Neutrino mass: The origins

Miha Nemevšek

~ JSI Ljubljana ~

w. Maiezza, Nesti, Popara, Senjanović, Tello, Vasquez, Zhang

PITT PACC NuTheories workshop

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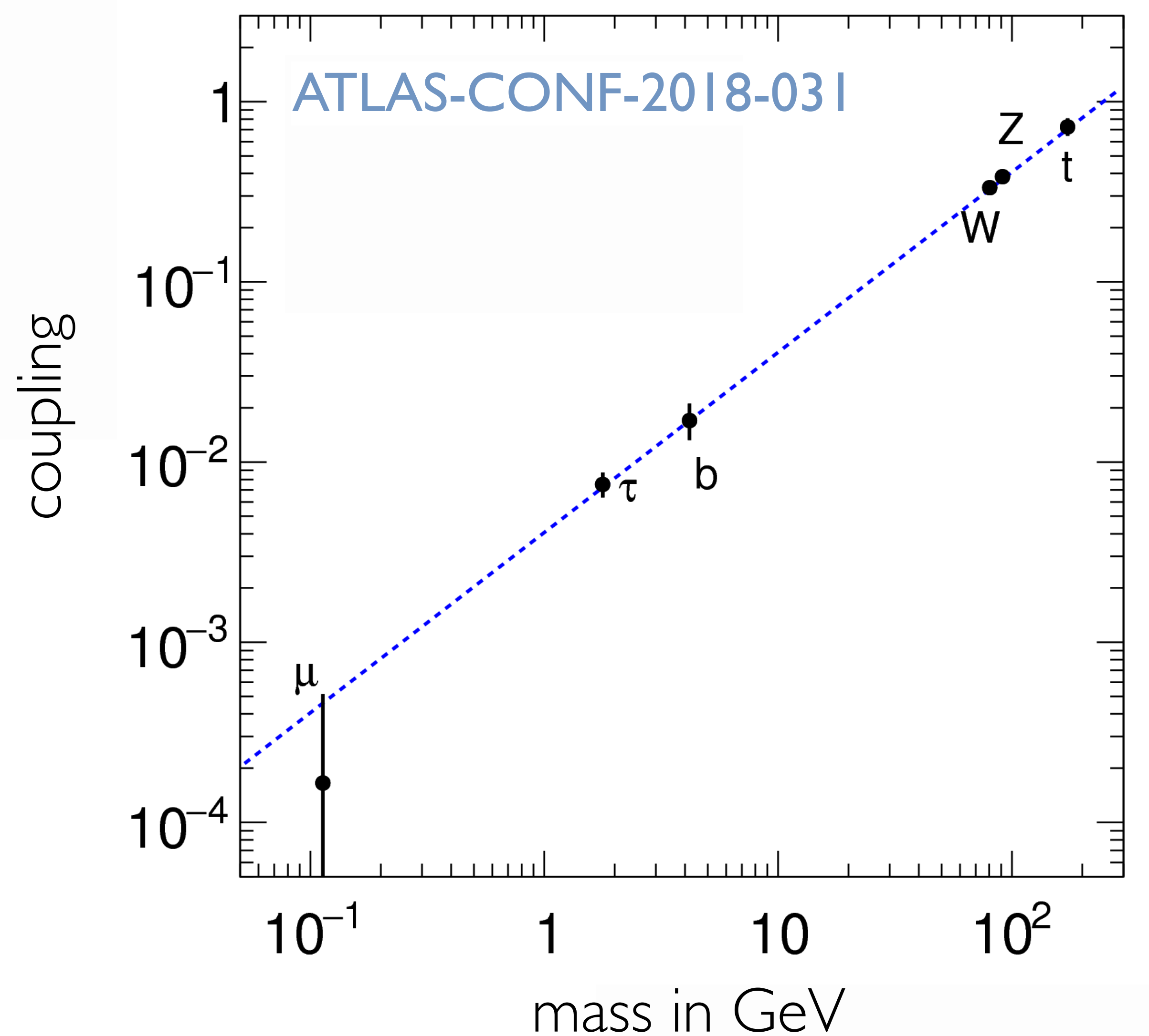
Fermion mass

Origin of fermion mass from SSB, e.g. the $SU(2)_L \times U(1)_Y$ Weinberg '67

Dirac term only $\mathcal{L}_f = y_\ell \, \overline{L} H \ell_R$ $\Gamma_{h\to\ell\bar{\ell}} \propto {y_\ell}^2$



EXP: all masses come from SSB

$$m_\ell = y_\ell \, v$$

Neutrinos

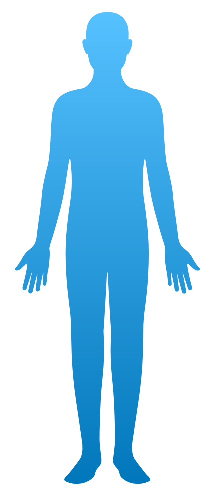
Massless by fiat in SM, does nature abhore gauge singlets?

Gauge extension motivations

unification of forces

$$SU(5), SO(10), E_6, \ldots$$

Glashow '79
Gell-Mann et al. '79,...

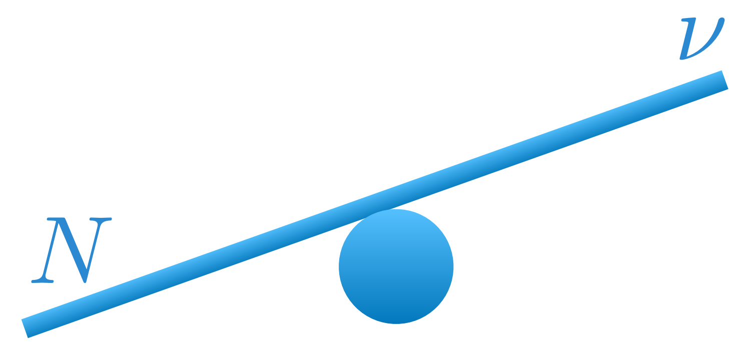


weak force asymmetry

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

$$SU(3)^3$$

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



minimal gauged seesaw

see Pavel's talk

$$U(1)_{B-L}$$

Origin of neutrino mass

Not as simple as charged fermions - enter Majorana - two sources

$$\frac{M_D}{v}\,\overline{L}HN + M_N\,N^TCN$$

Majorana '37

$$M_\nu = {M_D}^T {M_N}^{-1} M_D$$

Origin of neutrino mass

Not as simple as charged fermions - enter Majorana - two sources

oscillations,
0ν2β, endpoint,
cosmology,
N_{eff}, CνB,
…

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colliders,
meson decays,
warm DM,
leptogenesis,
...

Origin of neutrino mass

Not as simple as charged fermions - enter Majorana - two sources

$$\frac{M_D}{v}\,\overline{L}HN + M_N\, N^T C N$$

$$M_\nu = {M_D}^T {M_N}^{-1} M_D$$

$$= {M_D}^T {m_N}^{-1/2} \underbrace{{m_N}^{-1/2} M_D}_{OS}$$

$$O^T O = 1,$$

$$S^T = S,\ S = \sqrt{M_\nu}$$

Even so - connection to M_D is ambiguous

non-unitarity,
colliders, meson decays, 0ν2β,
eEDMs,
...

$$M_D = {m_N}^{-1/2}\, O\, \sqrt{M_\nu}$$

Finding the origins

Gauge extensions: additional W's, Z's and Higgsses

unification

$N \ni 16_F, 27_F, \ldots$

p-decay : $M_{GUT} \gtrsim 10^{16}$ GeV

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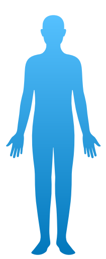
Pati, Salam '75



partial unification
Left-Right

$$L_R = \begin{pmatrix} N \\ \ell_R \end{pmatrix}$$

K-decay : $M_{PS} \gtrsim 10^{8}$ GeV

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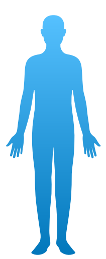

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K-decay : $M_{PS} \gtrsim 10^8$ GeV

K & *B* oscillations : $M_{W_R} \gtrsim 3 - 4$ TeV

Senjanović, Mohapatra '79,
Beall, Bander, Soni '82, many …
Bertolini, Nesti, Maiezza '14

mLRSM : flavor fixed

$V_R^q \simeq V_L^q$

nEDM, strong P breaking

Maiezza, MN '14

Finding the origins

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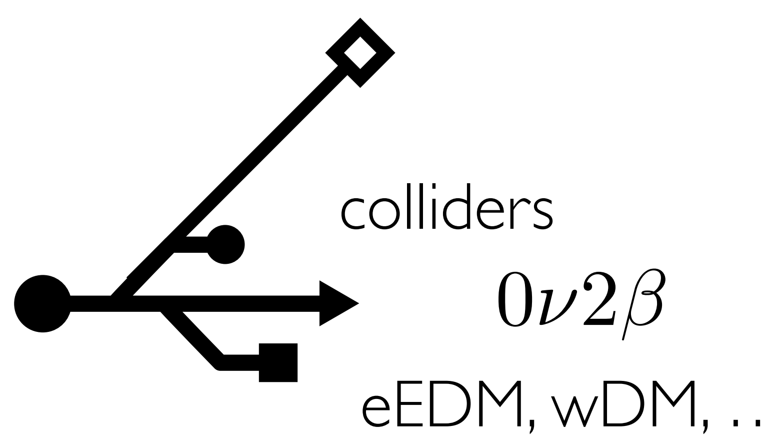
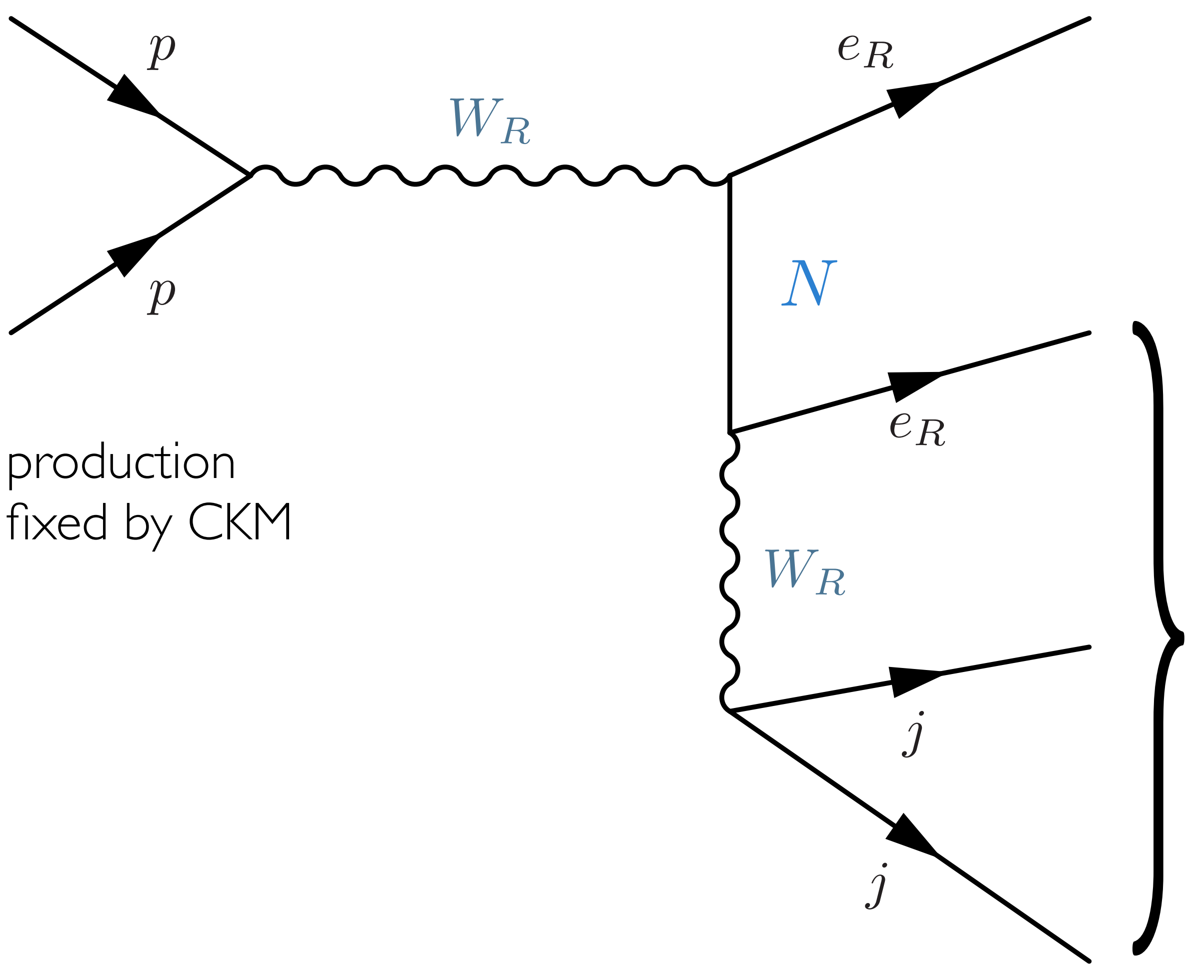


Colliders

Keung, Senjanović '83



production
fixed by CKM

Main feature: **L**epton **N**umber **V**iolation

On-shell Majorana fermion

$N \to \ell^{\pm} jj$ 50-50% same-opposite sign

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

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

~no missing energy

flavor states measure V_R^{ℓ} (free)

more on the Majorana nature

Gluza, Jelinski '15 '16
Das, Dev, Mohapatra '17

$$V_R^{\ell T} M_N V_R^{\ell} = m_N$$

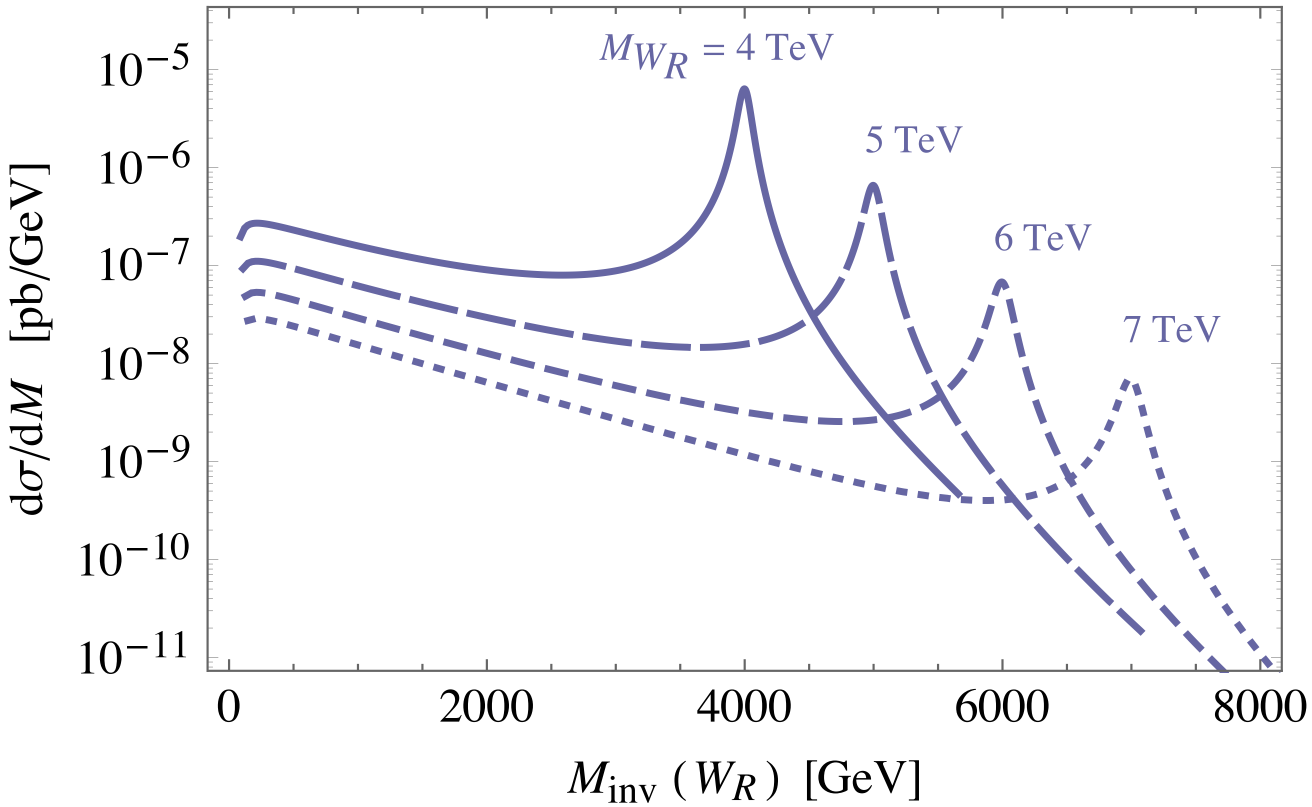
Golden channel: $pp \to W_R \to \ell_R N$

