

CP phases in leptonic flavor violation

Miha Nemevšek

University of Hamburg and Jožef Stefan Institute, Ljubljana

based on JHEP **0911**:023, 2009 and PLB **684**: 231-235, 2010

in collaboration with

Borut Bajc, Jernej F. Kamenik and Goran Senjanović

Neutrino mass data

- Oscillations imply at least two massive neutrinos

$\Delta m_{21}^2 [10^{-5} \text{eV}^2]$	7.6
$ \Delta m_{31}^2 [10^{-3} \text{eV}^2]$	2.4
$\sin^2 \theta_{12}$	0.32
$\sin^2 \theta_{23}$	0.50
$\sin^2 \theta_{13}$	0.007

Schwetz '09

- Overall mass scale and hierarchy unknown
- Nature of mass unknown (Dirac or Majorana)
- If Majorana, lepton number is broken
- Additional complex phases may appear

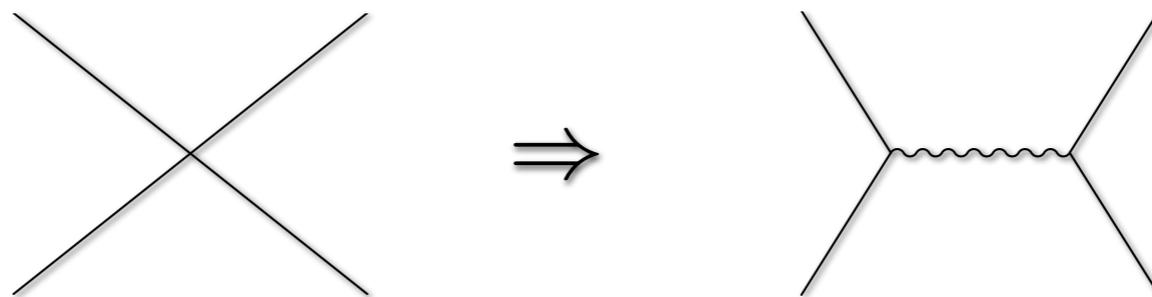
What about the theory?

- The Standard Model does not do
- A low energy non-renormalizable effective theory

$$\mathcal{O}_W = y_{ij} \frac{L_i H L_j H}{\Lambda}$$

Weinberg '79

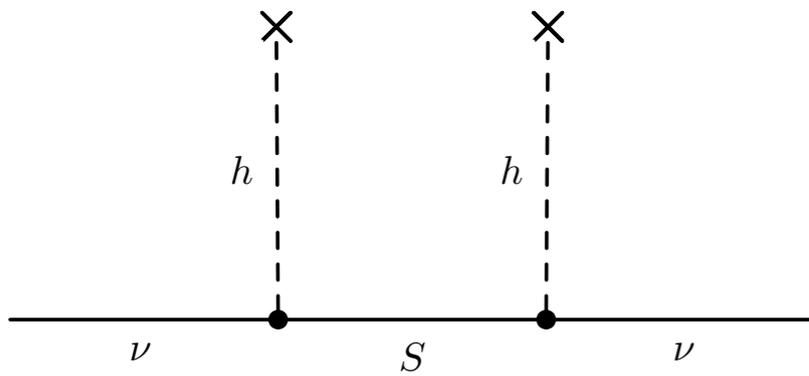
- Yukawa couplings and cutoff arbitrary
- Renormalizable models



- For a single representation only three scenarios at tree-level

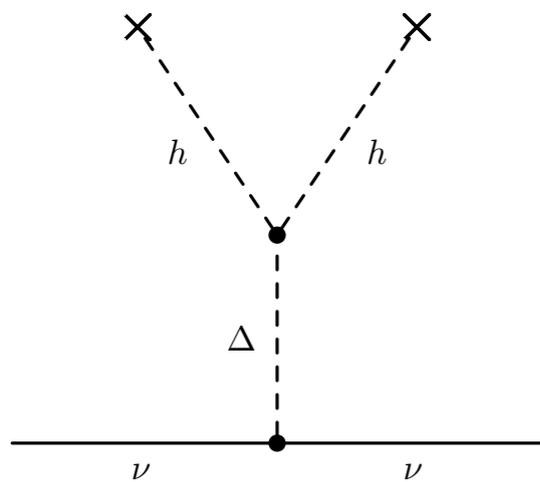
Ma '80

Seesaw scenarios



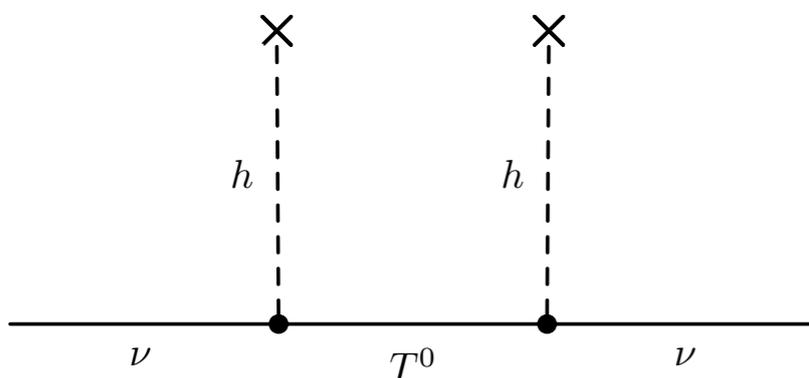
- Type I = fermionic singlet

Minkowski '77, Mohapatra, Senjanović '79, Yanagida '79,
Glashow '79, Gell-Mann, Ramond, Slansky '79



