Prompt and long-lived re-interpretations in Left-Right theory

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~ JSI Ljubljana ~

5th Re-interpretation workshop @ Imperial College

April 4th 2019

Motivation

…for complete coverage of new physics searches

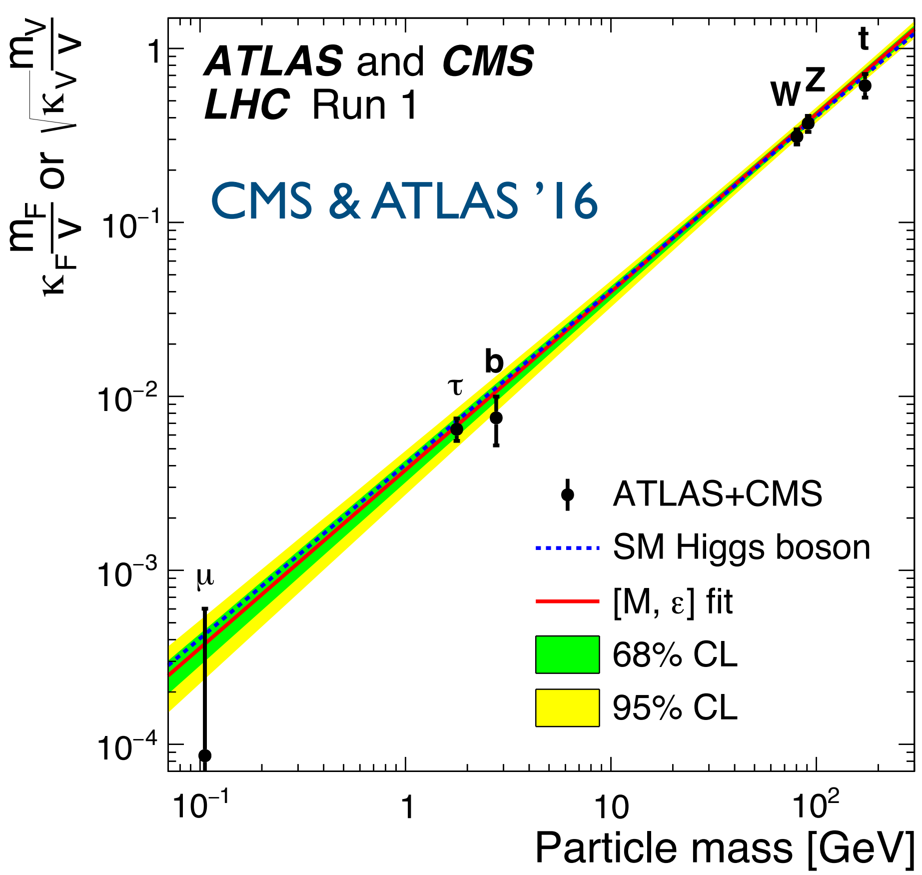
Neutrino oscillations $m_\nu \neq 0$ needs BSM

Lesson from the LHC on 3rd gen. charged fermions and the Higgs

$$y_f \overline{F}_L \, H \, f_R$$

$$\text{fermions} \;\leftrightarrow\; \text{anti-fermions}$$

Dirac '31



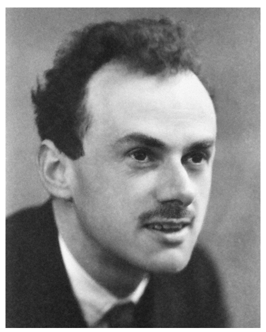
$$m_f = y_f \, v$$

Mass sourced via SSB due to the Higgs vev and a *single* Dirac type Yukawa coupling

Neutrinos

Special, both *Dirac* and *Majorana* mass possible

$$m_D \, \overline{\nu}_L \nu_R + m_L \, \nu_L^T C \nu_L + m_R \, \nu_R^T C \nu_R$$



$$\text{fermions} \;\; = \;\; \text{anti-fermions}$$

Majorana '37

Lepton number is broken

Racah, Furry '39

Seesaw contains both

$$m_\nu \simeq m_L - m_D^T m_R^{-1} m_D$$

Neutrinos

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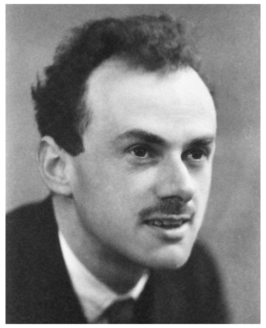

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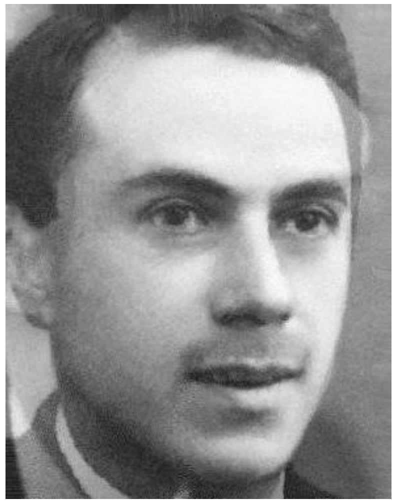
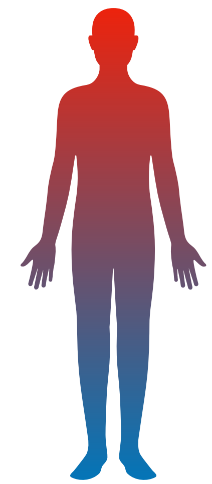
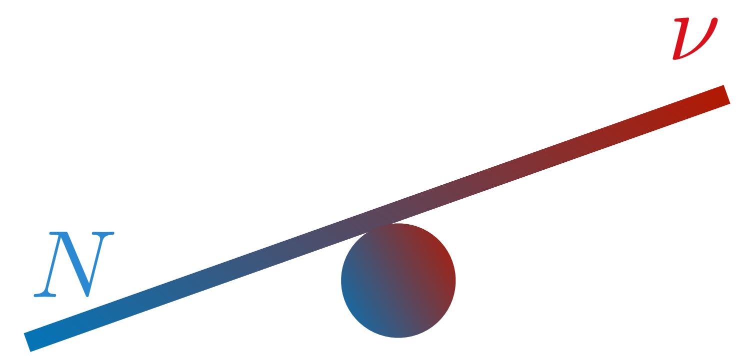


- Which is it?
- Are **all** neutrinos protected by gauge symmetry?
- If so, where are the 'Majorana' gauge and Higgs bosons?





unification of forces

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

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

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

talks by Wei Liu and
Jon Butterworth

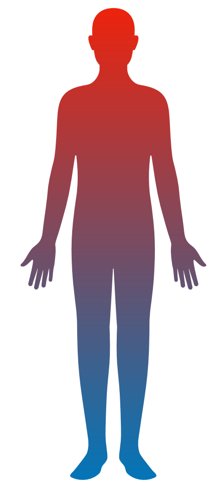
unification

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

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

unification of forces

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



weak force asymmetry

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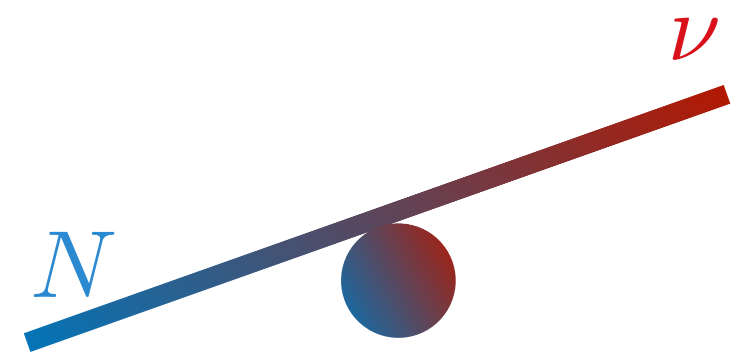
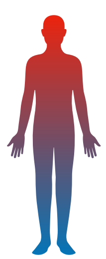


minimal gauged seesaw

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

Pati, Salam '75



partial unification
Left-Right

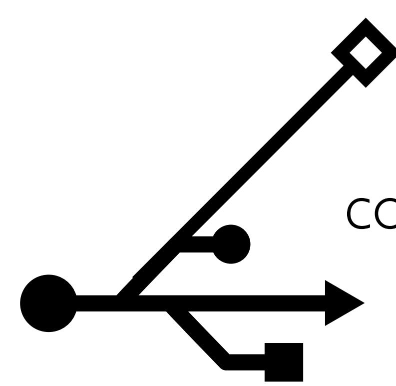
$$L_R = \begin{pmatrix} N \\ \ell_R \end{pmatrix}$$

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

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

mLRSM : flavor fixed

$$V_R^q \simeq V_L^q$$



colliders

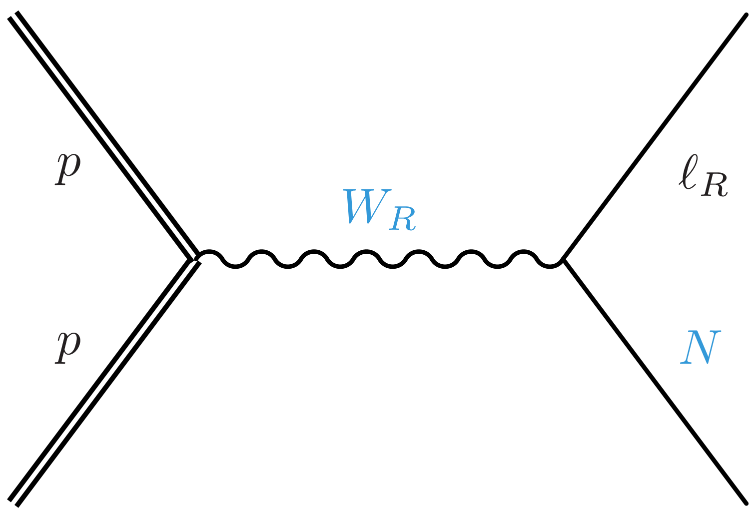
$0\nu2\beta$

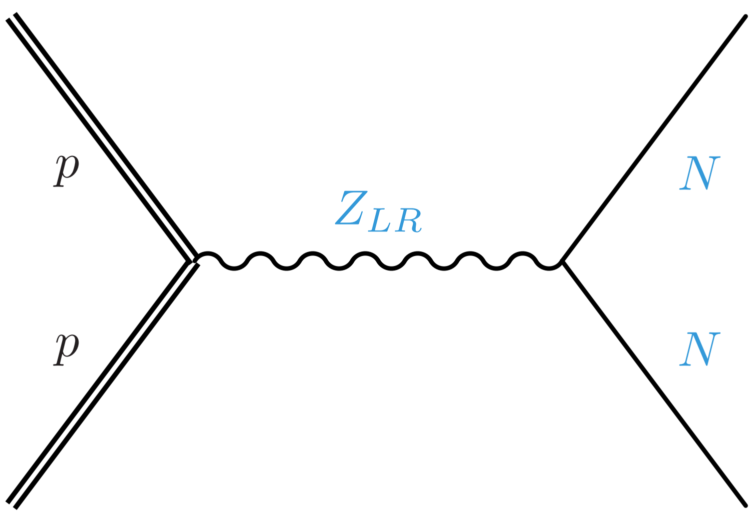
eEDM, wDM, …

Colliders

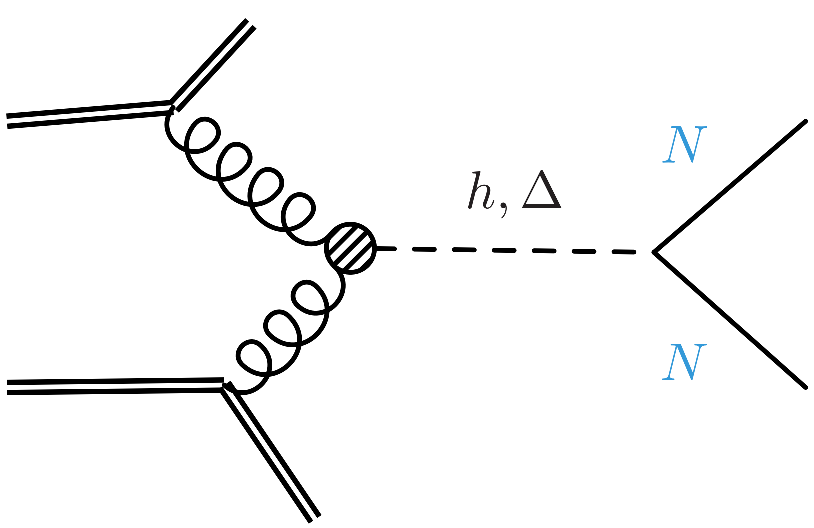
…striking signals of LNV, Left-Right as a paradigmatic example

New gauge bosons





New Higgses



On-shell Majorana fermion

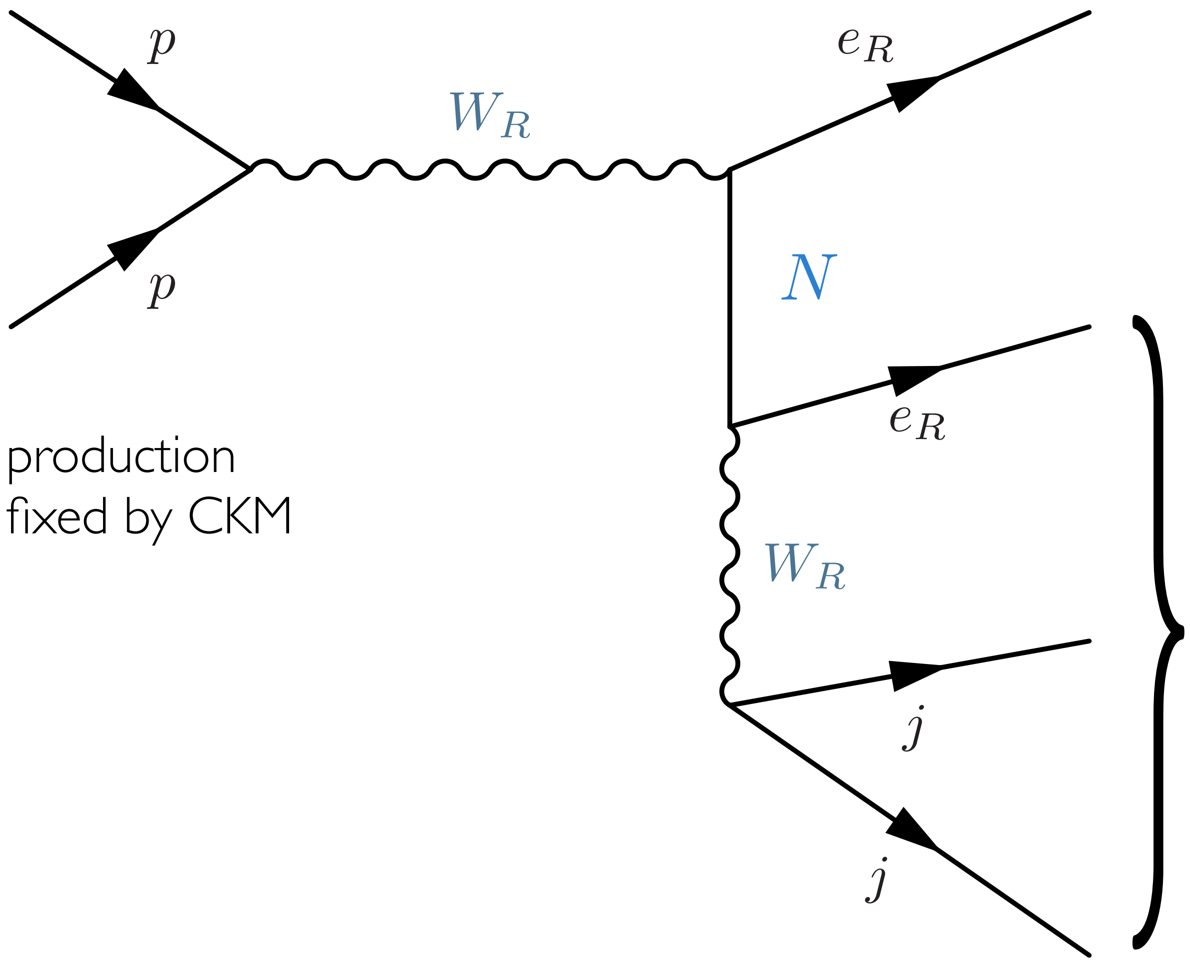
$N \to \ell^{\pm} jj$ 50-50% same-opposite sign

$$l_N \simeq \boxed{2.5 \text{ mm}} \left(\frac{M_{W_R}}{3 \text{ TeV}}\right)^4 \left(\frac{10 \text{ GeV}}{m_N}\right)^5$$

possibly displaced

Gauge sector

Keung, Senjanović '83



production
fixed by CKM

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

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

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

~no missing energy

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

flavor states measure V_R^ℓ (free)

predict Dirac couplings MN, Senjanović, Tello, '13

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

more on the Majorana nature

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

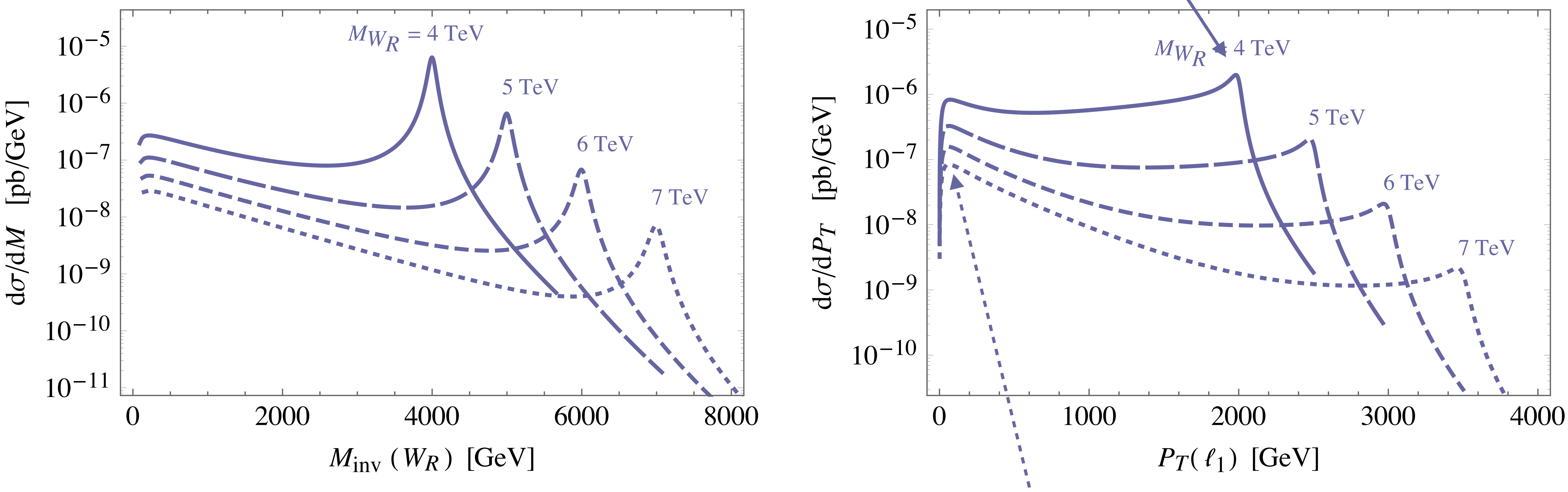
Golden channel: $pp \to W_R \to \ell_R N$

