LR symmetry
at hadron colliders

Fabrizio Nesti
L'Aquila University & INFN LNGS

Discrete 2024 in Ljubljana
03/12/2024

DSFC
Dipartimento
di Scienze Fisiche
e Chimiche

UNIVAQ

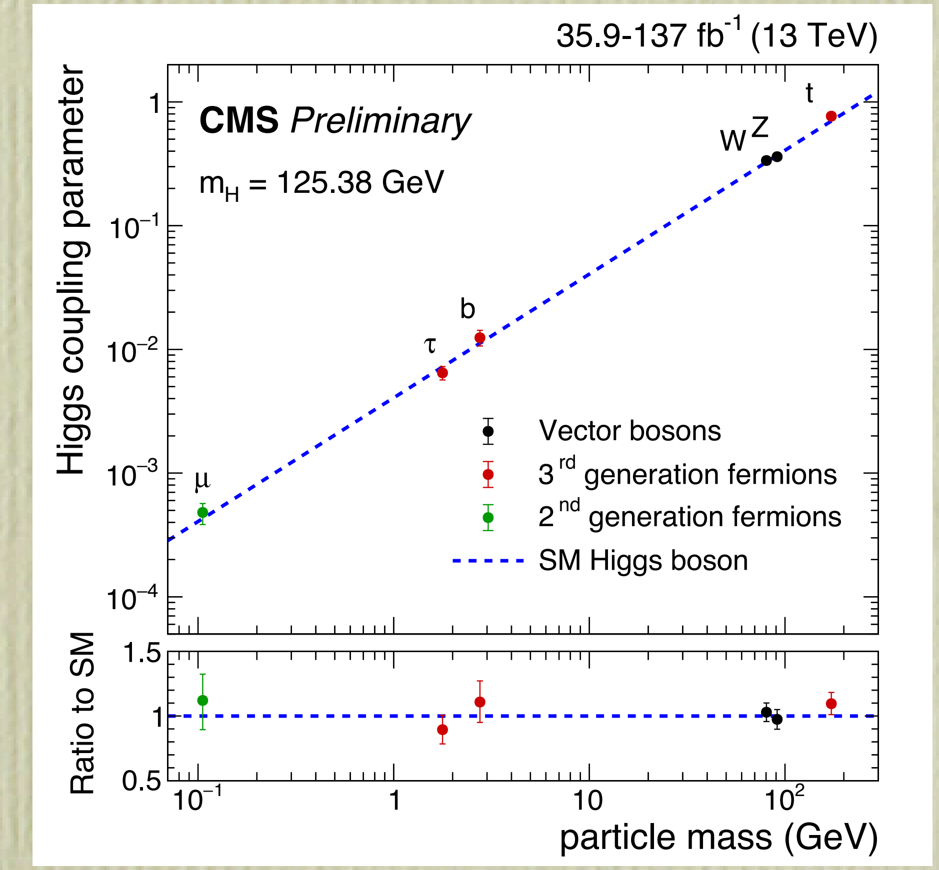
Bringing together

- Quest for neutrino mass origin (New physics)
- Parity into Left-Right Symmetry
- Lepton Number Violation at collider & low energy (Majorana)
- and in Higgs decays (test generation of masses)
- (+ new physics in Flavour, in Strong CP)

The last triumph of the SM

$$y_f = \frac{g}{2}\,\frac{m_f}{m_W} \quad \Rightarrow \quad \Gamma(h \to f\bar{f}) = \frac{G_F}{4\sqrt{2}\pi} m_h m_f^2$$

Mass versus
Higgs decays
as expected



We wish something similar for neutrinos…

…need a theory of neutrino mass.

Left-Right symmetry links Parity Restoration to Neutrino mass.

Hints from quantum numbers

	Lorentz	Q $(Y + T_{3L})$	Y	$SU(2)_L$ T_{3L}			$SU(3)$
u_L	**2**	2/3	1/6	1/2			**3**
d_L	**2**	−1/3	1/6	−1/2			**3**
ν_L	**2**	0	− 1/2	1/2			**1**
e_L	**2**	−1	− 1/2	−1/2			**1**
u_R	$\overline{\mathbf{2}}$	2/3	2/3	0			**3**
d_R	$\overline{\mathbf{2}}$	−1/3	− 1/3	0			**3**
ν_R	$\overline{\mathbf{2}}$	0	0	0			**1**
e_R	$\overline{\mathbf{2}}$	−1	− 1	0			**1**

Hints from quantum numbers

	Lorentz	Q $(Y+T_{3L})$	Y $(T_{3R}+\frac{(B-L)}{2})$	$SU(2)_L$ T_{3L}	$SU(2)_R$ T_{3R}	$B-L$	$SU(3)$
u_L	**2**	$2/3$	$1/6$	$1/2$	0	$1/3$	**3**
d_L	**2**	$-1/3$	$1/6$	$-1/2$	0	$1/3$	**3**
ν_L	**2**	0	$-1/2$	$1/2$	0	-1	**1**
e_L	**2**	-1	$-1/2$	$-1/2$	0	-1	**1**
u_R	$\bar{\mathbf{2}}$	$2/3$	$2/3$	0	$1/2$	$1/3$	**3**
d_R	$\bar{\mathbf{2}}$	$-1/3$	$-1/3$	0	$-1/2$	$1/3$	**3**
ν_R	$\bar{\mathbf{2}}$	0	0	0	$1/2$	-1	**1**
e_R	$\bar{\mathbf{2}}$	-1	-1	0	$-1/2$	-1	**1**

Hints from quantum numbers

	Lorentz	Q $(Y+T_{3L})$	Y $(T_{3R}+\frac{(B-L)}{2})$	$SU(2)_L$ T_{3L}	$SU(2)_R$ T_{3R}	$B-L$	$SU(3)$
u_L	**2**	$2/3$	$1/6$	$1/2$	0	$1/3$	**3**
d_L	**2**	$-1/3$	$1/6$	$-1/2$	0	$1/3$	**3**
ν_L	**2**	0	$-1/2$	$1/2$	0	-1	**1**
e_L	**2**	-1	$-1/2$	$-1/2$	0	-1	**1**
u_R	$\overline{\mathbf{2}}$	$2/3$	$2/3$	0	$1/2$	$1/3$	**3**
d_R	$\overline{\mathbf{2}}$	$-1/3$	$-1/3$	0	$-1/2$	$1/3$	**3**
ν_R	$\overline{\mathbf{2}}$	0	0	0	$1/2$	-1	**1**
e_R	$\overline{\mathbf{2}}$	-1	-1	0	$-1/2$	-1	**1**

Left-Right symmetry ...new RH neutrino and gauge bosons

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

Opens the path to unifications

Pati-Salam: $SU(2)_L \times SU(2)_R \times SU(4)$ [Pati Salam '74; Georgi '75]

GUT: SO(10) [Georgi, '75, Fritzsch Minkowski '75]

GraviGUT: SO(3,11), SO(7,7) [FN '07, FN Percacci '09, …, Maiezza FN '22]

(Minimal) Left-Right Symmetric Model

Theory of Neutrino Mass from Parity Restoration

[Pati, Salam '74] [Mohapatra, Pati '75]
[Senjanović, Mohapatra '75]

- $SU(2)_L$ $SU(2)_R$ $U(1)_{B\text{-}L}$ quarks and leptons...

$$W_L \quad L_L = \begin{pmatrix} \nu \\ \ell_L \end{pmatrix} \qquad L_R = \begin{pmatrix} N \\ \ell_R \end{pmatrix} \quad W_R$$

- Spontaneous parity breaking

$$v_R \gg v = \sqrt{v_1^2 + v_2^2}$$

$$\Delta_R = \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ v_R + \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix} \qquad \Phi = \begin{pmatrix} v_1 + \phi_1^0 & \phi_2^+ \\ \phi_1^- & v_2 e^{i\alpha} + \phi_2^0 \end{pmatrix} \qquad \Delta_L = \cdots$$

(Minimal) Left-Right Symmetric Model

Theory of Neutrino Mass from Parity Restoration

[Pati, Salam '74] [Mohapatra, Pati '75]
[Senjanović, Mohapatra '75]

- $SU(2)_L\, SU(2)_R\, U(1)_{B-L}$ quarks and leptons...

$$W_L \qquad L_L = \begin{pmatrix} \nu \\ \ell_L \end{pmatrix} \qquad L_R = \begin{pmatrix} N \\ \ell_R \end{pmatrix} \qquad W_R$$

- Spontaneous parity breaking

$$v_R \gg v = \sqrt{v_1^2 + v_2^2}$$

$$\Delta_R = \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ v_R + \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix} \qquad \Phi = \begin{pmatrix} v_1 + \phi_1^0 & \phi_2^+ \\ \phi_1^- & v_2 e^{i\alpha} + \phi_2^0 \end{pmatrix} \qquad \Delta_L = \cdots$$

- Heavy RH gauge boson, $M_{W_R} = g\, v_R$

- And mixes with W_L:

$$\zeta = \frac{M_{W_L}^2}{M_{W_R}^2} \sin 2\beta\, e^{i\alpha} < 10^{-4} \qquad \tan\beta = v_2/v_1$$

- Neutrino get massive via **seesaws:**

$$M_D = y_\Phi v \qquad M_N = y_\Delta v_R \qquad M_\nu = M_L - M_D^T \frac{1}{M_N} M_D$$

...structural LNV. Consequences in 0ν2β, collider...

... two possible LR Discrete symmetries

$$\mathcal{P}: \begin{cases} Q_L \leftrightarrow Q_R \\ \Phi \to \Phi^\dagger \end{cases}, \qquad \mathcal{C}: \begin{cases} Q_L \leftrightarrow (Q_R)^c \\ \Phi \to \Phi^T \end{cases}$$

$$Y = Y^\dagger \qquad\qquad Y = Y^T$$

$$M_u = v_1\, Y + v_2\, \mathrm{e}^{-i\alpha}\, \tilde{Y}$$

$$M_d = v_2\, \mathrm{e}^{i\alpha}\, Y + v_1\, \tilde{Y}$$

A lot is then rigidly predicted.

- e.g. Dirac mass matrix fixed, *unlike* standard seesaw:

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

and ...see later

[Nemevšek Senjanović Tello PRL '13]

RH quark mixing - CKM

free Phases or Signs

[Maiezza, Senjanovic, FN, PRD '10]

RH quark mixing - CKM

free Phases or Signs

[Maiezza, Senjanovic, FN, PRD '10]

- Case of *C* has $V_R = V_L^*$ plus 5 free phases

$$V_R = K_u V^* K_d \,, \qquad K_d = \mathrm{diag}\{\mathrm{e}^{i\theta_d}, \mathrm{e}^{i\theta_s}, \mathrm{e}^{i\theta_b}\} \qquad K_u = \mathrm{diag}\{\mathrm{e}^{i\theta_u}, \mathrm{e}^{i\theta_c}, \mathrm{e}^{i\theta_t}\}$$

RH quark mixing - CKM

free Phases or Signs

[Maiezza, Senjanovic, FN, PRD '10]

- Case of C has $V_R = V_L^*$ plus 5 free phases

$$V_R = K_u V^* K_d \,, \qquad K_d = \mathrm{diag}\{e^{i\theta_d}, e^{i\theta_s}, e^{i\theta_b}\} \quad K_u = \mathrm{diag}\{e^{i\theta_u}, e^{i\theta_c}, e^{i\theta_t}\}$$

- Case of P has $V_R \simeq V_L$ plus 5 free signs

$$V_{R,ij} = V_{ij} - i s_\alpha t_{2\beta} \left(V_{ij} t_\beta + \sum_{k=1}^{3} \frac{(V\, m_d\, V^\dagger)_{ik} V_{kj}}{m_{u\,ii} + m_{u\,kk}} + \frac{V_{ik} (V^\dagger\, m_u\, V)_{kj}}{m_{d\,jj} + m_{d\,kk}} \right) + \mathcal{O}(s_\alpha t_{2\beta})^2$$

$$V \to \mathrm{diag}\{s_u, s_c, s_t\}\, V\, \mathrm{diag}\{s_d, s_s, s_b\}$$

$$m_{ii} \to s_i m_{ii}$$

[Senjanović Tello PRL '15]

All mixings and CP phases predicted from one parameter $s_\alpha t_{2\beta}$.

CP phases θ_i are ~ $s_\alpha t_{2\beta} < 0.05$

RH quark mixing - CKM

free Phases or Signs

[Maiezza, Senjanovic, FN, PRD '10]

- Case of C has $V_R = V_L^*$ plus 5 free phases

$$V_R = K_u V^* K_d \,, \qquad K_d = \mathrm{diag}\{e^{i\theta_d}, e^{i\theta_s}, e^{i\theta_b}\} \qquad K_u = \mathrm{diag}\{e^{i\theta_u}, e^{i\theta_c}, e^{i\theta_t}\}$$

- Case of P has $V_R \simeq V_L$ plus 5 free signs

$$V_{R,ij} = V_{ij} - i s_\alpha t_{2\beta}\left(V_{ij} t_\beta + \sum_{k=1}^{3} \frac{(V\, m_d\, V^\dagger)_{ik} V_{kj}}{m_{u\,ii} + m_{u\,kk}} + \frac{V_{ik}(V^\dagger\, m_u\, V)_{kj}}{m_{d\,jj} + m_{d\,kk}} \right) + \mathcal{O}(s_\alpha t_{2\beta})^2$$

$$V \to \mathrm{diag}\{s_u, s_c, s_t\}\, V\, \mathrm{diag}\{s_d, s_s, s_b\}$$

$$m_{ii} \to s_i m_{ii}$$

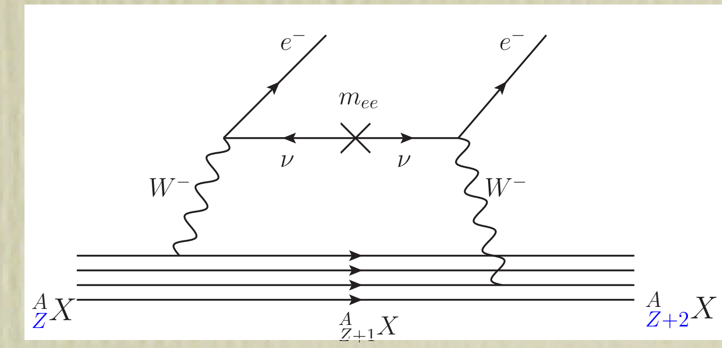
[Senjanović Tello PRL '15]

All mixings and CP phases predicted from one parameter $s_\alpha t_{2\beta}$.

CP phases θ_i are ~ $s_\alpha t_{2\beta} < 0.05$

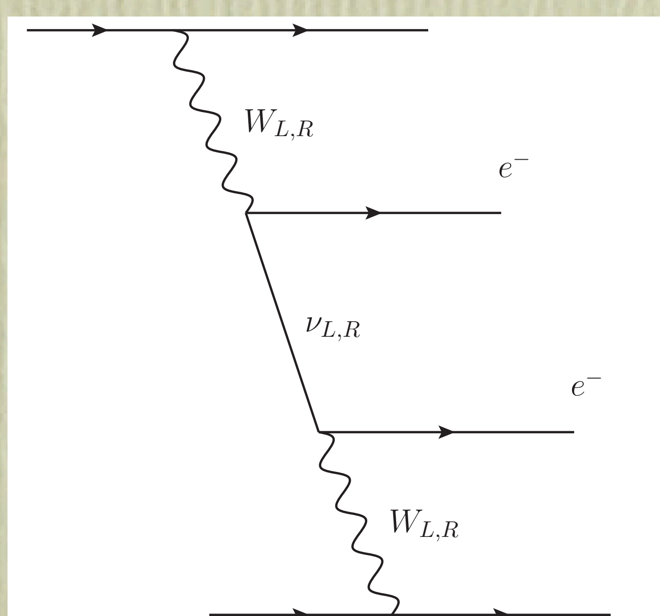
Let's start from low energy...

$0\nu2\beta$



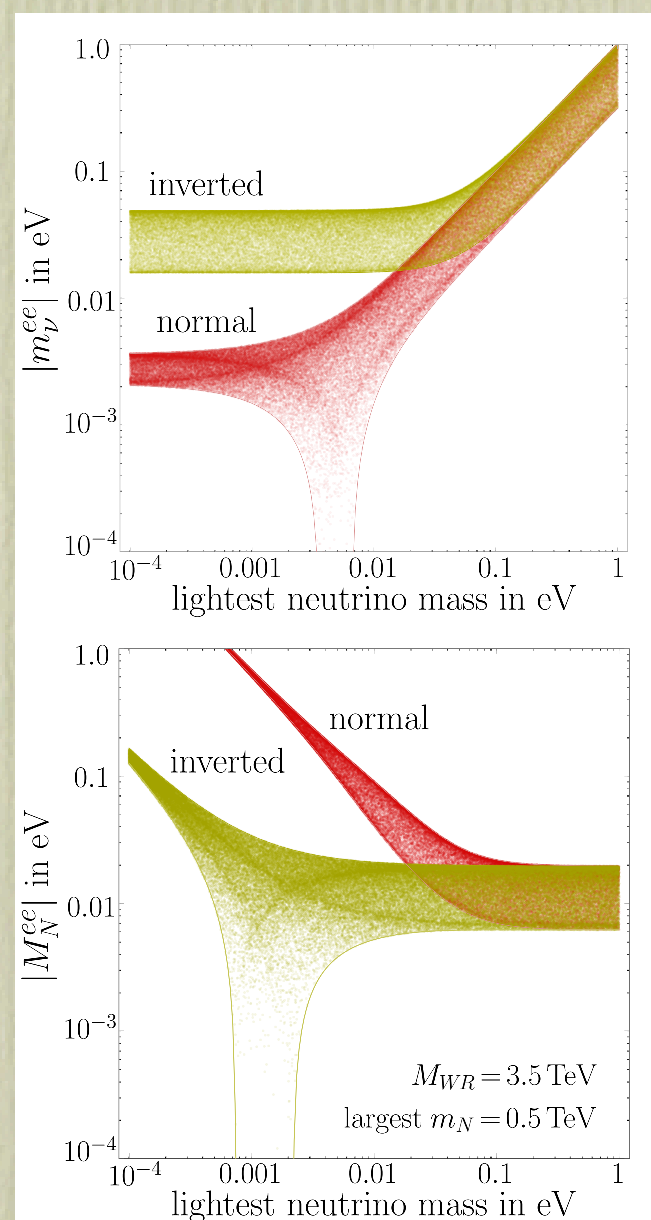
[Racah '37, Furry '38]

W_R & ν_R give new contributions

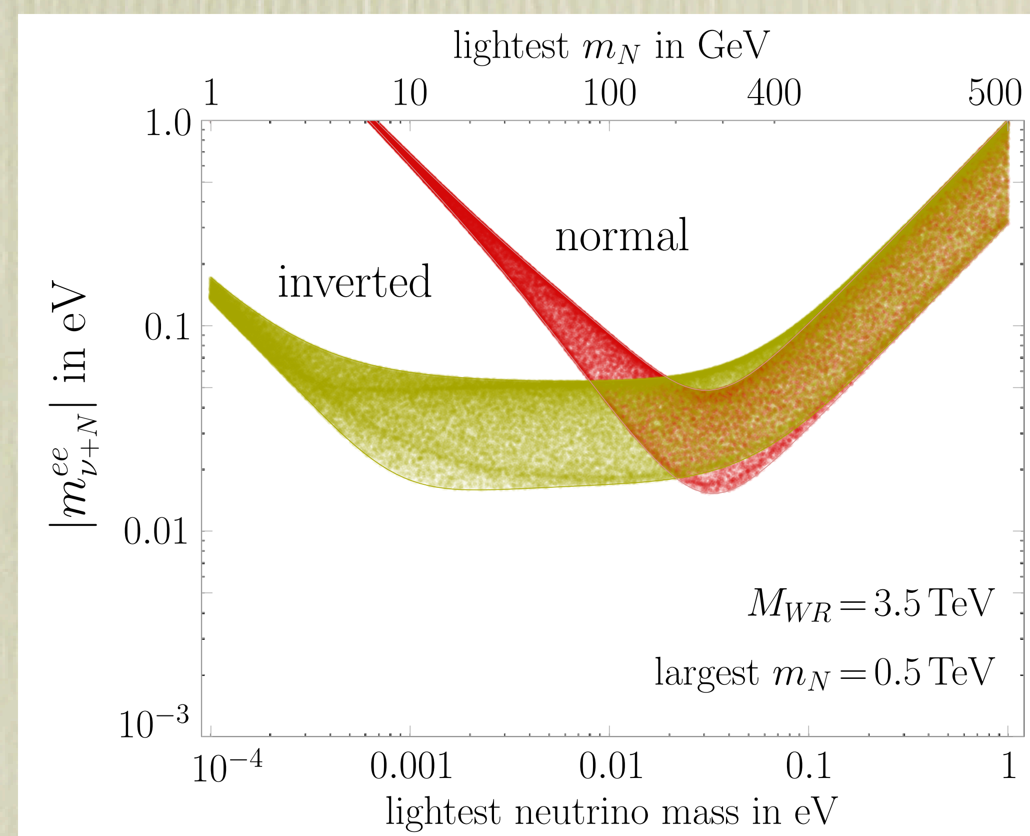


LL

RR

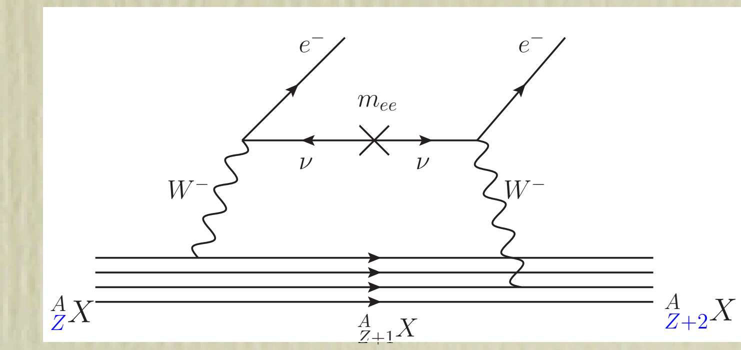


=



[Tello FN Senjanović PRL '10] (type-II limit)

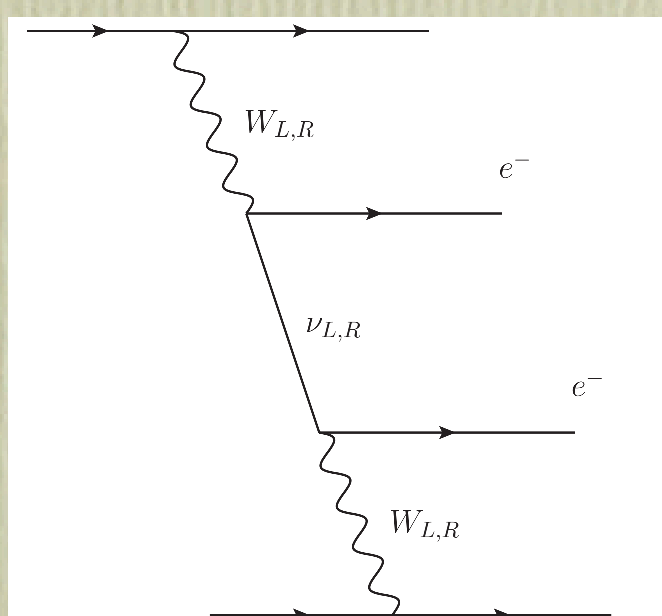
$0\nu2\beta$



[Racah '37, Furry '38]

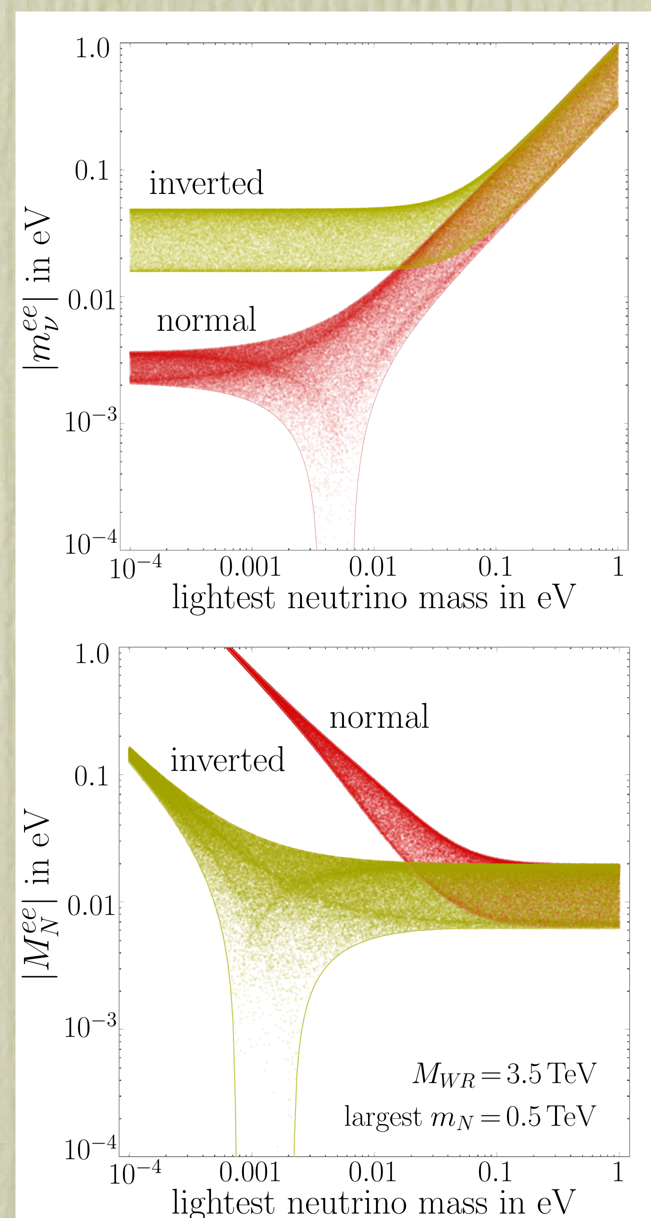
W_R & ν_R give new contributions

$0\nu2\beta$ connecting to W_R & m_N @LHC

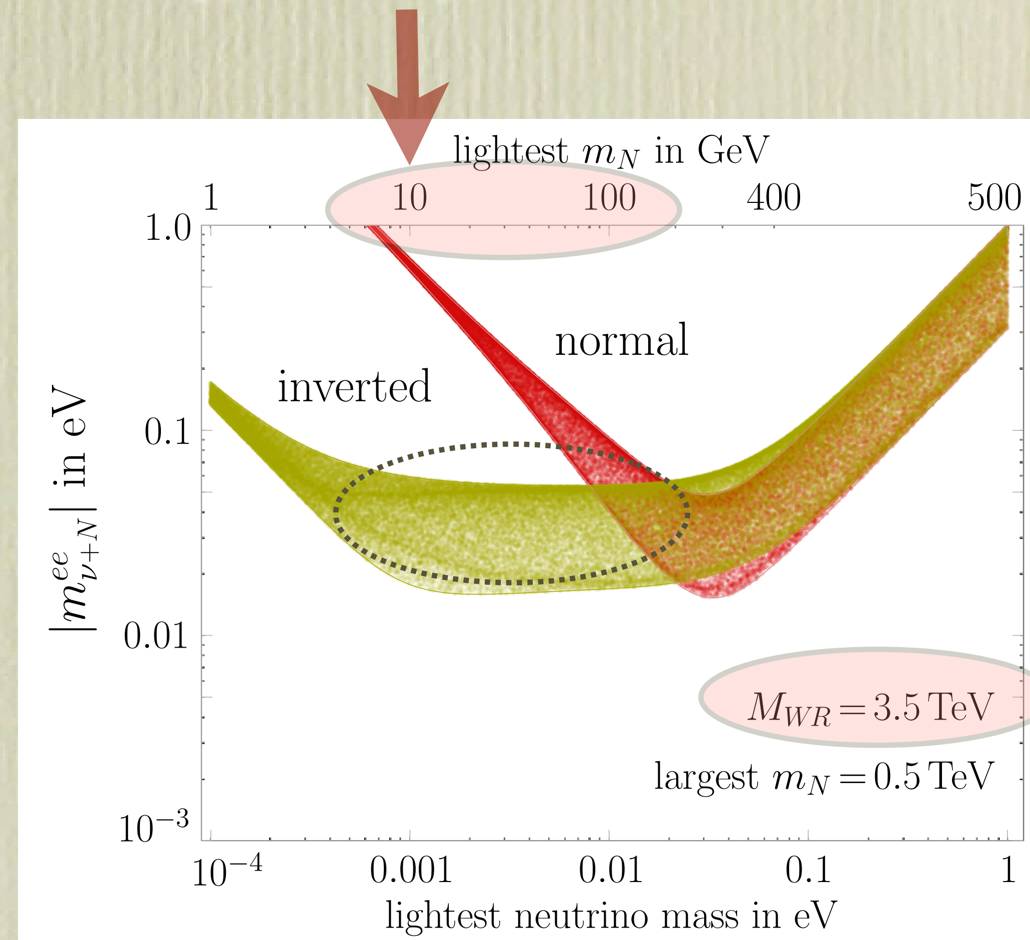


LL

RR



=

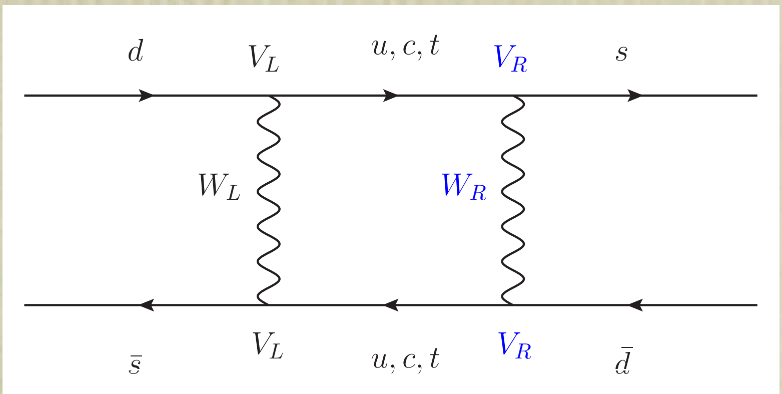


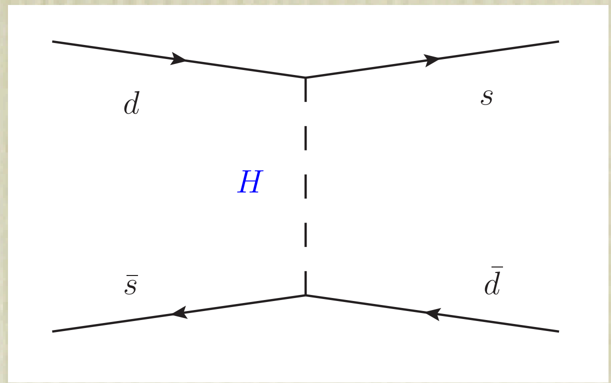
[Tello FN Senjanović PRL '10] (type-II limit)

But today W_R is bounded ...

Limits from flavor

(K-K, ϵ, ϵ', B-B)





- Classic Δs=2

  [Beall Bander Soni '82] $M_{W_R} > 1.6\text{TeV}$

  [Senjanović Senjanović '91] $M_H >$ few TeV

- Kaon sector revisited

  ϵ: LR enhanced in correct box calculation (gauge independent)

  ϵ': New LR operators for K→ππ. New current-current and chromomagnetic matrix elements [Bertolini Maiezza, FN '12,'13,'14]

  ΔM_K: Short Distance - enough; Long Distance - uncertain.

- B^0 mesons revisited

  $B\bar{B}$: Enhanced, in correct box. Useful free phase…

K, B meson mixing

...correlated bound M_{W_R} M_H :

[Bertolini Maiezza, FN ,'14]

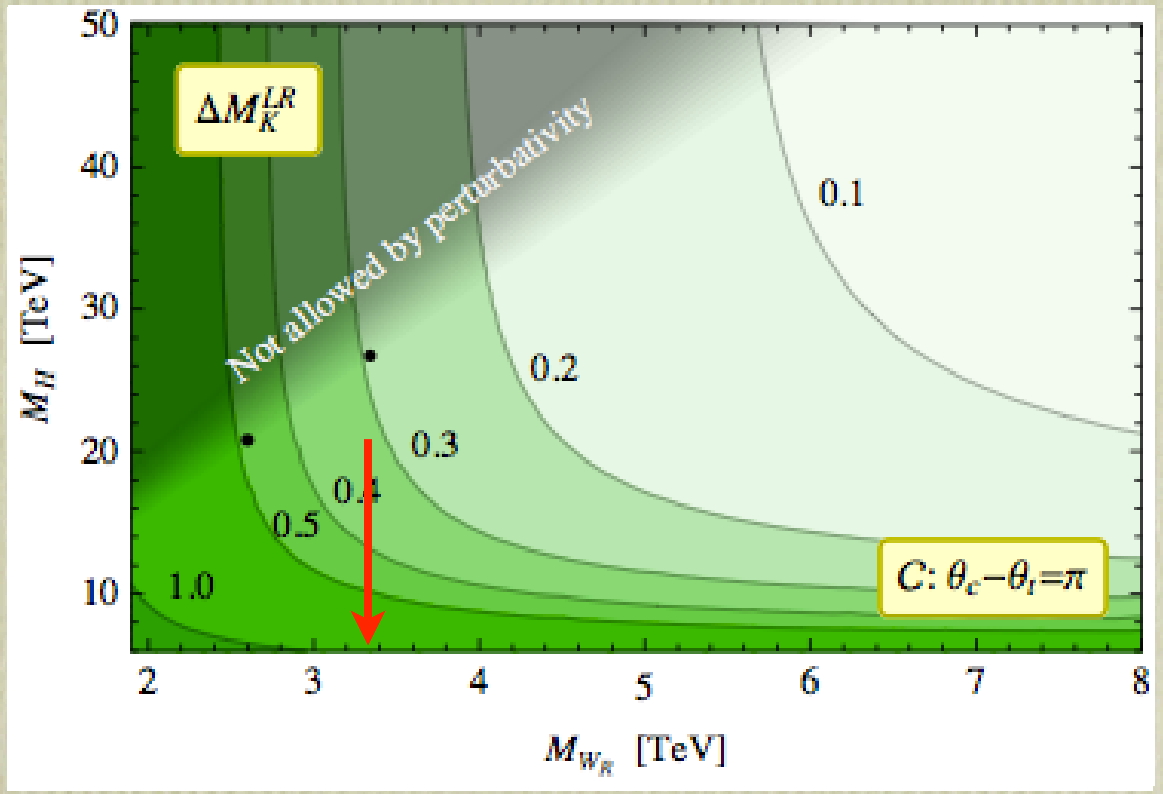


FIG. 9. Correlated bounds on M_R and M_{W_R} (region above the curves) for $|\Delta M_K^{LR}|/\Delta M_K^{exp} < 1.0, ..., 0.1$ and for $\theta_c - \theta_t = \pi/2$ in the case of $\mathcal{P}$ parity.

