

Heavy Neutral Leptons from Left to Right

Jonathan Kriewald

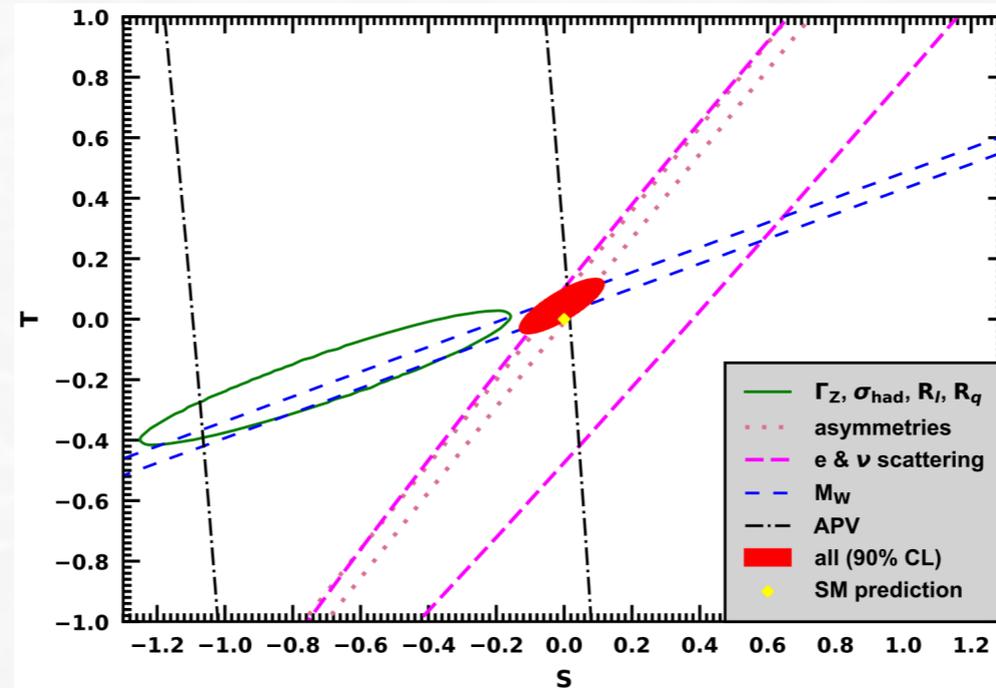
Jožef Stefan Institute

The Standard Model – A success story

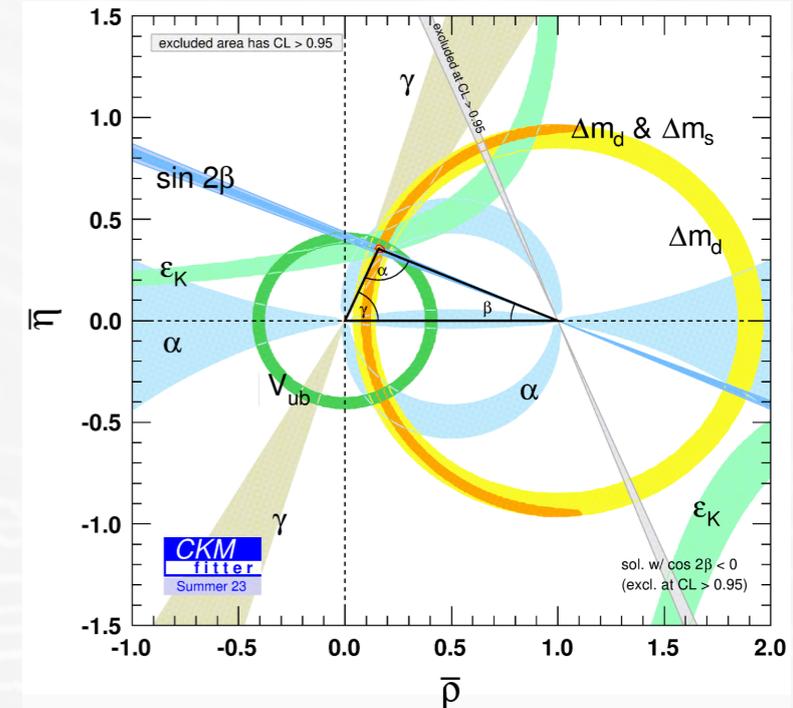
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \sum_i y_{ij} \bar{\psi}_i \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

$$\mathcal{G}_{SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

+ some *accidental* symmetries



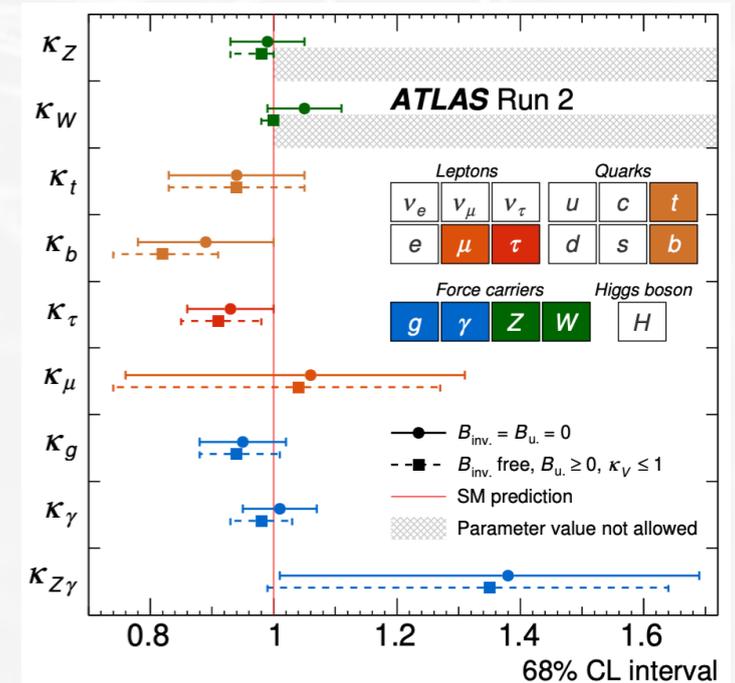
Electroweak fit



CKM paradigm of flavour mixing

Hundreds of experimental measurements overwhelmingly confirm the SM!

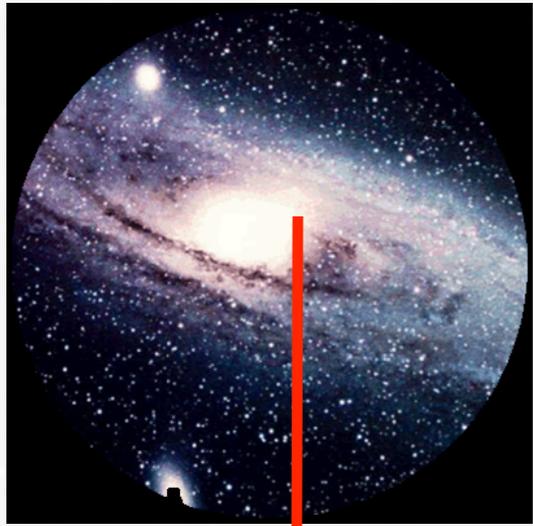
⇒ Just need to completely understand the **Higgs sector** now?



Higgs couplings

Strong arguments in **f(l)avour** of New Physics!

Some remaining puzzles of Nature:

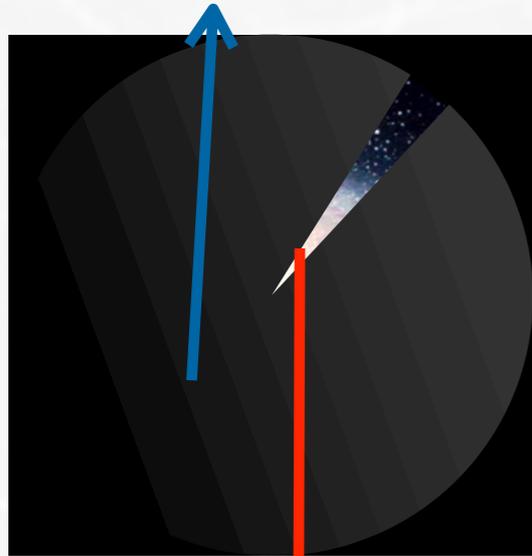


SM matter

Strong arguments in **f(l)avour** of New Physics!

Some remaining puzzles of Nature:

Dark matter

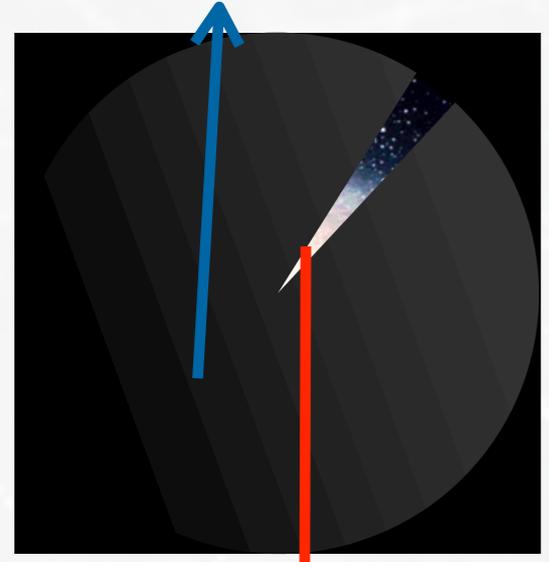


SM matter

Strong arguments in **f(l)avour** of New Physics!

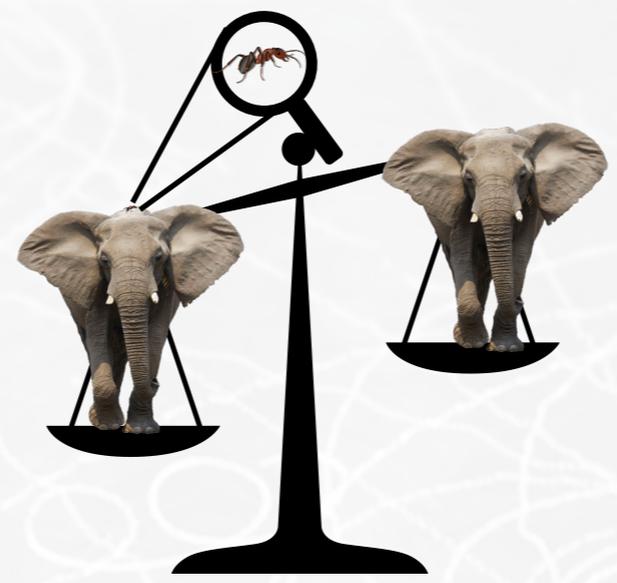
Some remaining puzzles of Nature:

Dark matter



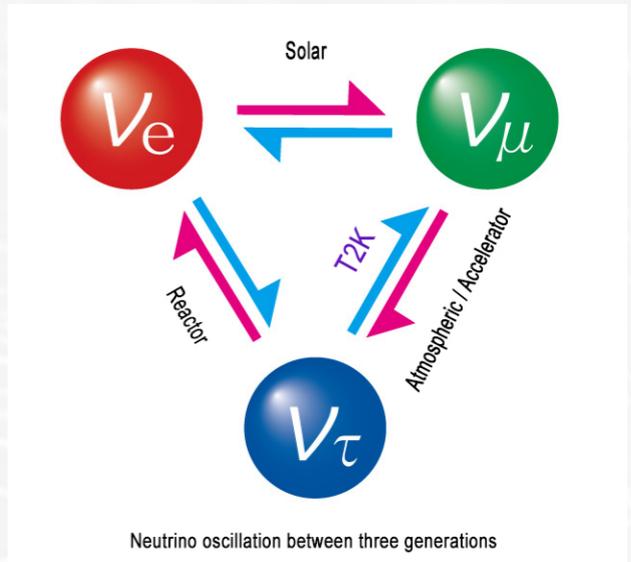
SM matter

Baryon asymmetry of the Universe



$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \mathcal{O}(10^{-10})$$

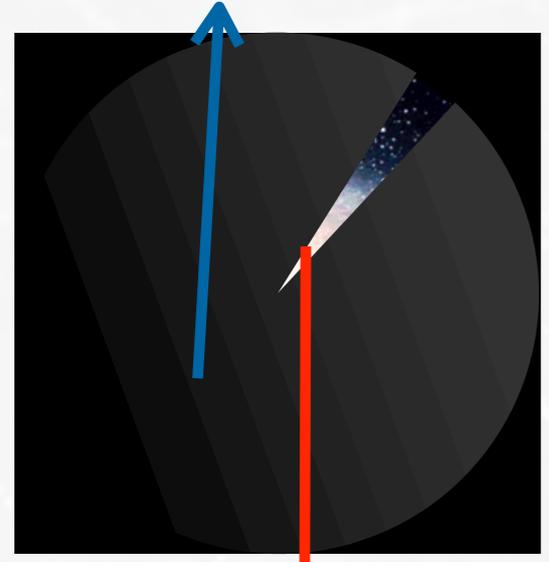
ν -oscillations



Strong arguments in **f(l)avour** of New Physics!

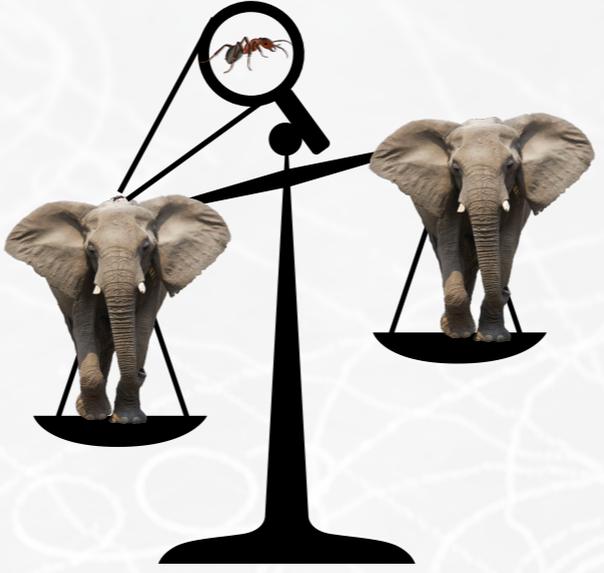
Some remaining puzzles of Nature:

Dark matter



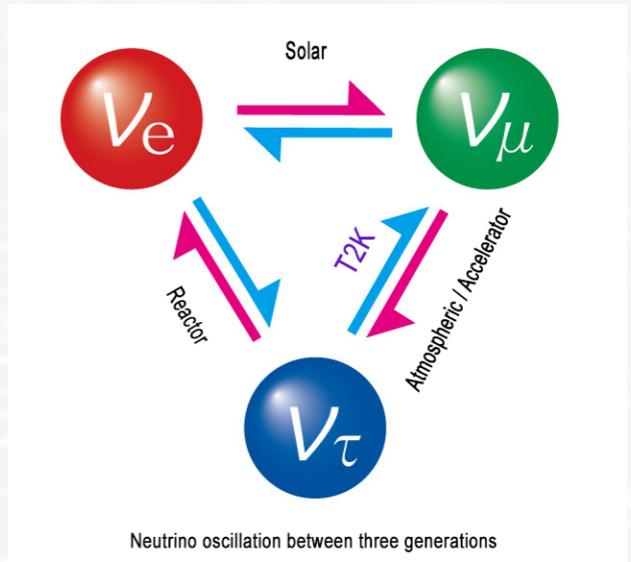
SM matter

Baryon asymmetry of the Universe



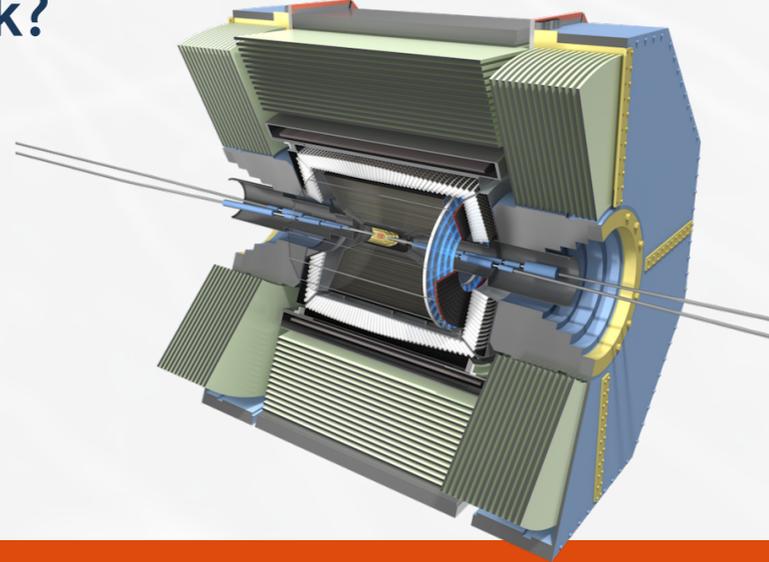
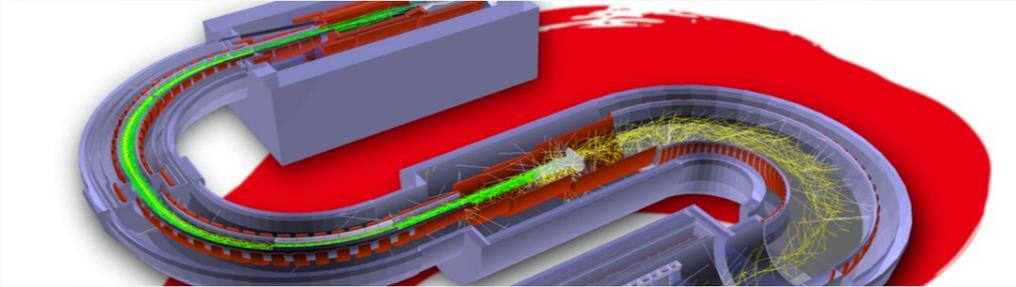
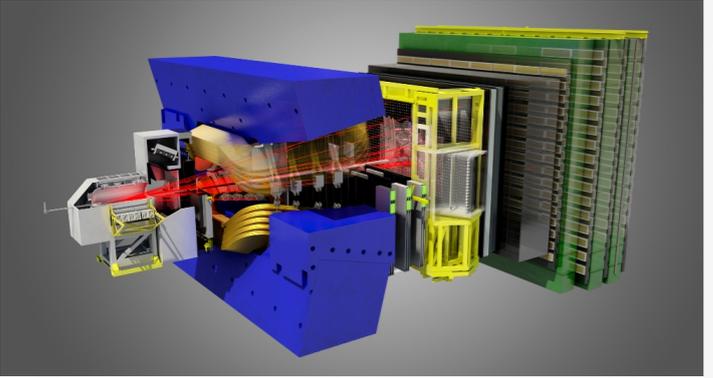
$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \mathcal{O}(10^{-10})$$

ν -oscillations

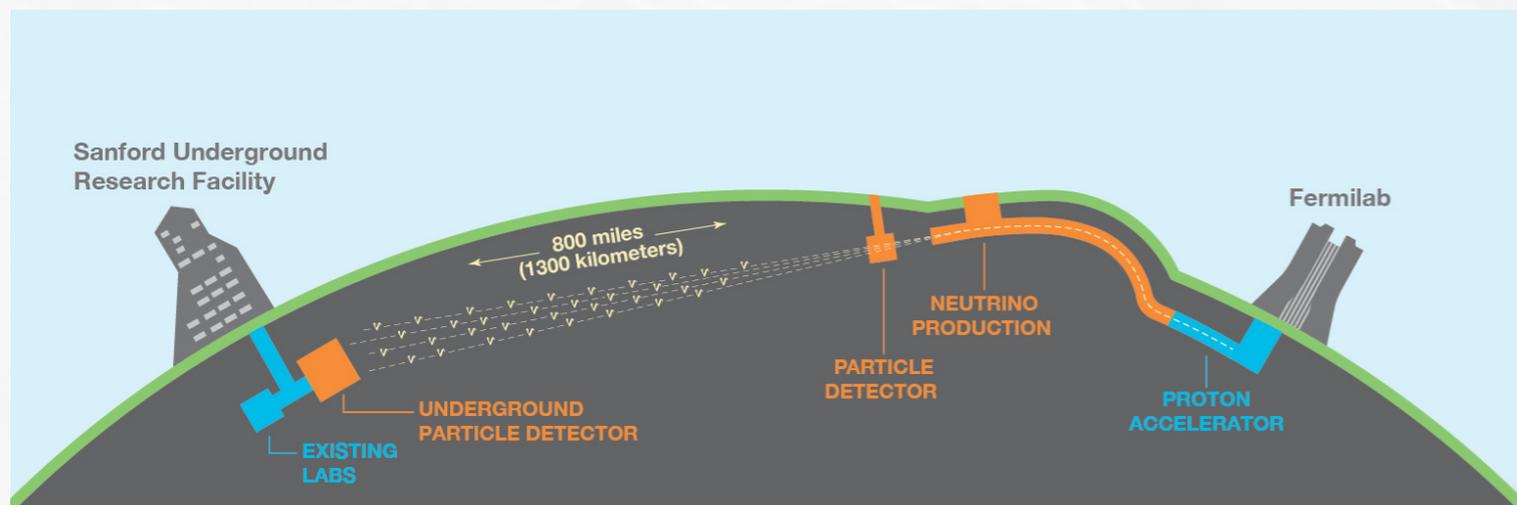


How to unveil the New Physics at work?

⇒ Test SM & its **symmetries**



Strong arguments in **f(l)avour** of New Physics!



ν -oscillations 1st laboratory *evidence* of New Physics!

