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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Neutrino Non-Standard Interactions: Complementarities Between LHC and Oscillation Experiments

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Based on: **arXiv: 2003.03383 [hep-ph]**
In collaboration with

K.S. Babu

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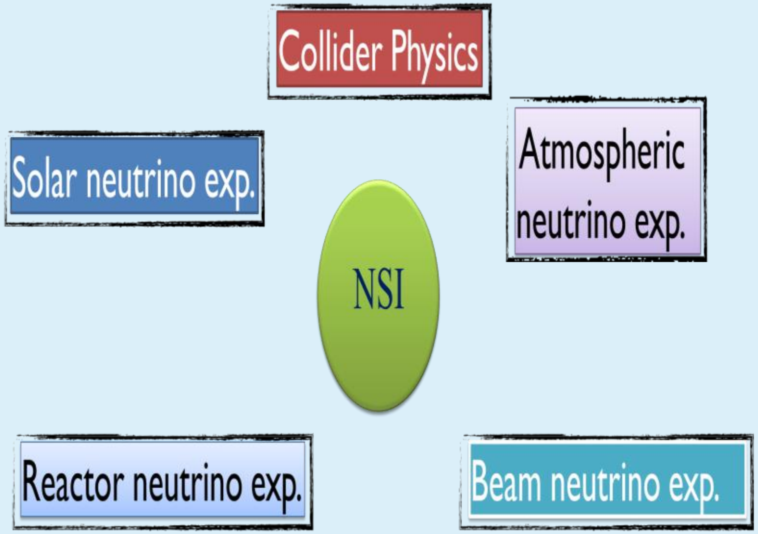
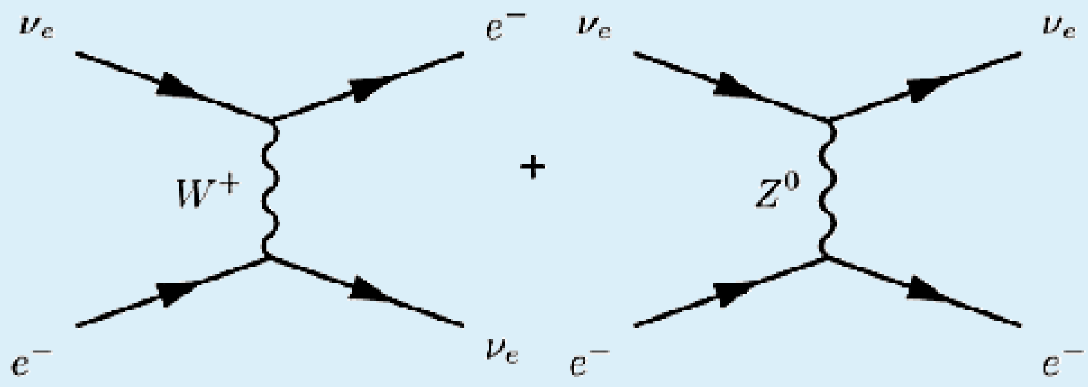
Outline

- ***Neutrino NSI***
- ***From EFTs to Simplified Models***
- ***Complementarity between LHC and neutrino experiments***
- ***Towards a UV complete scenario***
- ***Conclusion***



Neutrino Standard Interaction



Charged current and Neutral current

- Coherent forward scattering of ν_e off electron in matter generates a matter potential:

  $V = \sqrt{2} G_F N_e \approx 8.2 \times 10^{-12}$ eV in solar core (Wolfenstein)

- Modifies refractive index of ν_e (Mikheyev-Smirnov)
- Neutral current interaction is universal

Neutrino NSI

Unknown couplings involving neutrinos.

Many neutrino mass models naturally lead to NSI at some level. (see for example, B. Dev et al. (2019), K.S. Babu, B. Dev, SJ, A. Thapa (2019), Tommy Ohlsson (2012))

Potentially observable effects in neutrino oscillation experiments.

NSI effects happen in the neutrino production, propagation through matter, and the detection processes.

Most important effect of NSI is in neutrino propagation in matter

Wolfenstein (1978)

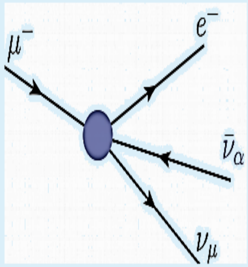
Relevant for accelerator, reactor, atmospheric, solar and supernova neutrinos.

Search for NSI is complementary to the direct search for new physics at the LHC.

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}\,G_F\varepsilon^{fP}_{\alpha\beta}\left(\overline{\nu}_\alpha\gamma_\rho\nu_\beta\right)\left(\overline{f}\gamma^\rho P f\right)$$

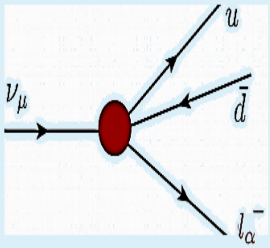
$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\delta\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\delta\mathcal{L}^{d=6} + \ldots$$

NSI affecting production



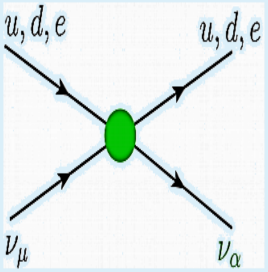
$\varepsilon^{e\mu,P}_{\mu\alpha}\left(\bar{e}\gamma^\rho P\mu\right)\left(\overline{\nu}_\mu\gamma_\rho P_L\nu_\alpha\right)$

NSI affecting detection



$\varepsilon^{ud,P}_{\mu\alpha}\left(\bar{d}\gamma^\rho Pu\right)\left(\overline{\nu}_\mu\gamma_\rho P_L l_\alpha\right)$

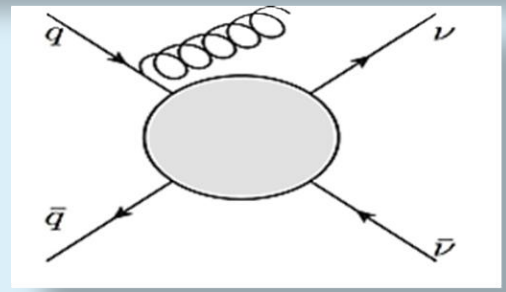
NSI affecting propagation

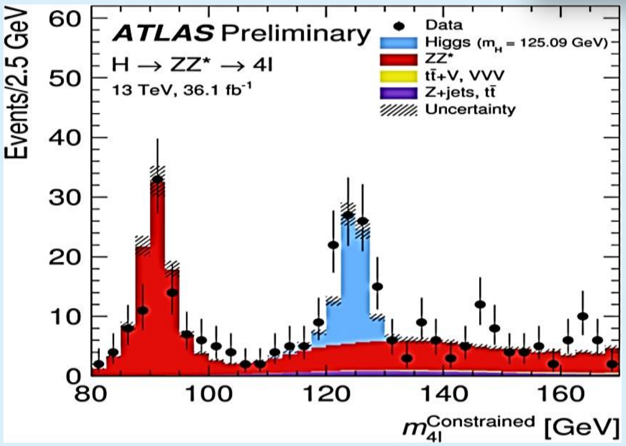


$\varepsilon^{f,P}_{\mu\alpha}\left(\bar{f}\gamma^\rho Pf\right)\left(\overline{\nu}_\mu\gamma_\rho P_L\nu_\alpha\right)$

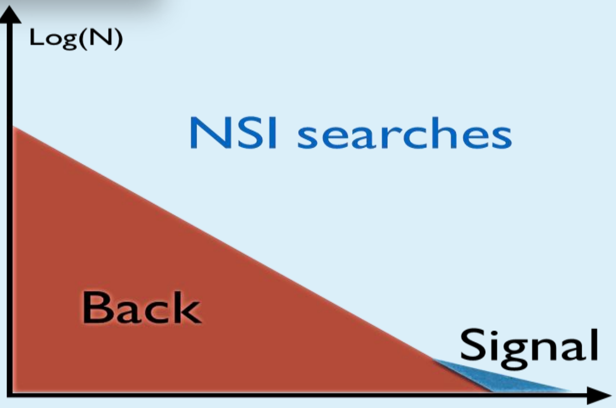
Neutrino NSI at the LHC

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}\, G_F \varepsilon^{fP}_{\alpha\beta} \left(\overline{\nu}_\alpha \gamma_\rho \nu_\beta\right) \left(\overline{f} \gamma^\rho P f\right)$$





vs.



