Effective operators in neutrino physics

A bottom-up approach to new physics

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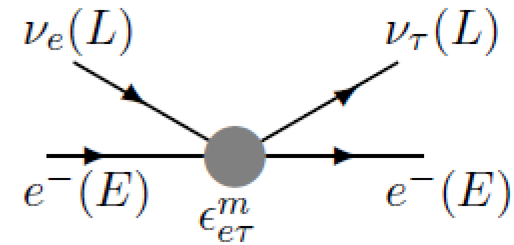
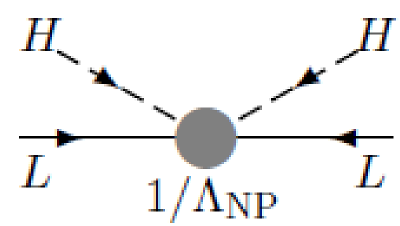
Outline

1 Non-standard neutrino interactions



- Motivations for NSI
- NSI in oscillation experiments
- Models of NSI with a bottom-up approach

2 Neutrino mass from *d>5* effective operators

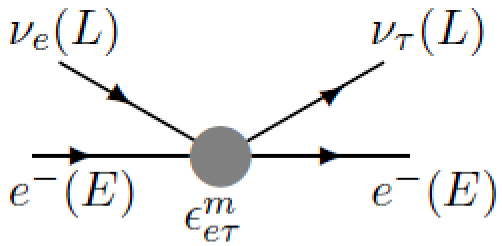


- Motivation
- Setup at the low energy scale
- Possible high energy completion
  — Bottom-up to the high energy scale

3 Summary

1 Non-standard neutrino interactions

- Motivations for NSI
- NSI in oscillation experiments
- Models of NSI with a bottom-up approach



Effective operators —— Common feature of effective theories

If the SM is an effective theory, Lagrangian at the low energy scale looks

$$\mathscr{L}_{\mathrm{eff}} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda_{\mathrm{NP}}}\mathcal{O}^{d=5} + \frac{1}{\Lambda_{\mathrm{NP}}^2}\mathcal{O}^{d=6} + \frac{1}{\Lambda_{\mathrm{NP}}^3}\mathcal{O}^{d=7} + \cdots$$

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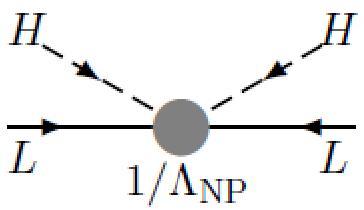
- **Dim.5**: Weinberg op. (Majorona neutrino mass) Weinberg (1979)

$$\mathcal{O}^{d=5} = (\overline{L^c} i\tau^2 H)(H^{\mathsf{T}} i\tau^2 L)$$
$$\to v\frac{v}{\Lambda_{\text{NP}}}\overline{\nu^c}\nu,$$



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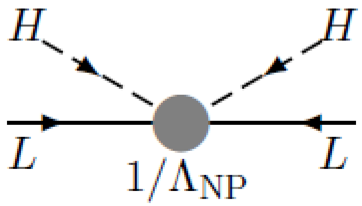
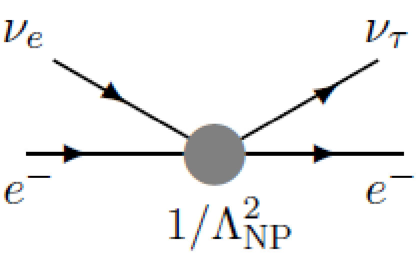


- **Dim.6**: Four-Fermi ops. For a complete list of Dim.6 ops, Buchmuller Wyler (1986)

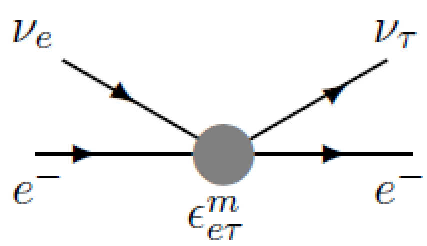
$$\mathcal{O}^{d=6} = (\bar{L}\gamma^{\rho}\mathrm{P}_L L)(\bar{E}\gamma_{\rho}\mathrm{P}_R E)$$

Non-Standard neutrino Interactions (NSI)



Effective ops. are a typical remnant of New Physics at high energy scales

Oscillation enhanced search for new physics



NSI

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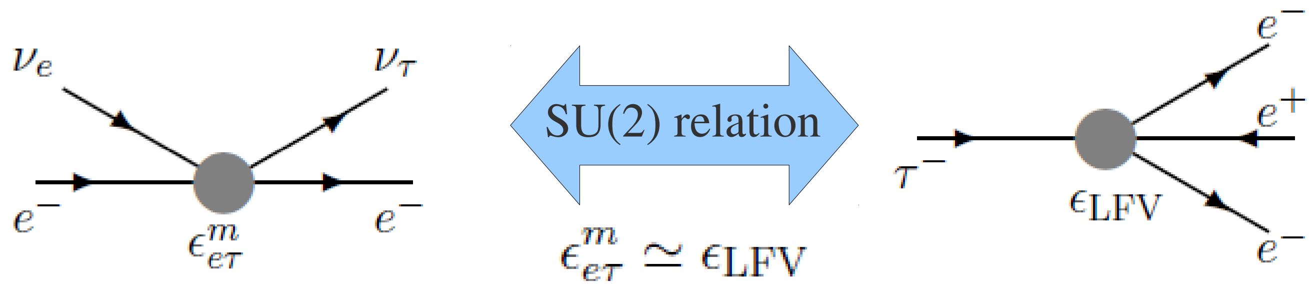

NSI — Charged lepton counter part

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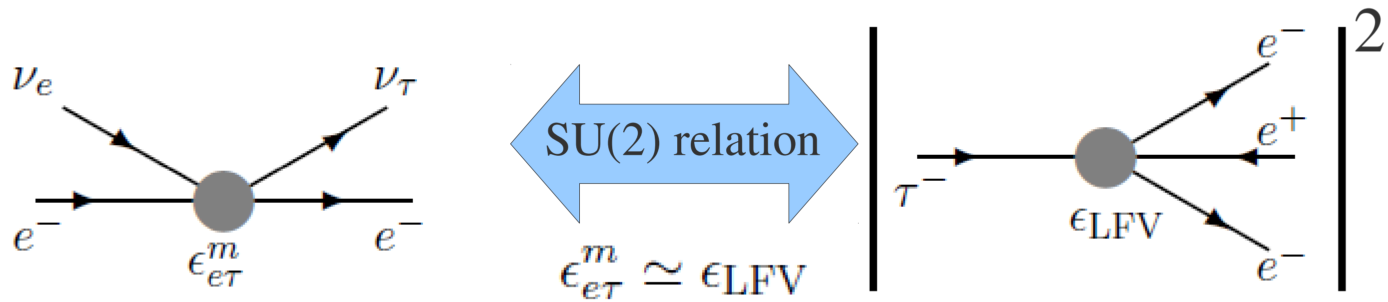

NSI

Charged lepton counter part

$$\mathrm{Br}(\tau \to 3e) = |\epsilon_{\rm LFV}|^2 < \mathcal{O}(10^{-8})$$

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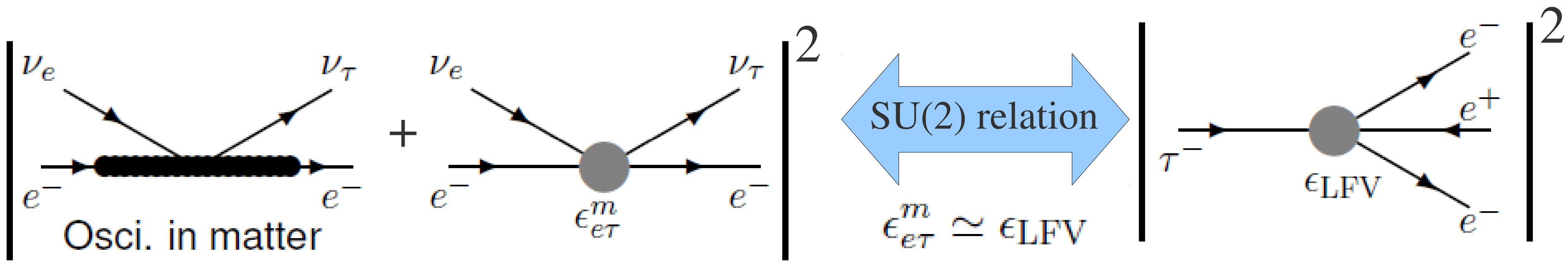


Standard Oscillation (SO) NSI Charged lepton counter part

$$P^{\text{SO}}_{\nu_e \to \nu_\tau} + \mathcal{O}(\epsilon^m_{e\tau})$$

NSI signal gets

Oscillation enhancement

(Interference between SO and NSI)

$$\text{Br}(\tau \to 3e) = |\epsilon_{\text{LFV}}|^2$$

$$< \mathcal{O}(10^{-8})$$

$$|\epsilon^m_{e\tau}| < \mathcal{O}(10^{-4})$$

Advantage against cLFV search:

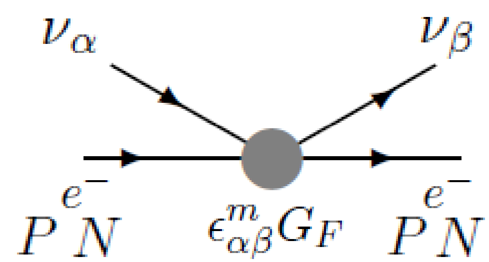
NSI signal in osc. appears at $\mathcal{O}(\epsilon)$ through the interference with SO.

On the other hand, LFV signal begins at $\mathcal{O}(\epsilon^2)$

Direct constraints to NSI

- NSI in propagation Biggio Blennow Fernandez-Martinez JHEP **0908** (2009) 090

$$|\epsilon^m_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}$$



NSI are not strictly constrained

Especially, tau-associated NSI can take a value of *O*(1).

although it is difficult to induce such a large NSI from high energy models

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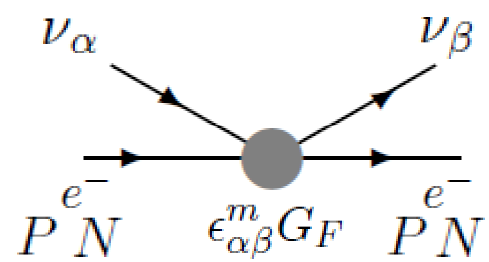

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3+1 Motivations for NSI

- Typical low-energy remnant of New Physics at high energy scale
- Oscillation enhancement (advantage against cLFV search)
- Only loosely constrained → Experimental test is awaited

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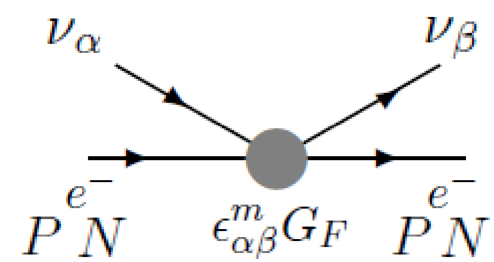

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Now, we have a chance to test them at high precision neutrino osci. exps!

NSI signals at neutrino oscillation experiments

- Standard oscillation

$$P_{\nu_\alpha \to \nu_\beta} = |\langle \nu_\beta | \mathrm{e}^{-\mathrm{i}HL} | \nu_\alpha \rangle|^2$$

Modified by NSI (and NU)
NU: NSIs with particular relations

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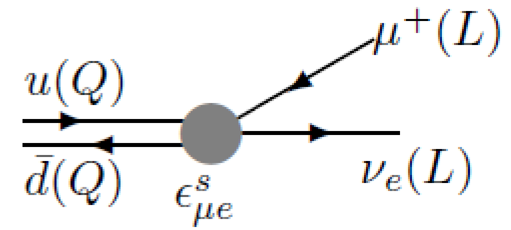
Modified by NSI (and NU)
NU: NSIs with particular relations

- CC type NSI — flavour mixture states at source and detection
Grossman PLB359 (1995) 141.

$$P_{\nu_\alpha \to \nu_\beta} = \left| \langle \nu^d_\beta | \mathrm{e}^{-\mathrm{i}HL} | \nu^s_\alpha \rangle \right|^2$$

$$|\nu^s_\alpha\rangle = |\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \epsilon^s_{\alpha\gamma} |\nu_\gamma\rangle, \qquad \text{e.g., } \pi^+ \xrightarrow{\epsilon^s_{\mu e}} \mu^+ \nu_e$$

$$\langle\nu^d_\alpha| = \langle\nu_\alpha| + \sum_{\gamma=e,\mu,\tau} \epsilon^d_{\gamma\alpha} \langle\nu_\gamma|, \qquad \text{e.g., } \nu_\tau N \xrightarrow{\epsilon^d_{\tau e}} e^- X$$



at source in superbeam exp.

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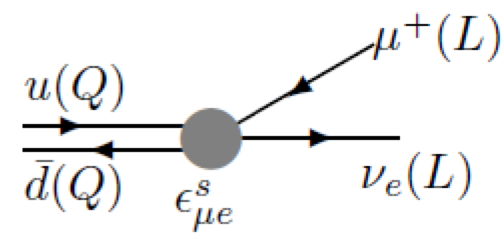


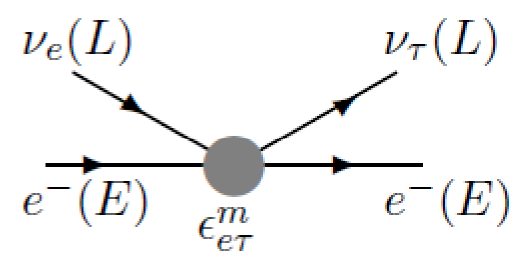
at source in superbeam exp.

- NC type NSI — extra matter effect in propagation
  e.g., Wolfenstein PRD17 (1978) 2369. Valle PLB199 (1987) 432. Guzzo Masiero Petcov PLB260 (1991) 154. Roulet PRD44 (1991) R935.

$$P_{\nu_\alpha \to \nu_\beta} = \left| \langle \nu_\beta | e^{-i(H+V_{\rm NSI})L} | \nu_\alpha \rangle \right|^2$$

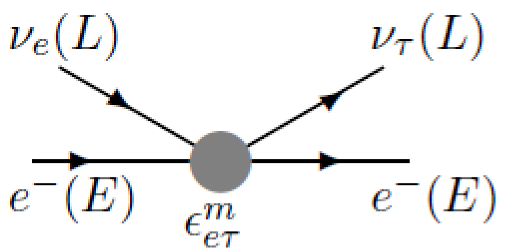
$$(V_{\rm NSI})_{\beta\alpha} = \sqrt{2} G_F N_e \begin{pmatrix} \epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix},$$

e.g., $\nu_e \xrightarrow{\epsilon^m_{e\tau}} \nu_\tau$ in propagation



extra matter effect

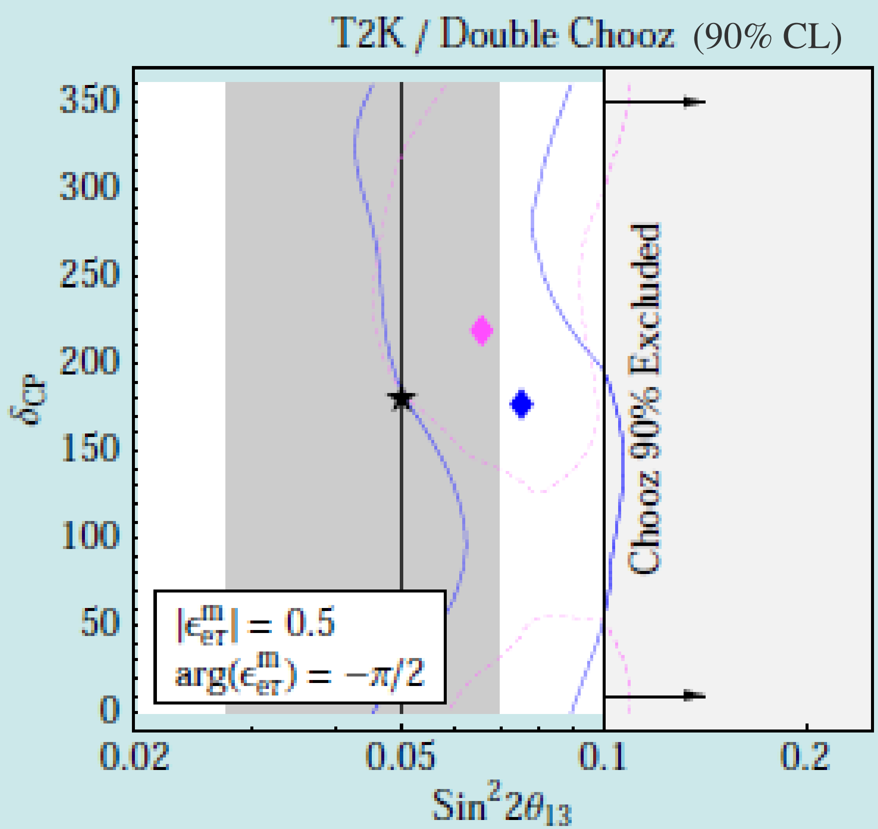
1. **Non-standard neutrino interactions**
   - Motivations for NSI
   - NSI in oscillation experiments
   - Models of NSI with a bottom-up approach



θ_{13} *search at reactor and superbeam*

ϵ^m (NSI in matter) affects only accelerator experiments
→ causes a **mismatch** between accelerator and reactor exps.

An example for Mismatch



SO params: $\sin^2 2\theta_{13}^{\text{true}} = 0.05$

$\delta_{CP}^{\text{true}} = \pi$

+ NSI: $\epsilon^m_{e\tau} = 0.5 e^{-i\pi/2}$

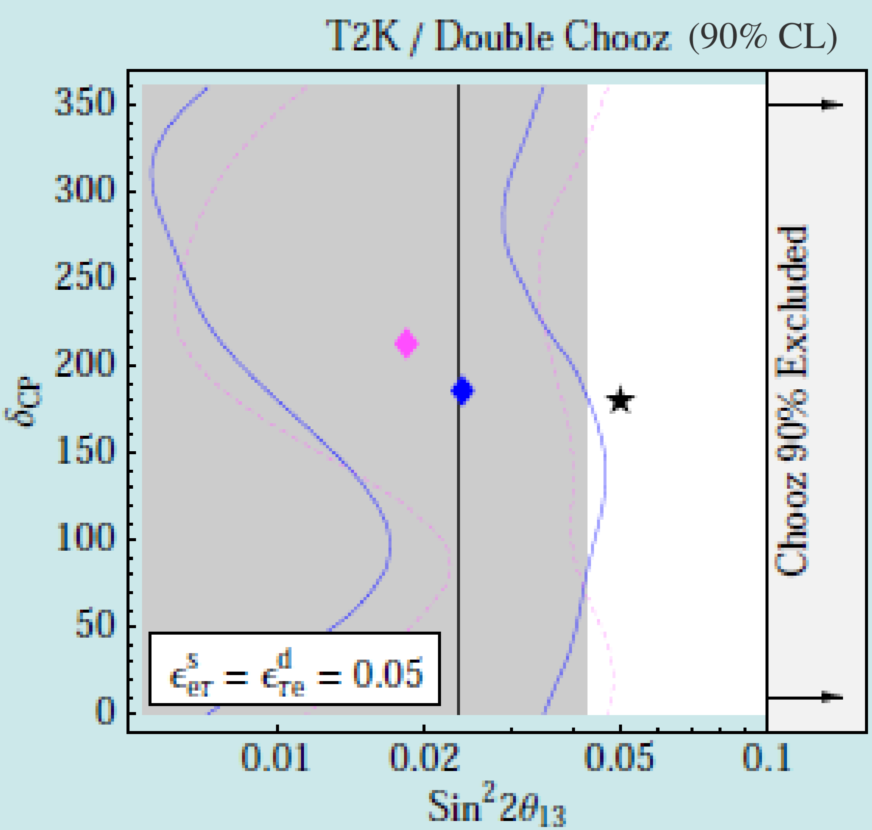
The best-fit point of **accelerator exp.** is excluded by **reactor exp**.