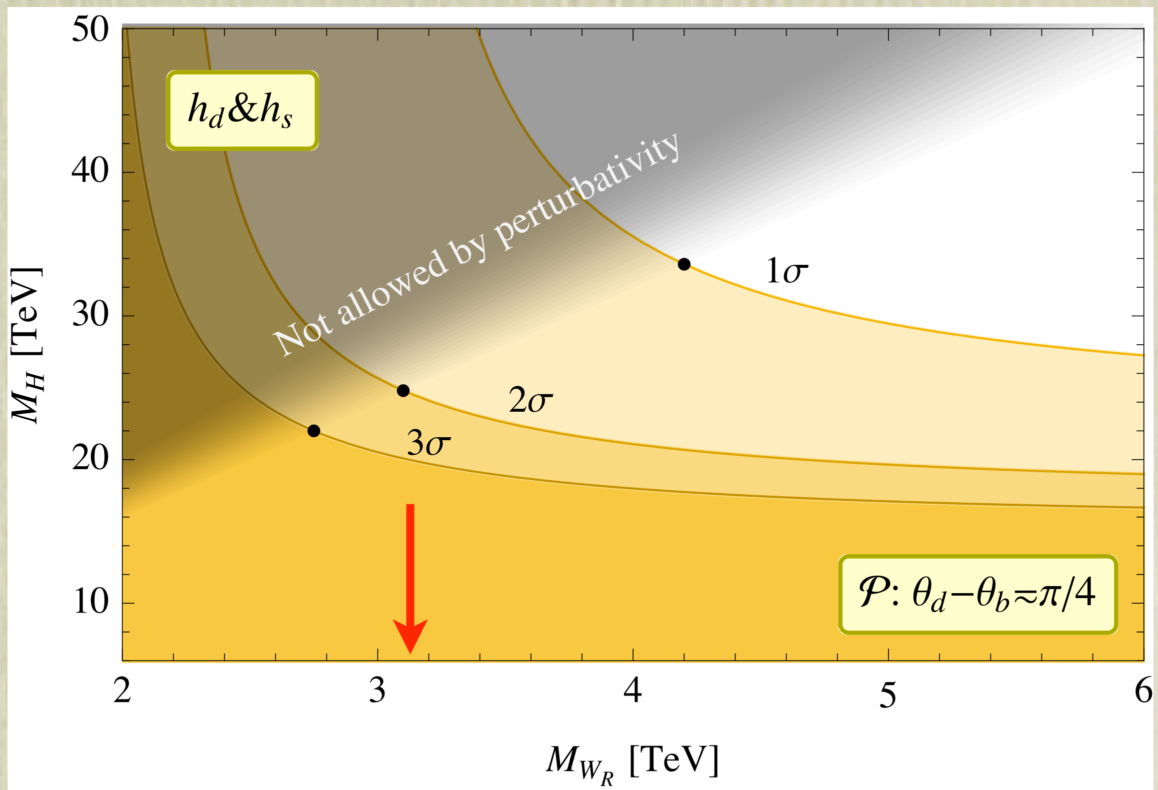


FIG. 10. Combined constraints on M_R and M_{W_R} from ε, ε' B_d and B_s mixings obtained in the $\mathcal{P}$ parity case from the numerical fit of the Yukawa sector of the model.

...still some room at LHC.

ΔM$_K$ afflicted by long-distance uncertainty, but
B-mesons competitive now, dominant in the future

K, B meson mixing

...correl... Maiezza, FN ,'14]

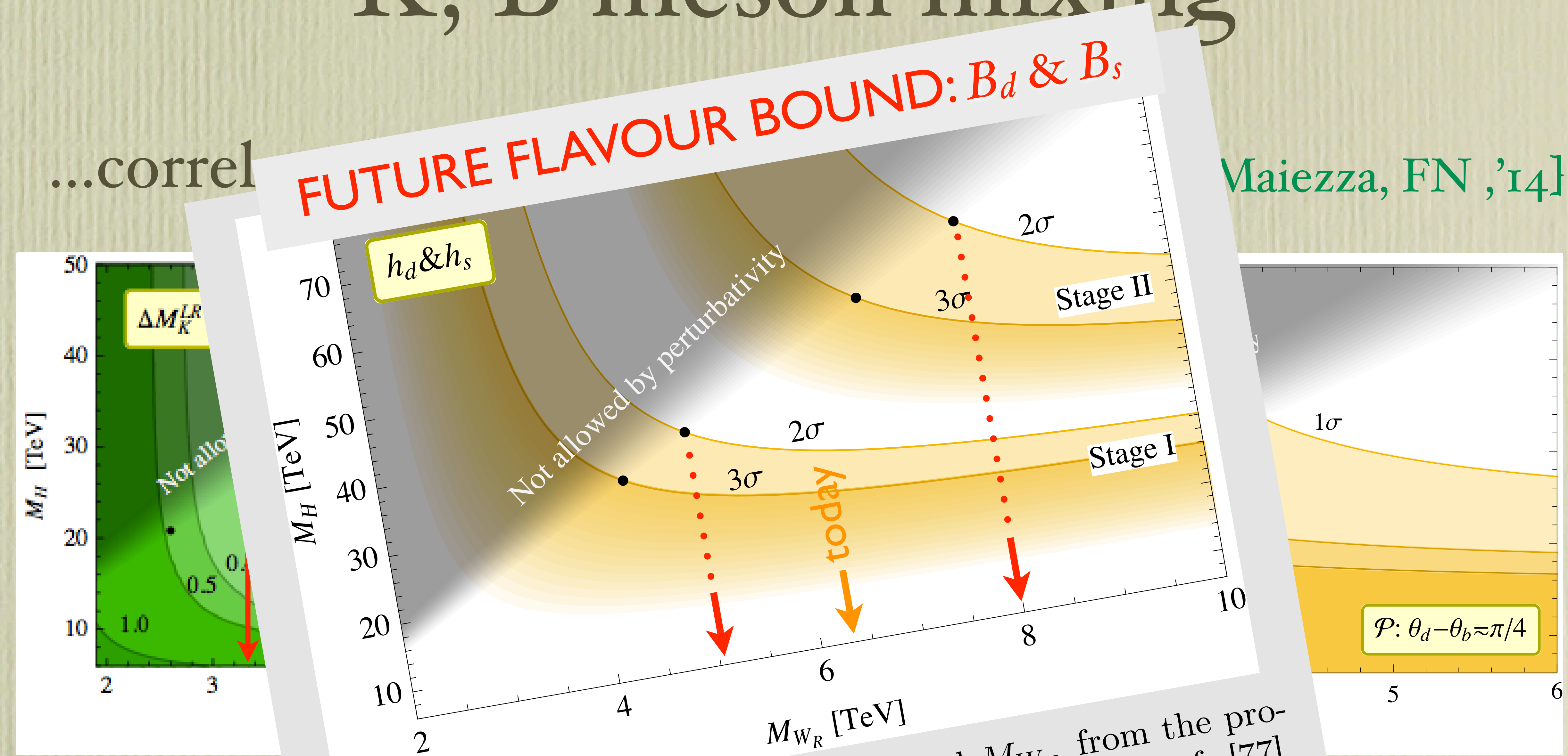


FIG. 9. Correlated bo... the curves) for $|\Delta M_K^{L}$... $\theta_t = \pi/2$ in the case of

...nd M_{W_R} from ε, ε' ...arity case from the ...model.

FIG. 11. Future constraints on M_R and M_{W_R} from the projected combined limits on h_d and h_s discussed in Ref. [77]. Stage I corresponds to a foreseen 7 fb^{-1} (5 ab^{-1}) data accumulation by LHCb (Belle II) by the end of the decade. Stage II assumes 50 fb^{-1} (50 ab^{-1}) data by the two experiments, achievable by mid 2020's.

ΔM_K a... distance uncertainty, but

B-mesons competitive now, dominant in the future

...and $d_n + \varepsilon + \varepsilon'$

after [Maiezza Nemevsek PRD '14]

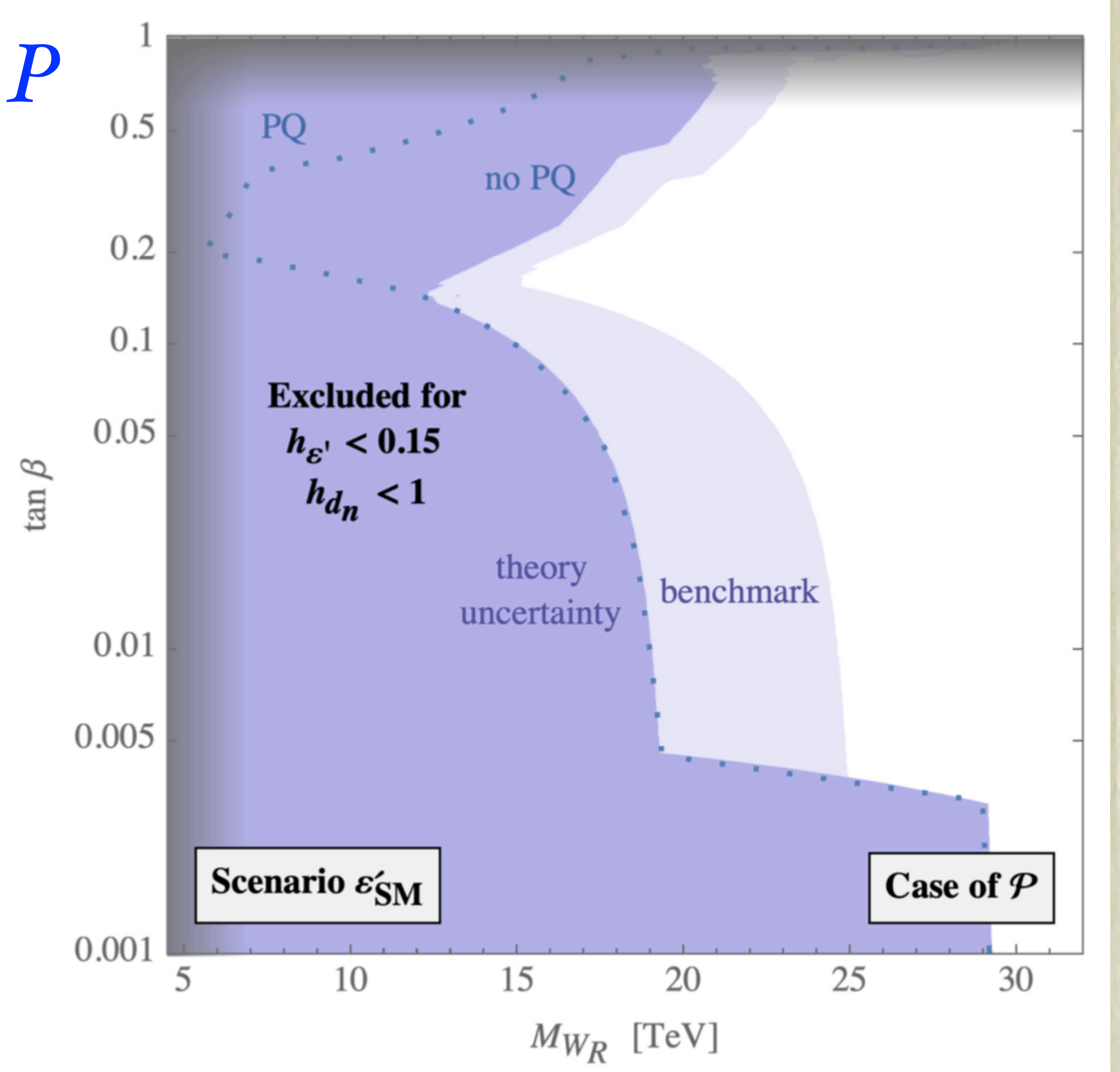


FIG. 4. Case of $\mathcal{P}$: The shaded regions in the M_{W_R}–t_β plane are excluded in order to have at most 15% new physics contribution to ε'/ε and d_n below the present experimental bound.

[Bertolini, Maiezza, FN, PRD '20]

P excluded
up to 15TeV?

(unless LRSM+axion...)

If with an axion, other PQ effects calculable and correlated...

Induced CPV Axion-nucleon coupling $\bar{g}_{aN}$

Interplay between ε, ε', d_n with $\bar{g}_{aN}$

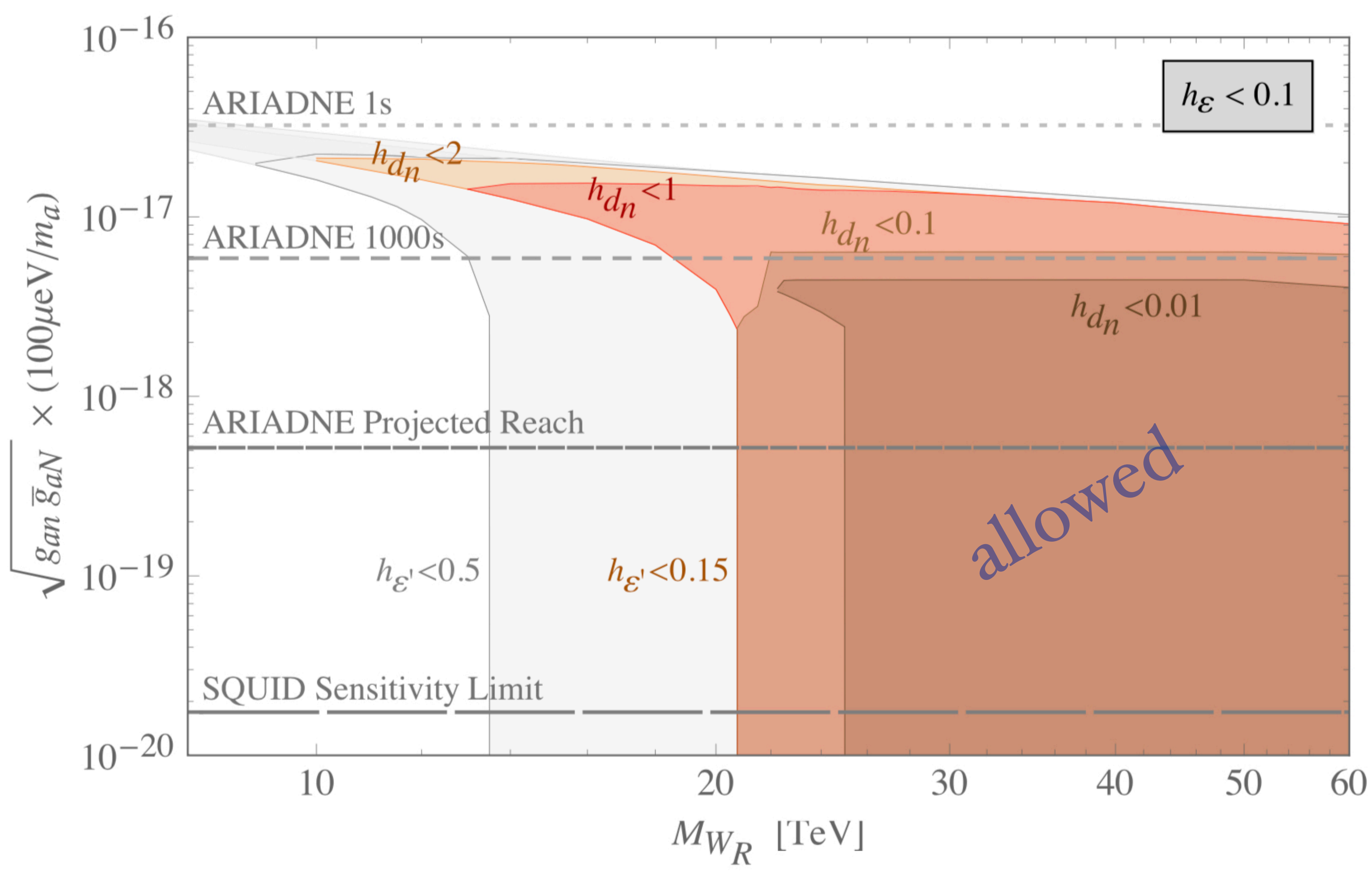


FIG. 1. Regions in the LR DFSZ model of the CPV axion nucleon coupling probed by ARIADNE.

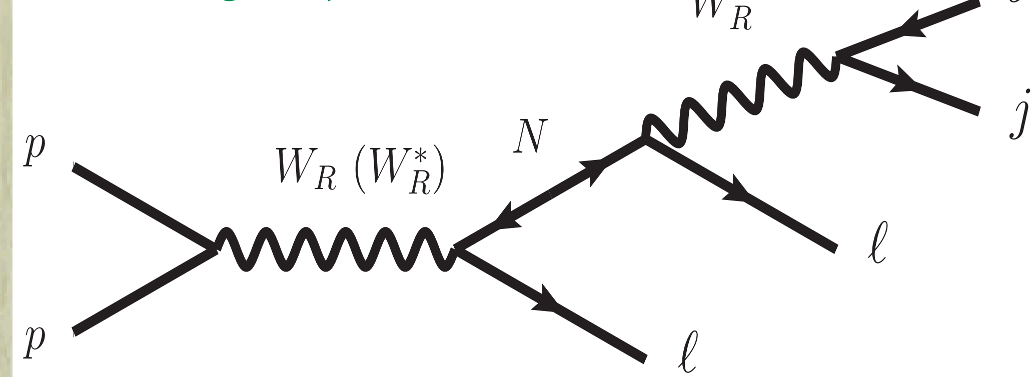
soon to be probed :)

[Bertolini, Di Luzio, FN, PRL '21]

LR at collider

KS process

[Keung Senjanović '83]



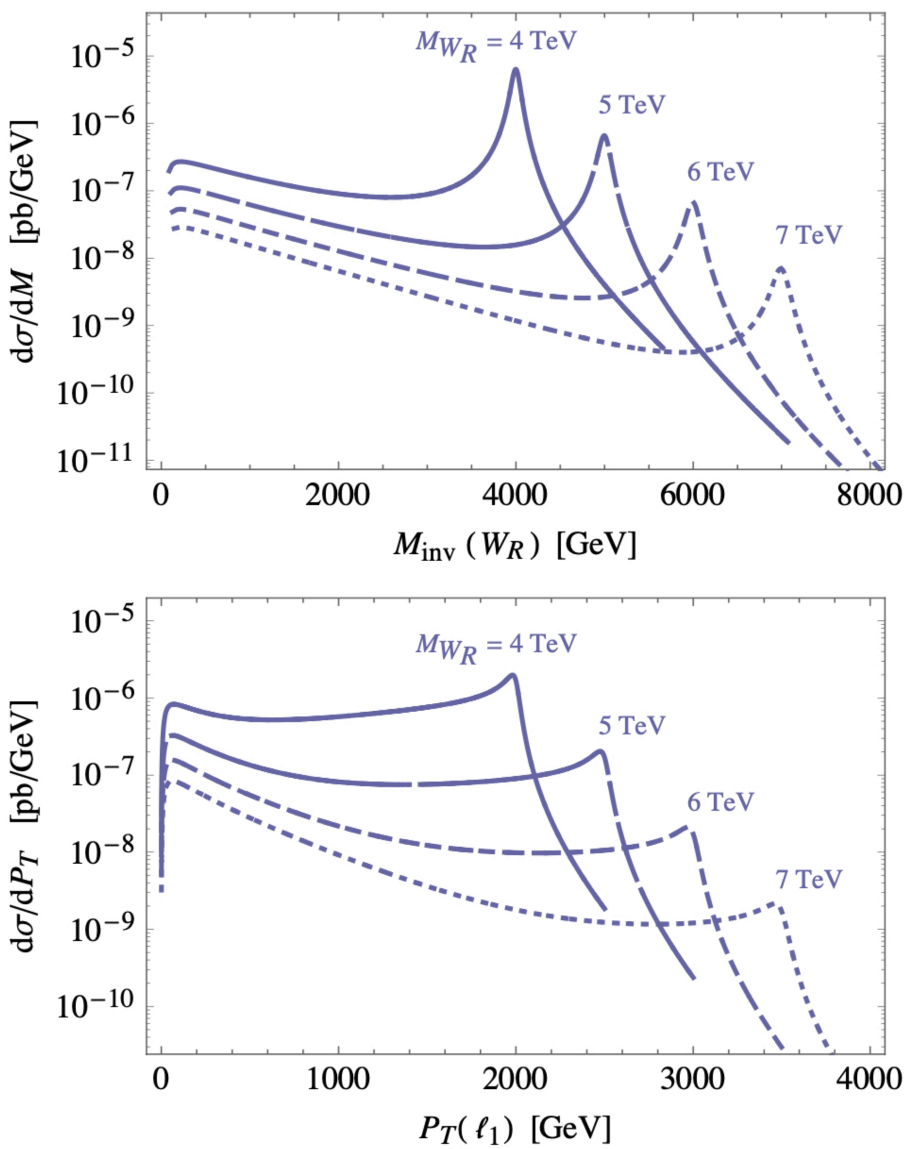


FIG. 2. W_R invariant mass distribution (upper) and primary lepton p_T distribution (lower), for M_{W_R} = 4–7 TeV (solid to dotted). For increasing M_{W_R} the events on the on-shell W_R

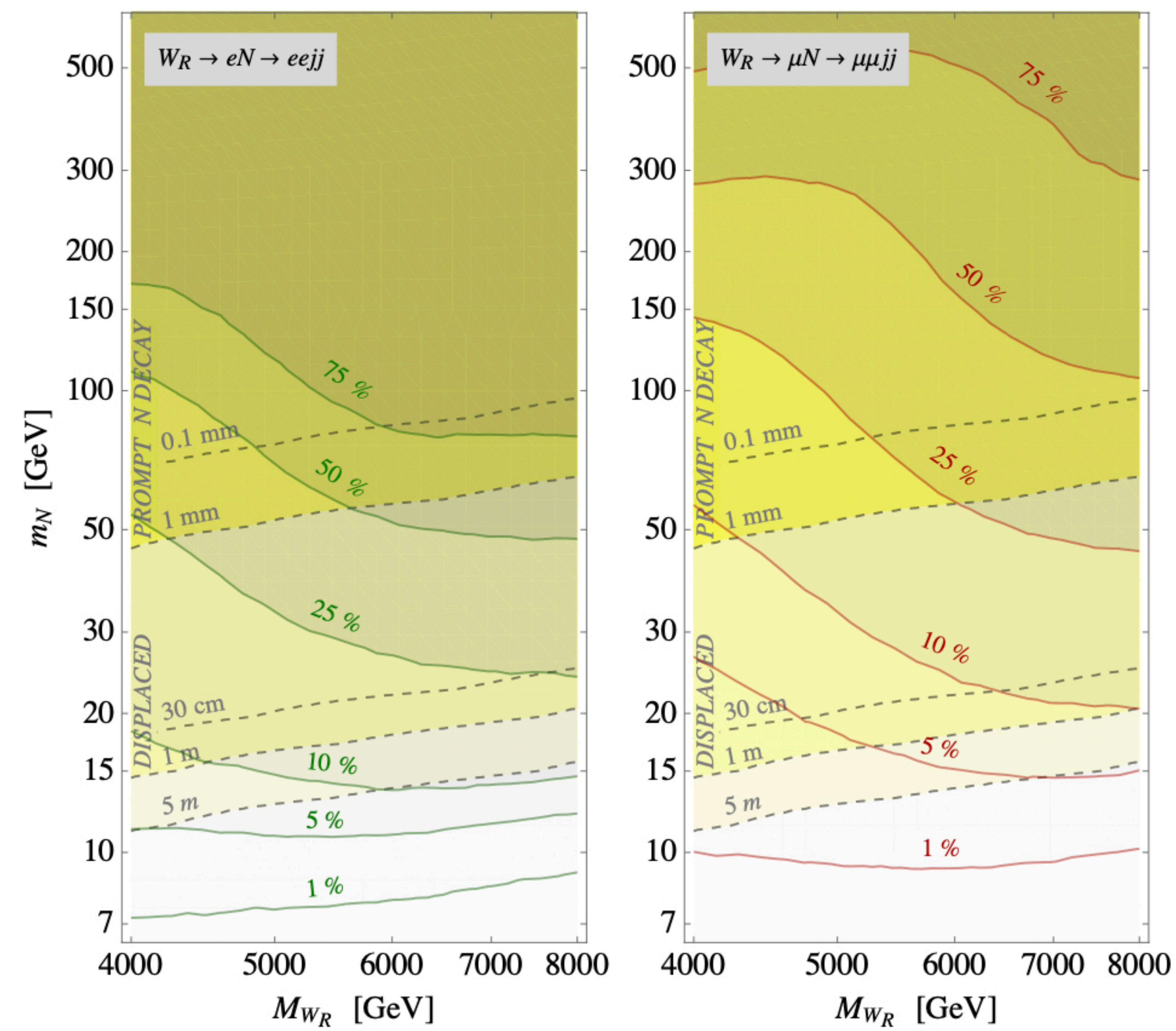


FIG. 4. Left (right) plot: percentage of secondary leptons passing the isolation requirements is shown by the solid

[Nemevsek, FN, Popara PRD '18]

LHC exclusion and reach

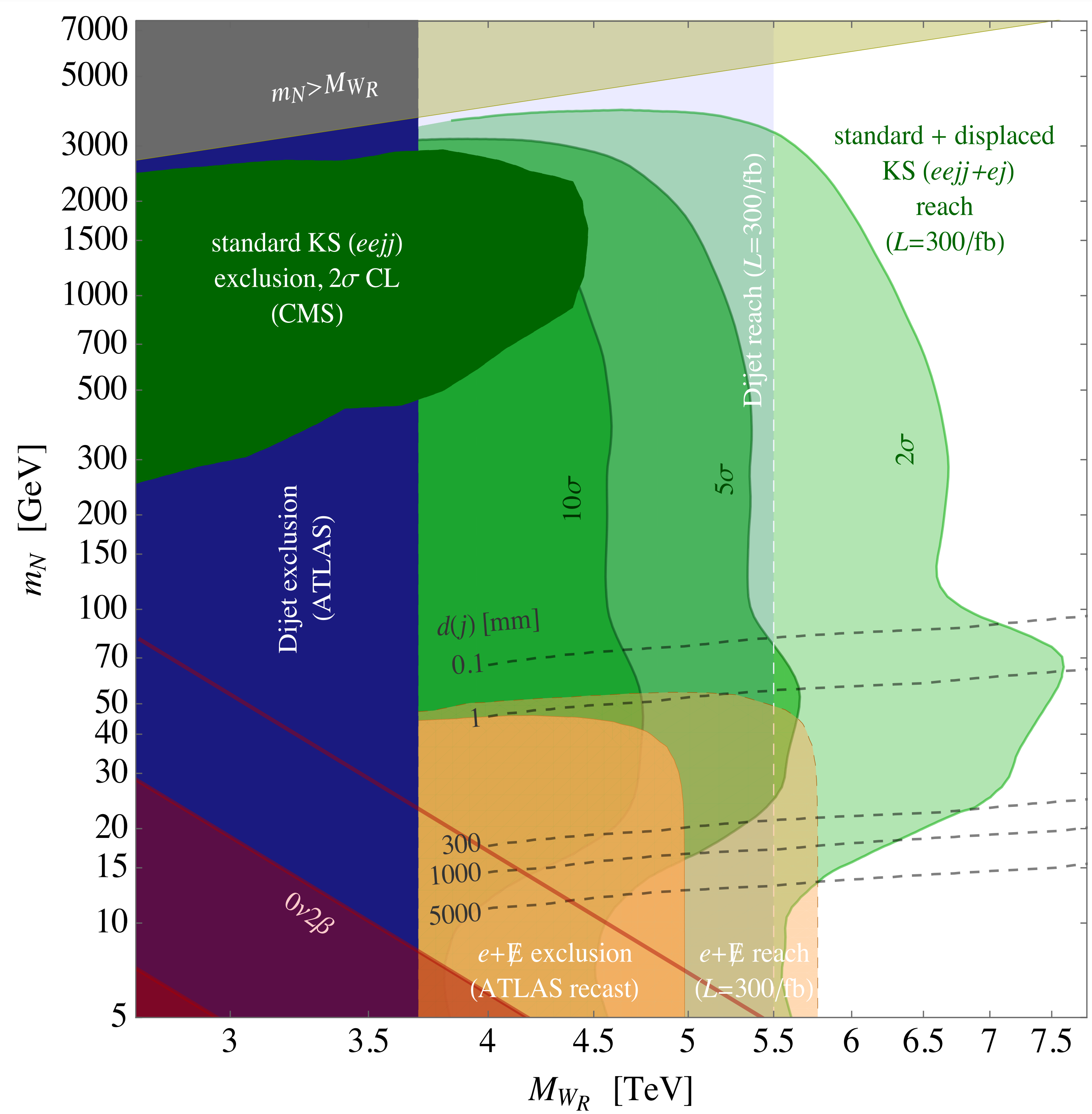
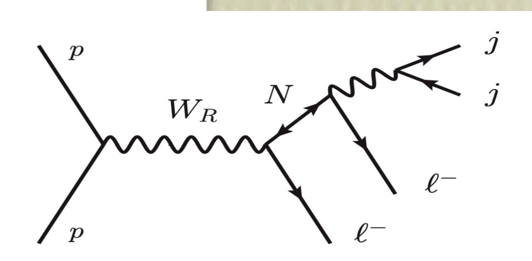
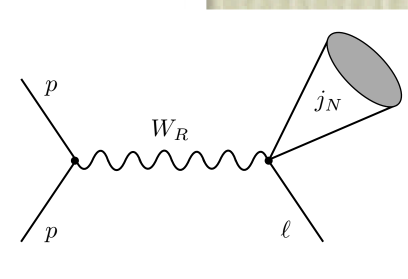
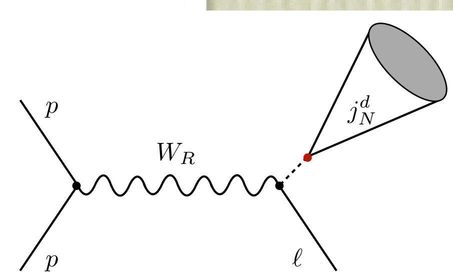
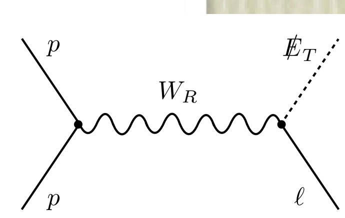


FIG. 9. Summary plot collecting all searches involving the KS process at LHC, in the electron channel. The green shaded areas represent the LH sensitivity to the KS process at 300/fb, according to the present work. The rightmost reaching contour represents the enhancement obtained by considering jet displacement.









