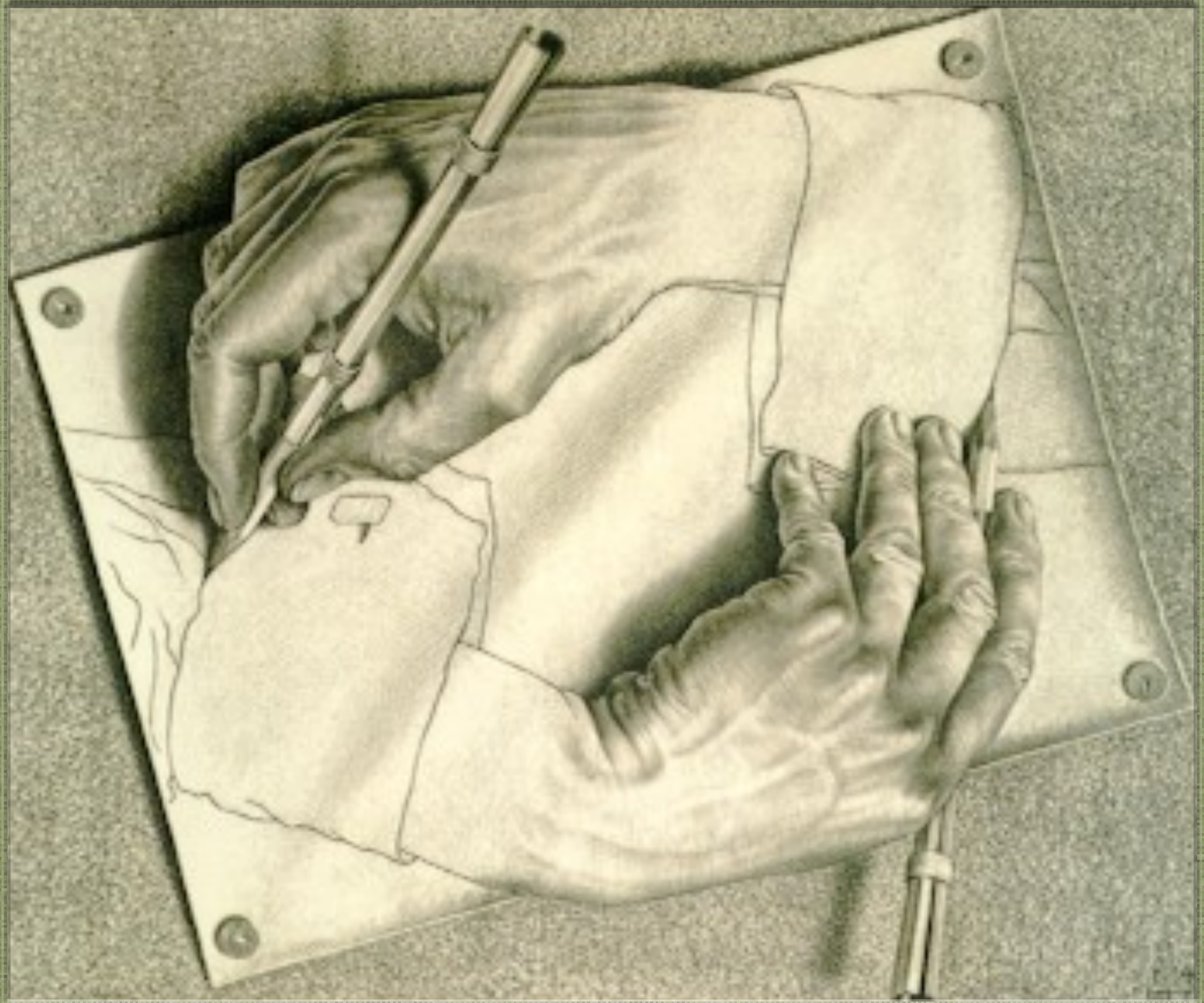
The LR renaissance



Goran Senjanović
LMU, Munich & ICTP, Trieste

RabiFest, UMD 2022

New York
1974

One late Friday afternoon

I walk reluctantly into the office
of a young assistant professor at CCNY

He shows me the true beauty of physics
… and forever changes my life

It wil lead to an unforgettable collaboration

The crux of it all

What is at the essence of the SM?