Keung, Senjanović '83

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

clear peak

mostly on-shell, N boosted



m_{inv} disappears

off-shell = soft lepton and N

Ruiz '17

Signal features for $pp \to W_R \to \ell_R N$

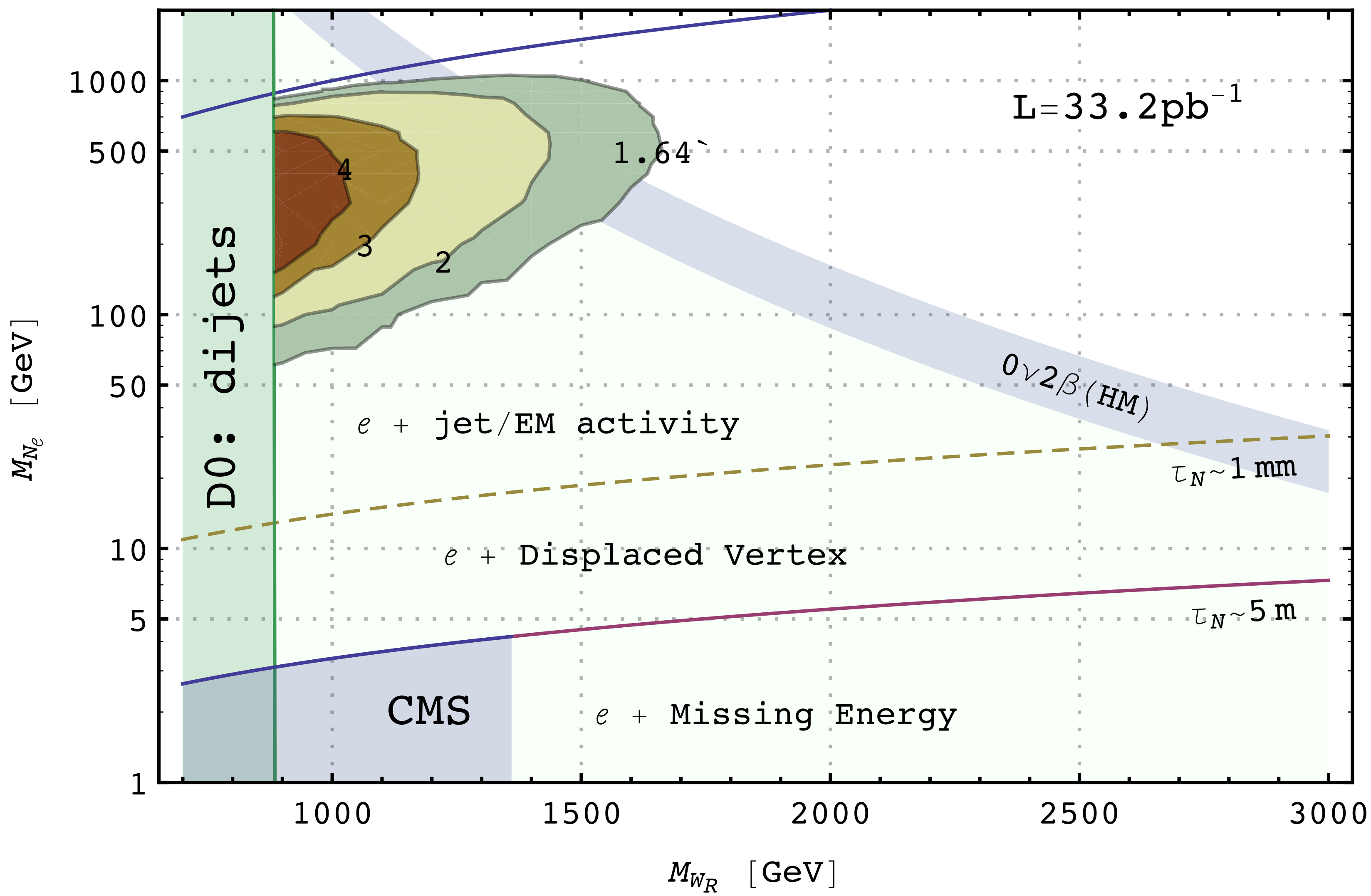
MN, Nesti, Senjanović, Zhang '11

separated eejj

merged neutrino jet

displaced jet

missing energy



first LHC data, low bound

LNV relation to 0ν2β

Tello, MN, Nesti, Senjanović, Vissani '10

Reach of 5-6 TeV at 14 TeV

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

Signal features for $pp \to W_R \to \ell_R N$

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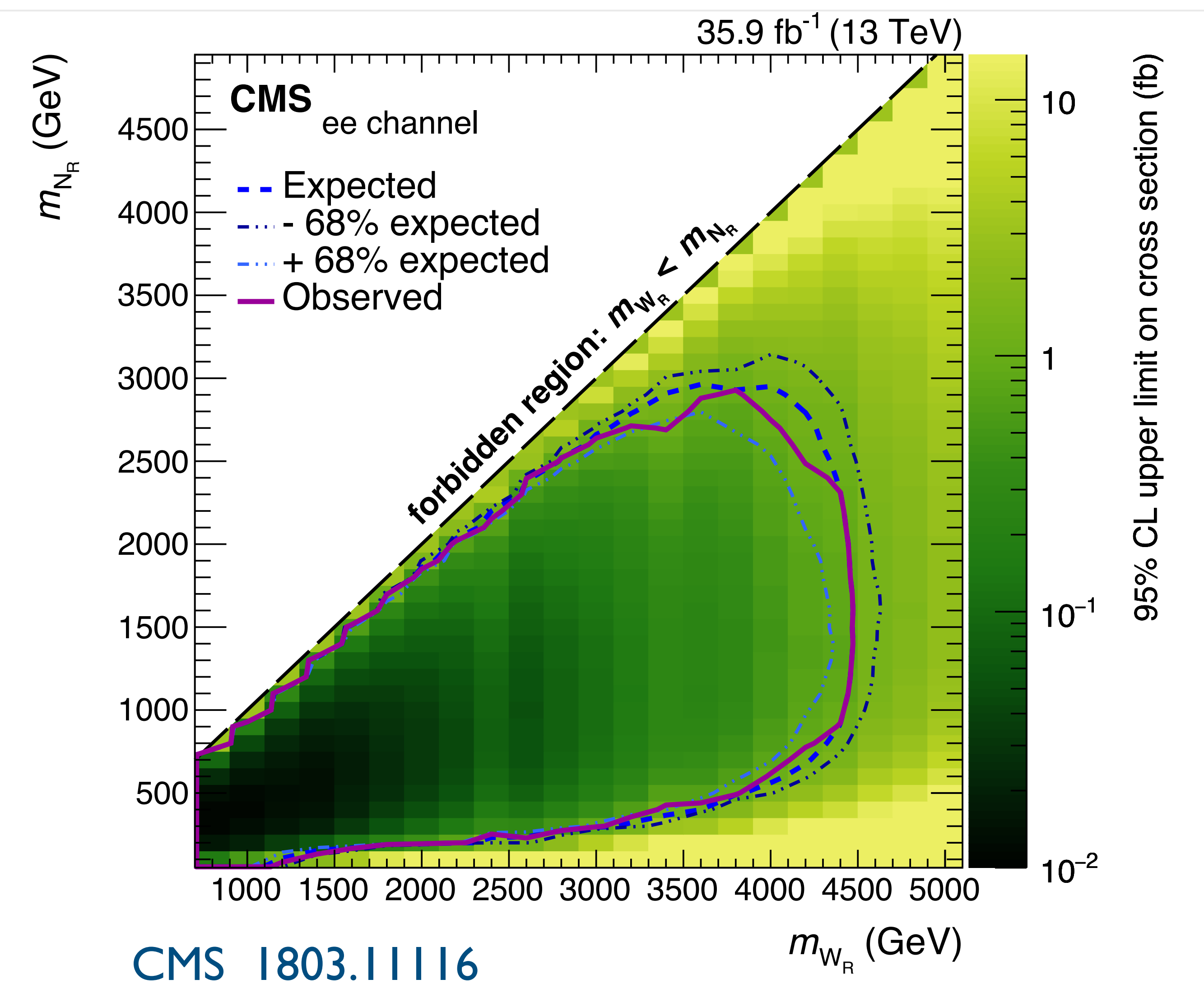
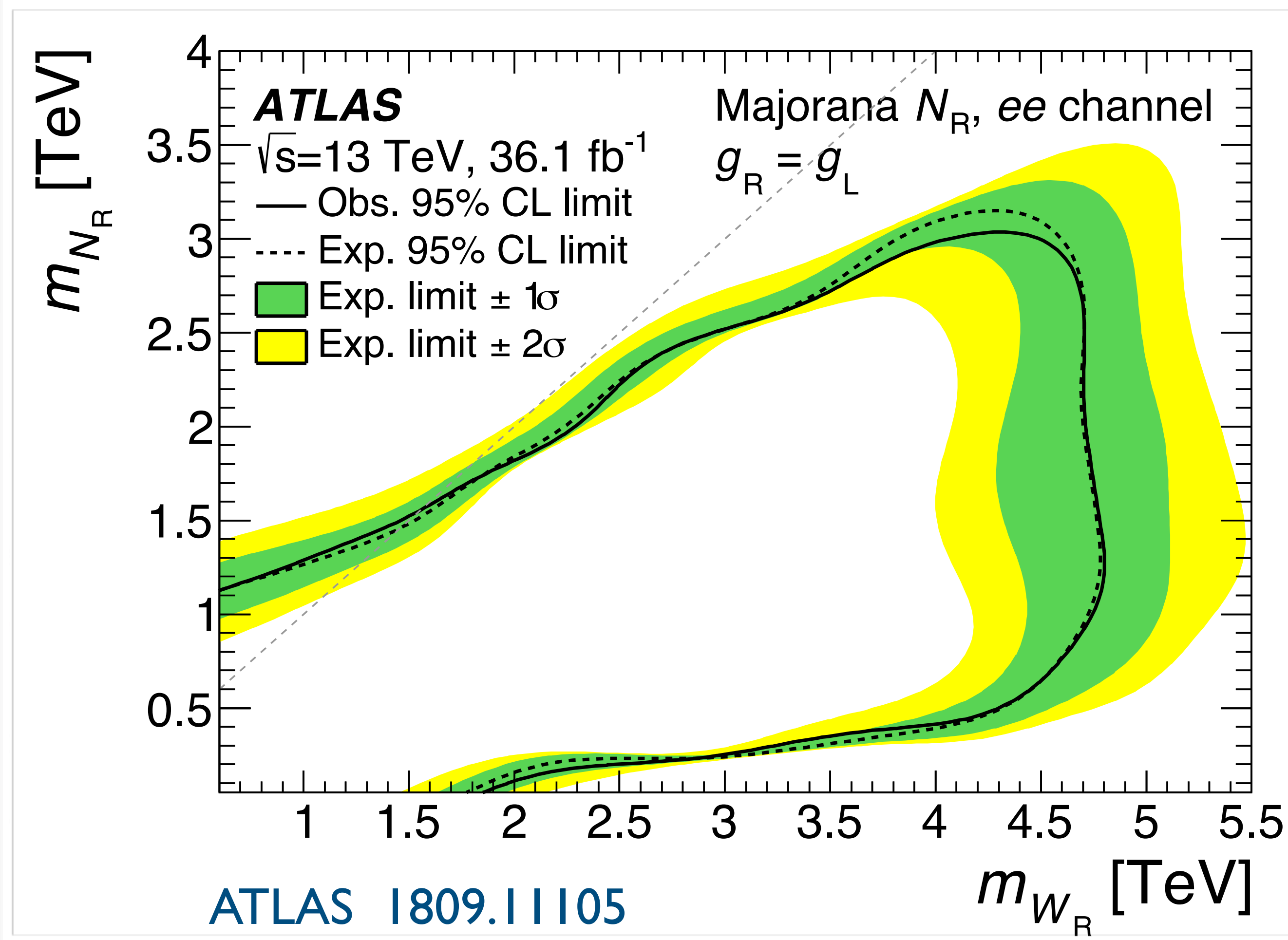




energy

Reach of 5-6 TeV at 14 TeV

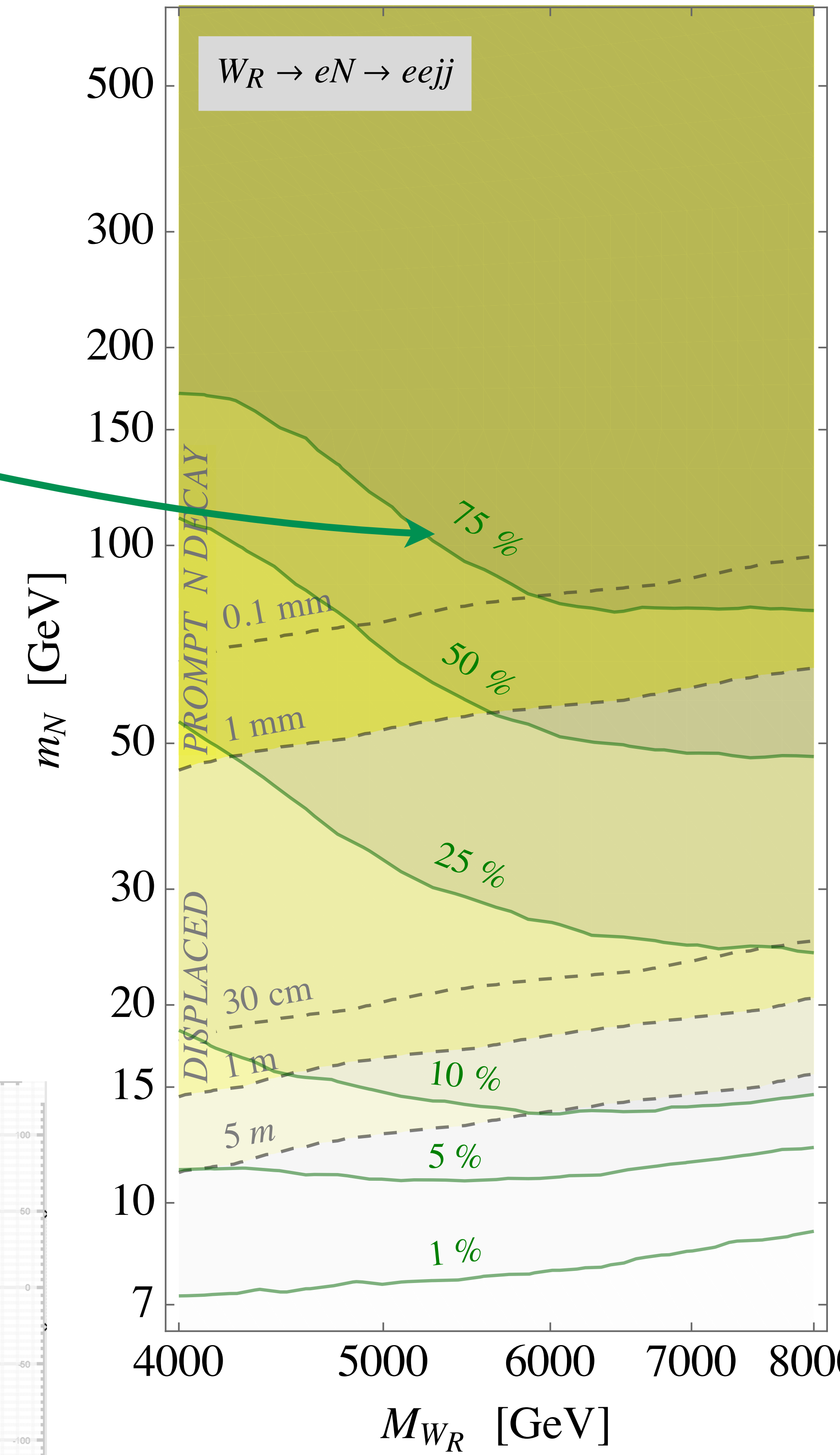
ATLAS: Ferrari et al. '00
CMS: Gninenko et al. '07

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

MN, Nesti, Popara '18

2nd lepton isolation depends on the boost of N

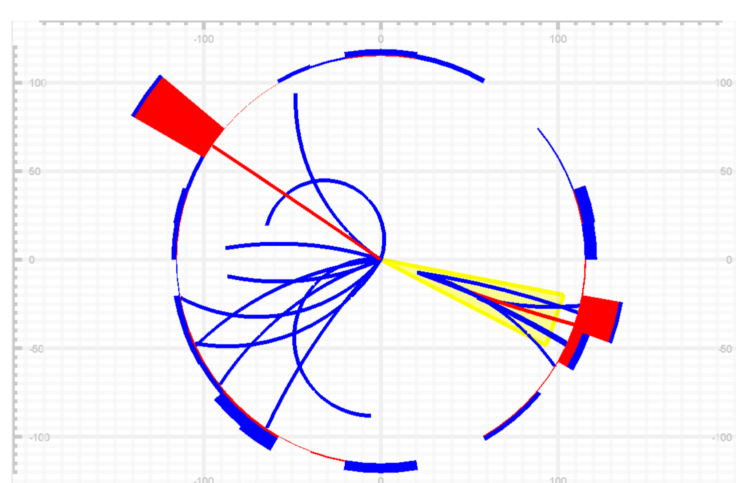
$$\gamma_N \simeq \begin{cases} \frac{M_{W_R}}{2m_N}, & W_R \to \text{on-shell}, \\ \frac{1\ \text{TeV}}{m_N}, & W_R \to \text{off-shell} \end{cases}$$



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 jets

MN, Nesti, Popara ’18

on simulating DJs

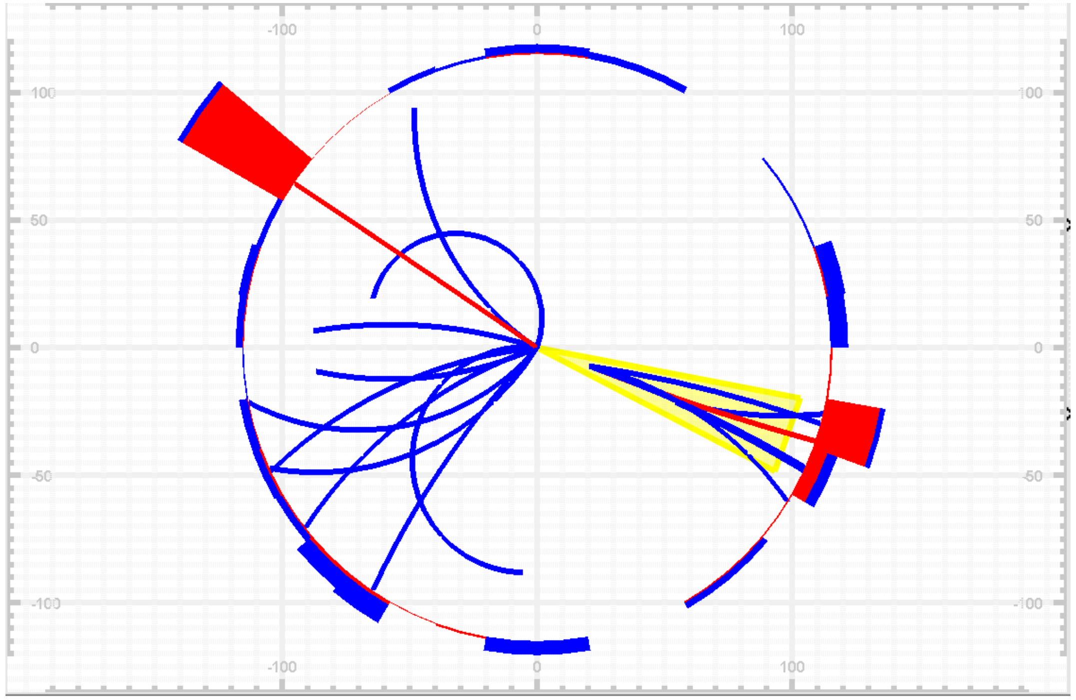
Modules available at sites.google.com/site/leftrighthep