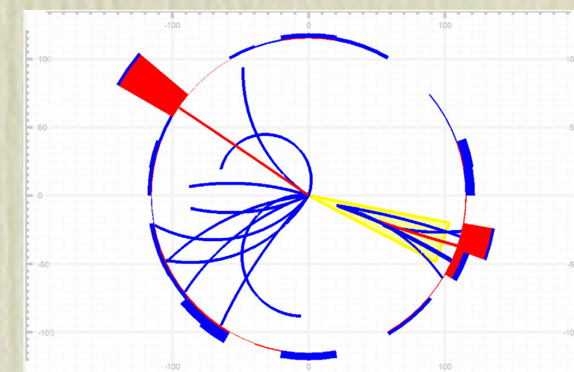


FIG. 6. A typical event featuring the prompt electron and a merged jet on the opposite side, including the secondary electron and hadronic tracks (blue) from a ~3 cm-displaced vertex. Both,

[Nemevsek, FN, Popara PRD '18]

LHC exclusion and reach

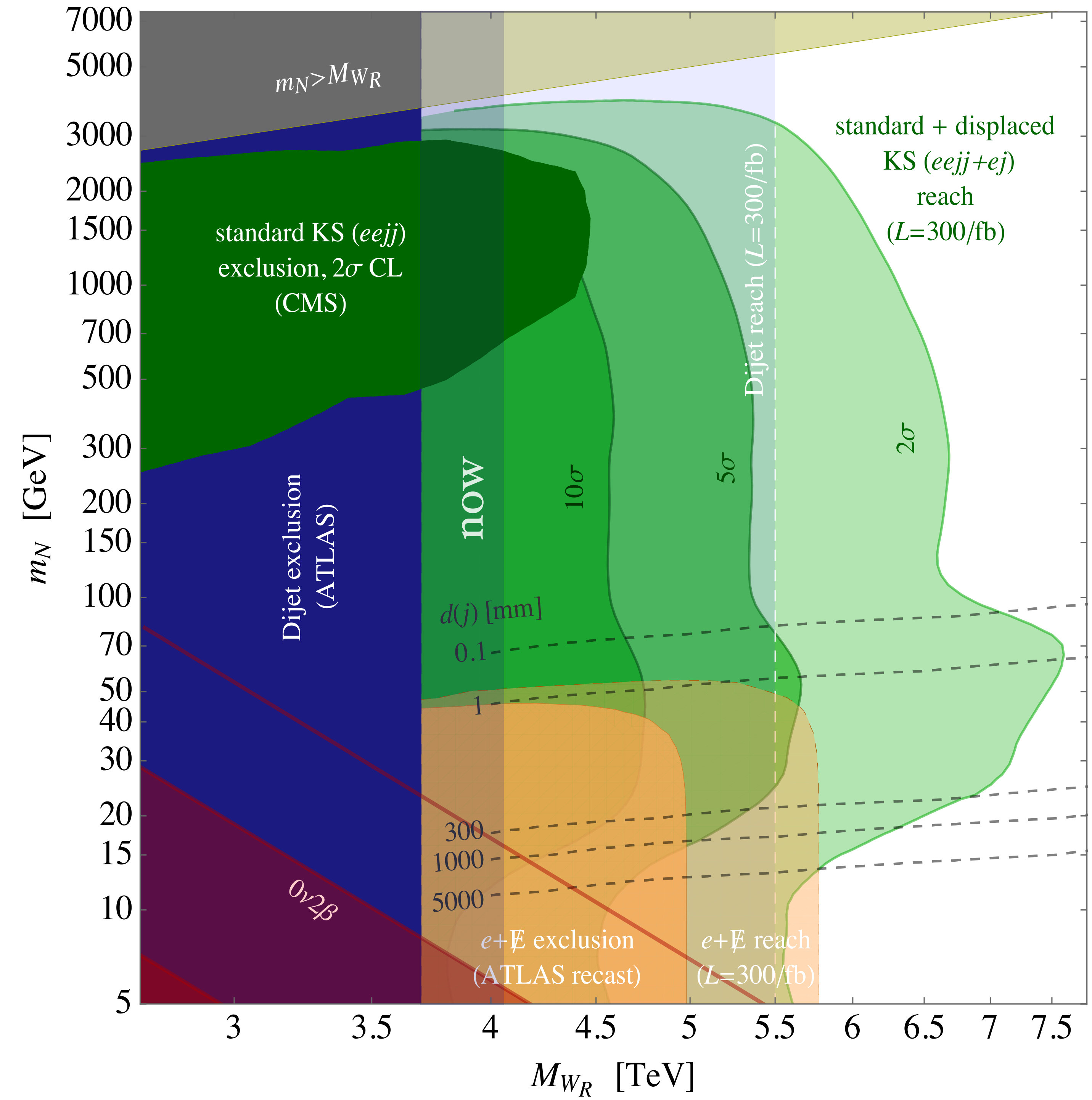
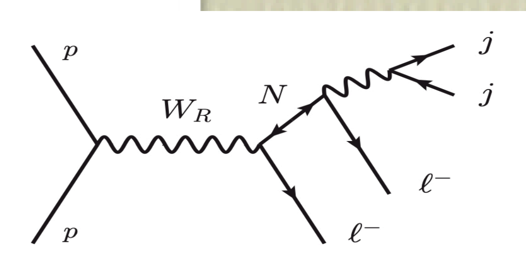
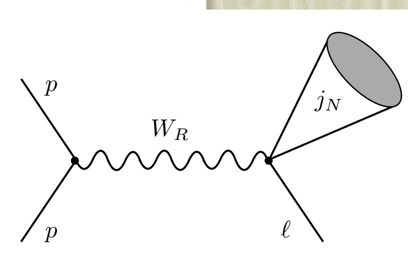
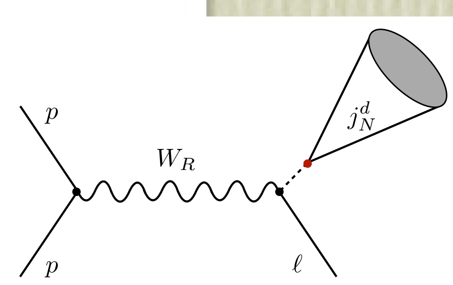
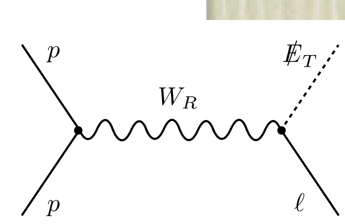


FIG. 9. Summary plot collecting all searches involving the KS process at LHC, in the electron channel. The green shaded areas represent the LH sensitivity to the KS process at 300/fb, according to the present work. The rightmost reaching contour represents the enhancement obtained by considering jet displacement.









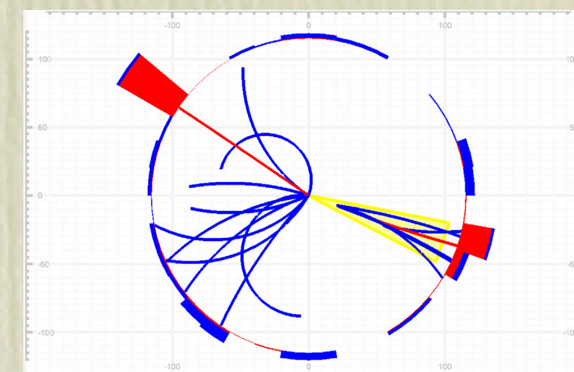


FIG. 6. A typical event featuring the prompt electron and a merged jet on the opposite side, including the secondary electron and hadronic tracks (blue) from a ~3 cm-displaced vertex. Both,

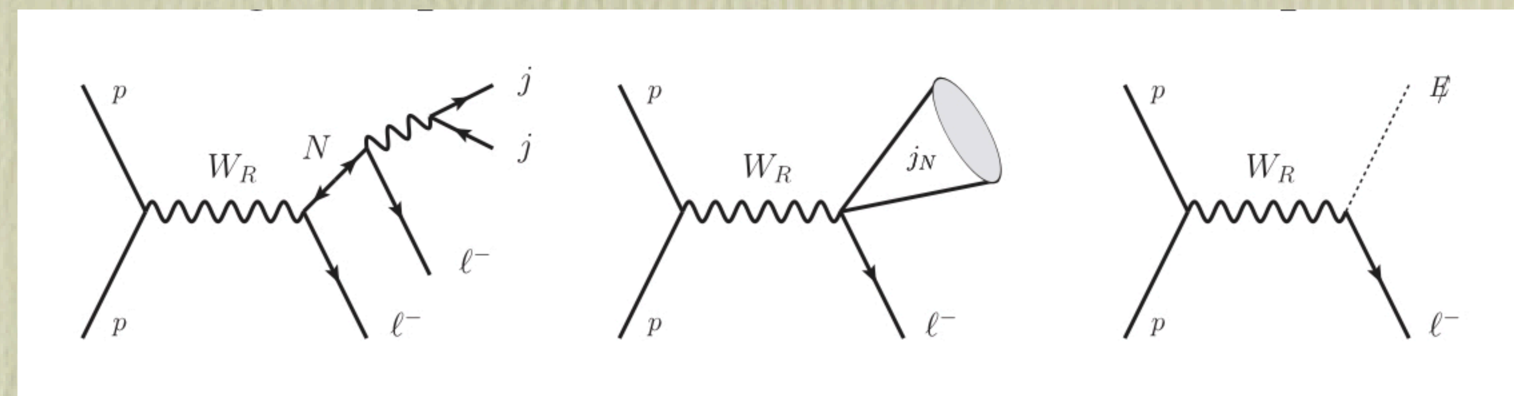
[Nemevsek, FN, Popara PRD '18]

and check a future collider

FCC-hh study

after
[Mitra et al '16] [Ruiz EPJC '17]

[Nemevsek, FN PRD '23]



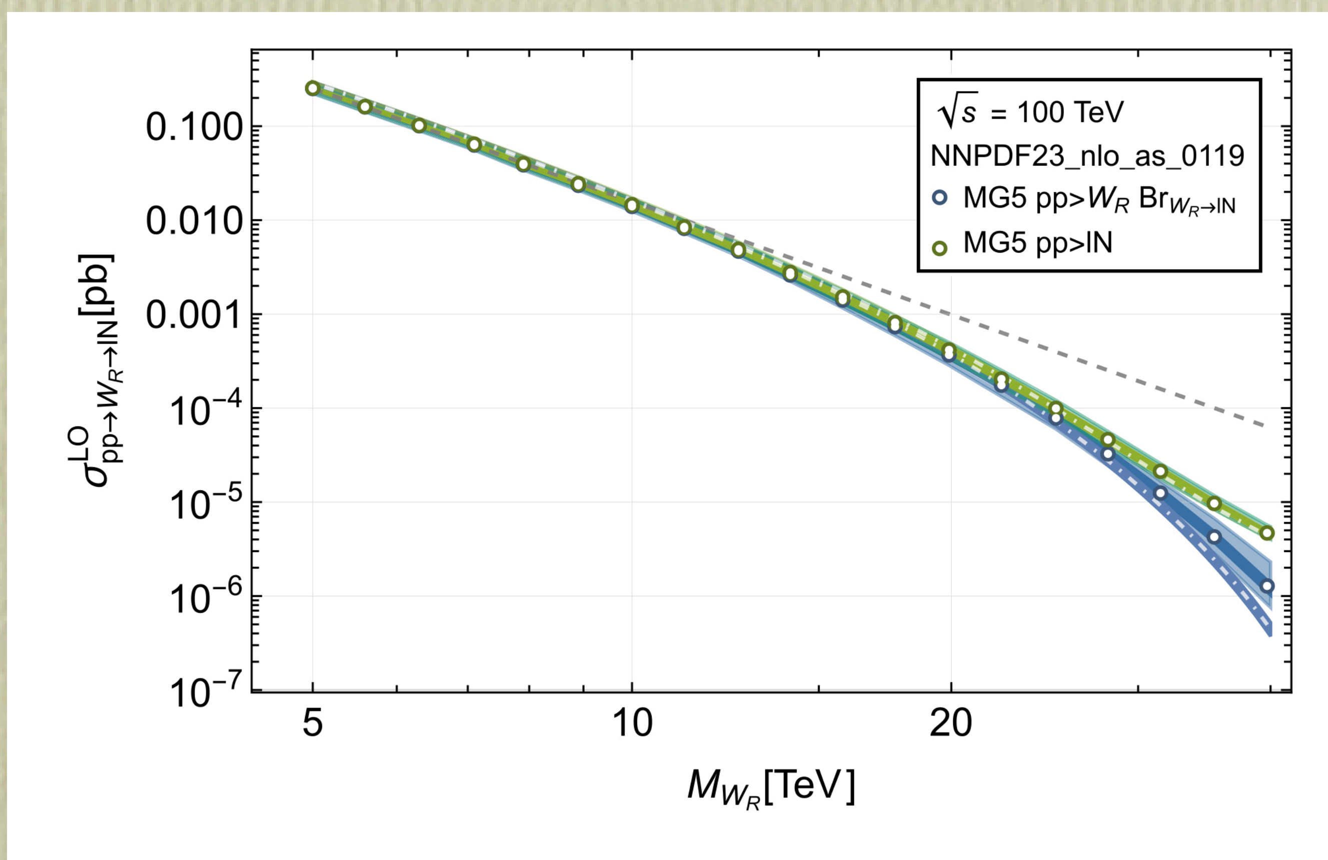
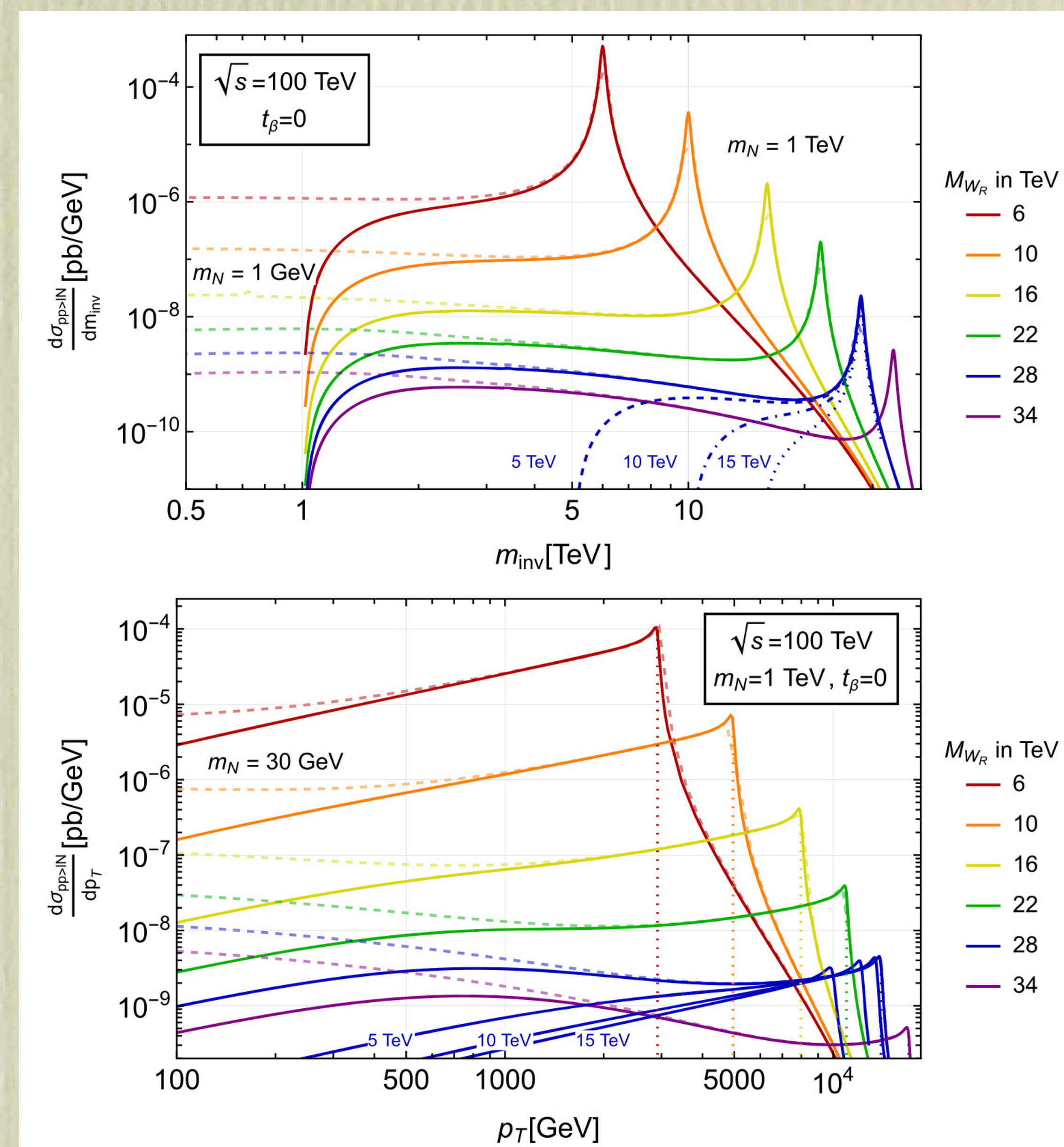
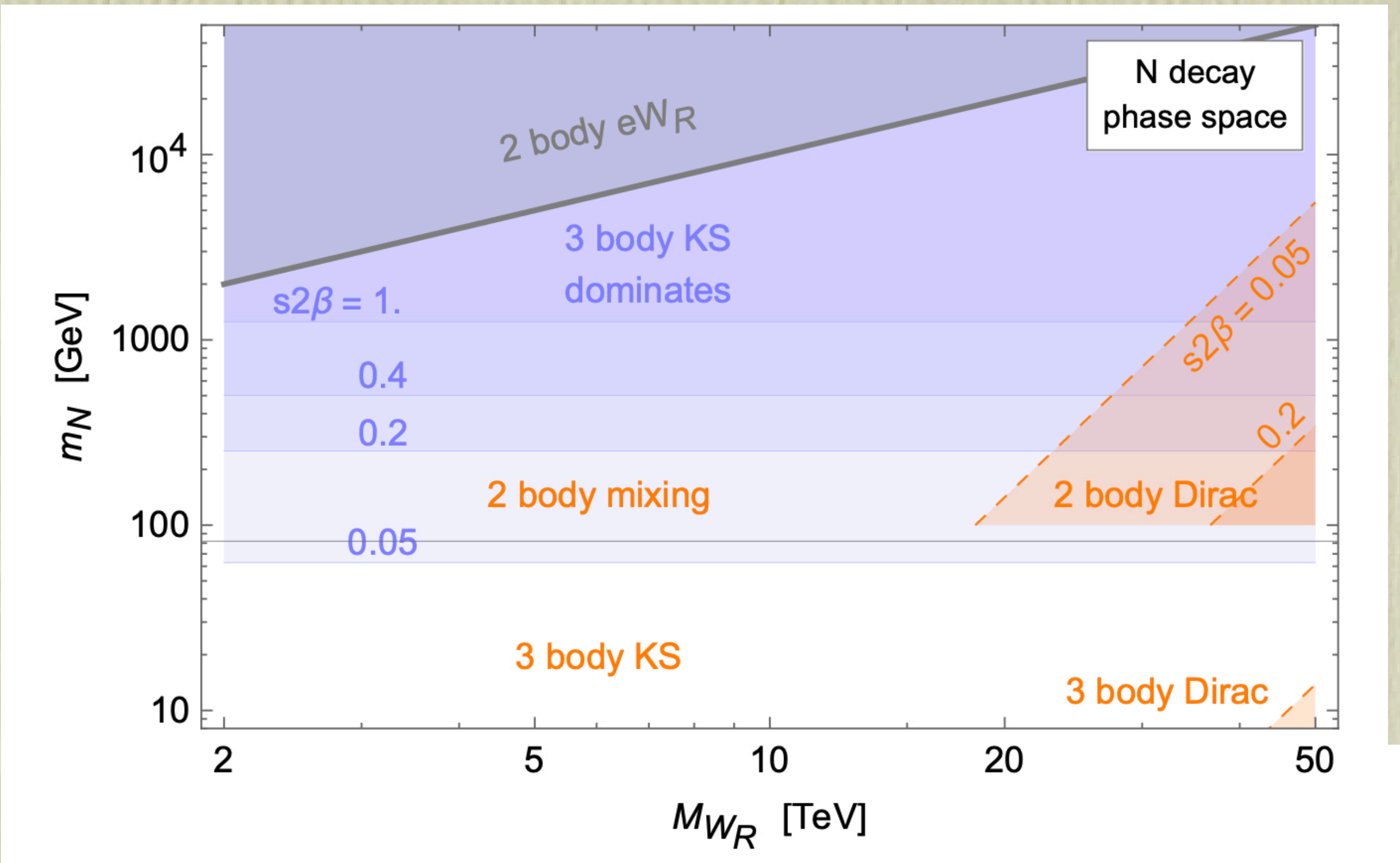


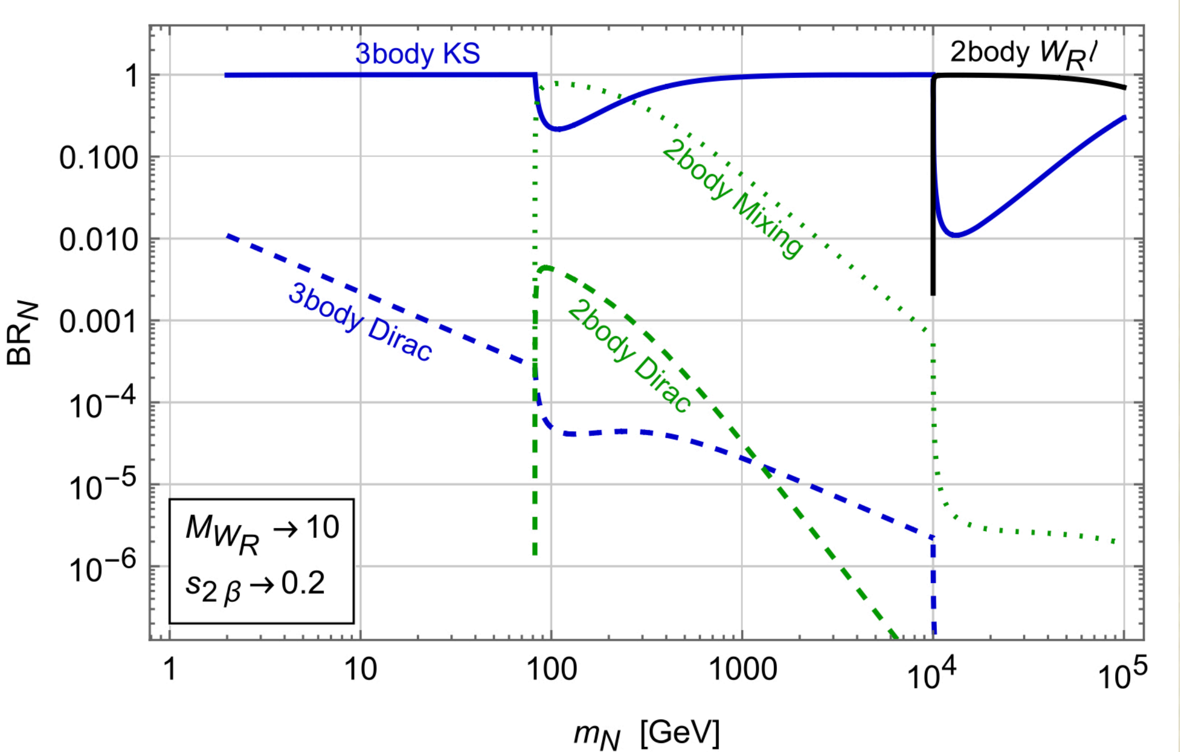
FIG. 2. The total cross section $pp \to W_R \to \ell N$, for fixed $m_N = 200$ GeV and $t_\beta = 0$. Blue dots (solid line) represent the



N decay

spaghetti and phase diagram





FCC-hh study

signal vs background

Backgrounds [pb] ($\sqrt{s} = 100$ TeV)	w+12j	DY+12j	vv+012j	tt+01j
xptj, xptl $>$ 50	5700	1000	180	480
xptj, xptl $>$ 500	4.0	0.45	0.110	0.031
+ xptl $>$ 1000	0.46	0.030	0.017	0.0045
+ misset $<$ 500	0.39	0.030	0.011	0.0028
+ xptj, xptl $>$ 1500 (detector)	**0.047**	**0.0025**	**0.001**	**0.000012**
+ k-factors	**0.023**	**0.0017**	**0.0015**	**0.000024**

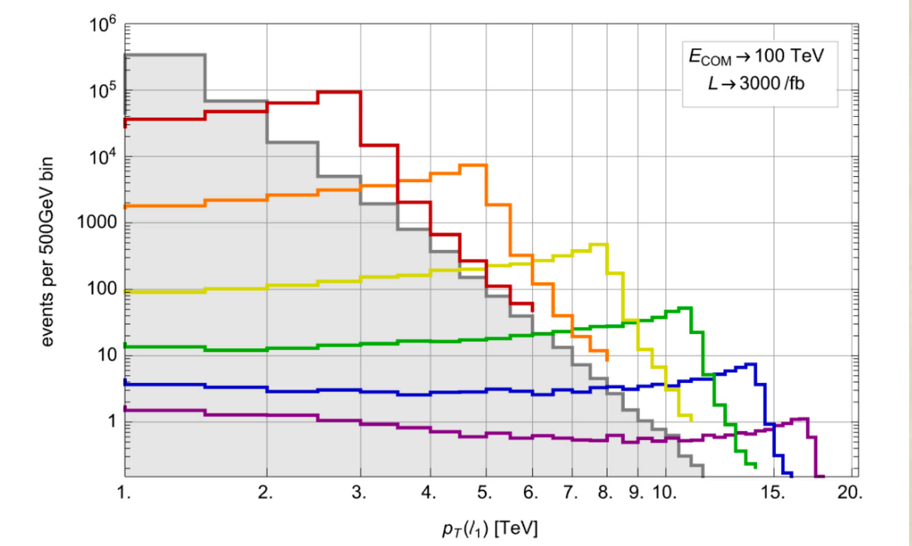
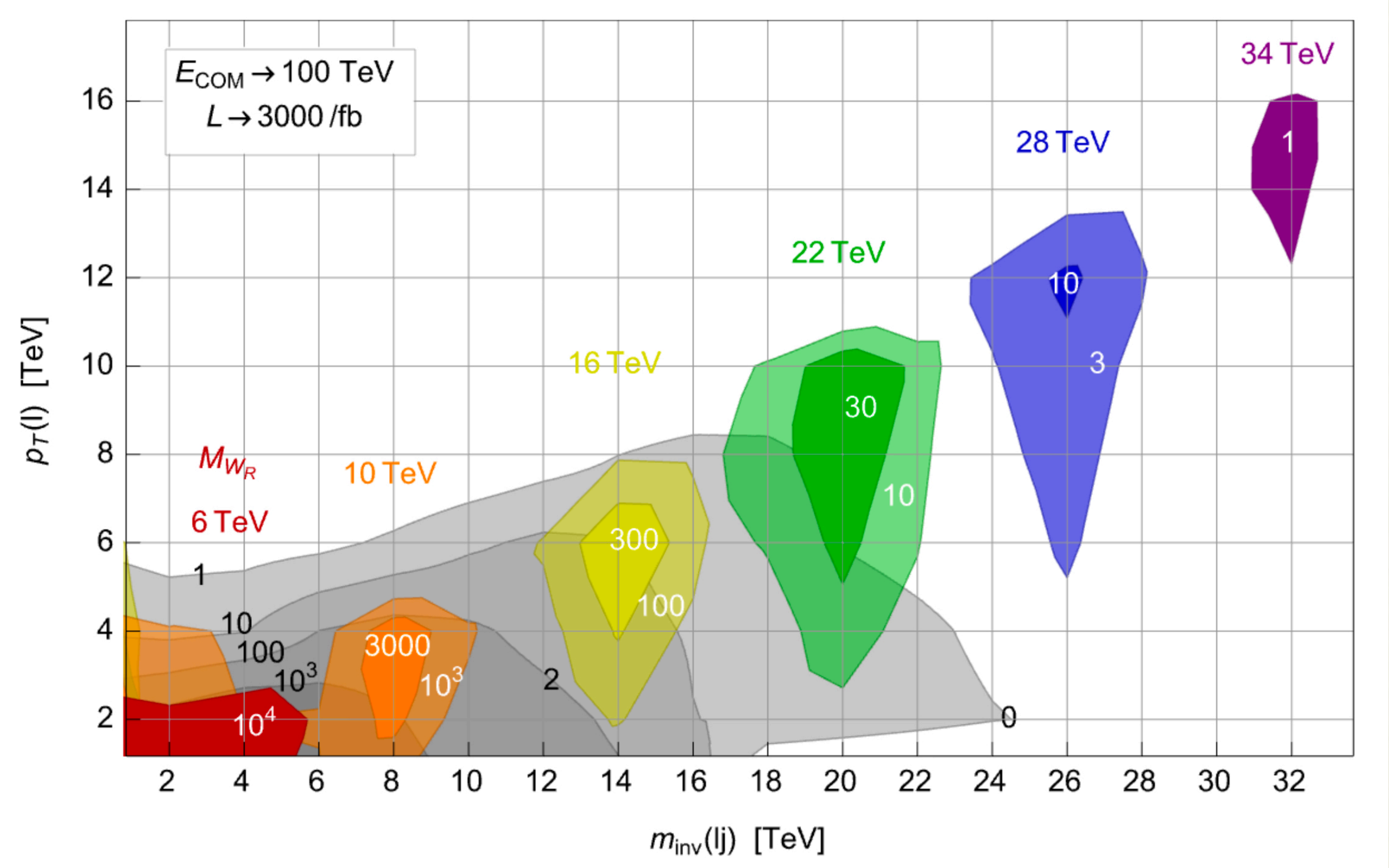


FIG. 6. Distribution of leading lepton p_T before cuts, for



FCC-hh study

kinematics

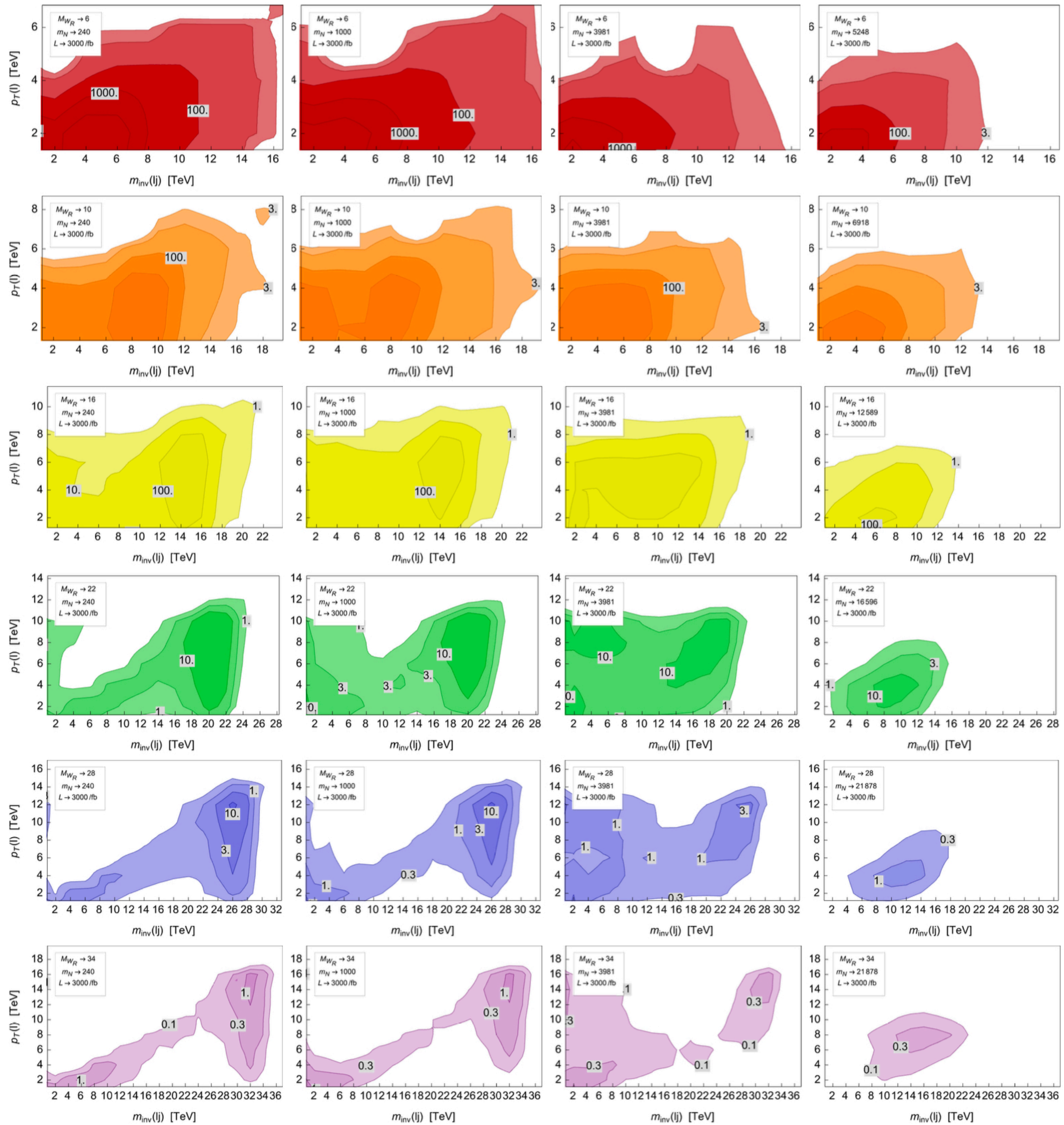
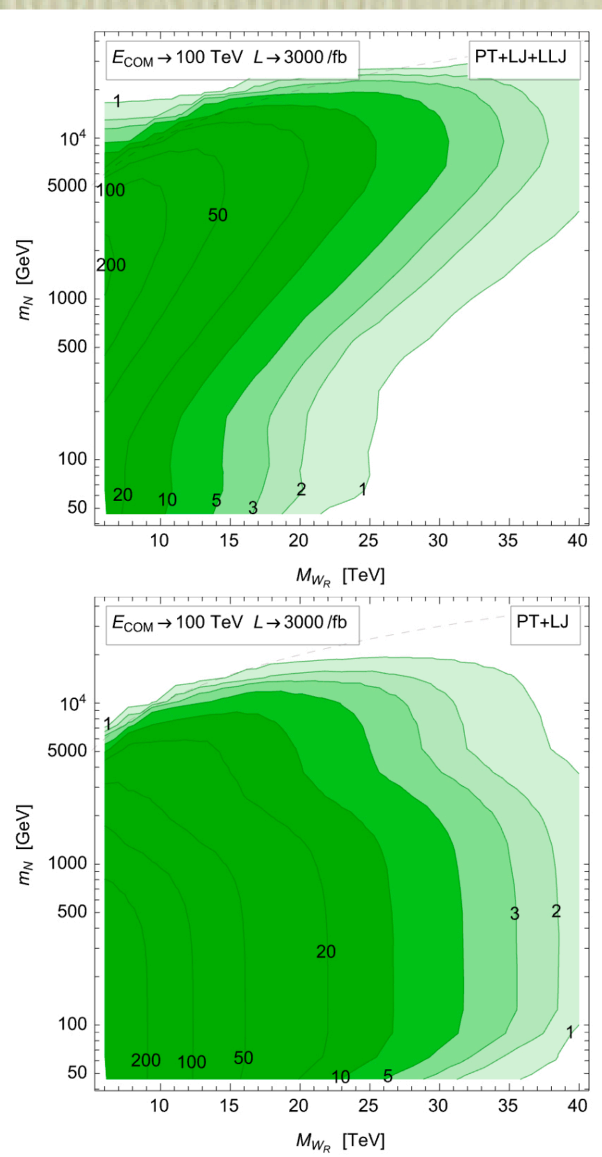


FIG. 8. Distribution of leading lepton $p_T(l_1)$ versus $m_{\rm inv}(l_1 j_1)$, for various heavy neutrino masses, and fixed M_{W_R}.