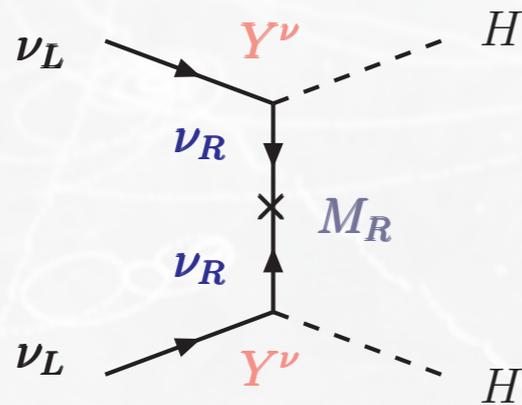
- ▶ New mechanism of mass generation? **Majorana fields?**
- ▶ New sources of **CP violation?**
- ▶ Neutral **lepton flavour violation** \Rightarrow **charged LFV?**

Several experimental puzzles remain:

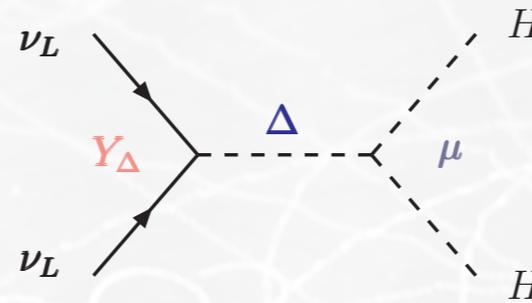
- ▶ Absolute **mass scale?**
- ▶ Mass ordering? (NO vs IO)
- ▶ Leptonic **CP violation?**

Making Majorana neutrinos

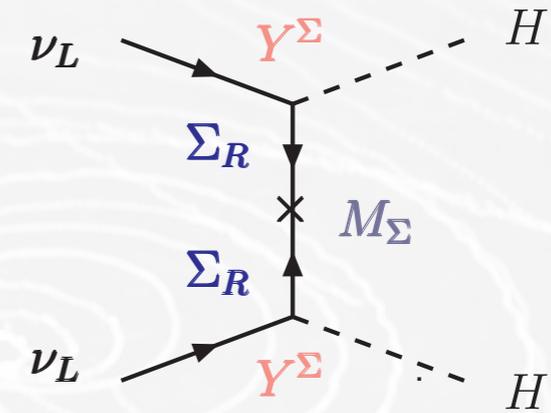
Effective mass term $\mathcal{L}_{\text{eff}} \sim \frac{m_{LL}}{2} \bar{\nu}_L \nu_L^C$ from Weinberg operator: $\mathcal{L}^{d=5} \sim \frac{h_{ij}}{2\Lambda} (H L_i H L_j)$



Type I (fermion singlet)
(Minkowski '77)



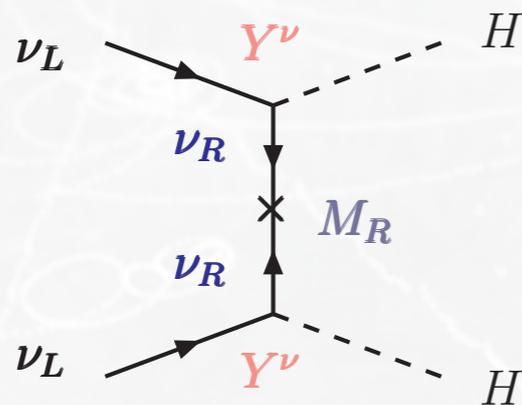
Type II (scalar triplet)
(e.g. Schechter & Valle '80)



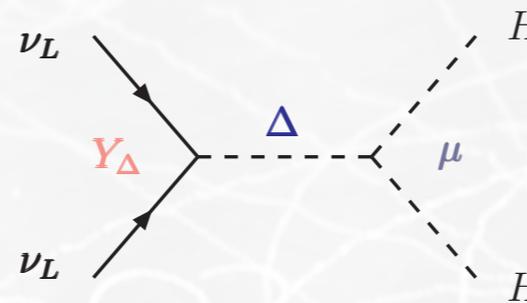
Type III (fermion triplet)
(e.g. Foot et al. '89)

Making Majorana neutrinos

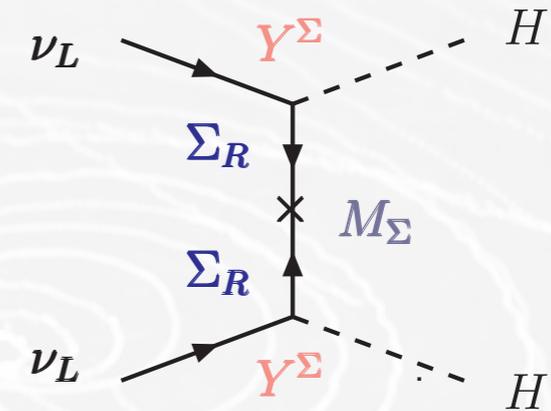
Effective mass term $\mathcal{L}_{\text{eff}} \sim \frac{m_{LL}}{2} \bar{\nu}_L \nu_L^C$ from Weinberg operator: $\mathcal{L}^{d=5} \sim \frac{h_{ij}}{2\Lambda} (H L_i H L_j)$



Type I (fermion singlet)
(Minkowski '77)



Type II (scalar triplet)
(e.g. Schechter & Valle '80)



Type III (fermion triplet)
(e.g. Foot et al. '89)

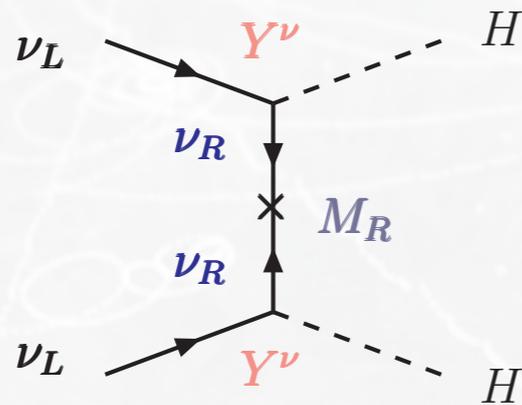
Mass terms: $m_\nu^I \sim -v^2 Y_\nu^T \frac{1}{M_R} Y_\nu,$

$m_\nu^{II} \sim -v^2 Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} \sim -Y_\Delta v_\Delta,$

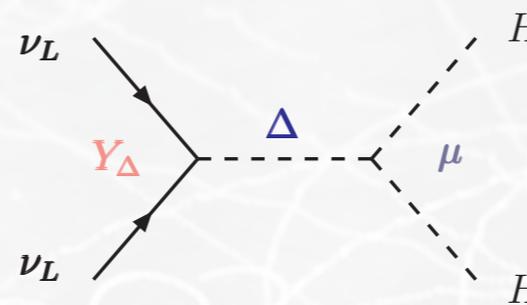
$m_\nu^{III} \sim -Y_\Sigma^T \frac{v^2}{2M_\Sigma} Y_\Sigma$

Making Majorana neutrinos

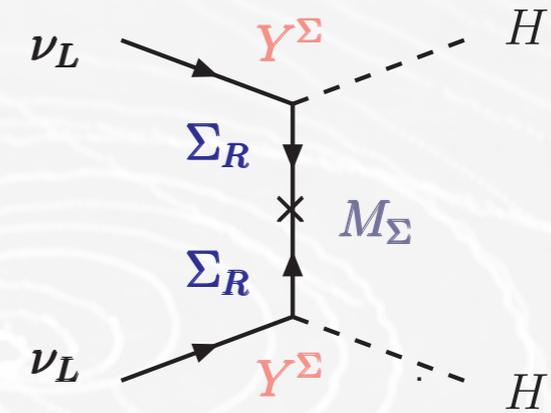
Effective mass term $\mathcal{L}_{\text{eff}} \sim \frac{m_{LL}}{2} \bar{\nu}_L \nu_L^C$ from Weinberg operator: $\mathcal{L}^{d=5} \sim \frac{h_{ij}}{2\Lambda} (H L_i H L_j)$



Type I (fermion singlet)
(Minkowski '77)



Type II (scalar triplet)
(e.g. Schechter & Valle '80)



Type III (fermion triplet)
(e.g. Foot et al. '89)

Mass terms: $m_\nu^I \sim -v^2 Y_\nu^T \frac{1}{M_R} Y_\nu,$

$m_\nu^{II} \sim -v^2 Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} \sim -Y_\Delta v_\Delta,$

$m_\nu^{III} \sim -Y_\Sigma^T \frac{v^2}{2M_\Sigma} Y_\Sigma$

Type I seesaw: M_R ad-hoc

Left-Right Symmetry: combination of **type I** & **type II**, M_R spontaneously generated

Introducing Left-Right: Motivation

Features:

Mohapatra, Senjanović '75

- ▶ Combination of **type I** & **type II** seesaw mechanism, new states $\sim \mathcal{O}(\text{TeV})$
- ▶ Can address the **strong CP problem** (see e.g. [[2107.10852](#)])
- ▶ Lightest right-handed neutrino can be a **Dark Matter candidate** [[2312.00129](#)]
- ▶ Low(ish)-scale **leptogenesis** can be implemented [[C. Hati et al. '18](#)]
- ▶ Left-right symmetry $\mathcal{G}_{\text{LR}} = SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

appears in the breaking of **GUTs**, e.g.:

$$SO(10) \rightarrow SU(4)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \rightarrow \mathcal{G}_{\text{LR}} \rightarrow \mathcal{G}_{\text{SM}}$$

Introducing Left-Right: Model overview

SM Gauge group is extended: $\mathcal{G}_{LR} = SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

Right-handed SM fermion singlets are promoted to $SU(2)_R$ -doublets

⇒ **Add RH neutrinos**, $U(1)_{B-L}$ -anomalies automatically cancelled

Physical spectrum: $SM + N_R, W_R^\pm, Z_R, \Delta_{R,L}^{\pm\pm}, \Delta_L^+, \Delta_L^0, \chi_L^0, \Delta_R^0, A^0, H^0, H^\pm$

Introducing Left-Right: Model overview

SM Gauge group is extended: $\mathcal{G}_{LR} = SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

Right-handed SM fermion singlets are promoted to $SU(2)_R$ -doublets

\Rightarrow **Add RH neutrinos**, $U(1)_{B-L}$ -anomalies automatically cancelled

Physical spectrum: **SM** + N_R , W_R^\pm , Z_R , $\Delta_{R,L}^{\pm\pm}$, Δ_L^+ , Δ_L^0 , χ_L^0 , Δ_R^0 , A^0 , H^0 , H^\pm

Heavy Scalars: A^0 , H^0 , H^\pm ($\gtrsim 20$ TeV), mediate FCNC's

Light Scalars: $\Delta_{R,L}^{\pm\pm}$, Δ_L^+ , Δ_L^0 , χ_L^0 , Δ_R^0 ($\sim \Lambda_{EW} - \mathcal{O}(\text{TeV})$)

Field content: $\mathcal{G}_{LR} = SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

Gauge Fields: $SU(2)_{L,R}$ -gauge fields, $A_{L,R} = A_{L,R}^a \frac{\sigma^a}{2}$, $A_{L,R}^\pm = \frac{A_{L,R}^1 \mp iA_{L,R}^2}{\sqrt{2}}$ $U(1)_{B-L}$ -gauge field B
+ QCD

Fermions: $Q_{L,R} = \begin{pmatrix} u \\ d \end{pmatrix}_{L,R}$, $L_{L,R} = \begin{pmatrix} \nu \\ \ell \end{pmatrix}$ (3 generations) $\nu_R / N_R = \text{HNLs!}$

Scalar Fields: $SU(2)_{L,R}$ triplets, $\Delta_{L,R} = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$, $(1,3,1,2)_L$ & $(1,1,3,2)_R$
Can be light(ish)

Heavy
 $SU(2)_{L,R}$ bi-doublet, $\phi = \begin{pmatrix} \phi_1^{0*} & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$, $(1, 2, 2, 0)$

Electrical charge: $Q = T_L^3 + T_R^3 + \frac{B-L}{2}$

Making Neutrino Masses

Majorana Mass from $SU(2)_R$ breaking

Discrete \mathcal{C} -symmetry:

$$\mathcal{C} : \phi \leftrightarrow \phi^T, \Delta_L \leftrightarrow \Delta_R^*$$

$$\mathcal{L}_Y^{\ell} \supseteq \bar{L}'_L (Y_{\ell} \phi + \tilde{Y}_{\ell} \tilde{\phi}) L'_R + \bar{L}'_L{}^c i \sigma_2 \Delta_L Y_L^M L'_L + L'_R{}^c i \sigma_2 \Delta_R Y_R^M L'_R$$

$$\Rightarrow Y_{\ell} = Y_{\ell}^T, \tilde{Y}_{\ell} = \tilde{Y}_{\ell}^T, Y_L^M = Y_R^M, M_D = M_D^T, M_L = \frac{v_L}{v_R} M_R$$

Majorana Mass terms

From the light and heavy masses

$$M_{\nu} \simeq M_L - M_D M_R^{-1} M_D^T, \quad M_N \simeq M_R$$

All Yukawas **fully determined** by measurable inputs

$$(m_{\nu_i}, m_{N_i}, \mathcal{U}_L, \mathcal{U}_R)$$

$$M_D = M_N \sqrt{\frac{v_L}{v_R} \mathbb{1} - M_N^{-1} M_{\nu}}$$

Nemevšek, Senjanović, Tello PRL'13

JK, Nemevšek, Nesti EPJC'24

Analytical matrix square-root

$$\sqrt{A} = c_0 \mathbb{1} + c_1 A + c_2 A.A$$

c_i are functions of invariants of A

Making Neutrino Masses

Majorana Mass from $SU(2)_R$ breaking

Discrete \mathcal{C} -symmetry:

$$\mathcal{C} : \phi \leftrightarrow \phi^T, \Delta_L \leftrightarrow \Delta_R^*$$

$$\mathcal{L}_Y^\ell \supseteq \bar{L}'_L (Y_\ell \phi + \tilde{Y}_\ell \tilde{\phi}) L'_R + \bar{L}'_L{}^c i\sigma_2 \Delta_L Y_L^M L'_L + L'_R{}^c i\sigma_2 \Delta_R Y_R^M L'_R$$

$$\Rightarrow Y_\ell = Y_\ell^T, \tilde{Y}_\ell = \tilde{Y}_\ell^T, Y_L^M = Y_R^M, M_D = M_D^T, M_L = \frac{v_L}{v_R} M_R$$

Majorana Mass terms

From the light

**(Heavy) Neutrino masses are
spontaneously generated!**

$$M_N \simeq M_R$$

All Yukawas

measurable inputs

$$(m_{\nu_i}, m_{N_i}, \mathcal{U}_L, \mathcal{U}_R)$$

Nemevšek, Senjanović, Tello PRL'13

JK, Nemevšek, Nesti EPJC'24

Analytical matrix square-root

$$\sqrt{A} = c_0 \mathbb{1} + c_1 A + c_2 A.A$$

c_i are functions of invariants of A

Left-Right HNLs vs type I HNLs

Interactions with SM

LRSM

HNL mixing:

$$U_{\alpha i} \simeq \sqrt{m_\nu / m_N} \text{ (tiny)}$$

W – ℓN vertex:

$$\text{Via } W_L - W_R \text{ mixing: } \simeq \sin \beta \times M_W / M_{W_R}$$

Z – NN vertex:

$$\text{Via } Z_L - Z_R \text{ mixing: } \simeq M_Z / M_{Z_R}$$

h – NN vertex:

$$\begin{aligned} \text{Via } h - \Delta_R \text{ mixing: } &\simeq \sin \theta \lesssim 0.1 - 0.2 \\ &\times Y_\Delta \simeq m_N / v_R \end{aligned}$$

Type I

$$U_{\alpha i} \simeq v_{EW} Y_D / m_N \text{ (can be sizeable)}$$

$$\text{Via HNL mixing } \simeq U_{\alpha i}$$

$$\begin{aligned} \text{Via HNL mixing } &\simeq U_{\alpha i}^2, Z - N\nu \text{ dominates!} \\ &\simeq U_{\alpha i} \end{aligned}$$

$$\begin{aligned} \text{Via HNL mixing } &\simeq U_{\alpha i}^2, h - N\nu \text{ dominates!} \\ &\simeq U_{\alpha i} \end{aligned}$$

Low-scale type I seesaw

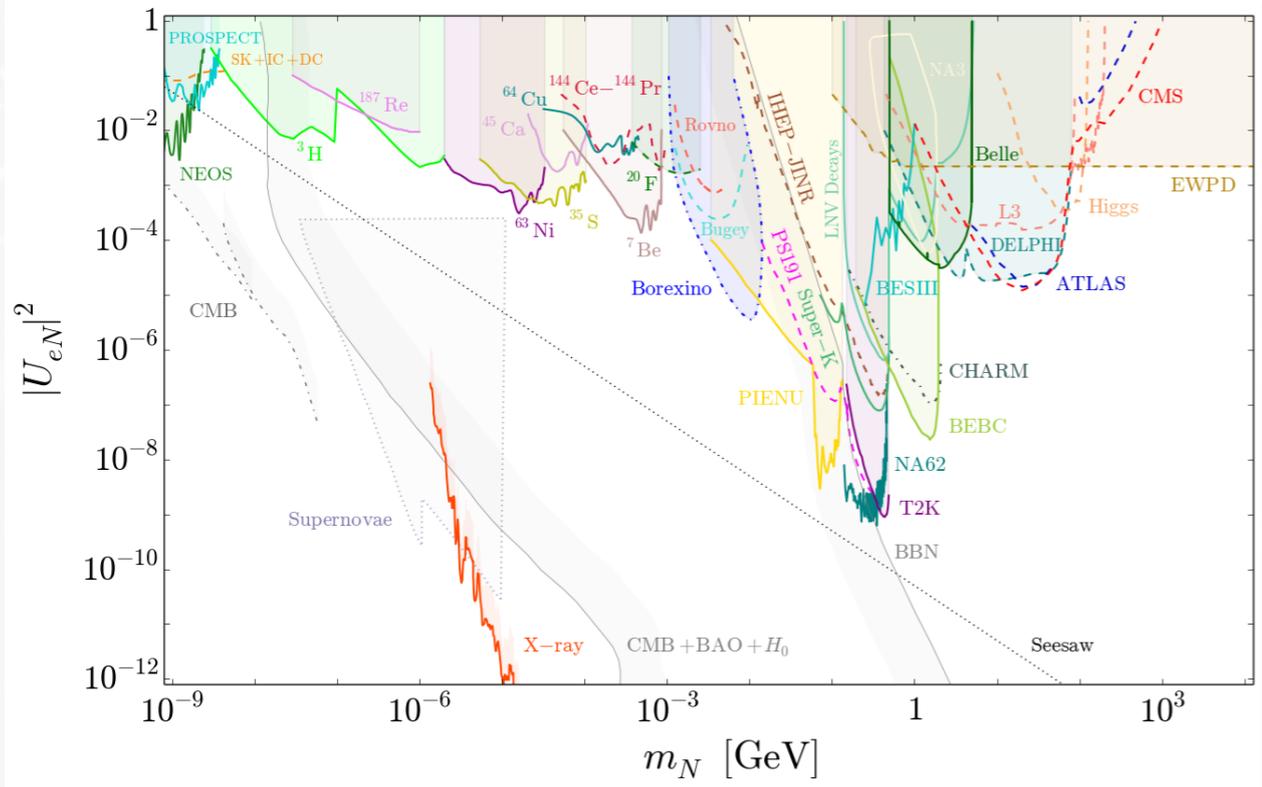
Extend SM with 3 “heavy” RH Majorana neutrinos: $\text{MeV} \lesssim m_{N_i} \lesssim 1 - 100\text{TeV}$

Masses and mixings: $m_\nu \simeq -v^2 Y_\nu^T M_N^{-1} Y_\nu$, $U^T \mathcal{M}_\nu^{6 \times 6} U = \text{diag}(m_i)$

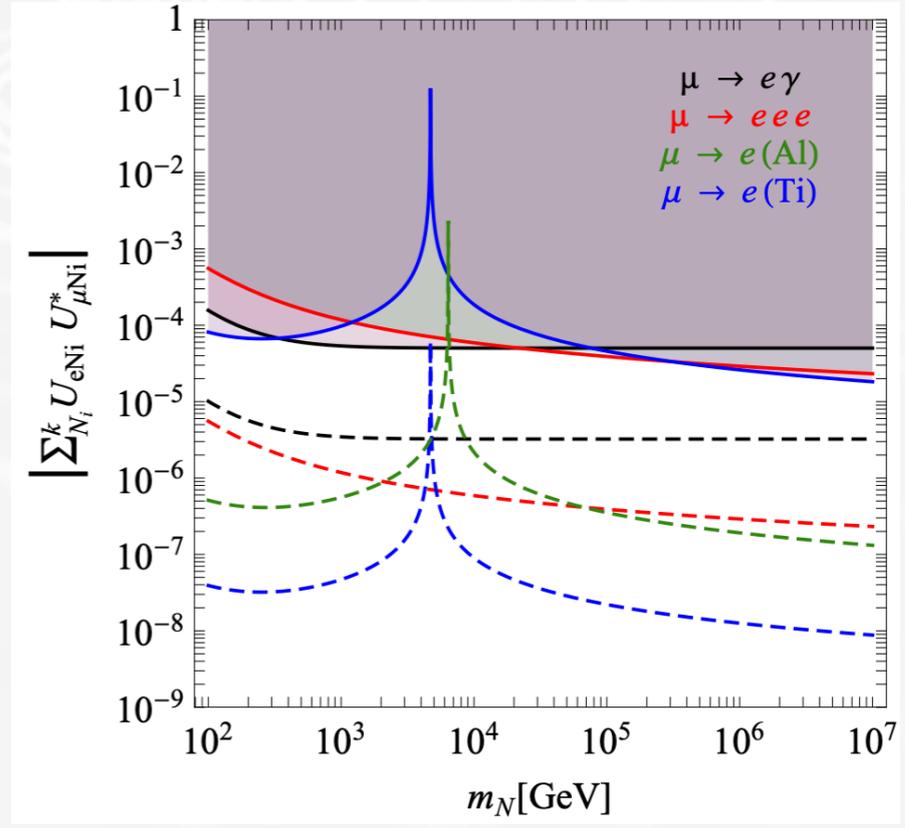
$$U = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix}, \quad U_{\nu\nu} \simeq (1 - \eta) U_{\text{PMNS}}$$

Heavy states not decoupled \Rightarrow neutral and charged lepton currents modified

\Rightarrow very rich phenomenology: colliders, cLFV, LNV, ...



<https://www.hep.ucl.ac.uk/~pbolton/plots.html>



Left-Right HNLs vs type I HNLs

Collider production

LRSM

Single HNL production:

Mainly via **KS-process** $pp \rightarrow W_R \rightarrow \ell N$

(Otherwise heavily suppressed)

Double HNL production:

via **Z_R -decay** $pp \rightarrow Z_R \rightarrow NN$

(Suppressed at LHC, $M_{Z_R} \gtrsim 10$ TeV)

via **Higgs-decay** $pp \rightarrow h + X, h \rightarrow NN$

via **Δ_R -decay** $pp \rightarrow \Delta_R + X, \Delta_R \rightarrow NN$

Type I

Mainly via **EW-boson decays**

$W \rightarrow \ell N, Z \rightarrow N\nu, h \rightarrow N\nu$

off-shell $W^* \rightarrow \ell N, Z^* \rightarrow N\nu$

**Doubly mixing suppressed,
single production dominates**

Left-Right HNLs vs type I HNLs

Decays & final states

LRSM

Decay modes:

Mainly **semi-leptonic** $N \rightarrow \ell W_R^* \rightarrow \ell q \bar{q}'$

(Purely Leptonic decays heavily suppressed)

Same-sign lepton signatures possible \Rightarrow **LNV!**

Lifetime:

$$N \text{ lifetime} \approx \mathcal{O}(1\text{mm}) \frac{(m_{W_R}/3 \text{ TeV})^4}{(m_N/10 \text{ GeV})^5}$$

\Rightarrow expect displacements for heavy W_R !

heavy $W_R \Rightarrow$ reduce single HNL production,
pair-production via scalar mildly affected

