LNV
Higgs
Collider

Portorož 2015

Fabrizio Nesti

Institut Ruđer Bošković, Zagreb

w/ A. Maiezza, M. Nemevšek

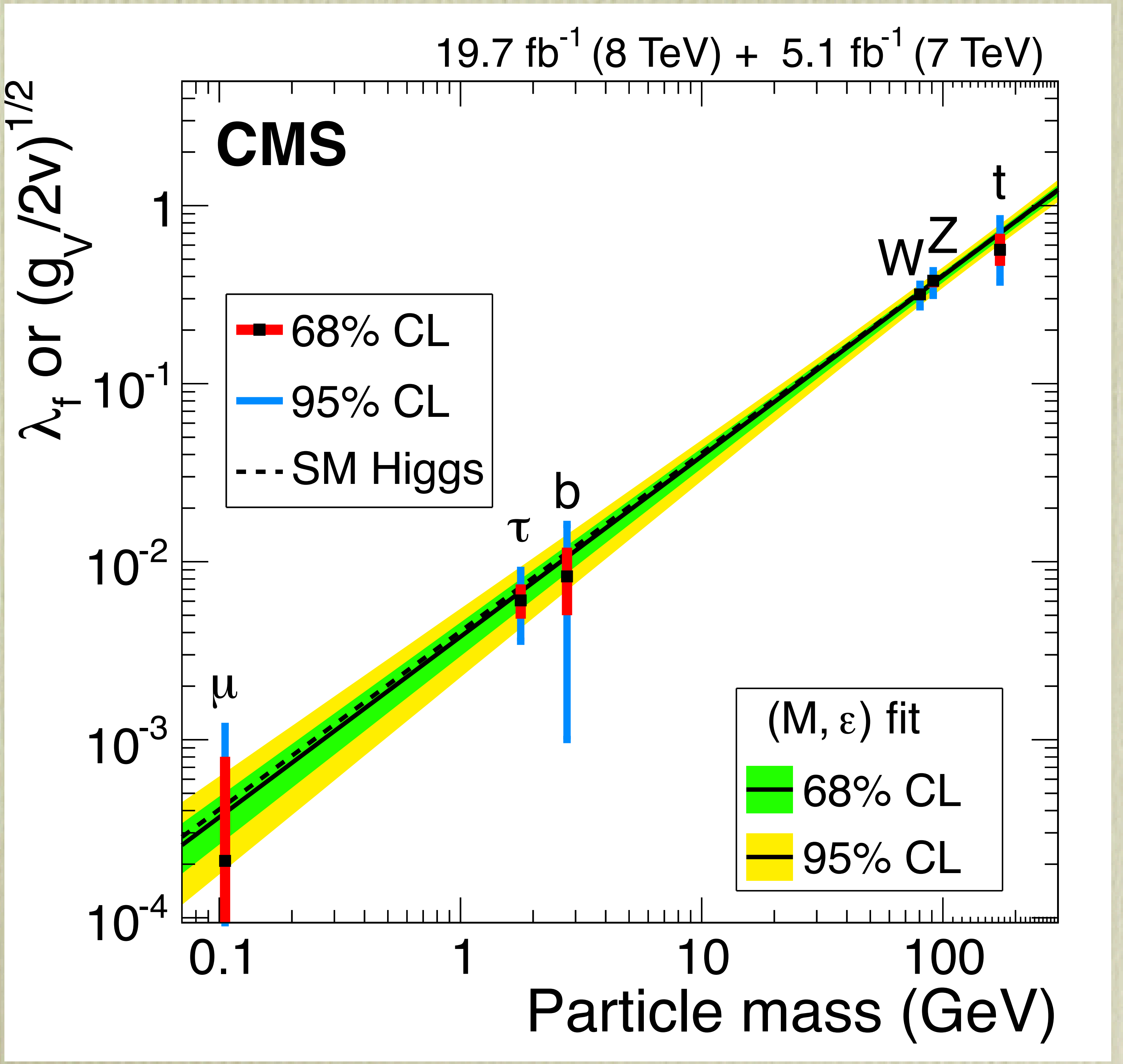
HRZZ project PhysMaB @ IRB

Bringing together

- Quest for neutrino mass origin (New physics)
- Lepton Number Violation (Majorana)
- In Higgs decays (test generation of masses)

Connection at LHC run II

The last triumph of the SM



Mass versus Higgs decays as expected

H→ττ ATLAS-CONF-2013-108

H→bb ATLAS-HIGG-2013-23-003

H→ττ CMS arXiv:1401.5041

H→bb CMS arXiv:1310.3687

CMS PAS HIG-14-009

Anything similar for neutrino masses?

- We measure neutrino mass differences (oscillations)
  ...thus nonzero neutrino mass.

- SM has only LH neutrinos...
  ...no Higgs coupling

$$M_\nu = 0$$

Need to go Beyond the SM
but a surprise: still Higgs may probe the mechanism

The Theory of Neutrino Mass and Parity Breaking

Left-Right symmetry

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

- $SU(2)_L\, SU(2)_R\, U(1)_{B\text{-}L}$ Spectrum is symmetric

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

- Spontaneous parity breaking

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

The Theory of Neutrino Mass and Parity Breaking

Left-Right symmetry

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

- $SU(2)_L SU(2)_R U(1)_{B-L}$ Spectrum is symmetric

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

- Spontaneous parity breaking

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

- Now, **neutral higgses mix**:

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

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

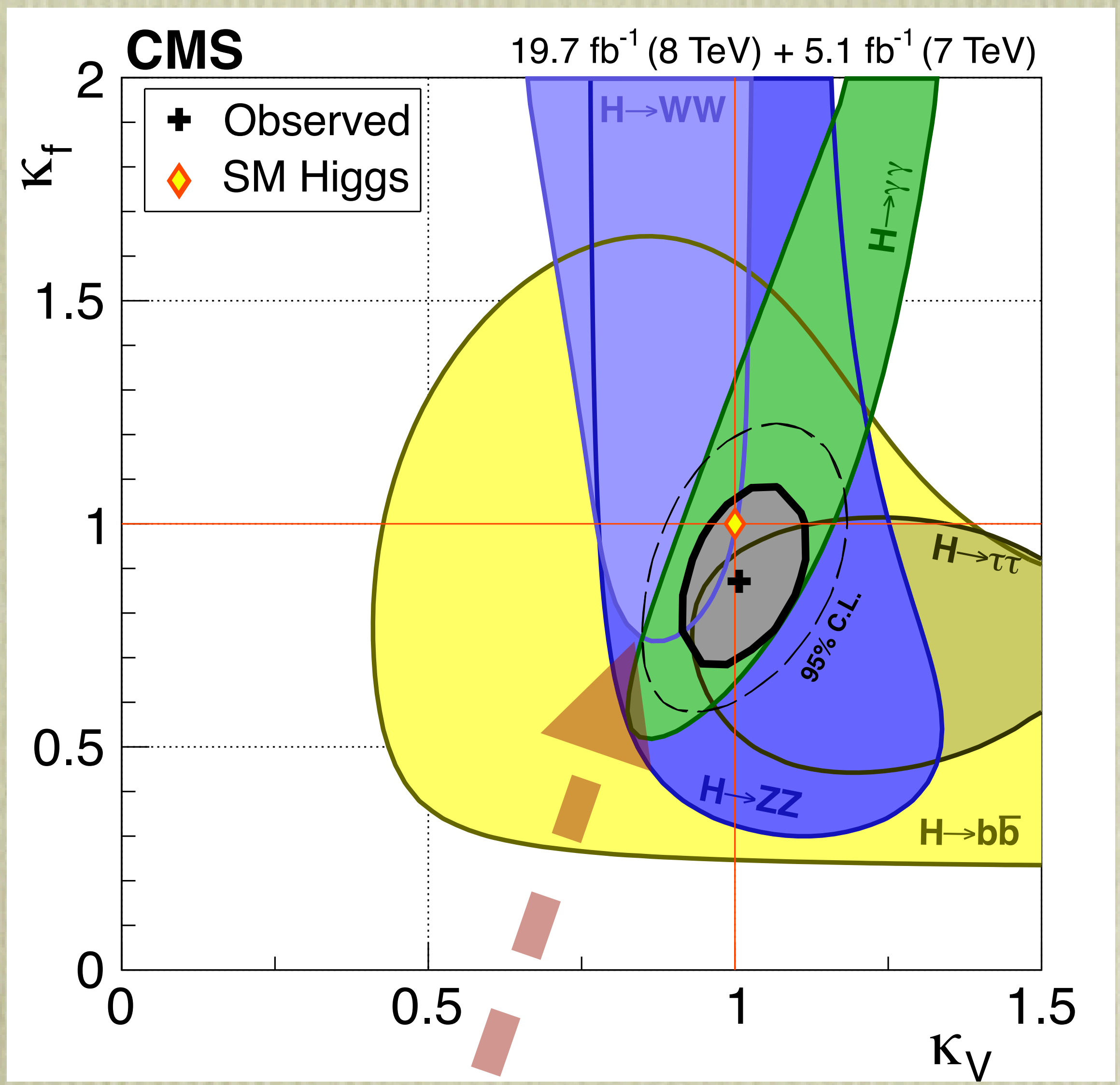
SM Higgs couplings reduced...

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

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

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

...allowed Higgs mixing?



[CMS PAS HIG-14-009]

