Exploring neutrino phenomenology in B-L extensions

Suchita Kulkarni (she/her)
Junior group leader

NB: all references to literature are 100% biased

NAWI Graz Natural Sciences

FWF Der Wissenschaftsfonds.

UNI GRAZ

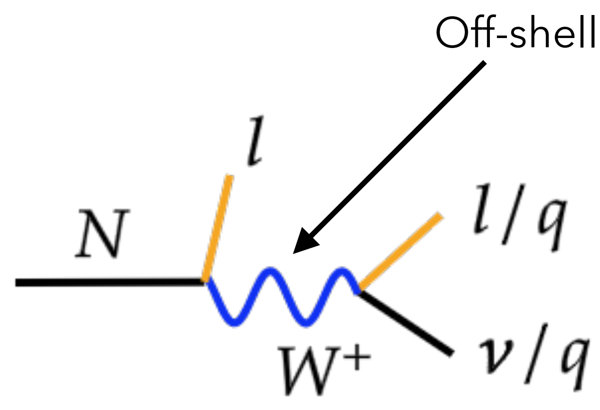
SM extensions with RH neutrino

See e.g. Deppisch, New J. Phys. 17 (2015) 075019

- Introduce Dirac mass term with new RH neutrinos

$$-\mathscr{L}_{Dirac} \supset m_D \bar{\psi}\,\psi = m_D \bar{\psi}_L \psi_R + m_D \psi_L \bar{\psi}_R$$

$$-\mathscr{L}_{Yukawa} = Y \bar{\nu}_L \phi N_R + h.c. \qquad \langle \phi^0 \rangle = v$$



- The RH neutrinos can have Majorana mass term

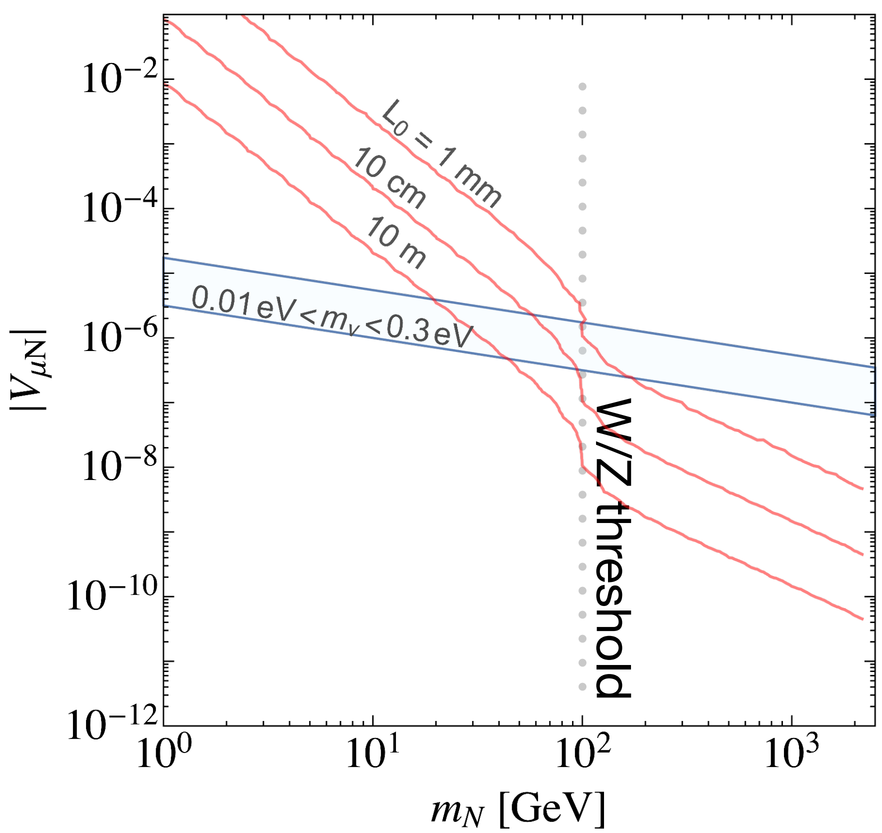
$$-\mathscr{L}_{R,Majorana} = M_N \overline{N_R^C}\, N_R + h.c.$$

- This generates (the famous) type - 1 seesaw mechanism

$$\mathscr{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \qquad m_\nu \approx -\frac{m_D^2}{M_N} = -V_{lN}^2 M_N$$

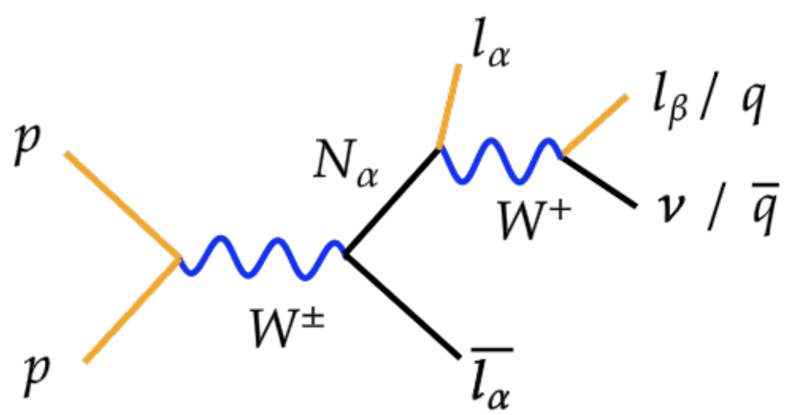
$$\Gamma_N \simeq c_{dec} \frac{a}{96\pi^3} G_F^2 V_{lN}^2 M_N^5$$

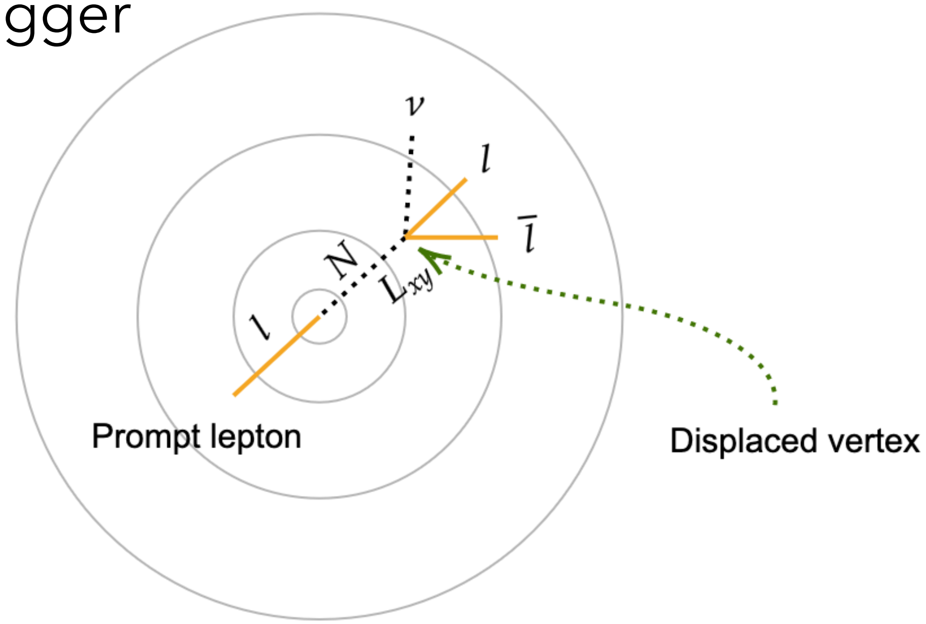
($c_{dec} = 1$ (Majorana), 1/2 (Dirac); $a \simeq 12$)



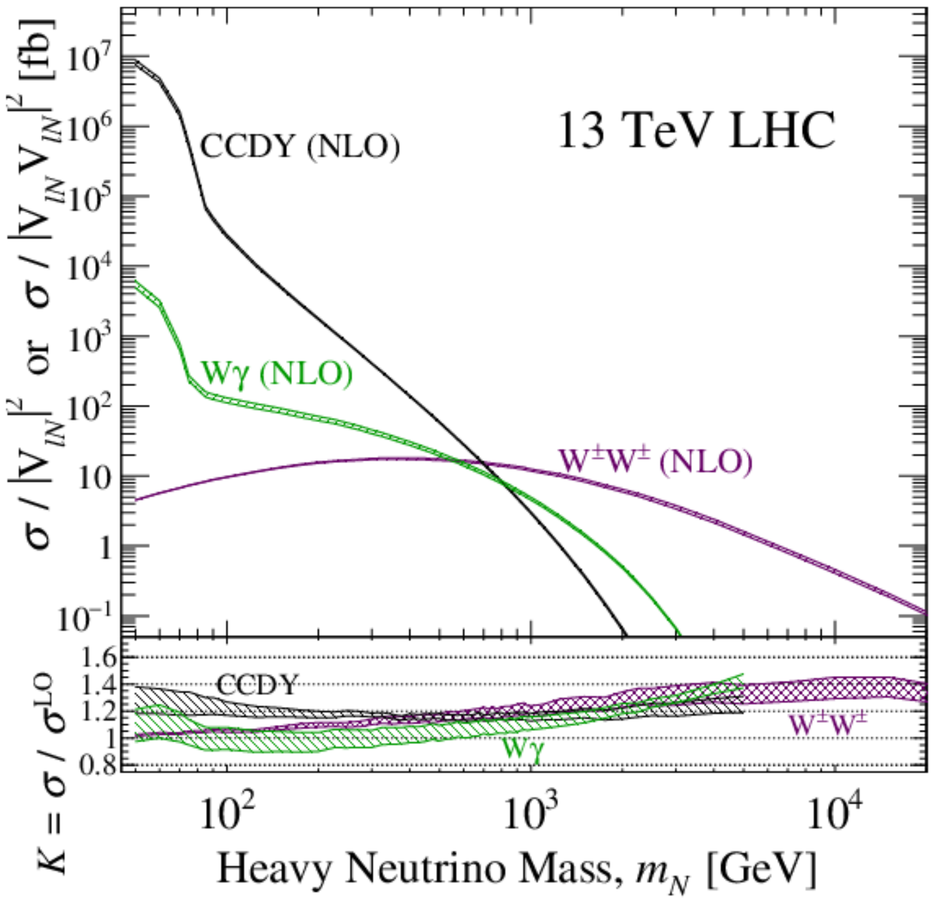
- Throughout this talk, assume only one heavy neutrino is within reach

- LHC strategies rely on existence of prompt lepton for e.g. trigger

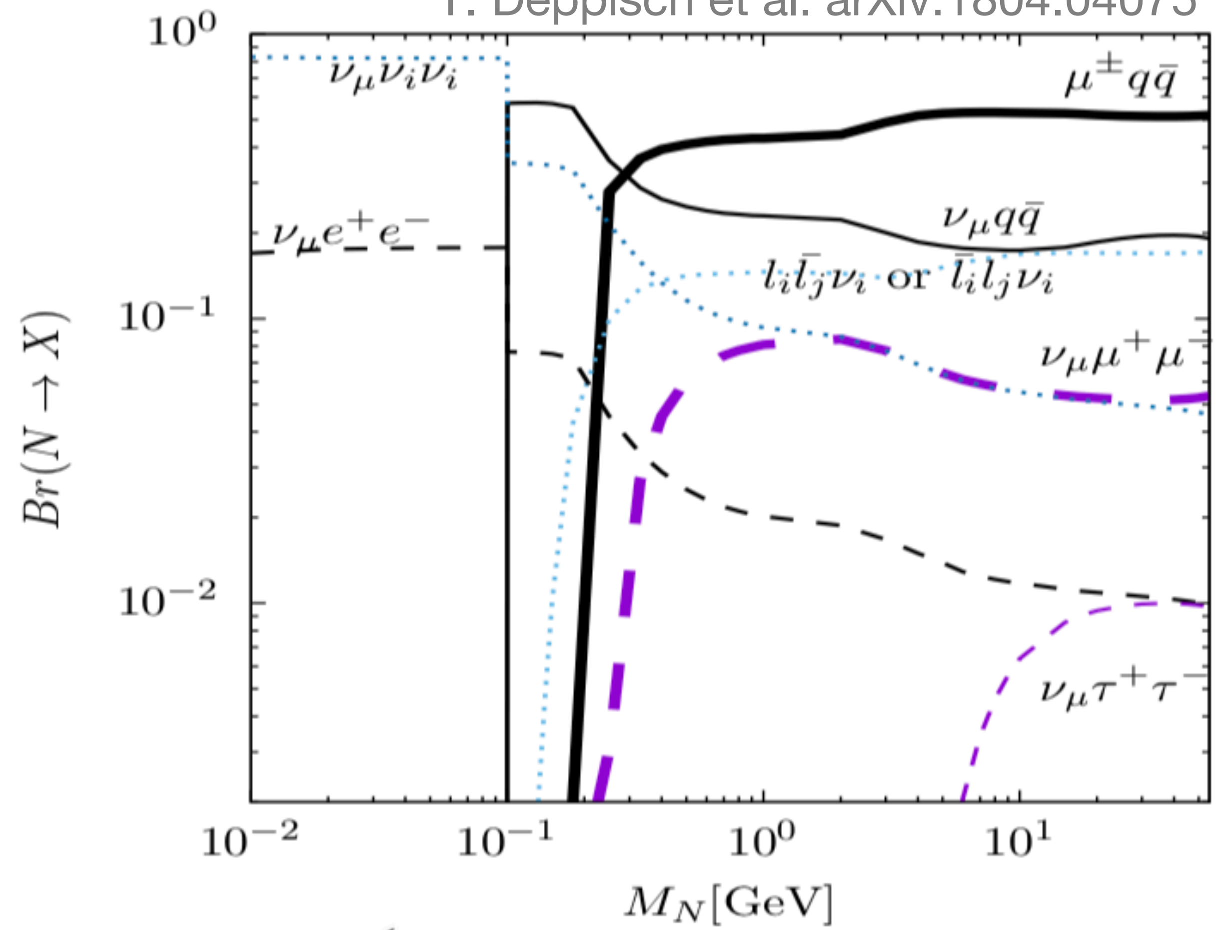




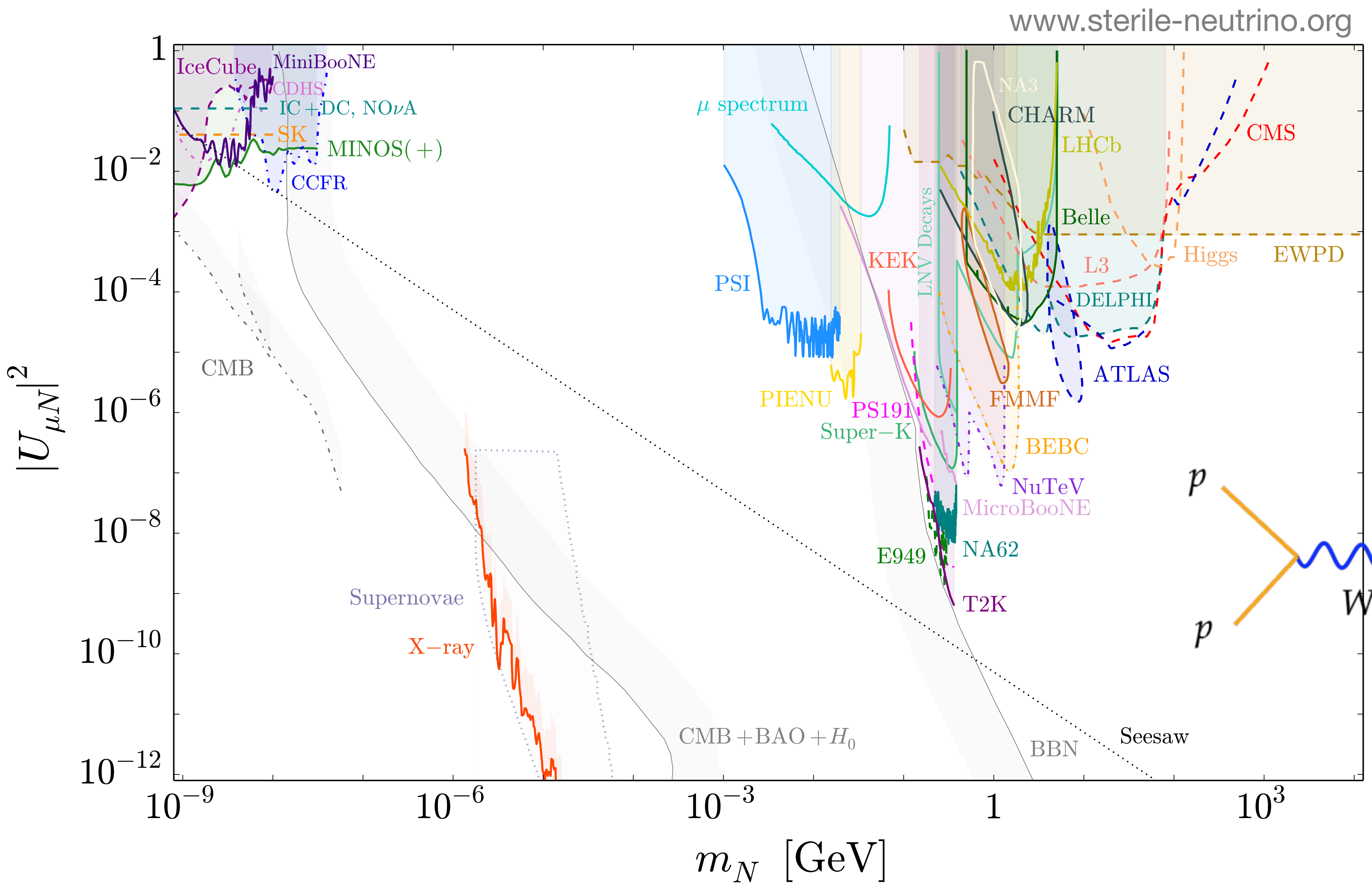
B. Fuks et al. arXiv:2011.02547

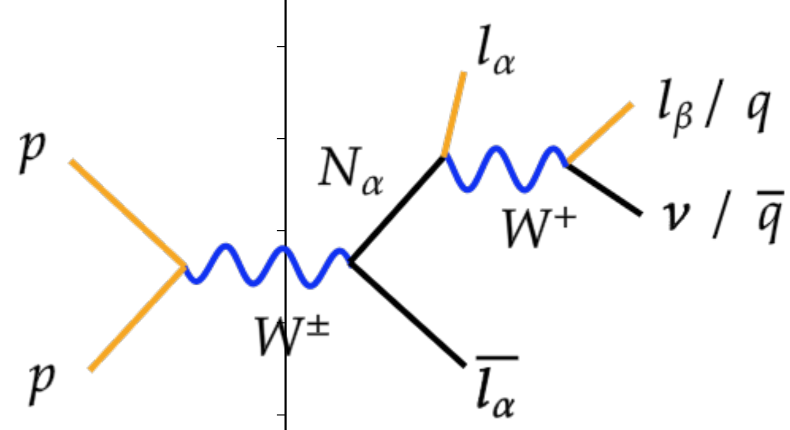


F. Deppisch et al. arXiv:1804.04075



Current status



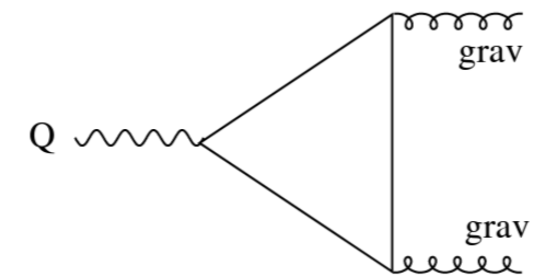


- For SM DY channel, HNL production cross section is limited by the mixing angle
- Can alternative HNL production mechanisms help?

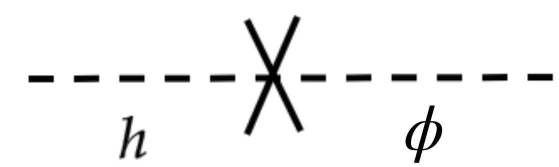
Neutrino masses - a simple model

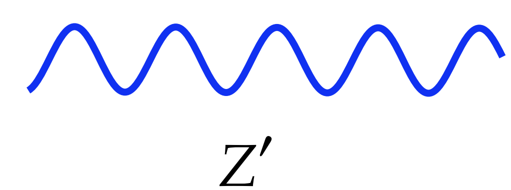
Mohapatra, Marshak (PRL 44 (1980) 1316-1319)

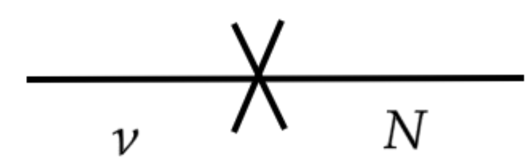
- B-L is the one global symmetry of the Standard Model
- Gravitational anomaly is cancelled if one adds three RH neutrinos
- Extend the SM gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
- $U(1)_{B-L}$ must be spontaneously broken for RH neutrinos to get masses
- Characteristics
  - Particle content: B-L gauge boson (Z'), Higgs boson (ϕ), 3 heavy neutrinos (N)
  - Couplings: g_{B-L} (B-L coupling), $\sin\alpha$ (ϕ, SM Higgs mixing), V_{lN} (neutrino mixing)
  - Free parameters: 5 masses, 5 couplings (diagonal V_{lN})
    - Assume only light muon neutrino → 3 masses, 3 couplings
  - Charges: ϕ: +2; N: -1; q: 1/3; l:-1
- Benchmark: one light RHN, light neutrino mass generation via type I seesaw



$$\sum_{a=0}^{N} Q_a = 0$$







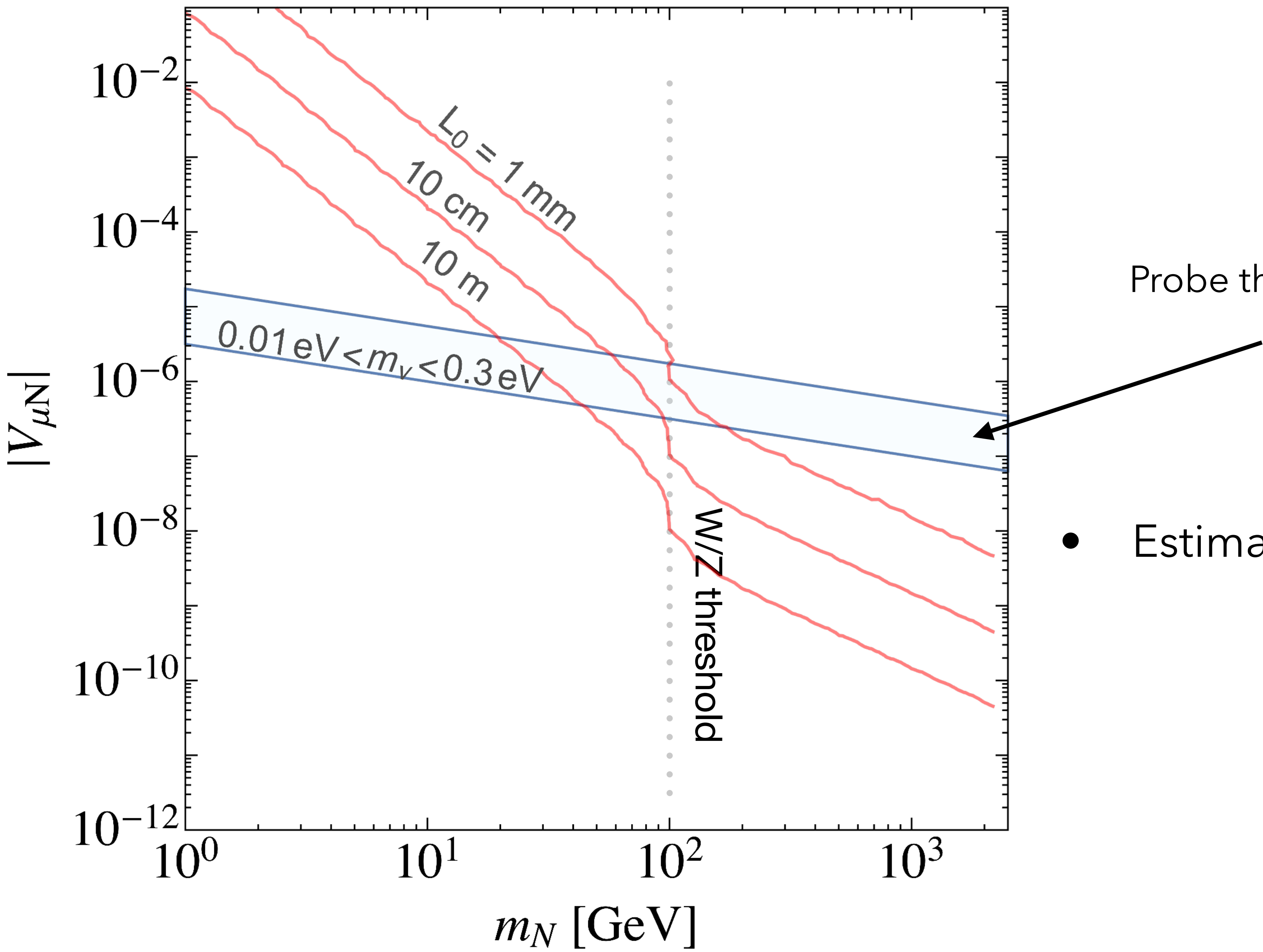
No considerations for lepton number violating signatures
= No BLED

BLED:

B-L Extension Detection strategies

SM extensions with RH neutrino

- What can help to get to the seesaw floor?

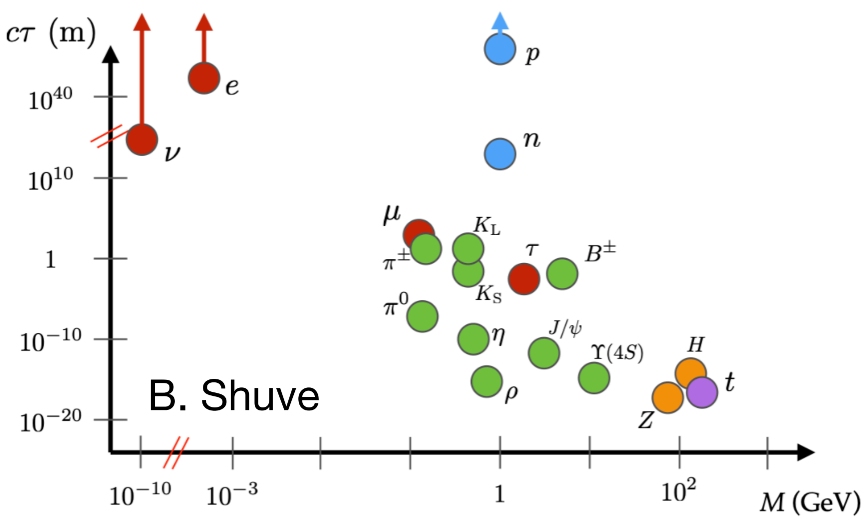


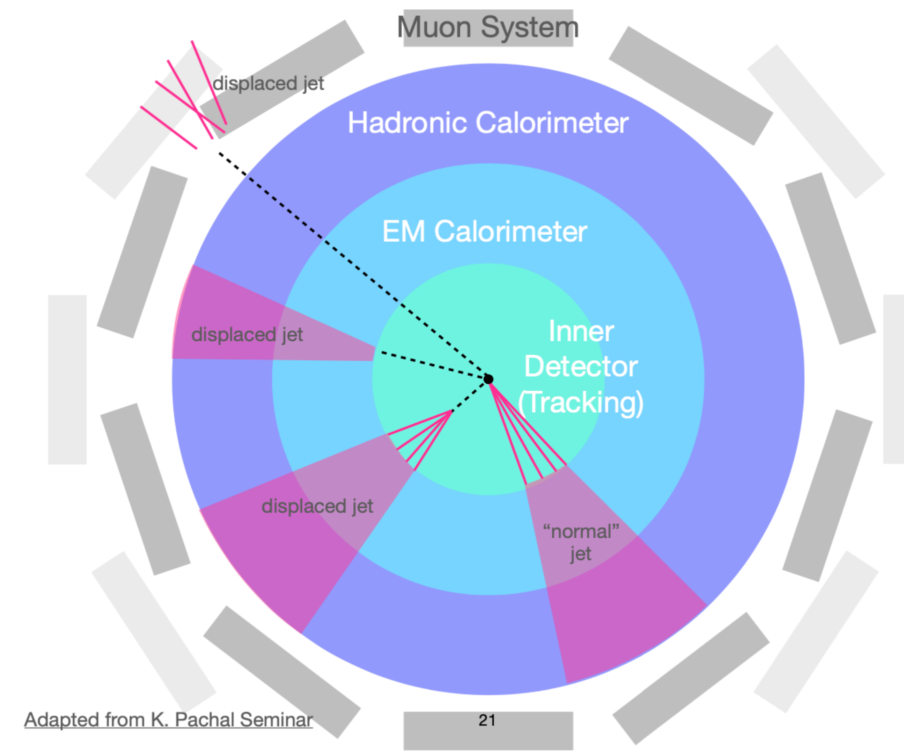
- Estimate sensitivity to displaced signatures

A theorists' approach to LLPs

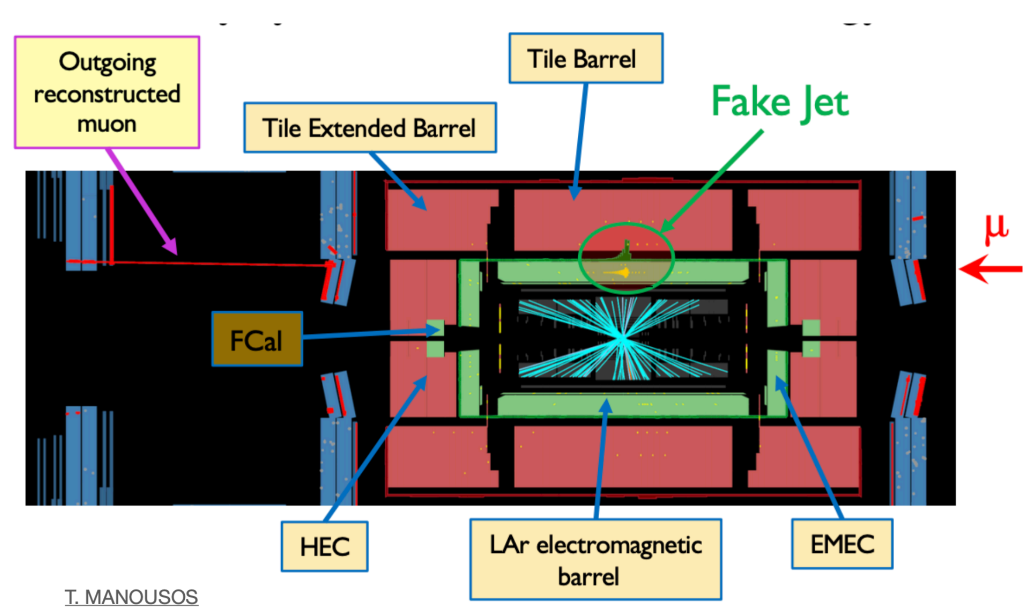
- No good theorist friendly detector simulation available
- Background estimations are challenging

'Real' QCD backgrounds



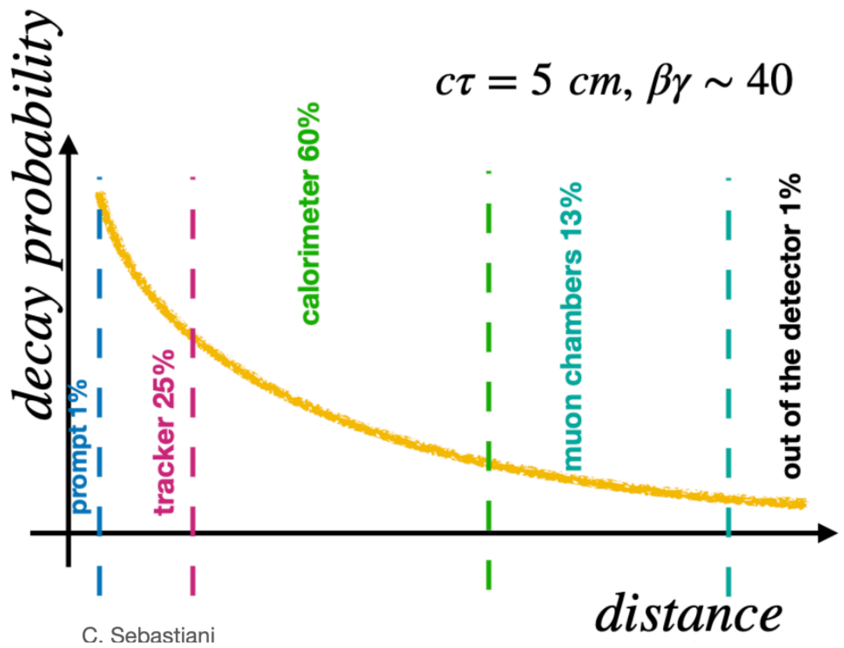


Fake backgrounds



- Typical background reduction strategies
  - Isolated leptons, number of tracks / high pT objects
- Typical theory assumptions
  - Assume an ideal detector, background free scenarios
  - Include effect of detector geometry

