So, the Standard Model is incomplete (but correct)

Gravity...

Dark Matter...

SM *aestetically* incomplete?

Global symmetries, $\not{B}$, $\not{L}$?

Neutrino masses *are* new physics

Dirac or Majorana

Low scale?

- Key questions: which theory? at which scale?

Theory?

A theory of neutrino masses. . .

In the SM:

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BSM:

- Or new states.
- Question: is it low or high scale physics?
- Physical consequences.

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- Dirac mass ($\Delta L = 0$) – need Right-Handed neutrino ν_R

$$M_D \overline{\nu_R} \nu_L + h.c. \equiv M_D \nu_R^{ct} C \nu_L \to M_D \nu^*_{R\,\dot\alpha} \nu_{L\,\beta}\, \delta^{\dot\alpha\beta} + h.c.\,.$$

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[Mohapatra, Pal, "Massive neutrinos in physics and astrophysics"]

[Denner et al, "Compact Feynman rules for Majorana fermions", PLB291]

[Dreiner, Haber, Martin, "Feynman Rules using two-component spinor notation"]

Seesaw (type-I)

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M_R large $\Rightarrow$ M_ν small.

(eigenstates: light Majorana and heavy Majorana)

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But what can M_D and M_R be?

Seesaw (type-I) - at which scale?

Scales m_D, m_R quite free... (yukawa perturbativity, $M_D < 500$GeV)

Some scenarios using $m_\nu = m_D^2/m_R \lesssim 1\,eV$ ignoring mixings

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Theory
Dirac vs Majorana
Seesaws
Diagonalization
Lepton Violation
$0\nu\beta\beta$
Experiments
New Physics

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- $m_D \sim 100\,\text{GeV}$ – (like heavy quarks?)

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  More interesting:
  m_R associated to physical states: observable (see later)

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Seesaw-I not the only possibility...

Seesaw (type-II)

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$$\mathcal{L}_{y_\Delta} = Y_\Delta \ell_L^t \tau_2 \Delta_L \ell_L$$

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- The triplet couples to Higgs, $m_\Delta^2 \Delta^2 + m_\Delta H \Delta H$. $(m_\Delta \gg v)$
So it has a naturally small VEV, $v_L \sim v^2/m_\Delta$.

$$M_\nu \sim Y_\Delta v^2/m_\Delta$$

Again, large $m_\Delta \to$ small M_L. [Magg, Wetterich, PLB '80]

Masses, general

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- Note, now that there can be cancelations to get light M_ν.

  And there can be cancelations also inside $M_D^t M_R^{-1} M_D$.

  (see Casas-Ibarra parametrization of M_D)

Masses, diagonalization

Now, as for quarks, mass eigenstates are not flavour ones.
Charged leptons-neutrino mismatch enters Left charged current.

$$\begin{aligned} M_e &= V_{eL}\, m_e V_{eR}^\dagger \\ M_\nu &= V_{\nu L}\, m_\nu V_{\nu R}^\dagger \end{aligned} \quad , \quad U_{PMNS} = V_{eL}^\dagger V_{\nu L} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} =$$

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- Majorana mass, complex symmetric $V_{\nu R} \equiv V_{\nu L}^*$
  Now the two phases α_1 and α_2 can not be removed!
  (i.e. Majorana mass breaks lepton numbers!)
  These phases however appear only in LNV processes.

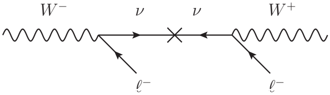
Neutrino - up to now

What we saw:

- Neutrino have masses (Dirac or Majorana)
- Need extension of the SM.
- Add heavy ν_R $\rightarrow$ seesaw-I.
- Add heavy Δ_L $\rightarrow$ seesaw-II.
- Majorana violates Lepton number by two units
- Two extra 'Majorana' CP phases in the mixing matrix U_{PMNS}.

let's look at consequences...

Lepton number violation, consequences



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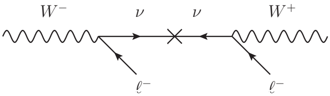

- Nuclear neutrinoless double beta decay:

  $${}^{A}_{Z}X \to {}_{Z+2}^{\;\;A}X + 2e^-$$

  $\ldots \tau_{0\nu\beta\beta} \gtrsim 10^{24} y$, but testable!

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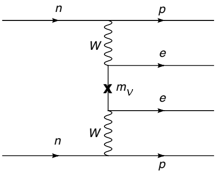

[Racah, Nuovo Cim. '37]

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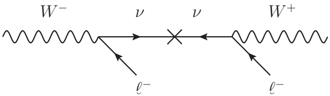

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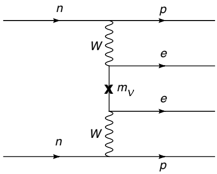

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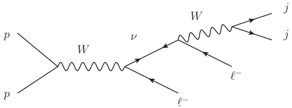
- Collider: same sign dileptons:

  Very small for standard W...



[Keung Senjanović '83]

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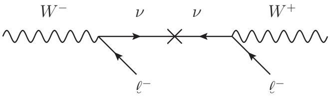

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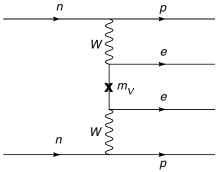

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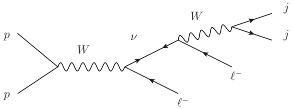

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- Meson neutrinoless double beta decay, e.g. $K^+ \to \pi^- \ell^+\ell^+$
  $BR < 10^{-20}$, much less than current limits, $BR \lesssim 10^{-10}$

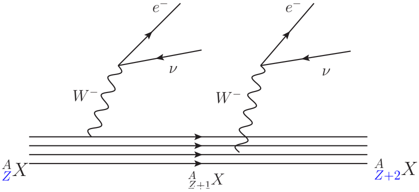
[Littenberg Schrok, '92]

$0\nu\beta\beta$

Two-neutrino double beta decay $0\nu\beta\beta$

- Double β-decay, two e^-

  Neutrino $p \sim 3\,\mathrm{MeV}$

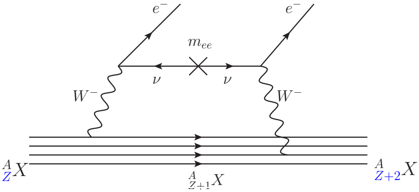


- no LNV

Neutrinoless double beta decay $0\nu\beta\beta$

- Actually a loop process:
  Released $Q \sim 3$ MeV.
  Neutrino $p \sim 100$ MeV

  Decay width:
  $\Gamma_{0\nu} = G(Q)\,|\mathcal{M}|^2$
  [phase space] [amplitude]



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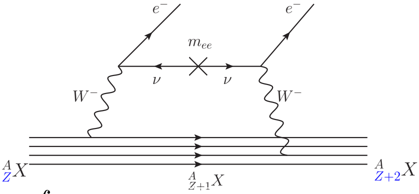

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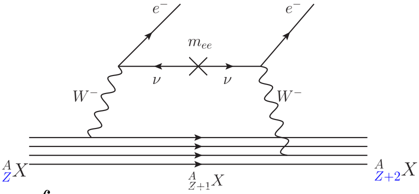

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- LNV explicitly related to Majorana neutrino masses.
  Light neutrinos ($M_\nu \ll p \sim 100\,\text{MeV}$) give

$$L_{\mu\nu} \propto M_\nu^{ee} \frac{1}{p^2}$$

$0\nu\beta\beta$ cont'd

Strenght of LNV in $0\nu\beta\beta$, from standard light neutrinos:

$$M_\nu^{ee} = \sum U_{ei}^2 m_i = m_1|U_{e1}^2| + m_2|U_{e2}^2|e^{i\alpha_1} + m_3|U_{e3}^2|e^{i\alpha_2}$$

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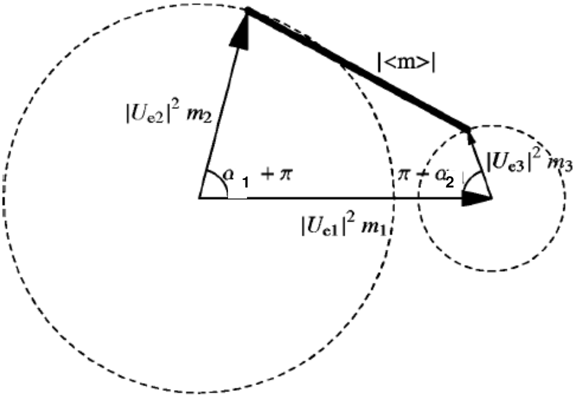
- So, from oscillations, $|U_{e1}^2| \sim 0.6$, $|U_{e2}^2| \sim 0.25$, $|U_{e3}^2| \sim 0.022$, ...Majorana phases important and there can be a cancelation!



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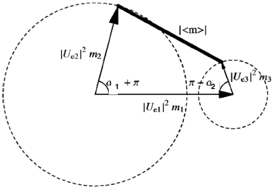
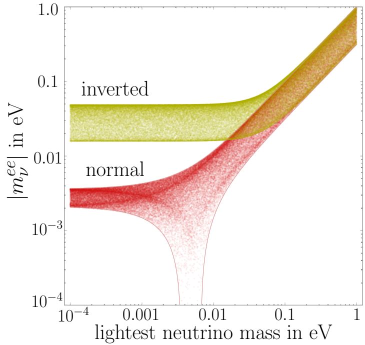
Strenght of LNV in $0\nu\beta\beta$, from standard light neutrinos:

$$M_\nu^{ee} = \sum U_{ei}^2 m_i = m_1|U_{e1}^2| + m_2|U_{e2}^2|e^{i\alpha_1} + m_3|U_{e3}^2|e^{i\alpha_2}$$

- So, from oscillations, $|U_{e1}^2| \sim 0.6$, $|U_{e2}^2| \sim 0.25$, $|U_{e3}^2| \sim 0.022$, ...Majorana phases important and there can be a cancelation!





- Possible $0\nu\beta\beta$, as a function of lightest neutrino mass:

[Vissani '02]

Can distinguish the hierarchy. And the absolute mass.

$0\nu\beta\beta$, matrix elements

Neutrino propagator, i.e. $1/r$ for light e^{-mr}/r for heavy neutrino.

- Well approximated by its typical momentum $p \sim 100 \div 200\,\text{MeV}$. Both for light or heavy neutrino exchange (no core suppression)

$$\left\langle \frac{m_\nu}{p^2} \right\rangle_{nuc} \simeq \frac{m_\nu}{p^2}\,, \qquad \left\langle \frac{1}{m_N} \right\rangle_{nuc} \sim \frac{1}{m_N}$$

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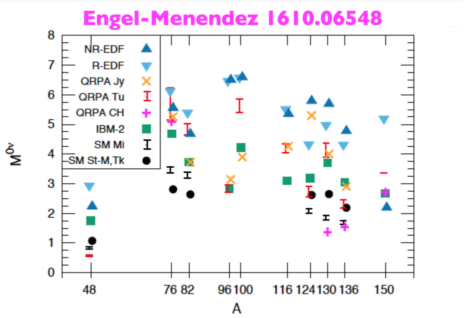
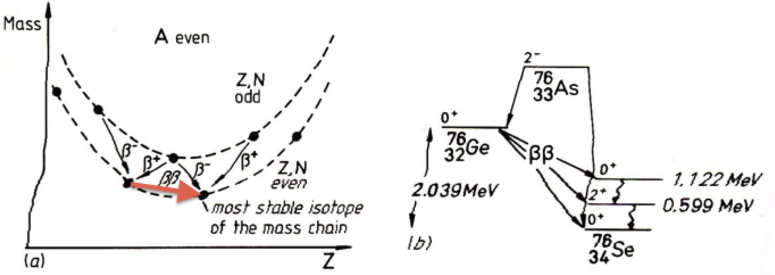
- Real calculation, w/ nuclear models, uncertain by a factor of 20–200–1000% (got worse)



Neutrinoless double beta decay, cont'd

Need to avoid the much more favored single beta decay.

- In some nuclei β-decay is forbidden! [Bethe-Weizsäcker formula]



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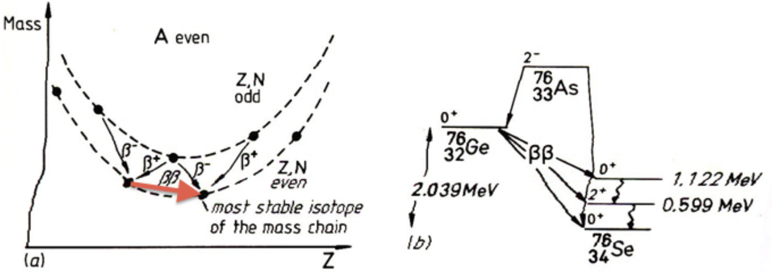
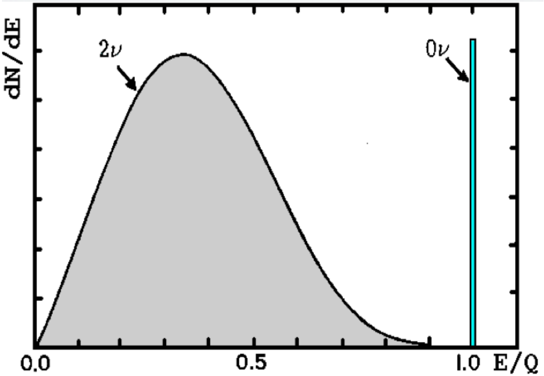


- Now, $\beta\beta$ can proceed through both $2\nu\beta\beta$, or $0\nu\beta\beta$..

How to distinguish them? – We don't detect neutrinos.

Neutrinoless double beta decay, cont'd

- Recognized by the spectrum of electrons (once again!)



- In real life, the line is not *so* definite...

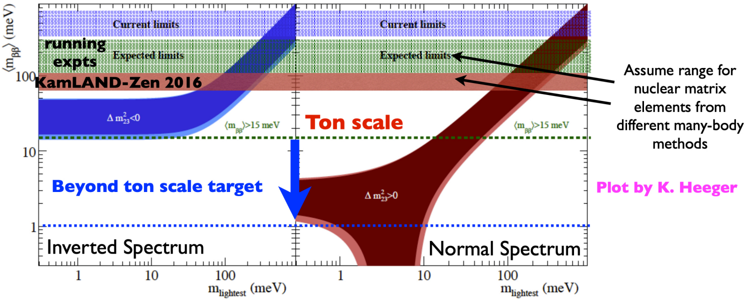
Experiments, ongoing

Isotope	$T^{0\nu}_{1/2}$ ($\times 10^{25}$ y)	$\langle m_{\beta\beta}\rangle$ (eV)	Experiment
^{48}Ca	$> 5.8 \times 10^{-3}$	$< 3.5 - 22$	ELEGANT-IV
^{76}Ge	> 8.0	$< 0.12 - 0.26$	GERDA
	> 1.9	$<$ 0.08-0.12	Majorana Demonstrator
^{82}Se	$> 3.6 \times 10^{-2}$	$< 0.89 - 2.43$	NEMO-3
^{96}Zr	$> 9.2 \times 10^{-4}$	$< 7.2 - 19.5$	NEMO-3
^{100}Mo	$> 1.1 \times 10^{-1}$	$< 0.33 - 0.62$	NEMO-3
^{116}Cd	$> 1.0 \times 10^{-2}$	$< 1.4 - 2.5$	NEMO-3
^{128}Te	$> 1.1 \times 10^{-2}$	—	—
^{130}Te	> 1.5	$< 0.11 - 0.52$	CUORE
^{136}Xe	> 10.7	$<$ 0.09-0.11	KamLAND-Zen
	> 1.8	$< 0.15 - 0.40$	EXO-200
^{150}Nd	$> 2.0 \times 10^{-3}$	$< 1.6 - 5.3$	NEMO-3

Notice the insanely large lifetime limit (age of universe is just 10^{10} y).

Ton experiment (e.g. Legend 1000) are coming to probe 100 times larger lifetimes.