Yesterday's Lebedev talk

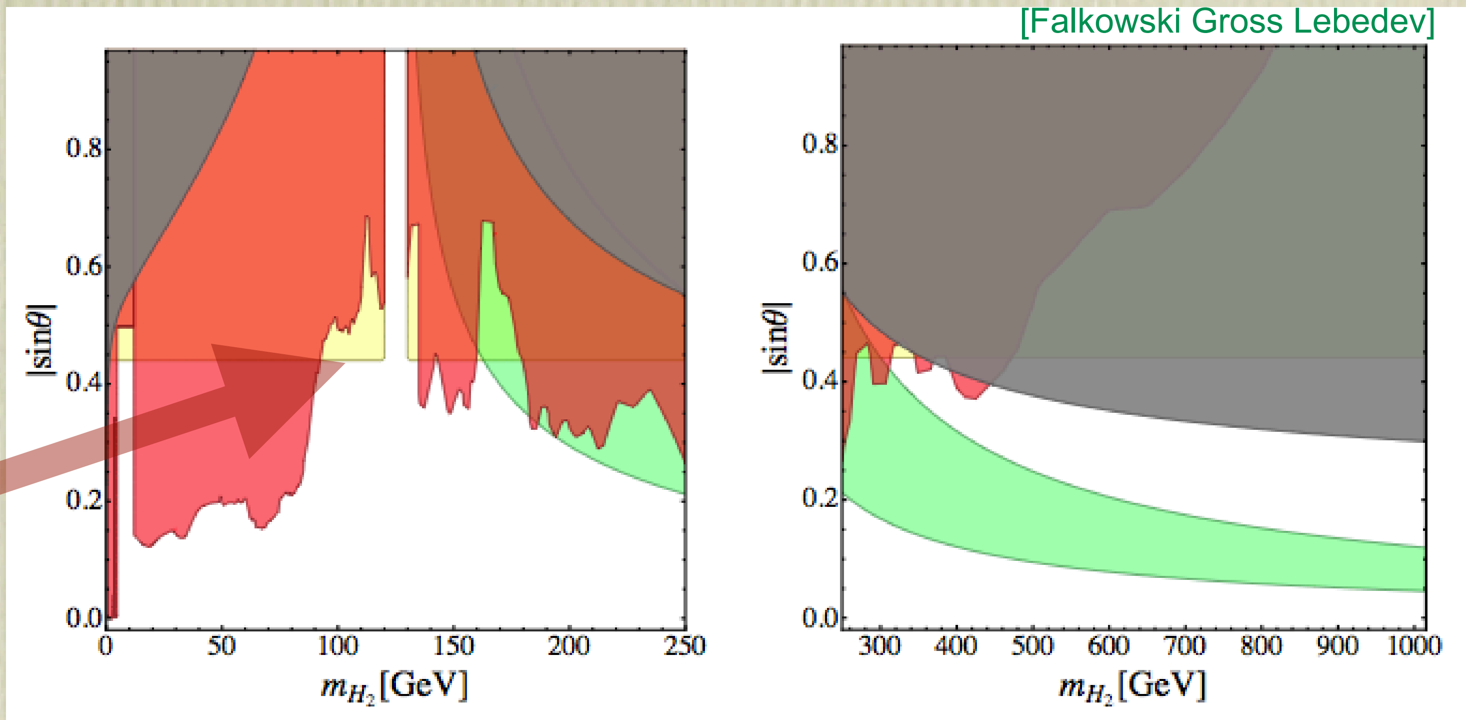


Figure 3: Left: Parameter space (for $m_{H_2} \leq 2m_{H_1}$) excluded at 95 % CL by direct searches (red), precision tests (gray), and H_1 couplings measurements (yellow). For

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]

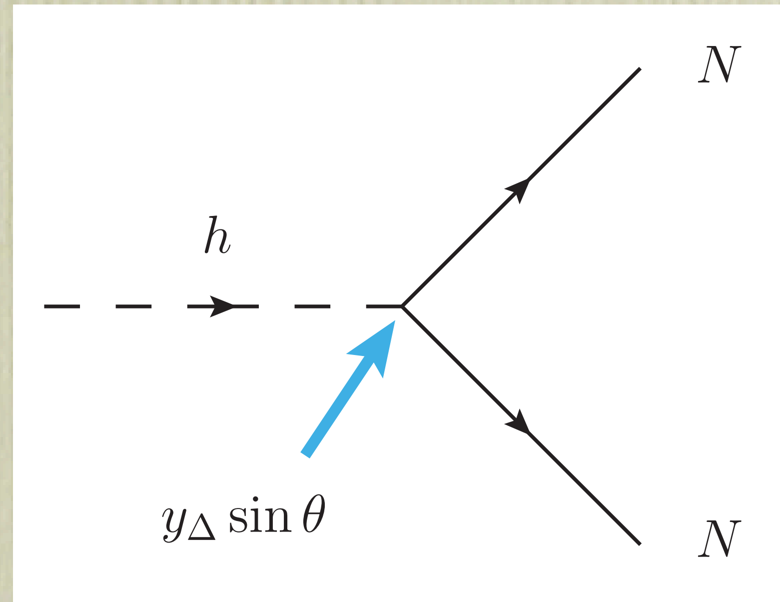
and Higgs probing neutrino masses

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

- gives Majorana neutrino mass, to check by Δ decay

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

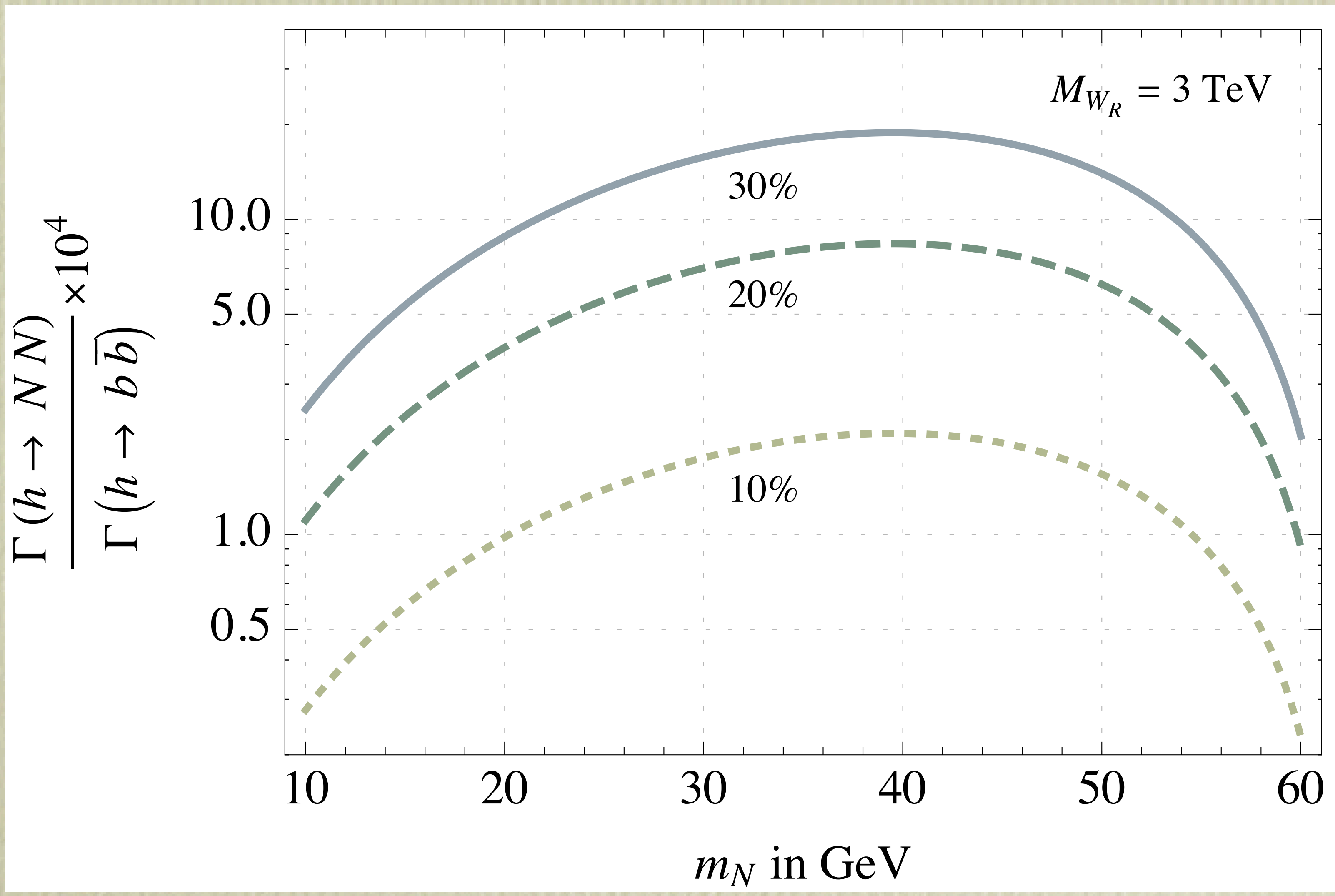
- with Δ-h mixing, now the Higgs can decay to NN



a new SM Higgs decay, checks RH neutrino mass

$h \to NN$ - large decay rate

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



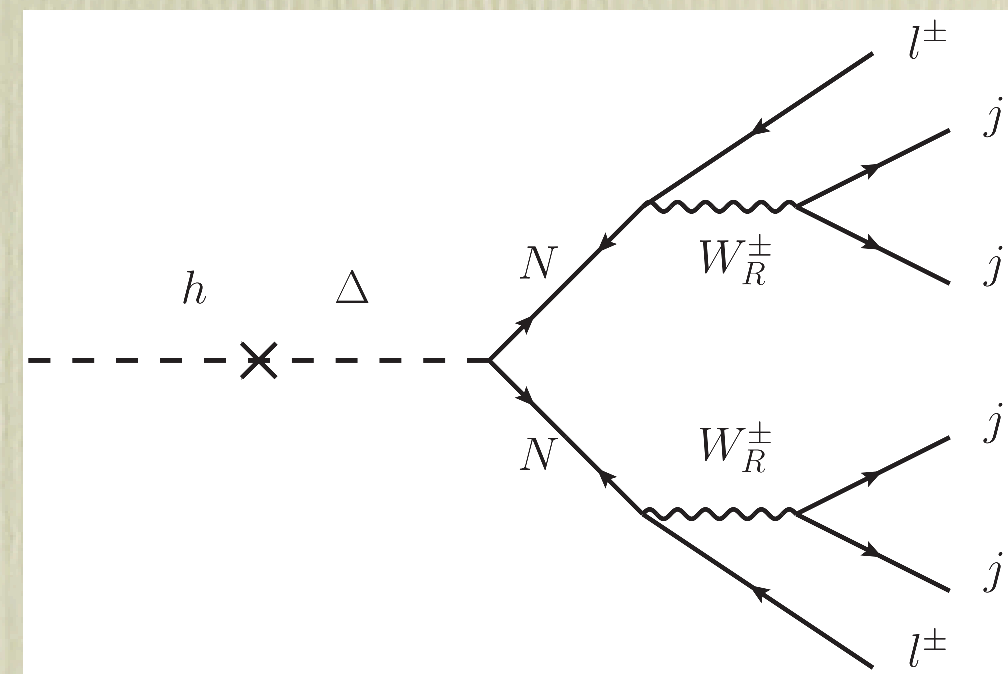
h to *NN* first proposed by Graesser as effective operators:

[M.L. Graesser, PRD 76 (2007) 075006; arXiv:0705.2190]

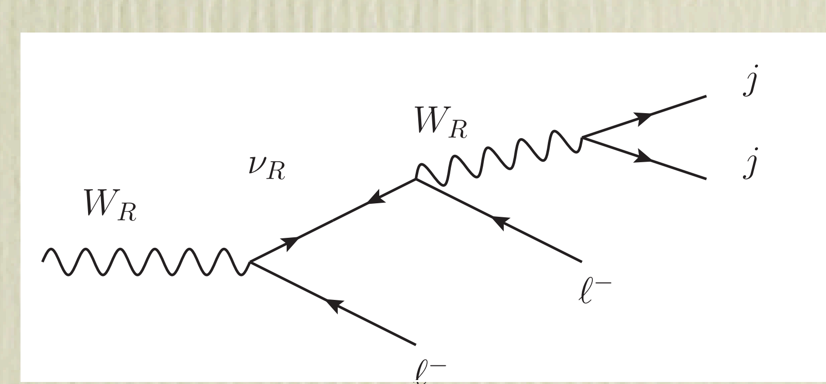
LNV Higgs decay

N is Majorana, thus LNV Higgs decays:

- 50% same sign dileptons
- light N, *i.e. long lifetime*
- In LR, N decay W_R mediated