LLP sensitivity: basics

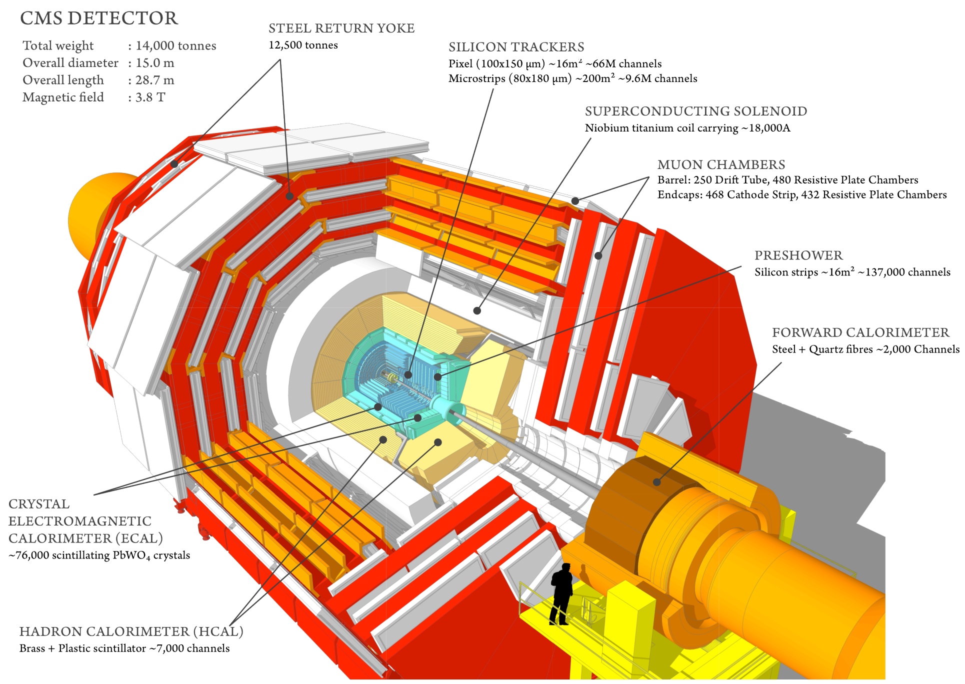


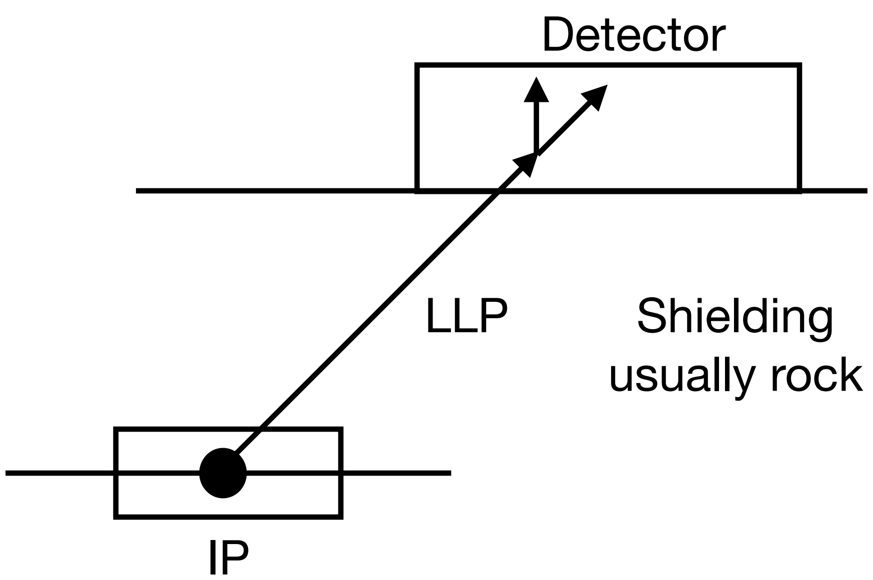
$$
\begin{aligned}
P_{\text{decay}}(b c\tau, L_1, L_2) &= e^{-\frac{L_1}{bc\tau}} - e^{-\frac{L_2}{bc\tau}} \\
&\approx \frac{L_2 - L_1}{bc\tau} \qquad \text{for } (L_2 - L_1) \ll bc\tau
\end{aligned}
$$

- Boost depends on production mechanism and mass hierarchy between progenitor and decay product

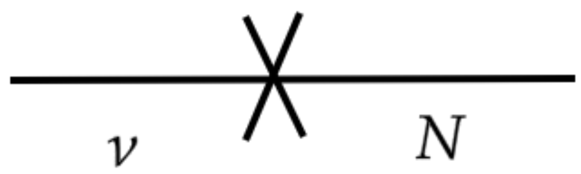
$$
N_{obs} \approx (\sigma_{sig}^{LHC} \mathcal{L})\, \epsilon_{LLP}^{detector}\, n_{LLP}\, \epsilon_{geometric}\, P_{decay}(\bar{b}c\tau, L_1, L_2)
$$

- Geometric acceptance depends on the distance and geometry of the detector

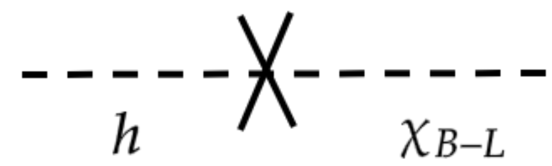




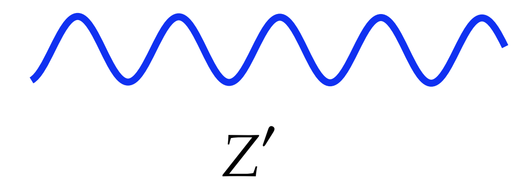
HNL pair production via Z'



Suppressed by V_{lN}

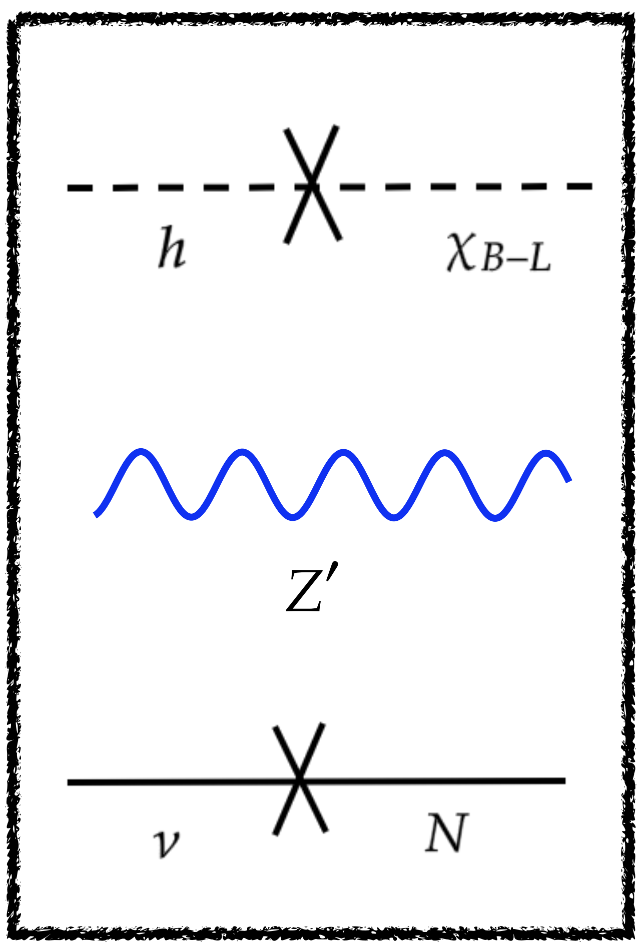


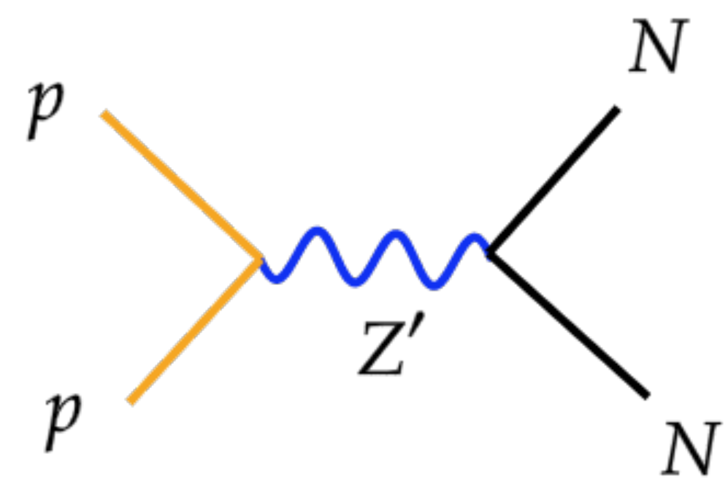
Suppressed by $\sin\alpha$



Suppressed by g_{B-L}

$\sin\alpha = 0, g_{B-L} = 10^{-3}$

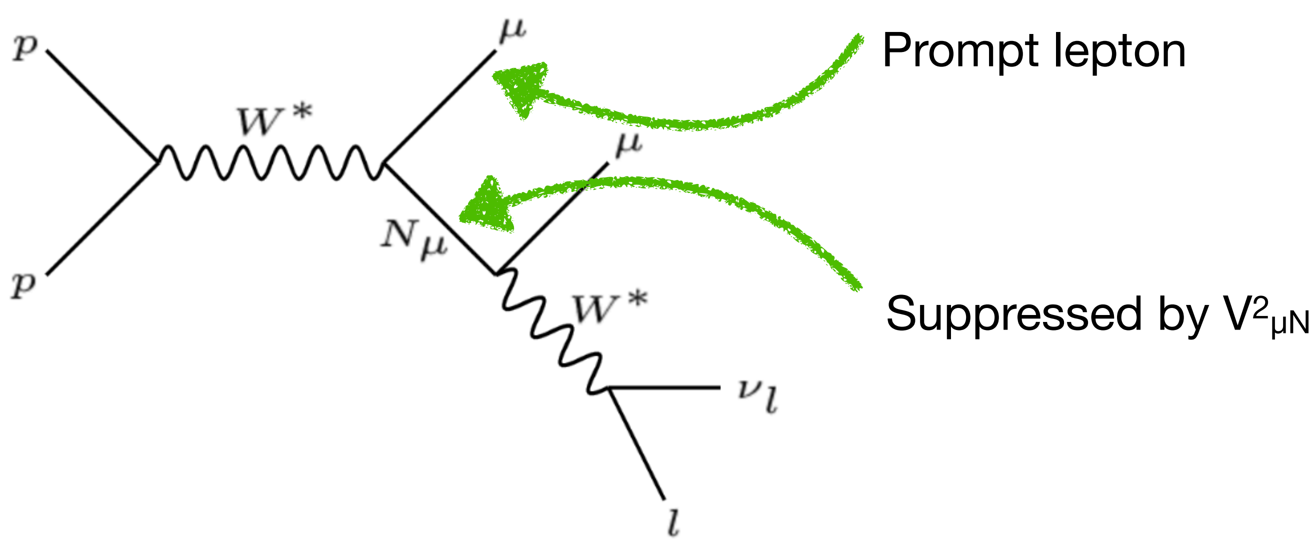


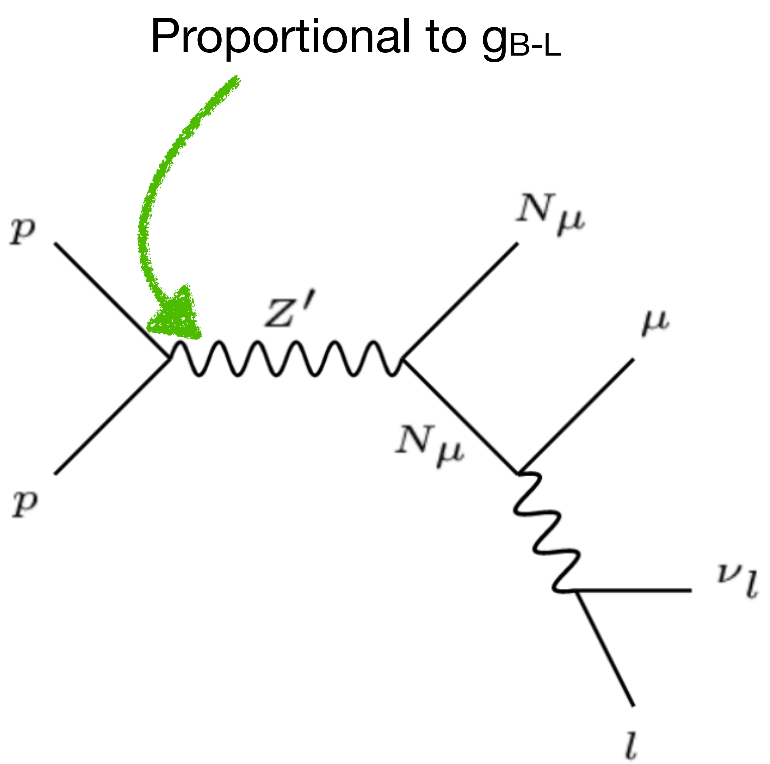


$M_{Z'} < m_h \to m_{Z'} < 100\,\mathrm{GeV}$

What do the experiments have to say about this mass range?

HNL production in B-L



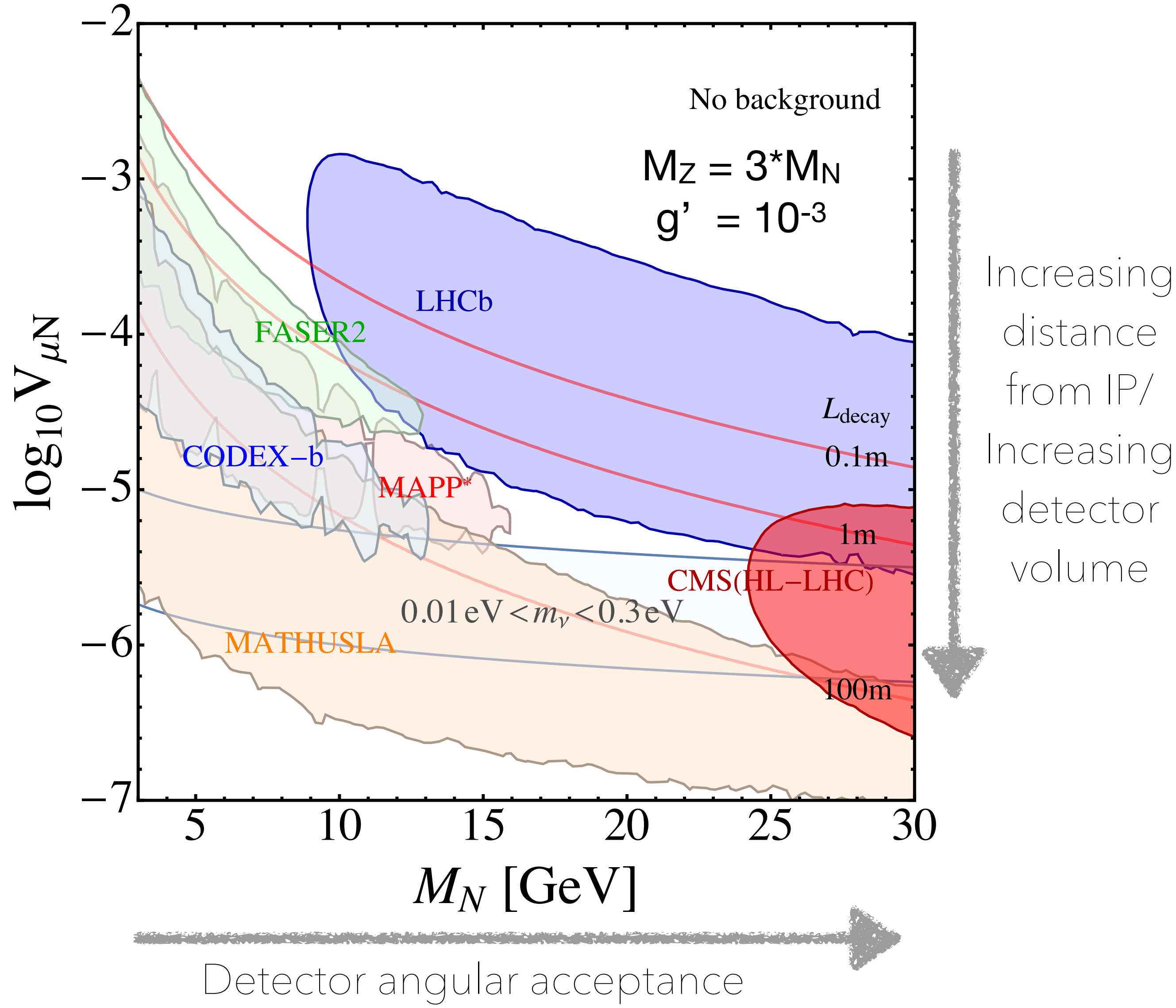


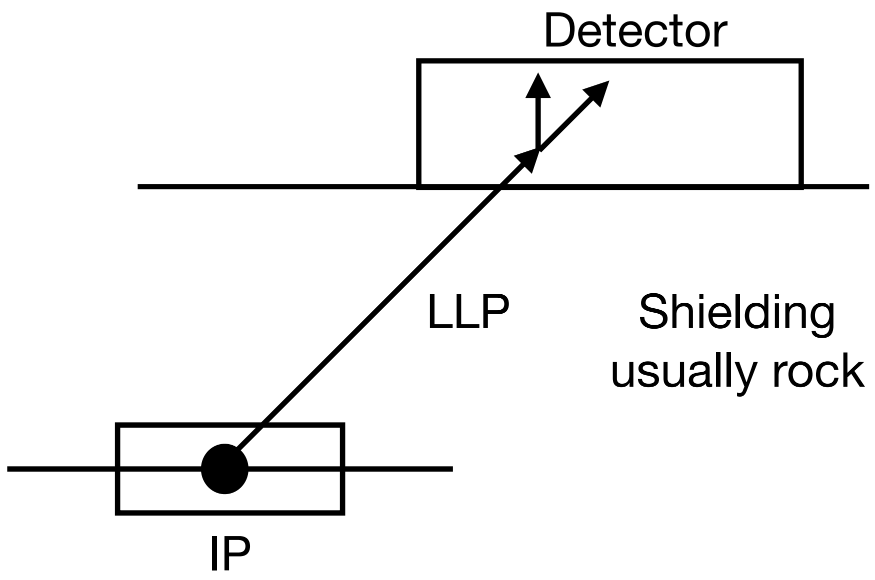
- Production can occur either via SM mediator or via B-L mediator
    - SM mediators : W, Z, h
    - B-L mediators: Z', ϕ
    - h, ϕ mediated production suppressed by Yukawa
    - Z mediated production leads to SM neutrino in final state
    - Only consider W and Z' channels

- $\sigma(pp \to W^*) \times \mathrm{BR}(W^* \to \mu N)$ Suppressed by $V^2_{\mu N}$
- $\mathrm{BR}(Z' \to NN) \sim$ constant (8% for only one light neutrinos 20% for three light neutrinos)
- $\sigma(pp \to Z') \times BR(Z' \to NN) \sim$ constant, independent of $V_{\mu N}$ mixing angle

HNL pair production via Z’

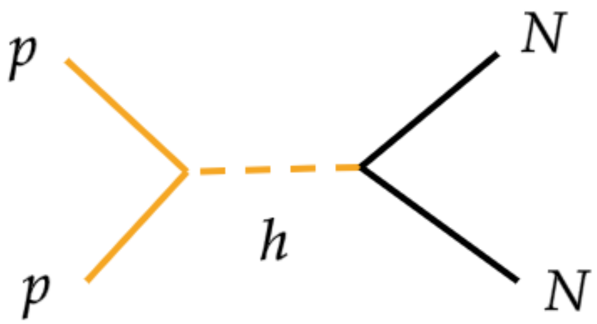
Deppisch, Kulkarni, Liu arXiv:1905.11889

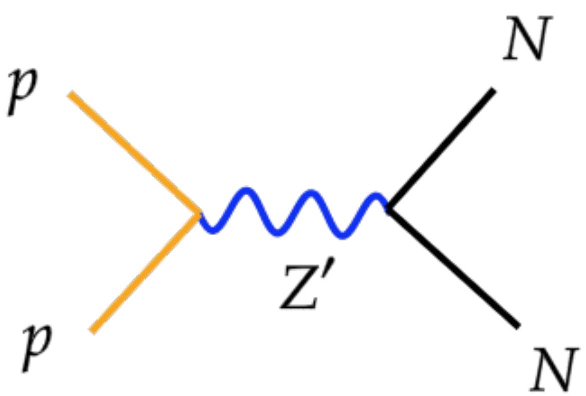


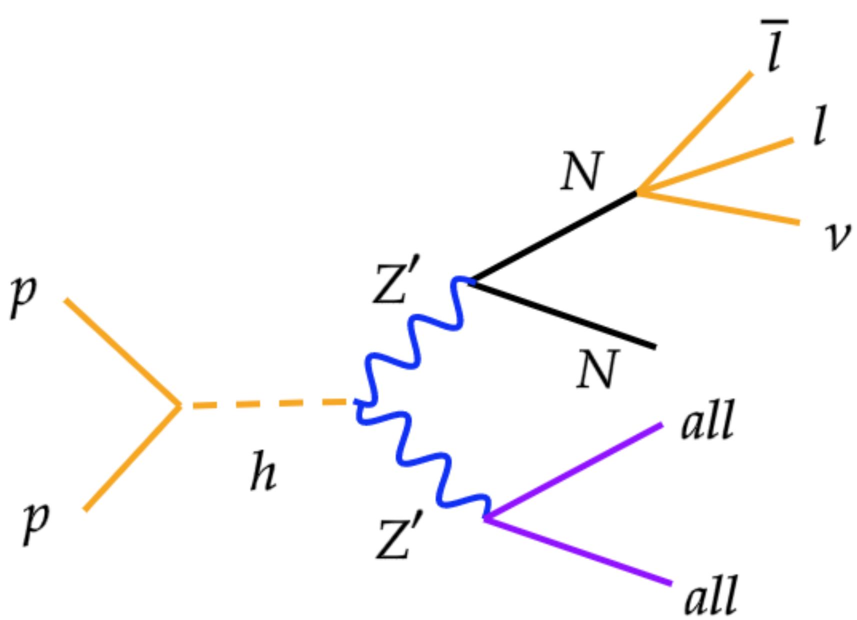


- For LHCb, use $\mu j j$ final state; CMS $\mu \mu \nu$
- For other detector any final state allowed
- Look at the decay of only one heavy neutrino
- Apply some minimal cuts on the p_T and $|\eta|$ on final state particles
- ATLAS/CMS trigger requirements too high

Z' production via Higgs

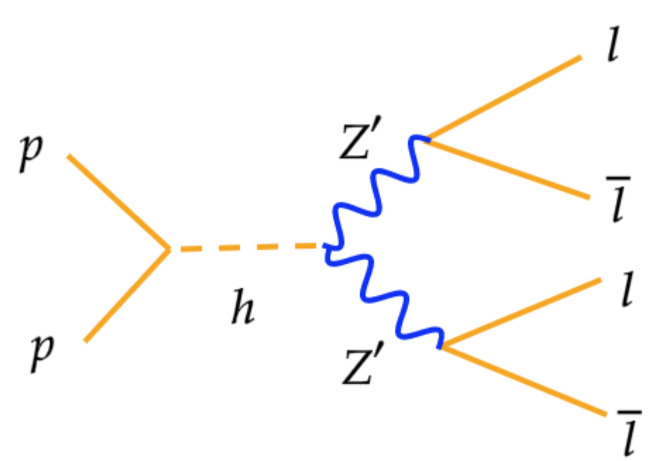




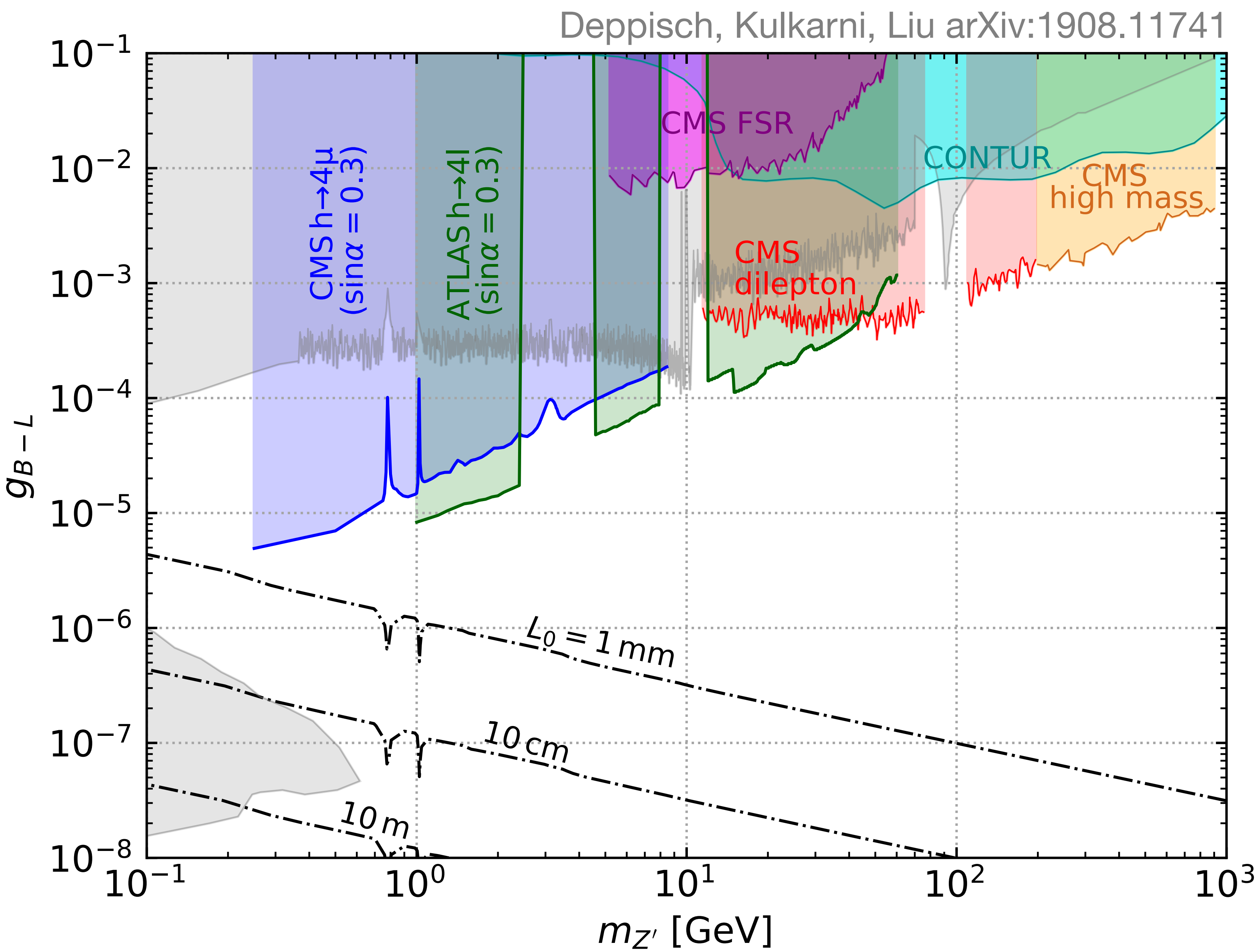


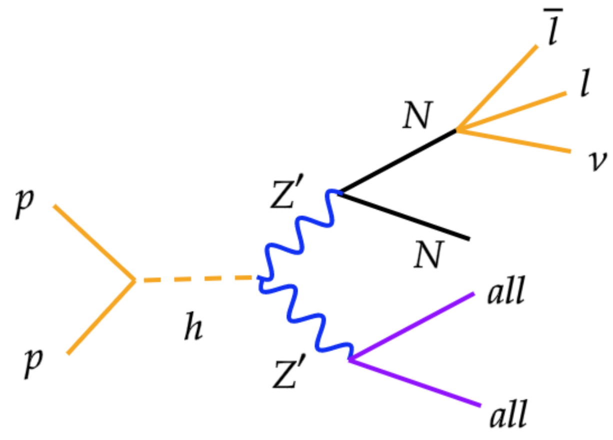
Vertex	Approximate coupling
$Z' - l - \bar{l}$	g_{B-L}
$h - Z' - Z'$	$g_{B-L}\ \cos\alpha\, m_{Z'}$
$h - N - N$	$g_{B-L}\ \cos\alpha\, m_N / m_{Z'}$
$Z' - N - N$	g_{B-L}

- Constraining g_{B-L} will constrain HNL production via Z' and h mediators
- Explore constraints via



Z' production via Higgs



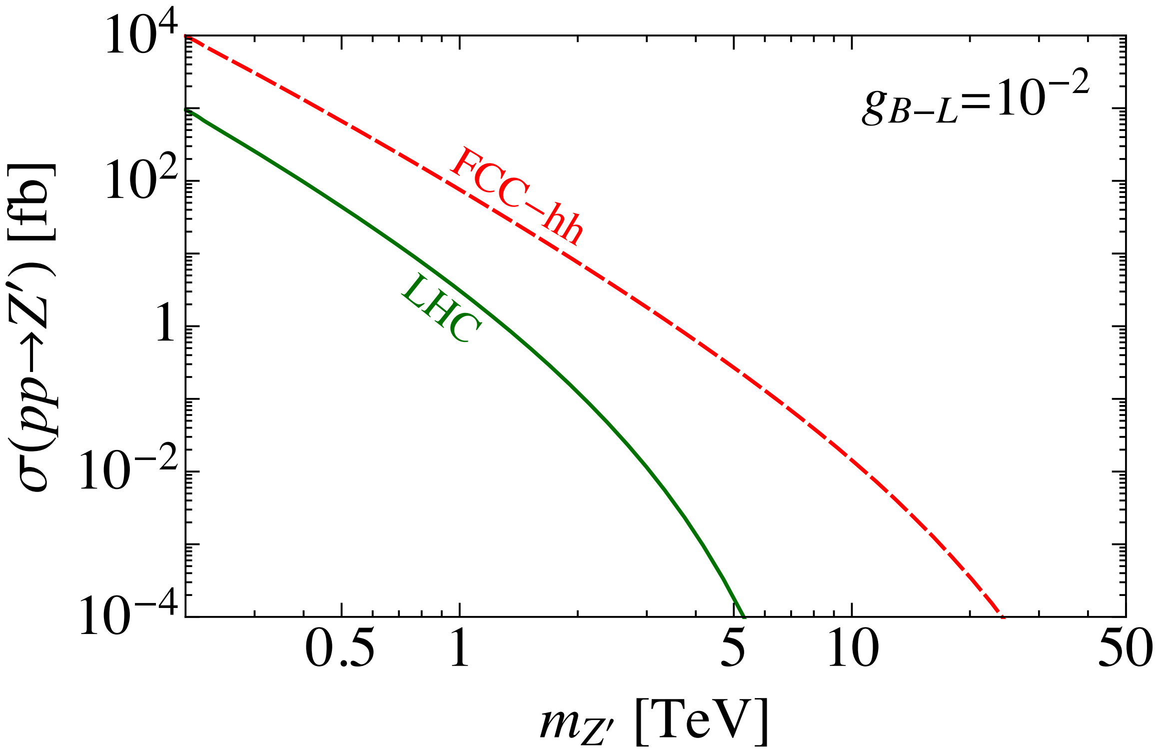


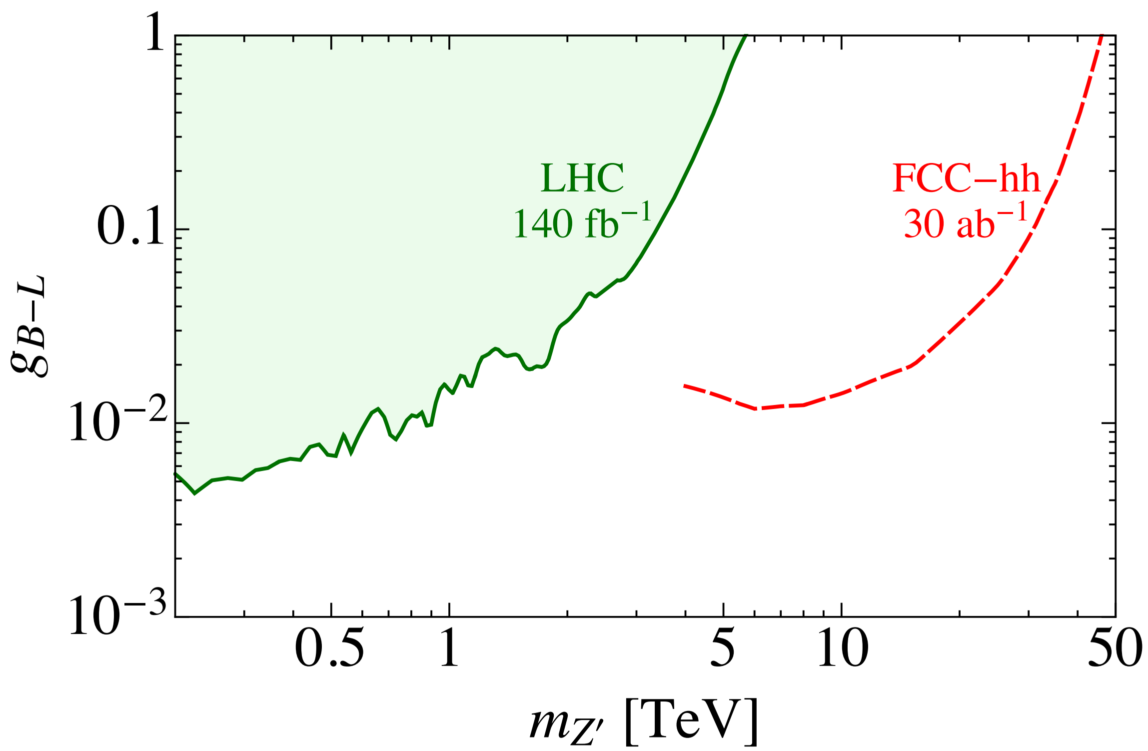
Hopeless at HL-LHC

- Very strong constraints on g_{B-L} rule out long cascades which produce HNL
- Interesting mediators for HNL pair production the SM Higgs and the Z' (one at a time)