- Type II = bosonic triplet, $Y=2$

Magg, Wetterich '80, Lazarides, Shafi, Wetterich '81,
Mohapatra, Senjanović '81



- Type III = fermionic triplet, $Y=0$

Foot, Lew, He, Joshi, '89

Framework for seesaw

- Simple-minded scenarios not much better than \mathcal{O}_W
- Yukawas unknown and scale not fixed
- Embedding into a theory may constrain both y_{ij} and Λ
- For example
 - left-right symmetric models (type I+II) Pati, Salam '74
 - minimal realistic SU(5) (type III) Bajc, Senjanović '06
 - fermionic triplet accessible at LHC Bajc, M.N., Senjanović '07

CP phases at high energies

- Produce the mediator at a collider
 Franceschini, Hambye, Strumia '08,
 del Aguila, Aguilar-Saavedra '08,
 Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanović '09
- Lifetimes and Br's determine Yukawa couplings
- A handle on Majorana phases for type II
 Kadastik, Raidal, Rebane '08, Garayoa, Schwetz '08,
 Fileviez-Perez, Han, Huang, Li, Wang '08
- and type III
 Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanović '09
- Using triple product correlations at colliders
 Rindani '94, Yuan '94

Low energy probes of CP phases

- Neutrino-less double beta decay, a text-book fact
- Lepton flavor violation (LFV) rates
- Neutrino-antineutrino oscillations see, e.g. de Gouvea, Kayser, Mohapatra '02
- Triple-correlation products of spins & momenta
 - with rare decays Farzan '07, Davidson '08, Farzan, Ayazi '09

Lepton flavor violation

- Studied in context of seesaw scenarios
 - LFV possible with fine tunings for type I and III

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon '06,
Abada, Biggio, Bonnet, Gavela, Hambye '07, Biggio '08, He, Oh '09
- Best bound from mu-e conversion for minimal type III Kamenik, M.N. (0908.3451)
- No fine-tuning for type II, a small vev is enough
- A study of LFV in L-R theories Cirigliano, Kurylov, Ramsey-Musolf, Vogel '04

Mu-e conversion

- Best experimental limits on LFV

$$\text{Br}_{\mu \rightarrow e} \equiv \Gamma(\mu N \rightarrow e N) / \Gamma(\mu \rightarrow e \nu \bar{\nu})$$

Titanium	$< 4.3 \times 10^{-12}$
Gold	$< 7 \times 10^{-13}$

Dohmen et al. '93

Bertl et al. '06

- A detailed numerical study with hep operators

Kitano, Koike, Okada '99

- Great improvement in the future

- PRISM/PRIME @ J-PARC

- Mu2e @ Fermilab

$$\text{Br}_{\mu \rightarrow e} \lesssim 10^{-16} - 10^{-18}$$

4-6 orders of magnitude!

- Experimental progress slower in other channels, e.g. $\mu \rightarrow e \gamma$ and $\mu \rightarrow e \bar{e} e$

COMMENTS!

DOE gives big boost to Fermilab's plans for new muon experiment

December 8, 2009 | 6:19 am

While all eyes have been on the startup of the Large Hadron Collider in Europe, the world's largest scientific experiment, a small team of researchers based in the US has been toiling away.

The group has focused its energies on planning an experiment that creates a plenitude of muons and could reveal new phenomena that could only result from unknown physics.

That narrow focus, say the members of the Muon-to-Electron-Conversion experiment, will allow the Mu2e collaboration to indirectly search for new particles and let them look for signs of new types of interactions at energies up to 10,000 trillion electronvolts, far beyond the LHC's grasp. It also would help scientists to better understand future LHC discoveries.

Mu2e got a big boost on November 24 with the US Department of Energy endorsement of the scientific need for the project, called Critical Decision-0. This marks the first stage of DOE's 4-stage approval process that projects must pass before construction can start.



From left: Amy Allen, Doug Glenzinski, and Craig Group work on the Mu2e experiment test stand at Fermilab. Mu2e just passed the first DOE approval stage. Photo Courtesy of Fermilab.

Triple spin correlations in LFV

- Conversion of a polarized muon in a nucleus
- Form a triple spin correlation $(\vec{s}_\mu \times \vec{s}_e) \cdot \vec{p}_e$
- E.g.: a vectorial coupling

$$\mathcal{L}_{eff} = G_F \sum_{q=u,d} (A_L \bar{e}_L \gamma^\mu \mu_L + A_R \bar{e}_R \gamma^\mu \mu_R) (V_L^q \bar{q}_L \gamma^\mu q_L + V_R^q \bar{q}_R \gamma^\mu q_R) + \text{h.c.}$$