Kopp Lindner O Sato PRD77 (2008) 013007

θ_{13} *search at reactor and superbeam*

ϵ^s, ϵ^d (NSI at source and detection) give an impact on both experiments
→ can make a **common off-set** of two exps. from true value

An example for Common Off-set



SO params: $\sin^2 2\theta_{13}^{\text{true}} = 0.05$

$\delta_{\rm CP}^{\text{true}} = \pi$

+ NSI: $\epsilon^s_{e\tau} = \epsilon^d_{\tau e} = 0.05$

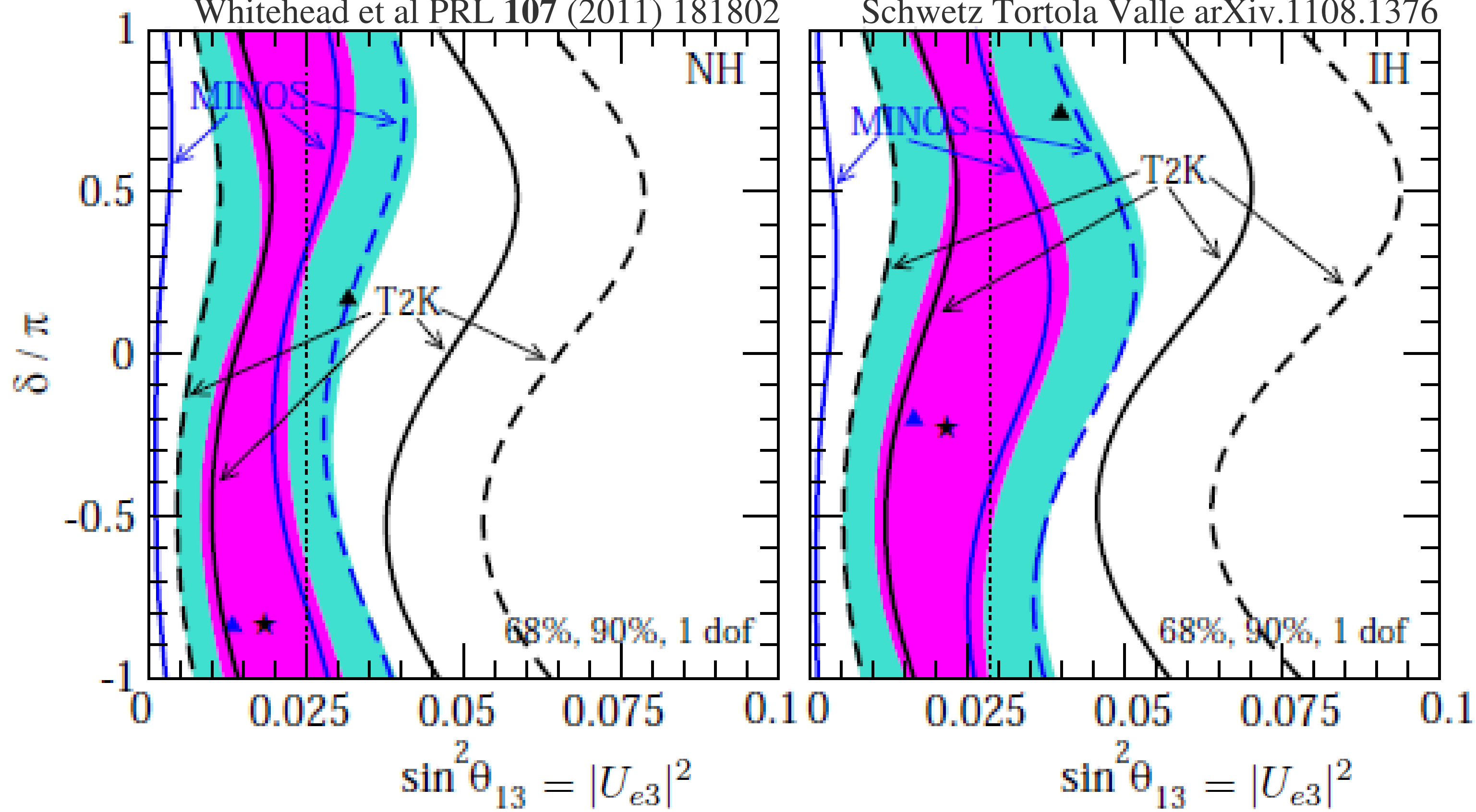
Accelerator exp. is consistent with **reactor exp.**, but the both suggest a wrong value of θ_{13}

Kopp Lindner O Sato PRD77 (2008) 013007

Current status of θ_{13} search at T2K, MINOS, and D-Chooz

Abe et al PRL **107** (2011) 041801
Whitehead et al PRL **107** (2011) 181802

Schwetz Tortola Valle arXiv.1108.1376



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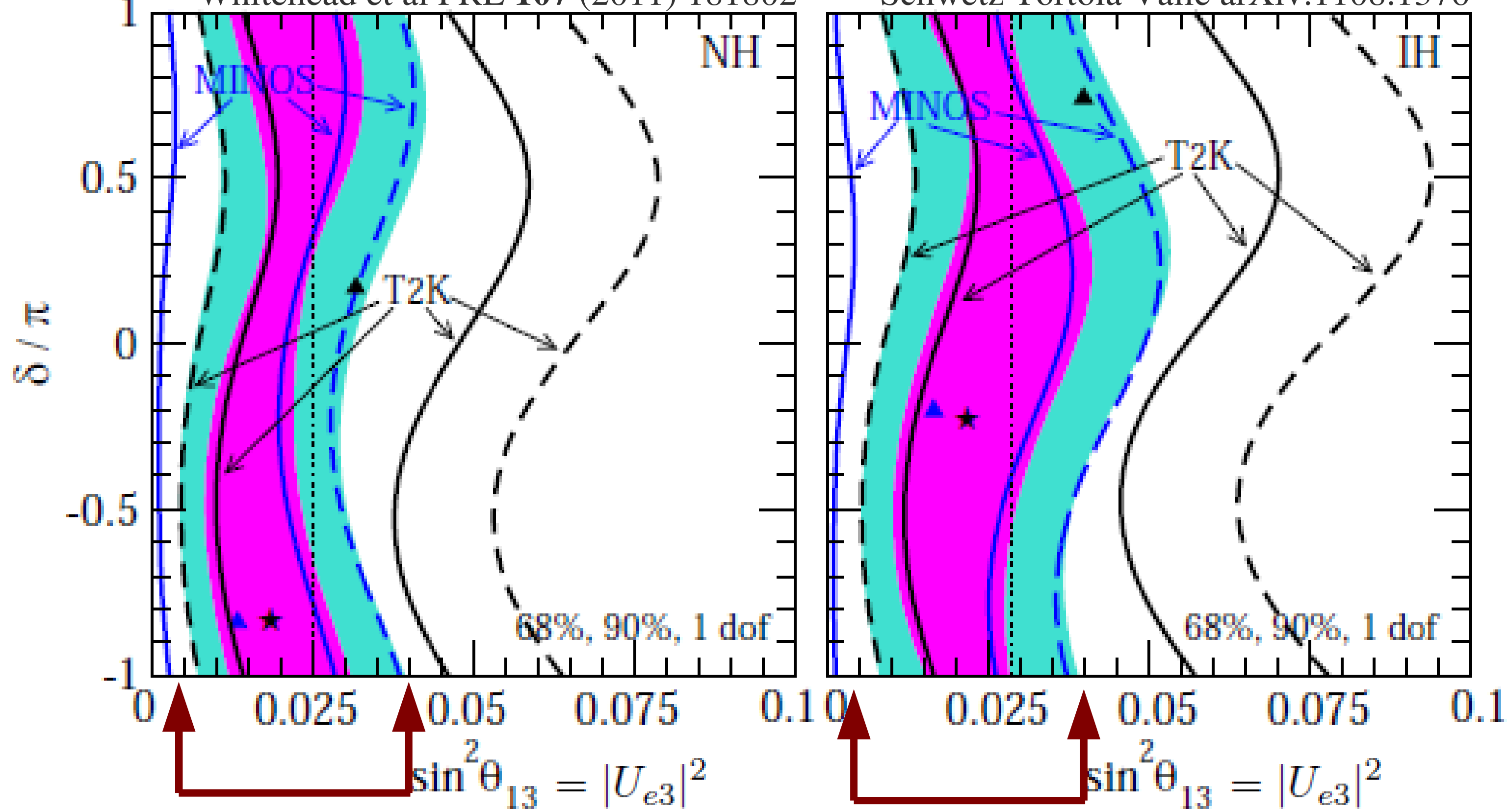


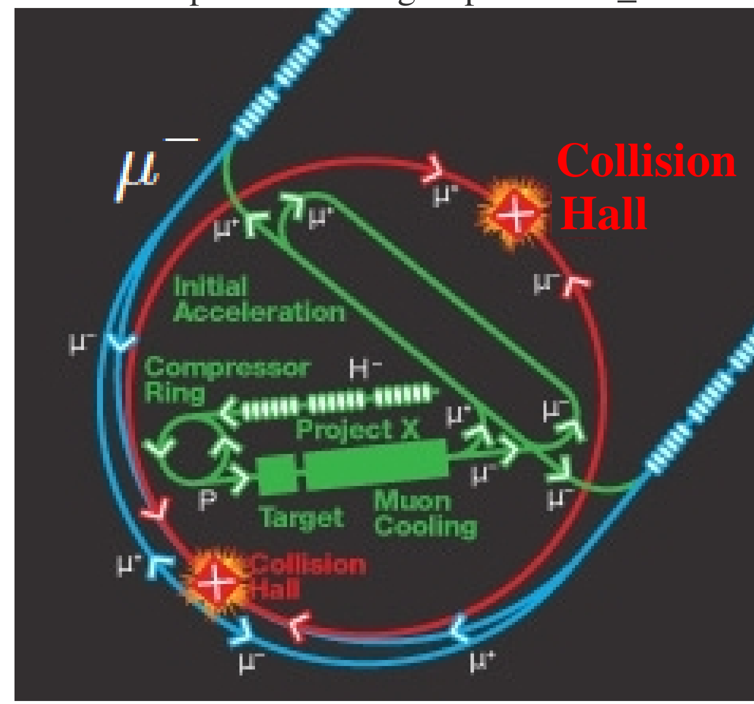
Double Chooz 1st result: $0.004 < \sin^2\theta_{13}^{\mathrm{DC}} < 0.04$ at 90%CL
Abe et al arXiv.1112.6353

Current results are perfectly consistent with each other in 1 sigma
No NSI? Common off-set? Important message: They are not redundant!

Sensitivity to NSI at an ultimate machine —— Neutrino factory

On the way from Project X to Muon collider

http://www.fnal.gov/pub/muon_collider/



Sensitivity to NSI at an ultimate machine —— *Neutrino factory*

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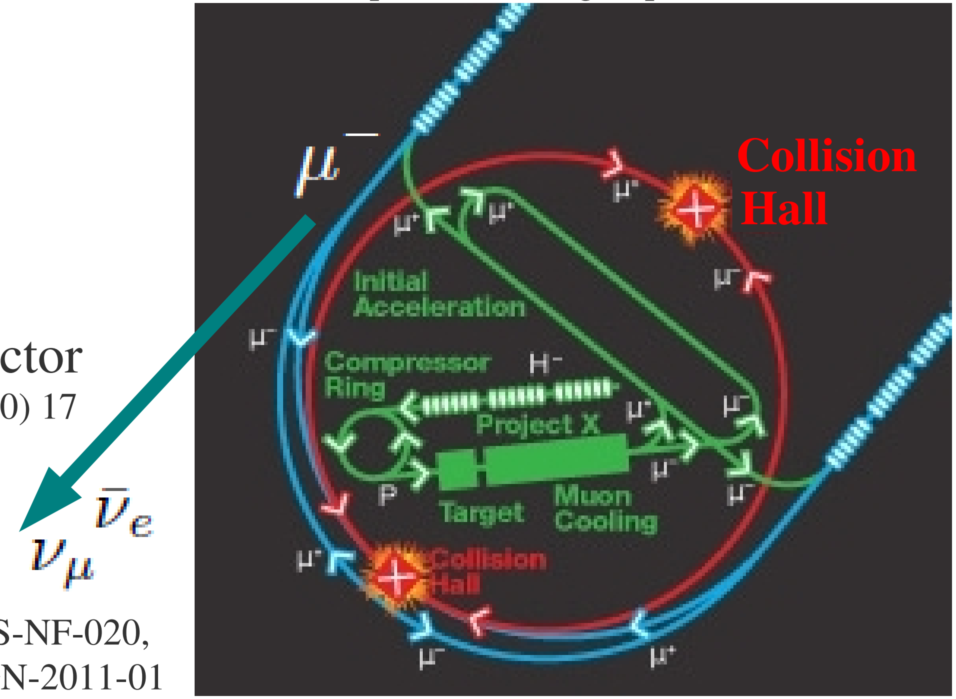
- Neutrino beam based on muon storage ring
- High energy & high intensity & low BG
- Long baseline with massive detectors
- ***Physics motivation:***
  Golden measurement of CP phase in lepton sector
  e.g., Cervera et al NP**B579** (2000) 17

$$\nu_e \to \nu_\mu \quad \text{vs} \quad \bar{\nu}_e \to \bar{\nu}_\mu$$



More on Nufact: Design report, arXiv:1112.2853, IDS-NF-020, FERMILAB-PUB-11-581-APC, FERMILAB-DESIGN-2011-01

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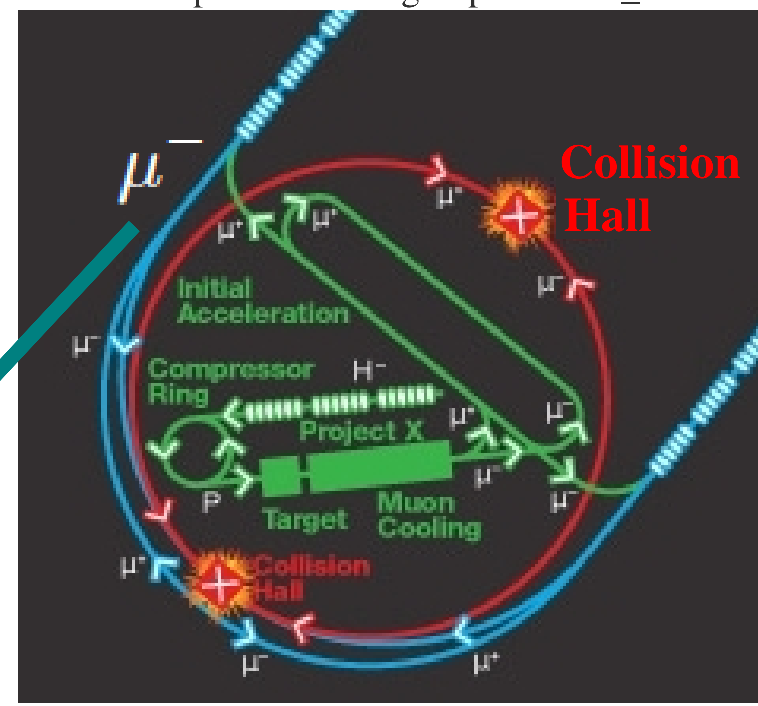
$\bar{\nu}_e$ ν_μ



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There are many questions for Nufact...

How sensitive Neutrino factory to NSI?
Current optimal setup for SO is good for NSI? What is the optimal setup for NSI?

How robust SO results against the disturbance by NSI?
Is the current optimal experimental setup for SO changed?

How can we distinguish the SO and NSI signal?
SO is background for NSI signal

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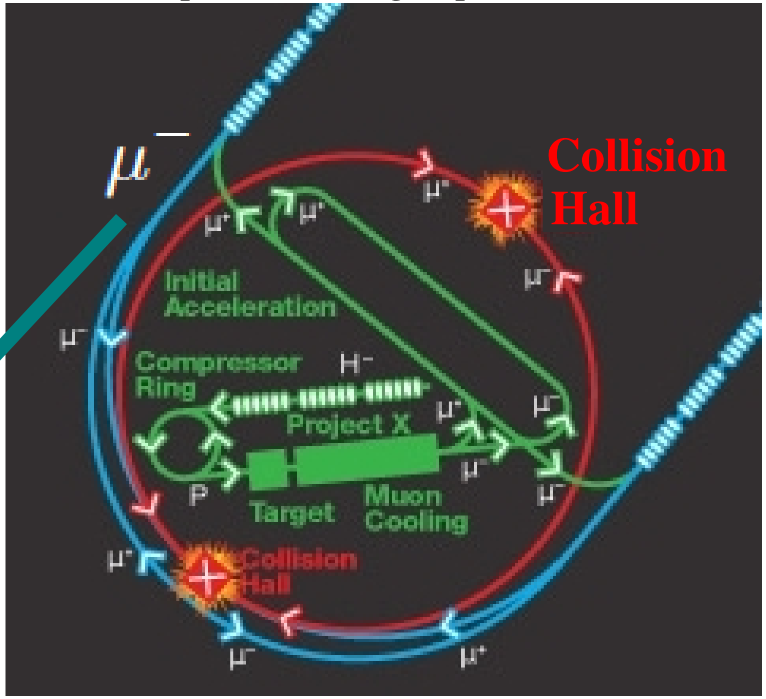

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In the next few slides, we will address

