UNIVERSITY OF LJUBLJANA

FMF Faculty of Mathematics and Physics

IJS

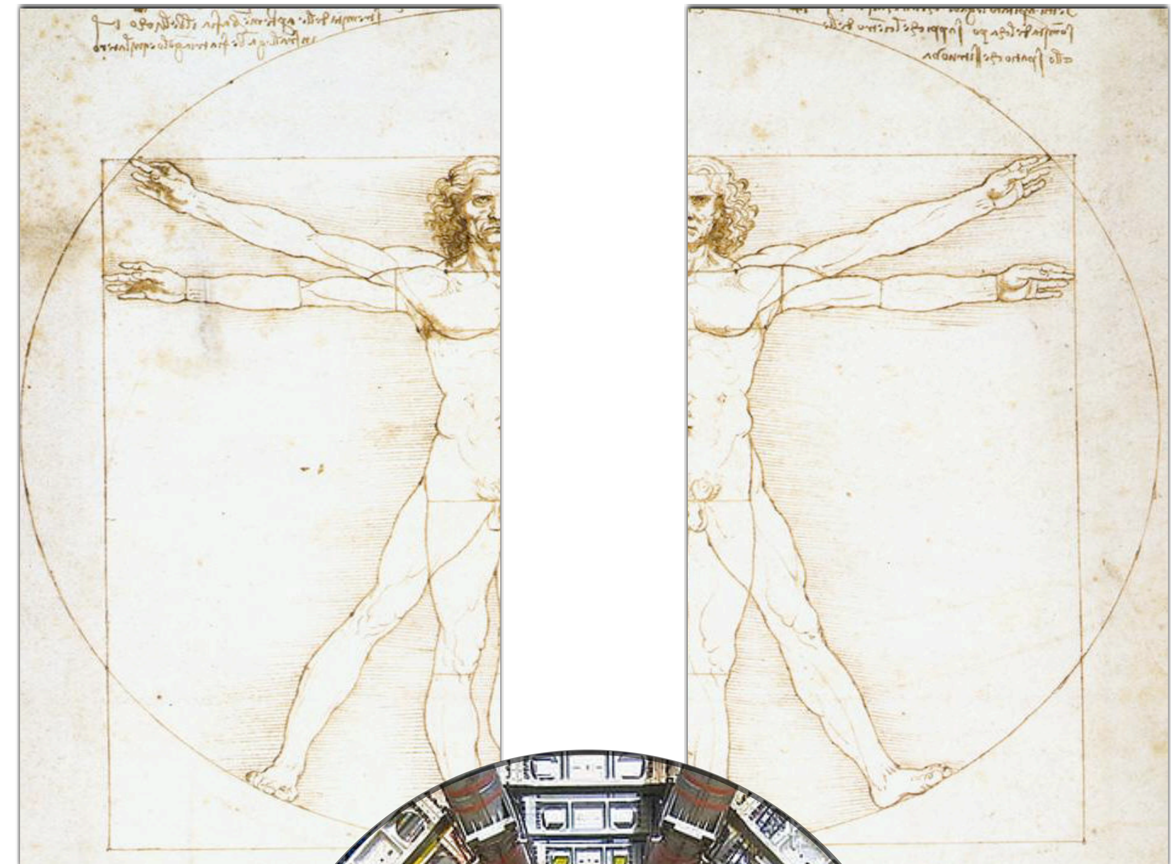
Left-Right Symmetry and Experimental Signals

BLV workshop 2024, KIT, Karlsruhe

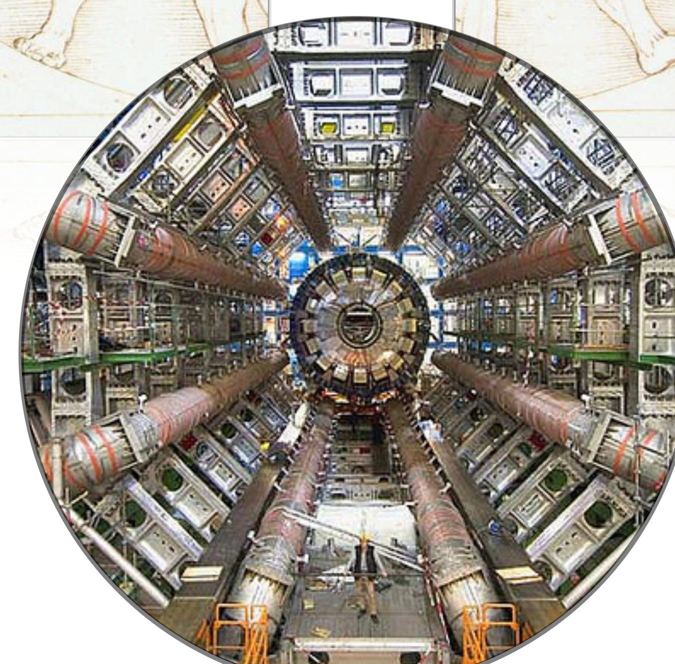
Miha Nemevšek, October 10, 2024

ARIS Slovenian Research and Innovation Agency

LRSM



Colliders & flavour



Dark matter

LRSM Left-Right symmetric model

Pati-Salam

$$SU(4)_c \otimes SU(2)_L \otimes SU(2)_R$$

Trinification

$$SU(3)^3$$

minimal Left-Right

Mohapatra, Pati '75
Senjanović, Mohapatra '75

$$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

Symmetric fermions $$Q = T_{3L} + T_{3R} + \frac{B-L}{2}$$

$$Q_L = \left(3, 2, 1, \frac{1}{3}\right), \qquad Q_R = \left(3, 1, 2, \frac{1}{3}\right)$$

$$L_L = \left(1, 2, 1, \frac{1}{3}\right), \qquad L_R = \left(1, 1, 2, \frac{1}{3}\right)$$

* alternative LR with additional vector-like states

Ma '87, ..., Frank, Fuks et al. '23

LRSM Left-Right symmetric model

Symmetric scalars $\phi = (1, 2, 2, 0)$ bi-doublet

$$\phi = \begin{pmatrix} \phi_1^{0*} & \phi_2^{+} \\ \phi_1^{-} & \phi_2^{0} \end{pmatrix}, \quad \langle \phi \rangle = \begin{pmatrix} v_1 & 0 \\ 0 & -e^{i\alpha} v_2 \end{pmatrix}$$

EWSB $v^2 = v_1^2 + v_2^2\,, \quad 0 \leq \tan\beta = \dfrac{v_2}{v_1} < 1$

LRSM Left-Right symmetric model

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Doublets $\chi_L = (1, 2, 1, 1)\,, \quad \chi_R = (1, 1, 2, 1)$ Dirac $\boldsymbol{\nu}$

this talk $\boxed{\text{Triplets} \quad \Delta_L = (1, 3, 1, 2)\,, \quad \Delta_R = (1, 1, 3, 2) \quad \text{Majorana } \boldsymbol{\nu}}$

$$\langle \Delta_{L,R} \rangle = \begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix}, \quad v_L \lesssim \text{GeV}\,, \quad v = 174 \text{ GeV}\,, \quad v_R \gtrsim \text{TeV}$$

LRSM Left-Right symmetric model

Yukawas

Dirac

$$\bar{Q}_L \left(Y_q \, \phi + \tilde{Y}_q \, \tilde{\phi} \right) Q_R \, , \quad \bar{L}_L \left(Y_\ell \, \phi + \tilde{Y}_\ell \, \tilde{\phi} \right) L_R$$

Majorana

$$\bar{L}_L^c i\sigma_2 \Delta_L Y_L^M L_L + \bar{L}_R^c i\sigma_2 \Delta_R Y_R^M L_R$$

LR Parity

$$\mathcal{P} : Y_D = Y_D^\dagger \qquad \mathcal{P} : Y_L^M = Y_L^R$$

$$\mathcal{C} : Y_D = Y_D^T \qquad \mathcal{C} : Y_L^M = Y_R^{M\,\dagger}$$

Masses and mixings

$$M_u = U_{uL} \, m_u \, U_{uR}^\dagger \, , \quad M_d = U_{dL} \, m_d \, U_{dR}^\dagger$$

$\mathcal{P} : V_R \simeq V_L$ Maiezza, MN, Nesti, Senjanović '10
Senjanović, Tello '14, '15

$\mathcal{C} : V_R = K_u V_L^* K_d$ Maiezza et al. '10

RH leptonic mixings are free

$$M_D = Y_\ell v_1 - \tilde{Y}_\ell e^{-i\alpha} v_2 \, ,$$

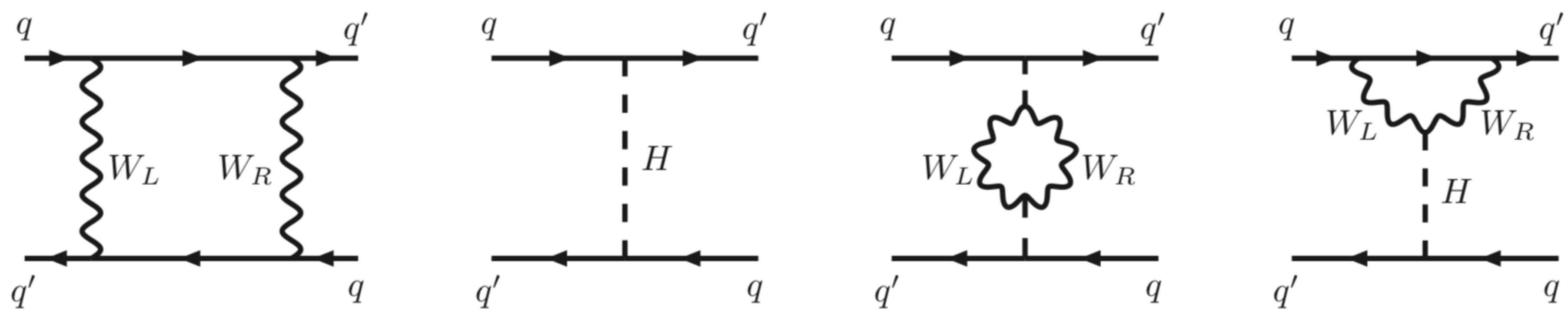
$$M_\ell = -Y_\ell e^{i\alpha} v_2 + \tilde{Y}_\ell v_1$$

* bound on $\tan\beta < 0.5$

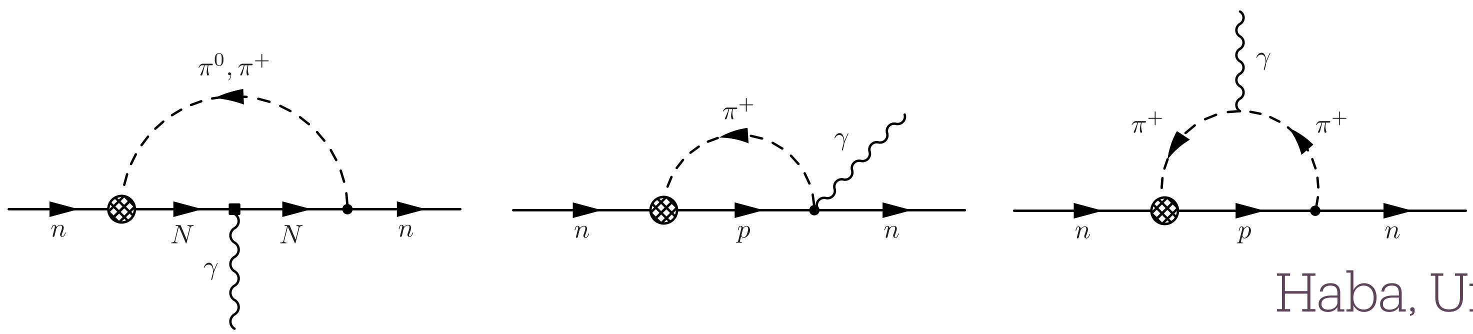
Flavor limits

Maiezza, Nesti, Bertolini '14
Cirigliano, Dekens, de Vries, Mereghetti '16
Dekens, Andreoli, de Vries, Mereghetti, Oosterhof '21

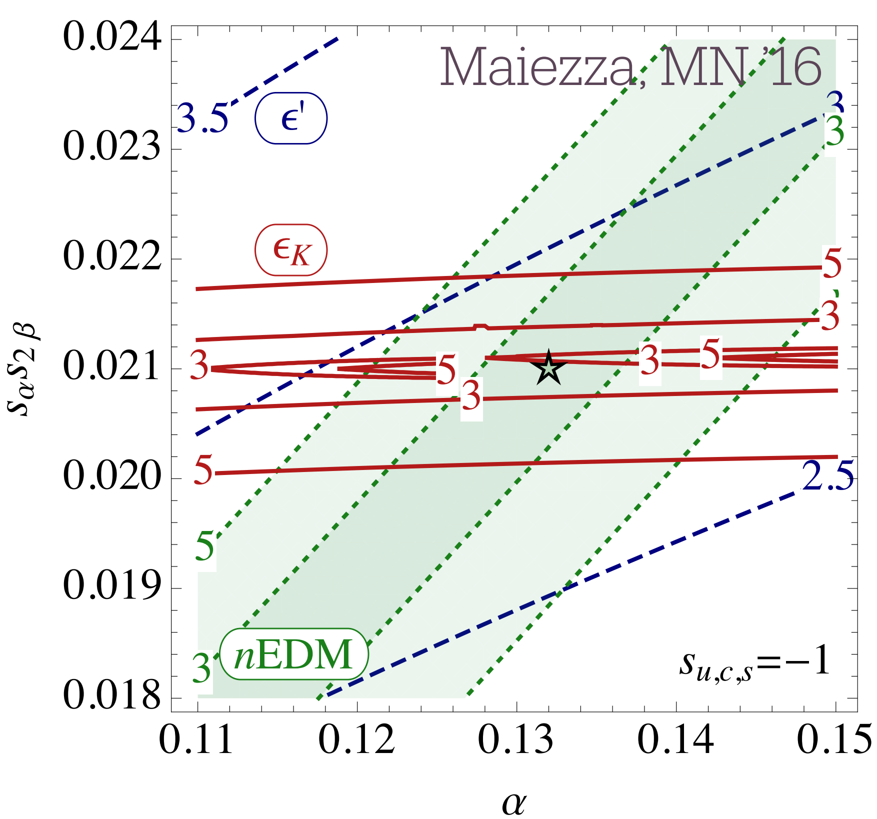
CP-**even** K and B meson mixing

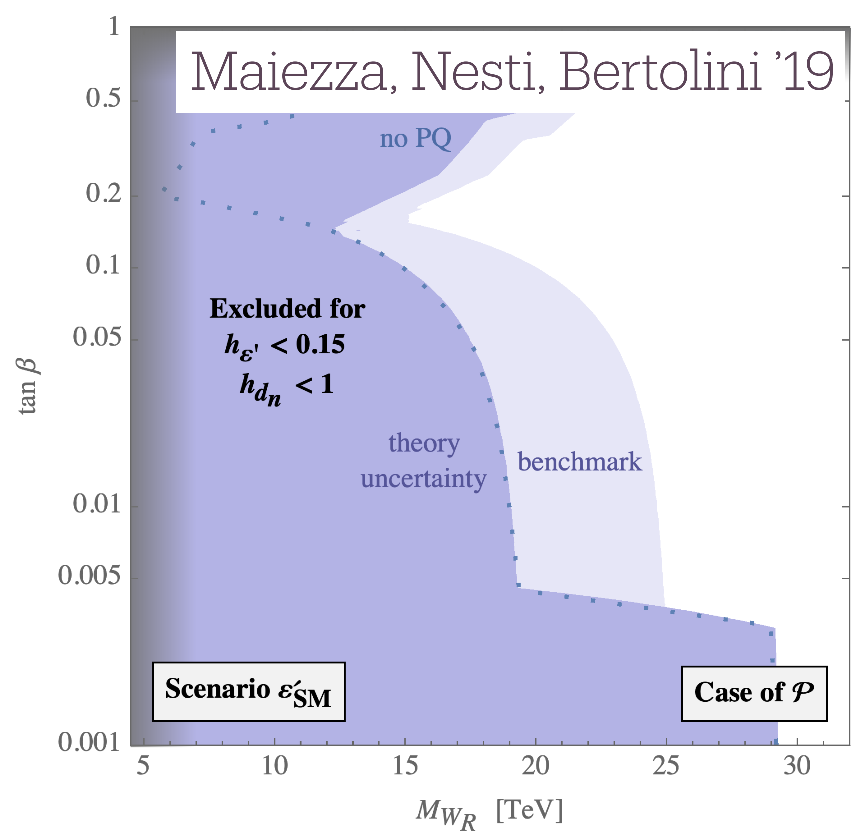


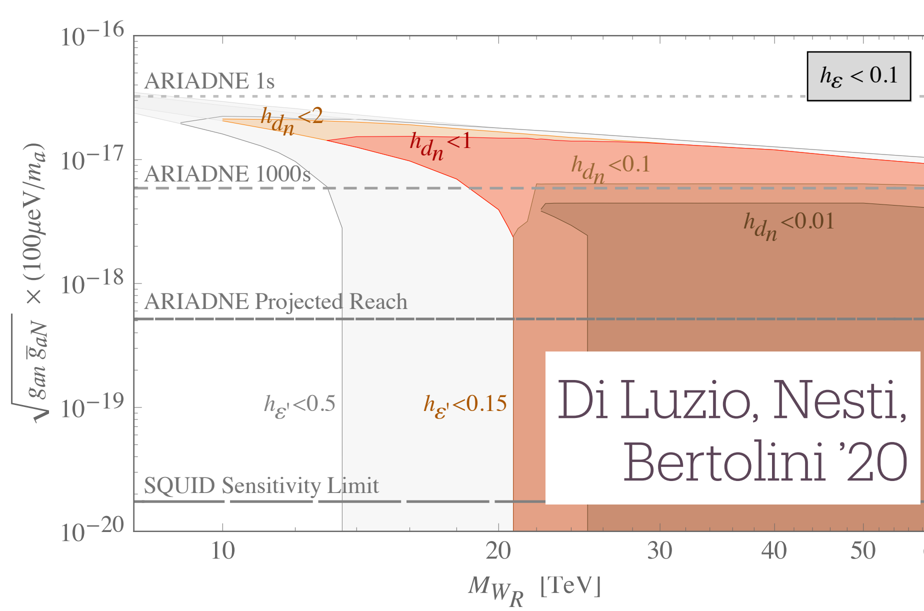
CP-**odd** $\varepsilon, \varepsilon'$ and nEDM



An, Ji, Xu '09
Maiezza, MN '16
Haba, Umeeda, Yamada '17, '18, '18
Ramsey-Musolf, Vasquez '20







Dirac vs. Majorana

Seesaw &
LR parities

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

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

MN, Senjanović, Tello '12

Dirac vs. Majorana

Seesaw &
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MN, Senjanović, Tello '12

Analytic solution via Cayley-Hamilton $p(\lambda_i) = 0 \Rightarrow p(A) = 0$

Kriewald, MN, Nesti '24

$$\sqrt{A} = c_0\,\mathbb{I} + c_1\,A + c_2\,A.A\,, \quad A \in \mathbb{C}_{3\times 3}$$

c_i depend on three invariants of A

Dirac vs. Majorana

Seesaw & LR parities

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

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MN, Senjanović, Tello '12

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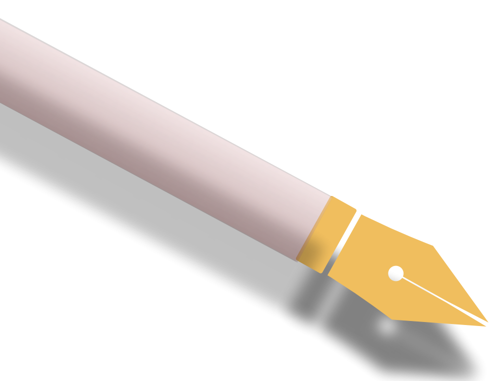


$$\sqrt{A} = c_0\,\mathbb{I} + c_1\,A + c_2\,A.A\,, \quad A \in \mathbb{C}_{3\times 3}$$
$$= \pm \frac{A^2 + \left(\tilde{T}_{1/2} - T_{1/2}^2\right) A - \sqrt{\Delta}\, T_{1/2}\,\mathbb{I}}{\sqrt{\Delta} - T_{1/2}\tilde{T}_{1/2}}$$

c_i depend on three invariants of A

$$\boxed{T} = \mathrm{tr}\ A\,,$$
$$T_2 = \mathrm{tr}\ A.A\,,$$
$$\boxed{\Delta} = \det A\,,$$

$$T_{1/2} = \mathrm{tr}\ \sqrt{A} = \frac{\pm\eta_s + s\,\chi}{2\sqrt{6\xi}}\,, s = \pm\,,$$
$$T_{2,1/2} = \mathrm{tr}\ \sqrt{A}.\sqrt{A} = \boxed{T}\,,$$
$$\Delta_{1/2} = \det\sqrt{A} = \sqrt{\boxed{\Delta}}\,,$$
$$\tilde{T}_{1/2} = \frac{1}{2}\left(T_{1/2}^2 - T\right)$$

$$\xi^3 = -32\left(5T^3 - 9TT_2 - 54\Delta\right) + 96 \sqrt{3\left(T^2 - 2T_2\right)\left(T^2 - T_2\right)^2 + 12T\left(9T_2 - 5T^2\right)\Delta + 324\Delta^2}\,,$$
$$\chi^2 = -16\,\sqrt[3]{2}\,T^2 + 48\,\sqrt[3]{2}\,T_2 + 8T\xi + \sqrt[3]{4}\,\xi^2\,,$$
$$\eta_\pm^2 = 16\,\sqrt[3]{2}\left(T^2 - 3T_2\right) + \xi\left(16T - \sqrt[3]{4}\,\xi \pm 96\sqrt{6}\,\chi^{-1}\sqrt{\Delta\xi}\right)$$

$\mathcal{P}$ complicated

Senjanović, Tello '16, '18
Kiers[2], Szynkman, Tarutina '23

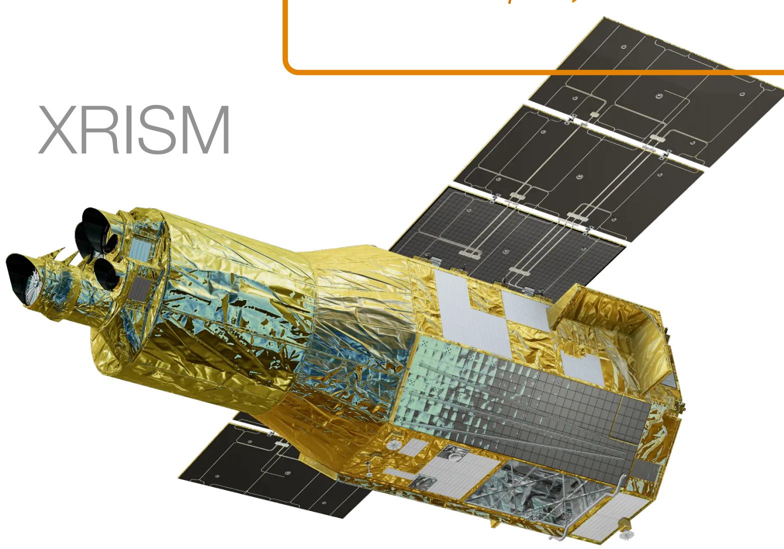
Colliders, wDM, $0\nu 2\beta$

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

Colliders, eEDM, $0\nu 2\beta$, X-rays,…

Oscillations, CnuB, cosmo, KATRIN, …

XRISM



Kriewald, MN, Nesti '24

Model file in FeynRules, UFOs at NLO

https://sites.google.com/site/leftrighthep/1-lrsm-feynrules
https://feynrules.irmp.ucl.ac.be/wiki/LRSM_NLO