HNL pair production at FCC-hh

Deppisch, Kulkarni, Liu arXiv:2202.07310

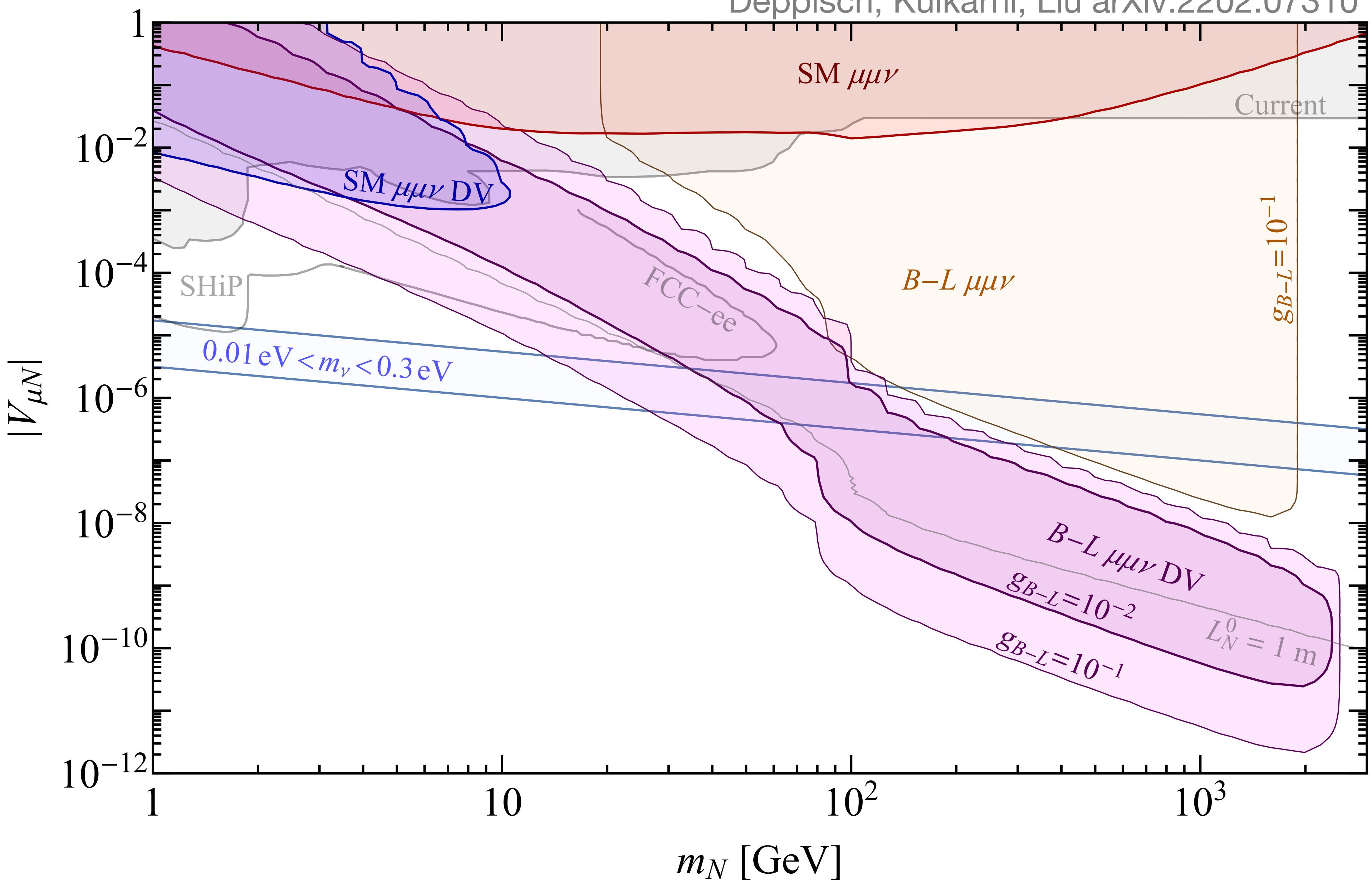




- Limits recast from arXiv:1902.11217 (Helsens, Jamin, Mangano, Rizzo, Selvaggi)
- FCC-hh has a reach to much heavier Z′
- Limits from dilepton searches give an upper limit on the B-L gauge coupling
- In principle B-L gauge coupling can be larger as the projection is for end of FCC lifetime
- We work in the most ‘hopeless’ scenario throughout this talk

Sensitivity estimates

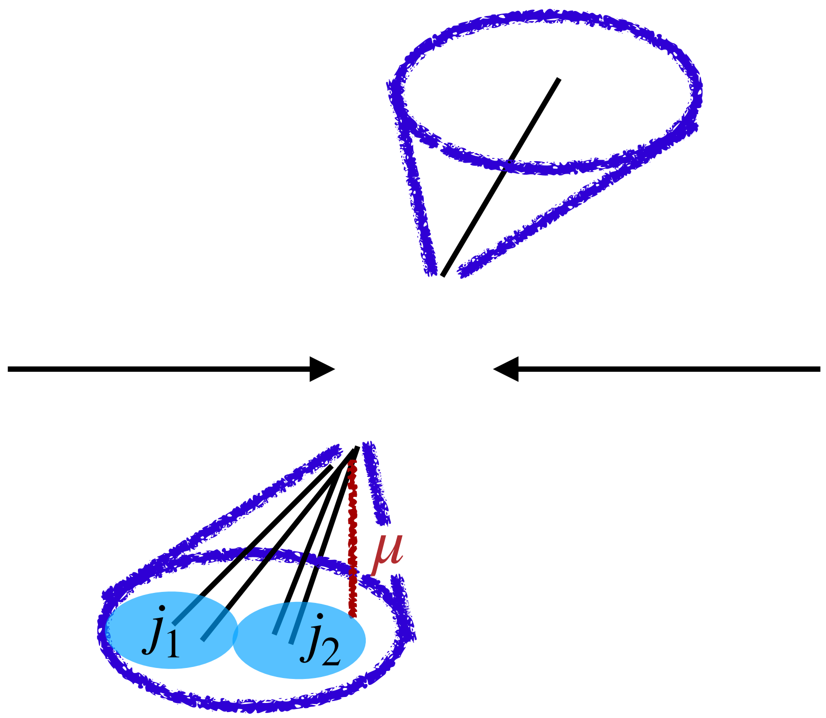
Deppisch, Kulkarni, Liu arXiv:2202.07310

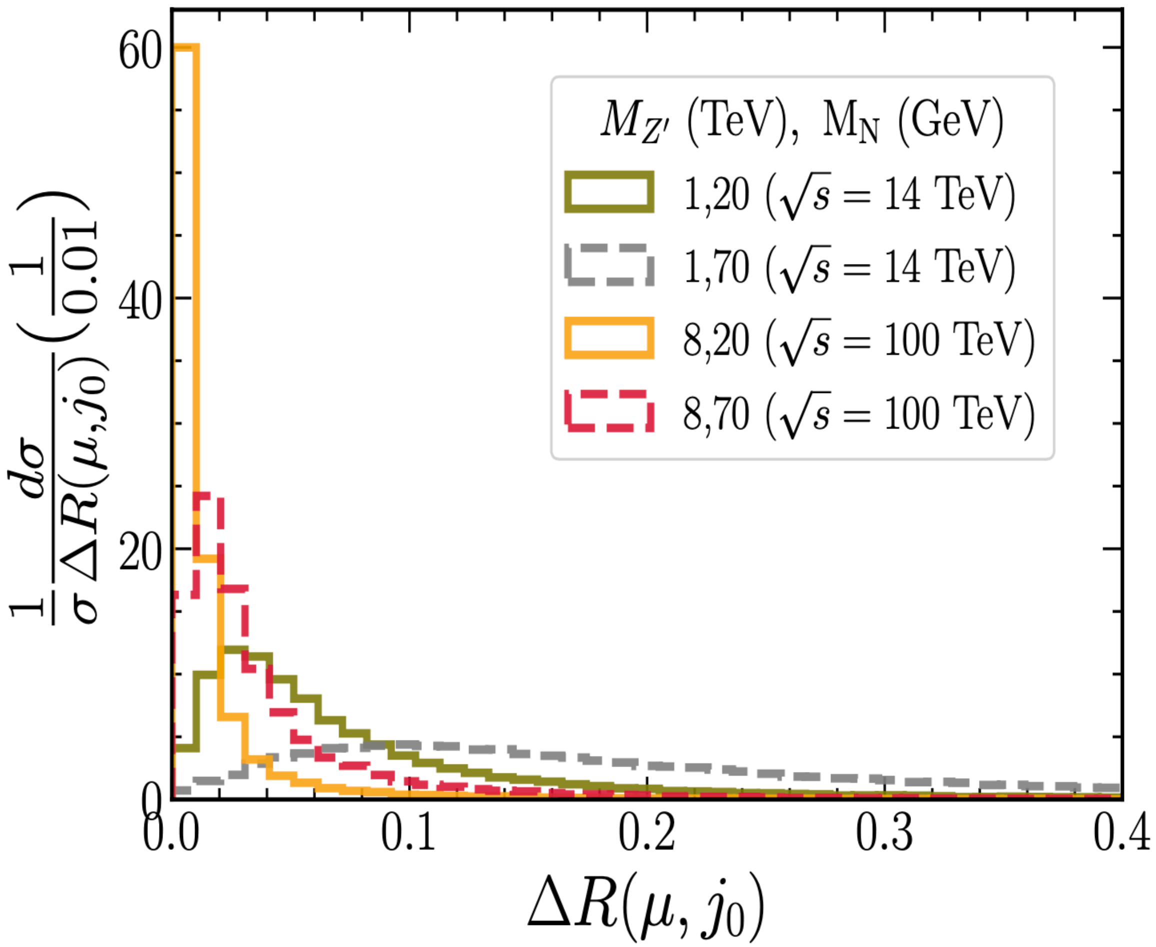


- Prompt channel: Both neutrinos decay to $\mu\,\mu\,\nu$ final state
- SM W mediated decays are not very powerful
- Combining displaced and prompt searches probes a large part of type-1 seesaw

HNL leading to fatjets

Padhan, Mitra, Kulkarni, Deppisch
arXiv: 2203.06114

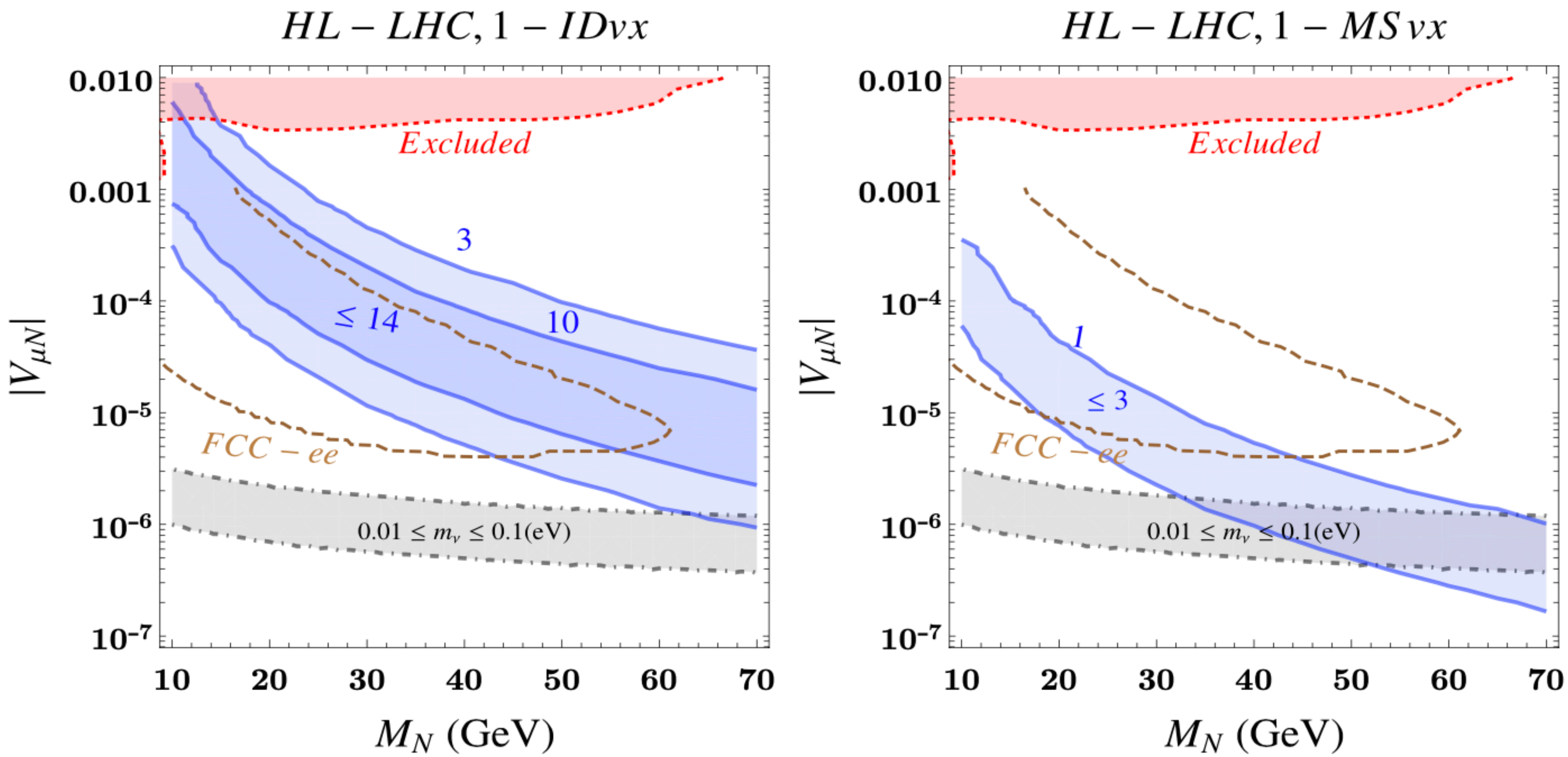




- Hierarchy of interest $m_{Z'} \gg m_N$
- The muon can be 'lost' inside the jet due to highly boosted heavy neutrino
- Possible at both LHC and FCC-hh
- Benchmarks $m_{Z'} = 1\,\text{TeV}\; g_{B-L} = 3 \times 10^{-2}$ (HL-LHC); $m_{Z'} = 8\,\text{TeV}\; g_{B-L} = 1 \times 10^{-1}$ (FCC-hh)

HNL fatjet sensitivity @LHC

Padhan, Mitra, Kulkarni, Deppisch
arXiv: 2203.06114



- 1 displaced vertex in the inner detector leads to largest sensitivity, however this may suffer from backgrounds
- One displaced vertex in muon spectrometer leads to lesser sensitivity but is likely background free
- Two displaced vertices in ID or MS also lead to good sensitivity, will have even less backgrounds

ATLAS LLP decaying in muon spectrometer

arXiv:1811.07370

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Rev. D

CERN-EP-2018-241
November 20, 2018

Search for long-lived particles produced in pp collisions at $\sqrt{s}$ = 13 TeV that decay into displaced hadronic jets in the ATLAS muon spectrometer

The ATLAS Collaboration

Table 1: Topologies considered in this paper, corresponding basic event selection and benchmark models.

Strategy	Basic event selection	Benchmarks
2MSVx	At least 2 MS vertices	Scalar portal, Higgs portal baryogenesis, Stealth SUSY
1MSVx+Jets	Exactly 1 MS vertex At least 2 jets with $E_T > 150$ GeV	Stealth SUSY
1MSVx+E_T^{miss}	Exactly 1 MS vertex $E_T^{miss} > 30$ GeV	Scalar portal with $m_\Phi = 125$ GeV, Higgs portal baryogenesis

CMS LLP decaying in endcap muon detector

CMS-EXO-20-015 ; CERN-EP-2021-125

Search for long-lived particles decaying in the CMS endcap muon detectors in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration

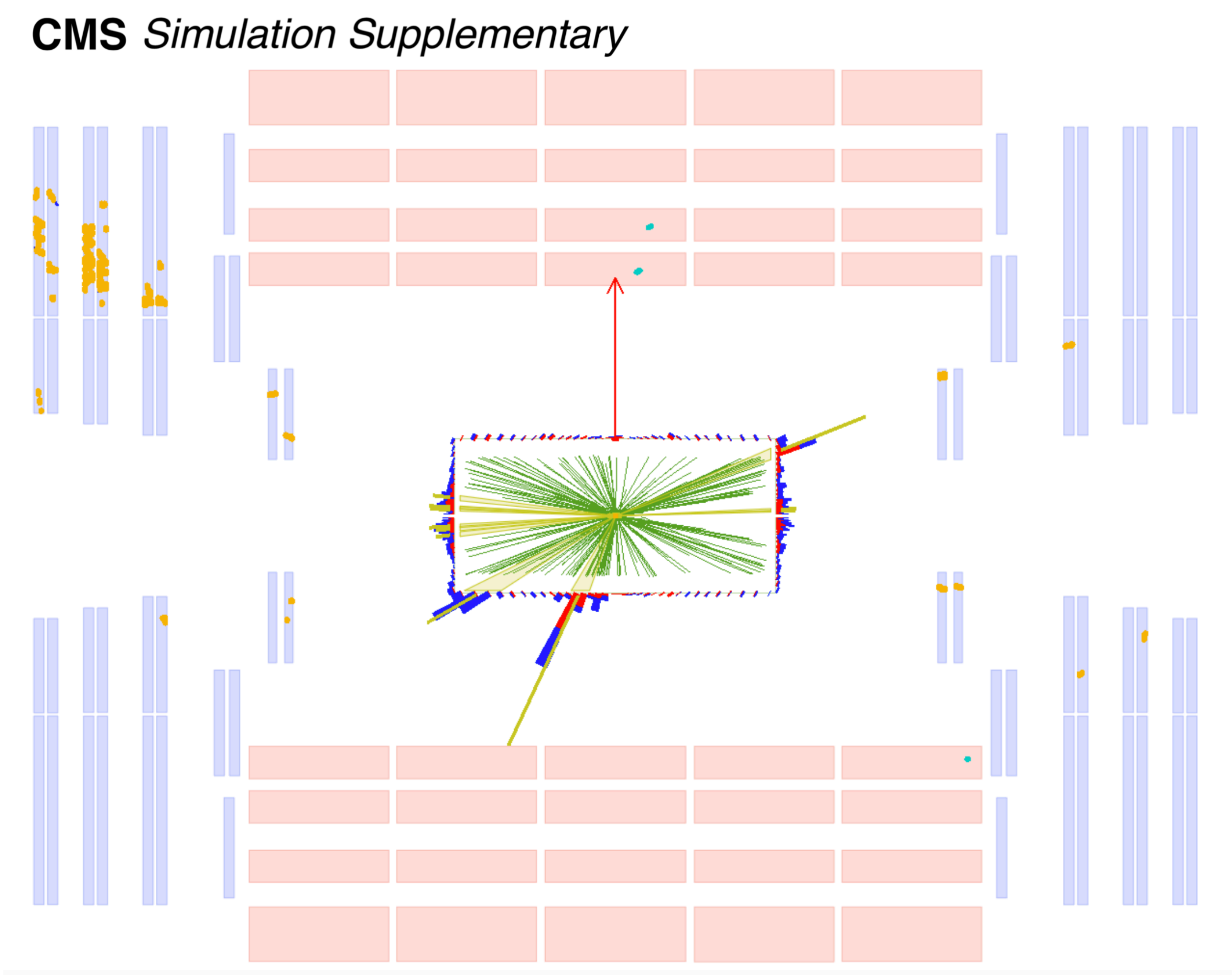
10 July 2021

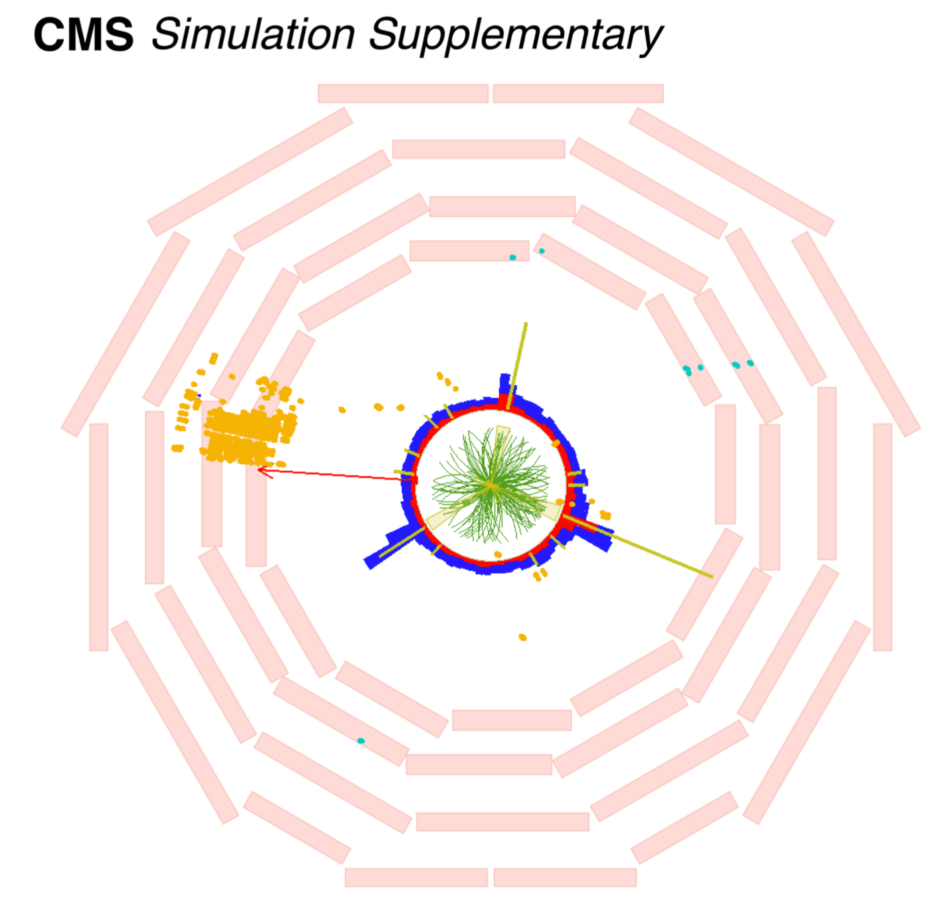
Phys. Rev. Lett. 127 (2021) 261804

Abstract: A search for long-lived particles (LLPs) produced in decays of standard model (SM) Higgs bosons is presented. The data sample consists of 137 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV, recorded at the LHC in 2016-2018. A novel technique is employed to reconstruct decays of LLPs in the endcap muon detectors. The search is sensitive to a broad range of LLP decay modes and to masses as low as a few GeV. No excess of events above the SM background is observed. The most stringent limits to date on the branching fraction of the Higgs boson to LLPs subsequently decaying to quarks and $\tau^+\tau^-$ are found for proper decay lengths greater than 6, 20, and 40 m, for LLP masses of 7, 15, and 40 GeV, respectively.

Links: e-print arXiv:2107.04838 [hep-ex] (PDF) ; CDS record ; inSPIRE record ; HepData record ; Physics Briefing ; CADI line (restricted) ;

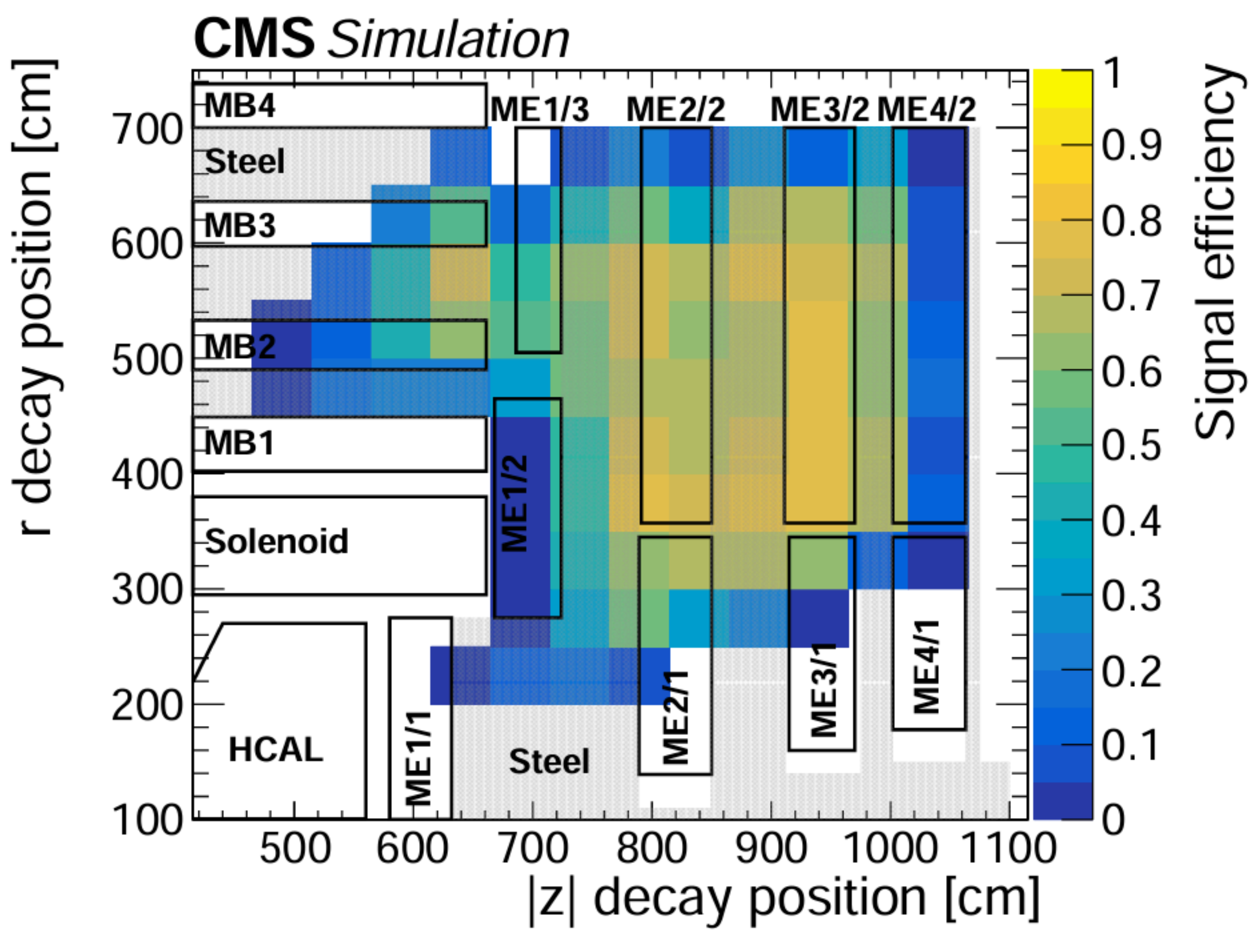
arXiv:2107.04838; 2402.18658

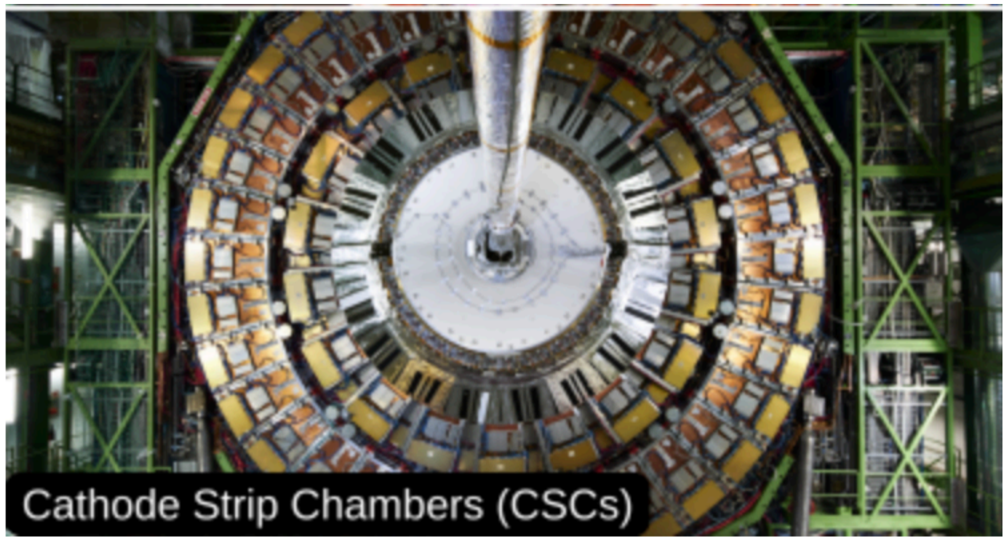




CMS LLP decaying in endcap muon detector

- Uses endcap muon detectors as sampling calorimeters to detect the decays of the LLP
- Central strategy: LLP decays to q, τ, e, γ in the endcap detector, decay products create a shower. Detect the shower in endcap to find the LLP
- Advantage: very inclusive, does not rely on complete shower reconstruction, ability to detect LLPs with large lifetimes

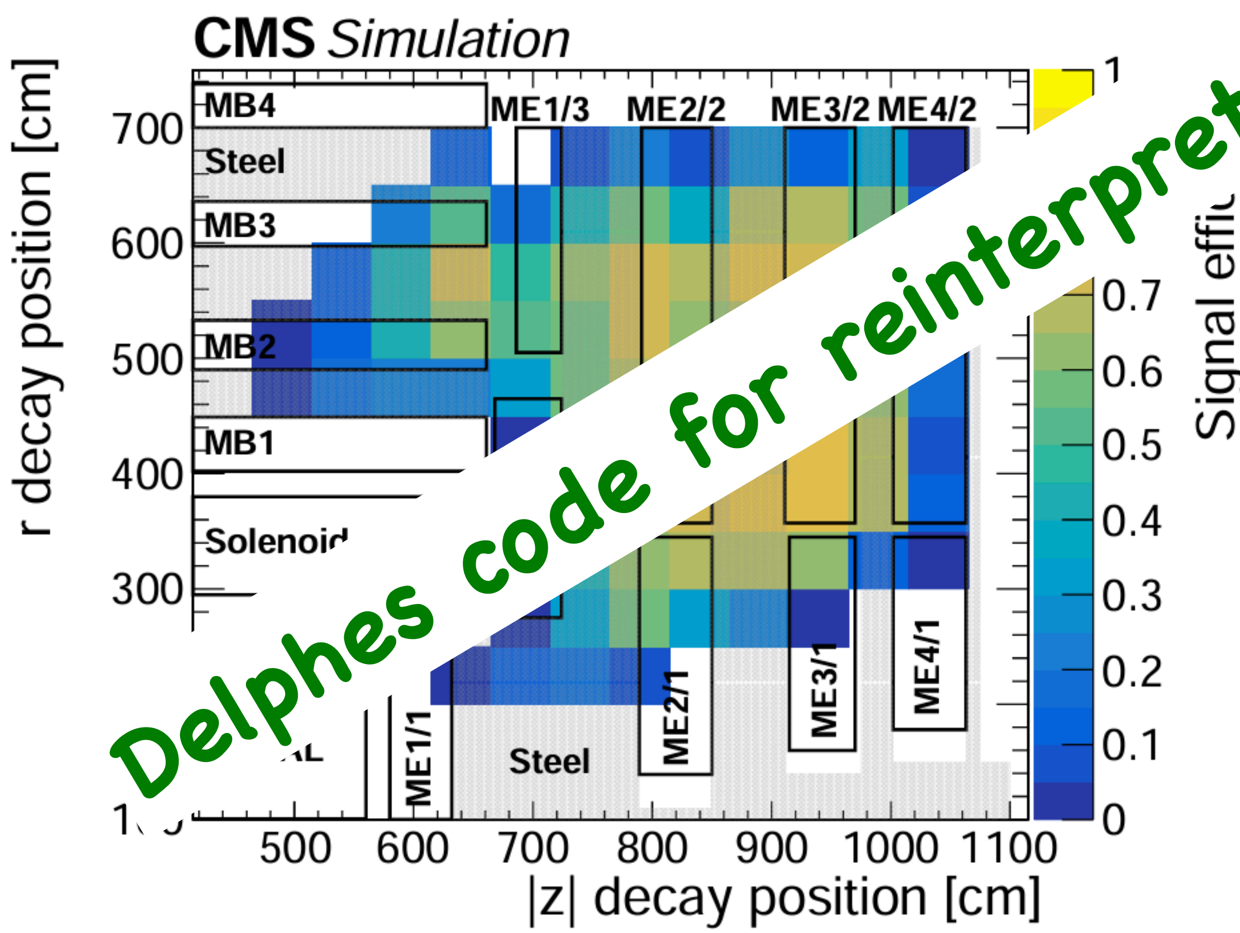


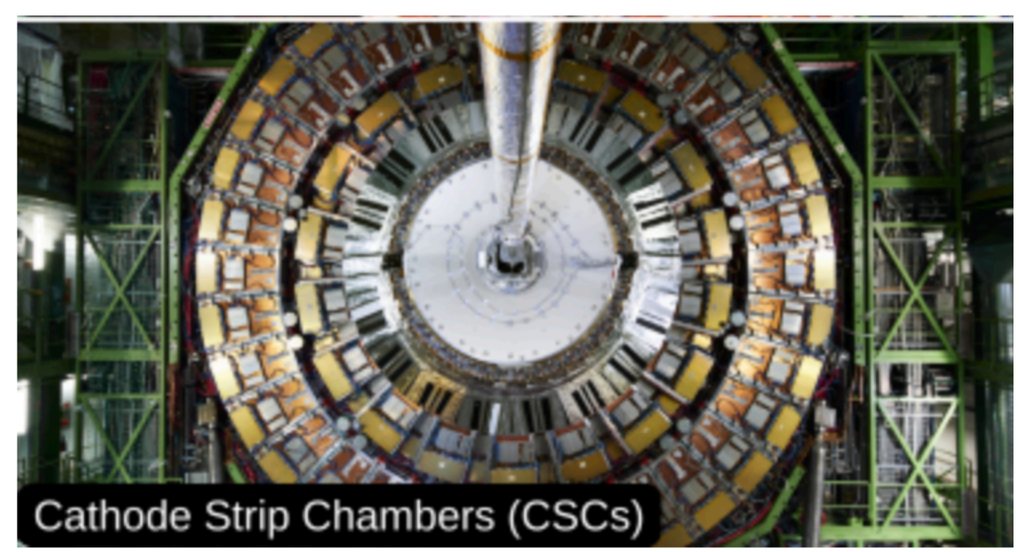


CMS LLP decaying in endcap muon detector

- Uses endcap muon detectors as sampling calorimeters to detect the decays of the LLP
- Central strategy: LLP decays to q, τ, e, γ in the endcap detector, decay prod… e a shower. Detect the shower in endcap to find the LLP
- Advantage: very inclusive, does not rely on complete shower r… …on, ability to detect LLPs with large lifetimes

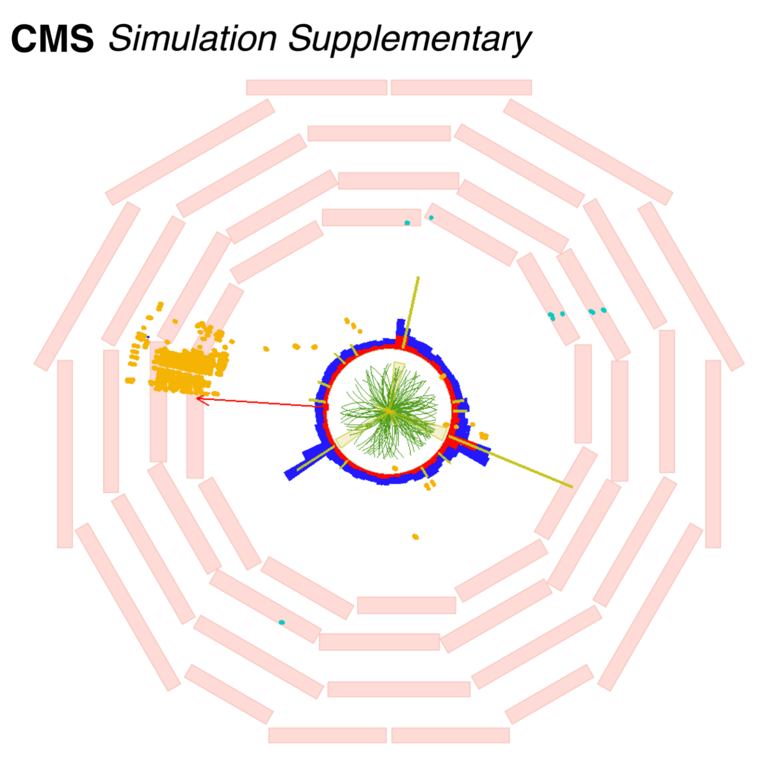
Delphes code for reinterpretation in different models!