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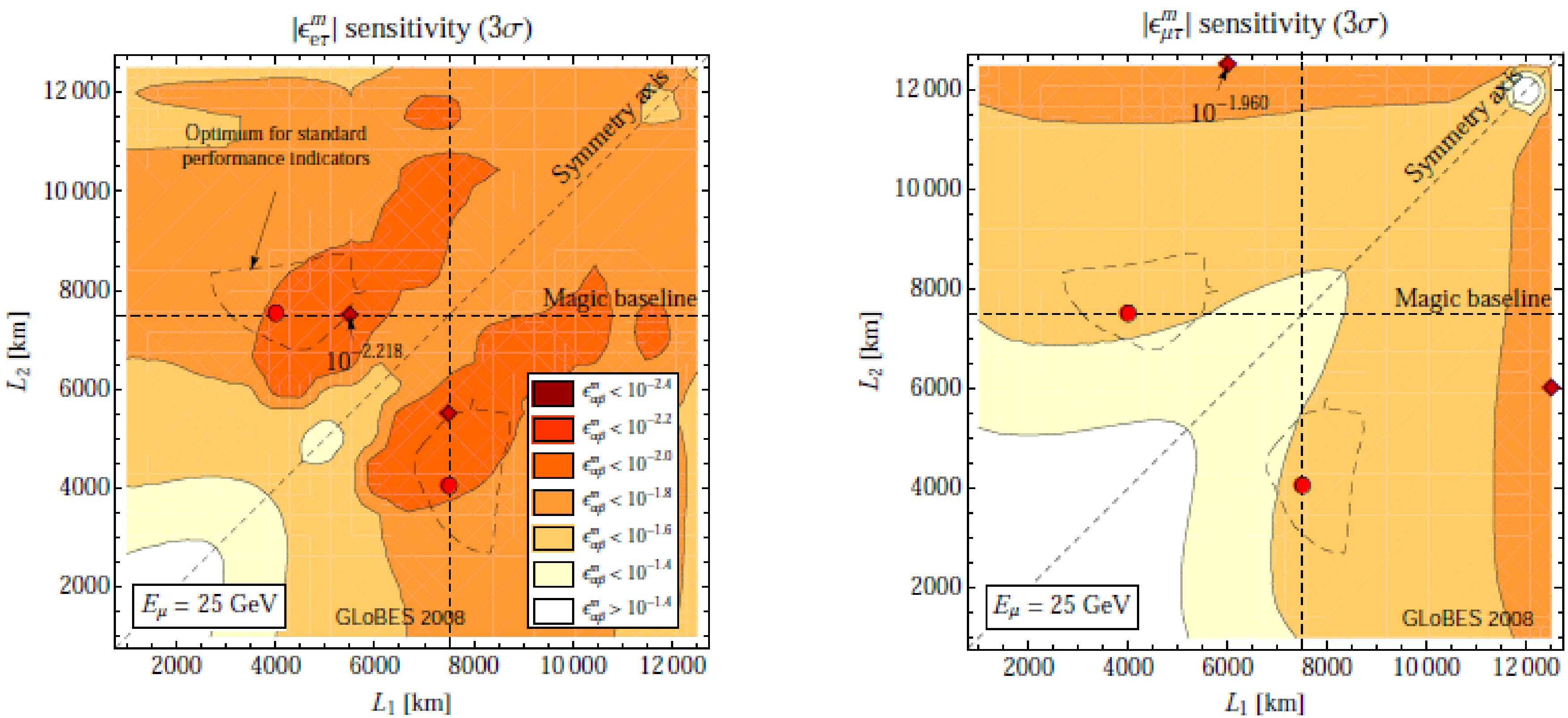
Optimization for NSI search in a neutrino factory

Kopp O Winter PRD**78** (2008) 053007

- Arrangement of two detectors (MINDs)



NSI signal is distinguished from SO signal by its energy dependence

For parameter correlations with NSI, Ribeiro et al JHEP **0712** (2007) 002
Coloma et al JHEP **1108** (2011) 036

Current IDS-NF setup is also good for NSI search

Optimization for NSI search in a neutrino factory

Kopp O Winter PRD**78** (2008) 053007

Current setup (IDS-NF)

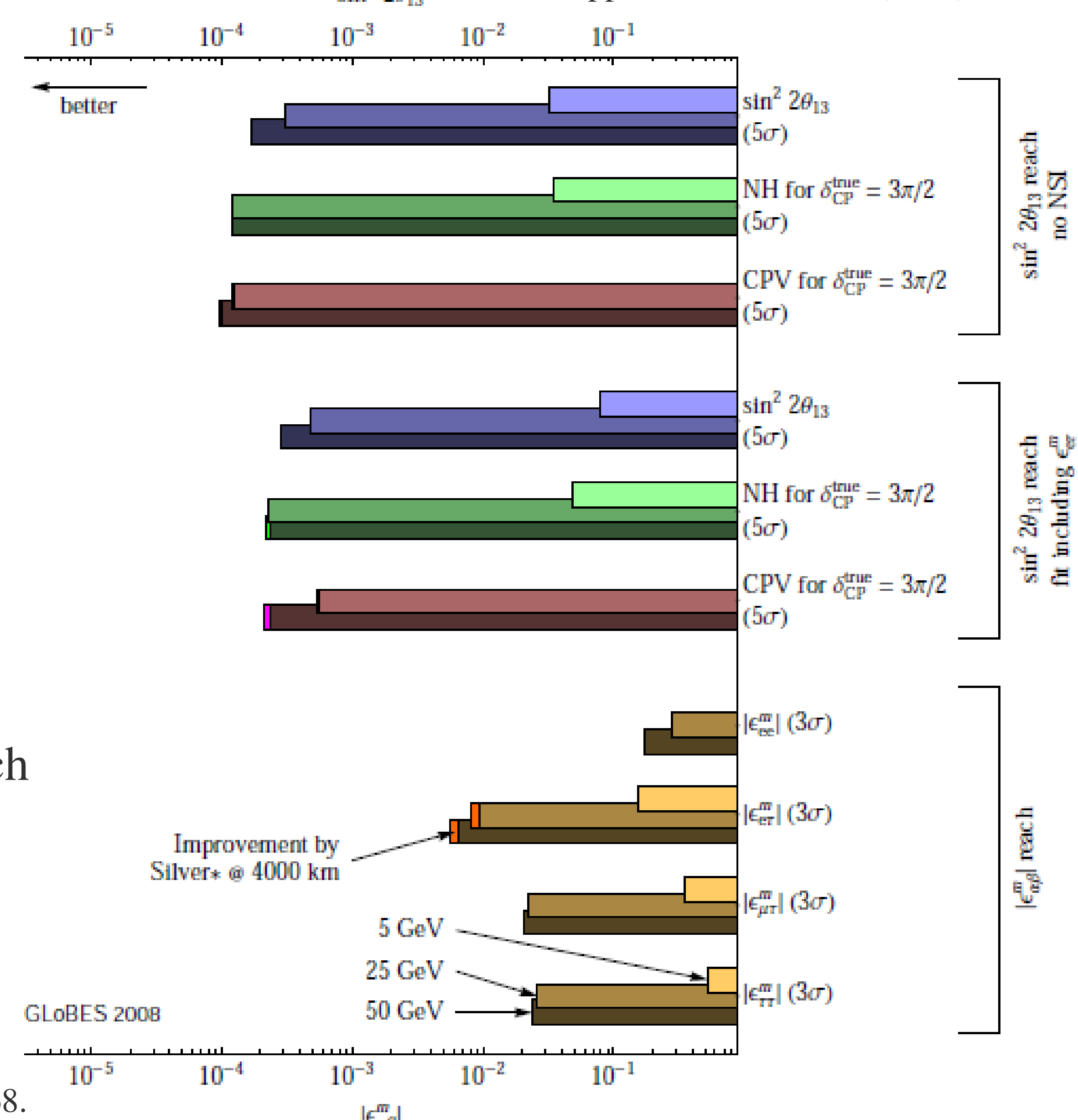
- Muon energy 25 GeV
- 2 MINDs (50kt each)
  @L=4000 km and 7500 km

  No tau detector

- Robust SO search against NSI
- NSI sensitivity: $|\epsilon^m_{\alpha\tau}| < \mathcal{O}(10^{-3})$

- Near tau detector for source NSI search
  ***MINSIS* proposal** Para
  http://www-off-axis-fnal.gov/MINSIS/index.html

Summary of MINSIS workshop arXiv:1009.0476
For Physics cases, Antusch et al JHEP **1006** (2010) 068.



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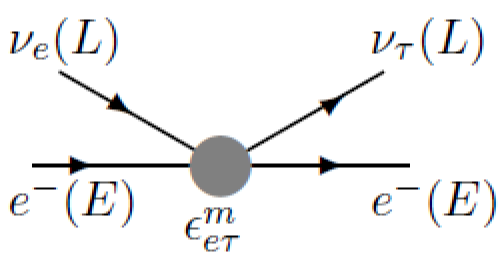
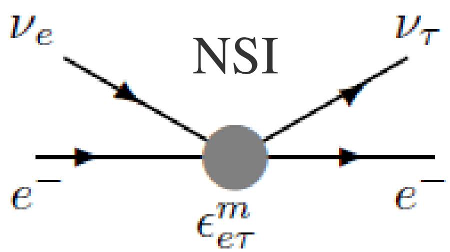


Gauge invariance in NSI

e.g., Bergmann Grossman Pierce PR**D61** (2000) 053005

Dim.6 (4-Fermi) —— Bound from SU(2) counter process



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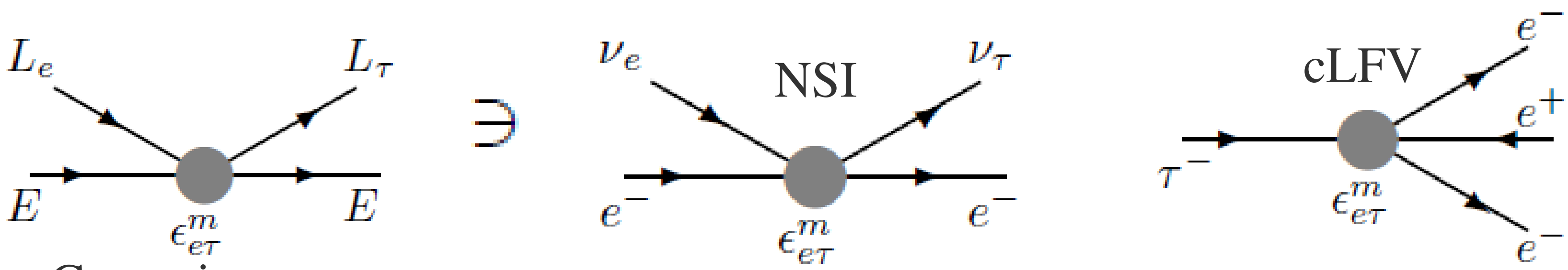

Gauge inv. op

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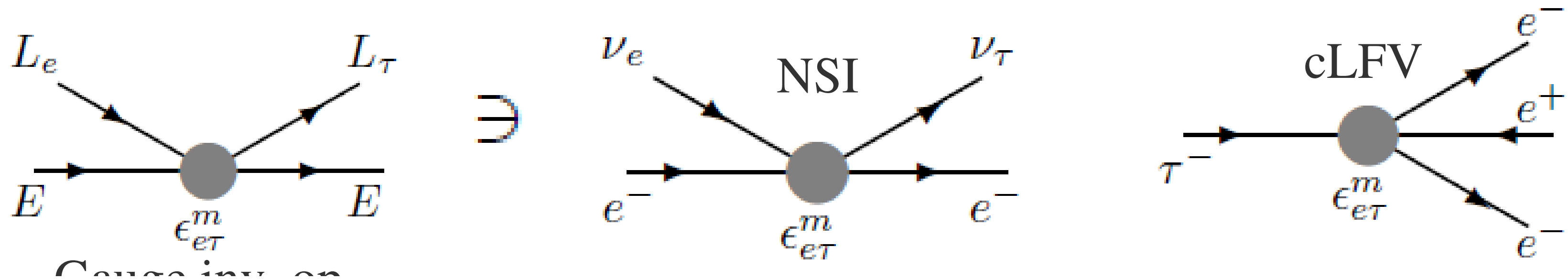
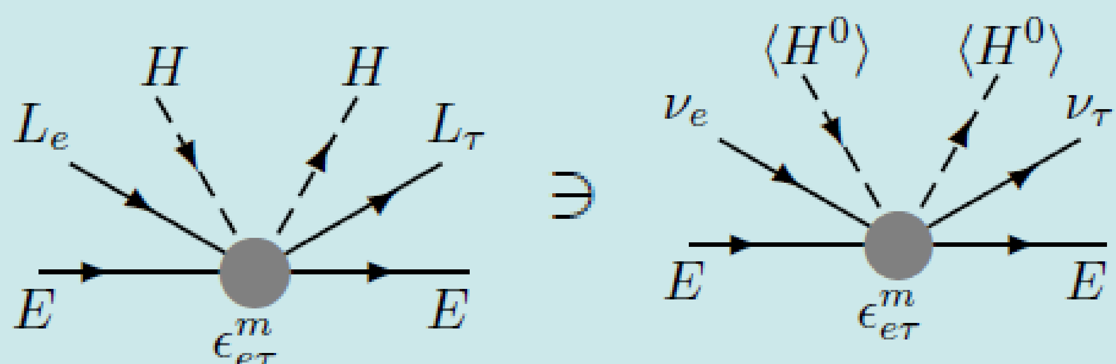


Dim.8 op. with Higgs doublets

Berezhiani Rossi PL**B535** (2002) 207, Davidson Pena-Garay Rius Santamaria JHEP **0303** (2003) 011



$$\frac{1}{\Lambda^4}\left[(\bar{L}^\tau i\tau^2 H)\gamma^\rho (H^\dagger i\tau^2 L_e)\right][\bar{E}\gamma_\rho E]$$

4-Fermi NSI

+ No 4-Fermi cLFV

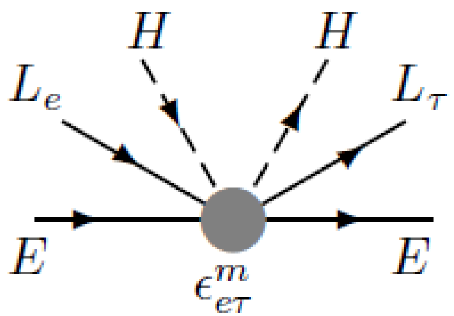
Evasion from SU(2) counter process

How does a high *E* model of Dim.8 NSI look like?

Can we really obtain constraint-free NSI through Dim.8 op?

Bottom-up approach ——— Operator decomposition

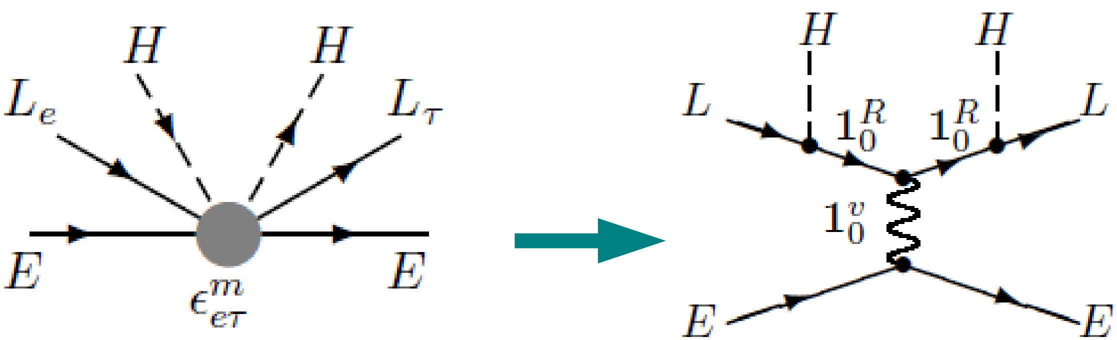
- An example of Dim.8 *LLEEHH* op.



Dim.8 effective op
without cLFV
Constraint-free?

Bottom-up approach —— *Operator decomposition*

- An example of Dim.8 *LLEEHH* op.

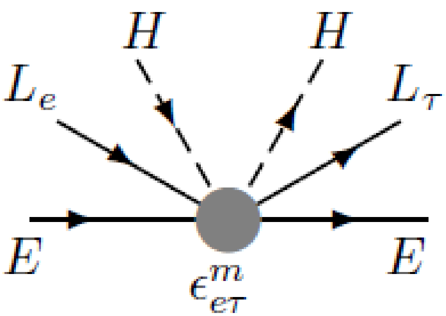


Dim.8 effective op
without cLFV
Constraint-free?

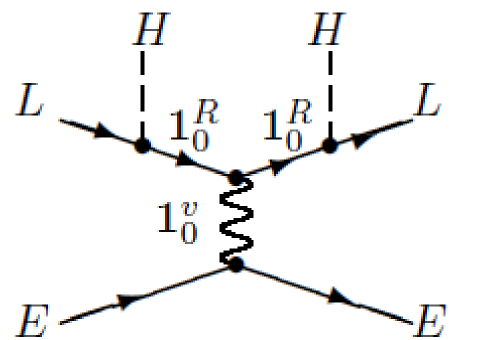
A decomposition with $1^v_0\, 1^R_0$

Bottom-up approach —— *Operator decomposition*

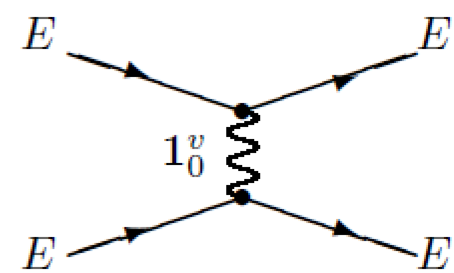
- An example of Dim.8 *LLEEHH* op.



Dim.8 effective op
without cLFV
Constraint-free?



A decomposition with $1^v_0\,1^R_0$

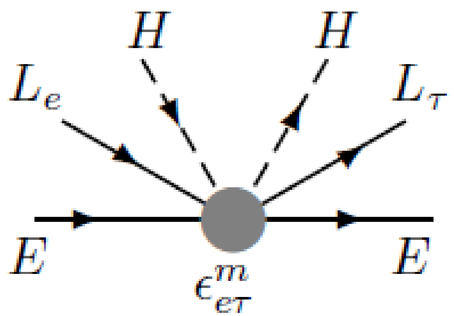


$\rightarrow$ Associated Dim.6 op
Constrained!

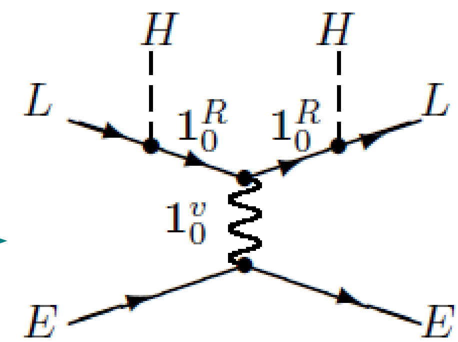
High energy completion of NSI

Bottom-up approach —— *Operator decomposition*

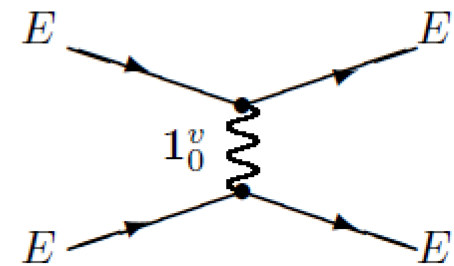
- An example of Dim.8 *LLEEHH* op.



Dim.8 effective op
without cLFV
Constraint-free?



A decomposition with $1^v_0\, 1^R_0$



→ Associated Dim.6 op
Constrained!

Q. Is Dim.8 NSI really Dim.6-free?

To check this, we decompose Dim.8 op. to all possible ways at tree level

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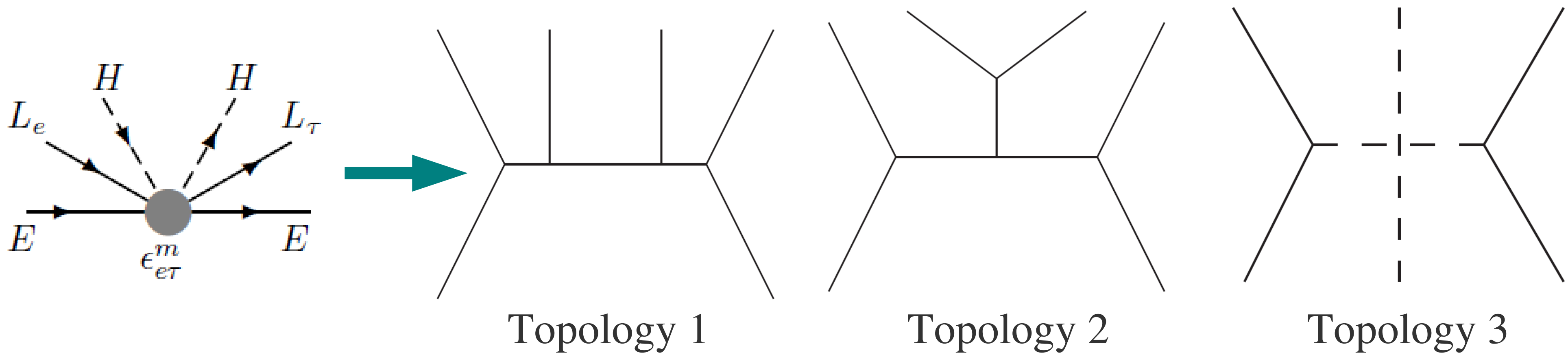
A. No. Any of high energy completions of Dim.8 NSI induce also Dim.6 effects.