LRSM model file complete FeynRules

Kriewald, MN, Nesti '24

physical input scheme: masses & mixings, quartics computed

gauge sector $M_W, M_Z, M_{W_R}, \tan\beta \quad \Rightarrow \quad M_{Z_{L,R}}, U_W, O_Z$

expansion and decoupling with $\boxed{\epsilon} = \dfrac{v}{v_R} \xrightarrow{v_R \to \infty} 0$

$$\frac{M_{Z_{LR}}}{M_{W_R}} \simeq \sqrt{\frac{2c_w^2}{c_{2w}}} \left(1 + \frac{\epsilon^2}{8} \frac{c_{2w}^2}{c_w^4}\right) \simeq 1.67$$

charged and neutral would-be-Goldstones in L and R

$$\mathcal{L}_{\text{kin}} \ni -i \sum_{i=L,R} M_{W_i} W_i^- \partial \varphi_i^+ \,, \quad \mathcal{L}_{\text{gf}} \ni -\sum_{i=L,R} \frac{1}{\xi_{W_i}} F_i^+ F_i^- \,, \quad F_i^+ = \partial W_i^+ + i \xi_{W_i} M_{W_i} \varphi_i^+$$

usual CKM with CPV $V_L^{\text{CKM}}, V_R = K_u V_R^{\text{CKM}} K_d$ RH PMNS free

allow for explicit parity breaking $\dfrac{g_R}{g_L} \equiv \zeta > \tan\theta_w \simeq 0.53$

LRSM model file

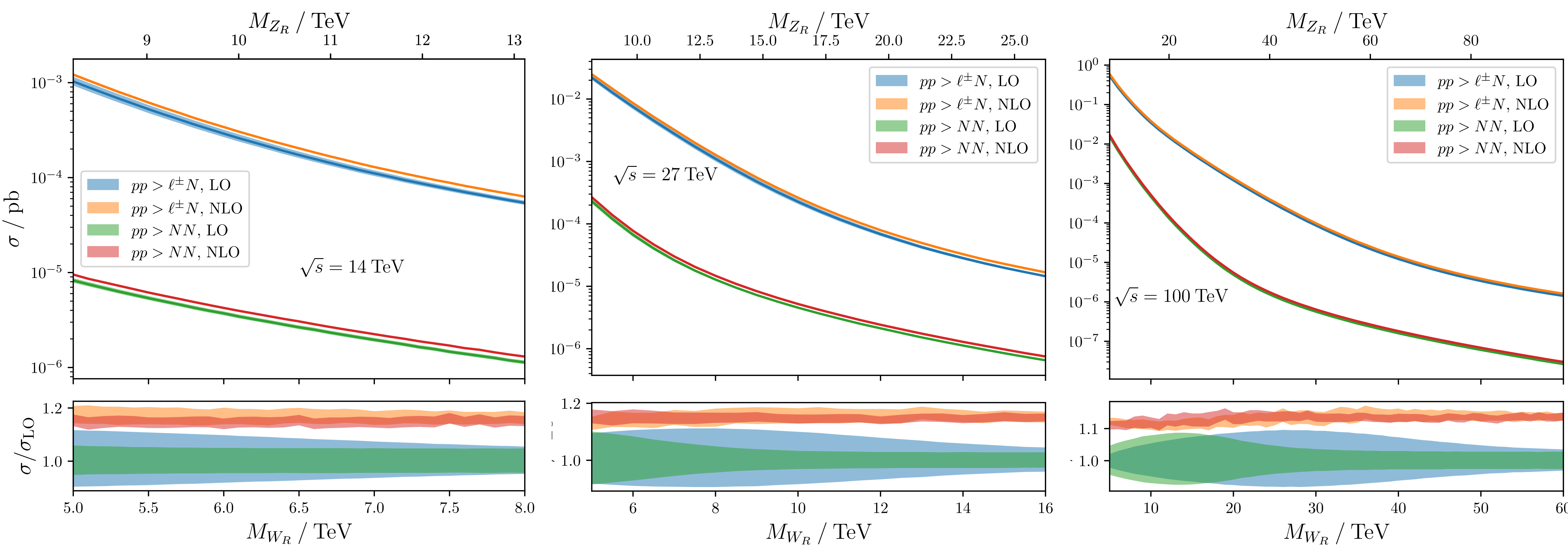
Kriewald, MN, Nesti '24

LRSM going to QCD NLO, using MoGRe

Frixione et al. '19

updated precise predictions $pp \to W_R, Z_{L,R}$ and $pp \to lN, NN$

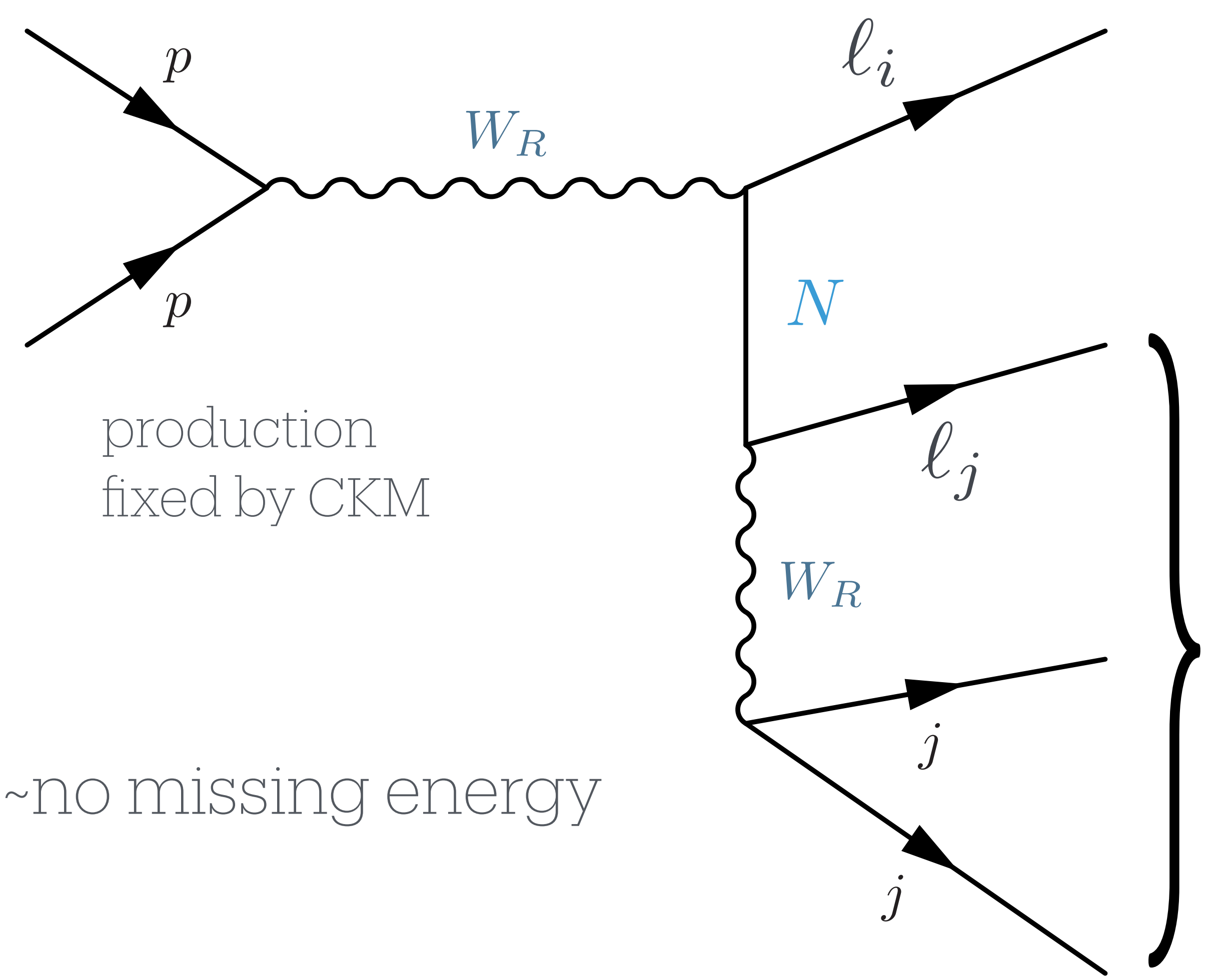
LHC FCC-hh



reduced uncertainties, K-factors of 1.1

Signal topologies

Keung, Senjanović '83



production
fixed by CKM

~no missing energy

Lepton Number Violation

Dual flavometer - six channels

$$M_N = V_R^* m_N V_R^\dagger$$

$$m_{\ell jj} = m_N$$

50-50% same-opposite sign

2 vs. 3 body decays via M_D and ξ

narrow mass peaks for $m_N < M_{W_R}$

more on the Majorana nature

LNV vs. LNC states

Gluza, Jelinski '15 '16,
Das, Dev, Mohapatra '17,
Godbole et al. '20

Golden channel: $pp \to W_R \to \ell_R N$

Keung, Senjanović '83

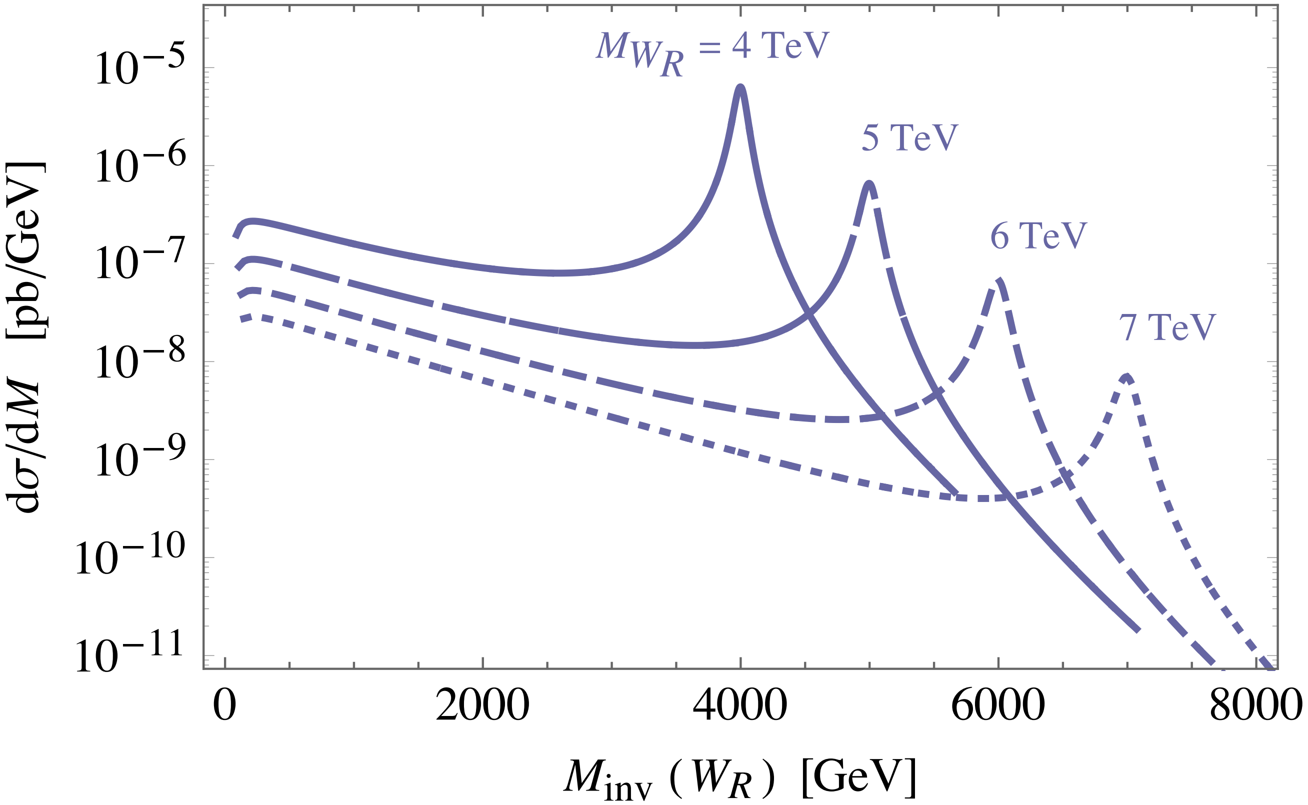
$$\hat\sigma_{ij}^{\ell N}(\hat s) = \frac{\alpha_2^2 \pi}{72 \hat s^2} \left|V_{ij}^{\rm CKM}\right|^2 \frac{\left(\hat s - m_N^2\right)^2 \left(2\hat s + m_N^2\right)}{\left(\hat s - M_{W_R}^2\right)^2 + M_{W_R}^2 \Gamma_{W_R}^2}$$

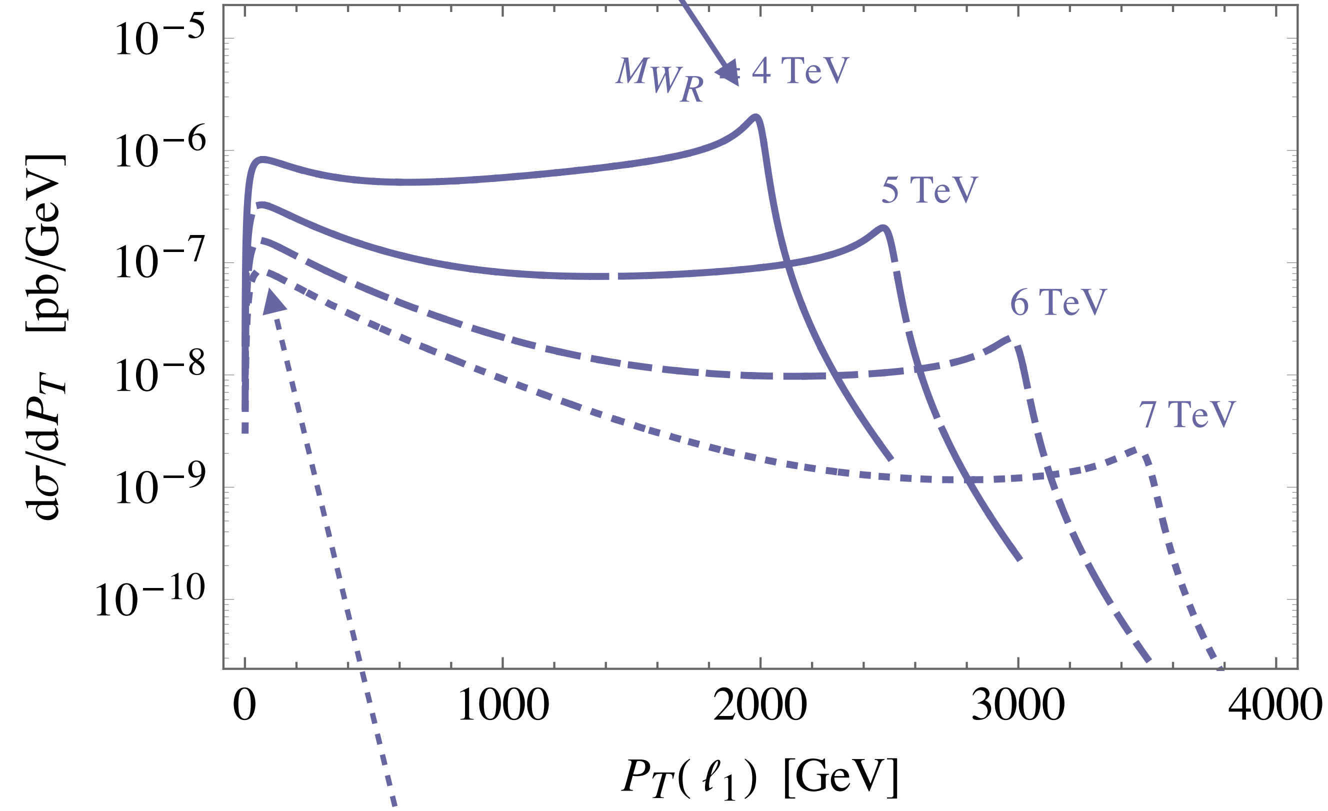
MN, Nesti, Popara '18

clear peaks

mostly on-shell, N boosted

MN, Nesti, Popara '18





$m_{\rm inv}$ disappears

off-shell = soft lepton and N

Ruiz '17

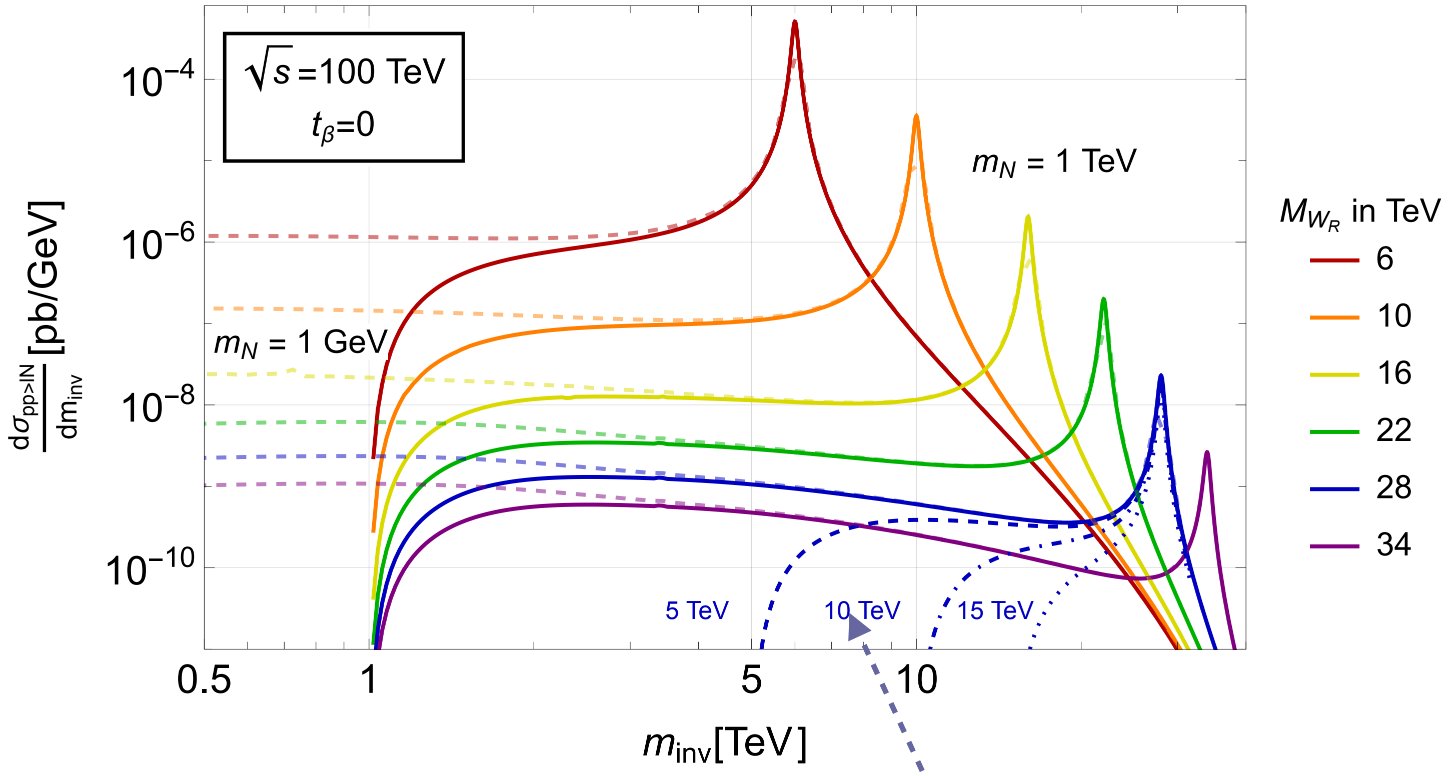
Golden channel: $pp \to W_R \to \ell_R N$

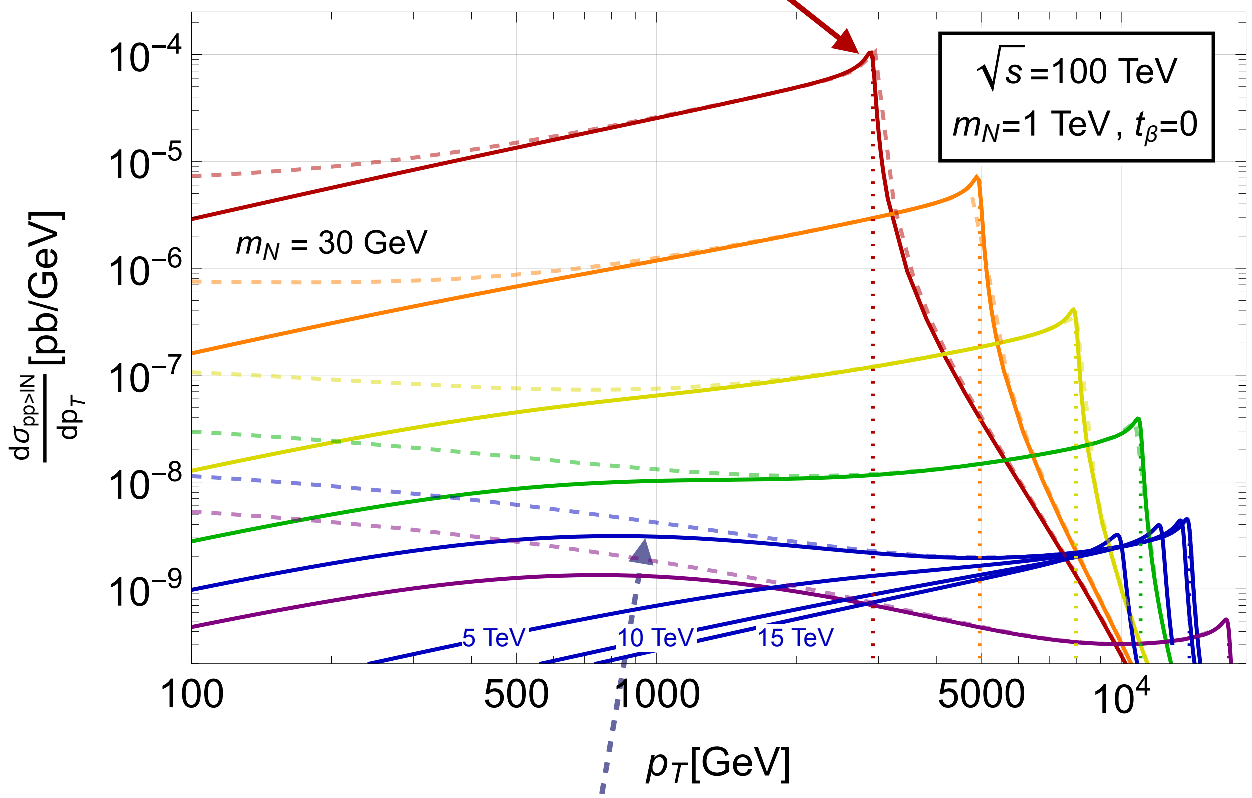
Keung, Senjanović '83

$$\hat{\sigma}_{ij}^{\ell N}(\hat{s}) = \frac{\alpha_2^2 \pi}{72 \hat{s}^2} \left| V_{ij}^{\rm CKM} \right|^2 \frac{\left(\hat{s} - m_N^2\right)^2 \left(2\hat{s} + m_N^2\right)}{\left(\hat{s} - M_{W_R}^2\right)^2 + M_{W_R}^2 \Gamma_{W_R}^2}$$