- Transverse electron polarization proportional to

$$\delta_{CP} = \frac{\text{Im}(A_L^* A_R)}{|A_L|^2 + |A_R|^2}$$

- Vanishes if couplings are real

Case of seesaw

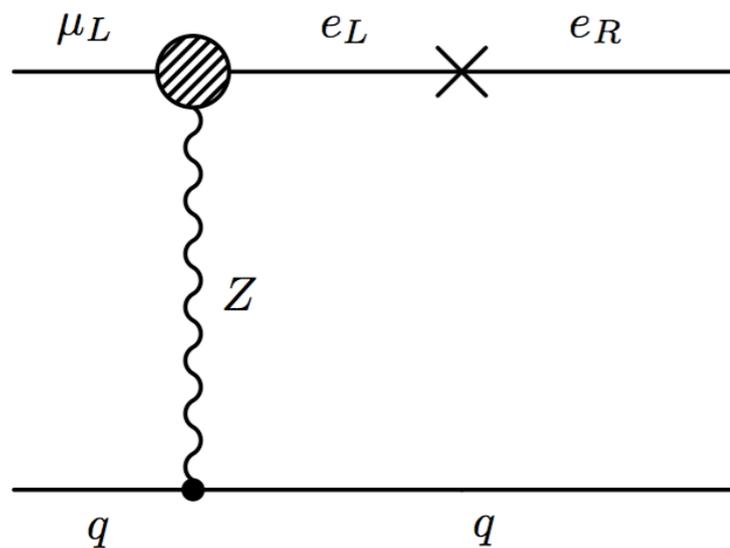
- Seesaw doing LFV, no other interactions Bajc, M.N., Senjanović (0911.1323)
- Only left-handed components coupled with Yukawas

$$\begin{array}{ll} \bar{L} H F_{new} & \text{type I \& III} \\ \bar{L} \Delta L & \text{type II} \end{array}$$

- They give A_L , but what about A_R ?
 - a) A mass insertion on the external leg
 - b) A Higgs loop

A no-go for seesaw

- Mass insertion

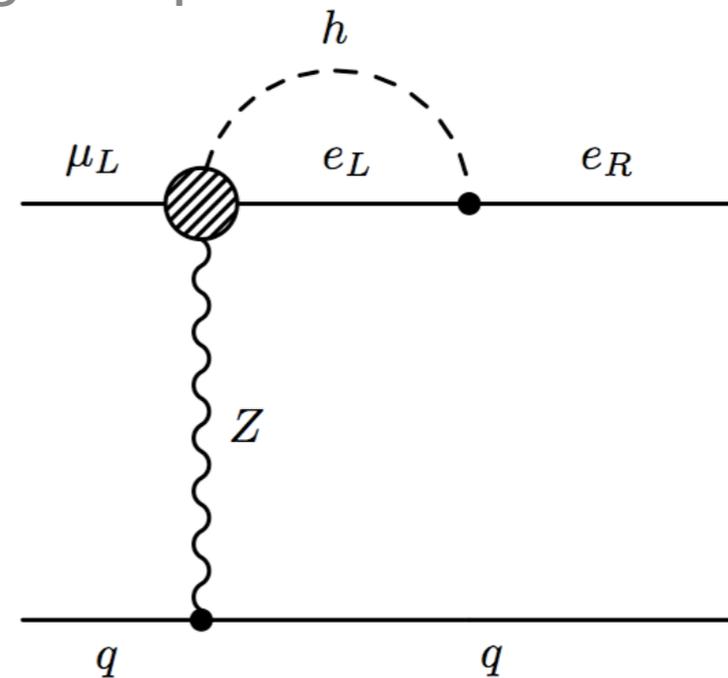


- Suppression $A_R = \frac{m_e}{m_\mu} A_L$

- No change in complexity!

$$\delta_{CP} \propto \text{Im}(|A_L|^2) = 0$$

- Higgs loop



- Suppression $\delta_{CP} = \frac{\alpha}{\pi} \frac{m_e}{m_W} \approx 10^{-7}$

- Hopeless for *any* type of seesaw

Left-right model

- Minimal left-right symmetric model $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- Minimal Higgs content $\Phi(2, 2, 0), \Delta_L(3, 1, 2), \Delta_R(1, 3, 2)$
- Additional Yukawa couplings $\mathcal{L}_\Delta = Y_\Delta (\ell_L \ell_L \Delta_L + \ell_R \ell_R \Delta_R) + \text{h.c.}$
- Parity restored around the TeV scale

