The Tiny Neutrino Mass and LARGE Hadron Collider: What Do They Have in Common?

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GoranFest, Split, June 11, 2010

The Inspirations

The story started in 1983 …

In a PRL paper with Wei-Yee Keung, Goran wrote

VOLUME 50, NUMBER 19 PHYSICAL REVIEW LETTERS 9 MAY 1983

Majorana Neutrinos and the Production of the Right-Handed Charged Gauge Boson

Wai-Yee Keung and Goran Senjanović
Physics Department, Brookhaven National Laboratory, Upton, New York 11973
(Received 14 February 1983)

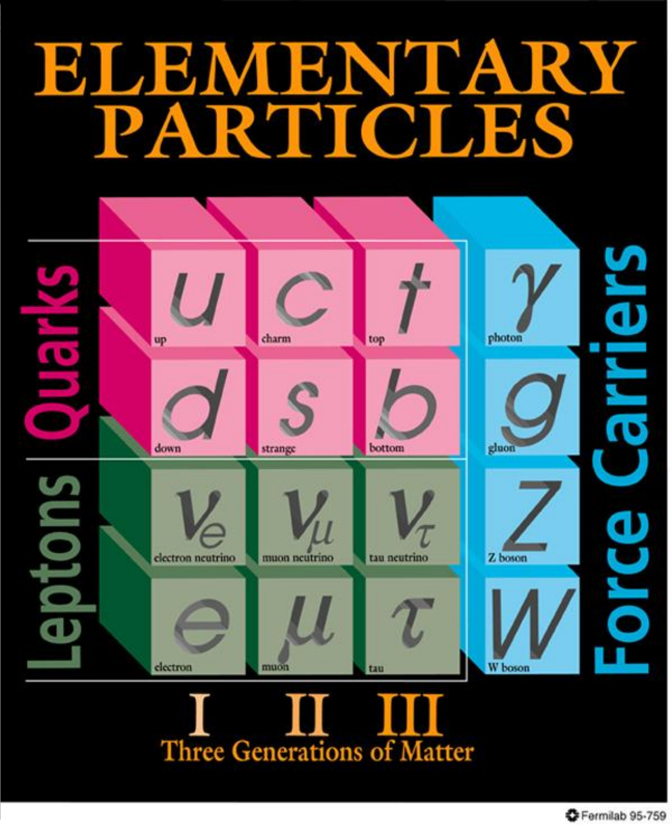
A possibility of a very clean signature for the production of $W_R^\pm$ is pointed out. If the right-handed neutrino is lighter than $W_R^\pm$, left-right symmetric gauge theory predicts the decay $W_R^+ \to \mu^+\mu^+ + 2$ hadronic jets, with the branching ratio $\simeq 3\%$. The lack of neutrinos in the final state and the absence of a sizable background make $W_R^\pm$ rather easy to detect (if it exists). Detailed predictions regarding the production and decay rates of W_R^+ are presented.

The paper first proposed

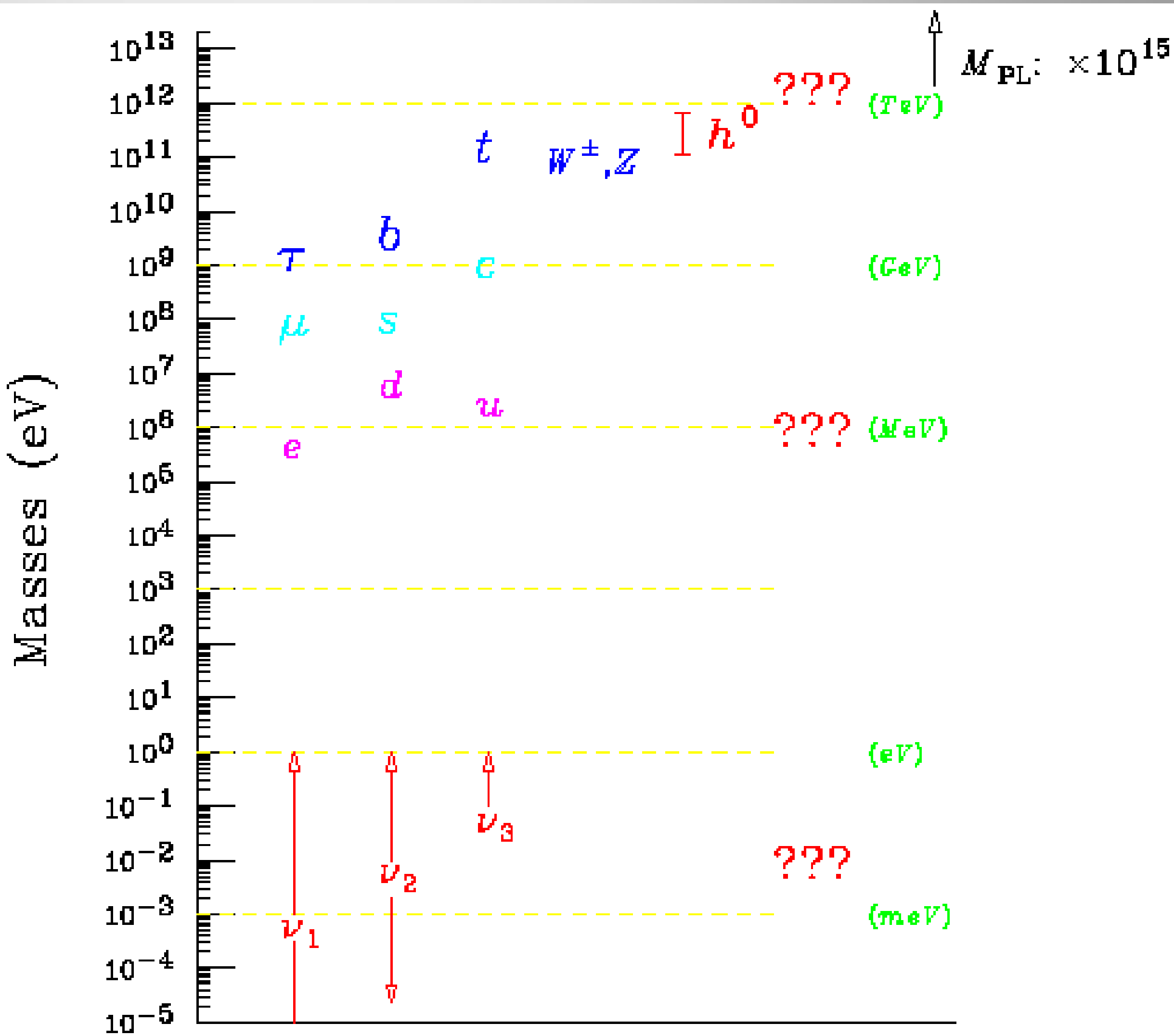
test Majorana neutrino N at TeV scale;
a nice channel for W_R signal;
a striking channel to search for $\Delta L=2$;
made the connection with collider expt.