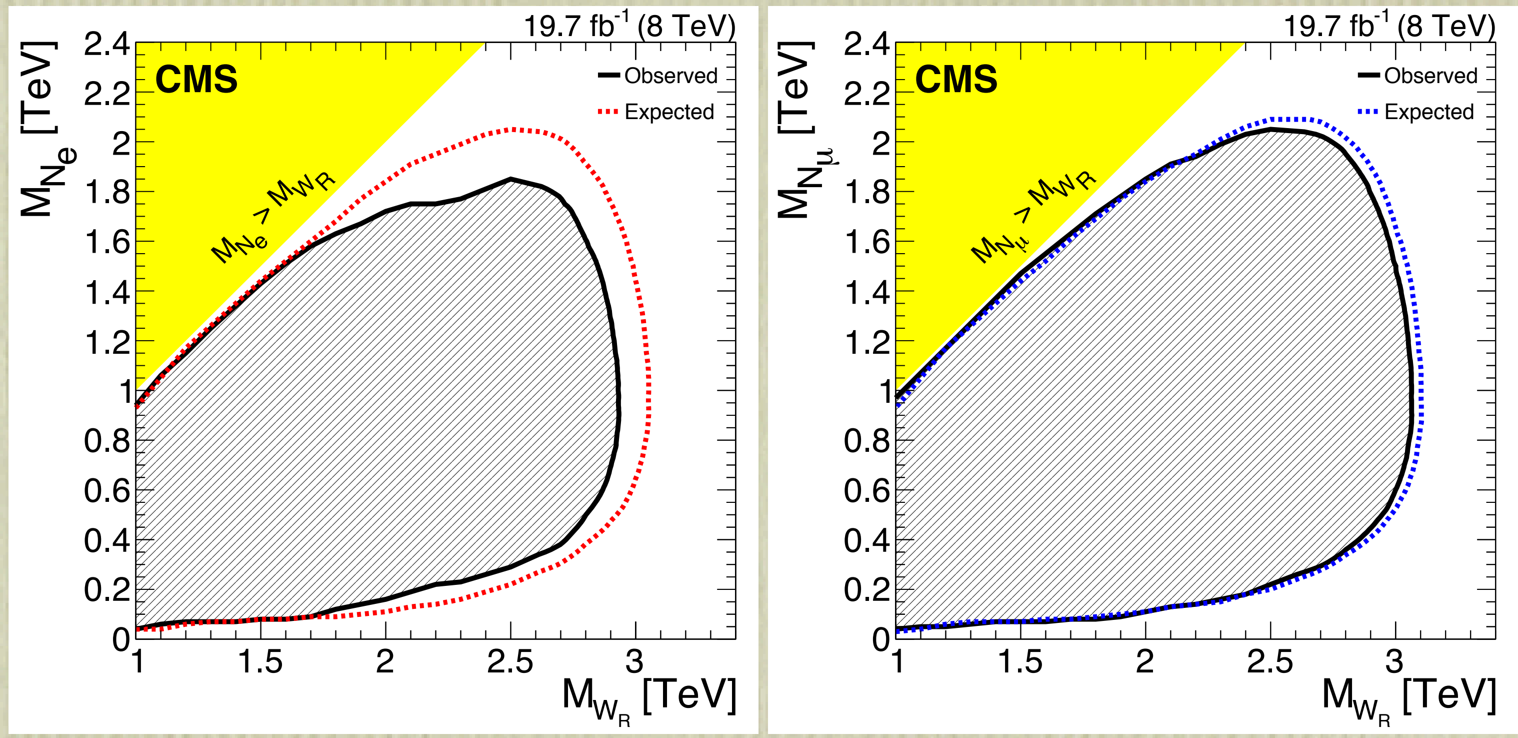


- LNVH complementary to W_R drell-yan production of N [Keung Senjanović '83]



Need to check existing limits...

Recent and Future Limits



EXP

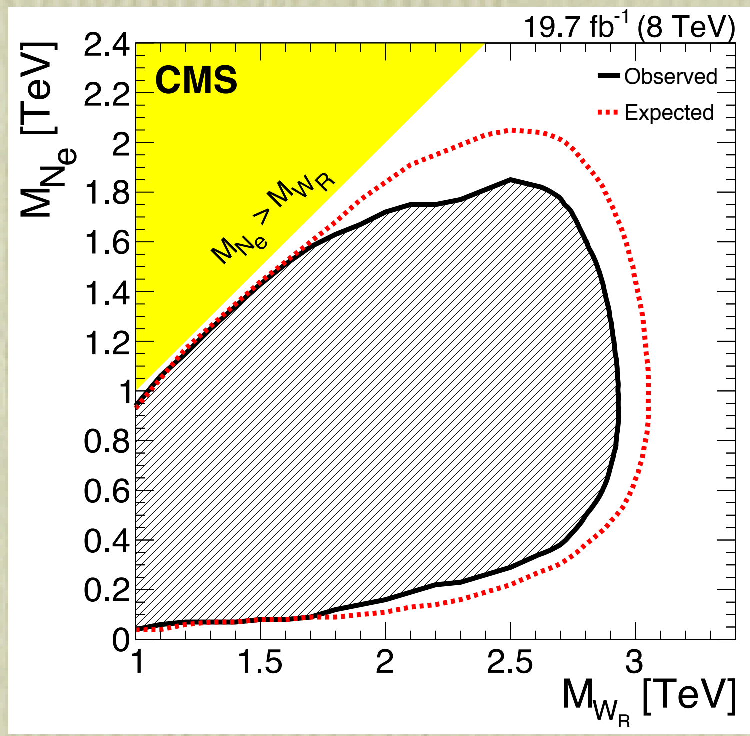
[CMS-EXO-13-008]

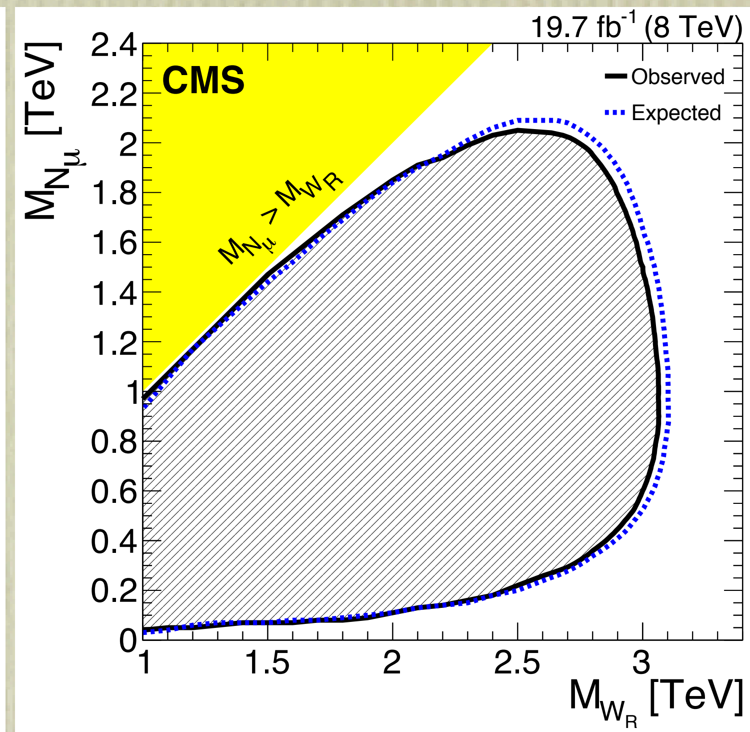
W_R-ν_R plane, beyond old theo bound 2.5TeV

[Maiezza+ '10]

[Maiezza, Nemevšek '14] [Bertolini (Eeg) Maiezza, FN '12,'13,'14]

Recent and Future Limits





EXP

[CMS-EXO-13-008]

W_R-ν_R plane, beyond old theo bound 2.5TeV

[Maiezza+ '10]

But:

THEO

from $\Delta M(K, B_d, B_s)$

indirect limit now shifted up to ~ 3-4 TeV

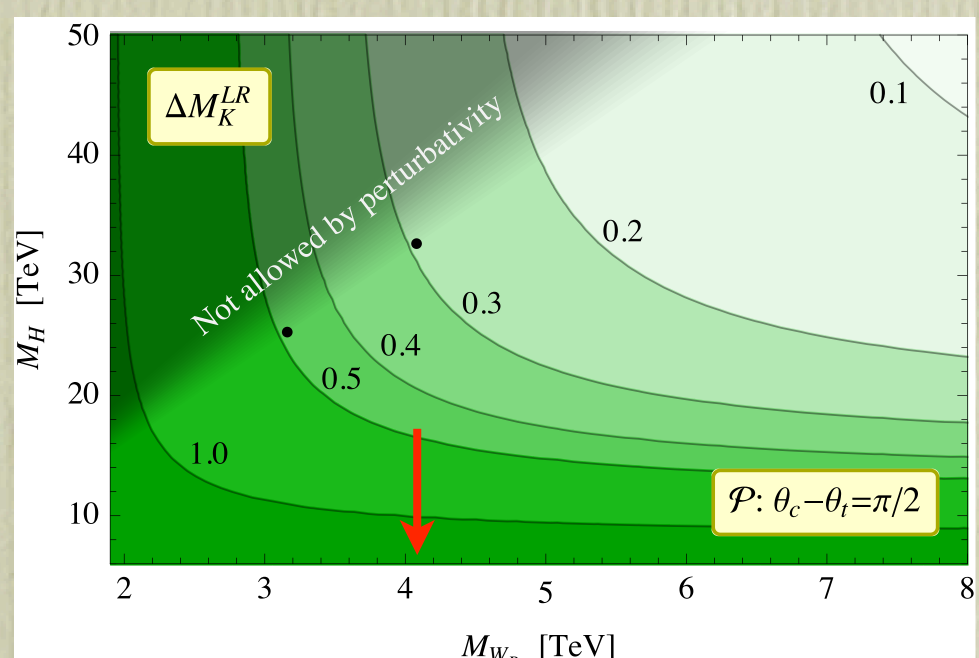


FIG. 9. Correlated bounds on M_R and M_{W_R} (region above the curves) for $\left|\Delta M_K^{LR}\right| / \Delta M_K^{exp} < 1.0, \ldots, 0.1$ and for $\theta_c - \theta_t = \pi/2$ in the case of $\mathcal{P}$ parity.