- Gauge principle + SSB
- Parity violation

} Deeply connected

Maximal parity violation -> SM

Lee, Yang '56

Wu et al '56

↓

V-A

Marshak, Sudarshan '57

↓

"V-A was the key"

Weinberg '09

Gauge ew theory

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad u_R \qquad d_R$$

↓

fermions (and gauge bosons) massless

Higgs in SM

Weinberg '67

need a Higgs doublet - and it suffices → gives mass to all: W, Z, Higgs, charged fermions

masses = dynamical parameters - related to physical processes

charged fermion mass m_f → $\Gamma(h \to f\bar{f}) \propto m_h (m_f/M_W)^2$

Imagine LR symmetric SM

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \qquad \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

direct mass term $\overline{q_L} M q_R$ miracle: how come M $\lesssim M_W$?

$$M_u = M_d$$

split: needs an adjoint (triplet) T

$$\mathcal{L}_Y = \overline{q_L}(M + Y_T T) q_R$$

$$\langle T \rangle = v\,\mathrm{diag}(1,-1)$$

↓

$$M_u = M + vY_T, \quad M_d = M - vY_T$$

but $M_Z = 0$

↓

needs more Higgs → all predictions gone

LR asymmetry a blessing - but a curse too

LR asymmetry → massless neutrino

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad e_R$$

vector-like world → massive neutrino

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

Left-Right Symmetric Model

Pati, Salam '74

Mohapatra, Pati '74

Mohapatra, GS '75

GS '79

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

neutrino is massive

$$q_L \equiv \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \ell_L \equiv \begin{pmatrix} \nu \\ e \end{pmatrix}_L \quad \ell_R \equiv \begin{pmatrix} \nu \\ e \end{pmatrix}_R \quad q_R \equiv \begin{pmatrix} u \\ d \end{pmatrix}_R$$

W_L W_R

$$M_{W_R} \gg M_{W_L}$$

Neutrino mass long before experiment

True theory in a sense of Feynman

Make a guess
say, gauge principle

↓

Minimal formulation
based on guess

↓

Leave it
so we can compute predictions

↓

Experiment

Unambiguous predictions = self-contained theory

Rabi - Goran complementarity

Rabi

You need a model?
Give me half an hour!

Goran

Forget a model - let's just sleep on this and dig deeper!

Berezhiani ~ '93-'94

Neutrino = Majorana

Minkowski '77

Mohapatra, GS '79

N = ν_R

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

$$M_N \propto M_{W_R}$$

small neutrino mass related to
near maximal parity violation

Neutrino = anti neutrino?

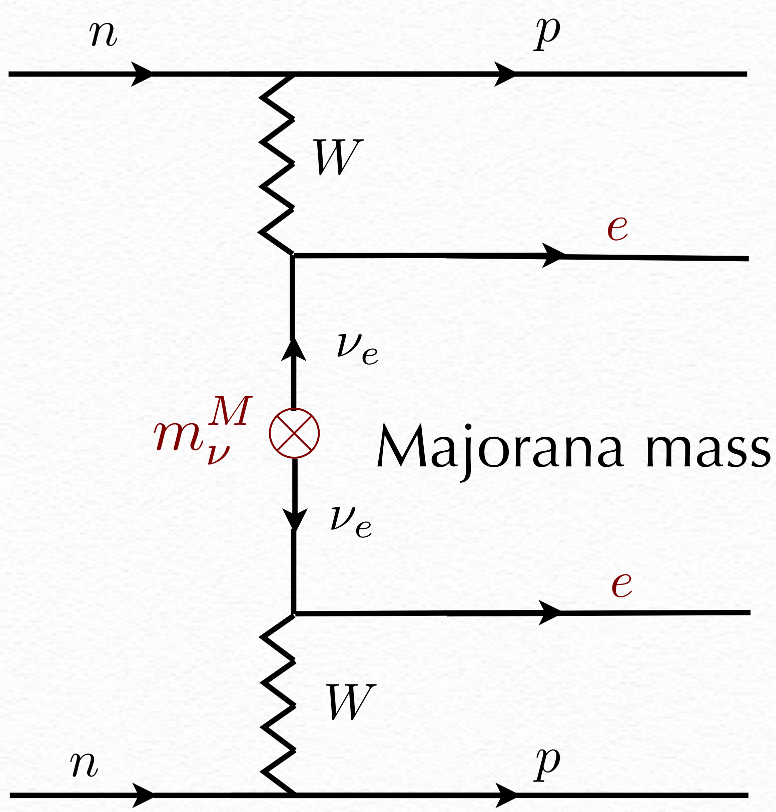
Majorana '37

↓

Lepton Number Violation (LNV)

- neutrinoless double beta decay — Furry '38
- hadron colliders — Keung, GS '83

Neutrino-less double beta decay



$$\mathcal{A}_\nu \propto \frac{G_F^2 m_\nu^{ee}}{p^2} \simeq G_F^2\ 10^{-8}\, GeV^{-1}$$

$$(p \simeq 100\, MeV)$$

$$\tau_{0\nu 2\beta} \gtrsim 10^{26} yr \quad \rightarrow \quad m_\nu^M \lesssim 0.3\, eV$$

GERDA 2021

Both e = LH

New physics involved?