Neutrinoless double beta decay, results



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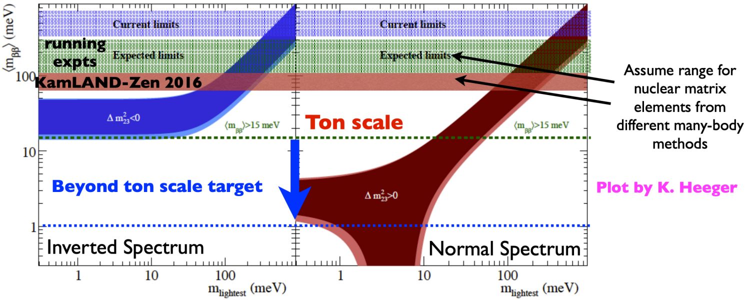
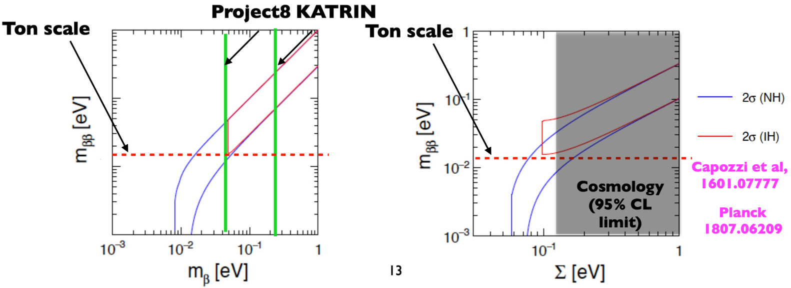
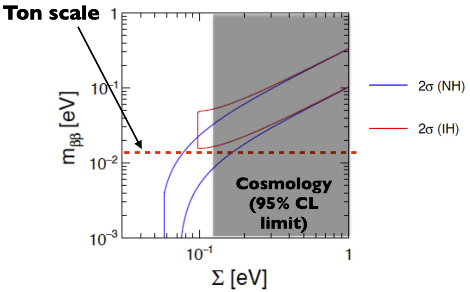




Possible future clash with cosmology or Tritium

- Shrinking limits the sum of neutrino masses,
  E.g. now from cosmology $\sum m_i \lesssim 0.12\,\text{eV}$ (Planck 95% C.L.)



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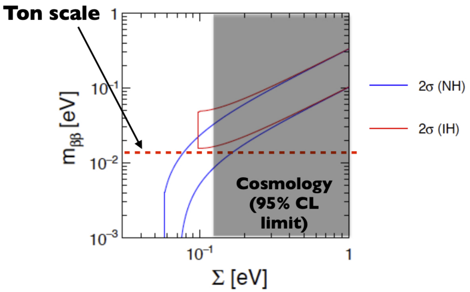

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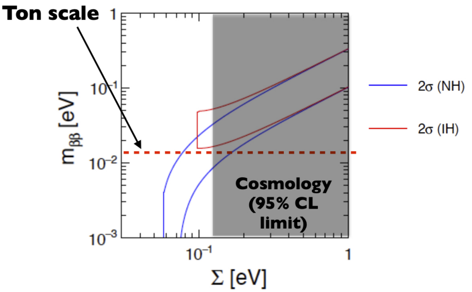

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...So $0\nu\beta\beta$ would probe new physics beyond light neutrinos!

New Physics - where? when?

If m_ν^{ee} excluded by cosmology, can new Physics do the job?

Try to guess at the level of effective operators...

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Result, the amplitudes are comparable for (say $\lambda \sim G_F^2 M_W^4$)

$$\Lambda \sim TeV.$$

...something would be expected at collider.

Recap up to now

- Neutrino have mass
- Majorana? ($\not{L}$, and possible $0\nu\beta\beta$).
- Possibly an effective operator: (not telling us the origin)

$$\frac{\lambda}{M}(\ell H)^t(H\ell)\,,$$

[Weinberg '79]

- Realizations, e.g. type-I seesaw: (y and M quite free)

$$y\,\bar{\ell}H\nu_R + M\nu_R^t\nu_R$$

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- So. . . maybe TeV M hints to something? New interactions?
  . . . e.g.: M breaks lepton number, $B-L$, ...
- Maybe we can test a low M and new forces at LHC?
  (Yes, because of $\not{L}$ at collider.)

What about theory?

In the SM:

- Lepton Number conserved. (also family L_e, L_μ, L_τ separately!)
- Only left neutrinos, there is no renormalizable mass term.
- Effective theory: a D = 5 nonrenormalizable operator?

BSM:

- Or new states.
- Question: is it low or high scale physics?
- Physical consequences.

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	$\overline{\mathbf{2}}$	$2/3$	$2/3$	0	$1/2$	$1/3$	**3**
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...new RH neutrino and RH gauge bosons.

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

- RH neutrino singlet of SM, but doublet of $SU(2)_R$
- Note, $Y = T_{3R} + (B-L)/2 \quad \rightarrow \quad Q = T_{3L} + T_{3R} + (B-L)/2 \;\; !$
- $B-L$ clearly anomaly free.

Path to further unifications

Looking into fermion quantum numbers opens the view on unification setups

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

$$q_L \in (\mathbf{2}, \mathbf{1}, 1/3, \mathbf{3}) \qquad q_R \in (\mathbf{1}, \mathbf{2}, 1/3, \mathbf{3})$$

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...one naturally tries to unify different factors:

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

$$(q_L + \ell_L) = \psi_L \in (\mathbf{2}, \mathbf{1}, \mathbf{4}) \qquad (q_R + \ell_R) = \psi_R \in (\mathbf{1}, \mathbf{2}, \mathbf{4})\,.$$

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

$$\psi_L + \psi_R^c \in (\mathbf{2}, \mathbf{1}, \mathbf{4}) + (\mathbf{1}, \mathbf{2}, \overline{\mathbf{4}}) = \mathbf{16}\,.$$

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- *Gravi*GUT: $SO(3, 11)$ [FN '07, FN Percacci '09]

$$(\mathbf{2}_{Lorentz}, \mathbf{16}_{SO(10)}) = \mathbf{64}_{MW} .$$

A word about parity

Take the Weyl basis $\Psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$

- As we know, Parity is represented as $\gamma_0 = \begin{pmatrix} \mathbf{0} & \mathbf{1} \\ \mathbf{1} & \mathbf{0} \end{pmatrix} = \mathbf{1} \otimes \sigma_1$
- It does not commute with all Lorentz, namely boosts $K_i = \sigma_i \otimes \sigma_3$, and also reverses spatial x^i .
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- Thus parity alone can not be restored, once the spectrum has chiral $SU(2)_L$ interactions.

Only possibility is to restore a generalized $\mathscr{P}$ by introducing a new interaction $SU(2)_R$ and have a $L \leftrightarrow R$ symmetric theory

(Somewhat automatic in GraviGUTs: SO(3,11), SO(13,1)...)

Parity restoration

So: the SM with minimal extension can restore parity!

By this we mean a generalized P:
Swap $\psi_L \leftrightarrow \psi_R$ and also gauge groups $SU(2)_L \leftrightarrow SU(2)_R$,

Left-Right symmetry

[Pati Salam '74, Mohapatra Pati '75, Senjanovi´c Mohapatra '75]
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Let's see the model for its predictions...

(Minimal) Left-Right Symmetric Model

Theory of Neutrino Mass and Parity Breaking

[Pat

- The gauge group:

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

- Fermions:

Quarks $q_{L,R}$, Leptons $\ell_{L,R}$.

- Gauge bosons

$$W^i_{L\mu} \quad W^i_{R\mu} \quad B_\mu \quad G^a_\mu$$

(with respective coupling constants g_L, g_R, g_{B-L}, g_s)

- Assume $L \leftrightarrow R$ symmetry exact at TeV scale.

so $g_L = g_R$

- Higgs:

complex bidoublet: ϕ
triplets: Δ_L, Δ_R

(Minimal) Left-Right Symmetric Model

- W's 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 $\qquad v_R \gg v = \sqrt{v_1^2 + v_2^2}$

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

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- Heavy RH gauge boson, $M_{W_R} = g\, v_R$, mixes with W_L:

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

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

- Heavy RH gauge boson, $M_{W_R}=g\, v_R$, mixes with W_L:

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

- 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, a number of consequences.

LR - Lagrangian

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

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

$$\begin{aligned}\mathcal{L}_{Fermion} &= \overline{q}_{Li} i \not{D} q_{Li} + \overline{\ell}_{Li} i \not{D} \ell_{Li} + (L \leftrightarrow R) \\ \mathcal{L}_{Yukawa\ q} &= \overline{q}_{Li}(Y_{ij}\phi + \tilde{Y}_{ij}\tilde{\phi}) q_{Rj} + h.c. \\ \mathcal{L}_{Yukawa\ \ell} &= \overline{\ell}_{Li}(h_{ij}\phi + \tilde{h}_{ij}\tilde{\phi}) \ell_{Rj} + h.c. \\ \mathcal{L}_{Majorana} &= Y^{ij}[\overline{\ell}^t_{Li} C\, \tau_2 \Delta_L\, \ell_{Lj} + (L \leftrightarrow R)] + h.c.\end{aligned}$$

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

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

$$\begin{aligned} D_\mu \phi &= \partial_\mu \phi + i g_L W_{L\mu}\, \phi - i g_R \phi\, W_{R\mu} \\ D_\mu \psi &= \partial_\mu \phi + i g_L W_{L,R\mu} \psi_{L,R} + i g' (B - L)/2 B_\mu \psi_{L,R} \\ D_\mu \Delta_{(L,R)} &= \partial_\mu \Delta_{(L,R)} + i g_{(L,R)} \left[W_{(L,R)\mu},\ \Delta_{(L,R)} \right] + i g' B_\mu \Delta_{(L,R)} \end{aligned}$$

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}
$$

LR - Higgs spectrum

Higgs state	m^2
$h^0 = \sqrt{2}\,\mathrm{Re}\,\left(\phi_1^{0*} + xe^{-i\alpha}\phi_2^0\right)$	$\left(4\lambda_1 - \frac{\alpha_1^2}{\rho_1}\right) v^2$
$H_1^0 = \sqrt{2}\,\mathrm{Re}\,\left(-xe^{i\alpha}\phi_1^{0*} + \phi_2^0\right)$	$\alpha_3 v_R^2$
$A_1^0 = \sqrt{2}\,\mathrm{Im}\,\left(-xe^{i\alpha}\phi_1^{0*} + \phi_2^0\right)$	$\alpha_3 v_R^2$
$H_2^0 = \sqrt{2}\,\mathrm{Re}\,\delta_R^0$	$4\rho_1 v_R^2$
$H_2^+ = \phi_2^+ + xe^{i\alpha}\phi_1^+ + \frac{1}{\sqrt{2}}\epsilon\delta_R^+$	$\alpha_3\left(v_R^2 + \frac{1}{2}v^2\right)$
δ_R^{++}	$4\rho_2 v_R^2 + \alpha_3 v^2$
$H_3^0 = \sqrt{2}\,\mathrm{Re}\,\delta_L^0$	$(\rho_3 - 2\rho_1)v_R^2$
$A_2^0 = \sqrt{2}\,\mathrm{Im}\,\delta_L^0$	$(\rho_3 - 2\rho_1)v_R^2$
$H_1^+ = \delta_L^+$	$(\rho_3 - 2\rho_1)v_R^2 + \frac{1}{2}\alpha_3 v^2$
δ_L^{++}	$(\rho_3 - 2\rho_1)v_R^2 + \alpha_3 v^2$

Leading order in $\epsilon = v/v_R$ and $x = v'/v$, and assuming $v_L = 0$.
The SM Higgs is identified with h^0.

W_L-W_R mixing

In the minimal model, the tree level W_L-W_R mixing angle is

$$\tan 2\zeta = \frac{2vv'}{v_r^2 + v^2} \simeq \frac{v'}{v} \frac{M_{W_L}^2}{M_{W_R}^2}$$

This is bound by 'Left' weak decays, $\zeta < 10^{-2}$ $(3\,10^{-3})$.

Thus, this translates into a limit on the W_R mass:

$$M_{W_R} > 1.5\,\text{TeV}\sqrt{\frac{2x}{1+x^2}}\,,$$

(Harmless bound, as nowadays W_R is constrained to be heavier.)

Interesting phenomenology is given by ζ

Two LR Discrete symmetries

and requirements on Yukawa matrices

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

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

A lot is then predicted for masses.

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

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

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

[Nemevšek Senjanović Tello PRL '13]

RH quark mixing ∼ CKM

[Maiezza, Nemevsek, Senjanovic, FN, PRD '10]

Phases or Signs

RH quark mixing ~ CKM

[Maiezza, Nemevsek, Senjanovic, FN, PRD ’10]

Phases or Signs

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

$$V_R = K_u V^* K_d \,,$$

$$K_d = \text{diag}\{e^{i\theta_d}, e^{i\theta_s}, e^{i\theta_b}\}$$

$$K_u = \text{diag}\{e^{i\theta_u}, e^{i\theta_c}, e^{i\theta_t}\}$$

RH quark mixing ~ CKM

[Maiezza, Nemevsek, Senjanovic, FN, PRD '10]

Phases or Signs

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$$K_u = \text{diag}\{e^{i\theta_u}, e^{i\theta_c}, e^{i\theta_t}\}$$

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

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

$$V \to \text{diag}\{s_u, s_c, s_t\}\, V\, \text{diag}\{s_d, s_s, s_b\}$$
$$m_{ii} \to s_i m_{ii}$$

[Senjanović Tello PRL '15]

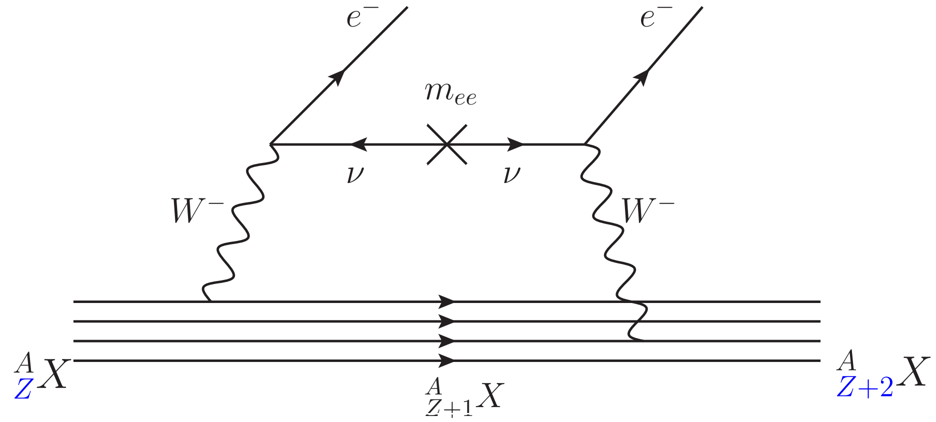
...mixings and phases predicted in terms of $s_\alpha t_{2\beta}$.