Delphes hack/extension

added track displacement info

smeared with the vertex resolutions

store for each track



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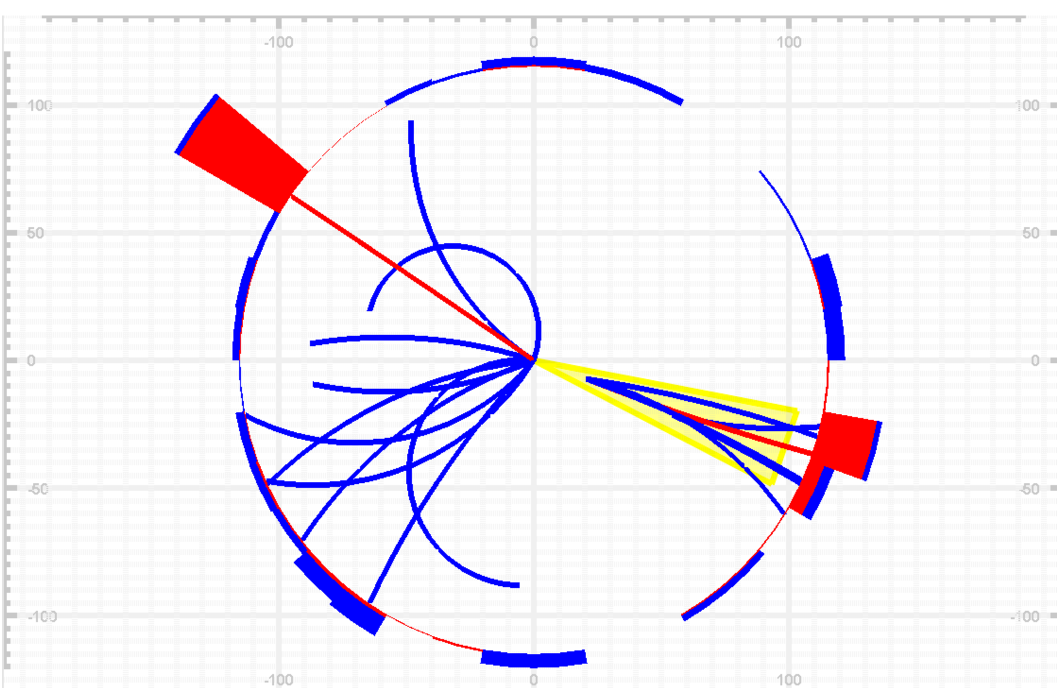
```
##################
# Jet displacement
##################

module JetDisplacement JetDisplacement {
  set JetInputArray FastJetFinder/jets
  set TrackInputArray TrackVertexSmearing/tracks

  set DeltaRTrack 0.3
  set fDisplTrackMinPT 20.

  set OutputArray jets
}
```



FastJet clustering as in the prompt case

remove soft tracks above certain p_T cut

define min track displacement as jet d_T

Displaced jets

MN, Nesti, Popara ’18

on simulating DJs

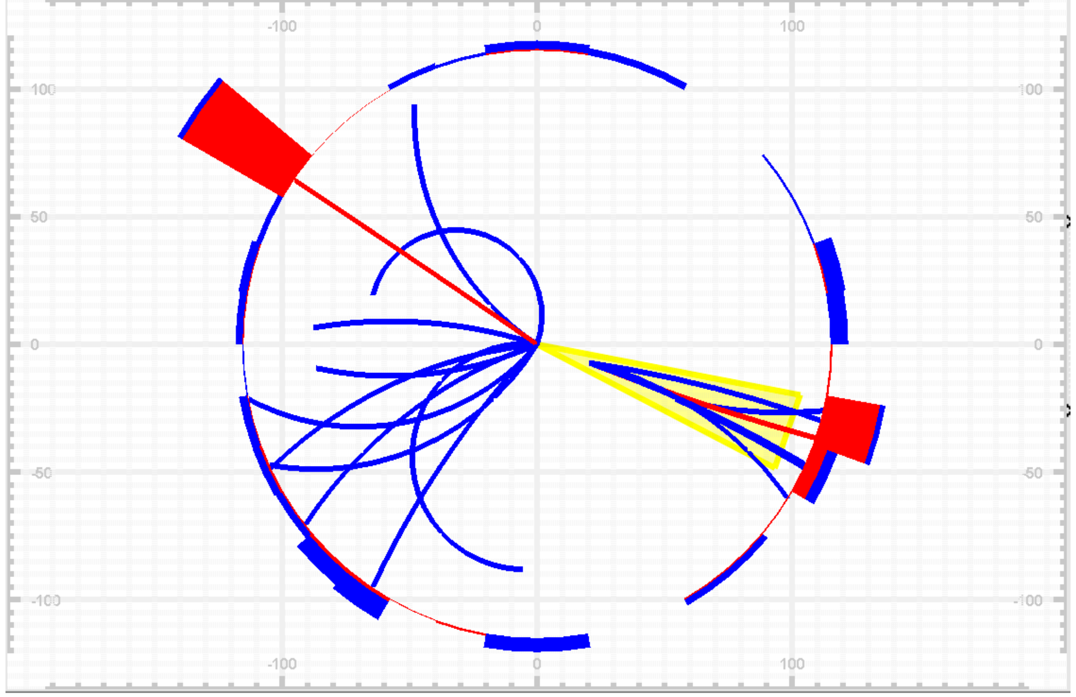
Modules available at sites.google.com/site/leftrighthep

Delphes hack/extension

- added track displacement info
- smeared with the vertex resolutions
- store for each track

Madanalysis use of cuts

- displacement info in .lhe .hep and .lhco
- use the last two fake entries for d_T, d_Z
- perform cuts as usual



FastJet clustering as in the prompt case

- remove soft tracks above certain p_T cut
- define min track displacement as jet d_T

Displaced jet discrimination

MN, Nesti, Popara '18

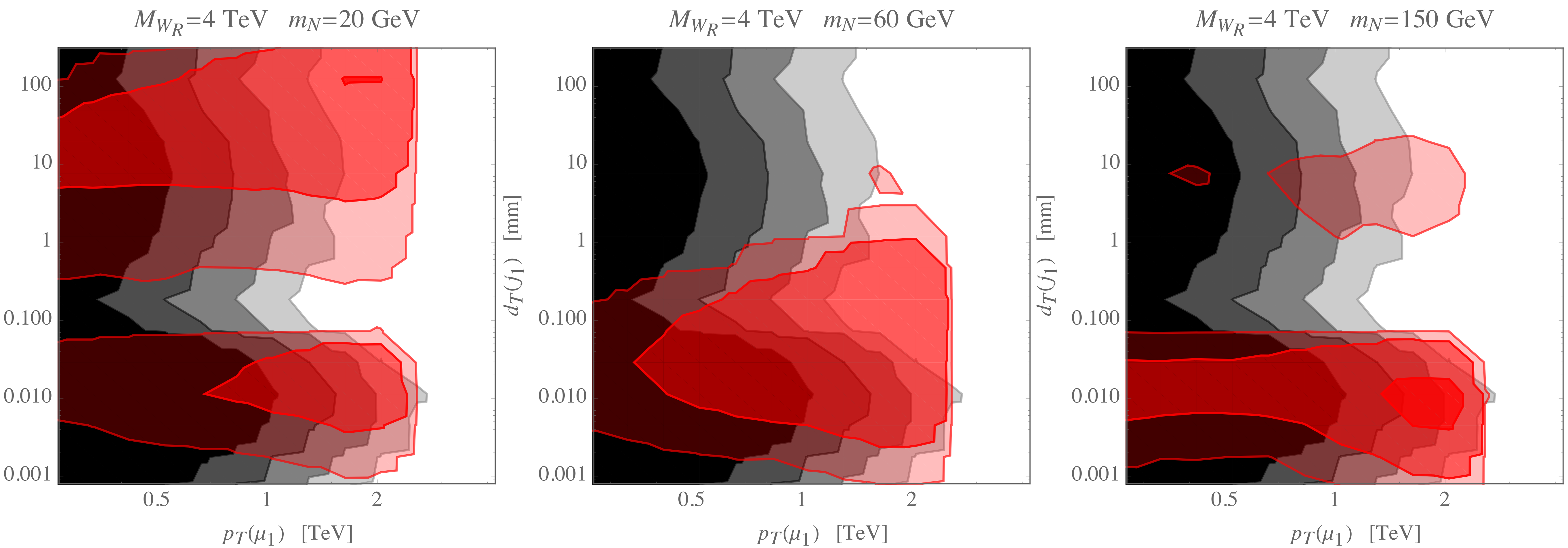
Event generation: custom generator KSEG, small width issues with MG5

talk by Goran Popara

Feynrules model file at sites.google.com/site/leftrighthep

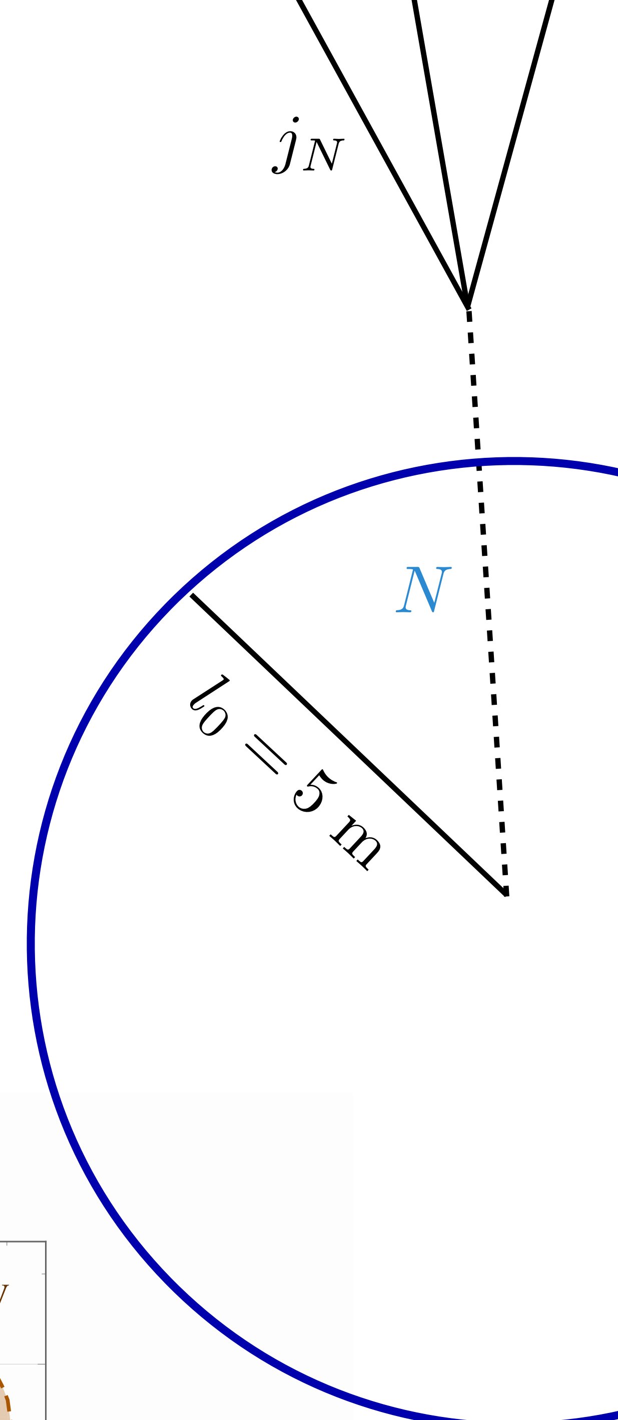
Main bckgs

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



Recast of the $W' \to \ell\nu$

MN, Nesti, Popara '18



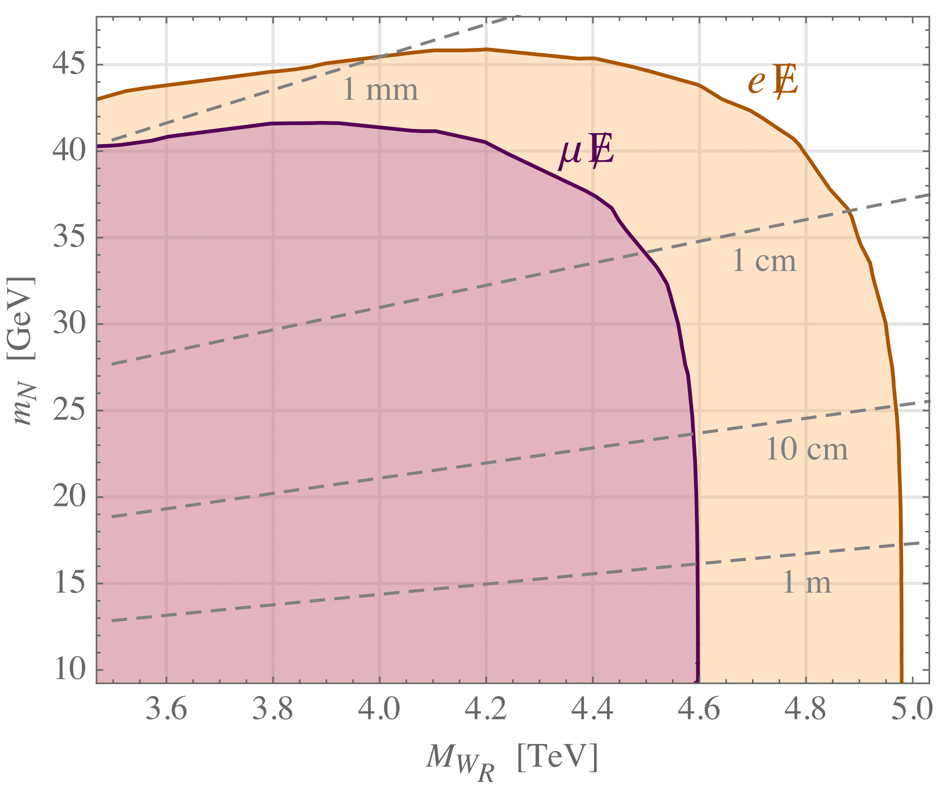
prompt hard leading lepton and significant missing energy

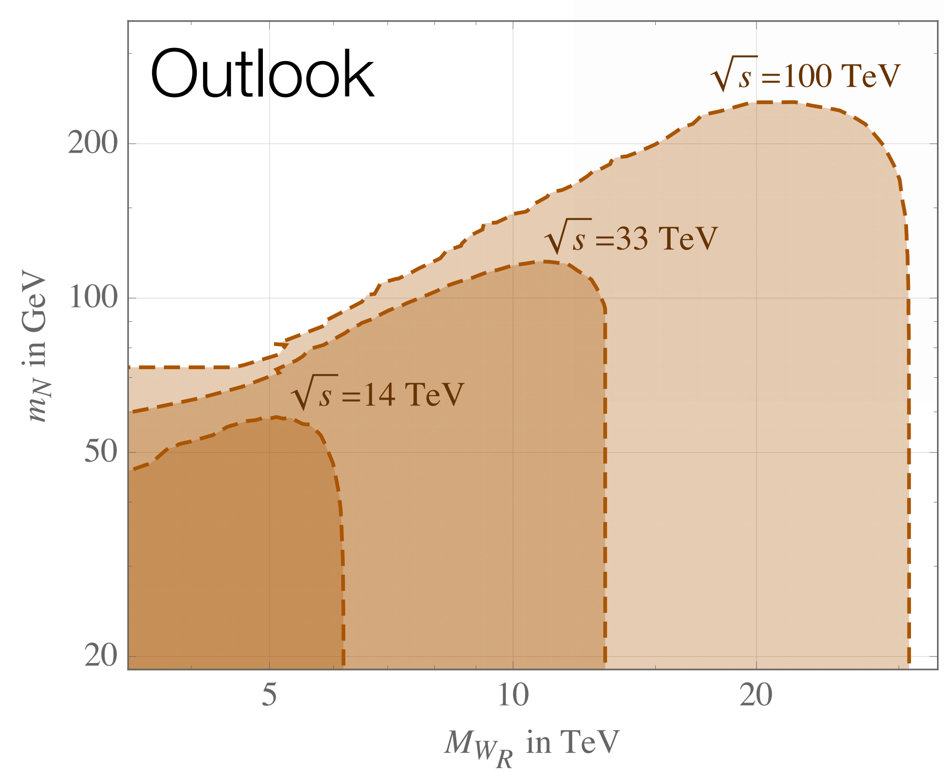
$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_T} = \alpha_2^2 \frac{\pi}{24} p_T \int_{\tau_-}^{1} \int_{\frac{\tau_-}{x_1}}^{1} \mathrm{d}x_{1,2} \frac{\left(\hat{s} - m_N^2 - 2p_T^2\right) \pm 1}{\sqrt{\left(\hat{s} - m_N^2\right)^2 - 4p_T^2 \hat{s}}}$$

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

exponential distributions have long tails

Recast from ATLAS 1706.04786



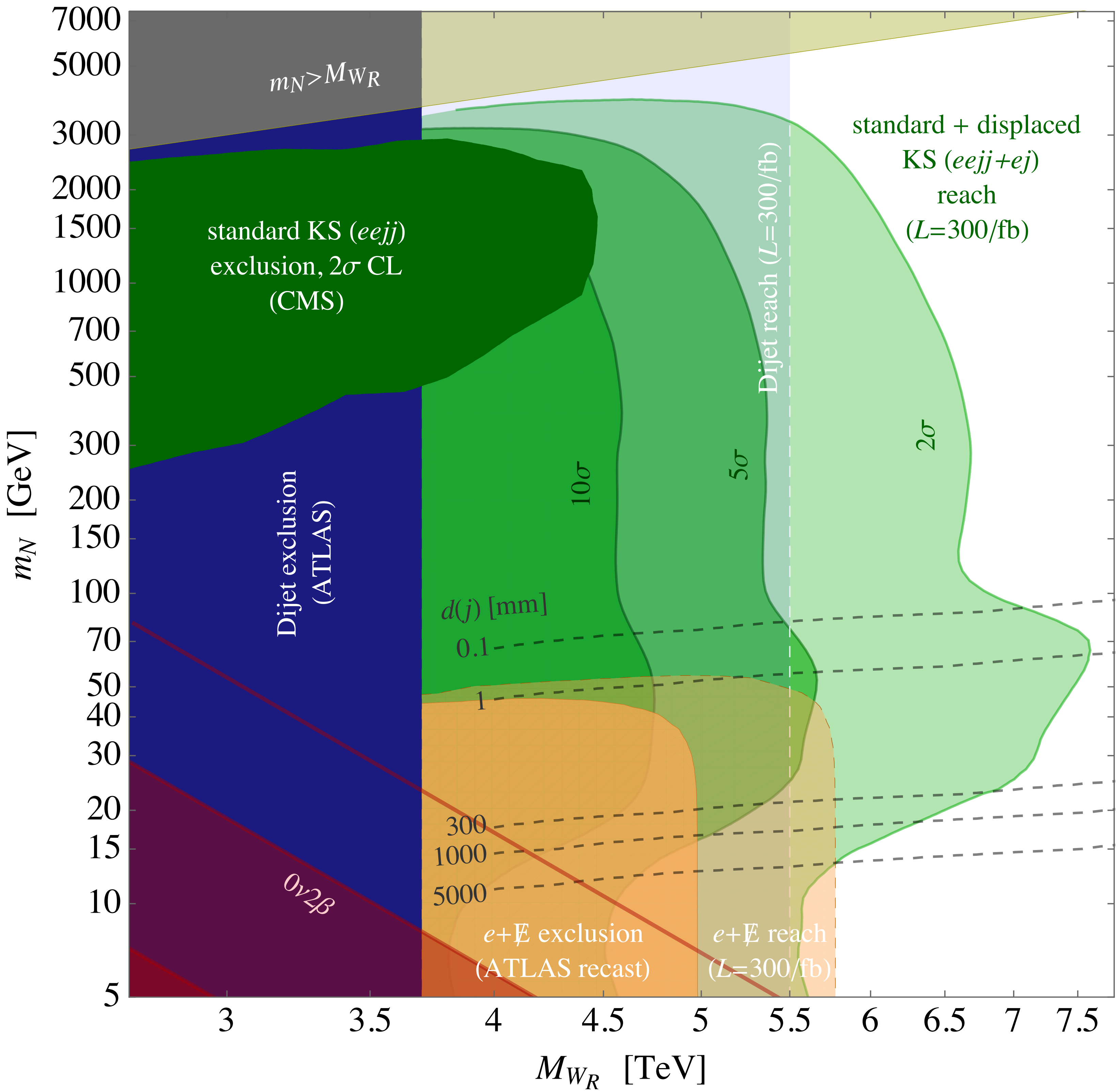


limited by lumi

taus ~ 4 TeV ATLAS 1807.11421

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

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.)