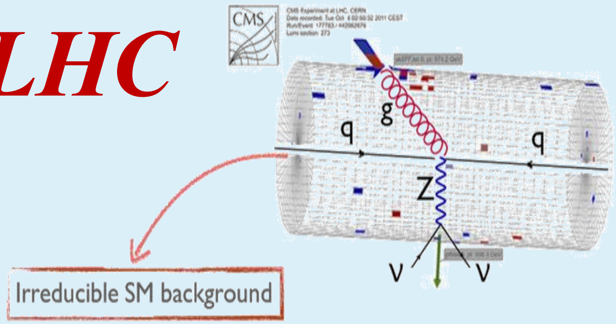
Overwhelming SM background

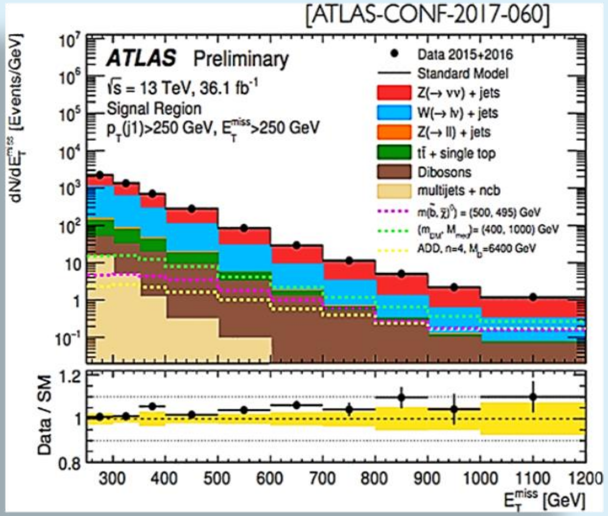
NSI contains both flavor-changing and flavor-diagonal interactions

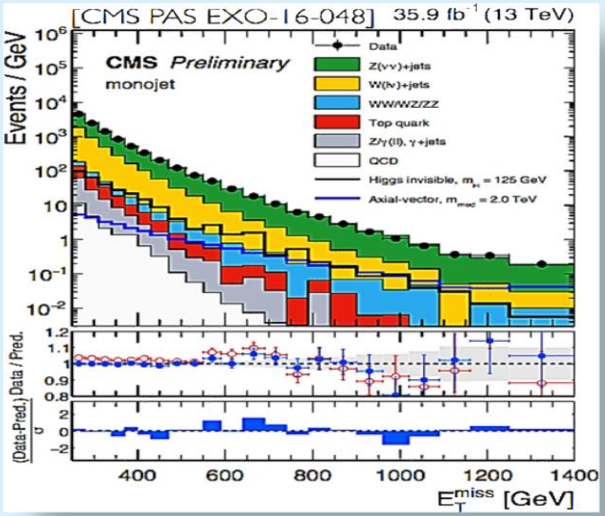
Signal: small enhancement in the tail of MET distribution

Big challenge: requires precise estimation of background

Neutrino NSI at the LHC







Dominant background:

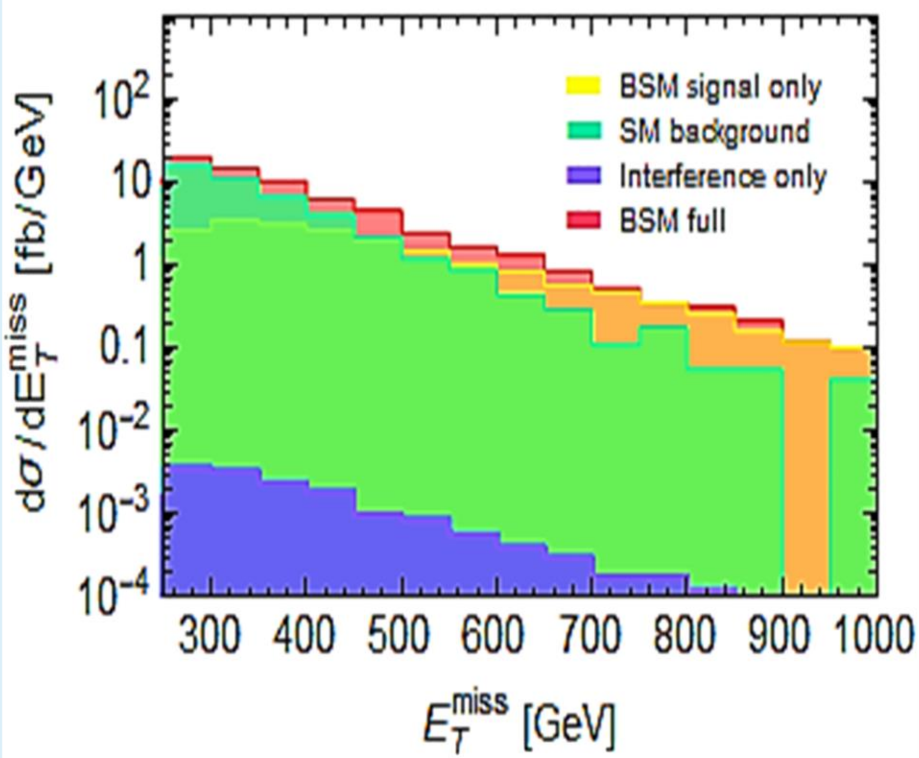
- ***pp → Z (→ νν) + jets → MET + jets***
- ***pp → W (→ lν) + jets → MET + jets (lost lepton or hadronic taus)***

Major limitation for NSI bounds: large and uncertain backgrounds. Background syst. ~5%

New theoretical and experimental efforts are significantly suppressing this syst. constraint

Neutrino NSI at the LHC

$$\sigma(pp \to j\bar{\nu}_\alpha \nu_\beta) \; = \; \sigma_{\rm SM} + \varepsilon \sigma_{\rm int} + \varepsilon^2 \sigma_{\rm NSI}$$



K.S. Babu, D. Gonçalves, **SJ**, P.A.N. Machado (2020)

NSI contains both flavor-changing and flavor-diagonal interactions

- *Flavor-changing - No SM analog*
- *Flavor-diagonal - Interfere with SM background (can display non-trivial differences to DM scenario)*

The interference effect to be negligible in the region of interest for the LHC sensitivity.

- *Therefore, the diagonal and non-diagonal NSIs result in equivalent bounds at LHC.*

Signal: small enhancement in the tail of MET distribution

Experimental bounds from mono-jet searches

E_T^{miss} [GeV]	IM1	IM2	IM3	IM4	IM5	IM6	IM7	IM8	IM9	IM10
	>250	>300	>350	>400	>500	>600	>700	>800	>900	>1000

Selection	$\langle\sigma\rangle_{obs}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}
IM1	531	19135	11700^{+4400}_{-3300}
IM2	330	11903	7000^{+2600}_{-2600}
IM3	188	6771	4000^{+1400}_{-1100}
IM4	93	3344	2100^{+770}_{-590}
IM5	43	1546	770^{+280}_{-220}
IM6	19	696	360^{+130}_{-100}
IM7	7.7	276	204^{+74}_{-57}
IM8	4.9	178	126^{+47}_{-35}
IM9	2.2	79	76^{+29}_{-21}
IM10	1.6	59	56^{+21}_{-16}

ATLAS collaboration (2018)