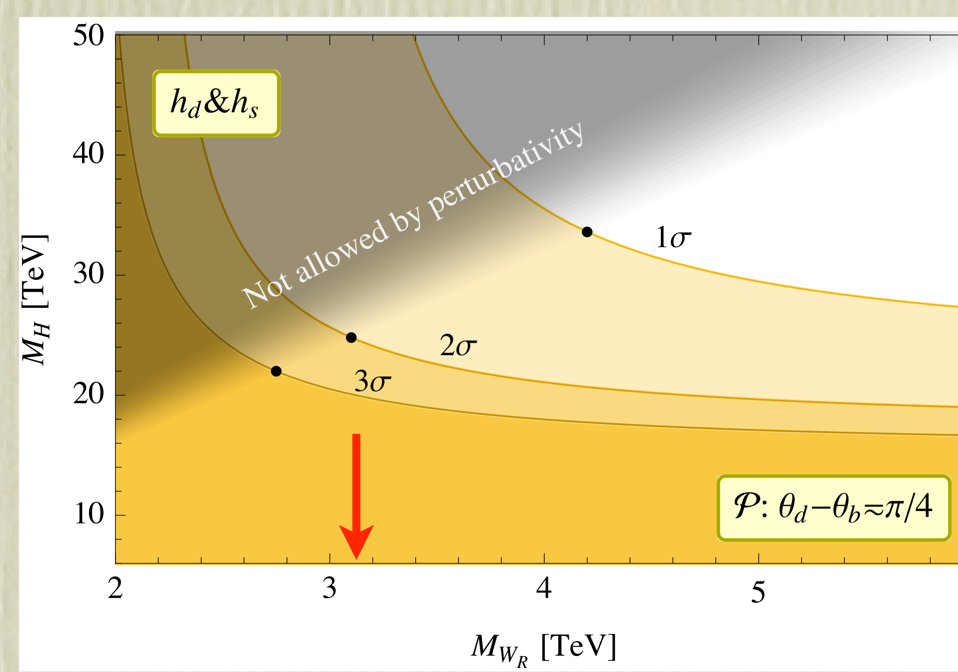
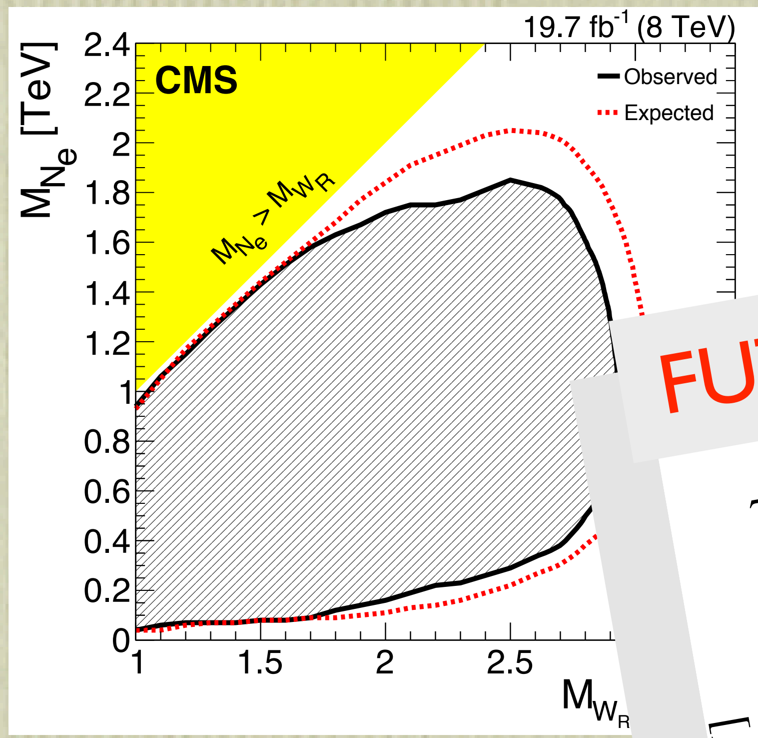
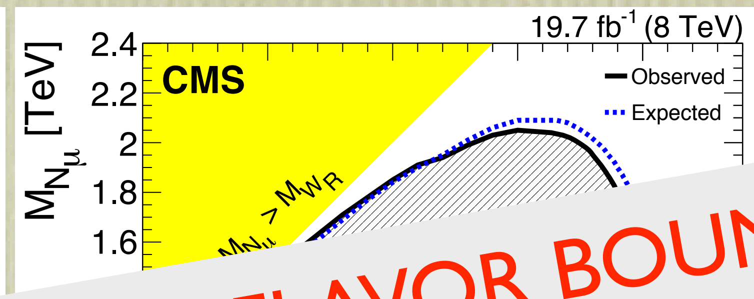


FIG. 10. Combined constraints on M_R and M_{W_R} from ε, ε', B_d and B_s mixings obtained in the $\mathcal{P}$ parity case from the numerical fit of the Yukawa sector of the model.

[Maiezza, Nemevšek '14] [Bertolini (Eeg) Maiezza, FN '12,'13,'14]

Recent and Future Limits





EXP

[EXO-13-008]

lane,

old

2.5TeV

Maiezza+ '10]

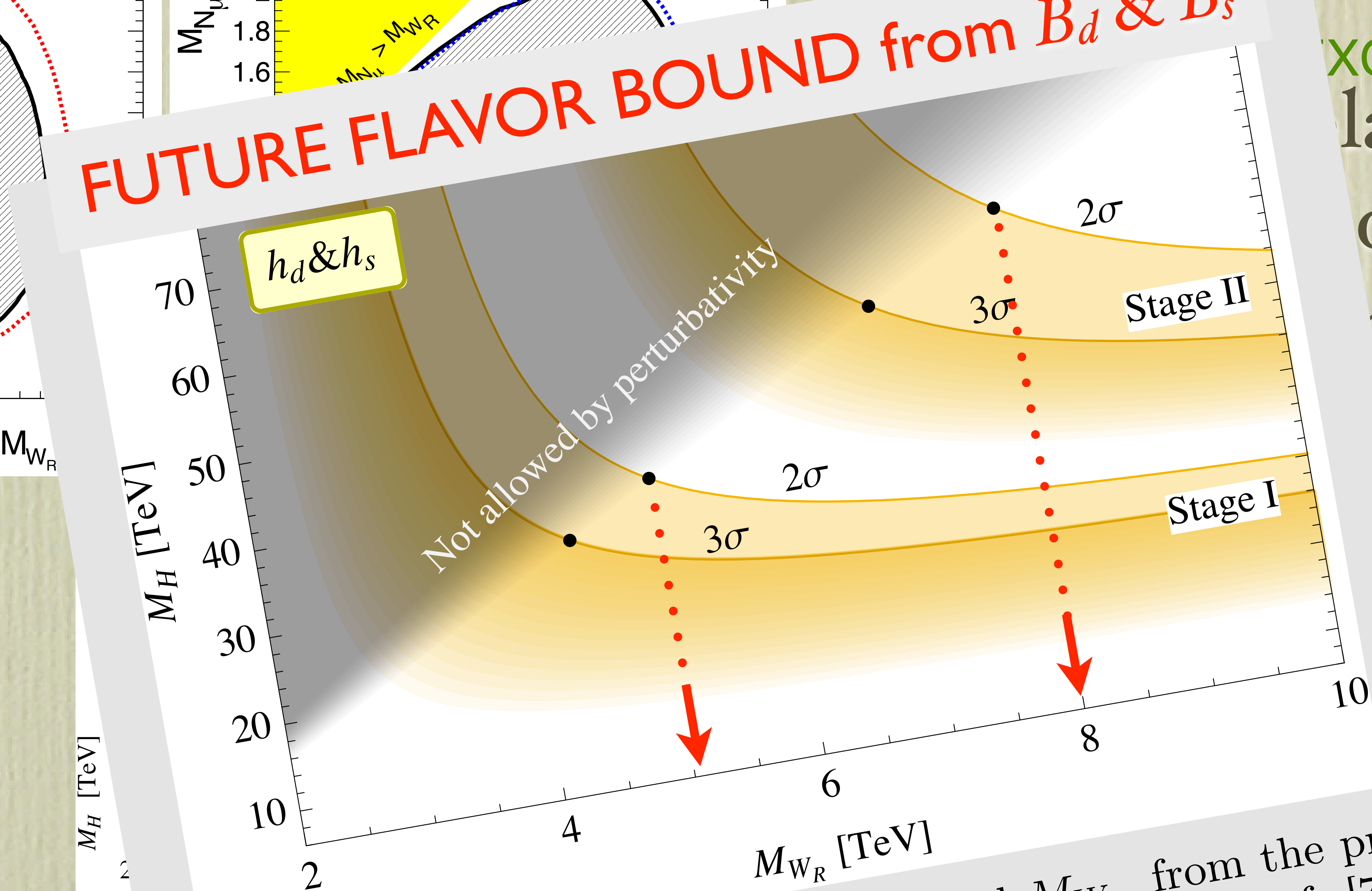


FIG. 11. Future constraints on M_R and M_{W_R} from the projected combined limits on h_d and h_s discussed in Ref. [77]. Stage I corresponds to a foreseen 7 fb^{-1} (5 ab^{-1}) data accumulation by LHCb (Belle II) by the end of the decade. Stage II assumes 50 fb^{-1} (50 ab^{-1}) data by the two experiments,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

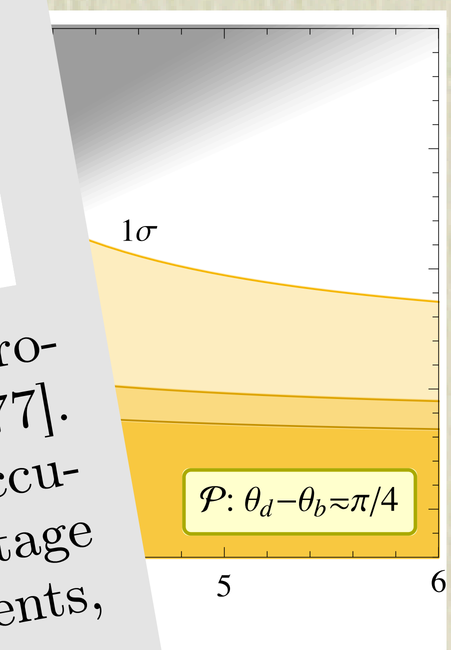


FIG. 9. ... and M_{W_R} from ε, ε' ... the curv... ...ed in the $\mathcal{P}$ parity case from the $\theta_t = \pi/2$ ... of the Yukawa sector of the model.