Higgs sector

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

Minkowski '77
Mohapatra, Senjanović '79

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

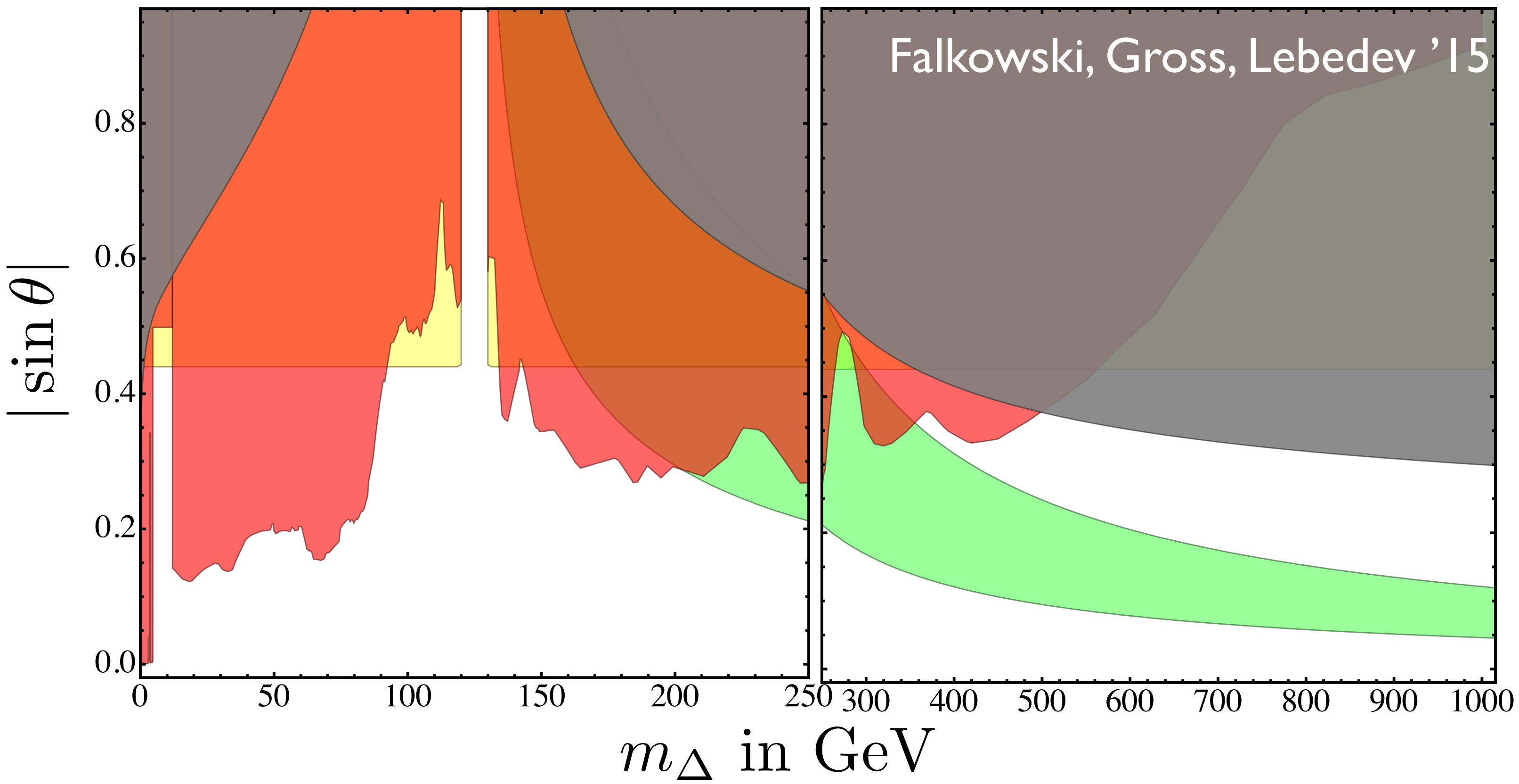
$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \qquad \langle\Phi\rangle = \begin{pmatrix} v & 0 \\ 0 & 0 \end{pmatrix}$$

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

same for $\mathcal{C}$-symmetry

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

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

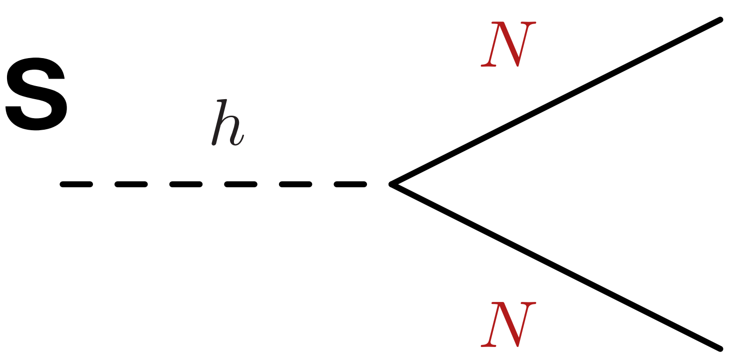


Future collider outlook

$$|\sin\theta| < .34$$

Buttazzo, Sala, Tesi '15

‘Majorana’ SM Higgs

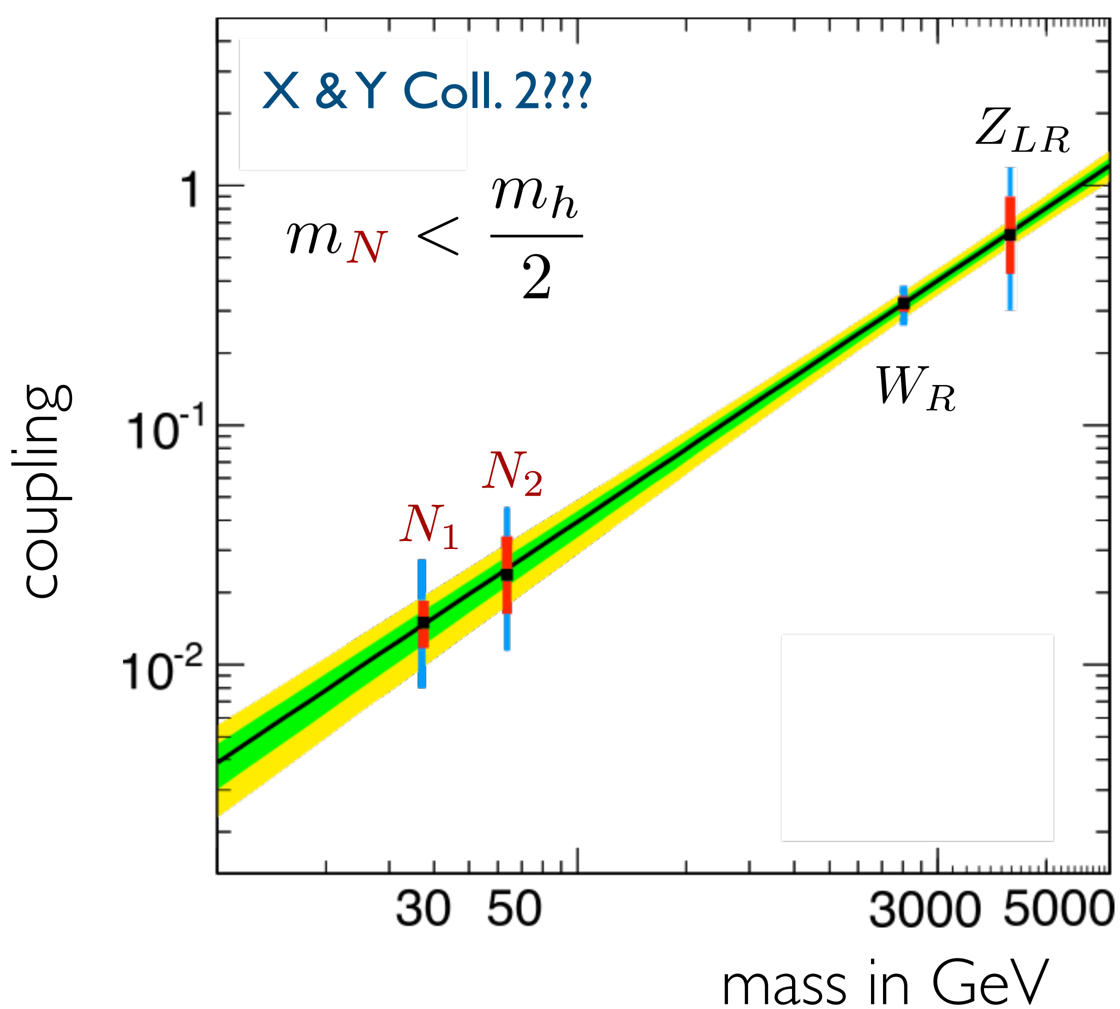


h decays

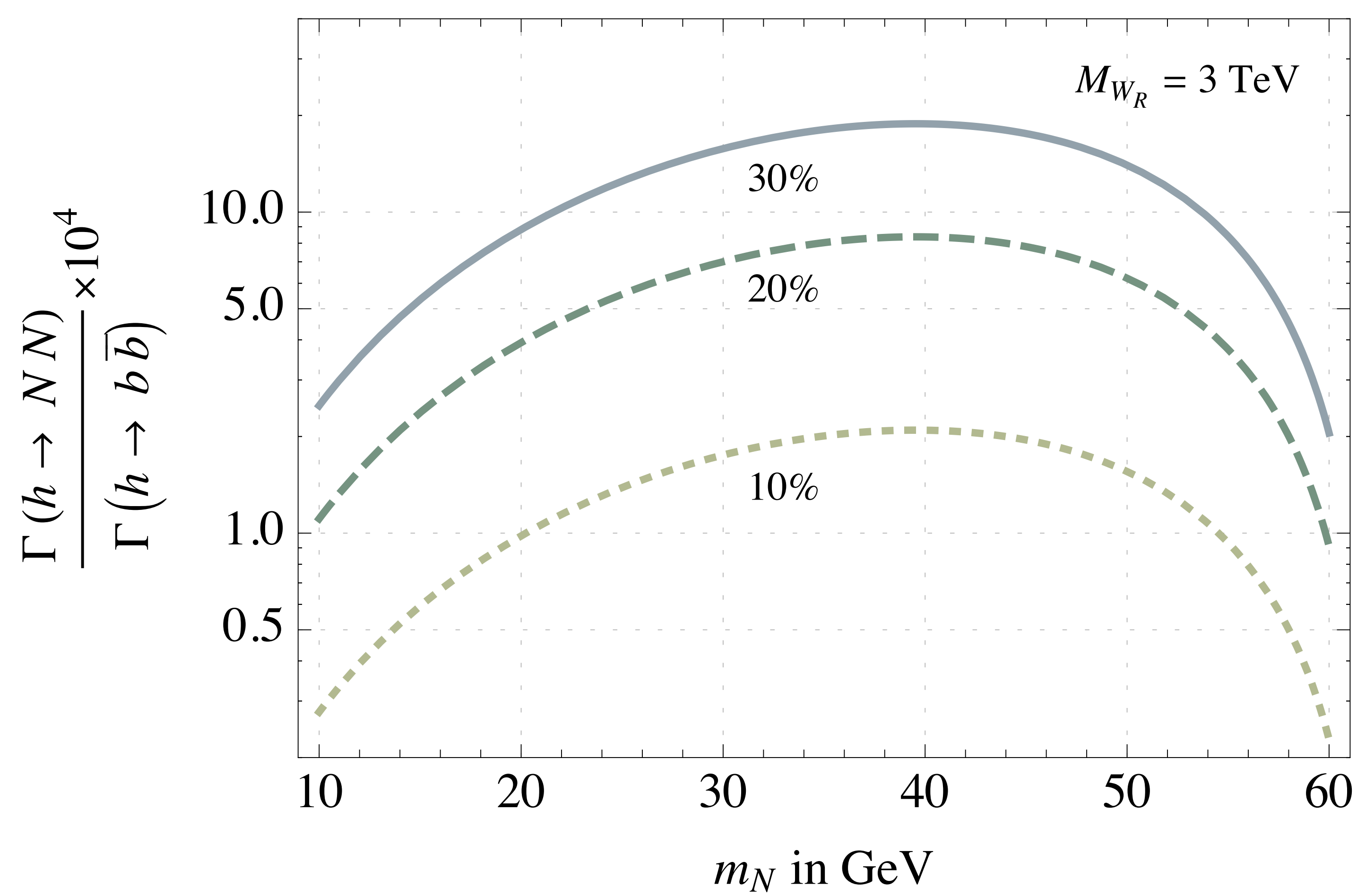
$$\Gamma_{h\to NN} \propto s_\theta^2\, m_N{}^2 \qquad \frac{\Gamma_{h\to NN}}{\Gamma_{h\to b\bar b}} \simeq \frac{\theta^2}{3}\left(\frac{m_N}{m_b}\right)^2\left(\frac{M_W}{M_{W_R}}\right)^2$$