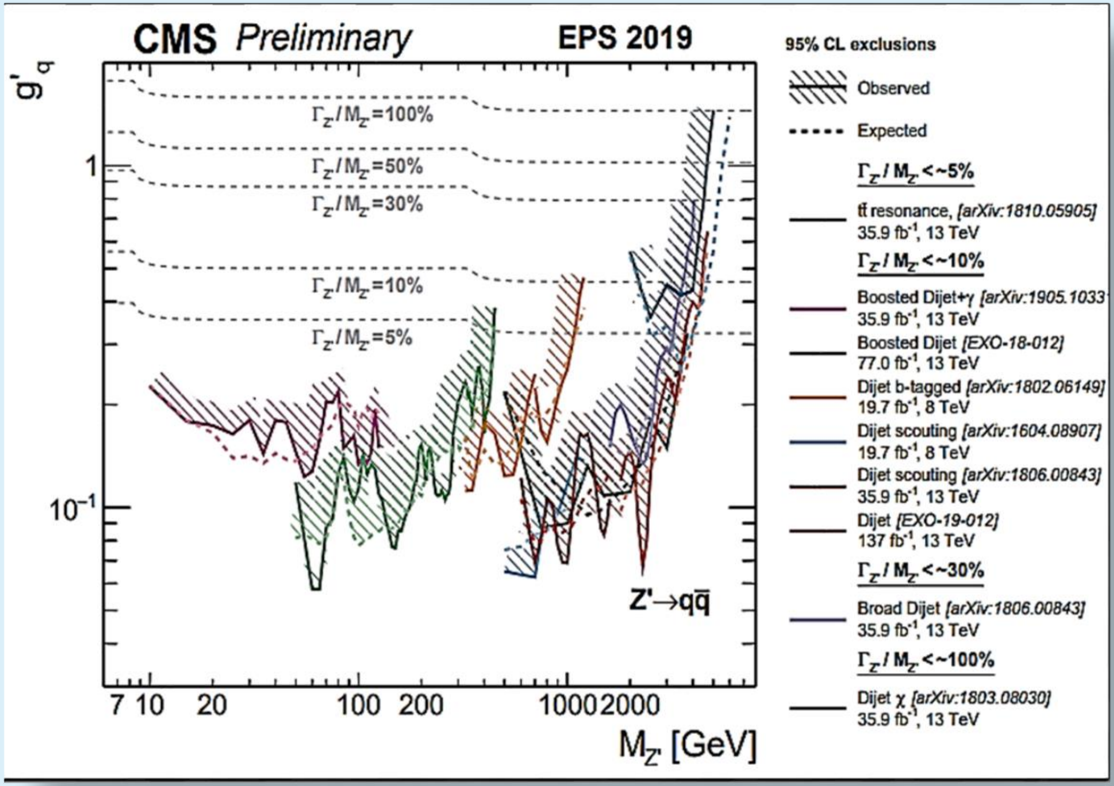
Following the recent 13 TeV ATLAS monojet study, we define jets with the anti-k_t jet algorithm and radius parameter R = 0.4, $p_{Tj} > 30$ GeV and $|\eta| < 2.8$

Events with identified electrons with $p_T > 20$ GeV or muons $p_T > 10$ GeV in the final state are vetoed.

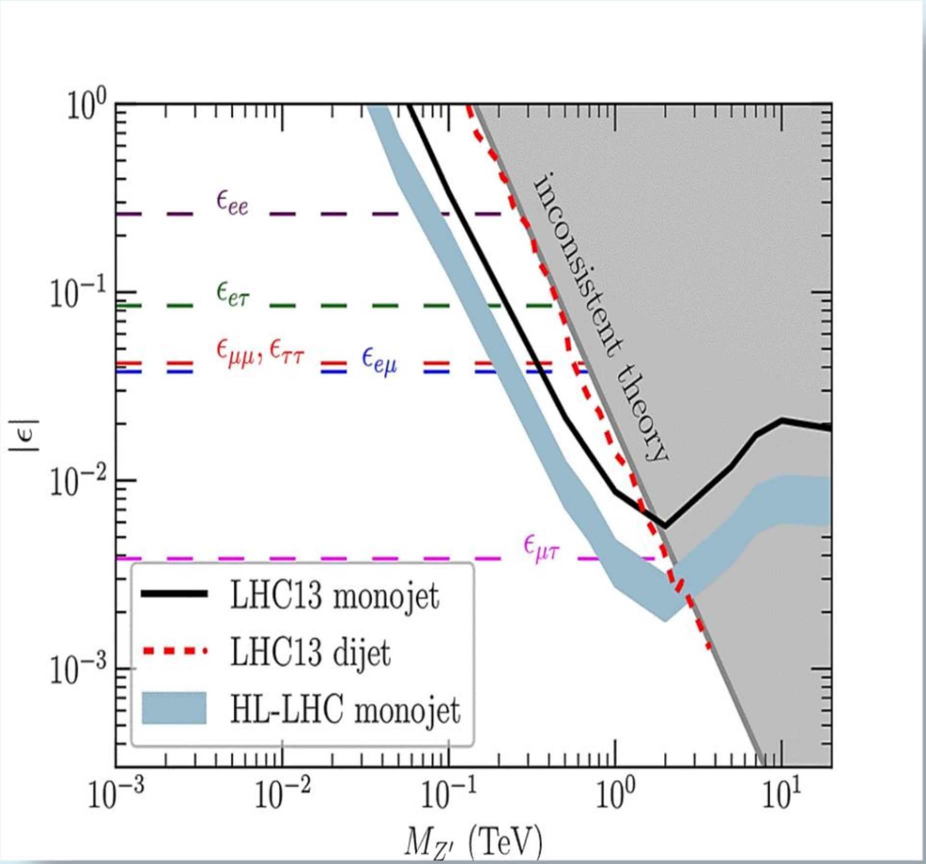
To suppress the Z+jets and W+jets backgrounds, the events are selected with missing $E_T > 250$ GeV recoiling against a leading jet with $p_{T\,j1} > 250$ GeV, $|\eta_{j1}| < 2.4$, and azimuthal separation $\Delta\varphi(j_1, \sim p_{T,miss}) > 0.4$.

Events with more than four jets are vetoed.

Experimental bounds from di-jet searches



From EFTs to Simplified Models



K.S. Babu, D. Gonçalves, **SJ**, P.A.N. Machado (2020)
P. Coloma, I. Esteban, M. C. Gonzalez-Garcia, and M. Maltoni (2019)

NSIs are generally parametrized in the EFT framework as:

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fY}\left(\bar{\nu}^{\alpha}\gamma_{\mu}\nu^{\beta}\right)\left(\bar{f}\gamma^{\mu}P_Y f\right)$$

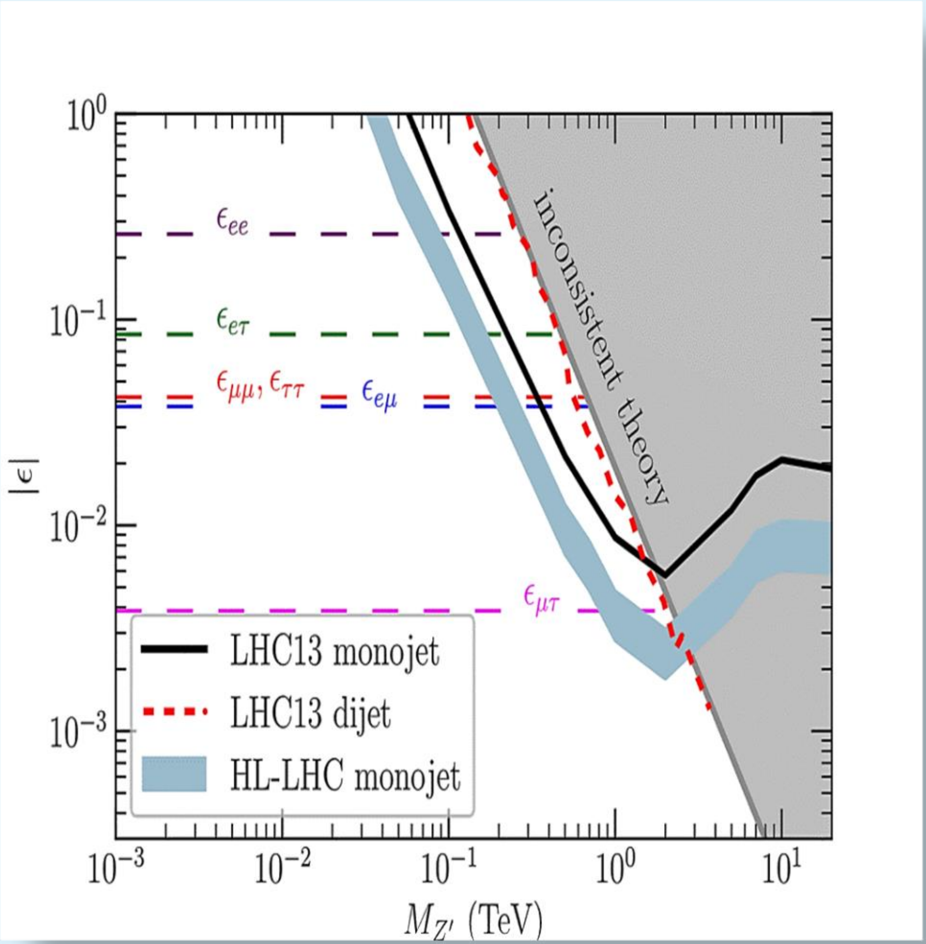
Adopting a simplified model approach, we parametrize the NSI as:

$$\mathcal{L}_{\text{NSI}}^{\text{Simp}} = \left(g_{\nu}^{\alpha\beta}\bar{\nu}_{\alpha}\gamma^{\mu}P_L\nu_{\beta} + g_{qi}^{Y}\bar{q}_i\gamma^{\mu}P_Y q_i\right) Z'_{\mu}$$

Neutrino NSIs arise in the simplified model as:

$$\epsilon_{\alpha\beta}^{u} = \epsilon_{\alpha\beta}^{d} \equiv \epsilon_{\alpha\beta} = \frac{(g_{\nu})_{\alpha\beta}\, g_{u,d}^{V}}{2\sqrt{2}G_F M_{Z'}^2}$$

Validity of this EFT at the LHC



K.S. Babu, D. Gonçalves, **SJ**, P.A.N. Machado (2020)

We can identify the EFT regime for the LHC when the mass of the mediator is much above the scale of the process involved.