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

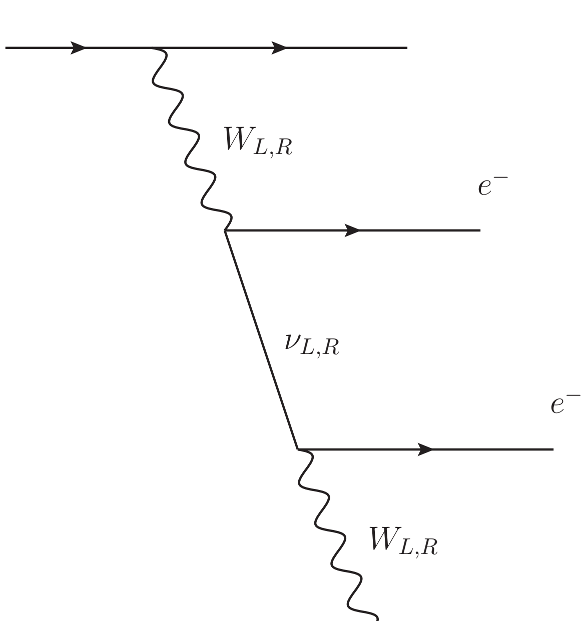
Low energy connection

Finally back to Neutrinoless double beta decay

0ν2β



W_R & ν_R give new contributions



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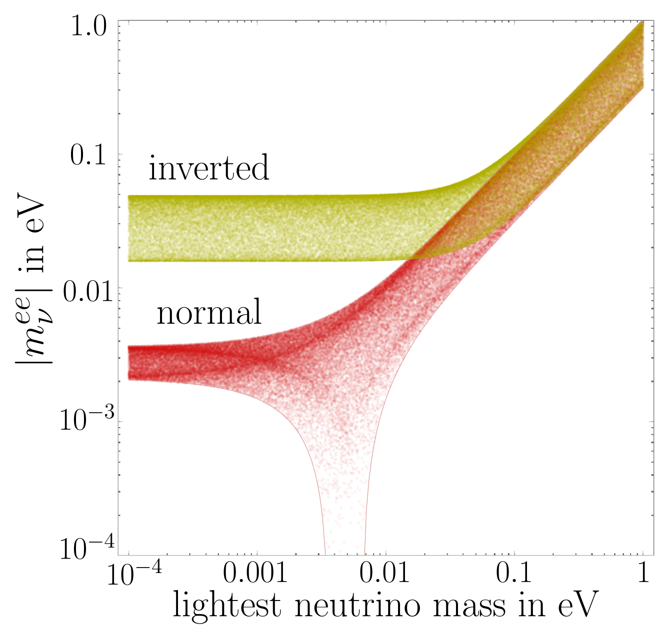
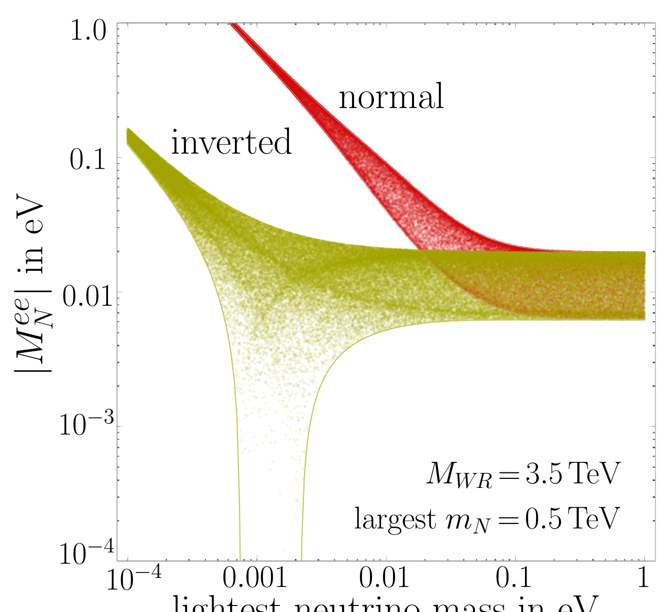


RR



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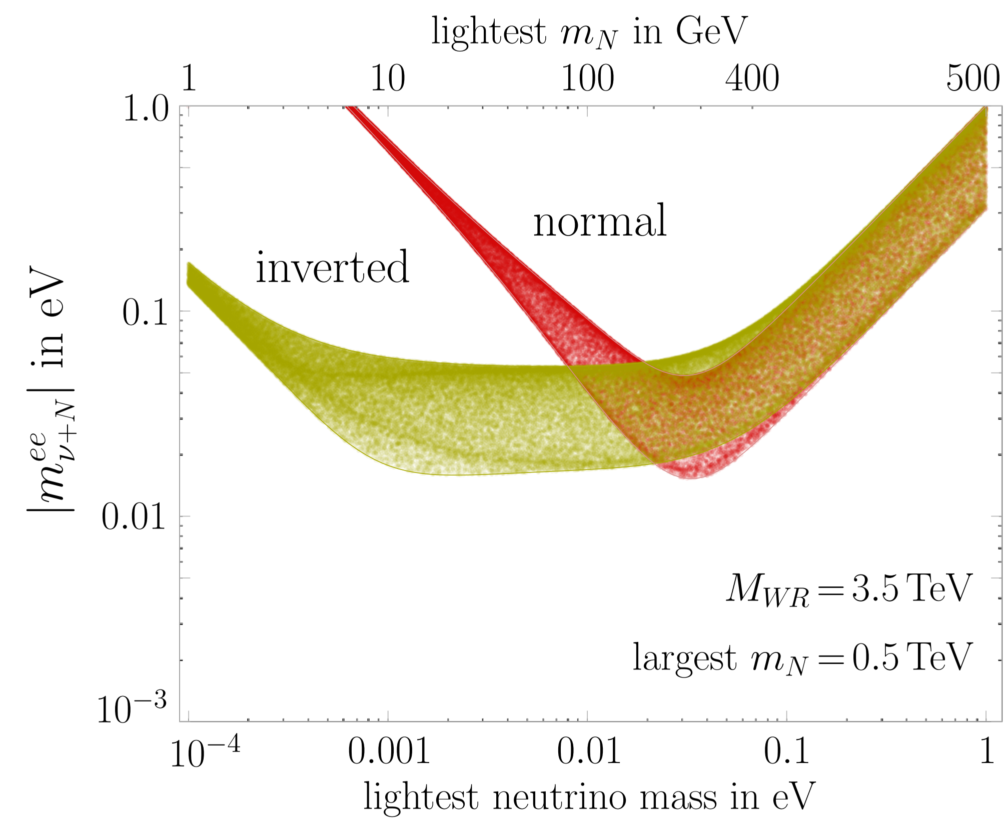
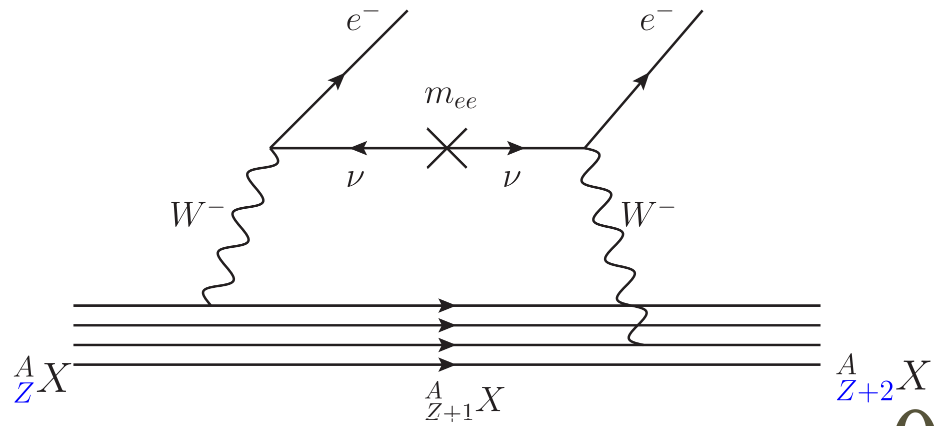
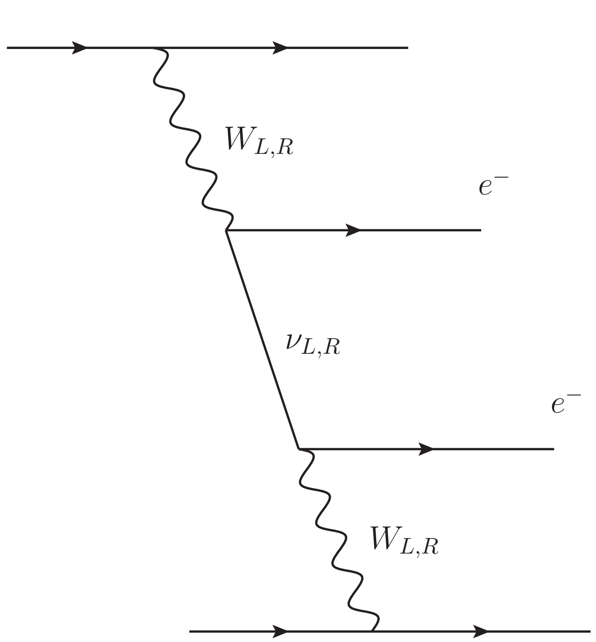


[Tello FN Senjanović PRL '10]
(type-II limit)

0ν2β



W_R & ν_R give new contributions



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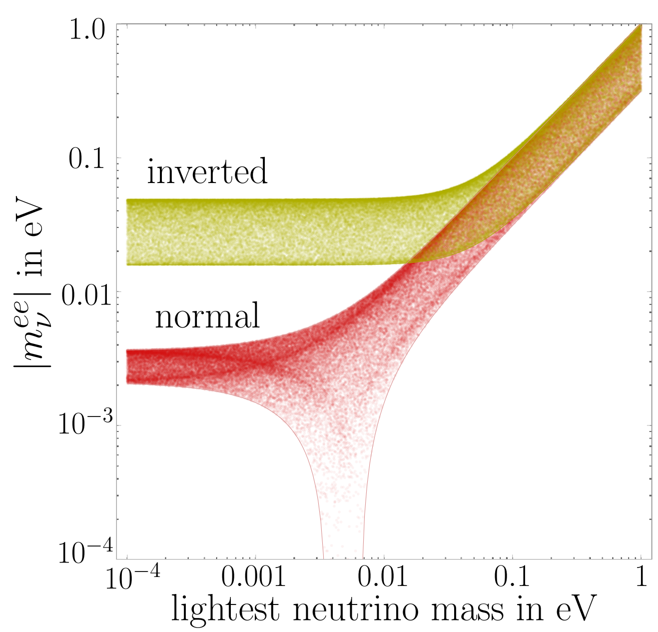

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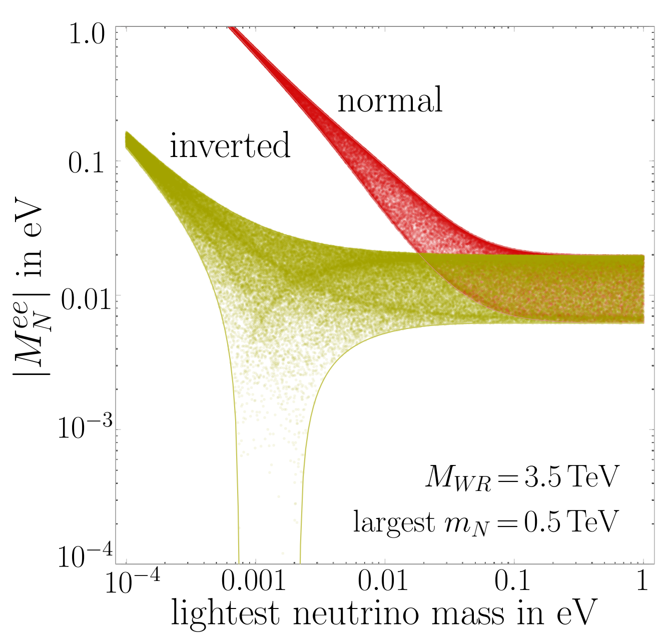
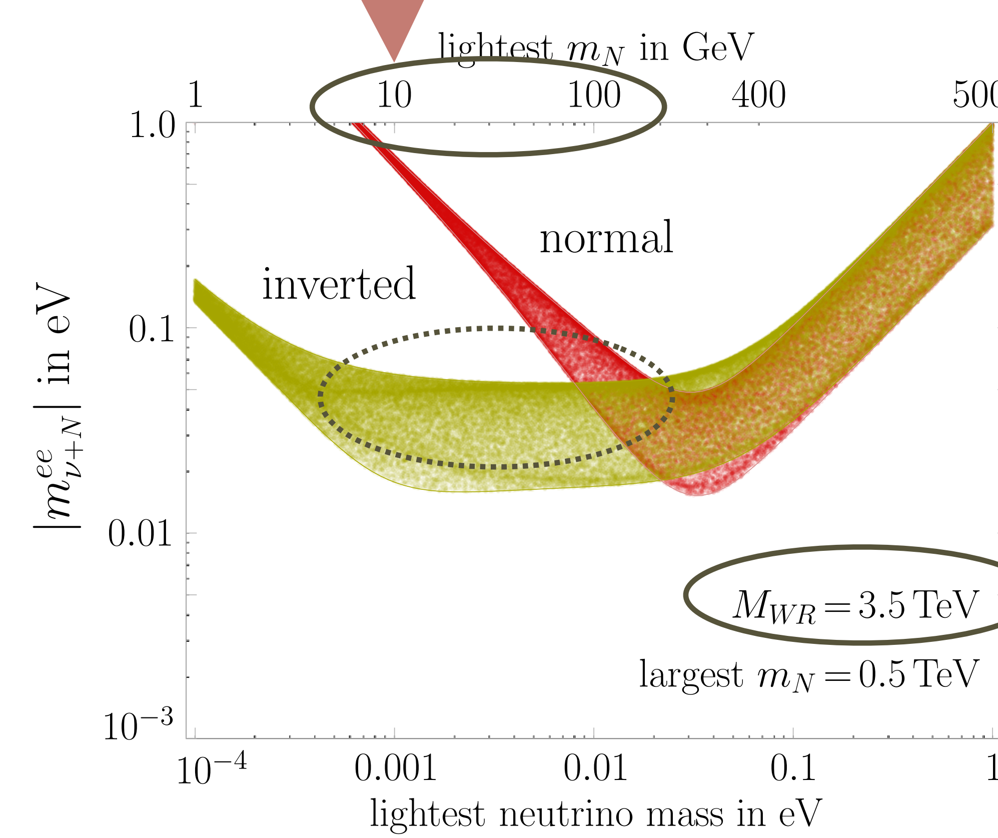


=

0ν2β connecting to W_R & m_N @LHC



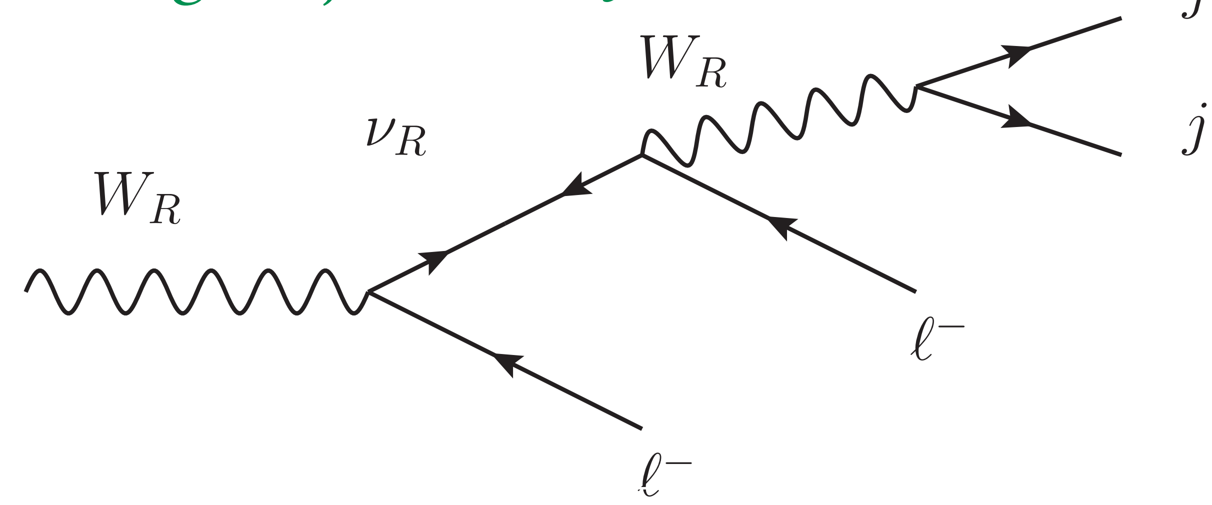
[Tello FN Senjanović PRL ’10]
(type-II limit)