But:

THEO

from $\Delta M(K, B_d, B_s)$

indirect limit now shifted up to ~ 3-4 TeV

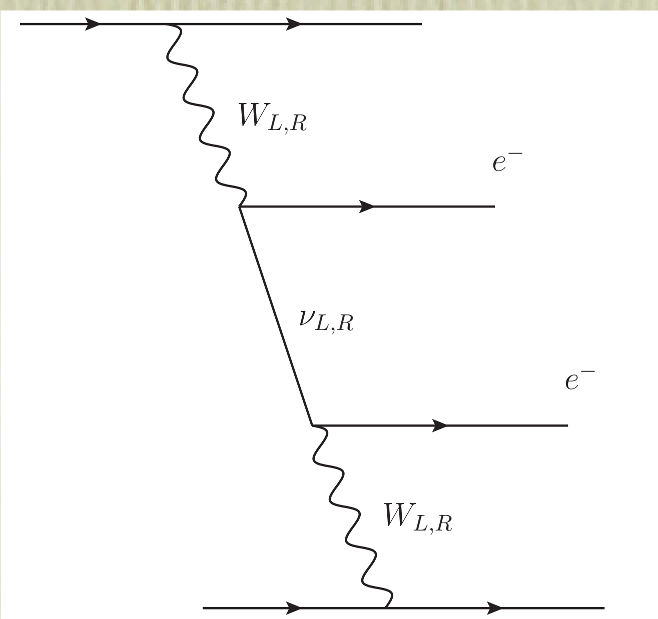
[Maie... ...evsek '14] [Bertolini (Eeg) Maiezza, FN '12,'13,'14]

0ν2β

W_R & ν_R give new contributions

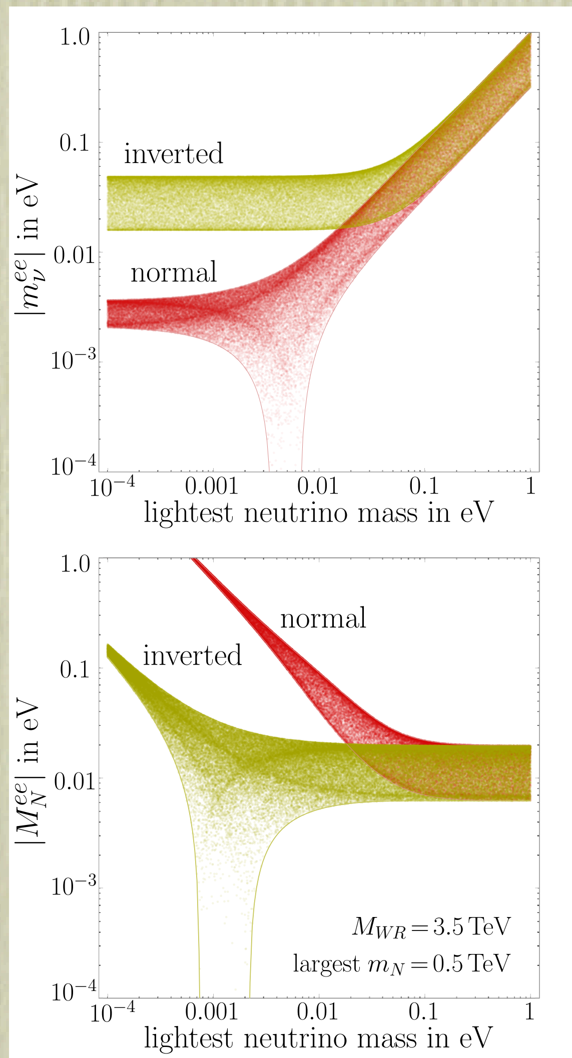
points to

W_R & m_N @LHC

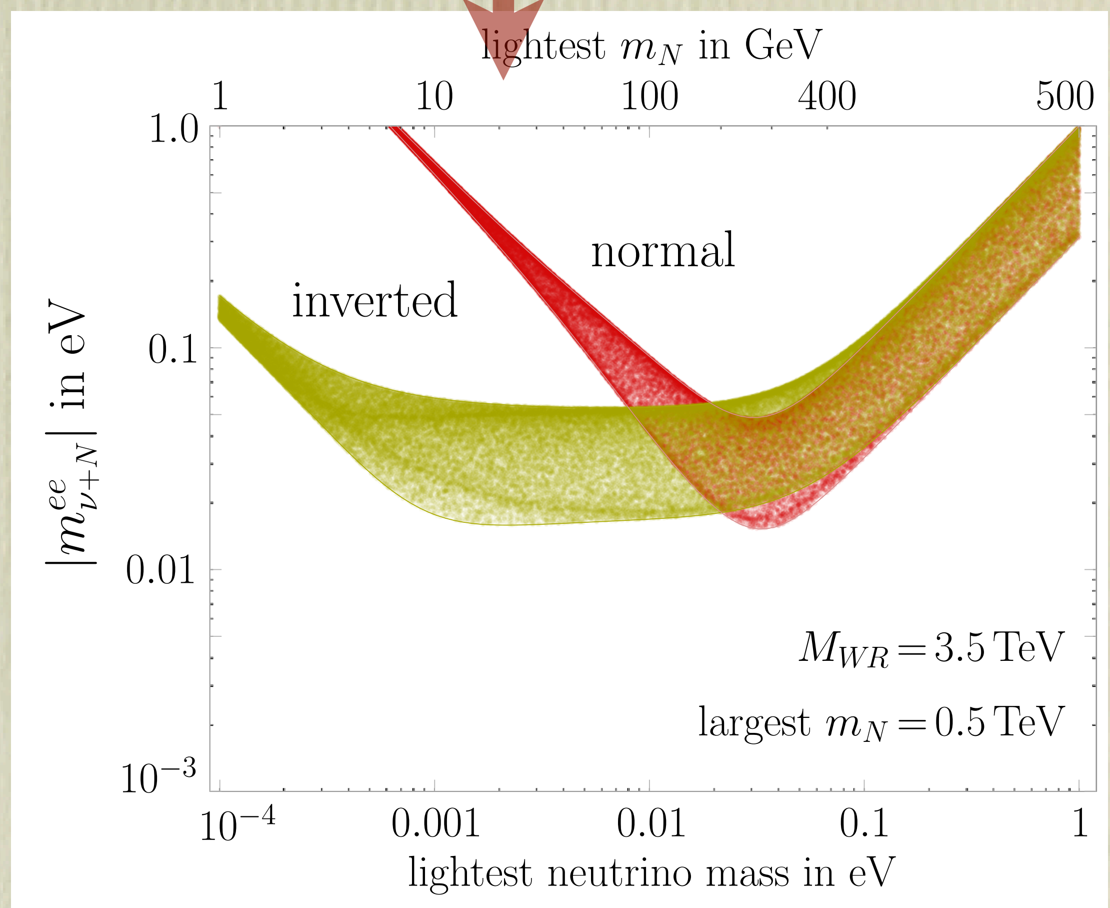


LL

RR

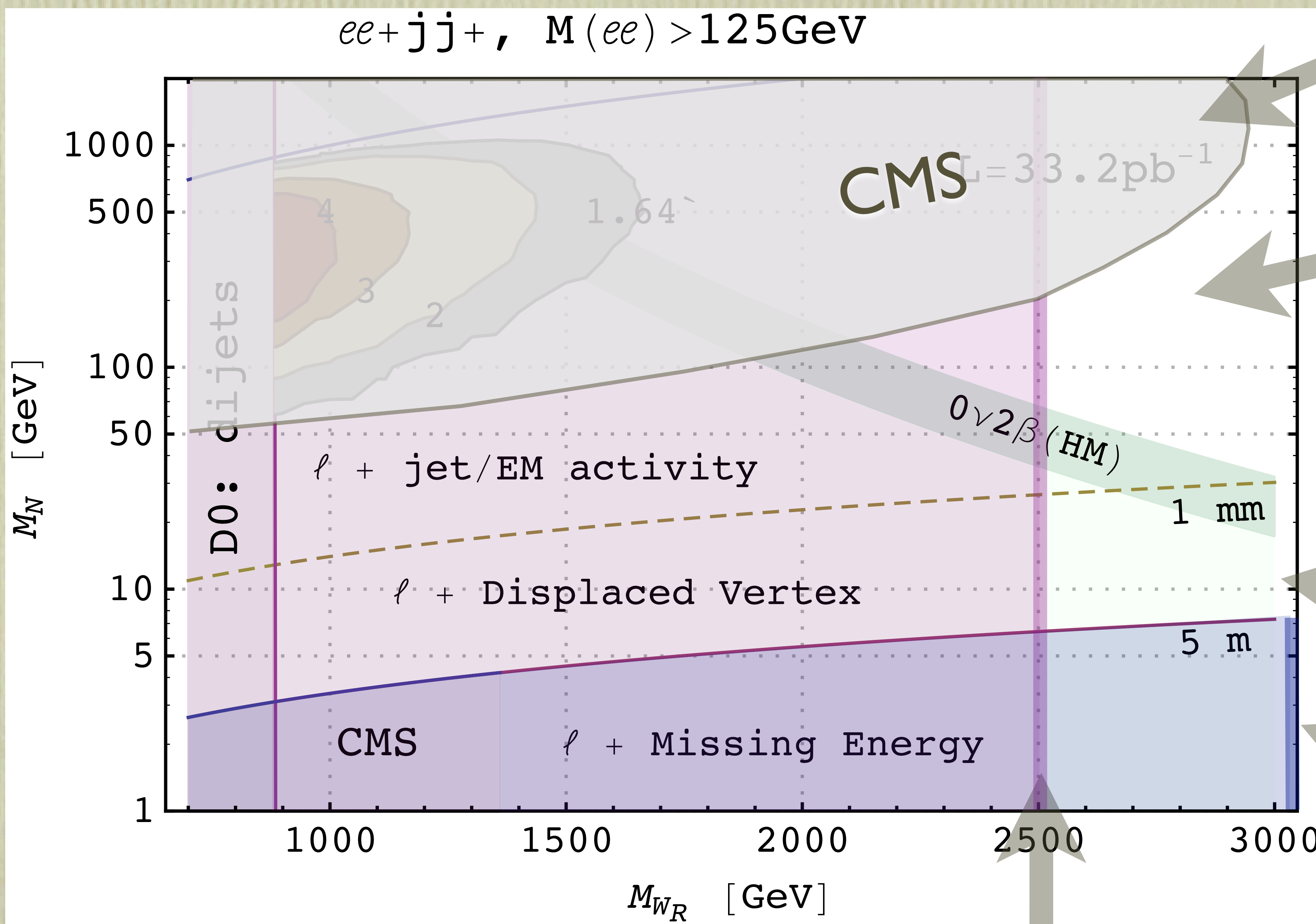


=



[Tello + '10] (type-II limit)

