Probing leptonic CP at LHC and rare decays

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Neutrino data

- Neutrinos oscillate
  - at least two are massive
  - lepton flavor is broken

$\Delta m^2_{21} [10^{-5} \mathrm{eV}^2]$	7.6
$\lvert\Delta m^2_{31}\rvert [10^{-3} \mathrm{eV}^2]$	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 unknown
- Nature (Dirac vs. Majorana) unknown
- New CP phases (1 vs. 3) are present

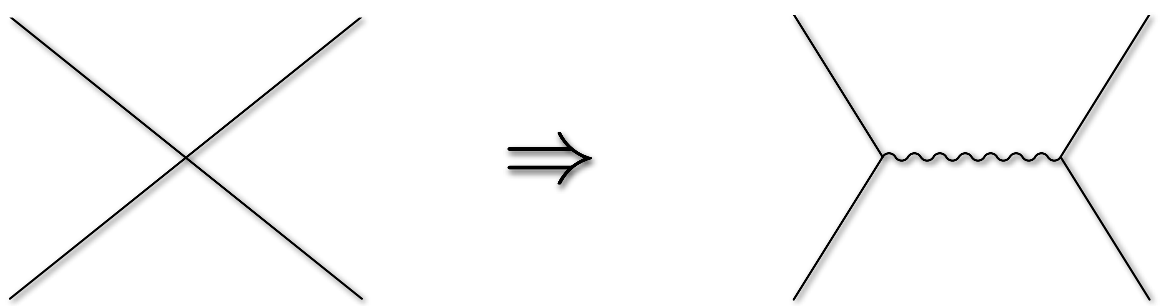
Theory of neutrino mass

- Standard Model is no good
  - Do it like Fermi = non-renormalizable d=5

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

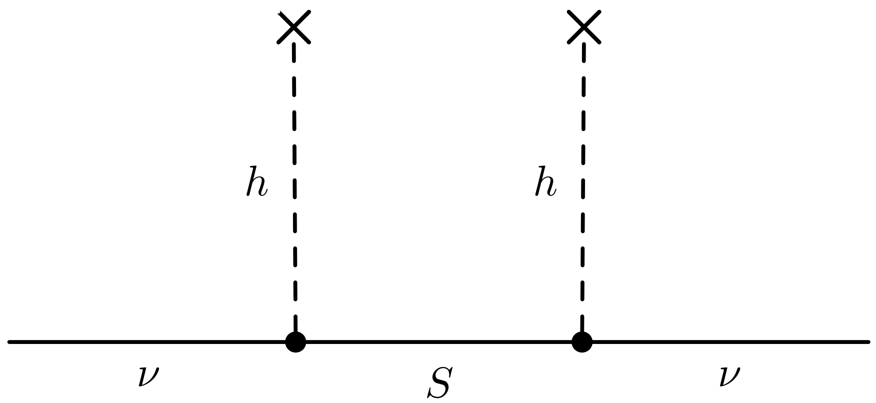
(Weinberg, 79)

- Couplings and cut-off unknown



- Renormalizable model, like Glashow-Weinberg-Salam
- Single additional representation leads to three scenarios (Ma, 80)

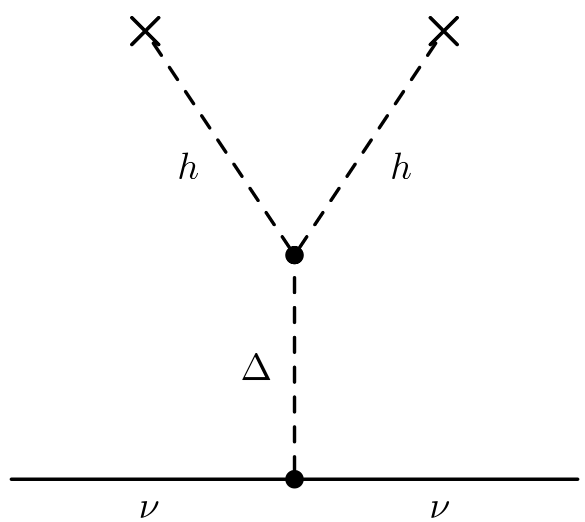
Seesaw scenarios



Type I

- Fermionic singlet

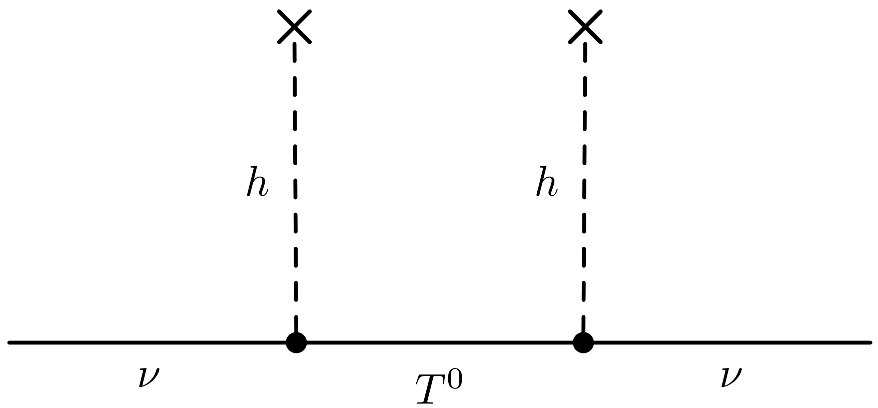
(Minkowski 77, Mohapatra, Senjanović 79, Yanagida 79, Glashow 79, Gell-Man, Ramond, Slansky 79)



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)

Theories with seesaw

- Seesaw as a language not predictive

$$m_\nu = -\frac{v^2}{2} Y^T M^{-1} Y$$

- Yukawa matrices Y and Majorana mass M arbitrary
- Theories with seesaw more constrained
  - e.g. in SO(10) Yukawas are related
  - mass scale M related to the GUT breaking vev and Y
  - hard to test experimentally, scale too high, p-decay
- What about the simplest GUT of all?

Simplest GUT

- Original proposal on SU(5) does not work (Georgi, Glashow 74)
  - no unification of couplings
  - neutrinos massless
  - wrong b-tau mass relation

- Minimal extension of the original model
  - in the Higgs sector, 15_H gives type II seesaw, not predictive (Doršner, Perez 05)
  - in the Fermionic sector, adjoint 24_F, type I and III (Bajc, Senjanović 06)

A predictive SU(5)