MN, Nesti '23 future colliders

mostly on-shell, N boosted





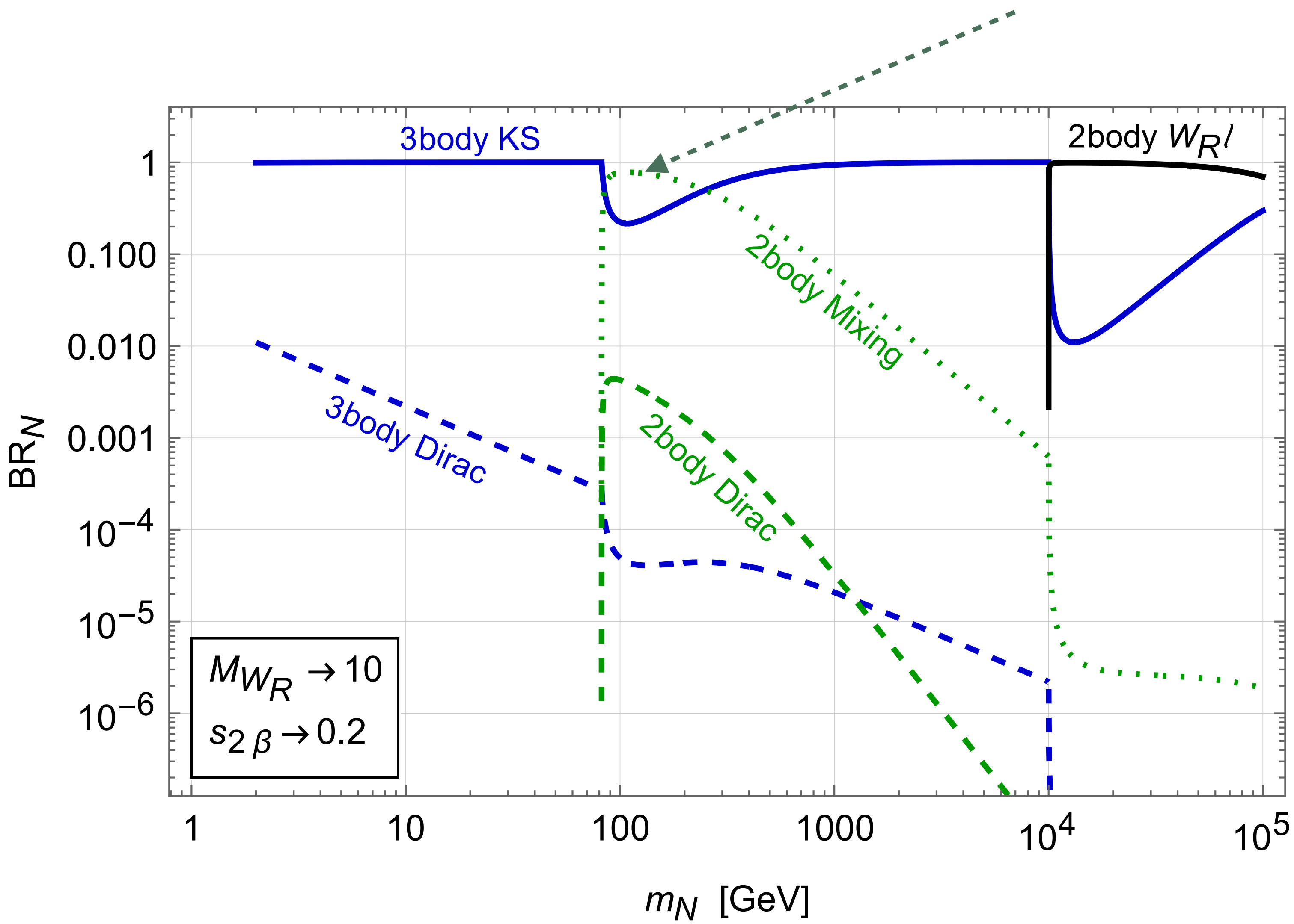
off-shell = soft lepton and N

phase space suppression

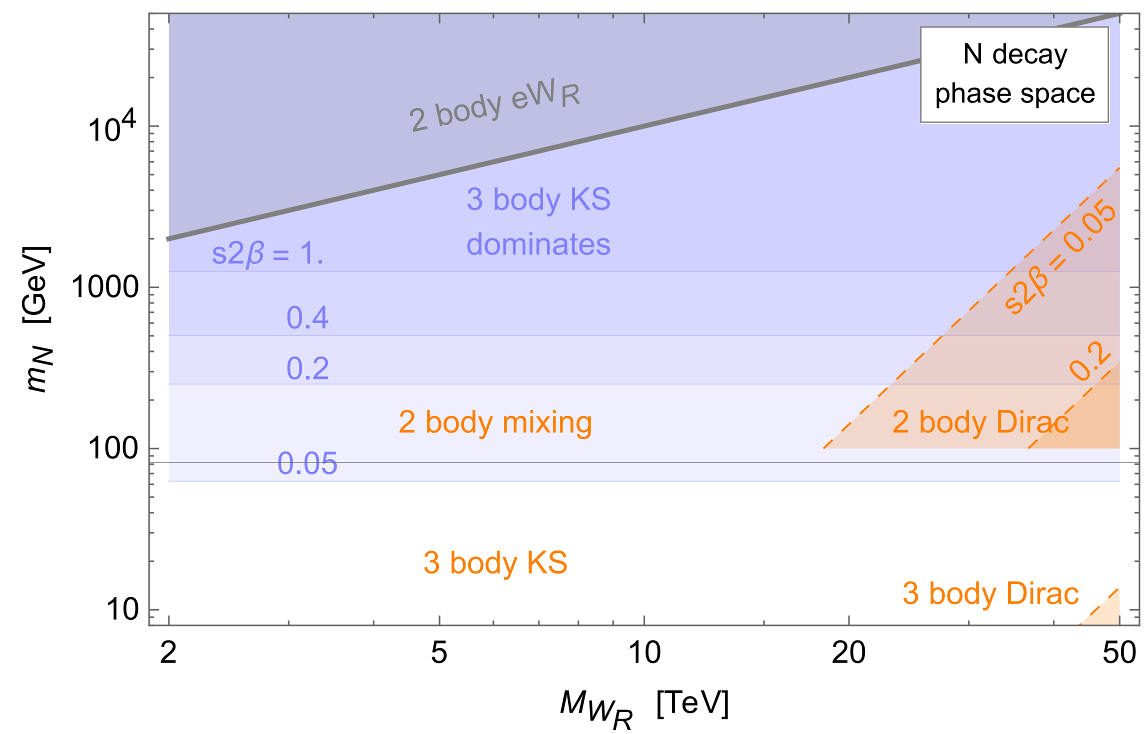
N decay phase space

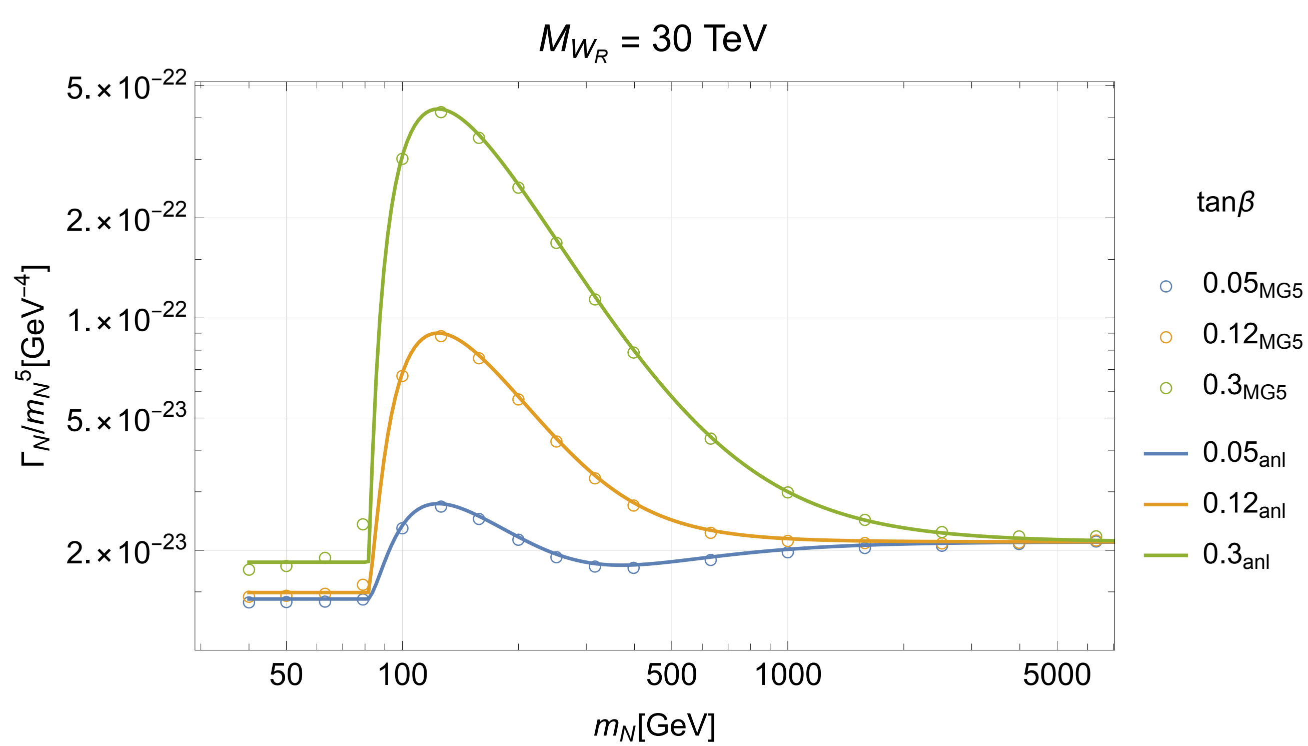
MN, Nesti '23

g.b. mixing



2 vs. 3 body decays via M_D and ξ





Total rate bumps up with two body decay

see also Li, Ramsey-Musolf, Vasquez '22

Displaced for large W_R

Sketch of a search : $pp \to W_R \to \ell_R N$

MN, Nesti, Senjanović, Zhang '11

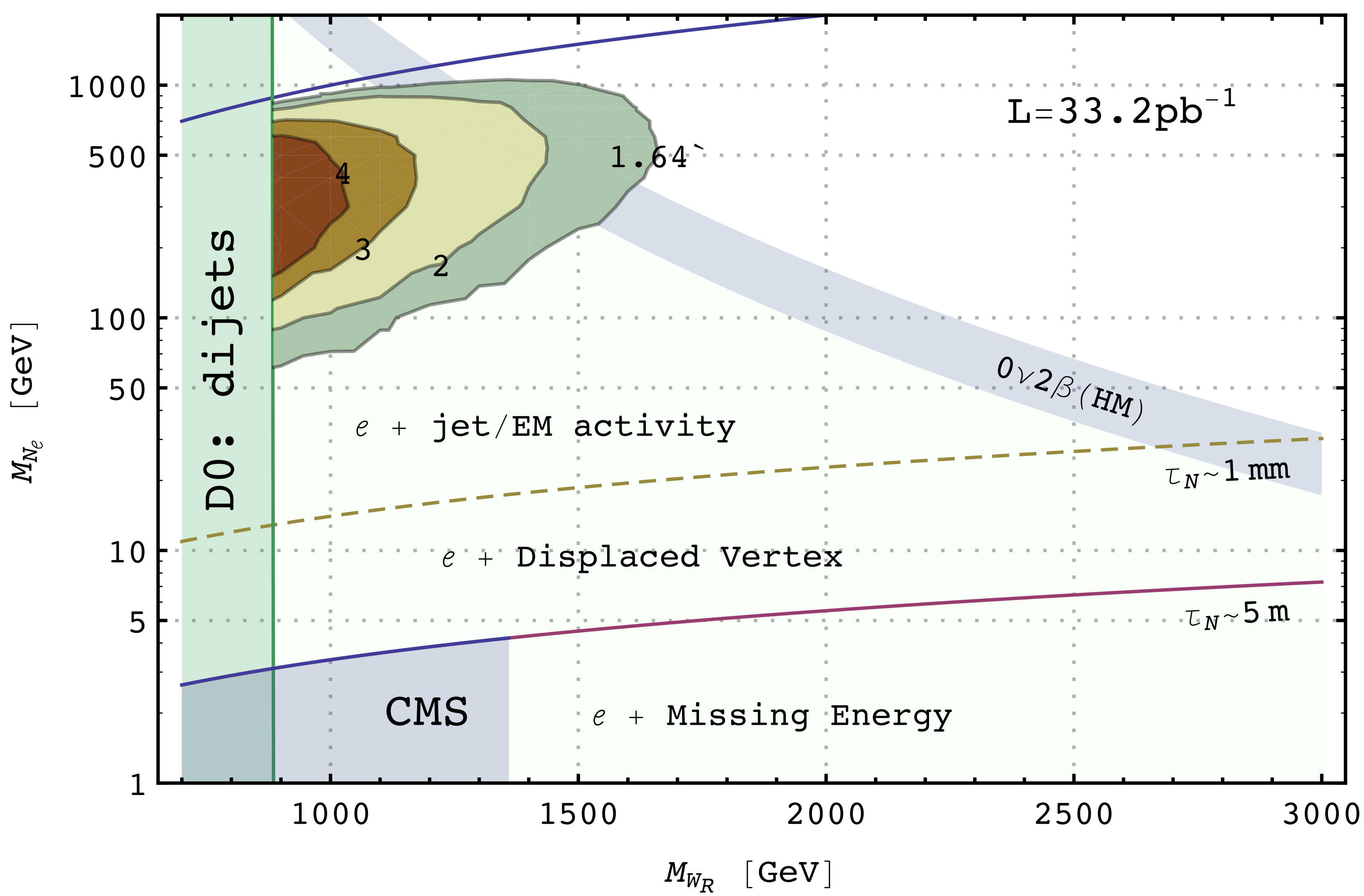
separated eejj

merged neutrino jet

Mattelaer, Mitra, Ruiz '16

displaced jet

missing energy



first LHC data, low bound

LNV relation to $0\nu2\beta$

Reach of 5-6 TeV at 14 TeV

ATLAS: Ferrari et al. '00
CMS: Gninenko et al. '07

Isolation and displacement $pp \to W_R \to \ell_R N$

MN, Nesti, Popara '18

2nd lepton isolation depends on the boost of N

$$\gamma_N \simeq \begin{cases} \frac{M_{W_R}}{2 m_N}, & W_R \to \text{on-shell}, \\ \frac{1\ \text{TeV}}{m_N}, & W_R \to \text{off-shell} \end{cases}$$

Lab decay length very sensitive to m_N

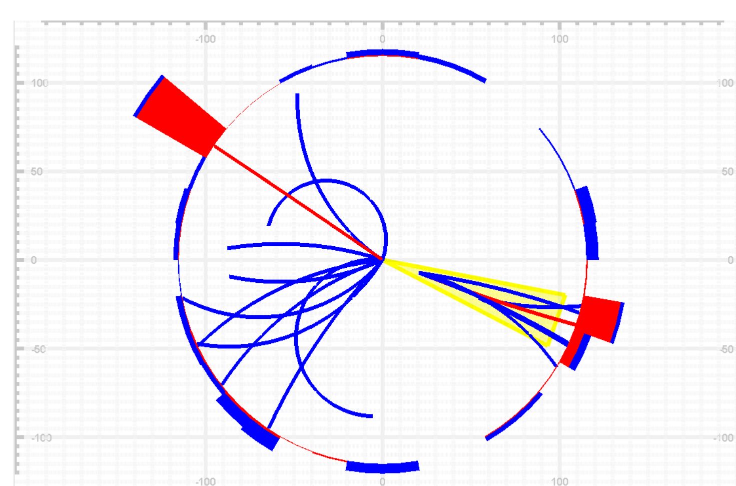
$$\Gamma_N^0 \sim \frac{\alpha_2^2 m_N^5}{64\pi M_{W_R}^4} \simeq \frac{1}{2.5\,\text{mm}} \frac{(m_N/10\ \ \text{GeV})^5}{(M_{W_R}/3\ \ \text{TeV})^4}$$

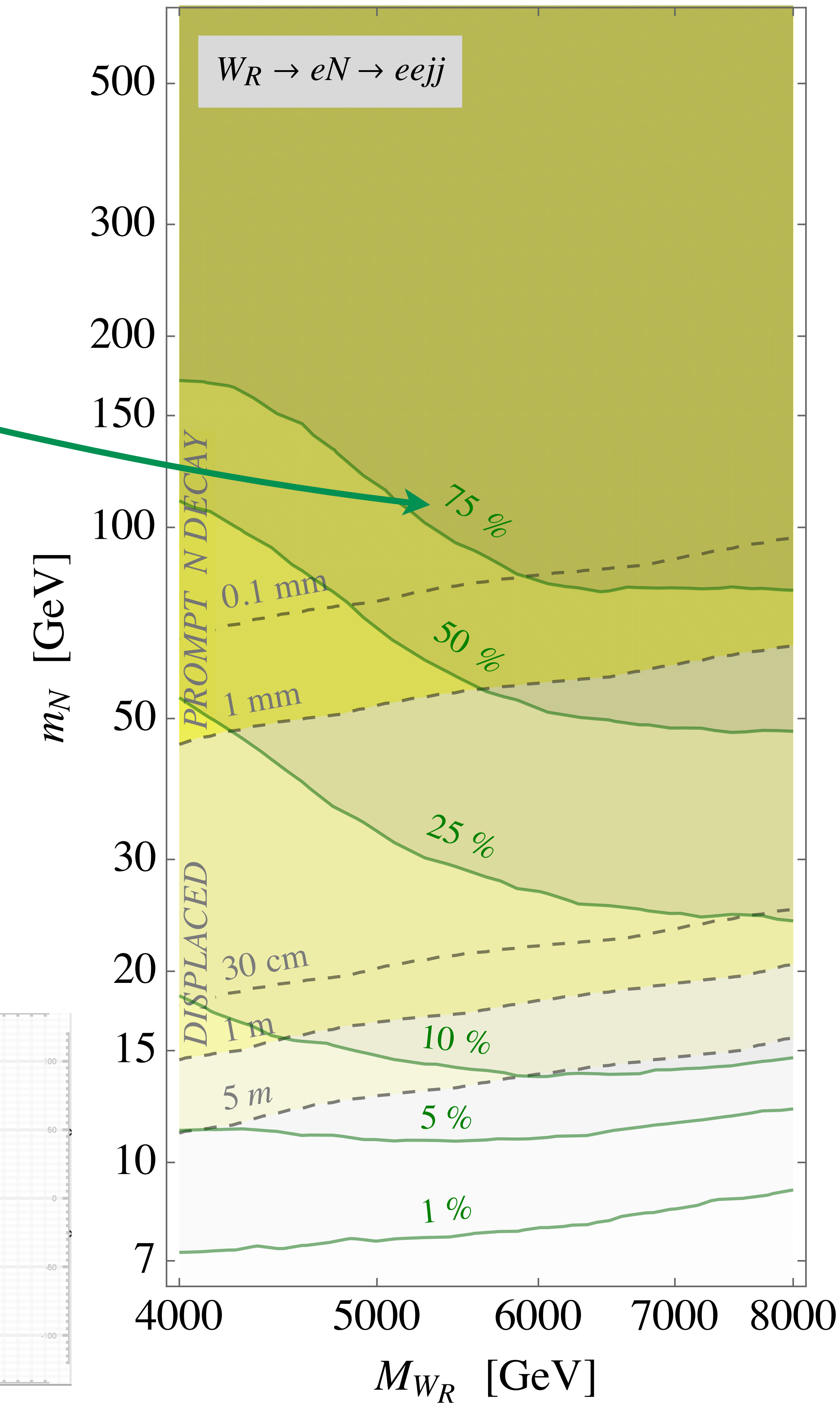
Simultaneous transition:

prompt isolated - displaced

merged, look for displaced

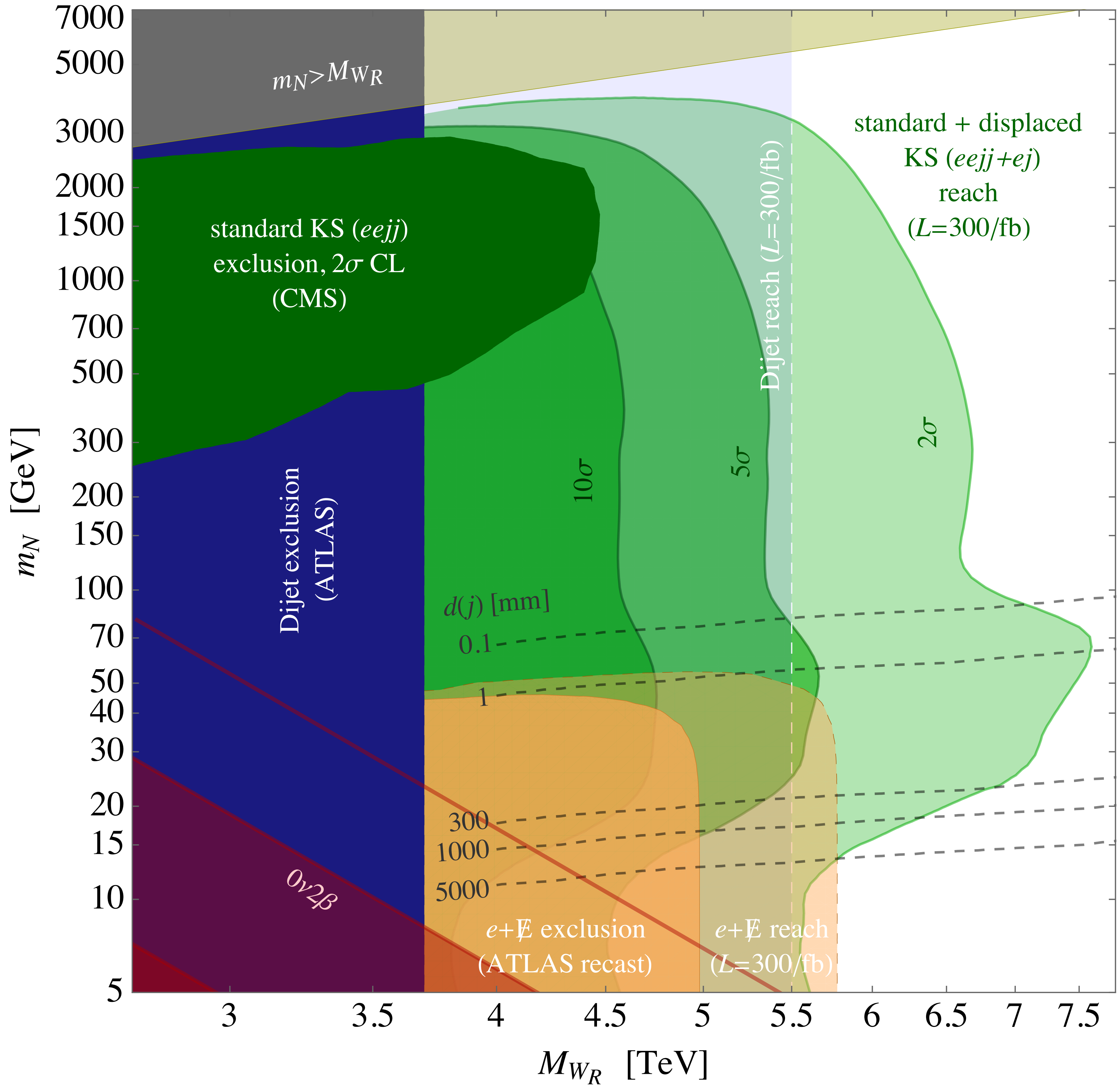
merged jets (tracks)