LHC connection

Direct search

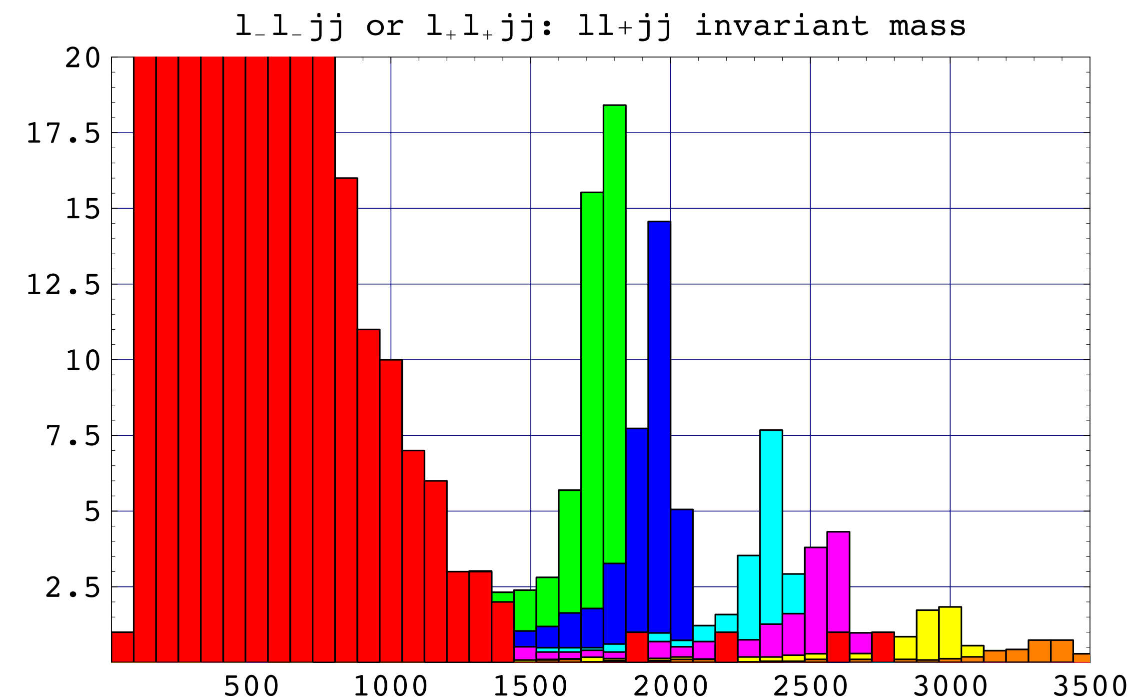
LNV @ LHC

[Keung Senjanović '83]



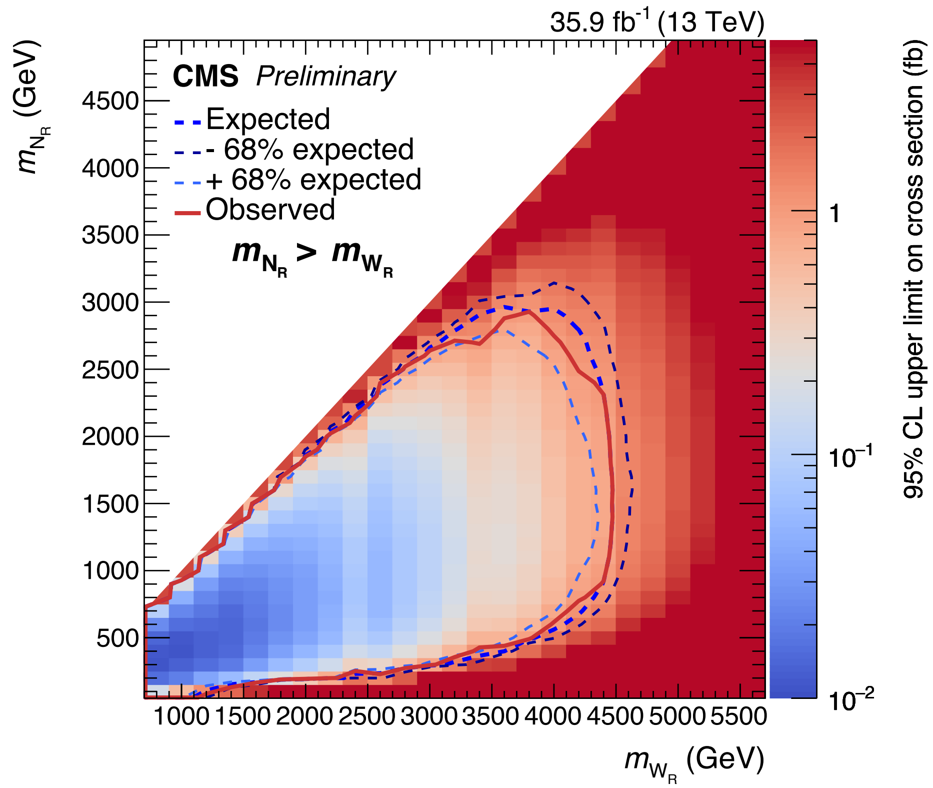
- On shell W_R and ν_R.
- Invariant masses reconstruct W and ν masses
- Probe of lepton flavour mixings
- LNV: 50% same sign leptons
- Almost backgroundless
- Searches ongoing...

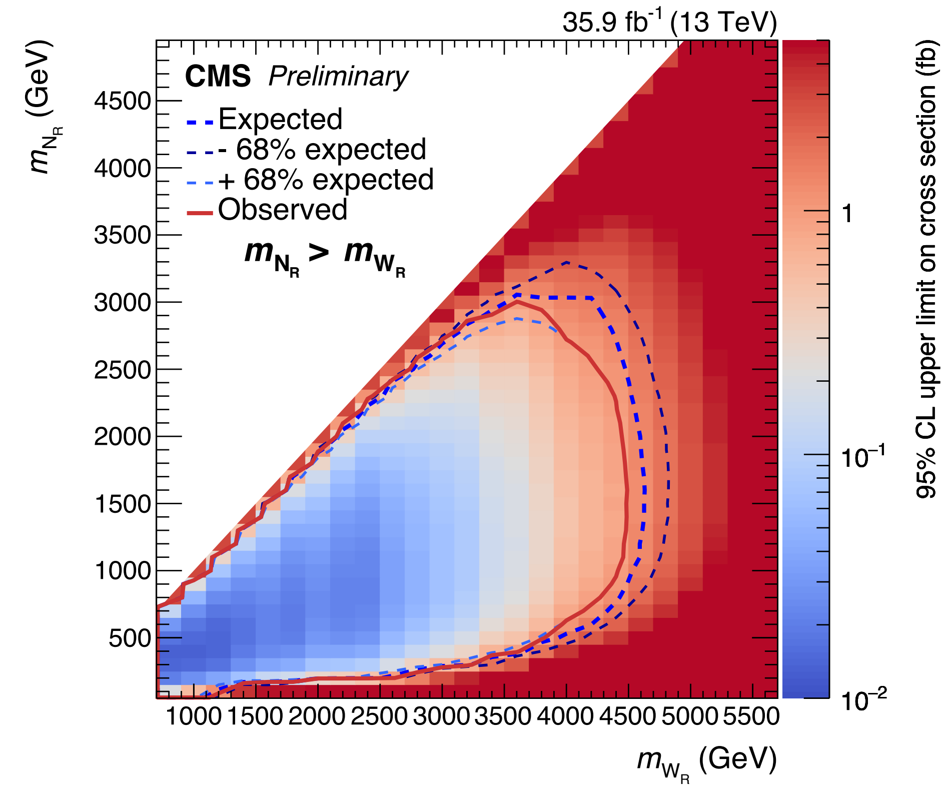
$$M_{W_R} \simeq m_{\ell\ell jj}$$
$$M_{\nu_R} \simeq m_{\ell jj}$$



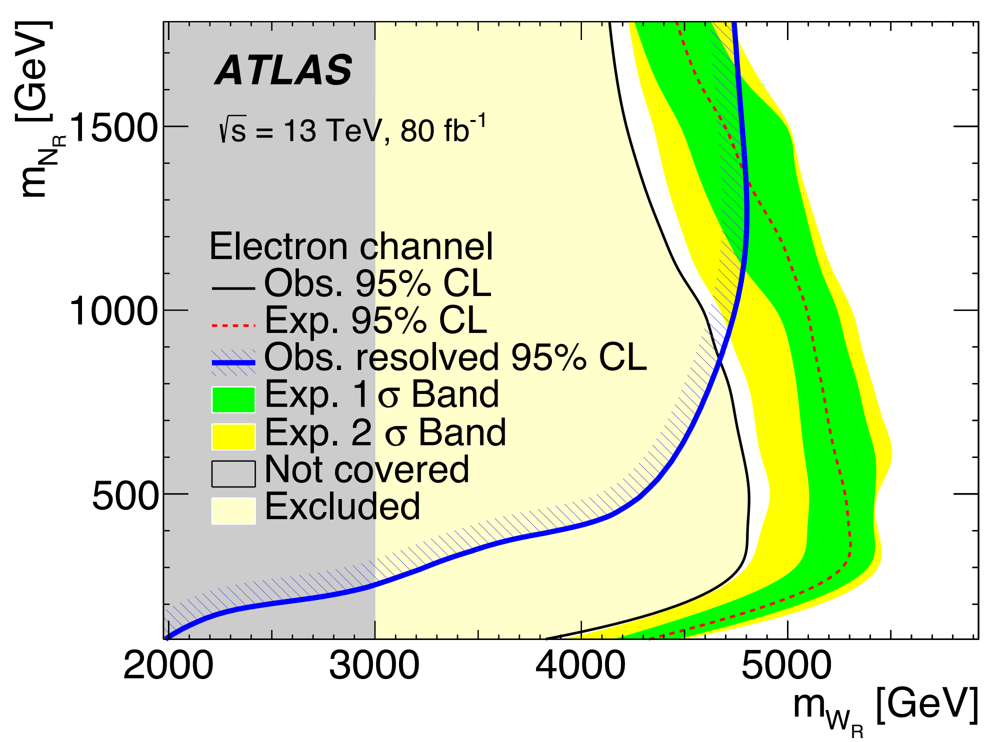
KS LHC search

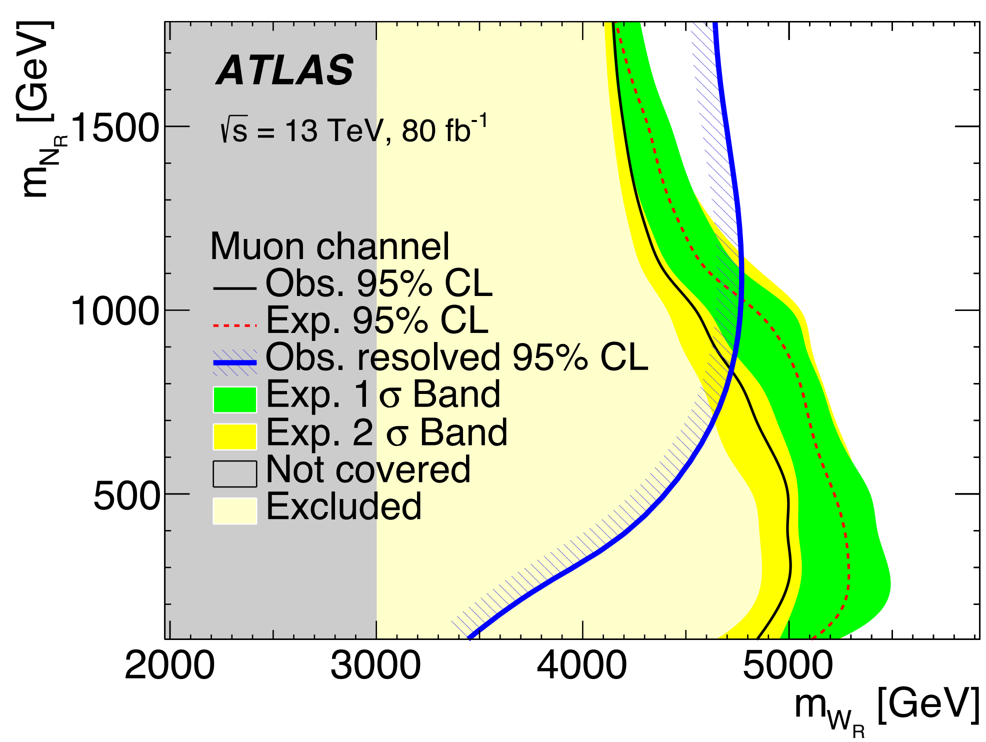
W_R - N plane





[CMS '18]





[ATLAS '19]

LHC reach

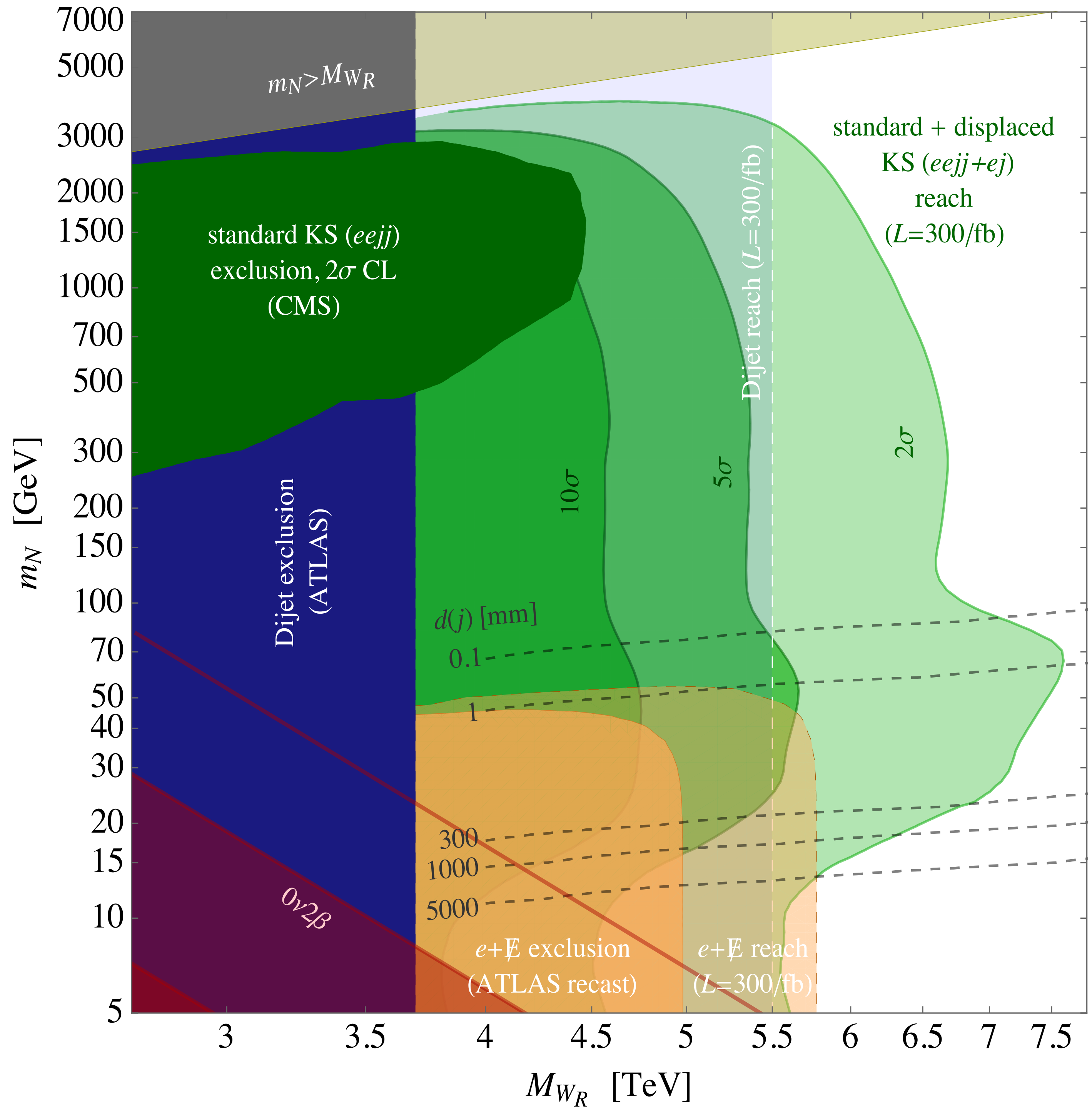
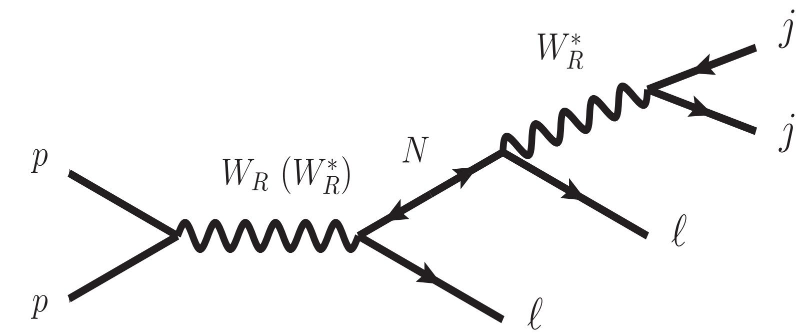
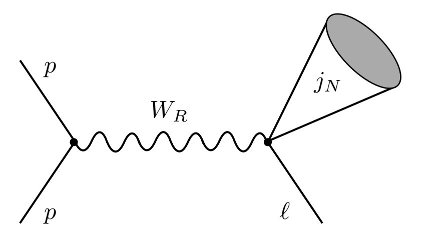
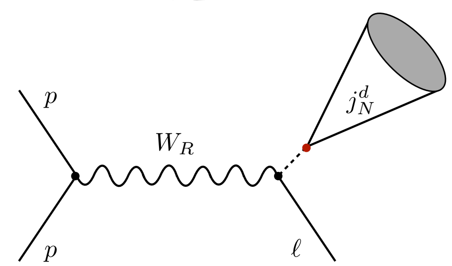
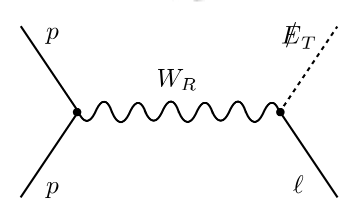