For any fixed ratio $\Gamma_{Z'}/M_{Z'}$, we can write the following inequality

$$|\epsilon| \leq \frac{\sqrt{3}\pi}{\sqrt{N} G_F M_{Z'}^2} \frac{\Gamma_{Z'}}{M_{Z'}}$$

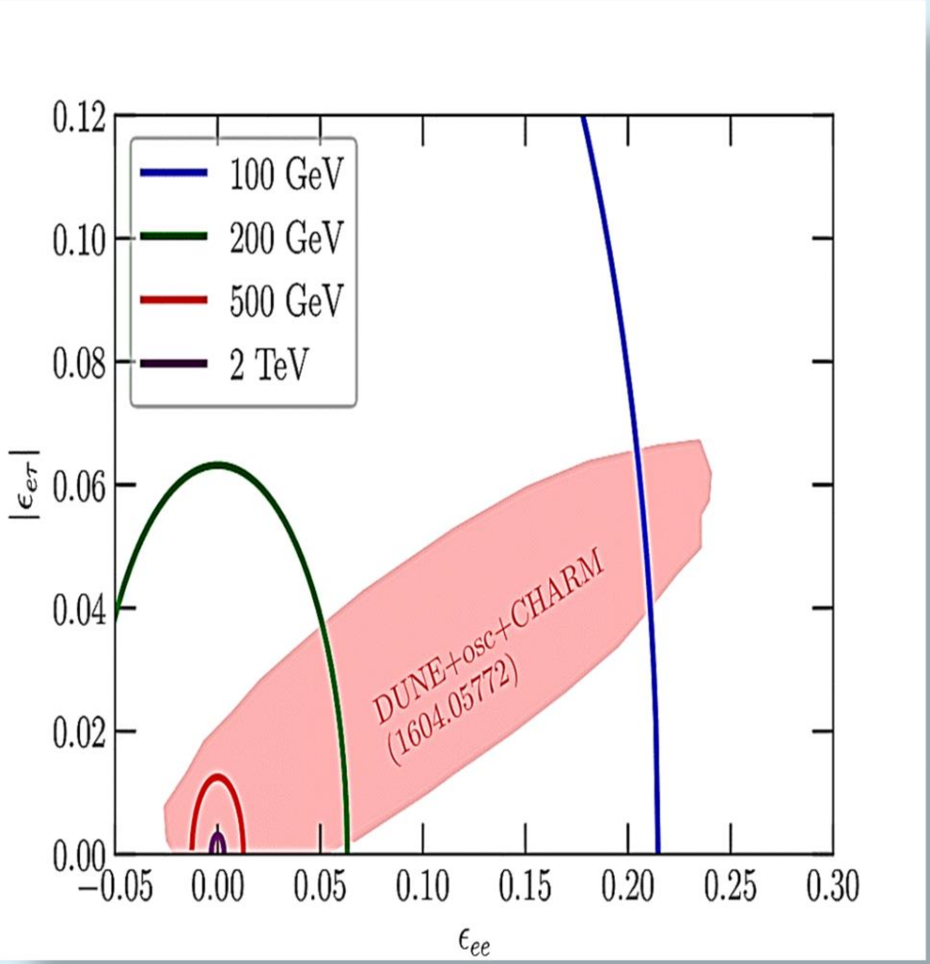
This constraint originates from the fact that the total width of the Z' should be larger than the partial widths to $q_i q_i$ and νν:

$$\Gamma_{Z'} \geq M_{Z'}/(24\pi)\left(g_\nu^2 + 3N\left\{\left(g_u^V\right)^2 + \left(g_d^V\right)^2\right\}\right)$$

Considering narrower Z' makes the constraint stronger, while broader Z' implies non-perturbativity

Traditional EFT analyses at the LHC using four-fermion operators will typically not be valid, at least having simple/minimal UV completions in mind.

Complementarity between LHC and neutrino experiments



K.S. Babu, D. Gonçalves, **SJ**, P.A.N. Machado (2020)
P. Coloma et al. (2016) , J. Liao et al. (2016)

Differently from the LHC, the effects of NSIs in neutrino oscillations strongly depend on the flavor structure of the NSI and the oscillation channel being studied.

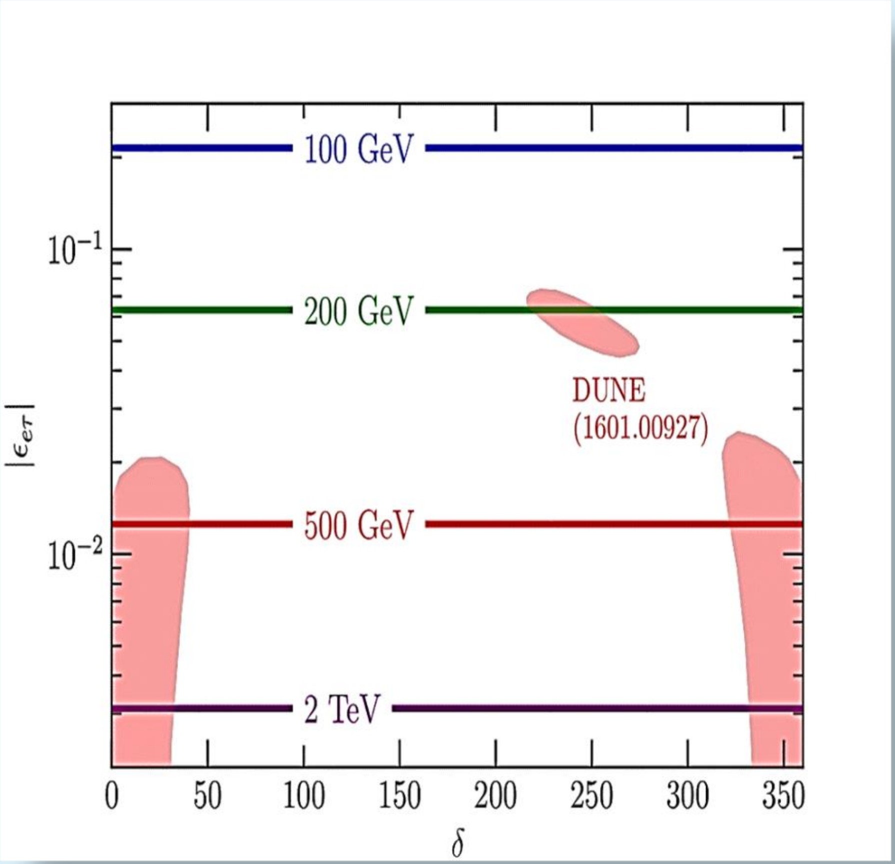
The effects of different NSIs and/or variations of the standard oscillation parameters can, in some cases, compensate each other and lead to well known degeneracies.

Disentangling those is a difficult task at neutrino facilities.

In contrast, the mono-jet signal at the LHC, does not distinguish between different choices of flavors

Besides constraining the currently allowed NSI parameter space, this feature can be further exploited to break relevant degeneracies.