Search overview $pp \to W_R \to \ell_R N$

MN, Nesti, Popara '18



standard prompt isolated

Ng et al. '15, Ruiz '17

merged neutrino jet $\quad \ell\, j_N$

Mitra, Ruiz, Spannowsky '16

displaced jet $\quad \ell\, j_N^d$

MN, Nesti, Popara '18
Cottin, Helo, Hirsch '18
Cottin, Helo, Hirsch, Silva '19

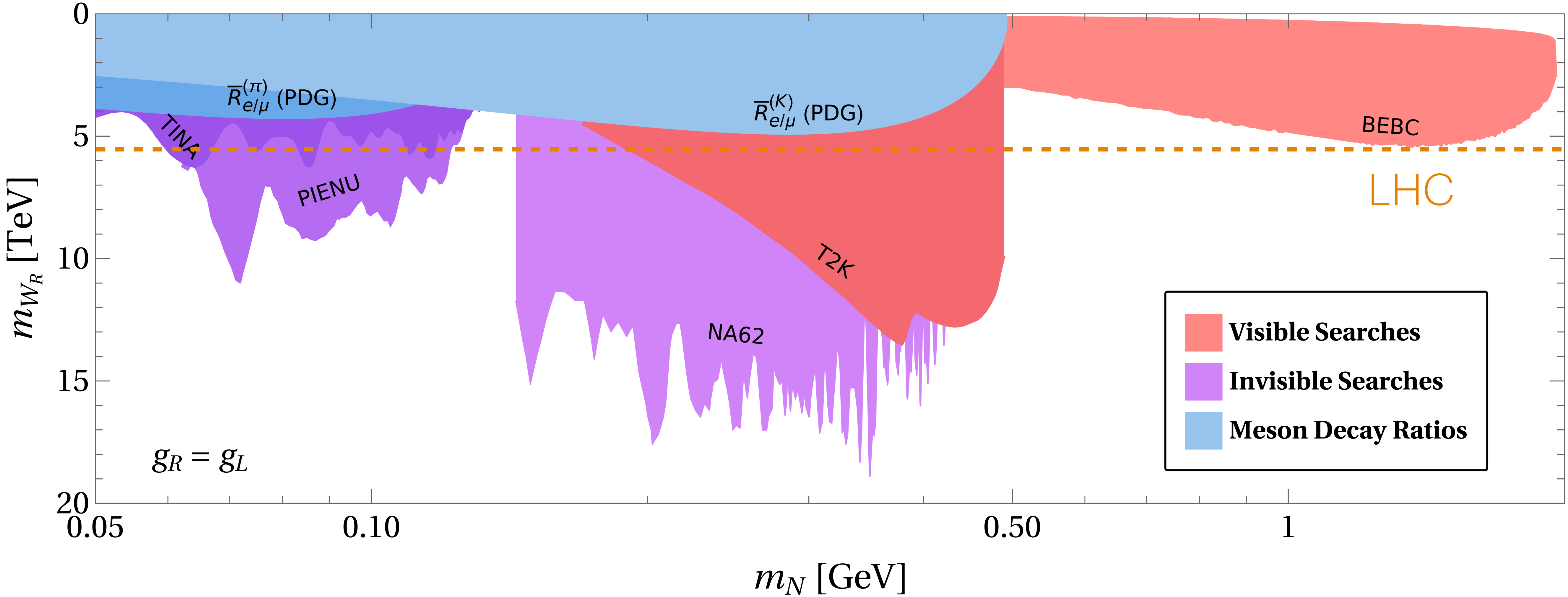
invisible: prompt $\quad \ell + \not{E}_T$

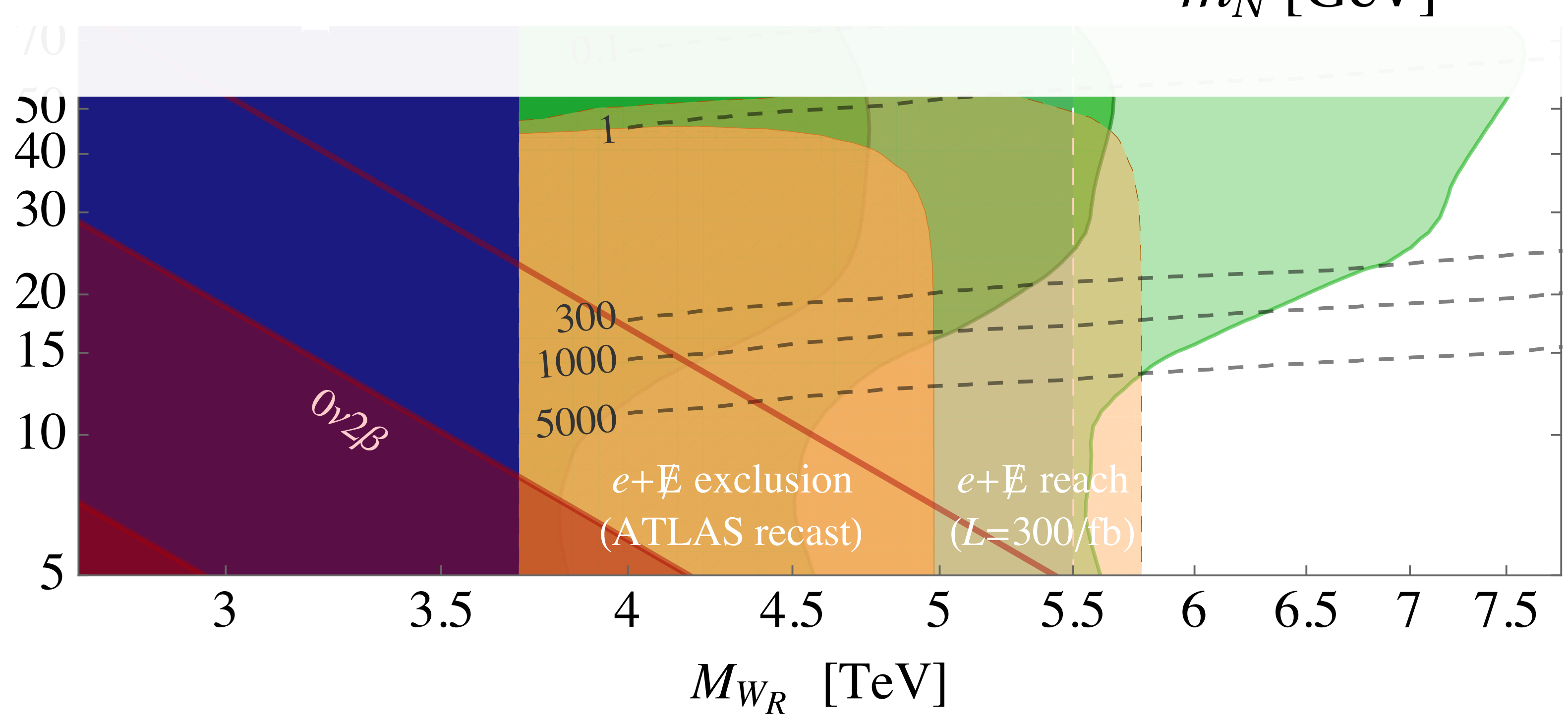
relevant for any light N search (SHIP, FASER, MATHUSLA, etc.)

talks by Mikulenko and Groot

Light region and meson decays

Alves, Fong, Leal, Zukanovich Funchal '23





MN, Nesti, Popara '18
Cottin, Helo, Hirsch '18
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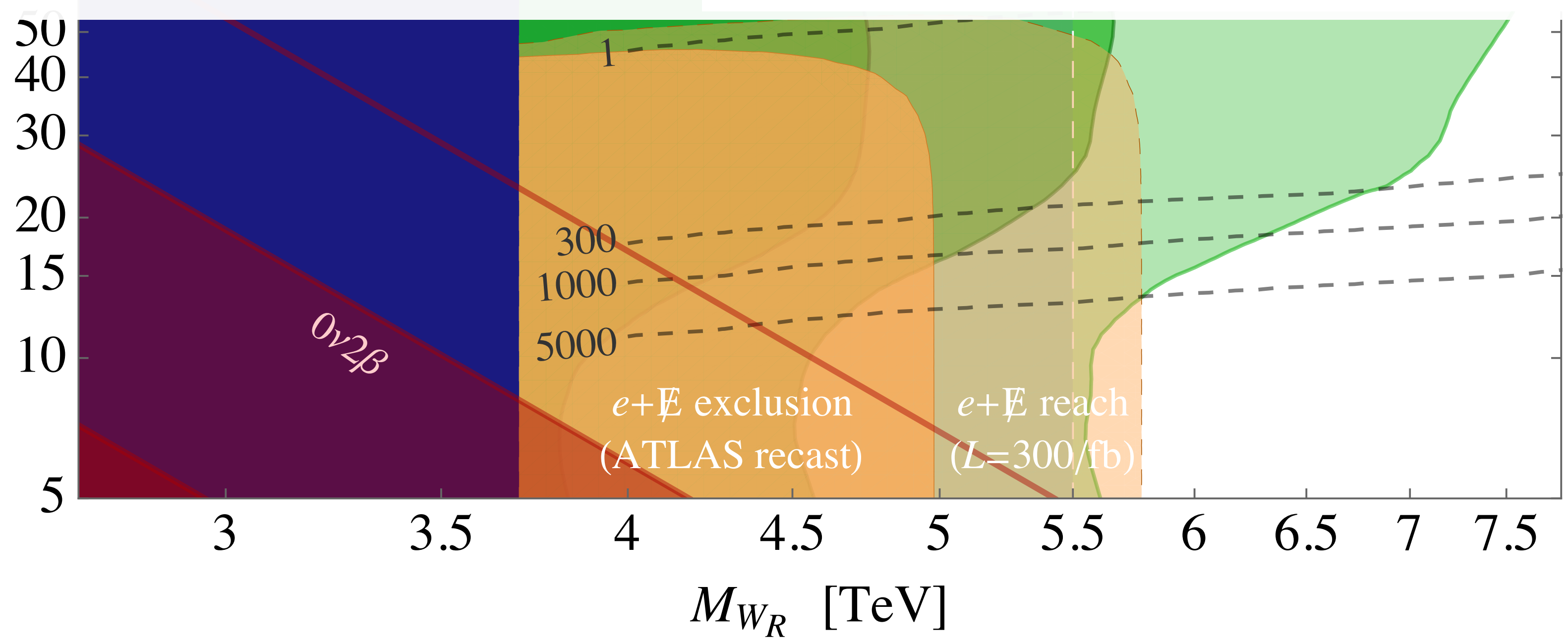
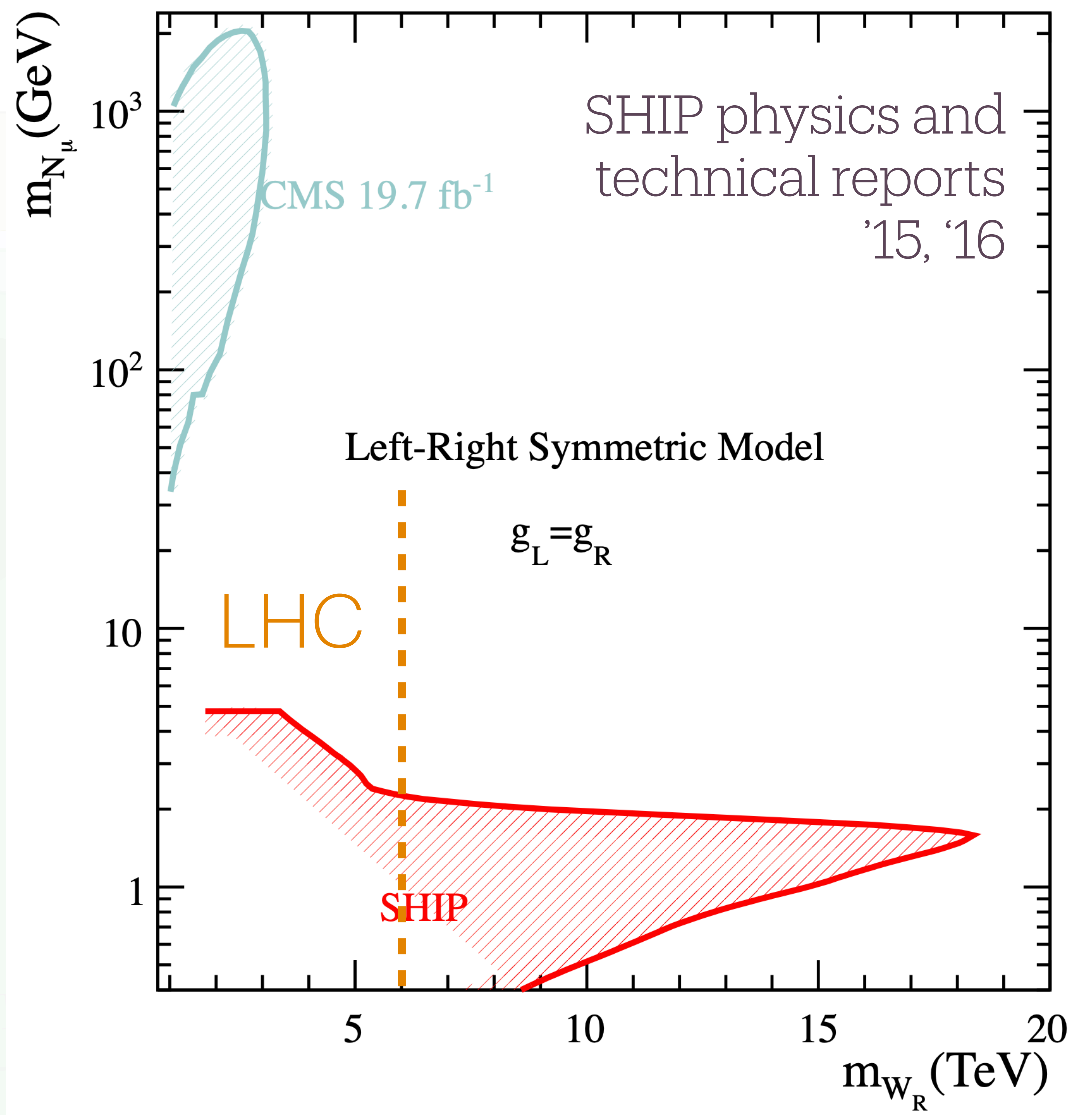




MN, Nesti, Popara '18
Cottin, Helo, Hirsch '18
Cottin, Helo, Hirsch, Silva '19

invisible: prompt $\ell + \not{E}_T$

relevant for any light N search (SHIP, FASER, MATHUSLA, etc.)

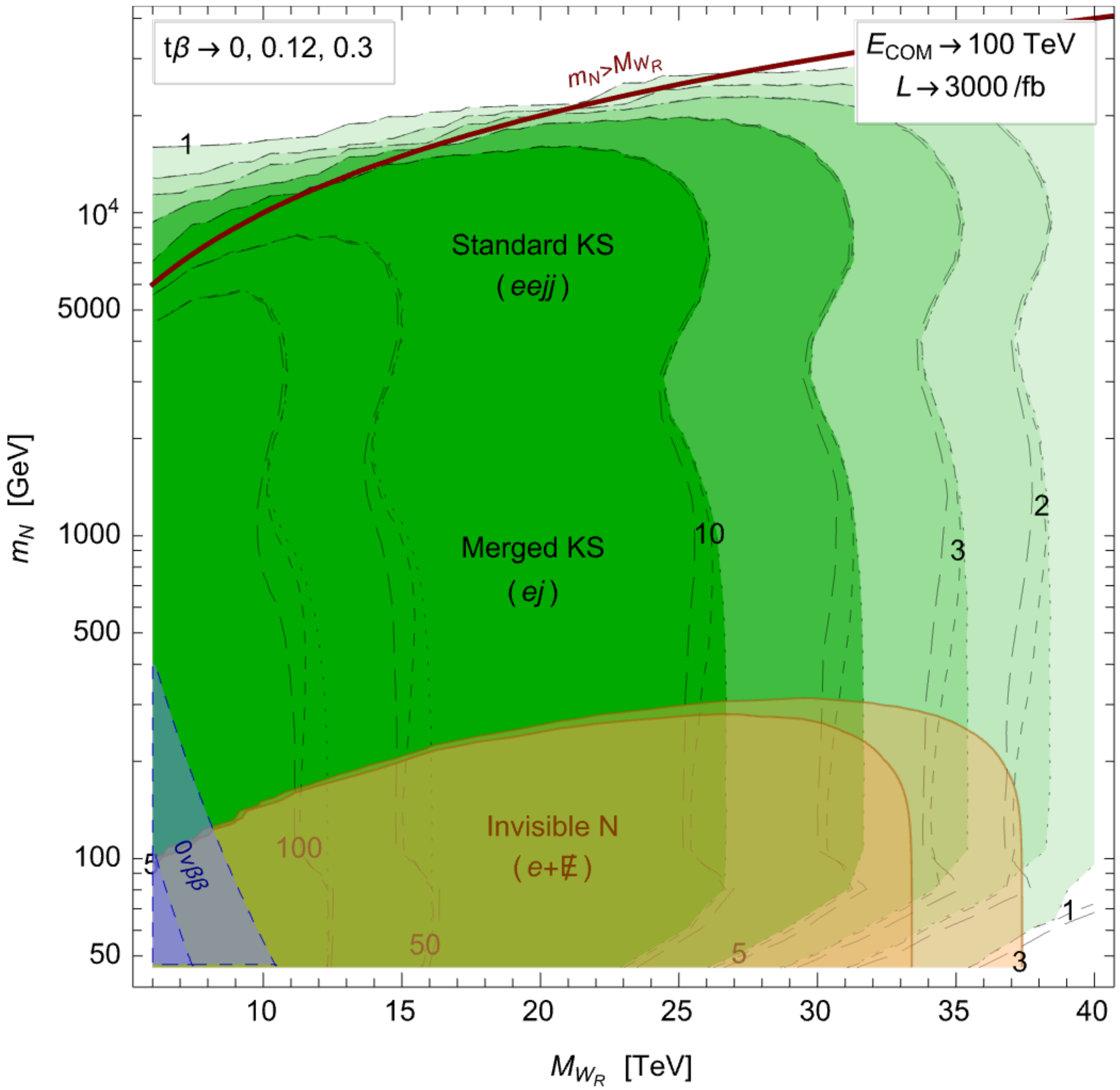
talks by Mikulenko and Groot

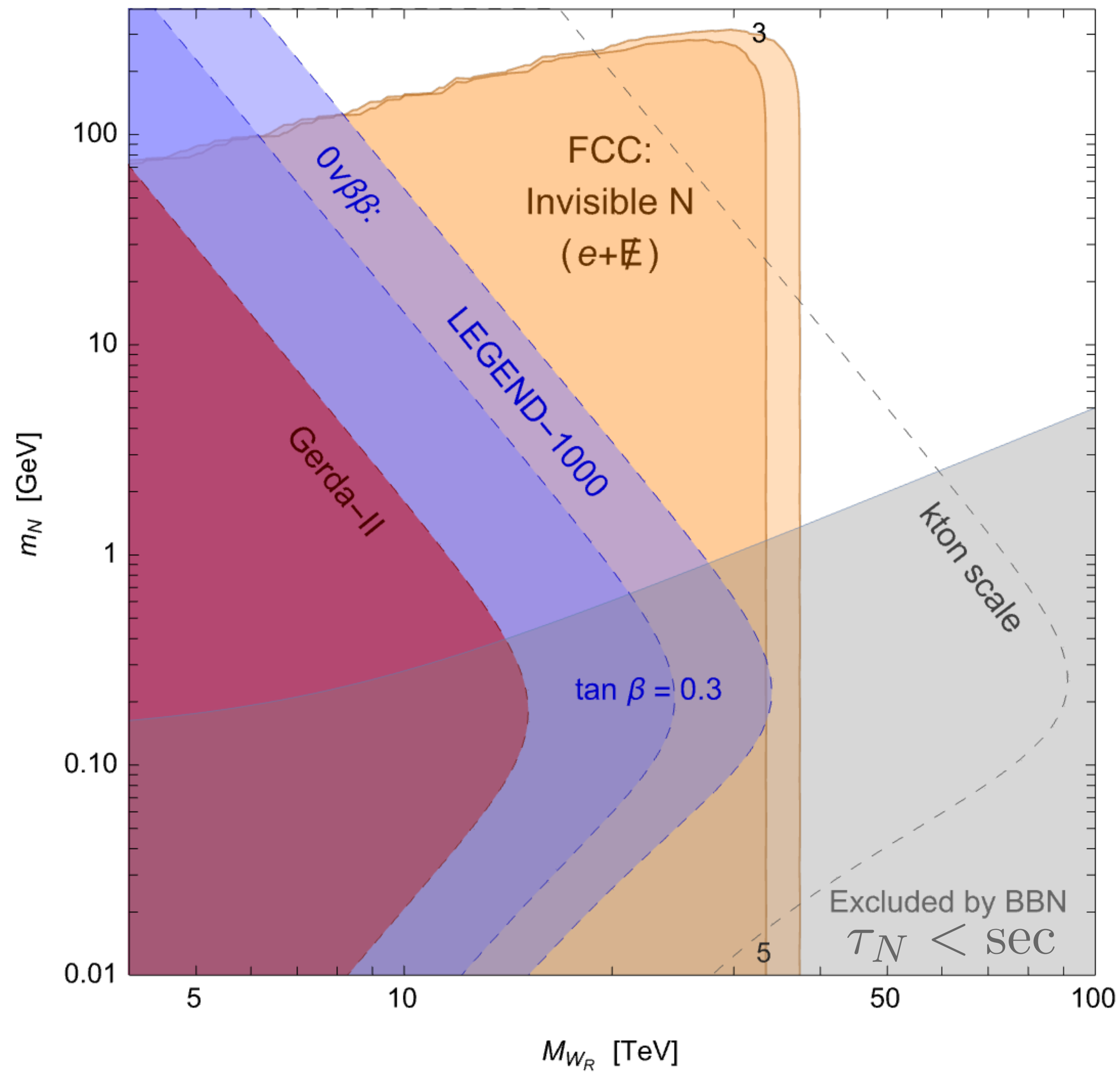
Future overview $pp \to W_R \to \ell_R N$

