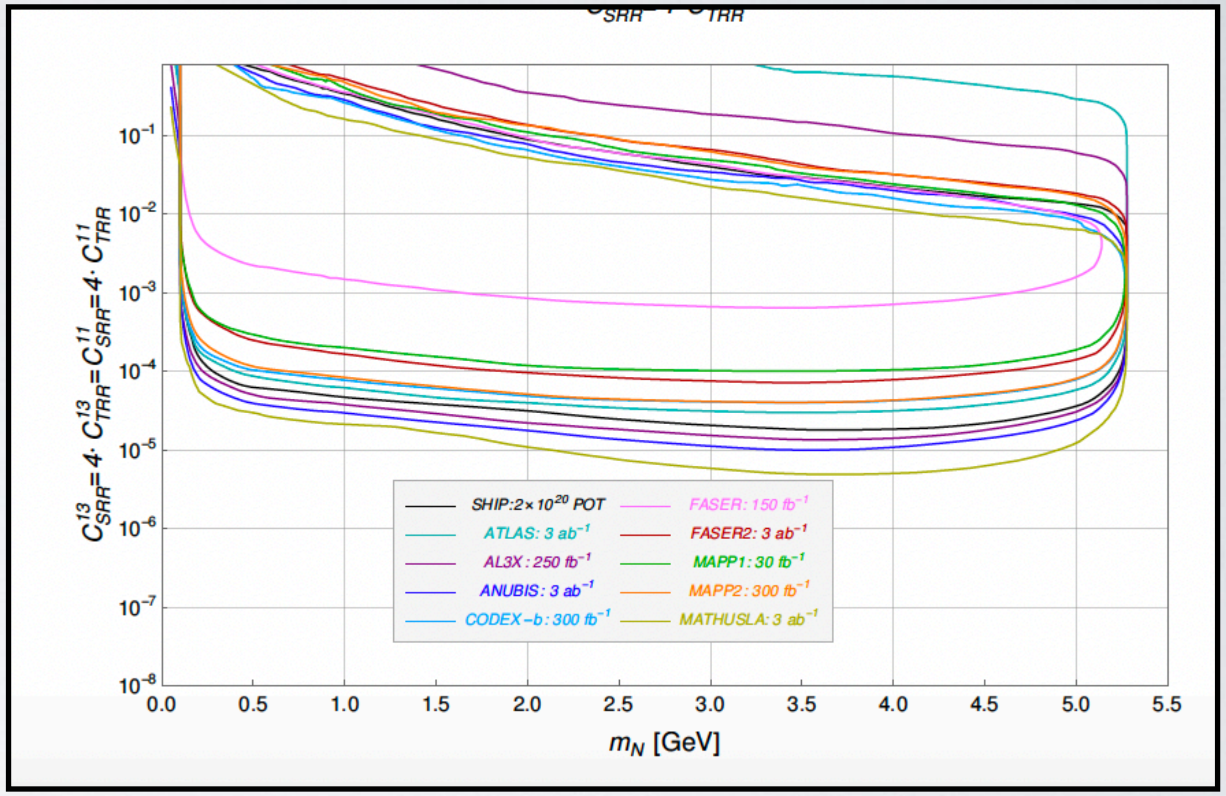
- Fixed sterile neutrino mass: minimal mixing can be relevant in parts of the space
- Sensitive to couplings at the $10^{-4,-5}$ level (MATHUSLA) to $10^{-2,-3}$ level (FASER)

$C \sim v^2/M_{LQ}^2 \rightarrow M_{LQ} \sim v/\sqrt{C}$ 5-10 TeV (FASER) to 50-100 TeV (MATHUSLA)

LeptoQuark inspired scenarios



Production coupling (D -> N + X)



Production coupling (B -> N + X)