FCC-hh study



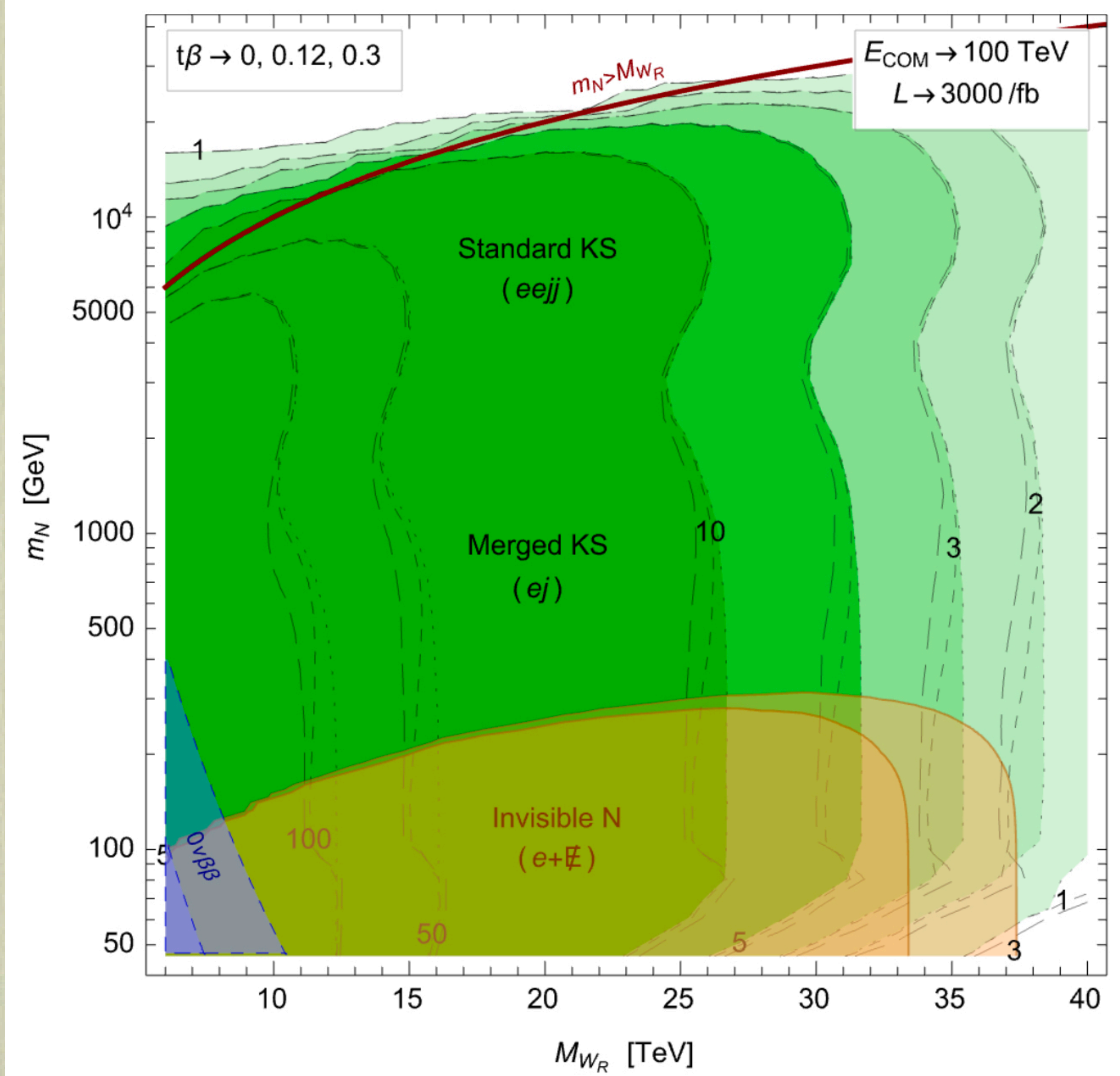
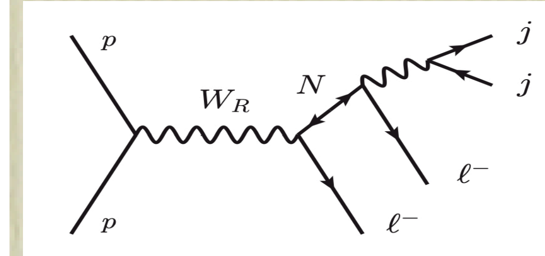
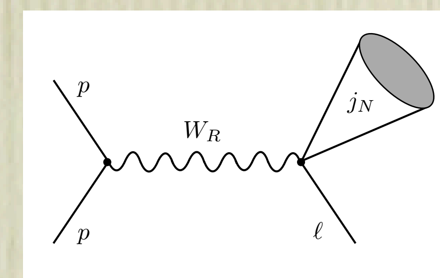
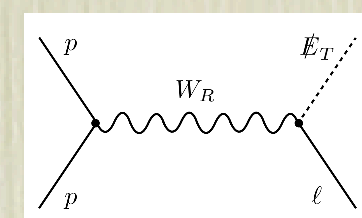


FIG. 10. The green areas show the final KS plus LJ sensitivity (in number of σs) achievable with 3/ab integrated luminosity. We show also the dependence on $t_\beta = 0, 0.12, 0.3$ (dotted, dashed, long-dashed). The overlayed orange shaded region in the lower part of the frame displays the 3 and 5 σ sensitivity to the $\ell + \not{E}$ signature.







Back to origin of neutrino masses?

Higgs(es)

Can we probe neutrino mass generation?

- From the two group breakings

$$\Phi = \begin{pmatrix} v + \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \qquad \Delta_R = \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ v_R + \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix}$$

  ϕ gives Dirac mass, Δ_R gives Majorana mass:

$$\mathcal{L}_{yuk} \supset \bar{L}_L(y_l\Phi + \tilde{y}_l\tilde{\Phi})L_R + y_\Delta L_R L_R \Delta_R$$

  plus

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

- Ideally one would like to see the higgs rates...

Higgs sector in more detail

$$\Phi = \begin{pmatrix} v + \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \qquad \Delta_R = \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ v_R + \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix}$$

- δ_R^0 responsible for the RH neutrino masses.

Higgs sector in more detail

$$\Phi = \begin{pmatrix} v + \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \qquad \Delta_R = \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ v_R + \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix}$$

- δ_R^0 responsible for the RH neutrino masses.

- But **neutral higgses mix**:

$$h = \phi_1^0 \cos\theta - \delta_R^0 \sin\theta$$
$$\Delta = \phi_1^0 \sin\theta + \delta_R^0 \cos\theta$$

$$\mathcal{V} = -\mu_1^2(\Phi^\dagger\Phi) - \mu_2^2(\widetilde{\Phi}\Phi^\dagger + \widetilde{\Phi}^\dagger\Phi) - \mu_3^2(\Delta_R^\dagger\Delta_R) + \lambda\,(\Phi^\dagger\Phi)^2 + \rho\,(\Delta_R^\dagger\Delta_R)^2 + \alpha(\Phi^\dagger\Phi)(\Delta_R^\dagger\Delta_R)$$

$$m_h^2 = 4\lambda v^2 - \alpha^2 v^2/\rho \qquad m_\Delta^2 = 4\rho\, v_R^2$$

$$\theta \simeq \left(\frac{\alpha}{2\,\rho}\right)\left(\frac{v}{v_R}\right)$$

SM Higgs couplings are reduced… still 20-30% mixing allowed (!)

[Pruna+ PRD '13; Profumo+ PRD '15; Chen+ PRD '15 ; Robens+ EPJC '15 Martin-Lozano+ 1501.03799; Falkowski Gross Lebedev 1502.01361; Godunov+ 1503.01618]

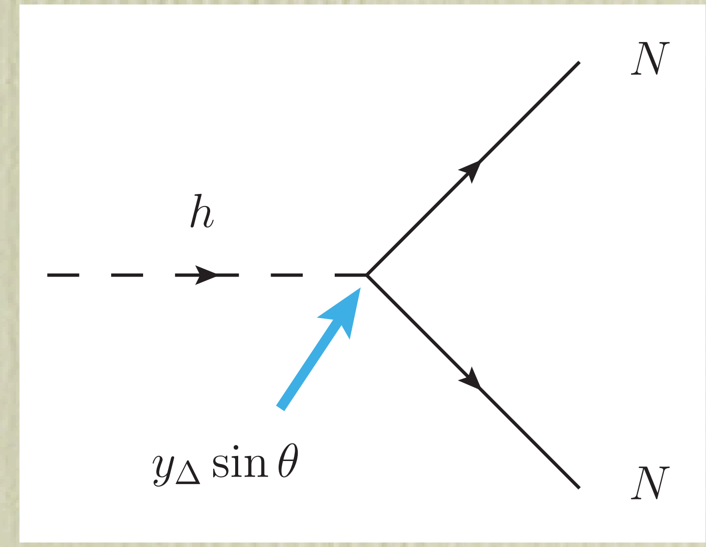
so, Higgs probing Majorana masses

$$\mathcal{L}_{yuk} = y_\Delta L_R L_R \Delta_R$$

- gives Majorana neutrino mass, to check by Δ decay

$$M_N = y_\Delta v_R \qquad\qquad \Gamma(\Delta \to NN) \propto y_\Delta^2$$

- with Δ-*h* mixing, now also Higgs can decay to *NN*



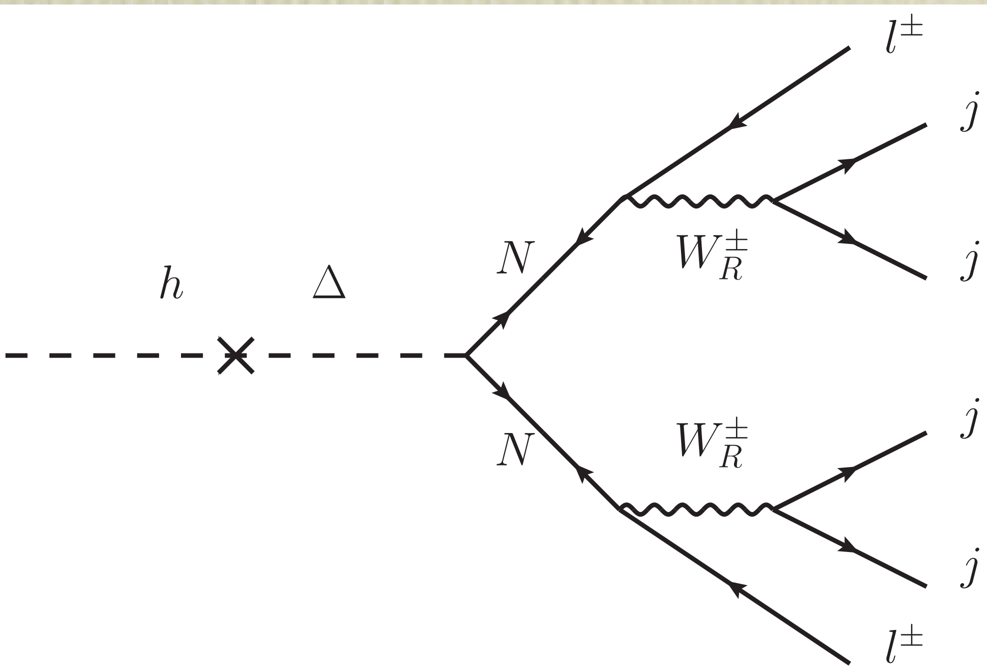
a new SM Higgs decay, checks RH neutrino mass

LNV Higgs decay

[Maiezza Nemevšek FN, PRL '15]

N is Majorana, thus LNV Higgs decays:

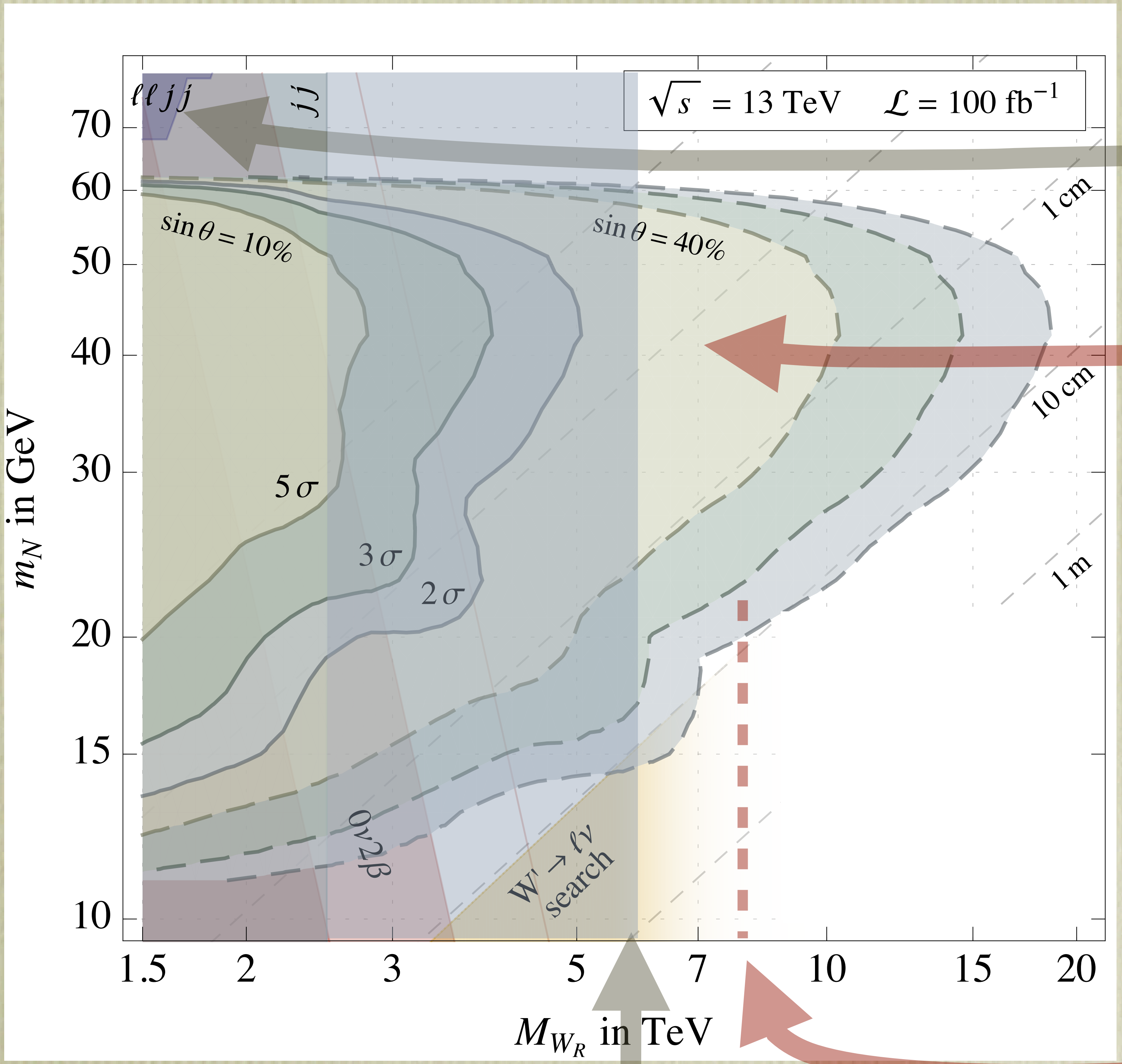
- 50% same sign dileptons
- In LR, N decay W_R-mediated
- heavy W_R, light N~30GeV, i.e. long lifetime
- N lifetime submillimeter to meters: *displaced vertices*



LNVH complementary to KS

H → NN LHC Sensitivity

[Maiezza, Nemevsek, FN, PRL '15]



Keung-Senjanovic
lljj

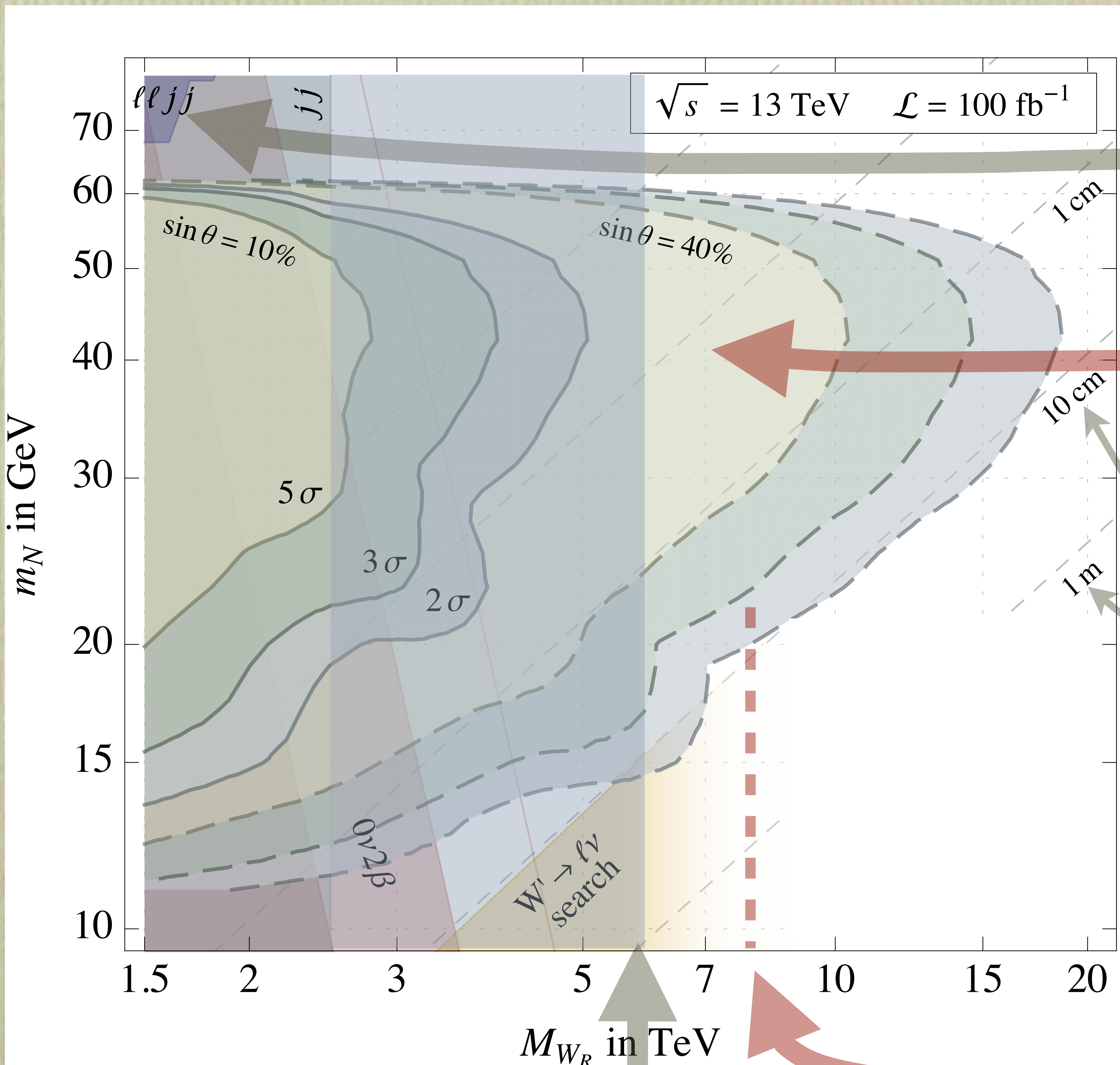
displaced
LNV Higgs decay
$h \to \mu^\pm \mu^\pm + jet(s)$

W'➛dijet search

Belle, LHCb
indirect reach

$H \to NN$ LHC Sensitivity

[Maiezza, Nemevsek, FN, PRL '15]



Keung-Senjanovic
lljj

displaced
LNV Higgs decay
$h \to \mu^\pm \mu^\pm + jet(s)$

N lifetime

W'➤dijet search

Belle, LHCb
indirect reach

Similar,

$\Delta \to$ NN

even more promising

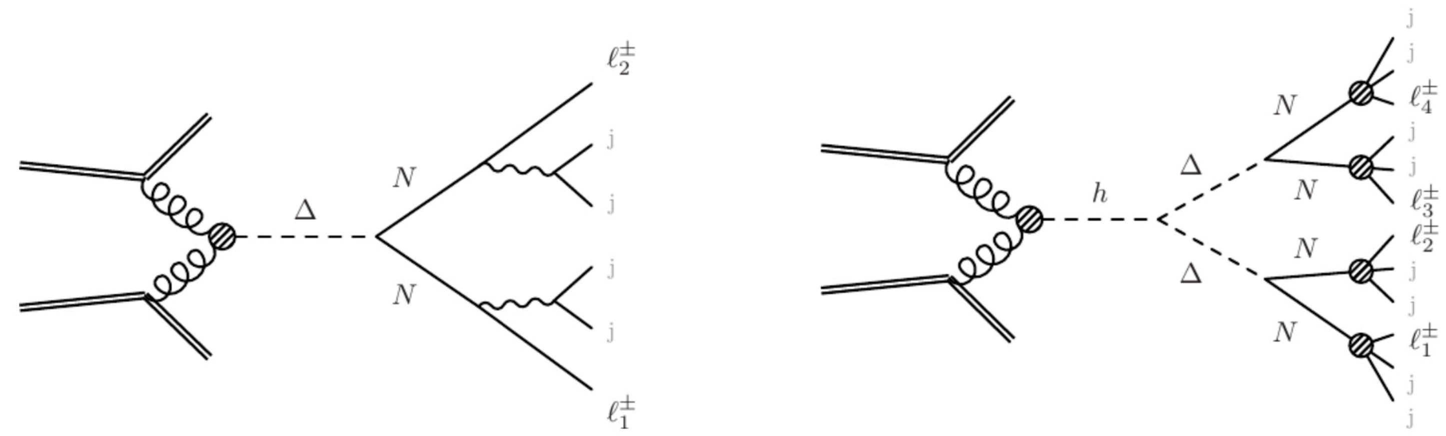


Figure 5. Left: Feynman diagrams for pair production of N through the Δ resonance that leads to two same-sign leptons and a $\Delta L = 0, 2$ signal. Right: pair-production of Δ via an exotic Higgs decay with four leptons in final states with $\Delta L = 0, 2, 4$.

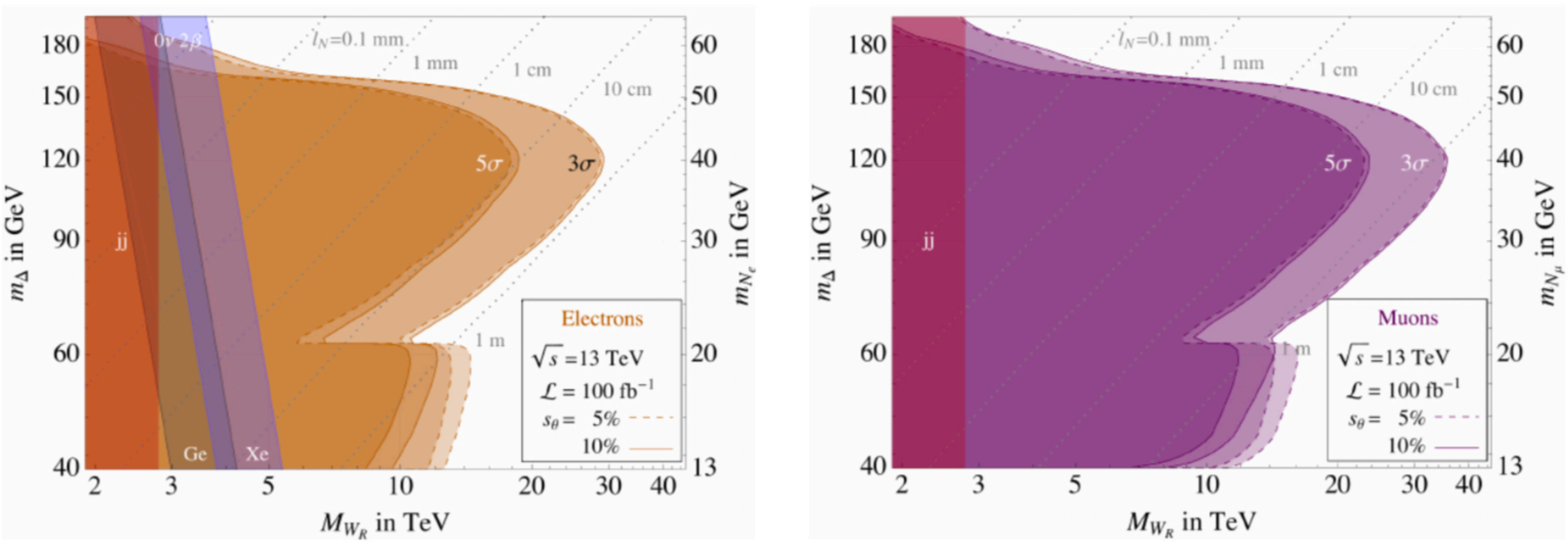


Figure 8. Contours of estimated combined sensitivities of the $h \to NN, \Delta \to NN$ and $\Delta\Delta \to 4N$ channels at 3 and 5 σ with solid (dashed) contours corresponding to $s_\theta = 0.05$ (0.1). The left panel

[Nemevsek, FN, Vasquez JHEP ‘17]

towards a joint study with ATLAS now

Just in: Full LRSM solution

e.g. Neutral scalars spectrum solution

$$
\begin{pmatrix}
4\epsilon^2\left(\lambda_1+\frac{4tc_\alpha\left(\lambda_4\left(t^2+1\right)+4\lambda_2 tc_\alpha\right)}{\left(t^2+1\right)^2}\right) & 2\epsilon\left(\alpha_1-\frac{t^2X\left(t^2-s_{2\alpha+\delta_2}/s_{\delta_2}\right)}{\left(t^2+1\right)^2}\right) & \frac{4\epsilon^2\left(t^2c_{2\alpha}-1\right)\left(\lambda_4\left(t^2+1\right)+8\lambda_2 tc_\alpha\right)}{\left(t^2+1\right)^2} & \frac{4t^2\epsilon^2 s_{2\alpha}\left(\lambda_4\left(t^2+1\right)+8\lambda_2 tc_\alpha\right)}{\left(t^2+1\right)^2} \\
2\epsilon\left(\alpha_1-\frac{t^2X\left(t^2-s_{2\alpha+\delta_2}/s_{\delta_2}\right)}{\left(t^2+1\right)^2}\right) & Y & \frac{2tX\epsilon\left(t^2c_{2\alpha}-1\right)s_{\alpha+\delta_2}/s_{\delta_2}}{\left(t^2+1\right)^2} & \frac{2t^3X\epsilon s_{2\alpha}s_{\alpha+\delta_2}/s_{\delta_2}}{\left(t^2+1\right)^2} \\
\frac{4\epsilon^2\left(t^2c_{2\alpha}-1\right)\left(\lambda_4\left(t^2+1\right)+8\lambda_2 tc_\alpha\right)}{\left(t^2+1\right)^2} & \frac{2tX\epsilon\left(t^2c_{2\alpha}-1\right)s_{\alpha+\delta_2}/s_{\delta_2}}{\left(t^2+1\right)^2} & X+\frac{16\lambda_2\epsilon^2\left(t^2c_{2\alpha}-1\right)^2}{\left(t^2+1\right)^2} & \frac{16\lambda_2 t^2\epsilon^2 s_{2\alpha}\left(t^2c_{2\alpha}-1\right)}{\left(t^2+1\right)^2} \\
\frac{4t^2\epsilon^2 s_{2\alpha}\left(\lambda_4\left(t^2+1\right)+8\lambda_2 tc_\alpha\right)}{\left(t^2+1\right)^2} & \frac{2t^3X\epsilon s_\alpha s_{\alpha+\delta_2}/s_{\delta_2}}{\left(t^2+1\right)^2} & \frac{16\lambda_2 t^2\epsilon^2 s_{2\alpha}\left(t^2c_{2\alpha}-1\right)}{\left(t^2+1\right)^2} & X+\frac{16\lambda_2 t^4\epsilon^2 s_{2\alpha}^2}{\left(t^2+1\right)^2}
\end{pmatrix} \tag{57}
$$

where for compactness we defined $X \equiv \frac{1+t^2}{1-t^2}\alpha_3$, $Y \equiv 4\rho_1$, and $t \equiv t_\beta$.

$$
m_h^2 = v^2\left(4\lambda_1+\frac{64\lambda_2 t^2 c_\alpha^2}{\left(t^2+1\right)^2}+\frac{16\lambda_4 tc_\alpha}{t^2+1}-Y\tilde{\theta}^2\right)
$$

$$
m_\Delta^2 = v_R^2\left[Y+\sec(2\eta)\left[(Y-X)s_\eta^2+\epsilon^2\left(Y\tilde{\theta}^2c_\eta^2-\frac{16\lambda_2\left(t^4-2c_{2\alpha}t^2+1\right)}{\left(t^2+1\right)^2}s_\eta^2\right)\right]\right],
$$

$$
m_H^2 = v_R^2\left[X-\sec(2\eta)\left[(Y-X)s_\eta^2+\epsilon^2\left(Y\tilde{\theta}^2s_\eta^2-\frac{16\lambda_2\left(t^4-2c_{2\alpha}t^2+1\right)}{\left(t^2+1\right)^2}c_\eta^2\right)\right]\right].
$$

$$
m_A^2 = v_R^2 X\,, \qquad X \equiv \frac{1+t^2}{1-t^2}\alpha_3\,.
$$

Full LRSM model file

[Kriewald, Nemevsek, Nesti , EPJC ’24] https://sites.google.com/site/leftrighthep/1-lrsm-feynrules

- Explicit solution of couplings in terms of physical masses and scalar mixings!
- Explicit solution of square root for Dirac neutrino mass! (Cayley Hamilton)

$$\sqrt{A} = \pm \frac{A^2 + \left(\tilde{T}_{1/2} - T_{1/2}^2\right) A - \sqrt{\Delta}\, T_{1/2}\, \mathbb{1}}{\sqrt{\Delta} - T_{1/2}\tilde{T}_{1/2}}\,.$$

- FeynRules & UFO implementation including QCD NLO

UFO @ LO	UFO @ NLO
mlrsm mlrsm-nu mlrsm-full	mlrsm-loop mlrsm-nu-loop
mlrsm-ug mlrsm-ug-nu mlrsm-ug-full	mlrsm-ug-loop (*) mlrsm-ug-nu-loop (*)

TABLE II. UFOs included in the mLRSM package, with various restrictions. Here, the first three lines list UFO models in Feynman gauge; the last three instead list models (-ug) where unitary gauge was enforced, stripping off ghosts and wbGs.

$$\frac{1+t^2}{1-t^2}\alpha_3 \equiv X \to \frac{m_A^2}{v_R^2}\,, \tag{72}$$

$$4\rho_1 \equiv Y \to \frac{m_\Delta^2 + \left(m_H^2 - m_\Delta^2\right) s_\eta^2}{v_R^2}\,, \tag{73}$$

$$\rho_2 \to \frac{m^2_{\Delta_R^{++}}}{4v_R^2} - \frac{\epsilon^2 X \left(t^2-1\right)^2}{4\left(t^2+1\right)^2}, \tag{74}$$

$$\rho_3 \to \frac{m^2_{\Delta_L}}{v_R^2} + \frac{Y}{2} - \frac{4\epsilon^2 X t^2 s_\alpha^2}{\left(t^2+1\right)^2}\,, \tag{75}$$

$$\lambda_1 \to \frac{m_h^2}{4v^2} + \frac{Y}{4}\tilde{\theta}^2 - 4\,t c_\alpha \left(\frac{\lambda_4}{t^2+1} + \frac{4 t c_\alpha \lambda_2}{\left(t^2+1\right)^2}\right), \tag{76}$$

$$\lambda_2 \to \frac{m_H^2 - m_A^2 - \left(m_H^2 - m_\Delta^2\right) s_\eta^2}{16\, v^2} \frac{\left(t^2+1\right)^2}{\left(t^4 - 2c_{2\alpha}t^2 + 1\right)}\,, \tag{77}$$

$$\lambda_3 \to 2\lambda_2\,, \tag{78}$$

$$\lambda_4 \to \tilde{\phi}\frac{X\left(t^2+1\right)}{4\left(t^2 c_{2\alpha} - 1\right)} + \tilde{\theta}\frac{X\eta_2}{2\left(t^2+1\right)} - 8\frac{t c_\alpha \lambda_2}{\left(t^2+1\right)} \tag{79}$$

$$\eta_2 \to \frac{\left(m_H^2 - m_\Delta^2\right)\left(t^2+1\right)^2 \sin(2\eta)}{4 m_A^2 \epsilon \sqrt{t^4 - 2c_{2\alpha}t^2 + 1}} \tag{80}$$

$$\delta_2 \to \tan^{-1}\left(\frac{t s_\alpha}{\eta_2 - t c_\alpha}\right), \tag{81}$$

$$\alpha_1 \to \frac{Y\tilde{\theta}}{2} + t\left(\frac{t\,X}{t^2+1} + \frac{(Y-X)c_\alpha t_{2\eta}}{2\,\epsilon\sqrt{t^4 - 2c_{2\alpha}t^2 + 1}}\right), \tag{82}$$

$$\alpha_2 \to \frac{X}{2}\frac{\left(\eta_2 - t c_\alpha\right)}{\left(t^2+1\right)}\sqrt{\frac{t^2 s_\alpha^2}{\left(\eta_2 - t c_\alpha\right)^2} + 1}\,. \tag{83}$$

Resume - Outlook

Neutrino masses exist - Left-Right symmetry predictive

- Lepton Number Violation
- Flavor & CP constraining, strikingly still surviving.
  B mixing ruling now, $\varepsilon + \varepsilon' + d_n$ predictive, $M_{W_R} \gtrsim$ 7-10TeV
- Borderline @ LHC ...
- LNV ... displaced for the brave - or next collider
- LNV in higgses
- New model file

Resume - Outlook

Neutrino masses exist - Left-Right symmetry predictive

- Lepton Number Violation
- Flavor & CP constraining, strikingly still surviving.
  B mixing ruling now, ε+ε'+d_n predictive, $M_{W_R} \gtrsim$7-10TeV
- Borderline @ LHC ...
- LNV ... displaced for the brave - or next collider
- LNV in higgses
- New model file

Thanks!