Type I

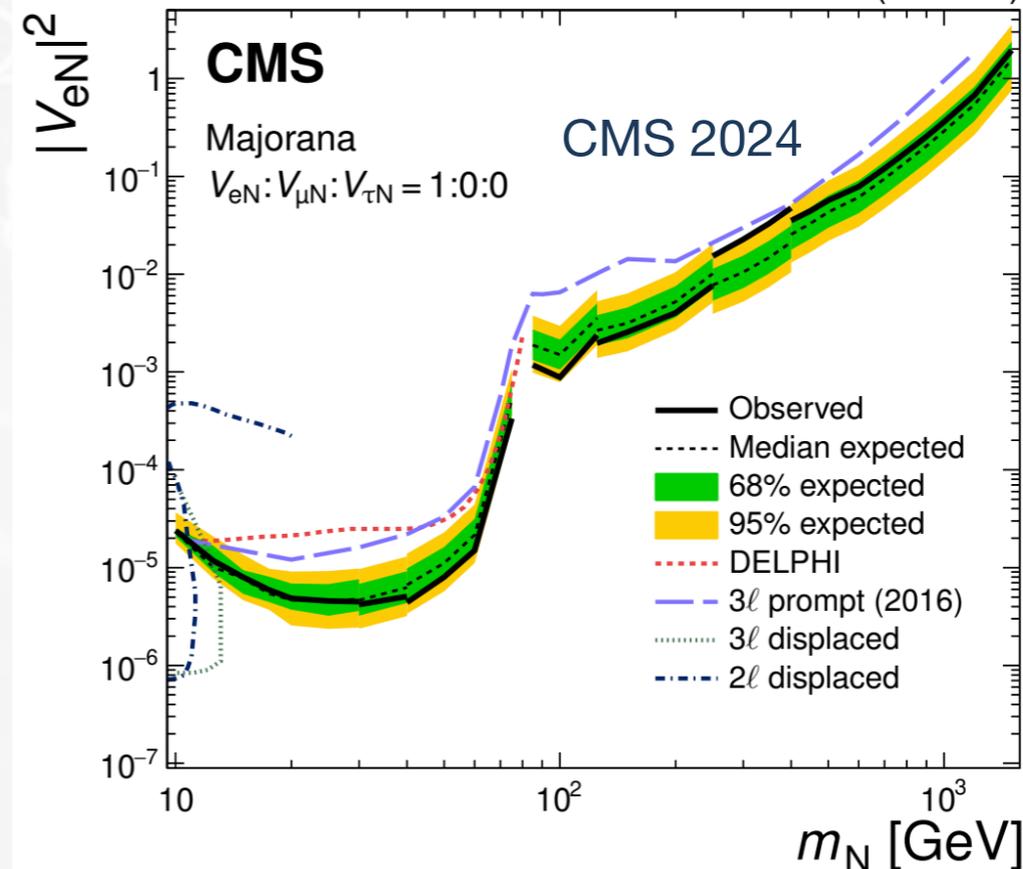
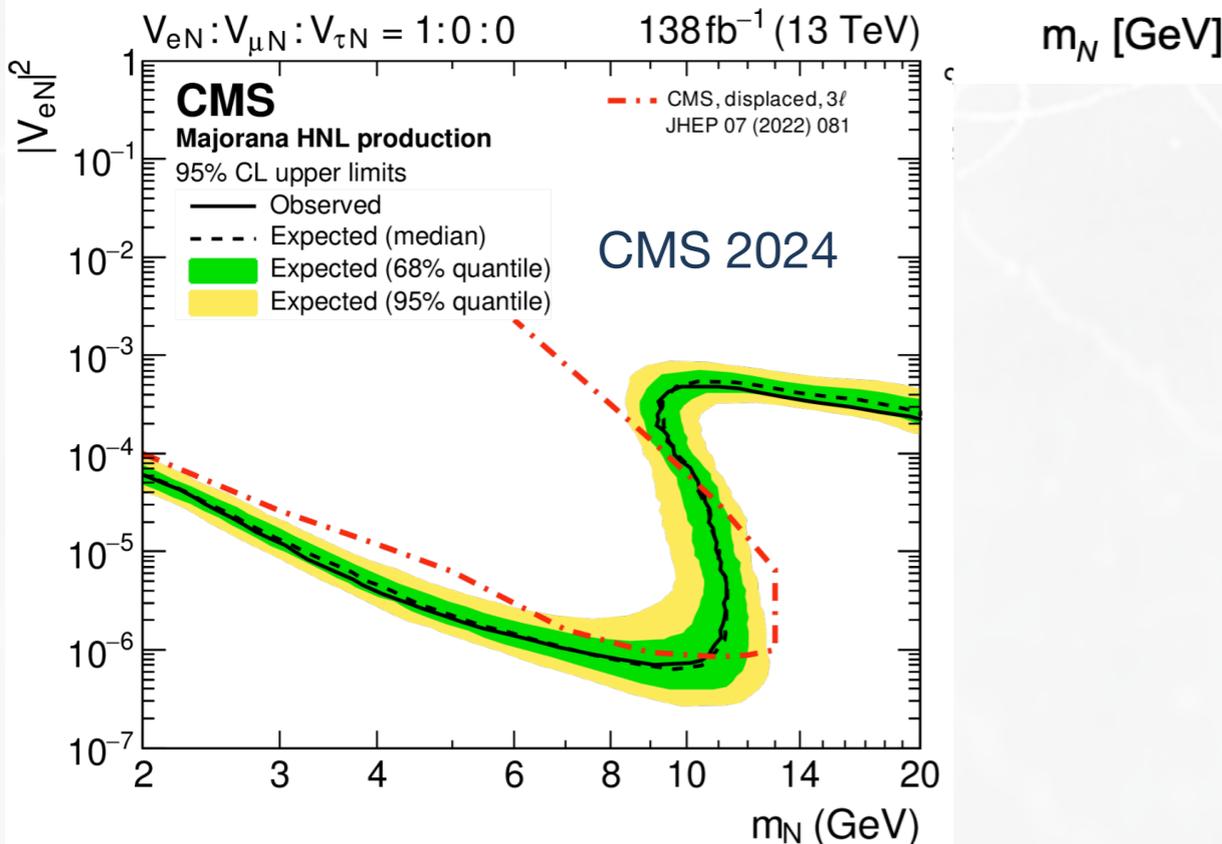
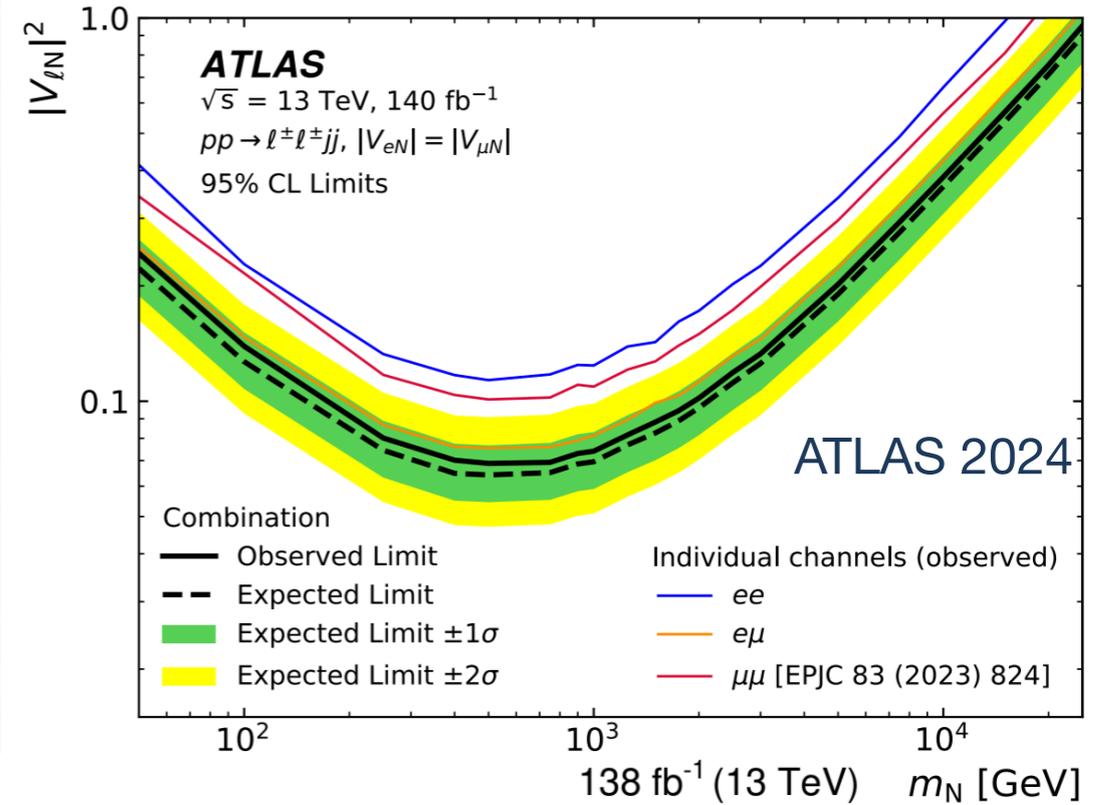
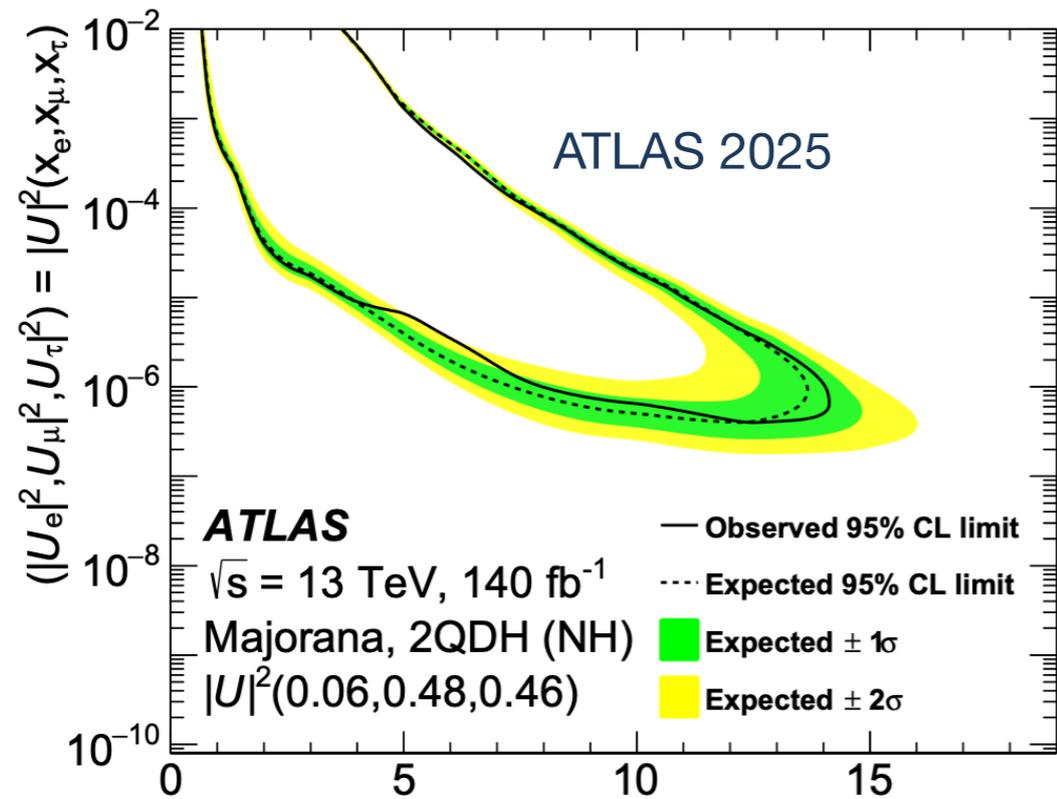
Via W : $N \rightarrow \ell W^{(*)} \rightarrow \ell q \bar{q}', \ell \ell \nu$

Via Z : $N \rightarrow \nu Z^{(*)} \rightarrow \nu q \bar{q}, \nu \ell \ell$

$$N \text{ lifetime} \approx \mathcal{O}(1\text{mm}) \frac{(|U_{\ell N}|/0.001)^2}{(m_N/10 \text{ GeV})^5}$$

\Rightarrow expect displacements for small mixing!

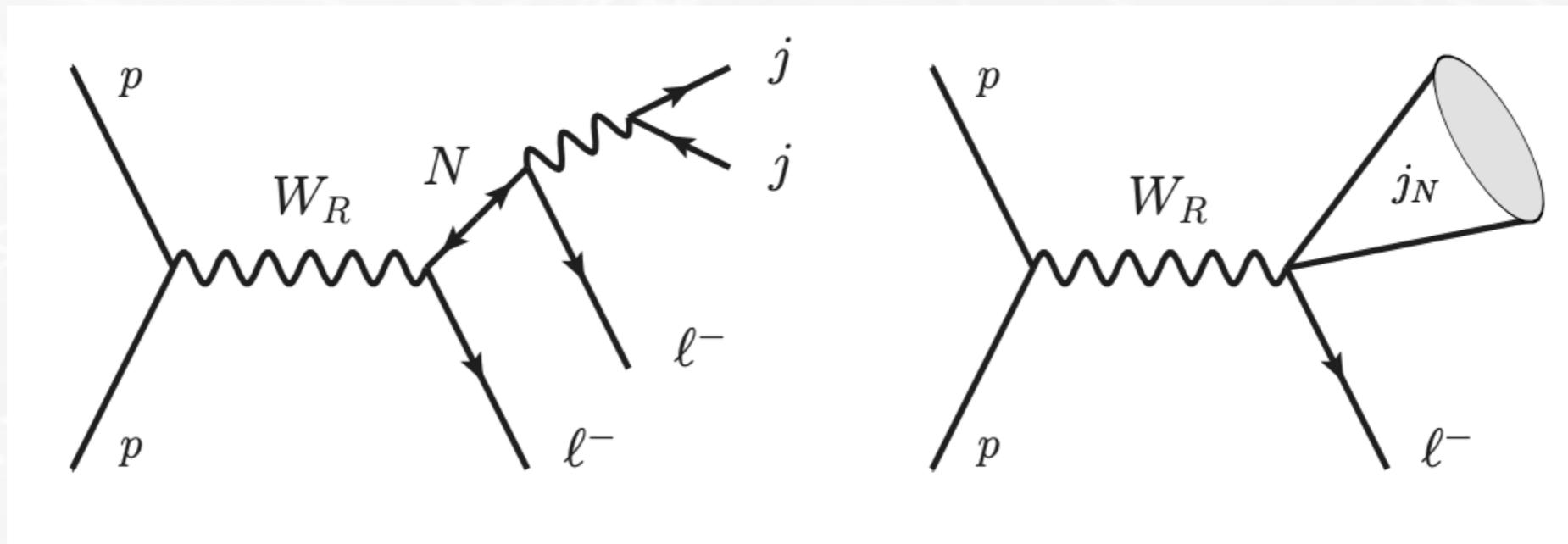
Small mixing \Rightarrow small HNL production



LVN at LHC in Left-Right: Keung Senjanović process

Production and decay of N via W_R

Keung, Senjanović PRL'83



$$N \text{ lifetime} \approx 2.5\text{mm} \frac{(m_{W_R}/3 \text{ TeV})^4}{(m_N/10 \text{ GeV})^5}$$

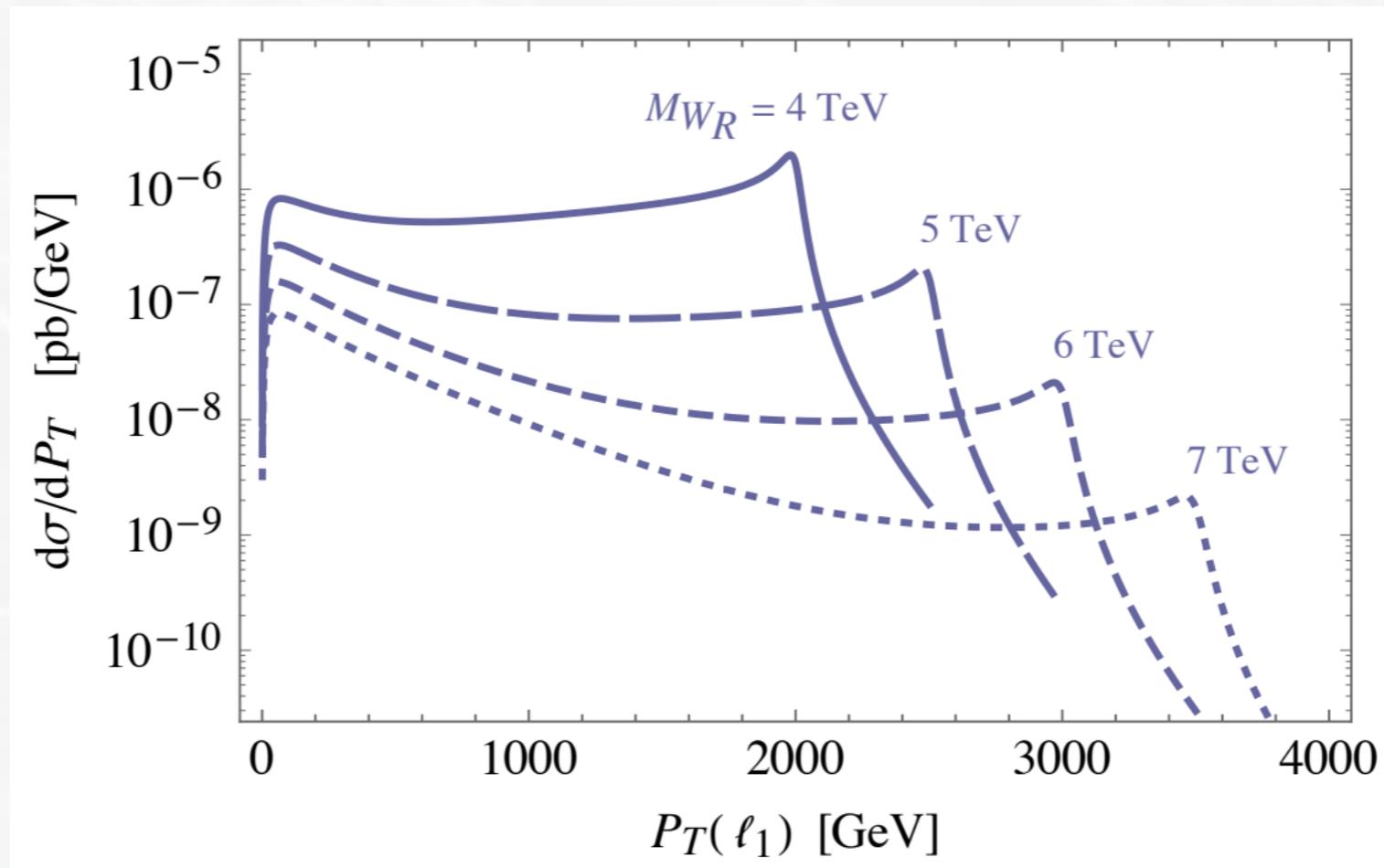
Signature:

- ▶ Same-sign di-leptons + jets, 1 very high- p_T lepton
- ▶ If N light \Rightarrow displaced/merged signatures

LVN at LHC in Left-Right: Keung Senjanović process

Production and decay of N via W_R

Nemevšek, Nesti, Popara PRD'18



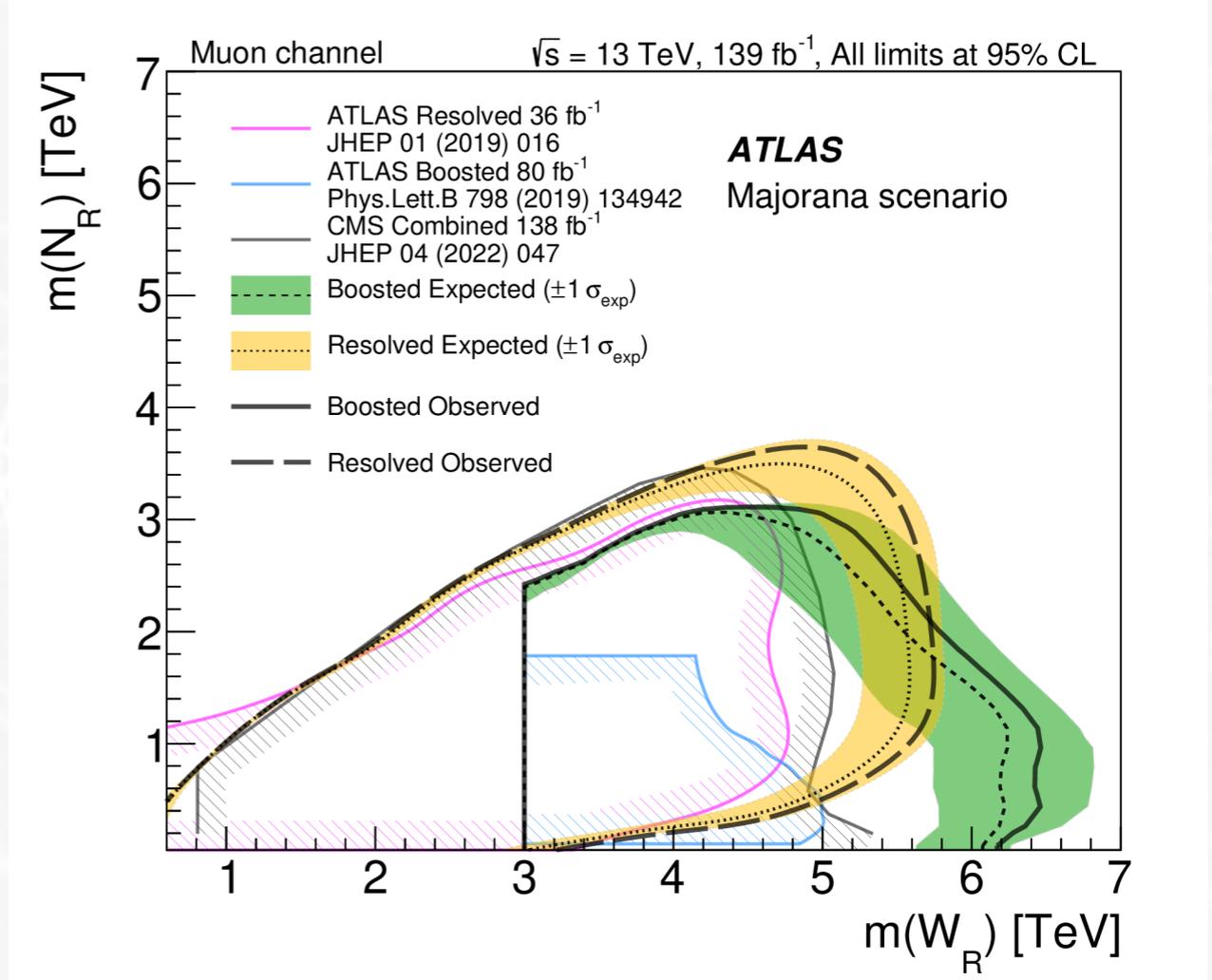
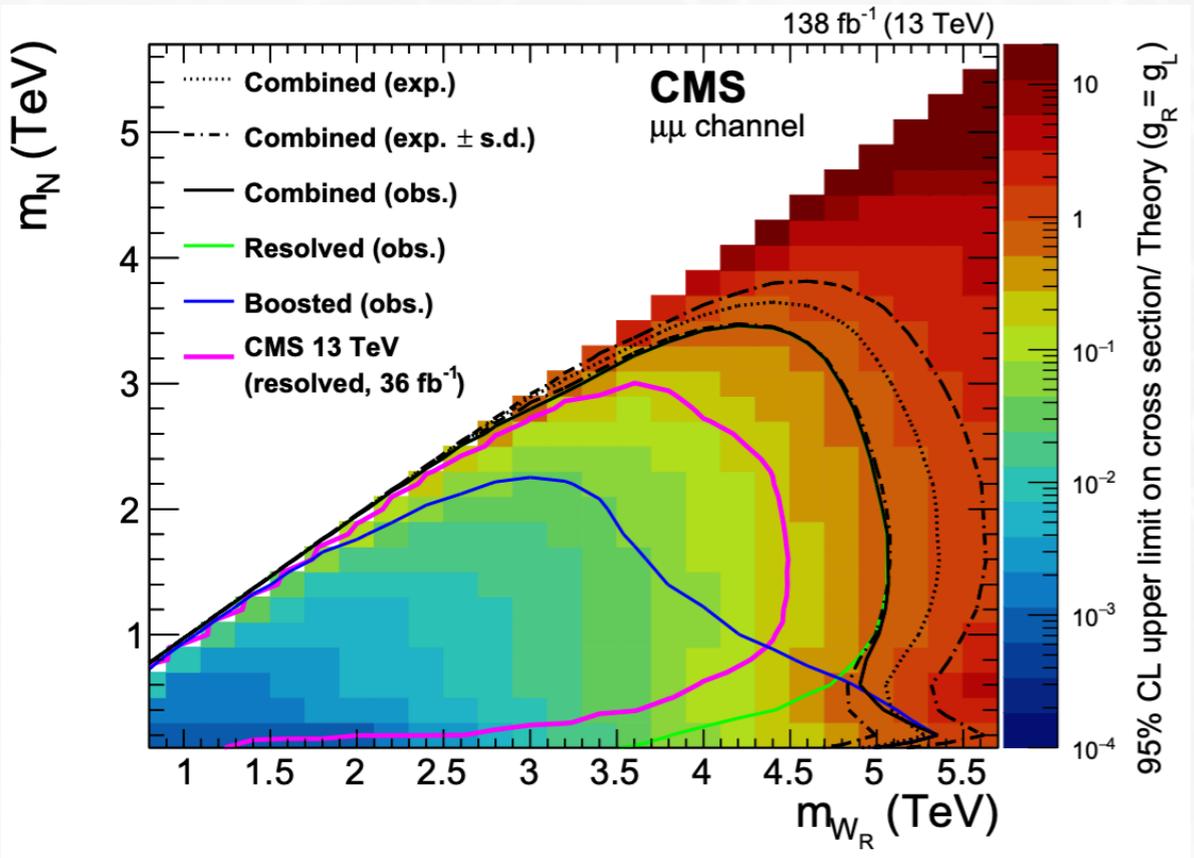
Signature:

- ▶ Same-sign di-leptons + jets, 1 very high- p_T lepton
- ▶ If N light \Rightarrow displaced/merged signatures

LVN at LHC in Left-Right: Keung Senjanović process

[ATLAS: 2304.09553]

[CMS: 2112.03949]