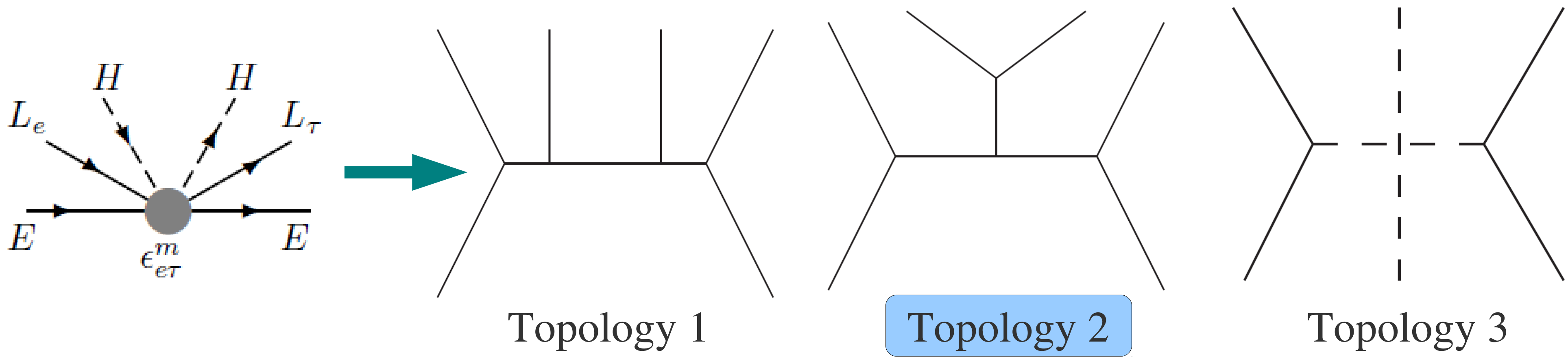
Procedure of Decomposition

1 List possible Topologies

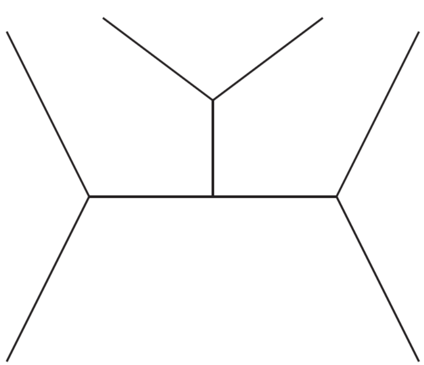


Procedure of Decomposition

1. **List possible Topologies**

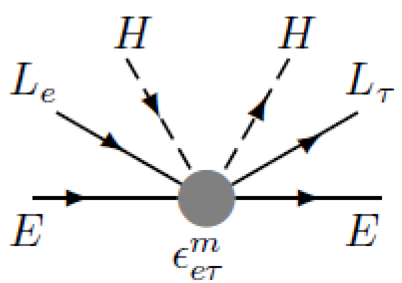


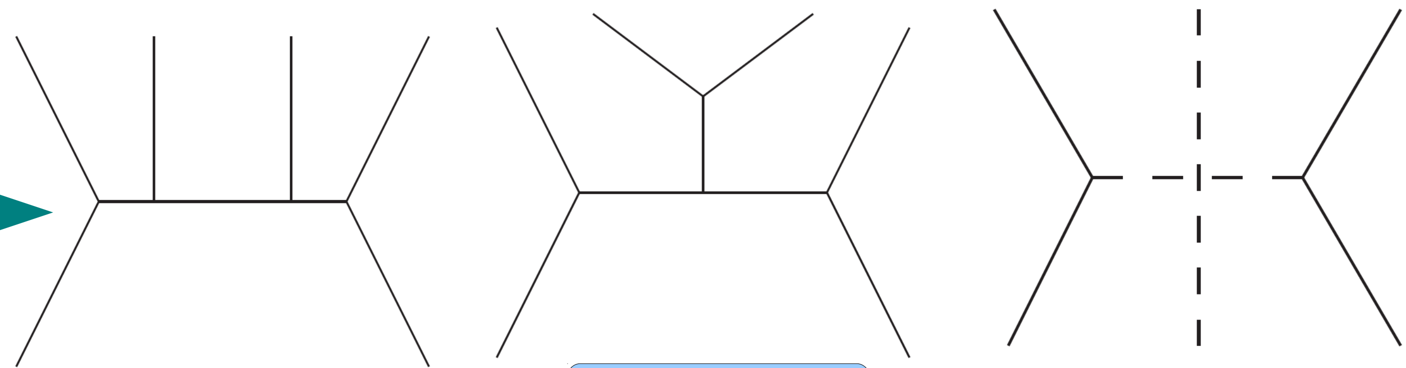
2. **Assign the fields on the outer legs and specify the mediation fields**



Procedure of Decomposition

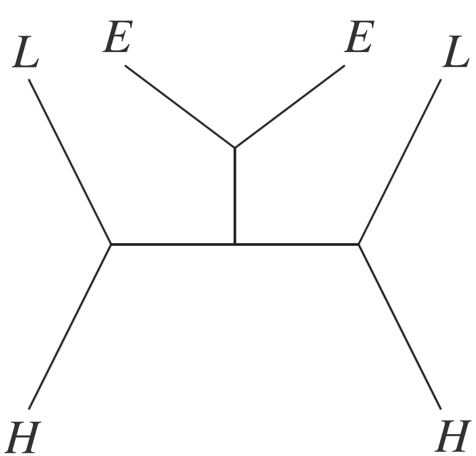
1 List possible Topologies





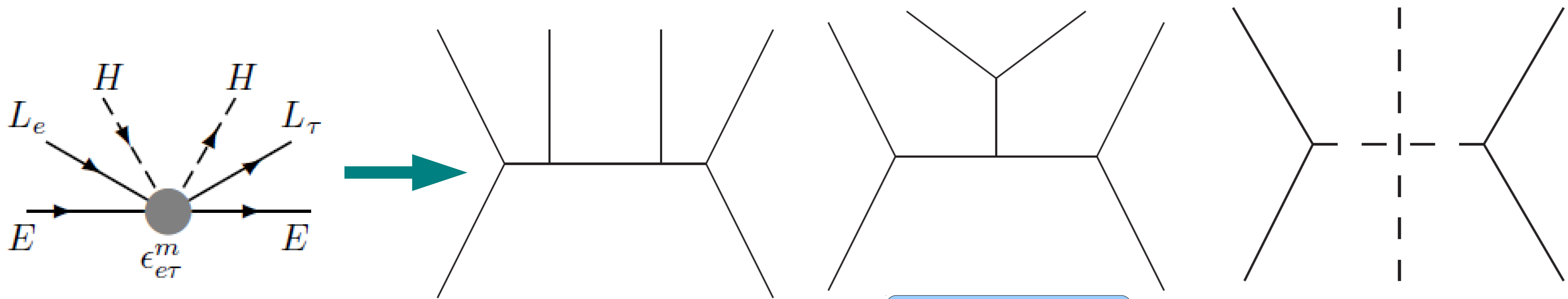
Topology 1 | Topology 2 | Topology 3

2 Assign the fields on the outer legs and specify the mediation fields



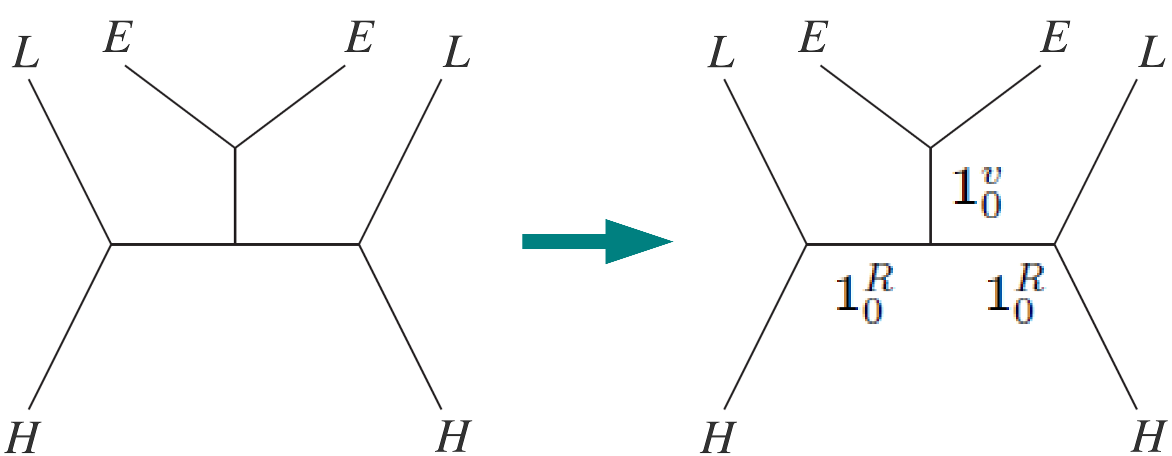
Procedure of Decomposition

1. **List possible Topologies**



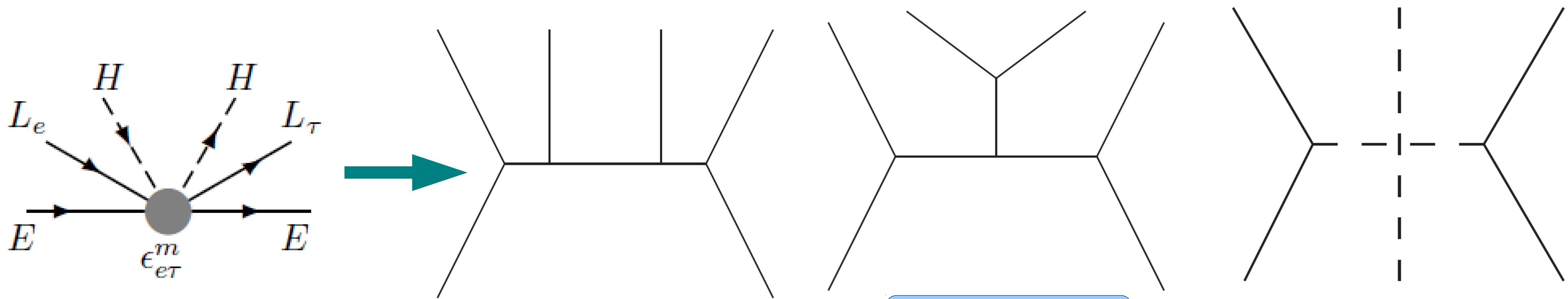
Topology 1 | Topology 2 | Topology 3

2. **Assign the fields on the outer legs and specify the mediation fields**



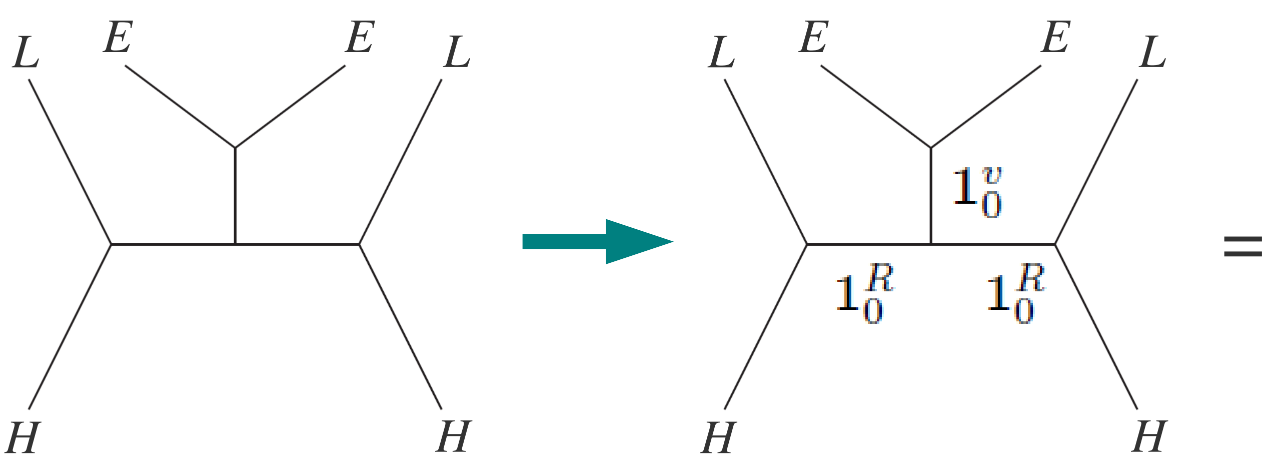
Procedure of Decomposition

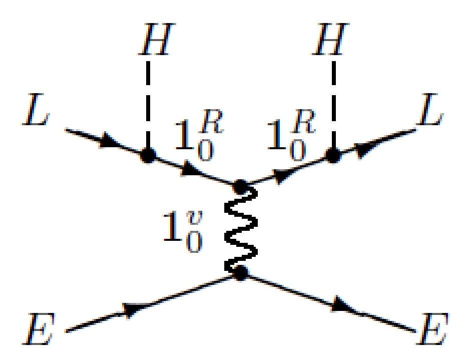
1 List possible Topologies



Topology 1 | Topology 2 | Topology 3

2 Assign the fields on the outer-legs and specify the mediation fields





Example shown in the last slide

High energy completion of NSI

(Part of) the list

- Decompositions with Topology 2
- Projection to Basis ops.

$$(\mathcal{O}^1_{LEH})^{\beta\delta}_{\alpha\gamma} = (\bar{L}^\beta \gamma^\rho L_\alpha)(\bar{E}^\delta \gamma_\rho E_\gamma)\,(H^\dagger H)\,,$$

$$(\mathcal{O}^3_{LEH})^{\beta\delta}_{\alpha\gamma} = (\bar{L}^\beta \gamma^\rho \vec{\tau} L_\alpha)(\bar{E}^\delta \gamma_\rho E_\gamma)\,(H^\dagger \vec{\tau} H)\,,$$

- Necessary Mediation fields
- $\mathcal{O}_{\rm NSI}$ CL-free at dim.8

Topology 2 and 3

All the Dim.8 Decoms. induce Dim.6 CL process

Gavela Hernandez O Winter PR**D79** (2009) 013007

#	Dim. eight operator	C^1_{LEH}	C^3_{LEH}	$\mathcal{O}_{\rm NSI}$?	Mediators
Combination $\bar{L}L$					
1	$(\bar{L}\gamma^\rho L)(\bar{E}\gamma_\rho E)(H^\dagger H)$	1			$\mathbf{1}^v_0$
2	$(\bar{L}\gamma^\rho L)(\bar{E}H^\dagger)(\gamma_\rho)(HE)$	1			$\mathbf{1}^v_0 + \mathbf{2}^{L/R}_{-3/2}$
3	$(\bar{L}\gamma^\rho L)(\bar{E}H^T)(\gamma_\rho)(H^* E)$	1			$\mathbf{1}^v_0 + \mathbf{2}^{L/R}_{-1/2}$
4	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{E}\gamma_\rho E)(H^\dagger \vec{\tau} H)$		1		$\mathbf{3}^v_0 + \mathbf{1}^v_0$
5	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{E}H^\dagger)(\gamma_\rho \vec{\tau})(HE)$		1		$\mathbf{3}^v_0 + \mathbf{2}^{L/R}_{-3/2}$
6	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{E}H^T)(\gamma_\rho \vec{\tau})(H^* E)$		1		$\mathbf{3}^v_0 + \mathbf{2}^{L/R}_{-1/2}$
Combination $\bar{E}L$					
7	$(\bar{L}E)(\bar{E}L)(H^\dagger H)$	$-1/2$			$\mathbf{2}^s_{+1/2}$
8	$(\bar{L}E)(\vec{\tau})(\bar{E}L)(H^\dagger \vec{\tau} H)$		$-1/2$		$\mathbf{2}^s_{+1/2}$
9	$(\bar{L}H)(H^\dagger E)(\bar{E}L)$	$-1/4$	$-1/4$	✓	$\mathbf{2}^s_{+1/2} + \mathbf{1}^R_0 + \mathbf{2}^{L/R}_{-1/2}$
10	$(\bar{L}\vec{\tau}H)(H^\dagger E)(\vec{\tau})(\bar{E}L)$	$-3/4$	$1/4$		$\mathbf{2}^s_{+1/2} + \mathbf{3}^{L/R}_0 + \mathbf{2}^{L/R}_{-1/2}$
11	$(\bar{L}i\tau^2 H^*)(H^T E)(i\tau^2)(\bar{E}L)$	$1/4$	$-1/4$		$\mathbf{2}^s_{+1/2} + \mathbf{1}^{L/R}_{-1} + \mathbf{2}^{L/R}_{-3/2}$
12	$(\bar{L}\vec{\tau}i\tau^2 H^*)(H^T E)(i\tau^2\vec{\tau})(\bar{E}L)$	$3/4$	$1/4$		$\mathbf{2}^s_{+1/2} + \mathbf{3}^{L/R}_{-1} + \mathbf{2}^{L/R}_{-3/2}$
Combination $\overline{E^c}L$					
13	$(\bar{L}\gamma^\rho E^c)(\overline{E^c}\gamma_\rho L)(H^\dagger H)$	-1			$\mathbf{2}^v_{-3/2}$
14	$(\bar{L}\gamma^\rho E^c)(\vec{\tau})(\overline{E^c}\gamma_\rho L)(H^\dagger \vec{\tau} H)$		-1		$\mathbf{2}^v_{-3/2}$
15	$(\bar{L}H)(\gamma^\rho)(H^\dagger E^c)(\overline{E^c}\gamma_\rho L)$	$-1/2$	$-1/2$	✓	$\mathbf{2}^v_{-3/2} + \mathbf{1}^R_0 + \mathbf{2}^{L/R}_{+3/2}$
16	$(\bar{L}\vec{\tau}H)(\gamma^\rho)(H^\dagger E^c)(\vec{\tau})(\overline{E^c}\gamma_\rho L)$	$-3/2$	$1/2$		$\mathbf{2}^v_{-3/2} + \mathbf{3}^{L/R}_0 + \mathbf{2}^{L/R}_{+3/2}$
17	$(\bar{L}i\tau^2 H^*)(\gamma^\rho)(H^T E^c)(i\tau^2)(\overline{E^c}\gamma_\rho L)$	$-1/2$	$1/2$		$\mathbf{2}^v_{-3/2} + \mathbf{1}^{L/R}_{-1} + \mathbf{2}^{L/R}_{+1/2}$
18	$(\bar{L}\vec{\tau}i\tau^2 H^*)(\gamma^\rho)(H^T E^c)(i\tau^2\vec{\tau})(\overline{E^c}\gamma_\rho L)$	$-3/2$	$-1/2$		$\mathbf{2}^v_{-3/2} + \mathbf{3}^{L/R}_{-1} + \mathbf{2}^{L/R}_{+1/2}$
Combination $H^\dagger L$					
19	$(\bar{L}E)(\bar{E}H)(H^\dagger L)$	$-1/4$	$-1/4$	✓	$\mathbf{2}^s_{+1/2} + \mathbf{1}^R_0 + \mathbf{2}^{L/R}_{-1/2}$
20	$(\bar{L}E)(\vec{\tau})(\bar{E}H)(H^\dagger \vec{\tau} L)$	$-3/4$	$1/4$		$\mathbf{2}^s_{+1/2} + \mathbf{3}^{L/R}_0 + \mathbf{2}^{L/R}_{-1/2}$
21	$(\bar{L}H)(\gamma^\rho)(H^\dagger L)(\bar{E}\gamma_\rho E)$	$1/2$	$1/2$	✓	$\mathbf{1}^v_0 + \mathbf{1}^R_0$
22	$(\bar{L}\vec{\tau}H)(\gamma^\rho)(H^\dagger \vec{\tau} L)(\bar{E}\gamma_\rho E)$	$3/2$	$-1/2$		$\mathbf{1}^v_0 + \mathbf{3}^{L/R}_0$
23	$(\bar{L}\gamma^\rho E^c)(\overline{E^c}H)(\gamma^\rho)(H^\dagger L)$	$-1/2$	$-1/2$	✓	$\mathbf{2}^v_{-3/2} + \mathbf{1}^R_0 + \mathbf{2}^{L/R}_{+3/2}$
24	$(\bar{L}\gamma^\rho E^c)(\overline{E^c}H)(\gamma^\rho)(H^\dagger L)$	$-3/2$	$1/2$		$\mathbf{2}^v_{-3/2} + \mathbf{3}^{L/R}_0 + \mathbf{2}^{L/R}_{+3/2}$
Combination HL					
25	$(\bar{L}E)(i\tau^2)(\bar{E}H^*)(H^T i\tau^2 L)$	$1/4$	$-1/4$		$\mathbf{2}^s_{+1/2} + \mathbf{1}^{L/R}_{-1} + \mathbf{2}^{L/R}_{-3/2}$
26	$(\bar{L}E)(\vec{\tau}i\tau^2)(\bar{E}H^*)(H^T i\tau^2\vec{\tau} L)$	$3/4$	$1/4$		$\mathbf{2}^s_{+1/2} + \mathbf{3}^{L/R}_{-1} + \mathbf{2}^{L/R}_{-3/2}$
27	$(\bar{L}i\tau^2 H^*)(\gamma^\rho)(H^T i\tau^2 L)(\bar{E}\gamma_\rho E)$	$-1/2$	$1/2$		$\mathbf{1}^v_0 + \mathbf{1}^{L/R}_{-1}$
28	$(\bar{L}\vec{\tau}i\tau^2 H^*)(\gamma^\rho)(H^T i\tau^2\vec{\tau} L)(\bar{E}\gamma_\rho E)$	$-3/2$	$-1/2$		$\mathbf{1}^v_0 + \mathbf{3}^{L/R}_{-1}$
29	$(\bar{L}\gamma^\rho E^c)(i\tau^2)(\overline{E^c}H^*)(\gamma_\rho)(H^T i\tau^2 L)$	$1/2$	$-1/2$		$\mathbf{2}^v_{-3/2} + \mathbf{1}^{L/R}_{-1} + \mathbf{2}^{L/R}_{+1/2}$
30	$(\bar{L}\gamma^\rho E^c)(\vec{\tau}i\tau^2)(\overline{E^c}H^*)(\gamma_\rho)(H^T i\tau^2\vec{\tau} L)$	$3/2$	$1/2$		$\mathbf{2}^v_{-3/2} + \mathbf{3}^{L/R}_{-1} + \mathbf{2}^{L/R}_{+1/2}$