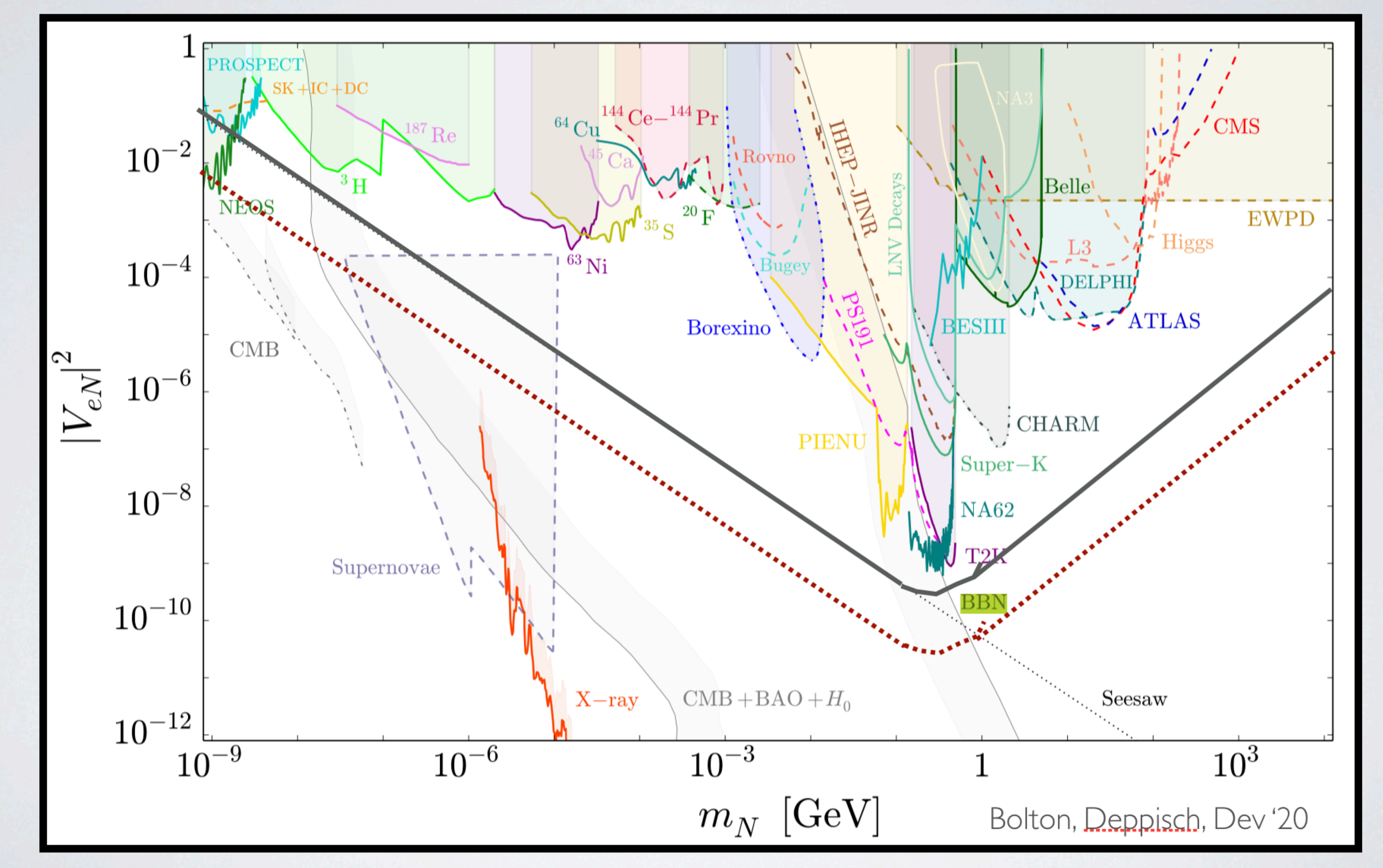
- LHC experiments do better for larger mass neutrinos (since more B production)

- Work in progress to match to `realistic models' (e.g. mLRSM)

- Not today, but for mB > m > mpi, other experiments cannot reach these bound
- Except perhaps for …..