- Contains the triplet and the singlet

$$24_F = (8,1)_0 + (3,1)_0 + (1,1)_0 + (3,2)_{\pm 5/6}$$

- Type I and III seesaw

$$\mathcal{L}_\ell = y_T \overline{L} H T + y_S \overline{L} H S + m_T \overline{T} T + m_S \overline{S} S + \text{h.c.}$$

give

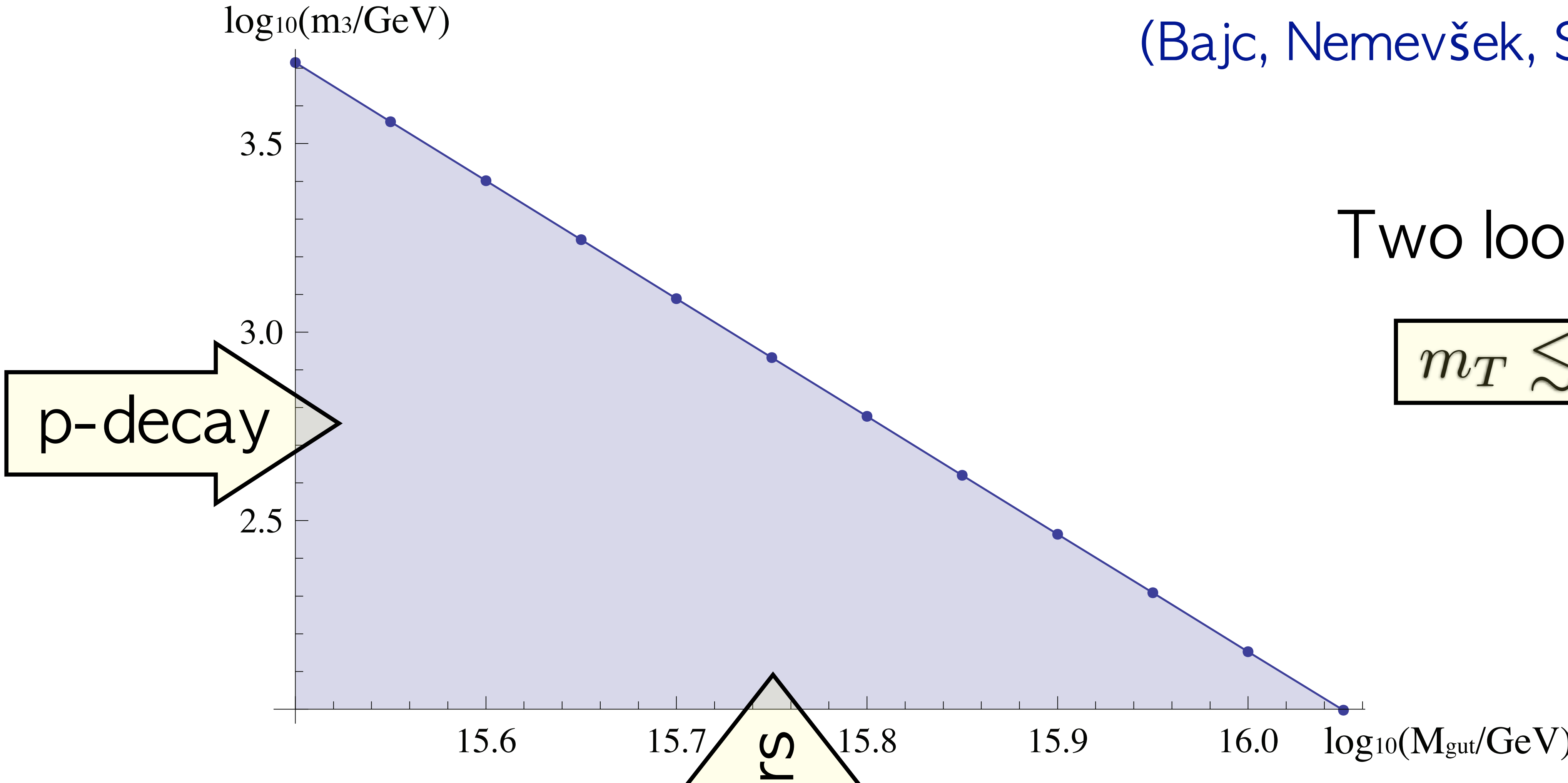
$$m_{\nu\ ij} \quad -\frac{v^2}{} \left(\frac{y_T^i y_T^j}{m_T} \quad \frac{y_S^i y_S^j}{m_S} \right)$$

- Rank 2, lightest state massless at tree level
- Two loop corrections unobservable (Davidson, Isidori, Strumia 06)
- A fourth generation rules out the model

Mass spectrum

- Charged degrees in 24_F alter the running
- GUT scale constrained by proton decay

(Bajc, Nemevšek, Senjanović 07)



Two loop analysis

$m_T \lesssim \text{TeV}$

- Typical spectrum, unique solution

$$m_T \simeq 10^3 \text{GeV}, \quad m_8 \simeq 10^8 \text{GeV}, \; m_{GUT} \gtrsim 10^{15.5} \text{GeV}$$

Type III seesaw

- Motivated by GUT, we study low scale type III
- Same Yukawa couplings in charged and neutral mass matrix

$$M_\ell^{\rm diag} = U^{+\dagger} \begin{pmatrix} v\sqrt{2} y_\ell^{ij} \delta^{ij} & 0 \\ v\, y_T^i & m_T \end{pmatrix} U^-$$

$$M_\nu^{\rm diag} = U^{0T} \begin{pmatrix} 0_{3\times 3} & v\, y_T^i & v\, y_S^i \\ v\, y_T^i & m_T & 0 \\ v\, y_S^i & 0 & m_S \end{pmatrix} U^0$$

- Chiral and vector-like states mix in the physical basis
  - Tree level FCNCs and non-unitary W couplings
  - Small right-handed couplings to W

Probing the phases

- Strategy for LHC
  - produce the mediator via gauge interaction
  - decay rates sensitive to phases

- Strategy for LFV
  - look for LFV
  - decay rates sensitive to phases
  - look for triple (spin) correlations vanish when no phases present

Production at the LHC

- Studied by different groups (see talk by del Aguila)

(Franceschini, Hambye, Strumia 07, del Aguila, Aguilar-Saavedra 08, Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanović 09)

- Drell-Yan production of triplets via gauge interactions

$$pp \to W^{\pm} \to T^{\pm} T^{0}$$
$$pp \to (Z, \gamma) \to T^{+} T^{-}$$

- Reach of 450 (700) GeV for 10 (100 fb-1) at 10 TeV through same-sign di-leptons and jets (Keung, Senjanović 83)

- Fastest decays through Yukawas (in the minimal case)

$$T^{\pm} \to Z \ell_i^{\pm} \qquad T^{0} \to Z \nu_i$$
$$T^{\pm} \to W^{\pm} \nu_i \qquad T^{0} \to W^{\pm} \ell_i^{\mp}$$

Testing the seesaw

- Invert the seesaw, use neutrino data for parametrization

$$y_T = 1/v\sqrt{m}_T O \sqrt{m}_\nu U^\dagger \qquad O^T O = 1$$

(Casas, Ibarra 01)

- Minimal cases with two mediators (Ibarra, Ross 03)
  - no overall scale uncertainty
  - a single complex angle in orthogonal O
  - correlations between Yukawa couplings related to neutrino mixing parameters
- Explicit dependence on the Majorana phase
- Non-minimal with three mediators allows more freedom

Probing CP at LHC

(Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanović 09)

- Minimal case example, normal hierarchy

$$y_T^{i*} = i\sqrt{2m_T}/v\left(U_{i2}\sqrt{m_2^\nu}\cos z \pm U_{i3}\sqrt{m_3^\nu}\sin z\right)$$

- U parametrized by $\theta_{12}, \theta_{23}, \theta_{13}, \delta, \phi$

$$\Gamma_T \approx m_T |y_T^i|^2$$

- Total lifetime

$$\tau \propto (|y_T^e|^2 + |y_T^\mu|^2 + |y_T^\tau|^2)^{-1} \approx \mathrm{mm}$$