MN, Nesti '24

Combination of off-shell, resolved, merged, displaced and invisible

Interplay FCC-hh, $0\nu2\beta$, BBN



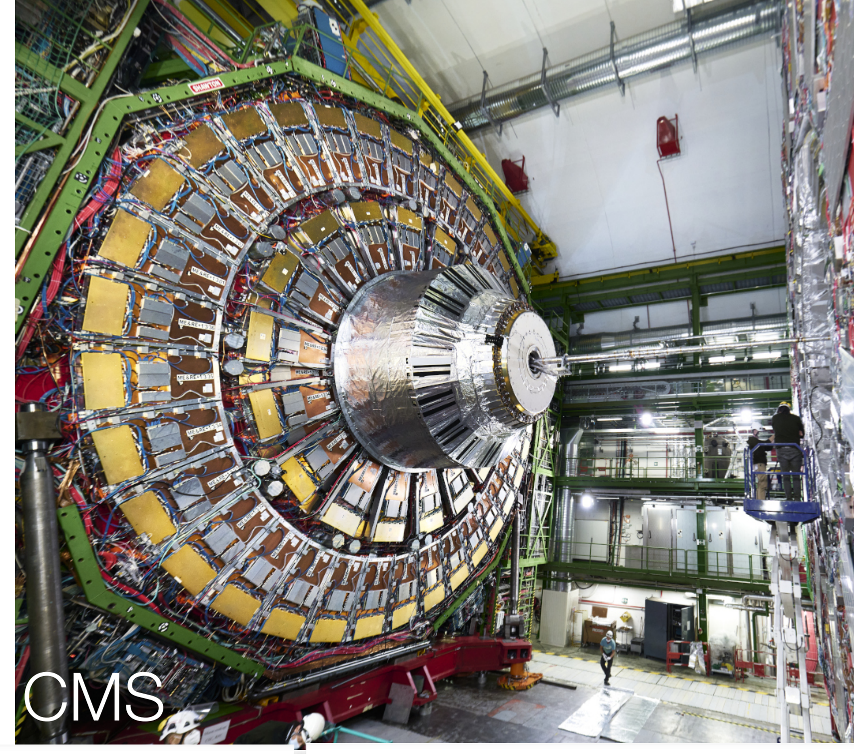


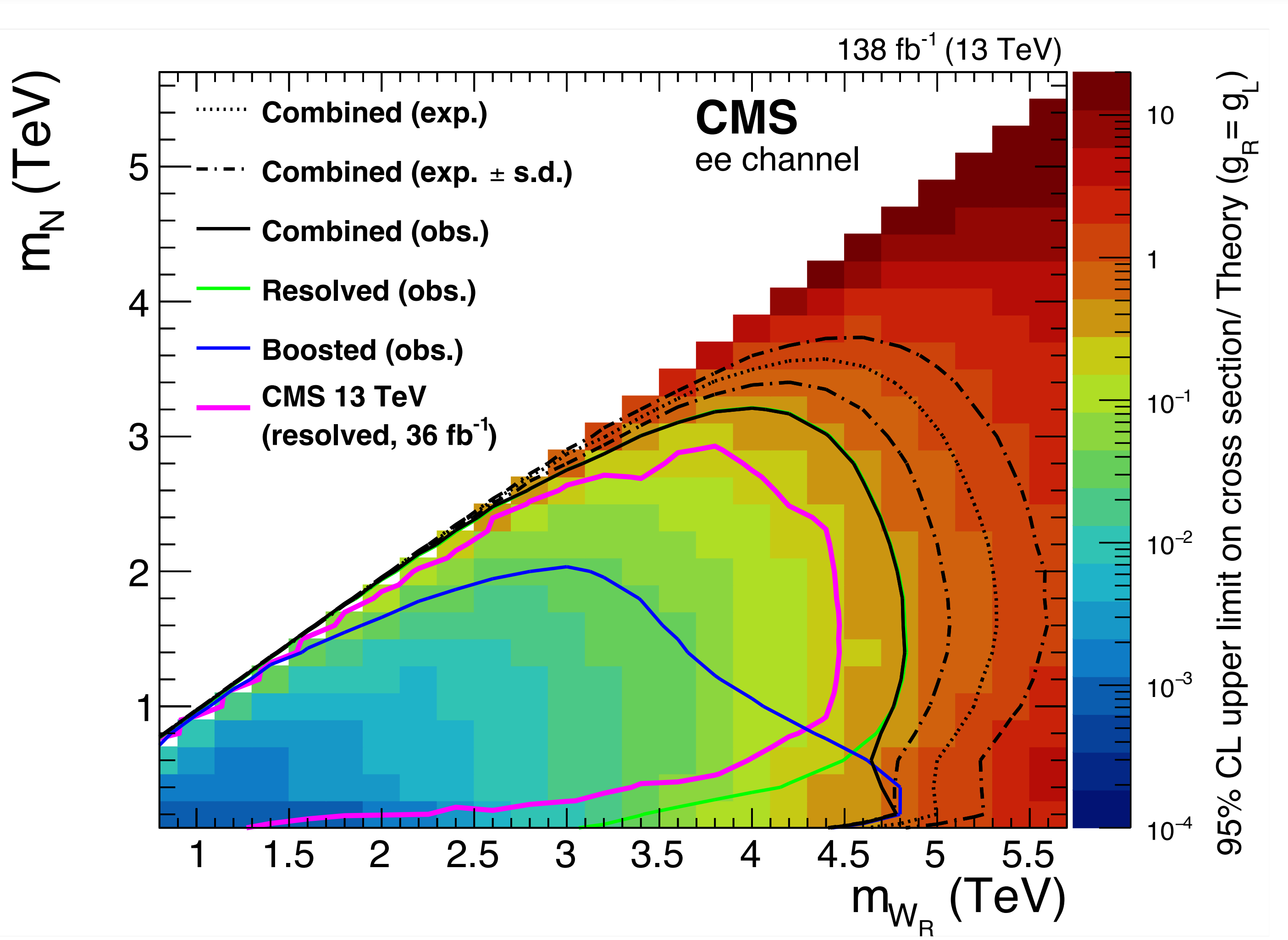
Extensive reach 35 TeV at 3 sigma

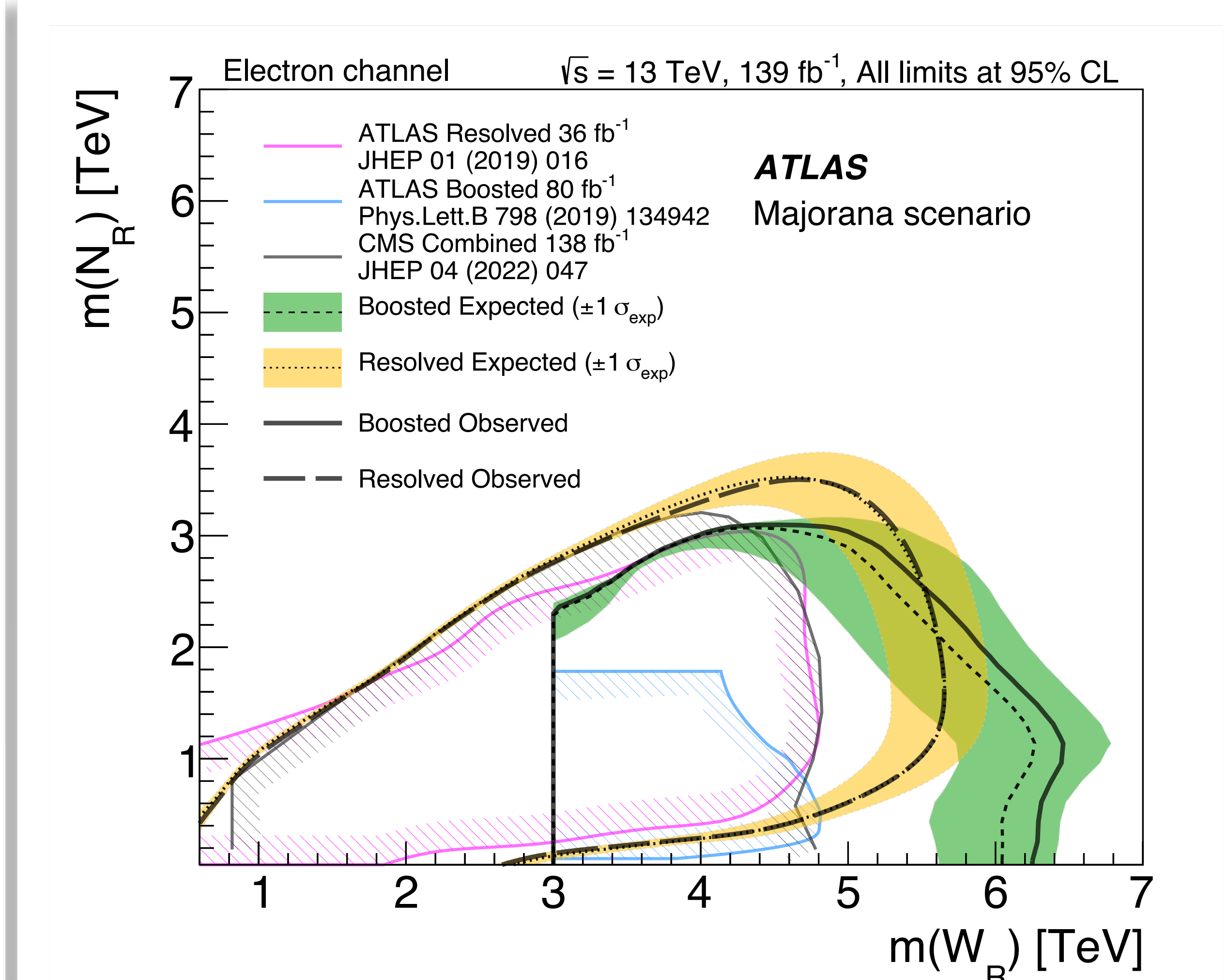
kton detectors exceed colliders

Resolved leptons and jets: search status in 2024

Lepton Number Violation





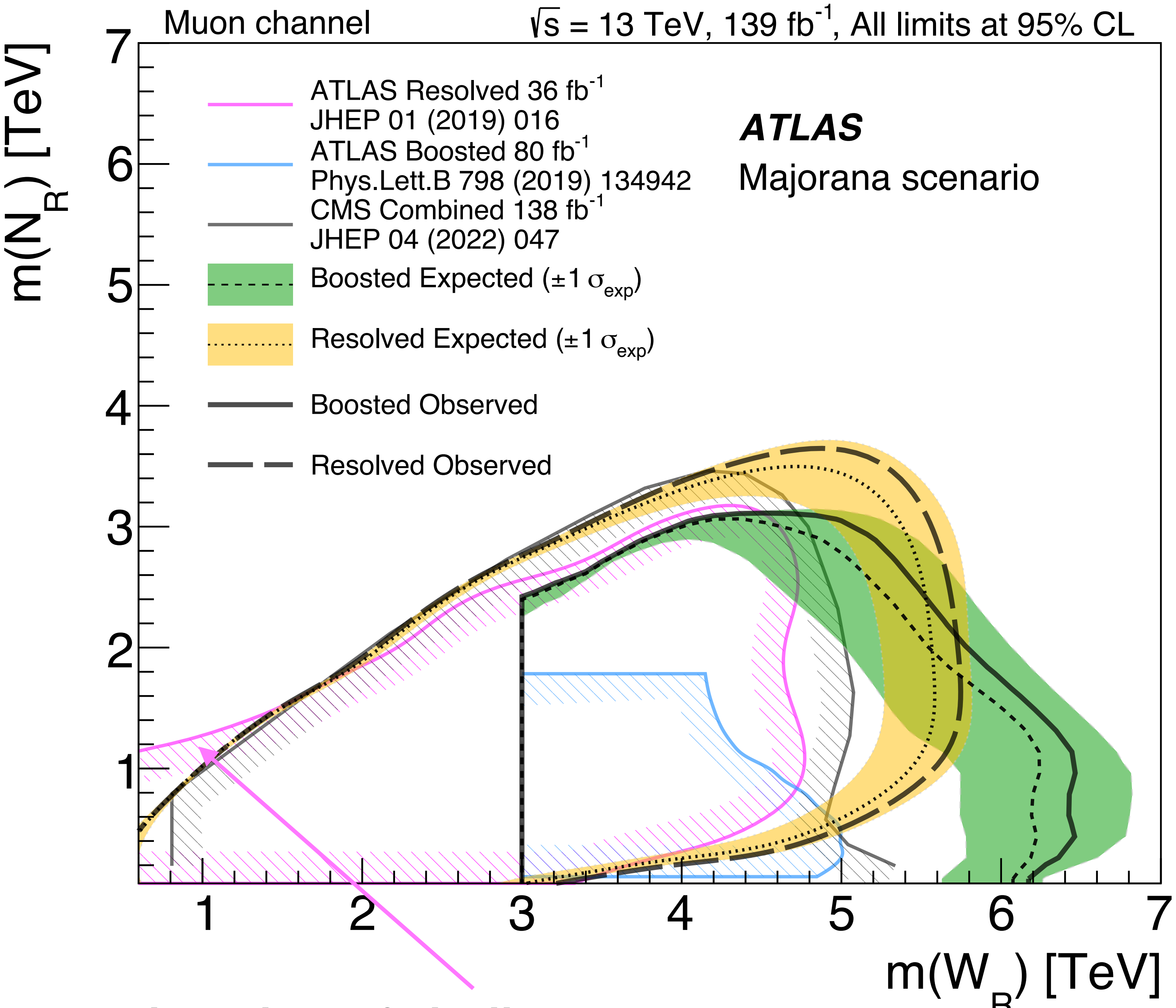


similar for muons

CMS 2112.03949

ATLAS 2304.09553

Experimental limits review in 2024



probes the off-shell N, too

Lepton Number Violation

standard prompt isolated mode

*e, mu	5.8 TeV	ATLAS 2304.09553
tau	3.5 TeV	CMS 2112.03949

lepton + missing energy

*e, mu $M_{W_R} \gtrsim 5.1(6)$ TeV		ATLAS 1906.05609
tau$_h$ $M_{W_R} > 5.0$ TeV		ATLAS 2402.16576

*interplay with $0\nu2\beta$

Mohapatra Senjanović '79
Tello, MN, Nesti, Senjanović, Vissani '10

dijets

$M_{W_R} > 4$ TeV — ATLAS 1910.08447

tb

$M_{W_R} > 4.5$ TeV — ATLAS 2308.08521

di-boson WZ mode $\propto \xi_{LR}$

~ 5.8 TeV — ATLAS 2402.10607, CMS 2210.00043

LRSM model file

Kriewald, MN, Nesti '24

physical input scheme: masses & mixings, quartics computed

Scalar sector: doubly, singly charged, neutral

Input masses, output mixings, some quartics $U_+, O_N, \lambda_i, \rho_i$

Goldstones, gauge fixing

for Δ_L LNV pheno, see talks by Kriewald and Ruiz

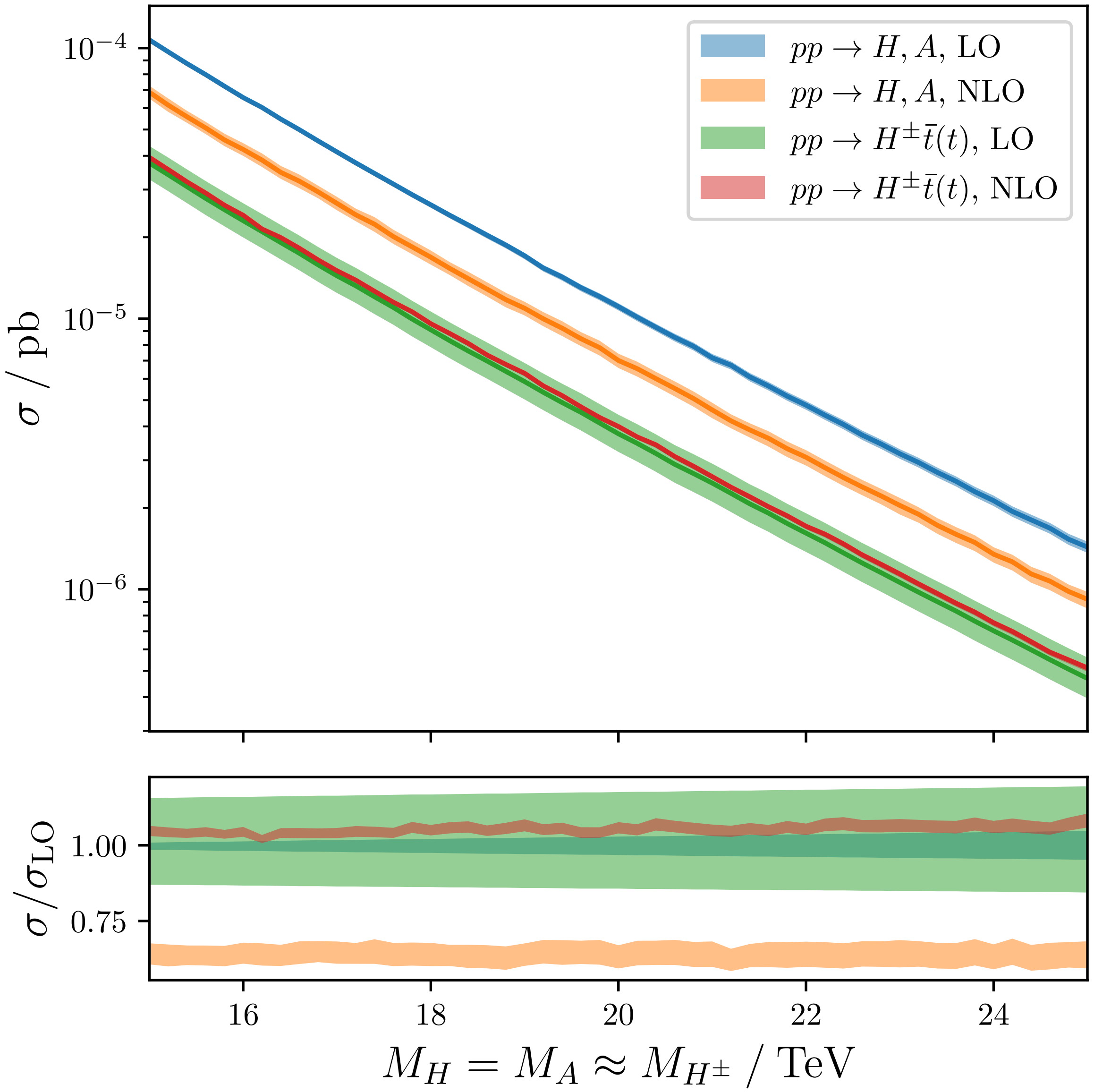
Bolton, Kriewald, MN, Nesti '24

$$
\begin{aligned}
\mathcal{V} = & \boxed{-\mu_1^2\left[\phi^\dagger\phi\right] - \mu_2^2\left(\left[\tilde\phi\phi^\dagger\right] + \left[\tilde\phi^\dagger\phi\right]\right) - \mu_3^2\left(\left[\Delta_L\Delta_L^\dagger\right] + \left[\Delta_R\Delta_R^\dagger\right]\right)} \quad \textit{minimization} \\
& + \lambda_1\left[\phi^\dagger\phi\right]^2 + \lambda_2\left(\left[\tilde\phi\phi^\dagger\right]^2 + \left[\tilde\phi^\dagger\phi\right]^2\right) + \lambda_3\left[\tilde\phi\phi^\dagger\right]\left[\tilde\phi^\dagger\phi\right] + \lambda_4\left[\phi^\dagger\phi\right]\left(\left[\tilde\phi\phi^\dagger\right] + \left[\tilde\phi^\dagger\phi\right]\right) \\
& + \rho_1\left(\left[\Delta_L\Delta_L^\dagger\right]^2 + \left[\Delta_R\Delta_R^\dagger\right]^2\right) + \rho_2\left(\left[\Delta_L\Delta_L\right]\left[\Delta_L^\dagger\Delta_L^\dagger\right] + \left[\Delta_R\Delta_R\right]\left[\Delta_R^\dagger\Delta_R^\dagger\right]\right) + \rho_3\left[\Delta_L\Delta_L^\dagger\right]\left[\Delta_R\Delta_R^\dagger\right] \\
& + \rho_4\left(\left[\Delta_L\Delta_L\right]\left[\Delta_R^\dagger\Delta_R^\dagger\right] + \left[\Delta_L^\dagger\Delta_L^\dagger\right]\left[\Delta_R\Delta_R\right]\right) + \alpha_1\left[\phi^\dagger\phi\right]\left(\left[\Delta_L\Delta_L^\dagger\right] + \left[\Delta_R\Delta_R^\dagger\right]\right) \\
& + \left(\alpha_2\left(\left[\tilde\phi\phi^\dagger\right]\left[\Delta_L\Delta_L^\dagger\right] + \left[\tilde\phi^\dagger\phi\right]\left[\Delta_R\Delta_R^\dagger\right]\right) + \text{h.c.}\right) + \alpha_3\left(\left[\phi\phi^\dagger\Delta_L\Delta_L^\dagger\right] + \left[\phi^\dagger\phi\Delta_R\Delta_R^\dagger\right]\right) \\
& + \boxed{\beta_1\left(\left[\phi\Delta_R\phi^\dagger\Delta_L^\dagger\right] + \left[\phi^\dagger\Delta_L\phi\Delta_R^\dagger\right]\right) + \beta_2\left(\left[\tilde\phi\Delta_R\phi^\dagger\Delta_L^\dagger\right] + \left[\tilde\phi^\dagger\Delta_L\phi\Delta_R^\dagger\right]\right) + \beta_3\left(\left[\phi\Delta_R\tilde\phi^\dagger\Delta_L^\dagger\right] + \left[\phi^\dagger\Delta_L\tilde\phi\Delta_R^\dagger\right]\right)}
\end{aligned}
$$

all small, induces v_Δ

LRSM scalars phenomenology

Kriewald, MN, Nesti '24



125 GeV

$$\begin{pmatrix}\Re\varphi_{10}\\ \Re\Delta_R\\ \Re\varphi_{20}\\ \Im\varphi_{20}\end{pmatrix} = O_N \begin{pmatrix} h\\ \Delta\\ H\\ A\end{pmatrix}$$