Feinberg, Goldhaber '59

Pontecorvo '64

d=9 operator

Mohapatra, GS '79, '81

$$\tau_{0\nu 2\beta} \gtrsim 10^{26} yr$$

$$\frac{1}{\Lambda^5}\, n\, n\, p\, p\, e\, e \quad \rightarrow \quad \Lambda \gtrsim 3\, TeV$$

LHC energies

e = RH → New physics at accessible energies

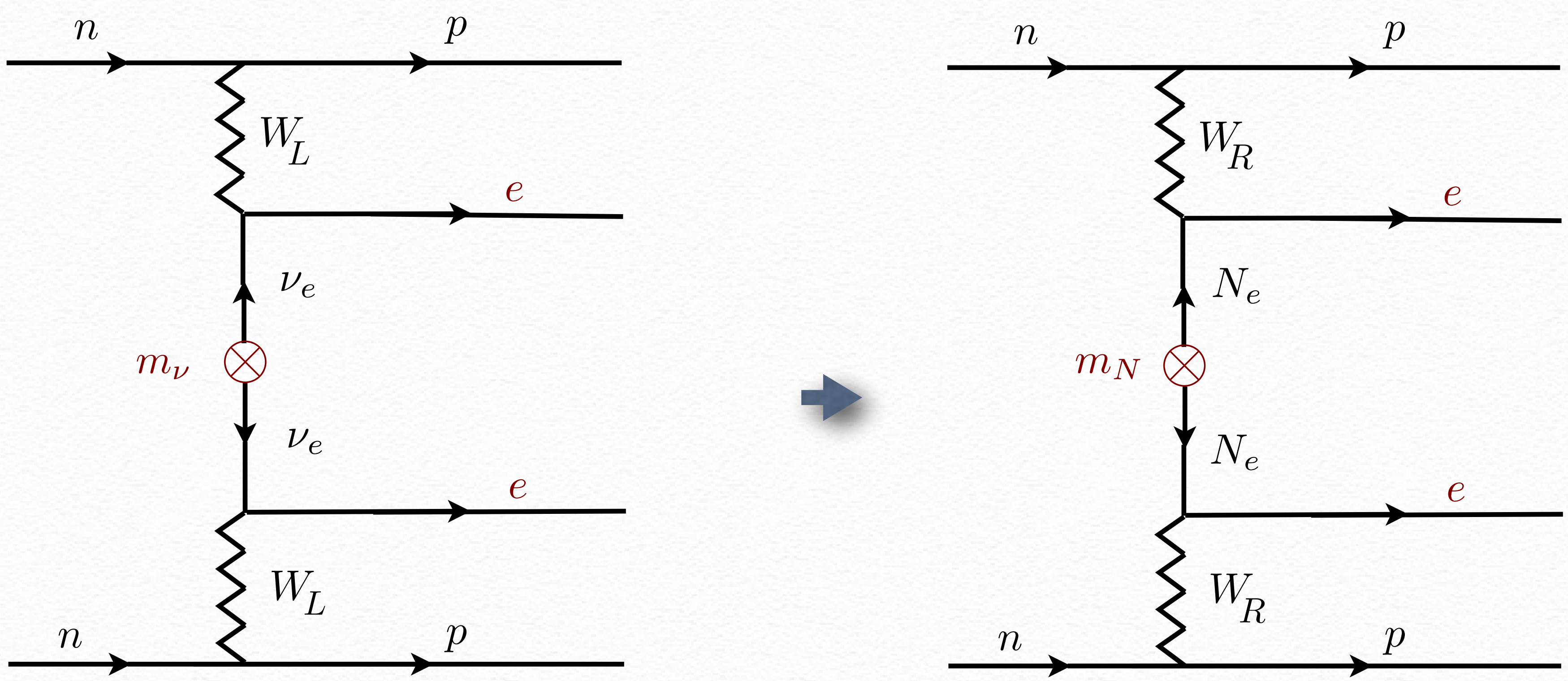
Compare with p decay

$$\frac{1}{\Lambda^2}\; q\, q\, q\, e \quad \rightarrow \quad \Lambda \gtrsim 10^{15} GeV$$