The paper came as a surprise …

(Wei-Yee Keung should have come to tell the story…)



HEP theory: the triumph & ignorance



$m_t \approx v \approx 173$ GeV

$m_\nu \leq 1$ eV

6/21/2010

The "Seesaw" spirit:

$m_{light} = y\ v^2 / M_{heavy}$

Type I (with N_R) :

With the fermionic singlets N_R, one can have

$$\sum_{b,b'=1}^{n\geq 2} \overline{N^c{}_{bL}}\ M_{bb'}\ N_{b'R} + h.c.$$

$\Longrightarrow$ mass-flavor mixing:

$$\nu_{aL} = \sum_{m=1}^{3} U_{am}\nu_{mL} + \sum_{m'=4}^{3+n} V_{am'} N^c_{m'L},$$

$$N^c_{aL} = \sum_{m=1}^{3} X_{am}\nu_{mL} + \sum_{m'=4}^{3+n} Y_{am'} N^c_{m'L},$$

$$m_\nu \approx \frac{D^2}{M}, \quad m_N \approx M, \quad UU^\dagger \approx I\ (PMNS), \quad VV^\dagger \approx \frac{m_\nu}{m_N}.$$

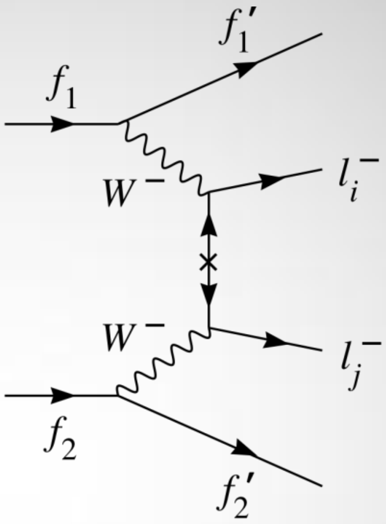
The charged currents:

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} W^+_\mu \sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U^*_{\ell m}\ \overline{\nu_m}\gamma^\mu P_L \ell + h.c.$$

$$+ \frac{g}{\sqrt{2}} W^+_\mu \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V^*_{\ell m'}\ \overline{N^c_{m'}}\gamma^\mu P_L \ell + h.c.$$

Keung+Senjanovic's 1983 paper Inspired the searches …

Fundamental diagram:

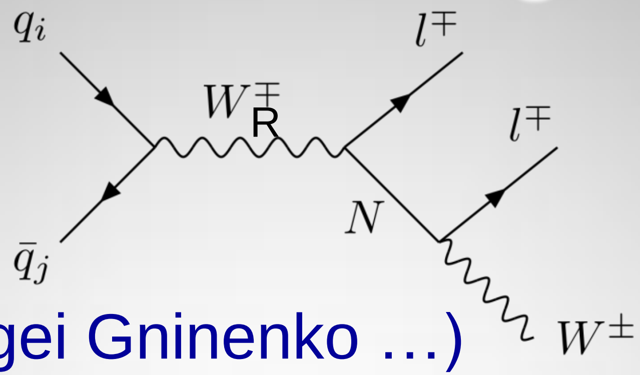


$$U_{iN} \frac{\not{p}+m_N}{p^2-m_N^2+i\epsilon} U_{jN}.$$

The transition rates are proportional to

$$|\mathcal{M}|^2 \propto \begin{cases} \langle m \rangle^2_{\ell_1\ell_2} = \left| \sum_{i=1}^{3} U_{\ell_1 i} U_{\ell_2 i} m_i \right|^2 & \text{for light } \nu; \\ \frac{\left| \sum_i^n V_{\ell_1 i} V_{\ell_2 i} \right|^2}{m_N^2} & \text{for heavy } N; \\ \frac{\Gamma(N \to i)\ \Gamma(N \to f)}{m_N \Gamma_N} & \text{for resonant N production.} \end{cases}$$