► Exclusion $m_{W_R} \gtrsim 6 - 7$ TeV

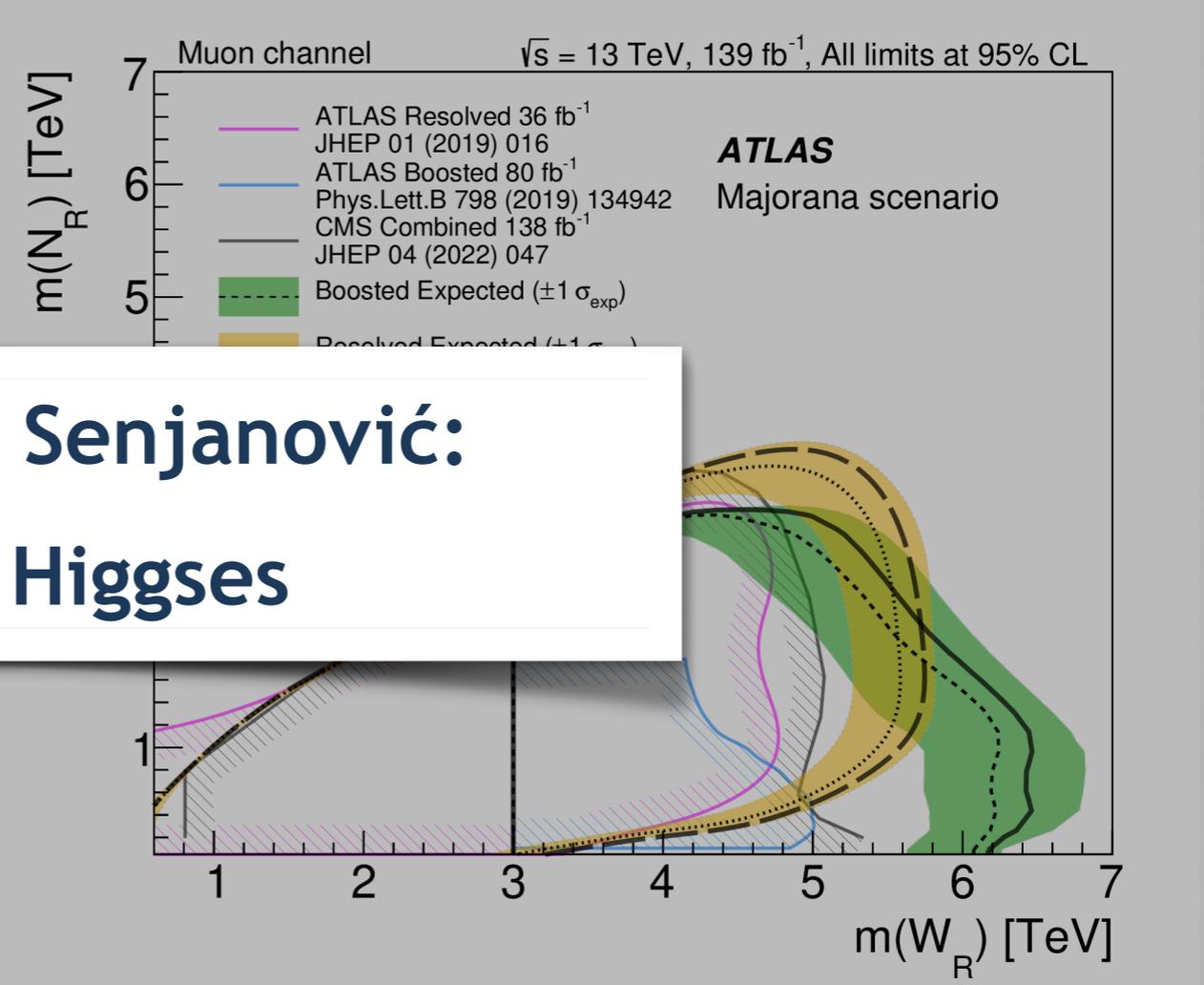
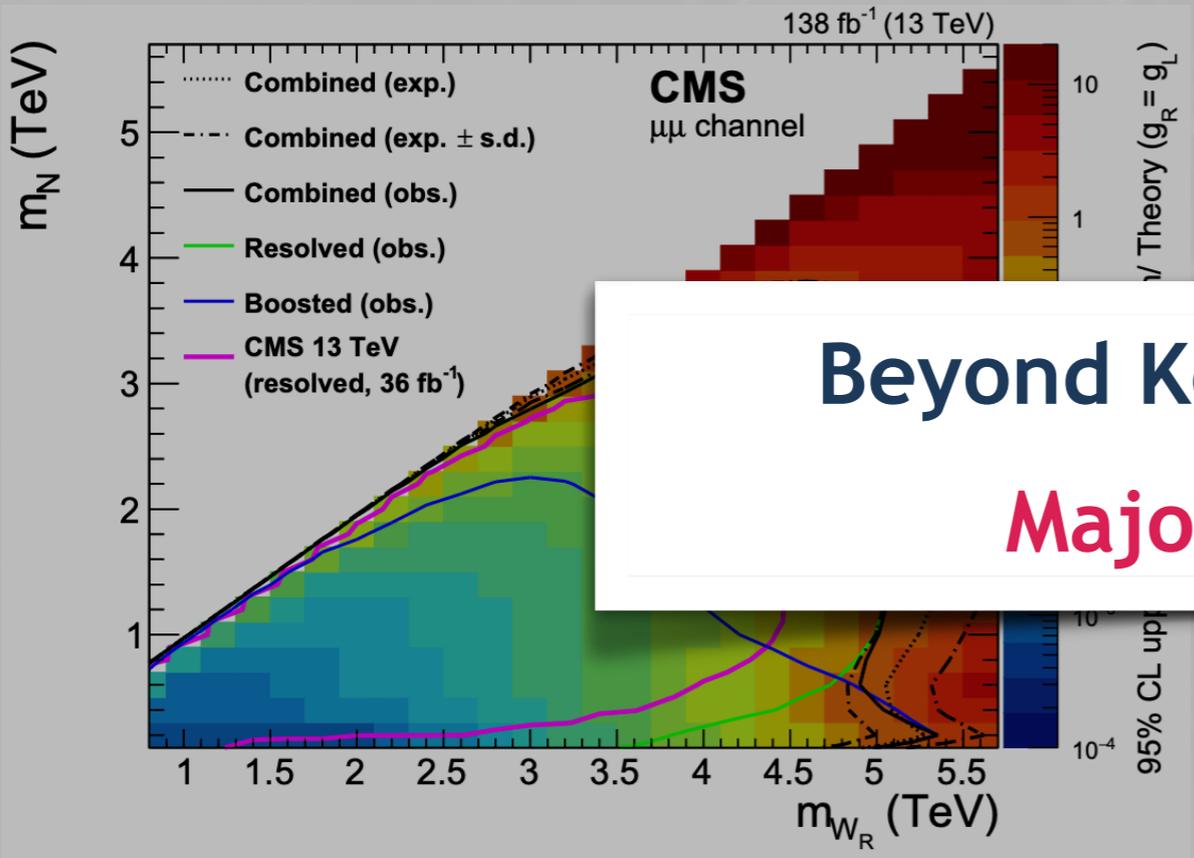
► Di-jet searches $m_{W_R} \gtrsim 4.5$ TeV

$$N \text{ lifetime} \approx 2.5 \text{mm} \frac{(m_{W_R}/3 \text{ TeV})^4}{(m_N/10 \text{ GeV})^5}$$

LVN at LHC in Left-Right: Keung Senjanović process

[ATLAS: 2304.09553]

[CMS: 2112.03949]



**Beyond Keung Senjanović:
Majorana Higgses**

▶ Exclusion $m_{W_R} \gtrsim 6 - 7 \text{ TeV}$

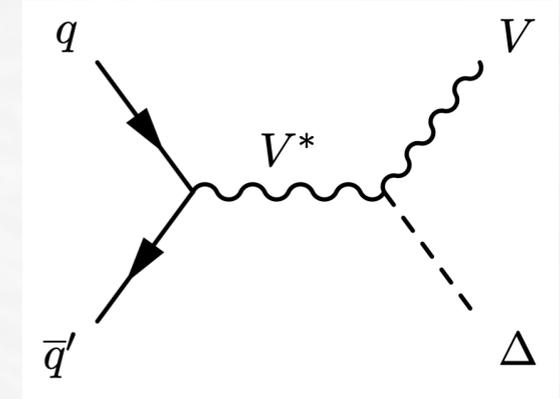
▶ Di-jet searches $m_{W_R} \gtrsim 4.5 \text{ TeV}$

$$N \text{ lifetime} \approx 2.5 \text{ mm} \frac{(m_{W_R}/3 \text{ TeV})^4}{(m_N/10 \text{ GeV})^5}$$

“Majorana Higgses”

Here: production and decay of h and $\Delta_R^0 \rightarrow NN$

Δ_R^0 and h mix with angle $\sin \theta$



$$\mathcal{L}_Y^\ell \supseteq \bar{L}'_L (Y_\ell \phi + \tilde{Y}_\ell \tilde{\phi}) L'_R + \bar{L}'_L{}^c i\sigma_2 \Delta_L Y_L^M L'_L + L'_R{}^c i\sigma_2 \Delta_R Y_R^M L'_R$$

$$\Delta_R = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta_R^{++} \\ \Delta_R^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$

$$\Gamma(\Delta_R^0 \rightarrow NN) \propto m_{\Delta_R^0} \frac{m_N^2}{m_{W_R}^2}$$

$$\Gamma(h \rightarrow NN) \propto m_h \frac{m_N^2}{m_{W_R}^2} \sin^2 \theta$$

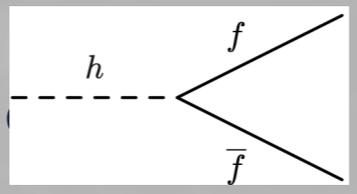
$\Rightarrow \Delta_R^0$ decays into SM states

$$\Gamma(\Delta_R^0 \rightarrow VV^{(*)}) \simeq \sin^2 \theta \Gamma(h \rightarrow VV^{(*)})$$

$$\Gamma(\Delta_R^0 \rightarrow f\bar{f}) \simeq \sin^2 \theta \Gamma(h \rightarrow f\bar{f})$$

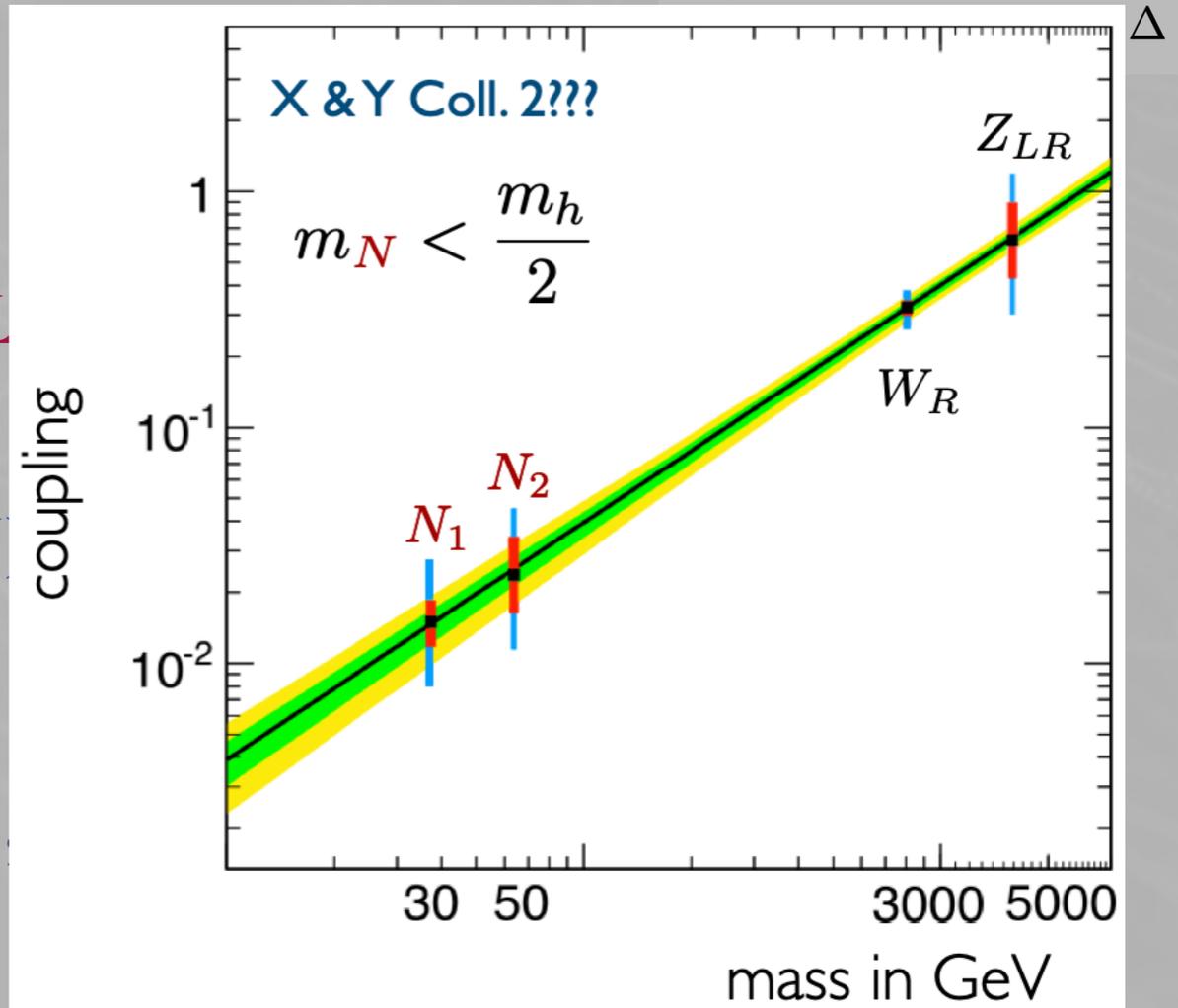
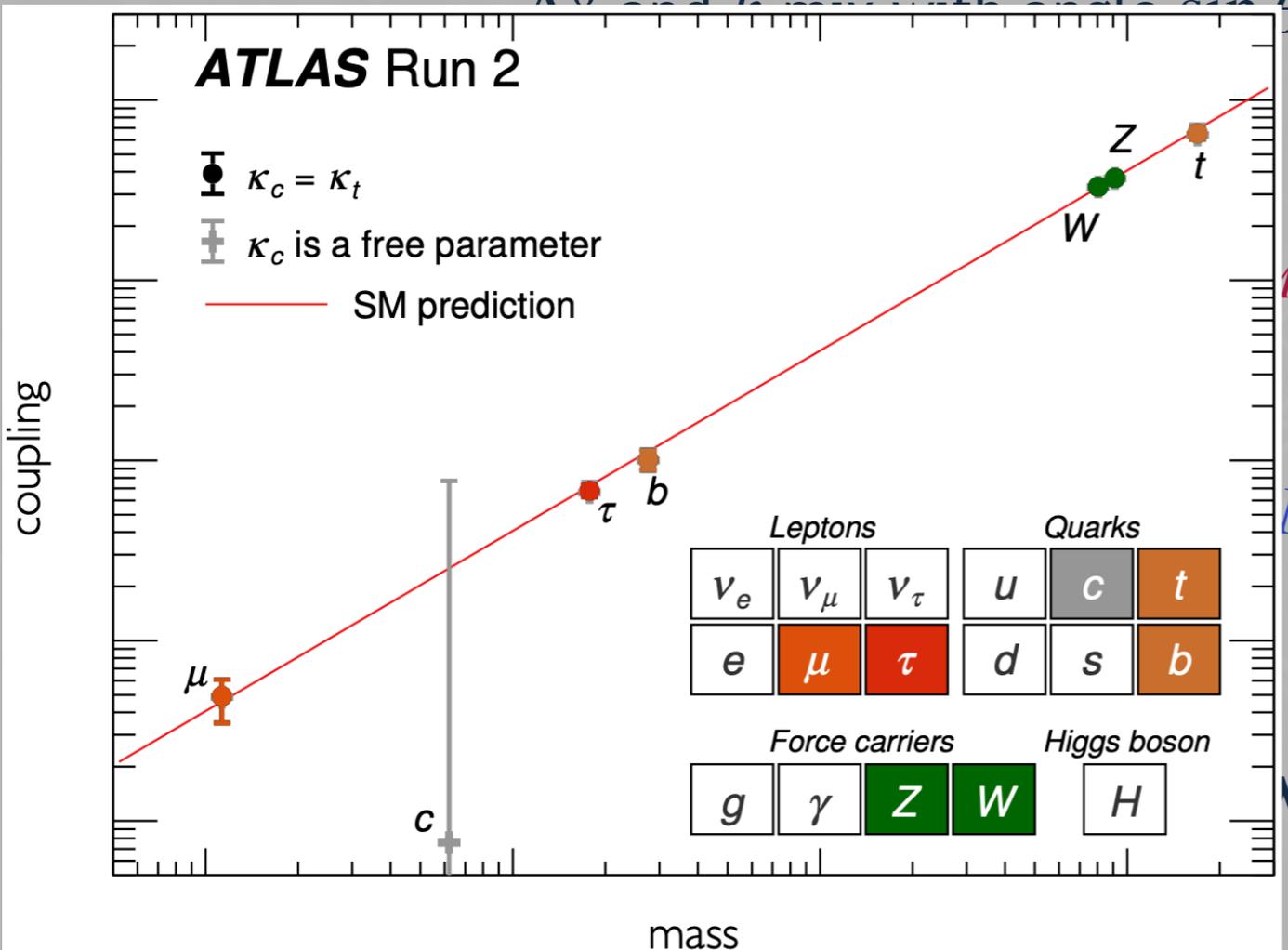
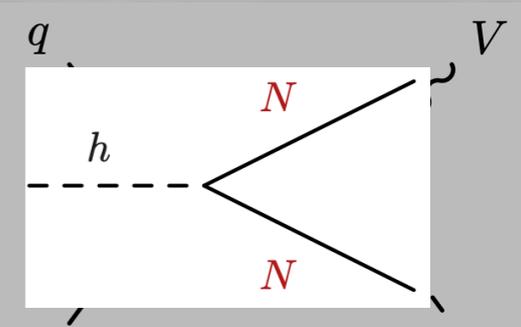
“Majorana Higgses”

$$\Gamma_{h \rightarrow f\bar{f}} \propto c_\theta^2 m_f^2$$



$\rightarrow NN$

$$\Gamma_{h \rightarrow NN} \propto s_\theta^2 m_N^2$$



$$\Gamma(\Delta_R^0 \rightarrow VV^{(*)}) \simeq \sin^2 \theta \Gamma(h \rightarrow VV^{(*)})$$

$$\Gamma(\Delta_R^0 \rightarrow ff) \simeq \sin^2 \theta \Gamma(h \rightarrow ff)$$

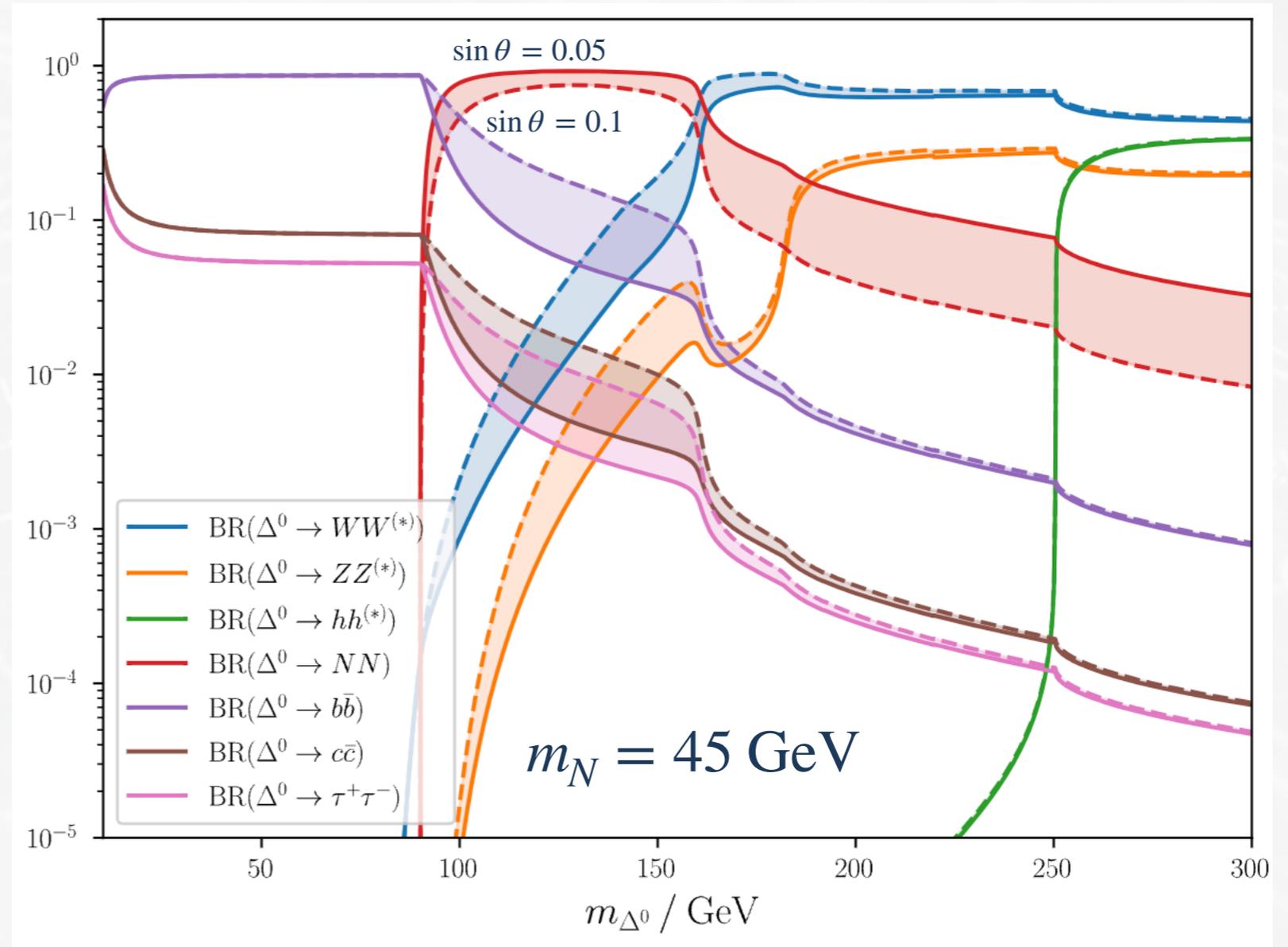
In **LRSM** we can (in principle) probe the origin of neutrino masses **directly!**

Decays of Δ

$$\Gamma(\Delta_R^0 \rightarrow NN) \propto m_{\Delta_R^0} \frac{m_N^2}{m_{W_R}^2}$$

Ample room for $\Delta_R^0 \rightarrow NN$!

Fuks, JK, Nemevšek, Nesti arXiv:2503.21354



$$\Gamma(\Delta_R^0 \rightarrow VV^{(*)}) \simeq \sin^2 \theta \Gamma(h \rightarrow VV^{(*)})$$

$$\Gamma(\Delta_R^0 \rightarrow f\bar{f}) \simeq \sin^2 \theta \Gamma(h \rightarrow f\bar{f})$$

“Majorana Higgses – $h \rightarrow NN$ ”

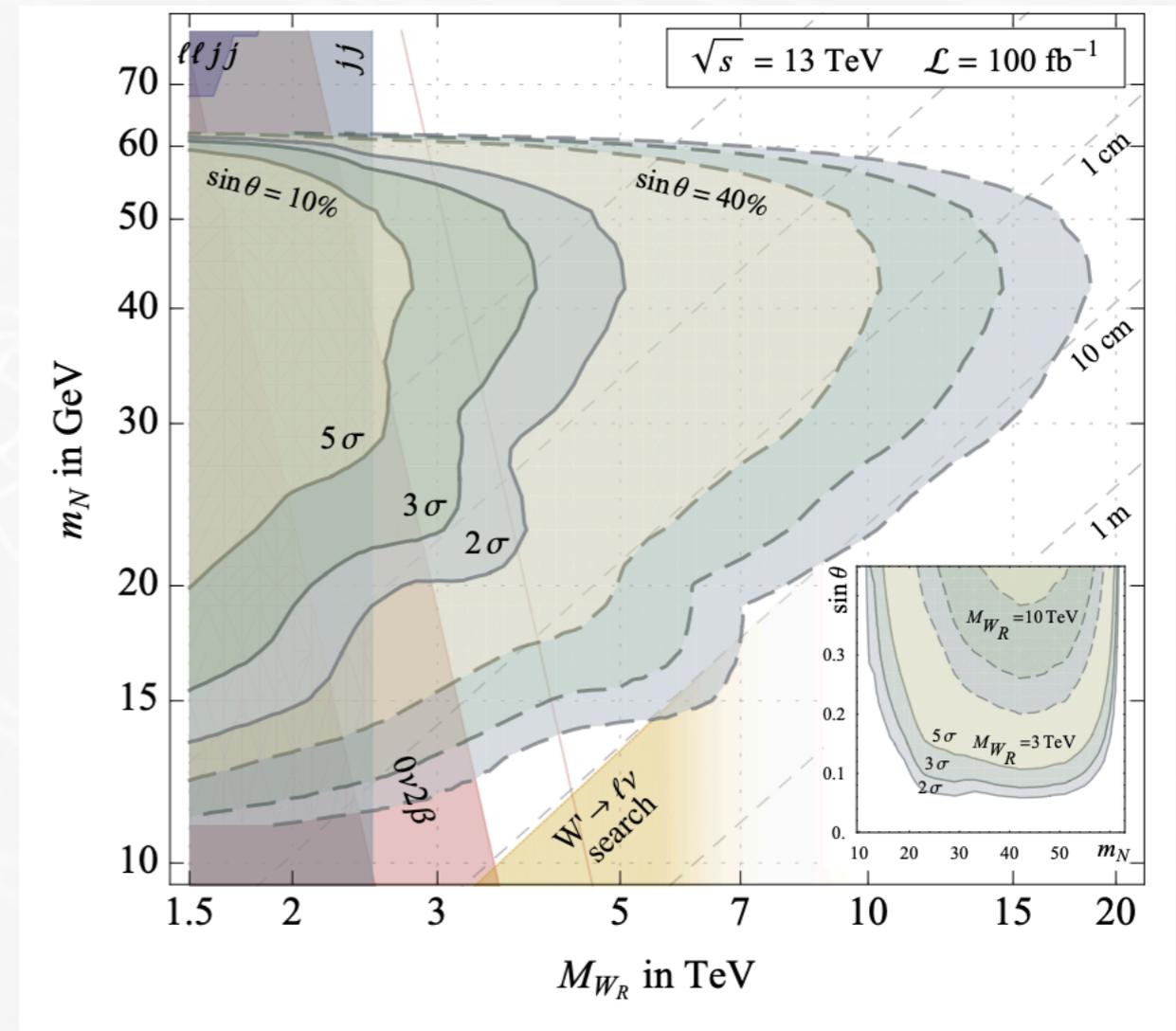
ggF Higgs production and $h \rightarrow NN$ decay

N has a long lifetime \Rightarrow **displaced** signal

Trigger problem: soft & displaced leptons + jets

Still: Sizeable reach on $M_{W_R} \lesssim 15$ TeV!