Backup

LR - Lagrangian

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \mathcal{L}_{fermion} + \mathcal{L}_{Yuk} + \mathcal{L}_{Maj}$$

$$\mathcal{L}_{Higgs} = \mathrm{Tr}[(D_\mu \Delta_L)^\dagger (D^\mu \Delta_L)] + \mathrm{Tr}[(D_\mu \Delta_R)^\dagger (D^\mu \Delta_R)] + \mathrm{Tr}[(D_\mu \phi)^\dagger (D^\mu \phi)] + V(\phi, \Delta_L, \Delta_R)$$

$$\mathcal{L}_{Fermion} = \overline{q}_{Li} i \not{D} q_{Li} + \overline{\ell}_{Li} i \not{D} \ell_{Li} + (L \leftrightarrow R)$$

$$\mathcal{L}_{Yukawa\, q} = \overline{q}_{Li}(Y_{ij}\phi + \tilde{Y}_{ij}\tilde{\phi}) q_{Rj} + h.c.$$

$$\mathcal{L}_{Yukawa\, \ell} = \overline{\ell}_{Li}(h_{ij}\phi + \tilde{h}_{ij}\tilde{\phi}) \ell_{Rj} + h.c.$$

$$\mathcal{L}_{Majorana} = Y^{ij}[\overline{\ell}^t_{Li} C\, \tau_2 \Delta_L\, \ell_{Lj} + (L \leftrightarrow R)] + h.c.$$

$$\mathcal{L}_{M_W} = \begin{pmatrix} W^-_{L\mu} & W^-_{R\mu} \end{pmatrix} \begin{pmatrix} \frac{1}{2} g^2 (v^2 + v'^2 + 2v_L^2) & -g^2 v v' e^{-i\alpha} \\ -g^2 v v' e^{i\alpha} & g^2 v_R^2 \end{pmatrix} \begin{pmatrix} W_L^{+\mu} \\ W_R^{+\mu} \end{pmatrix}$$

$$\begin{array}{ccc} W_{3L} & W_{3R} & B \end{array}$$
$$\begin{pmatrix} g^2/2(\kappa^2 + \kappa'^2 + 4v_L^2) & -g^2/2(\kappa^2 + \kappa'^2) & -2gg'v_R^2 \\ -g^2/2(\kappa^2 + \kappa'^2) & g^2/2(\kappa^2 + \kappa'^2 + 4v_R^2) & -2gg'v_R^2 \\ -2gg'v_L^2 & -2gg'^2 v_R^2 & 2g'^2(v_L^2 + v_R^2) \end{pmatrix}$$

$$D_\mu \phi = \partial_\mu \phi + i g_L W_{L\mu}\, \phi - i g_R \phi\, W_{R\mu}$$

$$D_\mu \psi = \partial_\mu \phi + i g_L W_{L,R\mu} \psi_{L,R} + i g' (B-L)/2 B_\mu \psi_{L,R}$$

$$D_\mu \Delta_{(L,R)} = \partial_\mu \Delta_{(L,R)} + i g_{(L,R)} \left[W_{(L,R)\mu},\ \Delta_{(L,R)} \right] + i g' B_\mu \Delta_{(L,R)}$$

LR - Scalar potential

$$
\begin{aligned}
V(\phi, \Delta_L, \Delta_R) = \\
& -\mu_1^2 \mathrm{Tr}(\phi^\dagger \phi) - \mu_2^2 \left[\mathrm{Tr}(\tilde{\phi}\phi^\dagger) + \mathrm{Tr}(\tilde{\phi}^\dagger \phi)\right] - \mu_3^2 \left[\mathrm{Tr}(\Delta_L \Delta_L^\dagger) + \mathrm{Tr}(\Delta_R \Delta_R^\dagger)\right] \\
& +\lambda_1 \left[\mathrm{Tr}(\phi^\dagger \phi)\right]^2 + \lambda_2 \left\{\left[\mathrm{Tr}(\tilde{\phi}\phi^\dagger)\right]^2 + \left[\mathrm{Tr}(\tilde{\phi}^\dagger \phi)\right]^2\right\} \\
& +\lambda_3 \mathrm{Tr}(\tilde{\phi}\phi^\dagger)\mathrm{Tr}(\tilde{\phi}^\dagger \phi) + \lambda_4 \mathrm{Tr}(\phi^\dagger \phi)\left[\mathrm{Tr}(\tilde{\phi}\phi^\dagger) + \mathrm{Tr}(\tilde{\phi}^\dagger \phi)\right] \\
& +\rho_1 \left\{\left[\mathrm{Tr}(\Delta_L \Delta_L^\dagger)\right]^2 + \left[\mathrm{Tr}(\Delta_R \Delta_R^\dagger)\right]^2\right\} \\
& +\rho_2 \left[\mathrm{Tr}(\Delta_L \Delta_L)\mathrm{Tr}(\Delta_L^\dagger \Delta_L^\dagger) + \mathrm{Tr}(\Delta_R \Delta_R)\mathrm{Tr}(\Delta_R^\dagger \Delta_R^\dagger)\right] \\
& +\rho_3 \mathrm{Tr}(\Delta_L \Delta_L^\dagger)\mathrm{Tr}(\Delta_R \Delta_R^\dagger) + \rho_4 \left[\mathrm{Tr}(\Delta_L \Delta_L)\mathrm{Tr}(\Delta_R^\dagger \Delta_R^\dagger) + \mathrm{Tr}(\Delta_L^\dagger \Delta_L^\dagger)\mathrm{Tr}(\Delta_R \Delta_R)\right] \\
& +\alpha_1 \mathrm{Tr}(\phi^\dagger \phi)\left[\mathrm{Tr}(\Delta_L \Delta_L^\dagger) + \mathrm{Tr}(\Delta_R \Delta_R^\dagger)\right] \\
& +\left\{\alpha_2 e^{i\delta_2}\left[\mathrm{Tr}(\tilde{\phi}\phi^\dagger)\mathrm{Tr}(\Delta_L \Delta_L^\dagger) + \mathrm{Tr}(\tilde{\phi}^\dagger \phi)\mathrm{Tr}(\Delta_R \Delta_R^\dagger)\right] + \mathrm{h.c.}\right\} \\
& +\alpha_3 \left[\mathrm{Tr}(\phi\phi^\dagger \Delta_L \Delta_L^\dagger) + \mathrm{Tr}(\phi^\dagger \phi \Delta_R \Delta_R^\dagger)\right] + \beta_1 \left[\mathrm{Tr}(\phi \Delta_R \phi^\dagger \Delta_L^\dagger) + \mathrm{Tr}(\phi^\dagger \Delta_L \phi \Delta_R^\dagger)\right] \\
& +\beta_2 \left[\mathrm{Tr}(\tilde{\phi}\Delta_R \phi^\dagger \Delta_L^\dagger) + \mathrm{Tr}(\tilde{\phi}^\dagger \Delta_L \phi \Delta_R^\dagger)\right] + \beta_3 \left[\mathrm{Tr}(\phi \Delta_R \tilde{\phi}^\dagger \Delta_L^\dagger) + \mathrm{Tr}(\phi^\dagger \Delta_L \tilde{\phi} \Delta_R^\dagger)\right]
\end{aligned}
$$

Neutral scalars spectrum solution

$$\begin{pmatrix} 4\epsilon^2\left(\lambda_1+\frac{4tc_\alpha\left(\lambda_4\left(t^2+1\right)+4\lambda_2 tc_\alpha\right)}{\left(t^2+1\right)^2}\right) & 2\epsilon\left(\alpha_1-\frac{t^2X\left(t^2-s_{2\alpha+\delta_2}/s_{\delta_2}\right)}{\left(t^2+1\right)^2}\right) & \frac{4\epsilon^2\left(t^2c_{2\alpha}-1\right)\left(\lambda_4\left(t^2+1\right)+8\lambda_2 tc_\alpha\right)}{\left(t^2+1\right)^2} & \frac{4t^2\epsilon^2 s_{2\alpha}\left(\lambda_4\left(t^2+1\right)+8\lambda_2 tc_\alpha\right)}{\left(t^2+1\right)^2} \\ 2\epsilon\left(\alpha_1-\frac{t^2X\left(t^2-s_{2\alpha+\delta_2}/s_{\delta_2}\right)}{\left(t^2+1\right)^2}\right) & Y & \frac{2tX\epsilon\left(t^2c_{2\alpha}-1\right)s_{\alpha+\delta_2}/s_{\delta_2}}{\left(t^2+1\right)^2} & \frac{2t^3X\epsilon s_{2\alpha}s_{\alpha+\delta_2}/s_{\delta_2}}{\left(t^2+1\right)^2} \\ \frac{4\epsilon^2\left(t^2c_{2\alpha}-1\right)\left(\lambda_4\left(t^2+1\right)+8\lambda_2 tc_\alpha\right)}{\left(t^2+1\right)^2} & \frac{2tX\epsilon\left(t^2c_{2\alpha}-1\right)s_{\alpha+\delta_2}/s_{\delta_2}}{\left(t^2+1\right)^2} & X+\frac{16\lambda_2\epsilon^2\left(t^2c_{2\alpha}-1\right)^2}{\left(t^2+1\right)^2} & \frac{16\lambda_2 t^2\epsilon^2 s_{2\alpha}\left(t^2c_{2\alpha}-1\right)}{\left(t^2+1\right)^2} \\ \frac{4t^2\epsilon^2 s_{2\alpha}\left(\lambda_4\left(t^2+1\right)+8\lambda_2 tc_\alpha\right)}{\left(t^2+1\right)^2} & \frac{2t^3X\epsilon s_\alpha s_{\alpha+\delta_2}/s_{\delta_2}}{\left(t^2+1\right)^2} & \frac{16\lambda_2 t^2\epsilon^2 s_{2\alpha}\left(t^2c_{2\alpha}-1\right)}{\left(t^2+1\right)^2} & X+\frac{16\lambda_2 t^4\epsilon^2 s_{2\alpha}^2}{\left(t^2+1\right)^2} \end{pmatrix} \tag{57}$$

where for compactness we defined $X \equiv \frac{1+t^2}{1-t^2}\alpha_3$, $Y \equiv 4\rho_1$, and $t \equiv t_\beta$.

$$m_h^2 = v^2\left(4\lambda_1+\frac{64\lambda_2 t^2 c_\alpha^2}{\left(t^2+1\right)^2}+\frac{16\lambda_4 tc_\alpha}{t^2+1}-Y\tilde{\theta}^2\right);$$

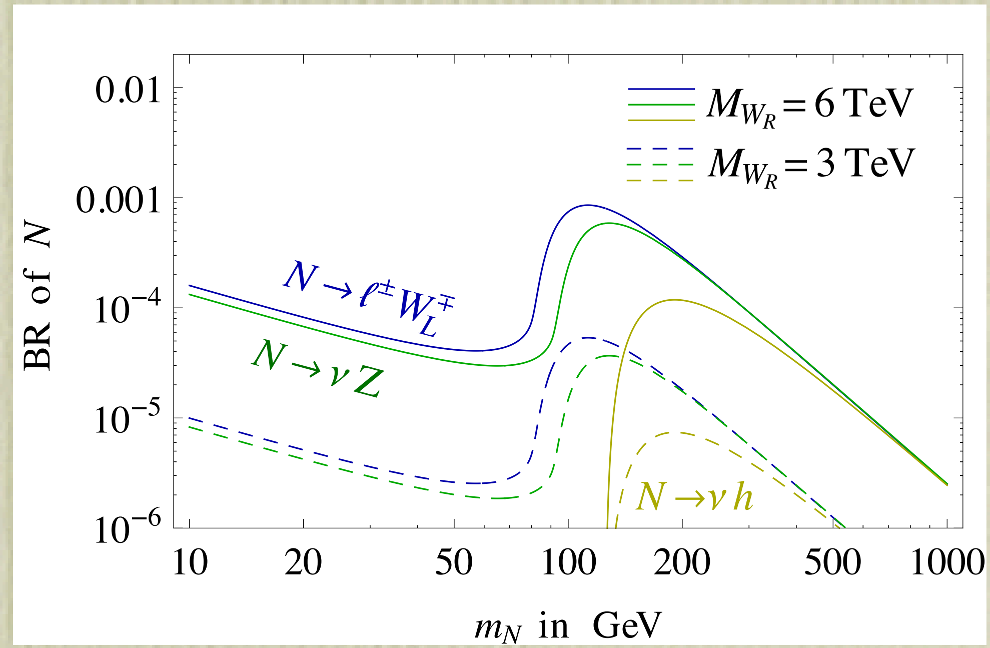
$$m_\Delta^2 = v_R^2\left[Y+\sec(2\eta)\left[(Y-X)s_\eta^2+\epsilon^2\left(Y\tilde{\theta}^2c_\eta^2-\frac{16\lambda_2\left(t^4-2c_{2\alpha}t^2+1\right)}{\left(t^2+1\right)^2}s_\eta^2\right)\right]\right],$$

$$m_H^2 = v_R^2\left[X-\sec(2\eta)\left[(Y-X)s_\eta^2+\epsilon^2\left(Y\tilde{\theta}^2s_\eta^2-\frac{16\lambda_2\left(t^4-2c_{2\alpha}t^2+1\right)}{\left(t^2+1\right)^2}c_\eta^2\right)\right]\right].$$

$$m_A^2 = v_R^2 X\,, \qquad X \equiv \frac{1+t^2}{1-t^2}\alpha_3\,.$$

Probe Dirac Mass?

- Recall M_D is predicted $$M_D = M_N \sqrt{\frac{v_L}{v_R} - \frac{1}{M_N} M_\nu},$$
- Too small to see h →lν, but *N* decays also through M_D:



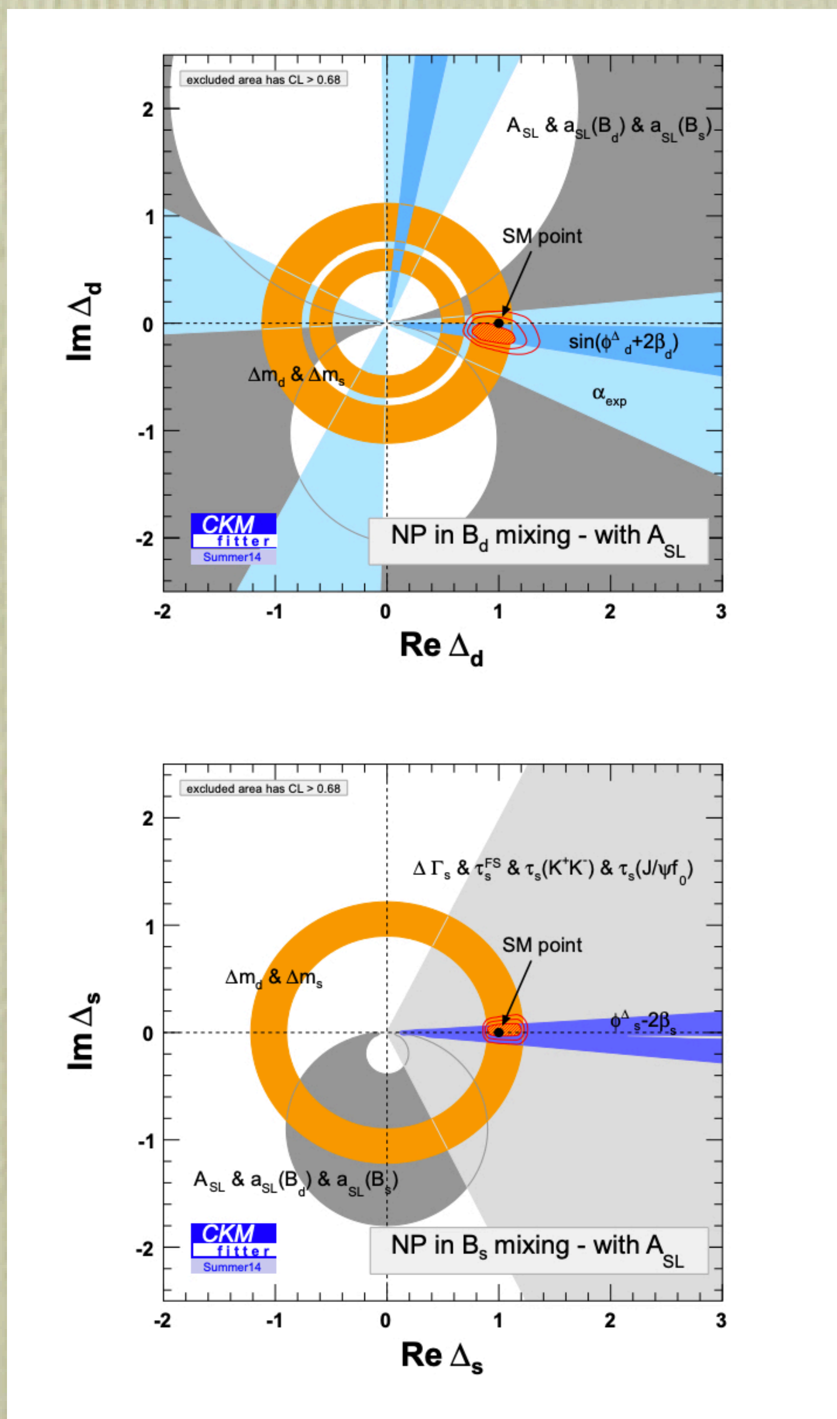
[Nemevšek Senjanović Tello PRL '13]

FIG. 1. Branching ratio for the decay of heavy N to the Higgs-Weinberg and SM gauge bosons, proceeding via Dirac couplings, exemplified $v_L = 0$ and $V_R = V_L^*$. The solid (dashed) line corresponds to $M_{W_R} = 6(3)$ TeV.

$$\frac{\Gamma_{N \to \ell_L jj}}{\Gamma_{N \to \ell_R jj}} \simeq 10^3 \frac{M_{W_R}^4}{M_{W_L}^2 m_N^2} \left| \frac{v_L}{v_R} - \frac{m_\nu}{m_N} \right|$$

Becomes more relevant for heavier W_R

BB limits shrinking towards phase III



[Charles et al 2015]

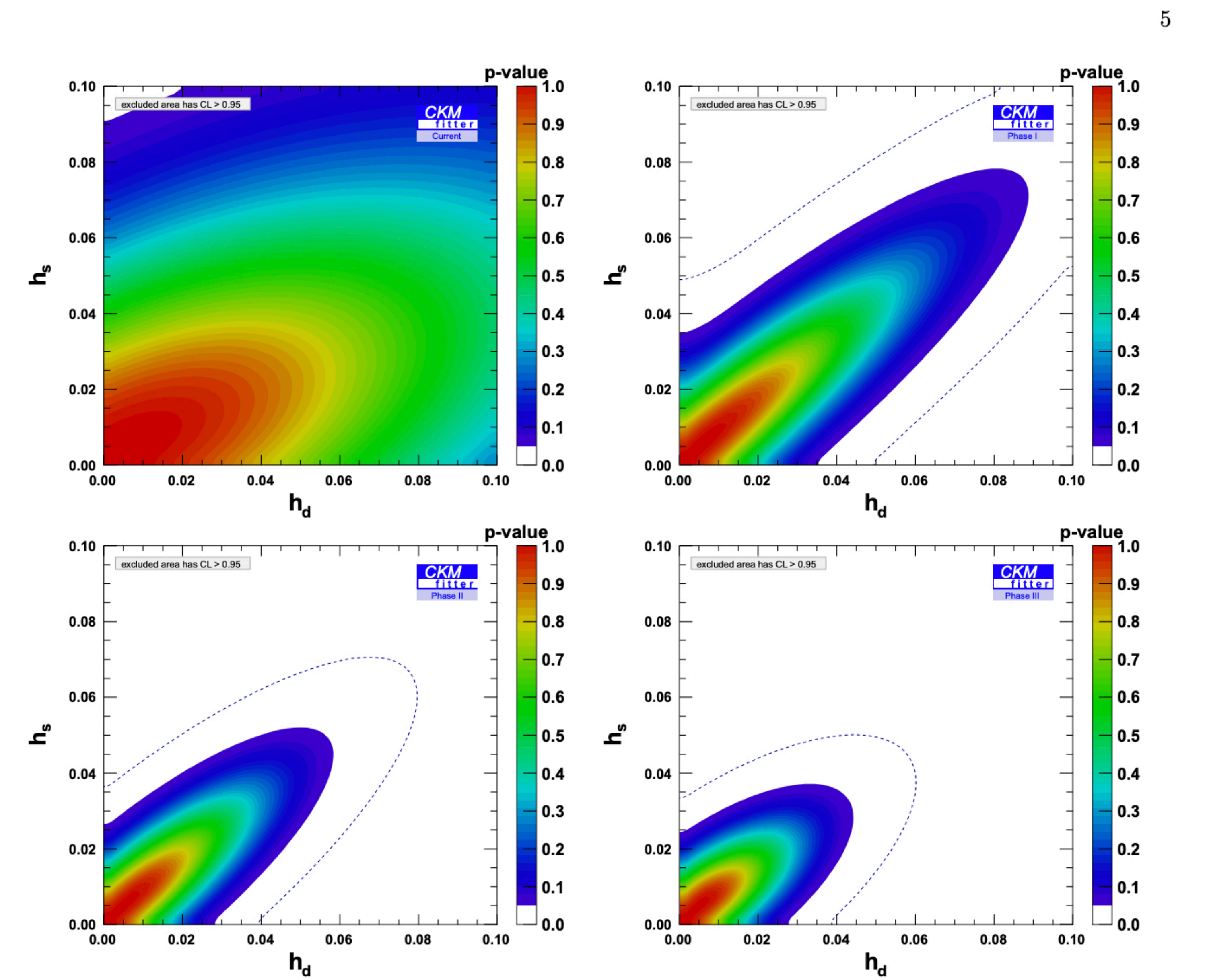


FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in B_d and B_s mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ) contours.

[Charles et al, 2020, PRD, 2006.04824]

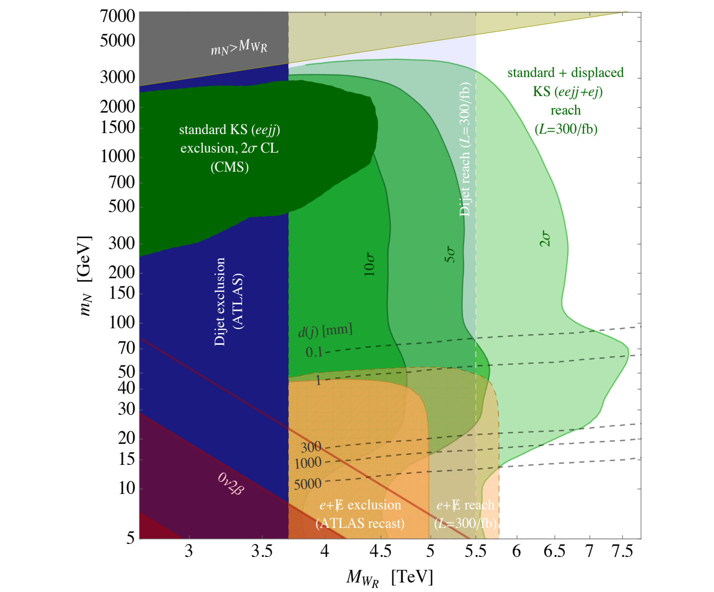
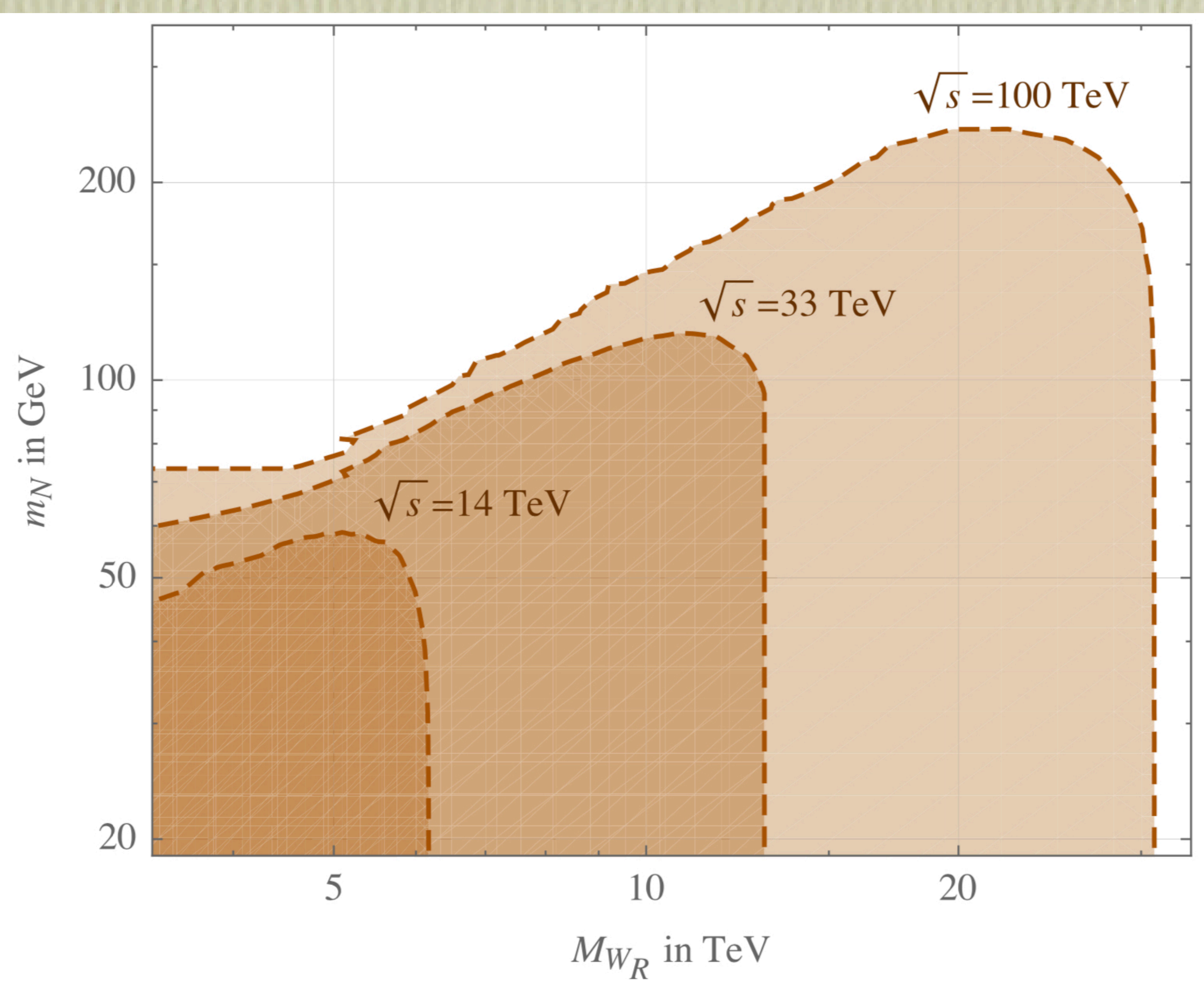


FIG. 9. Summary plot collecting all searches involving the KS process at LHC, in the electron channel. The green shaded areas represent the LH sensitivity to the KS process at 300/fb, according to the present work. The rightmost reaching contour represents the enhancement obtained by considering jet displacement.

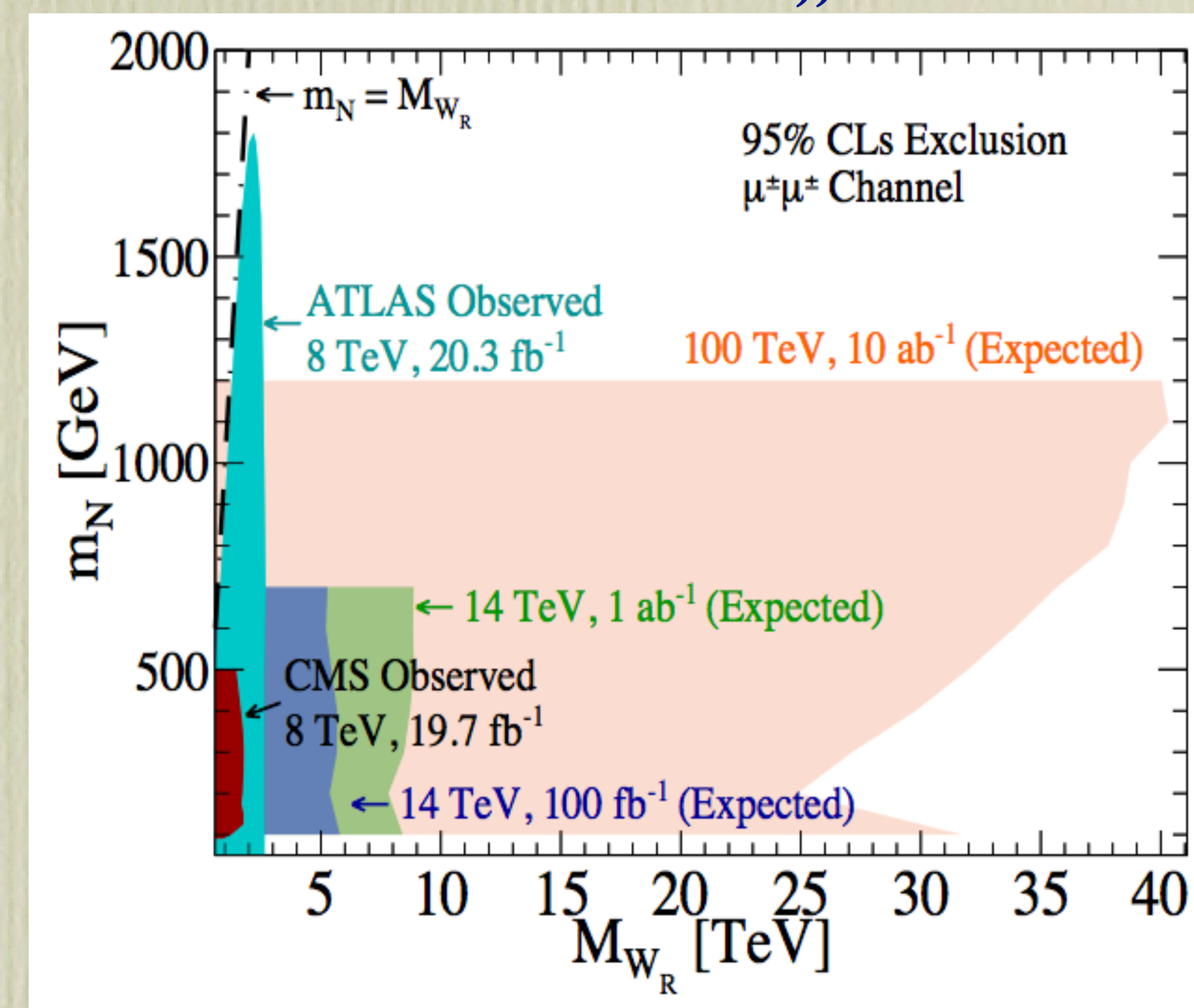
older
100 TeV collider reach

ℓ+MET



[Nemevsek, FN, Popara PRD '18]

KS: $\ell^\pm\ell^\pm jj$



[Ruiz EPJC '17]

CP phases

$$\theta_u + \theta_d \simeq \frac{s_\alpha t_{2\beta}}{2}\left[\sin^2\theta_{12}\left(\frac{2s_s}{m_s} - \frac{s_d}{m_d}\right)(m_c s_c \cos^2\theta_{23} + m_t s_t \sin^2\theta_{23}) - \frac{s_u}{m_u}(m_d s_d \cos^2\theta_{12} + s_s m_s \sin^2\theta_{12})\right] + \frac{s_u - s_d}{2}\pi\,,$$

$$\theta_u + \theta_s \simeq \frac{s_\alpha t_{2\beta}}{2}\left[\cos^2\theta_{12}\frac{s_s}{m_s}(m_c s_c \cos^2\theta_{23} + m_t s_t \sin^2\theta_{23}) - \frac{s_u}{m_u}(m_d s_d \cos^2\theta_{12} + m_s s_s \sin^2\theta_{12})\right] + \frac{s_u - s_s}{2}\pi\,.$$

K to $\pi\pi$ - LR matrix elements

	VSA	χQM	DQCD
$\langle Q_1^{LR} \rangle_0$	-1.8	-3.6	-1.1
$\langle Q_1^{LR} \rangle_2$	0.53	0.33	0.40
$\langle Q_2^{LR} \rangle_0$	-0.62	-1.2	-0.059
$\langle Q_2^{LR} \rangle_2$	0.16	0.092	-0.005

TABLE I. Comparison of $K^0 \to \pi\pi$ matrix elements of the left-right current-current operators $Q_{1,2}^{LR}$ in different approaches. The values are given at the scale of 1 GeV in units of GeV^3 for central values of the relevant input parameters.