FIG. 9. Summary plot collecting all searches involving the KS process at LHC, in the electron channel. The green shaded areas represent the LH sensitivity to the KS process at 300/fb, according to the present work. The rightmost reaching contour represents the enhancement obtained by considering jet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









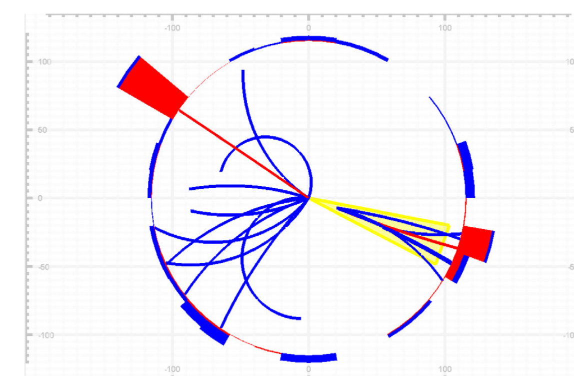


FIG. 6. A typical event featuring the prompt electron and a merged jet on the opposite side, including the secondary electron and hadronic tracks (blue) from a ∼3 cm-displaced vertex. Both,

[Nemevsek, FN, Popara PRD '18]

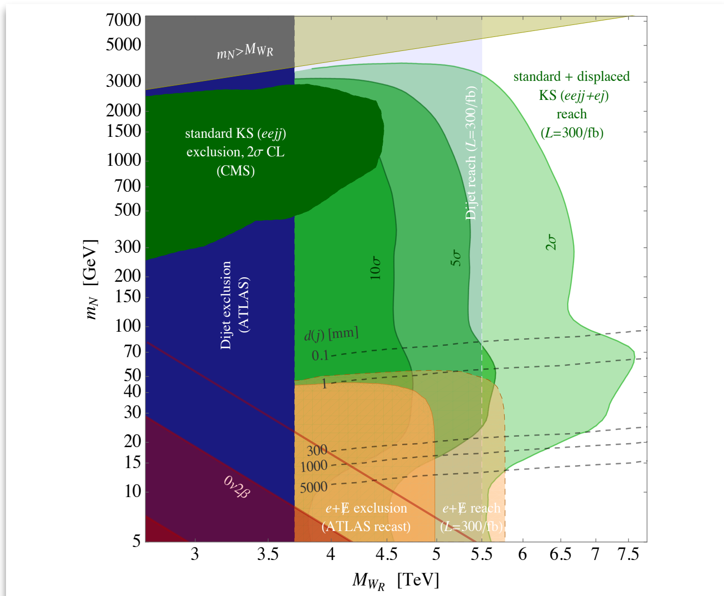
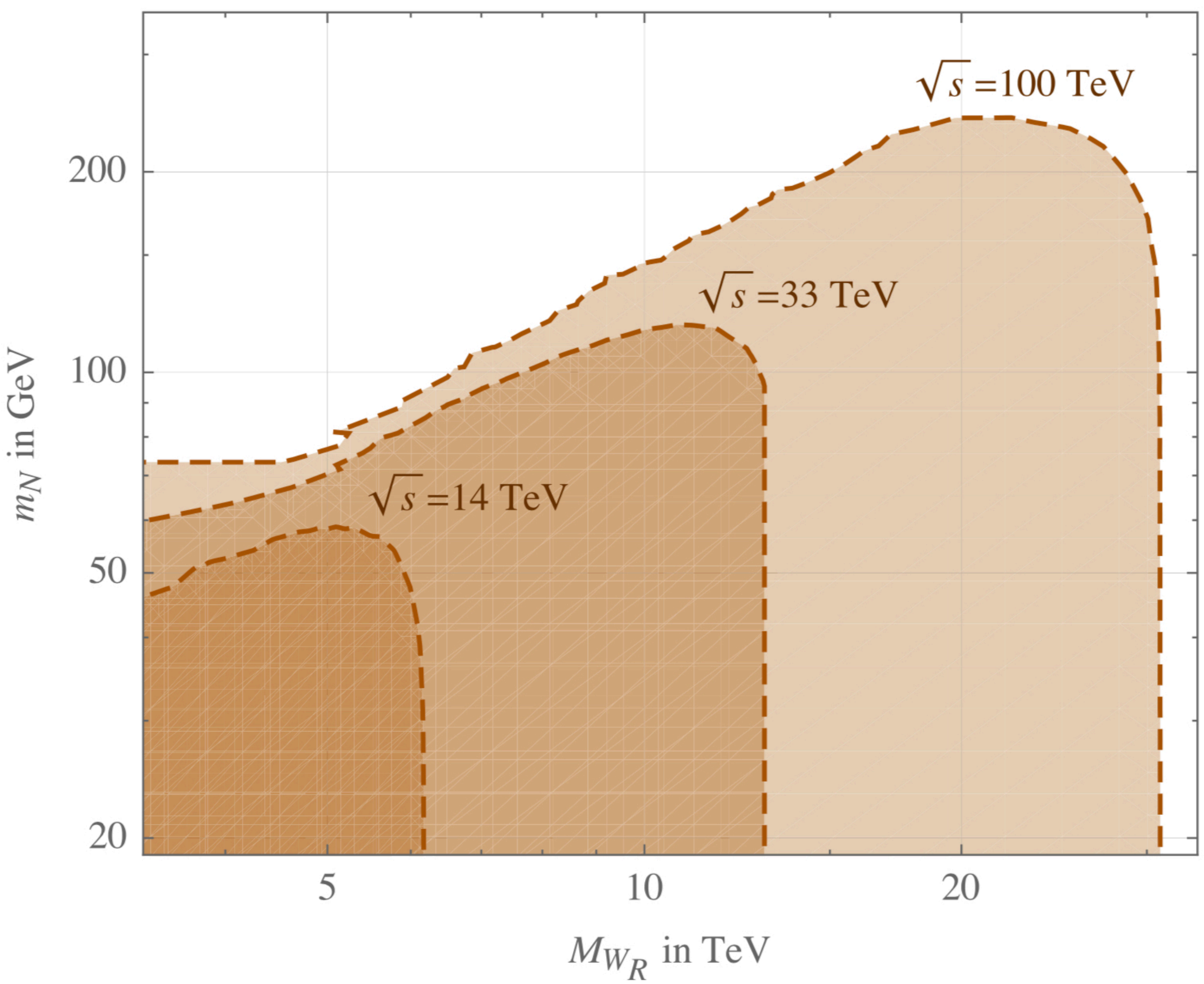


FIG. 9. Summary plot collecting all searches involving the KS process at LHC, in the electron channel. The green shaded areas represent the LH sensitivity to the KS process at 300/fb, according to the present work. The rightmost reaching contour represents the enhancement obtained by considering jet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

100 TeV collider reach

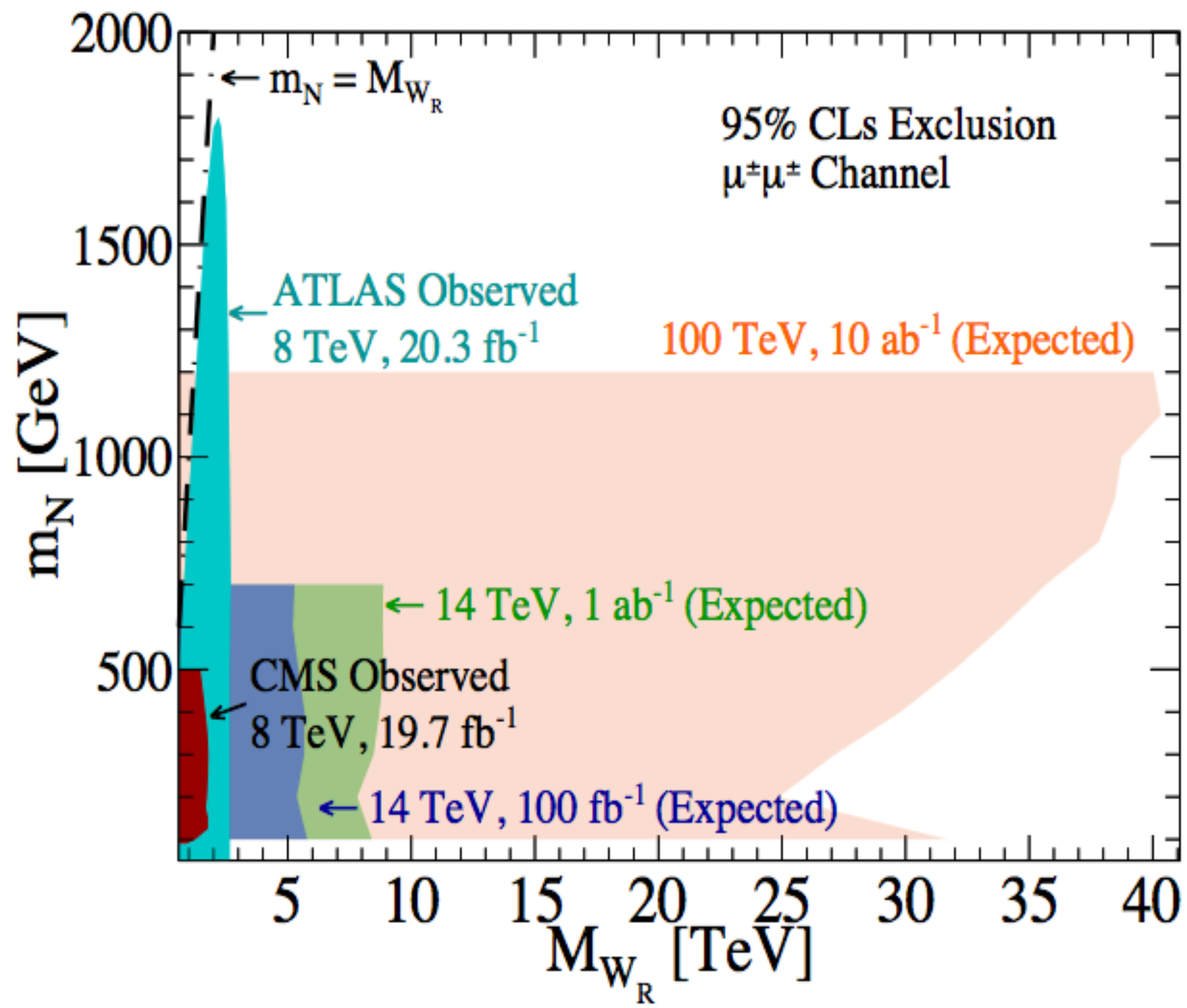
$M_{W_R} \sim$ 30-40 TeV

ℓ+MET



[Nemevsek, FN, Popara PRD '18]

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



[Ruiz EPJC '17]

Can we recognize that W_R is right?

- LHC is a *pp* symmetric machine, so it is not possible to use the simple A_{FB} asymmetry of W_R, to look for chirality of its interactions.

Can we recognize that W_R is right?

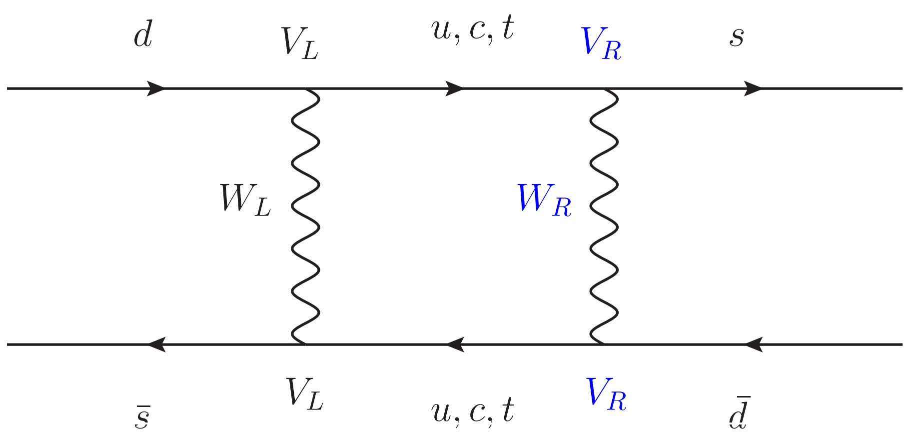
- LHC is a *pp* symmetric machine, so it is not possible to use the simple A_{FB} asymmetry of $\mathrm{W_R}$, to look for chirality of its interactions.
- One has to use the first decay $W_R \to e\,N$.
  - Determine the W_R direction (from the full event!)
  - Identify the first lepton. (the more energetic)
  - Its asymmetry wrt the W_R direction gives the 'Right' chirality.
- It is necessary to efficiently distinguish the two leptons.
  (More difficult for $M_N = 0.6 \div 0.8\, M_{W_R}$ [Ferrari '00])
- Also the subsequent decay $N \to ljj$ may be used.
  Polarization seems to be visible in a wide range of masses $M_{\nu R}$, M_{W_R}.