Maiezza, Nemevšek, Nesti PRL (1503.06834)



“Majorana Higgses – $gg \rightarrow \Delta \rightarrow NN$ ”

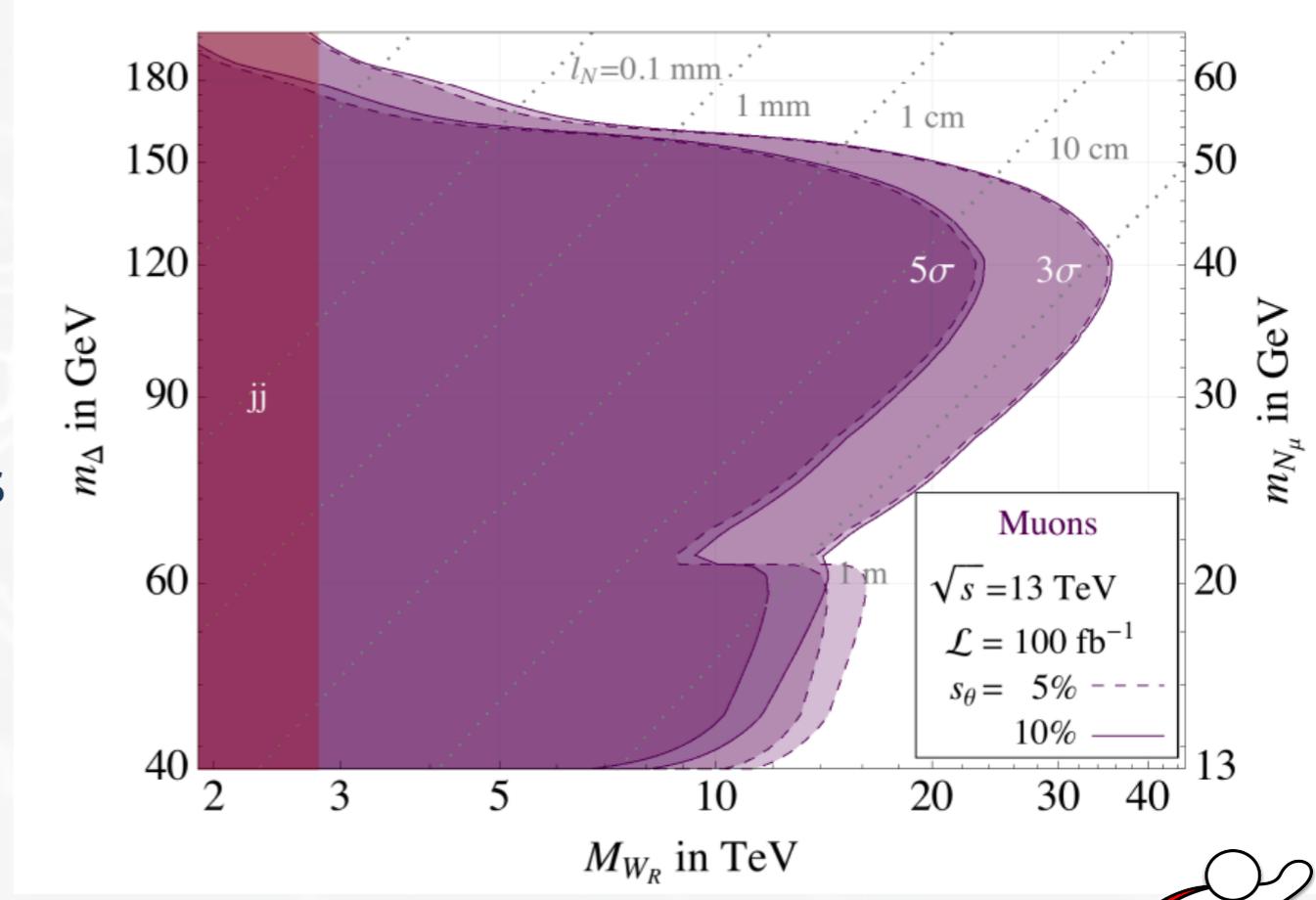
Nemevšek, Nesti, Vasquez ([1612.06840](#))

ggF Δ production and $\Delta \rightarrow NN$ decay

N has a long lifetime \Rightarrow **displaced** signal

Same Trigger problem: **soft & displaced leptons + jets**

Still: Sizeable reach on $M_{WR} \lesssim 30$ TeV!



Prompt: very hard, a lot of background

“Majorana Higgses – $gg \rightarrow \Delta \rightarrow NN$ ”

Nemevšek, Nesti, Vasquez ([1612.06840](#))

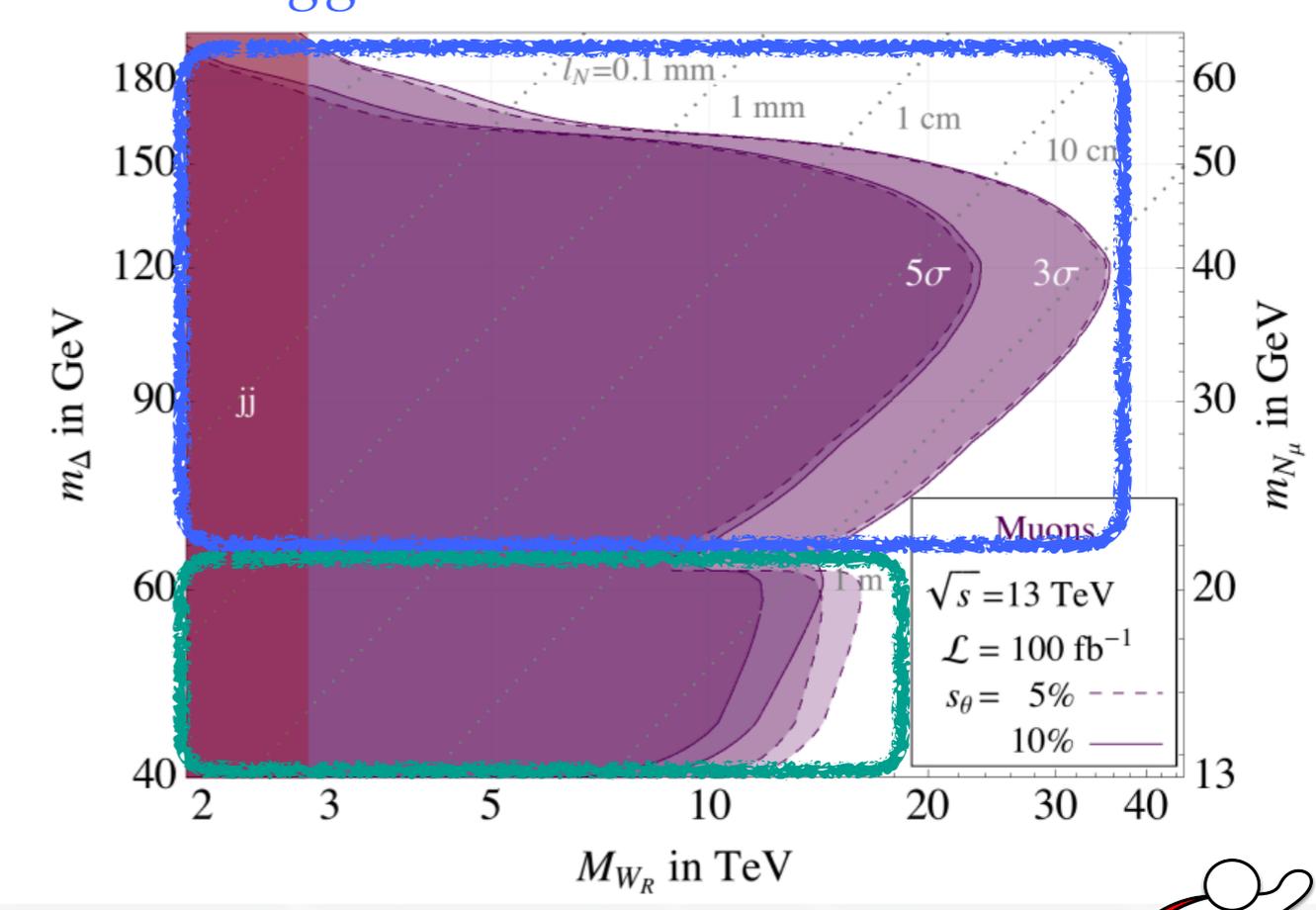
ggF Δ production and $\Delta \rightarrow NN$ decay

N has a long lifetime \Rightarrow **displaced** signal

Same Trigger problem: **soft & displaced leptons** + jets

Still: Sizeable reach on $M_{WR} \lesssim 30$ TeV!

$$gg \rightarrow \Delta \rightarrow NN$$



$$gg \rightarrow h \rightarrow \Delta\Delta \rightarrow 4N!!!$$

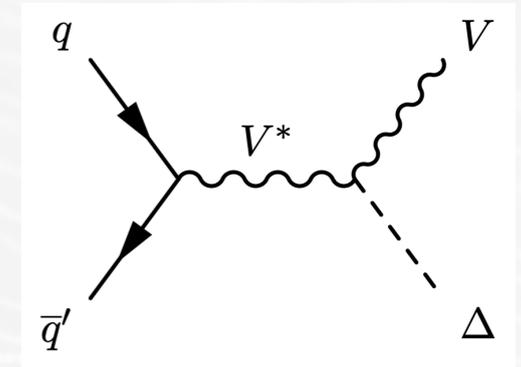
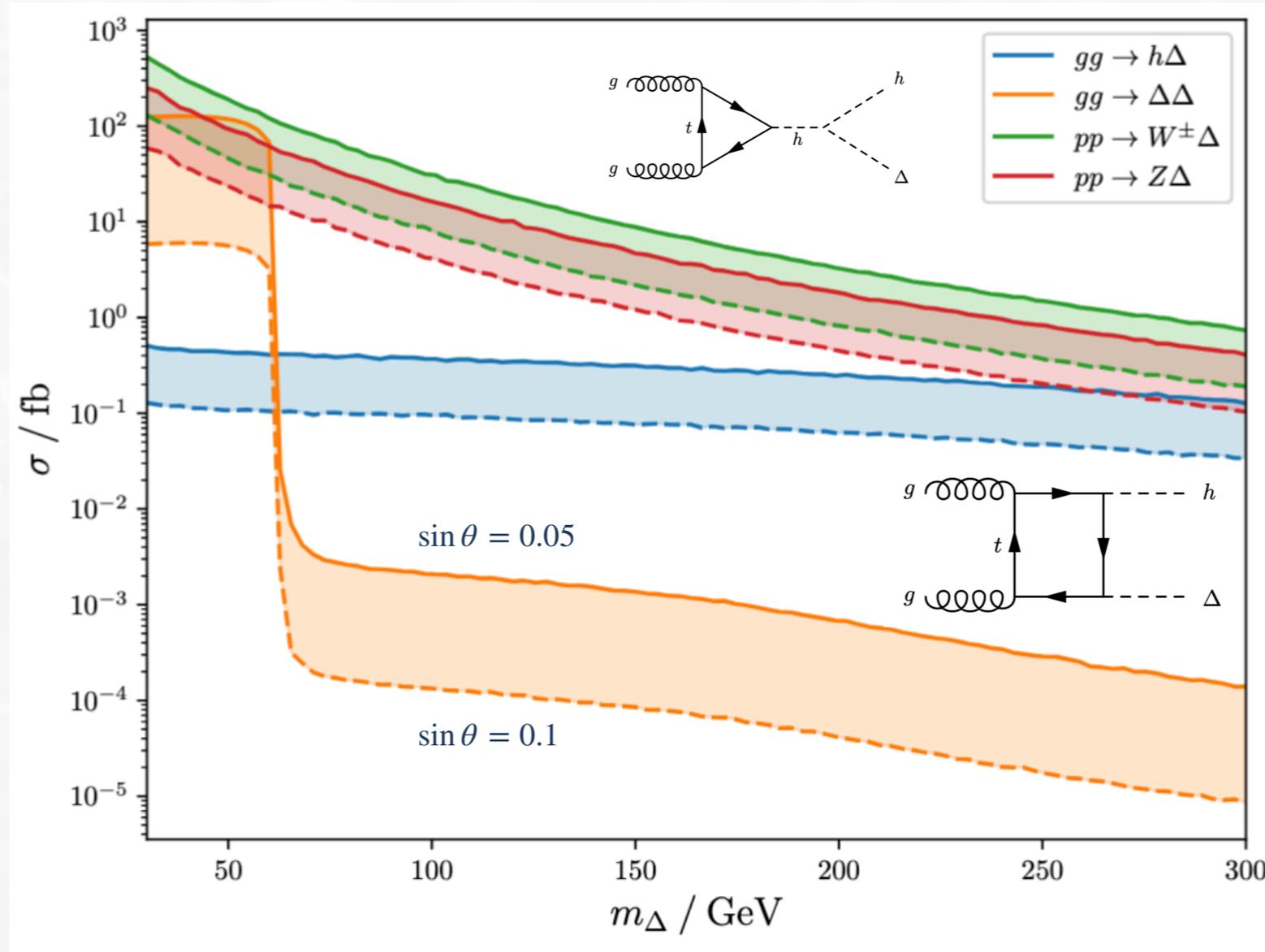
$\Delta L = 4$ signature!



Prompt: very hard, a lot of background

“Majorana Higgses – associate production”

Fuks, JK, Nemevšek, Nesti [arXiv:2503.21354](https://arxiv.org/abs/2503.21354)



NLO model-file JK, Nemevšek, Nesti EPJC'24

Sizeable production in “ Δ -strahlung” and gluon fusion

See also: <https://sites.google.com/site/leftrighthep>

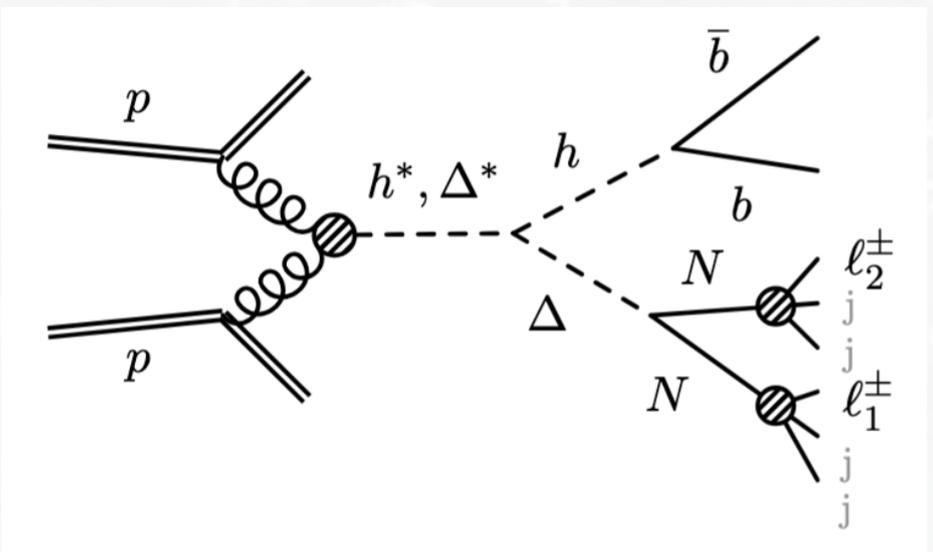
Trigger-friendly: accompanying boson (Z, W^\pm, h) \Rightarrow prompt & hard activity

(Transverse) displacement of N

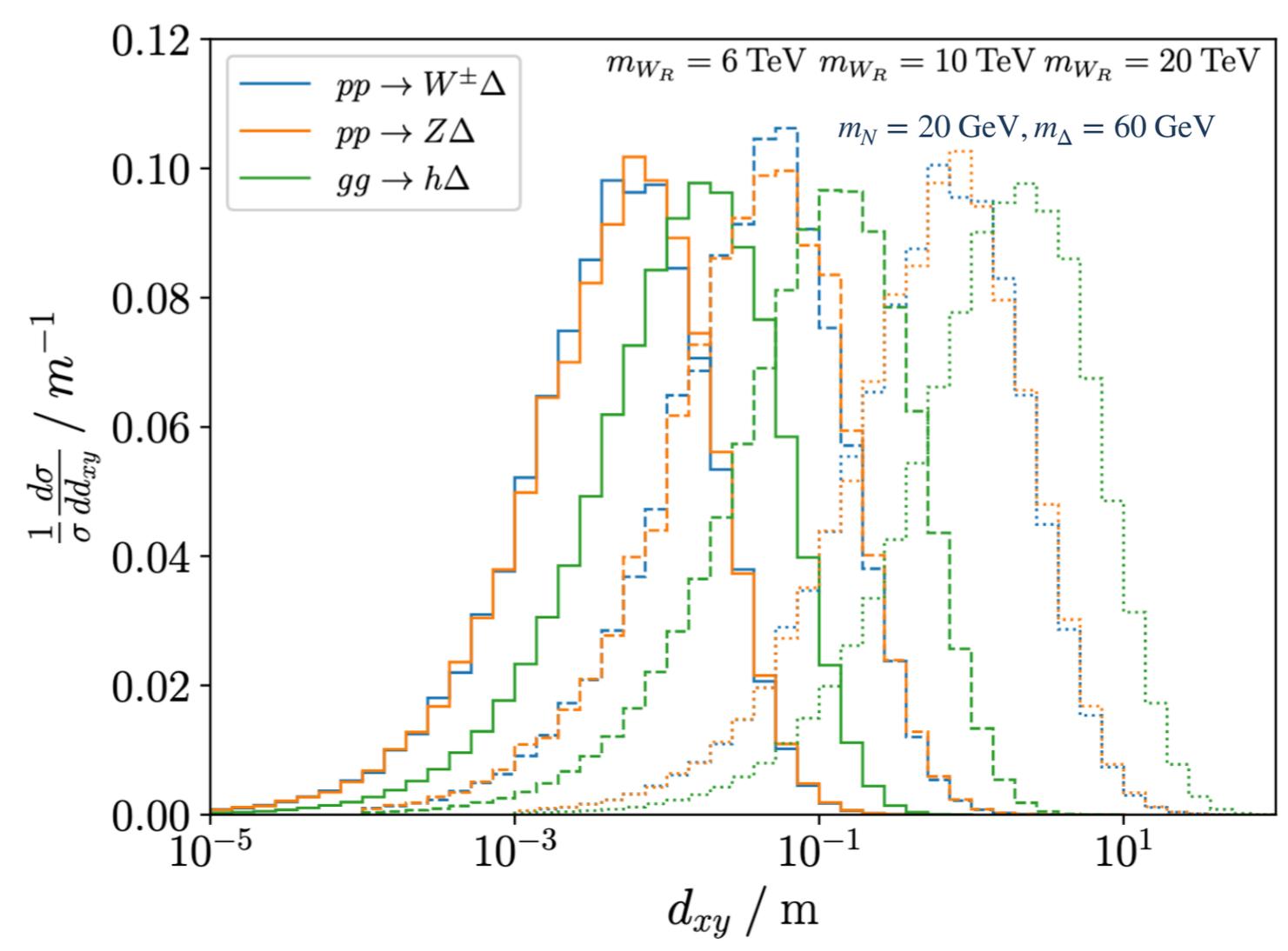
Fuks, JK, Nemevšek, Nesti [arXiv:2503.21354](https://arxiv.org/abs/2503.21354)

Sizeable **displacement** from N decay

⇒ Focus on **displaced** leptons/jets



⇒ Decay of associated boson triggers event



$$N \text{ lifetime} \approx 2.5 \text{ mm} \frac{(m_{WR}/3 \text{ TeV})^4}{(m_N/10 \text{ GeV})^5}$$

Analysis outline

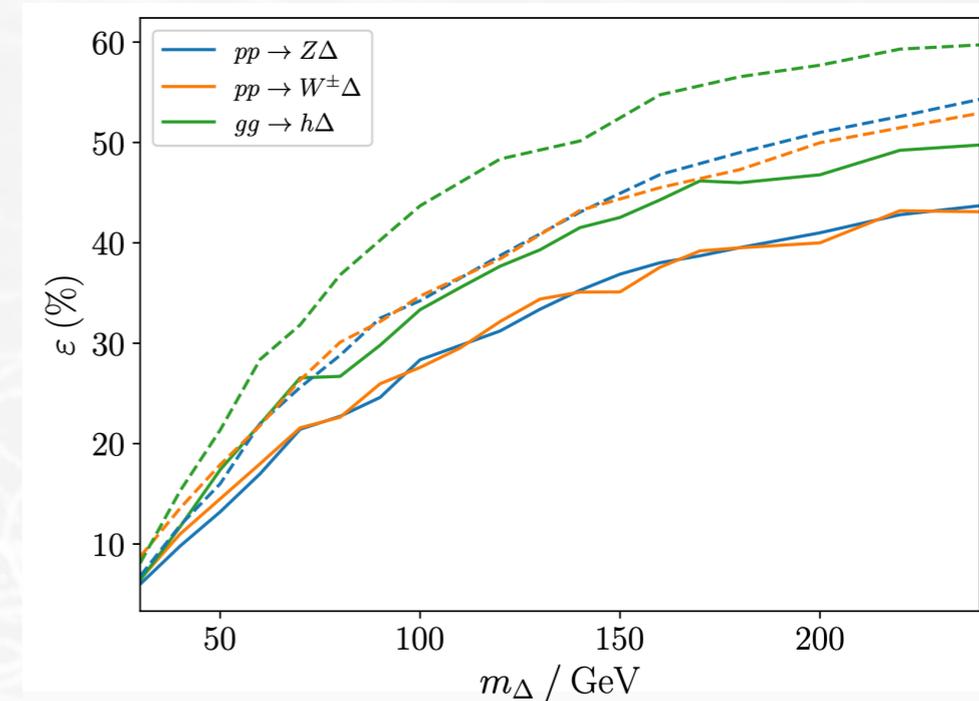
Select events with 2 **same-sign** leptons with

$\Delta R(\ell, j_c) > 0.25$ (lose most events due to soft-lepton isolation)

$|\eta(\ell)| < 2.4$ kinematic/isolation efficiencies: 20 – 40 %

$p_T(\ell) > 10 \text{ GeV}$

$0.1 \text{ mm} < d_{xy} < 30 \text{ cm}$ (Decay in inner tracker)



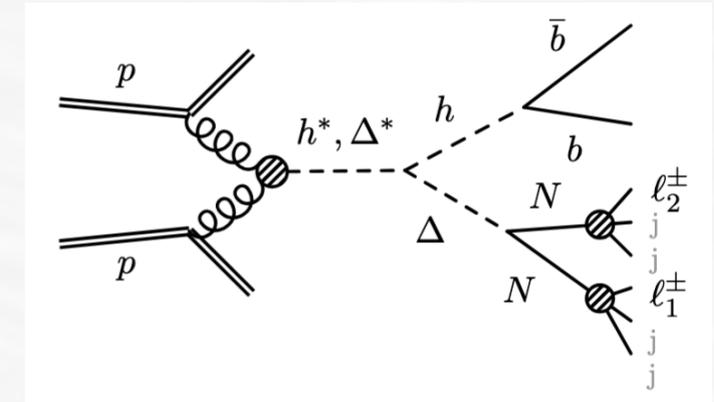
Simulation with MadGraph5, Pythia, Delphes, MadAnalysis tool-chain