Favorable diagram:



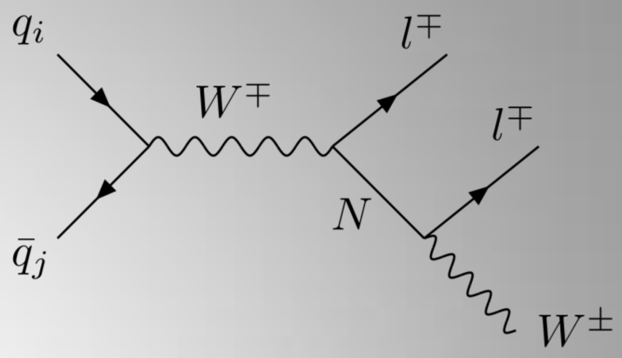
AT the LHC: (Sergei Gninenko …)

7 TeV: $M_{W'} \approx 1500$ GeV, $M_N \approx 600$ GeV;
14 TeV: $M_{W'} \approx 3500$ GeV, $M_N \approx 2300$ GeV.

My criteria for establishing the spontaneous P-violation:

1. Observing a new heavy W';
   determining W' right-handed couplings; AND $g_L = g_R$
2. Observing new heavy fermions (N, …);
   determining their right-handed nature
3. Observing the Higgs triplet
   AS WELL AS the bi-doublet

Mixing with SM:

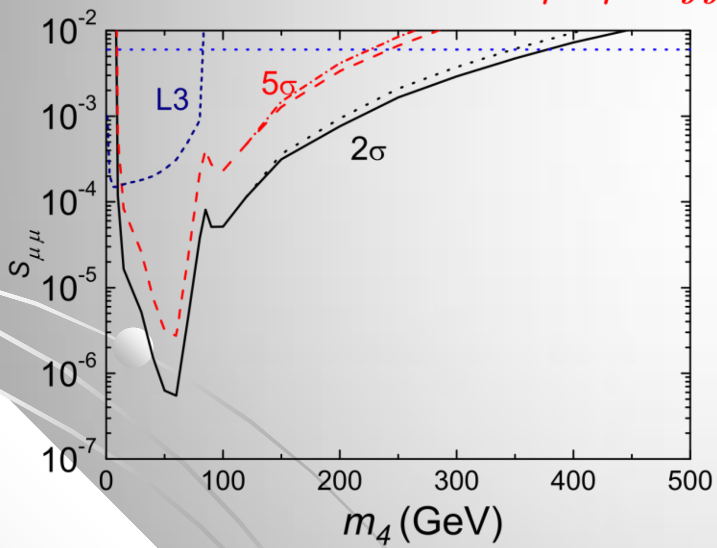


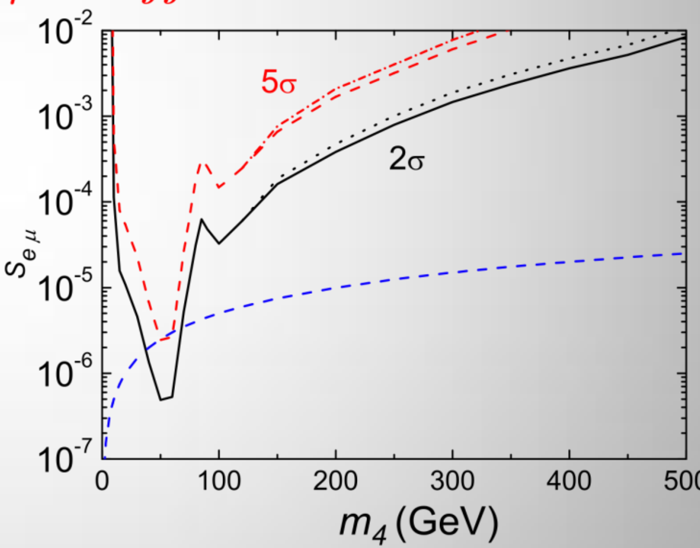
At the LHC:†

Main backgrounds:

- $t\bar{t} \to W^+ b, W^- \bar{b} \to b\mu^+, \ jj \ \bar{c} \ \mu^+ + E_T^{miss}$
- $pp \to W^\pm W^\pm \ jj;$
- $pp \to W^\pm W^\pm \ W^\mp.$

$\mu^\pm \mu^\pm \ jj$ and $\mu^\pm e^\pm \ jj$





Sensitivity reach:

$\mu\mu$ mode: $V_{\mu\mu}^2 \sim 5 \times 10^{-7}$, *or* $m_4 \sim 400$ GeV.

$e\mu$ mode: $V_{e\mu}^2$ below $0\nu\beta\beta$ bound at $m_4 \sim M_W$.