Gunion et al. Snowmass ’86

EFT SM+h+N Graesser ’07



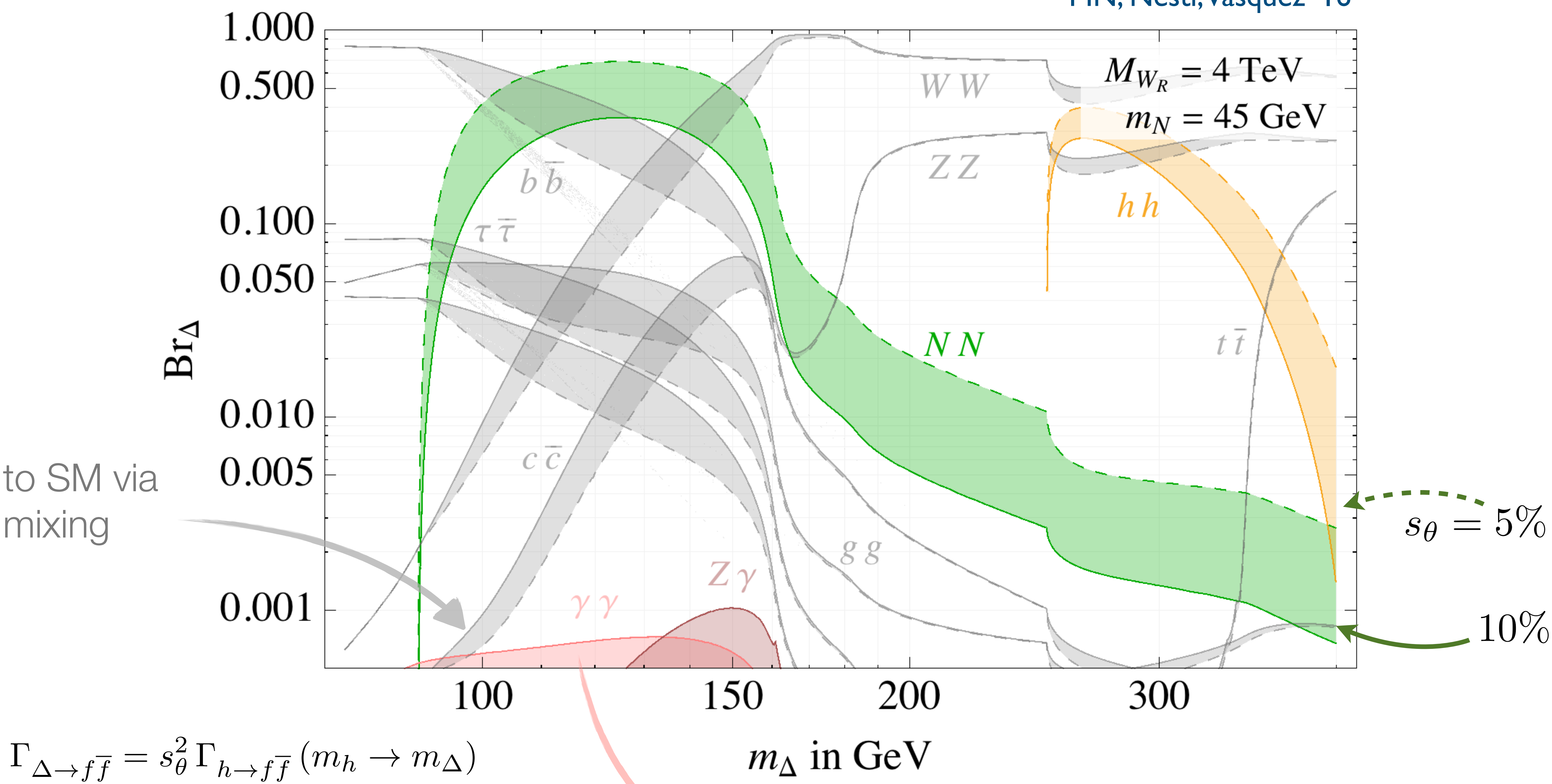
Maiezza, MN, Nesti ’15



‘Right-handed’ Higgs

Δ_R^0 decays

MN, Nesti, Vasquez ’16



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

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

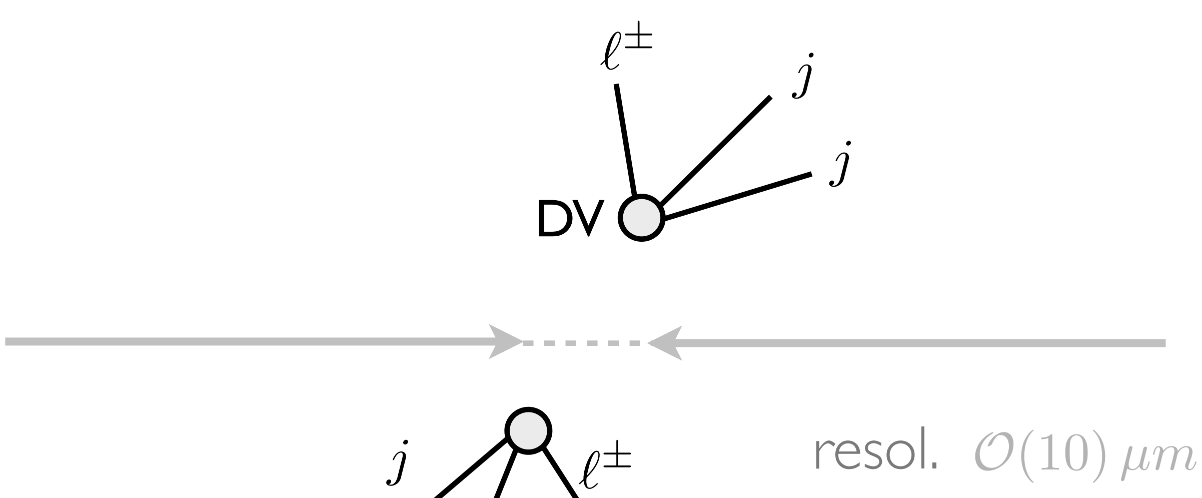
Region of interest for $\Delta \to NN$

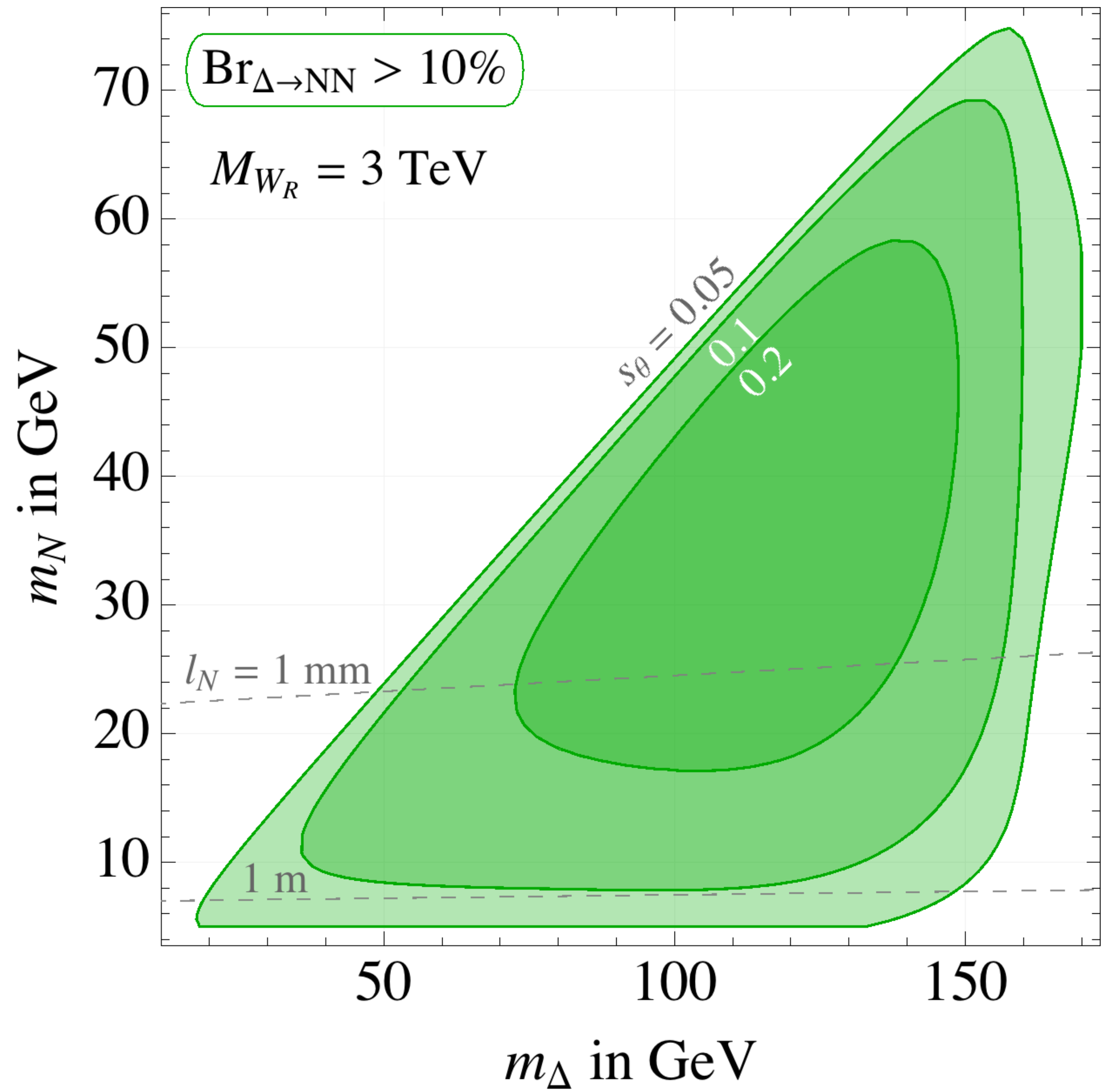
$$20 \text{ GeV} \lesssim m_\Delta \lesssim 170 \text{ GeV}$$

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

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

pair & associated

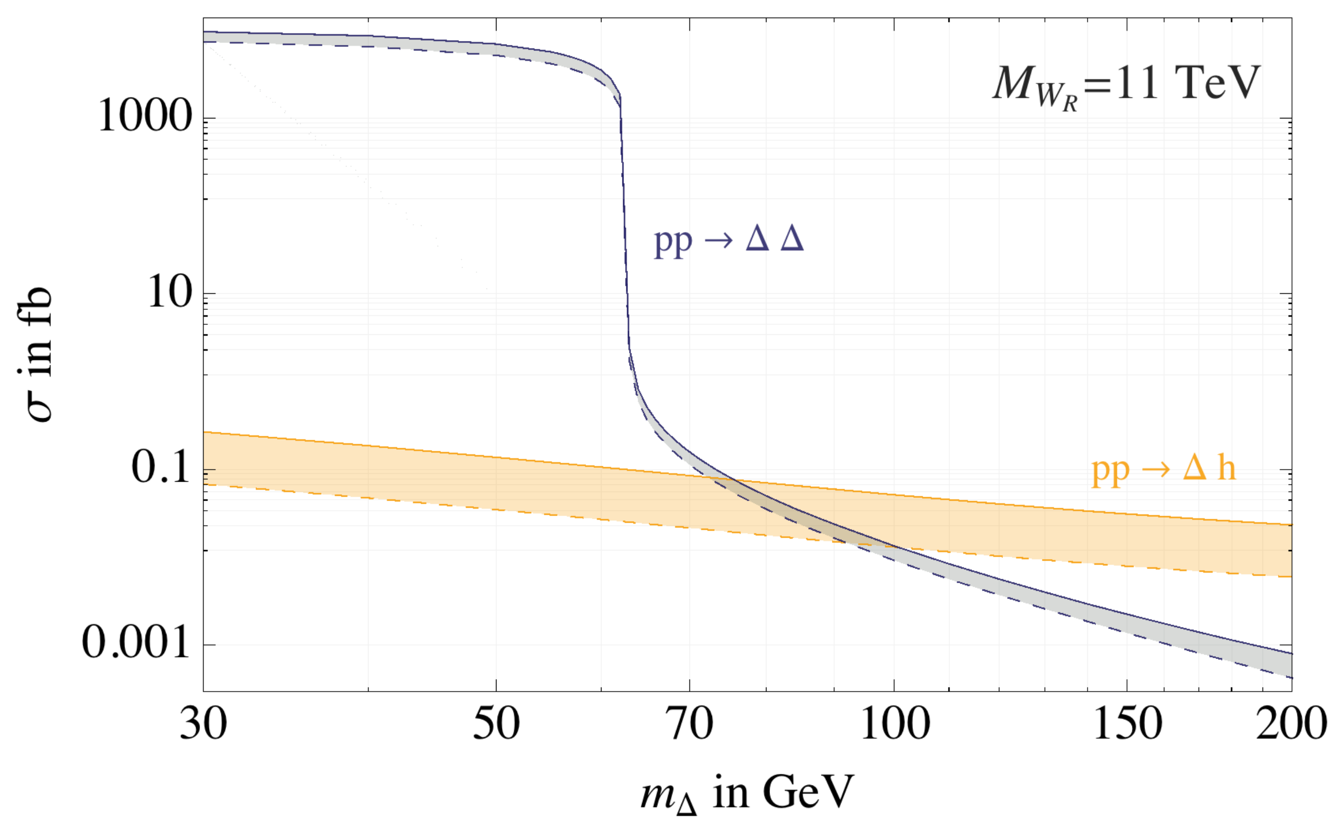
$$\hat{\sigma}_{gg\to\Delta S} \simeq \frac{c_\theta^2}{64\pi(1+\delta_{\Delta S})}\, \hat{s} \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{v_{hS\Delta}^2}{(\hat{s}-m_h^2)^2+\hat{s}\Gamma_h^2} |F_b + F_t|^2 \sqrt{\beta_{\hat{s}\Delta S}}$$

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

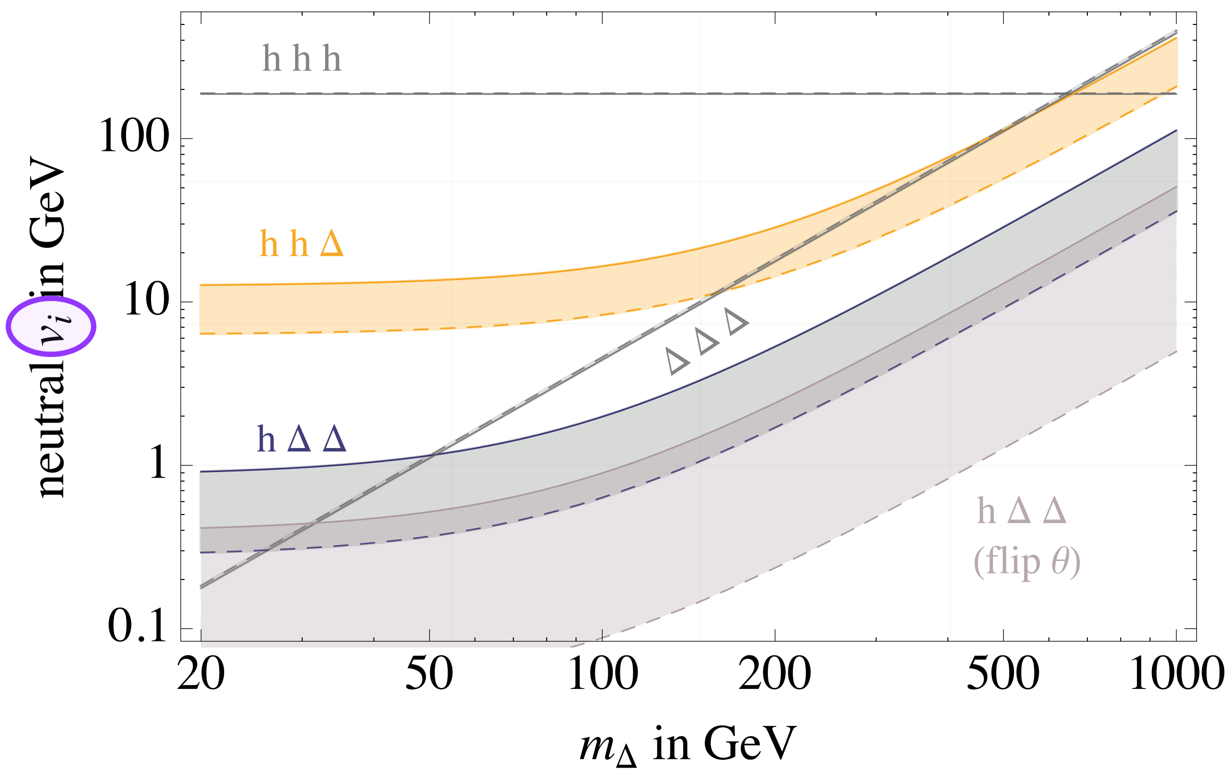
$$\sigma_{gg\to\Delta\Delta} \simeq \sigma_{gg\to h}\, \mathrm{Br}_{h\to\Delta\Delta}$$

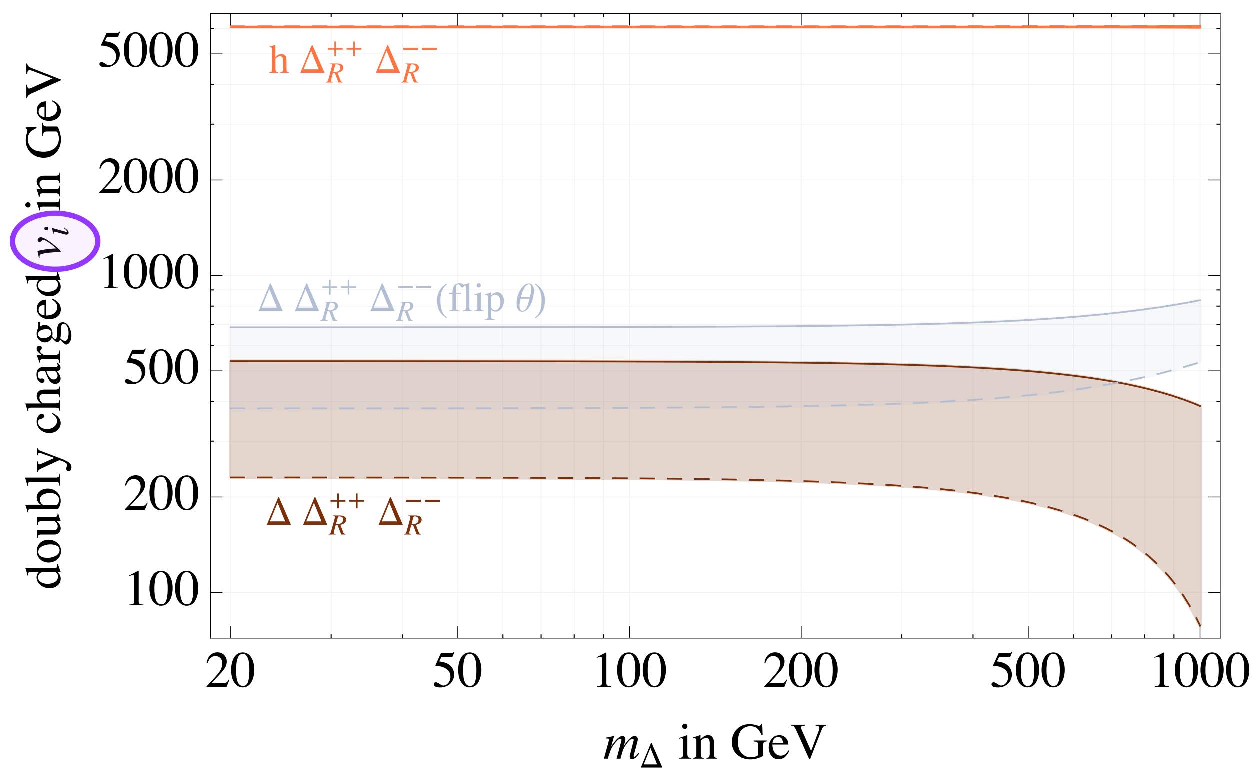
not very significant

(accidental cancellation)



Tri-linear Higgs @ LO





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

tree level

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

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

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

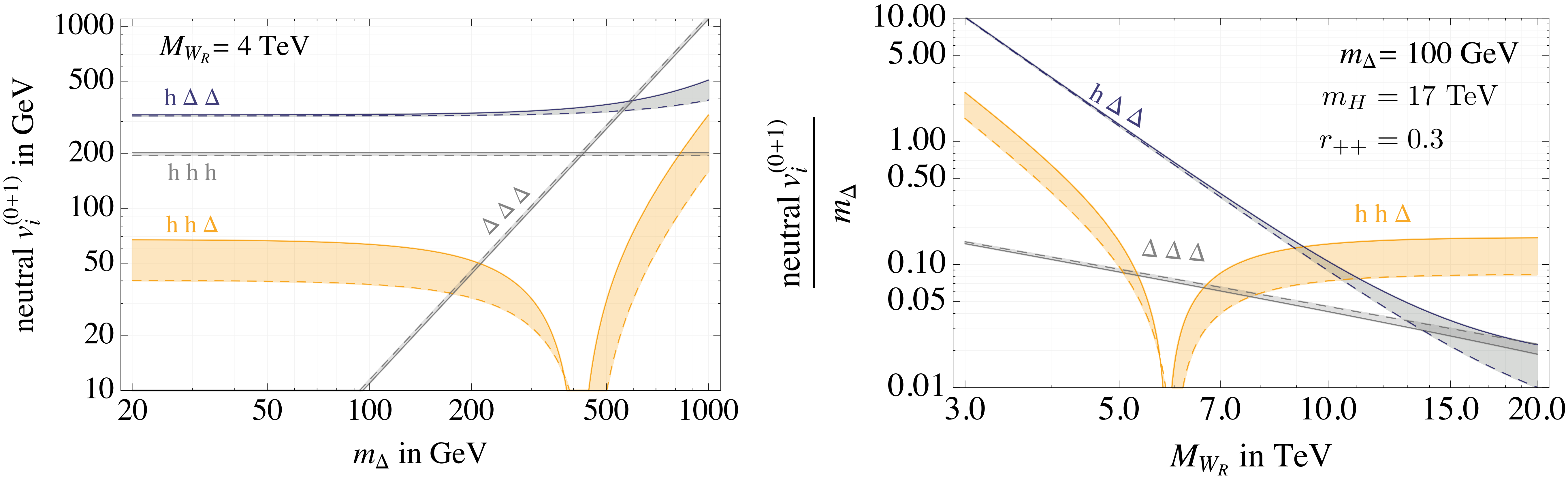
$$v_{\Delta\Delta\Delta} = \frac{3g}{2} m_\Delta^2 \left[\frac{s_\theta^3}{M_W} + \sqrt{2} \frac{c_\theta^3}{M_{W_R}} \right]$$