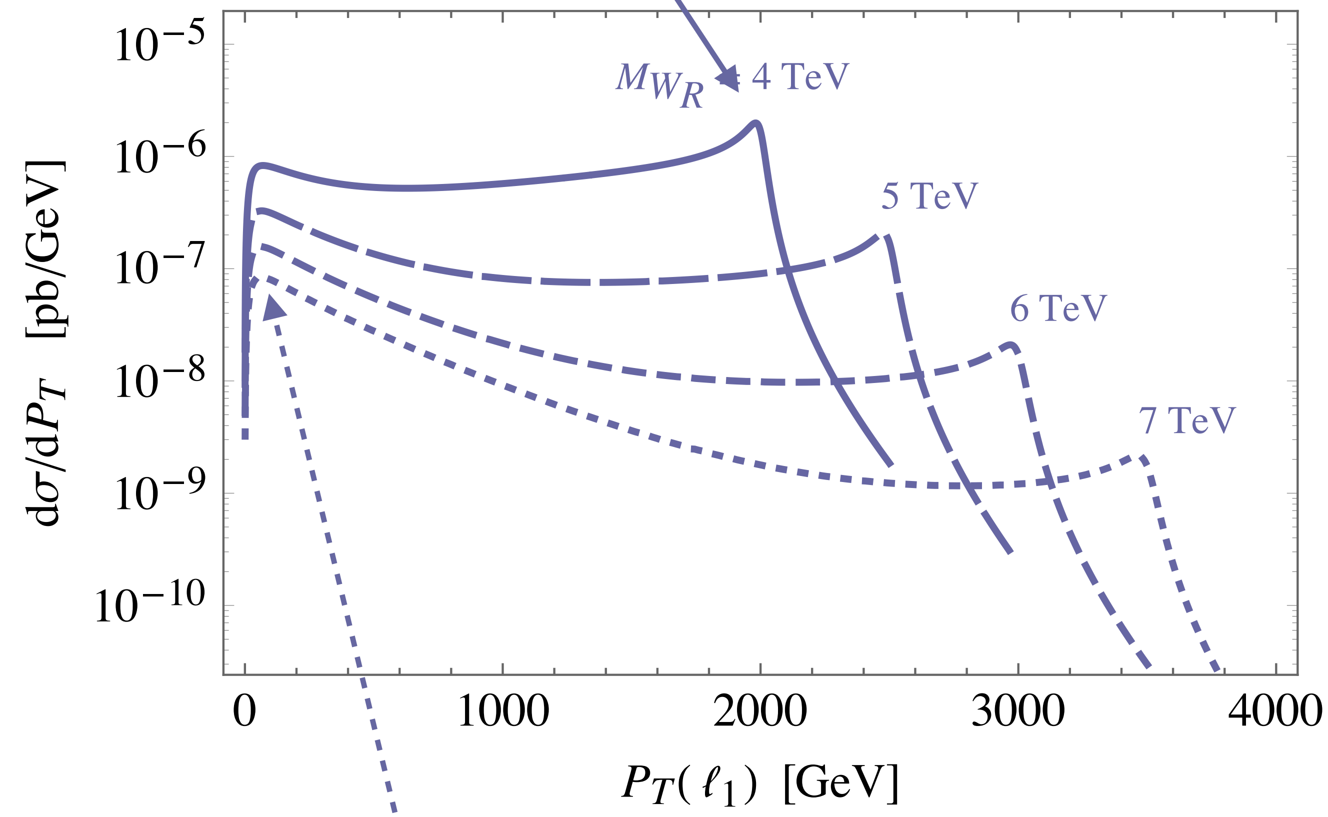
Keung, Senjanović '83

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

clear peak

mostly on-shell, N boosted





$m_{\rm inv}$ disappears

off-shell = soft lepton and N

Ruiz '17 see Richard's talk

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

MN, Nesti, Senjanović, Zhang '11

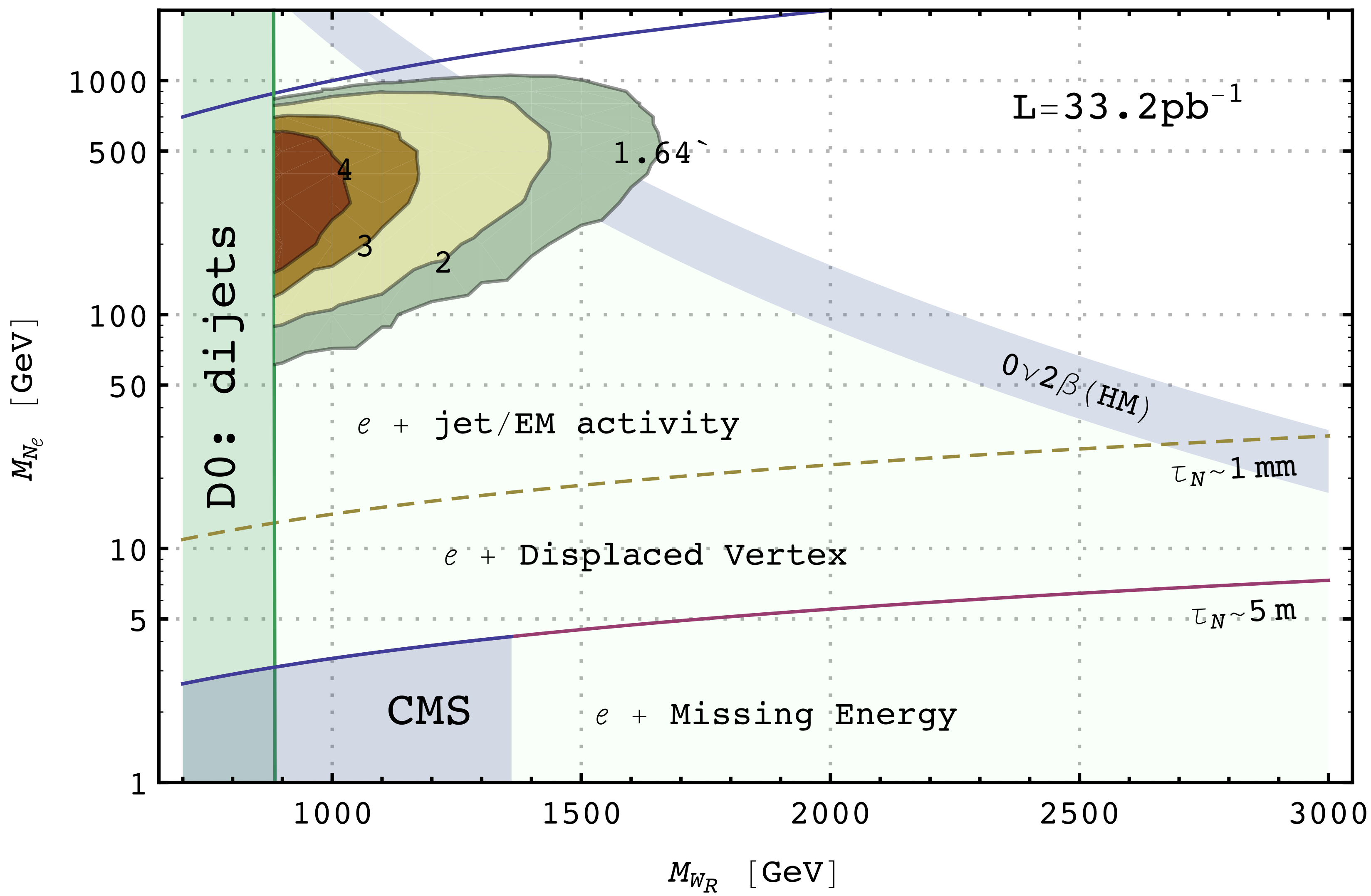
separated eejj

merged neutrino jet

Richard's talk

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

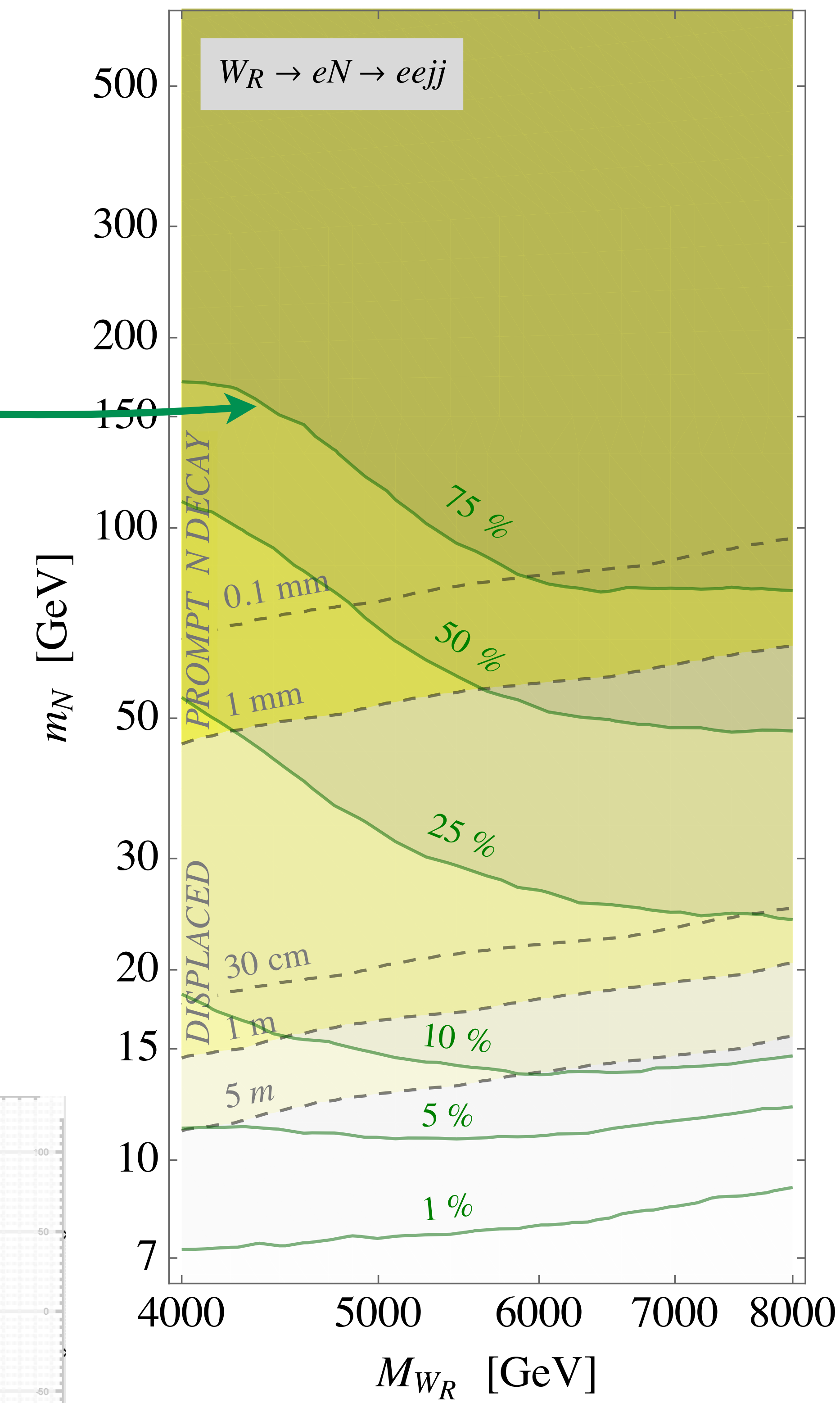
CMS: Gninenko et al. '07

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

MN, Nesti, Popara '18

2nd lepton isolation depends on the boost of N

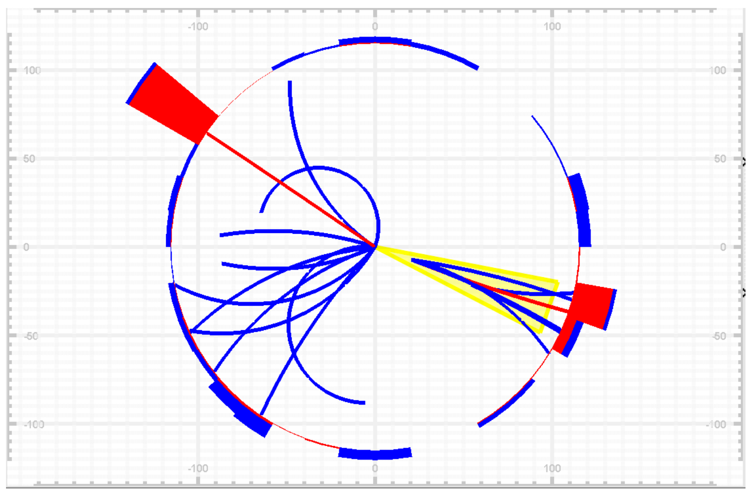
$$\gamma_N \simeq \begin{cases} \frac{M_{W_R}}{2m_N}, & W_R \to \text{on-shell}, \\ \frac{1\ \text{TeV}}{m_N}, & W_R \to \text{off-shell} \end{cases}$$



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 from prompt isolated to displaced merged - look for displaced merged jets (tracks)



Displaced jet discrimination

MN, Nesti, Popara '18

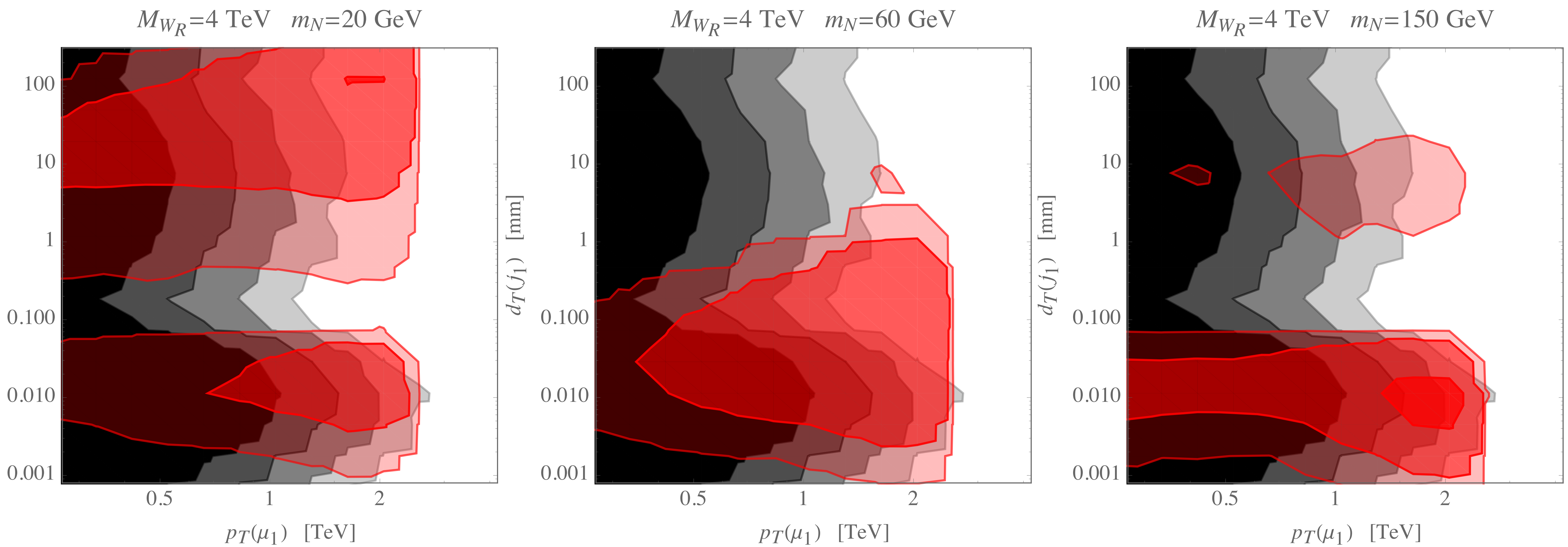
Event generation: custom generator KSEG, small width issues with MG5

also Feynrules model file and Delphes, Madanalysis displacement hack

sites.google.com/site/leftrighthep

Main bckgs

background	# generator	weight	# detector
$V + 012j$	22.46 M	0.021	9.93M
$VV + 012j$	10.55 M	0.0028	4.61M
$t\bar{t} + 012j$	10.47 M	0.024	4.38M



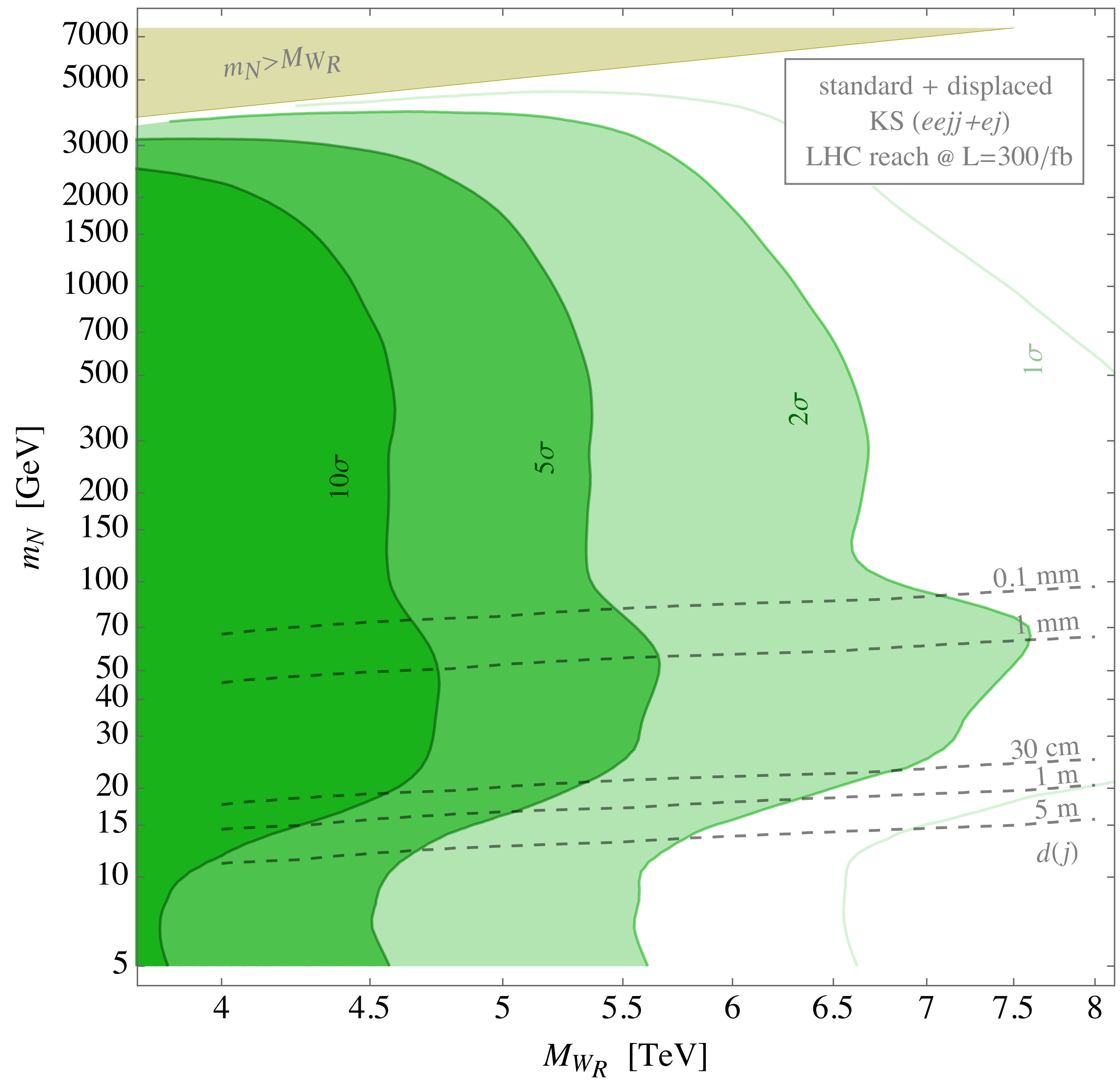
Sensitivity estimate

MN, Nesti, Popara '18

rough pre-selection

bin over 6 variables below

$$\text{sensitivity} = \sqrt{\sum_{i\in\text{bins}} \frac{s_i^2}{s_i + b_i}}$$

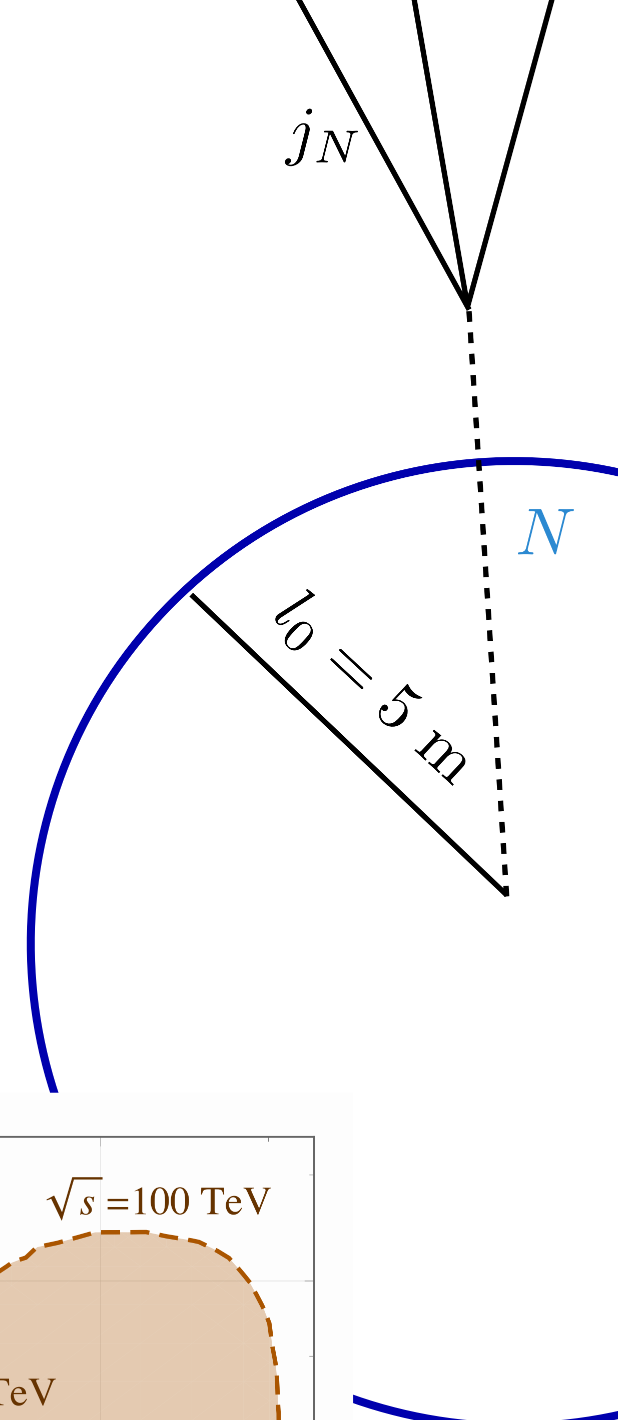


Sensitivities

Electron Channel	$\mathcal{L} = 300\,\text{fb}^{-1}$		M_{W_R}:	4 TeV	4 TeV	4 TeV	6 TeV	6 TeV
variable	range	# bins	m_N:	20 GeV	300 GeV	2 TeV	20 GeV	300 GeV
$p_T(\ell_1)$	$\{150, 4500\}$ GeV	35		14.19	13.82	7.19	1.03	1.77
$d_T(j_1)$	$\{0.001, 300\}$ mm	100		17.57	14.04	7.60	2.02	1.91
#(jets)	$1, 2, 3, 4$	4		17.88	14.20	7.94	2.24	2.04
#(leptons)	$1, 2$	2		17.97	14.90	9.08	2.30	2.23
#(same sign)	$0, 1$	2		18.00	15.71	9.85	2.32	2.61
$m^{\text{inv}}_{\ell_1 j_1}$	$\{200, 8500\}$ GeV	20		18.82	17.24	10.91	2.81	3.03