$$\tau_p \gtrsim 10^{34} yr$$

Neutrinoless double beta & LR

Mohapatra, GS ’79, ‘81



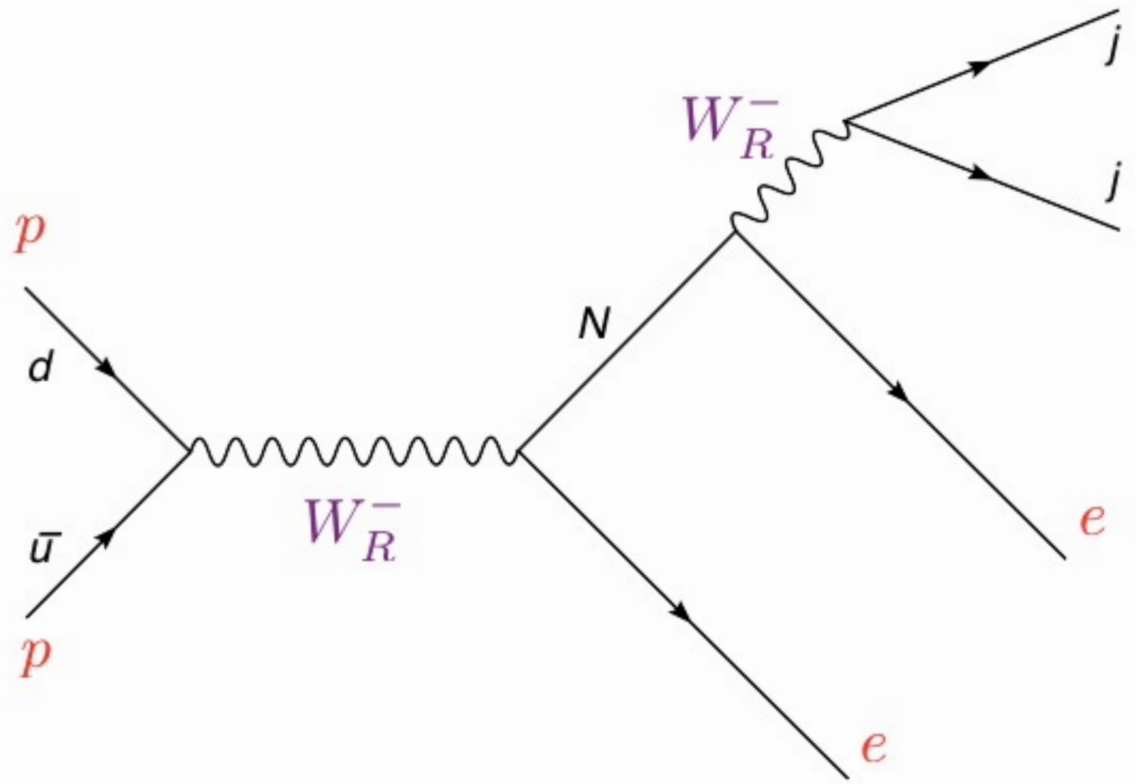
e = RH → deep connection with LHC

Tello et al ‘11

From Majorana to LHC

Keung, GS 1983

- direct probe of Majorana nature:



50% lepton
50 % anti-leptons

- Parity restoration
- Lepton Number Violation: same sign leptons
- Lepton Flavour Violation - connection with low E

Tello, PhD thesis 2012

Untangling seesaw

Nemevsek, GS, Tello '12

GS, Tello '16 -'20

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

LR = C

$$M_D^T = M_D \quad \Rightarrow \quad M_D = i M_N \sqrt{M_N^{-1} M_\nu}.$$

$$Y_D = M_D / v$$

compare with naive seesaw:

$$M_D = \sqrt{m_N}\,\mathcal{O}\,\sqrt{M_\nu}$$

O-arbitrary complex orthogonal

Minimal theory

$$\Gamma(N_i \to W\ell_j) \propto V_{ij}^2 m_{\nu_i} \frac{m_{N_i}^2}{M_W^2}$$ ⟷ $$\Gamma(h \to f\bar{f}) \propto m_h (m_f/M_W)^2$$