$$\langle \Delta_R \rangle \simeq M_{W_R}, \quad \langle \Delta_L \rangle = 0$$

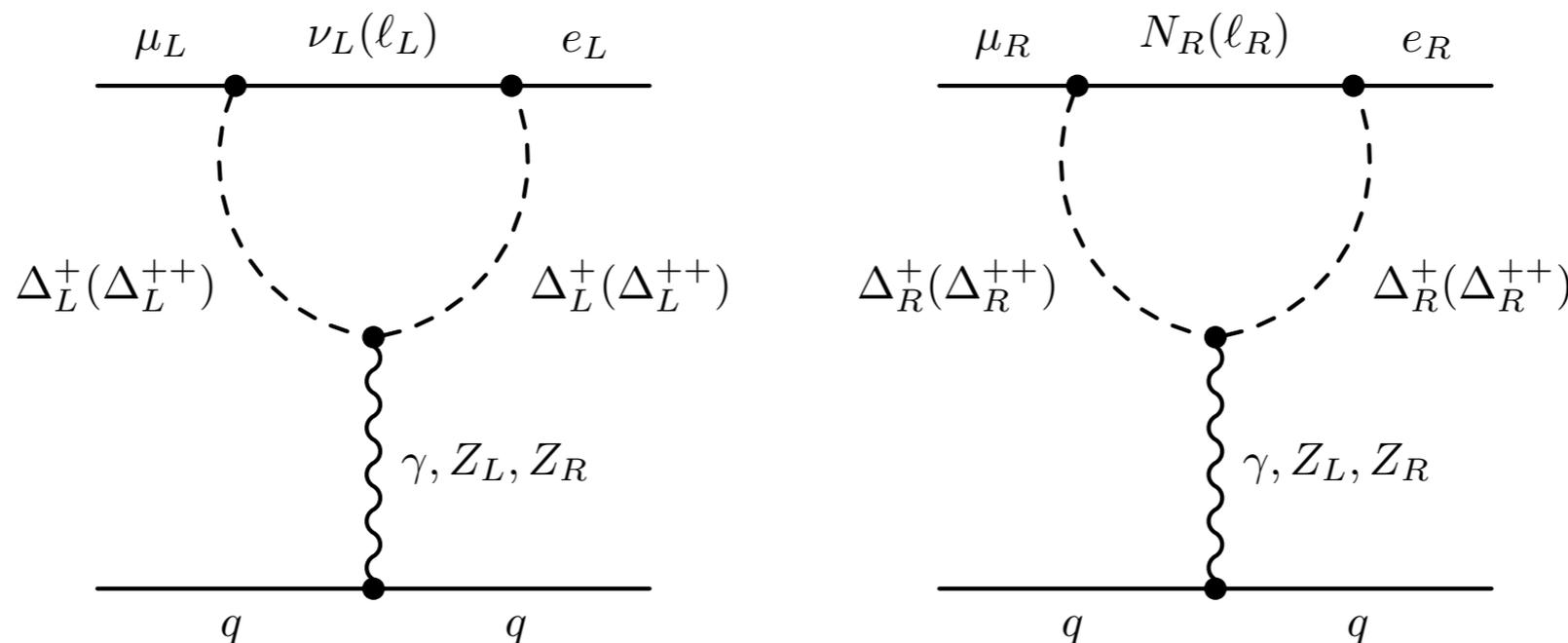
- The bi-doublet completes the breaking
- and induces a vev

$$\langle \Phi \rangle = M_L$$

$$\langle \Delta_L \rangle \propto \frac{\langle \Phi \rangle^2 \langle \Delta_R \rangle}{M_{\Delta_L}^2}$$

LFV in L-R

- Example of LFV contributions see Cirigliano, Kurylov, Ramsey-Musolf, Vogel '04
- A_L from W_L and Δ_L loops
- A_R from W_R and Δ_R loops (penguins and boxes)



- A signal possible with $M_R = (10 - 30) \text{ TeV}$

CP phases in L-R

- If the theory is symmetric, why $\delta_{CP} \neq 0$?
- While the Δ contributions are similar ($M_{\Delta_L} - M_{\Delta_R} \propto \langle \Delta_R \rangle$)

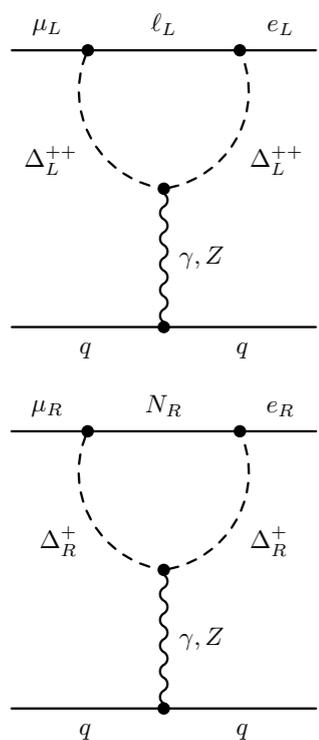
$$A_L(\Delta_L) \sim A_R(\Delta_R) \approx \frac{\alpha}{\pi} \left(\frac{M_L}{M_R} \right)^2 Y_\Delta^2$$

- The gauge contributions are asymmetric

$$A_L(W_L) \approx 0, \quad A_R(W_R) \approx \frac{\alpha}{\pi} \left(\frac{M_L}{M_R} \right)^2 \left(\frac{M_N}{M_{W_R}} \right)^2$$

- And generically: $\delta_{CP} = \frac{\text{Im}(A_L(\Delta_L) A_R^*(\Delta_R + W_R))}{|A_L|^2 + |A_R|^2} \neq 0$

Phase determination



$$A_L \propto U_L^\dagger U_{\nu N}^\dagger m_N^2 f(0) U_{\nu N} U_L$$

$$A_R \propto U_R^\dagger m_N^2 f\left(\frac{m_N^2}{M_R^2}\right) U_R$$

- In general: $U_{\nu N} \neq 1$
- Unless type II dominates
- δ_{CP} measures L-R phase mismatch