- Branchings

$$Br_e = |y_T^e|^2/(|y_T^e|^2 + |y_T^\mu|^2 + |y_T^\tau|^2)$$

$$Br_\mu = |y_T^\mu|^2/(|y_T^e|^2 + |y_T^\mu|^2 + |y_T^\tau|^2)$$

An example

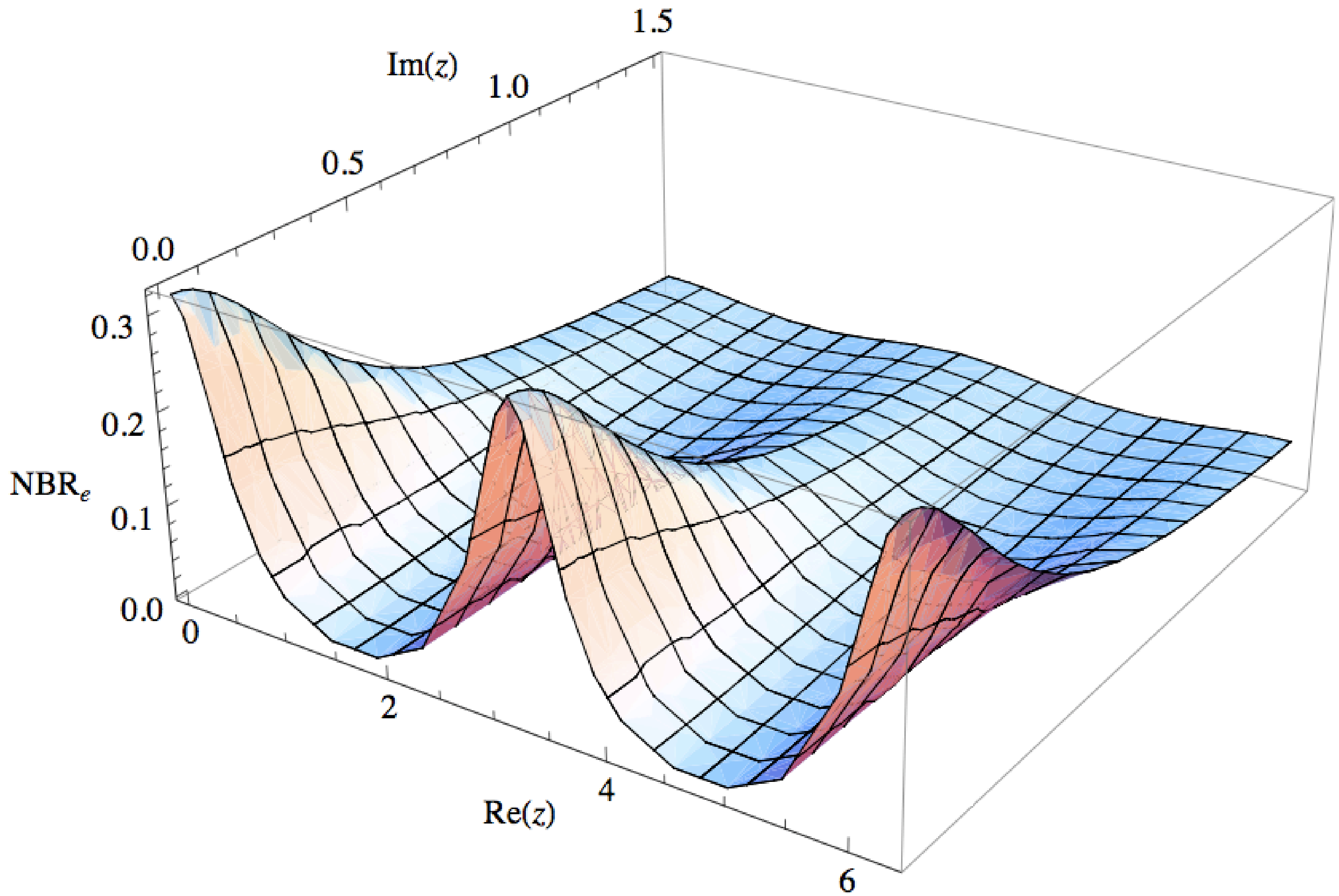
- A simplified case with normal hierarchy and