GeV – TeV

$\gtrsim 15$ TeV

$\propto v_R$

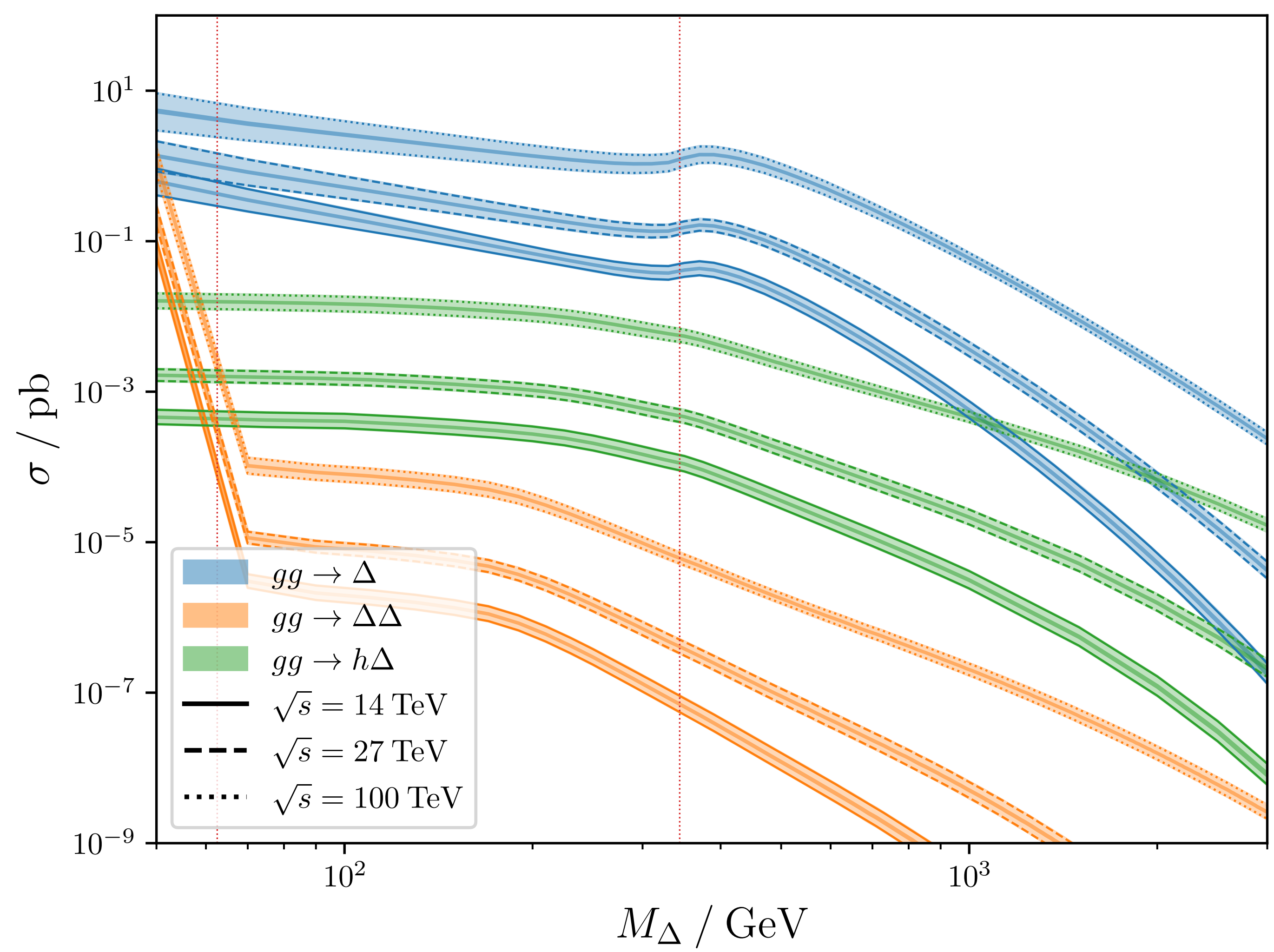
H, A mediate tree-level FCNCs

Maiezza, MN, Nesti, Senjanović '11
Bertolini, Nesti, Maiezza '14, '19
Mohapatra, Yan, Zhang '19

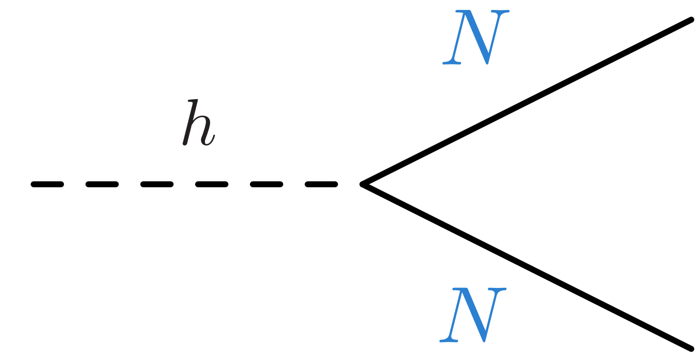
Neutral Δ_R^0 can be light

mass m_Δ vs. mixing $\sin\theta$

Majorana Higges!



‘Majorana’ SM Higgs



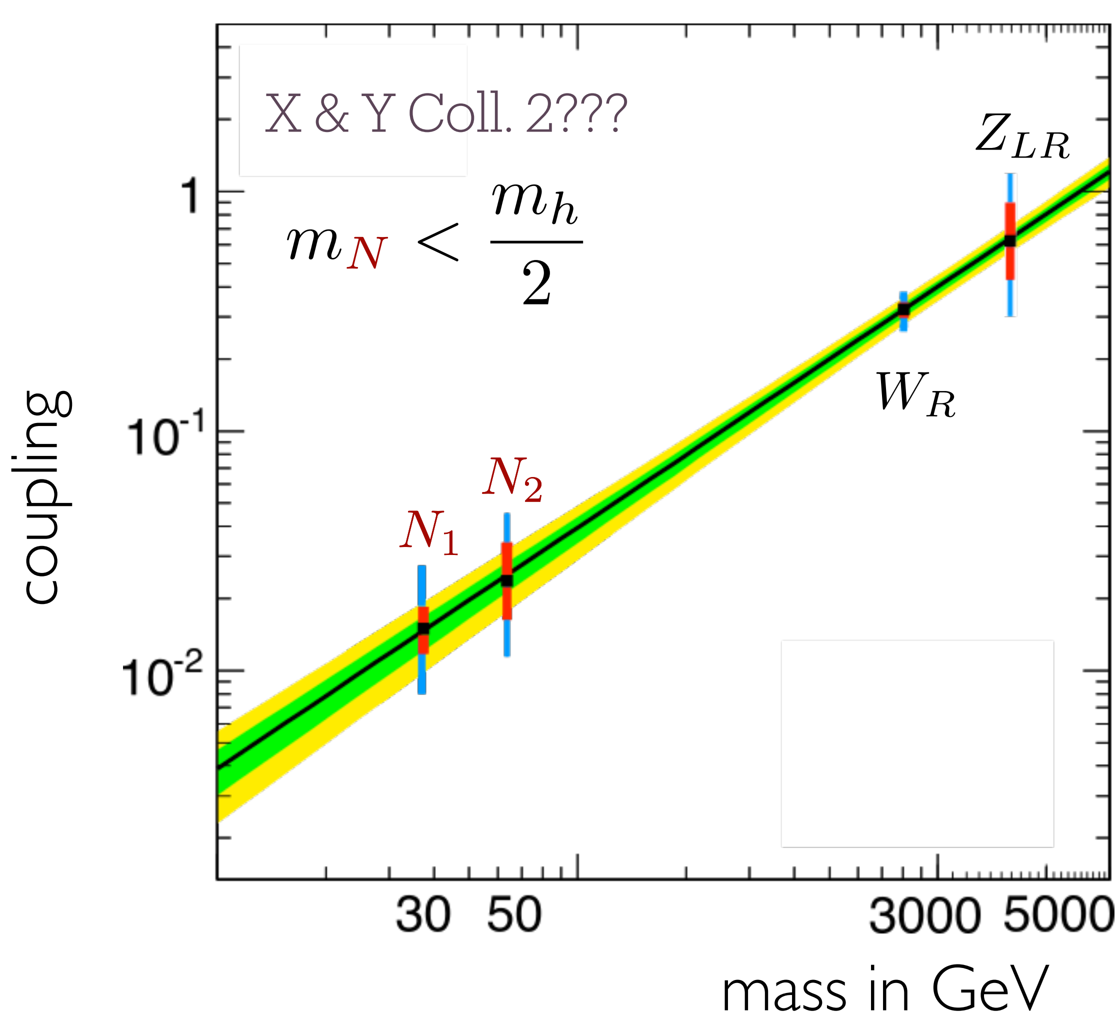
h decays

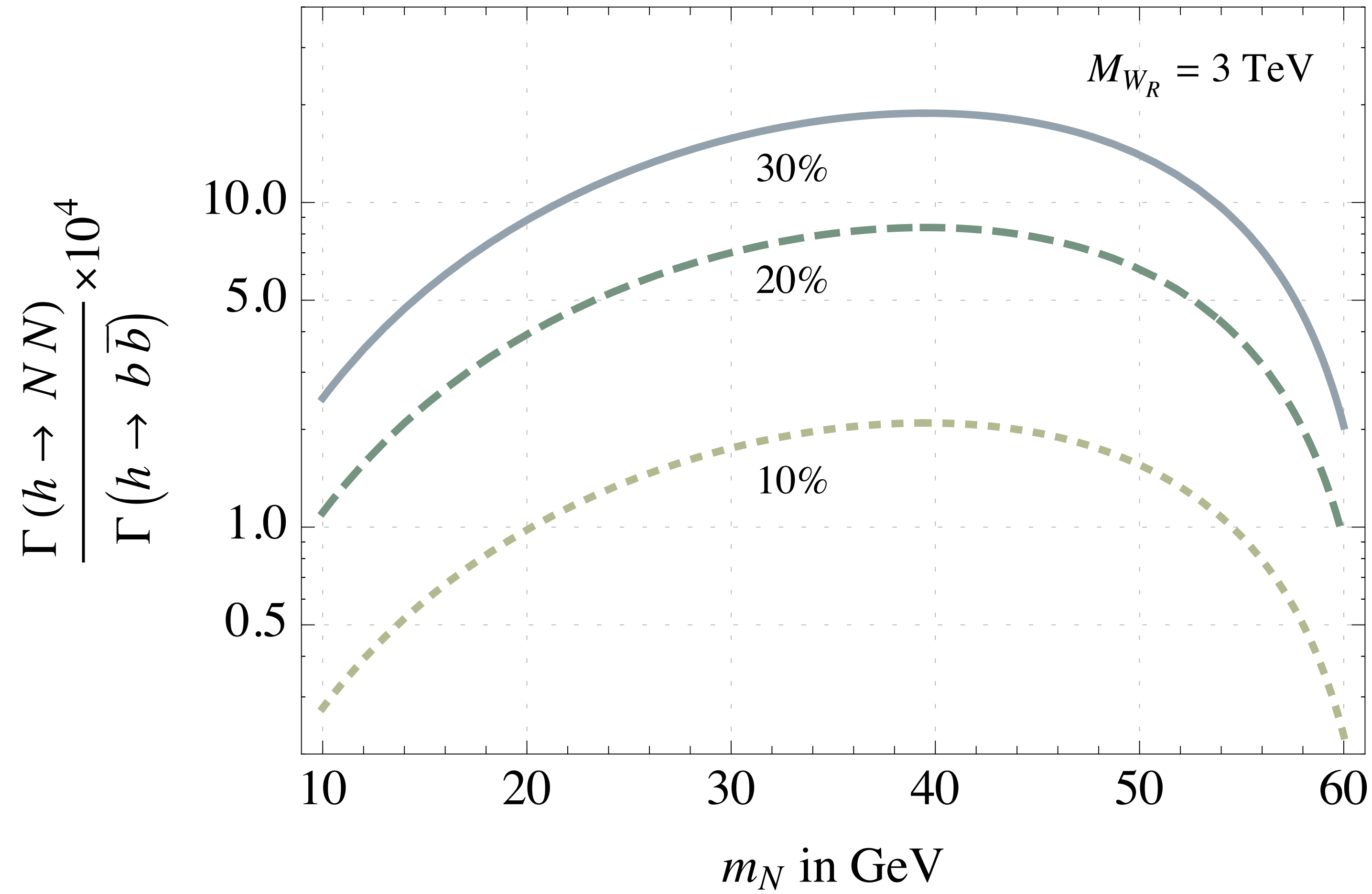
$$\Gamma_{h\to NN} \propto s_\theta^2 m_N{}^2 \qquad \frac{\Gamma_{h\to NN}}{\Gamma_{h\to b\bar b}} \simeq \frac{\theta^2}{3}\left(\frac{m_N}{m_b}\right)^2\left(\frac{M_W}{M_{W_R}}\right)^2$$

Gunion et al. Snowmass ’86

EFT SM+h+N Graesser ’07

Maiezza, MN, Nesti ’15

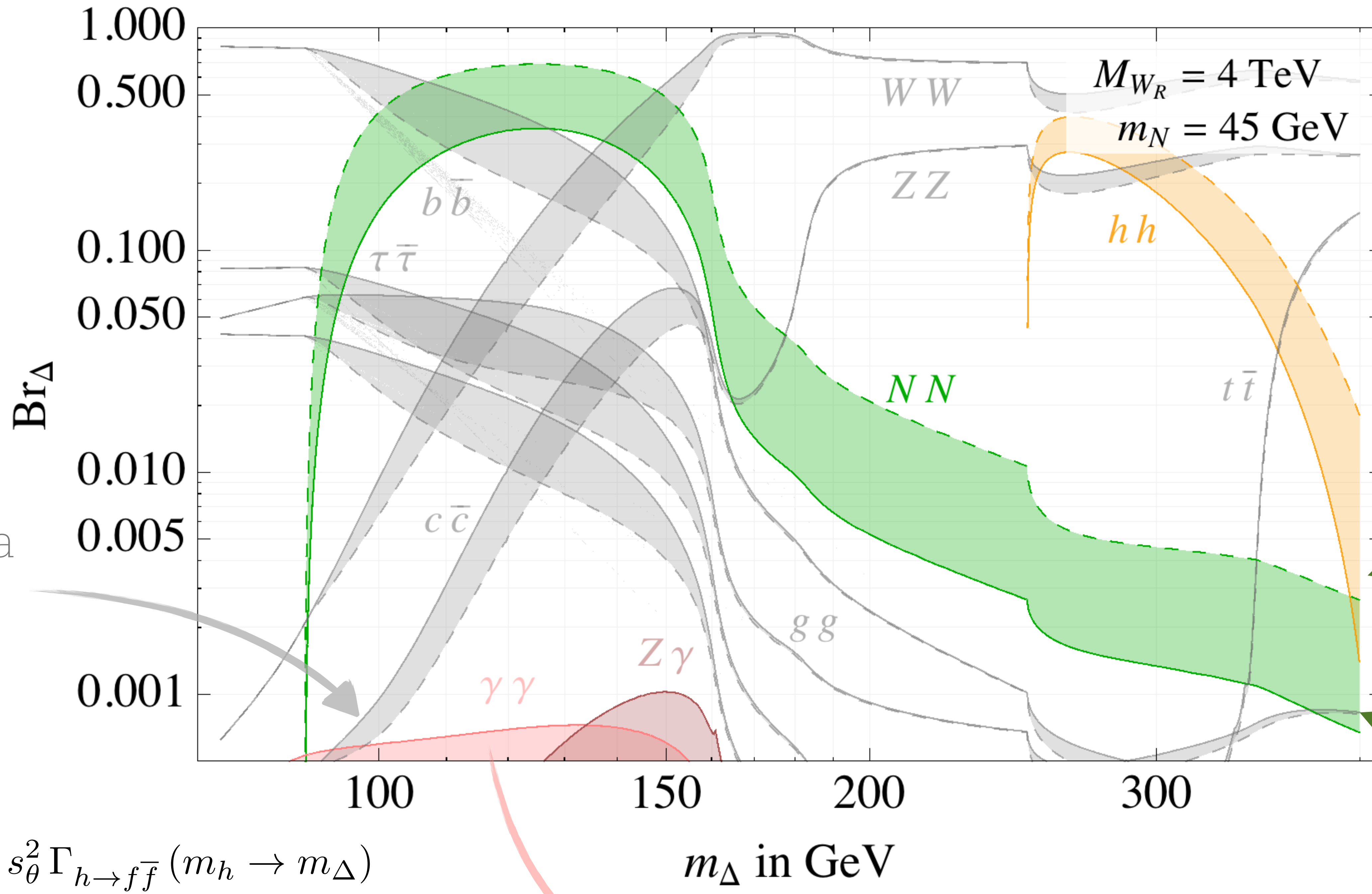




'Right-handed' Higgs

MN, Nesti, Vasquez '16

Δ_R^0 decays



to SM via mixing

$s_\theta = 5\%$

10%

$$\Gamma_{\Delta\to f\bar f} = s_\theta^2\,\Gamma_{h\to f\bar f}\,(m_h \to m_\Delta)$$

radiative loops

$(\mathrm{SM}, W_R, \Delta_{L,R}^{++})$

Displaced photons

Dev, Mohapatra, Zhang '16

$$\Gamma_{\Delta\to\gamma\gamma} = \frac{m_\Delta^3}{64\pi}\left(\frac{\alpha}{4\pi}\right)^2 |F_\Delta|^2$$

Lepton Number Violation

MN, Nesti, Vasquez '16

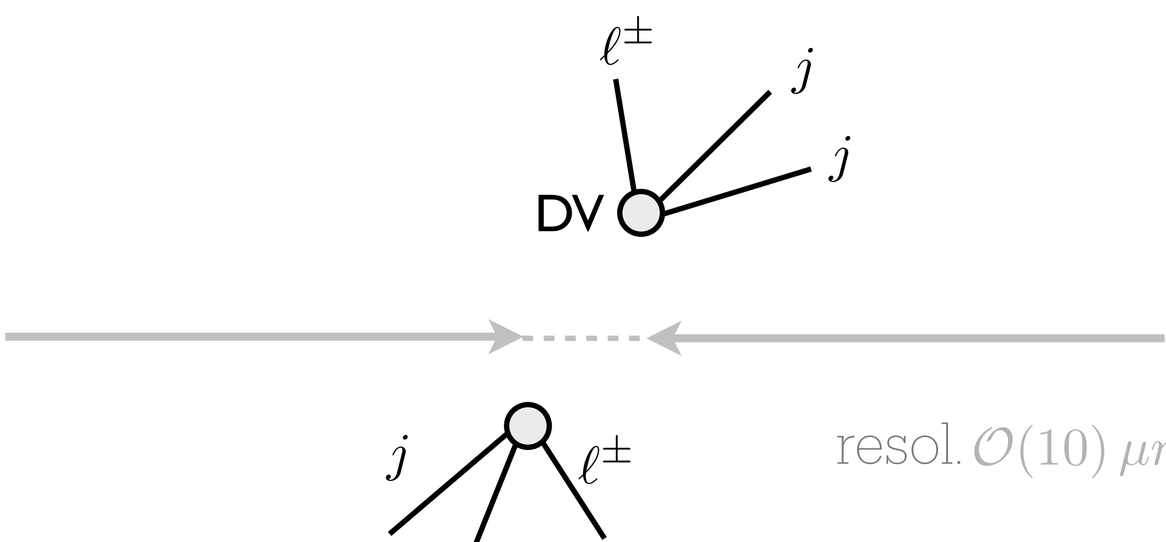
Region of interest for $\Delta \to NN$

$$20 \text{ GeV} \lesssim m_\Delta \lesssim 170 \text{ GeV}$$

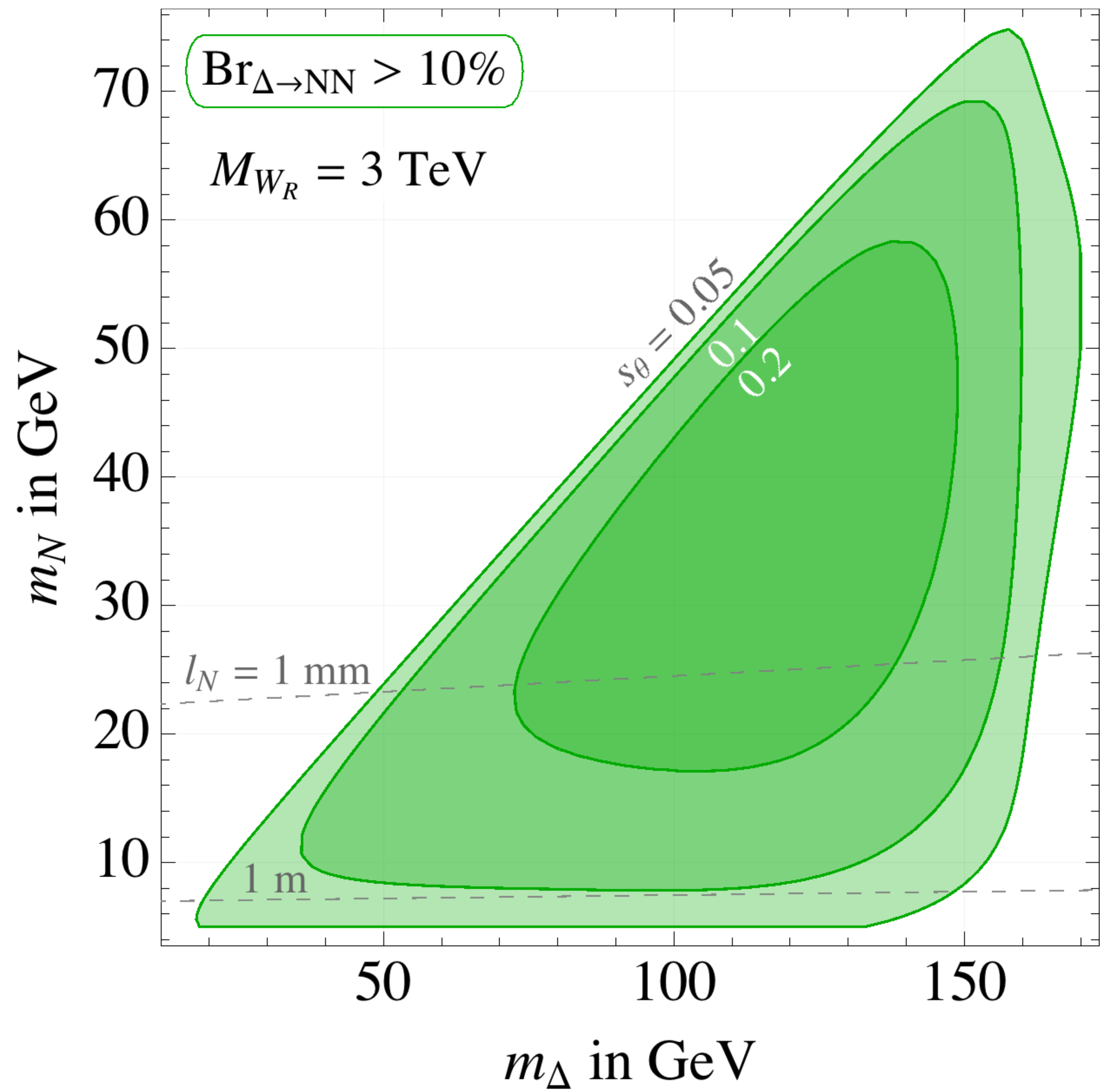
Decay length

$$c\tau_N^0 \simeq 0.1 \text{ mm} \left(\frac{40 \text{ GeV}}{m_N}\right)^5 \left(\frac{M_{W_R}}{5 \text{ TeV}}\right)^4$$