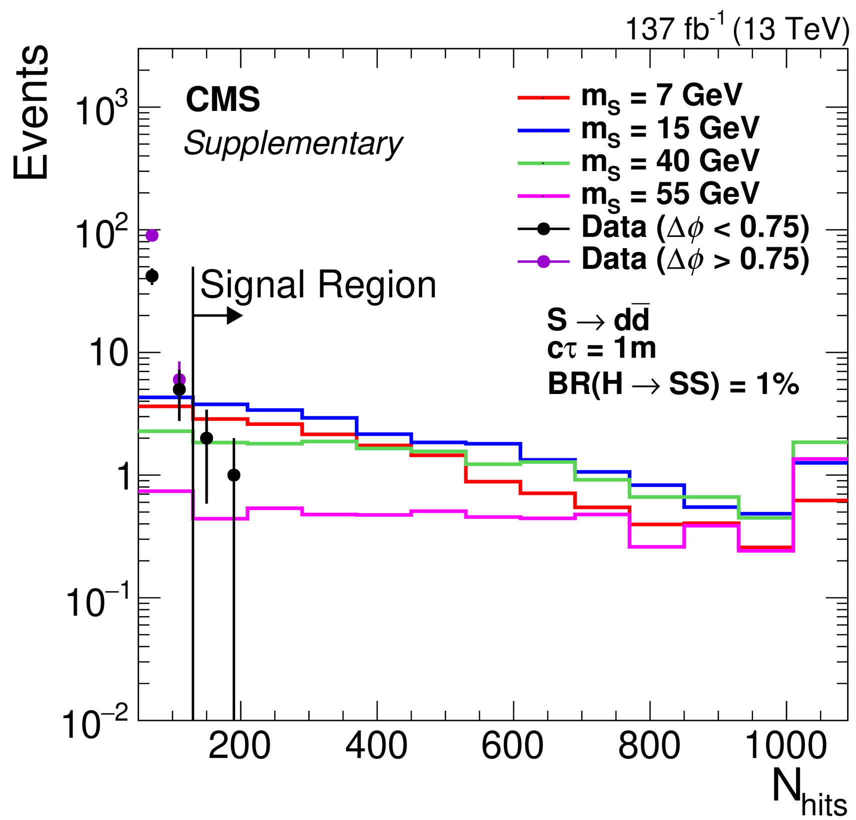




Analysis details

- Trigger on $E_T^{miss} > 200\,\mathrm{GeV}$, E_T^{miss} measured from deposits in the calorimeters and tracker
- No electron (muon) with $p_T > 35\,(25)\,\mathrm{GeV}$ and $|\eta| < 2.5\,(2.4)$ for suppressing W and top backgrounds
- Cluster should have $N^{hits} > 50$ and should originate from LLP decay: $|\Delta\phi(\mathrm{x_{csc}}, \mathrm{p_T^{miss}})| < 0.75$
- No events with clusters close to the jet
- Cluster originates relatively close to the collision time: $-5\,\mathrm{ns} < \langle \Delta \mathrm{t_{CSC}} \rangle < 12.5\,\mathrm{ns}$ (rejects clusters produced by out-of-time pileup)

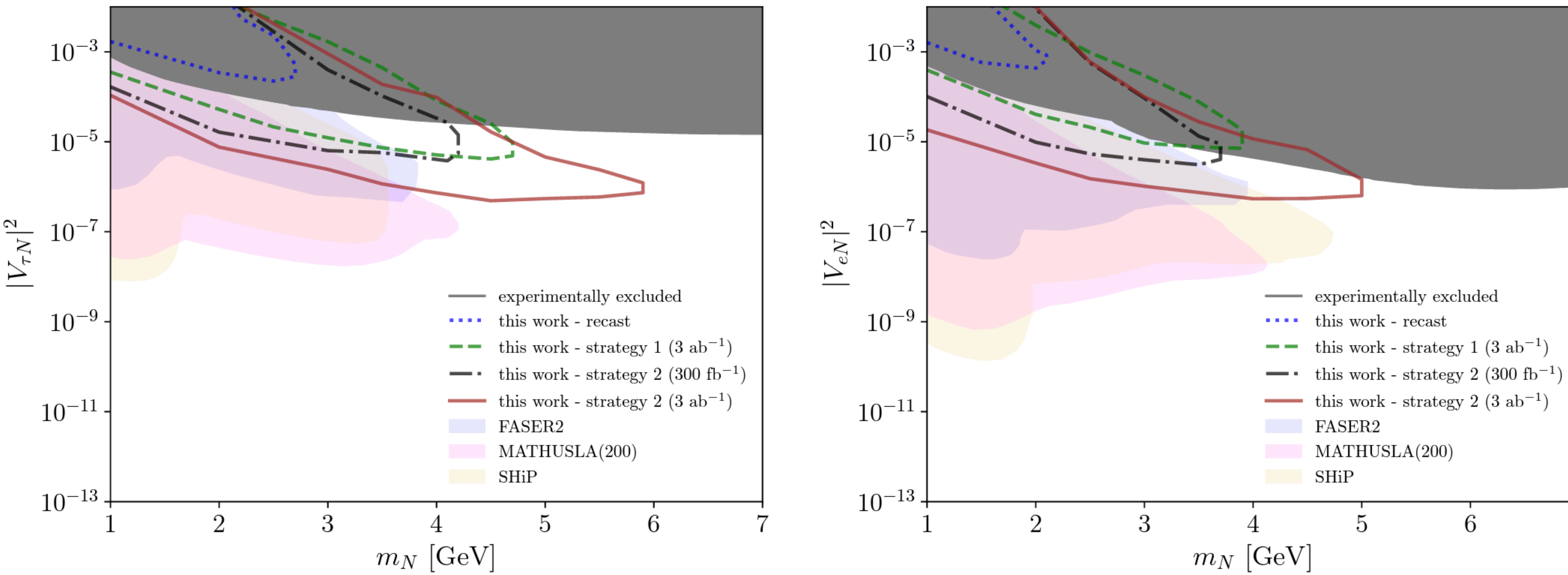




Increasing N^{hits} may be beneficial

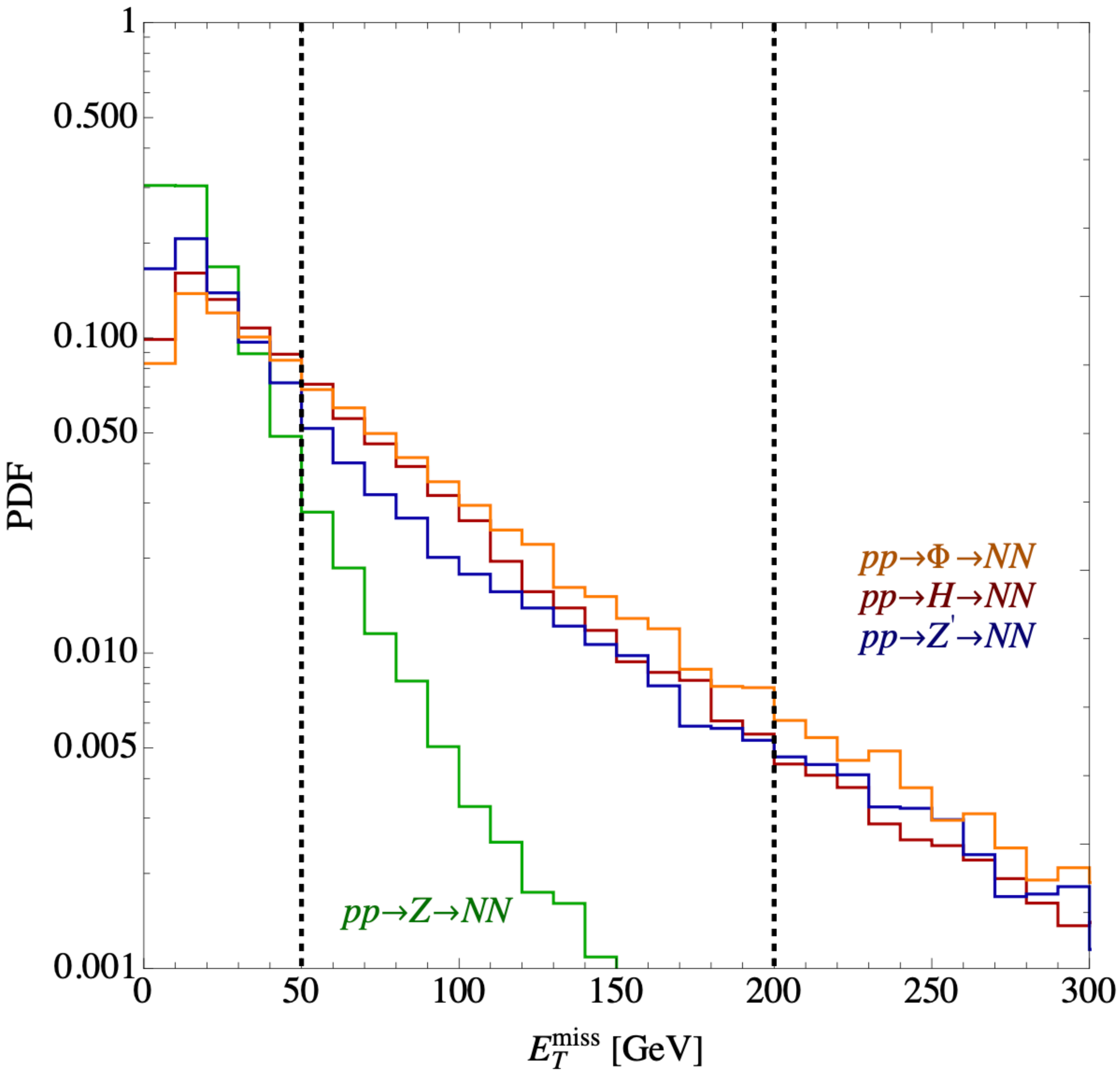
Reach for type-I seesaw

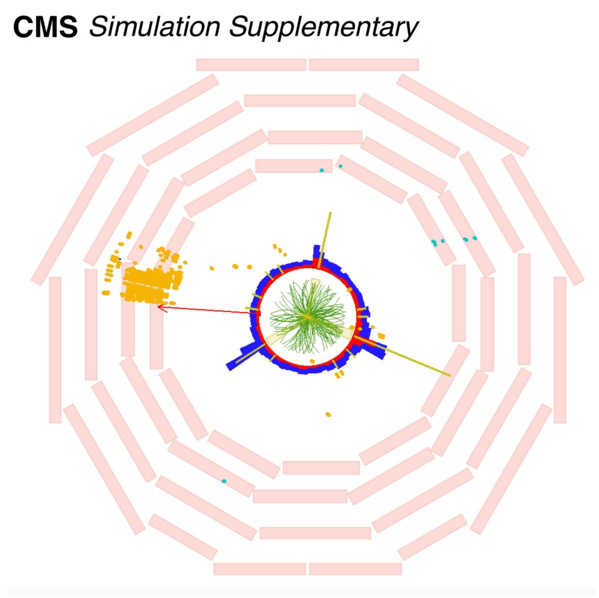
Cottin et al arXiv:2210.17446



- Works well for small HNL masses
- Strategy 1: keep high E_T^{miss} trigger and increase $N^{\text{hits}} > 210$
- Updated strategy with dedicate high level displaced trigger with $E_T^{\text{miss}} > 50\,\text{GeV}$, with larger CSC hits $N^{\text{hits}} > 290$

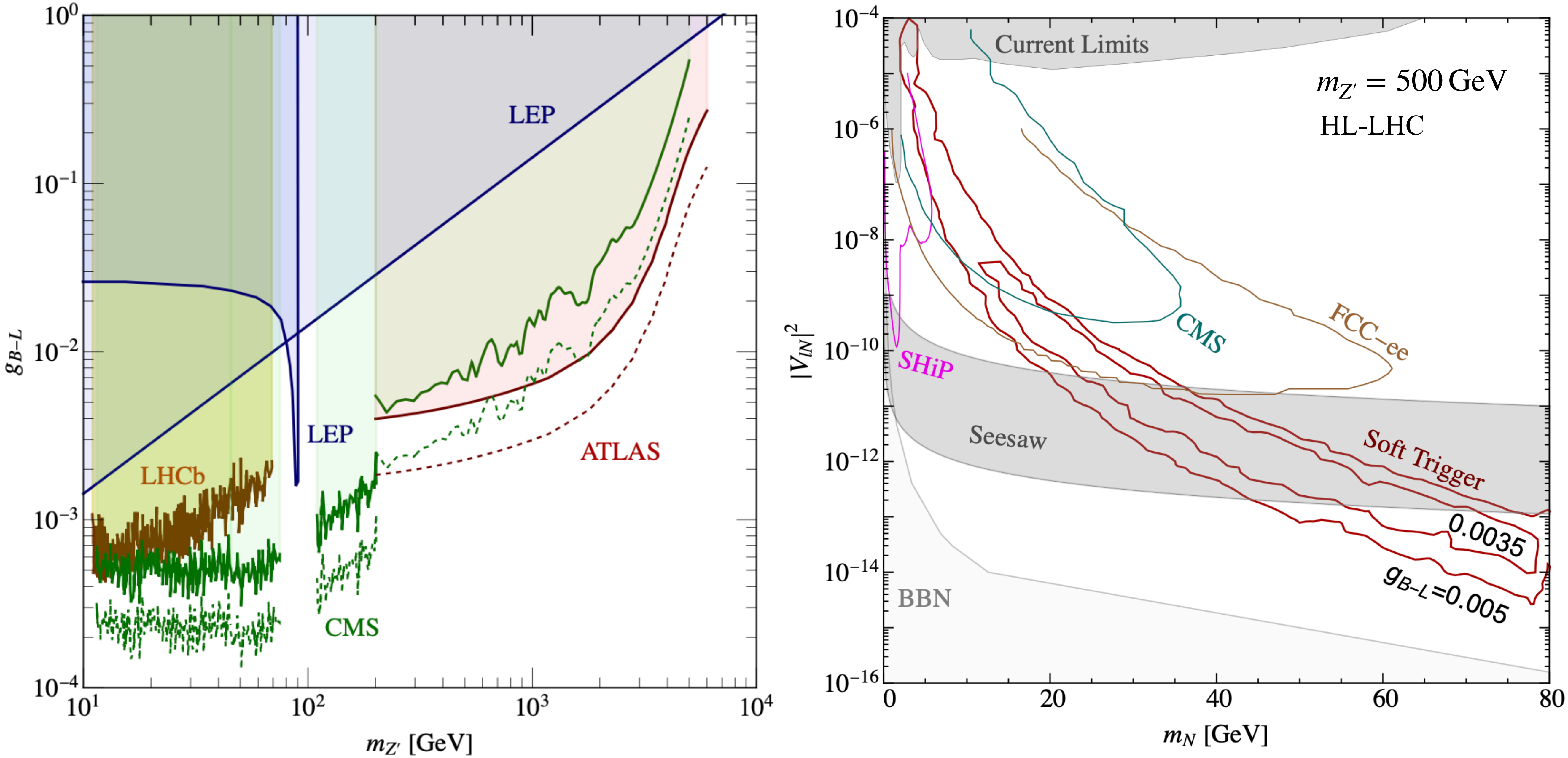
Generating required MET in B-L





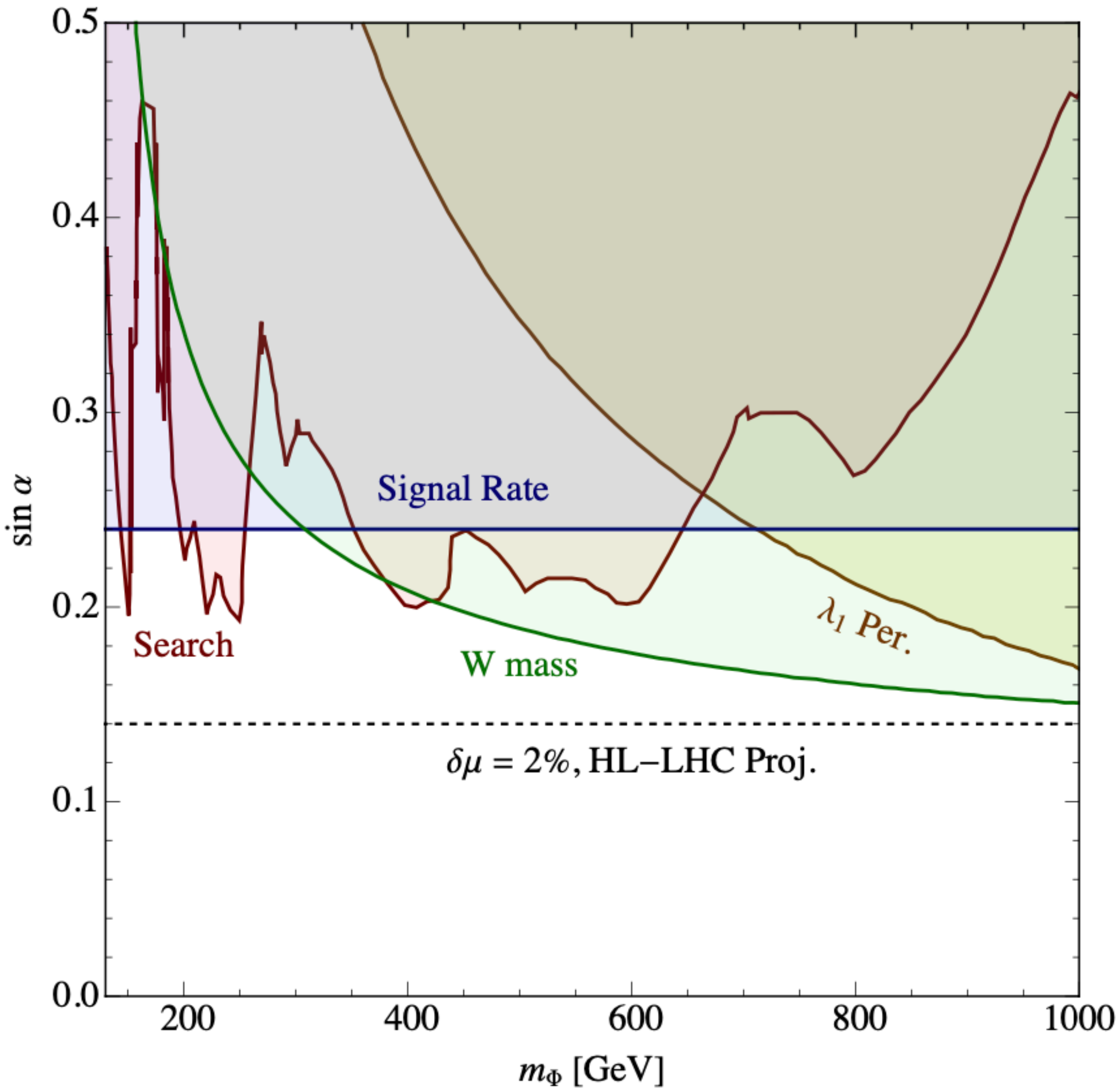
- LLPs do not decay in the calorimeter
- MET computed by means of ISR radiation
- ϕ, h, Z' mediators produce enough MET
- Z mediator does not work due to insufficient MET

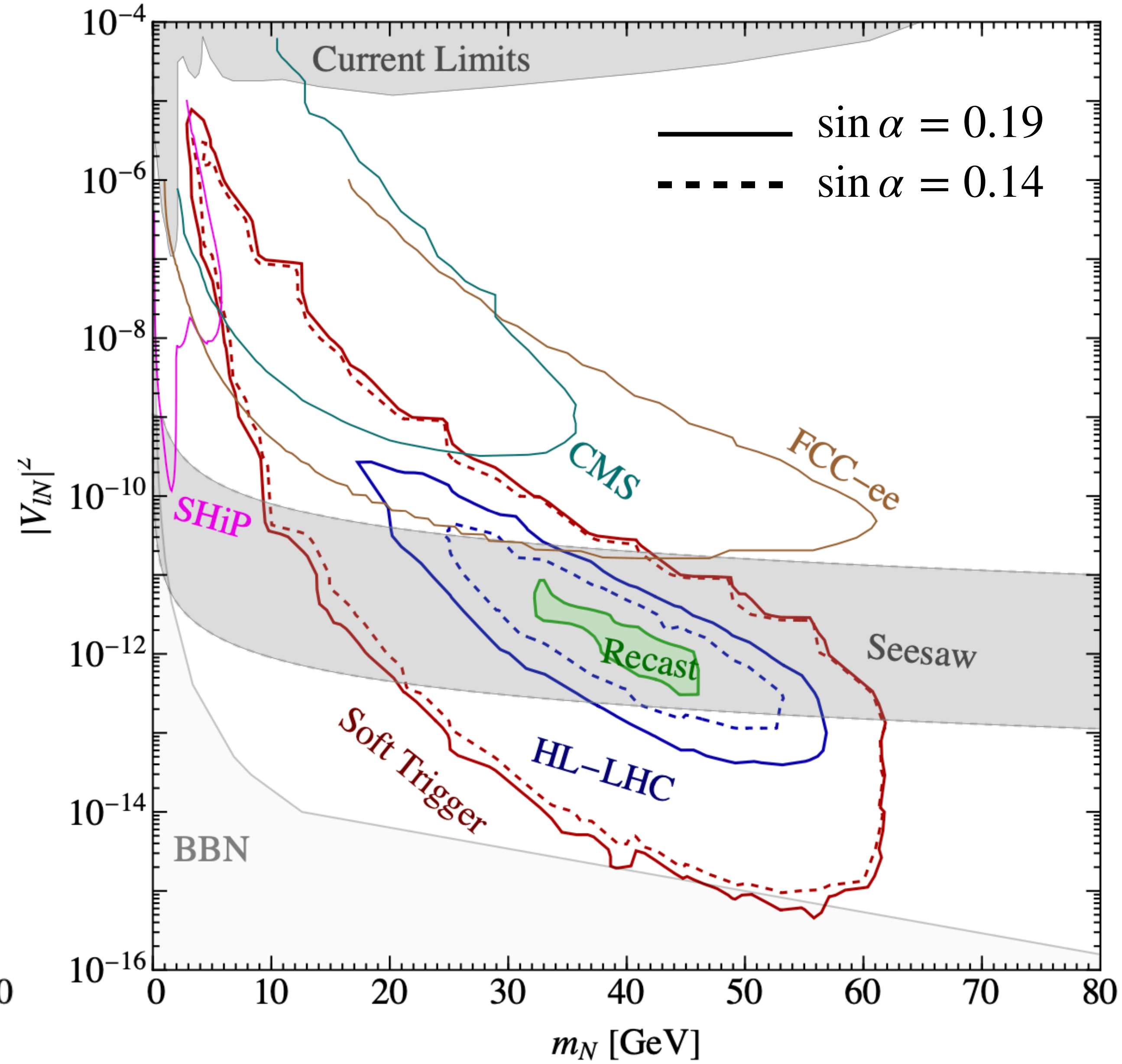
Gauge portal



- No sensitivity using existing analysis/results, possible future sensitivity at HL-LHC even for very small B-L gauge coupling with soft trigger

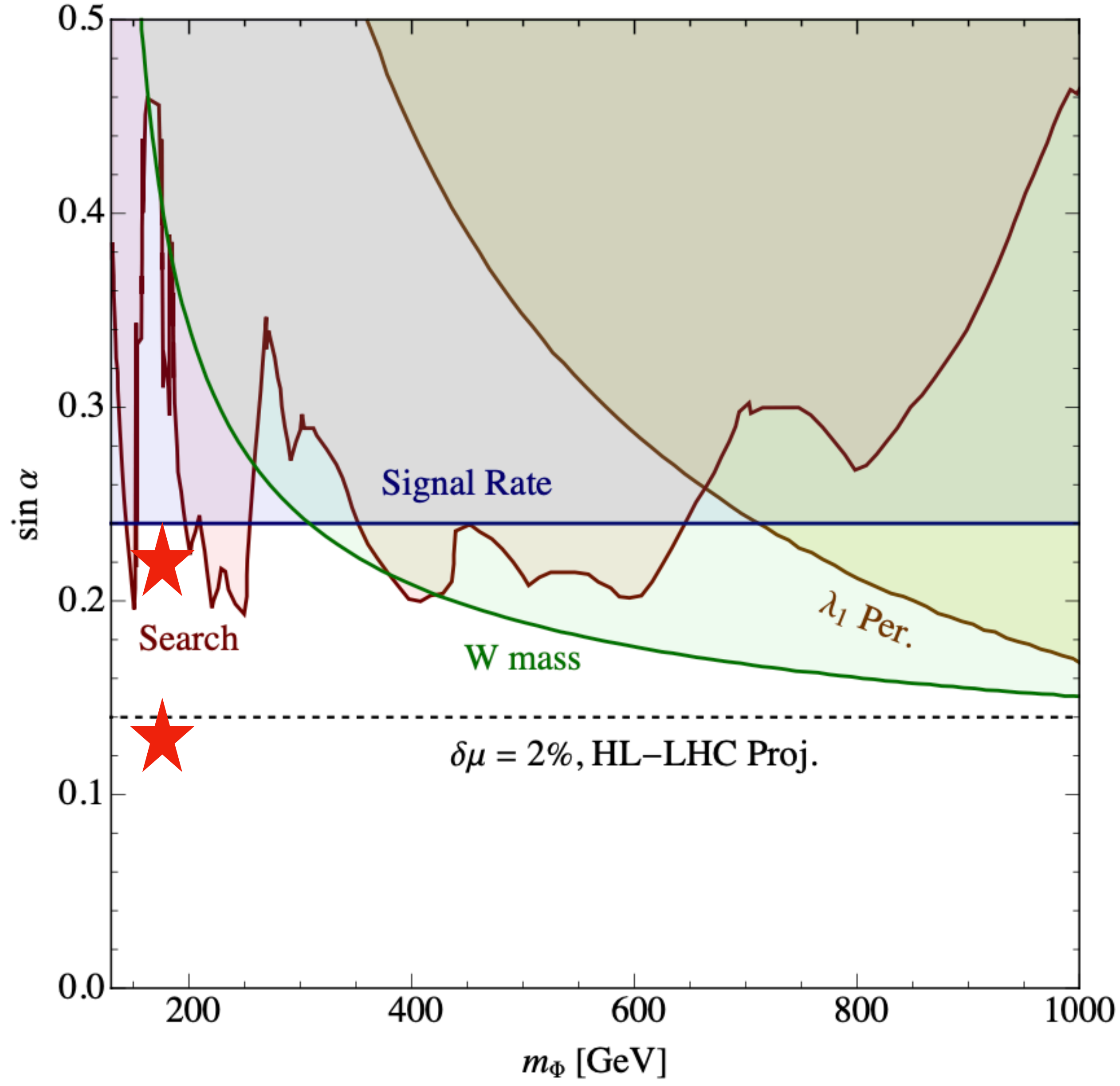
Higgs portal: SM Higgs

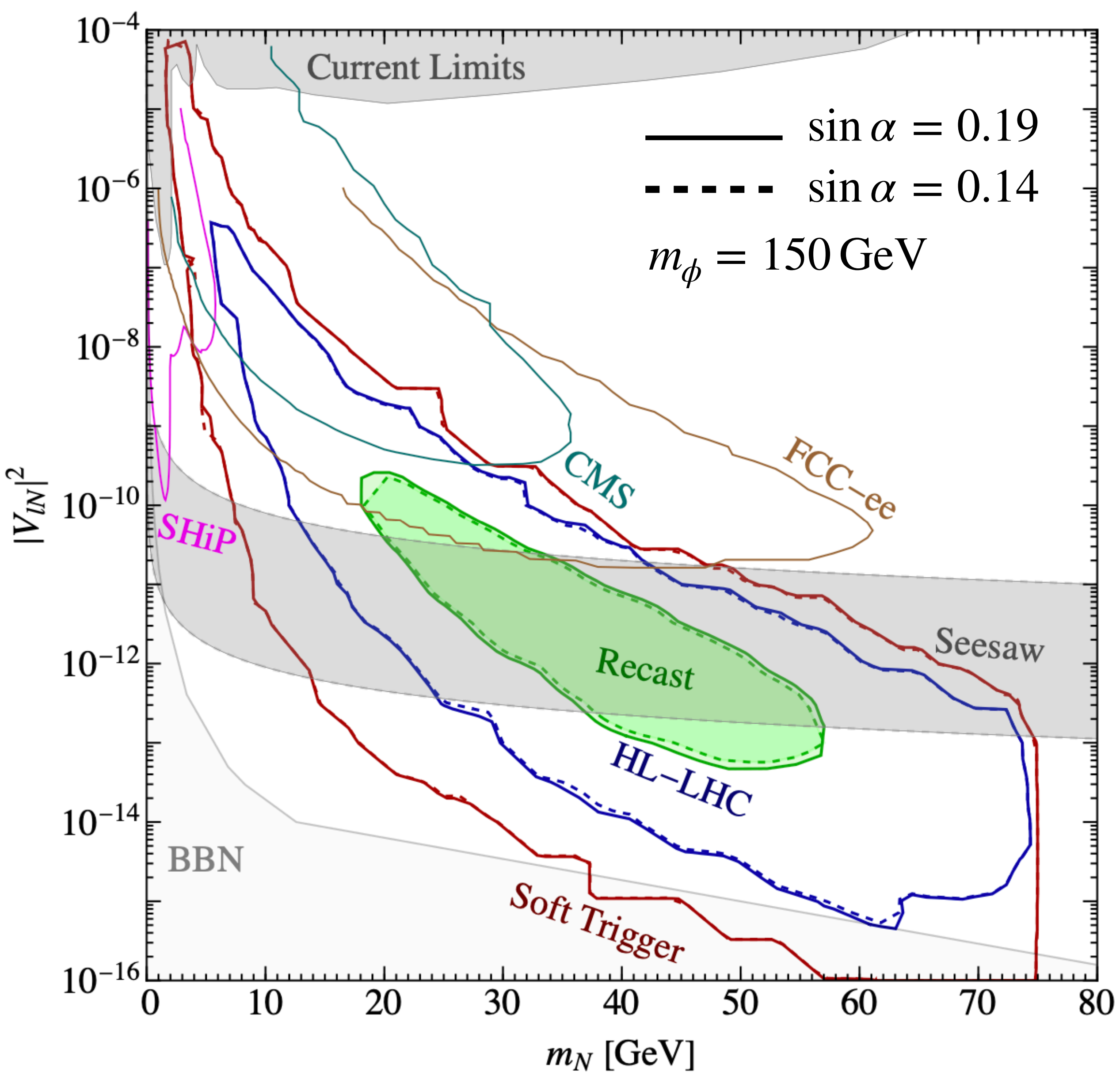




- SM Higgs to N N decays are suppressed by $\sin\alpha$, current limits on $\sin\alpha$ provide some sensitivity in a small part of seesaw favoured region
- Future sensitivity decreases as $\sin\alpha$ decreases

Higgs portal: B-L Higgs





- ϕ to N N decays are enhanced by $\cos\alpha$, current limits on $\sin\alpha$ provide good sensitivity in a large part of seesaw favoured region
- Works as long as $m_h < m_\phi \lesssim 150$

Conclusions

- Evidence of neutrino masses is one of the strongest motivations for beyond the Standard Model physics
- Typical BSM scenarios involving heavy neutrinos leave exotic new signatures such as displaced vertex at colliders
- Colliders will have limited sensitivity to minimal extensions with type-I seesaw containing only sterile neutrinos due to suppressed production cross section
- Necessitates considering other extensions which allow the probe of full seesaw compatible regions
- B-L is one such example
  - Z' mediated neutrino pair production is interesting and can be probed at forward physics experiments if Z' is light (< 100 GeV) and at HL-LHC and FCC-hh if Z' is heavy (> TeV)
  - Cascade decays ($h \to Z'Z' \to 2N + X$) are not very interesting given current limits on g_{B-L} from the LHC
  - When heavy neutrino is very boosted ($m_{Z'} \gg m_N$) it can lead to fatjet like signature, which would be very interesting to search for
  - Ongoing LHC searches are sensitive to a large region of B-L parameter space including the seesaw floor