$$\theta_{13} = 0$$

- Three unknowns: Re(z), Im(z) and ϕ

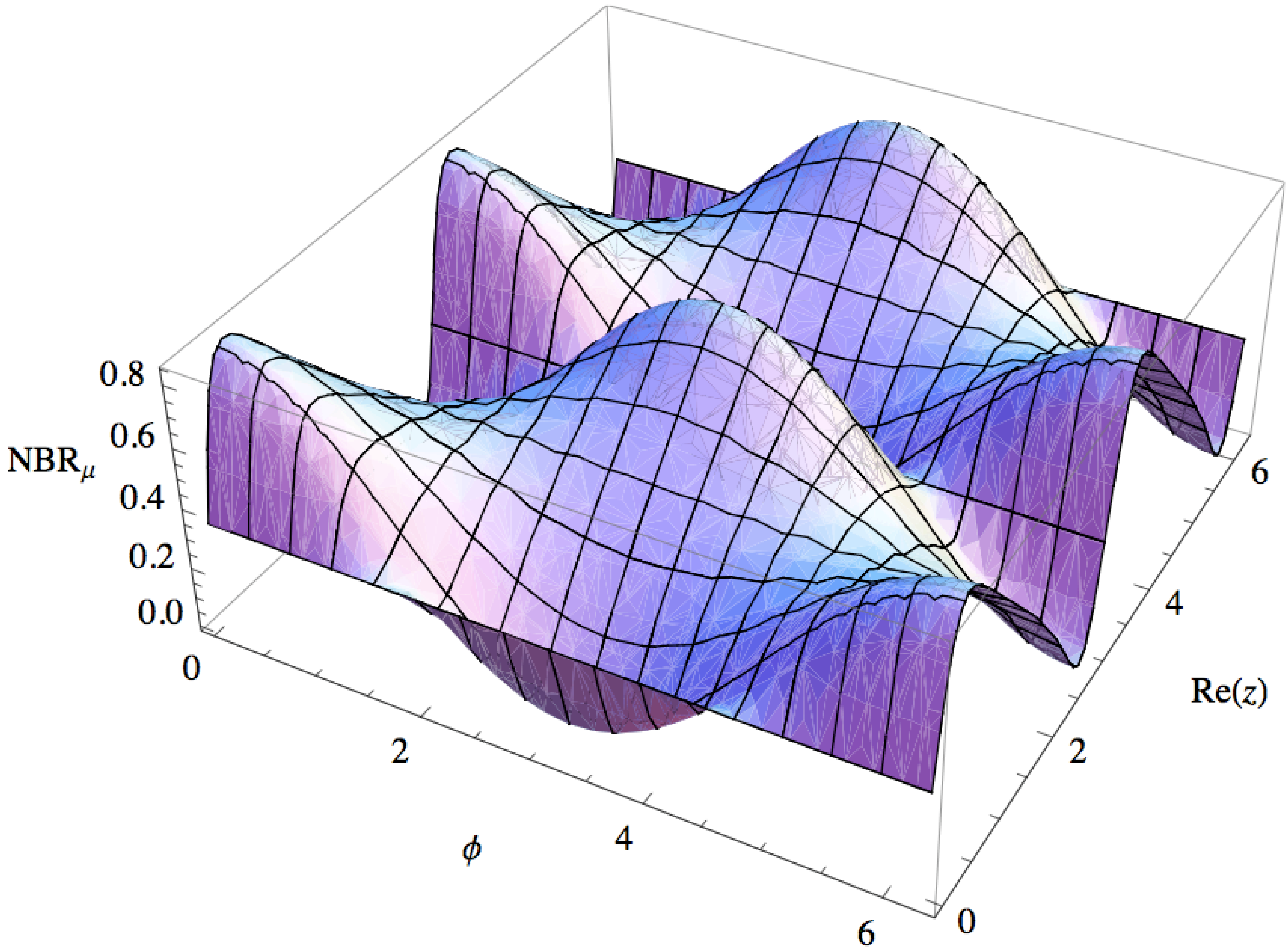
- τ and NBR_e do not depend on ϕ

- Fix Re(z) and Im(z)



Get the phase

- Once Re(z) and Im(z)fixed, only ϕ remains
- An example for Im(z) = 0



LFV and type III

- Non universality of Z couplings constrained by
  - tree-level Z $Z \to \ell_i \ell_j$
  - tree level 3 body decays $\ell_i \to \ell_j \overline{\ell_k} \ell_l$
  - tree level mu-e conversion
  - Neutral meson decays $\pi^0 \to e\mu, J/\Psi \to \ell_i \overline{\ell}_j, \ldots$
  - Semileptonic tau decays $\tau \to h^0 \ell, h^0 = \pi^0 \eta^{(\prime)}, \Phi$
- Non-unitary W couplings (LFU)
- Loop processes $\ell_i \to \ell_j \gamma$ $(g-2)_\mu$

Studies on LFV

(Antusch et al. 06, Abada et al. 07, Biggio, 08, He, Oh 09)

- Made no use of neutrino data
- Use Ibarra-Ross parametrization (Nemevšek, Kamenik 09)
  - Yukawas grow with Im(z) only
  - Correlations pinned by neutrino mixings
  - Rate sensitive to the Majorana phase
- In the limit of large Im(z), d=5 and d=6 decouple
  - fine-tuned in minimal cases, still useful because
  - tau channel is constrained
  - the singlet Yukawa, too

Mu-e conversion

- Best limit on Im(z) comes from conversion of a muon in a nucleus

- Rich physics, studied by many since '59

  (Weinberg, Feinberg 59, Czarnecki 97, Czarnecki, Marciano, Melnikov 99, Kuno, Okada 99)

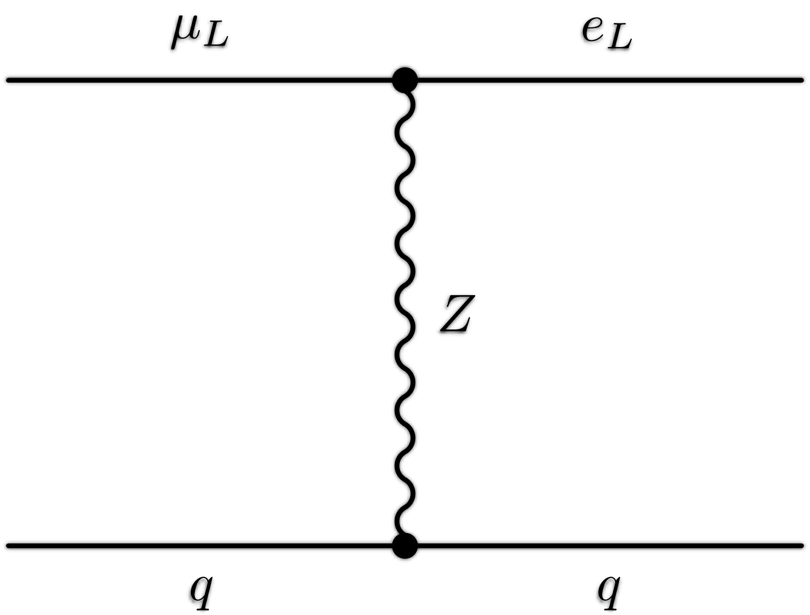
- A detailed study by (Kitano, Koike, Okada 99)

- Considered different operators from hep (Scalar, Vector, Dipole)

- Published experimental bounds by SINDRUM II

Titanium	$< 4.3 \times 10^{-12}$	(Dohmen et al. 93)
Gold	$< 7 \times 10^{-13}$	(Bertl et al. 06)

Best bound

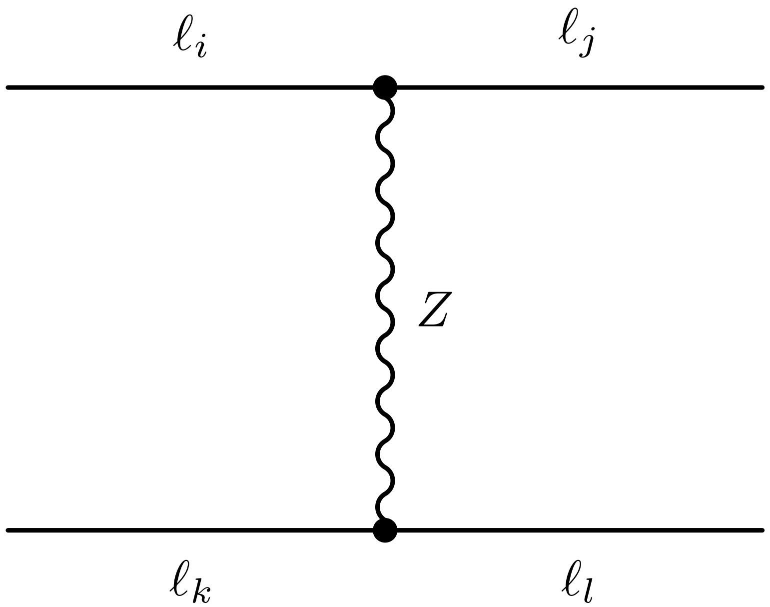


- Tree-level Z exchange $\propto |y_T^e y_T^\mu|^2$
- Vectorial coupling dominant
- Higgs contribution and loops are small

- Sets the limit on Im(z) in minimal scenarios
- Singlet and triplet at 100 GeV, Im(z)〈7.6(6.7) for normal (inverted) hierarchy
- Two triplets at 100 GeV, Im(z)〈6.4(6.1) for two triplets
- Depends on ϕ not on Re(z)
- Also singlet Yukawa small

$$y_T, y_S \lesssim 10^{-3.5}$$

Rare decays



- Tree level three body decays
- Experiment $\mathrm{Br}_{\tau-\ell} \lesssim 10^{-8}, \mathrm{Br}_{\mu-e} \lesssim 10^{-12}$
- Best tau channel

$$\Gamma_{\mu\to 3e} \propto |y_T^e y_T^\mu|^2,\ \Gamma_{\tau\to 3e} \propto |y_T^e y_T^\tau|^2,\ \Gamma_{\tau\to\mu 2e} \propto |y_T^\mu y_T^\tau|^2$$