Example shown in the last slide

High energy completion of NSI

(Part of) the list

- Decompositions with Topology 2
- Projection to Basis ops.

$$(\mathcal{O}^1_{LEH})^{\beta\delta}_{\alpha\gamma} = (\bar{L}^\beta \gamma^\rho L_\alpha)(\bar{E}^\delta \gamma_\rho E_\gamma)\,(H^\dagger H)\,,$$

$$(\mathcal{O}^3_{LEH})^{\beta\delta}_{\alpha\gamma} = (\bar{L}^\beta \gamma^\rho \vec{\tau} L_\alpha)(\bar{E}^\delta \gamma_\rho E_\gamma)\,(H^\dagger \vec{\tau} H)\,,$$

- Necessary Mediation fields
- $\mathcal{O}_{\rm NSI}$ CL-free at dim.8

Topology 2 and 3
All the Dim.8 Decoms.
induce Dim.6 CL process

Some of Decoms. in Top.1 do not induce Dim.6 CL, but they are always associated with Dim.6 op. of non-unitary PMNS.

Gavela Hernandez O Winter PR**D79** (2009) 013007

#	Dim. eight operator	C^1_{LEH}	C^3_{LEH}	$\mathcal{O}_{\rm NSI}$?	Mediators
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1	$(\bar{L}\gamma^\rho L)(\bar{E}\gamma_\rho E)(H^\dagger H)$	1			$\mathbf{1}^v_0$
2	$(\bar{L}\gamma^\rho L)(\bar{E}H^\dagger)(\gamma_\rho)(HE)$	1			$\mathbf{1}^v_0 + \mathbf{2}^{L/R}_{-3/2}$
3	$(\bar{L}\gamma^\rho L)(\bar{E}H^T)(\gamma_\rho)(H^* E)$	1			$\mathbf{1}^v_0 + \mathbf{2}^{L/R}_{-1/2}$
4	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{E}\gamma_\rho E)(H^\dagger \vec{\tau} H)$		1		$\mathbf{3}^v_0 + \mathbf{1}^v_0$
5	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{E}H^\dagger)(\gamma_\rho \vec{\tau})(HE)$		1		$\mathbf{3}^v_0 + \mathbf{2}^{L/R}_{-3/2}$
6	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{E}H^T)(\gamma_\rho \vec{\tau})(H^* E)$		1		$\mathbf{3}^v_0 + \mathbf{2}^{L/R}_{-1/2}$
Combination $\bar{E}L$					
7	$(\bar{L}E)(\bar{E}L)(H^\dagger H)$	−1/2			$\mathbf{2}^s_{+1/2}$
8	$(\bar{L}E)(\vec{\tau})(\bar{E}L)(H^\dagger \vec{\tau} H)$		−1/2		$\mathbf{2}^s_{+1/2}$
9	$(\bar{L}H)(H^\dagger E)(\bar{E}L)$	−1/4	−1/4	✓	$\mathbf{2}^s_{+1/2} + \mathbf{1}^R_0 + \mathbf{2}^{L/R}_{-1/2}$
10	$(\bar{L}\vec{\tau}H)(H^\dagger E)(\vec{\tau})(\bar{E}L)$	−3/4	1/4		$\mathbf{2}^s_{+1/2} + \mathbf{3}^{L/R}_0 + \mathbf{2}^{L/R}_{-1/2}$
11	$(\bar{L}i\tau^2 H^*)(H^T E)(i\tau^2)(\bar{E}L)$	1/4	−1/4		$\mathbf{2}^s_{+1/2} + \mathbf{1}^{L/R}_{-1} + \mathbf{2}^{L/R}_{-3/2}$
12	$(\bar{L}\vec{\tau}i\tau^2 H^*)(H^T E)(i\tau^2\vec{\tau})(\bar{E}L)$	3/4	1/4		$\mathbf{2}^s_{+1/2} + \mathbf{3}^{L/R}_{-1} + \mathbf{2}^{L/R}_{-3/2}$
Combination $\overline{E^c}L$					
13	$(\bar{L}\gamma^\rho E^c)(\overline{E^c}\gamma_\rho L)(H^\dagger H)$	−1			$\mathbf{2}^v_{-3/2}$
14	$(\bar{L}\gamma^\rho E^c)(\vec{\tau})(\overline{E^c}\gamma_\rho L)(H^\dagger \vec{\tau} H)$		−1		$\mathbf{2}^v_{-3/2}$
15	$(\bar{L}H)(\gamma^\rho)(H^\dagger E^c)(\overline{E^c}\gamma_\rho L)$	−1/2	−1/2	✓	$\mathbf{2}^v_{-3/2} + \mathbf{1}^R_0 + \mathbf{2}^{L/R}_{+3/2}$
16	$(\bar{L}\vec{\tau}H)(\gamma^\rho)(H^\dagger E^c)(\vec{\tau})(\overline{E^c}\gamma_\rho L)$	−3/2	1/2		$\mathbf{2}^v_{-3/2} + \mathbf{3}^{L/R}_0 + \mathbf{2}^{L/R}_{+3/2}$
17	$(\bar{L}i\tau^2 H^*)(\gamma^\rho)(H^T E^c)(i\tau^2)(\overline{E^c}\gamma_\rho L)$	−1/2	1/2		$\mathbf{2}^v_{-3/2} + \mathbf{1}^{L/R}_{-1} + \mathbf{2}^{L/R}_{+1/2}$
18	$(\bar{L}\vec{\tau}i\tau^2 H^*)(\gamma^\rho)(H^T E^c)(i\tau^2\vec{\tau})(\overline{E^c}\gamma_\rho L)$	−3/2	−1/2		$\mathbf{2}^v_{-3/2} + \mathbf{3}^{L/R}_{-1} + \mathbf{2}^{L/R}_{+1/2}$
Combination $H^\dagger L$					
19	$(\bar{L}E)(\bar{E}H)(H^\dagger L)$	−1/4	−1/4	✓	$\mathbf{2}^s_{+1/2} + \mathbf{1}^R_0 + \mathbf{2}^{L/R}_{-1/2}$
20	$(\bar{L}E)(\vec{\tau})(\bar{E}H)(H^\dagger \vec{\tau} L)$	−3/4	1/4		$\mathbf{2}^s_{+1/2} + \mathbf{3}^{L/R}_0 + \mathbf{2}^{L/R}_{-1/2}$
21	$(\bar{L}H)(\gamma^\rho)(H^\dagger L)(\bar{E}\gamma_\rho E)$	1/2	1/2	✓	$\mathbf{1}^v_0 + \mathbf{1}^R_0$
22	$(\bar{L}\vec{\tau}H)(\gamma^\rho)(H^\dagger \vec{\tau} L)(\bar{E}\gamma_\rho E)$	3/2	−1/2		$\mathbf{1}^v_0 + \mathbf{3}^{L/R}_0$
23	$(\bar{L}\gamma^\rho E^c)(\overline{E^c}H)(\gamma^\rho)(H^\dagger L)$	−1/2	−1/2	✓	$\mathbf{2}^v_{-3/2} + \mathbf{1}^R_0 + \mathbf{2}^{L/R}_{+3/2}$
24	$(\bar{L}\gamma^\rho E^c)(\overline{E^c}H)(\gamma^\rho)(H^\dagger L)$	−3/2	1/2		$\mathbf{2}^v_{-3/2} + \mathbf{3}^{L/R}_0 + \mathbf{2}^{L/R}_{+3/2}$
Combination HL					
25	$(\bar{L}E)(i\tau^2)(\bar{E}H^*)(H^T i\tau^2 L)$	1/4	−1/4		$\mathbf{2}^s_{+1/2} + \mathbf{1}^{L/R}_{-1} + \mathbf{2}^{L/R}_{-3/2}$
26	$(\bar{L}E)(\vec{\tau}i\tau^2)(\bar{E}H^*)(H^T i\tau^2\vec{\tau}L)$	3/4	1/4		$\mathbf{2}^s_{+1/2} + \mathbf{3}^{L/R}_{-1} + \mathbf{2}^{L/R}_{-3/2}$
27	$(\bar{L}i\tau^2 H^*)(\gamma^\rho)(H^T i\tau^2 L)(\bar{E}\gamma_\rho E)$	−1/2	1/2		$\mathbf{1}^v_0 + \mathbf{1}^{L/R}_{-1}$
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29	$(\bar{L}\gamma^\rho E^c)(i\tau^2)(\overline{E^c}H^*)(\gamma_\rho)(H^T i\tau^2 L)$	1/2	−1/2		$\mathbf{2}^v_{-3/2} + \mathbf{1}^{L/R}_{-1} + \mathbf{2}^{L/R}_{+1/2}$
30	$(\bar{L}\gamma^\rho E^c)(\vec{\tau}i\tau^2)(\overline{E^c}H^*)(\gamma_\rho)(H^T i\tau^2\vec{\tau}L)$	3/2	1/2		$\mathbf{2}^v_{-3/2} + \mathbf{3}^{L/R}_{-1} + \mathbf{2}^{L/R}_{+1/2}$

Short summary for NSI

NSI search in neutrino oscillation experiments

- Signal of New physic, Oscillation enhancement, Loose constraints
- Reactor and accelerator experiments are not redundant
- Expected sensitivity at neutrino factory: $|\epsilon^m_{\alpha\tau}| < \mathcal{O}(10^{-3})$

High energy completion of NSI

- Dim.6 → Charged lepton counter process
- Dim.8 with Higgs doublets → Constraint-free?

  Bottom-up (Operator Decomposition)

  → List all the possible high *E* completions

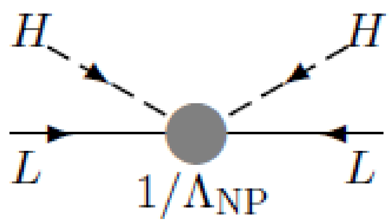
  For Genuine Dim.8 NSI, it is necessary to introduce something to cancel Dim.6.

An important aspect of Dim.8 = Loop-induced Dim.6 Biggio Blennow Fernandez-Martinez JHEP **0903** (2009) 239

→ Another application of Bottom-up approach: **Neutrino mass from high dim.**

2 Neutrino mass from *d*>5 effective operators

- Motivation
- Setup at the low energy scale
- Possible high energy completion
  — Bottom-up to the high energy scale



Overview: Neutrino mass from higher dim. ops.

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{d=5} + \cdots$$

$$\mathscr{L}_{d=5} = \frac{1}{\Lambda_{\rm NP}} LLHH$$

Seesaw

Minkowski PL**B67** (1977) 421,
Yanagida (1979),
Gell-Mann Ramond Slansky (1979),
Mohapatra Senjanovic PRL **44** (1980) 912,
Schechter Valle PR**D22** (1980) 2227.

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Seesaw — Zee, Dark-doublet... — Babu-Zee...

Seesaw: Minkowski PLB**67** (1977) 421, Yanagida (1979), Gell-Mann Ramond Slansky (1979), Mohapatra Senjanovic PRL **44** (1980) 912, Schechter Valle PRD**22** (1980) 2227.

Zee, Dark-doublet...: Zee PLB**93** (1980) 389, Ma PRL **81** (1999) 1171, etc.

Babu-Zee...: Babu PLB**203** (1988) 132, etc.

Overview: Neutrino mass from higher dim. ops.

If forbidden

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \cancel{\mathscr{L}_{d=5}} + \mathscr{L}_{d=6} + \mathscr{L}_{d=7} + \cdots$$

$$\mathscr{L}_{d=5} = \frac{1}{\Lambda_{\rm NP}} LLHH + \frac{1}{16\pi^2}\frac{1}{\Lambda_{\rm NP}} LLHH + \frac{1}{(16\pi^2)^2}\frac{1}{\Lambda_{\rm NP}} LLHH + \cdots$$

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- Next leading contribution to neutrino mass with the SM particle content

$$\mathscr{L}_{d=7} = \frac{1}{\Lambda^3_{\rm NP}} LLHHH^\dagger H + \frac{1}{16\pi^2}\frac{1}{\Lambda^3_{\rm NP}} LLHHH^\dagger H + \cdots$$

Overview: Neutrino mass from higher dim. ops.

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$$\mathscr{L}_{d=7} = \frac{1}{\Lambda_{\rm NP}^3} LLHHH^\dagger H + \frac{1}{16\pi^2}\frac{1}{\Lambda_{\rm NP}^3} LLHHH^\dagger H + \cdots$$

- **Neutrino mass from an *n*-loop dim-*d* diagram**

$$m_\nu = v \times \left(\frac{1}{16\pi^2}\right)^n \times \underline{\left(\frac{v}{\Lambda_{\rm NP}}\right)^{d-4}}$$

Additional suppression
↓
Lower NP scale

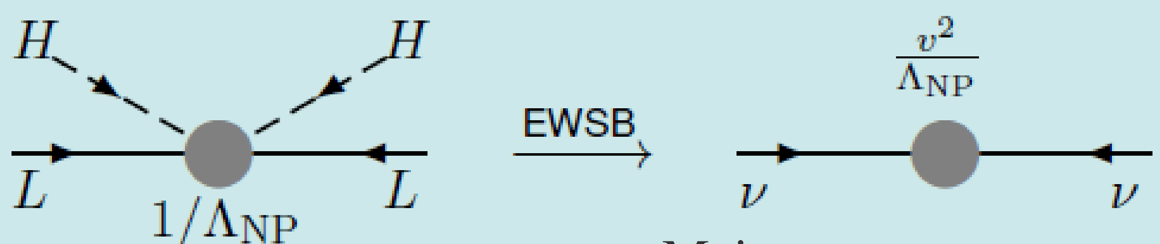
Recapitulation: Weinberg (d=5) op. and Seesaw mechanism

Lagrangian at EW scale

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}}\mathcal{O}^{d=5} + \frac{1}{\Lambda_{\rm NP}^2}\mathcal{O}^{d=6} + \frac{1}{\Lambda_{\rm NP}^3}\mathcal{O}^{d=7} + \cdots$$

- **Weinberg op. = Lowerst higher dimensional op.**

$$\frac{1}{\Lambda_{\rm NP}}\mathcal{O}^{d=5} = \frac{1}{\Lambda_{\rm NP}}(\overline{L^c}{\rm i}\tau^2 H)(H^{\sf T}{\rm i}\tau^2 L) \xrightarrow{\sf EWSB} \frac{v^2}{2\Lambda_{\rm NP}}\overline{\nu^c}\nu$$



Majorana mass suppressed by $v/\Lambda_{\rm NP}$

- The SM is an effective theory at the EW scale

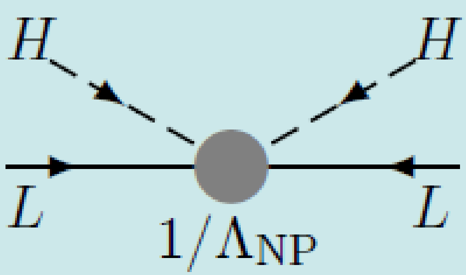
  → New Physics appears at the high energy scale $\Lambda_{\rm NP}$

Recapitulation: Weinberg (d=5) op. and Seesaw mechanism

- Effective operator at the EW scale is induced from a fundamental theory at the high energy scale $\Lambda_{\rm NP}$

- **High energy completion of Weinberg op. = Seesaw mechanism**

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}} (\overline{L^c} {\rm i}\tau^2 H)(H^{\sf T} {\rm i}\tau^2 L) + {\rm H.c.},$$