Backup

Analysis details

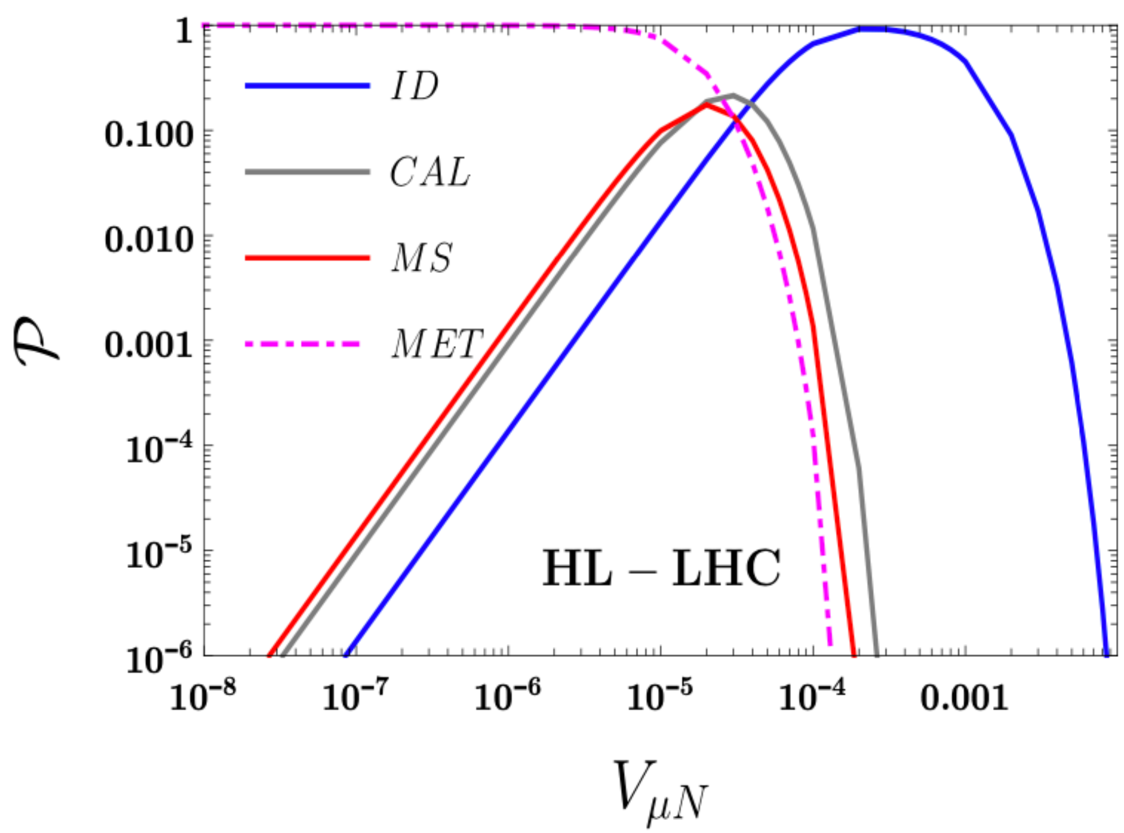
- Truth level analysis
- Consider two production mechanisms
  - SM W mediated
  - B-L Z' mediated
- Consider two final states
  - W hadronic decays: $\mu j j$
  - W leptonic decays: $\mu \mu \nu$
- Analysis cuts: two types of analysis, prompt and displaced
  - Detector geometry taken into account for L_{xy} and η cuts

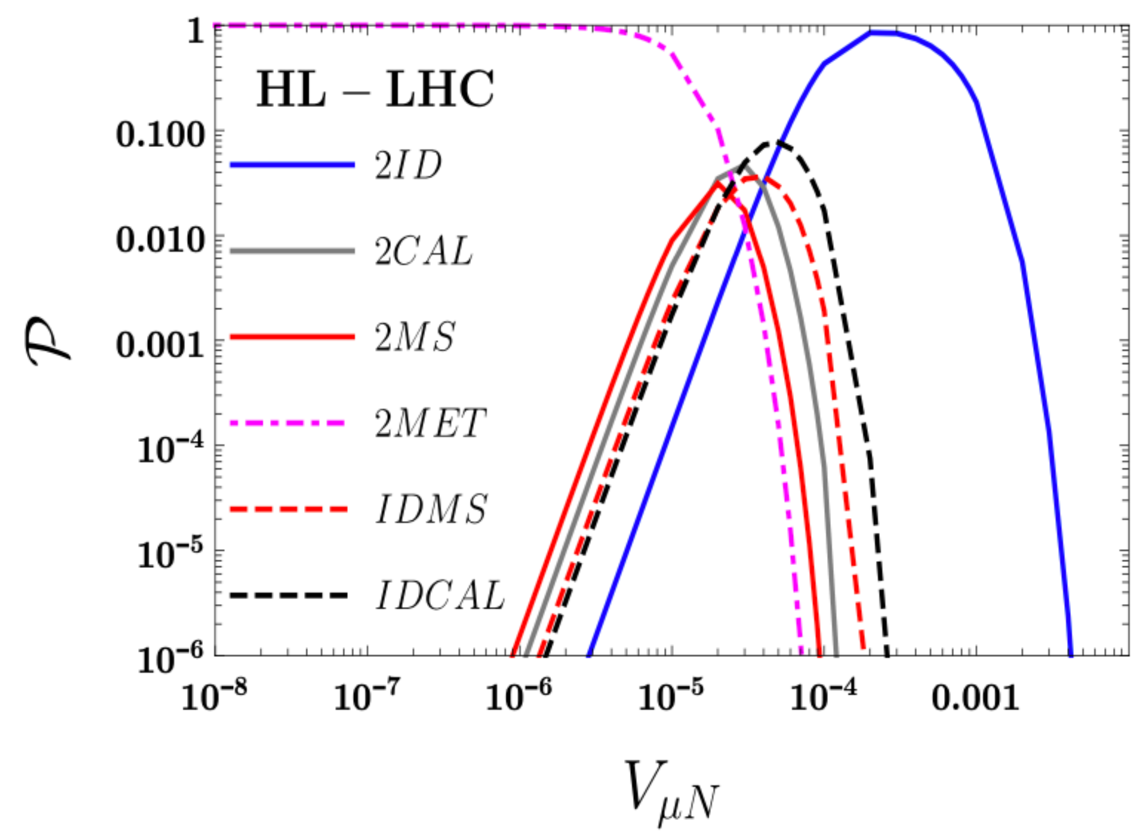
	Prompt	Displaced
Leptonic ($\mu\mu\nu$): $\{p_T(\mu_1), p_T(\mu_2)\} >$	$\{150, 50\}$ GeV	$\{200, 50\}$ GeV
Hadronic (μjj): $\{p_T(\mu), p_T(j)\} >$	$\{50, 300\}$ GeV	$\{50, 300\}$ GeV

- Hard cuts on final states to ensure compatibility with current FCC CDR

HNL decay probabilities

Padhan, Mitra, Kulkarni, Deppisch
arXiv: 2203.06114

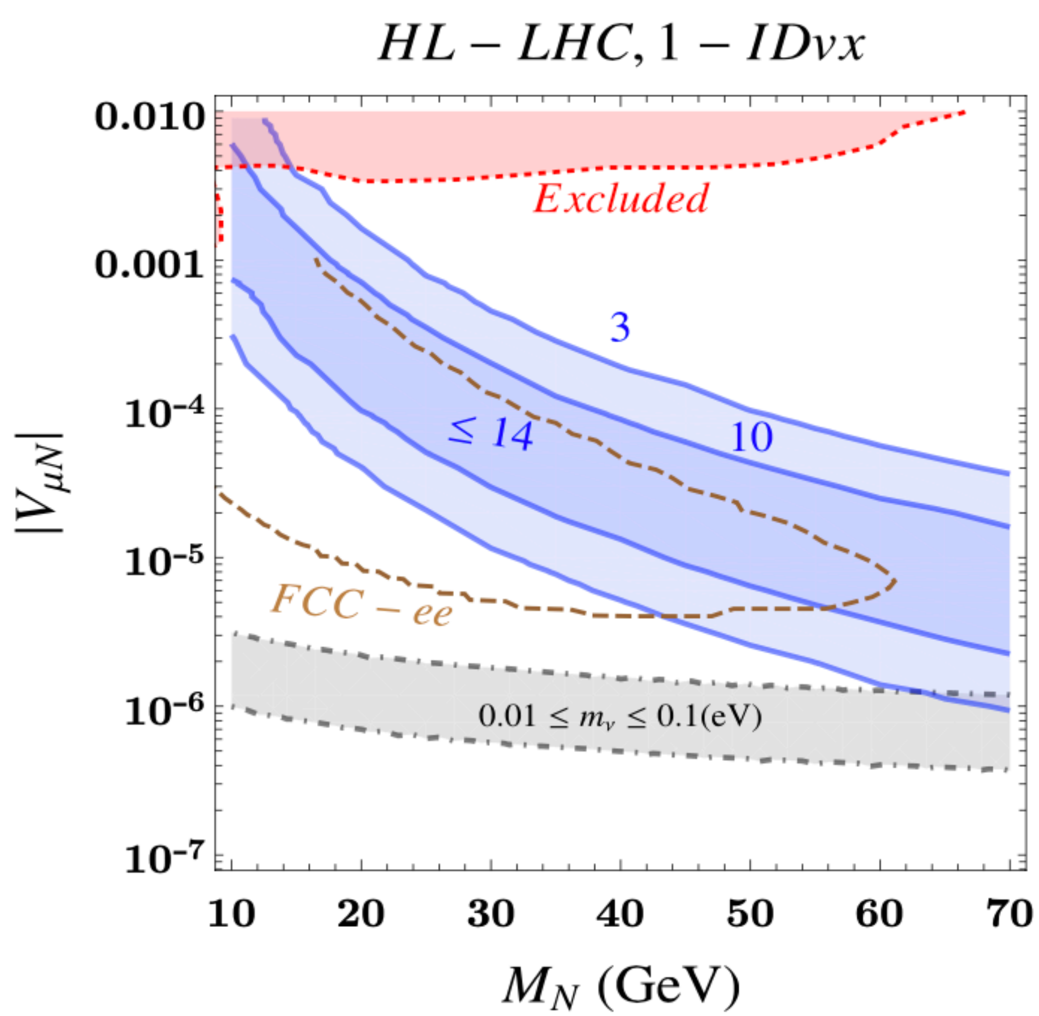


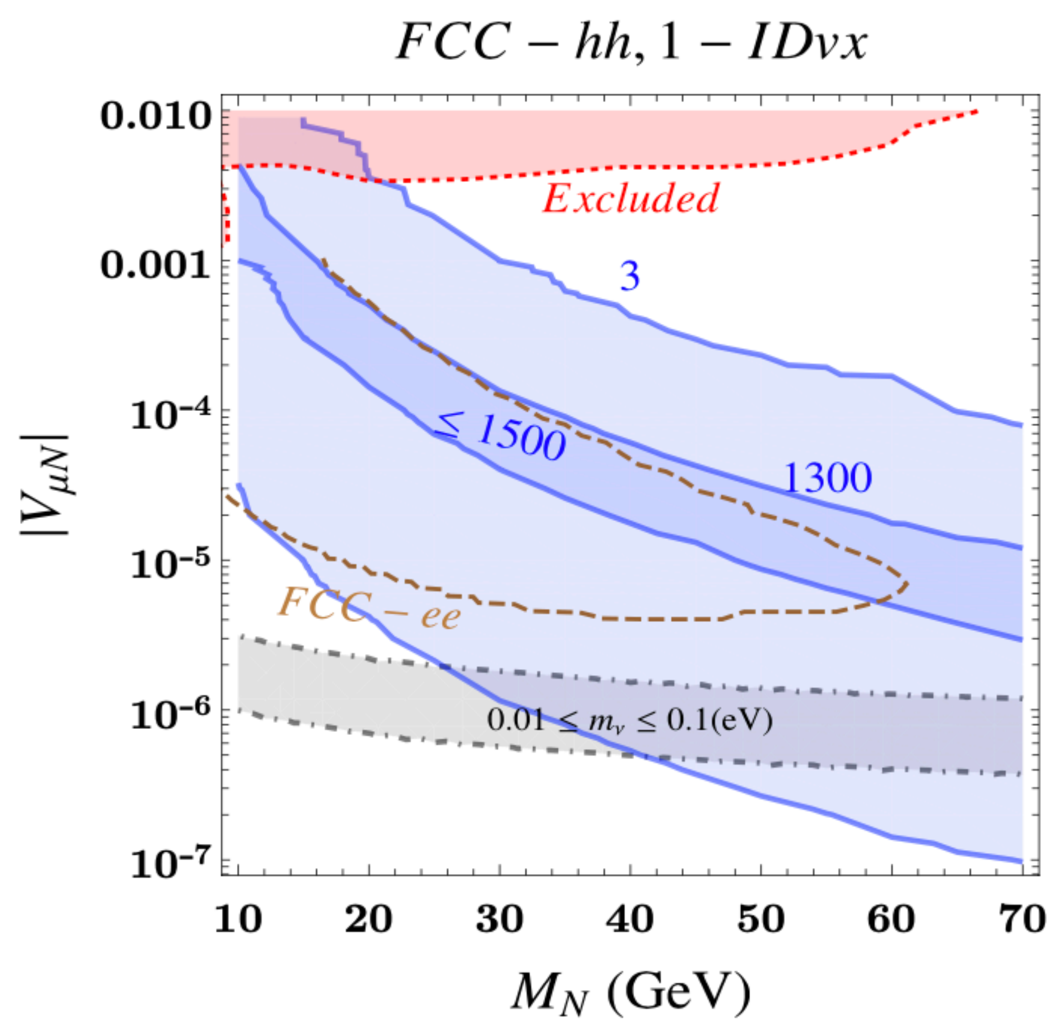


- Boosted neutrinos can decay anywhere in the detector depending on the decay length
- Two possible signatures: either consider decay of only one neutrino or decay of both neutrinos
- While considering decays two neutrinos looking at both decays in inner detector (ID) or muon spectrometer (MS) is more helpful than looking at combinations

HNL fatjet sensitivity: LHC vs FCC-hh

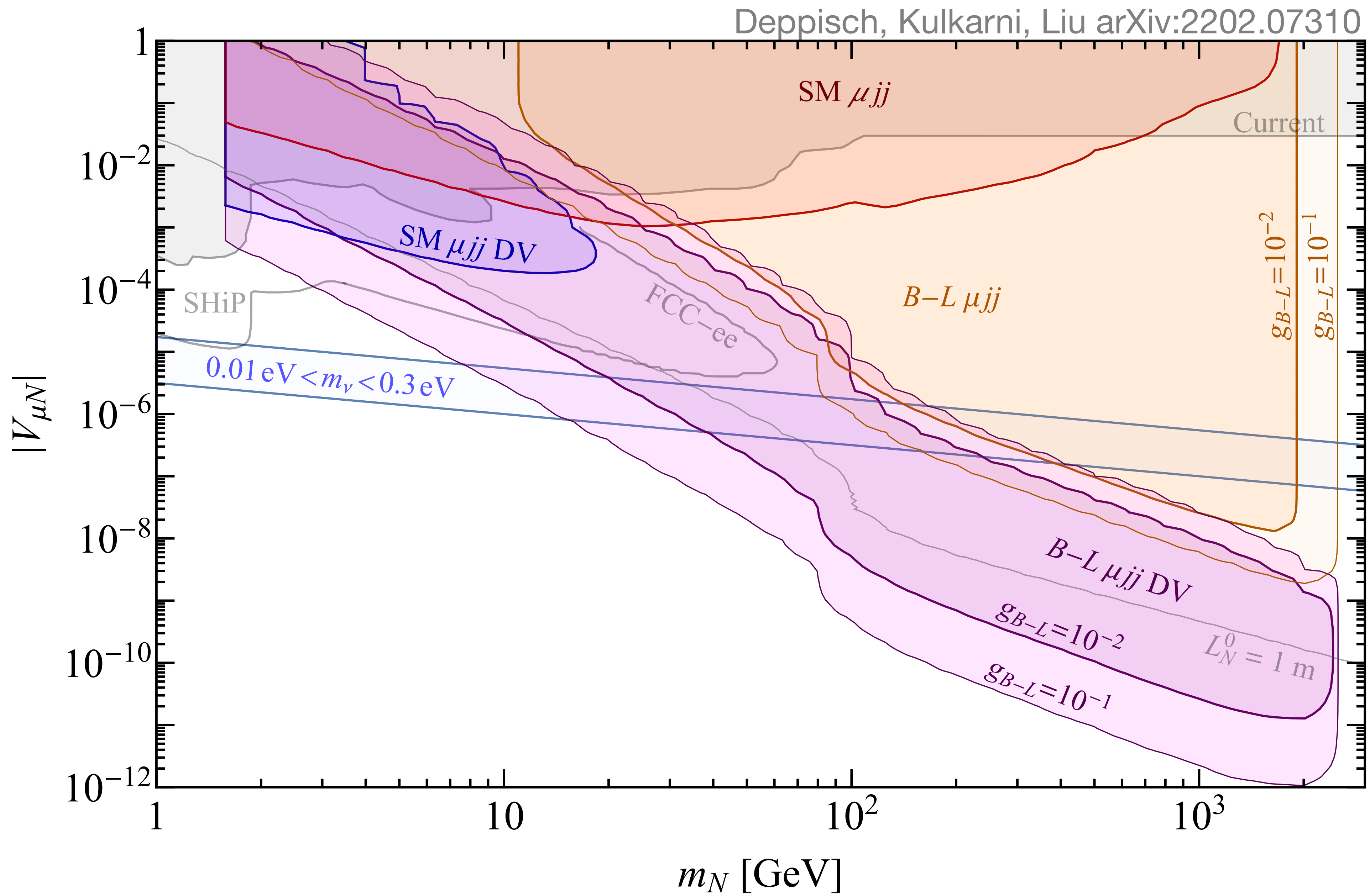
Padhan, Mitra, Kulkarni, Deppisch
arXiv: 2203.06114





- Decays in ID at FCC-hh will be much more sensitive than HL-LHC → potential to probe seesaw region for very light neutrinos at FCC-hh

Sensitivity estimates

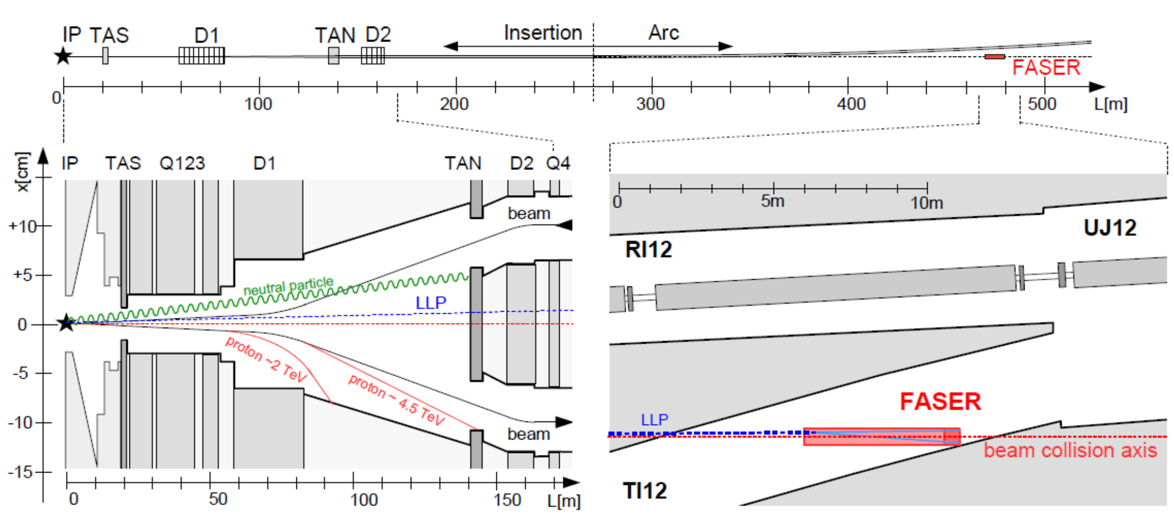


- Prompt channel: Both neutrinos decay to $\mu j j$ final state
- Better sensitivity compared to $\mu\mu\nu$ final state due to larger branching ratio

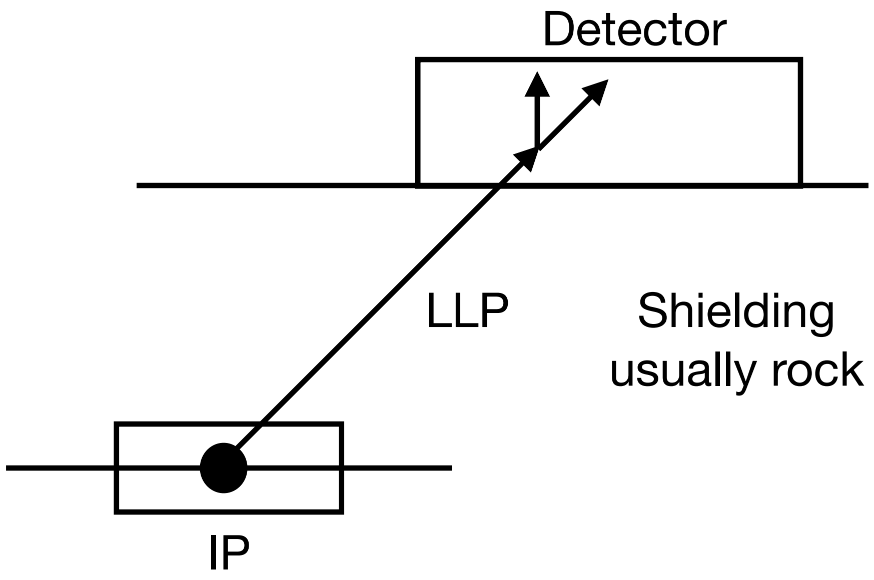
HNL production via Z’

FPF snowmass arXiv:2203.05090

Detector	Location	Distance from IP (m)	Dimensions (m)	Luminosity (fb^{-1})
FASER-2	ATLAS	480	Cylinder 5 X1	3000
CODEX-b	LHC cavity	3	10 X 10 X 10	300
MAPP	LHCb/ MoEDAL	50	7 - 10 tunnel 5 - 25 degrees angle	300
MATHUSLA	CMS	100	200 X 200 X 20	3000



Ongoing experiment



Anomaly cancellations

- SM B and L charges

	l_L	q_L	e_R	u_R	d_R	ν_R
B	0	$\frac{1}{3}$	0	$\frac{1}{3}$	$\frac{1}{3}$	0
L	1	0	1	0	0	1

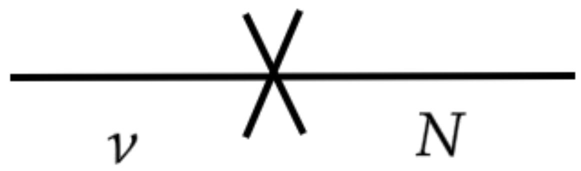
- Contributions from SU(2) and $U(1)_Y$, following for $U(1)_Y$

$$\sum_{\text{left}} BY^2 - \sum_{\text{right}} BY^2 = \frac{1}{3}\left(6 - 3 \times 4^2 - 3 \times (-2)^2\right) = -18$$

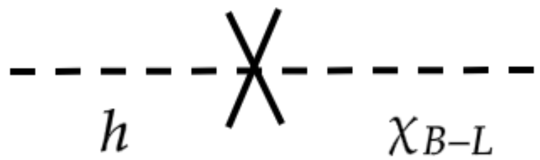
$$\sum_{\text{left}} LY^2 - \sum_{\text{right}} LY^2 = 2 \times (-3)^2 = -18$$

- Individually they are anomalous but B-L is conserved, same holds for SU(2)

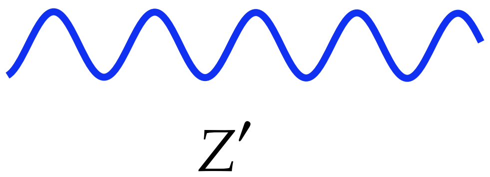
Higgs portal



Suppressed by V_{lN}

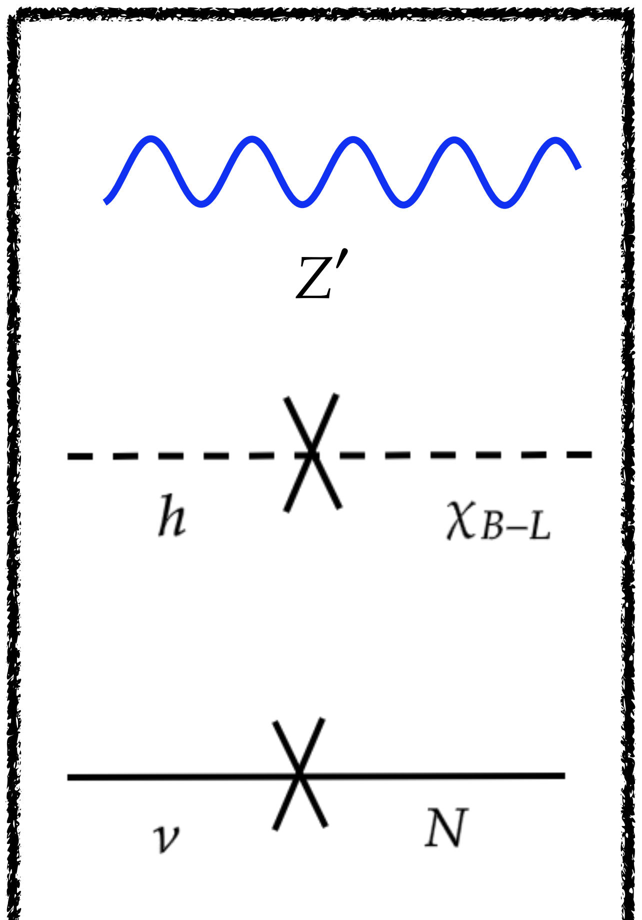


Suppressed by $\sin\alpha$

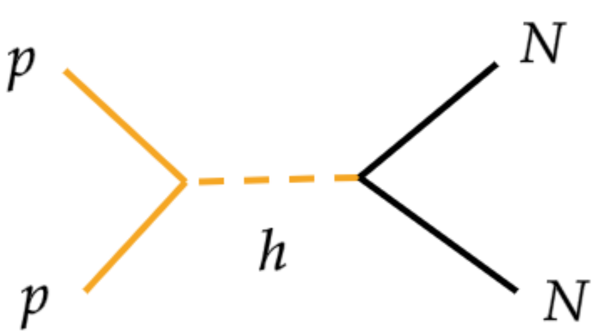


Suppressed by g_{B-L}

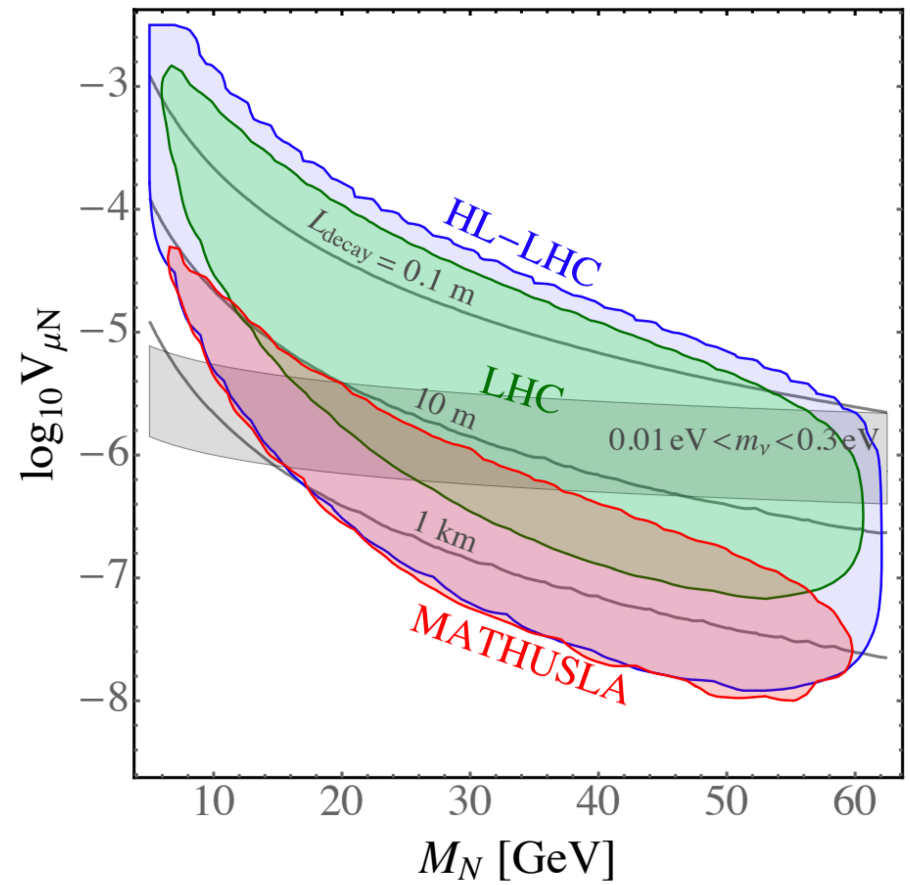
$\sin\alpha = 0.3, g_{B-L} = 10^{-3}$



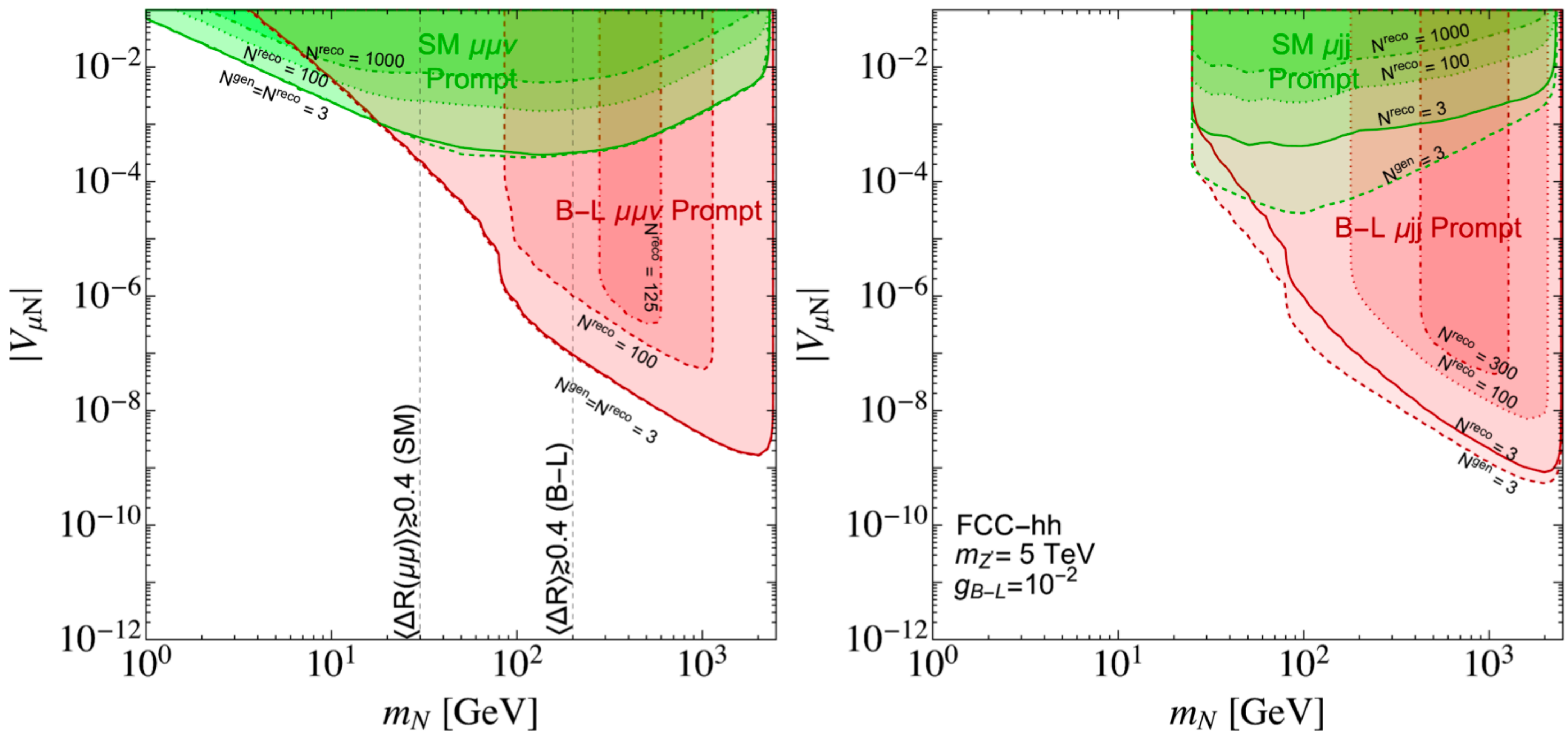
$h \to NN$ possible if $\sin\alpha$ is large