NLO model-file JK, Nemevšek, Nesti EPJC'24

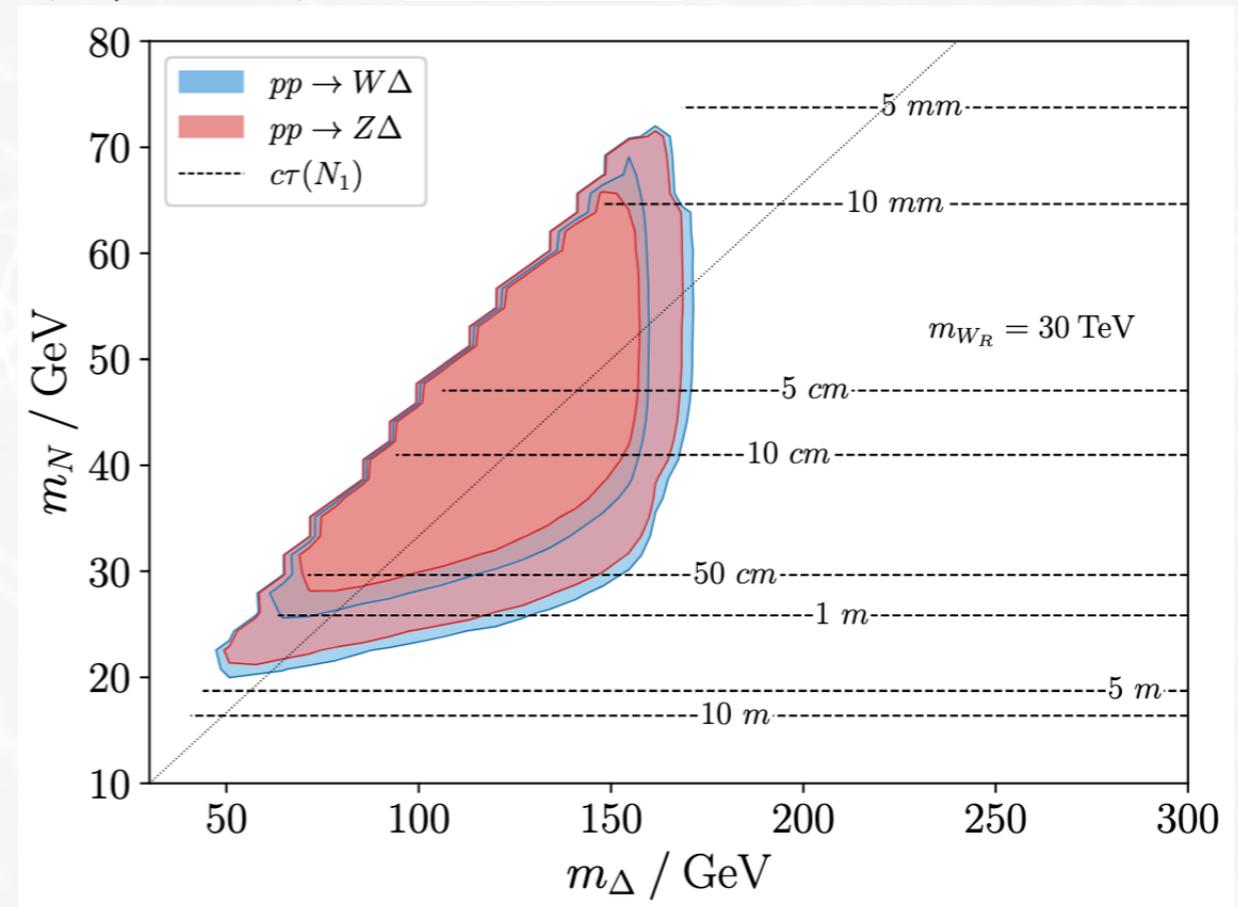
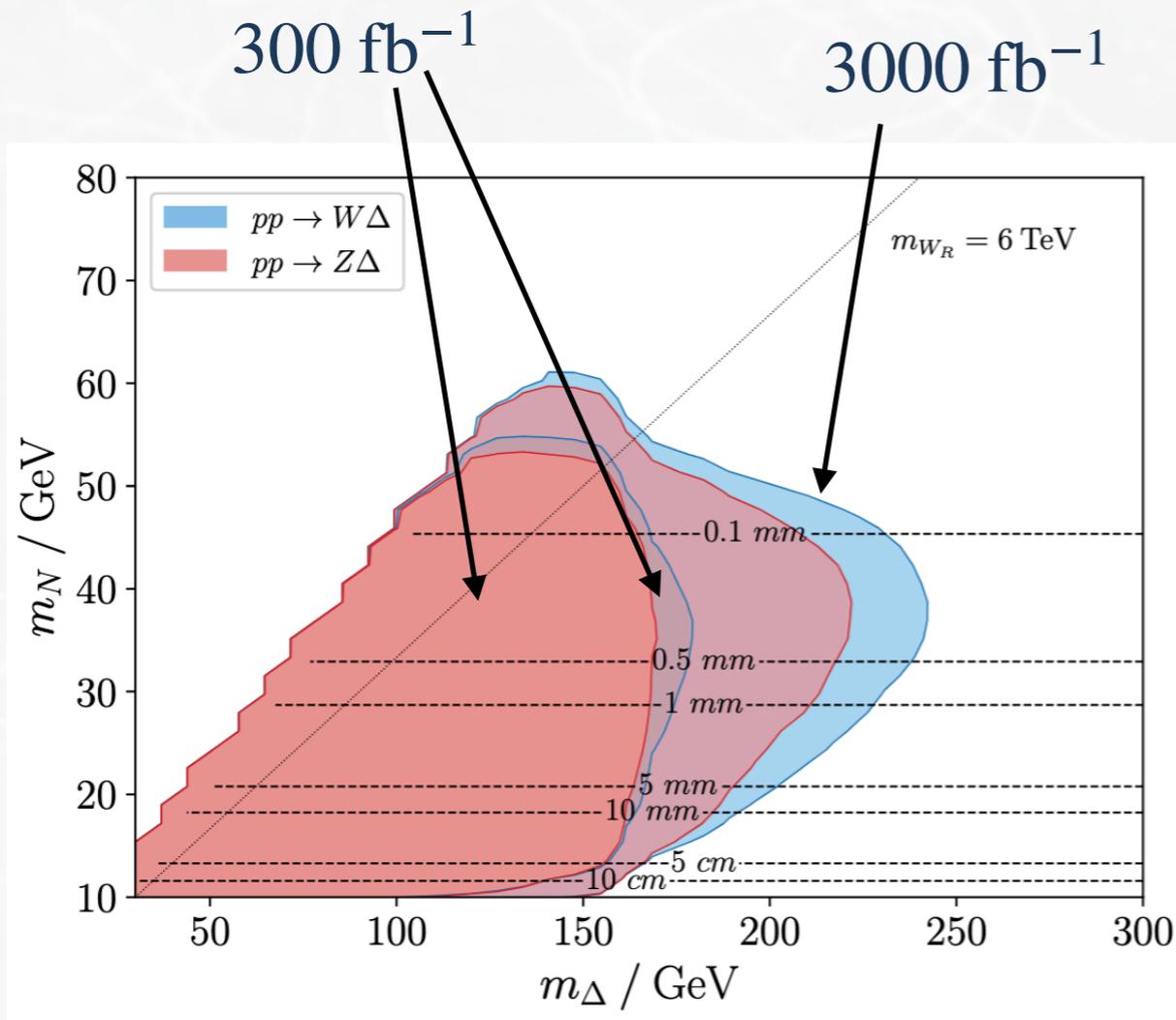
See also: <https://sites.google.com/site/leftrighthep>

Large displacements, same-sign leptons, $m_V(\ell jj) \gtrsim 10 \text{ GeV}$: no prompt backgrounds

Sensitivities at (HL)-LHC



Fuks, **JK**, Nemevšek, Nesti [arXiv:2503.21354](https://arxiv.org/abs/2503.21354)

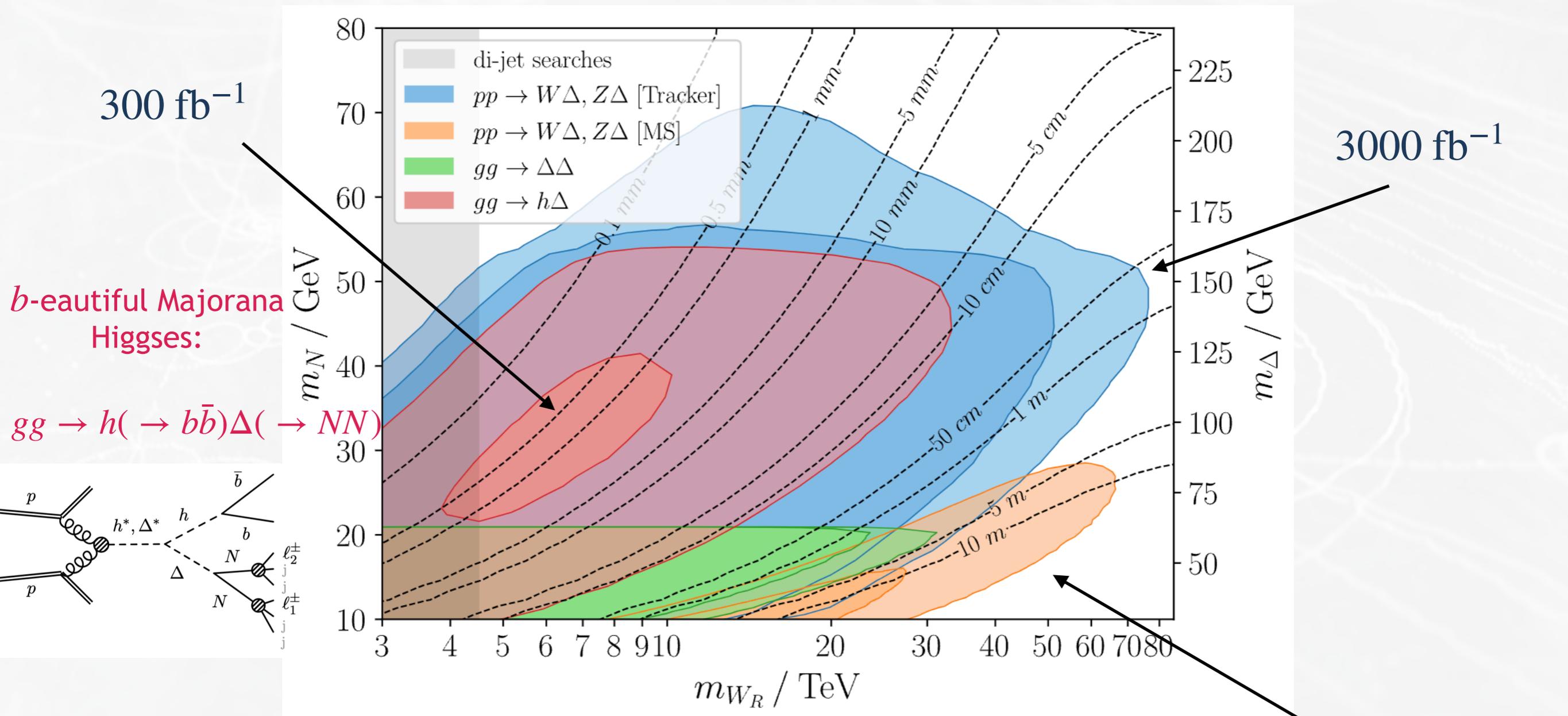


Trigger-friendly: accompanying boson (Z, W^\pm, h) \Rightarrow prompt & hard activity

Cut on displaced N -decay to kill backgrounds!

Sensitivities at (HL)-LHC

Fuks, JK, Nemevšek, Nesti [arXiv:2503.21354](https://arxiv.org/abs/2503.21354)



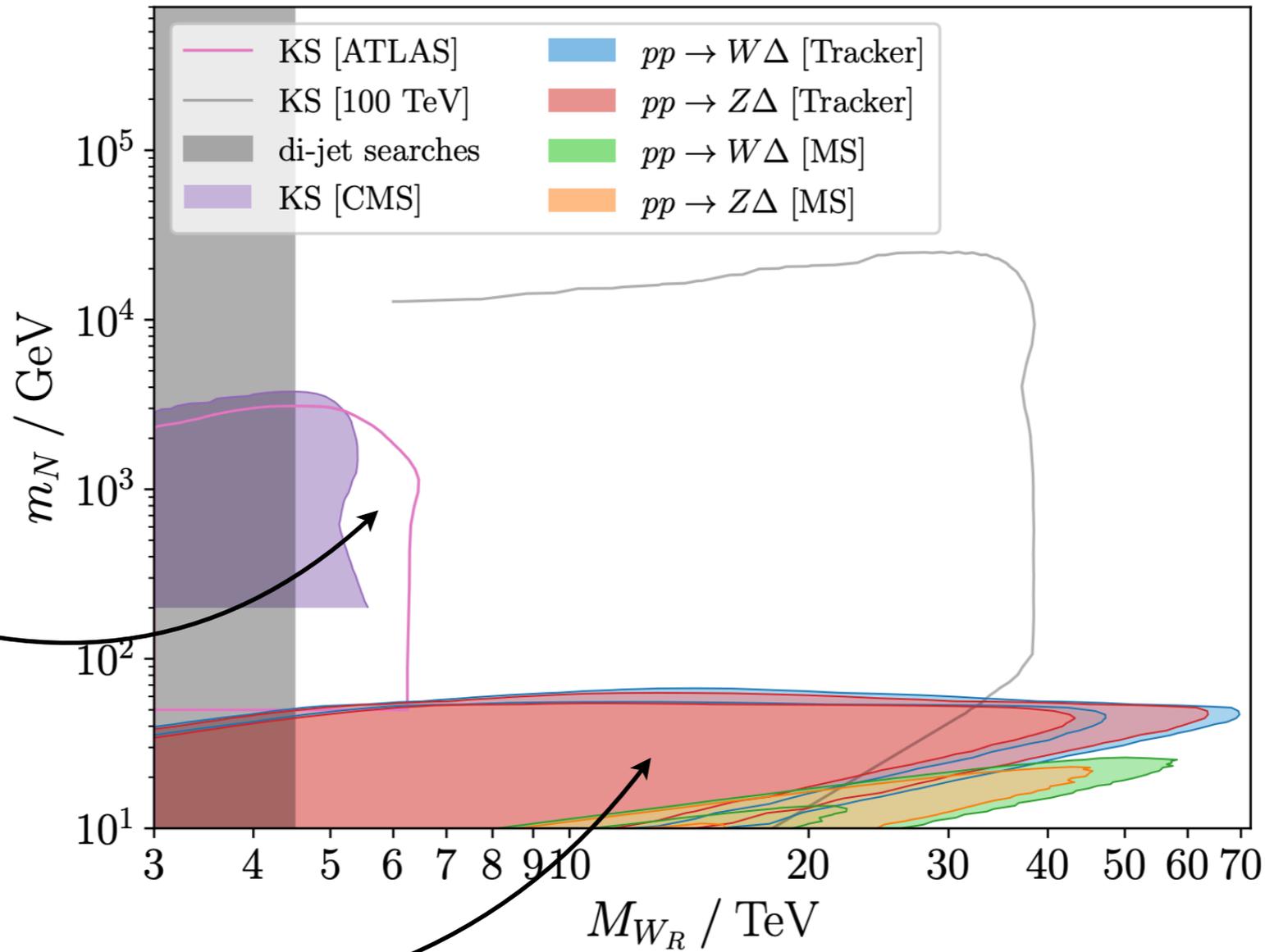
⇒ complementary parameter space, exclusion up to $m_{WR} \gtrsim 70 - 80$ TeV!

⇒ Large displacements up to Muon Spectrometer [MS] possible! $8 \text{ m} < d_{xy} < 13 \text{ m}$

Sensitivities at (HL)-LHC

Fuks, JK, Nemevšek, Nesti [arXiv:2503.21354](https://arxiv.org/abs/2503.21354)

Standard searches
 $pp \rightarrow W_R \rightarrow \ell N$

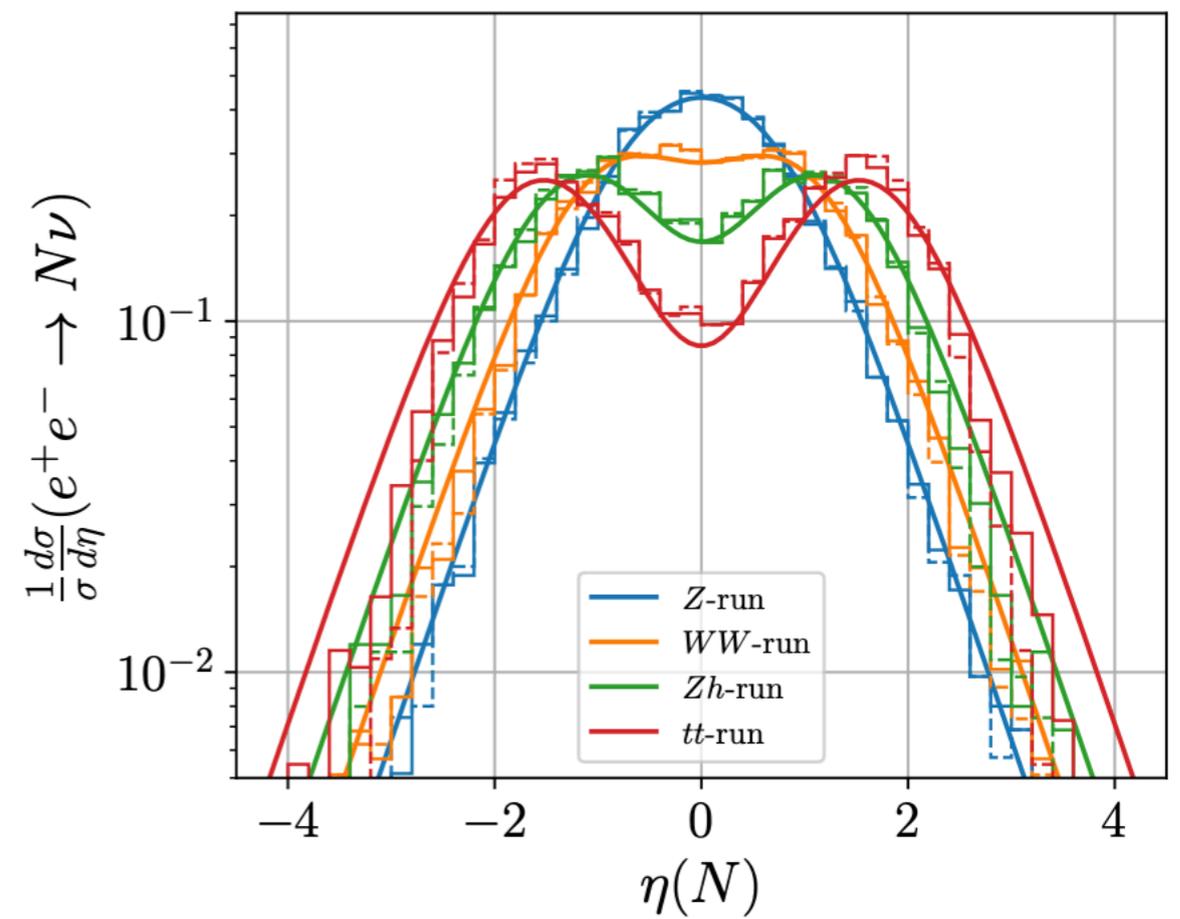
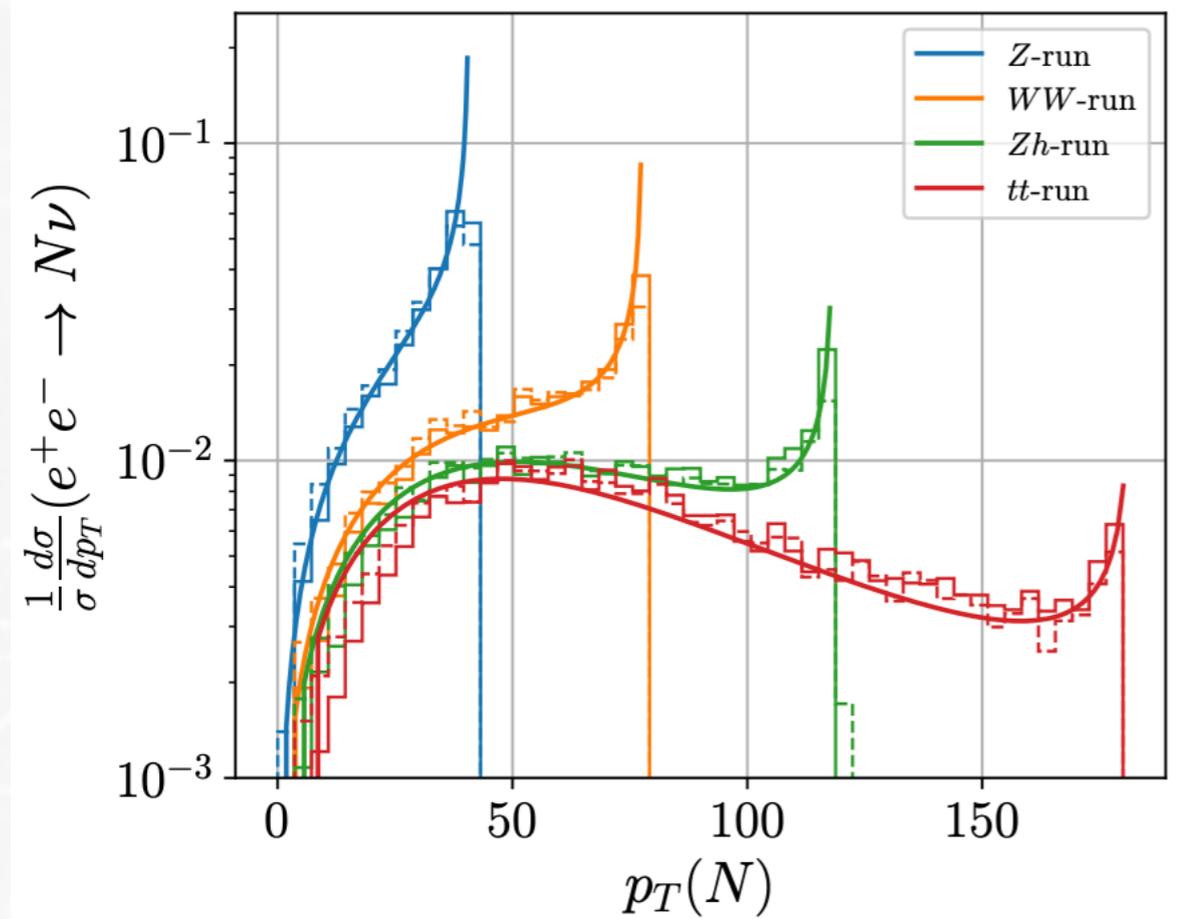


Displaced searches
 $pp \rightarrow \Delta X, \Delta \rightarrow NN$

⇒ complementary parameter space,
 exclusion up to $m_{W_R} \gtrsim 70 - 80$ TeV!