Recapitulation: Weinberg (d=5) op. and Seesaw mechanism

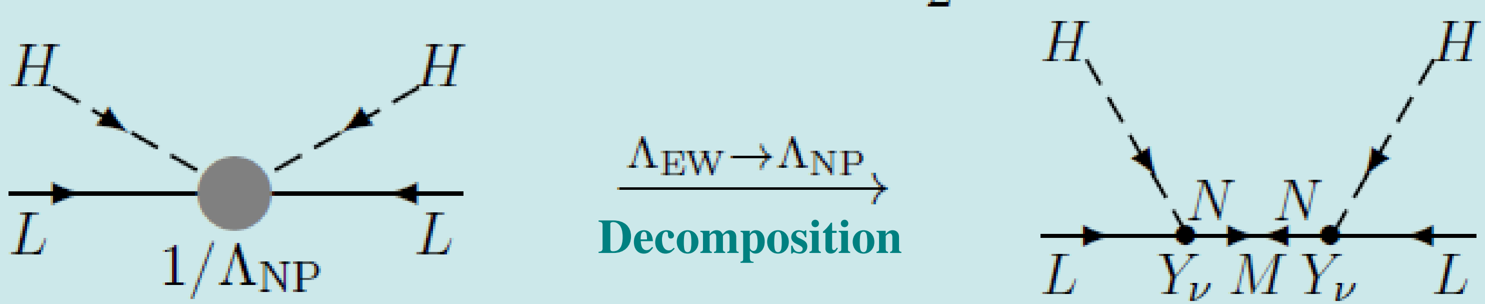
- Effective operator at the EW scale is induced from a fundamental theory at the high energy scale Λ_{NP}

- **High energy completion of Weinberg op. = Seesaw mechanism**

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda_{\mathrm{NP}}}(\overline{L^c} \mathrm{i}\tau^2 H)(H^{\mathsf{T}} \mathrm{i}\tau^2 L) + \mathrm{H.c.},$$

$$\xrightarrow{\Lambda_{\mathrm{EW}} \to \Lambda_{\mathrm{NP}}} \mathscr{L}_{\mathrm{SM}} + Y_\nu \bar{N} H \mathrm{i}\tau^2 L + \frac{1}{2} M \overline{N^c} N + \mathrm{H.c.}.$$

Type I Seesaw



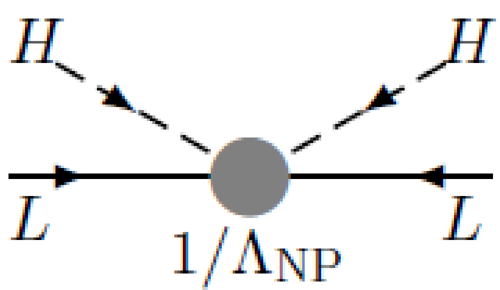
- This suggests $\Lambda_{\mathrm{NP}} = M \gtrsim \mathcal{O}(10^{13})$ GeV (with $Y_\nu \sim \mathcal{O}(1)$)

$\to$ Additional suppression factor helps to lower the scale Λ_{NP}

Depart from Dim.5

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{d=5} + \mathscr{L}_{d=6} + \mathscr{L}_{d=7} + \cdots$$

$$\mathscr{L}_{d=5} = \frac{1}{\Lambda_{\rm NP}} (\overline{L^c} {\rm i}\tau^2 H)(H^{\sf T} {\rm i}\tau^2 L) \to v \frac{v}{\Lambda_{\rm NP}} \overline{\nu^c}\nu,$$



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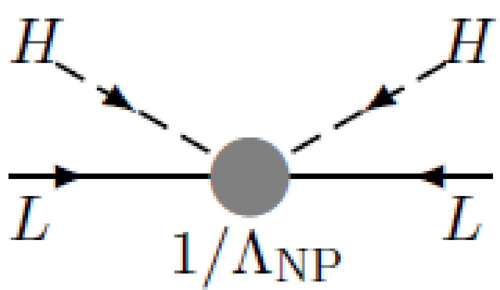
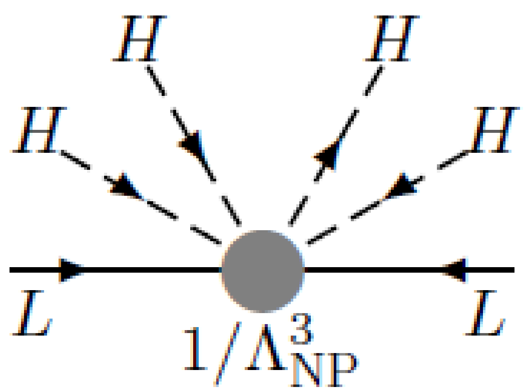
$$\mathscr{L}_{d=7} = \frac{1}{\Lambda^3_{\rm NP}} (\overline{L^c} i\tau^2 H)(H^{\sf T} i\tau^2 L)(H^\dagger H) \to v \left(\frac{v}{\Lambda_{\rm NP}}\right)^3 \overline{\nu^c} \nu,$$





- **Higher d = Lower $\Lambda_{\rm NP}$ → Collider testable**

If Dim.5 Weinberg op. is forbidden for some reason...

Symmetry

A complication to introduce Dim.7 op.

- When we allow us to have

$$\mathscr{L}_{d=7} = \frac{1}{\Lambda_{\rm NP}^3}(\overline{L^c} i\tau^2 H)(H^\top i\tau^2 L)(H^\dagger H) \to v\left(\frac{v}{\Lambda_{\rm NP}}\right)^3 \overline{\nu^c}\nu,$$

A complication to introduce Dim.7 op.

- When we allow us to have

$$\mathscr{L}_{d=7} = \frac{1}{\Lambda_{\rm NP}^3}(\overline{L^c} {\rm i}\tau^2 H)(H^{\sf T} {\rm i}\tau^2 L)\boxed{(H^\dagger H)} \to v \left(\frac{v}{\Lambda_{\rm NP}}\right)^3 \overline{\nu^c}\nu,$$

Singlet

we also have

$$\mathscr{L}_{d=5} = \frac{1}{\Lambda_{\rm NP}}(\overline{L^c} {\rm i}\tau^2 H)(H^{\sf T} {\rm i}\tau^2 L) \to v \frac{v}{\Lambda_{\rm NP}} \overline{\nu^c}\nu,$$

A complication to introduce Dim.7 op.

- When we allow us to have

$$\mathscr{L}_{d=7} = \frac{1}{\Lambda_{\rm NP}^3}(\overline{L^c}{\rm i}\tau^2 H)(H^{\sf T}{\rm i}\tau^2 L)(H^\dagger H) \to v\left(\frac{v}{\Lambda_{\rm NP}}\right)^3 \overline{\nu^c}\nu,$$

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$$\mathscr{L}_{d=5}^{\text{1-loop}} = \frac{1}{\Lambda_{\rm NP}^3}(\overline{L^c}{\rm i}\tau^2 H)(H^{\sf T}{\rm i}\tau^2 L)\,(\overbrace{H^\dagger H}) \to v\left(\frac{v}{\Lambda_{\rm NP}}\right)\frac{1}{16\pi^2}\overline{\nu^c}\nu.$$

A complication to introduce Dim.7 op.

- When we allow us to have

$$\mathscr{L}_{d=7} = \frac{1}{\Lambda_{\rm NP}^3}(\overline{L^c}\mathrm{i}\tau^2 H)(H^{\mathsf{T}}\mathrm{i}\tau^2 L)(H^\dagger H) \to v\left(\frac{v}{\Lambda_{\rm NP}}\right)^3 \overline{\nu^c}\nu,$$

we also have

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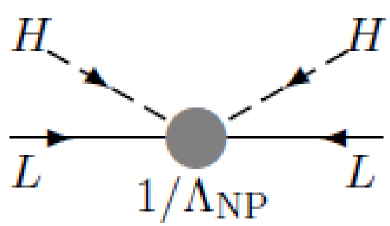
To forbid *d=5* op., we introduce

- Two Higgs doublets $H_u = (H_u^+, H_u^0)^{\mathsf{T}}$ and $H_d = (H_d^0, H_d^-)^{\mathsf{T}}$.
- Discrete symmetry (Matter parity) Z_n Ibáñez Ross NP**B368** (1992) 3,

2 Neutrino mass from *d>5* effective operators

- Motivation
- Setup at the low energy scale
- Possible high energy completion
  - — Bottom-up to the high energy scale



Setup at the EWSB scale

When we have

- SM particle content + an extra Higgs doublet H_u, H_d
- Z_5 matter parity with the following charge assignment

$$q_{H_u} = 0, \quad q_{H_d} = 3, \quad q_L = 1, \quad q_{e^c_R} = 1.$$

then, we do not have

$$\mathscr{L}_{d=5} = \frac{1}{\Lambda_{\rm NP}} (\overline{L^c} {\rm i}\tau^2 H_u)(H_u^{\sf T} {\rm i}\tau^2 L) \leftarrow \text{Forbidden}, \quad q(\text{Dim.5}) = 2$$

and we have

$$\mathscr{L}_{d=7} = \frac{1}{\Lambda_{\rm NP}^3} (\overline{L^c} {\rm i}\tau^2 H_u)(H_u^{\sf T} {\rm i}\tau^2 L)(H_d^{\sf T} {\rm i}\tau^2 H_u) \to v_u \frac{v_u^2 v_d}{\Lambda_{\rm NP}^3} \overline{\nu^c}\nu. \quad q(\text{Dim.7}) = 5$$

This Dim.7 op does not induce loop-Dim.5 op.

Systematic scan of matter parity

Conditions for Dim.7 op.

Forbid $d = 5$

$$LLH_uH_u : (2q_L + 2q_{H_u}) \mod n \neq 0$$
$$LLH_d^*H_u : (2q_L + q_{H_u} - q_{H_d}) \mod n \neq 0$$
$$LLH_d^*H_d^* : (2q_L - 2q_{H_d}) \mod n \neq 0$$

Allow $d = 7$

$$LLH_uH_uH_dH_u : (2q_L + 3q_{H_u} + q_{H_d}) \mod n = 0$$

and the SM interactions $\mathscr{L}_{\rm SM}$

Z_5 is the minimal symmetry that can satisfy all of them.

Extension: This can be generalized for $d = 9 \ldots$ with $Z_{n=7\ldots}$.

Picek Radovcic PL**B687** (2010) 338

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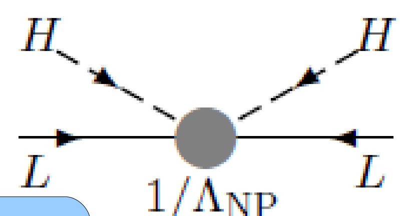

High energy completion of Dim.7

$d = 5$

Weinberg op. $(d = 5)$ is realized by the seesaw model, i.e.,

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}} (\overline{L^c} {\rm i}\tau^2 H)(H^{\sf T} {\rm i}\tau^2 L) + {\rm H.c.},$$

$$\xrightarrow{\text{high scale}} \mathscr{L}_{\rm SM} + Y_\nu \bar{N} H {\rm i}\tau^2 L + \frac{1}{2} M \overline{N^c} N + {\rm H.c.}.$$

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$d = 7$

Now, we have the effective Lagrangian,

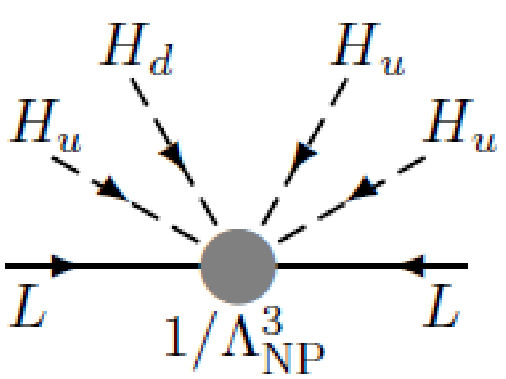
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}^3} (\overline{L^c} {\rm i}\tau^2 H_u)(H_u^{\sf T} {\rm i}\tau^2 L)(H_d^{\sf T} {\rm i}\tau^2 H_u)$$

$$\xrightarrow{\text{high scale}} \mathscr{L}_{\rm SM} + ???$$

- What kind of high energy modes can induce Dim.7 effective op. at the EW scale? → Examples...

High energy completion of Dim.7:Example 1

- Particle content:
  - 2 SM singlet (2-)spinors N_R N'_L $q_{N_R} = q_{N'_L} = 1$ under Z_5
  - A SM singlet scalar ϕ $q_\phi = 3$



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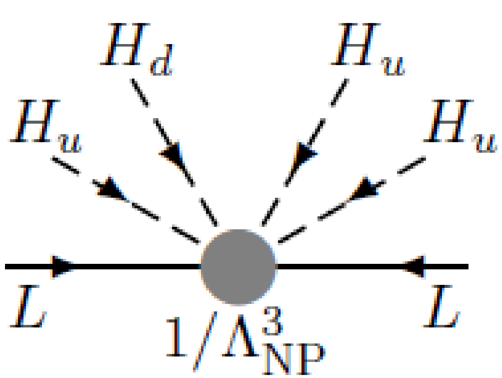
- Relevant part of Lagrangian

$$\mathscr{L} = \mathscr{L}_{\rm SM} + Y_\nu \overline{N_R} H_u {\rm i}\tau^2 L + M \overline{N_R} N'_L + \kappa \overline{N'^c_L} N'_L \phi + \mu \phi^* H_d {\rm i}\tau^2 H_u + M_\phi^2 \phi^* \phi.$$



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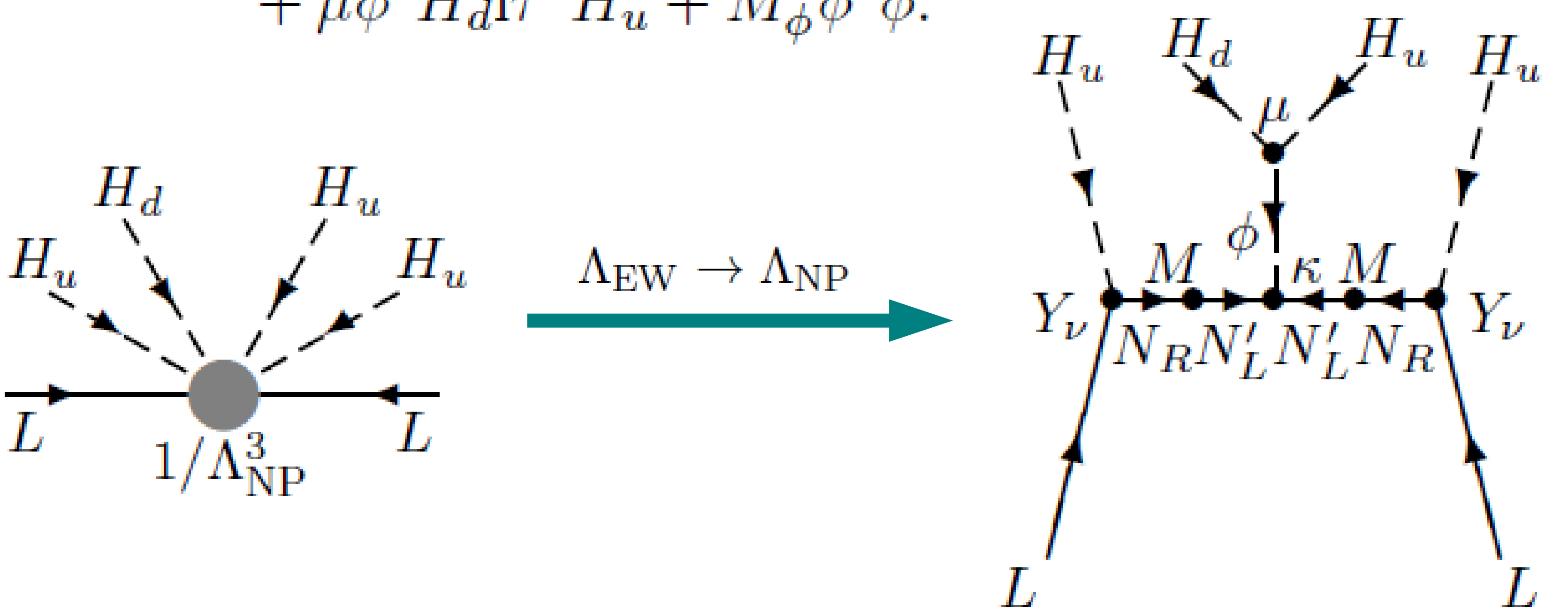

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- Relevant part of Lagrangian

For inverse seesaw, e.g., Gonzalez-Garcia Valle PL**B216** (1989) 360

$$\mathscr{L} = \frac{1}{2}\left(\overline{\nu_L^c} \quad \overline{N_R} \quad \overline{N_L'^c}\right)\begin{pmatrix} 0 & Y_\nu^{\mathsf{T}} H_u^0 & 0 \\ Y_\nu H_u^0 & 0 & M \\ 0 & M^{\mathsf{T}} & \Lambda^{-1} H_d^0 H_u^0 \end{pmatrix}\begin{pmatrix} \nu_L \\ N_R^c \\ N_L' \end{pmatrix} + \text{H.c.},$$

where $\Lambda^{-1} = 2\kappa\mu/M_\phi^2$

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where $\Lambda^{-1} = 2\kappa\mu / M_\phi^2$

- Neutrino mass

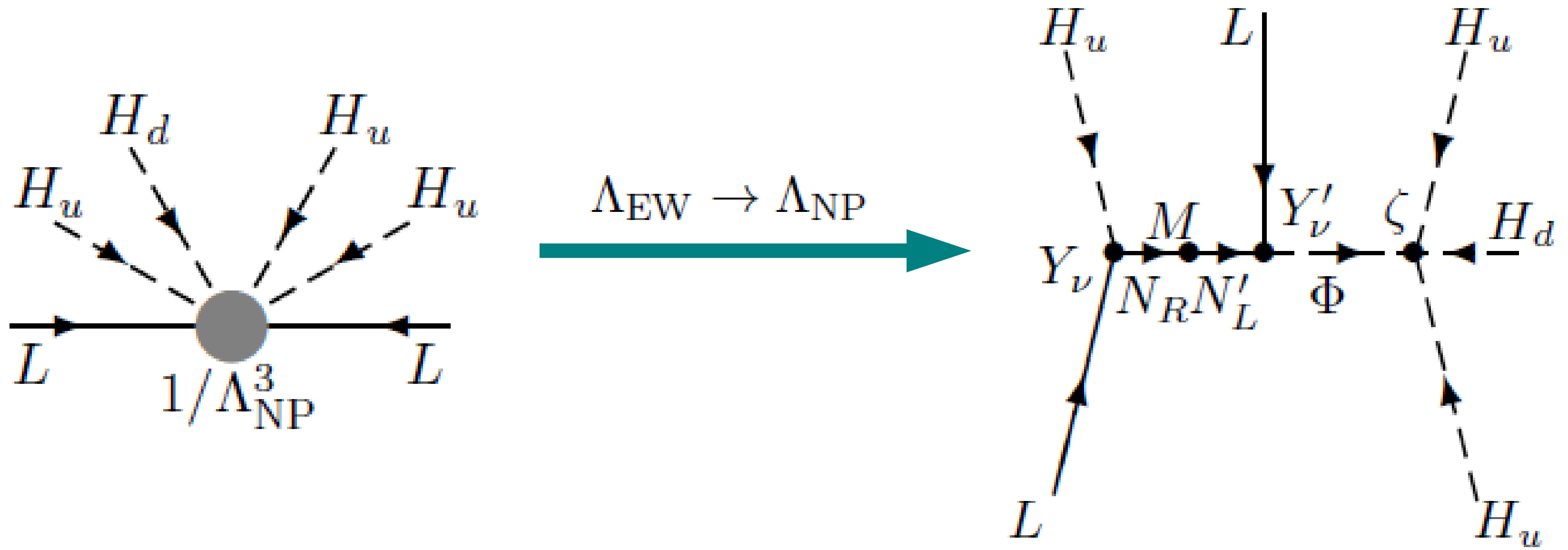
$$m_\nu = \frac{v_u^3 v_d}{4} Y_\nu^\mathsf{T} (M^{-1})^\mathsf{T} \Lambda^{-1} M^{-1} Y_\nu \sim \mathcal{O}\left(v \frac{v^3}{\Lambda_{\rm NP}^3} \right)$$