$\Delta F = 2$ Hamiltonians

Effective **Hamiltonians** from the box diagrams:

$$\mathcal{H}_{LL}^{\Delta F=2} = \frac{G_F^2 M_{W_L}^2}{4\pi^2} \sum_{d,d'=d,s,b} \bar{d}'\gamma_\mu P_L d\, \bar{d}'\gamma_\mu P_L d \sum_{i,j=c,t} \lambda_i^{LL}\lambda_j^{LL} S_{LL}(x_i,x_j)\,\eta_{LL,ij}$$

$$\mathcal{H}_{LR}^{\Delta F=2} = \frac{G_F^2 M_{W_L}^2}{4\pi^2}\, 8\,\beta \sum_{d,d'=d,s,b} \bar{d}' P_L d\, \bar{d}' P_R d \sum_{i,j=u,c,t} \lambda_i^{LR}\lambda_j^{RL} S_{LR}(x_i,x_j,\beta)\,\eta_{LR,ij}$$

$$\mathcal{H}_{RR}^{\Delta F=2} = \frac{G_F^2 M_{W_L}^2}{4\pi^2}\, \beta \sum_{d,d'=d,s,b} \bar{d}'\gamma_\mu P_R d\, \bar{d}'\gamma_\mu P_R d \sum_{i,j=c,t} \lambda_i^{RR}\lambda_j^{RR} S_{RR}(x_i,x_j,\beta)\,\eta_{RR,ij}$$

where

$$\lambda_i^{AB} = V_{id'}^{A*} V_{id}^{B}\,, \quad x_i = (m_i/M_{W_L})^2\,, \quad \beta = M_{W_L}^2/M_{W_R}^2$$

and **Matrix elements** for meson M^0-$\overline{M}^0$ are:

$$\left\langle M^0 \left| \bar{d}'\gamma_\mu P_L d\, \bar{d}'\gamma_\mu P_L d \right| \overline{M}^0 \right\rangle = \frac{2}{3} f_M^2 m_M \mathcal{B}_M^{LL}$$

$$\left\langle M^0 \left| \bar{d} P_L d'\, \bar{d} P_R d' \right| \overline{M}^0 \right\rangle = \frac{1}{2} f_M^2 m_M \mathcal{B}_M^{LR} \left[\left(\frac{m_M}{m_{d'} + m_d} \right)^2 + \frac{1}{6} \right].$$

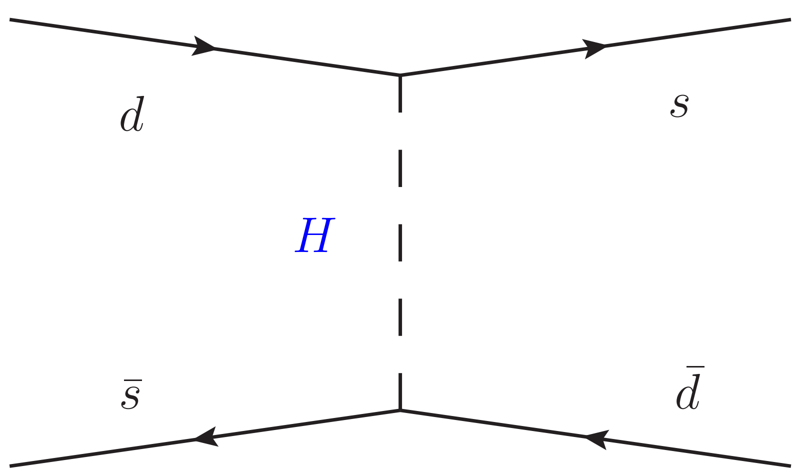
ΔF = 2 FC Higgs

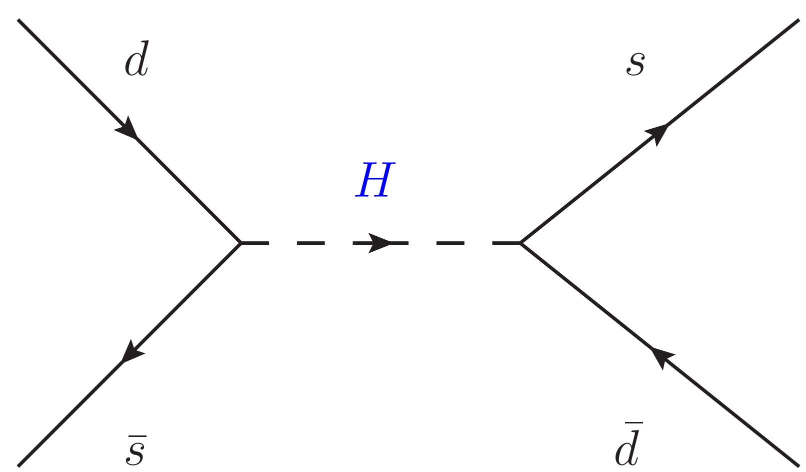
Effective **Hamiltonians** from the tree level Higgs:

$$\mathcal{H}_H^{\Delta F=2} = -\frac{4G_F}{\sqrt{2}M_H^2} \sum_{d,d'=d,s,b} \bar{d}' P_L d \, \bar{d}' P_R d \sum_{i,j=u,c,t} \lambda_i^{LR} \lambda_j^{RL} m_i m_j \,,$$

where again

$$\lambda_i^{AB} = V_{id'}^{A*} V_{id}^{B} \,, \quad x_i = (m_i/M_{W_L})^2$$





KS process vs background

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

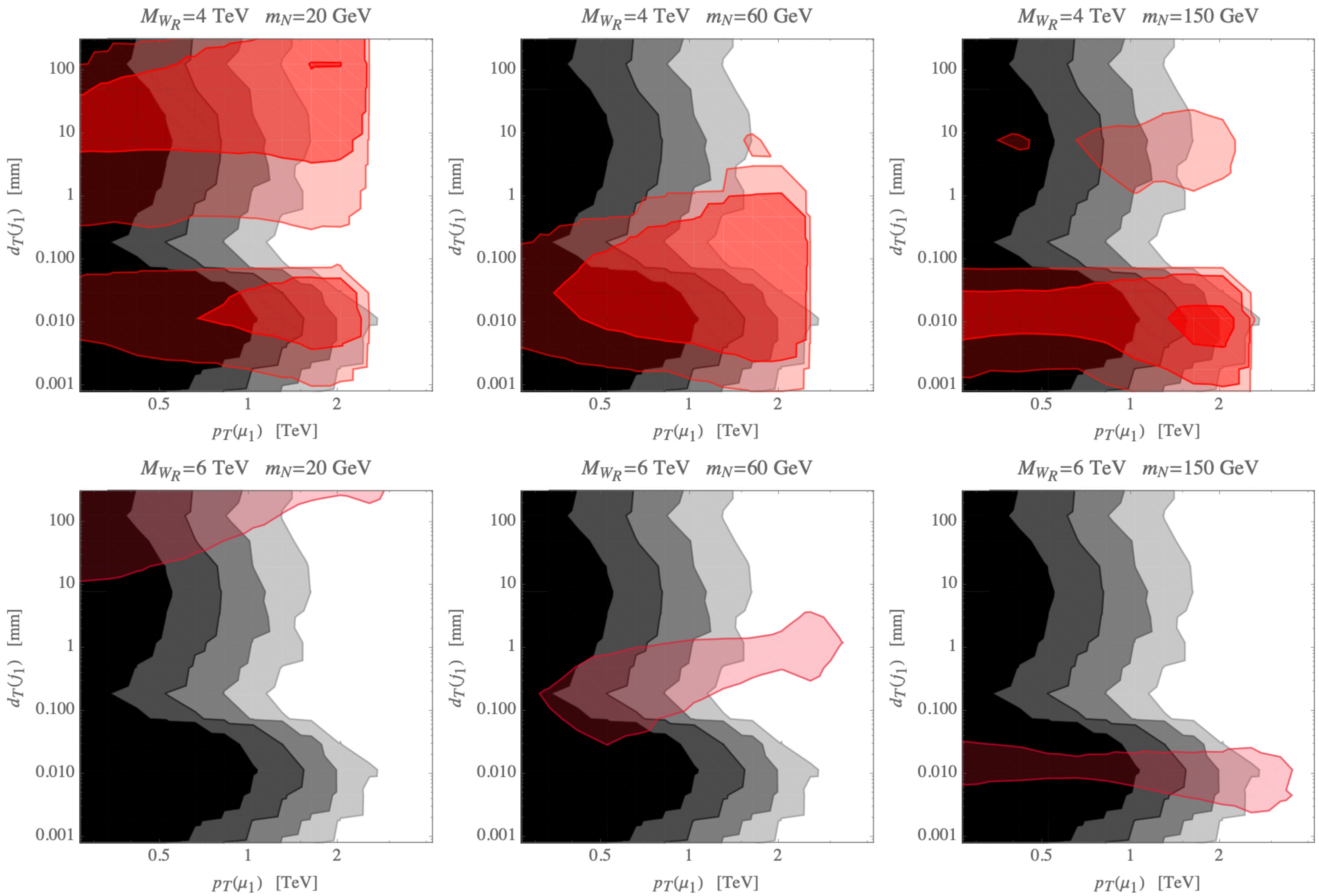


FIG. 6. Event distribution in p_T and displacement of the hardest jet. Shown are background (gray) and signal (red) for some sample values of $M_{W_R} = 4, 6$ TeV (upper, lower) and $m_N = 20, 60, 150$ GeV (left to right). The distributions are exemplified with a binning grid of 15×15, the increasingly dark shading referring to bins with respectively more than 0.1, 1, 10, 100 events.

Signal VS background with displacement

How Right is W_R ?

LHC is pp symmetric: not possible to use a simple A_{FB} asymmetry of W_R .

- Use the first decay $W_R \to eN$.
    - Determine the W_R direction (from the full event)
    - Identify the first lepton. (the more energetic)
    - Its asymmetry wrt the W_R direction gives the 'Right' chirality.
- It is necessary to efficiently distinguish the two leptons. (Easier for $M_N \sim 0.7\ M_{W_R}$ [Ferrari '00])
- Also the subsequent decay $N \to ljj$ may be used.

Polarization visible in a wide range of masses M_N, M_{W_R}.

LNVH

LNVH in other models_

- Seesaw type-I and III: $h \to \nu N$ decay may turn into $h \to NN$ LNV decays, by paying a price of M_{Dirac}. However, mixing is now excluded [CMS-EXO-12-057]

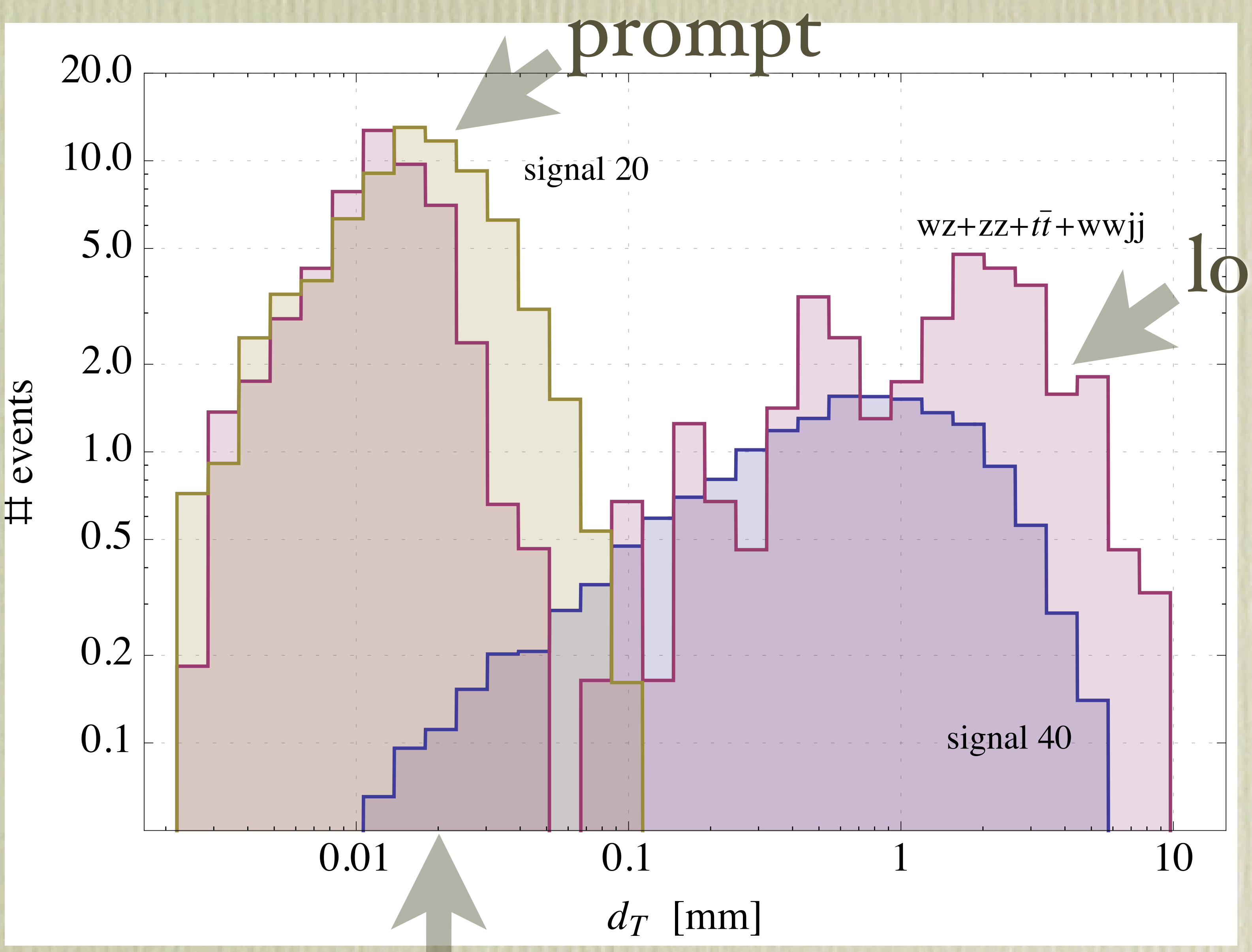
- SUSY with R-parity violation [Allanach, Kom, Pas '09] Not excluded, need a dedicated study, e.g. [T. Banks, JHEP '08]. Current limits pose a challenge.

- Scalar singlet + N ok, but no neutrino connection [Graesser '07][Shoemaker+ '10]

- Simplified model may be B-L spontaneous breaking.

Our analysis applies to generic models / lifetime scenarios.

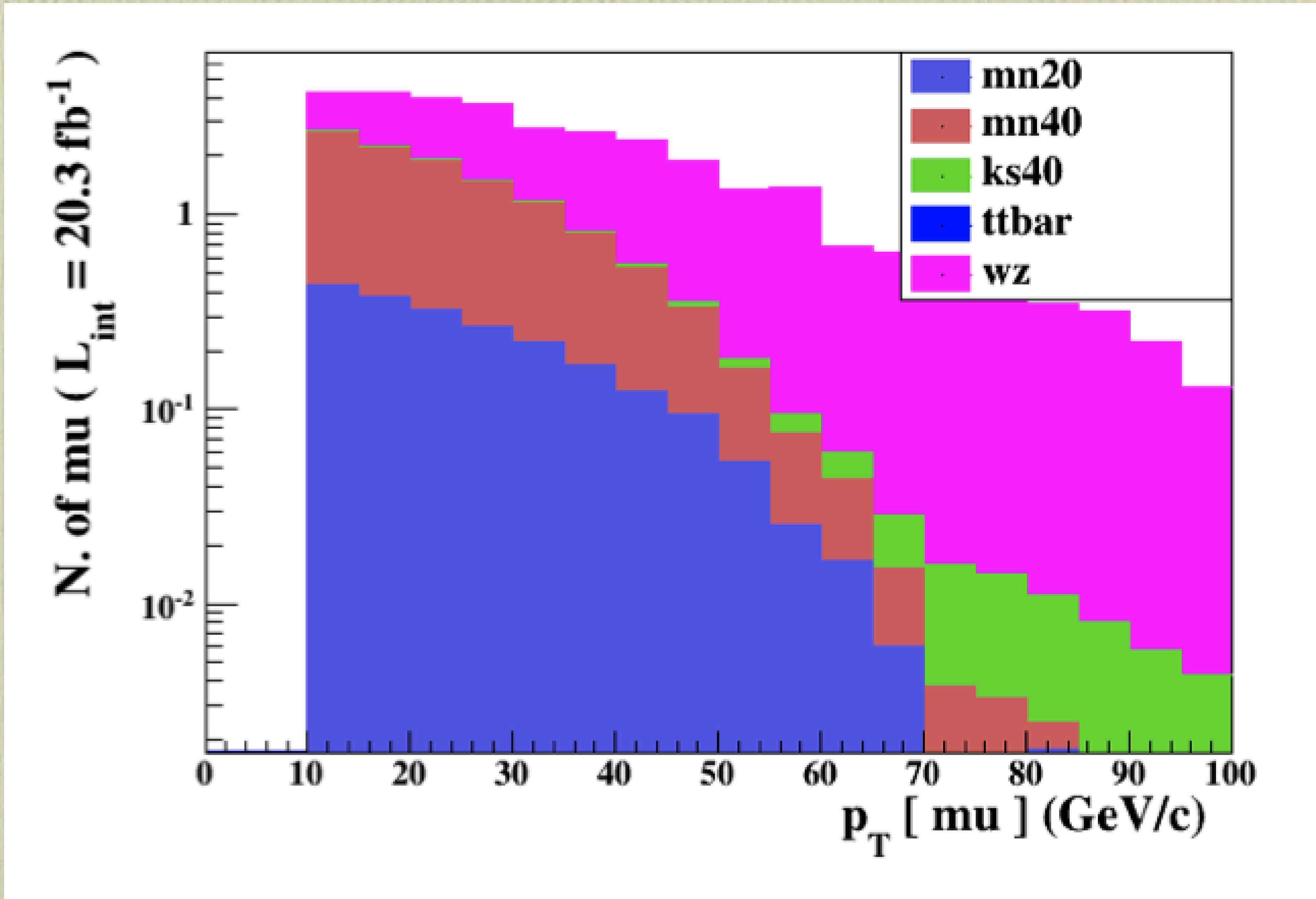
displaced vertices after cuts



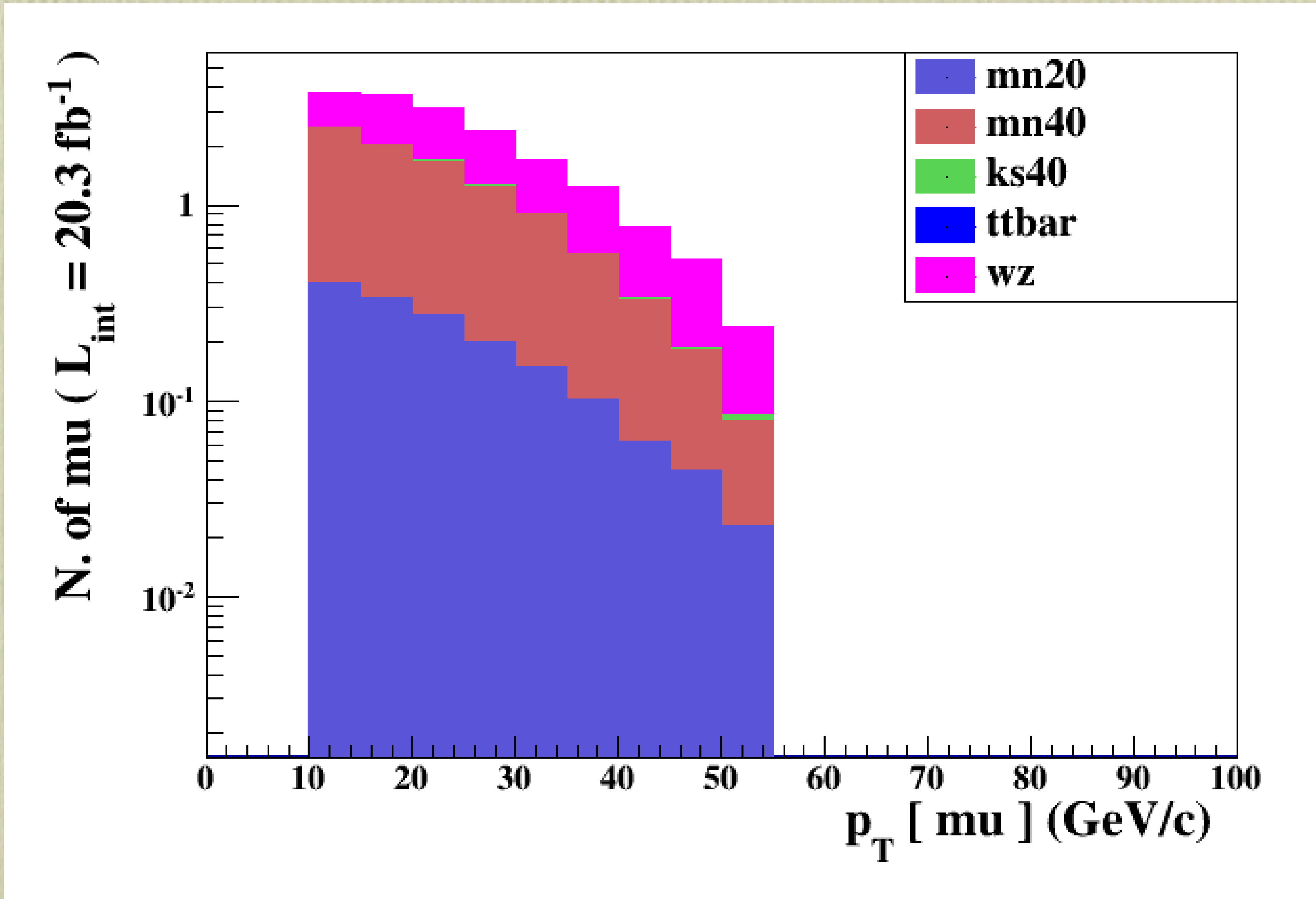
Track vertex resolution ~ 20 μm

We cut on a sliding window function of m_N

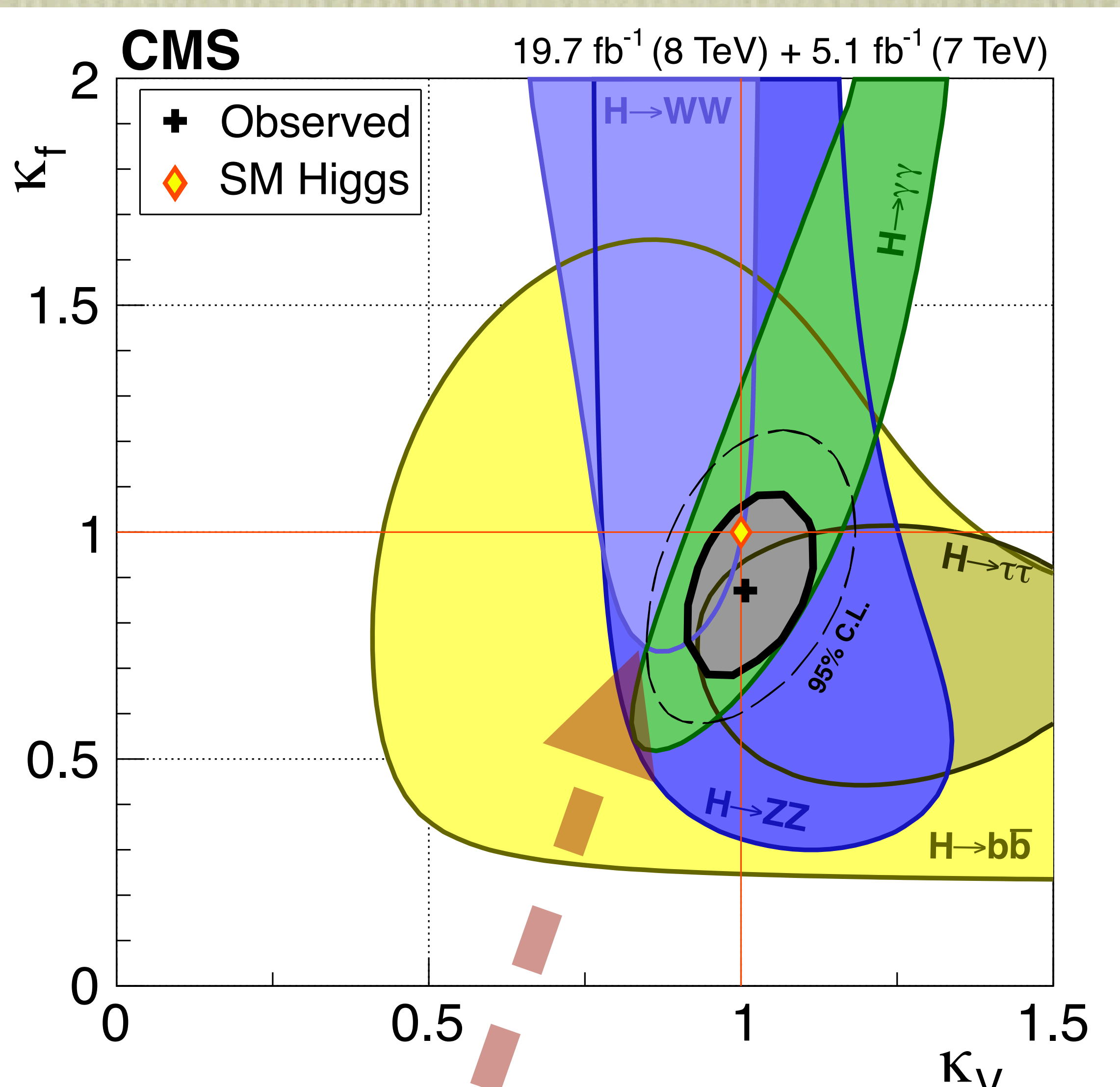
muon P_T - before/after cuts



muon P_T - before/after cuts



...allowed Higgs mixing?



[CMS PAS HIG-14-009]

[Falkowski Gross Lebedev]

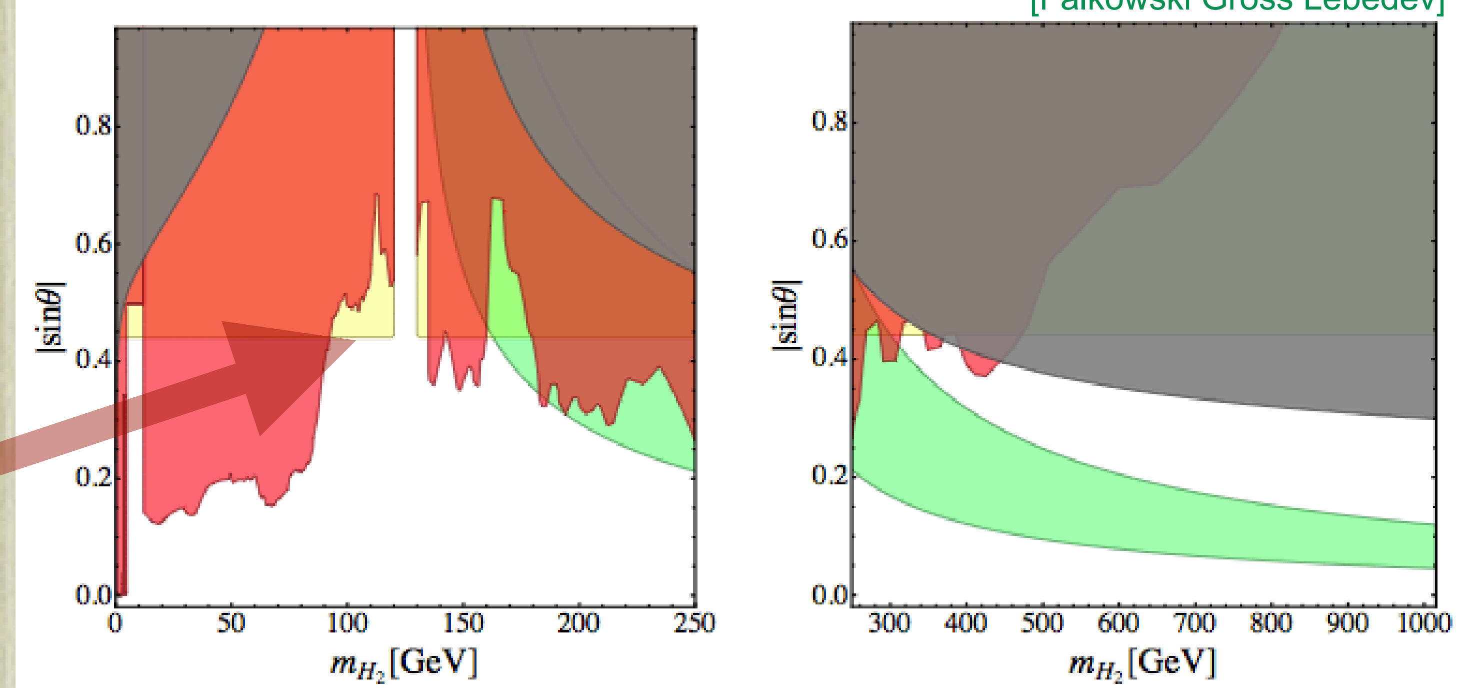


Figure 3: Left: Parameter space (for $m_{H_2} \leq 2m_{H_1}$) excluded at 95 % CL by direct searches (red), precision tests (gray), and H_1 couplings measurements (yellow). For

sinθ~40% possible (95%CL)

[Pruna+ PRD '13; Profumo+ PRD '15; Chen+ PRD '15 ; Robens+ EPJC '15 Martin-Lozano+ 1501.03799; Falkowski Gross Lebedev 1502.01361; Godunov+ 1503.01618]

$h \to NN$ - large decay rate

$$\frac{\Gamma_{NN}}{\Gamma_{b\bar{b}}} \simeq \frac{\theta^2}{3}\left(\frac{m_N}{m_b}\right)^2\left(\frac{M_W}{M_{W_R}}\right)^2\left(1-\frac{4m_N^2}{m_h^2}\right)^{\frac{3}{2}}$$

h to *NN* first mentioned in LR by [Gunion+ '89]