Signals at FCC-ee

Fuks, JK, Nemevšek, Nesti [arXiv:2602.09095](https://arxiv.org/abs/2602.09095)

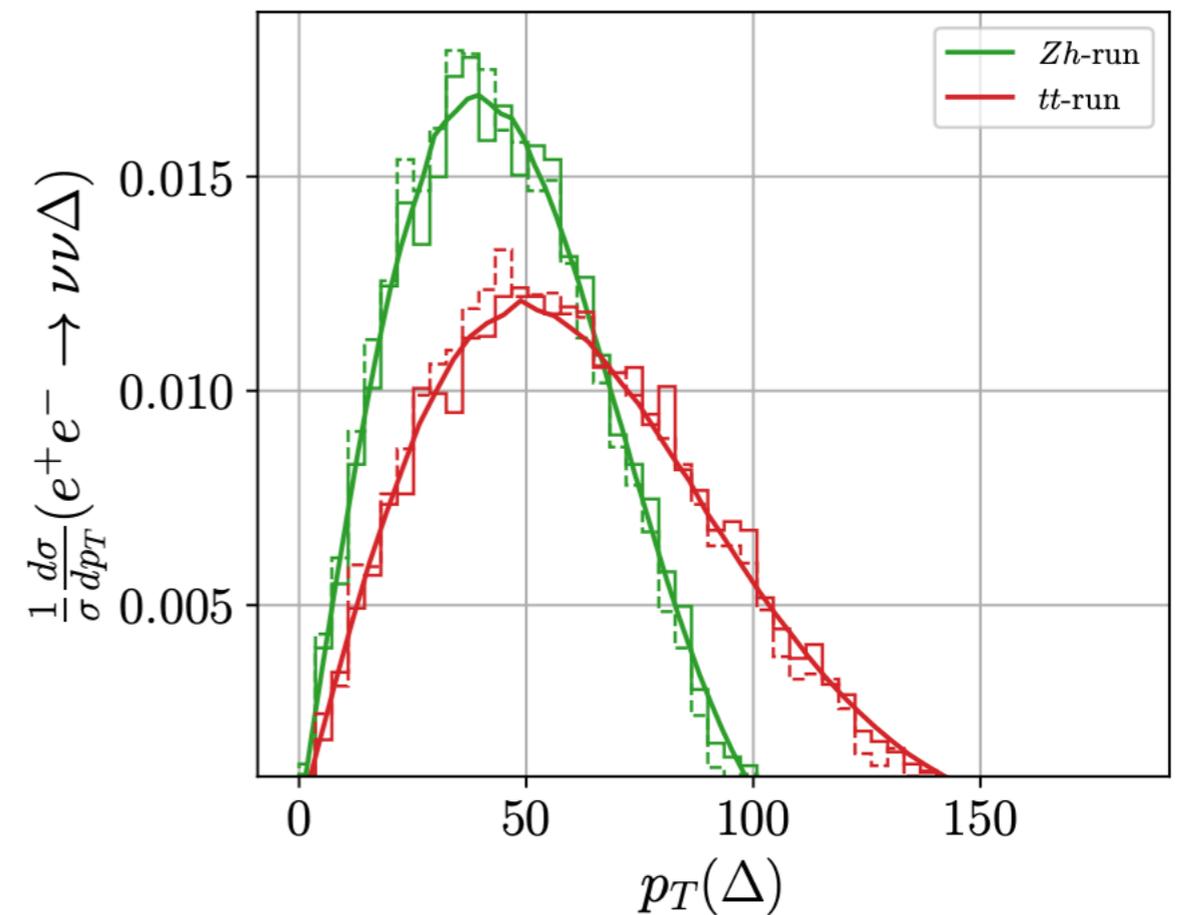
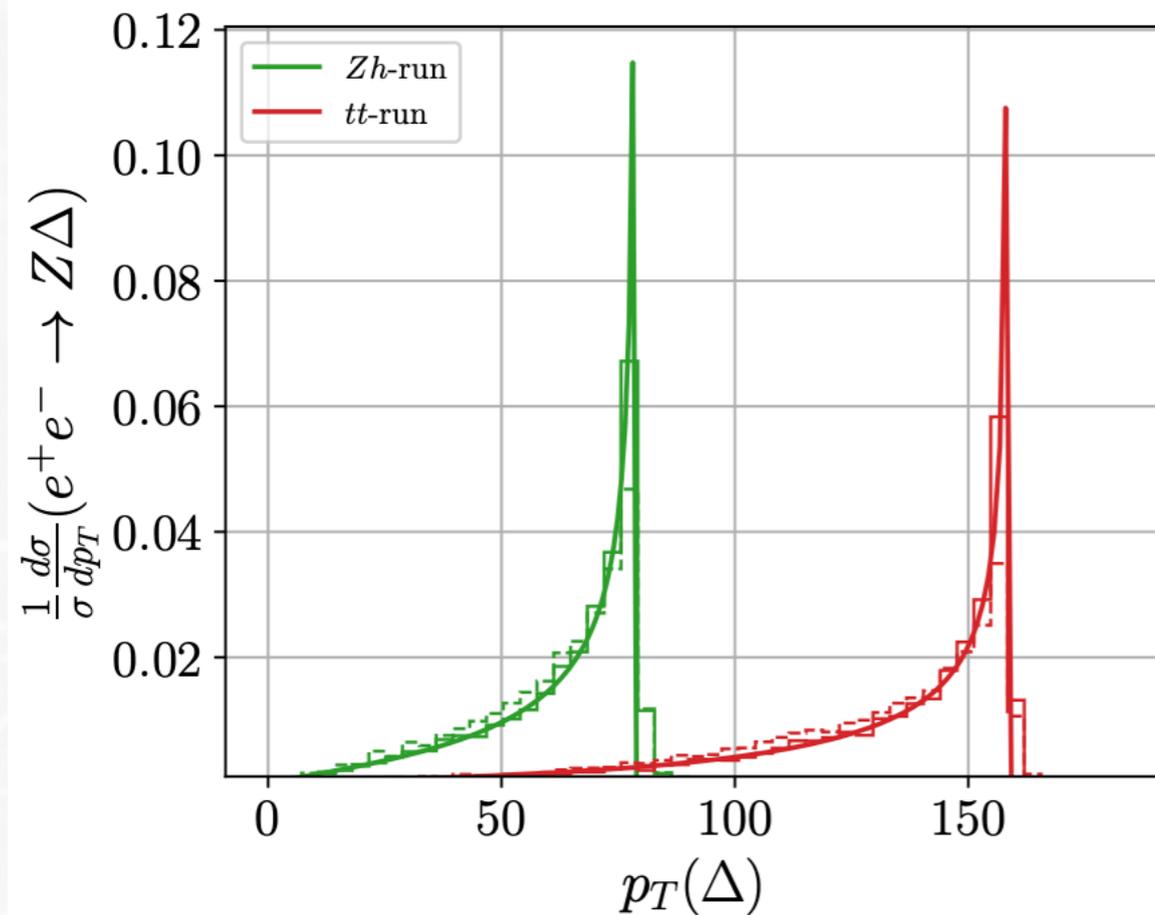


With proper Vertexing: can reconstruct full kinematics of N !

Graph-based vertexing tools in Delphes: JK [arXiv:2510.00856](https://arxiv.org/abs/2510.00856)

Signals at FCC-ee

Fuks, **JK**, Nemevšek, Nesti [arXiv:2602.09095](https://arxiv.org/abs/2602.09095)



With proper Vertexing: can reconstruct full kinematics of N and even of Δ !

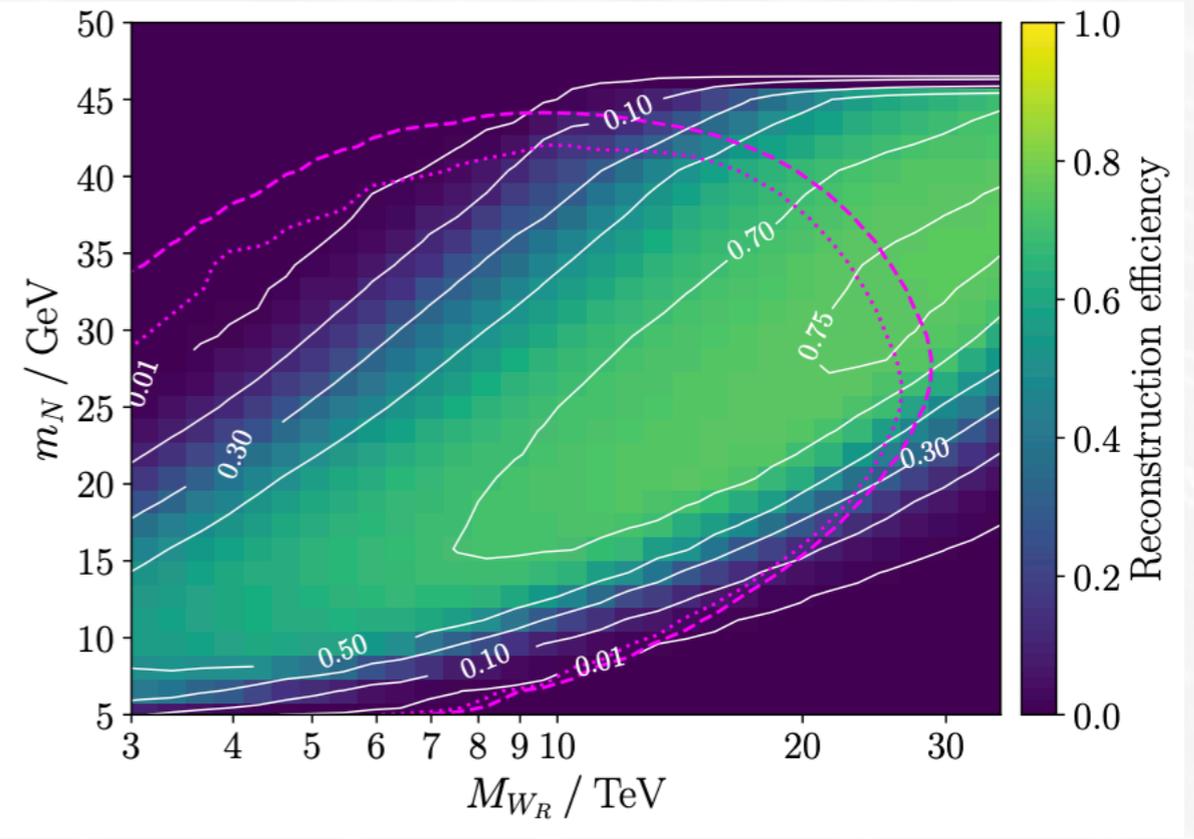
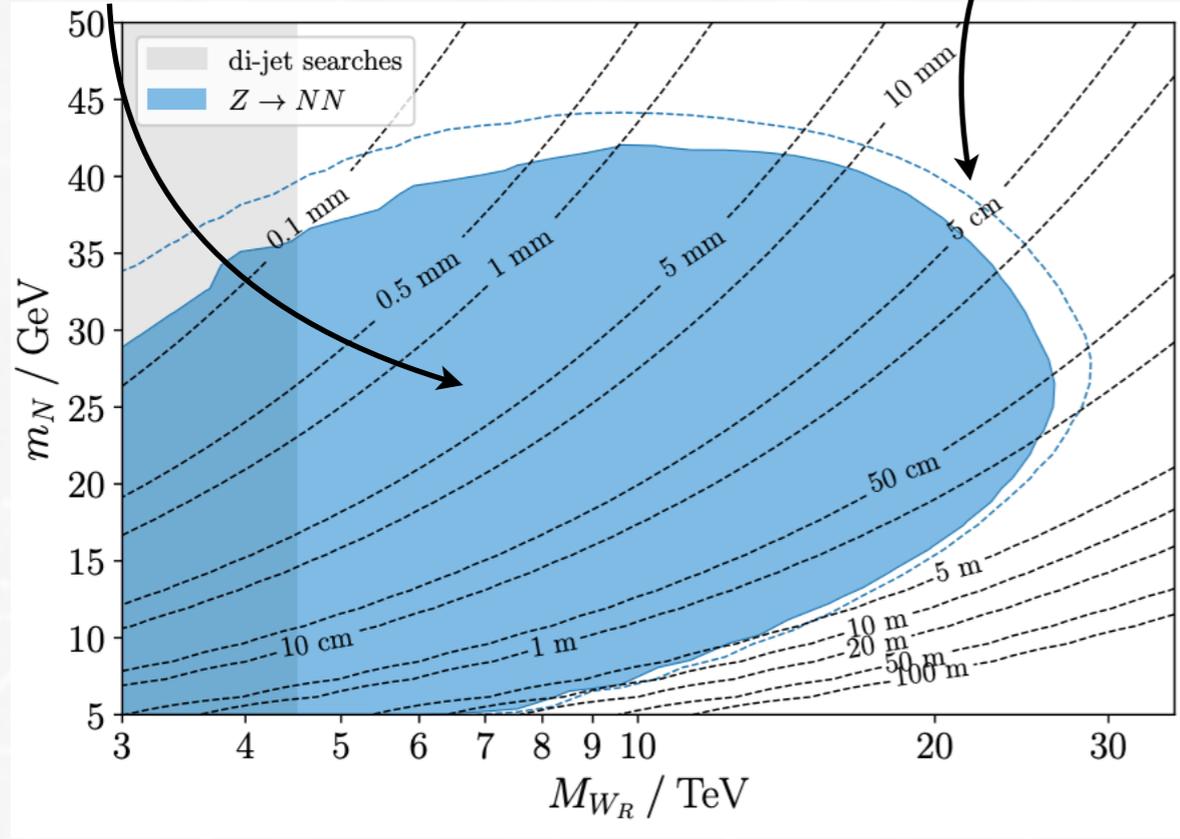
Graph-based vertexing tools in Delphes: **JK** [arXiv:2510.00856](https://arxiv.org/abs/2510.00856)

Signals at FCC-ee

Full vertexing analysis

Theoretical limit

Fuks, JK, Nemevšek, Nesti [arXiv:2602.09095](https://arxiv.org/abs/2602.09095)



Beyond Event-tags: kinematical cuts on reconstructed LLP 4-momenta

⇒ Reaching reconstruction efficiencies of 70 – 75 % with **negligible background**

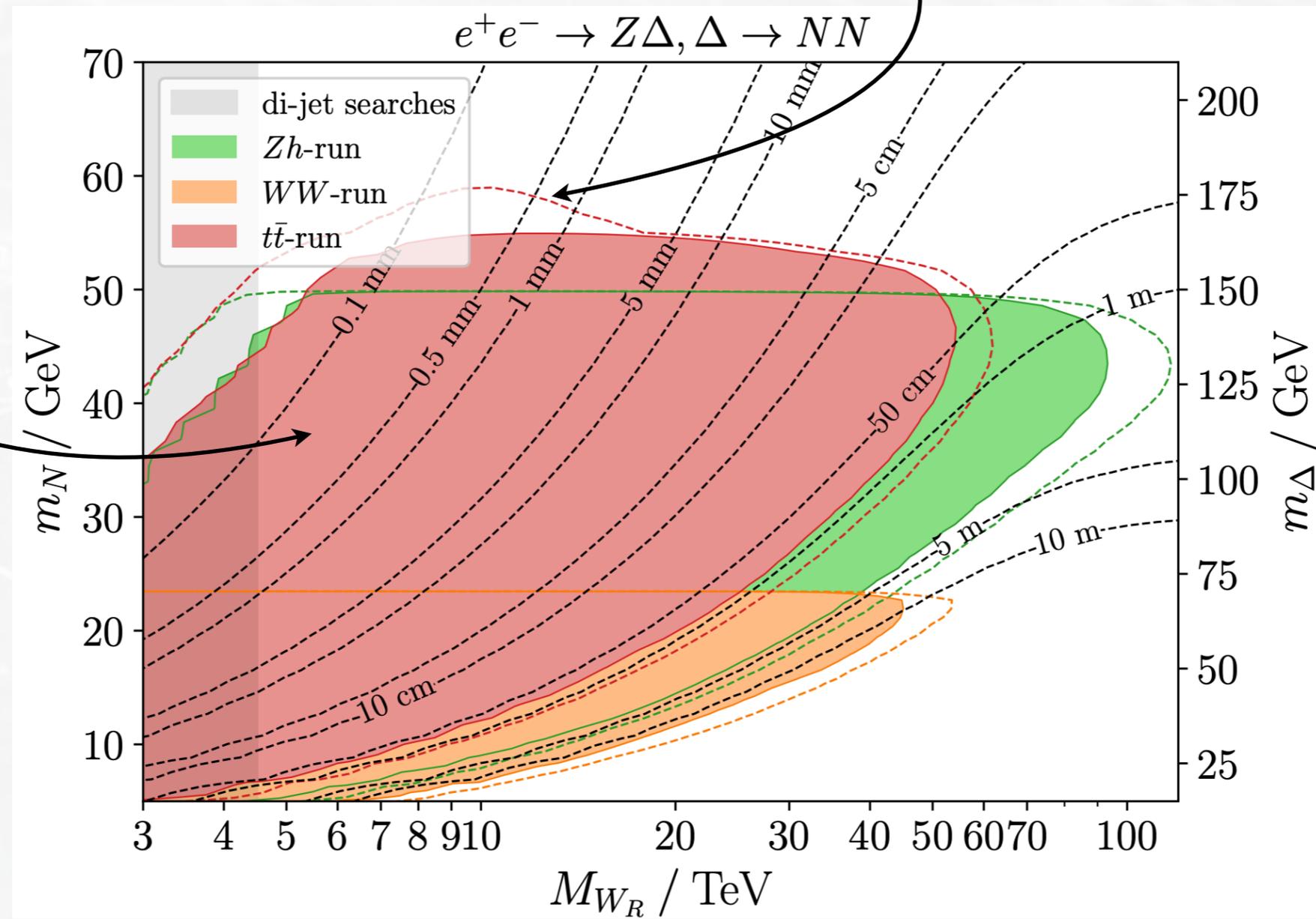
Graph-based vertexing tools in Delphes: JK [arXiv:2510.00856](https://arxiv.org/abs/2510.00856)

Sensitivities at FCC-ee

Theoretical limit

Fuks, JK, Nemevšek, Nesti [arXiv:2602.09095](https://arxiv.org/abs/2602.09095)

Full vertexing analysis



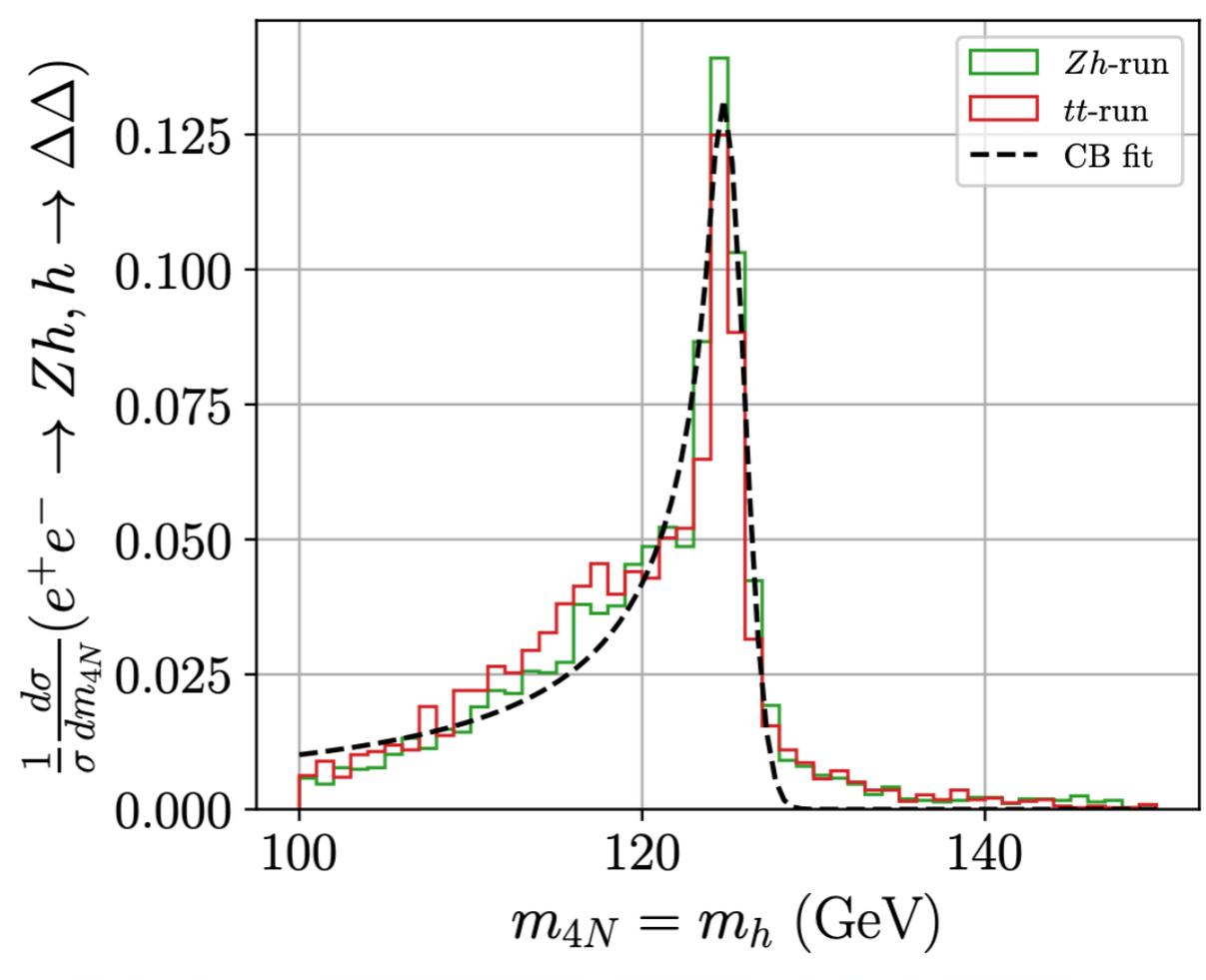
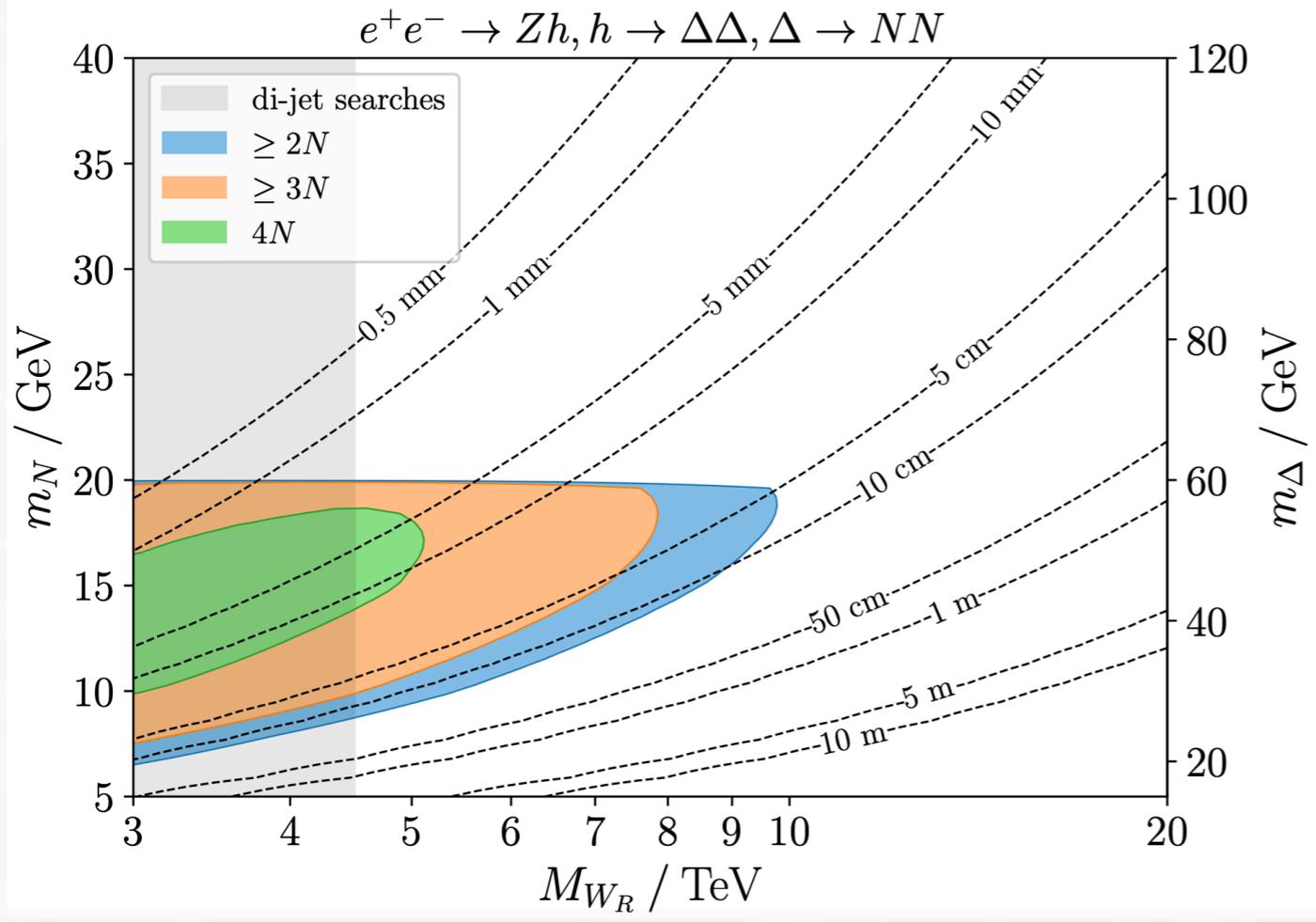
Graph-based vertexing tools in Delphes: JK [arXiv:2510.00856](https://arxiv.org/abs/2510.00856)

More channels in back-up

Sensitivities at FCC-ee

$$h \rightarrow \Delta\Delta \rightarrow 4N$$

Fuks, JK, Nemevšek, Nesti [arXiv:2602.09095](https://arxiv.org/abs/2602.09095)



Reconstructed Higgs mass from 4 displaced N decays!