Recasting the $W' \to \ell\nu$

MN, Nesti, Popara '18

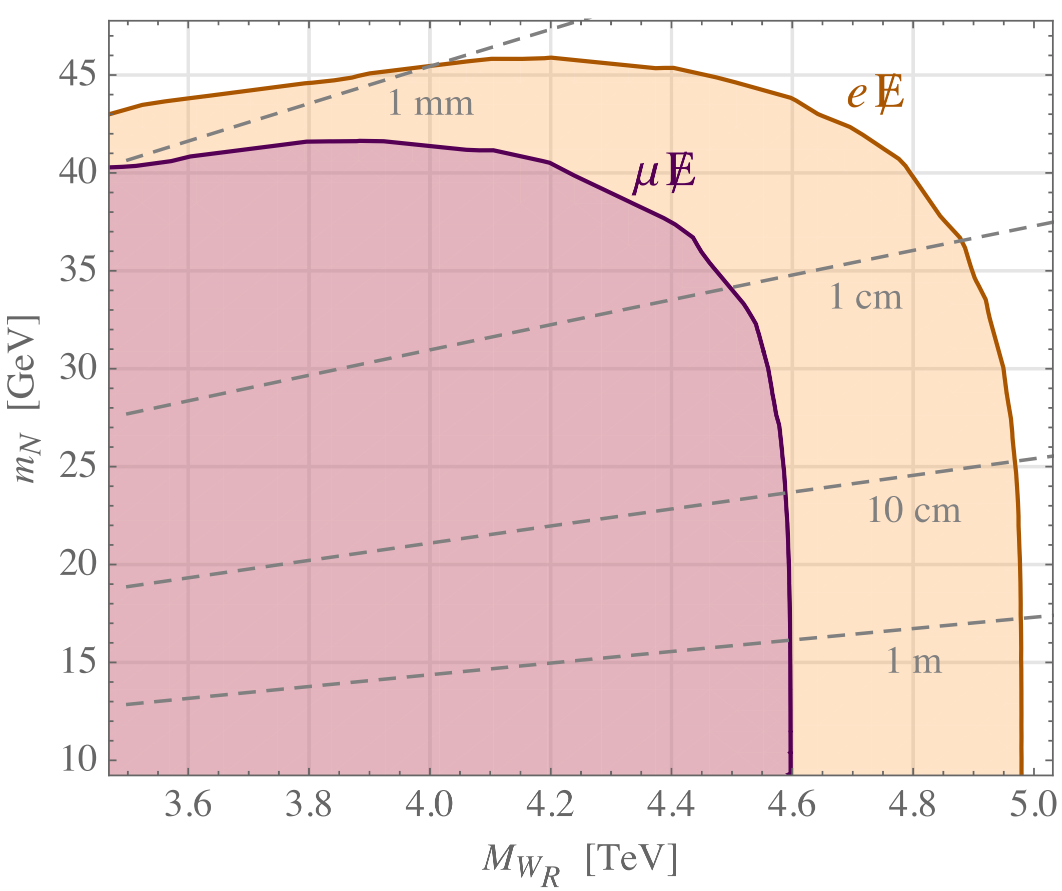


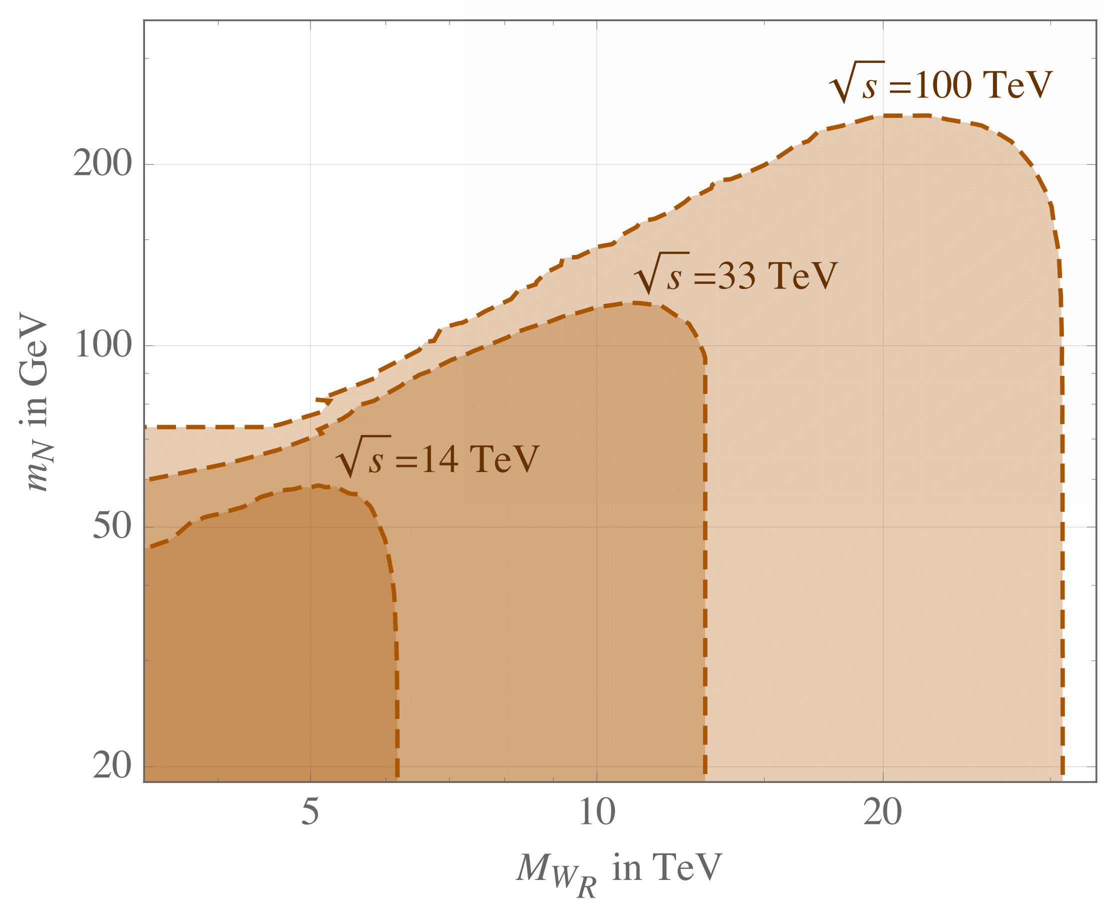
prompt hard leading lepton and significant missing energy

$$\frac{d\sigma}{dm_T} = \alpha_2^2 \frac{\pi}{24} p_T \int_{\tau_-}^{1} \int_{\frac{\tau_-}{x_1}}^{1} dx_{1,2} \frac{\left(\hat{s} - m_N^2 - 2p_T^2\right) \pm 1}{\sqrt{\left(\hat{s} - m_N^2\right)^2 - 4p_T^2 \hat{s}}}$$

$$\frac{\varepsilon_\ell^\pm(p_T, \eta_\ell)}{\left(\hat{s} - M^2\right)^2 + (\Gamma M)^2} \left|V_{ud} V_{\ell N}\right|^2 f_u(x_{1,2}) f_{\bar{d}}(x_{2,1}) e^{-l_0/L_\pm}$$

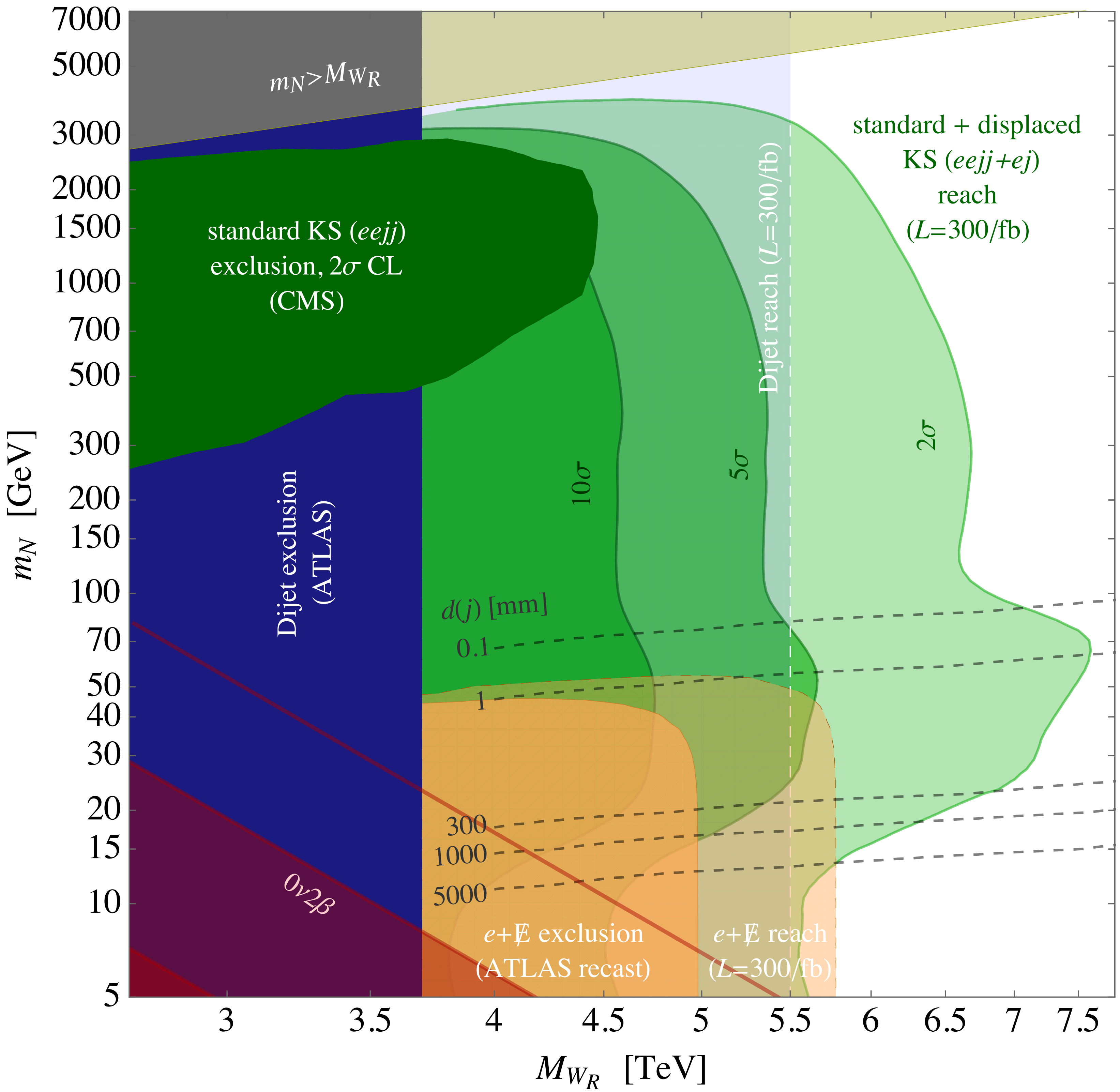
exponential distributions have tails





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

MN, Nesti, Popara '18



standard prompt isolated mode

Ng et al.'15, Ruiz '17

merged neutrino jet $\ell\, j_N$

Mitra, Ruiz, Spannowsky '16

Richard's talk

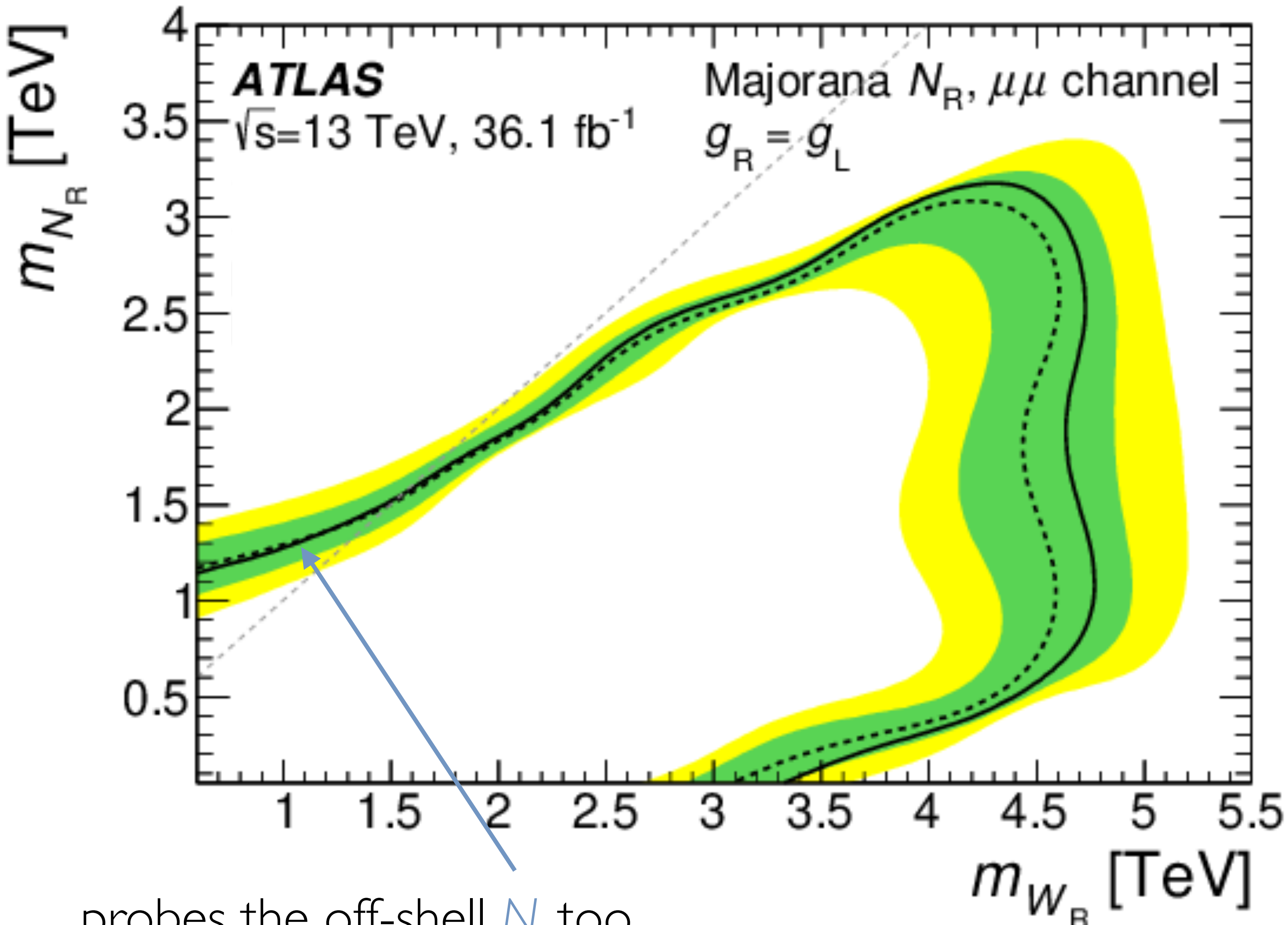
displaced jet $\ell\, j_N^d$

Cottin, Helo, Hirsch '18

invisible: prompt $\ell + E_{miss}$

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

Experimental limits review $pp \to W_R \to \ell_R N, \ldots$



probes the off-shell N, too

standard prompt isolated mode

*e, mu	4.7 TeV	ATLAS 1809.11105
tau	3.5 TeV	CMS 1811.00806

lepton + missing energy

*e, mu	$M_{W_R} \gtrsim 5$ TeV	ATLAS 1706.04786
tau$_h$	$M_{W_R} > 3.7$ TeV	ATLAS 1801.06992

*interplay with $0\nu2\beta$

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

dijets

$M_{W_R} > 3.6$ TeV — ATLAS 1703.09127

tb

$M_{W_R} > 3$ TeV — ATLAS 1801.07893

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

up to ~ 5 TeV — ATLAS 1808.02380

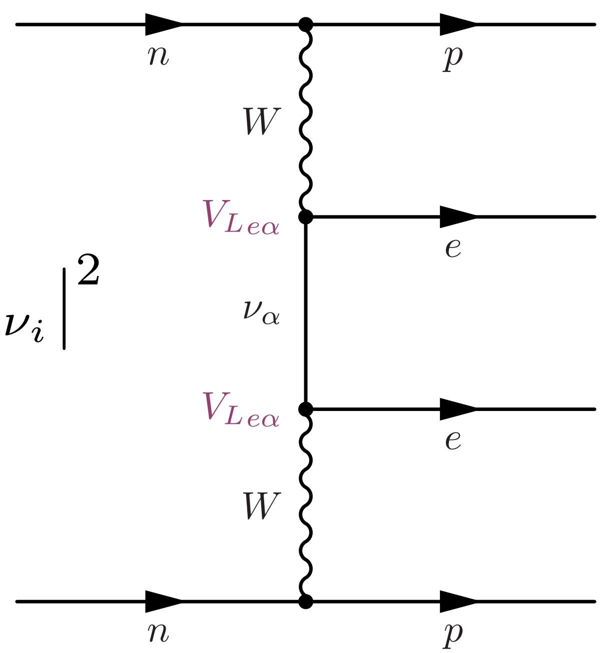
LNV interplay

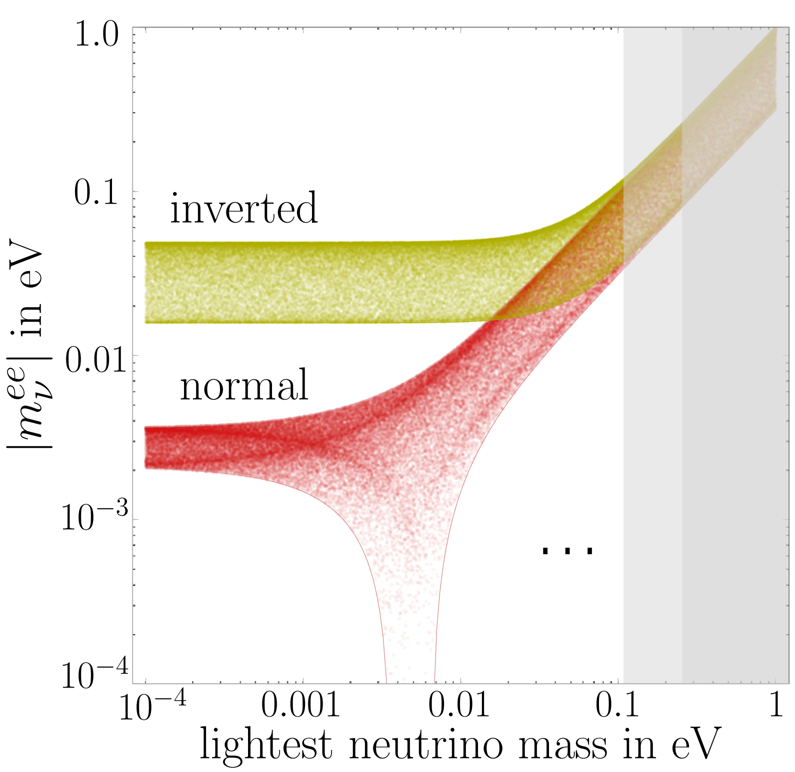
Nuclear vs. collider physics

Immediate proposal after Majorana: $0\nu 2\beta$ via light neutrino exchange

Furry '39

$$\Gamma \propto \left| m_\nu^{ee} = V_{ei}^2 m_{\nu_i} \right|^2$$





Cosmology, KATRIN, …

Possible tension

Vissani '02

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Mohapatra, Senjanović '79

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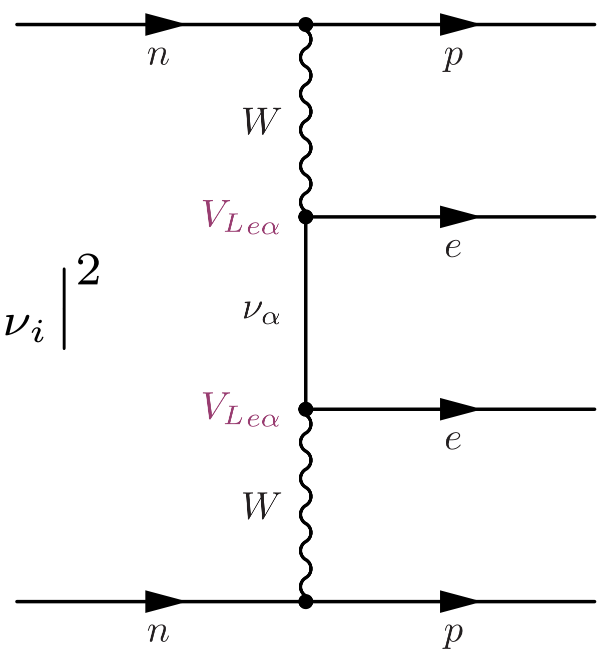
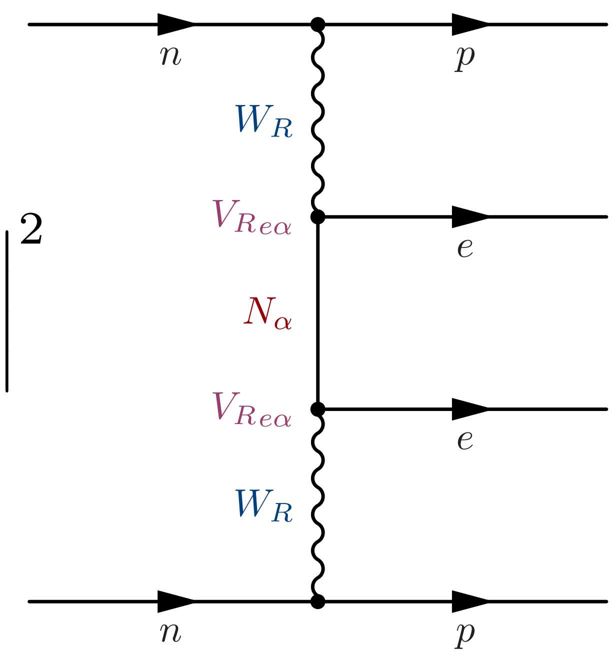
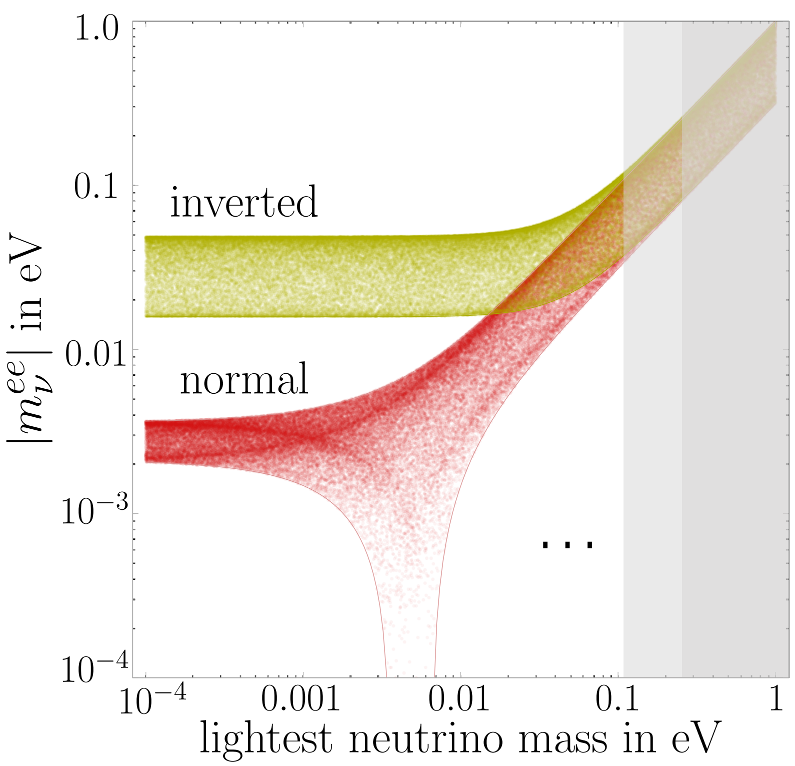