- Radiative $\ell_i \to \ell_j \gamma$ loop calculation
  - Done in R_ξ gauge
  - Arbitrary left-right couplings
  - Arbitrary external masses
  - Divergencies and $\xi_{w,z}$ cancellations

Experiment

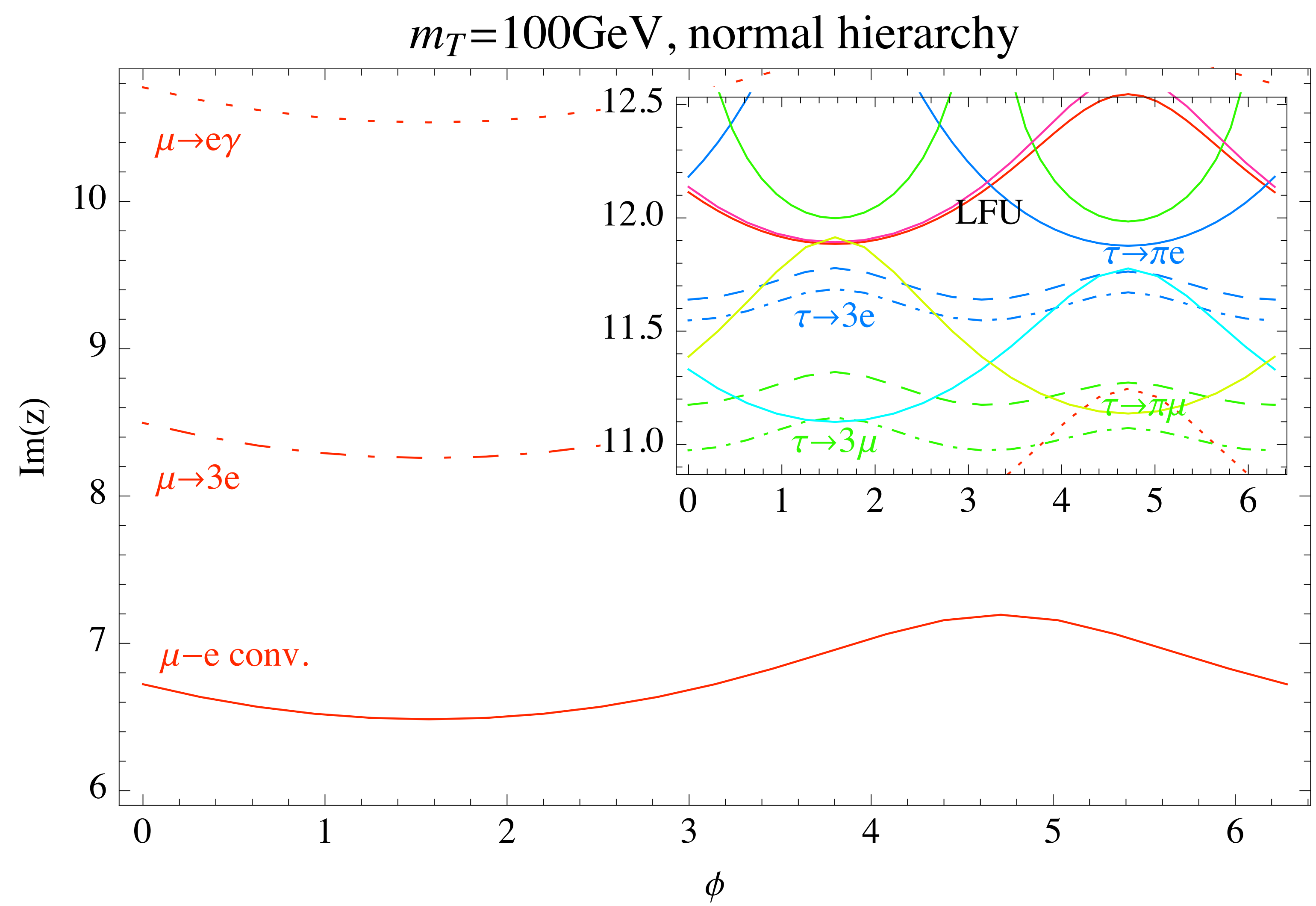
$\mathrm{Br}_{\mu\to e\gamma} < 10^{-11}$

$\mathrm{Br}_{\tau\to\ell_i\gamma} \lesssim 10^{-7}$

Summary

- Two parameters: Im(z) and ϕ

process	Im(z)
conversion	⟨7
$\mu \to 3e$	⟨8
$\mu \to e\gamma$	⟨10
$\tau \to h^0 \ell$	⟨11
$Z \to \ell_i \bar{\ell}_j$	⟨12
LFU	⟨12
$h^0 \to \ell_i \bar{\ell}_j$	⟨14



- Singlet coupling small =⟩ no production @ LHC
- No tau decays, they rule out minimal models

Beyond minimality

- Take three mediators
  - lightest neutrino may be massive, scale uncertain
  - three complex parameters in O
- Some correlations remain with Im(z)〉1 since elements of O are summed over

$$\Gamma_{\mu-e} \propto \left| \sum_{\alpha=1}^{n_T} \sum_{i,j=1}^{3} \left(\sqrt{m_i^\nu m_j^\nu / m_\alpha} O_{\alpha i} O_{\alpha j} U_{ei} U_{\mu j} \right) \right|^2$$

- Tau channel can be opened
- May loose the long-lived Yukawa-sensitive channel

$$\Gamma(T^\pm \to T^0 \pi^\pm) \simeq \frac{2 G_F^2 f_\pi^2 |V_{ud}|^2}{3\pi} \Delta m_T^3$$

Outlook

- Future sensitivity in meson and tau decays hopeless
- Improvement expected from MEG and SINDRUM

$$\mathrm{Br}_{\mu\to e\gamma}@10^{-14}$$

$$\mathrm{Br}_{\mu\to 3e}@10^{-13}$$

Limited by detector resolution

- Proposals for mu-e conversion
  - COMET (PRISM/PRIME) at J-PARC
  - Mu2e at Fermilab

$$\mathrm{Br}_{\mu\to e}@10^{-16}-10^{-18}$$

Limited by the beam

symmetrybreaking
extra dimensions of particle physics
A joint Fermilab/SLAC publication

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VIEW CURRENT ISSUE

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.