Direct search limits



Keung-Senjanović
$lljj$

jets merge lj

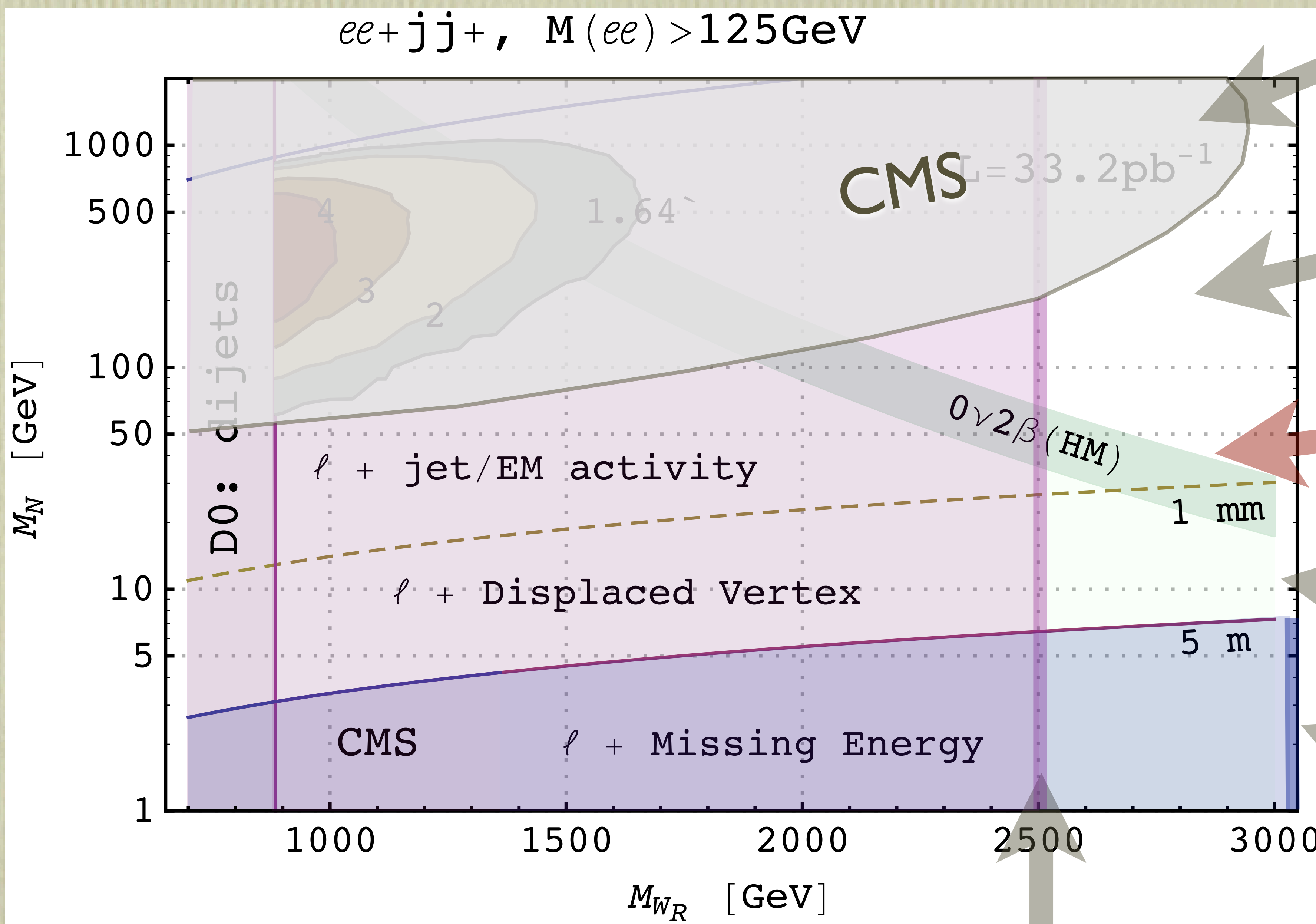
displaced l + jet

$W' \rightarrow l + \nu$ search

$W' \rightarrow$ dijet search

(update of LR@LHC "roadmap" [Nemevšek, FN, Senjanović, Zhang '11])

Direct search limits



Keung-Senjanović *l l j j*

jets merge *l j*

h → NN region, gives 0ν2β

displaced *l* + jet

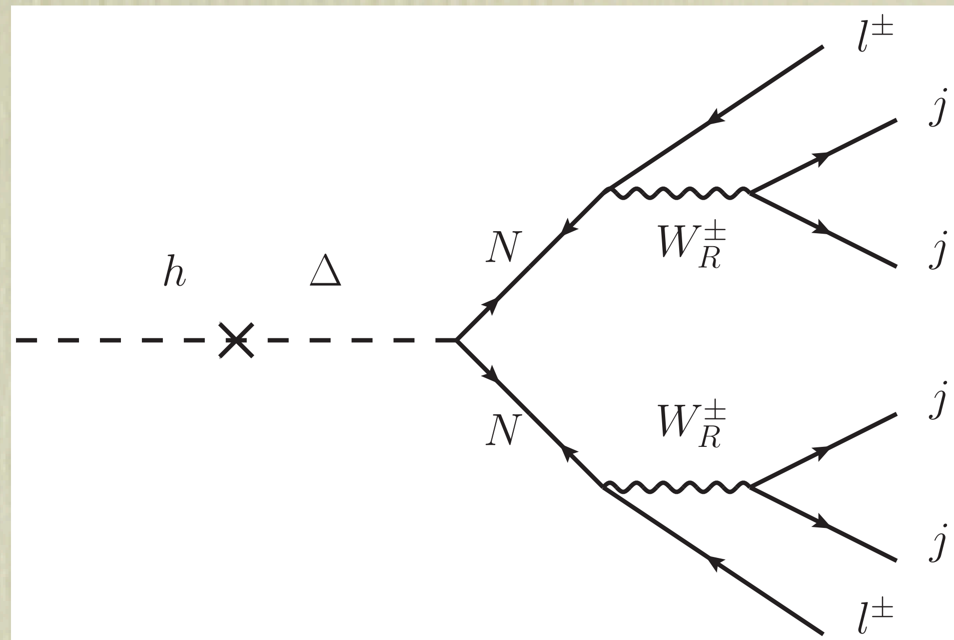
W'➛*l*+ν search

W'➛dijet search

(update of LR@LHC "roadmap" [Nemevšek, FN, Senjanović, Zhang '11])

LNV Higgs decay - parton level

Same-sign $l\,l + jjjj$:



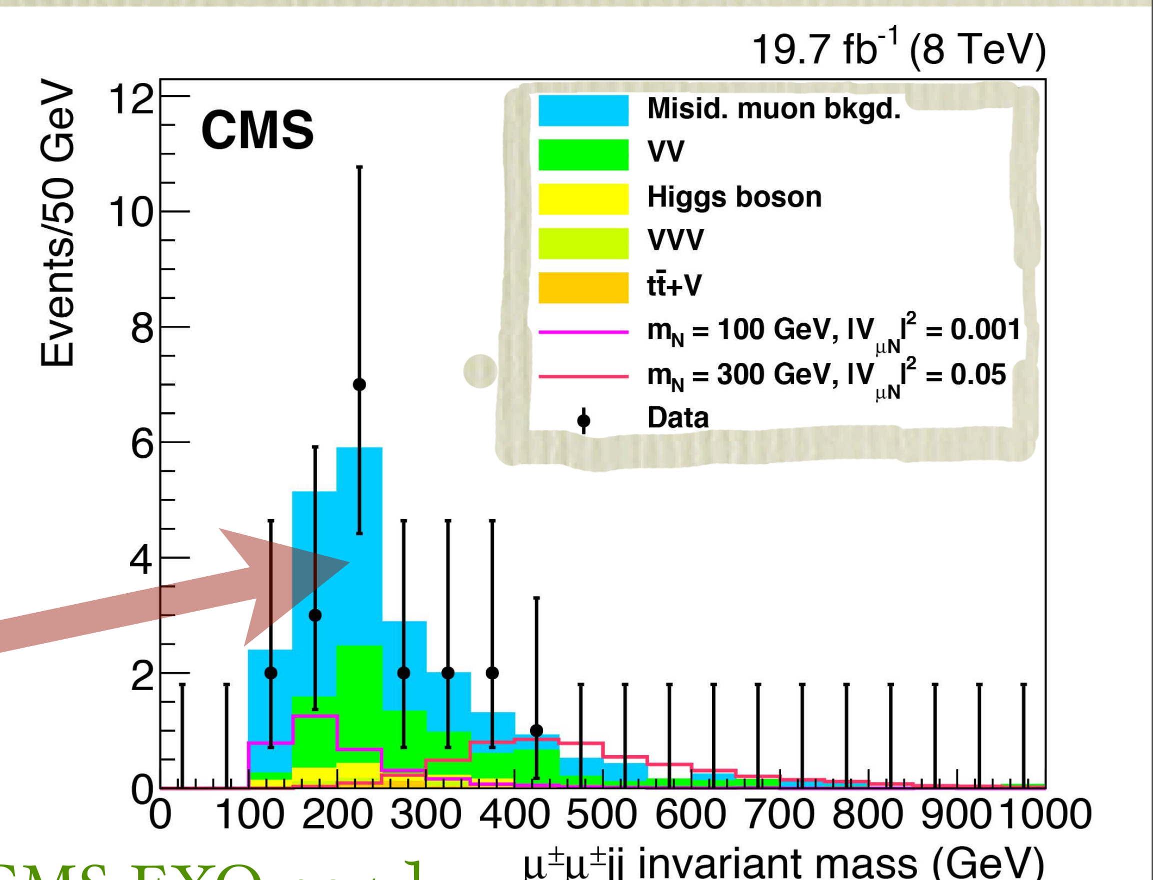
- M(lljjjj) reconstructs higgs mass
- M(ljj) the neutrino mass peak
- Flavour of leptons reconstructs leptonic V_R
  (NB. Quark and lepton mixing structure predicted in LR
  [Nemevšek Senjanović Tello PRL '14] [Senjanović Tello PRL '15])
- Low typical momenta mh/6~ 20 GeV
- *N* lifetime submillimeter to meters: *displaced vertices*

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_{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 $100\,\text{fb}^{-1}$ 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...

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

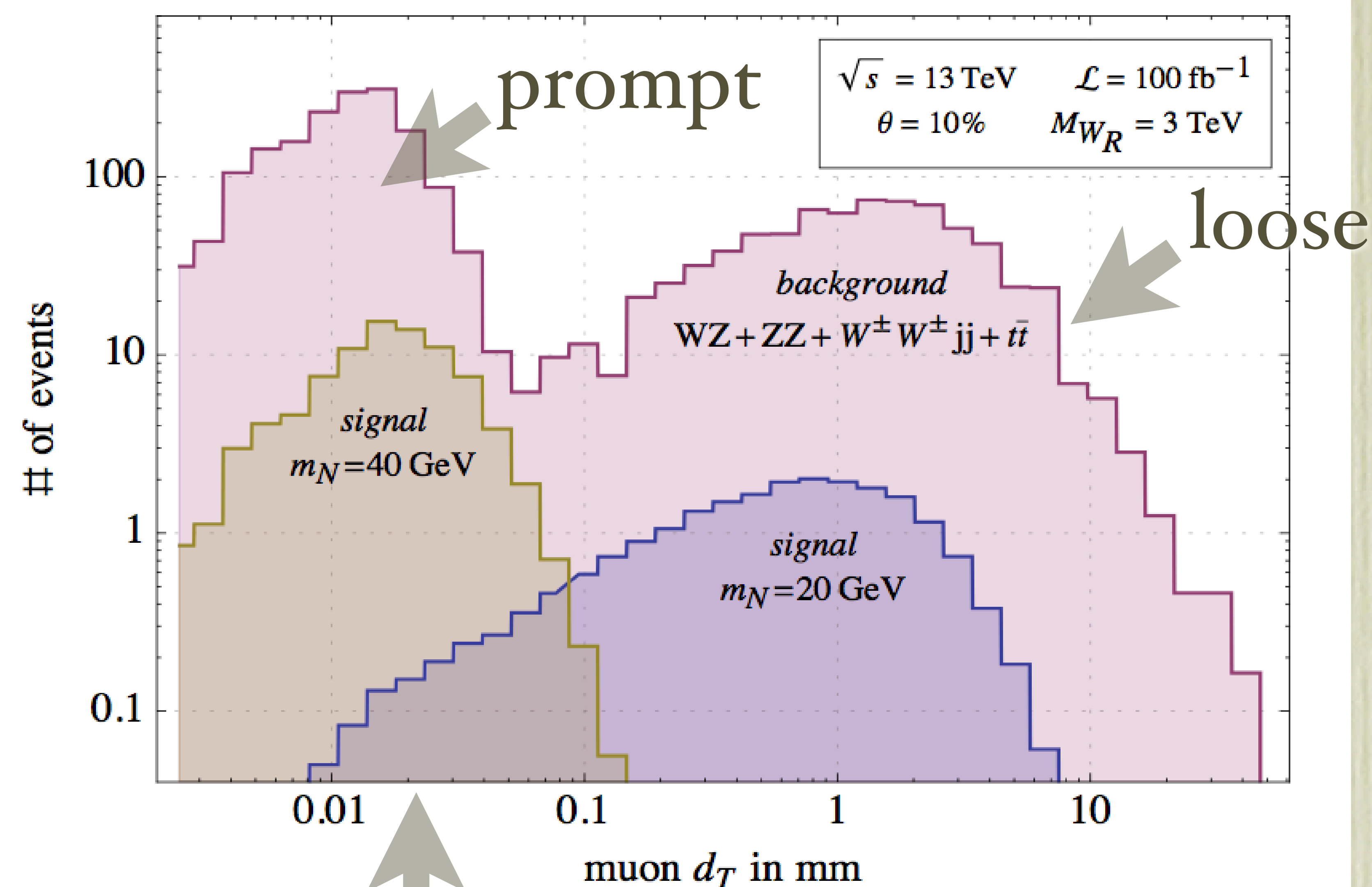


FIG. 3. Reconstructed transverse muon displacement after $\mu^{\pm}\mu^{\pm}+n_j$ event selection and before other cuts.