Leads to two DV with LNV



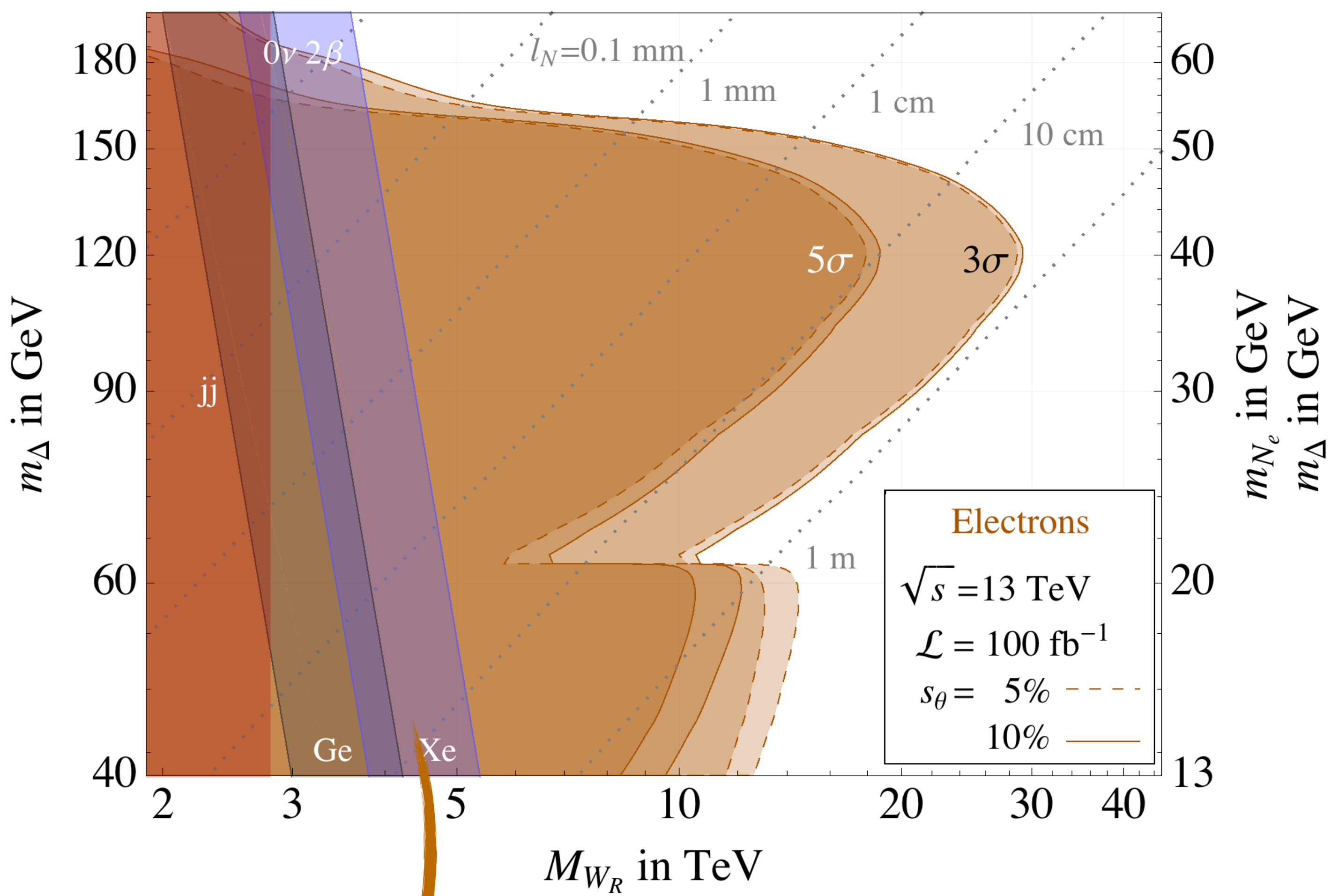
resol. $\mathcal{O}(10)\ \mu m$

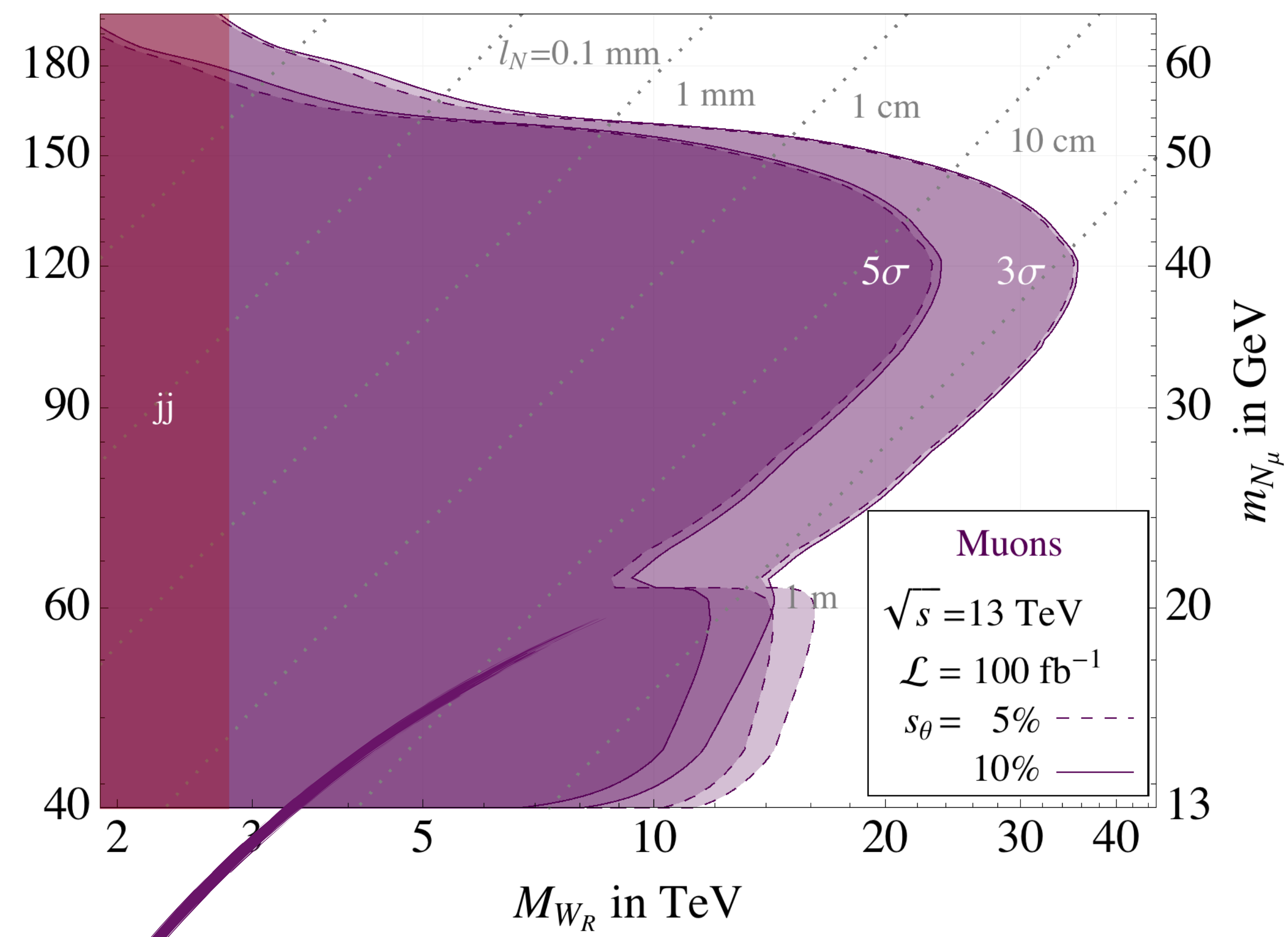


Sensitivity

MN, Nesti, Vasquez '16

Combined $h \to NN$ $\Delta \to NN$ $\Delta\Delta \to NNNN$





connection to $0\nu 2\beta$

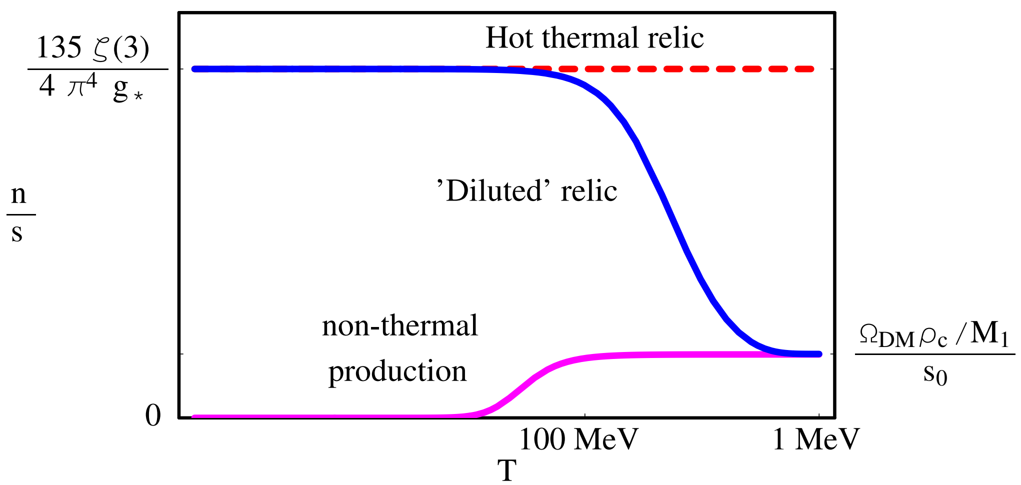
GERDA, Neutrino '16
KamLAND-Zen '16

$h \to \Delta\Delta \to NNNN$

displaced 0.01 mm to 1m

discovery reach beyond direct searches

LRSM dark matter



Bezrukov, Hettmansperger, Lindner '09

sterile neutrinos + gauge interactions

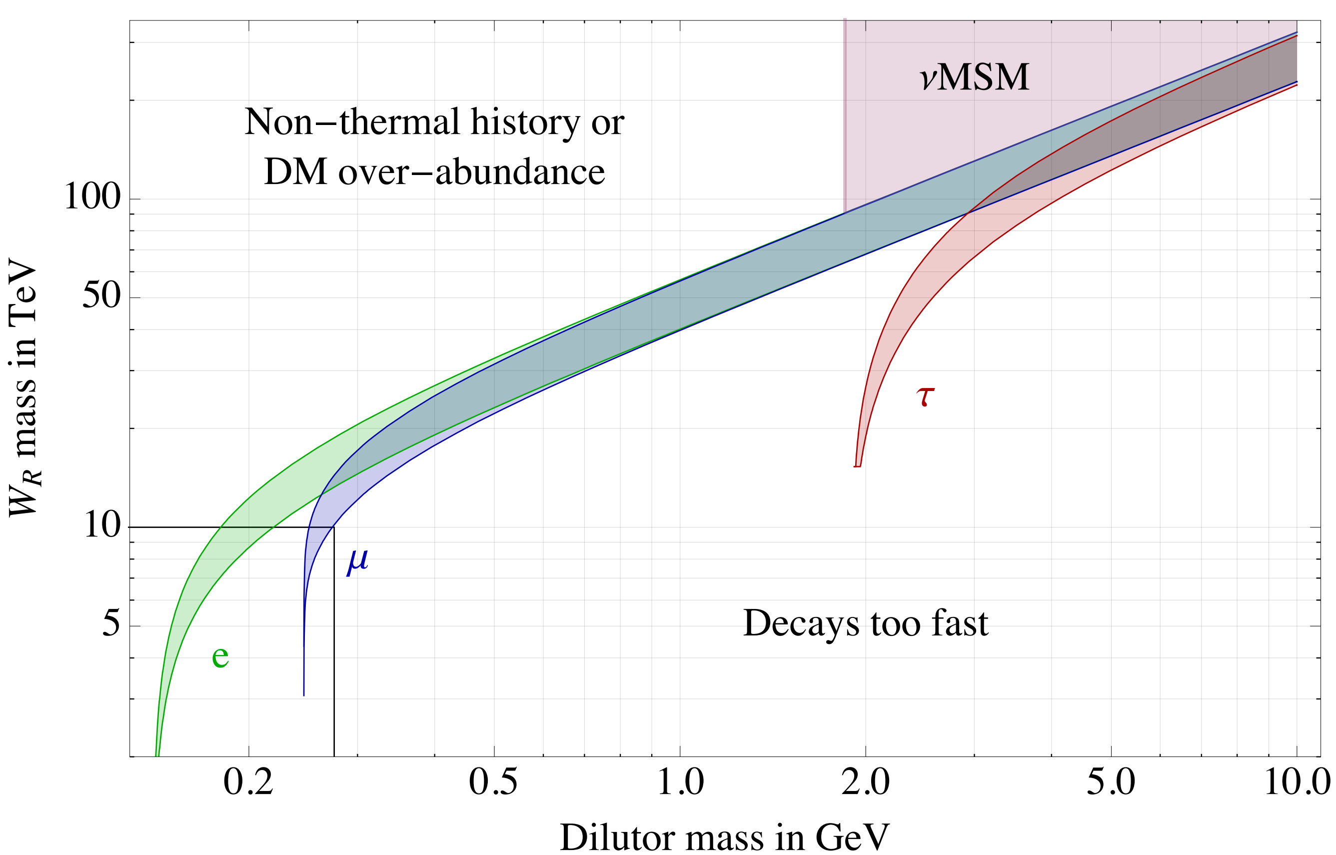
overpopulation solved by entropy dilution

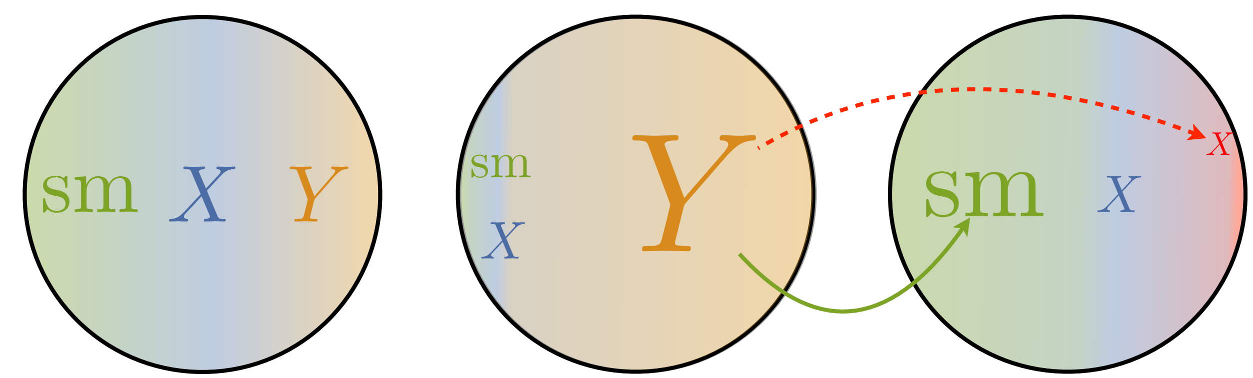
Scherrer, Turner '85

hunting for light W_R

MN, Senjanović, Zhang '12

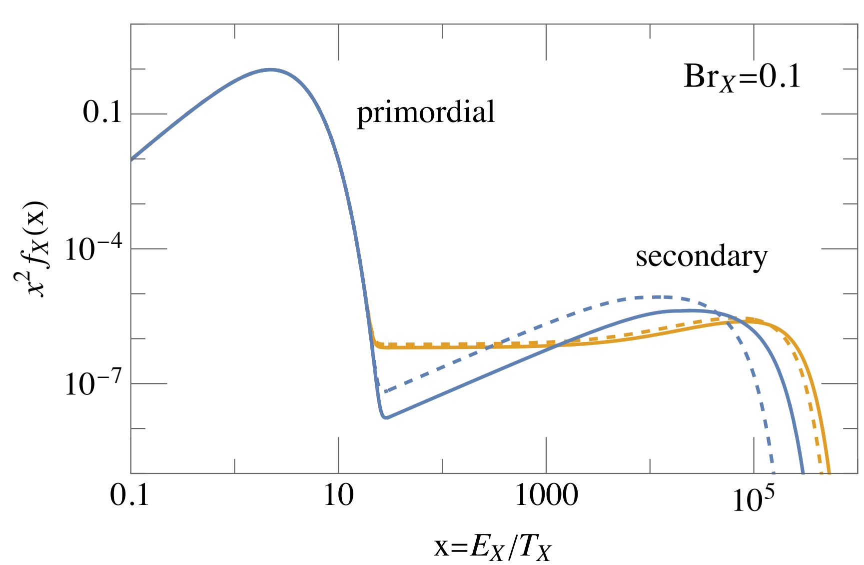
repopulation issue





secondary DM population

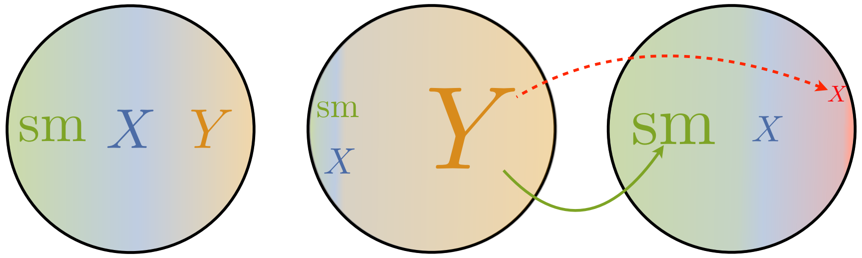
MN, Zhang '23



TeV scale window?

LRSM dark matter

MN, Zhang '23



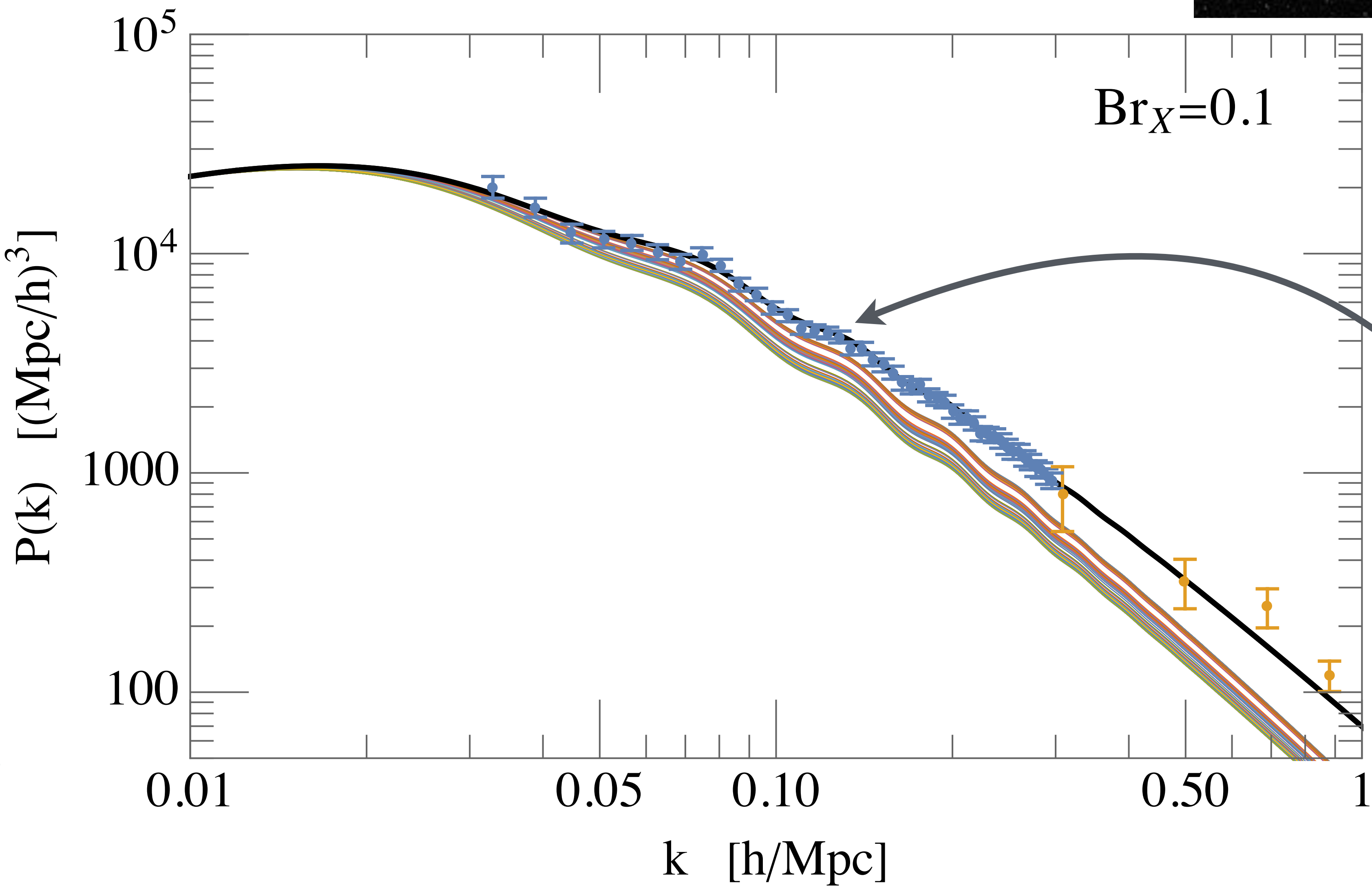
Warm component affects the linear matter power spectrum

Somewhat independent of dynamics: 2 body ~ 3 body

Thermal production of X and Y, independent of m_Y

$f_X(x)$

CLASS '11 (3x)



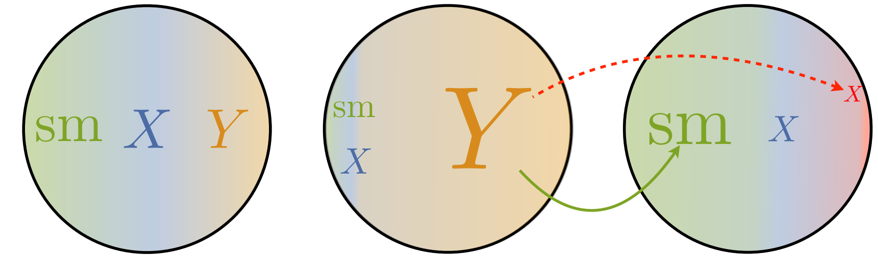
Limit on Br_X

$\boxed{Br_X \lesssim 1\%}$

fiducial DM+ data

usual wDM suppression at large k

LRSM dark matter



Anatomy of LRSM DM candidates

MN, Zhang '24

tough...