Deppisch et al, JHEP 1808 (2018) 181



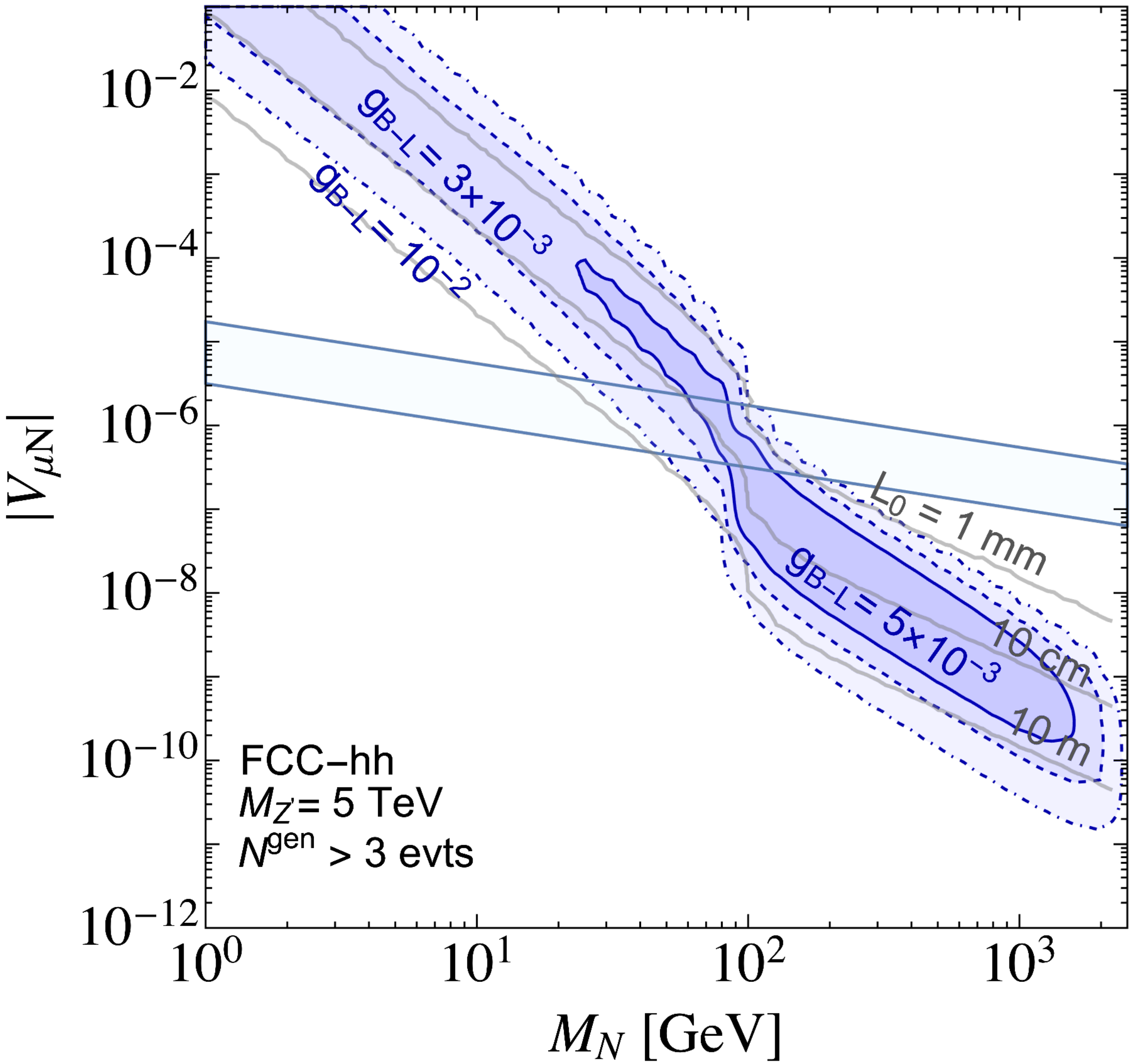
Going to reconstructed level



Default FCC Delphes card

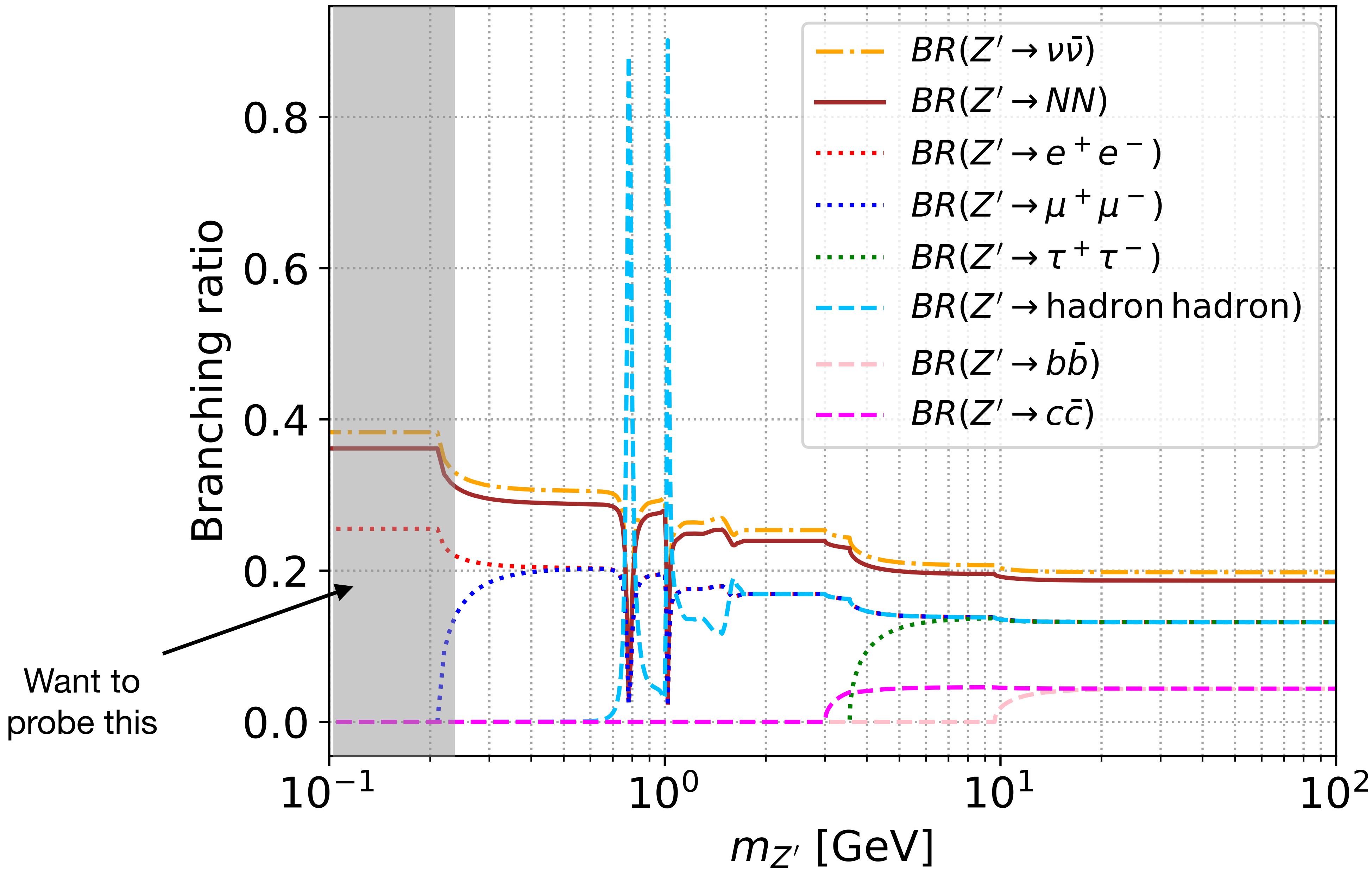
- For μμν channel going to reconstruction level makes small difference, stronger impact on μjj channel
- Non-negligible backgrounds to be expected
- Shown are contours of maximum number of events obtained for B-L channel, comparison with SM channel
- B-L prompt μjj can be hopeful for $g_{B\text{-}L} = 10^{-2}$, prompt μμν may not be realistic

Variation of g_{B-L}



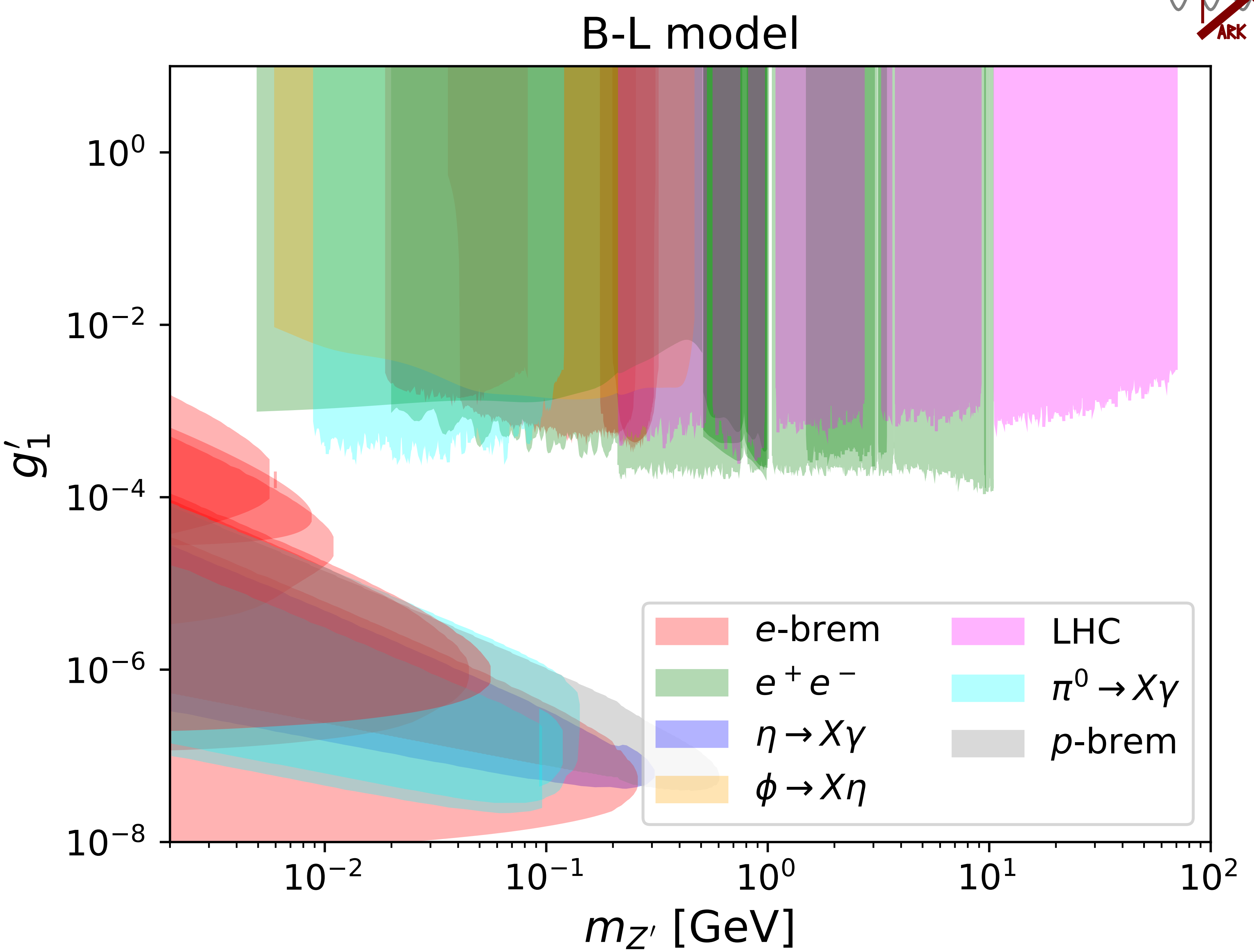
- Displaced final states - no backgrounds accounted for
- In principle can probe even smaller values of g_{B-L}
- Effect of smaller g_{B-L} two fold
  - Reduces the sensitivity from lower and upper side
  - Reduces sensitivity for smaller M_N as they lead to softer final states
- Potential for probing small g_{B-L} and neutrino mass generation mechanisms

Going for extremely light masses

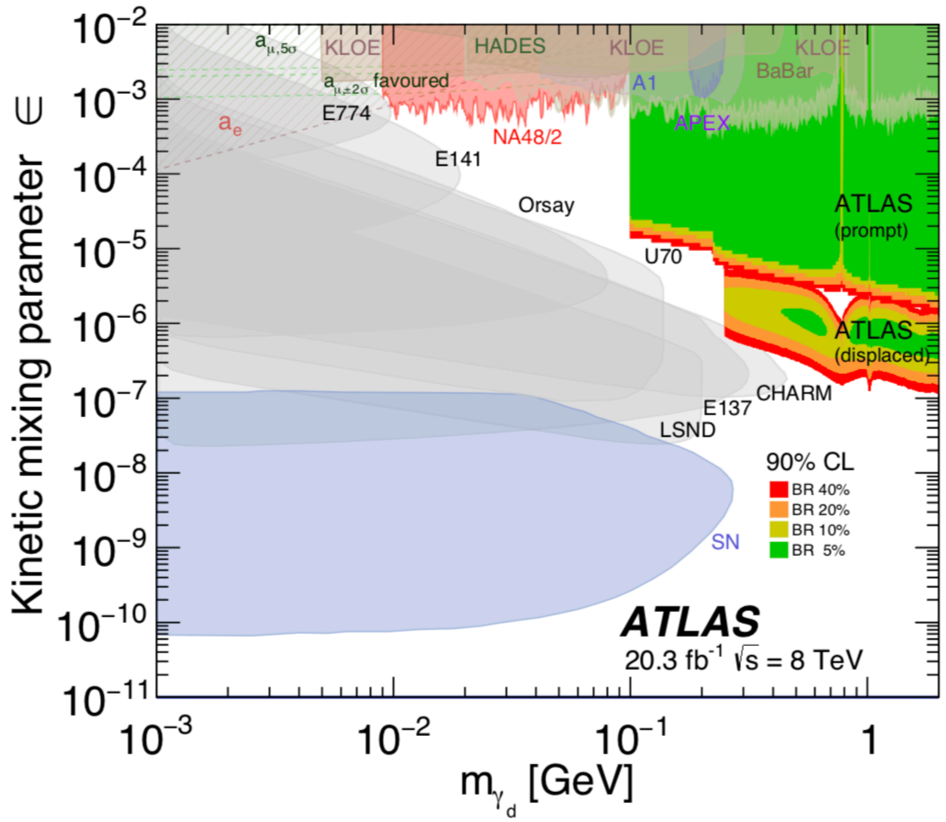


- Possibility of extending Higgs portal analyses for electron final states?
- Mono-jet constraints?

Light Z' allowed parameter space

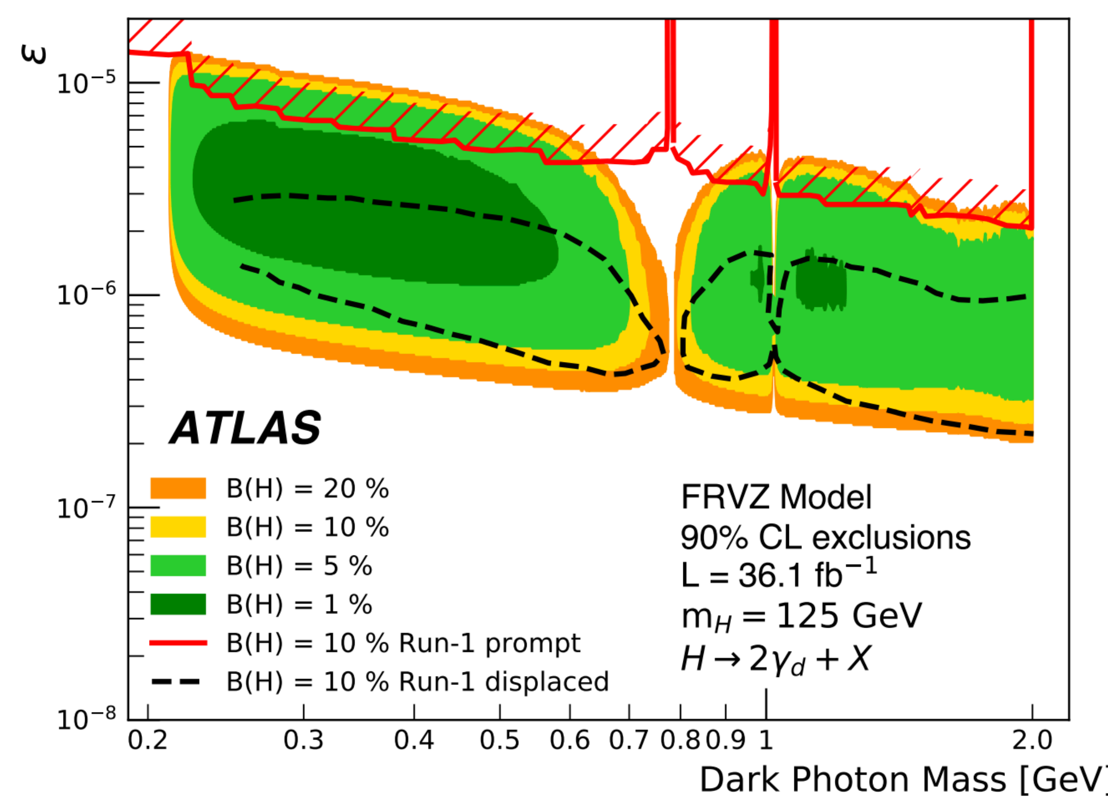


Additional ATLAS analyses

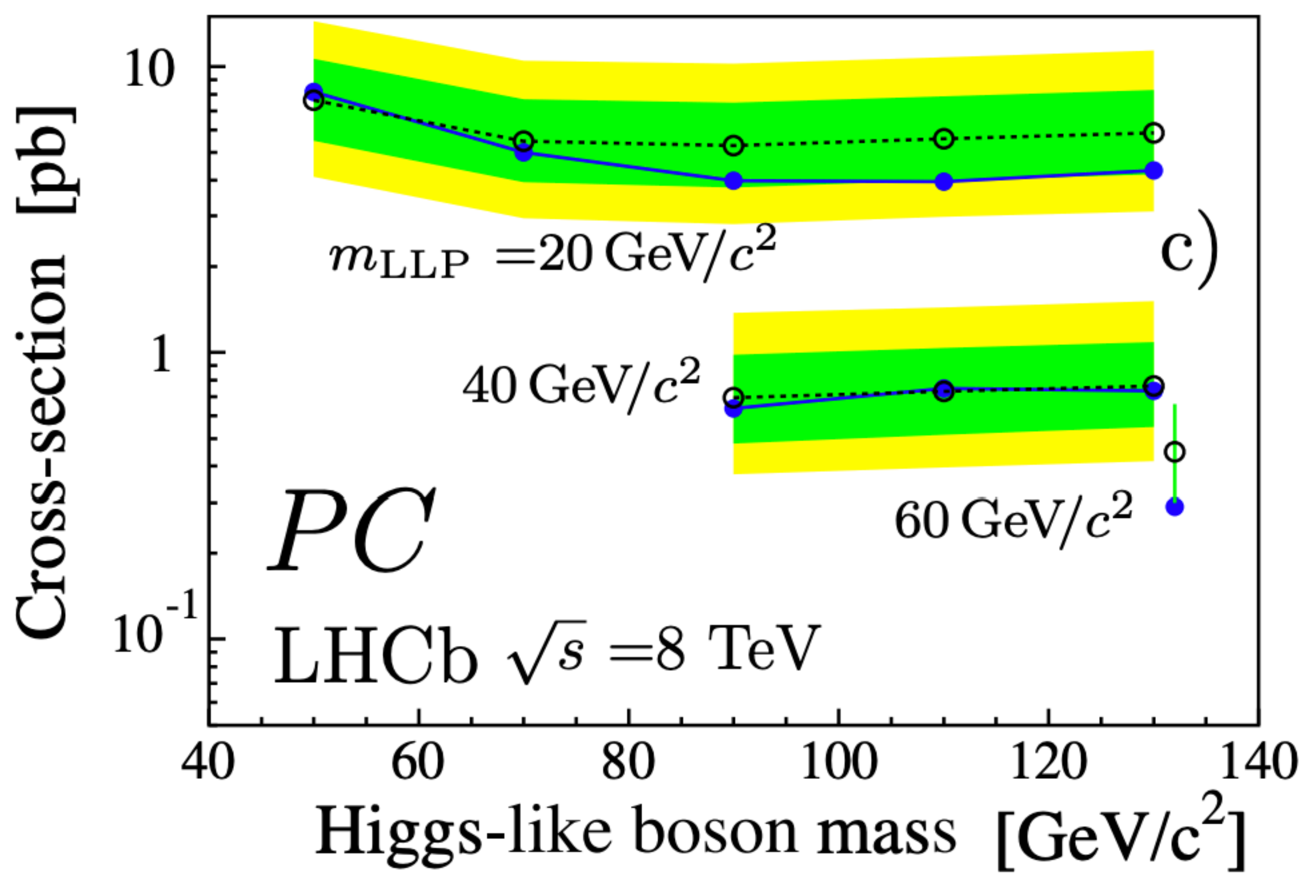


- **ATLAS-EXOT-2014-09 (8 TeV, 20.3 fb^{-1})**
  - Prompt lepton - jets analysis
  - Limits as a function of FRVZ Z_D mass
  - Both electron and muon final states
  - Mass range from 0.25 to 1.5 GeV
  - Competitive (but not better) limits than CMS at low mass

- **ATLAS-EXOT-2017-28 (13 TeV, 36 fb^{-1})**
  - Displaced lepton - jets analysis
  - Electron and muon LJ
- Prompt analysis as sensitive as CMS analysis
- Displaced analysis 8 TeV not sensitive; 13 TeV potentially sensitive
  - 13 TeV analysis hard to reinterpret

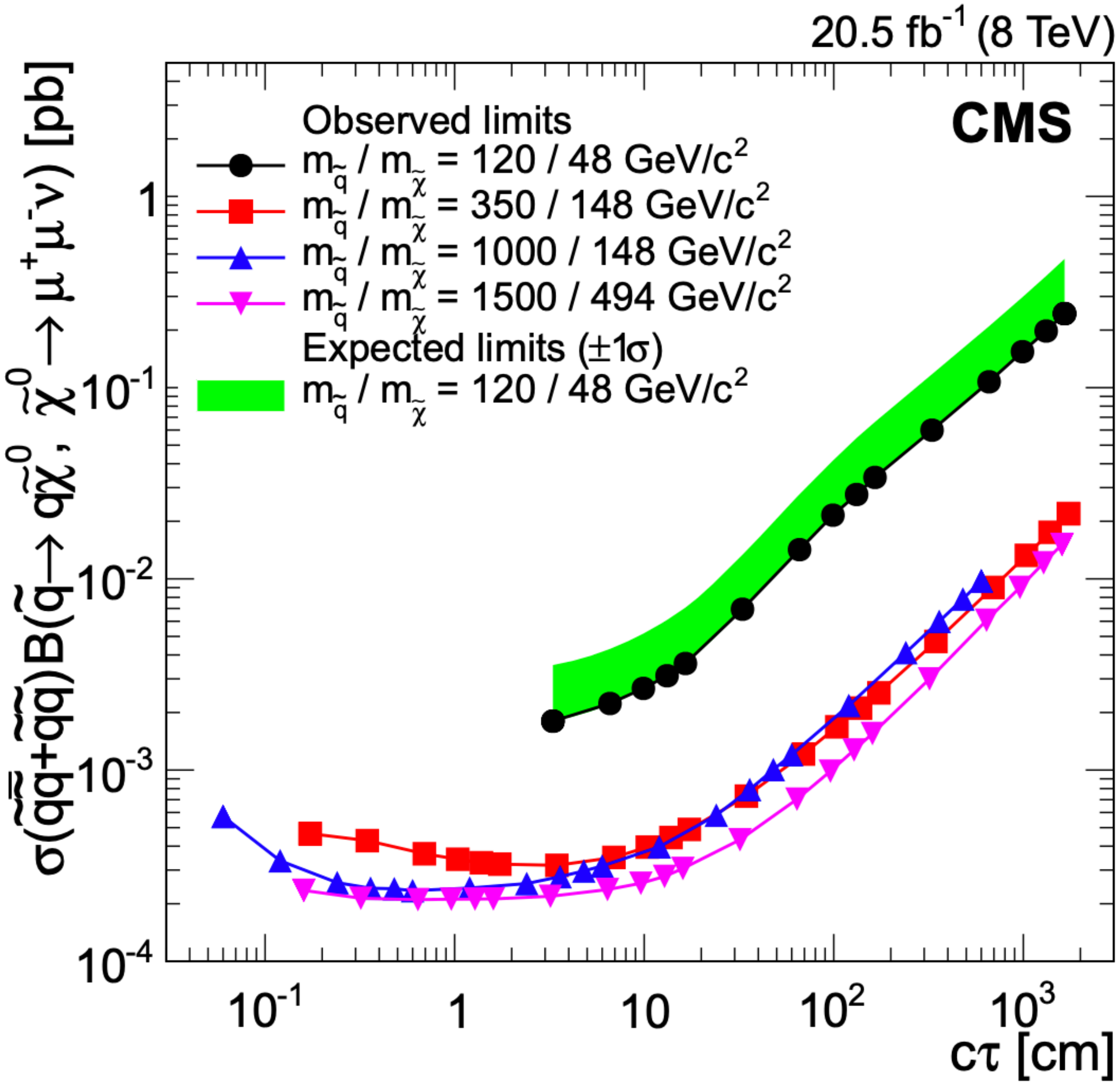


- LHCb-PAPER-2016-047: (7+8 TeV, 3 fb^{-1})
  - 'Inclusive displaced vertex search'
  - Trigger muons pT > 10 GeV
  - Final state muon and two jets
  - $p_T(\mu) > 12$ GeV, $d_{IP} > 0.25$ mm, Rxy > 0.55 mm
  - Invariant mass of tracks > 4.5 GeV
  - Interpretation in terms of GUT scale SUSY RPV models



CMS DV search

- CMS-EXO-12-037: (8 TeV, 20 fb^{-1})
  - Inclusive displaced vertex search for pair of electron or muon final states
  - Electron E_T > 36 (22) GeV; Muon p_T > 23 GeV (reconstructed in muon detectors)
  - Generated Lvtx < 50 cm
  - $p_T(\mu)$ > 12 GeV, d_{IP} > 0.25 mm, Rxy > 0.55 mm
  - Interpretation for three body decays

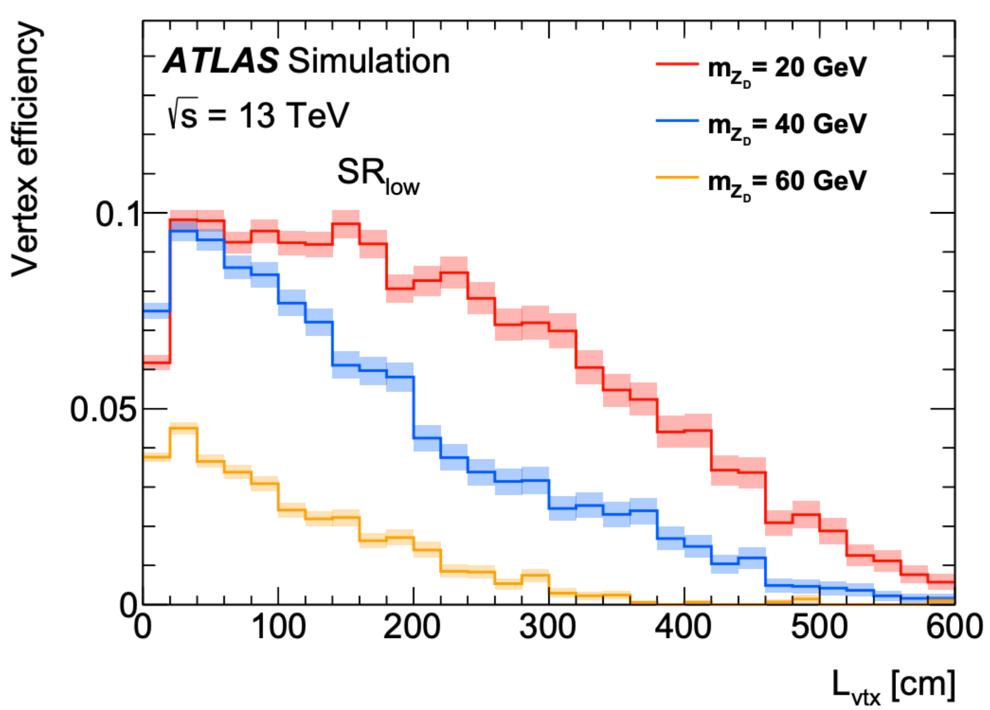


ATLAS DV search

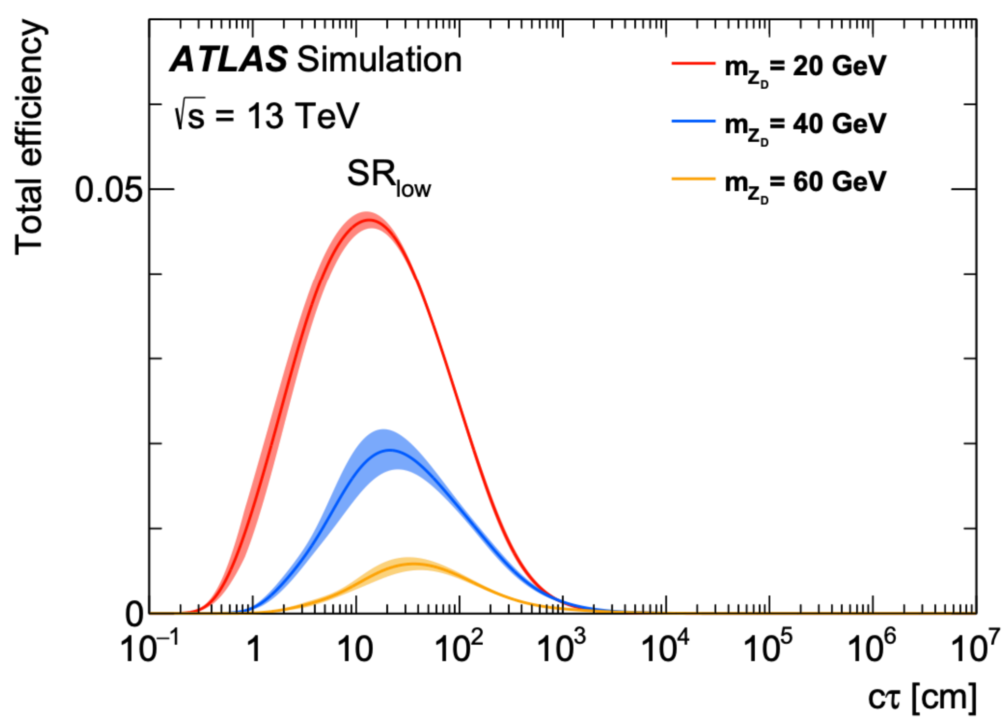
- **ATLAS-EXOT-2017-03 (13 TeV, 32.9 fb^{-1})**
  - Inclusive search in displaced muon vertex

Signal type	Trigger	Description	Thresholds
High mass	E_T^{miss} single muon	missing transverse momentum single muon restricted to the barrel region	$E_T^{miss} > 110$ GeV muon $\|\eta\| < 1.05$ and $p_T > 60$ GeV
Low mass	collimated dimuon trimuon	two muons with small angular separation three muons	p_T of muons > 15 and 20 GeV and $\Delta R_{\mu\mu} < 0.5$ $p_T > 6$ GeV for all three muons

+

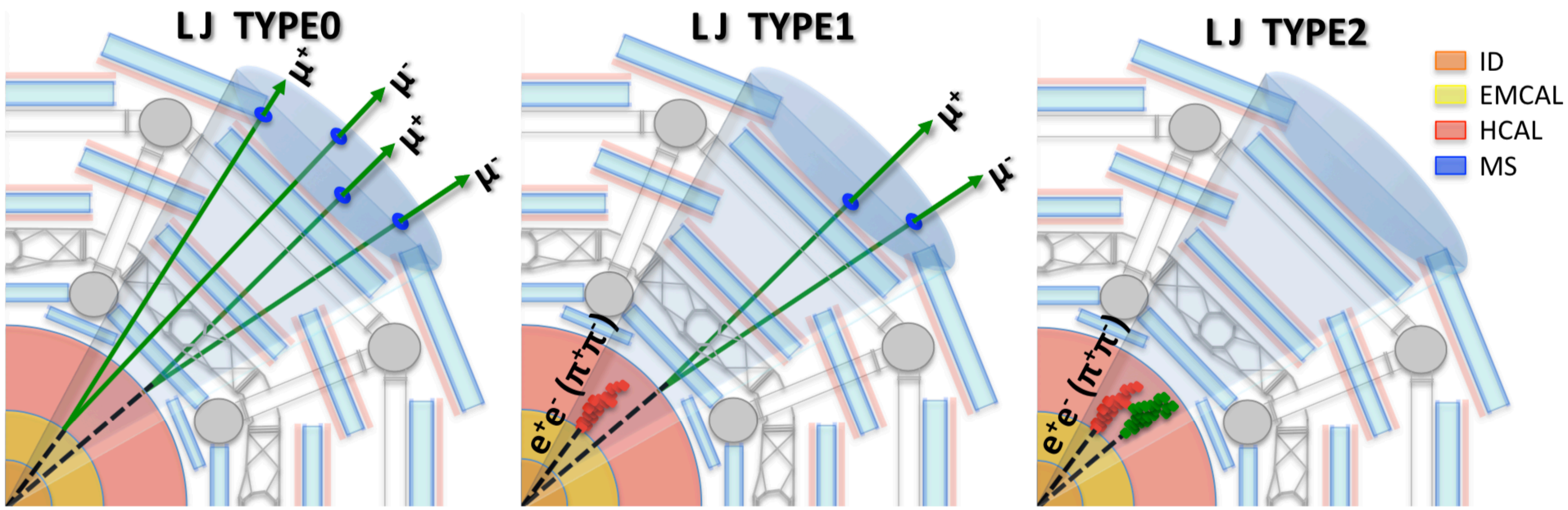


≠



ATLAS LJ search

- **ATLAS-EXOT-2013-22 (sqrt 13 TeV, 20 fb^{-1})**

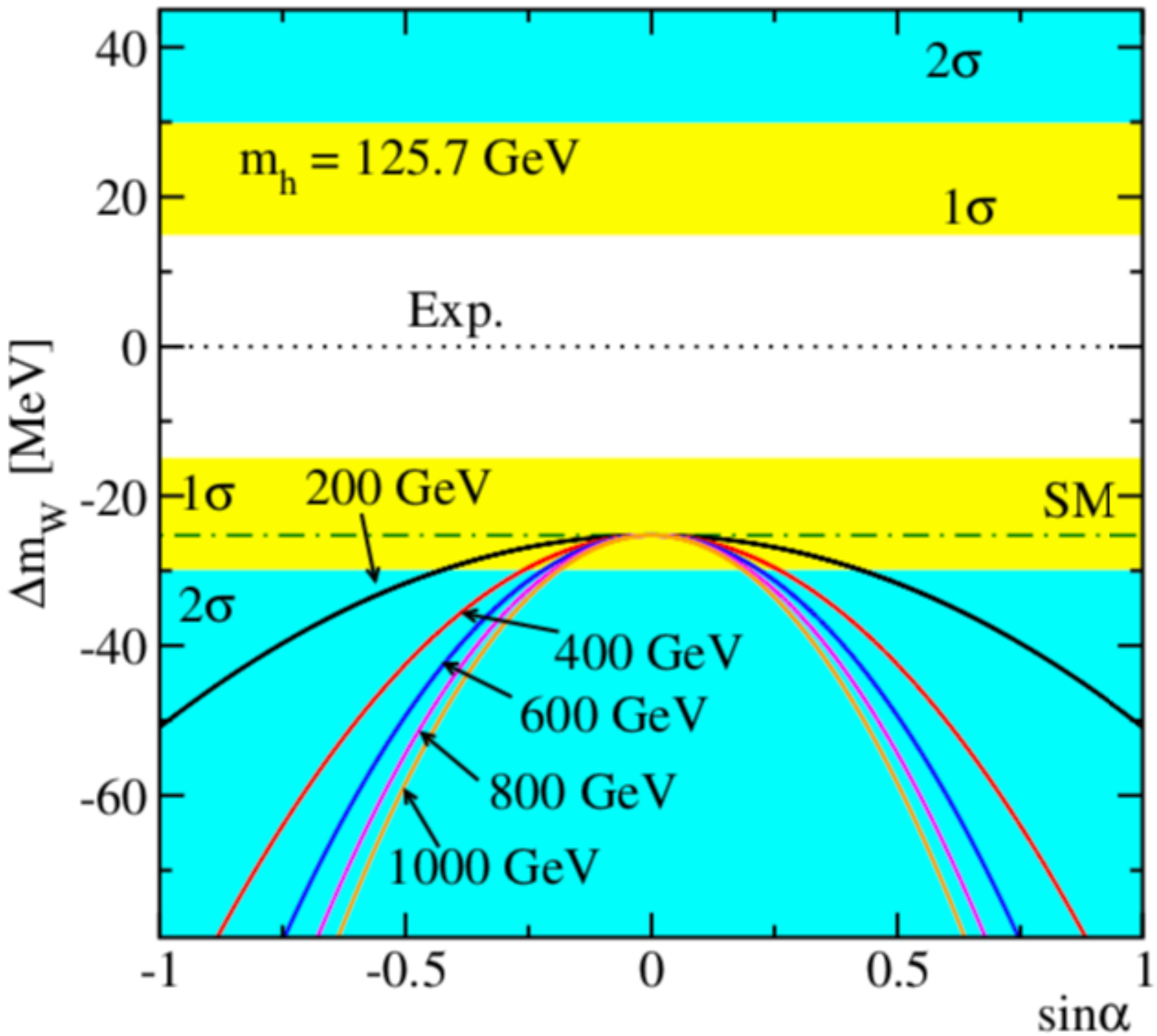


- Categorization of lepton jets:
  - Electron-jet if at least one electron candidate with E_T>10 GeV, 2 or more tracks w/ p_T>10 GeV, no muons
  - Muon-jet if at least 2 muons with pT>10 GeV and no electrons
  - Mixed-jet if at least one electron w/ E_T>10 GeV and at least one muon with p_T>10 GeV
- Triggers:
  - Single e w/ E_T>60 or double e w/ E_T>35/25 GeV
  - Single μ w/ p_T>36 or double μ w/ p_T>13/13 GeV