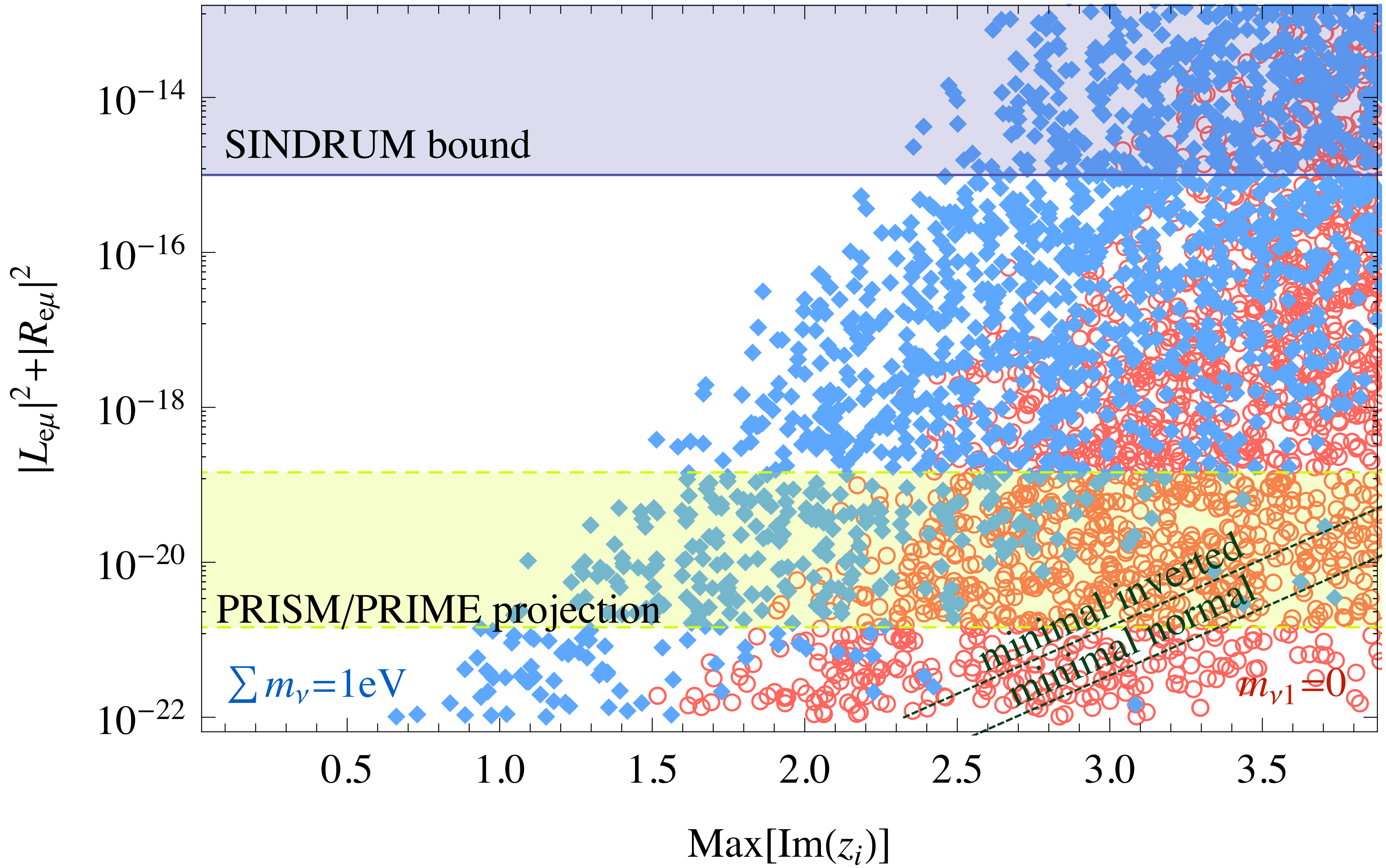
Data taking in 2017

Projections for type III

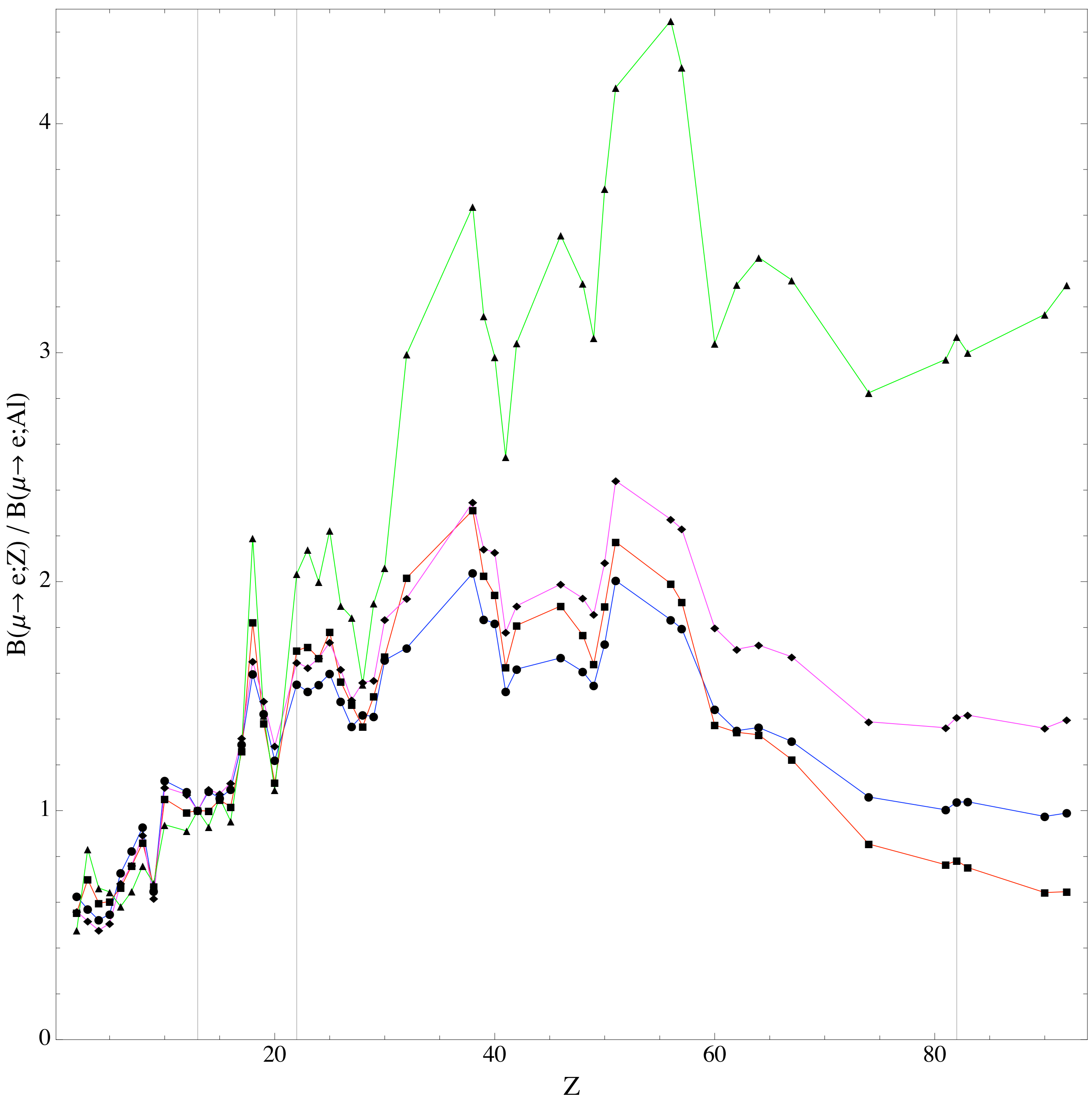
- Probes Im(z) 〈 Pi for minimal models
  - this fixes ratios of triplet decays

$$\Gamma(\tau)/\Gamma(\mu) = \tan^2\theta_{23}$$

- Im(z)〈1 for non-minimal model



Additional info on mediators



- Conversion rate nucleus dependent

(Kitano, Koike, Okada 99)

- One mediator hypothesis
  - 5% for two light-light
  - 20% for two heavy-light

(Cirigliano, Kitano, Okada, Tuzon 09)