$$\Gamma \propto \left| m_N^{ee} = \frac{V_{ei}^{R2}}{m_{N_i}} \right|^2$$

'heavy' neutrinos

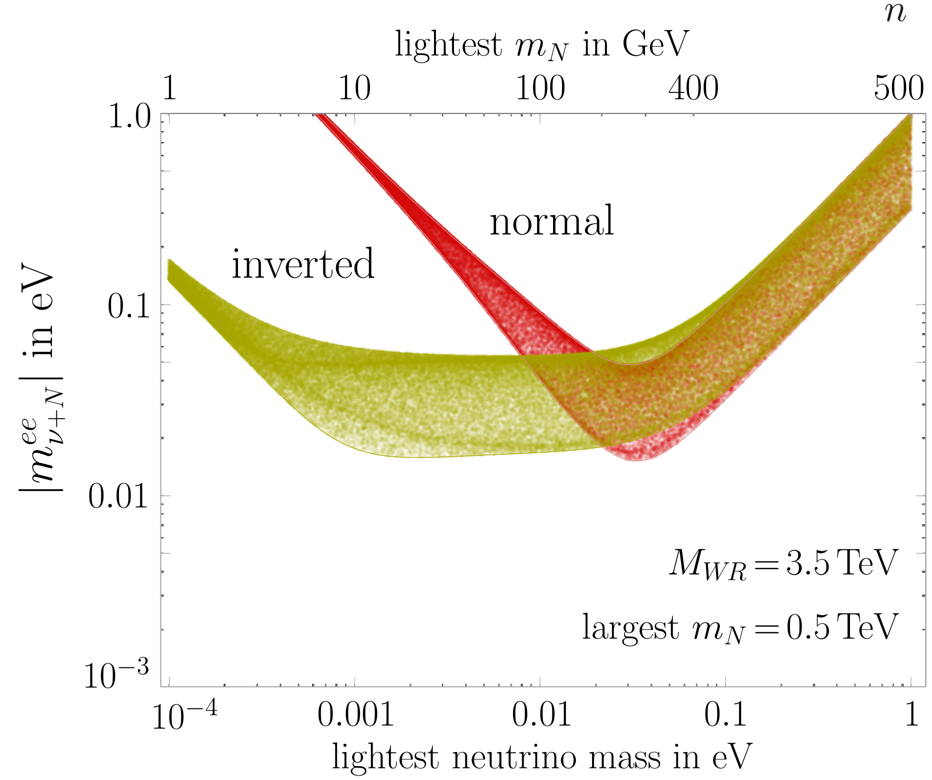




Cosmology, KATRIN, …

Possible tension

Vissani '02



Tello, MN, Nesti, Senjanović, Vissani '11

no tension with LR

$$V_R = V_{PMNS}$$

connection to LFV

+other diagrams

Majorana - Dirac connection

$$M_\nu = {M_D}^T {M_N}^{-1} M_D + M_L,$$

MN, Senjanović, Tello, '12

$$\mathcal{C}: {M_D}^T = M_D,$$

$$M_L = \frac{v_L}{v_R} M_N$$

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

Majorana - Dirac connection

Colliders

$$M_\nu = {M_D}^T {M_N}^{-1} M_D + M_L,$$

MN, Senjanović, Tello, '12

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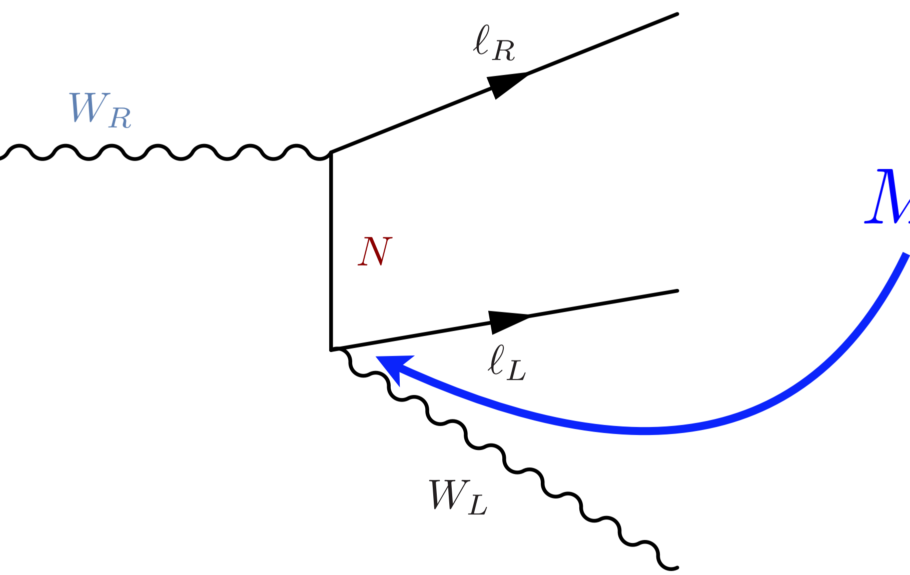
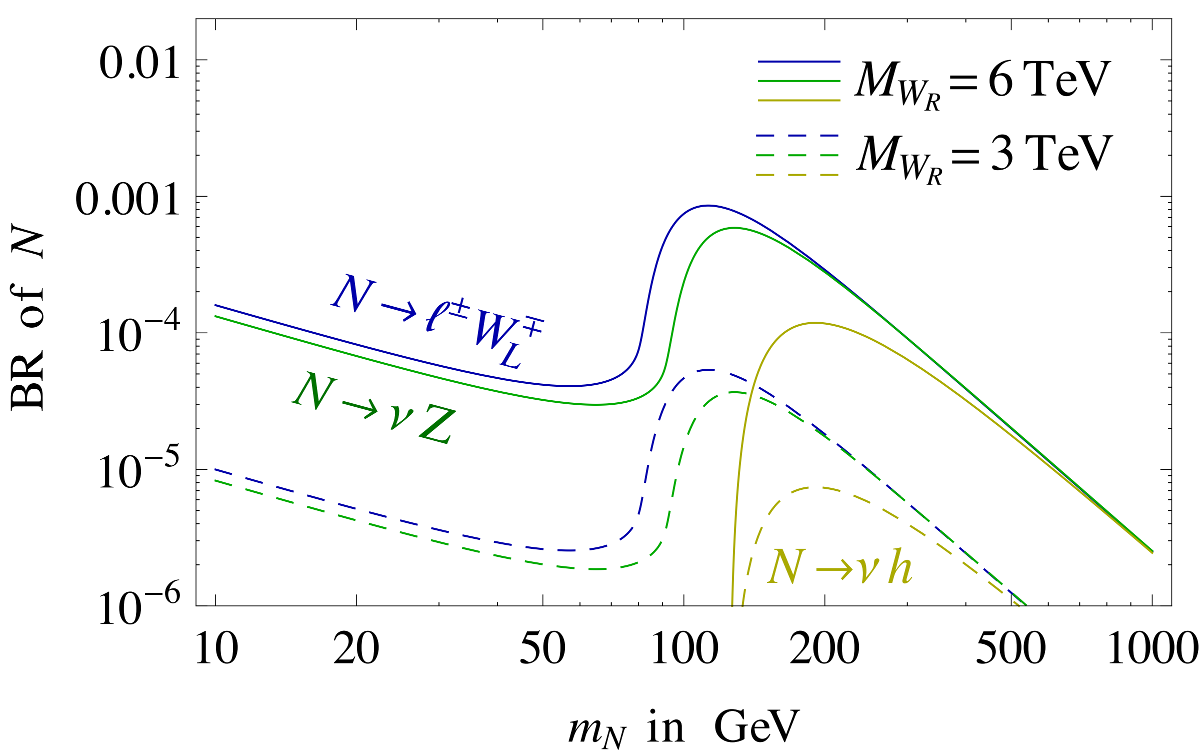


$$M_D = M_N \sqrt{{M_N}^{-1} M_\nu - \frac{v_L}{v_R}}$$



Sub-dominant decays, needs high lumi

Six flavor channels for M_D

Polarimetry

Han, Luiz, Ruiz, Si '12

Majorana - Dirac connection

eEDM

$$M_\nu = {M_D}^T {M_N}^{-1} M_D + M_L,$$

MN, Senjanović, Tello, '12

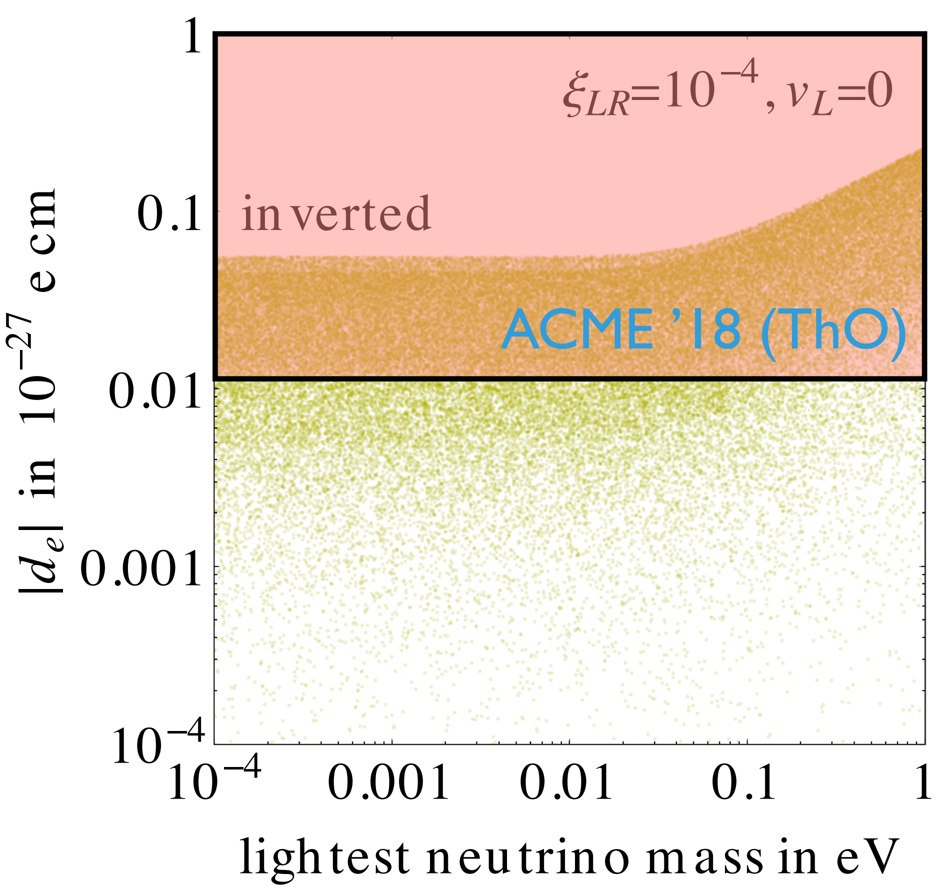
$$\mathcal{C} : {M_D}^T = M_D,$$

$$M_L = \frac{v_L}{v_R} M_N$$

SM is ~zero

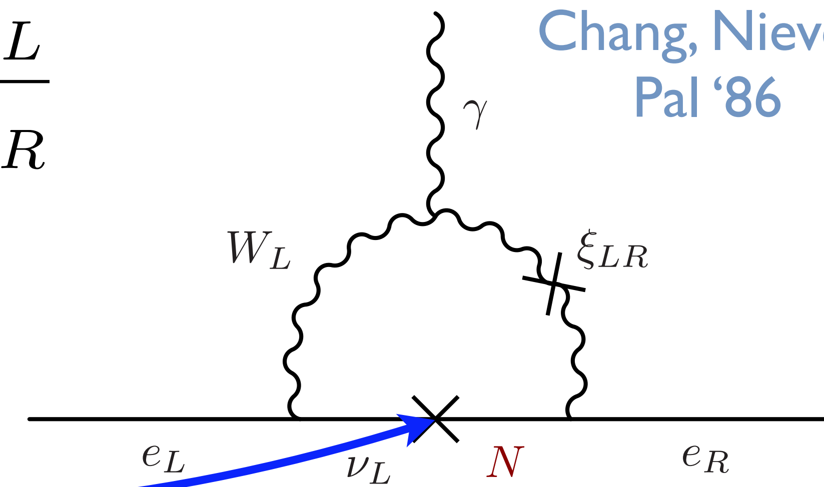
$$d_e^{SM} \lesssim 10^{-38} \text{ e cm}$$

Pospelov, Ritz '05



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

Chang, Nieves, Pal '86



$$d_e = \frac{e G_F}{4\sqrt{2}\pi^2} \text{ Im} \left[\xi_{LR} V_R \mathcal{F}(t) {V_R}^\dagger M_D \right]_{ee}$$

T-odd, sensitive to Majorana phases

$$\mathcal{F}(t) = \frac{t^2 - 11t + 4 + 6t^2 \log t/(t-1)}{2(t-1)^2},$$

$$t = (m_N/M_W)^2$$

Higgs sector

$\Delta_L(3,1,2),\ \Phi(2,2,0),\ \Delta_R(1,3,2)$

Minkowski '77
Mohapatra, Senjanović '79

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \qquad \langle\Phi\rangle = \begin{pmatrix} v & 0 \\ 0 & 0 \end{pmatrix}$$

$$\Delta_R = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}_R \quad \langle\Delta_R\rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$$

SSB of parity

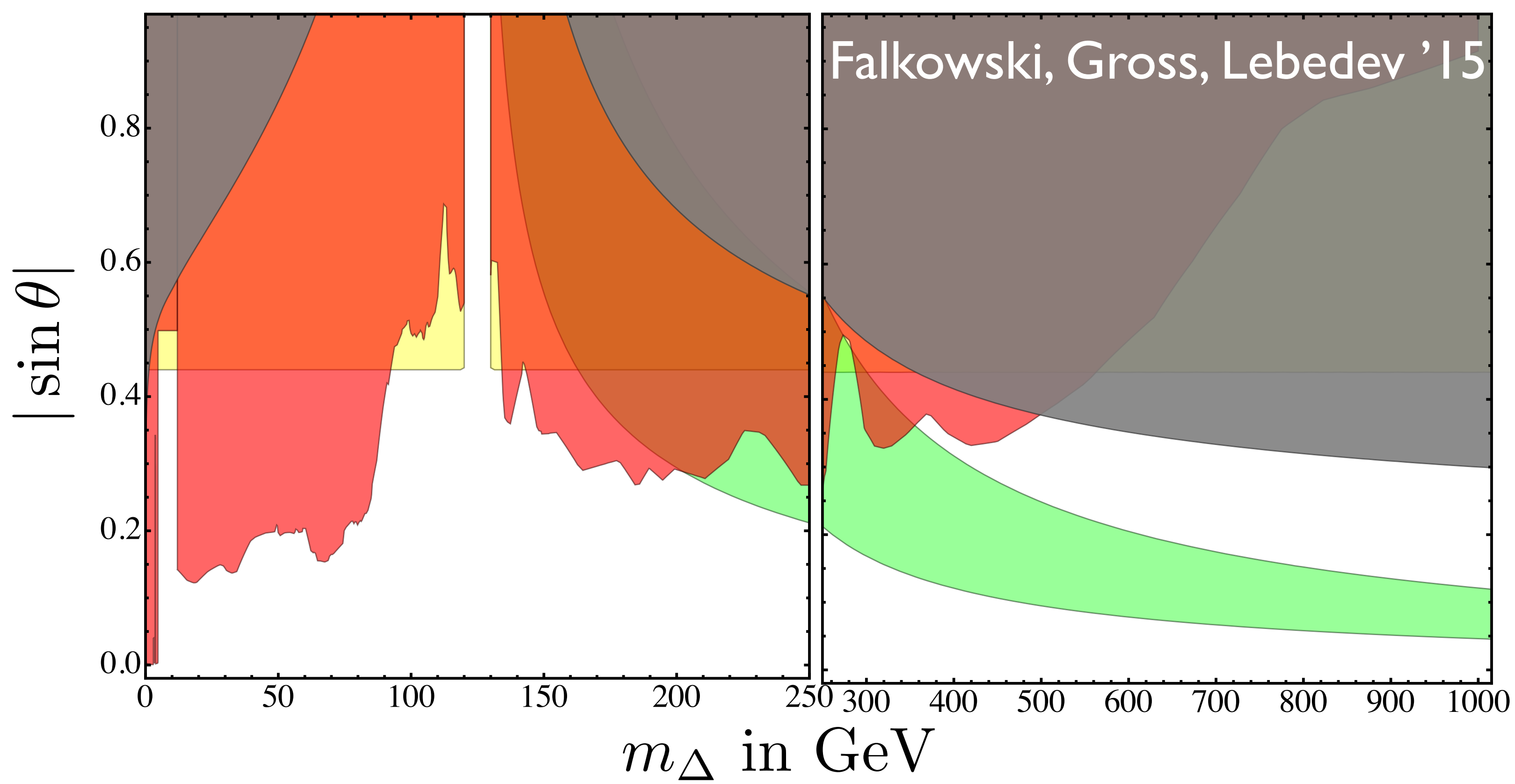
$$\mathcal{P}:\begin{cases} \Delta_L \leftrightarrow \Delta_R,\ \Phi \to \Phi^\dagger \\ Q_L \leftrightarrow Q_R,\ L_L \leftrightarrow L_R \end{cases}$$

Senjanović, Mohapatra '75

$$V \in \lambda\,(\Phi^\dagger\Phi)^2 + \alpha(\Phi^\dagger\Phi)(\Delta_R^\dagger\Delta_R) + \rho\,(\Delta_R^\dagger\Delta_R)^2$$

same for $\mathcal{C}$-symmetry

$h-\Delta$ mixing: $\theta \simeq \left(\frac{\alpha}{2\,\rho}\right)\left(\frac{v}{v_R}\right) \lesssim .44$