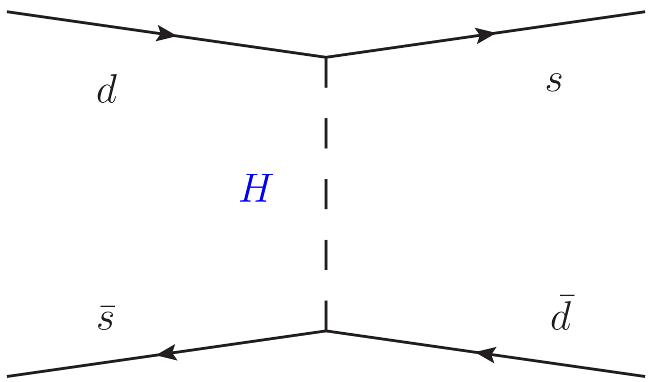
Limits

Flavour changing & CP

Perturbativity

The classic limit from ΔS=2 — ΔM_K





- Early limit $M_{W_R} > 1.6$TeV [Beall Bander Soni ’82]

- Flavour Changing Higgs $M_H >$ TeV [Senjanović Senjanović ’91]

(Predictive: RH mixing angles - fixed... $V_R \simeq V_L$)

Modern assessment, K-K, ϵ, ϵ', B-B

Modern assessment, K-K, ϵ, ϵ', B-B

- **Kaon sector revisited**

ϵ: enhanced in correct box calculation
ϵ': Effect of new LR current-current operators $K \to \pi\pi$
LR matrix elements for $K \to \pi\pi$
Chromomagnetic operator [Bertolini Maiezza, FN '12,'13,'14]

ΔM_K: Short Distance now almost enough. (NNLO [Brod '12])
but Long Distance still unknown
± 10 to $+30\%$ [Buras+ '14] -10% [Bertolini+ '99] -5 to 15% [Soni+ '13]

Modern assessment, K-K, ϵ, ϵ', B-B

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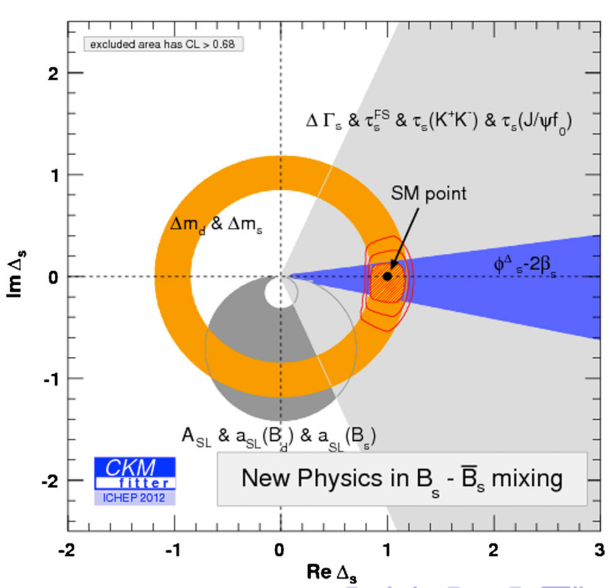
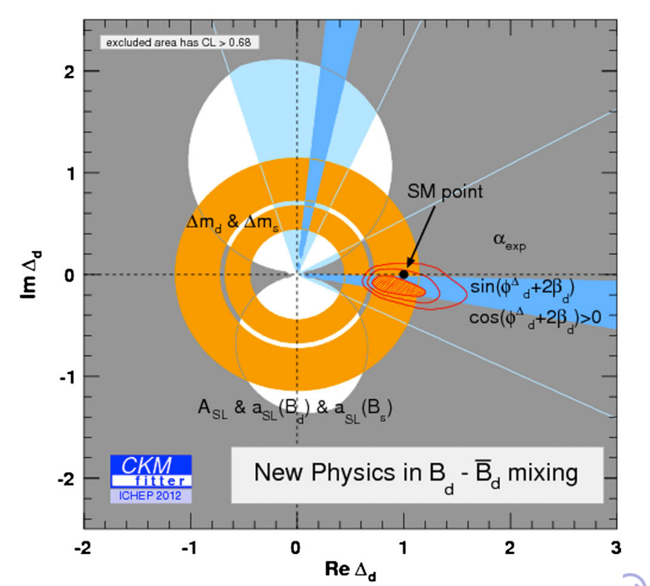
±10 to +30% [Buras+ '14] −10% [Bertolini+ '99] −5 to 15% [Soni+ '13]

- B^0 mesons revisited

Enhanced in correct calculation
Useful free phase





K, B meson mixing

...correlated bound $M_{W_R}\, M_H$:

[Bertolini Maiezza, FN ,'14]

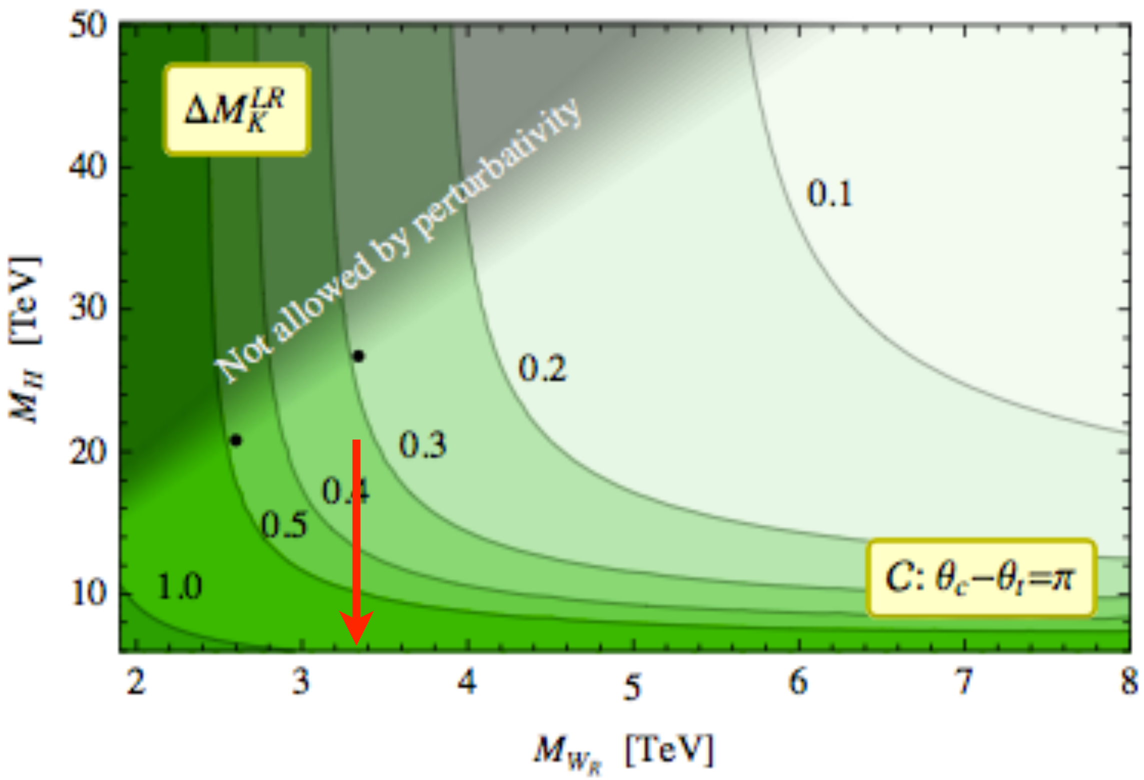


FIG. 9. Correlated bounds on M_R and M_{W_R} (region above the curves) for $\left|\Delta M_K^{LR}\right| / \Delta M_K^{exp} < 1.0, ..., 0.1$ and for $\theta_c - \theta_t = \pi/2$ in the case of $\mathcal{P}$ parity.

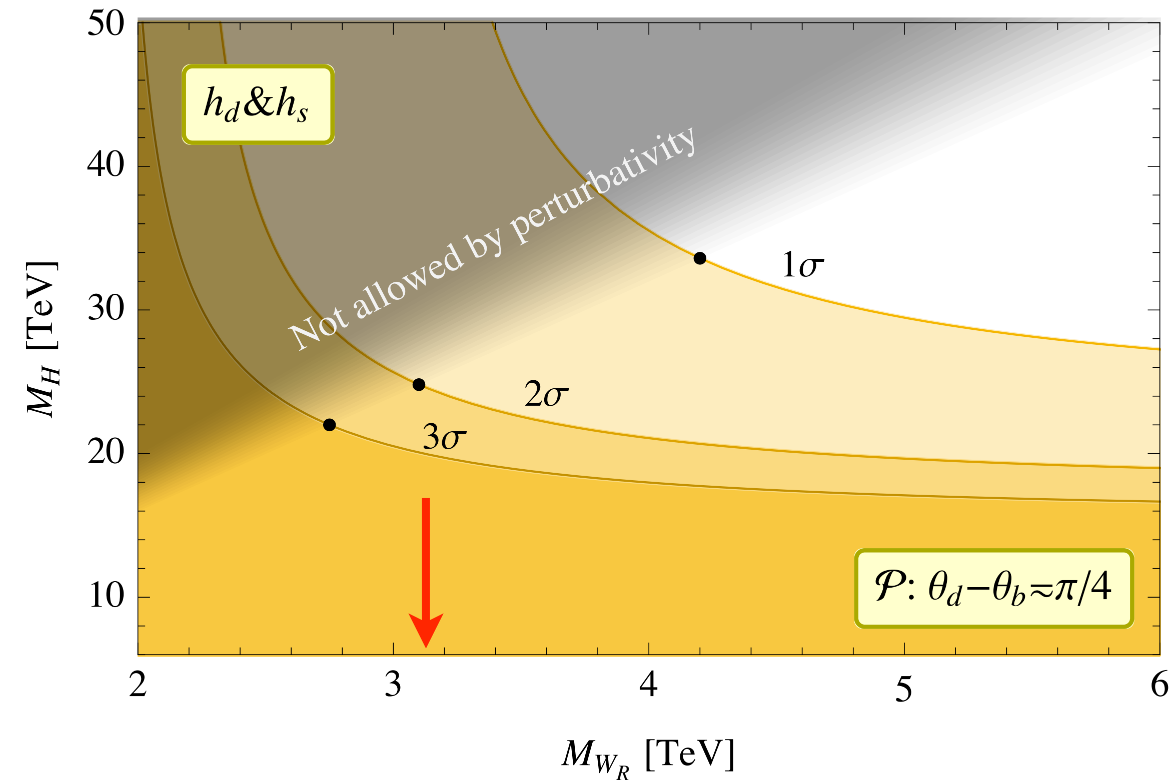


FIG. 10. Combined constraints on M_R and M_{W_R} from ε, ε' B_d and B_s mixings obtained in the $\mathcal{P}$ parity case from the numerical fit of the Yukawa sector of the model.

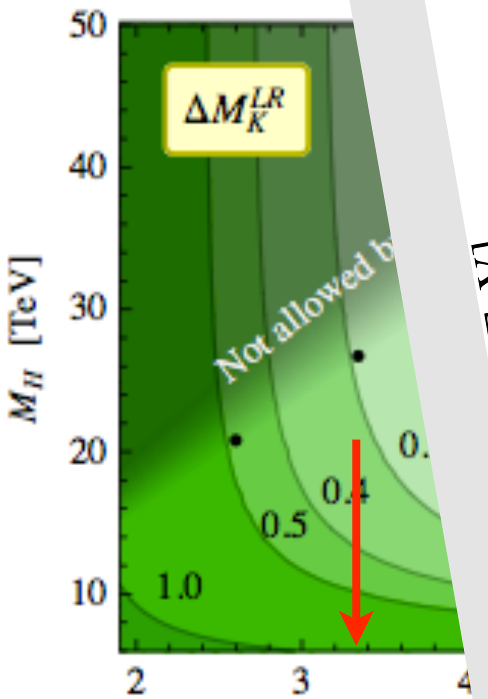
...indirect limit now 3-4 TeV - still room at LHC.

ΔM_K plagued by Long Distance uncertainty

B-mesons competitive now, dominant in the future

K, B meson mixing

...correlat iezza, FN ,'14]



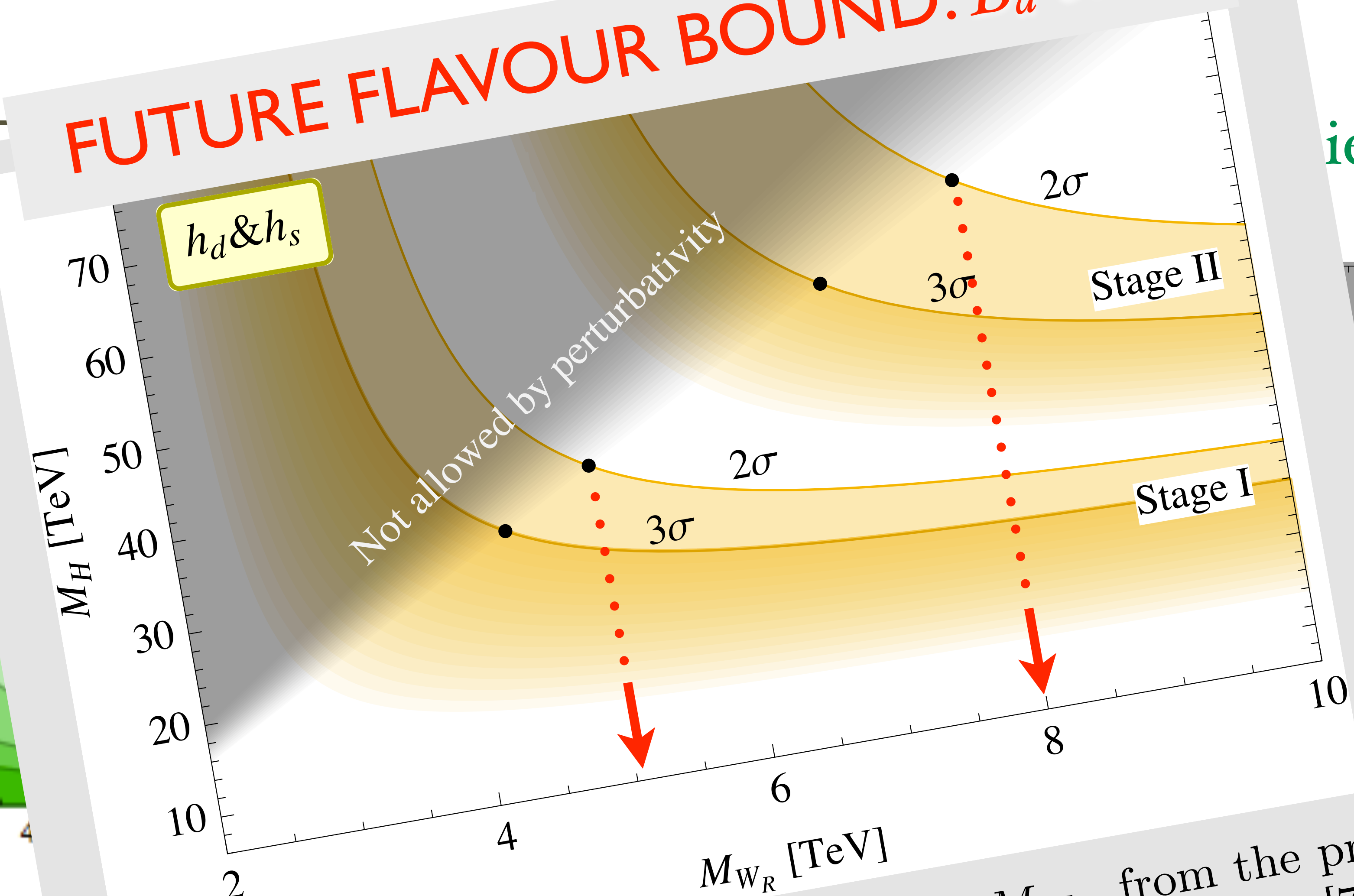


FIG. 11. Future constraints on M_R and M_{W_R} from the projected combined limits on h_d and h_s discussed in Ref. [77]. Stage I corresponds to a foreseen 7 fb^{-1} (5 ab^{-1}) data accumulation by LHCb (Belle II) by the end of the decade. Stage II assumes 50 fb^{-1} (50 ab^{-1}) data by the two experiments,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

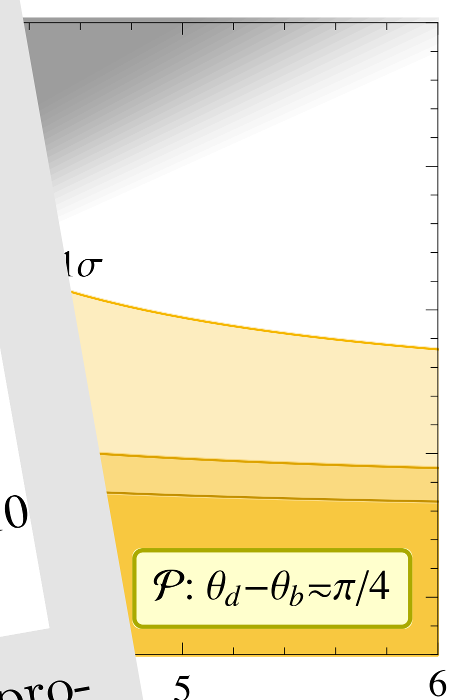


FIG. 9. Correlated bound M_{W_R} from ε, ε'
the curves) for $|\Delta M_K^{LR}|/$ case from the
$\theta_t = \pi/2$ in the case of $\mathcal{P}$ p el.

...indirec LHC.

ΔM$_K$ p Long Distance uncertainty

B-mesons competitive now, dominant in the future

Perturbativity in LRSM

Heavy FCH generates tension...