$\Lambda_{\rm NP} \sim \mathcal{O}(1)$ TeV $\rightarrow$ Collider testable (with $Y_\nu \sim Y_\mu$)

High energy completion of Dim.7:Example 2

- Particle content:
  - 2 SM singlet (2-)spinors N_R N'_L $\quad q_{N_R} = q_{N'_L} = 1$ under Z_5
  - A SU(2) doublet scalar Φ $\quad q_\Phi = 2$
- Relevant part of Lagrangian

$$\mathscr{L} = \mathscr{L}_{\rm SM} + Y_\nu \overline{N_R} H_u i\tau^2 L + Y'_\nu \overline{N'^c_L} \Phi^\dagger L + M \overline{N_R} N'_L + \zeta \left\{ (H_d i\tau^2 H_u)(\Phi i\tau^2 H_u) \right\} + M_\Phi^2 \Phi^\dagger \Phi.$$



High energy completion of Dim.7:Example 2

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  - A SU(2) doublet scalar Φ $\qquad q_\Phi = 2$
- Relevant part of Lagrangian

For this type of mass matrix, Abada Biggio Bonnet Gavela Hambye JHEP **0712** (2007) 061

$$\mathscr{L} = \frac{1}{2} \left(\overline{\nu_L^c} \quad \overline{N_R} \quad \overline{N_L'^c} \right) \begin{pmatrix} 0 & Y_\nu^{\mathsf{T}} H_u^0 & Y_\nu'^{\mathsf{T}} \zeta \frac{H_d^0 H_u^{02}}{M_\Phi^2} \\ Y_\nu H_u^0 & 0 & M \\ Y_\nu' \zeta \frac{H_d^0 H_u^{02}}{M_\Phi^2} & M^{\mathsf{T}} & 0 \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^c \\ N_L' \end{pmatrix} + \text{H.c.}.$$

- Neutrino mass

$$m_\nu = \frac{\zeta v_u^3 v_d}{4 M_\Phi^2} \left[Y_\nu^{\mathsf{T}} (M^{-1}) Y_\nu' + Y_\nu'^{\mathsf{T}} (M^{-1})^{\mathsf{T}} Y_\nu \right] \sim \mathcal{O}\left(v \frac{v^3}{\Lambda_{\rm NP}^3} \right)$$

$\Lambda_{\rm NP} \sim \mathcal{O}(1)$ TeV $\rightarrow$ Collider testable (with $Y_\nu \sim Y_\mu$)

A typical signature of the models: Non-unitary PMNS matrix

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \cancel{\mathscr{L}_{d=5}} + \mathscr{L}_{d=6} + \mathscr{L}_{d=7} + \cdots$$

Forbidden

Neutrino mass

A typical signature of the models: Non-unitary PMNS matrix

Forbidden
Neutrino mass

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{d=5} + \mathscr{L}_{d=6} + \mathscr{L}_{d=7} + \cdots$$

$$\mathscr{L}_{d=6} = \left[Y_\nu^\dagger (M^{-1})^\dagger M^{-1} Y_\nu\right] (\overline{L} {\rm i}\tau^2 H_u) {\rm i}\partial\!\!\!/ (H_u {\rm i}\tau^2 L)$$

Non-unitary PMNS matrix Abada Biggio Bonnet Gavela Hambye JHEP **0712** (2007) 061.

$$N = \left[1 - \frac{v_u^2}{4} Y_\nu^\dagger (M^{-1})^\dagger M^{-1} Y_\nu\right] U.$$

Unitary part

$\rightarrow$ Neutrino oscillation experiements

$\rightarrow$ charged LFV @ one-loop level

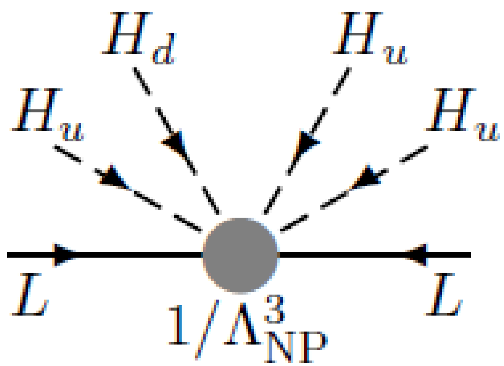
e.g., Antusch Biggio Fernandez-Martinez Gavela Lopez-Pavon JHEP **0610** (2006) 084.

$$\text{Br}(\ell_\alpha \rightarrow \ell_\beta \gamma) \sim \frac{100\alpha_{\rm em}}{96\pi} \frac{\left|(NN^\dagger)_\beta{}^\alpha\right|}{\left|(NN^\dagger)_\alpha{}^\alpha\right| \left|(NN^\dagger)_\beta{}^\beta\right|}$$

With a help of synergy of collider, oscillation, and flavour, we have a chance to reveal the origin of neutrino mass.

Systematic search for high energy completion: Decomposition

Dim.7 operator



can be decomposed to

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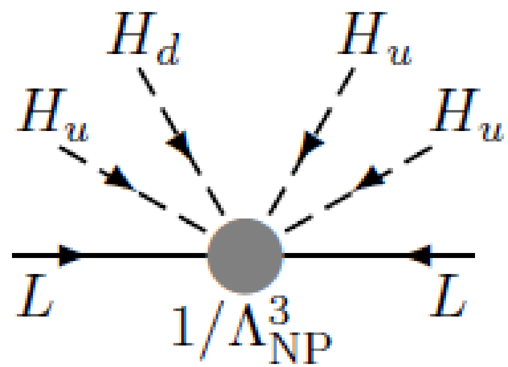
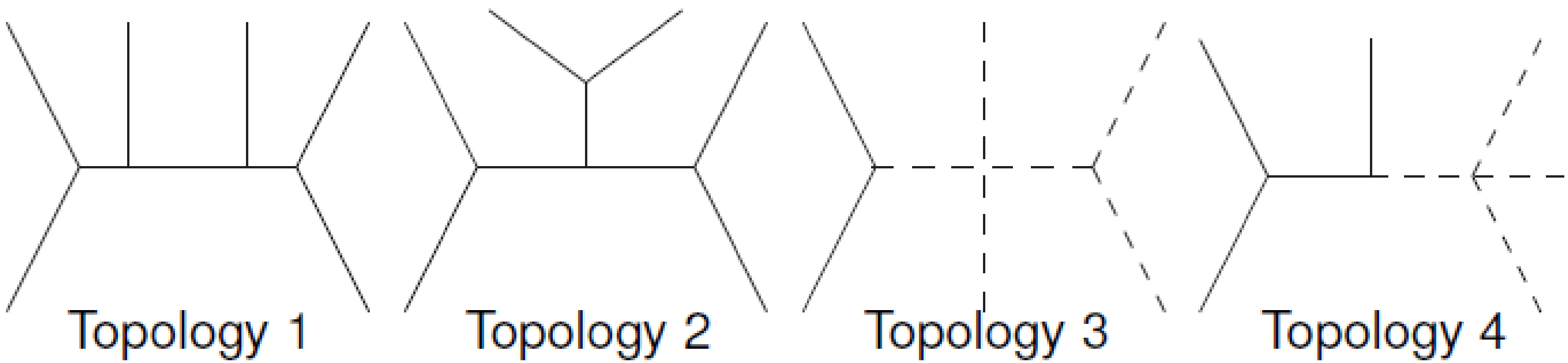


can be decomposed to



Assigning the fields to the outer-legs, we can list the models...

List of the models

#	Operator	Top.	Mediators	Phenom. NU	Phenom. δg_L	Phenom. 4ℓ
1	$(H_u i\tau^2 L^c)(H_u i\tau^2 L)(H_d i\tau^2 H_u)$	2	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{1}_0^s$	✓		
2	$(H_u i\tau^2 \vec{\tau} L^c)(H_u i\tau^2 L)(H_d i\tau^2 \vec{\tau} H_u)$	2	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$ $\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{3}_0^s$	✓	✓	
3	$(H_u i\tau^2 \vec{\tau} \overline{L^c})(H_u i\tau^2 \vec{\tau} L)(H_d i\tau^2 H_u)$	2	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{1}_0^s$	✓	✓	
4	$(-i\epsilon^{abc})(H_u i\tau^2 \tau^a \overline{L^c})(H_u i\tau^2 \tau^b L)(H_d i\tau^2 \tau^c H_u)$	2	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{3}_0^s$	✓	✓	
5	$(\overline{L^c} i\tau^2 \vec{\tau} L)(H_d i\tau^2 H_u)(H_u i\tau^2 \vec{\tau} H_u)$	2/3	$\mathbf{3}_{-1}^s$, $\mathbf{3}_{-1}^s/\mathbf{1}_0^s$			✓
6	$(-i\epsilon^{abc})(\overline{L^c} i\tau^2 \tau^a L)(H_d i\tau^2 \tau^b H_u)(H_u i\tau^2 \tau^c H_u)$	2/3	$\mathbf{3}_{-1}^s$, $\mathbf{3}_{-1}^s/\mathbf{3}_0^s$			✓
7	$(H_u i\tau^2 \overline{L^c})(L i\tau^2 \vec{\tau} H_d)(H_u i\tau^2 \vec{\tau} H_u)$	2	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{3}_{-1}^R$, $\mathbf{3}_{-1}^L$, $\mathbf{3}_{-1}^s$	✓	✓	
8	$(-i\epsilon^{abc})(H_u i\tau^2 \tau^a \overline{L^c})(L i\tau^2 \tau^b H_d)(H_u i\tau^2 \tau^c H_u)$	2	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{3}_{-1}^R$, $\mathbf{3}_{-1}^L$, $\mathbf{3}_{-1}^s$	✓	✓	
9	$(H_u i\tau^2 \overline{L^c})(i\tau^2 H_u)(L)(H_d i\tau^2 H_u)$	1	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$, $\mathbf{1}_0^s$	✓		
10	$(H_u i\tau^2 \vec{\tau} \overline{L^c})(i\tau^2 \vec{\tau} H_u)(L)(H_d i\tau^2 H_u)$	1	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$, $\mathbf{1}_0^s$	✓	✓	
11	$(H_u i\tau^2 \overline{L^c})(i\tau^2 H_u)(\vec{\tau} L)(H_d i\tau^2 \vec{\tau} H_u)$	1	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$, $\mathbf{3}_0^s$	✓		
12	$(H_u i\tau^2 \tau^a \overline{L^c})(i\tau^2 \tau^a H_u)(\tau^b L)(H_d i\tau^2 \tau^b H_u)$	1	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$, $\mathbf{3}_0^s$	✓	✓	
13	$(H_u i\tau^2 \overline{L^c})(L)(i\tau^2 H_u)(H_d i\tau^2 H_u)$	1/4	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{2}_{-1/2}^s$, $(\mathbf{1}_0^s)$	✓		
14	$(H_u i\tau^2 \vec{\tau} L^c)(\vec{\tau} L)(i\tau^2 H_u)(H_d i\tau^2 H_u)$	1/4	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{2}_{-1/2}^s$, $(\mathbf{1}_0^s)$	✓	✓	
15	$(H_u i\tau^2 \overline{L^c})(L)(i\tau^2 \vec{\tau} H_u)(H_d i\tau^2 \vec{\tau} H_u)$	1/4	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{2}_{-1/2}^s$, $(\mathbf{3}_0^s)$	✓		
16	$(H_u i\tau^2 \tau^a \overline{L^c})(\tau^a L)(i\tau^2 \tau^b H_u)(H_d i\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{2}_{-1/2}^s$, $(\mathbf{3}_0^s)$	✓	✓	
17	$(H_u i\tau^2 \overline{L^c})(H_d)(i\tau^2 H_u)(H_u i\tau^2 L)$	1	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$	✓		
18	$(H_u i\tau^2 \vec{\tau} \overline{L^c})(\vec{\tau} H_d)(i\tau^2 H_u)(H_u i\tau^2 L)$	1	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$, $\mathbf{1}_0^R$, $\mathbf{1}_0^L$	✓	✓	
19	$(H_u i\tau^2 \overline{L^c})(H_d)(i\tau^2 \vec{\tau} H_u)(H_u i\tau^2 \vec{\tau} L)$	1	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$, $\mathbf{3}_0^R$, $\mathbf{3}_0^L$	✓	✓	
20	$(H_u i\tau^2 \tau^a \overline{L^c})(\tau^a H_d)(i\tau^2 \tau^b H_u)(H_u i\tau^2 \tau^b L)$	1	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$,	✓	✓	
21	$(\overline{L^c} i\tau^2 \tau^a L)(H_u i\tau^2 \tau^a)(\tau^b H_d)(H_u i\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}_{-1}^s$, $\mathbf{2}_{+1/2}^s$, $(\mathbf{3}_{-1}^s)$			✓
22	$(\overline{L^c} i\tau^2 \tau^a L)(H_d i\tau^2 \tau^a)(\tau^b H_u)(H_u i\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}_{-1}^s$, $\mathbf{2}_{+3/2}^s$, $(\mathbf{3}_{-1}^s)$			✓
23	$(\overline{L^c} i\tau^2 \vec{\tau} L)(H_u i\tau^2 \vec{\tau})(H_u)(H_d i\tau^2 H_u)$	1/4	$\mathbf{3}_{-1}^s$, $\mathbf{2}_{+1/2}^s$, $(\mathbf{1}_0^s)$			✓
24	$(\overline{L^c} i\tau^2 \tau^a L)(H_u i\tau^2 \tau^a)(\tau^b H_u)(H_d i\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}_{-1}^s$, $\mathbf{2}_{+1/2}^s$, $(\mathbf{3}_0^s)$			✓
25	$(H_d i\tau^2 H_u)(\overline{L^c} i\tau^2)(\vec{\tau} L)(H_u i\tau^2 \vec{\tau} H_u)$	1	$\mathbf{1}_0^s$, $\mathbf{2}_{+1/2}^L$, $\mathbf{2}_{+1/2}^R$, $\mathbf{3}_{-1}^s$			
26	$(H_d i\tau^2 \tau^a H_u)(\overline{L^c} i\tau^2 \tau^a)(\tau^b L)(H_u i\tau^2 \tau^b H_u)$	1	$\mathbf{3}_0^s$, $\mathbf{2}_{+1/2}^L$, $\mathbf{2}_{+1/2}^R$, $\mathbf{3}_{-1}^s$			
27	$(H_u i\tau^2 \overline{L^c})(i\tau^2 H_d)(\vec{\tau} L)(H_u i\tau^2 \vec{\tau} H_u)$	1	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{2}_{+1/2}^R$, $\mathbf{2}_{+1/2}^L$, $\mathbf{3}_{-1}^s$	✓		
28	$(H_u i\tau^2 \tau^a \overline{L^c})(i\tau^2 \tau^a H_d)(\tau^b L)(H_u i\tau^2 \tau^b H_u)$	1	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{2}_{+1/2}^R$, $\mathbf{2}_{+1/2}^L$, $\mathbf{3}_{-1}^s$	✓	✓	
29	$(H_u i\tau^2 \overline{L^c})(L)(i\tau^2 \vec{\tau} H_d)(H_u i\tau^2 \vec{\tau} H_u)$	1/4	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{2}_{+1/2}^s$, $(\mathbf{3}_{-1}^s)$	✓		
30	$(H_u i\tau^2 \tau^a \overline{L^c})(\tau^a L)(i\tau^2 \tau^b H_d)(H_u i\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{2}_{+1/2}^s$, $(\mathbf{3}_{-1}^s)$	✓	✓	
31	$(\overline{L^c} i\tau^2 \tau^a H_d)(i\tau^2 \tau^a H_u)(\tau^b L)(H_u i\tau^2 \tau^b H_u)$	1	$\mathbf{3}_{+1}^L$, $\mathbf{3}_{+1}^R$, $\mathbf{2}_{+1/2}^L$, $\mathbf{2}_{+1/2}^R$, $\mathbf{3}_{-1}^s$	✓	✓	
32	$(\overline{L^c} i\tau^2 \tau^a H_d)(\tau^a L)(i\tau^2 \tau^b H_u)(H_u i\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}_{+1}^L$, $\mathbf{3}_{+1}^R$, $\mathbf{2}_{-3/2}^s$, $(\mathbf{3}_{-1}^s)$	✓	✓	
33	$(\overline{L^c} i\tau^2 \vec{\tau} H_d)(i\tau^2 \vec{\tau} H_u)(H_u)(H_u i\tau^2 L)$	1	$\mathbf{3}_{+1}^L$, $\mathbf{3}_{+1}^R$, $\mathbf{2}_{+1/2}^L$, $\mathbf{2}_{+1/2}^R$, $\mathbf{1}_0^L$, $\mathbf{1}_0^R$	✓	✓	
34	$(\overline{L^c} i\tau^2 \tau^a H_d)(i\tau^2 \tau^a H_u)(\tau^b H_u)(H_u i\tau^2 \tau^b L)$	1	$\mathbf{3}_{+1}^L$, $\mathbf{3}_{+1}^R$, $\mathbf{2}_{+1/2}^L$, $\mathbf{2}_{+1/2}^R$, $\mathbf{3}_0^L$, $\mathbf{3}_0^R$	✓	✓	

Bonnet Hernandez O Winter JHEP **0910** (2009) 076

Decompositions (with $\mathbf{X} \leq 3$)

For $\mathbf{X} = 4$, Babu Nandi Tavartkiladze PRD80 (2009) 071702.