- δ_{CP} vanishes if

a. W_R decouples i.e. $M_{W_R} \gg M_{\Delta_{L,R}}$

a.1) Type II dominates

a.2) Universal charged mixing

a.3) $m_N \ll M_{\Delta_{L,R}}$

b. $M_{\Delta_L} \ll M_{\Delta_R} \Rightarrow \frac{A_R}{A_L} \rightarrow 0$

$M_{\Delta_R} \ll M_{\Delta_L} \Rightarrow \frac{A_L}{A_R} \rightarrow 0$

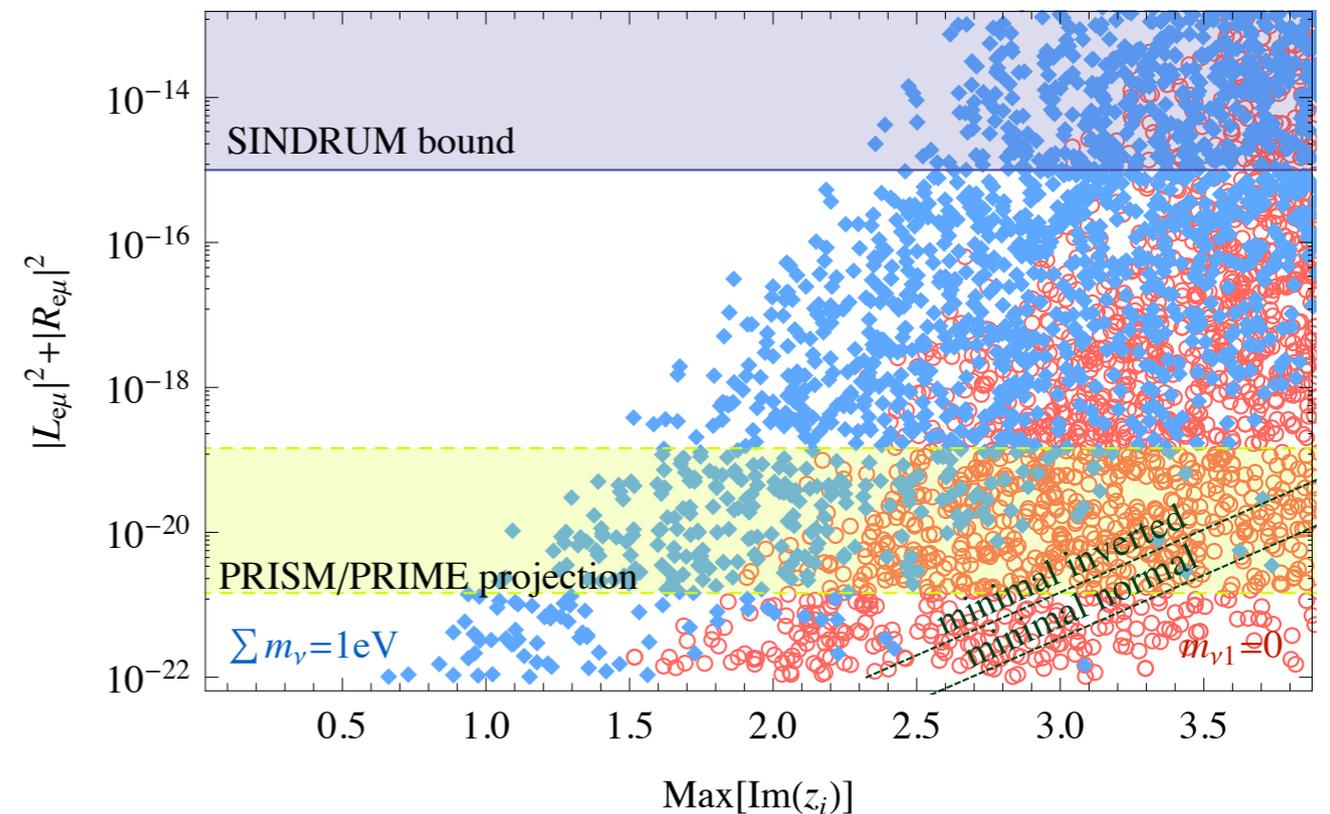
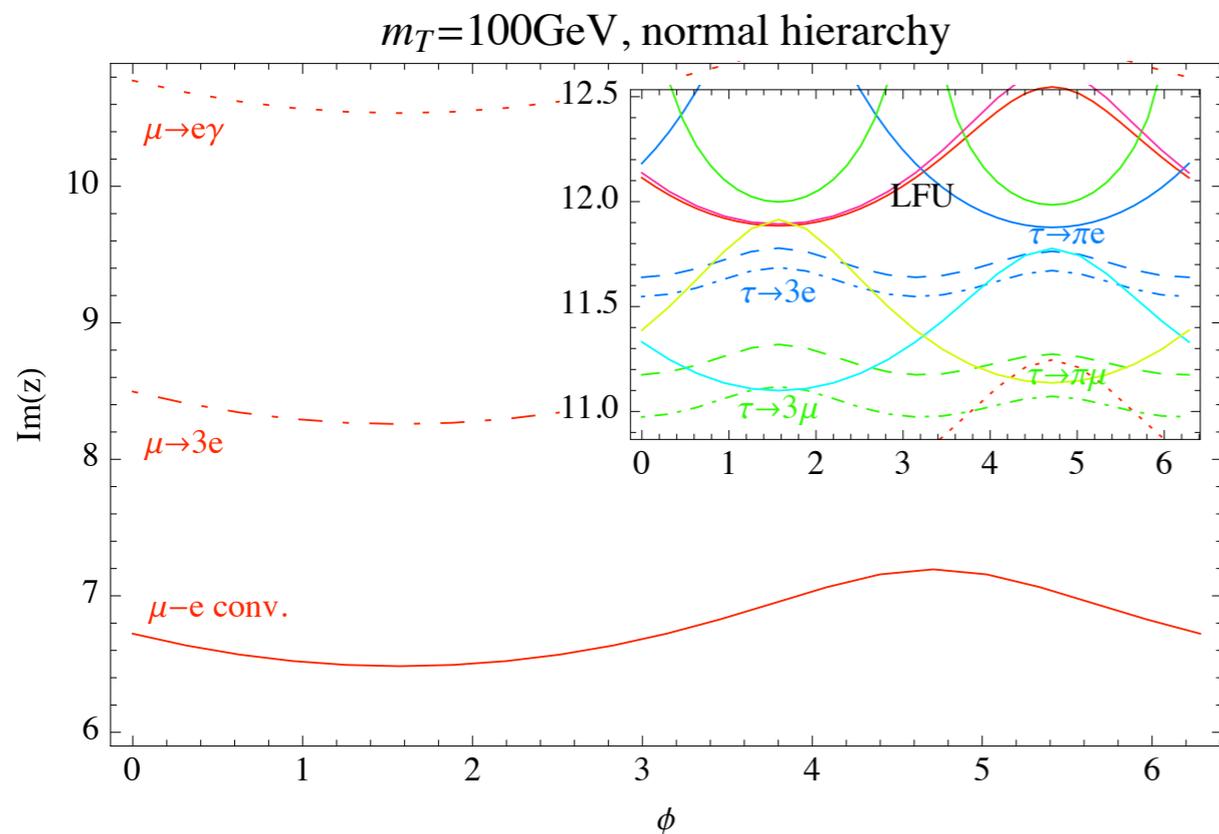
Conclusions