Nemevsek, GS, Tello '12 GS, Tello '16- '20 Weinberg '67

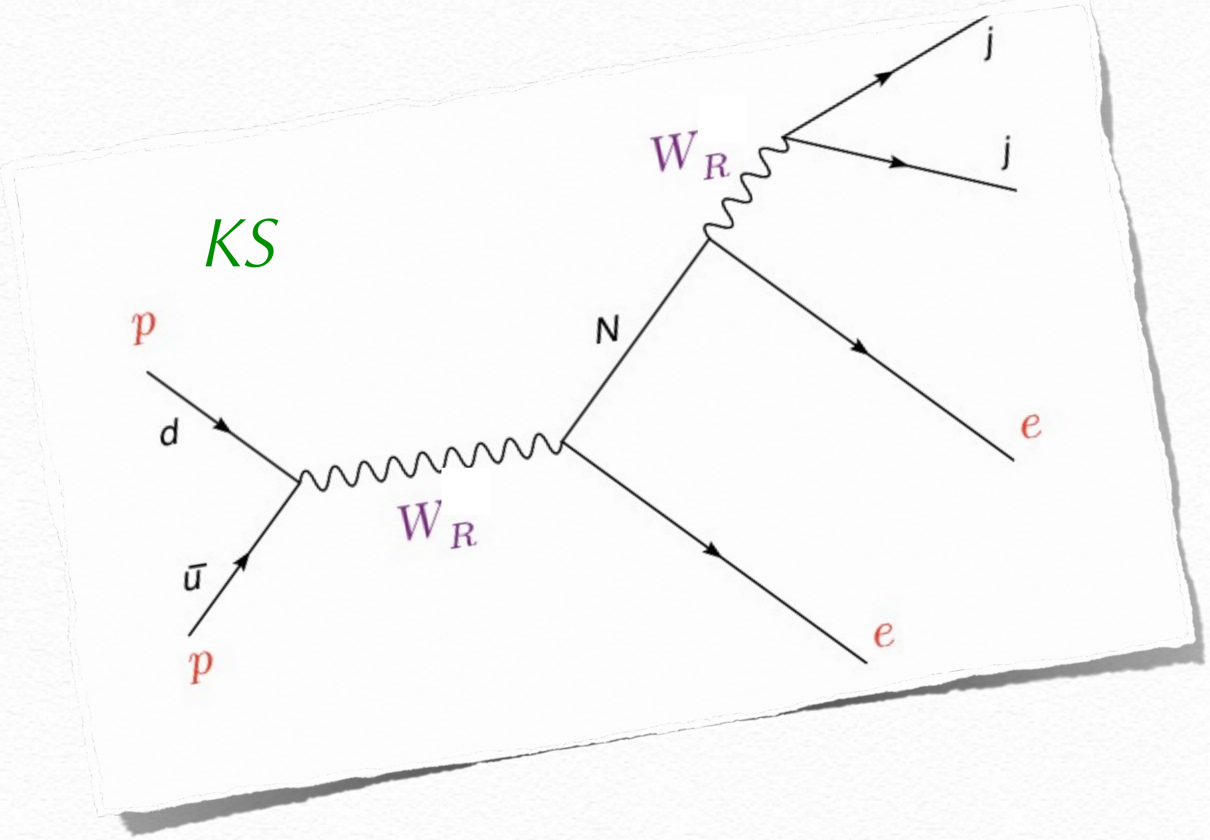
plethora of other processes, all depend on M_D and/or M_N

GS, Tello '18

LR@LHC

ATLAS. CMS

KS



$$M_{W_R} \gtrsim 5\, TeV$$

neutrinos (N_R). A search for W_R boson and N_R neutrino production in a final state containing two charged leptons and two jets ($\ell\ell jj$) with $\ell = e, \mu$ is presented here. The exact process of interest is the Keung–Senjanović (KS) process [10], shown in Figure 1. When the W_R boson is heavier than

Also $M_{W_R} \gtrsim 5\, TeV$ from $W_R \to j + j$

Scale of LR?

Need input from experiment: CDF?