Neutrinoless double beta decay (0vbb)

- If sterile states are Majorana there can be large 0vbb rates

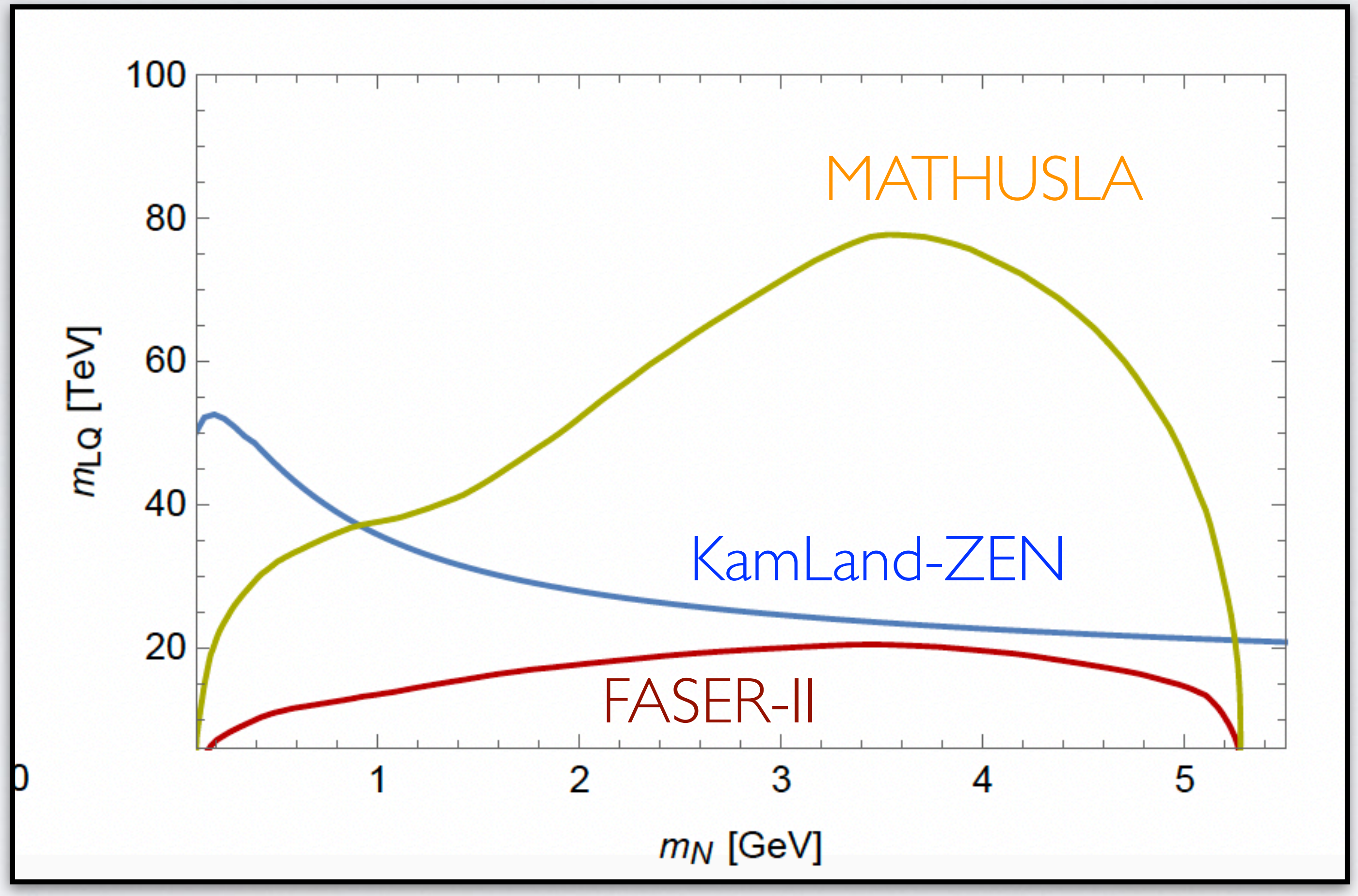


Bolton, Deppisch, Dev '20

- But of course these bounds are avoided if Dirac or suppressed if Pseudo-Dirac
- Or for couplings to muons !