- Probing CP phases remains a hard issue
- Possible to determine at colliders, esp. type II and III
- LFV sensitive to Majorana phase
- Triple correlations in mu-e conversion compelling
 - No-go for seesaw
 - Left-right symmetric theories a good candidate
- Light W_R exciting for LHC and $0\nu 2\beta$

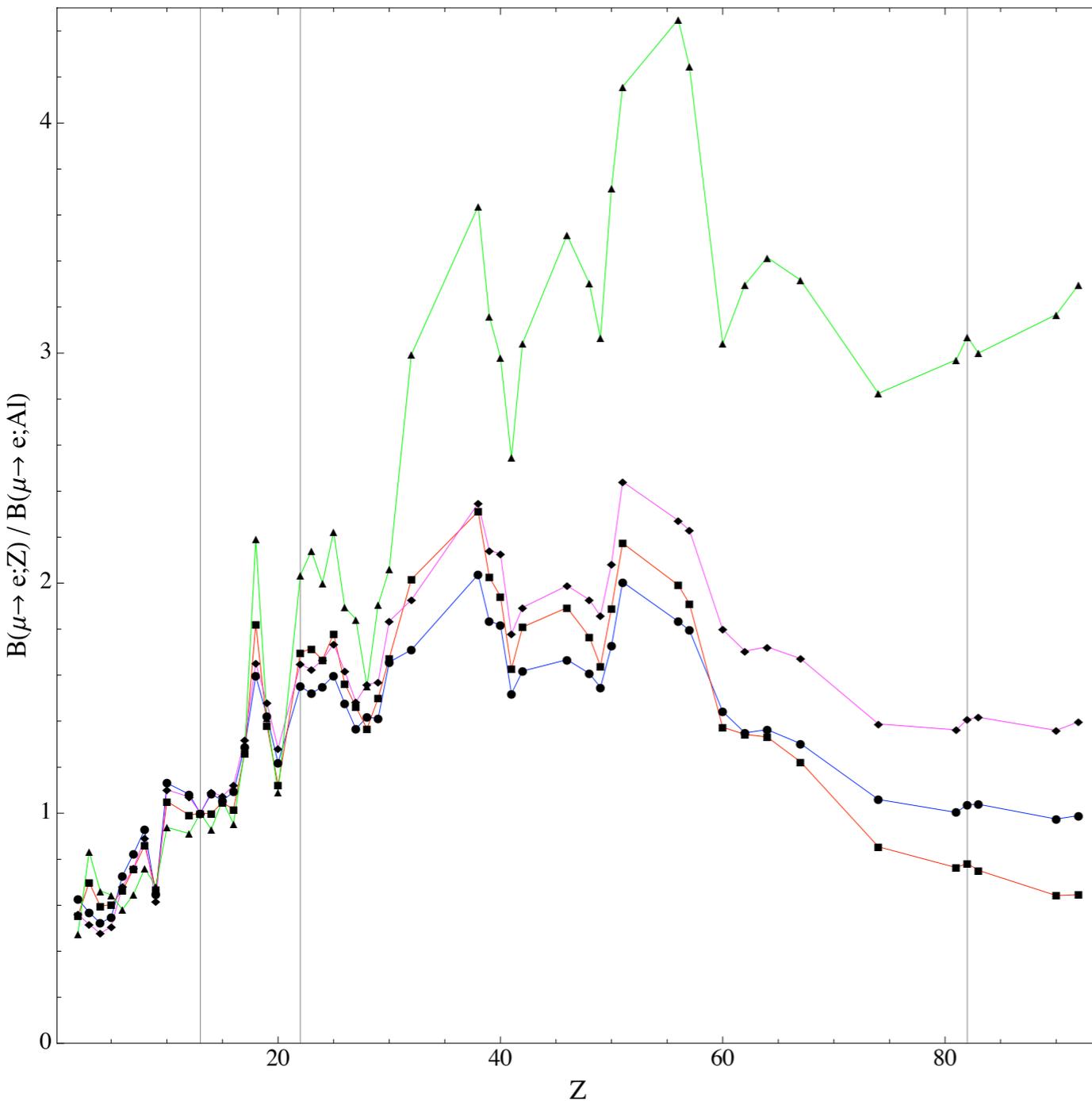
Backup slides

LFV in type III

- Casas-Ibarra-Ross parametrization $y_T = 1/v \sqrt{m_T} O(z_i) \sqrt{m_\nu} U^\dagger$ and $OO^T = 1$
- $O = O(z_i)$, $z_i \in \mathbb{C}$ with $n_T = 2$, $i = 1$ (minimal) $n_T = 3$, $i = 3$
- LFV rate $\Gamma \propto |y_T^e y_T^\mu|^2$ can be large if $\text{Im}(z_i) \gg 1$ i.e. $d = 5$ & $d = 6$ decouple



Nucleus dependence



- Conversion rate nucleus dependent