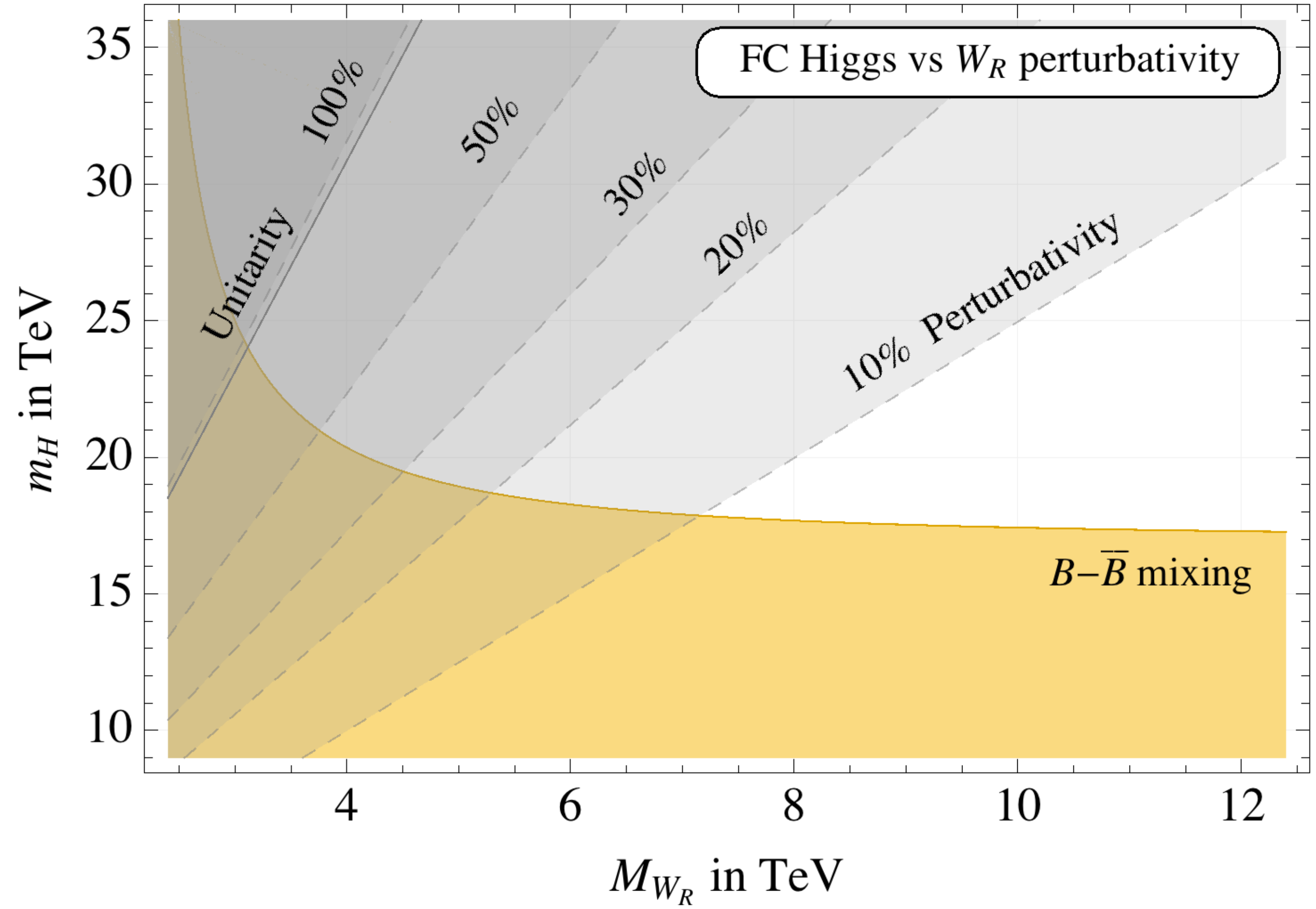


FIG. 3. Perturbativity assessment of $\mathcal{V}_{eff}$ (dashed) and tree-level unitarity (solid) of α_3, together with the bound on M_{W_R} vs. m_H from $B^0_{d,s} - \overline{B}^0_{d,s}$ (see [19] for details).

...points to higher $M_{W_R} \gtrsim 6 - 7$ TeV.

[Maiezza Nemevšek, FN 1603.00360] (all relevant scalars one loop/tree level ratio)

back to
origin of neutrino masses?

Higgs

Can we probe the neutrino mass generation?

Can we probe the 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:

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

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

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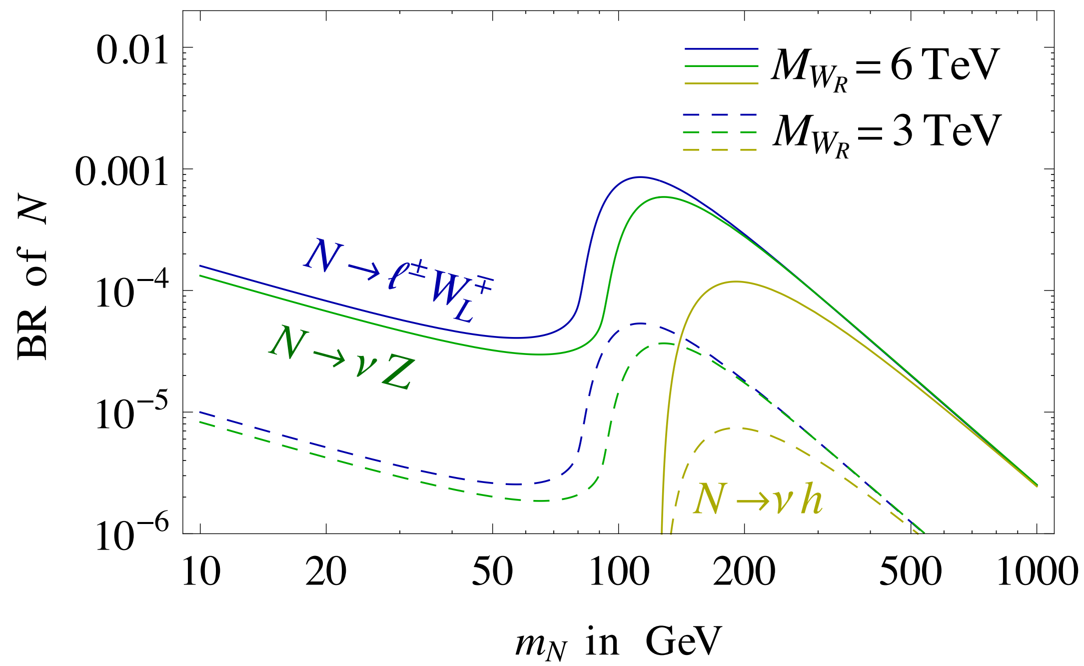
- Ideally one would like to see the higgs rates...

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

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

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- δ_R^0 responsible for the RH neutrino masses.

- But **Neutral higgses mix:**

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

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

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

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

SM Higgs couplings are reduced... but 40% 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]

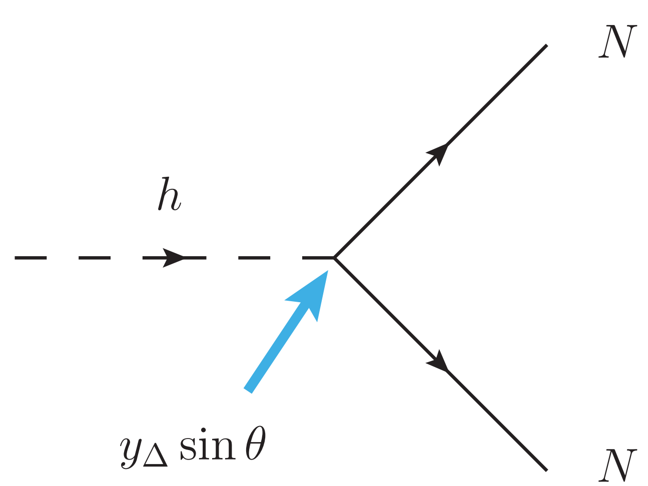
so, Higgs probing Majorana masses

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

- 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



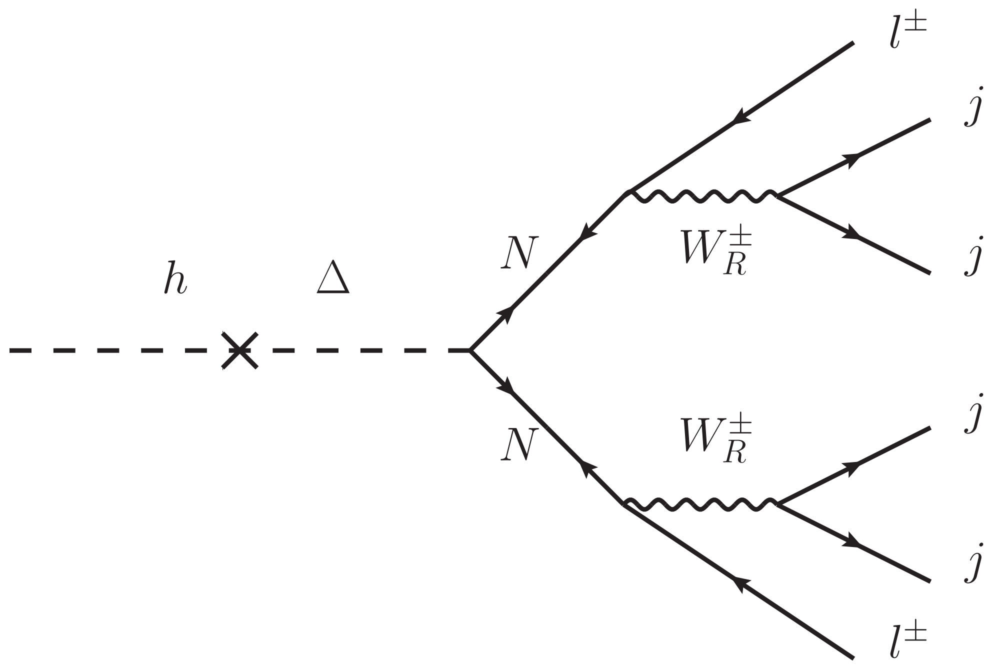
a new SM Higgs decay, checks RH neutrino mass

LNV Higgs decay

[Maiezza, Nemevsek, 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

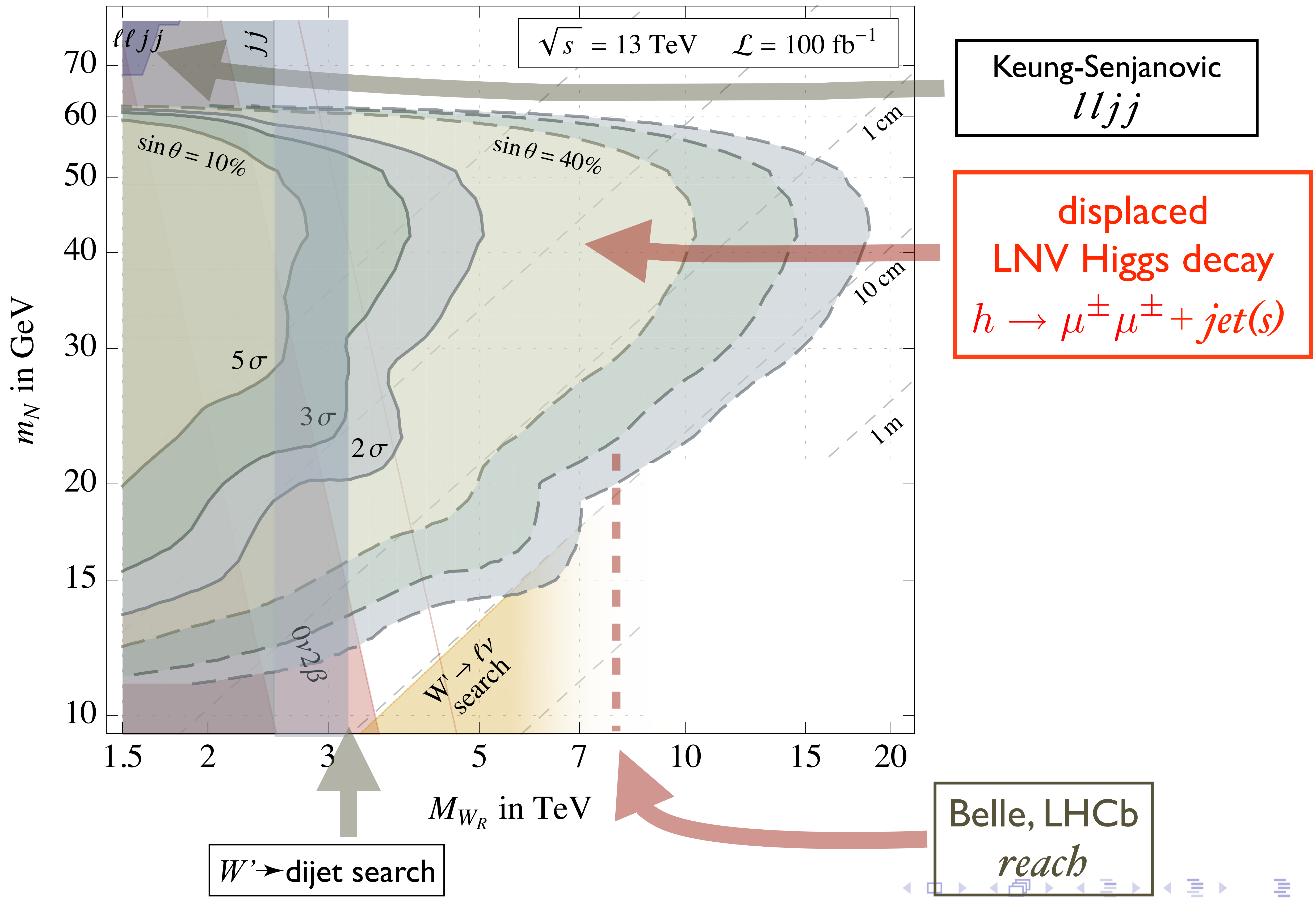


- N lifetime submillimeter to meters: *displaced vertices*

LNVH complementary to KS

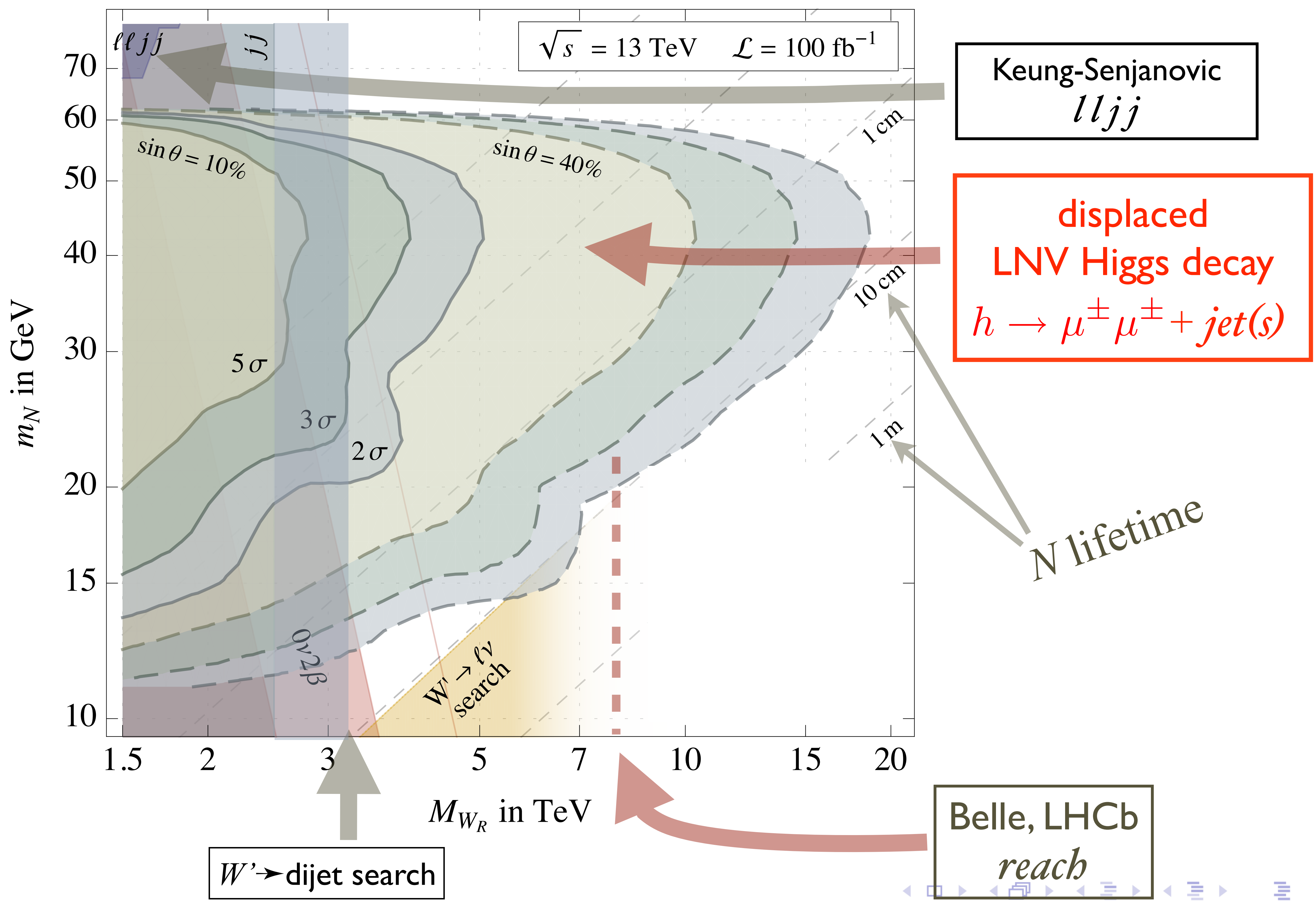
$H \to NN$ Sensitivity

[Maiezza, Nemevsek, FN, PRL '15]