Complementarity between LHC and neutrino experiments



K.S. Babu, D. Gonçalves, **SJ**, P.A.N. Machado (2020)
P. Coloma et al. (2016) , J. Liao et al. (2016)

*The **LHC** sensitivity displays a **strong dependence** on the **mediator mass**, but it is **free of parameter degeneracies**.*

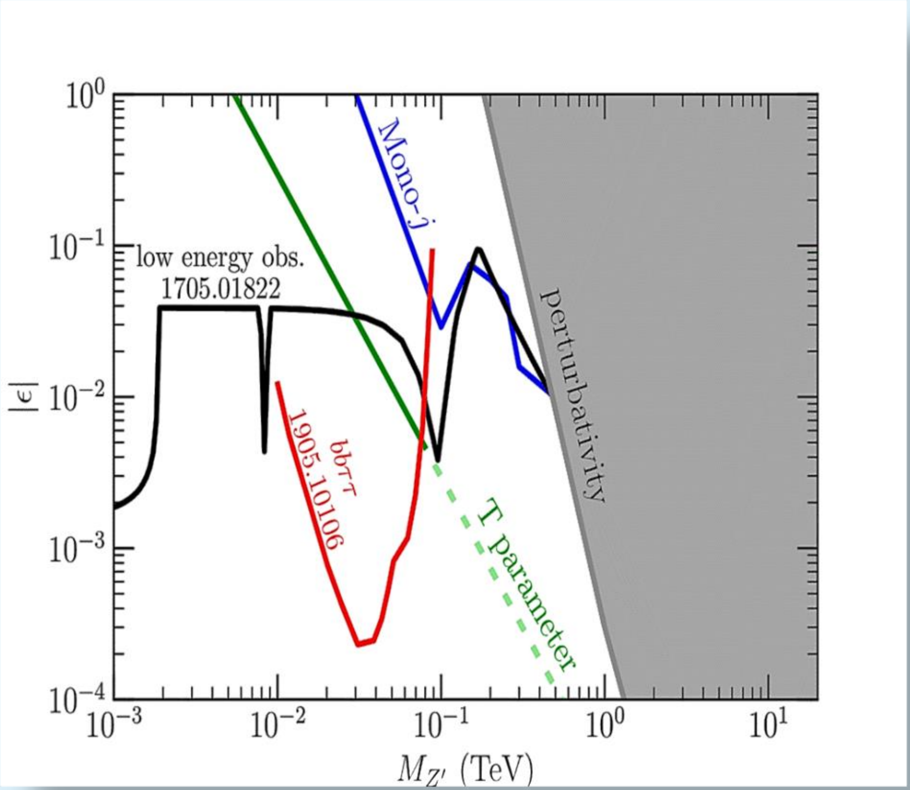
Neutrino oscillation** measurements, on the other hand, exhibit the opposite behavior: **significant degeneracies** and **no mediator mass dependence.

*The matter potential induced when neutrinos travel through a medium is not affected by a diagonal, universal contribution (as this just induces an overall phase shift on the neutrino state). On the other hand, **LHC** data is **sensitive to each and all NSI parameters independently**.*

Neutrino oscillations** are **not sensitive to axial interactions**, while **LHC** data is **sensitive to both vector and axial new physics contributions.

All these features show the synergies between oscillation measurements and collider data on probing new physics in the neutrino sector.

Towards a UV complete scenario



K.S. Babu, D. Gonçalves, **SJ**, P.A.N. Machado (2020)

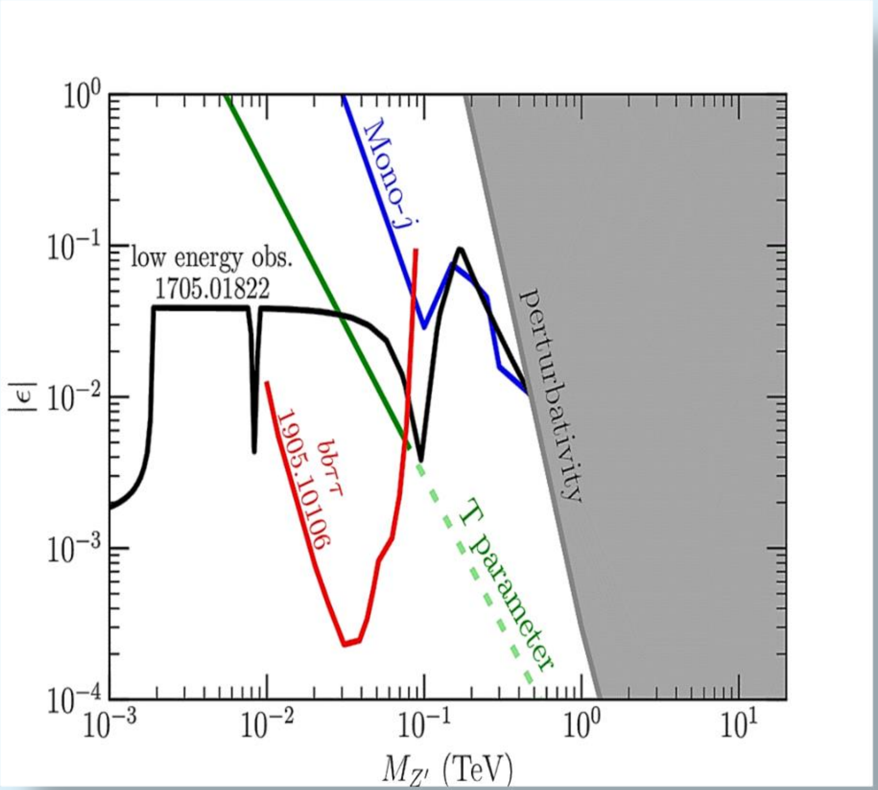
*Any **UV complete model** of neutrino NSI is expected to provide a more extensive phenomenology, especially since neutrinos are in the same $SU(2)_L$ doublet as charged leptons.*

In this UV completion the $B-L$ number is gauged, but only for the third family.

Heavy mediators are strongly constrained by LHC data.

Low mediators constrained by low-energy experiments.

Towards a UV complete scenario



K.S. Babu, D. Gonçalves, **SJ**, P.A.N. Machado (2020)
K.S. Babu, A. Friedland, P.A.N. Machado, I. Mocioiu (2017)
F. Elahi and A. Martin (2019)

Low energy constraints, dedicated LHC searches, and missing energy signatures provide strong constraints for different masses of the mediator.

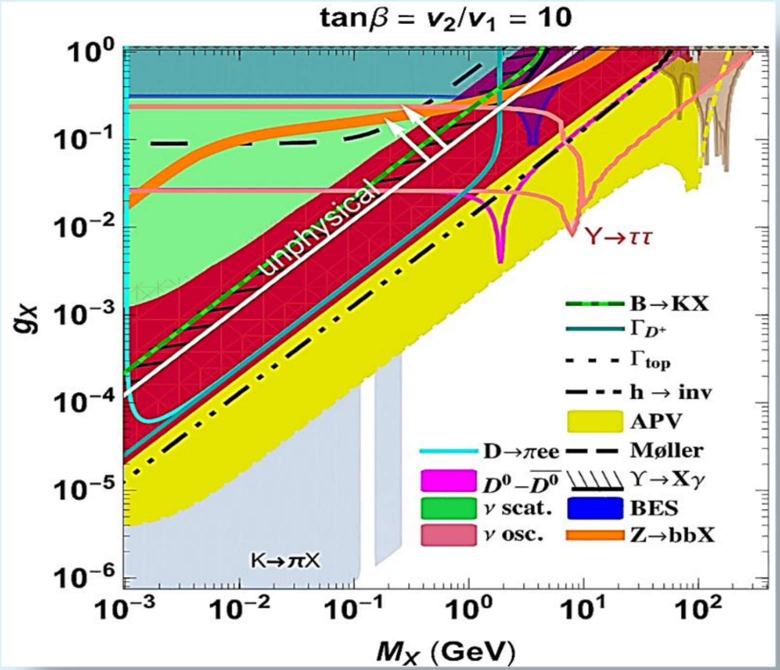
*For masses **below about 10 GeV**, low energy observables tend to dominate.*