cancellation

+ corrections due to H mixing

Tri-linear Higgs @ NLO

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



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

decouple with v_R

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

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

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

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

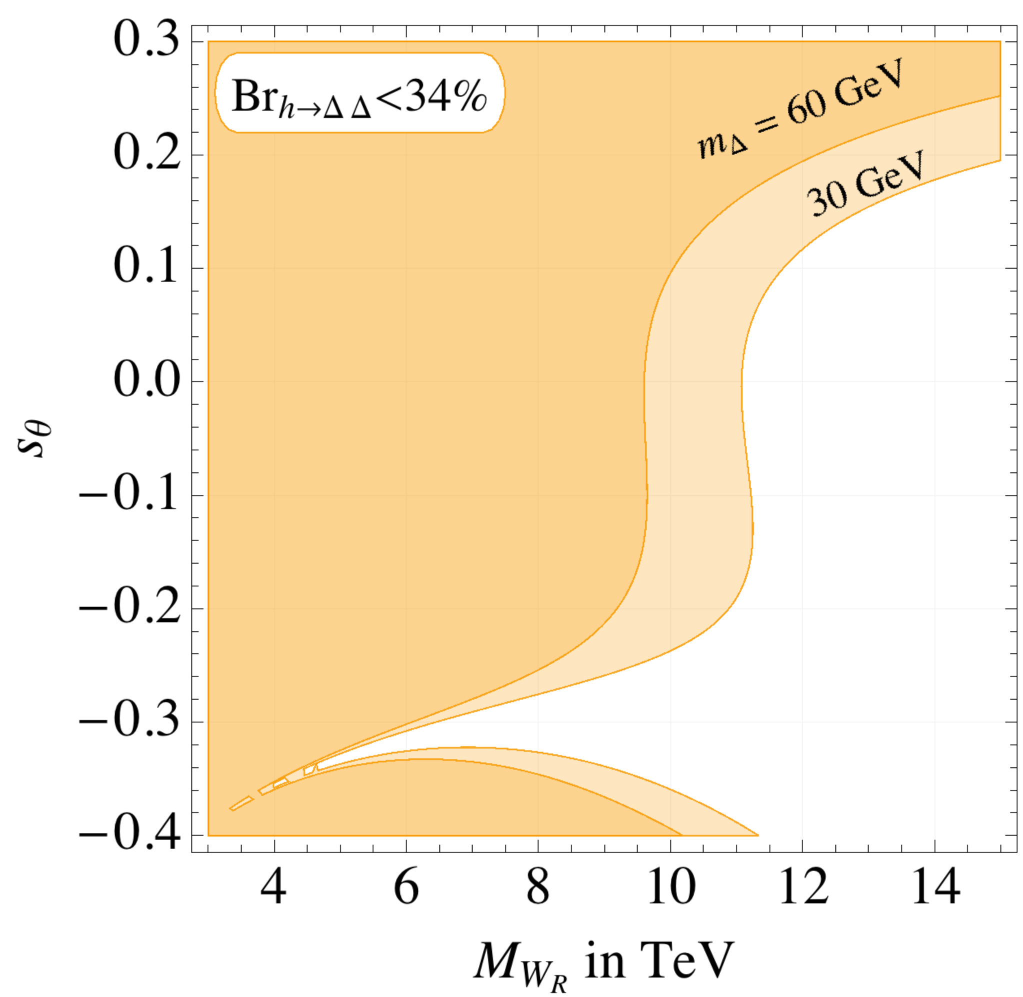
Δ production

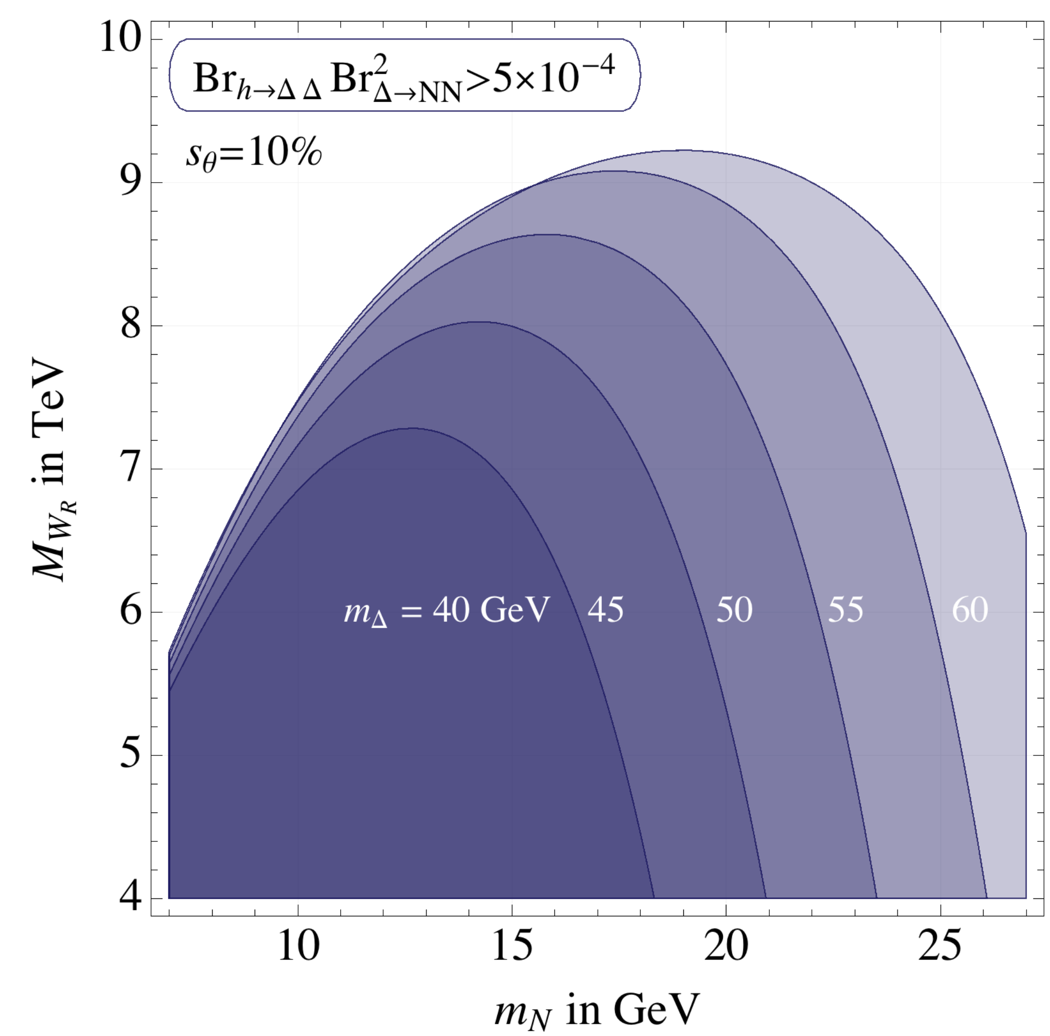
Δ^* suppressed

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

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

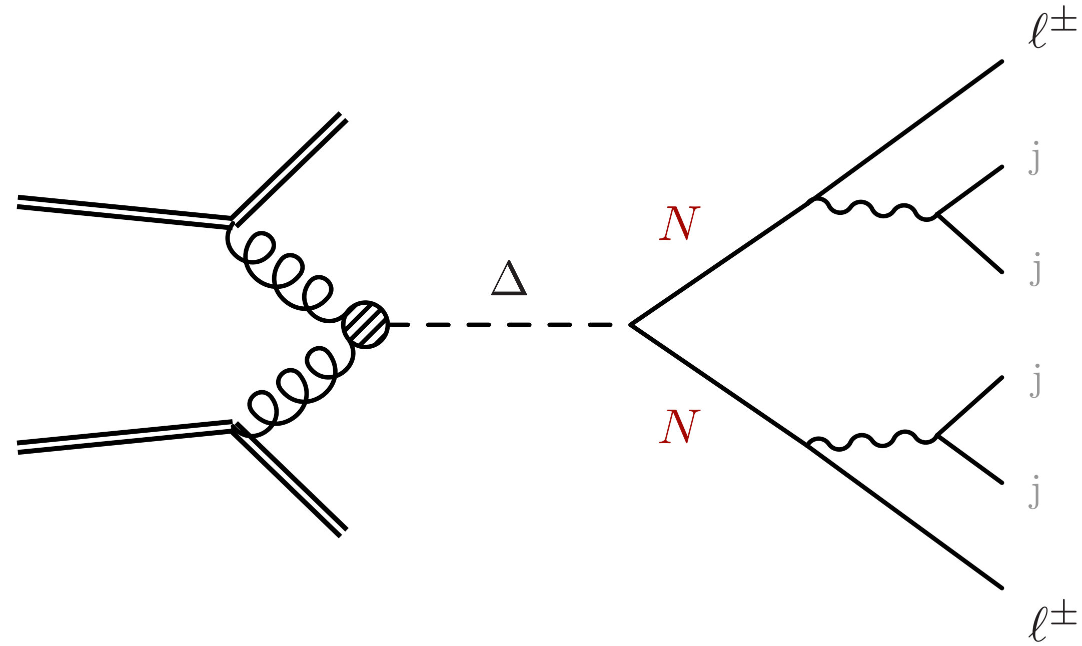
$\sigma_{gg\to h}$ N^{3}LO Anastasiou et al. '16