†A. Atre, T. Han, S. Pascoli, B. Zhang, arXiv.0901.3589.

The Compact Muon Solenoid Experiment

Analysis Note

The content of this note is intended for CMS internal use and distribution only

01 June 2009 (v9, 15 July 2009)

Searching for Majorana Neutrinos By Same-Sign Dilepton Final State at $\sqrt{s} = 10$ TeV at The LHC

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Abstract

The Standard Model can be extended to include massive neutrinos as observed in the recent oscillation experiments. Perhaps the most commonly studied model is the Type-I seesaw. This model introduces a new neutrino with a Majorana nature with an unknown mass. In this study we present the potential for the discovery of a Majorana neutrino during the first year of data collection from the Large Hadron Collider. In the analysis we used muon triggers, muon isolation, jet energy corrections, b-tagging, and an examination of the combinatorial background. We found that the mass can be reconstructed using one of the isolated muons and two jets with proper jet corrections applied; whereas the contribution from the various backgrounds was small. We conclude that the discovery potential can be reached in the first year of running at the LHC at $\sqrt{s} = 10$ TeV with the CMS detector for the Majorana mass range near 100 GeV.

Type II (with a scalar triplet) :

Mohapatra, Senjanovic (1981)

With a scalar triplet Φ $(Y = 2)$: $\phi^{\pm\pm}, \phi^{\pm}, \phi^0$

Add a gauge invariant/renormalizable term:

$$Y_{ij} L_i^T C (i\sigma_2) \Phi L_j + h.c.$$

That leads to the Majorana mass:

$$M_{ij} \nu_i^T C \nu_j + h.c.$$

where

$$M_{ij} = Y_{ij} \langle \Phi \rangle = Y_{ij} v' \lesssim 1 \text{ eV},$$

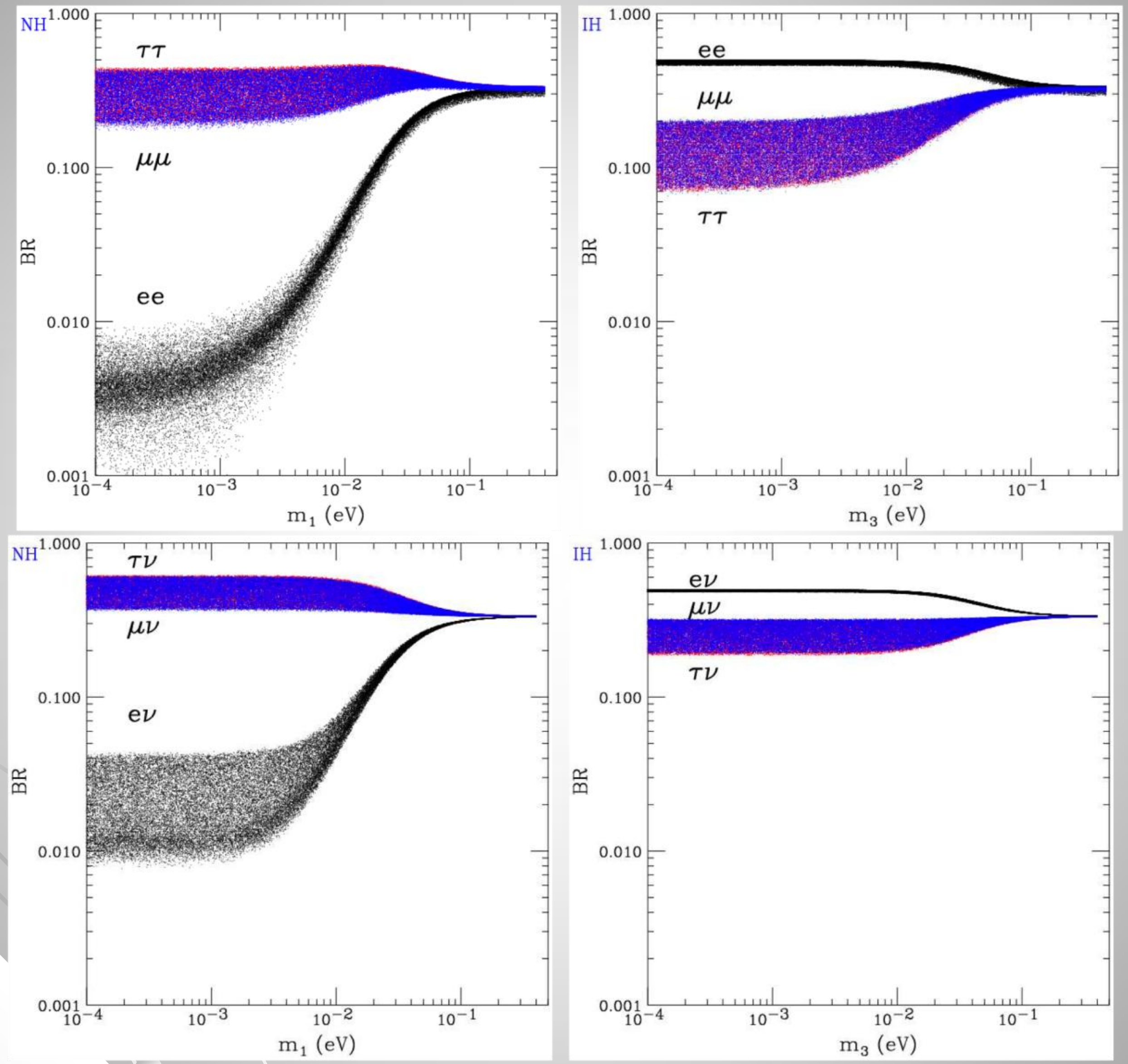
Very same gauge invariant/renormalizable term:

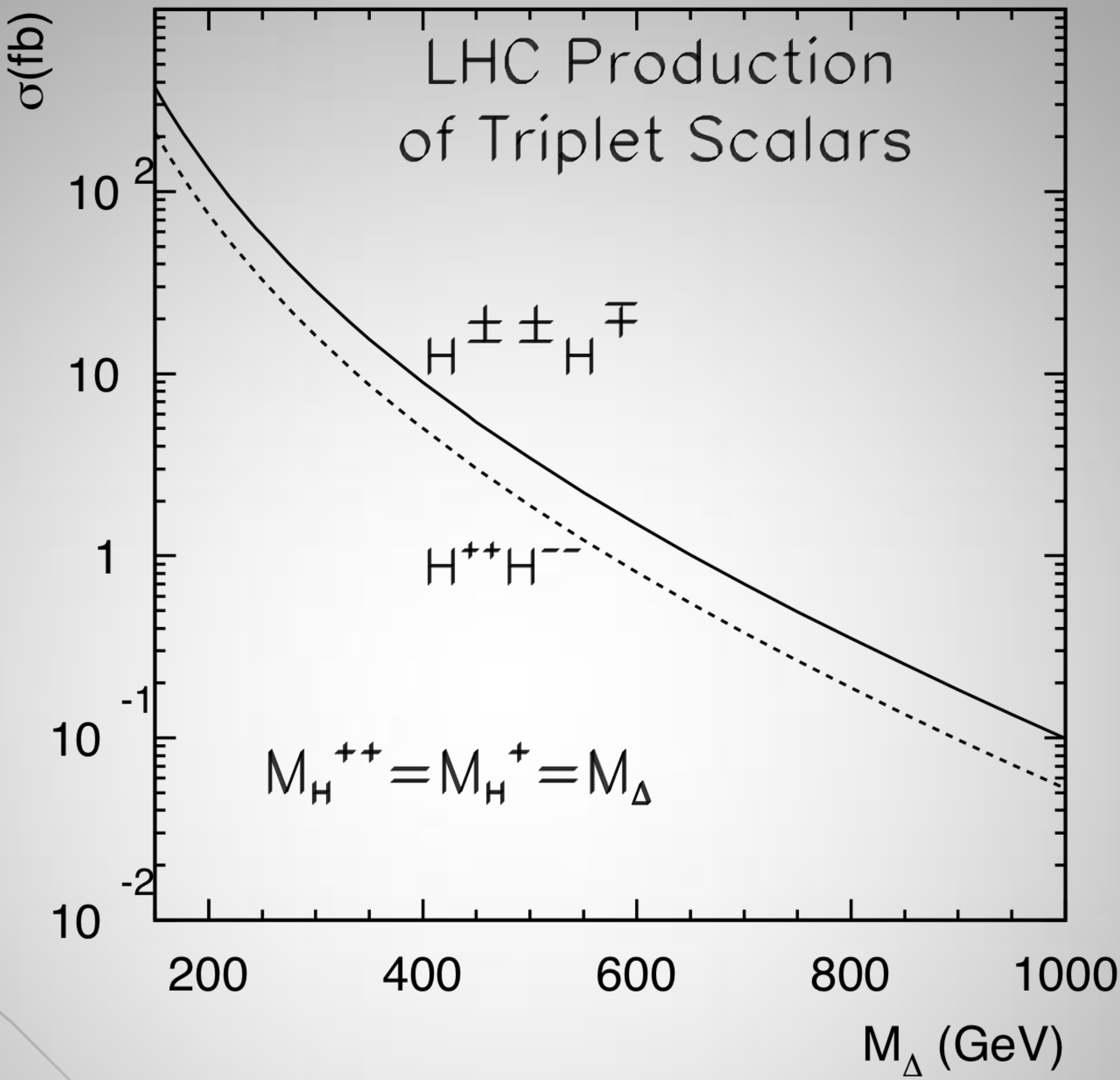
$$\mu H^T (i\sigma_2) \Phi^\dagger H + h.c.$$

predicts

$$v' = \mu \, \frac{v^2}{M_\phi^2}.$$

$H^{\pm\pm}, H^{\pm}$ decays predicted by the light neutrino spectrum:

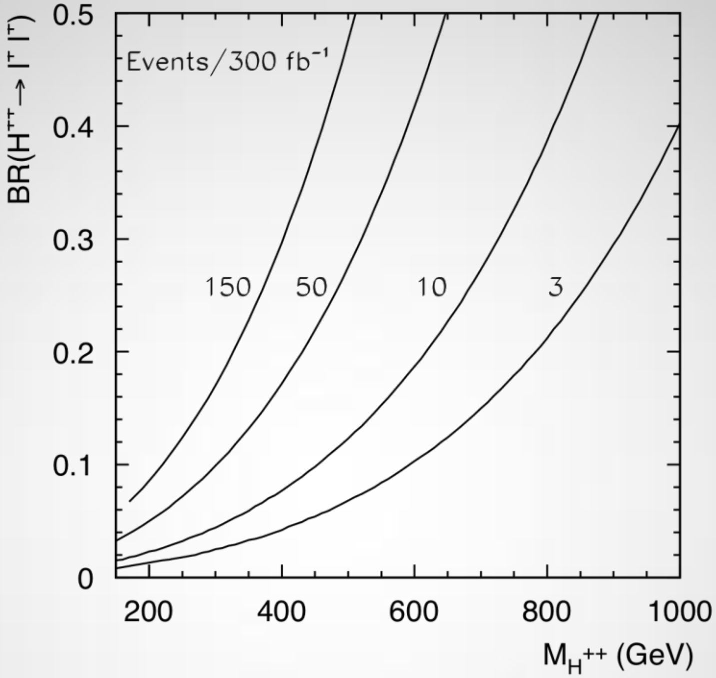




$\gamma\gamma \to H^{++}H^{--}$ 10% of the DY.

Sensitivity to $H^{++}H^{--} \to \ell^+\ell^+,\ \ell^-\ell^-$ Mode: †

Nearly background-free.



With 300 fb^{-1} integrated luminosity,
a coverage upto $M_{H++} \sim 1$ TeV even with $BR \sim 40 - 50\%$.

Possible measurements on BR's.

†Pavel Fileviez Perez, Tao Han, Gui-Yu Huang, Tong Li, Kai Wang, arXiv:0803.3450 [hep-ph]

Type III (with a leptonic triplet) :
(With GUT: Bajc, Senjanovic)

With a lepton triplet T $(Y=0)$: T^+ T^0 T^-, add the terms:

$$-M_T(T^+T^- + T^0T^0/2) + y_T^i H^T i\sigma_2 T L_i + h.c.$$

These lead to the Majorana mass:

$$M_{ij} \approx y_i y_j \frac{v^2}{2M_T}.$$

Demand that $M_T \lesssim 1$ TeV, $M_{ij} \lesssim 1$ eV,
Thus the Yukawa couplings:†

$$y_j \lesssim 10^{-6},$$

making the mixing $T^{\pm,0} - \ell^{\pm}$ very weak.

Main features:

T^0 a Majorana neutrino;
Decay via mixing (Yukawa couplings);
$T\overline{T}$ Pair production via EW gauge interactions.

The Collaboration

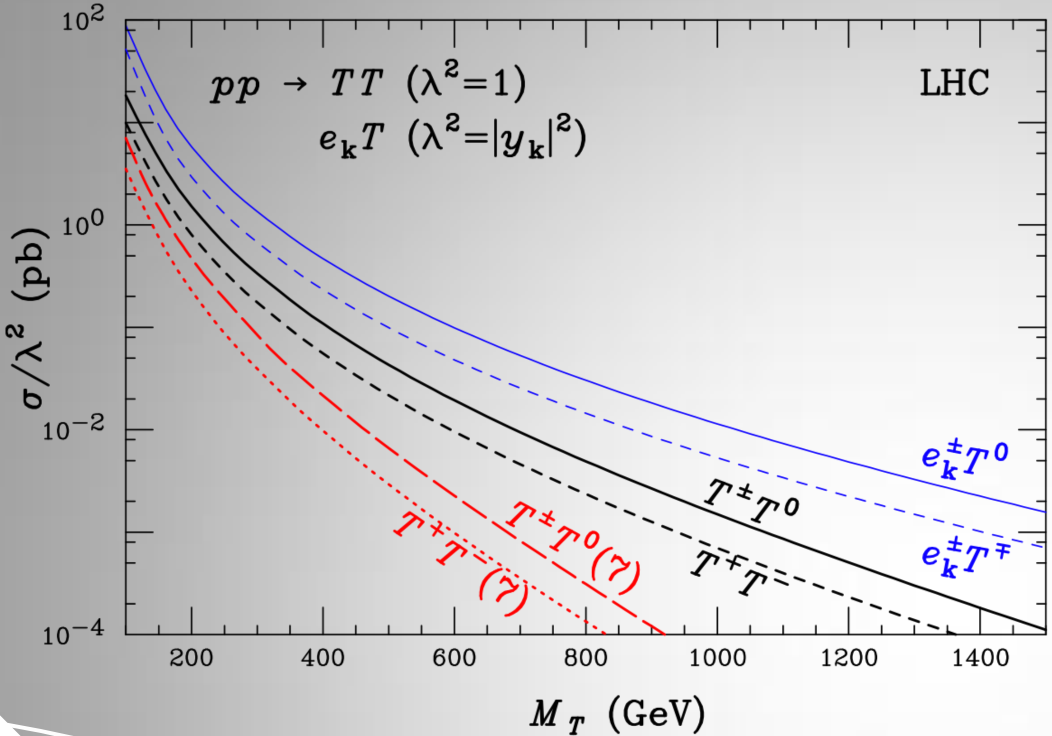
In the summer of 2007:
the “BCSPIN” summer school in Beijing …