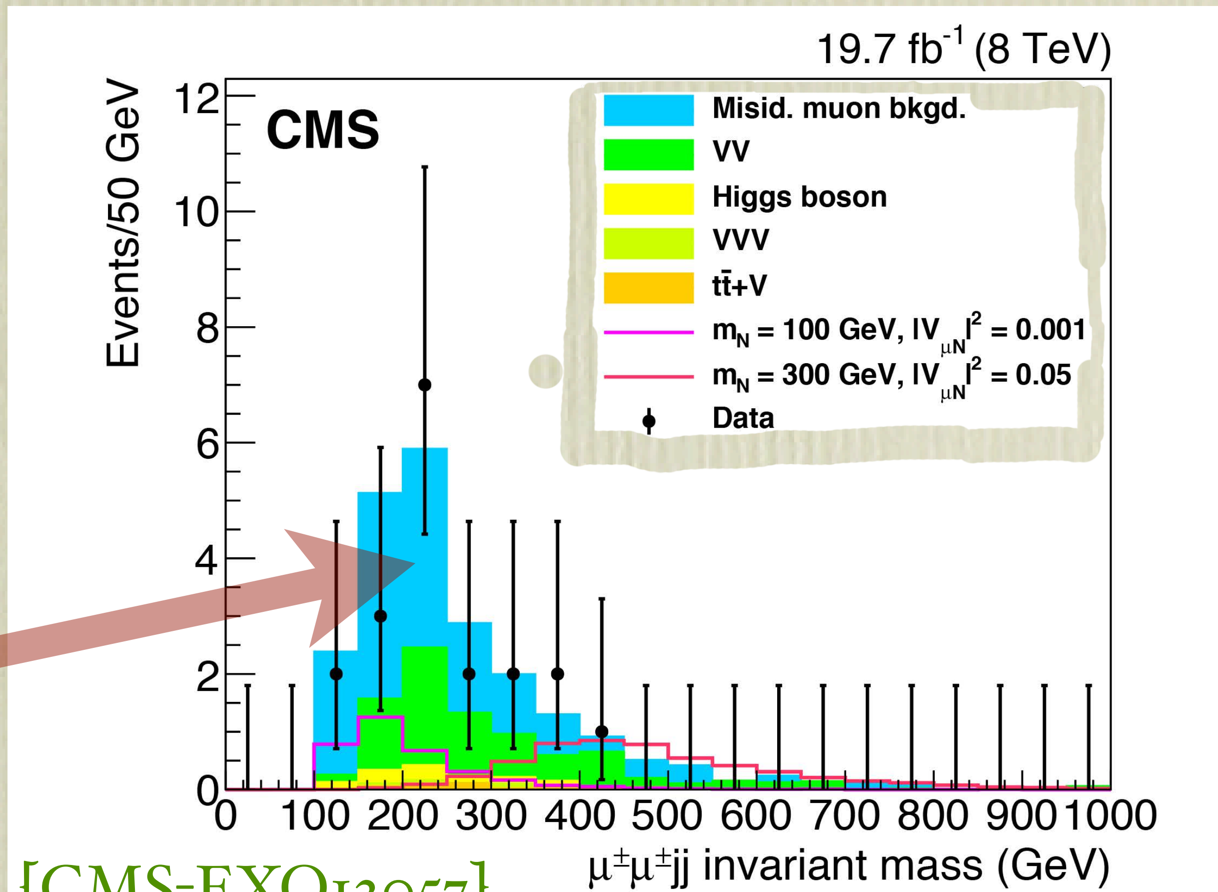
Graesser studied effective operators: [Graesser PRD 76 (2007) 075006; arXiv:0705.2190]

SM Background, same sign

- Electron channel - forget it:
  charge misidentification + photoproduction
  need to be experimentally measured

- Muon channel: challenging
  - prompt muons from *WZ+ZZ+VVjj+ttbar*
  - nonprompt muons from
    QCD jets +
    hadron misidentified
    as a muon

To be measured
in control regions.
We try to estimate it



[CMS-EXO12057]

Basic cuts and Event count

- Model implemented w/ Feynrules (extension of [Roitgrund+ 1401.3345])
  (available at https://sites.google.com/site/leftrighthep)
- Collider simulation with Madgraph5+Pythia6+Delphes3
- *WZ+ZZ+WW2j+ttbar* simulated, QCD estimated =*2.5 factor

Cuts [GeV]

$\not{E} < 30$
$P_T(\mu) < 55$
$M(\mu\mu) < 80$
$M_T(\mu\, \not{p}_T) < 30$

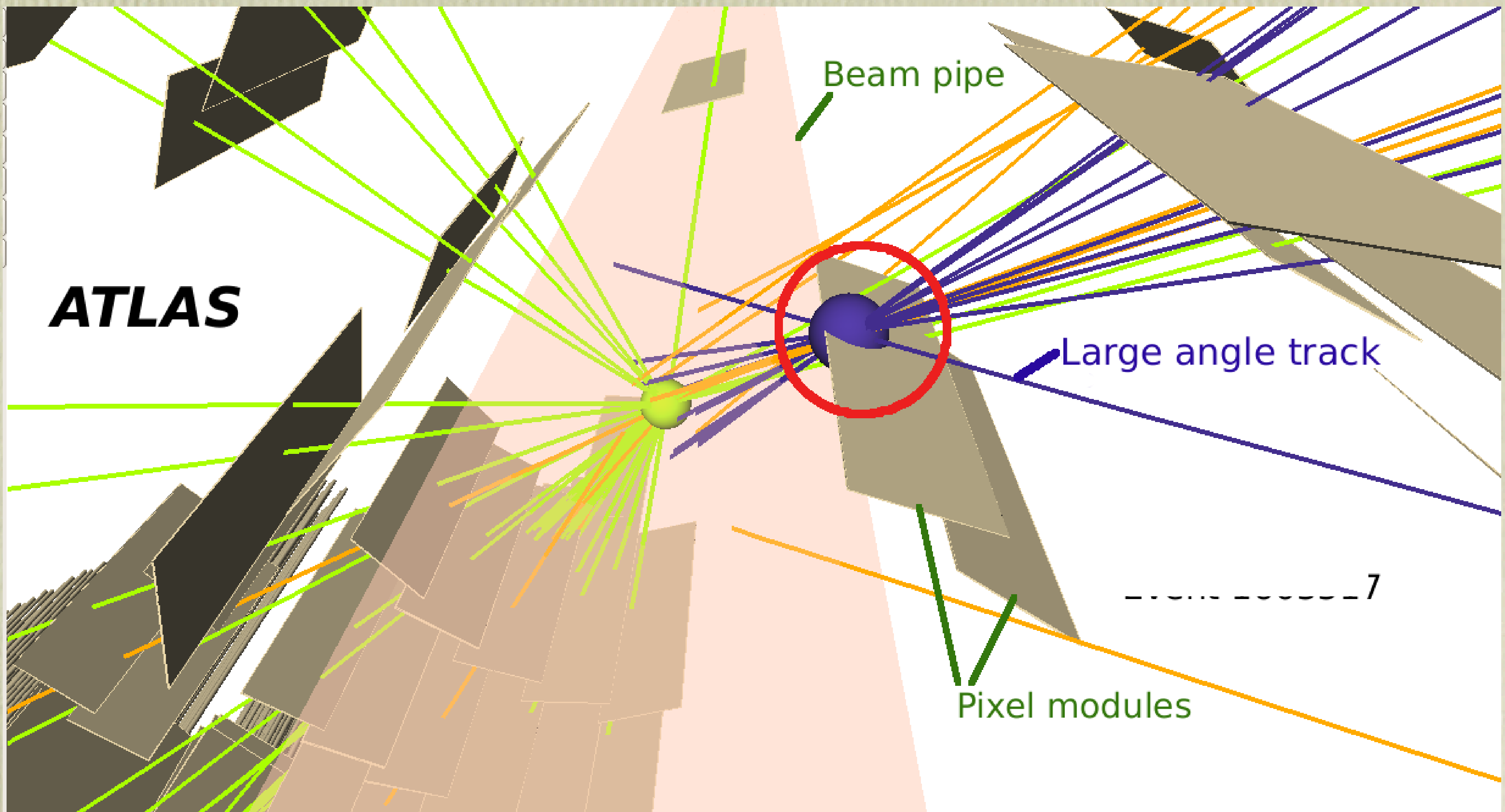
$\Delta R < 0.4$, etc.
min $P_T(j)$=20
isol μ >0.3
min $P_T(\mu)$=10

Process	No cuts	Imposed cuts				
		$\mu^\pm\mu^\pm + n_j$	$\not{E}_T$	p_T	m_T	$m_{\rm inv}$
WZ	2 M	544	143	78	40	20
ZZ	1 M	55	29	16	12	8
$W^\pm W^\pm 2j$	389	115	16	5	3	1
$t\bar{t}$	10 M	509	97	40	22	14
Signal (20)	254	11	11	10	9	8
Signal (40)	543	44	43	41	38	37

TABLE I. Number of expected events at the 13 TeV LHC run with 100 fb^{-1} collected luminosity after sequential cuts described in the text. The signal is generated with $m_N = 20$ and 40 GeV, $\sin\theta = 10\,\%$, $M_{W_R} = 3$ TeV and $n_j = 1, 2, 3$.

s:37 vs b:100
already
sensitive

On top, let's take advantage of vertex displacement...


ATLAS
Beam pipe
Large angle track
Pixel modules

Simulation and Displaced Vertices

- *Madgraph 5* event generator - updated
  (module to add decay time in parton events)
- *Pythia 6* hadronization (writes lifetime in stdhep)
- *Delphes 3* detector - updated
  (new module for vertex track resolution smearing)
  (extended lhco format to hold vertex info)
- *Madanalysis 5* analysis package - updated
  (to read new formats and treat displacement)

(...becoming a complete suite)

LNV Higgs - displaced vertices

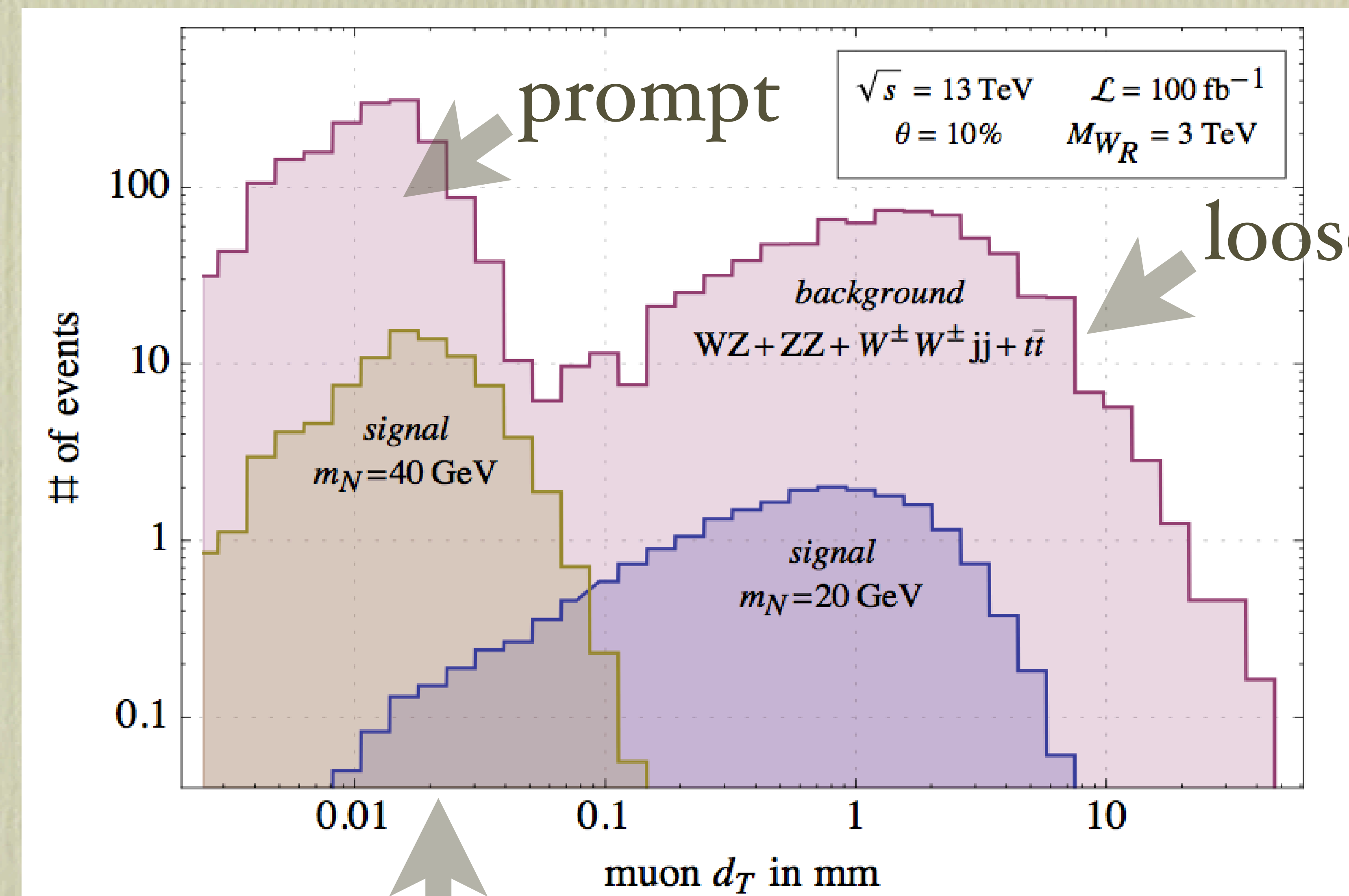


FIG. 3. Reconstructed transverse muon displacement after $\mu^\pm\mu^\pm+n_j$ event selection and before other cuts.

We cut on a sliding window function of m_N

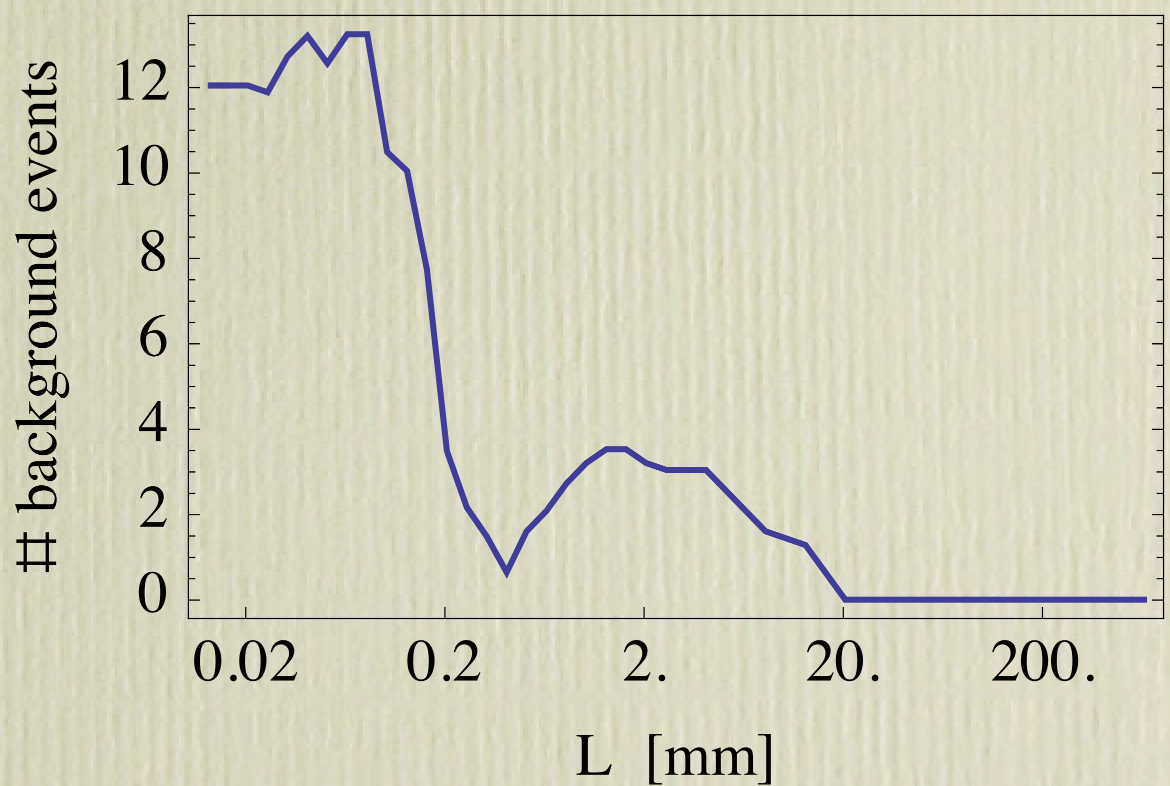
Track vertex resolution ~ 20 μm

Displaced vertices power

- Background: usually one prompt + one loose muon
- Signal: muons are both displaced

  N lifetime depending on m_N and M_{WR}

- Thus we require two displacements, and employ a sliding window cut: $L/10 < d_T < L*5$
- Background is greatly reduced:



- For each N mass/lifetime, we optimize on L.

Improvements
Challenges

- Relax minimum muon P_T below 10GeV?
  (x 2 more signal!)
- Tighter missing energy? <20GeV?
- Go to better jet recognition/substructure
- Displaced jets (naively doable)
- Displacements vs pileup problems?
- Triggering at low pt?

Joint study with Atlas

NB: need one loop EFT

- At such small $m_\Delta{}^2$…
  trilinear couplings as ΔΔΔ or hΔΔ are loop dominated:

$\rho_1 \sim 10^{-4}$ (!) $\alpha_3 \sim 20$ (!) $m_H{}^2 \sim (20\text{TeV})^2$

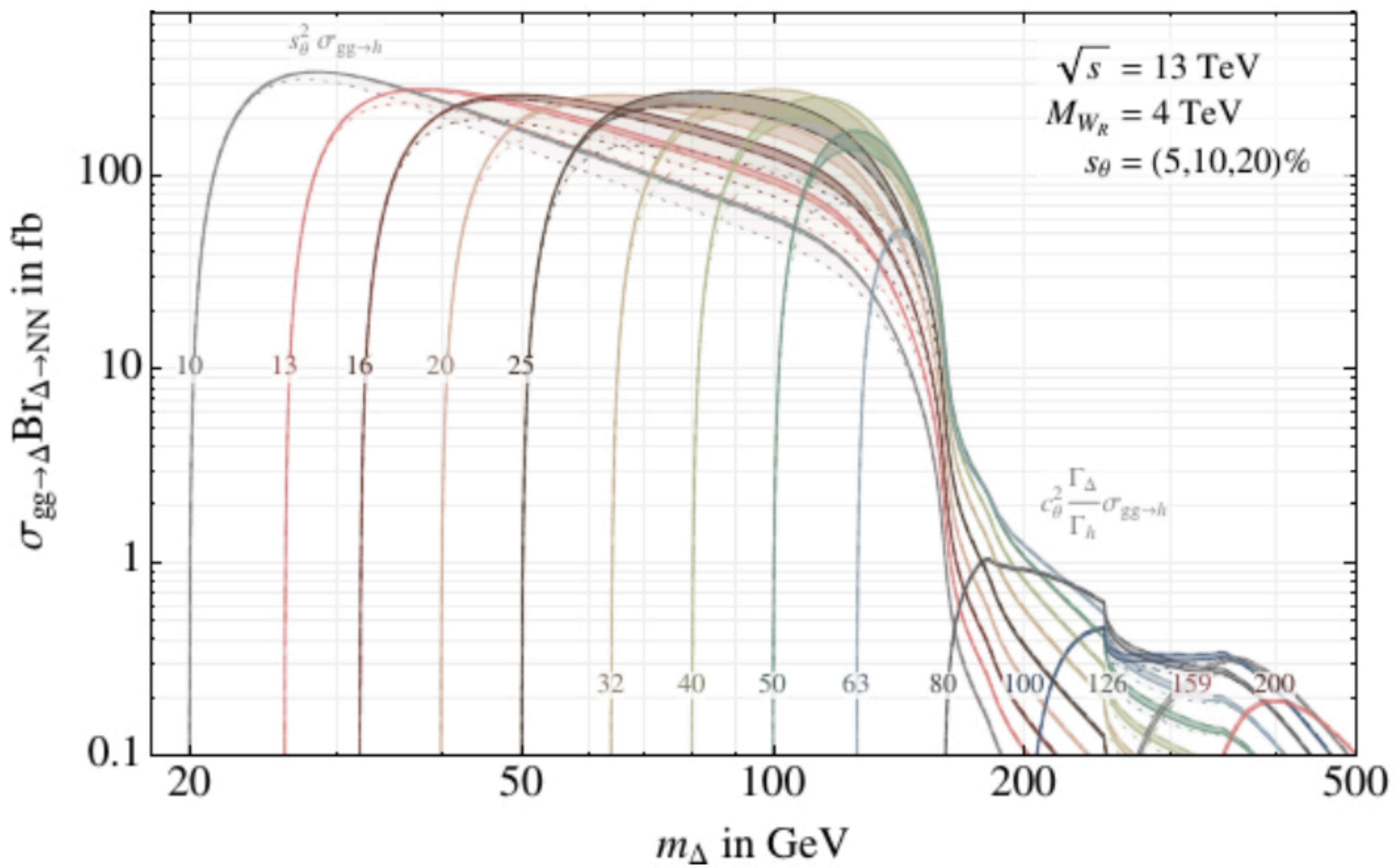
$$\mathcal{V}_{eff} = 4v_R^2\rho_1 {\Delta_R^0}^2 + \left[4\rho_1 + \frac{2}{(4\pi)^2}\left(\frac{4}{3}\alpha_3^2 + 18\rho_1^2\right)\right] v_R {\Delta_R^0}^3 + \left[\rho_1 + \frac{1}{(4\pi)^2}\left(\frac{8}{3}\alpha_3^2 + 27\rho_1^2\right)\right] {\Delta_R^0}^4 + \mathcal{O}\left({\Delta_R^0}^5\right). \quad (18)$$

[A. Maiezza, M. Nemevsek, FN PRD '16]

More couplings and fields involved…

Tree level potential (neutrals only)

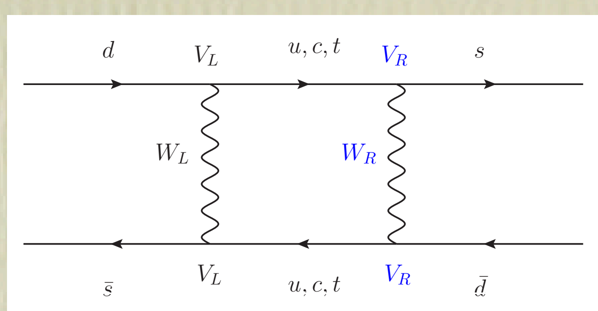
$$
\begin{aligned}
&\frac{1}{8}\Big(2\,\lambda1\,h^4 + 2\,\lambda2\,h^4 + \lambda3\,h^4 + 8\sqrt{2}\,\epsilon\,\lambda1\,h^3 + 8\sqrt{2}\,\epsilon\,\lambda2\,h^3 + 4\sqrt{2}\,\epsilon\,\lambda3\,h^3 + 8\,H\,\lambda2\sin(2\,\beta)\,h^3 + \\
&\quad 2\,\alpha1\,\Delta0^2\,h^2 + \alpha3\,\Delta0^2\,h^2 - 4\,\mu1^2\,h^2 + 4\,\alpha1\,h^2 + 2\,\alpha3\,h^2 + 4\sqrt{2}\,\alpha1\,\Delta0\,h^2 + 2\sqrt{2}\,\alpha3\,\Delta0\,h^2 + 4\,H^2\,\lambda1\,h^2 + \\
&\quad 24\,\epsilon^2\,\lambda1\,h^2 + 4\,H^2\,\lambda2\,h^2 + 24\,\epsilon^2\,\lambda2\,h^2 + 2\,H^2\,\lambda3\,h^2 + 12\,\epsilon^2\,\lambda3\,h^2 - 8\sqrt{2}\,\epsilon\,\mu1^2\,h + 4\sqrt{2}\,\alpha1\,\Delta0^2\,\epsilon\,h + \\
&\quad 2\sqrt{2}\,\alpha3\,\Delta0^2\,\epsilon\,h + 8\sqrt{2}\,\alpha1\,\epsilon\,h + 4\sqrt{2}\,\alpha3\,\epsilon\,h + 16\,\alpha1\,\Delta0\,\epsilon\,h + 8\,\alpha3\,\Delta0\,\epsilon\,h + 8\sqrt{2}\,H^2\,\epsilon\,\lambda1\,h + \\
&\quad 8\sqrt{2}\,H^2\,\epsilon\,\lambda2\,h + 4\sqrt{2}\,H^2\,\epsilon\,\lambda3\,h - 8\,H^3\,\lambda2\sin(2\,\beta)\,h + 2\,H^2\,\alpha1\,\Delta0^2 + H^2\,\alpha3\,\Delta0^2 + 4\,\alpha1\,\Delta0^2\,\epsilon^2 + 2\,\alpha3\,\Delta0^2\,\epsilon^2 + \\
&\quad 8\,\alpha1\,\epsilon^2 + 4\,\alpha3\,\epsilon^2 + 8\sqrt{2}\,\alpha1\,\Delta0\,\epsilon^2 + 4\sqrt{2}\,\alpha3\,\Delta0\,\epsilon^2 - 4\,H^2\,\mu1^2 - 8\,\epsilon^2\,\mu1^2 - 4\,\Delta0^2\,\mu3^2 - 8\sqrt{2}\,\Delta0\,\mu3^2 - \\
&\quad 8\,\mu3^2 - \left(h^4 + 4\sqrt{2}\,\epsilon\,h^3 - 6\left(H^2 - 2\,\epsilon^2\right)h^2 - 12\sqrt{2}\,H^2\,\epsilon\,h + H^4 - 12\,H^2\,\epsilon^2\right)(2\,\lambda2 + \lambda3)\cos^2(\beta) + \\
&\quad \left(h^4 + 4\sqrt{2}\,\epsilon\,h^3 - 6\left(H^2 - 2\,\epsilon^2\right)h^2 - 12\sqrt{2}\,H^2\,\epsilon\,h + H^4 - 12\,H^2\,\epsilon^2\right)(2\,\lambda2 + \lambda3)\sin^2(\beta) + \\
&\quad 4\,H^2\,\alpha1 + 2\,H^2\,\alpha3 + 4\sqrt{2}\,H^2\,\alpha1\,\Delta0 + 2\sqrt{2}\,H^2\,\alpha3\,\Delta0 + 2\,H^4\,\lambda1 + 8\,H^2\,\epsilon^2\,\lambda1 + 2\,H^4\,\lambda2 + \\
&\quad 8\,H^2\,\epsilon^2\,\lambda2 + H^4\,\lambda3 + 4\,H^2\,\epsilon^2\,\lambda3 + 2\,\Delta0^4\,\rho1 + 8\sqrt{2}\,\Delta0^3\,\rho1 + 24\,\Delta0^2\,\rho1 + 16\sqrt{2}\,\Delta0\,\rho1 + 8\,\rho1 + \\
&\quad 2\Big(2\,\lambda4\,h^4 + 8\sqrt{2}\,\epsilon\,\lambda4\,h^3 + 4\left(6\,\epsilon^2\,\lambda4 - \mu2^2\right)h^2 + \left(H\,\alpha3\left(\Delta0^2 + 2\sqrt{2}\,\Delta0 + 2\right) - 8\sqrt{2}\,\epsilon\,\mu2^2\right)h + \\
&\qquad 4\,H^2\,\mu2^2 - 8\,\epsilon^2\,\mu2^2 + \sqrt{2}\,H\,\alpha3\,\Delta0^2\,\epsilon + 2\sqrt{2}\,H\,\alpha3\,\epsilon + 4\,H\,\alpha3\,\Delta0\,\epsilon - 2\,H^4\,\lambda4 + \\
&\qquad 2\,\alpha2\left(\left(\Delta0^2 + 2\sqrt{2}\,\Delta0 + 2\right)h^2 + 2\left(\sqrt{2}\,\Delta0^2 + 4\,\Delta0 + 2\sqrt{2}\right)\epsilon\,h - \left(\Delta0^2 + 2\sqrt{2}\,\Delta0 + 2\right)\left(H^2 - 2\,\epsilon^2\right)\right)\cos(\delta2)\Big)\sin(\beta) + \\
&\quad \cos(\beta)\Big(8\,H\,\lambda4\,h^3 - \alpha3\,\Delta0^2\,h^2 - 2\,\alpha3\,h^2 - 2\sqrt{2}\,\alpha3\,\Delta0\,h^2 + 24\sqrt{2}\,H\,\epsilon\,\lambda4\,h^2 - 16\,H\,\mu2^2\,h - 2\sqrt{2}\,\alpha3\,\Delta0^2\,\epsilon\,h - 4\sqrt{2}\,\alpha3\,\epsilon \\
&\qquad\quad h - 8\,\alpha3\,\Delta0\,\epsilon\,h + 8\,H^3\,\lambda4\,h + 48\,H\,\epsilon^2\,\lambda4\,h + H^2\,\alpha3\,\Delta0^2 - 2\,\alpha3\,\Delta0^2\,\epsilon^2 - 4\,\alpha3\,\epsilon^2 - 4\sqrt{2}\,\alpha3\,\Delta0\,\epsilon^2 - 16\sqrt{2}\,H\,\epsilon\,\mu2^2 + \\
&\qquad 2\,H^2\,\alpha3 + 2\sqrt{2}\,H^2\,\alpha3\,\Delta0 + 8\sqrt{2}\,H^3\,\epsilon\,\lambda4 + 8\,H\,\alpha2\left(h\left(\Delta0^2 + 2\sqrt{2}\,\Delta0 + 2\right) + \left(\sqrt{2}\,\Delta0^2 + 4\,\Delta0 + 2\sqrt{2}\right)\epsilon\right)\cos(\delta2) + \\
&\qquad 8\,H\left(\lambda3\,h^3 + 3\sqrt{2}\,\epsilon\,(2\,\lambda2 + \lambda3)\,h^2 + \left(6\,\epsilon^2\,(2\,\lambda2 + \lambda3) - H^2\,\lambda3\right)h - \sqrt{2}\,H^2\,\epsilon\,\lambda3\right)\sin(\beta)\Big) - 8\sqrt{2}\,H^3\,\epsilon\,\lambda2\sin(2\,\beta)\Big)
\end{aligned}
$$


$s_\theta^2\ \sigma_{gg\to h}$
$\sqrt{s}$ = 13 TeV
M_{W_R} = 4 TeV
s_θ = (5,10,20)%
100
10
1
0.1
$\sigma_{gg\to\Delta}\mathrm{Br}_{\Delta\to NN}$ in fb
10
13
16
20
25
32
40
50
63
80
100
126
159
200
$c_\theta^2 \frac{\Gamma_\Delta}{\Gamma_h}\sigma_{gg\to h}$
20
50
100
200
500
m_Δ in GeV

Kaon CP versus Strong CP

Kaons: ε, ε′

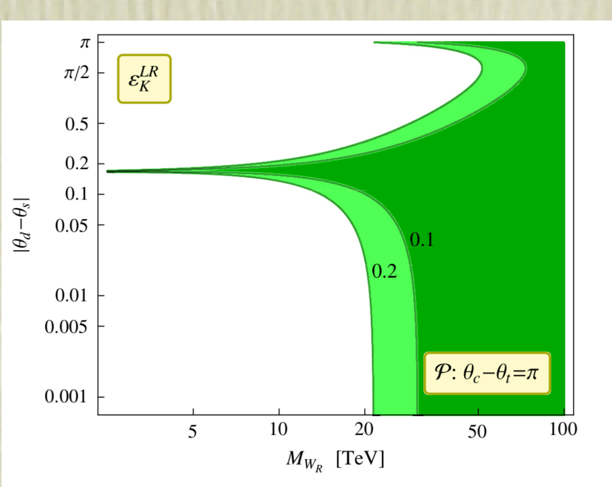
(measure of New Physics h=NP/EXP)



- h_ε<10% correlates θ_d and θ_s, for low W_R:

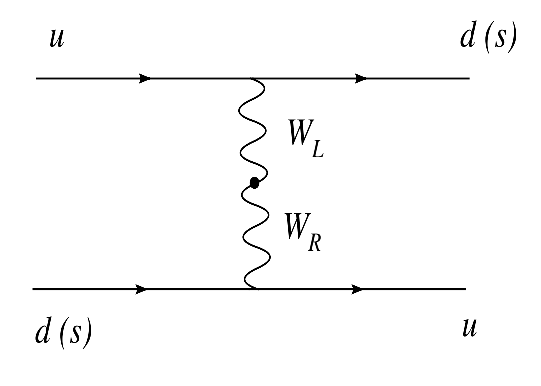
$$C)\ |\sin(\theta_s-\theta_d)| < \left(\frac{M_{W_R}}{71\ \text{TeV}}\right)^2 \longrightarrow \theta_s\text{-}\theta_d \sim 0$$

$$P)\ |\sin(\theta_s-\theta_d-0.16)|_{s_c s_t=1} < \left(\frac{M_{W_R}}{71\ \text{TeV}}\right)^2 \longrightarrow \theta_s\text{-}\theta_d \sim 0.16$$



- ε′ mediated by LR mixing ζ ....

$$h_{\varepsilon'} \simeq 0.92\times 10^6\,|\zeta|\left[\sin(\alpha-\theta_u-\theta_d)+\sin(\alpha-\theta_u-\theta_s)\right]$$



So, a single combination is relevant, e.g. (α - θ_u - θ_d).