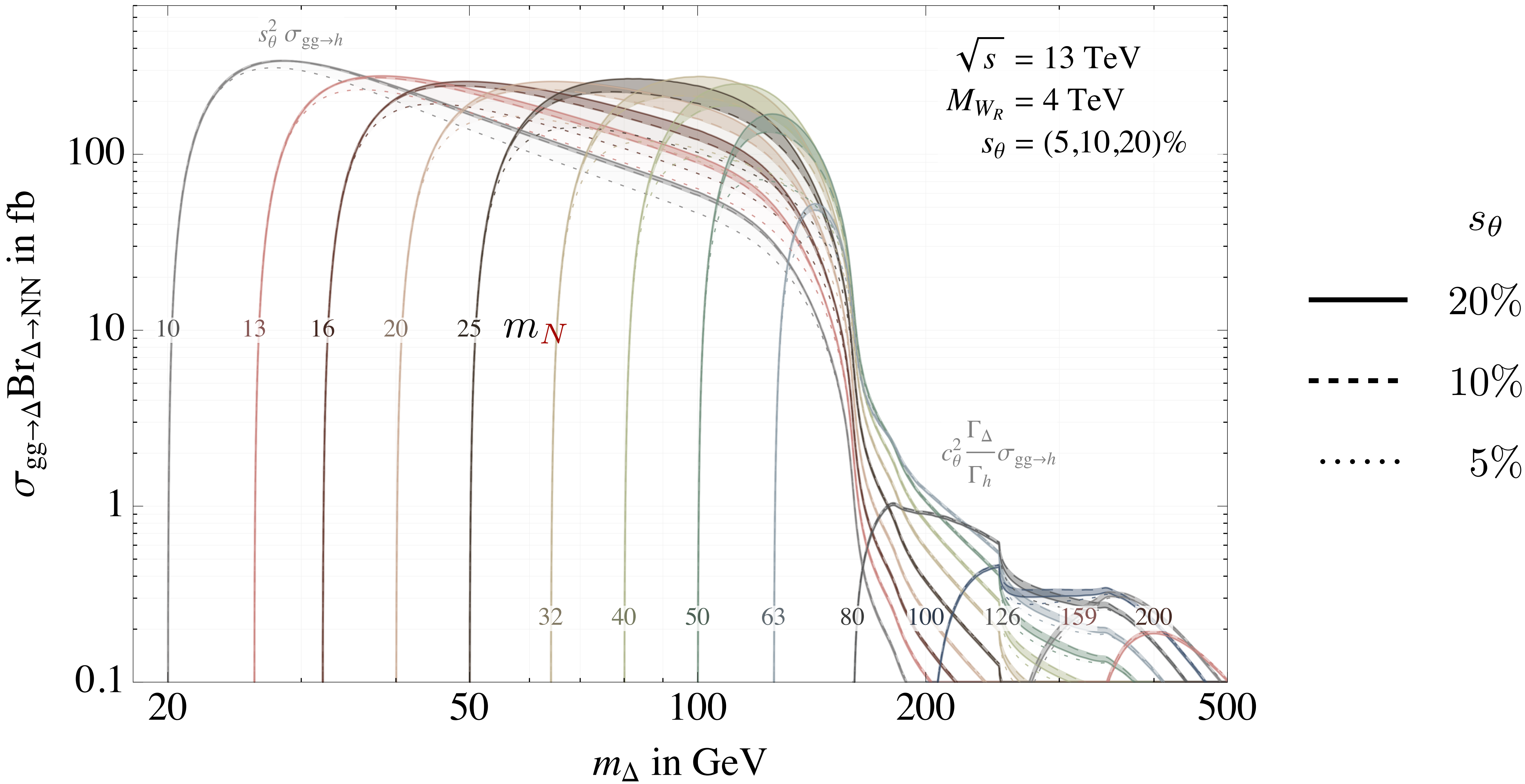


Δ signals

single

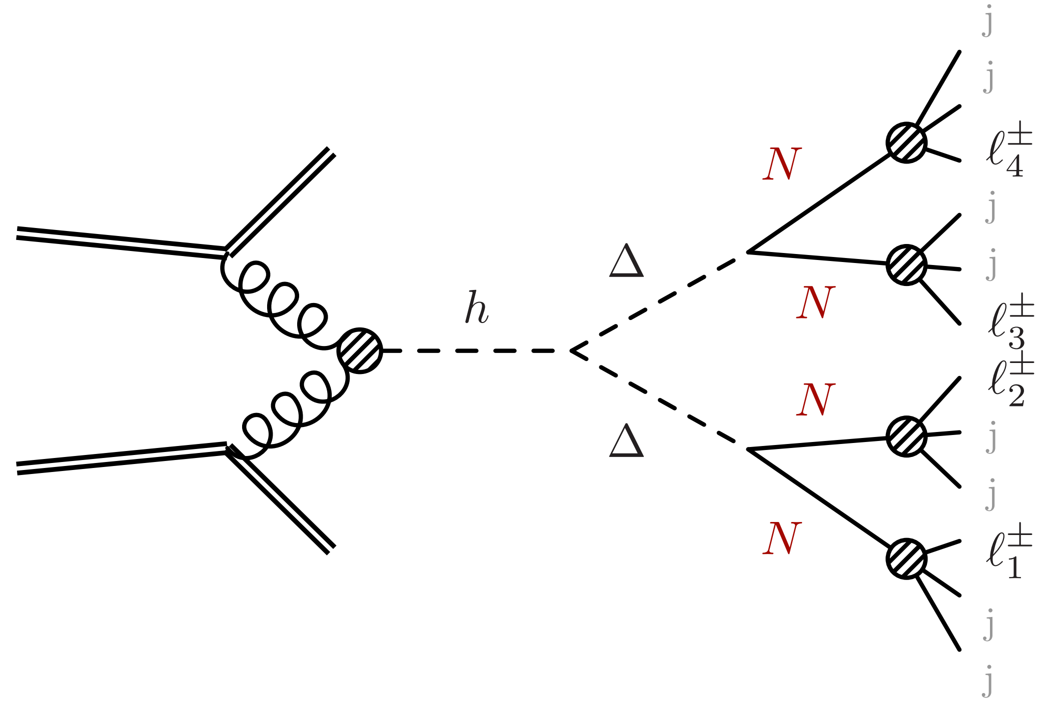


$\Delta L = 0, 2$

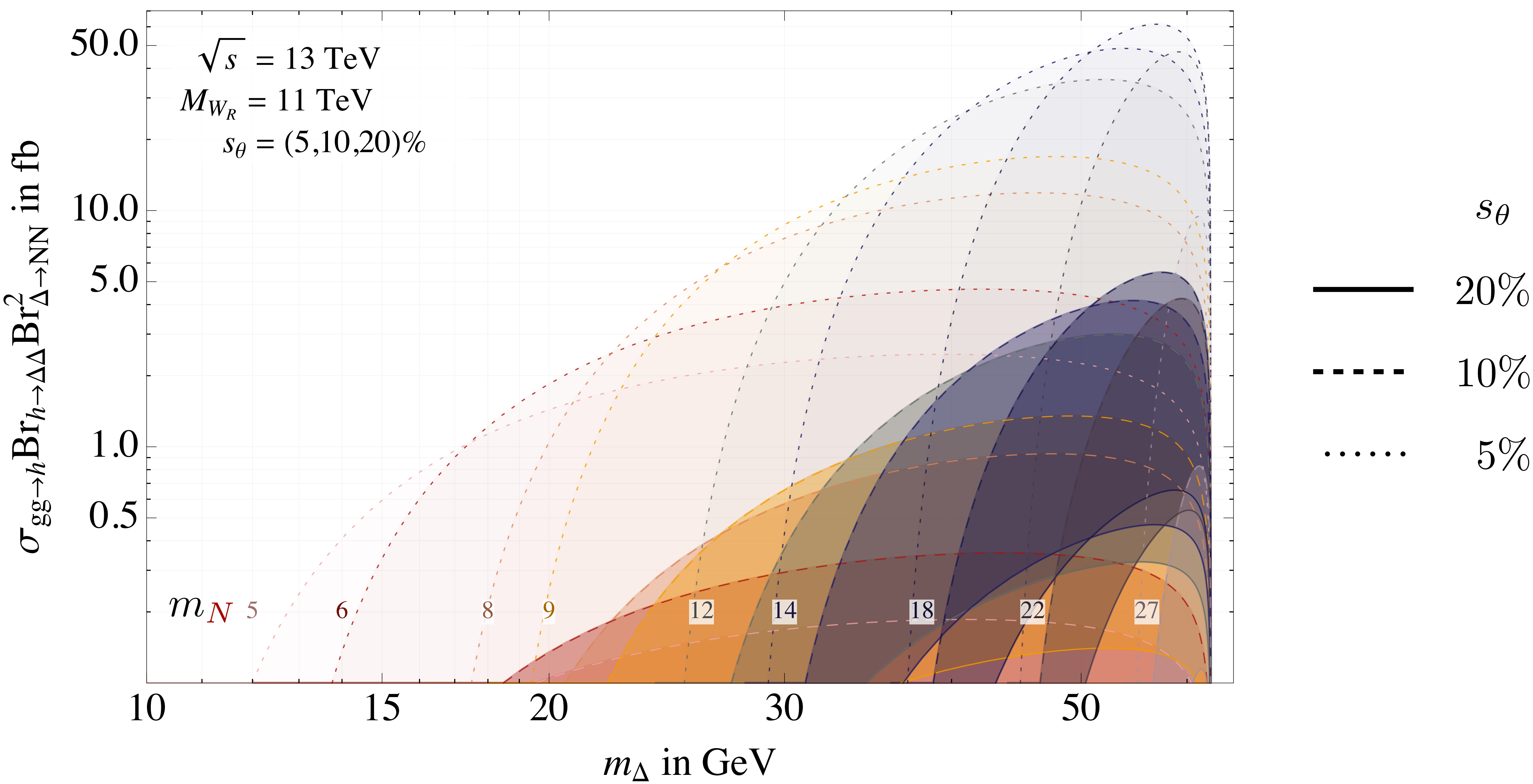


Δ signals

pair



$\Delta L = 0, 2, 4$



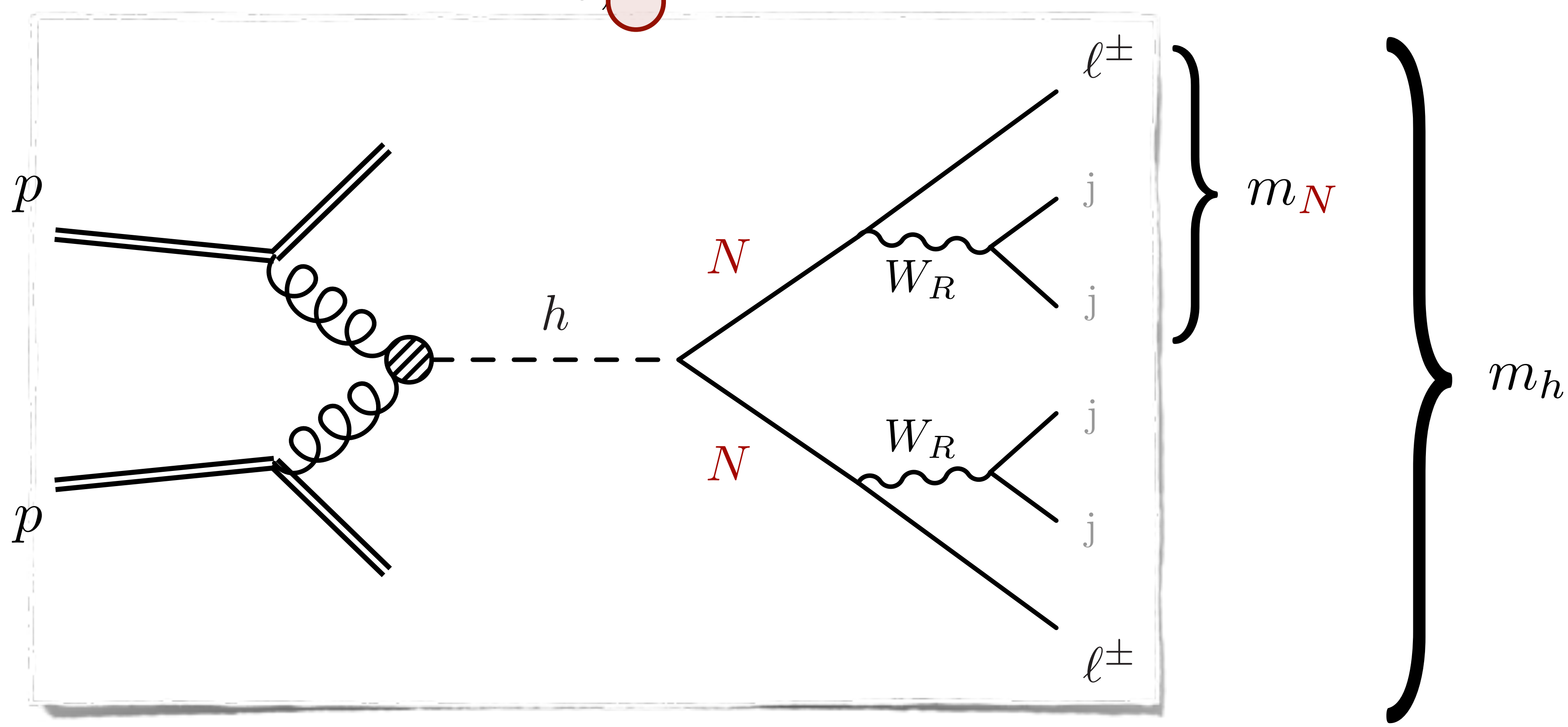
‘Majorana’ Higgses at LHC

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

no missing energy

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

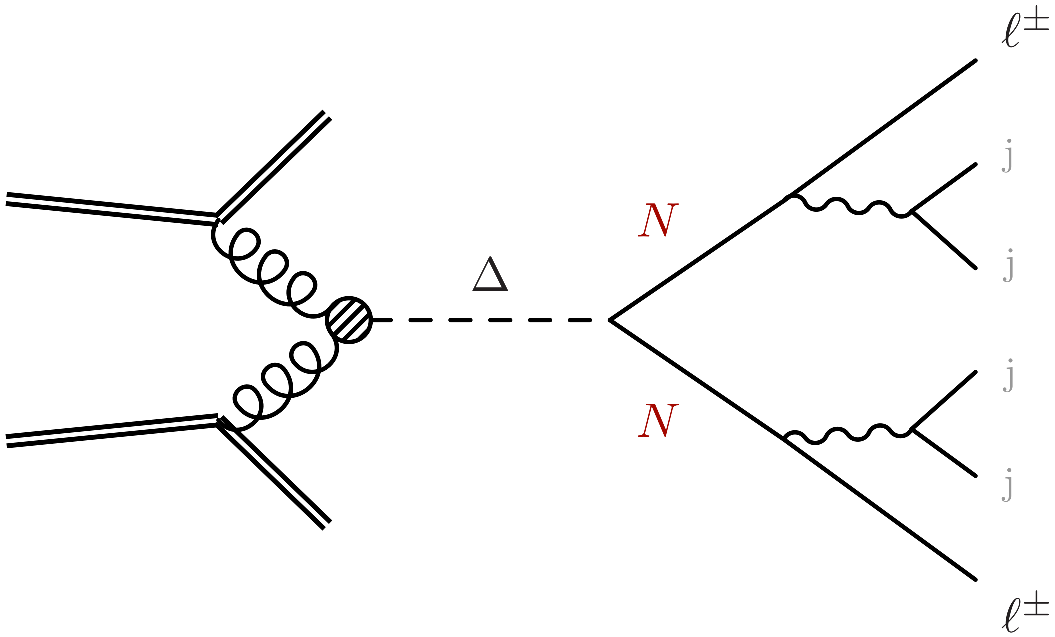
soft products $p_T \simeq m_h/6 \sim 20$ GeV

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

low background (LNV)

‘Majorana’ Higgses at LHC

$\Delta L = 0, 2$

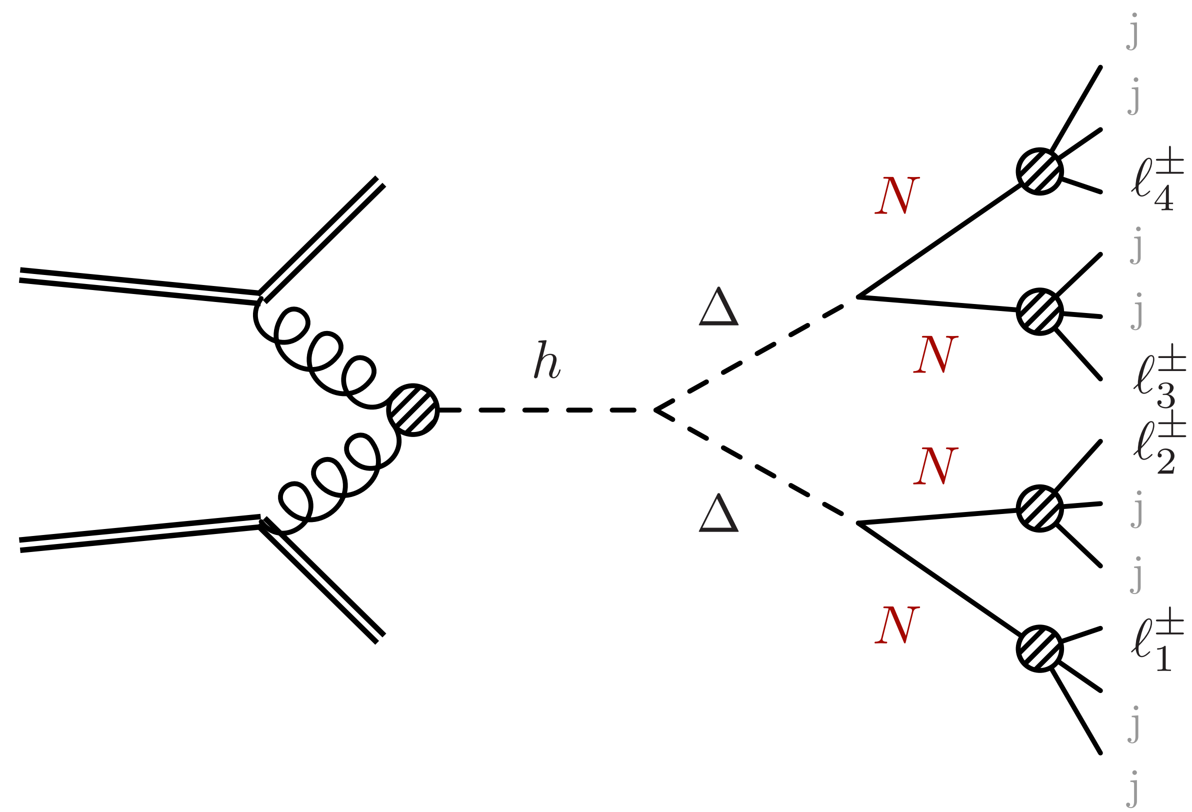


similar to $h \to NN$

ggF of CP even scalar

Anastasiou et al. ’16

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



(same-sign) multi-leptons

$2^4 = 16$ possibilities

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

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

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_{inv}	$m_{\ell\ell} < 80\,\mathrm{GeV}$ $m_{\ell\not{p}_T} < 60\,\mathrm{GeV}$
$l_{T\ell}$	$l_{T\ell} > 0.1\ \mathrm{mm}$

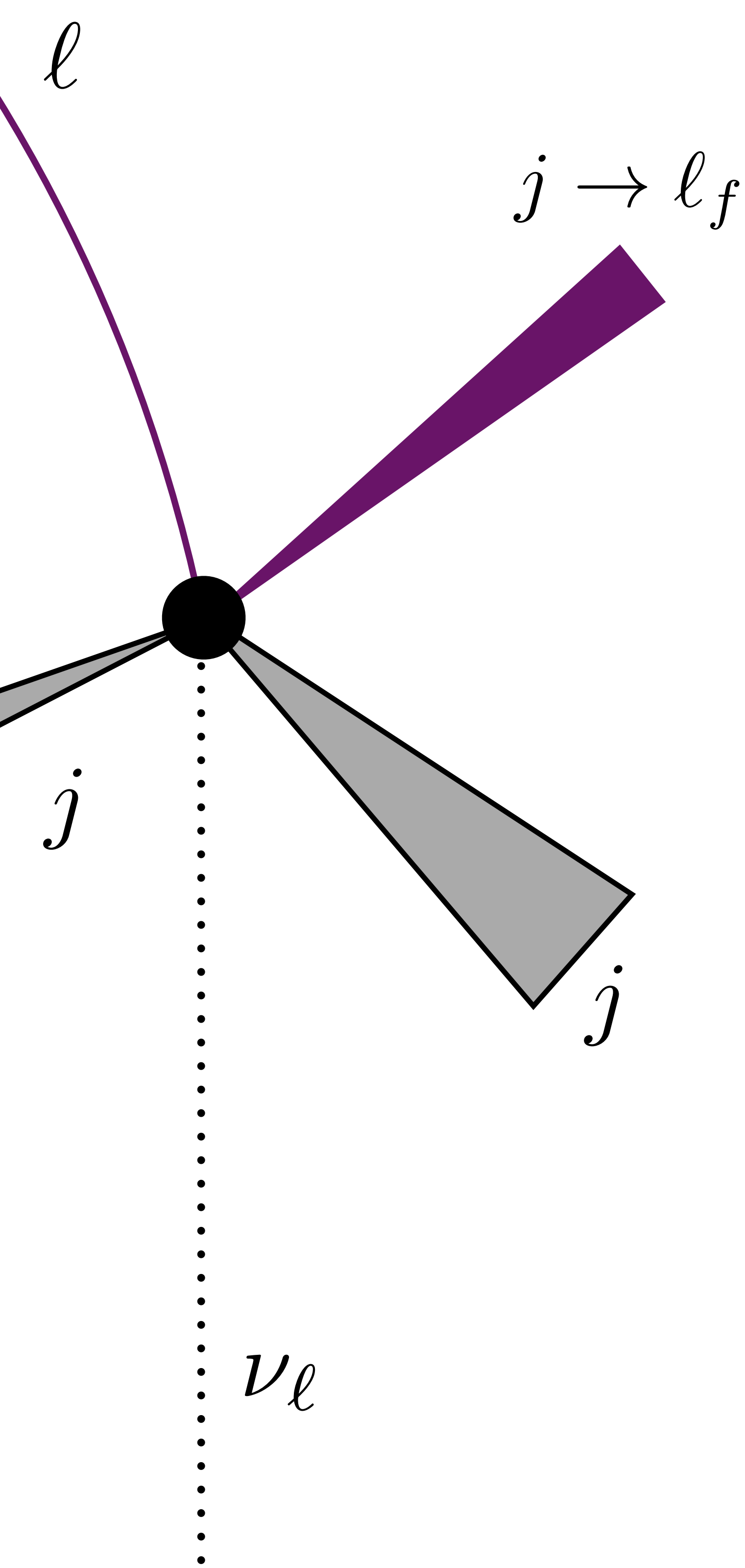
all contain missing energy

one prompt, one displaced lepton

$Wjjj$

Backgrounds

on jet fake simulation



use the Delphes
`JetFakeParticle` module

sites.google.com/site/leftrighthep

conversion rate

$$\varepsilon_{j\to\ell}(\cancel{p_T,\eta})$$

softened momentum

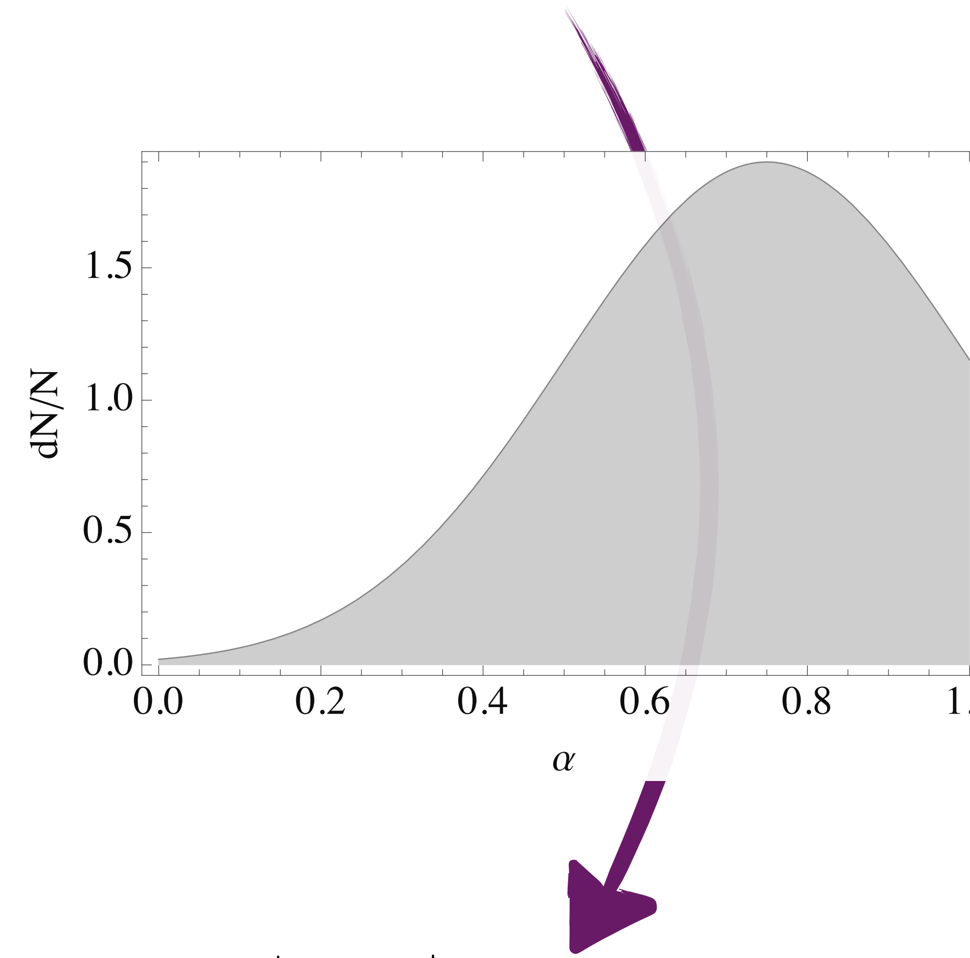
$$p_{T\ell} = (1-\alpha)p_{T\text{jet}}$$