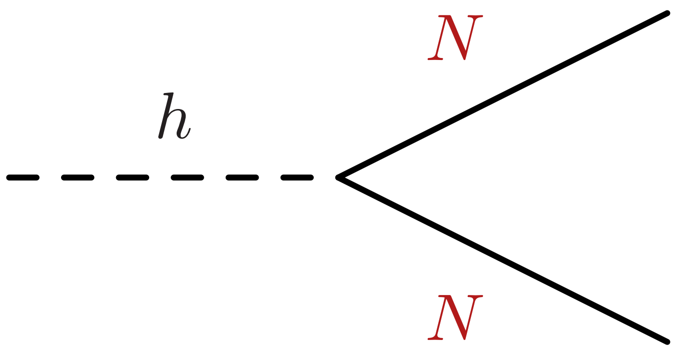


Future collider outlook

$|\sin\theta| < .34$

Buttazzo, Sala, Tesi '15

‘Majorana’ SM Higgs

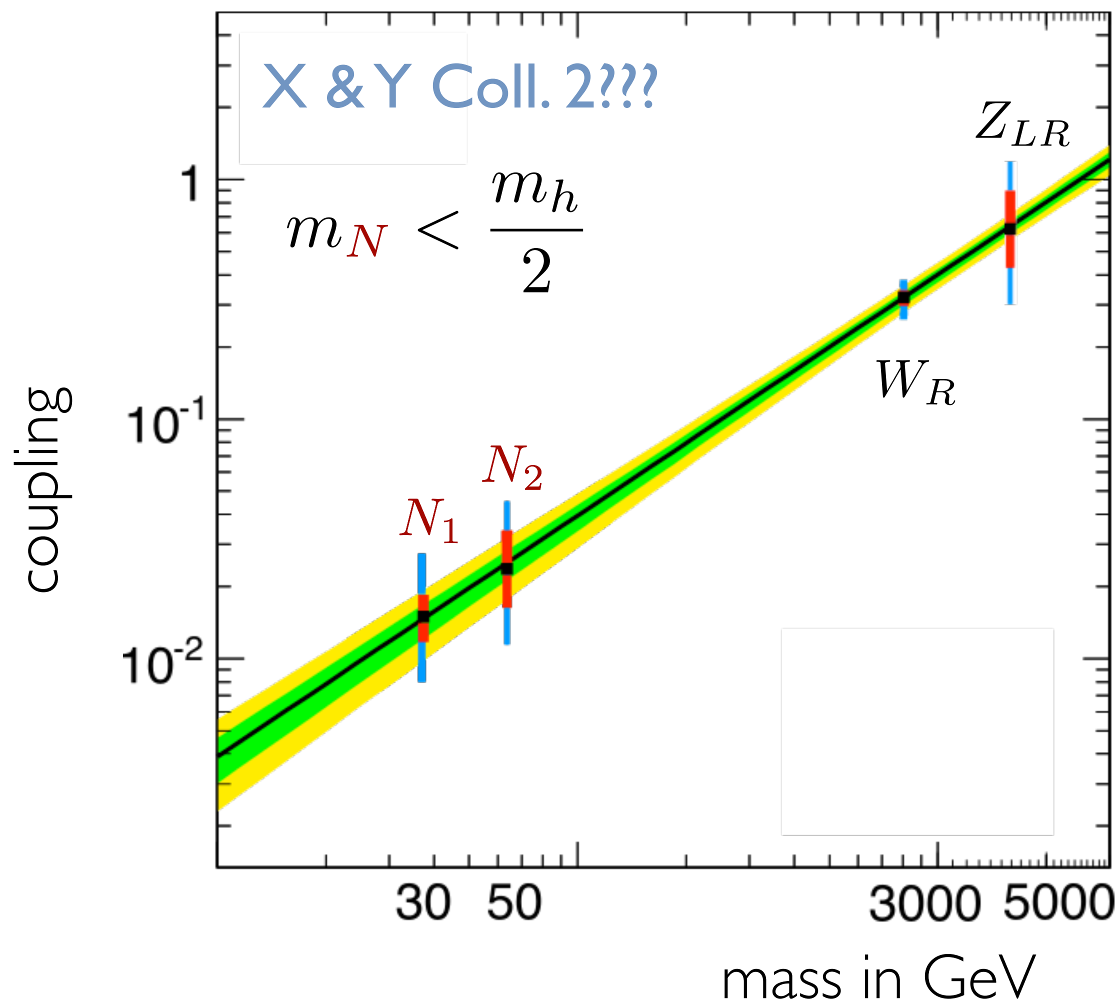


h decays

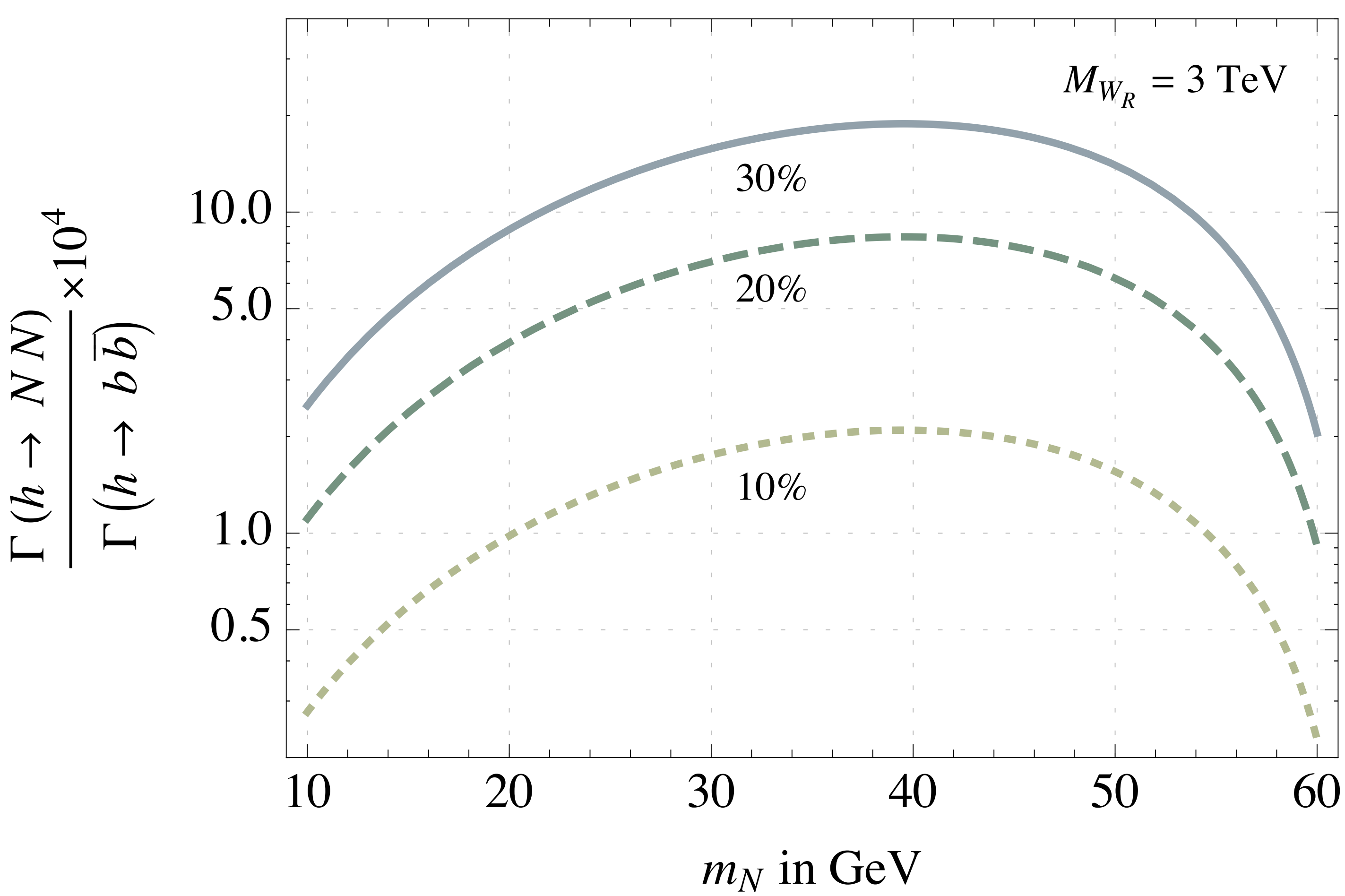
$$\Gamma_{h\to NN} \propto s_\theta^2\, m_N{}^2 \qquad \frac{\Gamma_{h\to NN}}{\Gamma_{h\to b\bar b}} \simeq \frac{\theta^2}{3}\left(\frac{m_N}{m_b}\right)^2\left(\frac{M_W}{M_{W_R}}\right)^2$$

Gunion et al. Snowmass ’86

EFT SM+h+N Graesser ’07



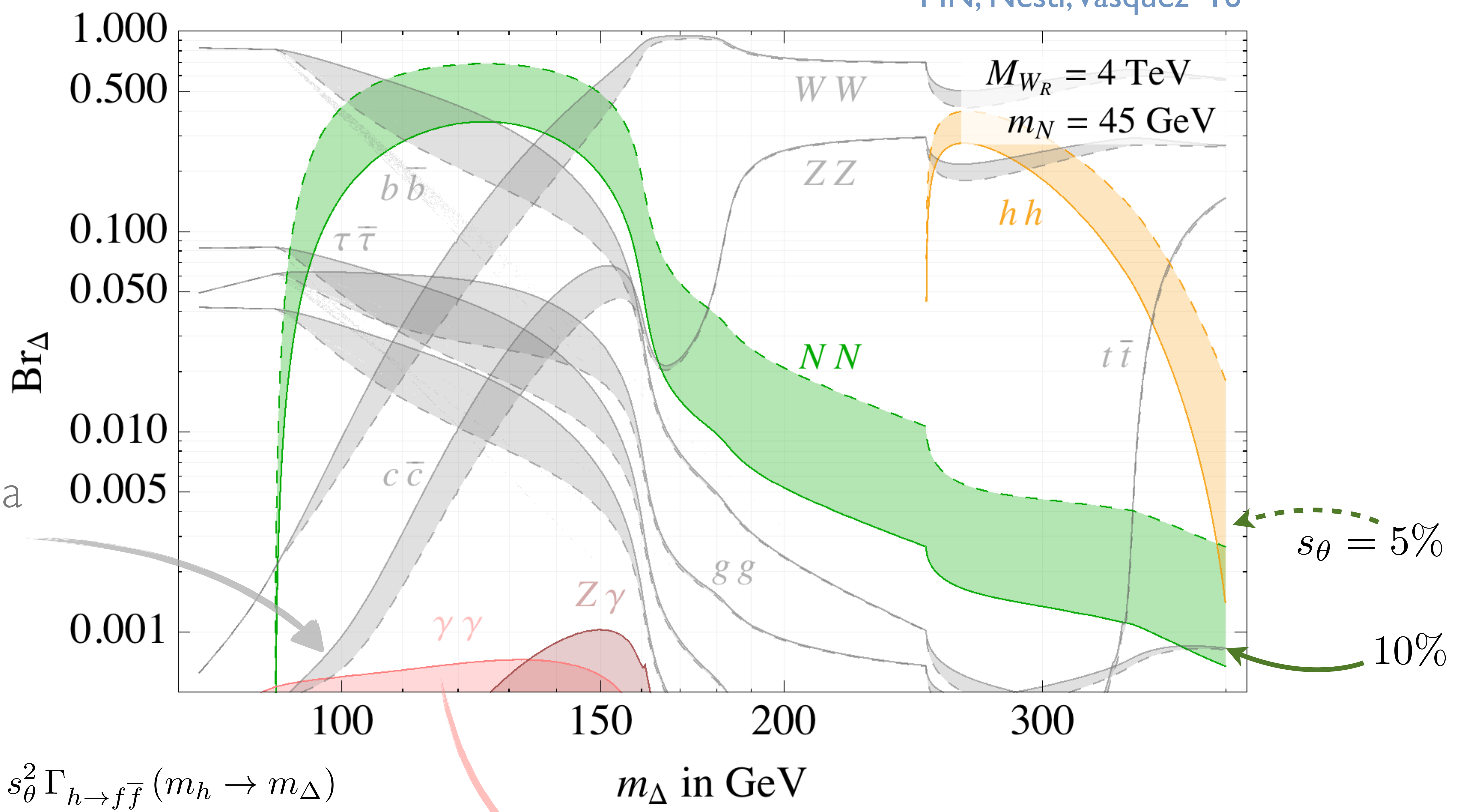
Maiezza, MN, Nesti ’15



‘Right-handed’ Higgs

Δ_R^0 decays

MN, Nesti, Vasquez ’16



to SM via mixing

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

radiative loops

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

Displaced photons Dev, Mohapatra, Zhang ’16

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

‘Right-handed’ Higgs

Δ decays

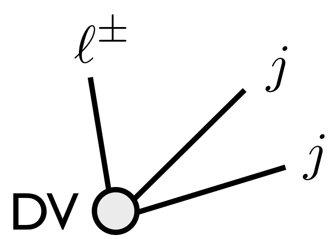
Region of interest for $\Delta \to \color{red}{NN}$

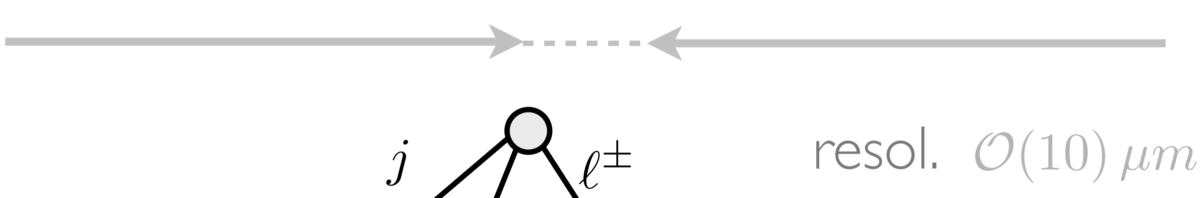
$$20 \text{ GeV} \lesssim m_\Delta \lesssim 170 \text{ GeV}$$

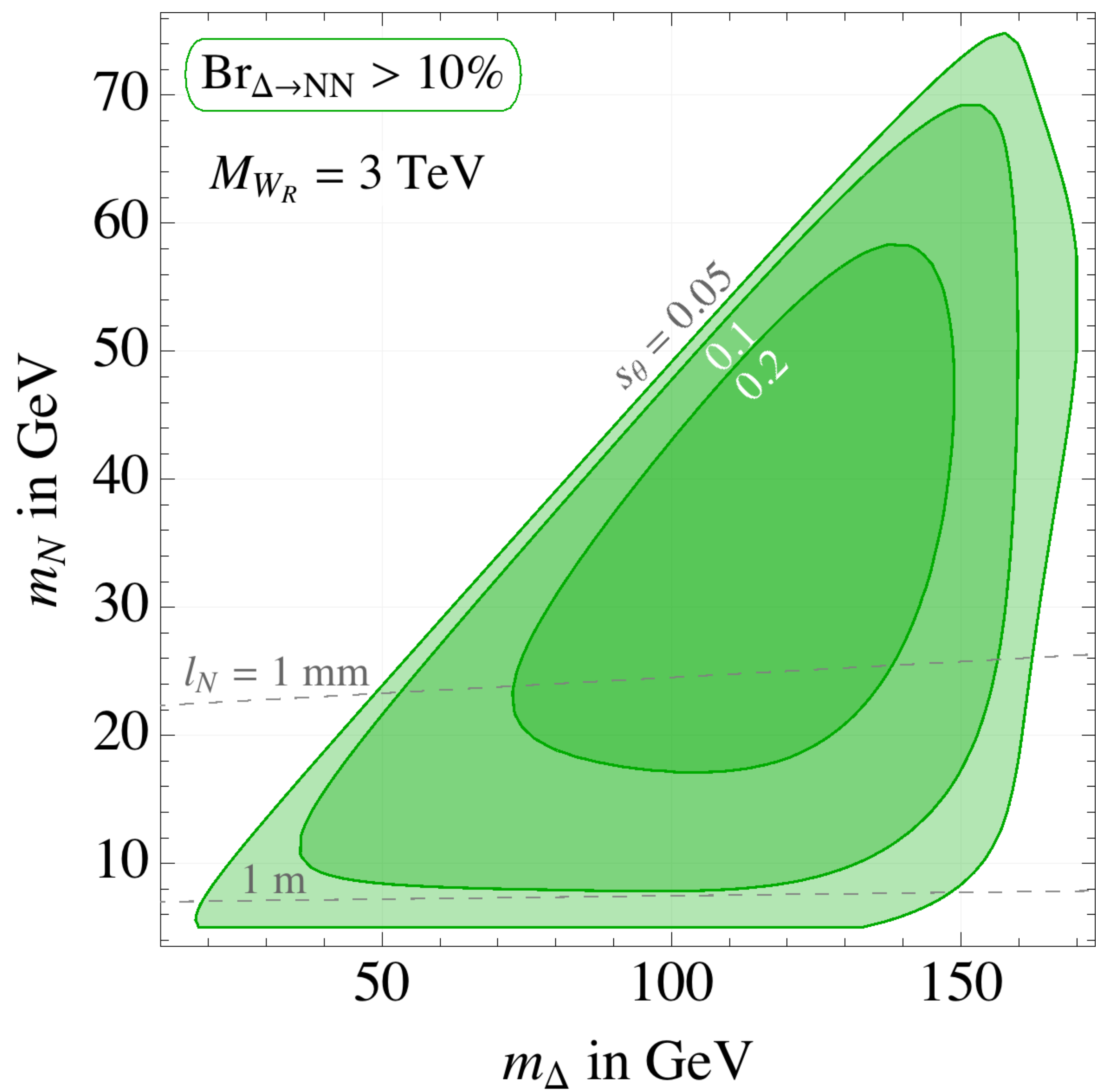
Decay length

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

Leads to two DV with LNV







'Right-handed' Higgs

Δ production

single $\quad \sigma(gg \to \Delta) = s_\theta^2\, \sigma(gg \to h)$ $\quad$ N³LO $\quad$ Anastasiou et al. '16

$$\sigma(pp \to V\Delta) = s_\theta^2\, \sigma(pp \to Vh)$$

pair & associated

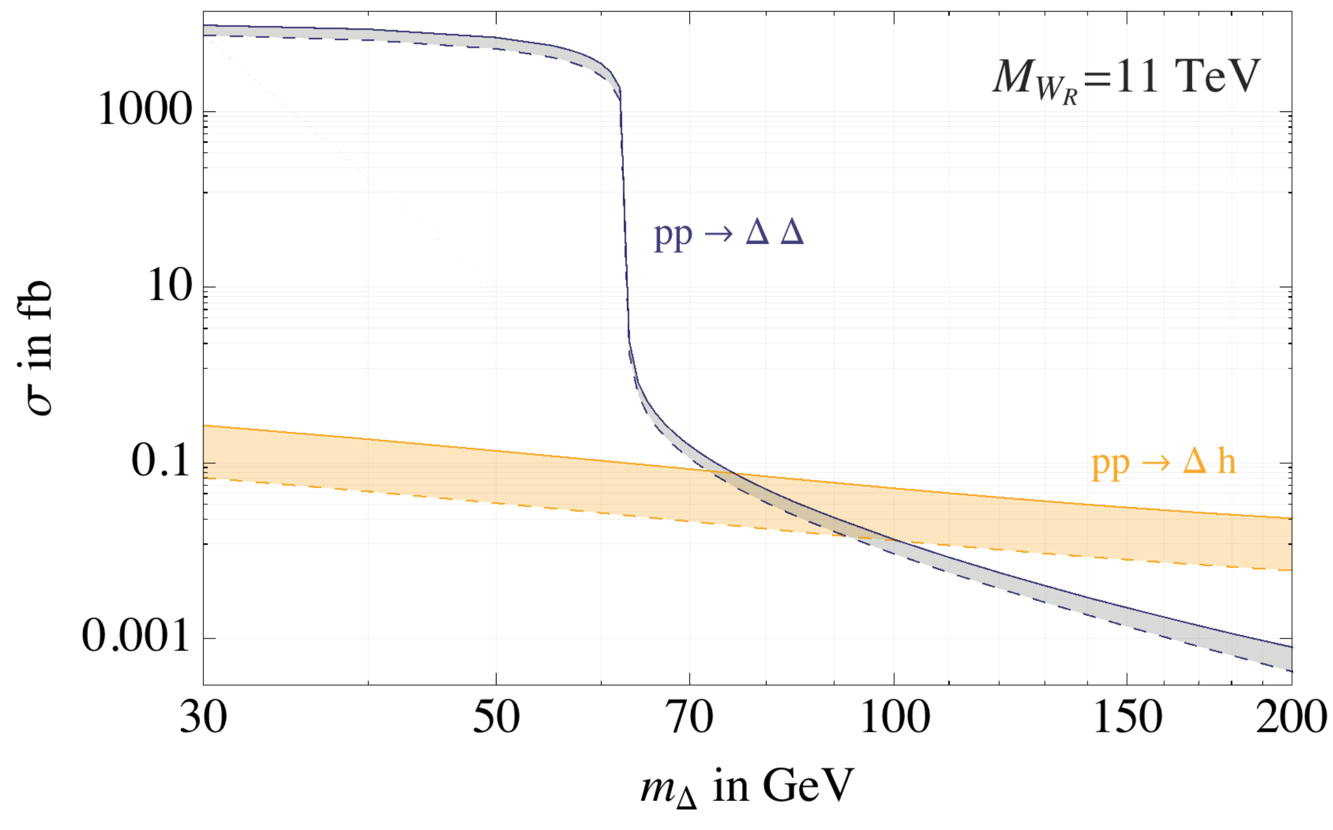
$$\hat\sigma_{gg\to\Delta S} \simeq \frac{c_\theta^2}{64\pi(1+\delta_{\Delta S})}\, \hat s \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{v_{hS\Delta}^2}{(\hat s - m_h^2)^2 + \hat s \Gamma_h^2} \left|F_b + F_t\right|^2 \sqrt{\beta_{\hat s \Delta S}}$$

large rate for $m_\Delta < m_h/2$

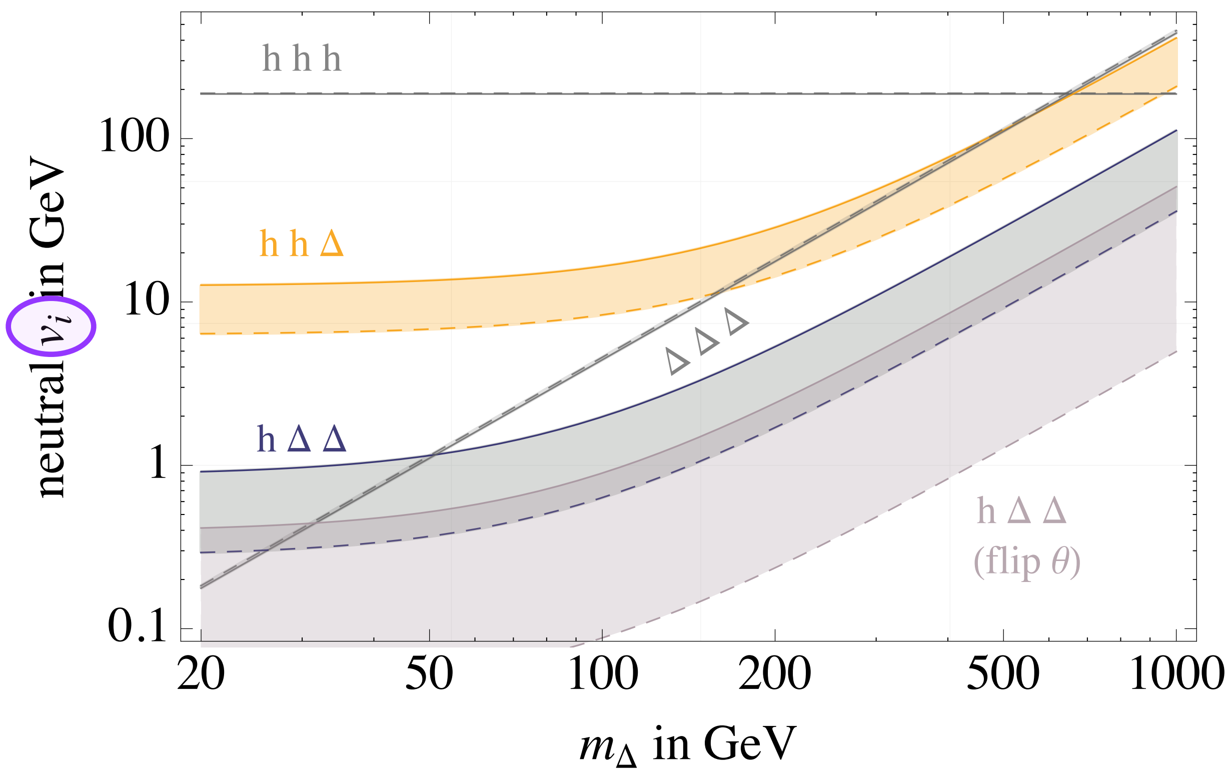
$$\sigma_{gg\to\Delta\Delta} \simeq \sigma_{gg\to h}\, \mathrm{Br}_{h\to\Delta\Delta}$$