Track vertex resolution ~ 20 μm

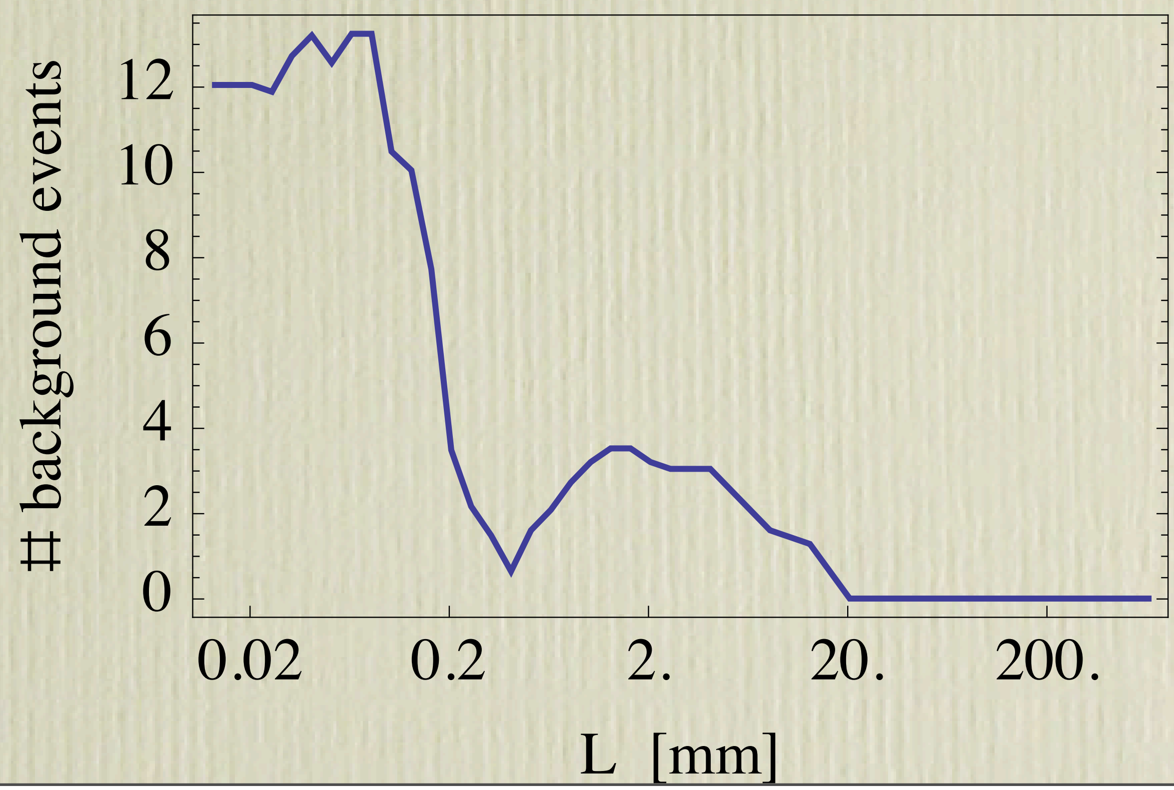
We cut on a sliding window function of m_N

Displaced vertices power

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

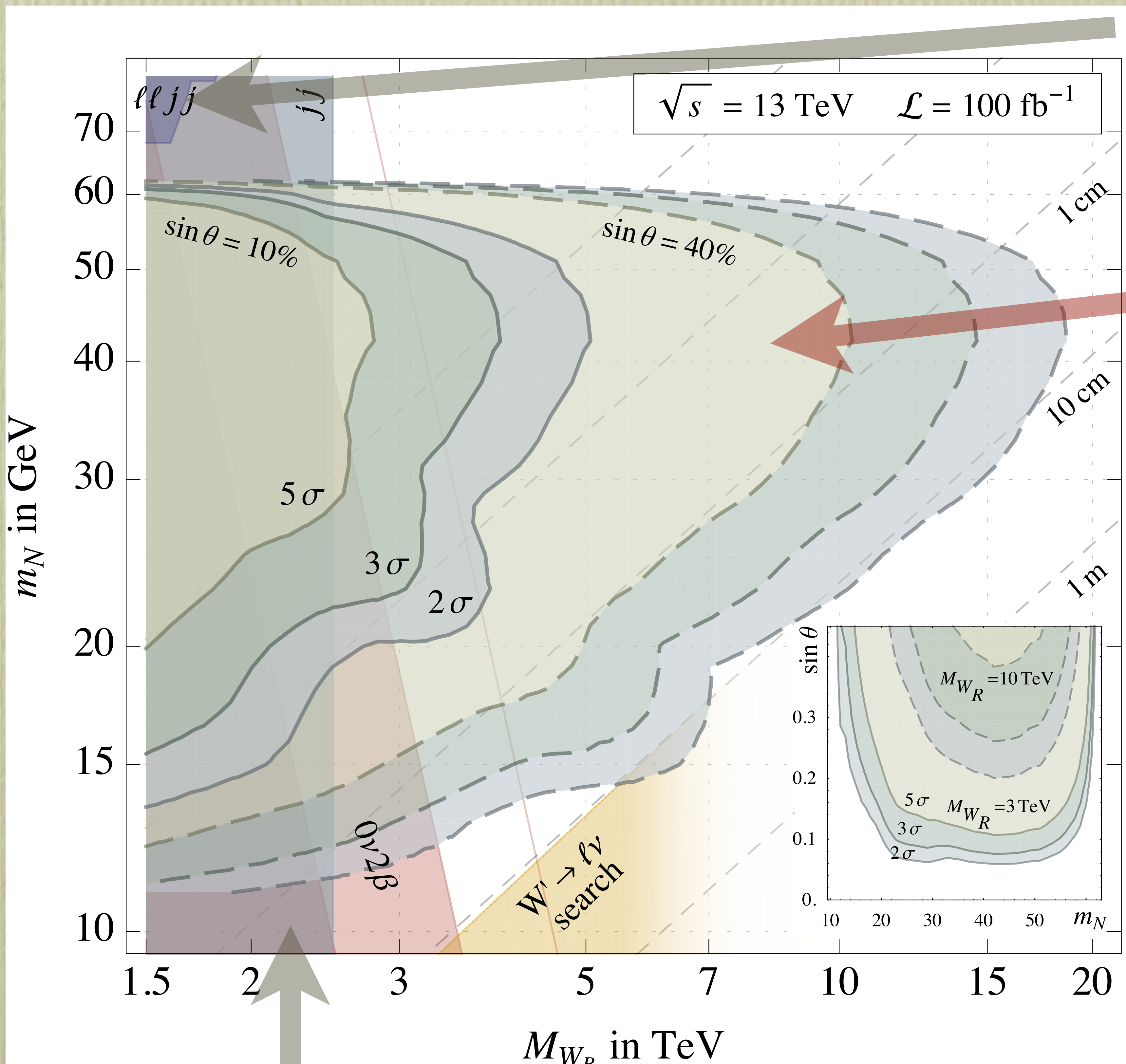
  N lifetime depending on m_N and M_{WR}

- 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*.

LHC Sensitivity



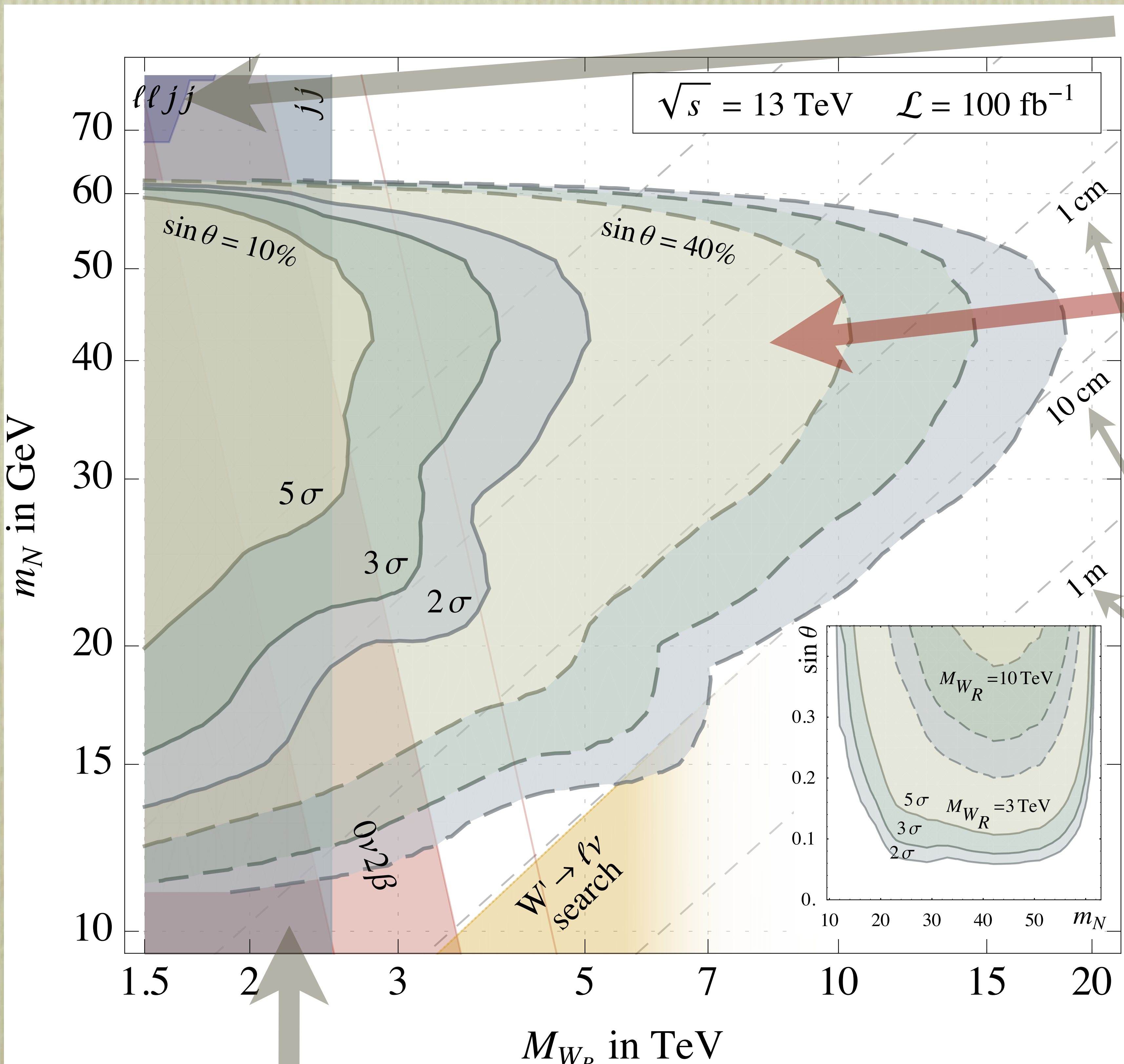
Keung-Senjanovic
$lljj$

displaced
LNVH decay
$h \to \mu^{\pm}\mu^{\pm} + jet(s)$

W'➛dijet search

[Maiezza, Nemevsek, FN 1503.06834]