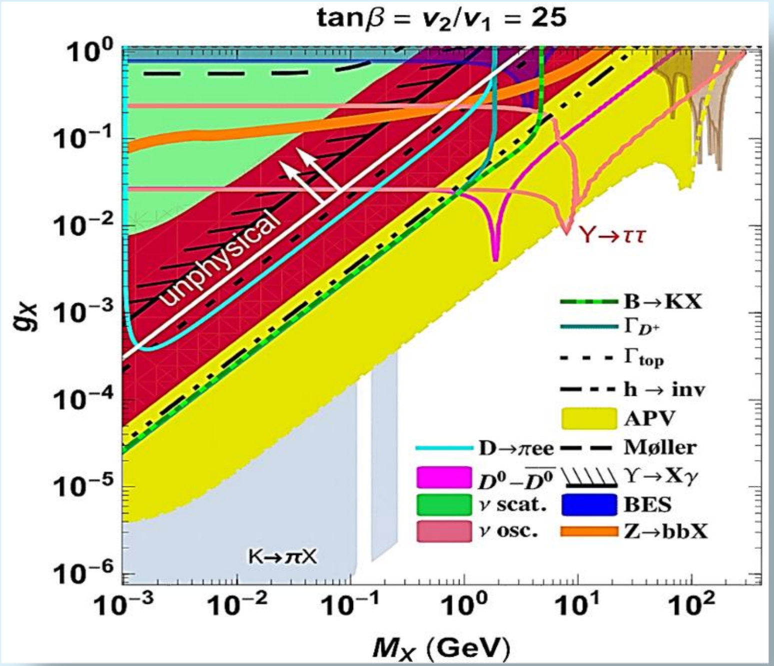
*In the intermediate regime **10 − 100 GeV**, dedicated searches for visible signatures at the LHC become more relevant.*

*Finally, from **0.1 − 1 TeV** LHC mono-jet searches, low energy observables and electroweak precision observables (up to the T parameter model dependence) play the leading role.*

This makes manifest the complementarities among collider data, oscillation measurements, and other low energy observables.

Towards a UV complete scenario





K.S. Babu, D. Gonçalves, **SJ**, P.A.N. Machado (2020)

For other collider studies on NSI: See A. Friedland, M. L. Graesser, I. M. Shoemaker, and L. Vecchi (2011), D. Choudhury, K. Ghosh, and S. Niyogi (2018), T. Han, J. Liao, H. Liu, and D. Marfatia (2019), J. Heeck, M. Lindner, W. Rodejohann, S. Vogl (2018), D. Liu, C. Sun, J. Gao (2020)

NSI in radiative neutrino mass models

An alternative to high scale seesaw *for neutrino mass generation is "radiative mechanism"*

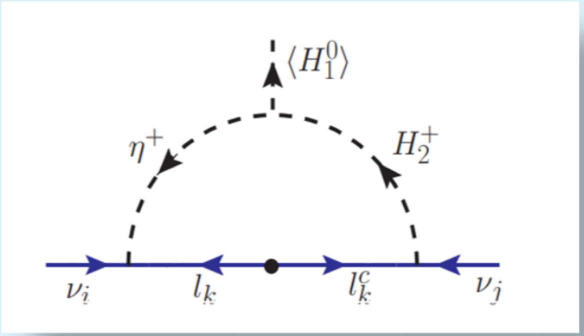
Small, finite Majorana masses are generated at the quantum level.

The charged scalars ***induce NSI at tree level***

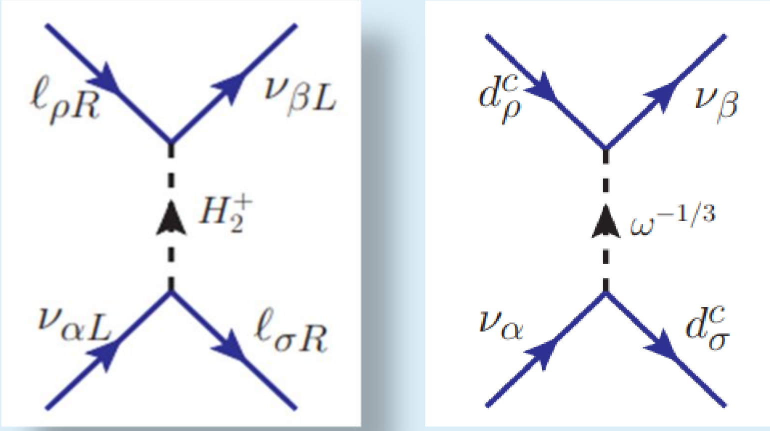
Smallness of neutrino mass is explained via ***loop and chiral suppression.***

Simple realization is the Zee Model, which has a second Higgs doublet and a charged singlet.

We have systematically analyzed these models for their predicted NSI.



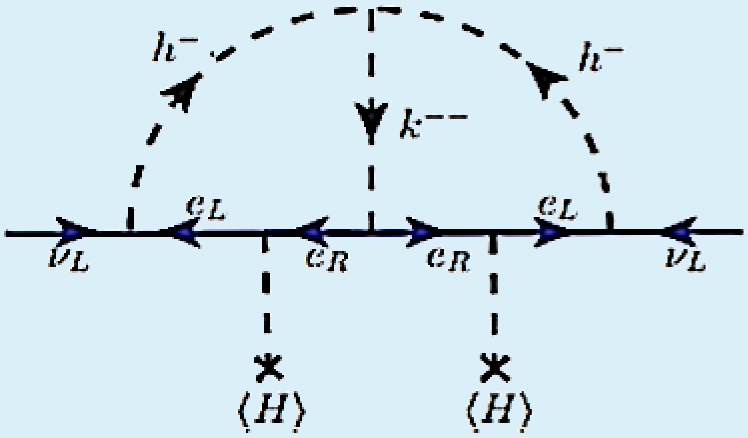
Neutrino mass



NSI in radiative models

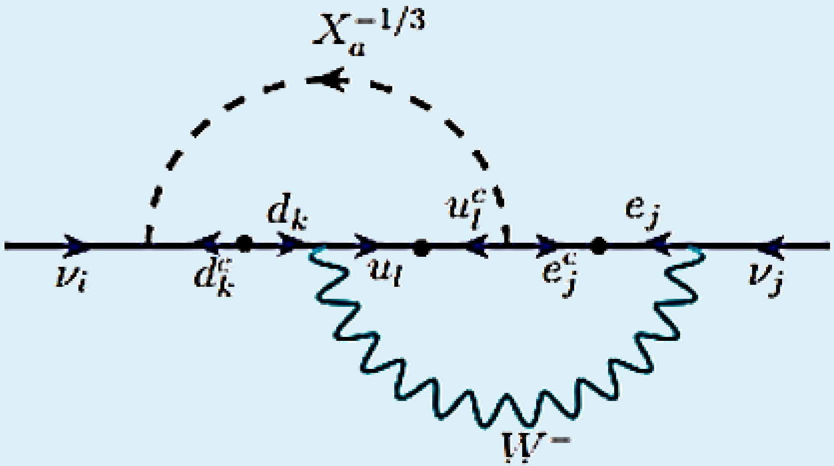
Type-I Radiative Mechanism

- Obtained from effective d = 7, 9, 11... operators with $\Delta L = 2$ selection rule
- If the loop diagram has at least one Standard Model particle, this can be cut to generate such effective operators



$\mathcal{O}_9 = L_i L_j L_k e^c L_l e^c \epsilon^{ij} \epsilon^{kl}$

Zee, Babu



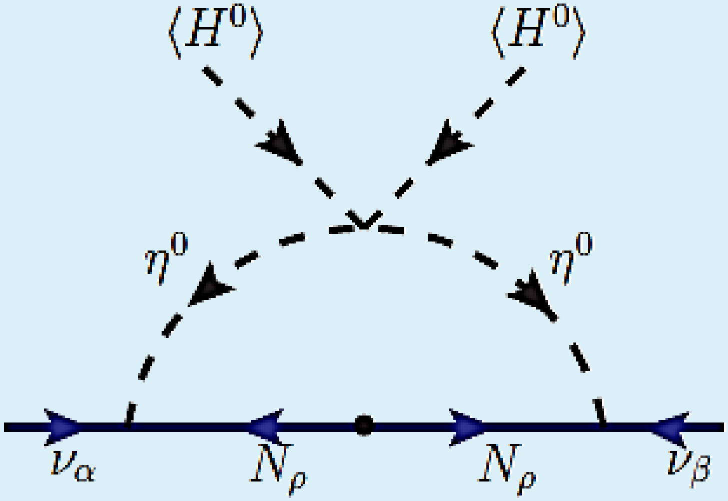
$\mathcal{O}_8 = L_i \bar{e^c} \bar{u^c} d^c H_j \epsilon^{ij}$