Cirigliano, Kitano, Okada, Tuzon '09
- D-blue, S-red, V(gamma)-magenta and V(Z)-green scale differently
- Test one mediator hypothesis
 - 5% for light-light
 - 20% for heavy-light
- Type III = V(Z) dominance
- L-R contributions spectrum dependent

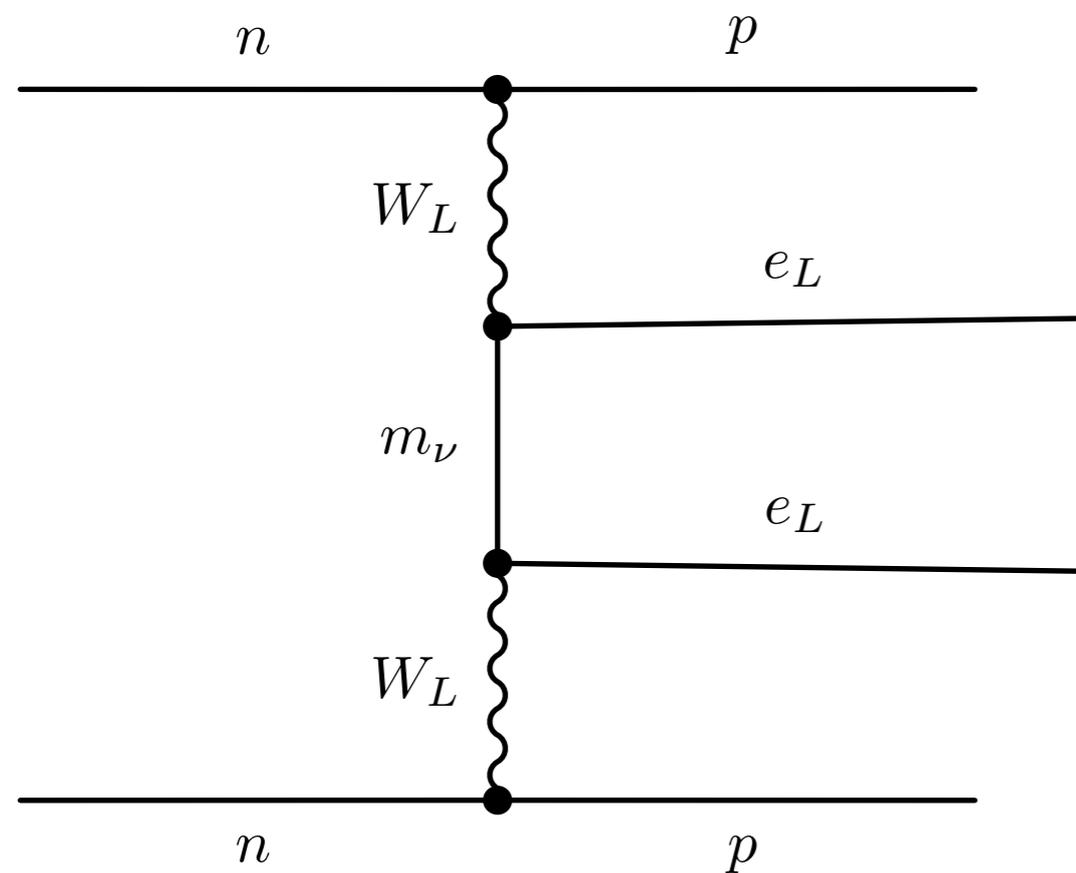
Limits on L-R

- Direct searches at Tevatron
 - CDF $m_{W_R} > 720$ GeV for heavy r.h. neutrinos
 - D0 $m_{W_R} > 640$ GeV ($m_N < 410$ GeV)
 - Model-dependent indirect limits
 - V_L^{CKM} and V_R^{CKM} unrelated, no existing limit
 - Left-right = (**P**)arity $M_{W_R} > 4$ TeV (from ε') Zhang, An, Ji, Mohapatra '07
 - Left-right = (**C**)harge conjugation $M_{W_R} > 2.5$ TeV (from Δm_K)
Maiezza, Nesti, M.N., Senjanović (to appear)
- Moriond, Mar. '10 Miha Nemevšek