Neutrinoless double beta decay (0vbb)

- If sterile states are Majorana there can be large 0vbb rates JdV et al, 2020



- With non-standard interactions, future experiments can beat 0vbb bounds even for Majorana neutrinos Dreiner et al, 2020

- Work in progress: combine low-scale leptogenesis + 0vbb + long-lived searches

Summary and outlook

- **A lot of motivation for sterile neutrinos (neutrino masses, leptogenesis, neutrino portal) but mass range unclear**
- Renewed focus on long-lived particles is pretty exciting

Summary and outlook

- **A lot of motivation for sterile neutrinos (neutrino masses, leptogenesis, neutrino portal) but mass range unclear**
- Renewed focus on long-lived particles is pretty exciting
- Herbi has always been extremely supportive and a great friend and collaborator
- Hope to continue working together! And of course Happy Birthday !

Lecture on Tuesday. Was thinking I could wear this to a PhD defense at UvA.

NOS Teletekst 830

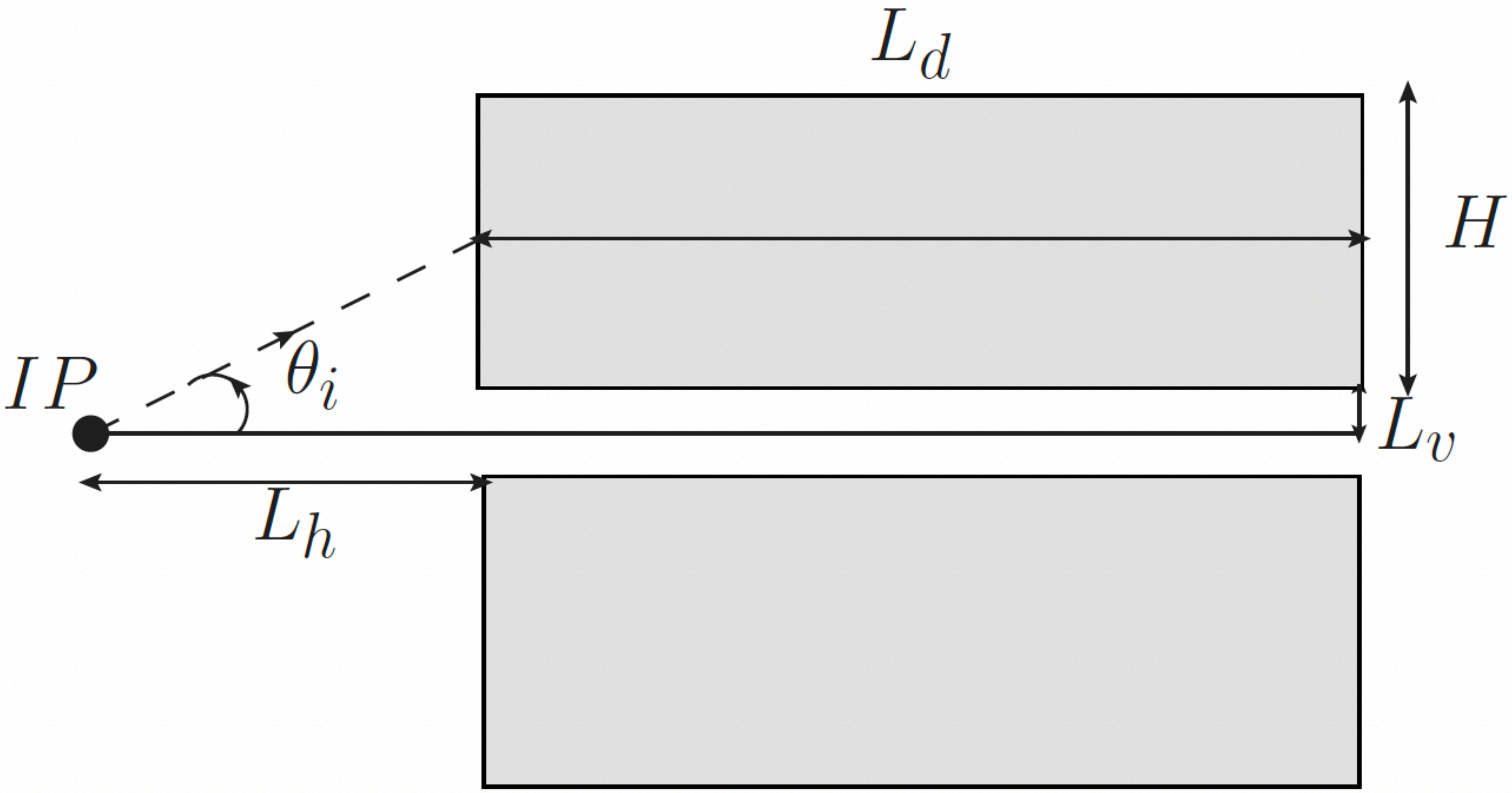
VOETBAL 1/3

Keuk.kamp.divisie,stand per 26/03

1.	PEC Zwolle +	30	22	3	5	69	81-32
2.	Heracles +	30	21	3	6	66	86-35
3.	Almere City	29	16	4	9	52	42-32
4.	VVV-Venlo	30	15	7	8	52	48-39
5.	Willem II	30	14	8	8	50	51-34
6.	FC Eindhoven	30	13	8	9	47	44-42
7.	MVV Maastr.	30	13	5	12	44	53-54
8.	NAC Breda	30	13	4	13	43	49-54
9.	Telstar	30	11	10	9	43	31-41
10.	Roda JC	30	12	5	13	41	41-40
11.	Jong AZ	30	11	8	11	41	49-49
12.	Graafschap	30	11	6	13	39	47-41