LHC Sensitivity



Keung-Senjanovic
lljj

displaced
LNVH decay
$h \to \mu^{\pm}\mu^{\pm} + jet(s)$

N lifetime

Study applies to
generic LNV models

W'➛dijet search

[Maiezza, Nemevsek, FN 1503.06834]

So, the Higgs to neutrino mass roadmap

Search for $h \rightarrow NN$:

- Find N, check vs yukawa (*mass generation!*)
- Estimate θ mixing. Perturbativity says:

$$m_\Delta \lesssim 5\,\mathrm{TeV}\left(\frac{0.4}{\theta}\right)$$

- Look for Δ and its NN decays  (*confirm mass generation*)
  Look for W_R (*parity restoration*)
- ...if necessary, at a future collider :)

(*e^+e^- particularly clean*)

Improvements
Challenges

- Relax minimum muon P_T below 10GeV?
  (x 2 more signal!)

- Go to tighter missing energy? <20GeV?
  (really hard?)

- Displaced jets (naively doable)

- Displacements vs larger impact par. problems?

e.g. talk by Golling

- Triggering at low pt?

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.

Resume - Outlook

- Neutrino masses exist - Left-Right natural theory
- Contains Higgs mixing and
- Offers new Lepton Number Violating Higgs decays
- Higgs a gateway to the neutrino mass mechanism
- Can probe parity restoration to ~20 TeV
- Unexplored territory (e.g. physics of neutral Δ) 

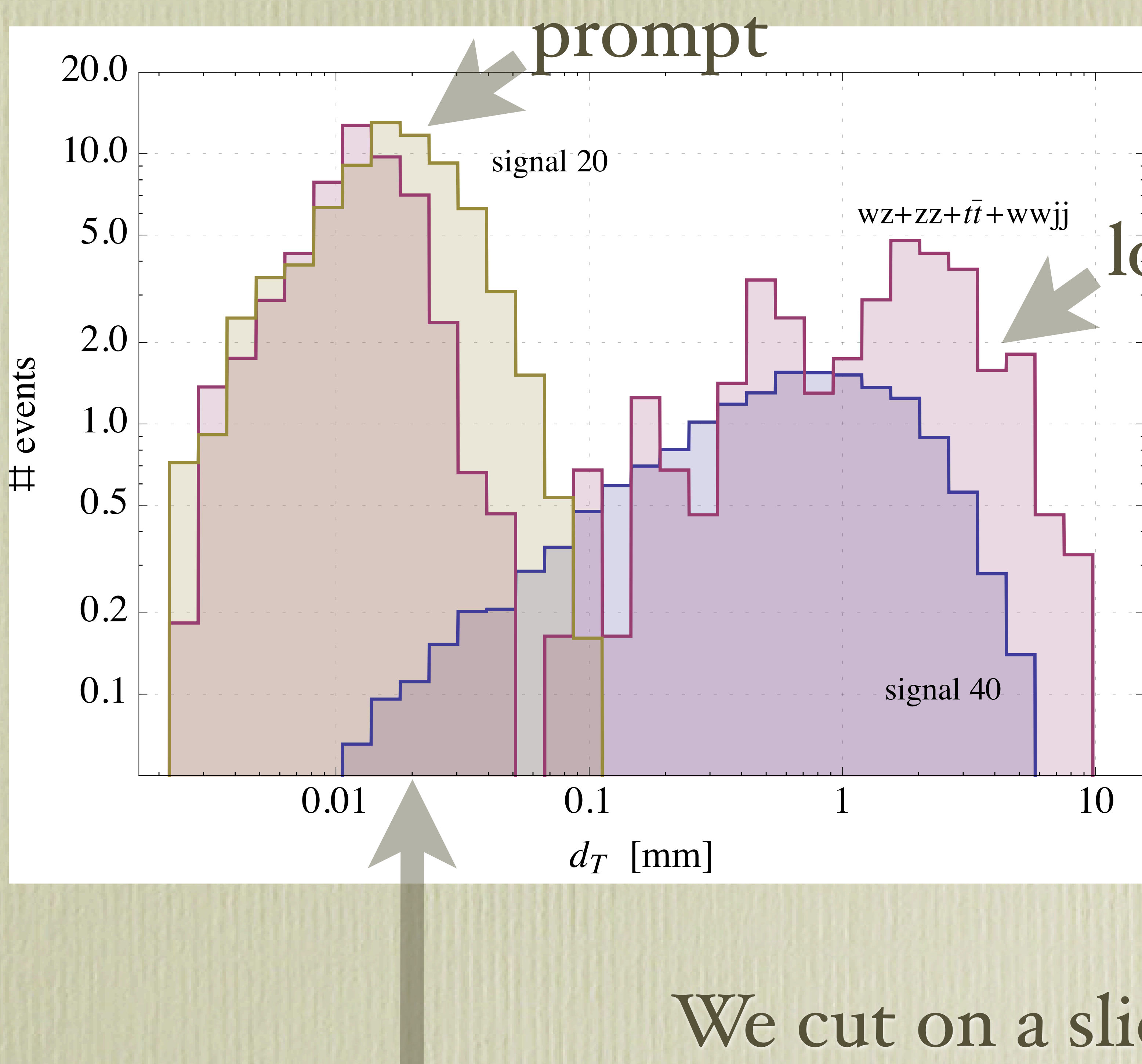
Resume - Outlook

- Neutrino masses exist - Left-Right natural theory
- Contains Higgs mixing and
- Offers new Lepton Number Violating Higgs decays
- Higgs a gateway to the neutrino mass mechanism
- Can probe parity restoration to ~20 TeV
- Unexplored territory (e.g. physics of neutral Δ) 

Thanks!

Backup

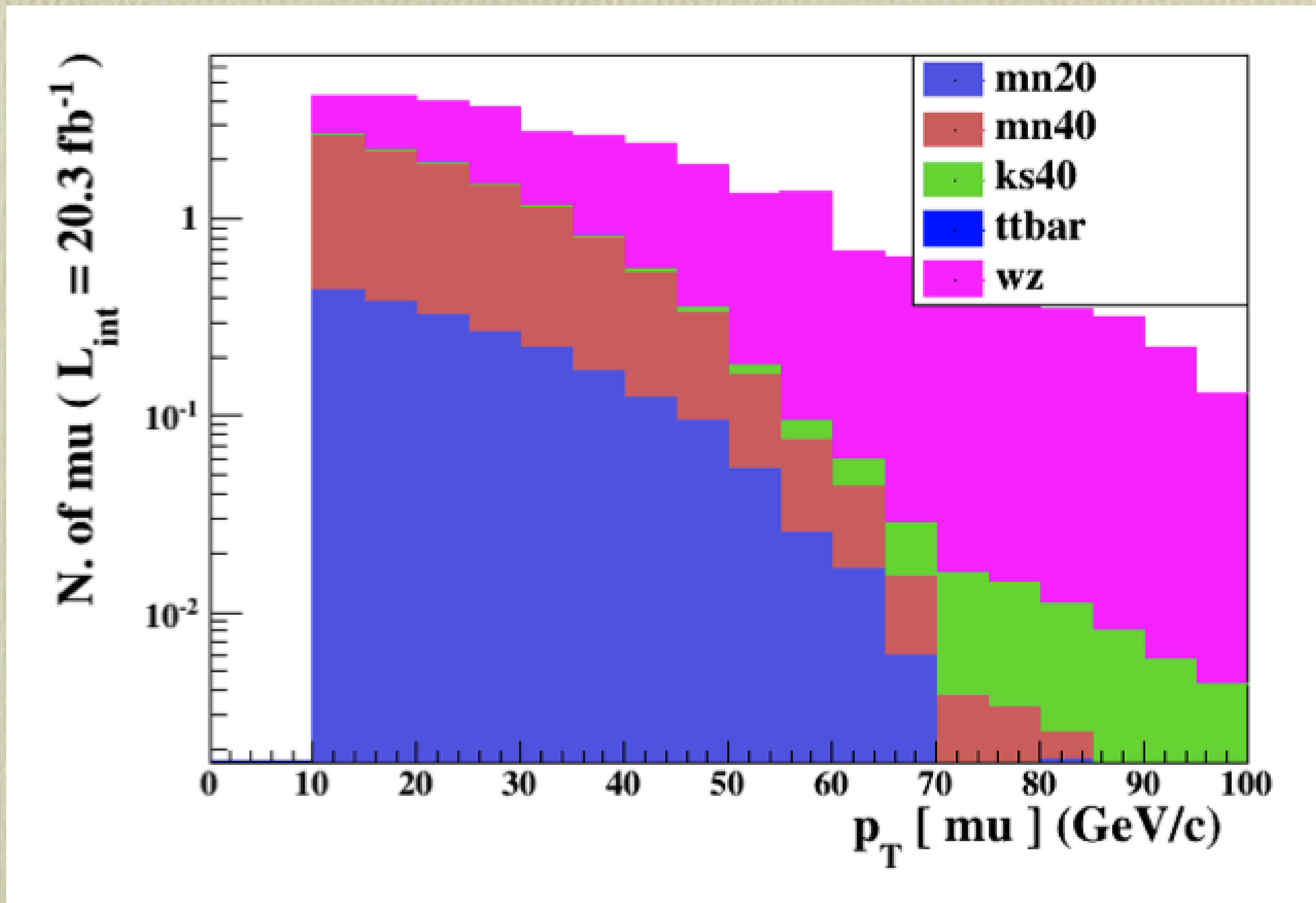
displaced vertices after cuts



We cut on a sliding window function of m_N

Track vertex resolution ~ 20 μm

muon P_T - before/after cuts



muon P_T - before/after cuts