LHC prospects for L-R

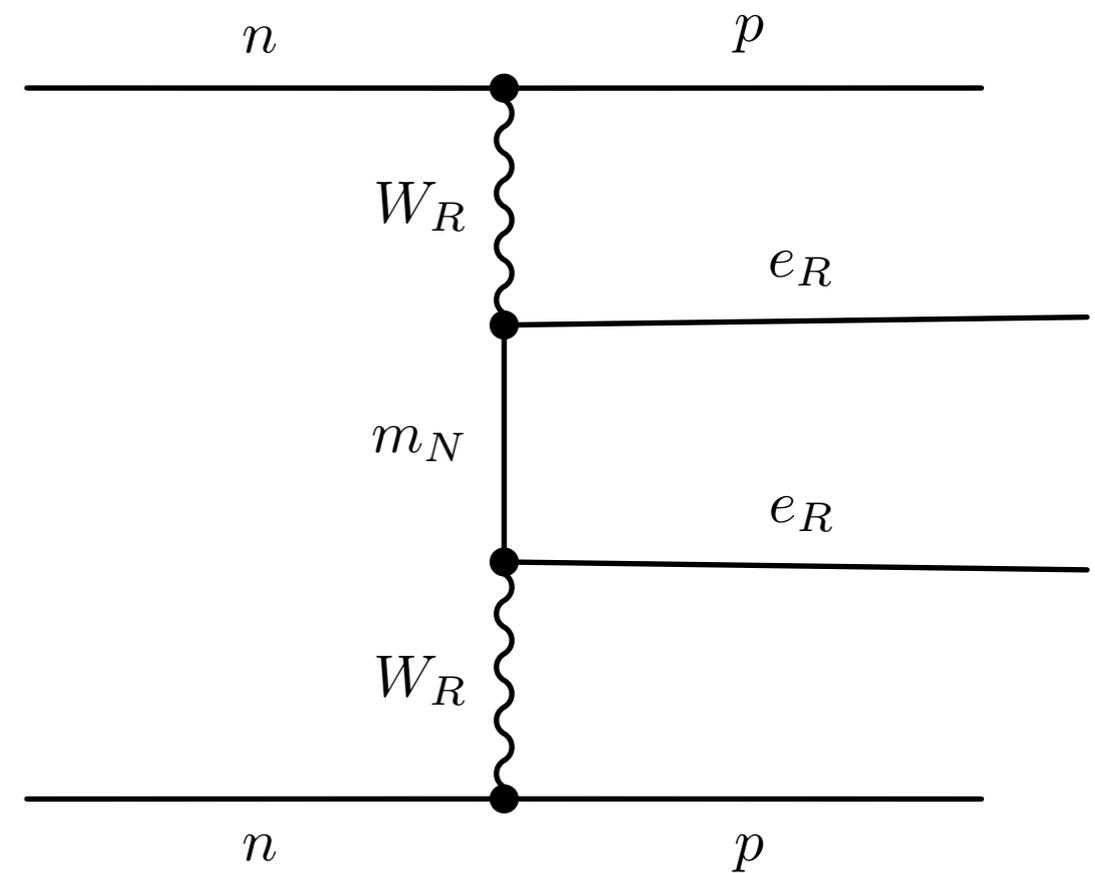
- CMS with $\sqrt{s} = 14$ TeV and $\mathcal{L}_t = 30$ fb⁻¹ Gninenko, Kirsanov, Krasnikov, Matveev '07
 - Reach of $M_{W_R} < 4$ TeV and $m_N < 2.4$ TeV
- Update at $\sqrt{s} = 10$ TeV and $\mathcal{L}_t = 100$ pb⁻¹ see talk by Kirsanov in Würzburg '09
 - With low luminosity: $M_{W_R} < 1.8$ TeV and $m_N < 0.9$ TeV
- ATLAS with $\sqrt{s} = 14$ TeV and $\mathcal{L}_t = 300$ fb⁻¹ Ferrari et al. '00
 - High luminosity: $M_{W_R} < 6$ TeV and $m_N < 4$ TeV

Neutrino-less double beta decay



$$\mathcal{A}_{LL} \propto \frac{m_\nu}{p^2} \leq 10^{-8} \text{ GeV}^{-1}$$

vs.



$$\mathcal{A}_{RR} \propto \left(\frac{M_L}{M_R} \right)^4 \frac{1}{M_N}$$

- RR contribution can dominate the signal e.g. if

$$M_{W_R} \simeq 2.5 \text{ TeV}$$

$$m_N \simeq 100 \text{ GeV}$$