The “Magnificent Seven” collaboration:
Abdesslam Arhrib, Borut Bajc, Dilip Ghosh, Guiyu Huang,
Tao Han, Ivica Puljak, Goran Senjanovic

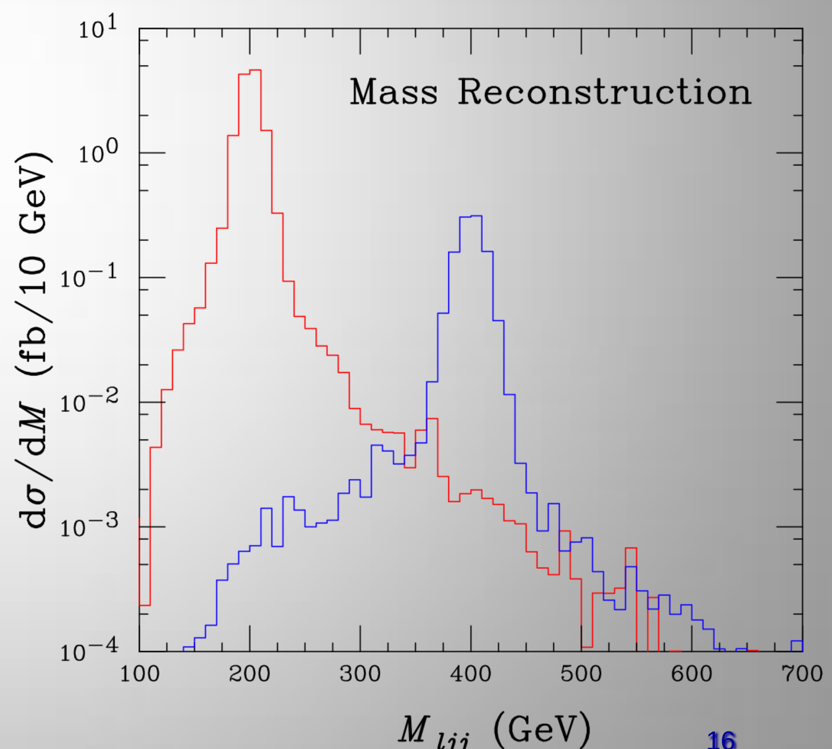
Type III phenomenology at the LHC:

T^0, $T^\pm$ with $\Delta L = 2$ transition ➔ Majorana nature

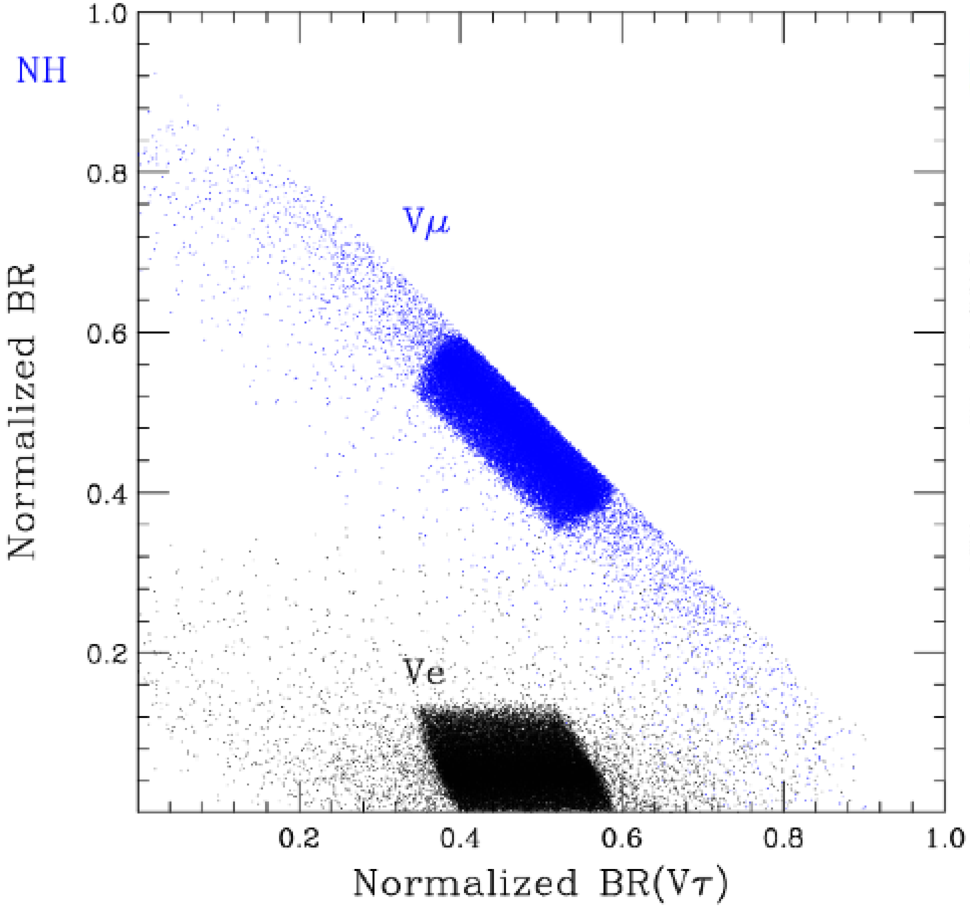
$$T^0T^\pm \to (\ell^\pm W^\mp)(\ell^\pm Z/h), \text{ or } \ell^\pm\ell^\pm W^\mp Z/h$$