$H \to NN$ Sensitivity

[Maiezza, Nemevsek, FN, PRL '15]



Similar $\Delta \to$ NN

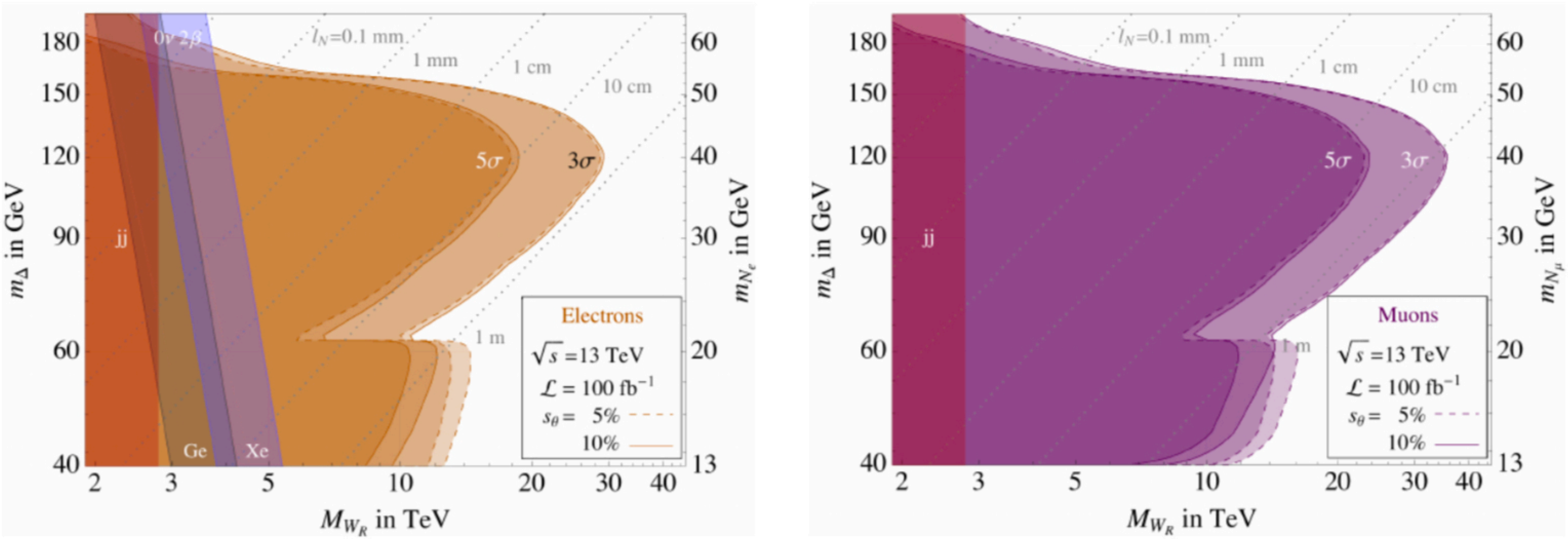


Figure 8. Contours of estimated combined sensitivities of the $h \to NN, \Delta \to NN$ and $\Delta\Delta \to 4N$ channels at 3 and 5 σ with solid (dashed) contours corresponding to $s_\theta = 0.05$ (0.1). The left panel

[Nemevsek, FN, Vasquez JHEP '17]

So, Majorana Higgs to neutrino mass *roadmap?*

Search for $h \to NN$:

- Find N, check vs its yukawa and Dirac (*mass generation*)
- So we see 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 :)

Kaon CP versus Strong CP

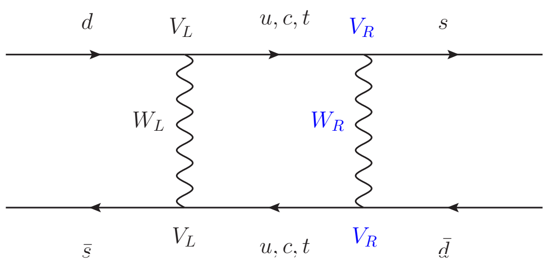
$\varepsilon,\ \varepsilon'$

(measure of New Physics, h=LR/Exp < 100%, < 10%....)

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

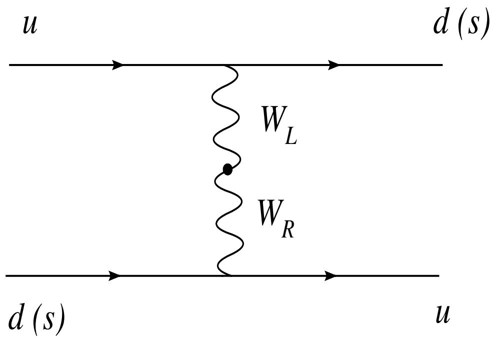
$$C)\ |\sin(\theta_s-\theta_d)| < \left(\frac{M_{W_R}}{71\,\mathrm{TeV}}\right)^2 \longrightarrow \theta_s\text{-}\theta_d \sim 0$$

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



- 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...

θQCD and arg det M in LRSM

- Case of C: both are free - no prediction.
- Case of P: $\theta_{\rm QCD}$ zero at high scale, but due to the spontaneous P breaking, arg det M calculable:

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

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

Then → all phases vanish

Then → ε constraint can only be satisfied if

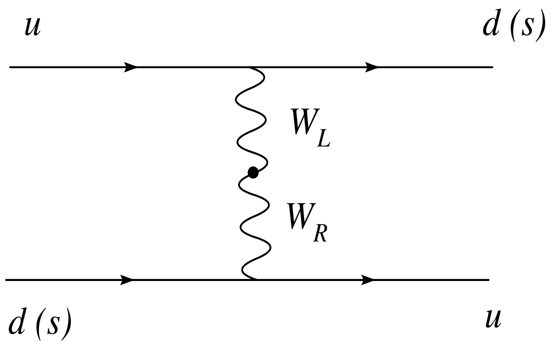
$$M_{W_R} \gtrsim 30\text{TeV}$$

[Maiezza Nemevsek PRD '14]

Situation changes if some mechanism like PQ cancels $\bar\theta$ ...

Without $\bar{\theta}$ - still CP is broken - I

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



- At low scale give meson tadpoles, i.e. shift chiral vacuum

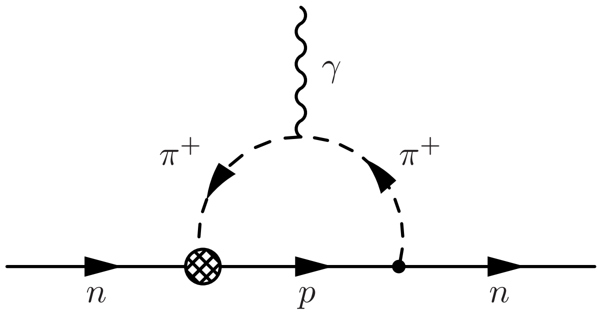
$$\langle \pi^0 \rangle \simeq \frac{G_F}{\sqrt{2}} (\mathcal{C}_{1ud} - \mathcal{C}_{1du}) \frac{4\, c_3}{B_0 F_\pi (m_d + m_u)}$$

- 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. :

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



Without $\bar{\theta}$ - still CP is broken - II

- The operator 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'.

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

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

(The chiral vacuum shift differs with axion or not. In PQ the axion gets an induced $\bar{\theta}$, and it turns out that this cancels the dominant d_n !)

(d_{Hg} *and others*…)

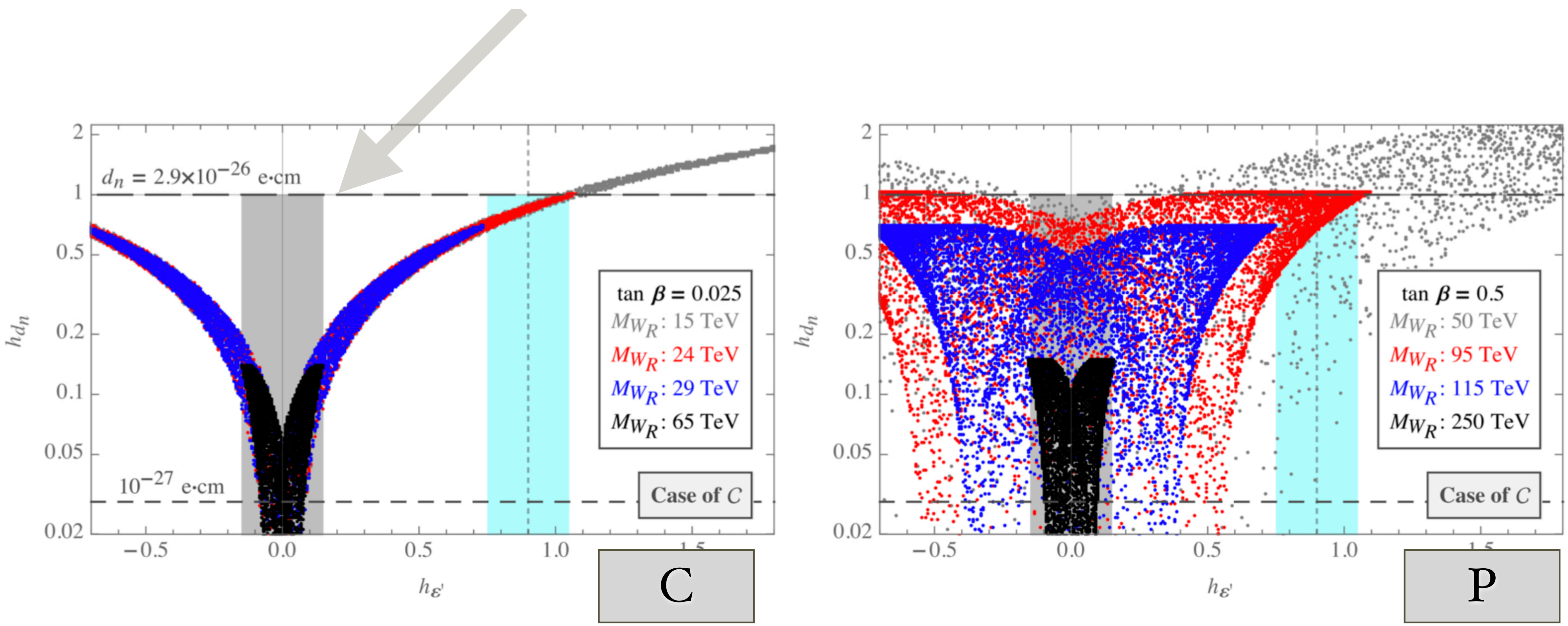
"Direct" CP Violation in K decay is tight

- SM saturates ε'

$$\langle (2\pi)_I | (-i) H_{\Delta S=1} | K^0 \rangle = A_I e^{i\delta_I}$$

$$\epsilon' = \frac{i}{\sqrt{2}} \omega \left(\frac{\mathrm{Im} A_2}{\mathrm{Re} A_2} - \frac{\mathrm{Im} A_0}{\mathrm{Re} A_0} \right) \frac{q}{p} e^{i(\delta_2 - \delta_0)}$$

$h_{d_n} < 1.$ and $|h_{\varepsilon'}| < 0.15$



[Bertolini, Maiezza, FN, 1911.09472]

Results, ε'=SM scenario

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

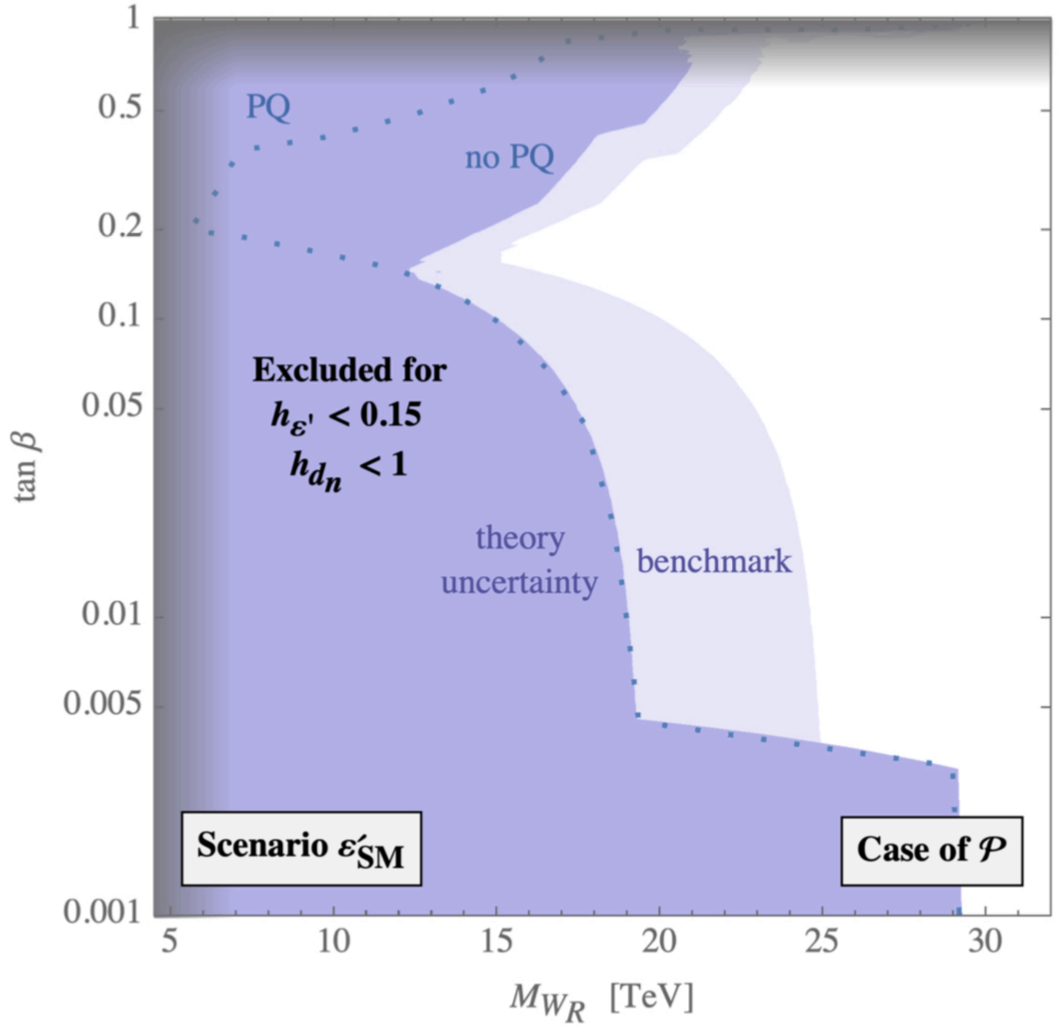


FIG. 4. Case of $\mathcal{P}$: The shaded regions in the M_{W_R}–t_β plane are excluded in order to have at most 15% new physics contribution to ε'/ε and d_n below the present experimental bound.

[Bertolini, Maiezza, FN, 1911.09472]

STOP

Resume - Outlook

Neutrino masses exist... led us quite far:

- Left-Right restoring parity is a predictive theory
- Lepton Number Violation in low and high energy
- Flavor constraining, but still not ruled out
  (B mixing the future)
- ε, ε', d_n correlation predictive for P :
  $\varepsilon' = \text{SM}$ $\quad M_{W_R} > 10\,\text{TeV}$
- Borderline @ LHC - next collider :)
- SM Higgs and Δ Higgs gateway to neutrino mass mechanism - probe to ~20 TeV