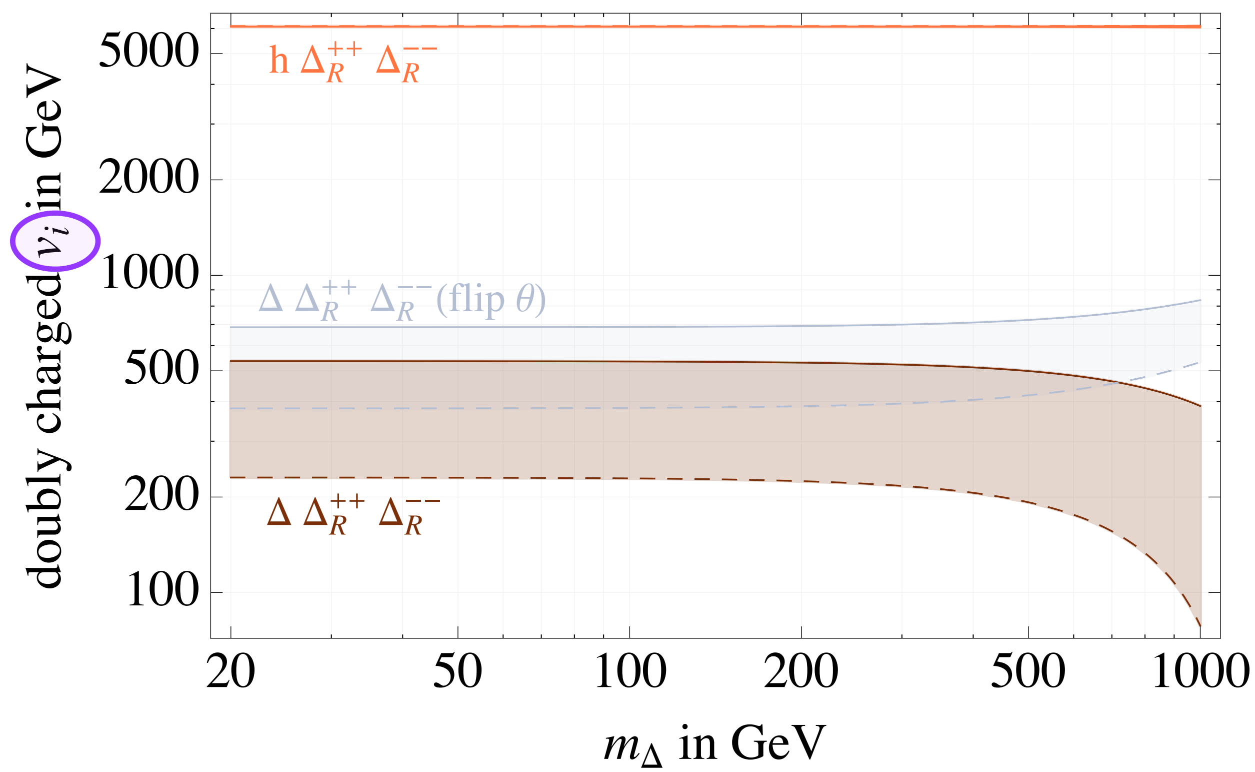
not very significant

(accidental cancellation)



Tri-linear Higgs @ LO





2 x 2 matrix, mixing suppressed by flavor and $\langle \Delta_L \rangle$

tree level

$$v_{hhh} = \frac{3g}{2} m_h^2 \left[\frac{c_\theta^3}{M_W} - \sqrt{2}\frac{s_\theta^3}{M_{W_R}} \right]$$

$$v_{hh\Delta} = \frac{g}{4} s_{2\theta} \left(m_\Delta^2 + 2m_h^2 \right) \left[\frac{c_\theta}{M_W} + \sqrt{2}\frac{s_\theta}{M_{W_R}} \right] \xrightarrow{\theta \to 0} 0$$

$$v_{h\Delta\Delta} = \frac{g}{4} s_{2\theta} \left(m_\Delta^2 + 2m_h^2 \right) \left[\frac{s_\theta}{M_W} - \sqrt{2}\frac{c_\theta}{M_{W_R}} \right] \xrightarrow{\theta \to 0} 0$$

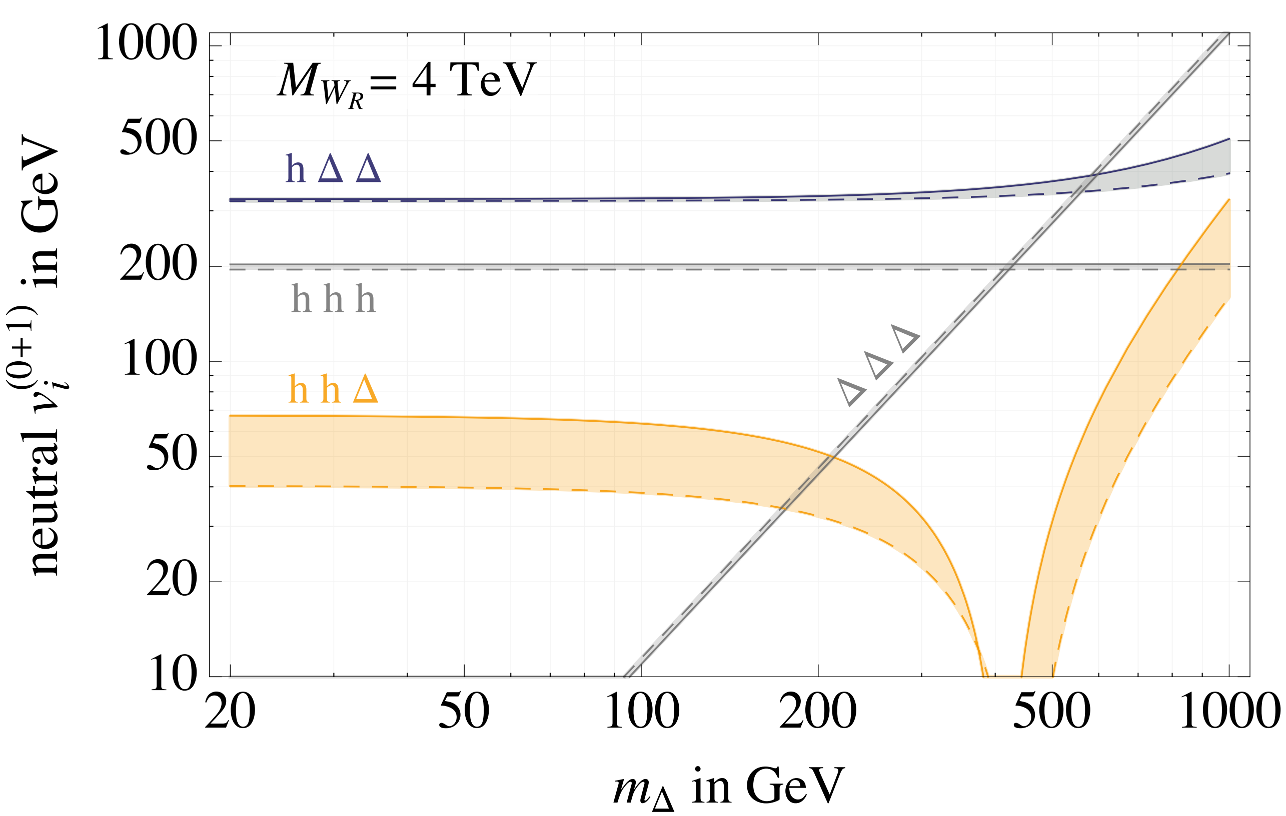
$$v_{\Delta\Delta\Delta} = \frac{3g}{2} m_\Delta^2 \left[\frac{s_\theta^3}{M_W} + \sqrt{2}\frac{c_\theta^3}{M_{W_R}} \right]$$

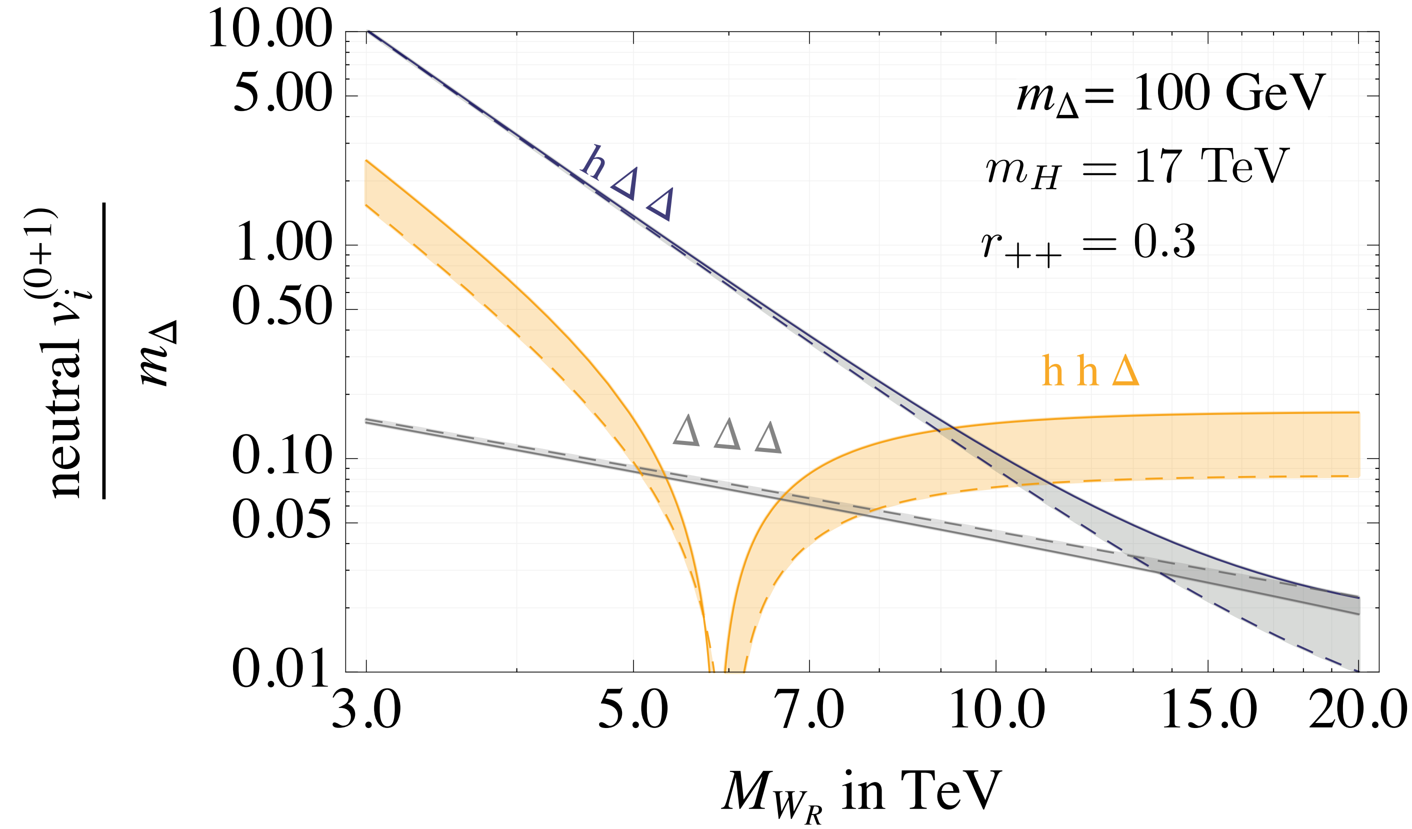
cancellation

+ corrections due to H mixing

Tri-linear Higgs @ NLO

loop corrections, ~top in the hhh vertex of the SM





$$v_{hhh}^{(1)} \simeq c^{(1)} \left(1 + \frac{17}{3}\frac{1}{r_{++}}\right)\left(\frac{v}{v_R}\right)^2 v \qquad v_{hh\Delta}^{(1)} \simeq c^{(1)}\, 11 \left(\frac{v}{v_R}\right) v$$

decouple with v_R

$$v_{h\Delta\Delta}^{(1)} \simeq c^{(1)} \left(4 + 10\, r_{++}\right) v \qquad v_{\Delta\Delta\Delta}^{(1)} \simeq c^{(1)} \left(8 + 16\, r_{++}^2\right) v_R$$

$$c^{(1)} = \frac{1}{\sqrt{2}(4\pi)^2}\left(\frac{m_H}{v_R}\right)^4, \qquad r_{++} = \left(\frac{m_{\Delta^{++},\Delta_L^{0,+,++}}}{m_H}\right)^2$$

upper bound $v_{\Delta\Delta\Delta}^{(1)} \leq \left(\frac{7}{3}\right) v_{\Delta\Delta\Delta}^{\text{tree level}}$ from vacuum stability

Linde '76, Weinberg '76
Mohapatra '86
Basecq, Wyler '89

Δ production

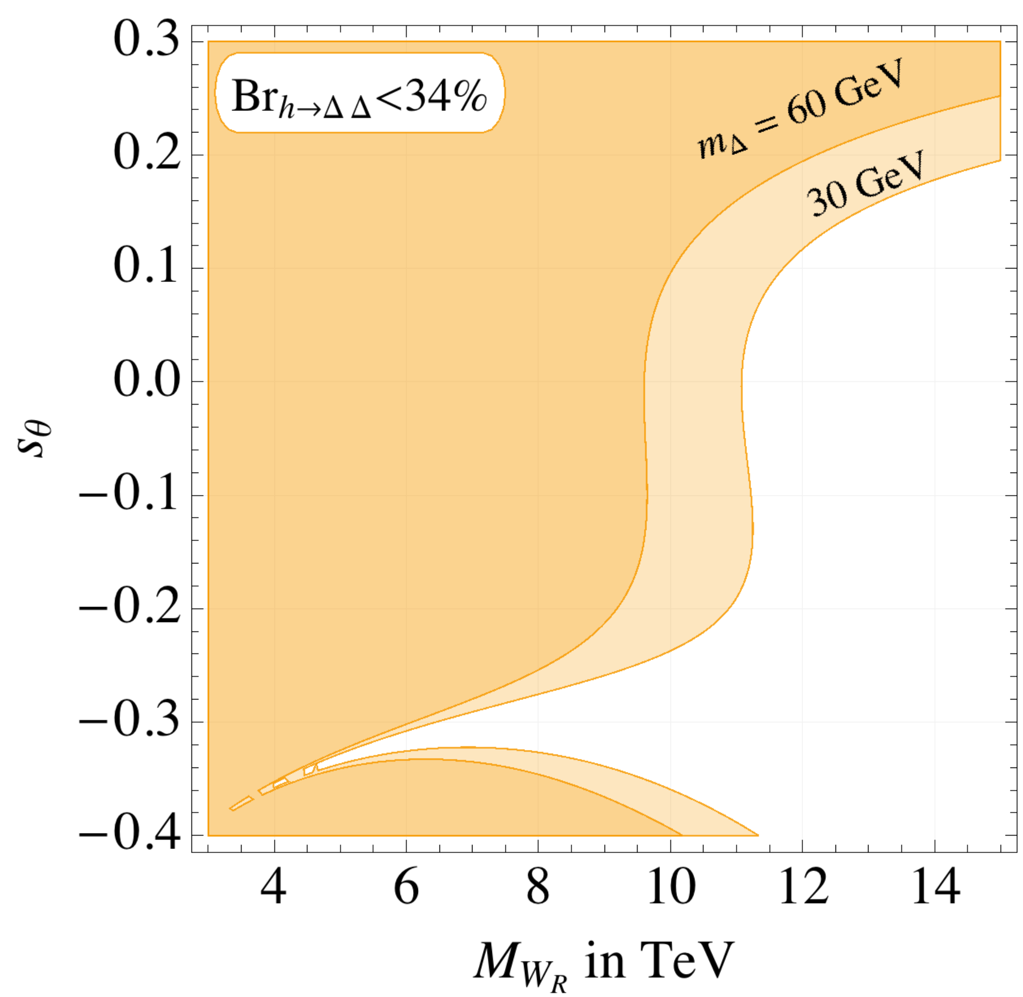
Δ^* suppressed

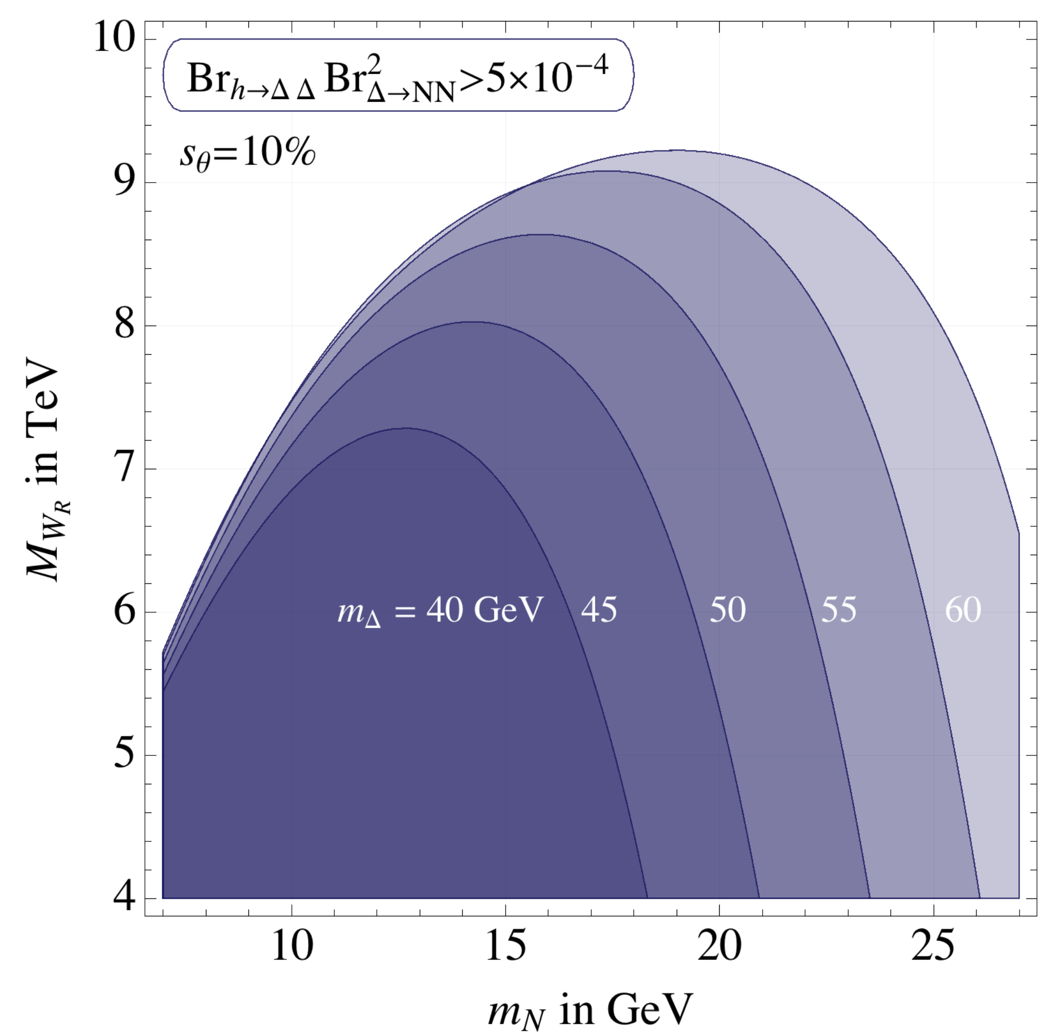
pair & associated

$$\hat{\sigma}_{gg\to\Delta S} \simeq \frac{c_\theta^2}{64\pi(1+\delta_{\Delta S})}\,\hat{s}\left(\frac{\alpha_s}{4\pi}\right)^2 \frac{v_{hS\Delta}^2}{(\hat{s}-m_h^2)^2+\hat{s}\Gamma_h^2}\,|F_b+F_t|^2\sqrt{\beta_{\hat{s}\Delta S}}$$

$\sigma_{gg\to\Delta\Delta} \simeq \sigma_{gg\to h}\,\mathrm{Br}_{h\to\Delta\Delta}$ leads to $pp\to NNNN$

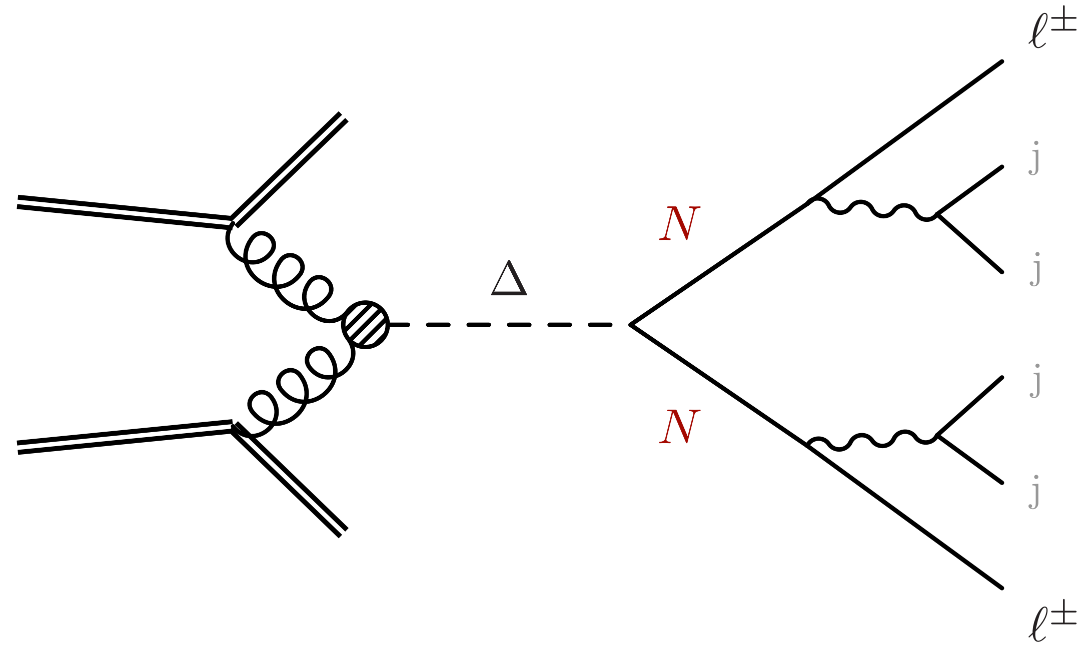
$\sigma_{gg\to h}$ N[3]LO Anastasiou et al. '16