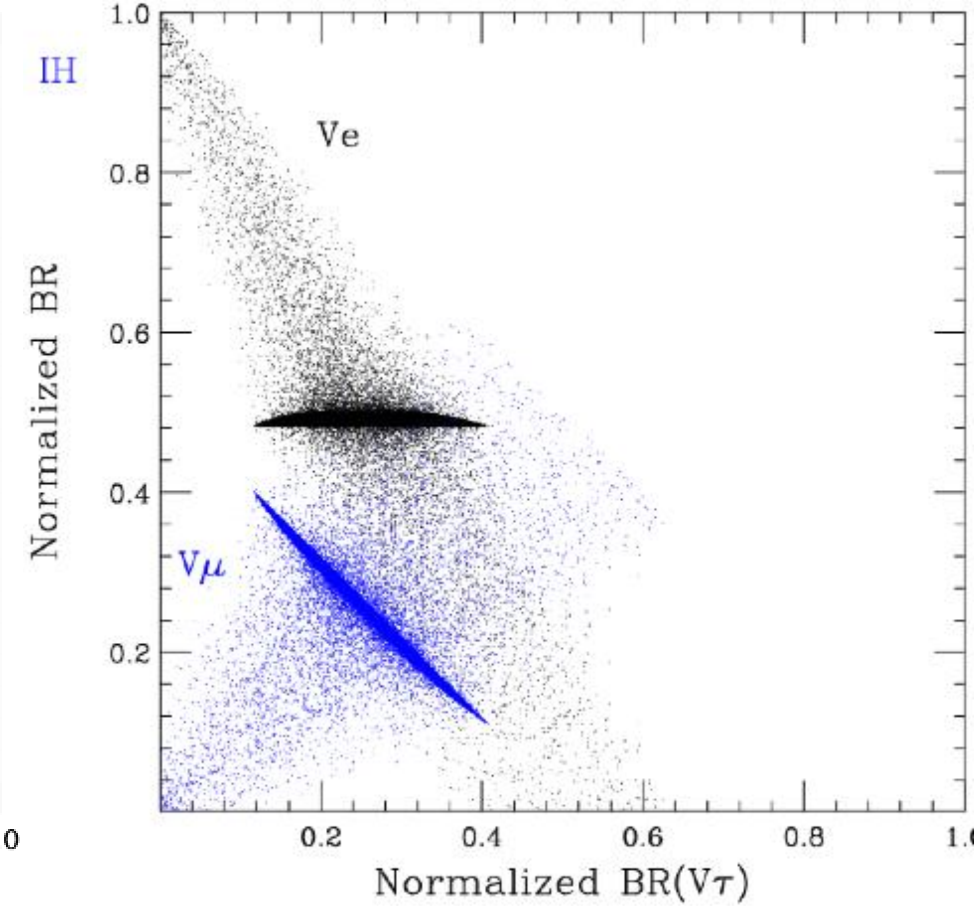


➔ $\ell^\pm\ell^\pm\ j_1j_1'\ j_2j_2'$



(Almost) background free signal !





$$\mu\mu, \mu\tau, \tau\tau \gg ee, \quad \text{for NH},$$

$$\mu\mu, \mu\tau, \tau\tau < ee, \quad \text{for IH}.$$

So, what do they have in common?

N_R, $W_R^{\pm}$, $T^{\pm}$ …

$\Delta L=2$ at LHC

A collaborator, a teacher, an idol

Inspirational, and a quality guard.

Reliable resource with breadth and depth.

1) Neutrino Masses and Mixings in Gauge Models with Spontaneous Parity Violation.
Rabindra N. Mohapatra, Goran Senjanovic, Phys.Rev.D23:165,1981. Cited 1197 times
2) Neutrino Mass and Spontaneous Parity Violation.
Rabindra N. Mohapatra, Goran Senjanovic, Phys.Rev.Lett.44:912,1980. Cited 2444 times
3) Exact Left-Right Symmetry and Spontaneous Violation of Parity.
G. Senjanovic, Rabindra N. Mohapatra, Phys.Rev.D12:1502,1975. Cited 1184 times

Confucius said:

" 三十而立，四十不惑，五十知天命，
六十耳顺，七十从心所欲"

"Turn 30: independent
Turn 40: not being confused
Turn 50: knowing the laws of nature
Turn 60: deep understanding of everything
Turn 70: achieve anything as wish"

We all admire and celebrate what you have achieved !

Happy Birthday, Goran!

(On behalf of Vernon Barger and Pavel Fileviez Perez as well)

Many thanks to the organizers
for such an enjoyable festivity !
Ivica Puljak, Alejandra Melfo,
Francesco Vissani, M.Tello, C.Aulakh… …

(We will be back for the 61th celebration !)