- **No equivalent CMS electron LJ search yet**

W mass constraint

Lopez-Val, Robens arXiv:1406.1043



$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha_{EM}}{\sqrt{2}G_F}(1+\Delta r)$$

$$\Delta m_W=-\frac{1}{2}m_W\frac{\sin^2\theta_W}{\cos^2\theta_W-\sin^2\theta_W}\delta(\Delta r)$$

- Constraints can be derived when lighter or heavier Higgs is 125 GeV
- Much stronger constraints when lighter Higgs is 125 GeV and heavier Higgs is heavy
- Driven by discrepancy between observed and predicted value of W mass
- When lighter Higgs is at 125 GeV, higher order EW corrections increase the discrepancy
- When heavy Higgs is at 125 GeV, somewhat better situation however, it is strongly constrained by Higgs signal strengths

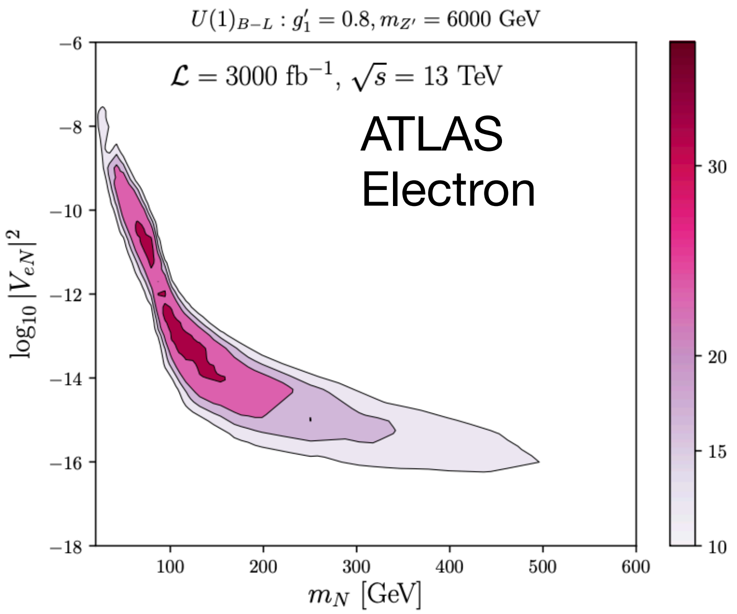
HNL high mass region

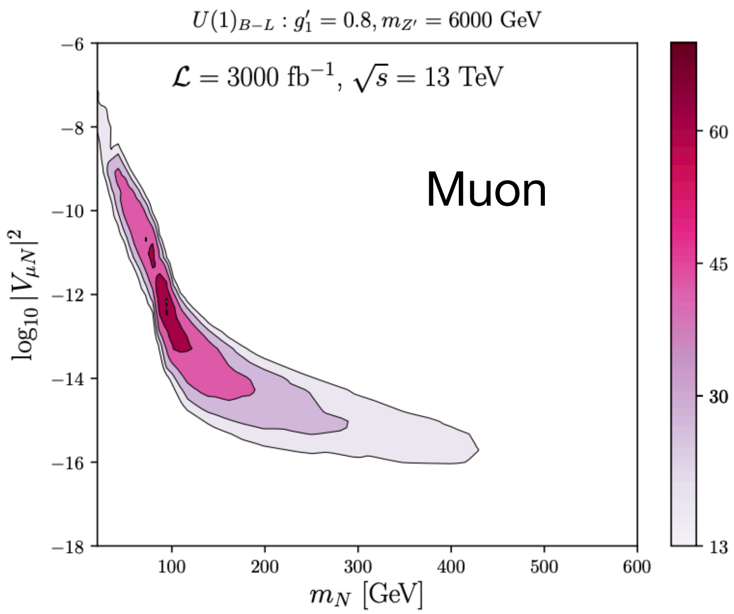
ATLAS

Trigger	Muon: $\|\eta\| < 1.07$ and $p_T > 55$ GeV. Electron: $p_T > 120$ GeV
DV region	DV within 4 mm $< r_{DV} <$ 300 mm and $\|z_{DV}\| <$ 300 mm
DV selection	Made from tracks with $\|d_0\| >$ 2 mm and with $p_T >$ 1 GeV
	DV track multiplicity $N_{trk} \geq 4$ and invariant mass $m_{DV} \geq 5$ GeV

CMS

Trigger	$H_T > 1000$ GeV
Jet selection	At least 4 jets with $p_T > 20$ GeV and $\|\eta\| < 2.5$
DV region	2 DVs within 0.1 mm $< r_{DV} <$ 20 mm and $d_{VV} >$ 0.4 mm
DV selection	Made from tracks with $\|d_0\| \geq 0.1$ mm, $p_T > 20$ GeV and $\|\eta\| < 2.5$.
	$\sum p_T \geq 350$ GeV, correcting for b quarks.



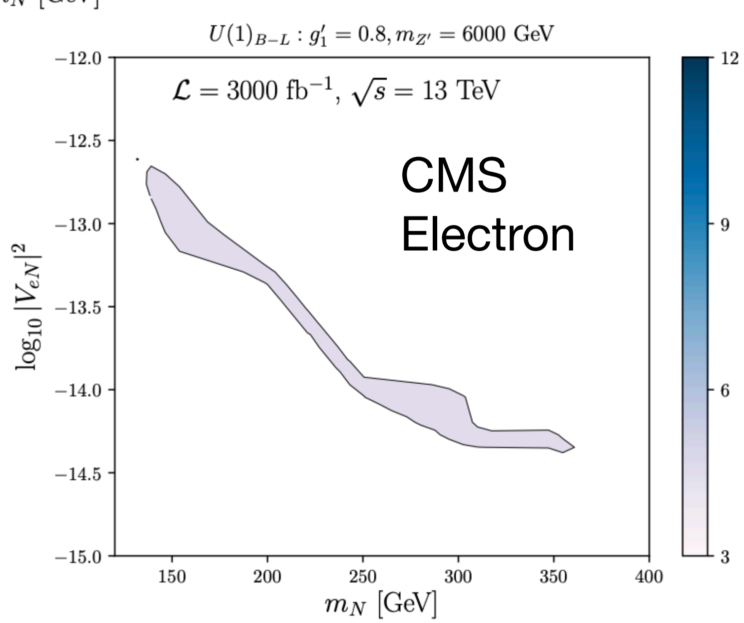


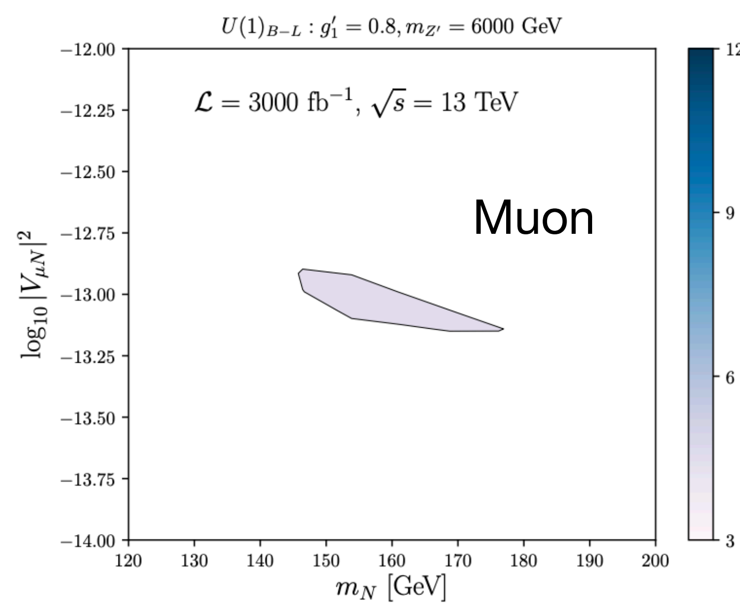
At least one DV in inner tracker

Efficiencies derived by 'fitting' to the limits

Exactly two DVs

Gen level selection + approximate event level efficiencies





arXiv:1908.09838

Fatjet analyses

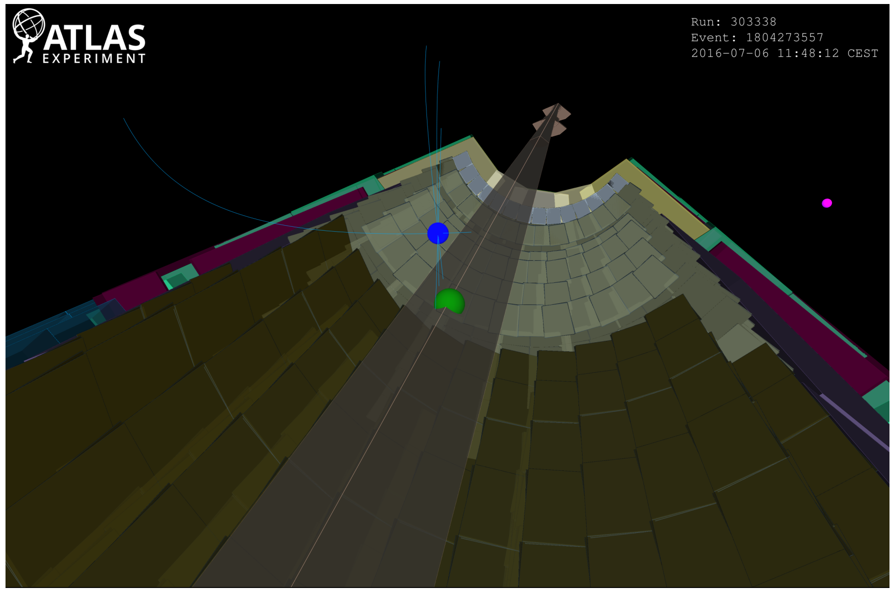
Detector Geometry		
	HL-LHC	FCC-hh
Inner detector (ID)	(2-300) mm	(25-1550) mm
Calorimeter (CAL)	(2000-4000) mm	(2700-4700) mm
Muon Spectrometer (MS)	(4000-7000) mm	(6000-9000) mm

HL-LHC MS analysis: ATLAS arXiv:1911.12575

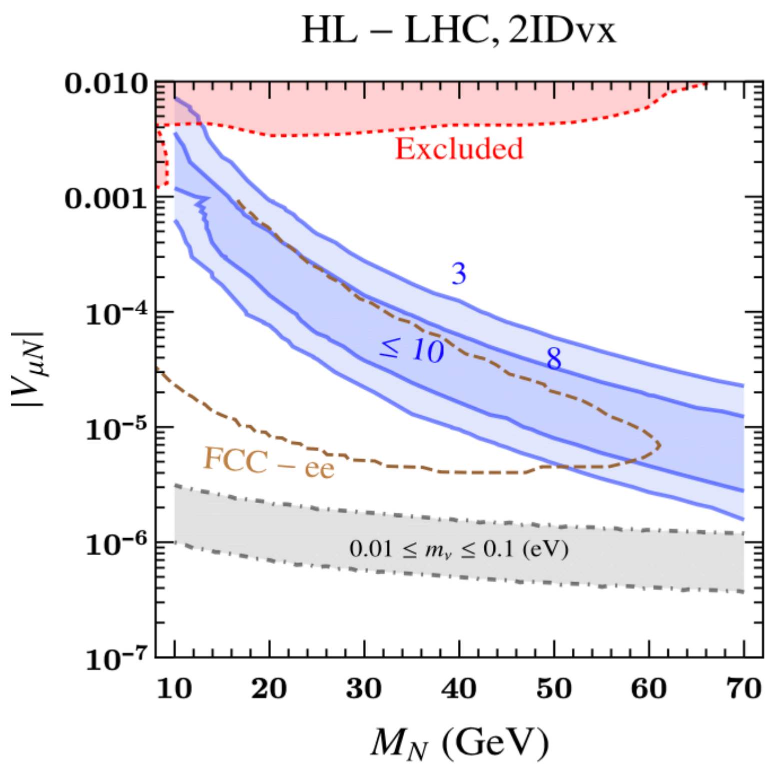
- $4000\,\text{mm} \leq L_{xy} \leq 7000\,\text{mm}$ (outer edge of HCAL and middle section of MS where muon ROI trigger efficiency is high)
- $p_T(track) > 1\,\text{GeV}, |\eta(track)| < 2.7, n_{trk} \geq 4$
- $\sum_{track} p_T(track) > 60\text{GeV}$

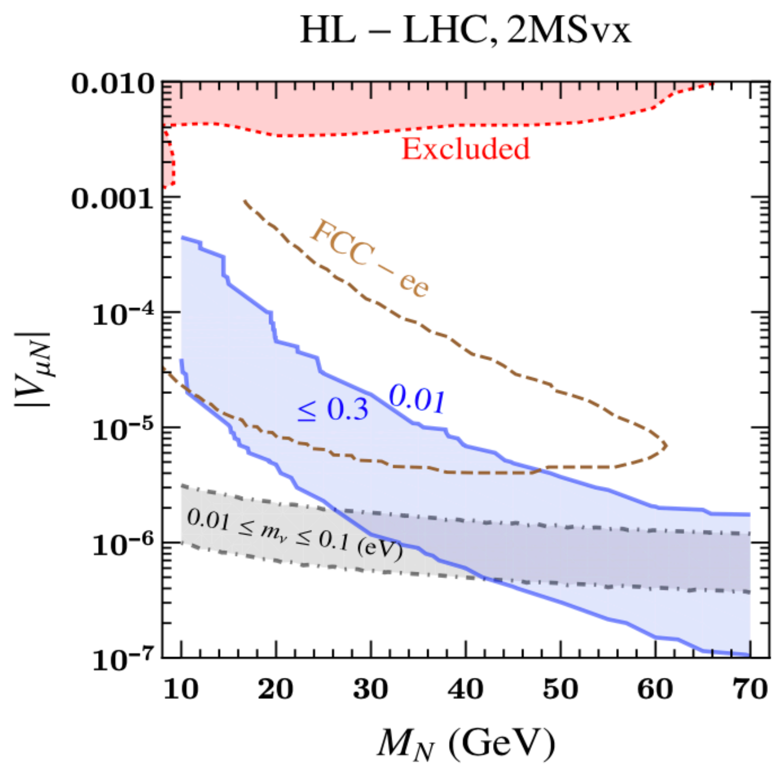
HL-LHC ID analysis:

- $2\,\text{mm} \leq L_{xy} \leq 300\,\text{mm}$
- $|\eta(j_{0,1})| < 4.5, p_T(j_{0,1}) > 150\,\text{GeV}$
- $p_T(track) > 1\,\text{GeV}, |\eta| < 2.5, n_{trk} \geq 4$

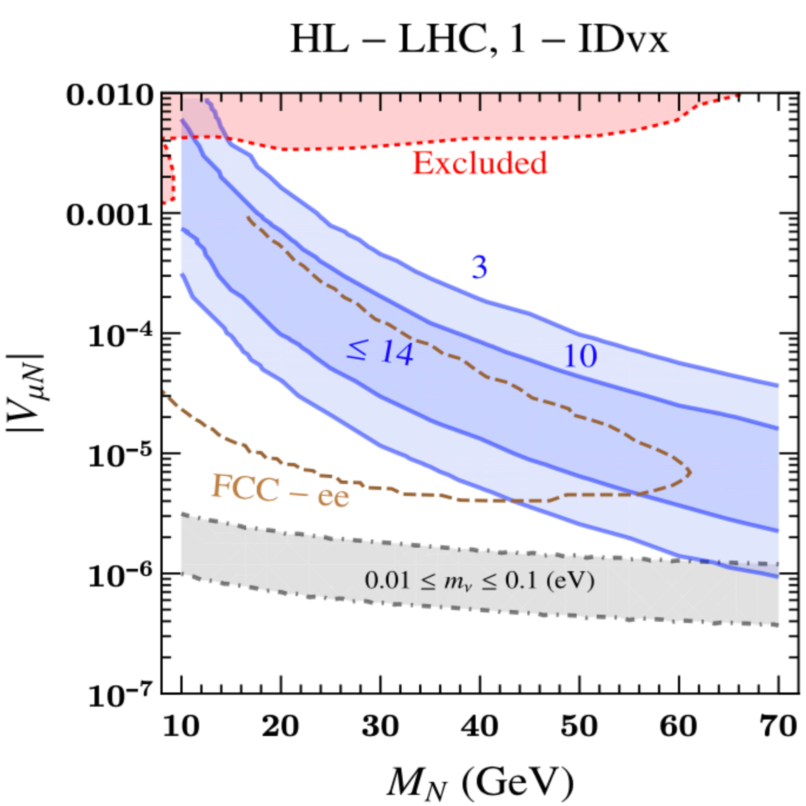


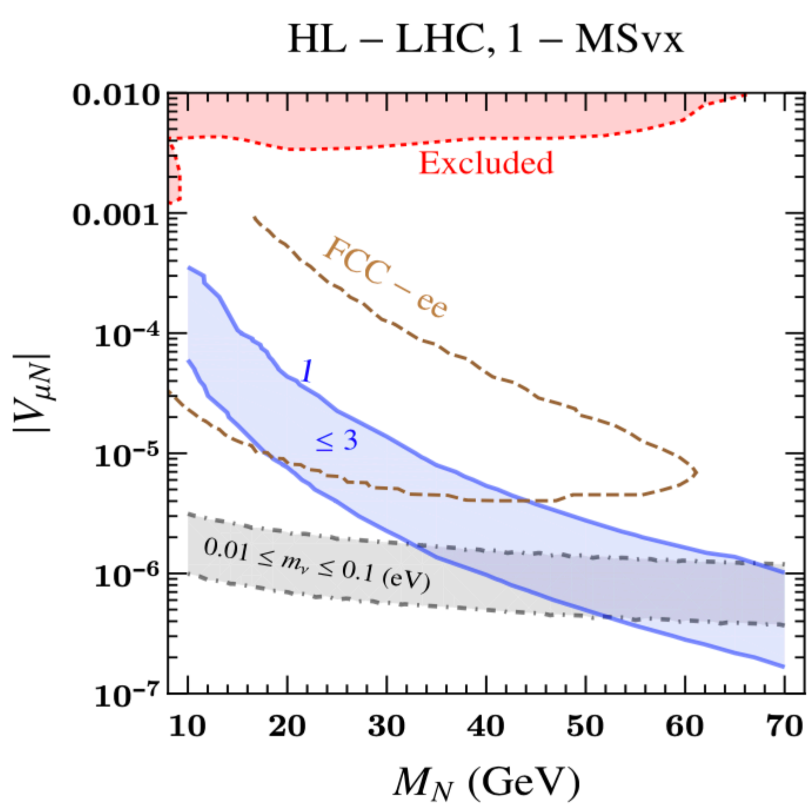
Fatjet LHC sensitivity

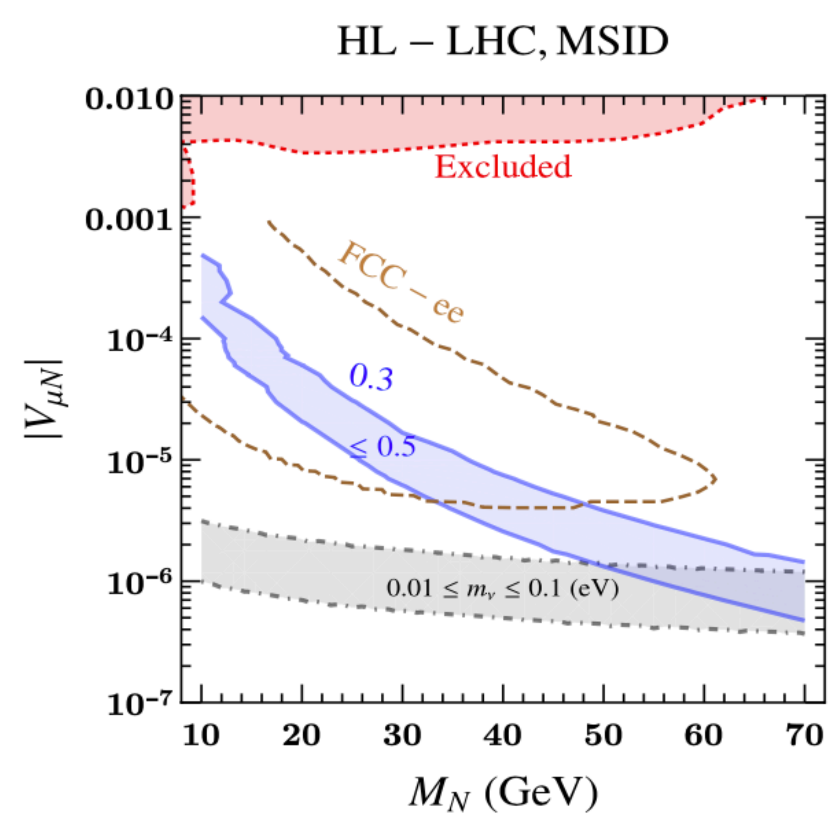




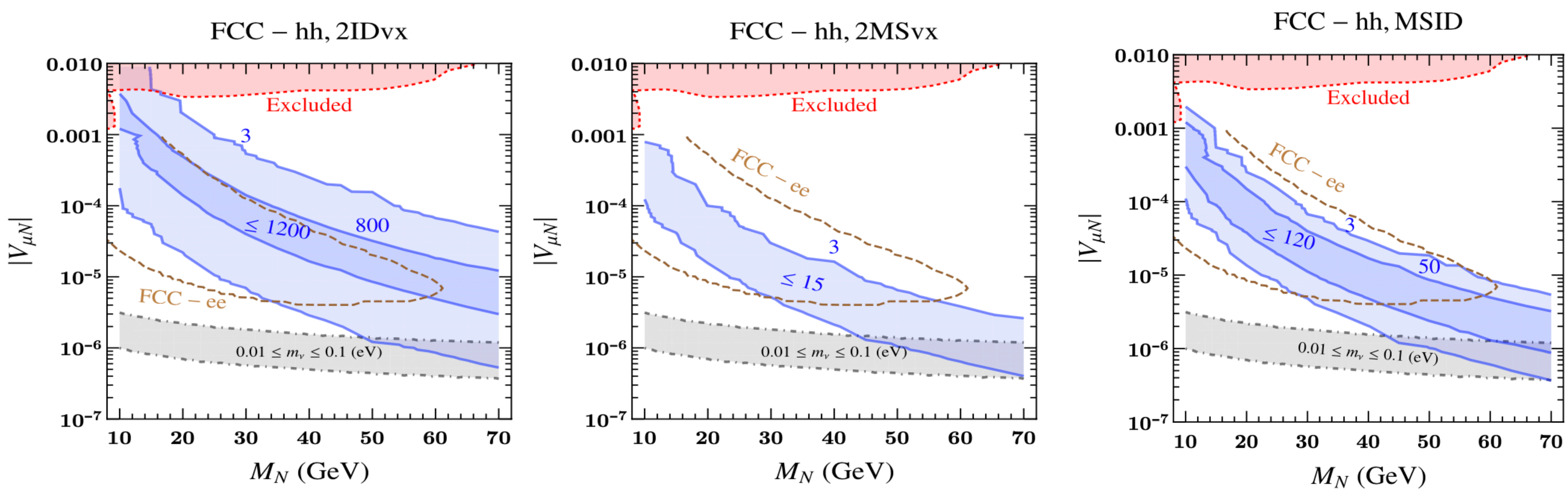
$m_{Z'} = 1\,\text{TeV} \quad g_{B-L} = 3\times10^{-3}$

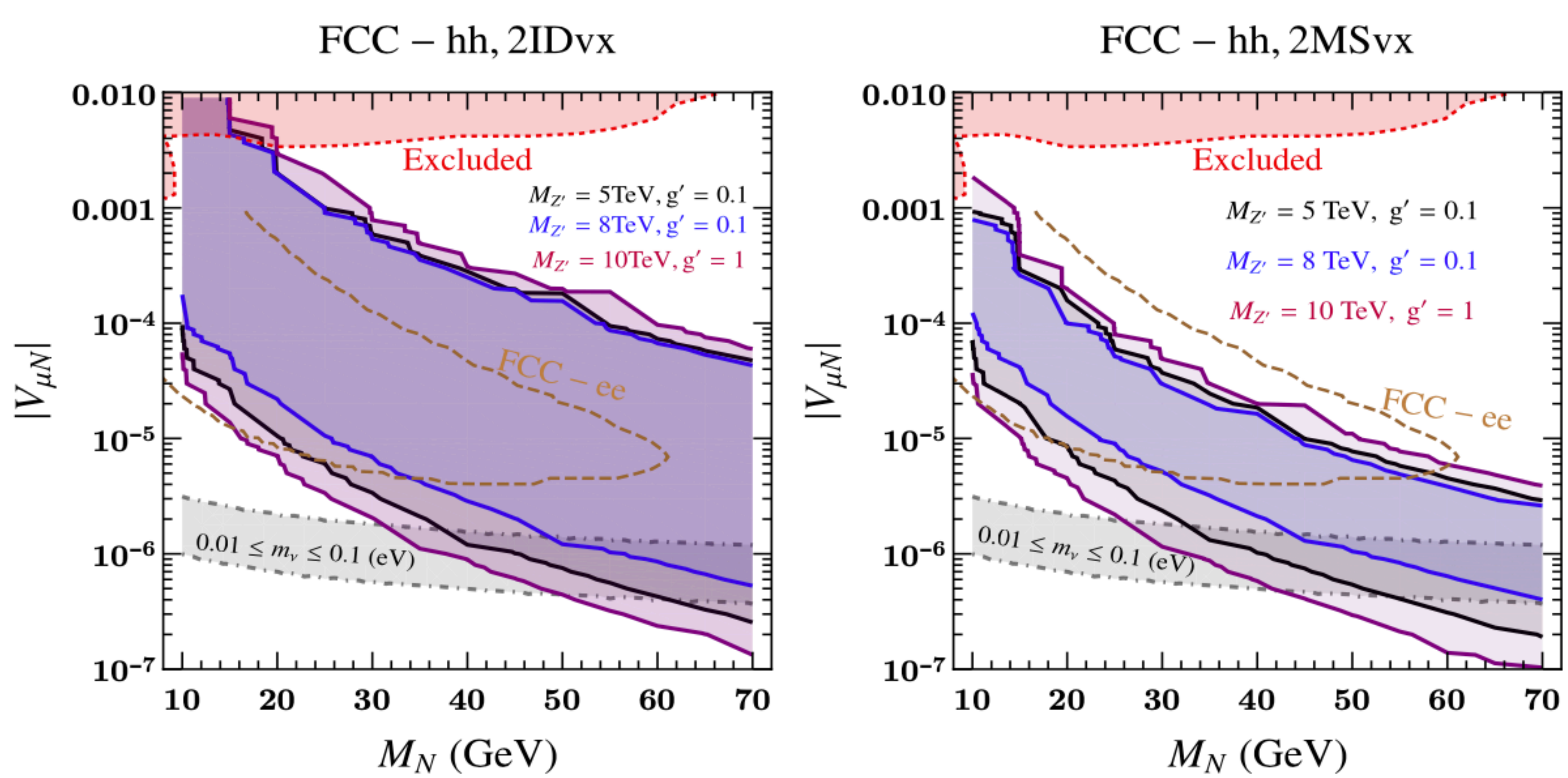






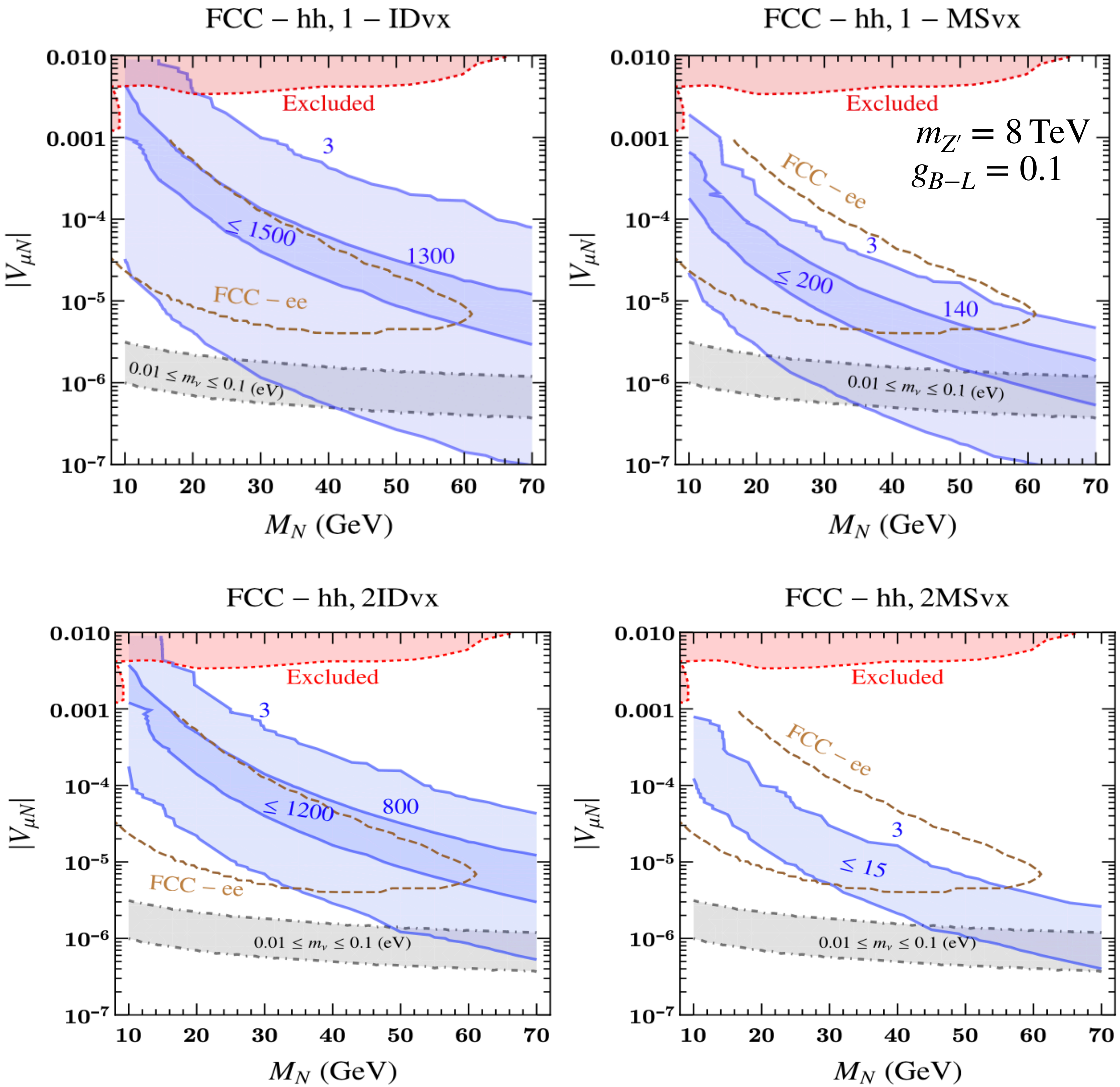
FCC-hh sensitivity: other Z' masses





Padhan, Mitra, Kulkarni, Deppisch
arXiv: 2203.06114

FCC-hh sensitivity

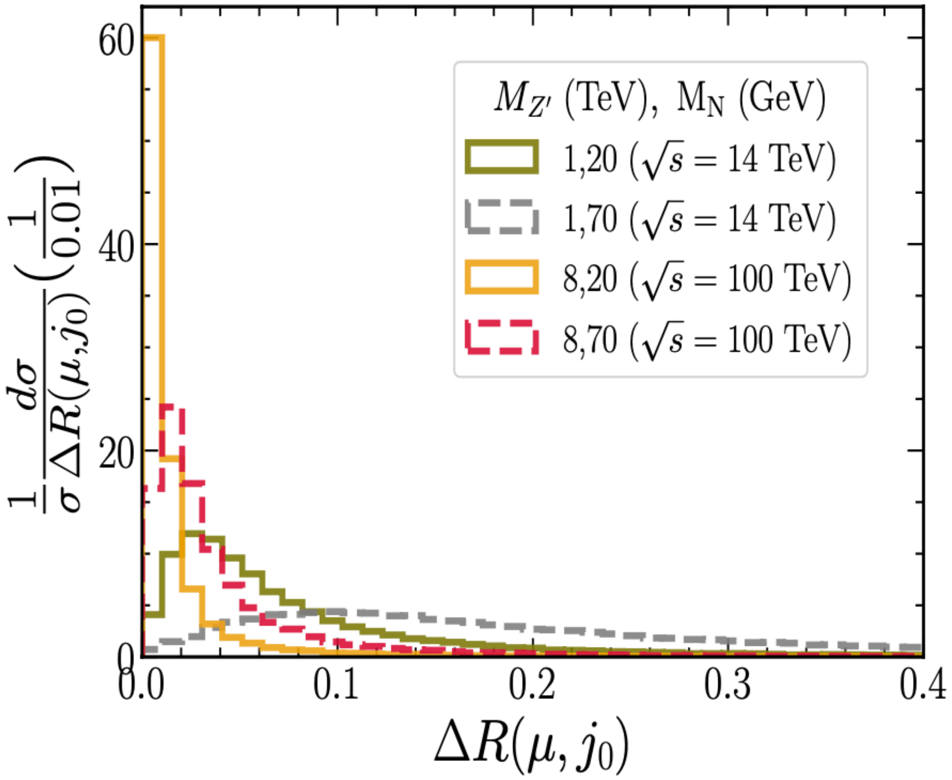


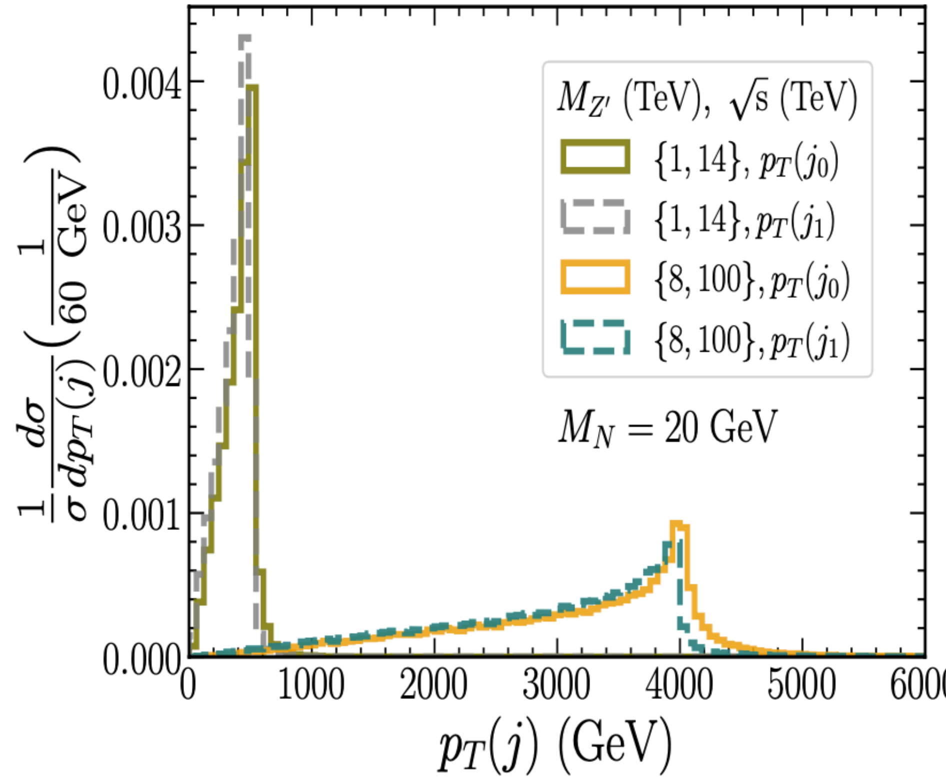
- 1 displaced vertex in the inner detector leads to largest sensitivity, however this may suffer from backgrounds
- One displaced vertex in muon spectrometer leads to lesser sensitivity but is likely background free
- Two displaced vertices in ID or MS also leads to good sensitivity, will have even less backgrounds