Babu, Julio (2010)

Classification: Babu, Leung (2001),
de Gouvea, Jenkins (2008)
Volkas et al. (2017)

Type-II Radiative Mechanism

- No Standard Model particles inside loop
- Cannot be cut to generate $d = 7, 9, \ldots$ operators
- Scotogenic model is an example



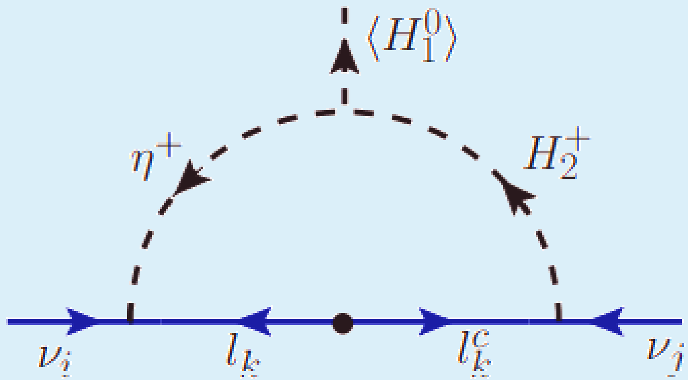
- Neutrino mass has no chiral suppression; new scale can be large
- Other considerations (dark matter) require TeV scale new physics Ma (2006)
- These models predict negligible NSI

NSI in Zee model

- Yukawa coupling matrices:

$$f = \begin{pmatrix} 0 & f_{e\mu} & f_{e\tau} \\ -f_{e\mu} & 0 & f_{\mu\tau} \\ -f_{e\tau} & -f_{\mu\tau} & 0 \end{pmatrix}, \qquad Y = \begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

- Neutrino mass



$$M_\nu = \kappa \left(f M_l Y^T + Y M_l f^T \right)$$
$$\kappa = \frac{1}{16\pi^2} \sin 2\varphi \log \frac{m_{h^+}^2}{m_{H^+}^2}$$

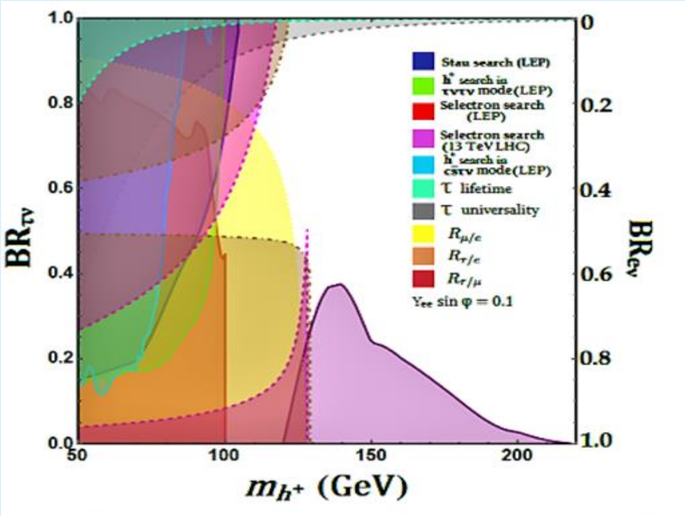
- If $Y \propto M_l$, which happens with a Z_2, then model is ruled out

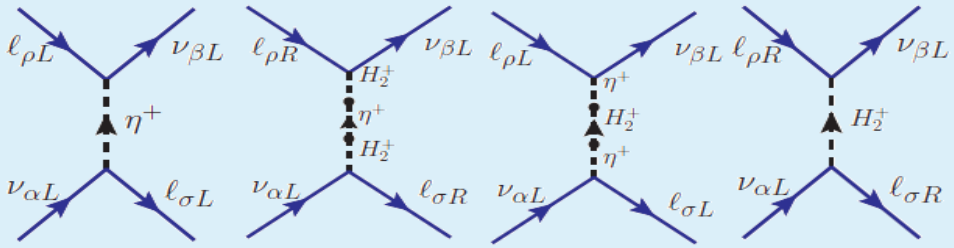
Wolfenstein (1980)

- In general, Y is not proportional to M_l, and the model gives reasonable fit to oscillation data
- NSI arises via the exchange of $h^\pm$ and $H^\pm$

NSI in Zee model

- Electroweak T parameter sets limits on mixing $\sin\varphi$
- $\mu \to e + \gamma$ type processes limit products of couplings
- $\mu \to 3e$ type processes lead to further constraints
- τ lifetime and universality constraints
- Lepton universality in $W^\pm$ decays
- Theoretical constraint from avoiding charge breaking minima
- LEP direct search limits on charged scalars
- Constraints from LHC searches
- Higgs precision physics limits





- The singly-charged scalars η^+ and H^+ induce NSI at tree level:

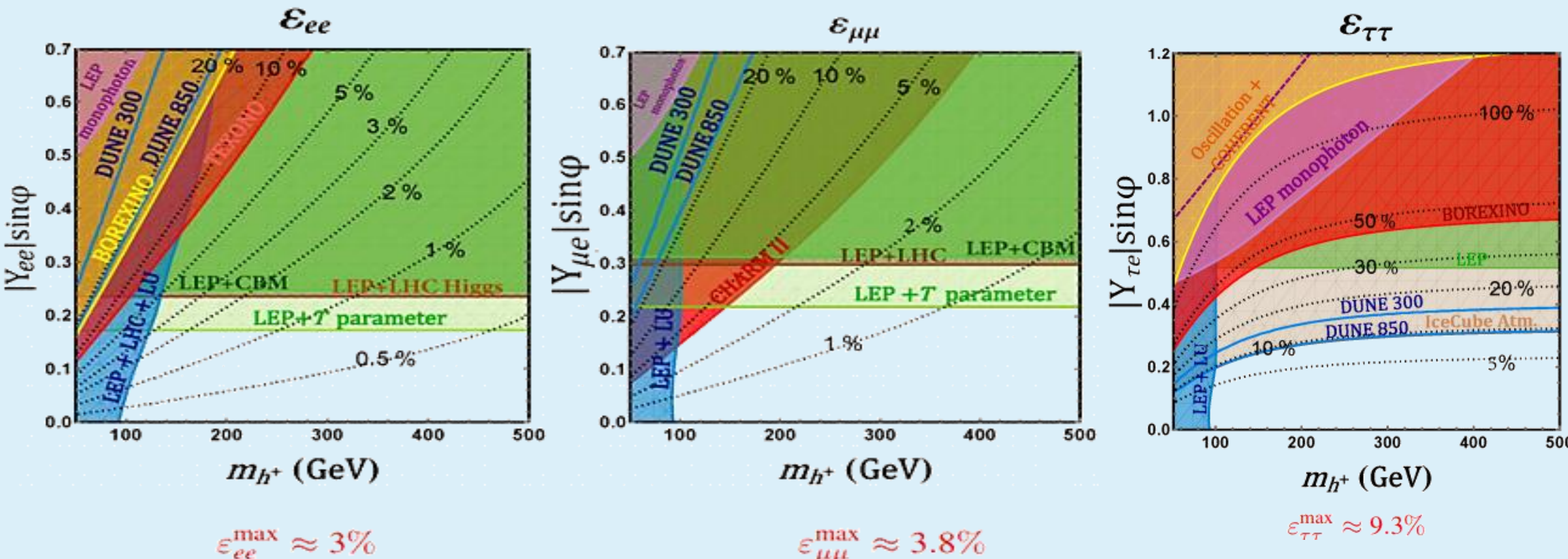
$$\varepsilon_{\alpha\beta} \equiv \varepsilon_{\alpha\beta}^{(h^+)} + \varepsilon_{\alpha\beta}^{(H^+)} = \frac{1}{4\sqrt{2}G_F} Y_{\alpha e} Y_{\beta e}^\star \left(\frac{\sin^2\varphi}{m_{h^+}^2} + \frac{\cos^2\varphi}{m_{H^+}^2} \right)$$