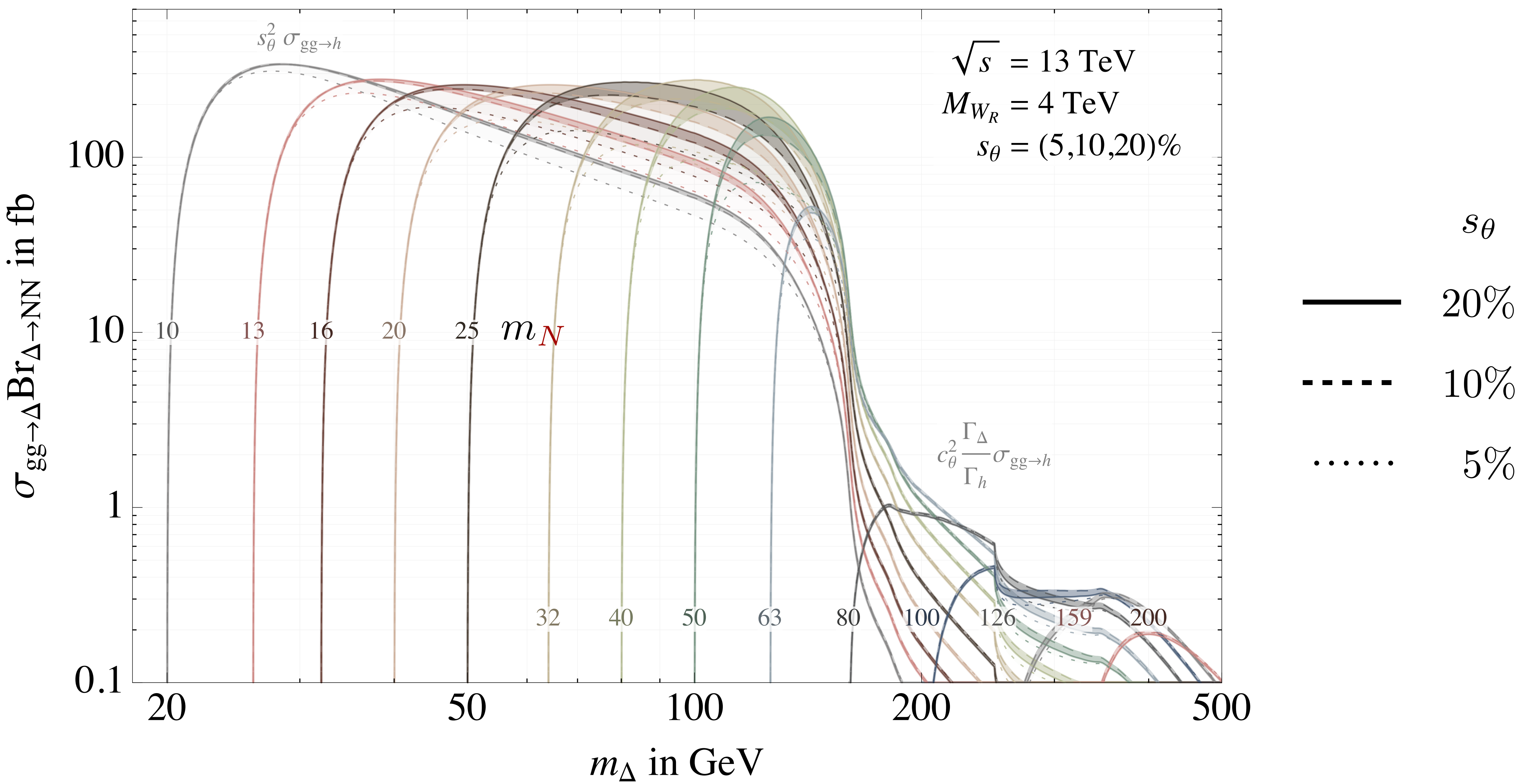


Δ signals

single

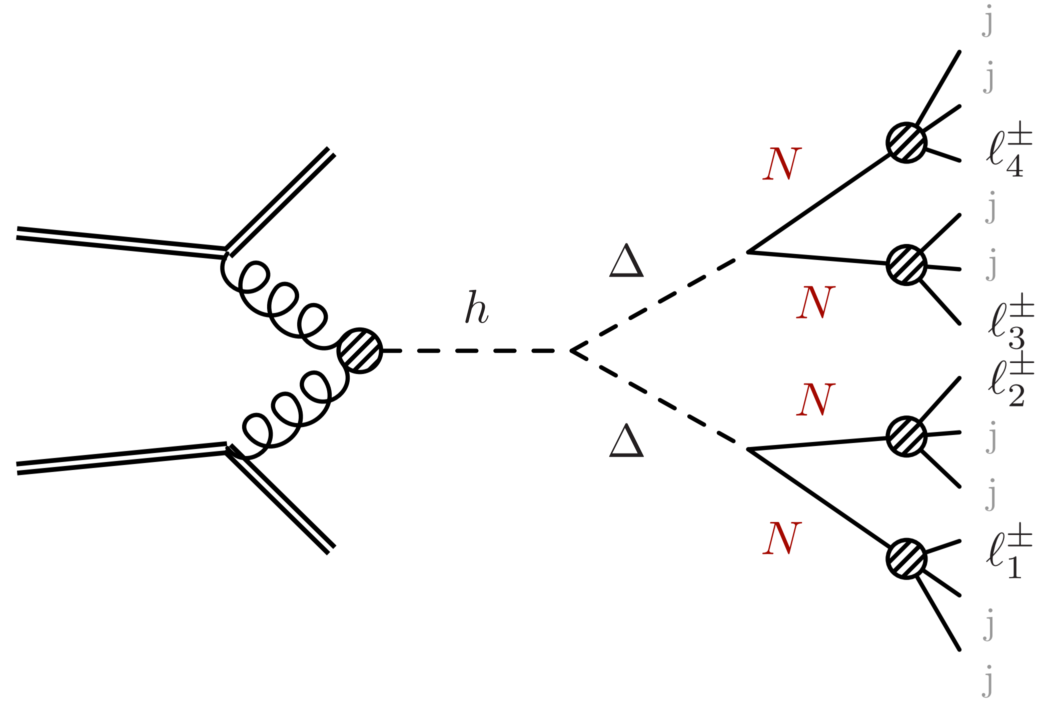


$\Delta L = 0, 2$

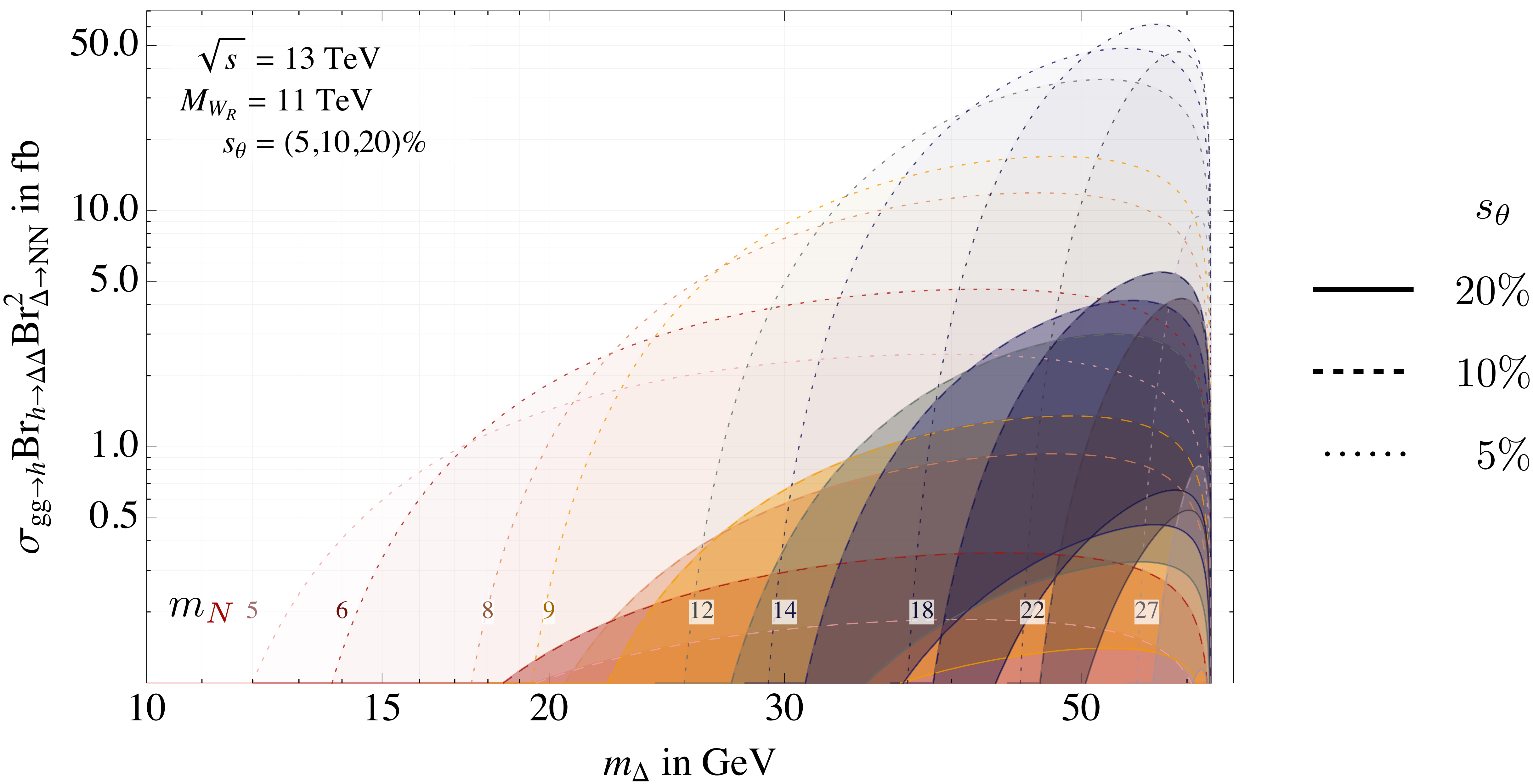


Δ signals

pair



$\Delta L = 0, 2, 4$



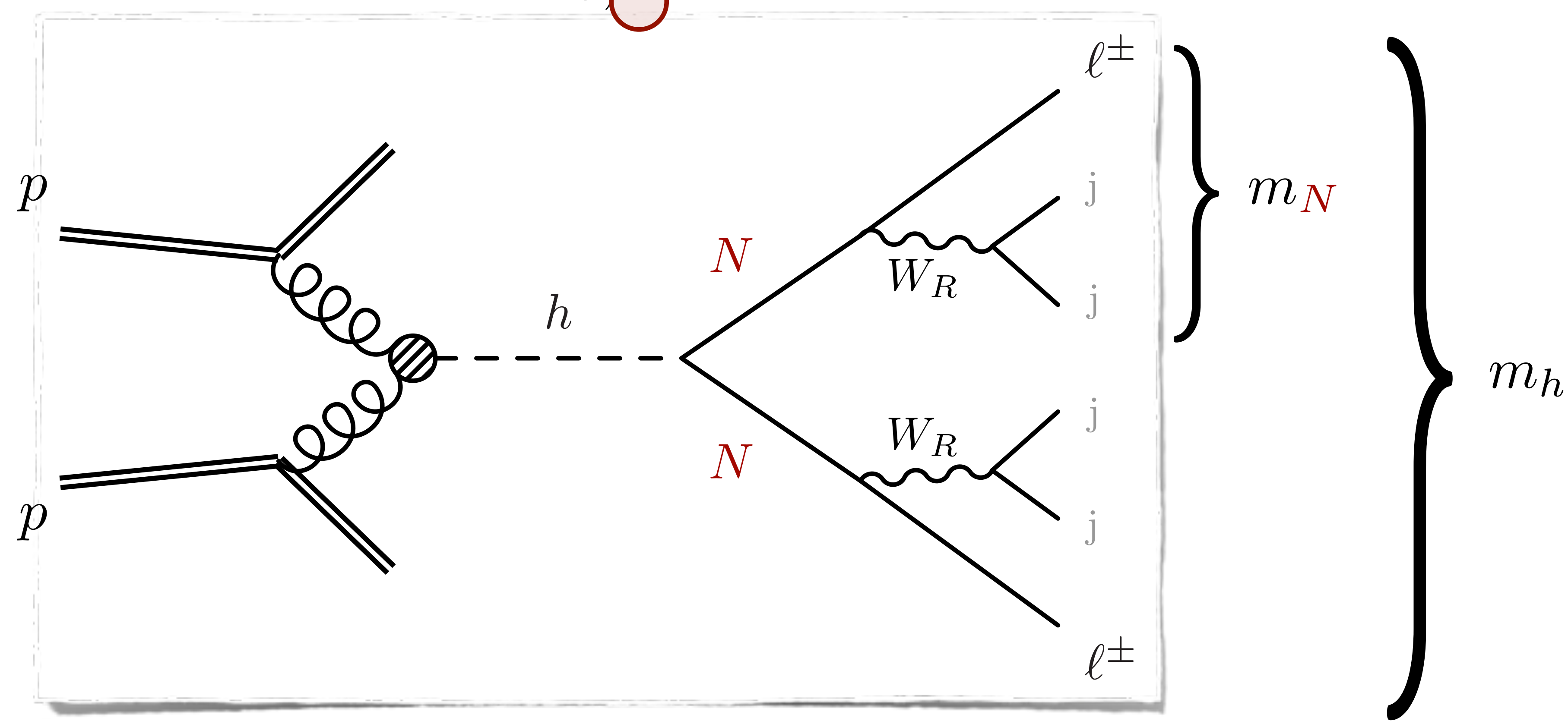
'Majorana' Higgses at LHC

ggF production $\sigma_{gg\to h} \simeq 45$ pb   N³LO   Anastasiou et al. '14

$\Delta L = 0, 2$ MN, Nesti, Vasquez '16

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

$\mathrm{Br}_{h\to NN} \simeq 10^{-3}$



small couplings, no tuning

light jets only $V_L^q = V_R^q$

Kiers et al. '02, Zhang et al. '07
Maiezza et al. '10, Senjanović, Tello '14

no missing energy

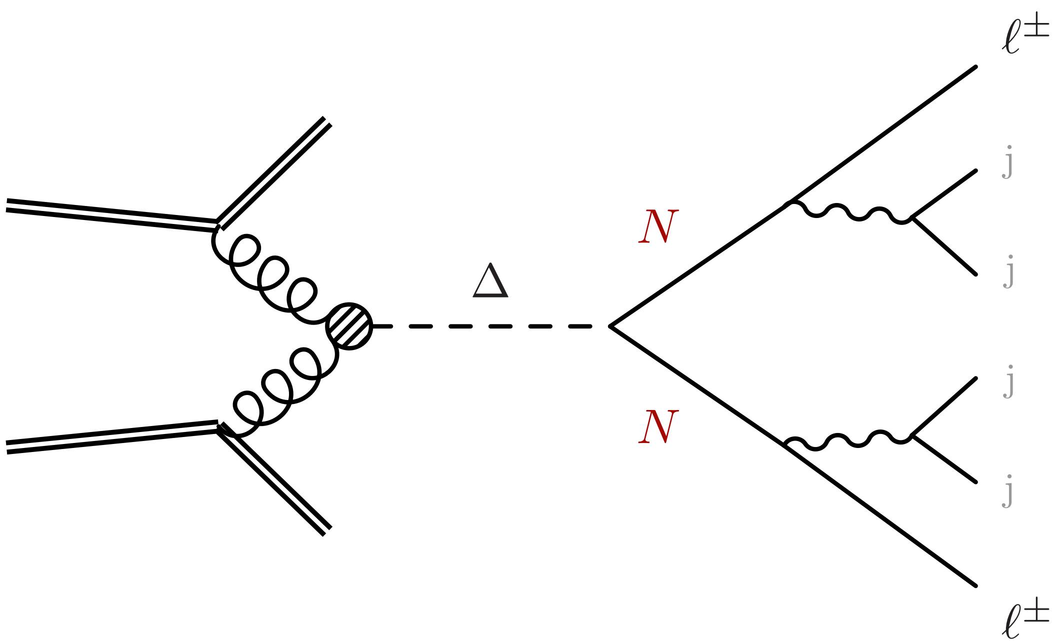
soft products $p_T \simeq m_h/6 \sim 20$ GeV

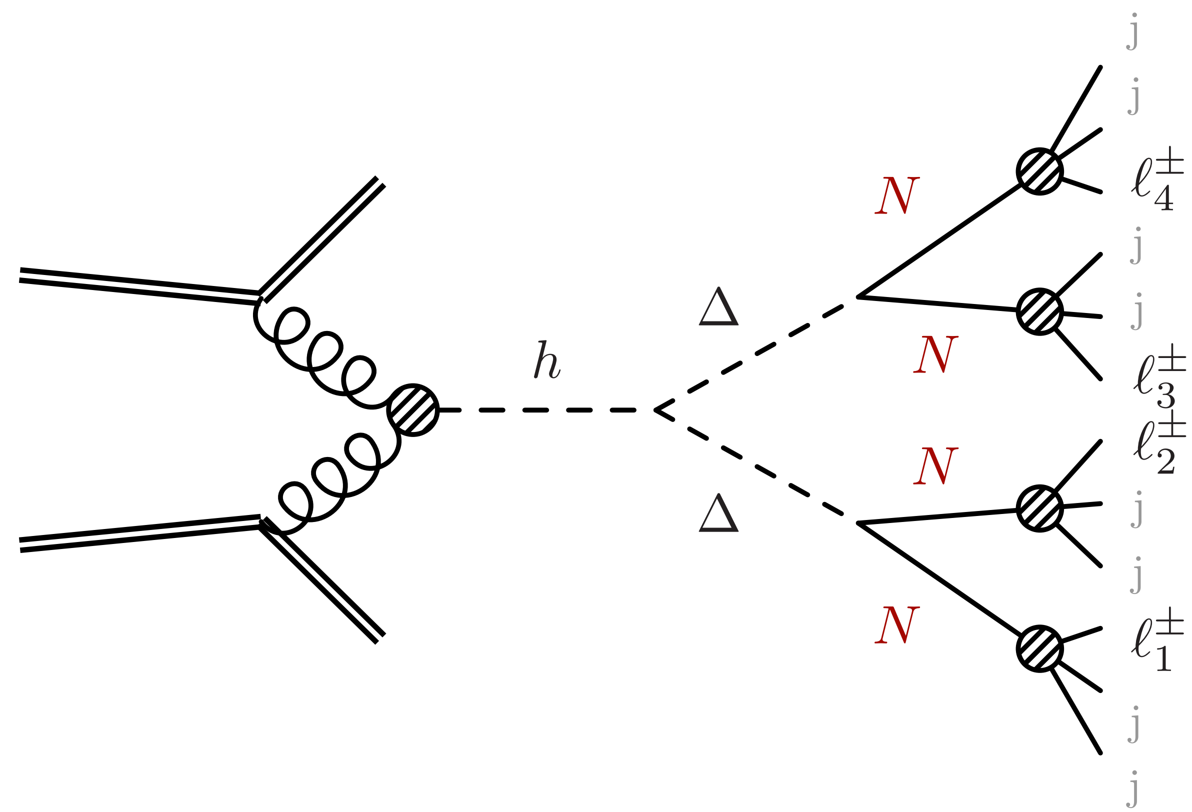
low background (LNV)

'Majorana' Higgses at LHC

$\Delta L = 0, 2$

$\Delta L = 0, 2, 4$ MN, Nesti, Vasquez '16





similar to $h \to NN$

(same-sign) multi-leptons

ggF of CP even scalar

$2^4 = 16$ possibilities

Anastasiou et al. '16

$\Delta L_0 : \Delta L_2 : \Delta L_4 = 3 : 4 : 1$

$\mathcal{R}^{\#\ell}_{\Delta L} \Rightarrow \mathcal{R}^2_2,\, \mathcal{R}^3_3,\, \mathcal{R}^4_2,\, \mathcal{R}^4_4$