Let's see strong CP…

θ_{QCD} and arg det M in LRSM

- Case of C: both are free - no prediction.
- Case of P: fix θ_{QCD} zero at high scale, but after spontaneous P breaking, arg det M is calculable:

$$\bar{\theta} \simeq \frac{1}{2} s_\alpha \, t_{2\beta} \, \mathrm{Re}\,\mathrm{tr}\left(m_u^{-1} V m_d V^\dagger - m_d^{-1} V^\dagger m_u V\right)$$

Then → EDM limit requires vanishing $s_\alpha t_{2\beta}$

Then → all phases vanish

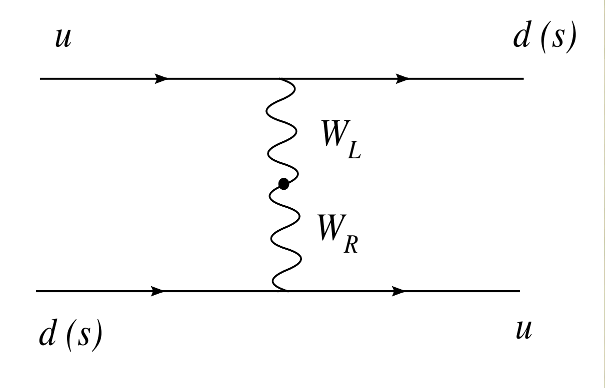
Then → h_ε constraint can only be satisfied if

$$M_{W_R} \gtrsim 30\text{TeV}$$

[Maiezza Nemevsek PRD '14]

Situation changes if some mechanism (like PQ) cancels $\bar{\theta}$ *...*

nEDM ? Even with $\bar{\theta} = 0$ (PQ?) still CP is broken - I



- W_L-W_R exchange brings CP violation in effective operators, as $Q_{ud} = (\bar{u}d)_L(\bar{d}u)_R$. Rearranged:

$$\mathcal{O}_1^{q'q} = \bar{q}'q'\bar{q}i\gamma_5 q, \qquad \mathcal{O}_2^{q'q} = \bar{q}'_\alpha q'_\beta \bar{q}_\beta i\gamma_5 q_\alpha,$$

$$\mathcal{O}_3^{q'q} = \bar{q}'\sigma^{\mu\nu}q'\,\bar{q}\sigma_{\mu\nu}i\gamma_5 q,$$

$$\mathcal{O}_4^{q'q} = \bar{q}'_\alpha\sigma^{\mu\nu}q'_\beta\,\bar{q}_\beta\sigma_{\mu\nu}i\gamma_5 q_\alpha,$$

$$\mathcal{O}_1^q = \bar{q}q\bar{q}i\gamma_5 q, \qquad \mathcal{O}_2^q = \bar{q}\sigma_{\mu\nu}q\,\bar{q}\sigma^{\mu\nu}i\gamma_5 q,$$

$$\mathcal{O}_3^q = -\frac{e}{16\pi^2}e_q m_q\,\bar{q}\sigma_{\mu\nu}i\gamma_5 q F^{\mu\nu},$$

$$\mathcal{O}_4^q = -\frac{g_s}{16\pi^2}m_q\bar{q}\sigma_{\mu\nu}i\gamma_5 T^a q G^{a\mu\nu},$$

$$\mathcal{O}_5 = -\frac{1}{3}\frac{g_s}{16\pi^2}f^{abc}G^a_{\mu\sigma}G^{b,\sigma}_{\nu}\tilde{G}^{c,\mu\nu}.$$

- Run at low-energy...

- ...and bosonize:
  $\rightarrow$ CPV operators in meson Chiral Lagrangian, e.g.

$$+\,iC_{1qq'}\,c_3\left([U^\dagger]_{qq}[U]_{q'q'} - [U]_{qq}[U^\dagger]_{q'q'}\right)$$

(Low energy constants in large N as $c_3 \sim \frac{F_\pi^4 B_0^2}{4}$.)

Still CP is broken - II

- they give **meson tadpoles**, i.e. shift chiral vacuum

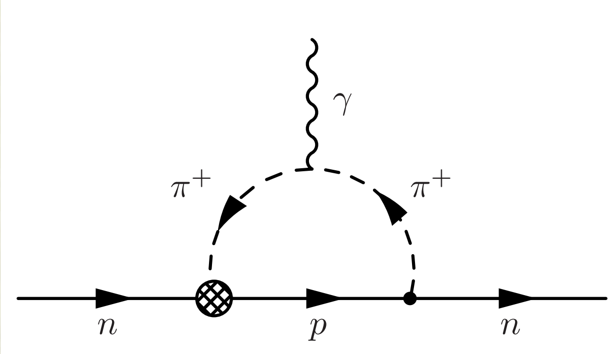
$$\langle \pi^0 \rangle \simeq \frac{G_F}{\sqrt{2}} (\mathcal{C}_{1ud} - \mathcal{C}_{1du}) \frac{4\, c_3}{B_0 F_\pi (m_d + m_u)}$$

- which induce new **CP violating couplings**,

$$\bar{g}_{np\pi} \simeq \frac{2\sqrt{2} B_0}{F_\pi^2} (b_D + b_F)(m_d - m_u) \langle \pi^0 \rangle$$

- which give **EDM at loop**, e.g. :

$$d_n \simeq -\frac{e}{8\pi^2 F_\pi} \frac{\bar{g}_{np\pi}}{\sqrt{2}} (D + F) \left(\log \frac{m_\pi^2}{m_N^2} - \frac{\pi m_\pi}{2 m_N} \right)$$



...still CP is broken - III

- The UV coefficient has V_R phases and W mixing:

$$C_{1,ud} = \frac{G_F}{\sqrt{2}} \,\mathrm{Im}(\zeta^* V_{L,ud} V^*_{R,ud}) \sim |\zeta| \,\sin(\alpha - \theta_u - \theta_d)$$

So it's the same phase combination as ε′.

$$h_{d_n}^{\rm noPQ} \simeq 10^6 |\zeta| \times 1.65 \sin\left(\alpha - \theta_u - \theta_d\right)$$

$$h_{d_n}^{\rm PQ} \simeq 10^6 |\zeta| \times 0.21 \sin\left(\alpha - \theta_u - \theta_d\right)$$

(comment below, for the PQ suppression)

(*d_{Hg} and others…*)

Resulting bound: d_n plus ε, ε′

C

Case of C: no bounds,
the free phases can be taken zero
to cancel all CP violation.

Limit still given by K and B
oscillations, $M_{W_R} \gtrsim 7$TeV

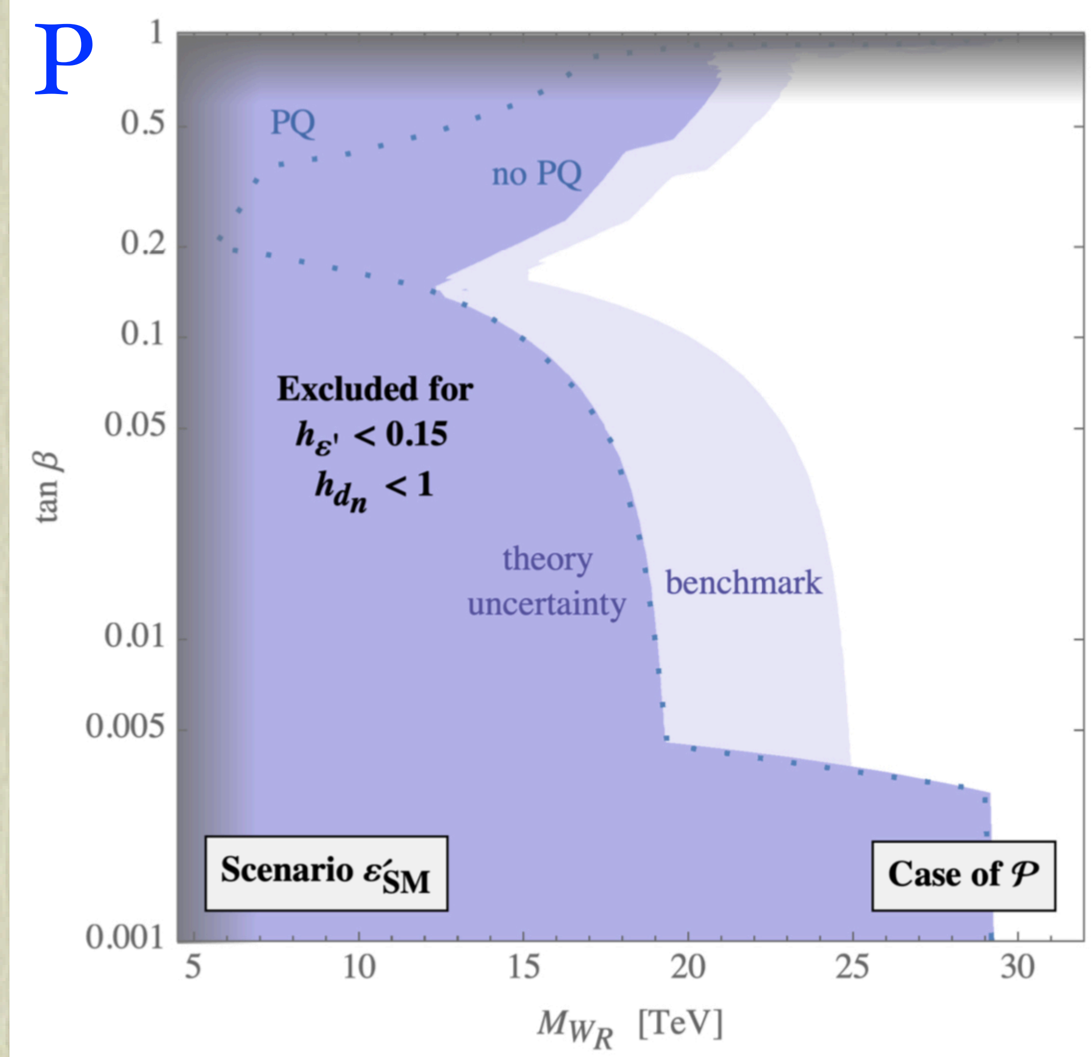


FIG. 4. Case of $\mathcal{P}$: The shaded regions in the M_{W_R}–t_β plane are excluded in order to have at most 15% new physics contribution to ε'/ε and d_n below the present experimental bound.

[Bertolini, Maiezza, FN, PRD '20]

Insides of CP and PQ

- Important to use single approach, as χPT.

- E.g. the induced axion VEV $\bar{\theta}_{eff}$ consistent with the meson ones...

$$\frac{\langle \pi^0 \rangle}{F_\pi} \simeq \frac{G_F}{\sqrt{2}} C_1^{[ud]} \frac{c_3}{B_0 F_\pi^2} \frac{m_u + m_d + 4 m_s}{m_u m_d + m_d m_s + m_s m_u},$$

$$\frac{\langle \eta_8 \rangle}{F_\pi} \simeq \frac{G_F}{\sqrt{2}} C_1^{[ud]} \frac{\sqrt{3} c_3}{B_0 F_\pi^2} \frac{m_d - m_u}{m_u m_d + m_d m_s + m_s m_u},$$

$$\bar{\theta}_{\rm eff} \simeq \frac{G_F}{\sqrt{2}} C_1^{[ud]} \frac{2 c_3}{B_0 F_\pi^2} \frac{m_d - m_u}{m_u m_d},$$

- When inserted into $\bar{g}_{np\pi}$, this cancels exactly

$$\bar{g}_{np\pi} = \frac{B_0}{F_\pi}(b_D + b_F) 2\sqrt{2} \left[(m_d - m_u) \frac{\langle \pi^0 \rangle}{F_\pi} - \frac{(m_u + m_d)}{\sqrt{3}} \left(\frac{\langle \eta_8 \rangle}{F_\pi} + \sqrt{2} \frac{\langle \eta_0 \rangle}{F_0} \right) - 2 \frac{m_u m_d m_s \, \bar{\theta}_{\rm eff}}{m_s m_d + m_s m_u + m_u m_d} \right] = 0\,.$$

(i.e. the dominant d_n vanishes! hence the PQ suppression)

...a general result, only depends on the operators.

[Bertolini, Di Luzio, FN, PRL '21]

Other PQ effects calculable and correlated...

Induced CPV Axion-nucleon coupling $\bar{g}_{aN}$

Interplay between ε, ε′, d_n and $\bar{g}_{aN}$

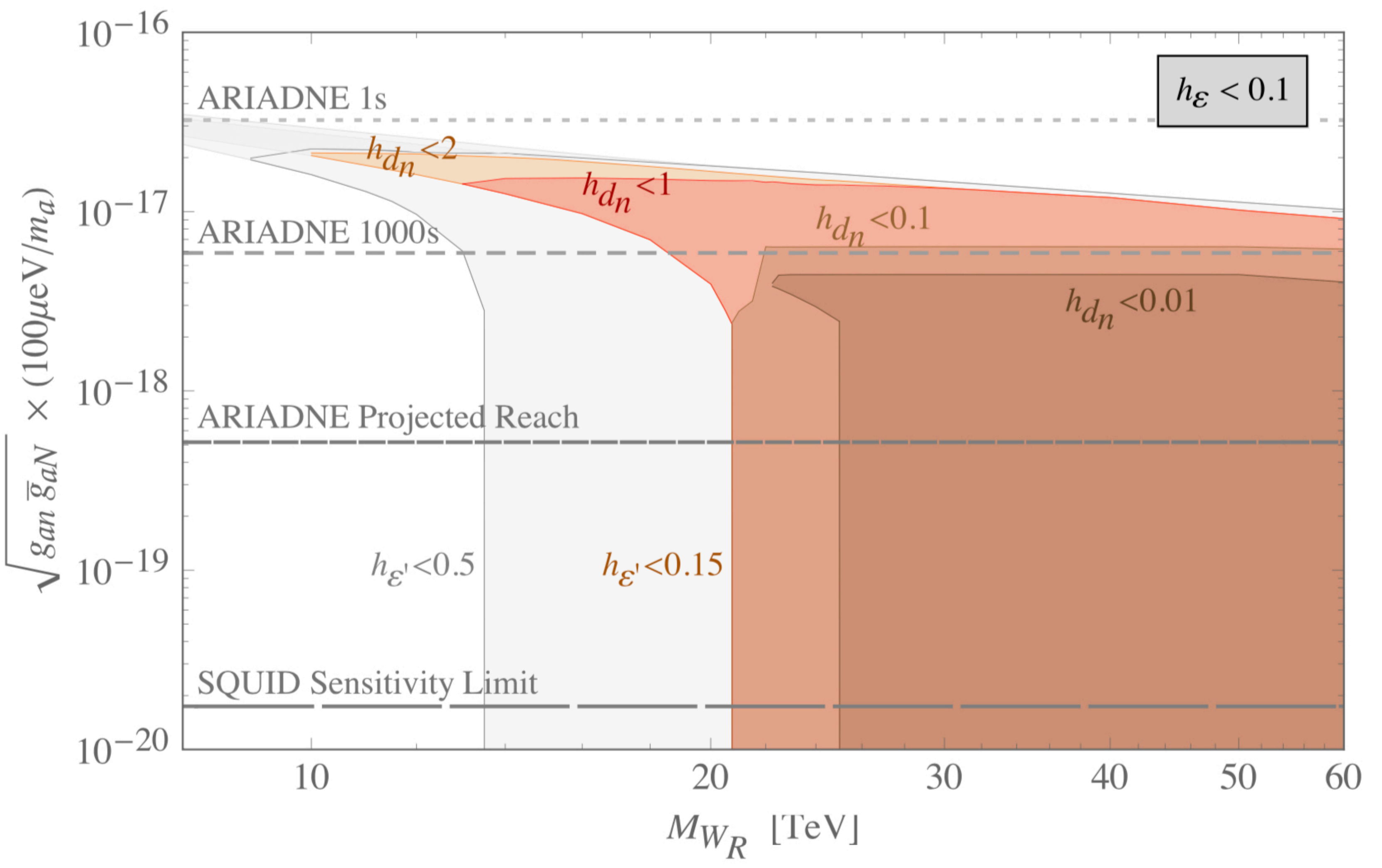


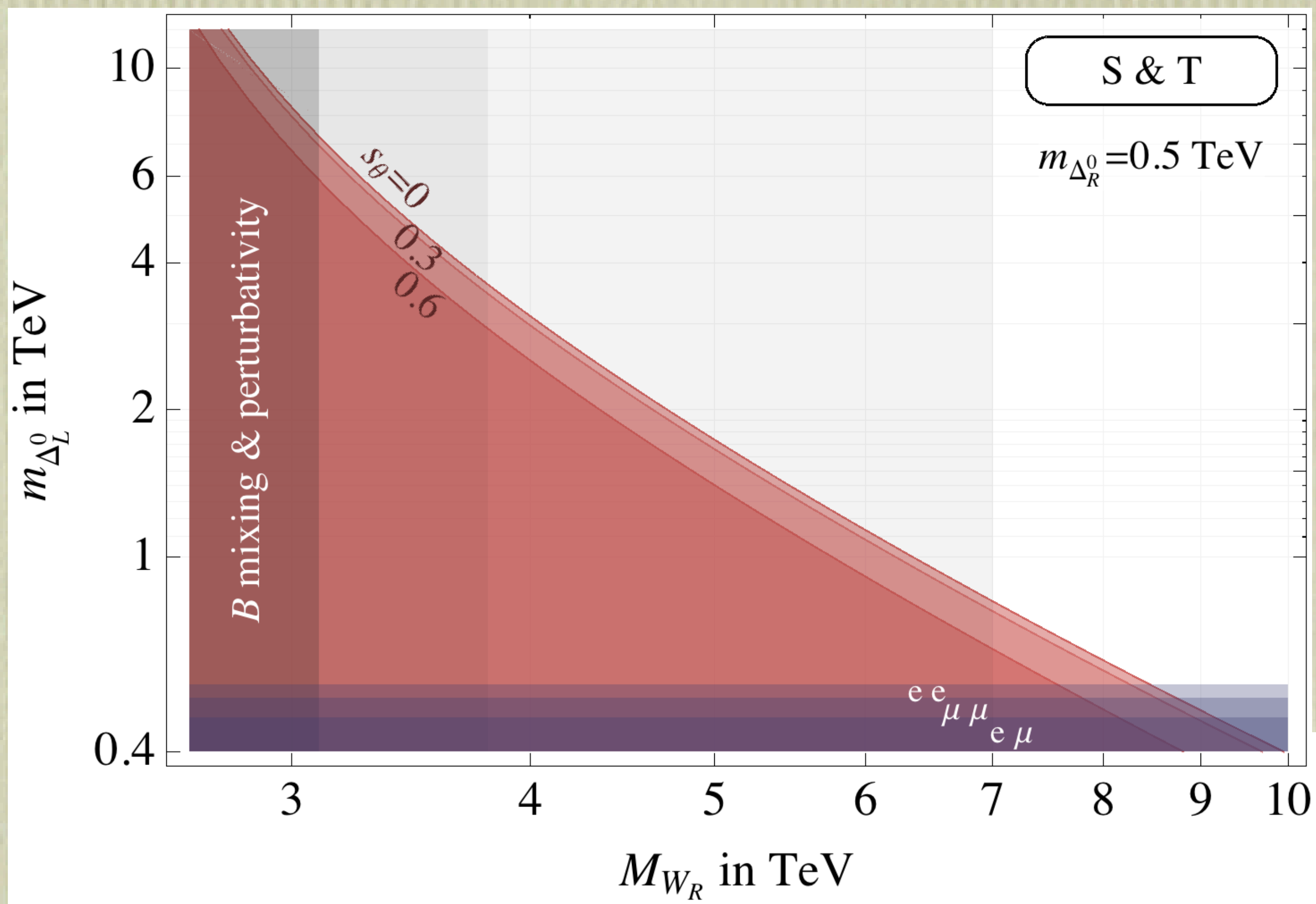
FIG. 1. Regions in the LR DFSZ model of the CPV axion nucleon coupling probed by ARIADNE.

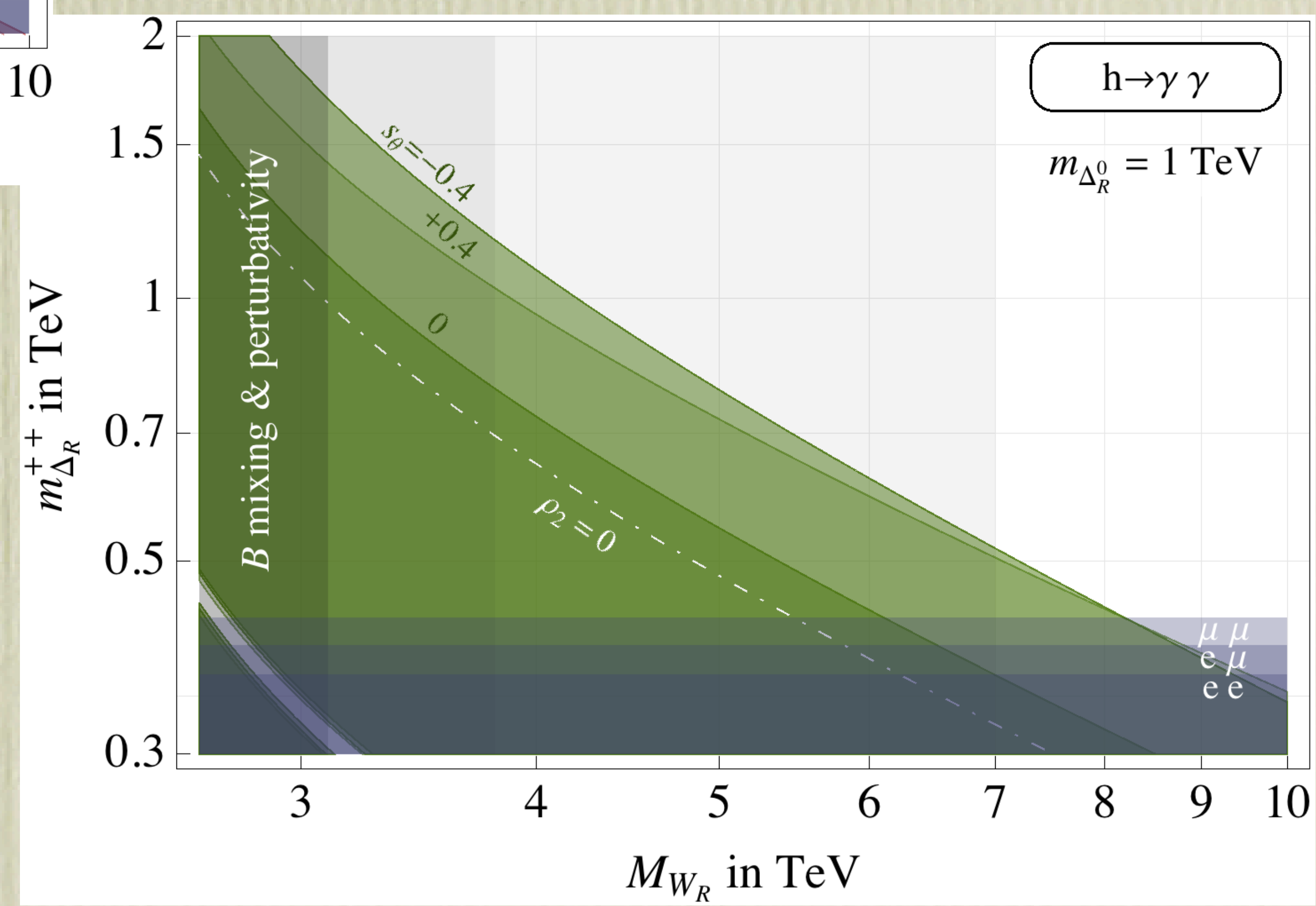
[Bertolini, Di Luzio, FN, PRL '21]

soon to be measured :)

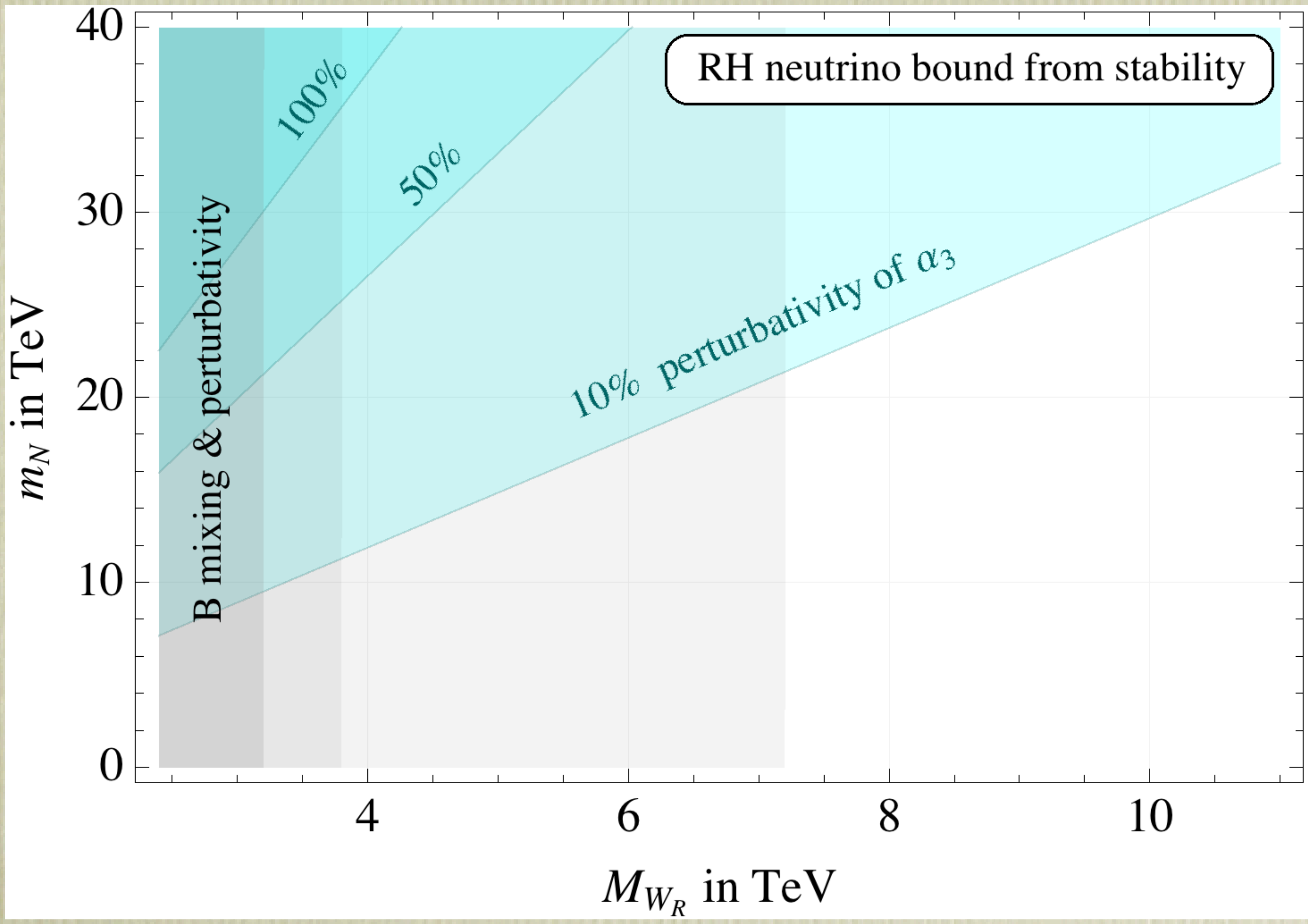
Perturbativity

EWPT and h to photons





RH neutrino bound from stability and perturbativity



Perturbativity in LRSM

(all relevant scalars one loop/tree level ratio)

Heavy FCH generates tension…

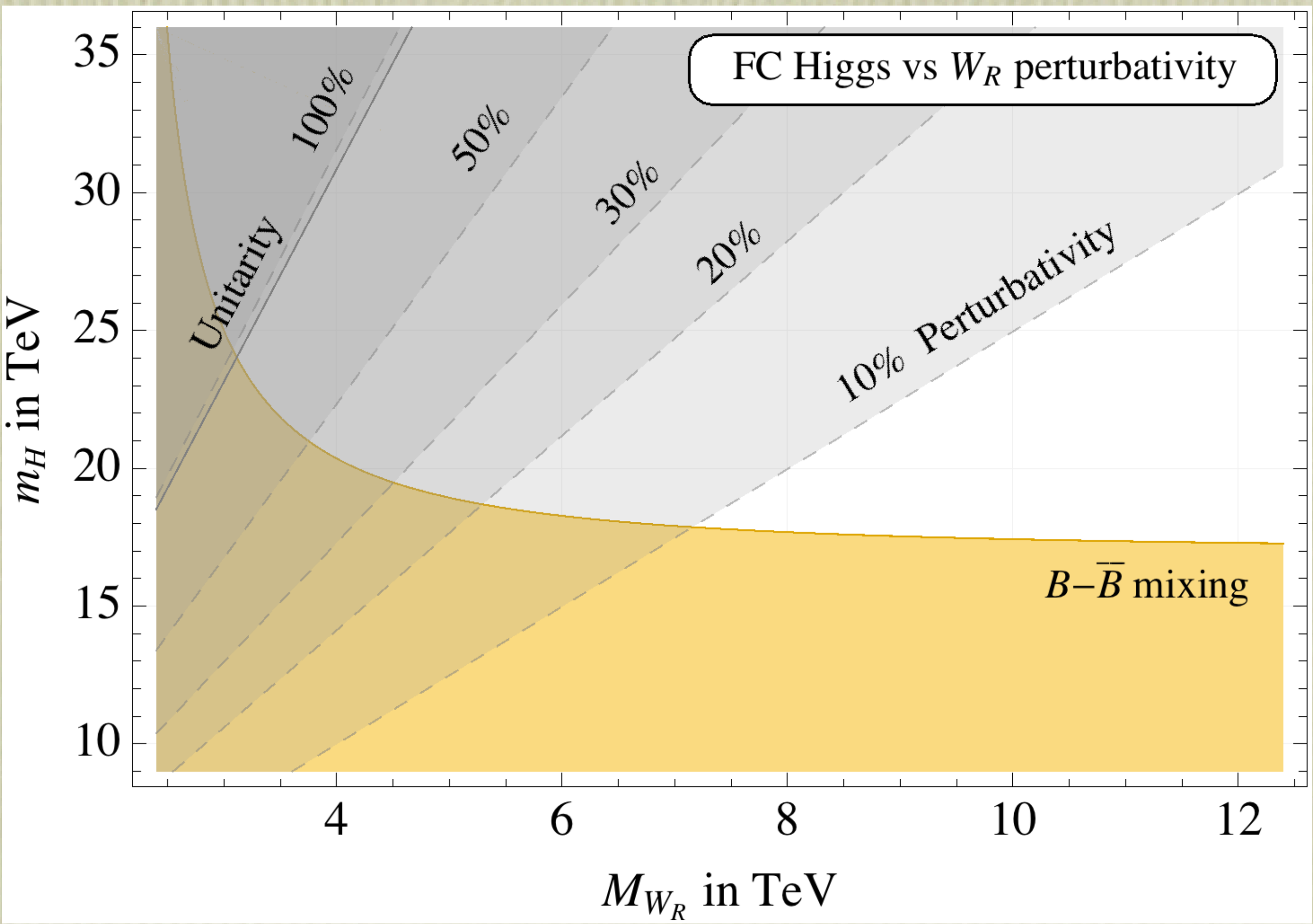
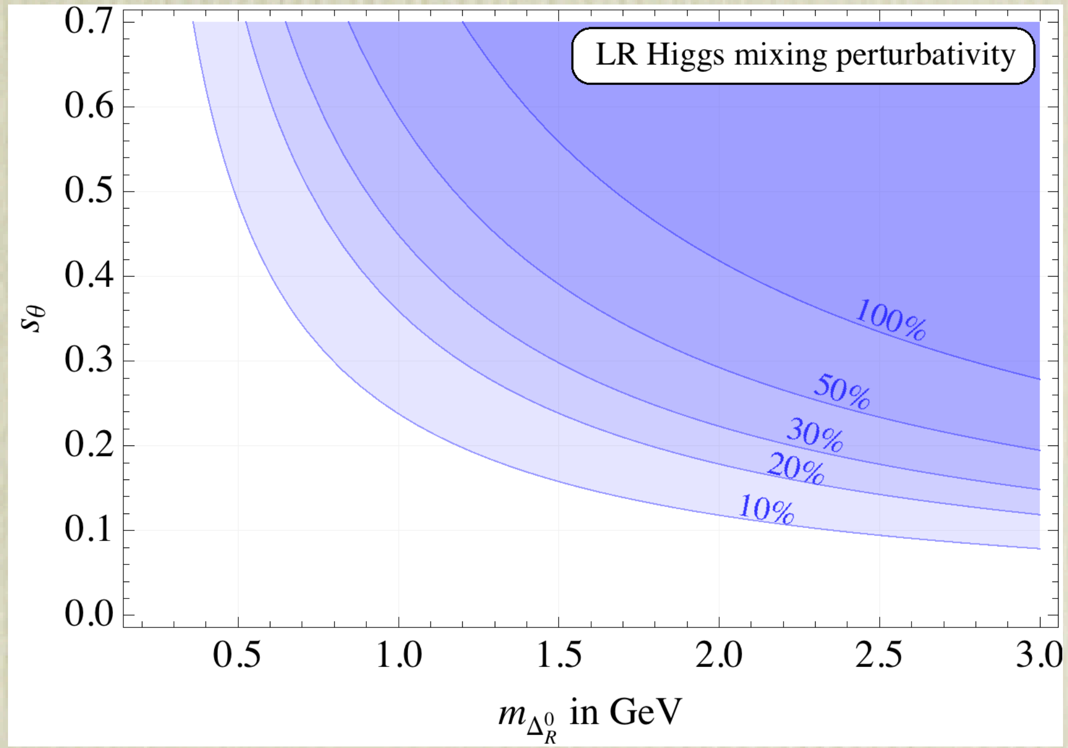


FIG. 3. Perturbativity assessment of $\mathcal{V}_{eff}$ (dashed) and tree-level unitarity (solid) of α_3, together with the bound on M_{W_R} vs. m_H from $B^0_{d,s} - \overline{B}^0_{d,s}$ (see [19] for details).

…points to heavier W_R.

(Still one can have sizeable higgs mixing)



[Maiezza Nemevšek, FN 1603.00360]