$$P(\alpha) = \frac{1}{\mathcal{N}}\, e^{\frac{(\alpha-\mu)^2}{2\sigma^2}}$$

Curtin, Galloway, Wacker '13
Izaguirre, Shuve, '15

$$\ell^\pm + \not{E}_T + j + j + j$$

prompt lepton + jets

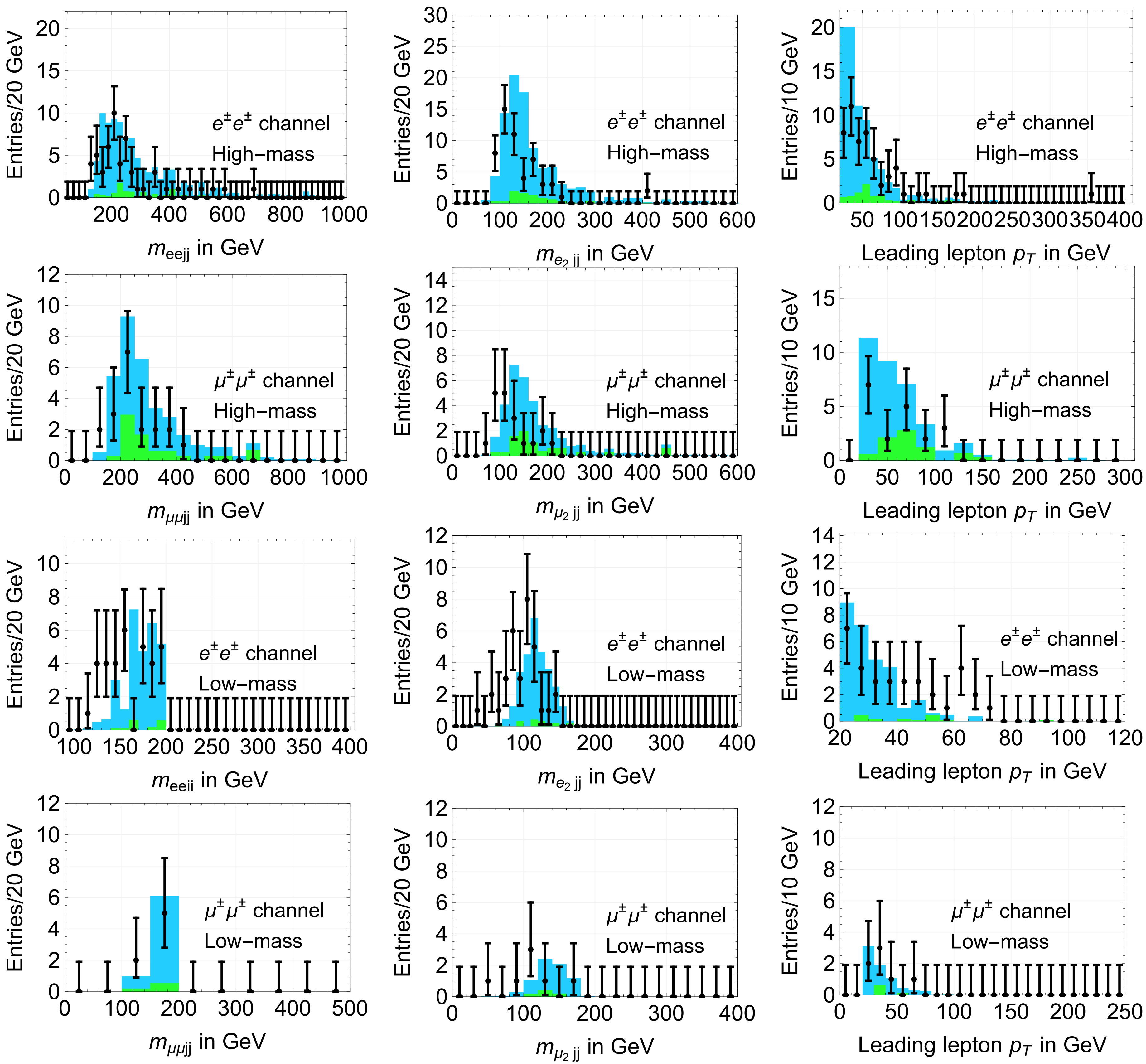


$$\ell^\pm + \ell_f^\pm + \not{E}_T + j + j$$

prompt + softer fake
lepton + jets

Backgrounds

jet fakes



$Wjjj$

$jjjj$

$t\bar{t} + j + jj$

$VV + j + jj$

$\varepsilon(j \to e) = 5 \times 10^{-4}$ *

*overestimated for Q mis-id

$\varepsilon(j \to \mu) = 3 \times 10^{-4}$

$\alpha = 0.75 \qquad \sigma = 0.25$

data from CMS
mumu 1501.05566
ee, emu 1603.02248

Backgrounds

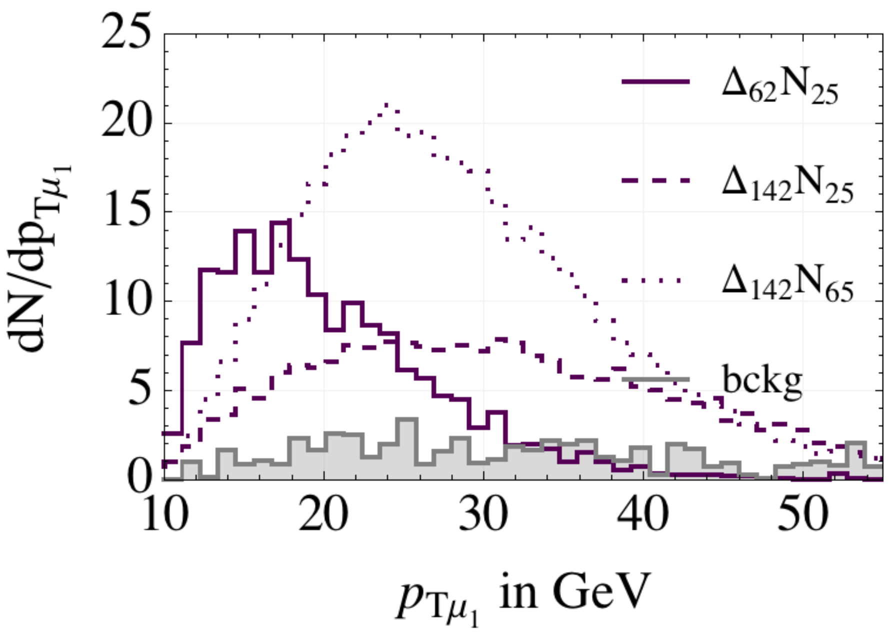
$\ell^{\pm}\ell^{\pm} + n_j$

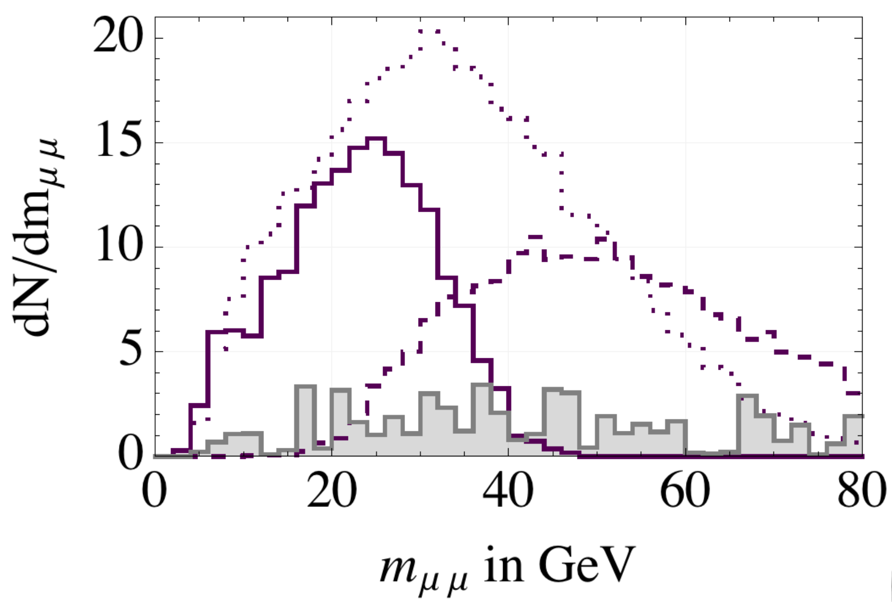
	$t\bar{t}$	$t\bar{t}h$	$t\bar{t}Z$	$t\bar{t}W$	WZ	Wh	ZZ	Zh	$WWjj$	fakes
select	806	4	5	26	1241	87	147	16	1.5	2651
$\not{E}_T$	313	0.5	0.7	3	400	21	129	7	0.2	782
p_T	112	0.2	0.1	0.7	174	8.4	63	4	0.05	284
m_T	60	0.1	0.04	0.3	80	4	56	2	0.03	106
m^{inv}	35	0.03	0.03	0.2	25	2	36	2	0	80
l_{Te}	0	0	0	0	0.7	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

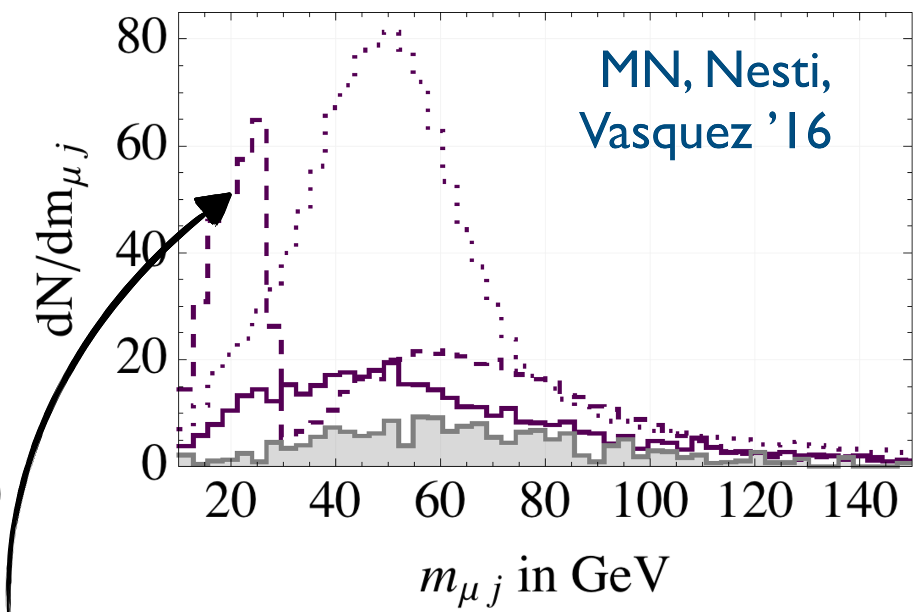
all contain missing energy

one prompt, one displaced lepton

Kinematics

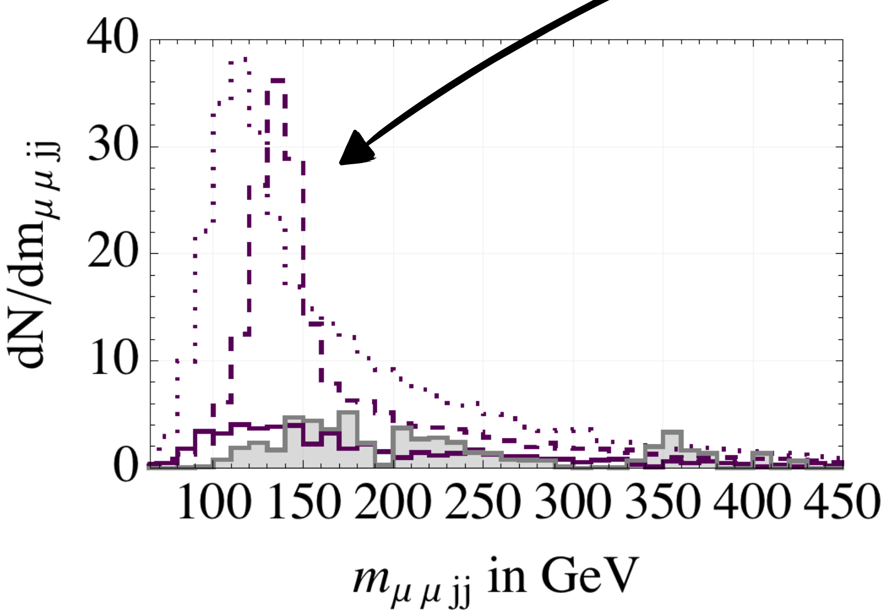


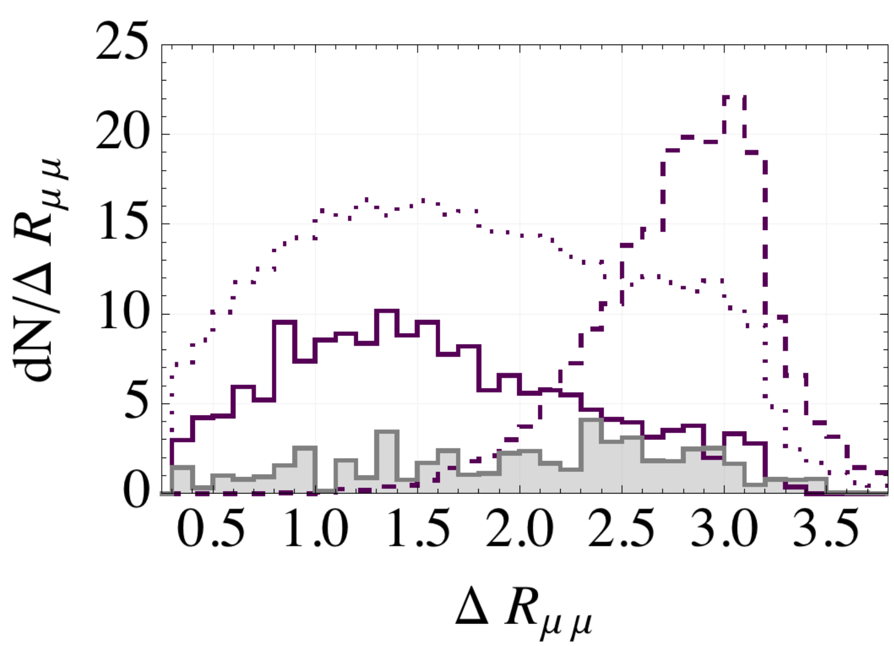


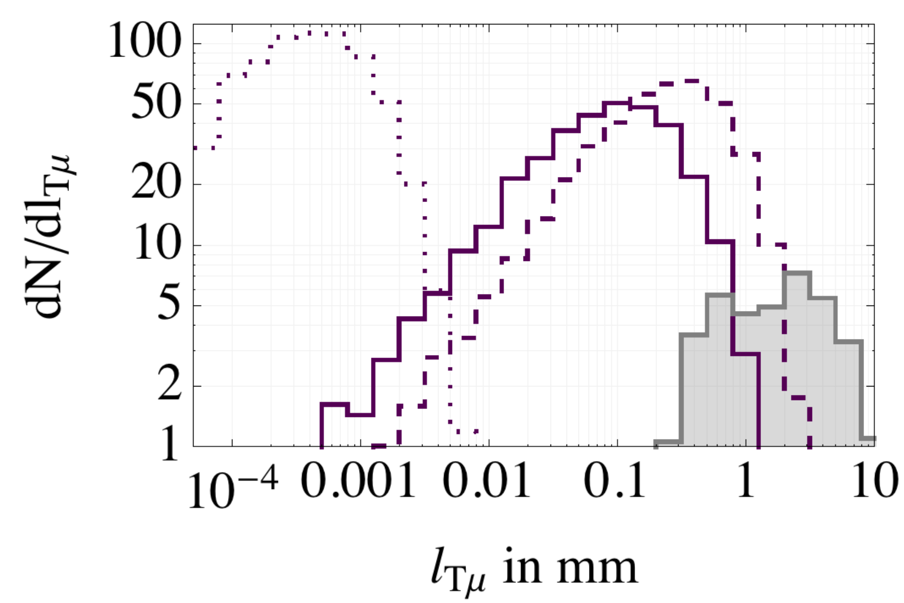


~soft leptons

characteristic mass peaks





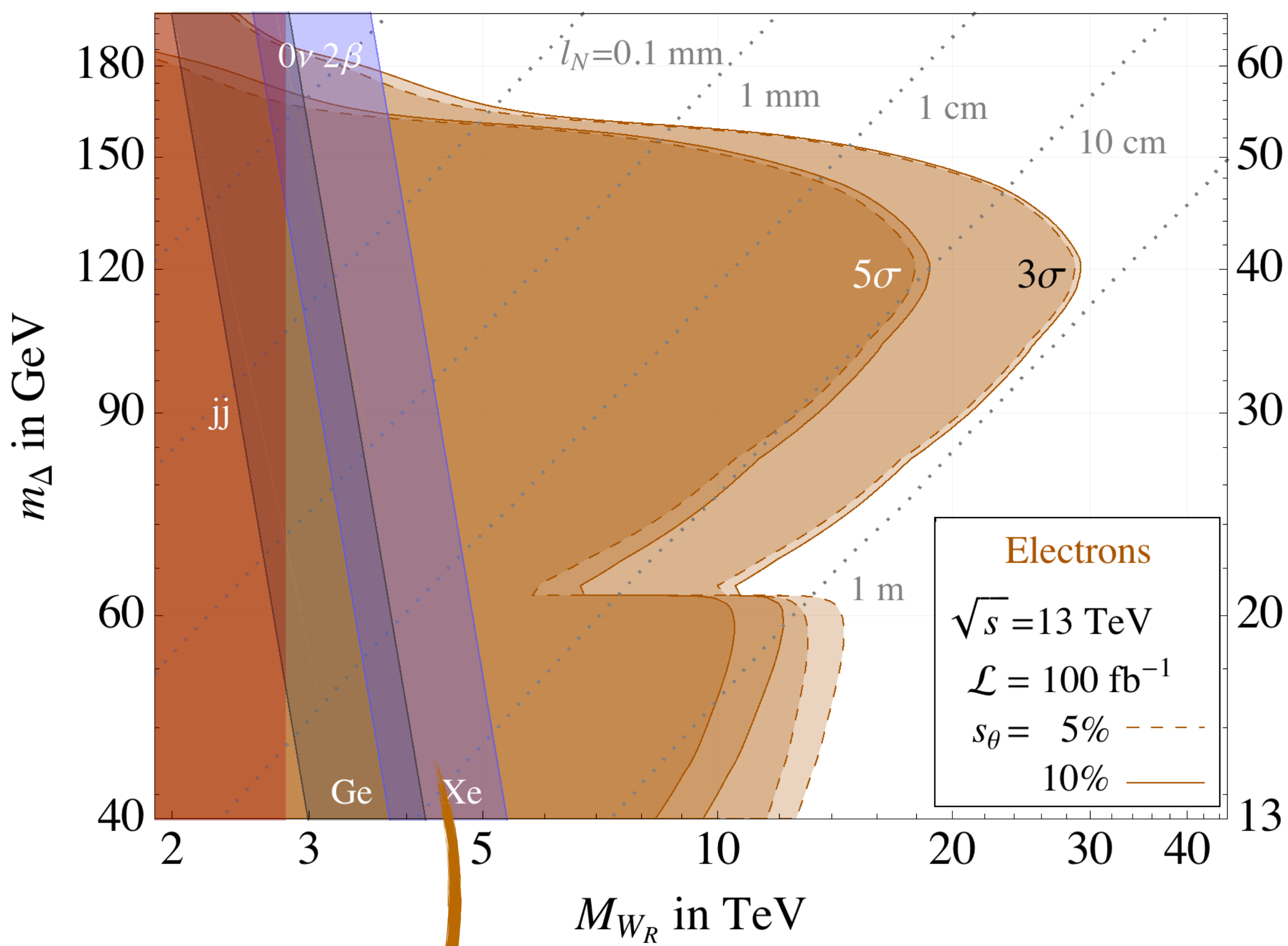


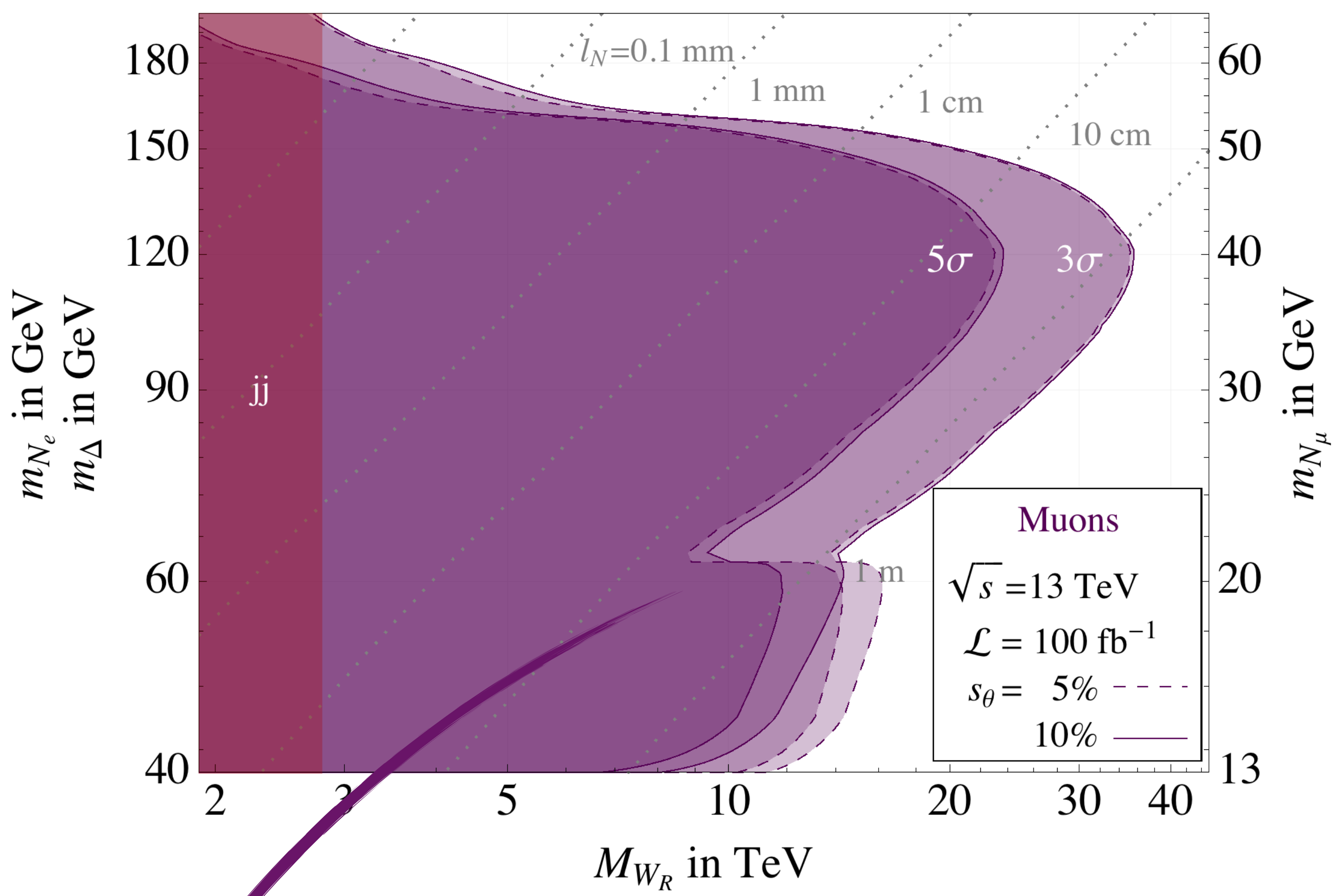
angular separation

displacement

Sensitivity

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





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

Summary

Origin of neutrino mass and and LNV testable at the LHC

Prompt searches covered, while experimental opportunities remain in

$W_R \to \ell_R \, j_N^d$ $h, \Delta \to NN$ $h \to \Delta\Delta \to 4N$

Feasible in Run-2, prepare to optimize for Run-3

Pheno tools for LLPs under development

Displaced jets & use of fakes

Interplay needed between hep-ph and hep-ex