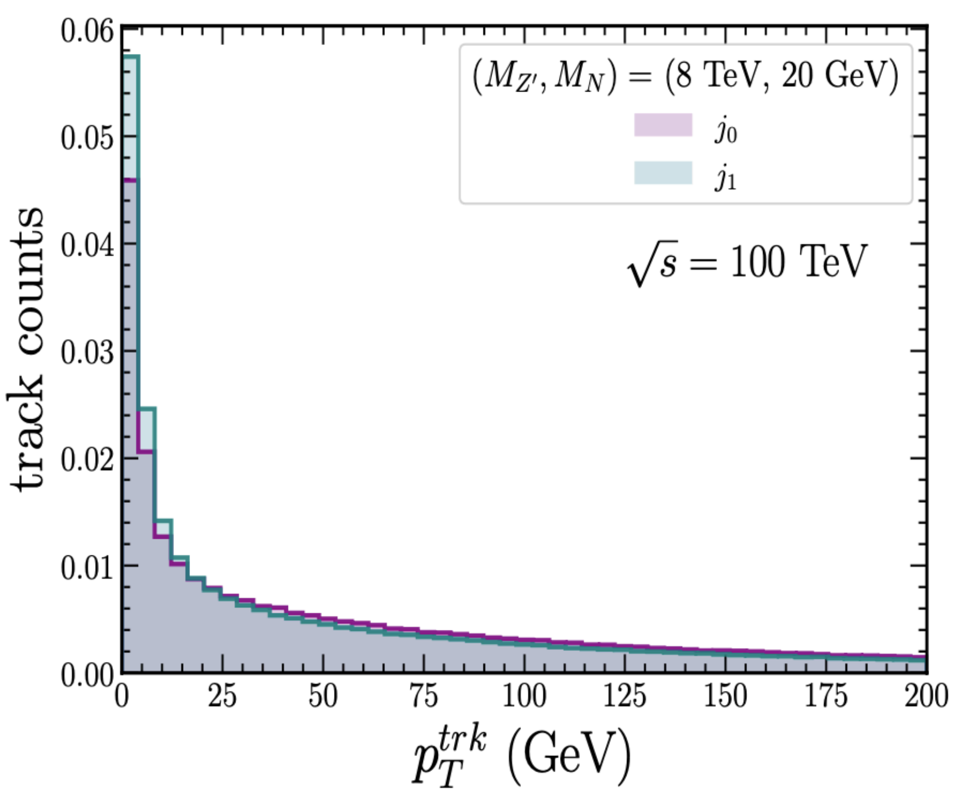
Padhan, Mitra, Kulkarni, Deppisch
arXiv: 2203.06114

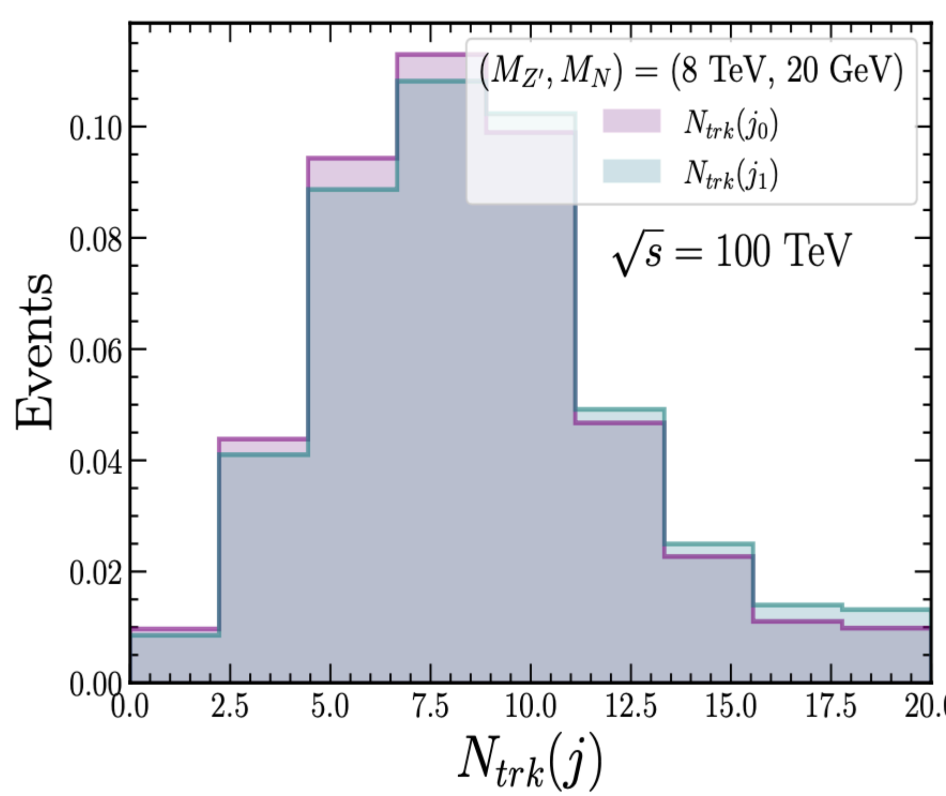
Analysis strategy

Padhan, Mitra, Kulkarni, Deppisch
arXiv: 2203.06114









- Use fatjets in the ID
- Cuts on fatjet $p_T(j_{1,2}), \eta(j_{1,2}), n_{trk}, p_T^{trk}$

- Use tracks in MS
- Cuts on $n_{trk}, p_T^{trk,min}, \sum p_T^{trk}$

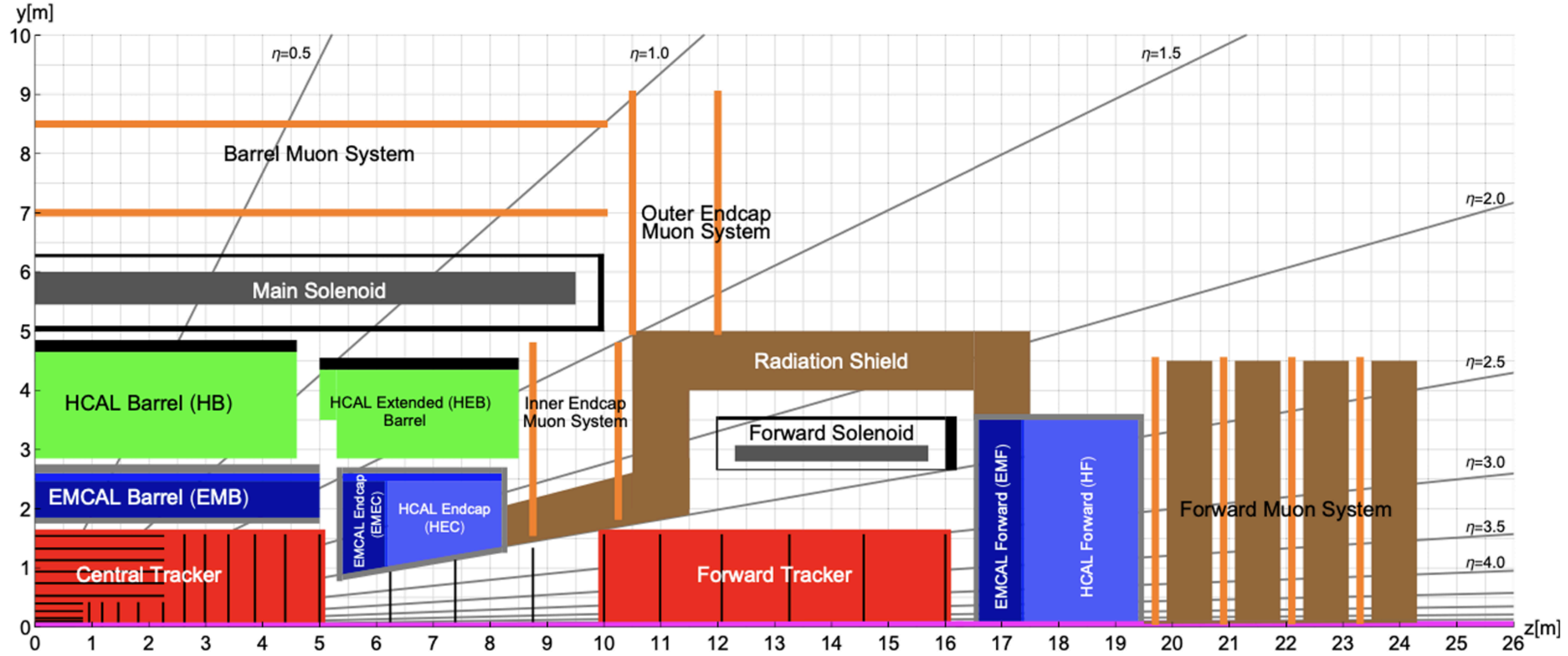
Background reduction strategies

Deppisch, Kulkarni, Liu arXiv:2202.07310

SM Prompt	Background	σ(fb)	M($t\bar{t}$)	N_{B}
Leptonic ($\mu\mu\mu\not{E}_T$)	$\mu^{\pm}\nu Z$	11.9	-	3.55×10^5
Hadronic OS ($\mu^{\pm}\mu^{\mp}jj$)	$t\bar{t}$ (leptonic decay)	1.84	-	5.52×10^4
Hadronic SS ($\mu^{\pm}\mu^{\pm}jj$)	$t\bar{t}$ (leptonic decay)	1.84×10^{-3}	-	55.2
$B-L$ Prompt	Background	σ(fb)	M($t\bar{t}$)	N_{B}
Leptonic ($\mu\mu\mu\mu\not{E}_T$)	ZWW	5.92×10^{-2}	-	1.78×10^3
Hadronic OS ($\mu^{\pm}\mu^{\mp}jjjj$)	$t\bar{t}$ (leptonic decay)	1.85	8.73×10^{-2}	2.62×10^3
Hadronic SS ($\mu^{\pm}\mu^{\pm}jjjj$)	$t\bar{t}$ (leptonic decay)	1.85×10^{-3}	Negligible	Negligible
Displaced Vertex	Background	σ(fb)	M($t\bar{t}$)	N_{B}
Leptonic ($\mu\mu\not{E}_T$)	-	-	-	Negligible
Hadronic (μjj)	-	-	-	Negligible

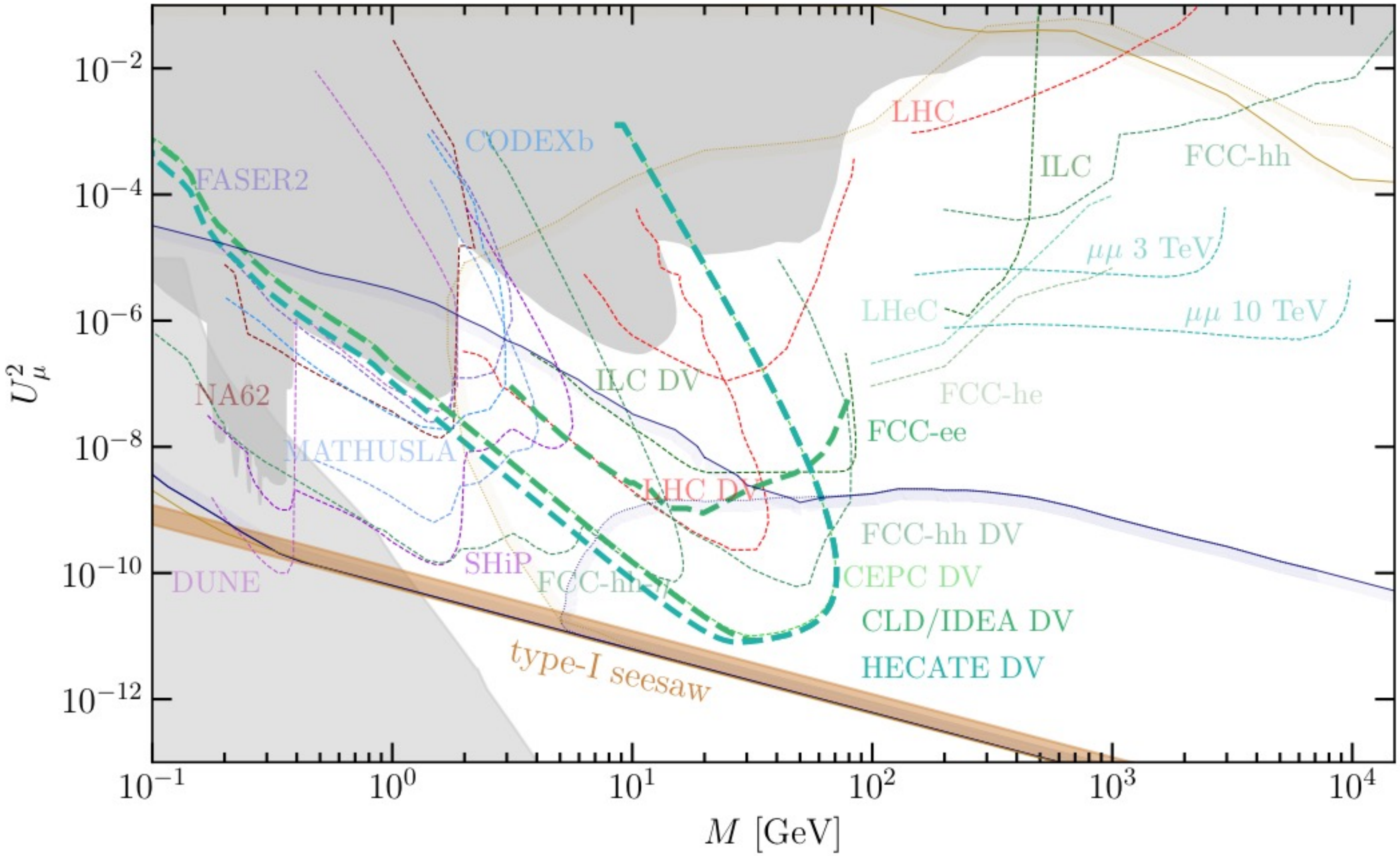
- Prompt final state: backgrounds consist of $t\bar{t}, ZWW, \mu\nu Z$ processes
- Can be controlled either by invariant mass requirement, lepton charge requirements
- Displaced final state: background free analysis

FCC-hh detector



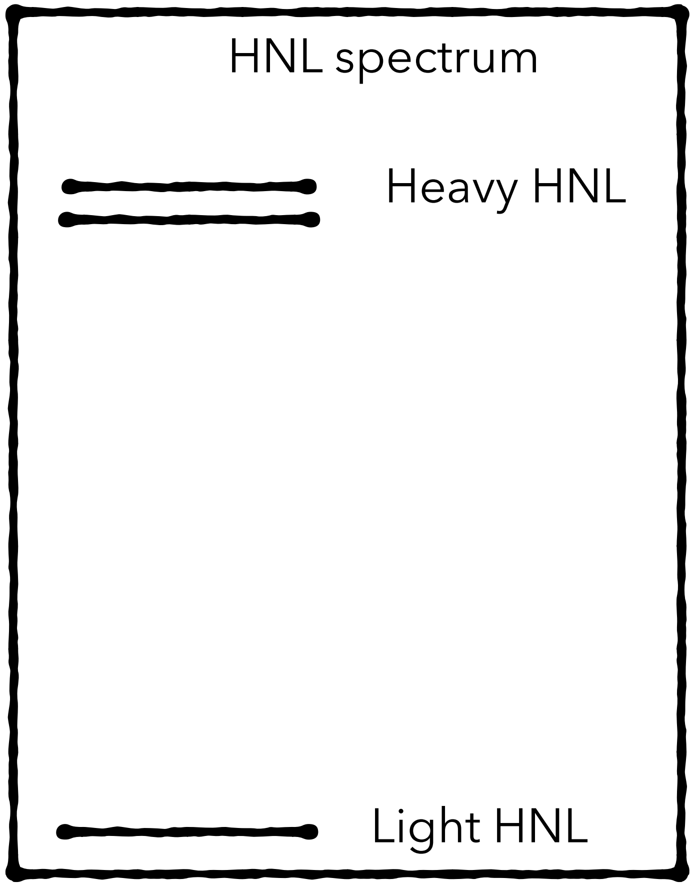
- Inner tracker: $0.025\text{ m} < L_{xy} < 1.55\text{ m}$ and $L_z < 5\text{ m}$,
- Region 2 (calorimeter): $1.7\text{ m} < L_{xy} < 7\text{ m}$ and $L_z < 9\text{ m}$,
- Forward tracker: $2.5 < |\eta| < 4$, $0.025\text{ m} < L_{xy} < 1.55\text{ m}$ and $10\text{ m} < L_z < 16\text{ m}$,
- Forward Region 2 (calorimeter):
  $2.5 < |\eta| < 4$, $0.025\text{ m} < L_{xy} < 4\text{ m}$ and $16.5\text{ m} < L_z < 19.5\text{ m}$.

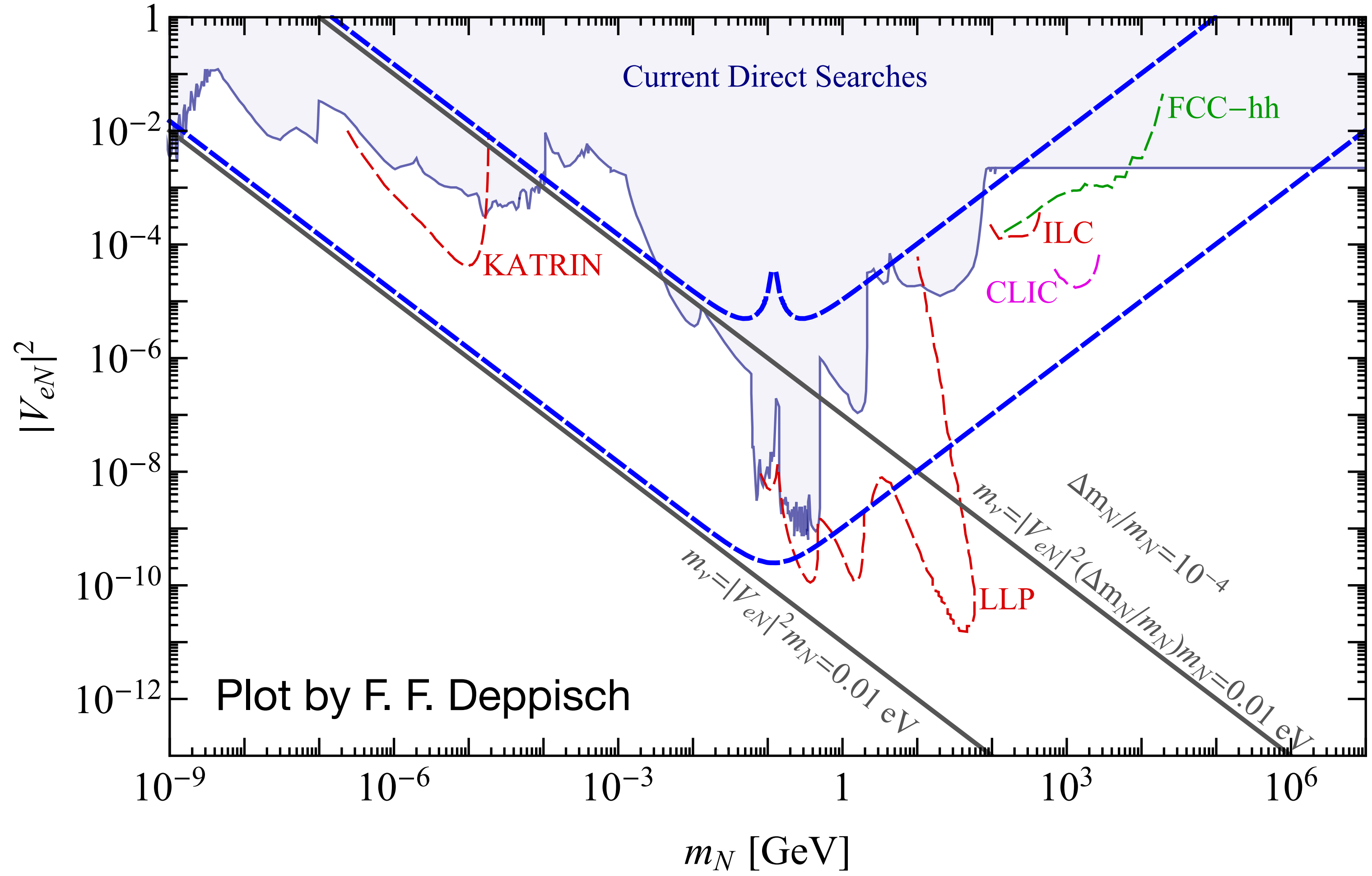
FCC-ee HNL reach



- Phenomenological study, combination of all final states ≥ 2 charged tracks, corresponds to 4 observed events
- 5×10^{12} Z produced, no backgrounds, ideal detector

HNL complementarity with 0nubb





$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

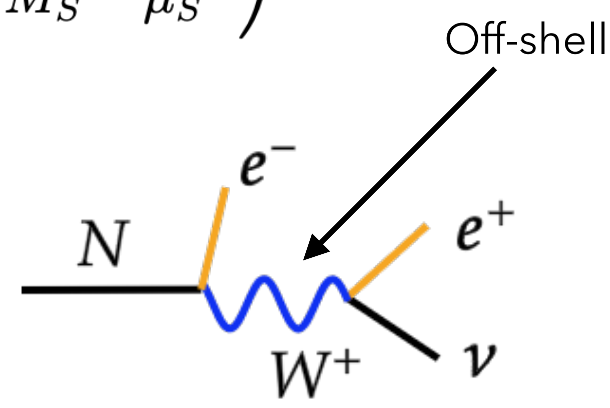
$$m_\nu \approx \frac{m_D^2}{M_R} = |V_{\mu N}|^2 \times m_R$$

$$\mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D & \mathbf{0} \\ M_D^T & \mu_R & M_S^T \\ \mathbf{0} & M_S & \mu_S \end{pmatrix}$$

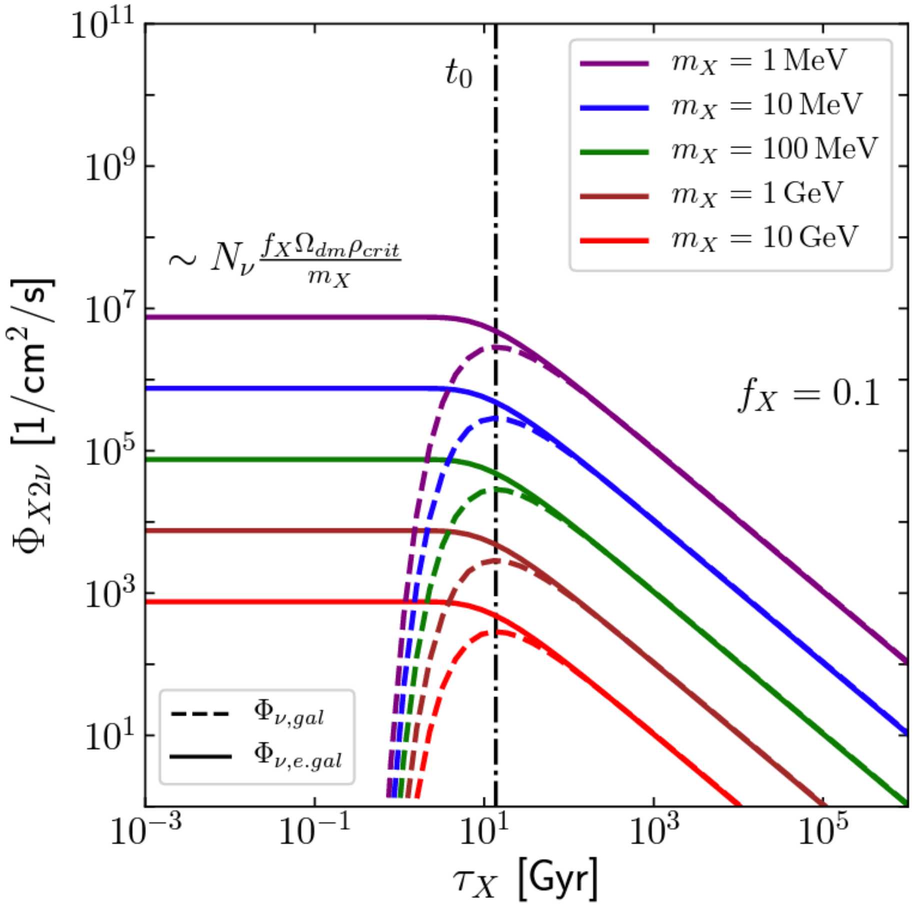
- Heavy neutrino decay width $M_N < m_Z$ (Drewes arXiv:2210.17110)

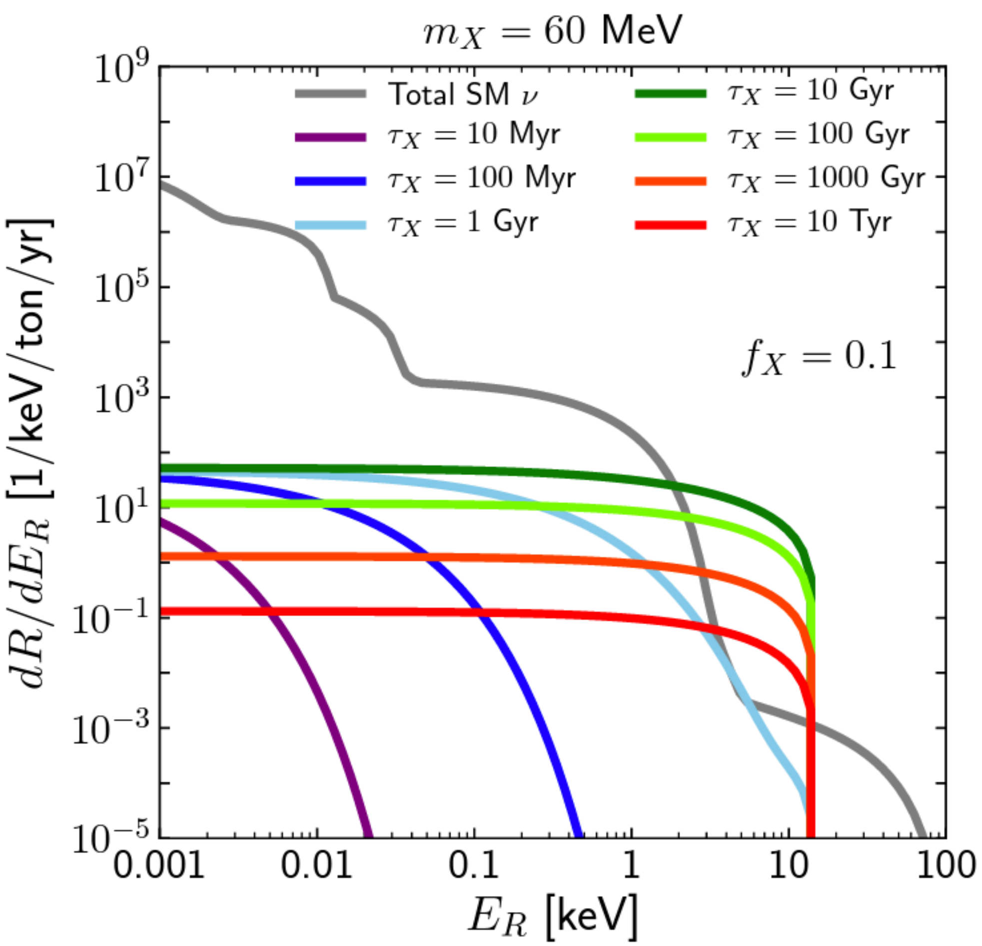
$$\Gamma_N \simeq c_{dec} \frac{a}{96\pi^3} G_F^2 V_{lN}^2 M_N^5$$

($c_{dec} = 1$ (Majorana), 1/2 (Dirac); $a \simeq 12$)



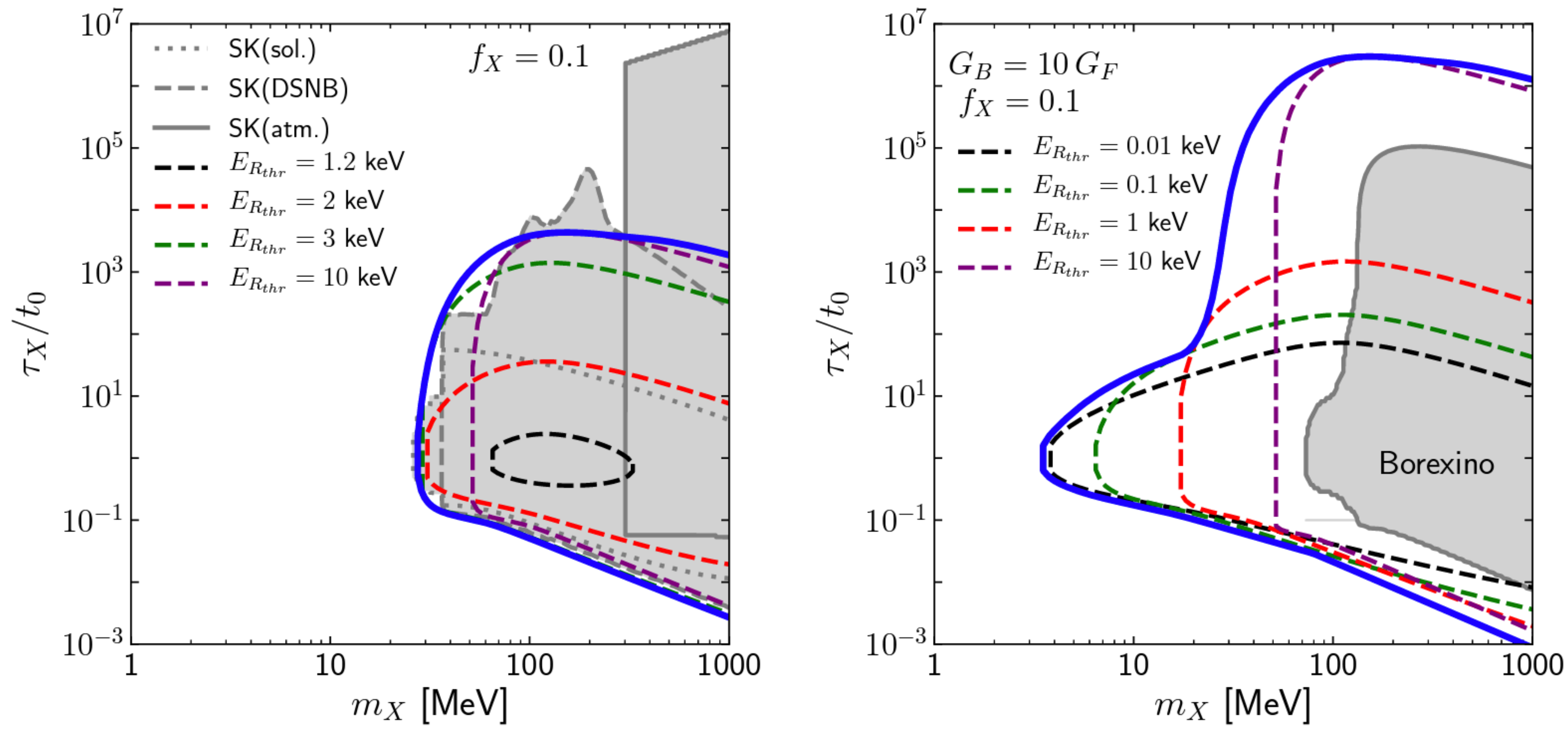
Neutrinos from dark radiation





- Progenitor X decays to $\nu\bar{\nu}$; large progenitor lifetime generates galactic and extragalactic neutrino flux
- Introduction of new neutrino flux with 'higher' energy can introduce recoils at direct detection experiments

Neutrinos from dark radiation



- Left: discovery limits from SM $\nu\bar{\nu}$ final states
- Right: discovery limits from baryonic neutrino final states
- Upshot: for SM neutrino final states, discovery of dark radiation at direct detection experiments is unlikely

Neutrinos at coherent scattering