- Top.: Topology
- Mediators: Necessary new fields $\mathbf{X}_Y^{\mathcal{L}}$
  $\mathbf{X}$: $SU(2)$, Y: $U(1)_Y$
  $\mathcal{L}$: Lorentz property
- NU: Non-Unitary PMNS matrix
- δg_L: shift of the gauge coupling of charged leptons
- 4ℓ: four-charged lepton processes

Higher dimension, more suppression

$$
\begin{aligned}
\mathscr{L} = \mathscr{L}_{\rm SM} \quad & + \mathscr{L}^{d=5}_{\text{tree}} + \mathscr{L}^{d=5}_{\text{1-loop}} + \mathscr{L}^{d=5}_{\text{2-loop}} + \cdots \\
& + \mathscr{L}^{d=7}_{\text{tree}} + \mathscr{L}^{d=7}_{\text{1-loop}} + \mathscr{L}^{d=7}_{\text{2-loop}} + \cdots \\
& + \mathscr{L}^{d=9}_{\text{tree}} + \mathscr{L}^{d=9}_{\text{1-loop}} + \mathscr{L}^{d=9}_{\text{2-loop}} + \cdots \\
& + \mathscr{L}^{d=11}_{\text{tree}} + \mathscr{L}^{d=11}_{\text{1-loop}} + \mathscr{L}^{d=11}_{\text{2-loop}} + \cdots \\
& + \cdots
\end{aligned}
$$

More suppression
Lower $\Lambda_{\rm NP}$

Higher dimension, more suppression

Seesaw Zee Babu-Zee

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}^{d=5}_{\text{tree}} + \mathscr{L}^{d=5}_{\text{1-loop}} + \mathscr{L}^{d=5}_{\text{2-loop}} + \cdots$$
$$+ \mathscr{L}^{d=7}_{\text{tree}} + \mathscr{L}^{d=7}_{\text{1-loop}} + \mathscr{L}^{d=7}_{\text{2-loop}} + \cdots$$
$$+ \mathscr{L}^{d=9}_{\text{tree}} + \mathscr{L}^{d=9}_{\text{1-loop}} + \mathscr{L}^{d=9}_{\text{2-loop}} + \cdots$$
$$+ \mathscr{L}^{d=11}_{\text{tree}} + \mathscr{L}^{d=11}_{\text{1-loop}} + \mathscr{L}^{d=11}_{\text{2-loop}} + \cdots$$
$$+ \cdots$$

More suppression
Lower $\Lambda_{\rm NP}$

Higher dimension, more suppression

Forbidden by Z_5

$$\mathscr{L} = \mathscr{L}_{\rm SM} \; \xcancel{+ \mathscr{L}^{d=5}_{\text{tree}} + \mathscr{L}^{d=5}_{\text{1-loop}} + \mathscr{L}^{d=5}_{\text{2-loop}} + \cdots}$$

$$\boxed{+ \mathscr{L}^{d=7}_{\text{tree}}} + \mathscr{L}^{d=7}_{\text{1-loop}} + \mathscr{L}^{d=7}_{\text{2-loop}} + \cdots$$

$$+ \mathscr{L}^{d=9}_{\text{tree}} + \mathscr{L}^{d=9}_{\text{1-loop}} + \mathscr{L}^{d=9}_{\text{2-loop}} + \cdots$$

$$+ \mathscr{L}^{d=11}_{\text{tree}} + \mathscr{L}^{d=11}_{\text{1-loop}} + \mathscr{L}^{d=11}_{\text{2-loop}} + \cdots$$

$$+ \cdots$$

More suppression
Lower $\Lambda_{\rm NP}$

- **Dim.7 tree** —— Z_5 symmetry

Higher dimension, more suppression

Forbidden by Z_7

$$\mathscr{L} = \mathscr{L}_{\text{SM}} \quad + \mathscr{L}^{d=5}_{\text{tree}} + \mathscr{L}^{d=5}_{\text{1-loop}} + \mathscr{L}^{d=5}_{\text{2-loop}} + \cdots$$

$$+ \mathscr{L}^{d=7}_{\text{tree}} + \mathscr{L}^{d=7}_{\text{1-loop}} + \mathscr{L}^{d=7}_{\text{2-loop}} + \cdots$$

$$+ \mathscr{L}^{d=9}_{\text{tree}} + \mathscr{L}^{d=9}_{\text{1-loop}} + \mathscr{L}^{d=9}_{\text{2-loop}} + \cdots$$

$$+ \mathscr{L}^{d=11}_{\text{tree}} + \mathscr{L}^{d=11}_{\text{1-loop}} + \mathscr{L}^{d=11}_{\text{2-loop}} + \cdots$$

$$+ \cdots$$

More suppression
Lower Λ_{NP}

- **Dim.7 tree** —— Z_5 symmetry
- **Dim.9 tree** —— Z_7 symmetry

Higher dimension, more suppression

Forbidden by Z_5

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}^{d=5}_{\text{tree}} + \mathscr{L}^{d=5}_{\text{1-loop}} + \mathscr{L}^{d=5}_{\text{2-loop}} + \cdots$$

$$+ \mathscr{L}^{d=7}_{\text{tree}} + \mathscr{L}^{d=7}_{\text{1-loop}} + \mathscr{L}^{d=7}_{\text{2-loop}} + \cdots$$

Forbidden by Z_2

$$+ \mathscr{L}^{d=9}_{\text{tree}} + \mathscr{L}^{d=9}_{\text{1-loop}} + \mathscr{L}^{d=9}_{\text{2-loop}} + \cdots$$

$$+ \mathscr{L}^{d=11}_{\text{tree}} + \mathscr{L}^{d=11}_{\text{1-loop}} + \mathscr{L}^{d=11}_{\text{2-loop}} + \cdots$$

$$+ \cdots$$

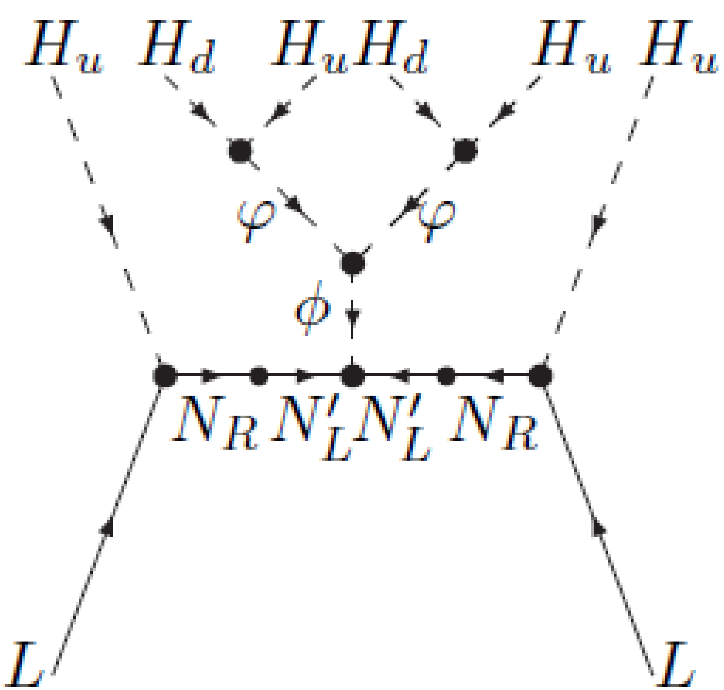
More suppression
Lower $\Lambda_{\rm NP}$

- **Dim.7 tree** —— Z_5 symmetry
- **Dim.9 tree** —— Z_7 symmetry
- **Dim.7 loop** —— $Z_5 \times Z_2$ symmetry

Extension 1: Dim.9 tree

We introduce Z_7 and the following new fields,

- two SM singlet fermions, N_R and N'_L, $q_{N_R} = q_{N'_L} = 1$
- two SM singlet scalars, ϕ and φ, $q_\phi = 5$, $q_\varphi = 6$.



- Inverse seesaw type mass matrix

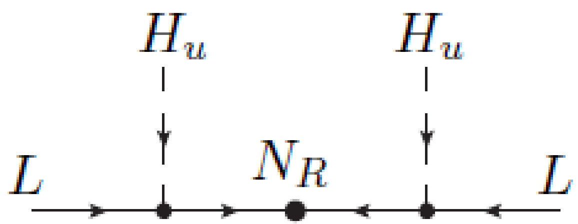
$$\begin{pmatrix} 0 & Y_\nu^{\mathsf{T}} H_u^0 & 0 \\ Y_\nu H_u^0 & 0 & M \\ 0 & M^{\mathsf{T}} & \Lambda^{-3} H_d^{02} H_u^{02} \end{pmatrix}$$

where $\Lambda^{-3} \sim 1/\Lambda_{\mathrm{NP}}^3$

Extension 2: Dim.7 loop

A trick to make a loop diagram from the tree diagram

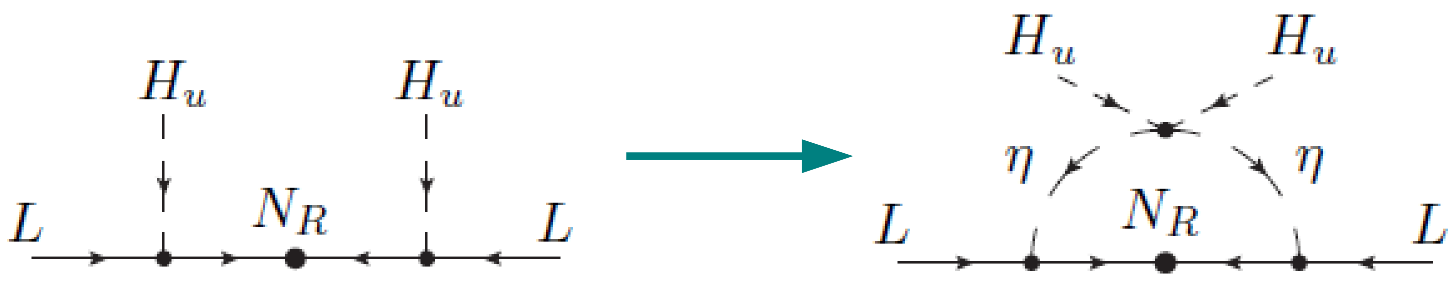
Dim.5



Extension 2: Dim.7 loop

A trick to make a loop diagram from the tree diagram

Dim.5



Dark doublet model Ma PRD73 (2006) 077301

- Introduce additional Z_2 parity
- Assign Z_2 odd charge to N_R and a new scalar doublet η
- Introduce the quatic intaraction

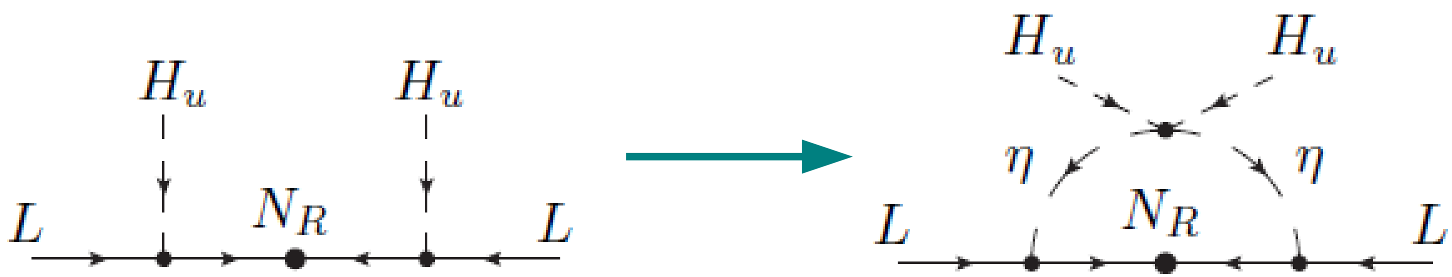
Dark doublet

$$\mathscr{L} = \frac{\lambda}{2}(\eta^\dagger H_u)(\eta^\dagger H_u) + \text{H.c.},$$

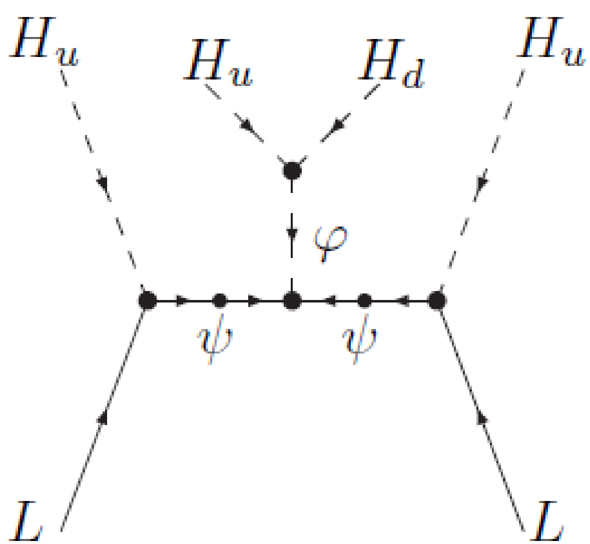
Extension 2: Dim.7 loop

A trick to make a loop diagram from the tree diagram

Dim.5



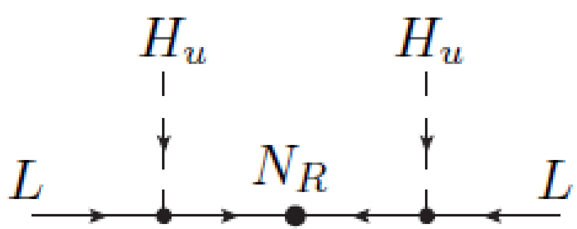
Dim.7

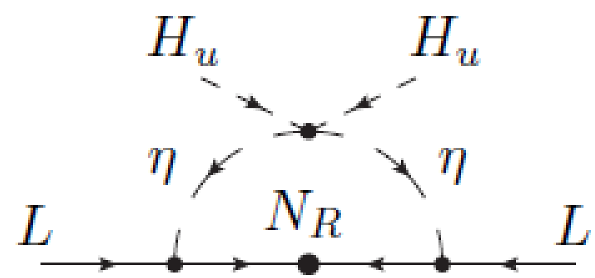


Extension 2: Dim.7 loop

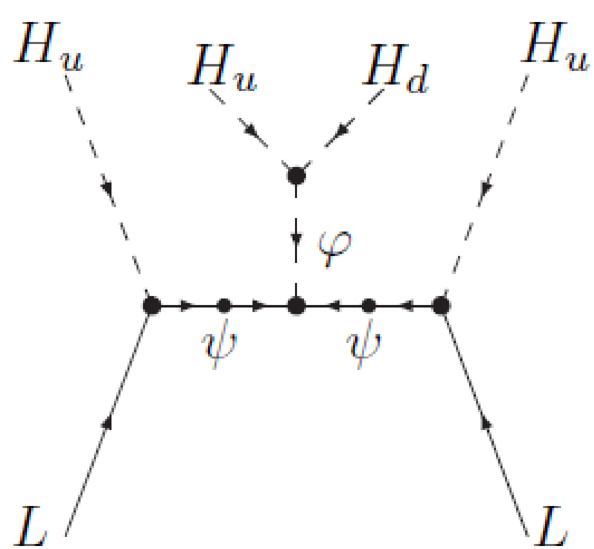
A trick to make a loop diagram from the tree diagram

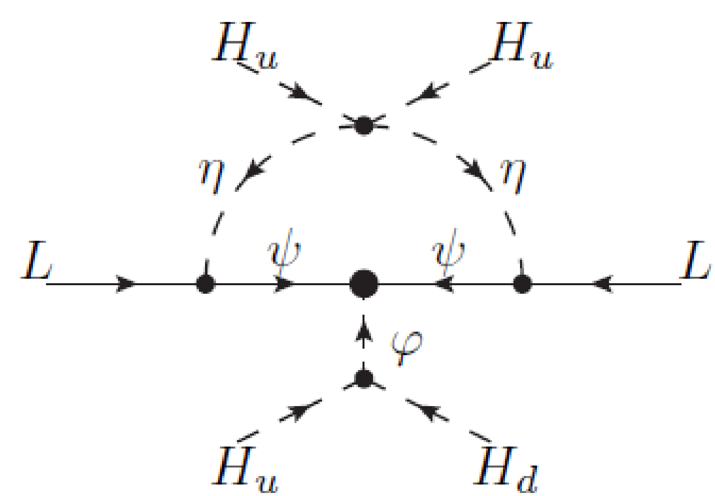
Dim.5





Dim.7



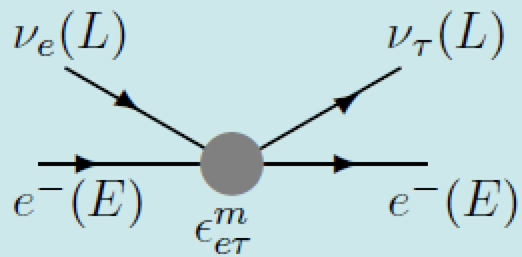


Kanemura O PL**B**694 (2010) 233

3 Summary

Summary

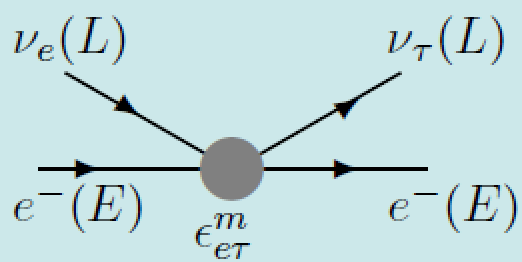
Non-standard neutrino interactions (NSI)



- New physics signal in oscillation experiments
- Expected sensitivity at Nufact: $|\epsilon^m_{\alpha\tau}| < \mathcal{O}(10^{-3})$
- What does a NSI tell us about New physics at the high *E* scales?

Bottom-up approach: List necessary interactions and mediation fields for a large (constraint-free) NSI from *d=8* ops.

Non-standard neutrino interactions (NSI)



- New physics signal in oscillation experiments
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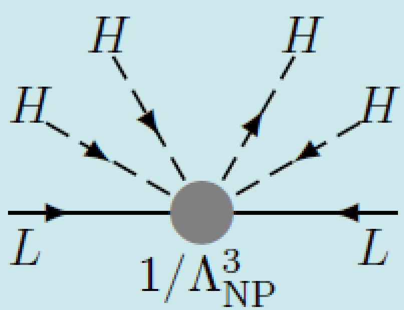
Bottom-up approach: List necessary interactions and mediation fields for a large (constraint-free) NSI from *d=8* ops.

Neutrino mass from d>5 operators



- Collider testable neutrino mass generation mechanism
- Matter parity (Z_n) forbids *d=5* Weinberg op.
- How does the high *E* completion look like?

Bottom-up approach: List the possible ways to derive the *d=7* eff. op. through tree-diagrams ——— ***Seesaw for d=7***

→ Application of Bottom-up approach: 0nu2beta, nu-DM interaction etc...

Back up

A problem in d=7 neutrino mass generation?

Goldstone boson

We introduce $Z_{n=5}$ $\rightarrow$ But $\mathscr{L}$ respects $U(1)$
$\rightarrow$ H_d which is charged under $Z_{n=5} \subset U(1)$ takes vev
$\rightarrow$ $U(1)$ is spontaneously broken
$\rightarrow$ Goldstone boson of new $U(1)$.

Way out

We allow a soft $U(1)$ violation term

$$\mathscr{L} = m_3^2 H_d \mathrm{i}\tau^2 H_u + \mathrm{H.c.}.$$

$\rightarrow$ Goldstone boson gets mass $\sim m_3$.
$\rightarrow$ Another problem: Loop $d = 5$ comes back

$$\delta \mathscr{L}^{d=7}_{\text{tree}} = \frac{1}{\Lambda^3_{\text{NP}}} (\overline{L^c} \mathrm{i}\tau^2 H_u)(H_u^{\mathsf{T}} \mathrm{i}\tau^2 L)\, (\overbrace{H_d \mathrm{i}\tau^2 H_u})$$

But the loop contribution does not dominate — controllable.

A problem in d=7 neutrino mass generation?

Goldstone boson

We introduce $Z_{n=5}$ $\rightarrow$ But $\mathscr{L}$ respects $U(1)$
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$\rightarrow$ Goldstone boson gets mass $\sim m_3$.
$\rightarrow$ Another problem: Loop $d = 5$ comes back

$$\delta \mathscr{L}^{d=5}_{\text{1-loop}} = \frac{m_3^2}{16\pi^2 \Lambda_{\mathrm{NP}}^3} (\overline{L^c} \mathrm{i}\tau^2 H_u)(H_u^{\mathsf{T}} \mathrm{i}\tau^2 L)$$

But the loop contribution does not dominate — controllable.