$X = N_1, \cancel{\Delta_R^0}$ stable, decays via $N_1 \to 3\nu, \nu\gamma$

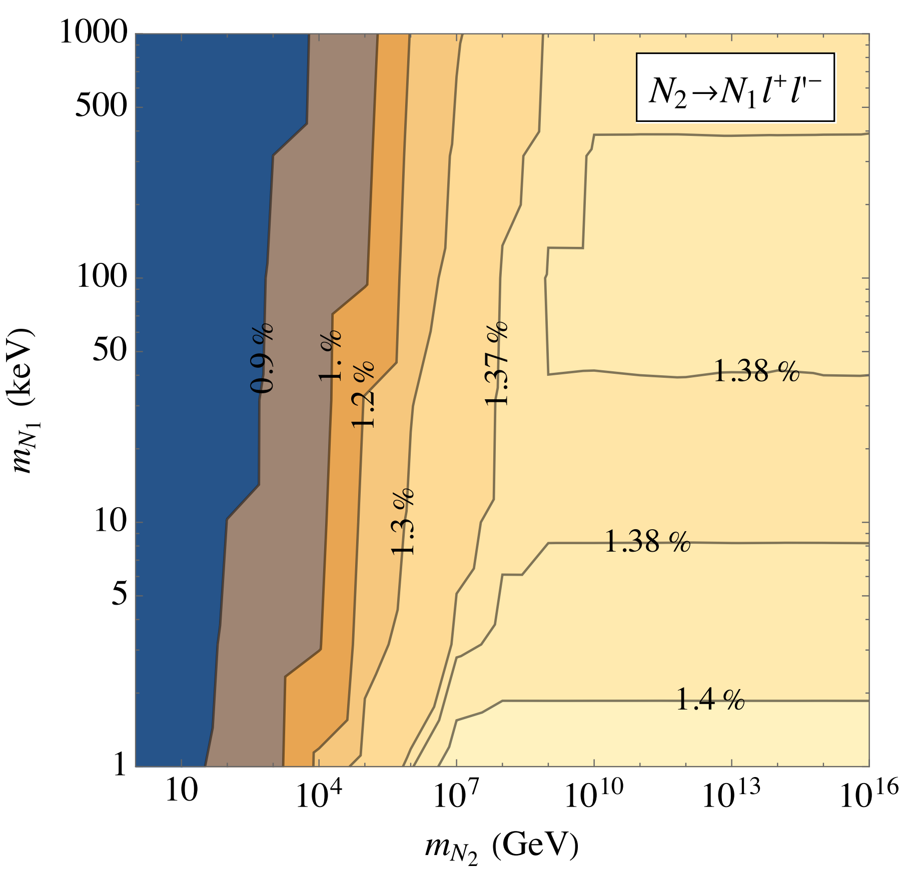
fast 2 body

Dilutors $Y = N_{2,3}, \Delta_R^0$ $\quad N_i \to \ell q q, \boxed{\ell\ell N_1}, \ell\ell\nu, 3\nu, \ell W$

dangerous 3 body

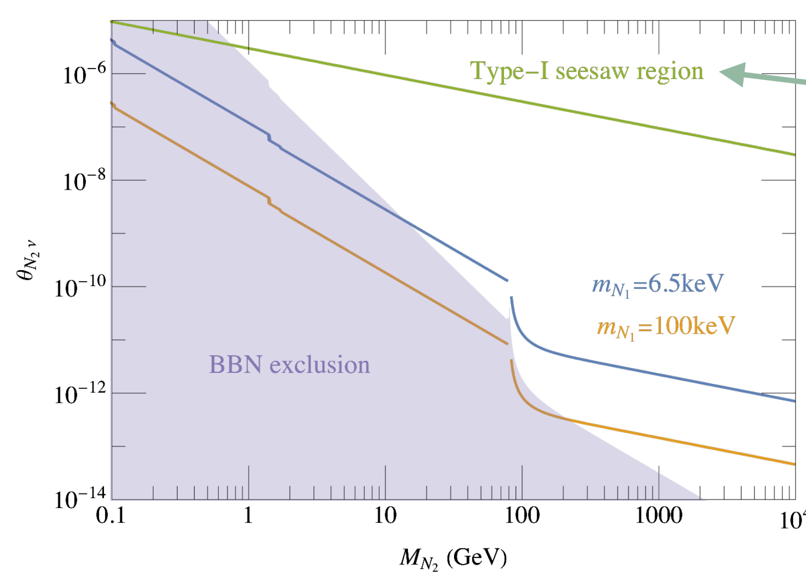
$$\Omega_X \simeq 0.26\,(1 + n\mathrm{Br}_X)\left(\frac{m_X}{1\,\mathrm{keV}}\right)\left(\frac{2.2\,\mathrm{GeV}}{m_Y}\right)\sqrt{\frac{1\,\mathrm{sec}}{\tau_Y}}$$

$$T_{\mathrm{RH}} \simeq \frac{0.4\,\mathrm{MeV}}{g_*(T_{\mathrm{RH}})^{1/4}}\frac{m_Y}{10^6 m_X}$$



need to suppress Br_X below 1%

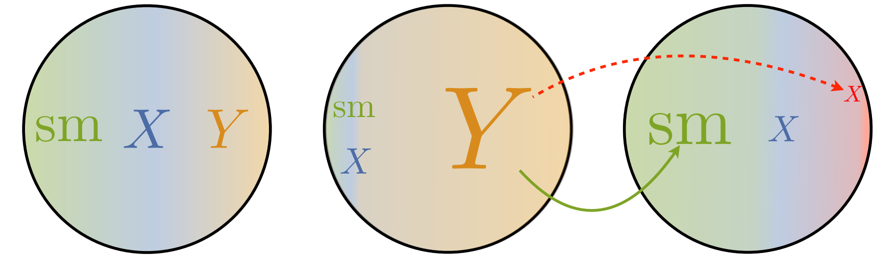
no-go via type I seesaw, Dirac $\cancel{\tau_{N_2} \gtrsim 160\,\mathrm{sec}}$ BBN



need to be here, no-go

What about ξ and Δ_R^0?

LRSM dark matter

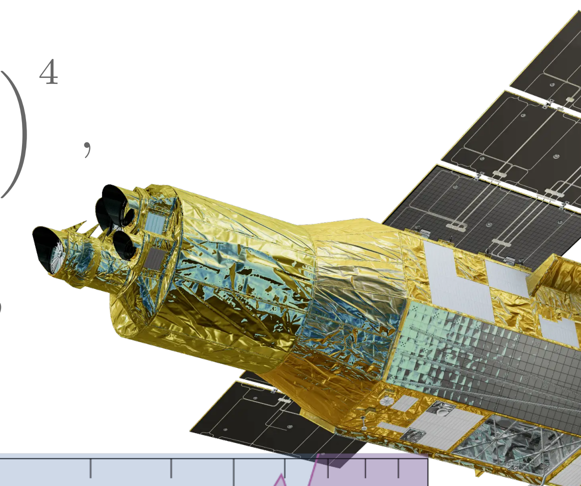


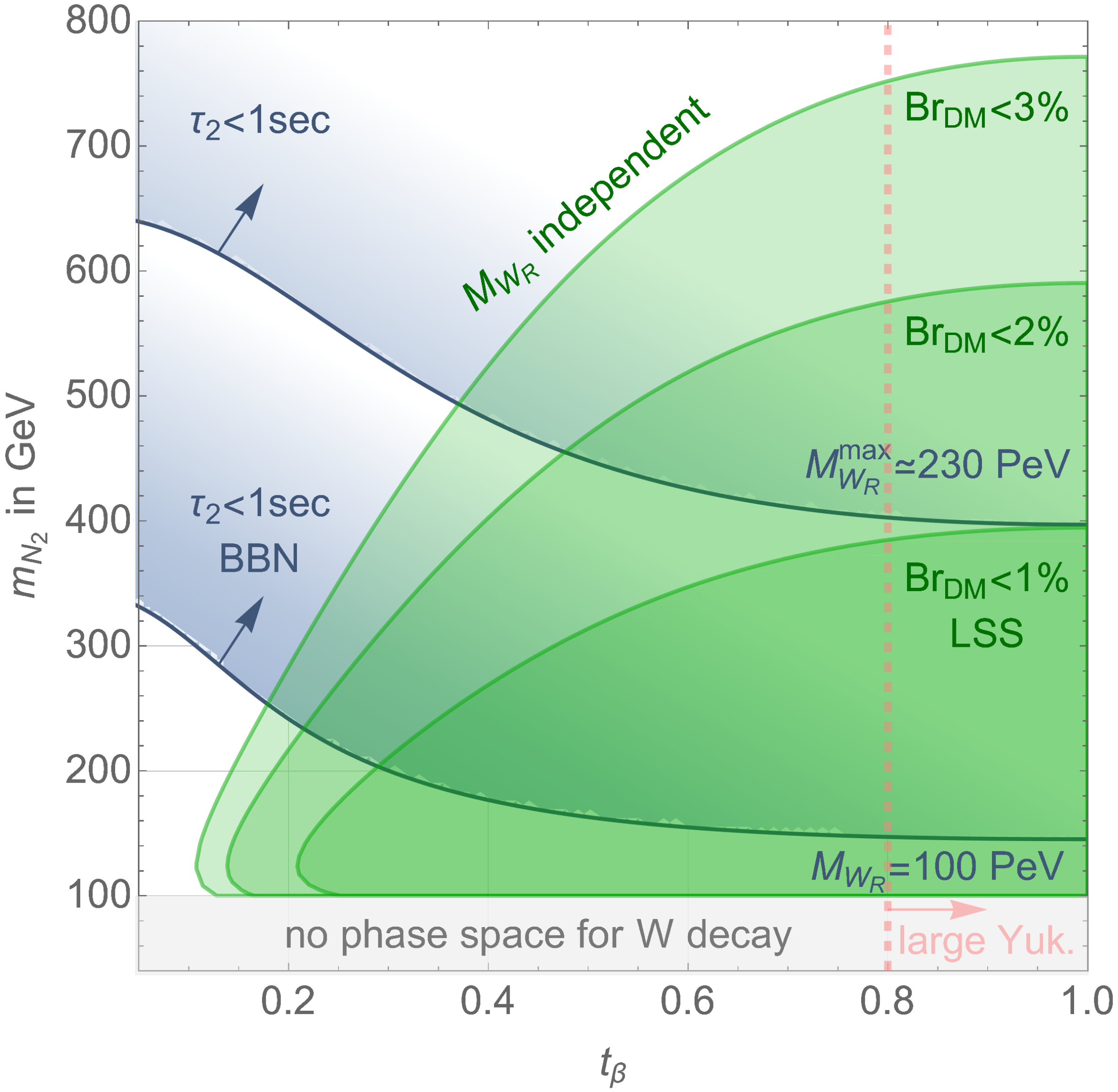
Gauge boson mixing dilution works, so does Δ_R^0

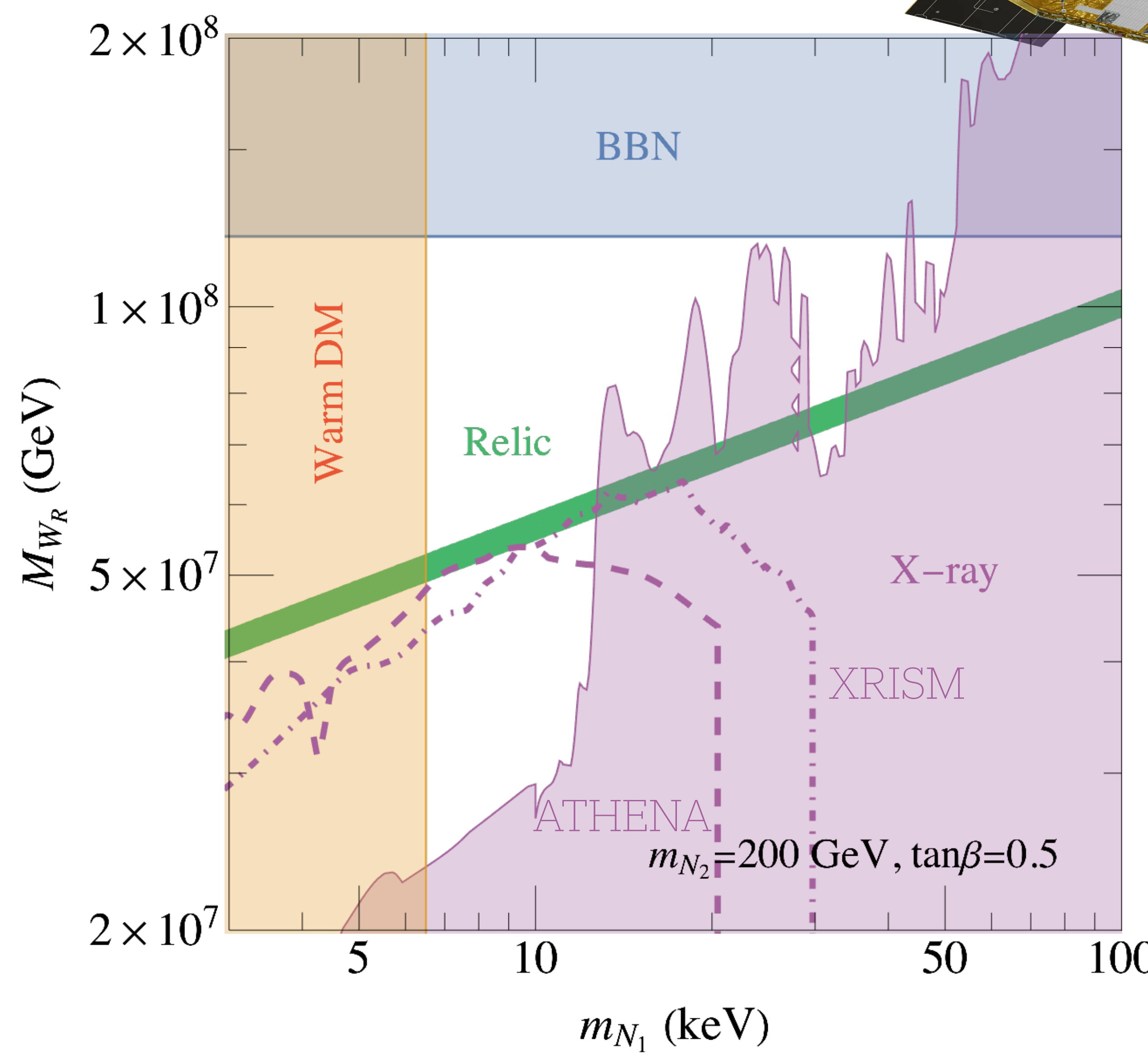
MN, Zhang '24

$$\Gamma_{N_2\to N_1\ell^+\ell'^-} = \frac{G_F^2 m_{N_2}^5}{96\pi^3}\left(\frac{M_W}{M_{W_R}}\right)^4, \qquad \Gamma_{N_2\to\ell q\bar{q}'} = \frac{\mathfrak{m}\, G_F^2 m_{N_2}^5}{96\pi^3}\left(\frac{M_W}{M_{W_R}}\right)^4,$$

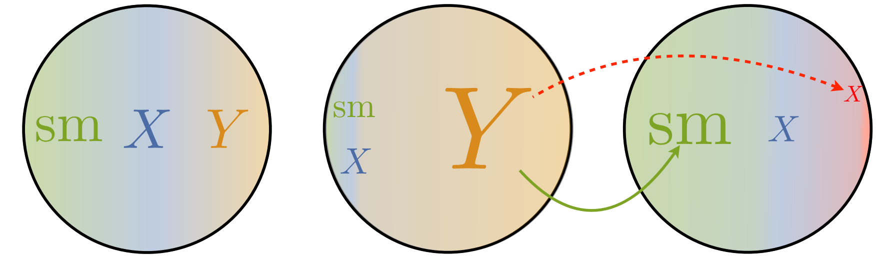
$$\Gamma_{N_2\to\ell W} = \frac{g^2|\xi|^2 m_{N_2}}{32\pi}\left(\frac{m_{N_2}}{M_W}\right)^2\left(1-\frac{M_W^2}{m_{N_2}^2}\right)\left(1+\frac{M_W^2}{m_{N_2}^2}-\frac{2M_W^4}{m_{N_2}^4}\right),$$







LRSM dark matter

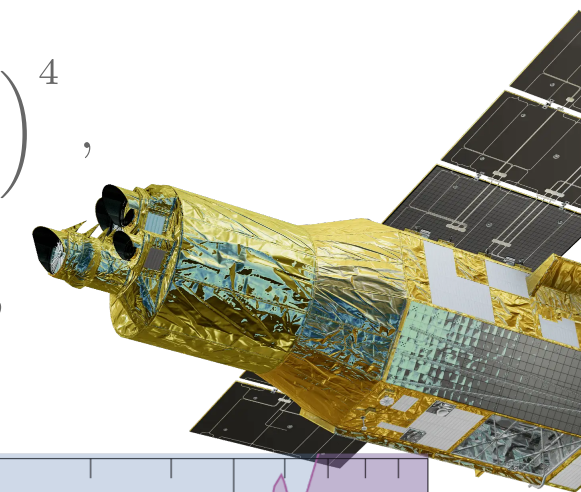


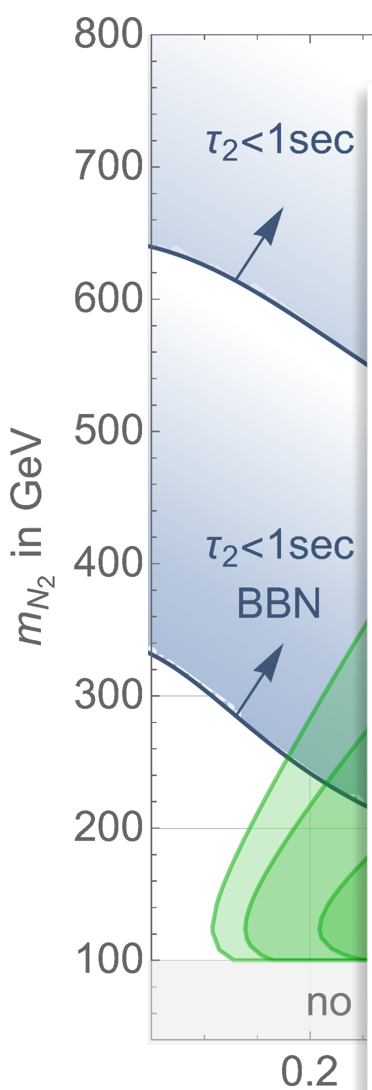
Gauge boson mixing dilution works, so does Δ_R^0

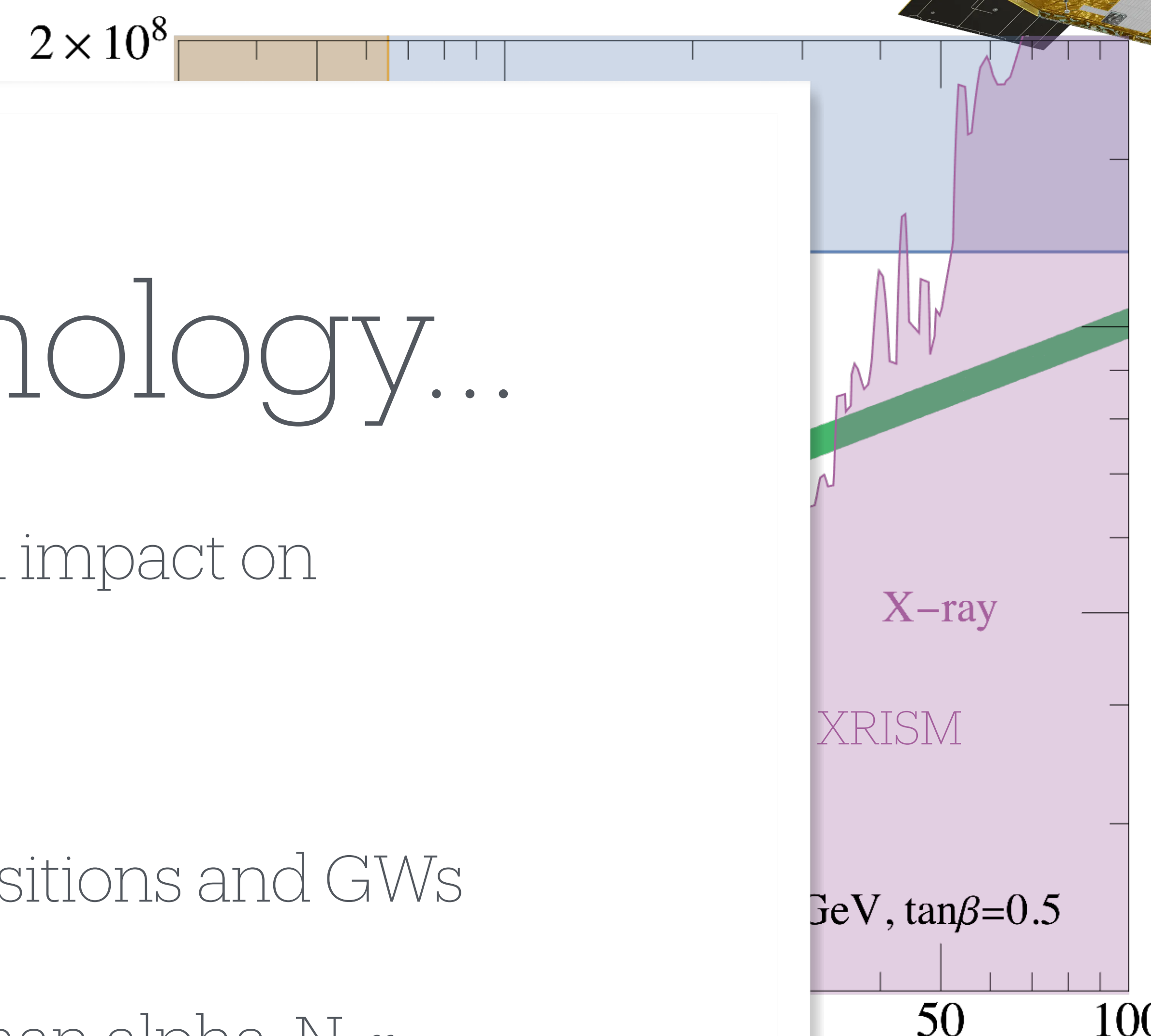
MN, Zhang '24

$$\Gamma_{N_2 \to N_1 \ell^+ \ell'^-} = \frac{G_F^2 m_{N_2}^5}{96\pi^3} \left(\frac{M_W}{M_{W_R}}\right)^4 , \qquad \Gamma_{N_2 \to \ell q \bar{q}'} = \frac{\mathfrak{m}\, G_F^2 m_{N_2}^5}{96\pi^3} \left(\frac{M_W}{M_{W_R}}\right)^4 ,$$

$$\Gamma_{N_2 \to \ell W} = \frac{g^2 |\xi|^2 m_{N_2}}{32\pi} \left(\frac{m_{N_2}}{M_W}\right)^2 \left(1 - \frac{M_W^2}{m_{N_2}^2}\right) \left(1 + \frac{M_W^2}{m_{N_2}^2} - \frac{2M_W^4}{m_{N_2}^4}\right) ,$$







More Cosmology...

New RH interactions and impact on

vacuum stability

1st order phase transitions and GWs

BBN, 21 cm line, Lyman alpha, Neff

9th International Workshop on

BARYON and LEPTON NUMBER VIOLATION

thanks for a great BLV '24 meeting!