Conclusion

▶ Heavy Neutral Leptons in type I seesaw and **Left-Right** are very different objects:

Different **production modes** (single vs. double production)

Different **final states** (fully semi-leptonic vs. leptonic)

Different **lifetimes** (mostly displaced vs. mostly prompt)

▶ Suggest new searches for (light) Δ_R^0 in **Left-Right symmetric model**

▶ **Same-sign leptons** from $\Delta_R^0 \rightarrow NN \rightarrow \ell^\pm \ell^\pm + \text{jets}$ decay \Rightarrow **discover LNV**

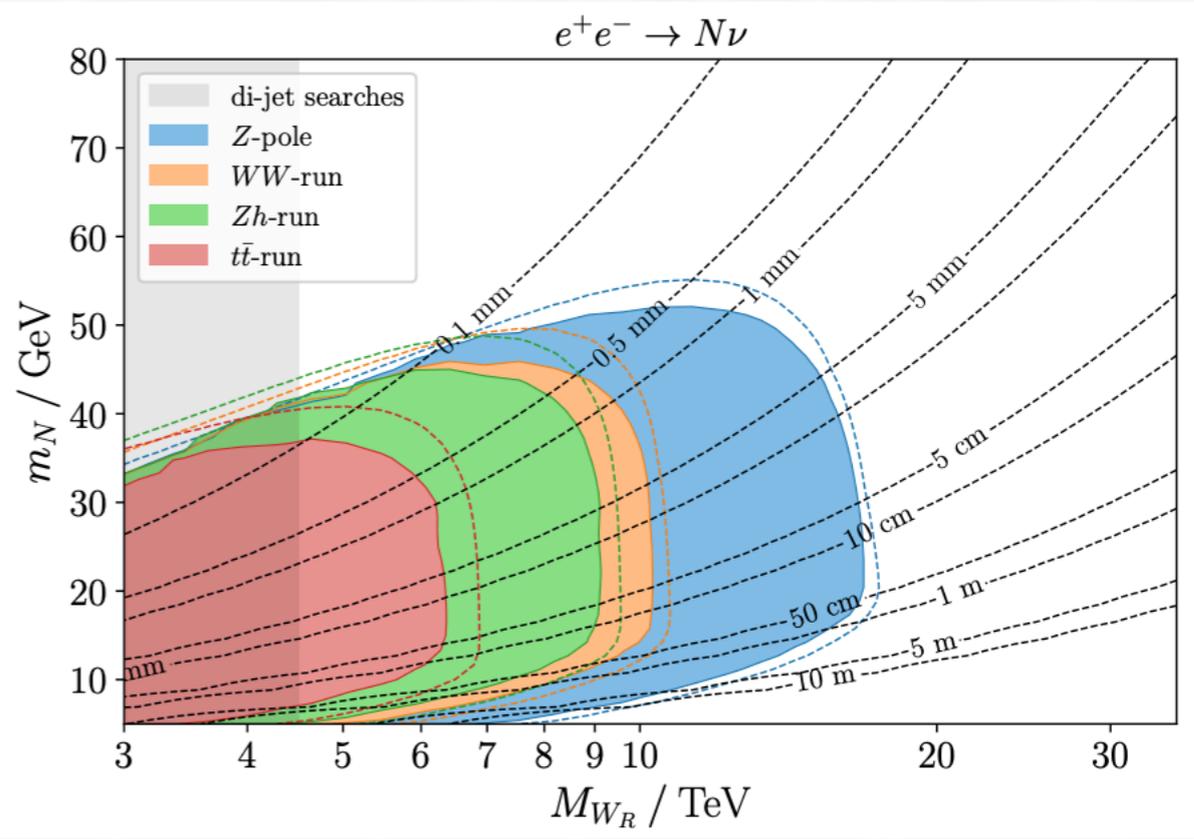
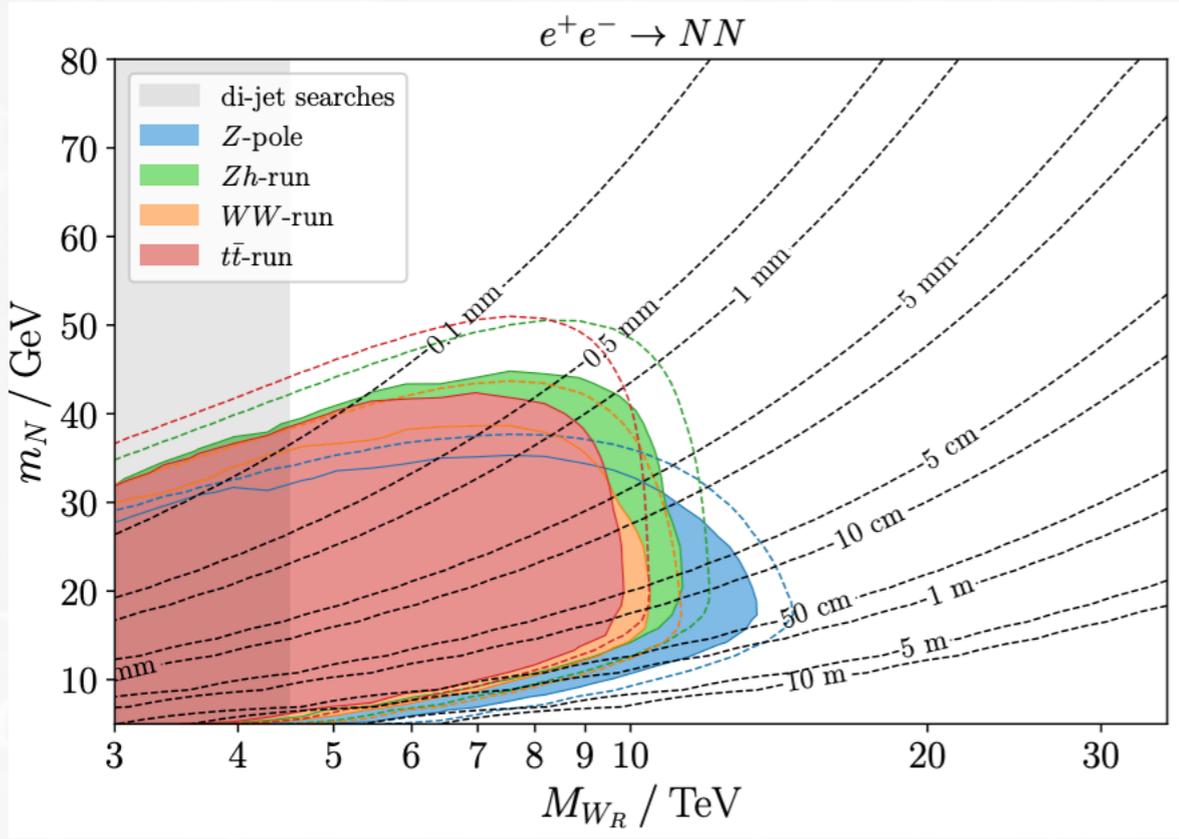
▶ Dedicated **displaced vertex analyses**: $\Rightarrow m_{W_R} \gtrsim 70 - 80 \text{ TeV @ LHC}$

$\Rightarrow m_{W_R} \gtrsim 100 \text{ TeV @ FCC-ee}$

Sensitivities at FCC-ee

Gauge modes

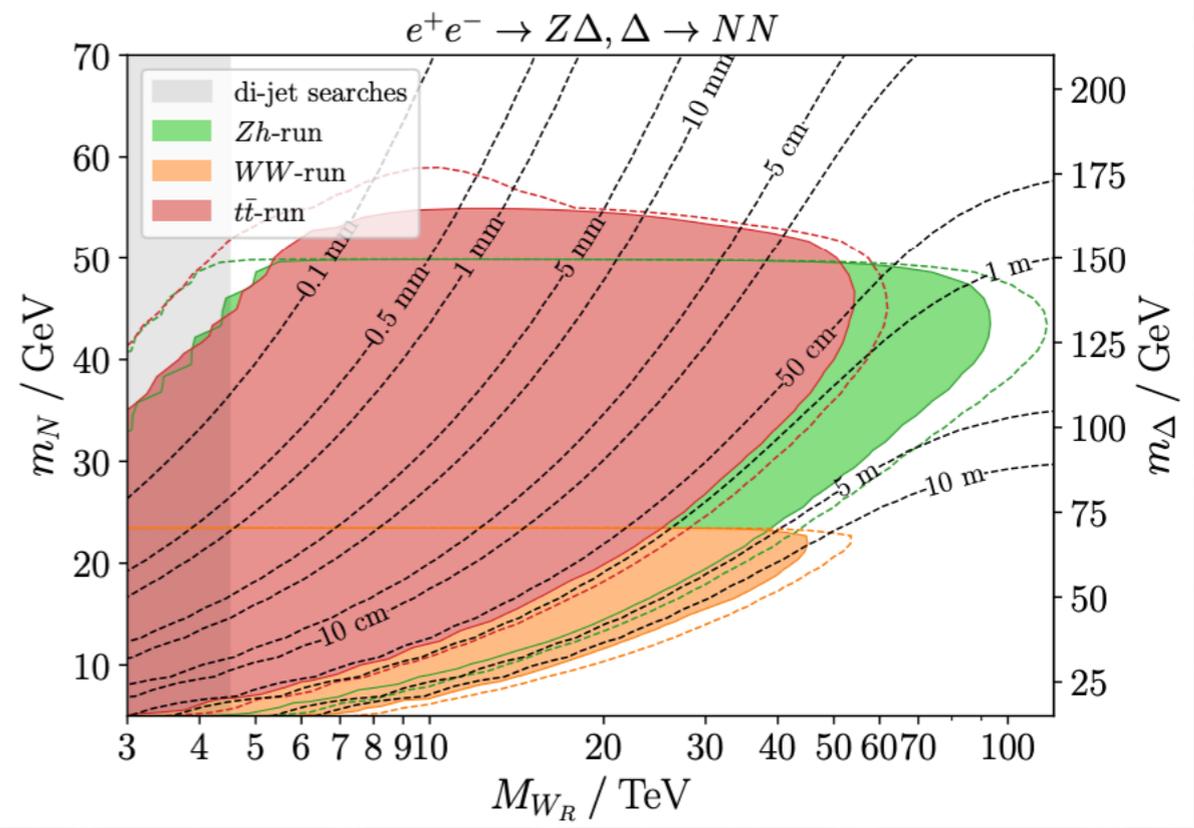
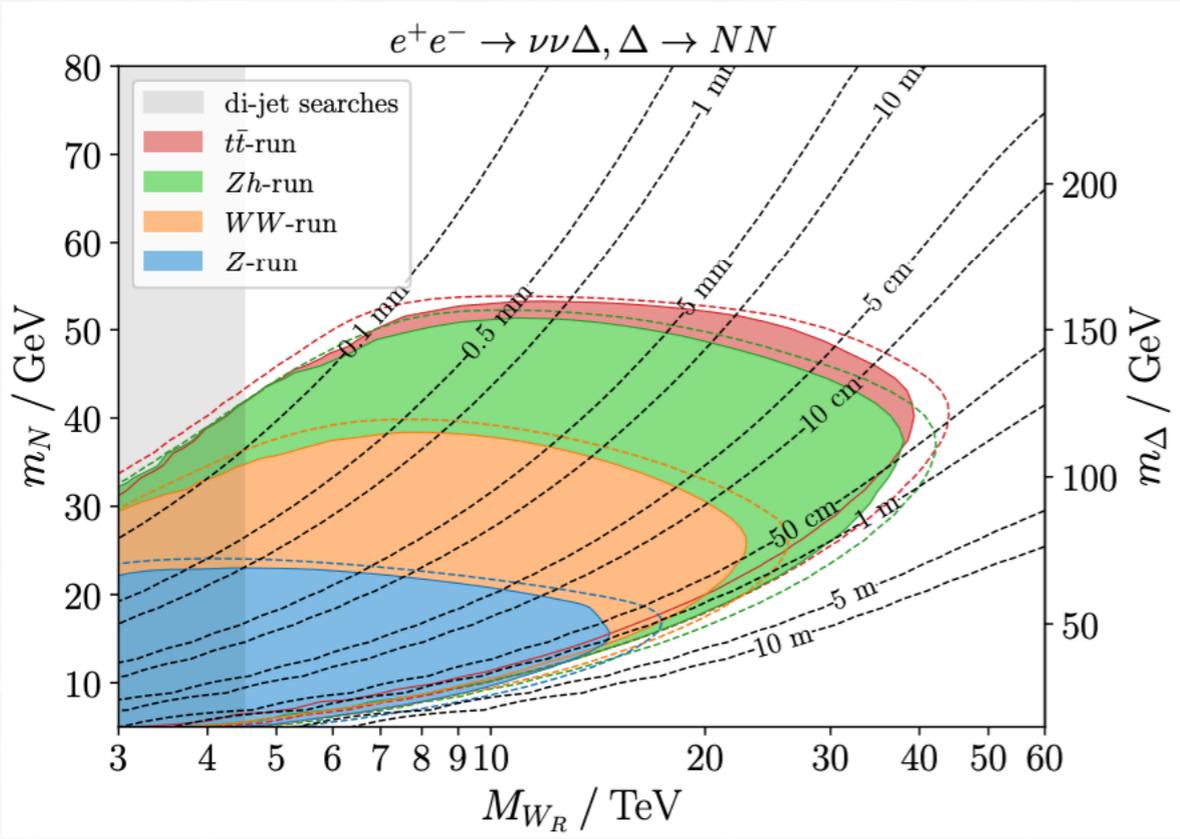
Fuks, **JK**, Nemevšek, Nesti [arXiv:2602.09095](https://arxiv.org/abs/2602.09095)



Sensitivities at FCC-ee

Δ modes

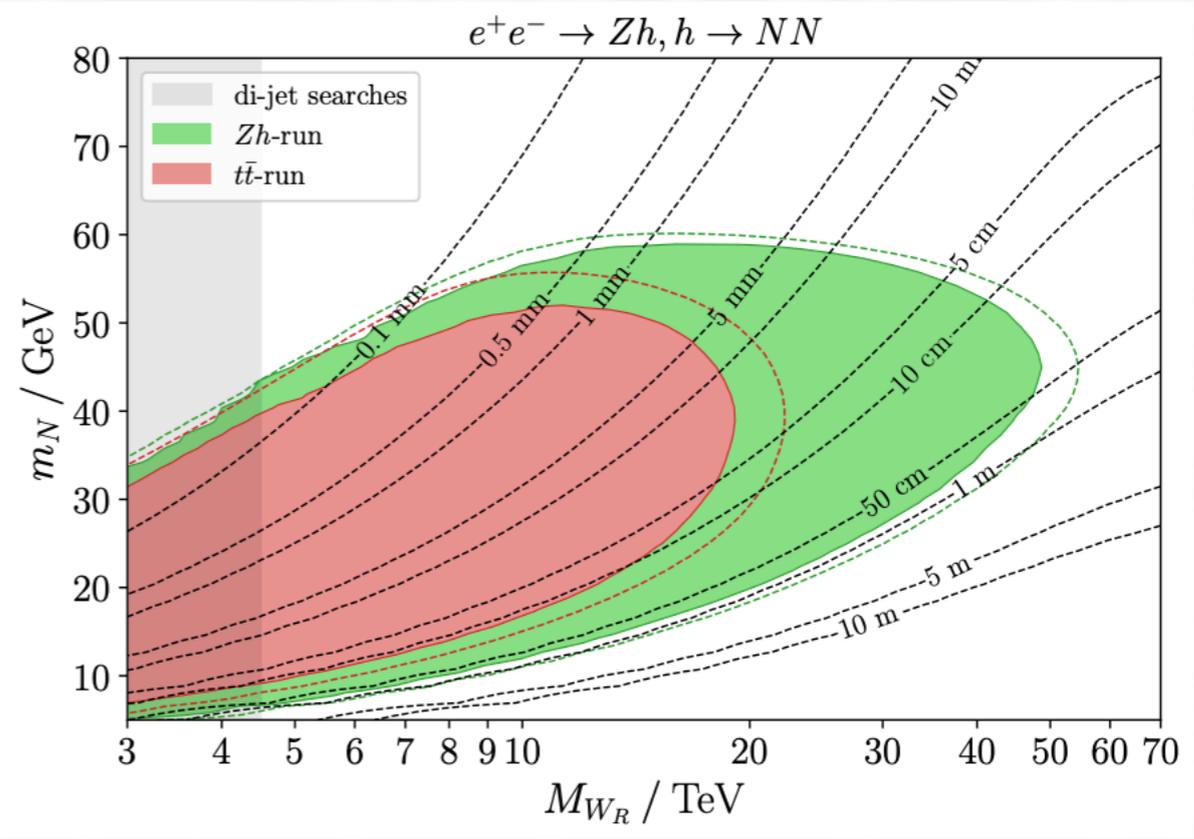
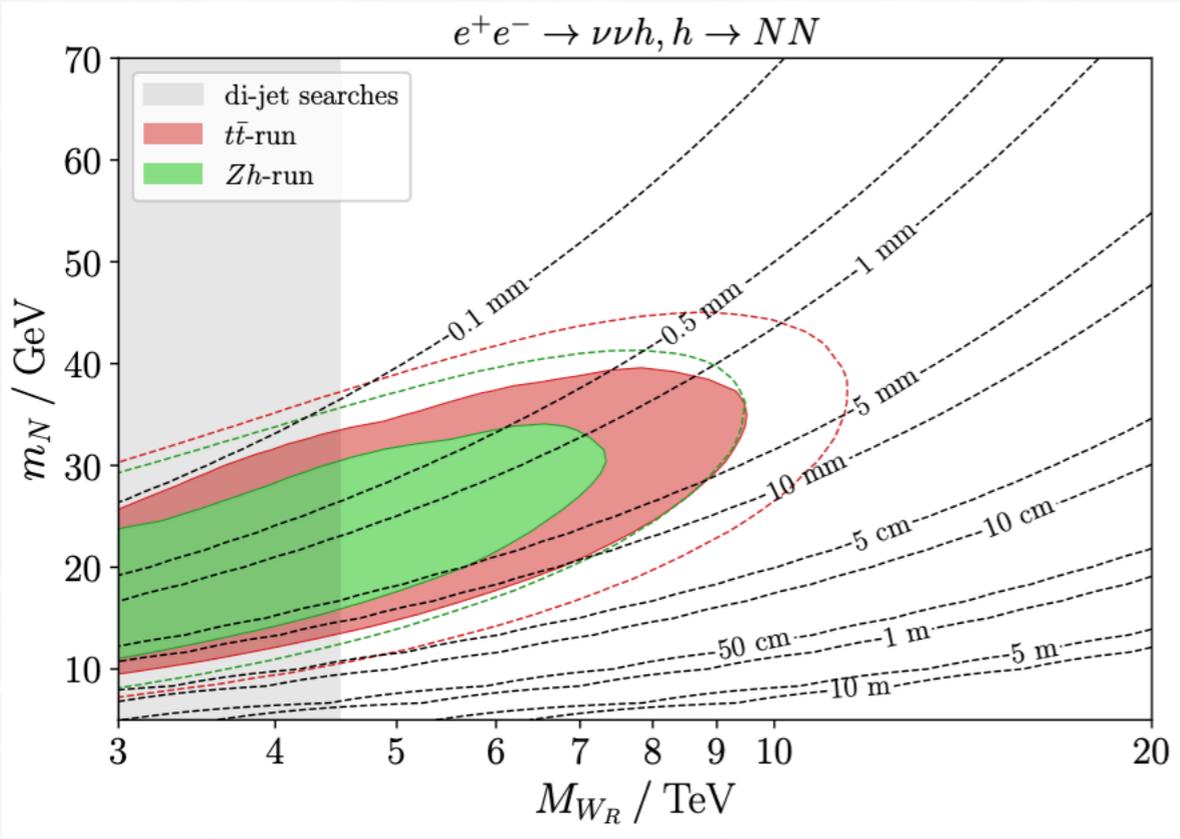
Fuks, **JK**, Nemevšek, Nesti [arXiv:2602.09095](https://arxiv.org/abs/2602.09095)



Sensitivities at FCC-ee

Higgs modes

Fuks, **JK**, Nemevšek, Nesti [arXiv:2602.09095](https://arxiv.org/abs/2602.09095)



Vertex finding

Need to determine a set of tracks to be fitted \Rightarrow **pattern recognition**

Traditional (iterative) methods: optimised for PV finding in **high pile-up**
close secondaries for **flavour tagging**

\Rightarrow not suitable for **exotic LLP topologies**

(recently also optimised graph and GNN methods by ATLAS & CMS)

Vertex finding

Need to determine a set of tracks to be fitted \Rightarrow **pattern recognition**

Traditional (iterative) methods: optimised for PV finding in **high pile-up**
close secondaries for **flavour tagging**

\Rightarrow not suitable for **exotic LLP topologies**

(recently also optimised graph and GNN methods by ATLAS & CMS)

Graph-based approach: tracks are **nodes of compatibility graph**

JK [arXiv:2510.00856]



Vertex finding

Need to determine a set of tracks to be fitted \Rightarrow **pattern recognition**

Traditional (iterative) methods: optimised for PV finding in **high pile-up**
close secondaries for **flavour tagging**

\Rightarrow not suitable for **exotic LLP topologies**

(recently also optimised graph and GNN methods by ATLAS & CMS)

Graph-based approach: tracks are **nodes of compatibility graph**

JK [arXiv:2510.00856]

Build **edges** if $\chi_2^2 \lesssim 9$

(Edge score = pair-fit χ^2)



Vertex finding

Need to determine a set of tracks to be fitted \Rightarrow **pattern recognition**

Traditional (iterative) methods: optimised for PV finding in **high pile-up**
close secondaries for **flavour tagging**

\Rightarrow not suitable for **exotic LLP topologies**

(recently also optimised graph and GNN methods by ATLAS & CMS)

Graph-based approach: tracks are **nodes of compatibility graph**

JK [arXiv:2510.00856]

Build **edges** if $\chi^2_2 \lesssim 9$

(Edge score = pair-fit χ^2)

Erase edges w/o **triplet support**



Vertex finding

Need to determine a set of tracks to be fitted \Rightarrow **pattern recognition**

Traditional (iterative) methods: optimised for PV finding in **high pile-up**
close secondaries for **flavour tagging**

\Rightarrow not suitable for **exotic LLP topologies**

(recently also optimised graph and GNN methods by ATLAS & CMS)

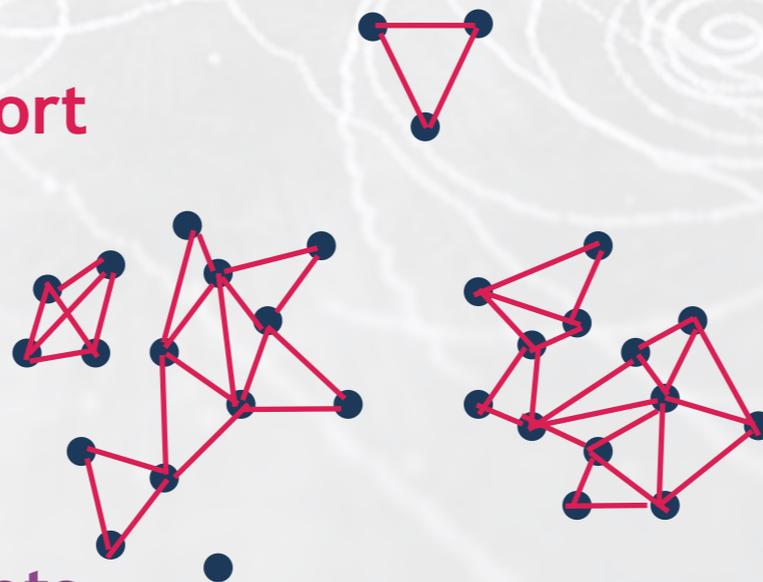
Graph-based approach: tracks are **nodes of compatibility graph**

JK [arXiv:2510.00856]

Build **edges** if $\chi_2^2 \lesssim 9$

(Edge score = pair-fit χ^2)

Erase edges w/o **triplet support**



More pruning/safeguards: timing consistency, mutual kNN , bridge finding/pruning, tests for intra-connectedness,...

Extract **connected components**

\Rightarrow 4 **vertex candidates** to be fitted (+ 1 outlier track)

Vertexing performance

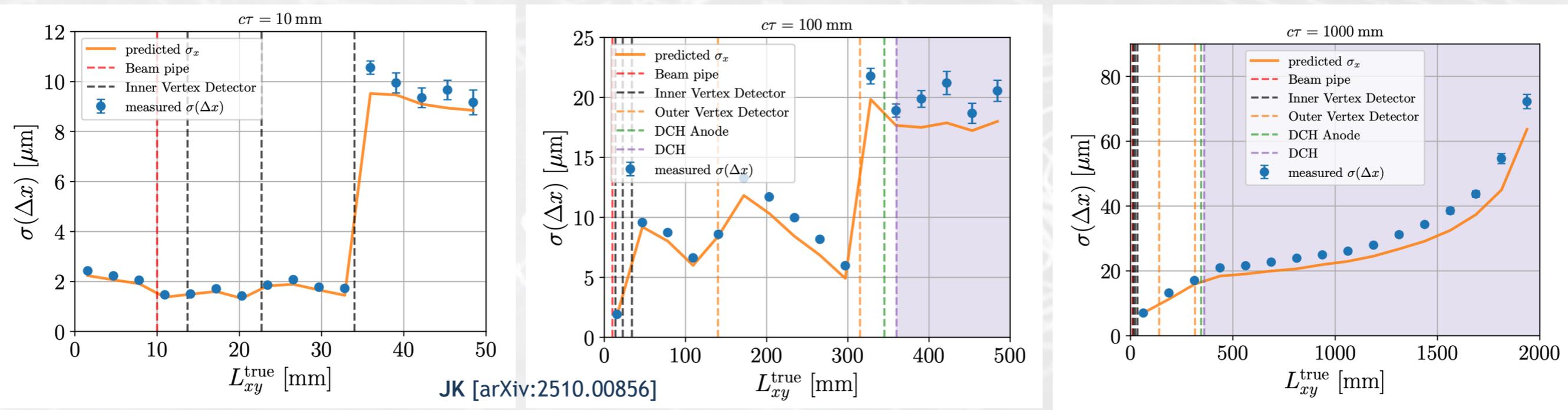
Example process at FCC-ee: $e^+e^- \rightarrow Zh, h \rightarrow NN$ with $N \rightarrow \ell^\pm q\bar{q}'$

Use IDEA detector concept as benchmark: fast sim. with Delphes



DELPHES
fast simulation

Reconstruct **two vertices simultaneously**, $m_N = 45 \text{ GeV}$



Resolution $\lesssim 2 \mu\text{m}$ in the inner vertex Detector!

Uncertainty model agrees well with MC-data (within 5-10%)