↓

$$M_R \lesssim 10\, TeV$$

Neutrinoless double beta: e = RH

↓

$$M_R \lesssim 10\, TeV$$

Quark sector

Determine RH mixings ~ 40 years challenge

Zhang, An, Ji, Mohapatra '07

$$(V_R)_{ij} \simeq (V_L)_{ij} - i\epsilon \frac{(V_L)_{ik}(V_L^\dagger m_u V_L)_{kj}}{m_{d_k} + m_{d_j}}$$

$\epsilon \ll 1$ - not predicted

GS, Tello 1408.3835 (hep-ph)

GS, Tello 1502.05704 (hep-ph)

$$\theta_R \simeq \theta_L$$

justifies quoted limits on M_R
- assume same L & R mixings

Minimal LRSM:
self-contained, predictive theory of neutrino mass

Hope to have convinced you all - including Rabi :)

Thank you, Rabi

LHC reach

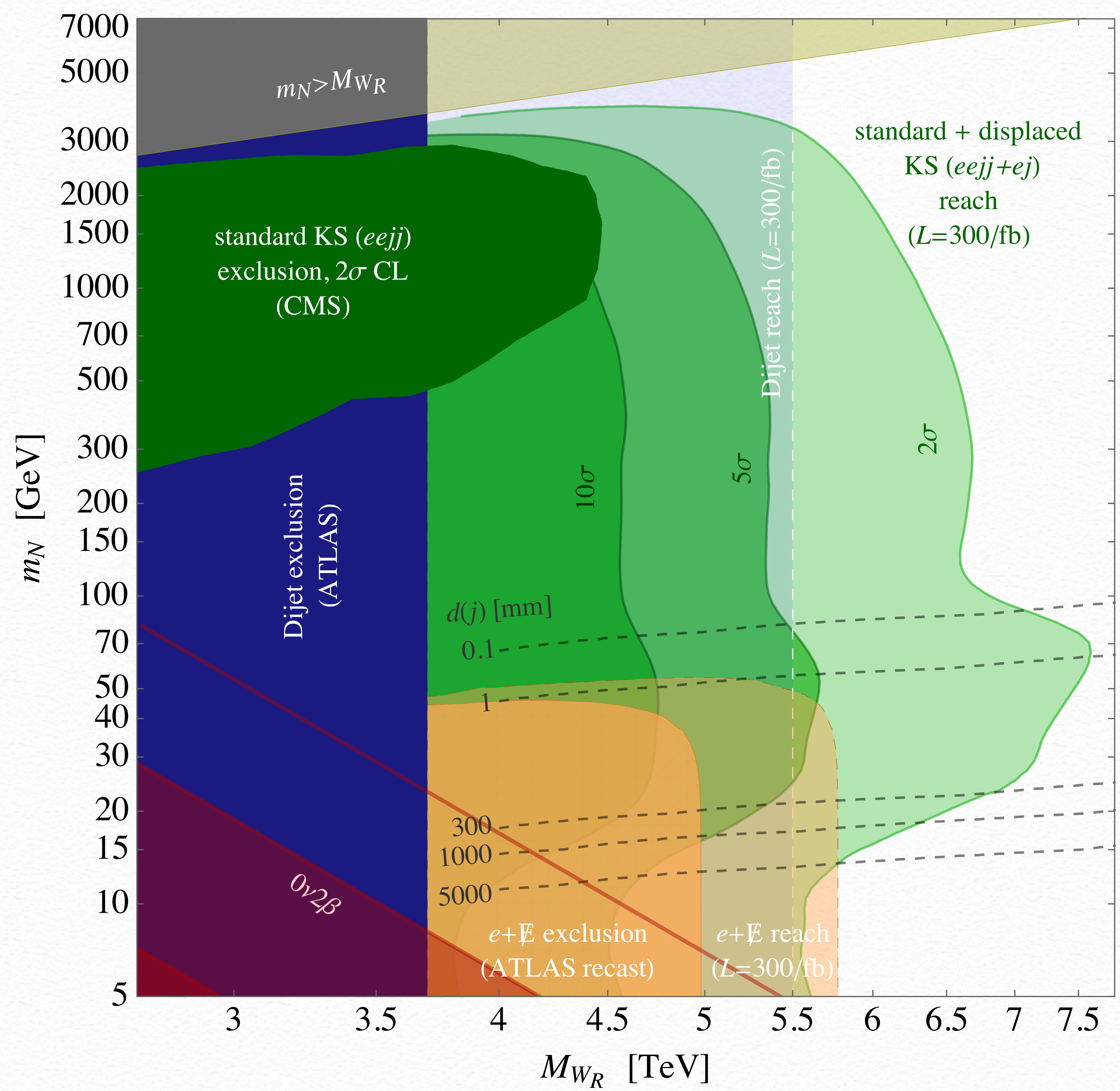


FIG. 9. Summary plot collecting all searches involving the KS process at LHC, in the electron channel. The green shaded areas represent the LH sensitivity to the KS process at 300/fb, according to the present work. The rightmost reaching contour represents the enhancement obtained by considering jet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

Nemevsek, Nesti, Popara 1801.05813 (hep-ph)