- Type III = single vector dominance

- D - blue, S - red, V(gamma) - magenta, V(Z) - green

CP phases in LFV

- Polarized muons give information on CP phases
  - studied recently by (Ayazi, Farzan 08, Davidson 09)
- Form triple spin correlations $(\vec{s}_\mu \times \vec{s}_e) . \vec{p}_e$
- Transverse polarization of the outgoing electron sensitive to CP phases
- Taking an effective Lagrangian

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

- leads to an transverse electron polarization proportional to

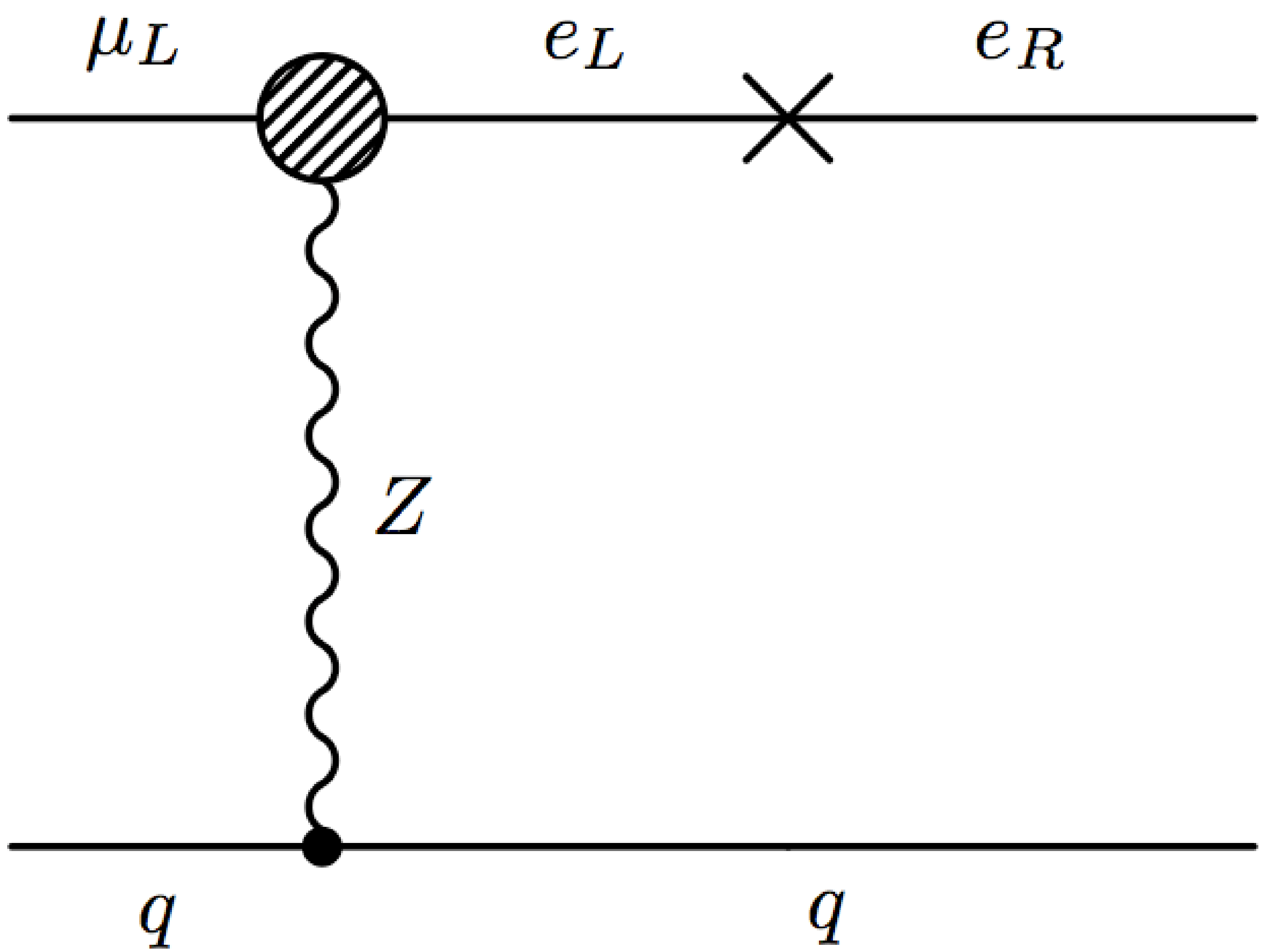
$$\delta_{CP} = \frac{\text{Im}(A_L^* A_R)}{|A_L|^2 + |A_R|^2}$$

The case of seesaw

(Bajc, Nemevšek, Senjanović 09)

- All scenarios contain only left-handed charged leptons
  - type I and/or III $\overline{L} H F_{\rm new}$
  - type II $\overline{L} \Delta L$
- Type I requires fine-tuning
- Type II and III not necessarily
- But how to get A_R?