13.	ADO Den Haag	30	10	9	11	39	36-44
14.	Jong PSV	30	10	8	12	38	46-49
15.	Helmond Sp.	30	9	7	14	34	28-45
16.	Jong Ajax	30	7	10	13	31	51-58
17.	TOP Oss	30	9	3	18	30	34-55
18.	FC Den Bosch	30	9	3	18	30	42-73
19.	FC Dordrecht	30	7	6	17	27	32-51
20.	Jong Utrecht	29	5	5	19	20	27-50

AL3X

- A Laboratory for Long-Lived eXotics: a cylindrical detector at IP2 (ALICE) of the LHC [1810.03636]



Extracted from [1811.01995]

L_d (m)	L_h (m)	L_v (m)	H (m)	$\phi/2\pi$	$\mathcal{L}$ (fb^{-1})
12	5.25	0.85	4.15	1	100/250

Comparison to other works

- [1905.11375, 2007.00673]:
  Pion decays ($\Lambda \gtrsim 36$ TeV), tau decays, and $l + \not{E}_T$ ($\Lambda \gtrsim 2 - 5$ TeV)
- [2005.01543, 2007.15408]:
  The most stringent bounds are on the operators $C^{(6)}_{L\nu Qd}$, $C^{(6)}_{LdQ\nu}$, and $C^{(6)}_{Qu\nu L}$ involving an up quark, a down (strange) quark and an electron using LFU constraints: $\Lambda \gtrsim 74$ (110) TeV for massless N
  Other operators and flavor combindations: $\Lambda \gtrsim 0.5 - 8$ TeV
- [2004.06726]:
  $b \to c\tau\overline{\nu}$ including light N ($m_N \lesssim 100\,\text{MeV}$): $\Lambda \gtrsim \mathcal{O}(1)$ TeV
- [2005.01543, 2004.13869, 1905.08699]:
  Limits from ECνNS based on the `COHERENT` experiment:
  $m_N \lesssim 0.5\,\text{MeV}$, $\Lambda \gtrsim 1\,\text{TeV}$
- We conclude that the sensitivities of the experiments considered here are competitive with and complementary to existing constraints