Backgrounds

Selection criteria

	$t\bar{t}$	$t\bar{t}h$	$t\bar{t}Z$	$t\bar{t}W$	WZ	Wh	ZZ	Zh	$WWjj$	fakes

Selection	$\ell^\pm \ell^\pm + n_j$
$\not{E}_T$	$\not{E}_T < 30\,\mathrm{GeV}$
p_T	$p_T(\ell_1) < 55\ \mathrm{GeV}$
m_T	$m^T_{\ell \not{p}_T} < 30\,\mathrm{GeV}$
$m_{\rm inv}$	$m_{\ell\ell} < 80\,\mathrm{GeV}$ $m_{\ell \not{p}_T} < 60\,\mathrm{GeV}$
$l_{T\ell}$	$l_{T\ell} > 0.1\ \mathrm{mm}$

all contain missing energy

one prompt, one displaced lepton

Backgrounds

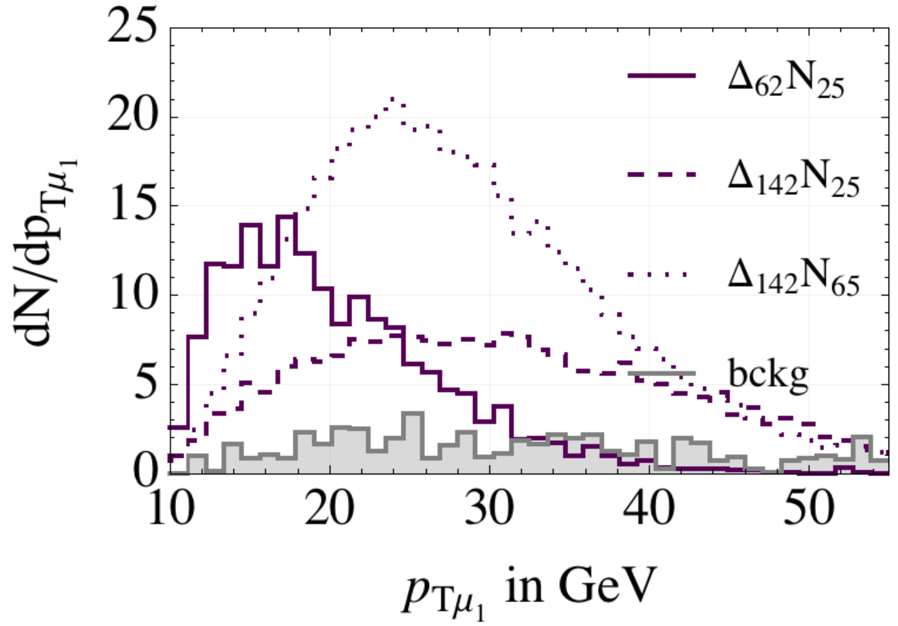
$\ell^{\pm}\ell^{\pm} + n_j$

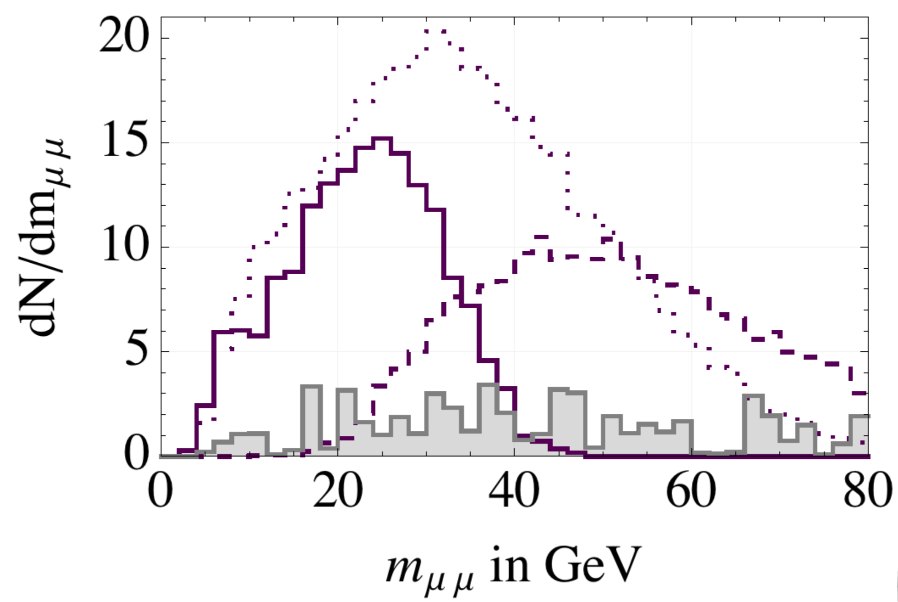
	$t\bar{t}$	$t\bar{t}h$	$t\bar{t}Z$	$t\bar{t}W$	WZ	Wh	ZZ	Zh	$WWjj$	fakes
select	806	4	5	26	1241	87	147	16	1.5	2651
$\not{E}_T$	313	0.5	0.7	3	400	21	129	7	0.2	782
p_T	112	0.2	0.1	0.7	174	8.4	63	4	0.05	284
m_T	60	0.1	0.04	0.3	80	4	56	2	0.03	106
m^{inv}	35	0.03	0.03	0.2	25	2	36	2	0	80
l_{Te}	0	0	0	0	0.7	0.1	0.9	0.05	0.001	2
	$t\bar{t}$	$t\bar{t}h$	$t\bar{t}Z$	$t\bar{t}W$	WZ	Wh	ZZ	Zh	$WWjj$	fakes
select	670	4	6	32	750	133	68	16	2	1676
$\not{E}_T$	130	0.5	0.9	3.5	200	32	33	6	0.3	391
p_T	57	0.2	0.2	1	95	17	16	3	0.1	152
m_T	32	0.1	0.1	0.5	51	9	12	2	0.05	49
m^{inv}	17	0.04	0.04	0.2	23	5	8	1	0.01	40
$l_{T\mu}$	0	0	0	0	1.4	0.4	1	0.15	0.005	3

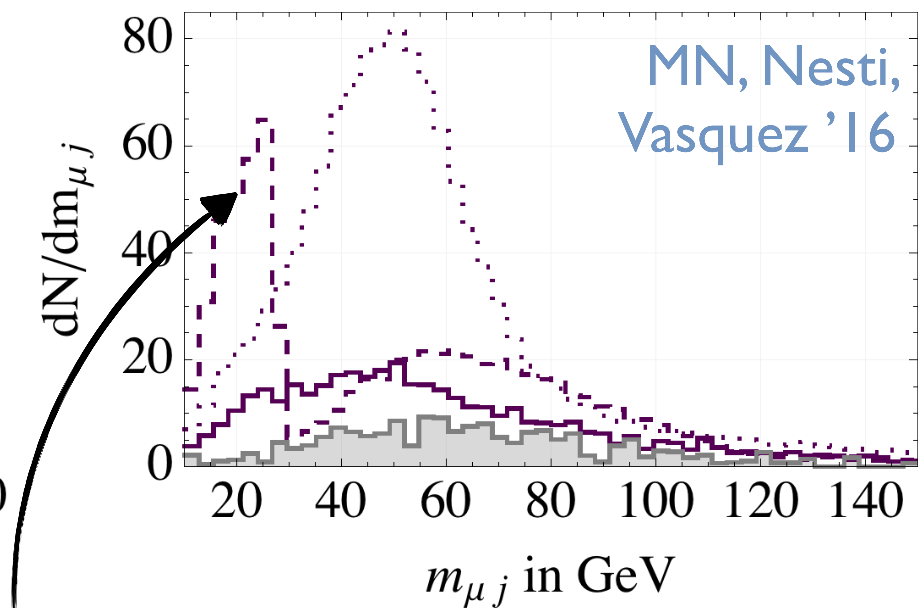
all contain missing energy

one prompt, one displaced lepton

Signal features

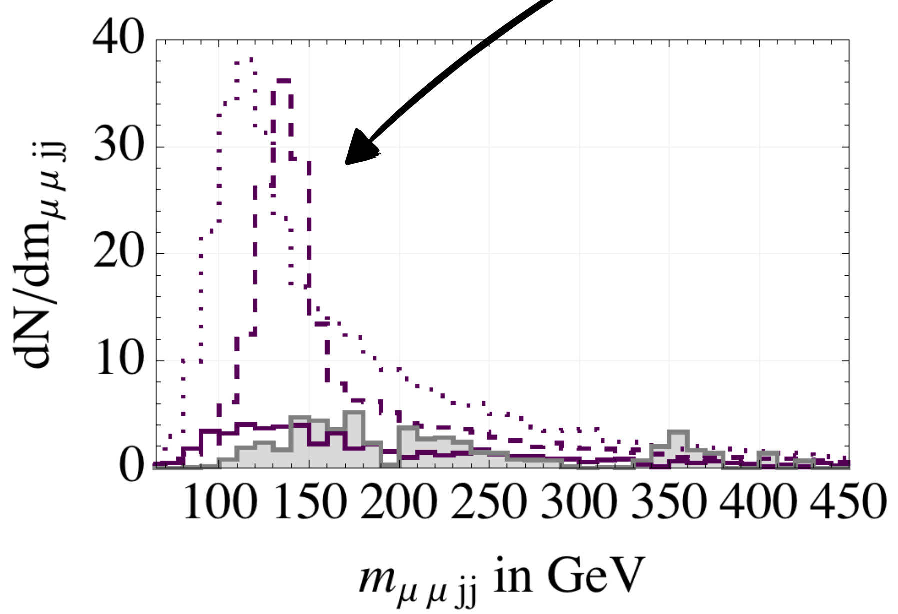


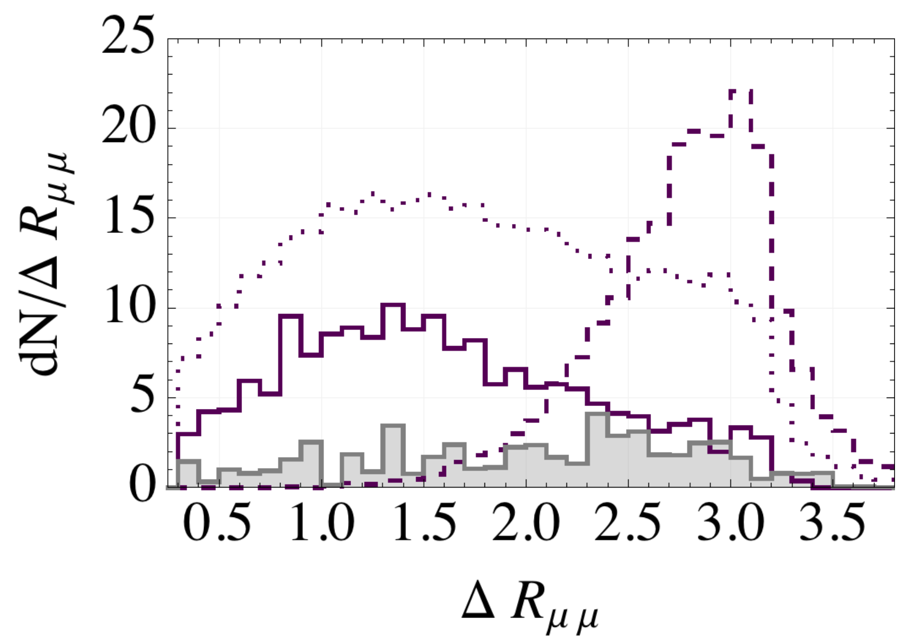


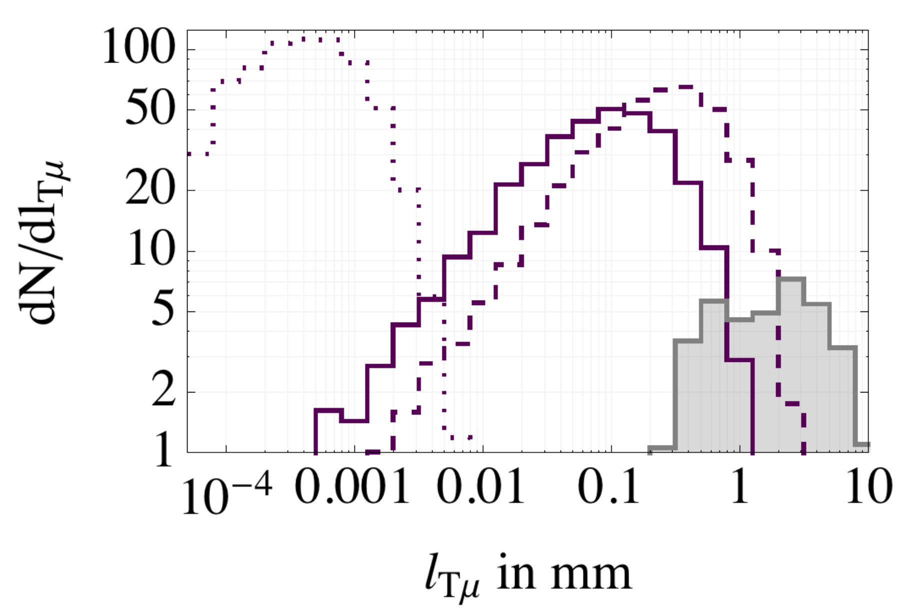


soft leptons

characteristic mass peaks







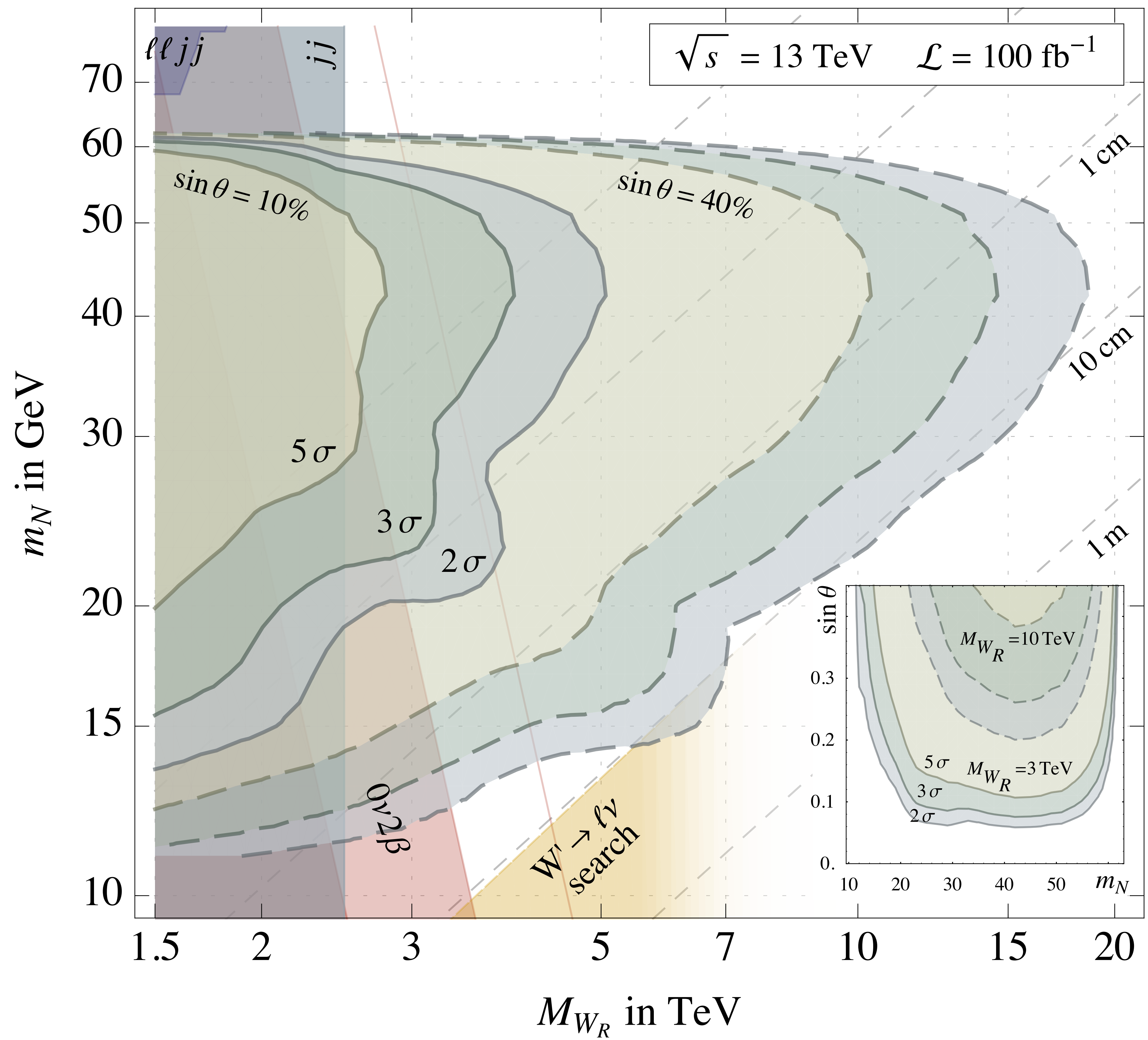
angular separation

displaced

Sensitivity

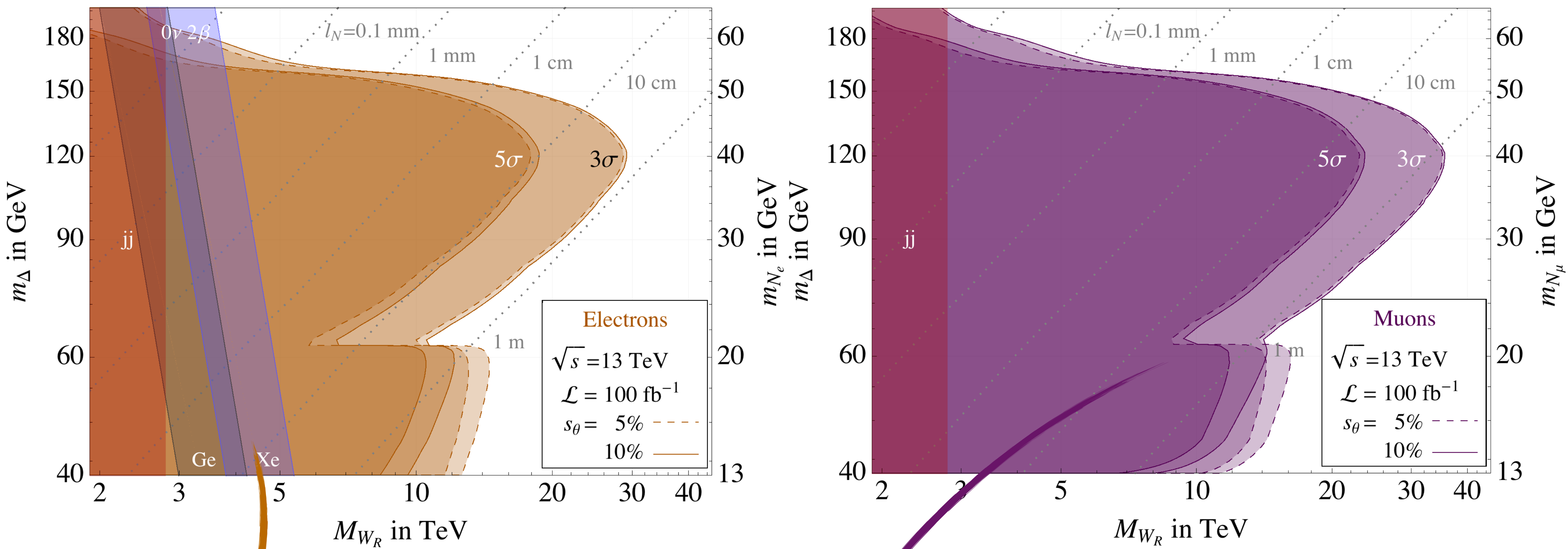
$h \to NN$

Maiezza, MN, Nesti '14



Sensitivity

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 - >1m

discovery reach beyond direct searches

more LNV Higgs candidates

No-go for vanilla see-saw(s)

Fourth generation $h \to \nu_4 \nu_4$

Pilaftsis '92
Carpenter '11

EFT from SM + *h* + *N*

Graesser '07
Caputo, Hernandez, Lopez-Pavon '17

SM + *h* + *N* + singlet scalar

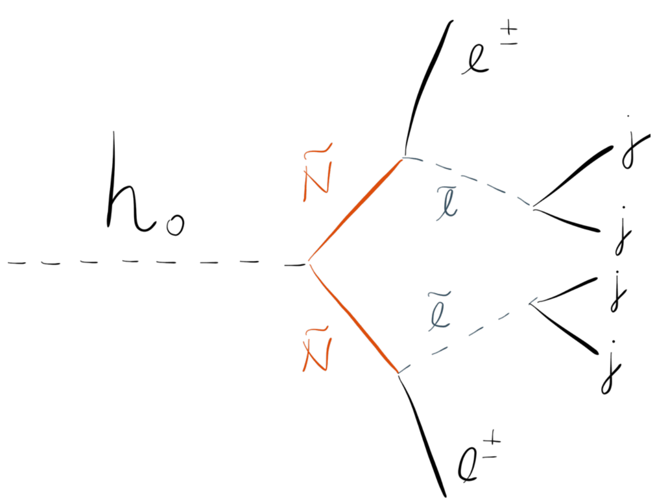
Shoemaker, Petraki, Kusenko '10

Spontaneous B-L

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

Deppisch, Mitra '18

RPV Susy



LNV disfavored

$m_{\tilde{l}} \simeq m_{\tilde{\nu}}$

needs post-LHC revision

Banks, Carpenter Fortin '08

Summary

Conclusions

Neutrino masses provide a clear path beyond the SM

Testing LNV is a fundamental issue, similar to baryon number

TeV Colliders can discover the origin of neutrino mass

Outlook

Perform the non-trivial searches, including other channels

Improve theoretical tools, vertexing, data driven backgrounds

More studies needed for future colliders, HE-HL LHC, FCC-ee, eh, hh

Thanks to

organizers for hospitality and

participants for talks and discussions