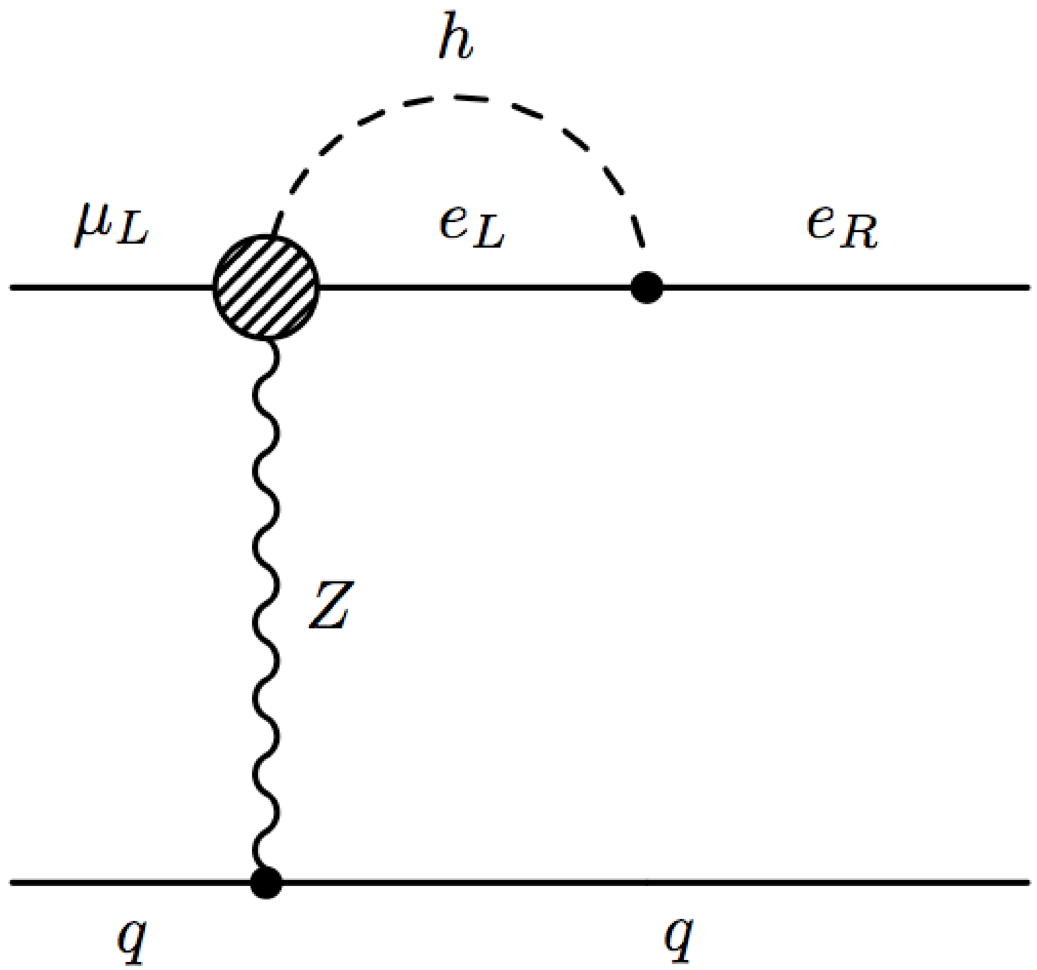
a) Do the mass insertion



- a suppression of
- no change of complexity

$$A_R = \frac{m_e}{m_\mu} A_L$$
$$\delta_{CP} \propto \mathrm{Im}(|A_L|^2) = 0$$

b) Do the Higgs loop.



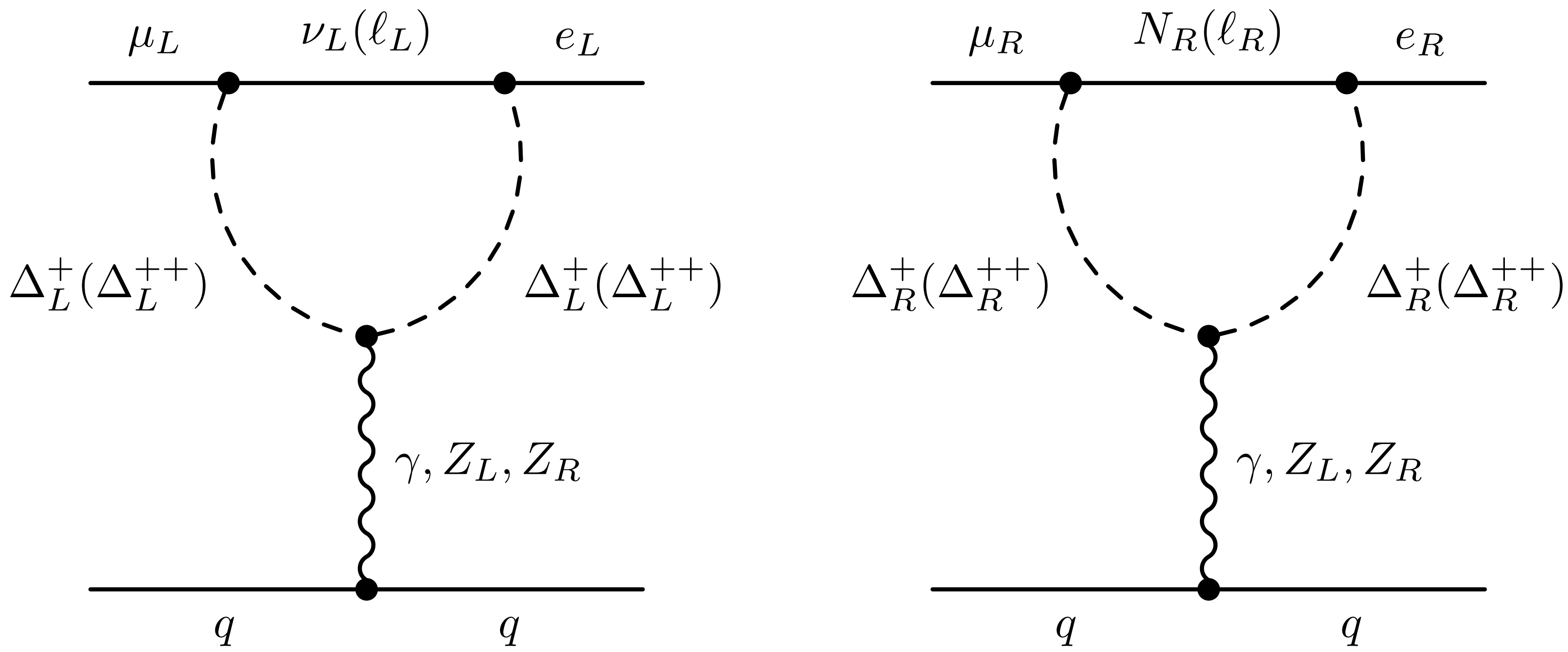
- estimate a suppression of $\delta_{CP} = \frac{\alpha}{\pi} \frac{m_e}{m_W} \approx 10^{-7}$
- hopeless, even for $\text{Br}_{\mu \to e} \simeq 10^{-18}$
- valid for all seesaw types

Left-right and LFV

- Introduce an interaction (see talk by Nesti)
- Consider the minimal model $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$$\Phi(2,2,0), \quad \Delta_L(3,1,2), \quad \Delta_R(1,3,2)$$

- A_L comes from the Δ_L and W_L
- A_R comes from the Δ_R and W_R



Phases in L-R

- But the model is left-right symmetric! Why $\delta_{CP} \neq 0$?
- While deltas are similar

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

- There is no symmetry in W loops

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

- Unless some cancellations occur

$$\delta_{CP} \neq 0$$

Conclusions LHC

- A minimal extension of SU(5) predicts a light triplet
  - bounded by proton decay
  - the reach of LHC to 700 GeV
- Decay rates and branching ratios
  - constrain unknown parameters
  - can determine the phase

Conclusions LFV

- LFV constraints useful for minimal models
  - no tau decays
  - no singlet production
- Muon conversion exciting
  - a handle on the CP phases
  - no-go for any seesaw
  - very interesting for L-R

Thank you

Backup slides

Feynman rules

$$f_i = \left(e, \mu, \tau, T^-\right),\ f'_i = \left(\nu_e, \nu_\mu, \nu_\tau, T^0, S\right)$$

$$\mathcal{L}_{int} = -e\,\overline{f}_i \not{A} f_i + g/c_w\,\overline{f}_i \not{Z} (L^Z P_L + R^Z P_R)_{ij} f_j +$$
$$g\,\overline{f}'_i \not{W}^+ (L^W P_L + R^W P_R)_{ij} f_j + \text{h.c.}$$

- General expressions for type I + III

$$L^W_{ij} = U^{0*}_{\alpha i} U^-_{\alpha j}/\sqrt{2} + U^{0*}_{\beta i} U^-_{\beta j}$$
$$R^W_{ij} = U^0_{\beta i} U^+_{\beta j}$$
$$L^Z_{ij} = (s_w^2 - 1/2) U^{-*}_{\alpha i} U^-_{\alpha j} - c_w^2 U^{-*}_{\beta i} U^-_{\beta j}$$
$$R^Z_{ij} = s_w^2 U^{+*}_{\alpha i} U^+_{\alpha j} - c_w^2 U^{+*}_{\beta i} U^+_{\beta j}$$

- Exact relations help understand loops

$$\left(L^{W\dagger} L^W\right)_{ij} = -L^Z_{ij}, \quad i \neq j$$