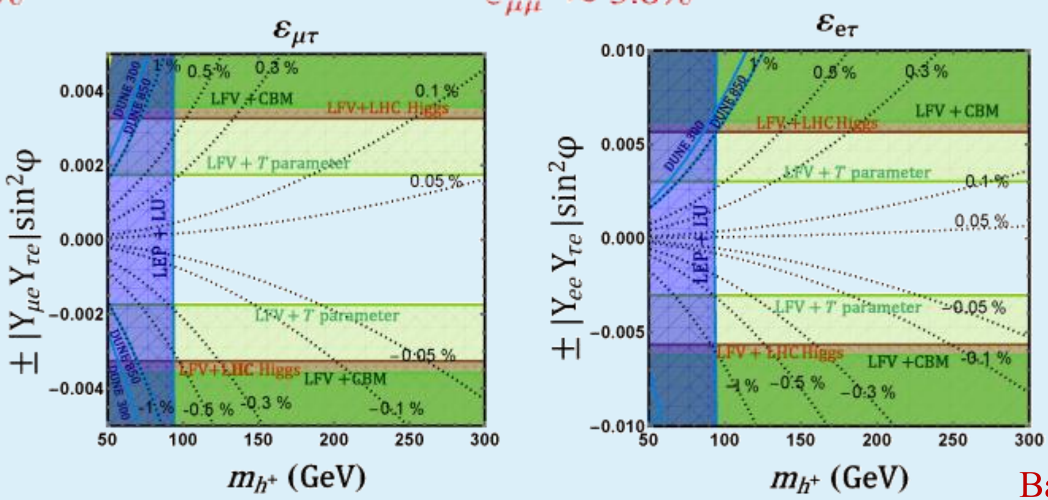
- For a benchmark value of 100 GeV masses, we have:

$$\varepsilon_{ee}^{\max} \approx 3.5\%\,, \quad \varepsilon_{\mu\mu}^{\max} \approx 5.6\%\,, \quad \varepsilon_{\tau\tau}^{\max} \approx 71.6\%$$

Babu, Dev, **SJ**, Thapa (2019)

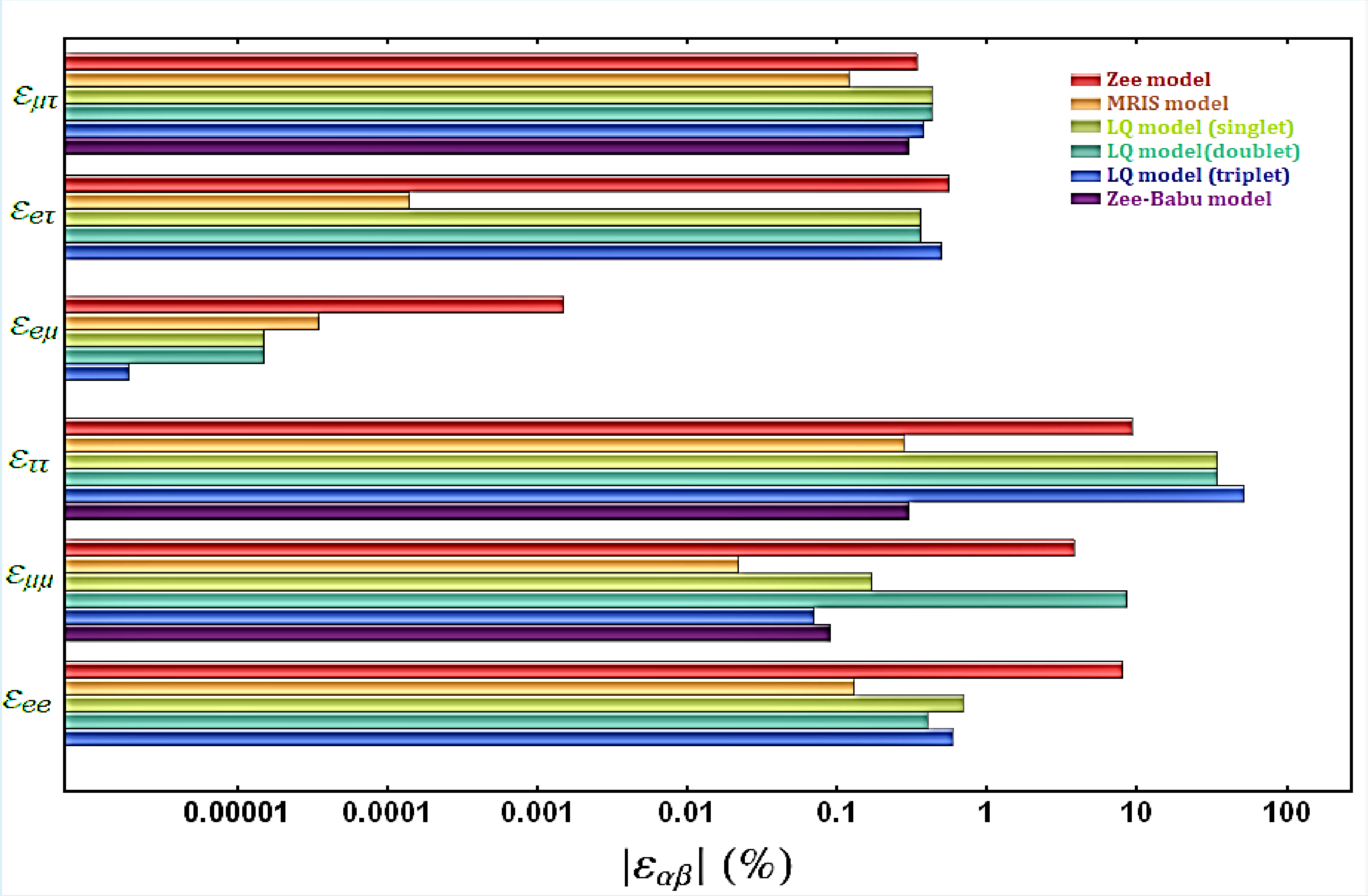
NSI in Zee model





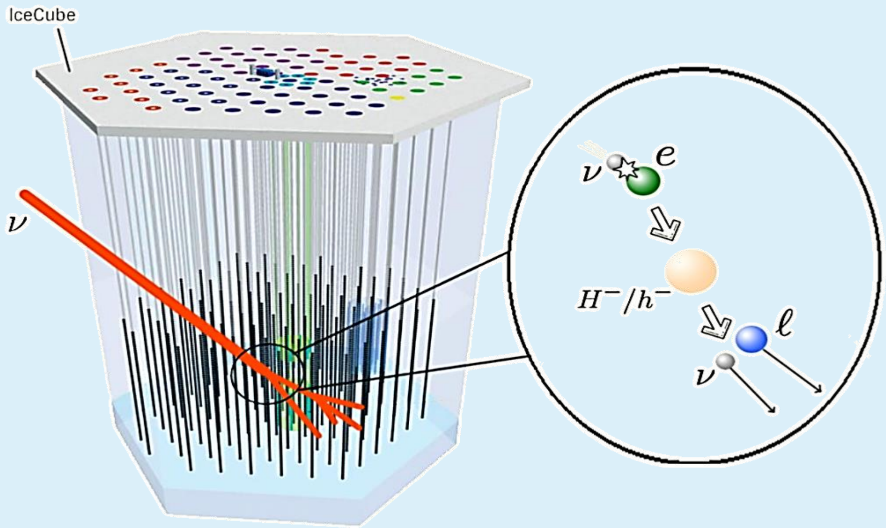
Babu, Dev, **SJ**, Thapa (2019)

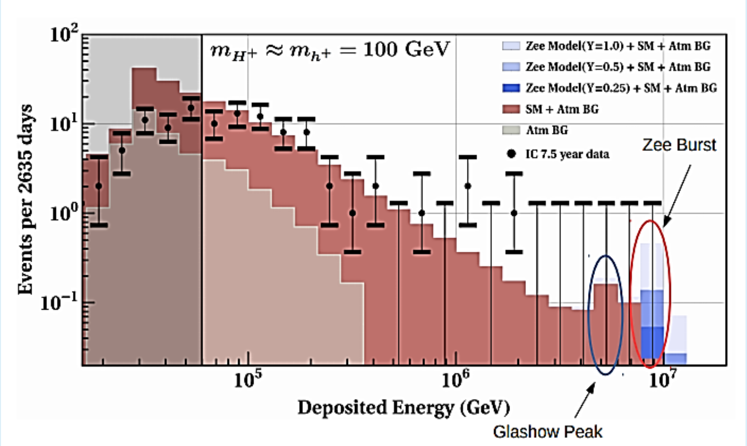
Summary of NSI in radiative models



Babu, Dev, **SJ** , Thapa (2019)

Zee-Burst: A new test of NSI at IceCube





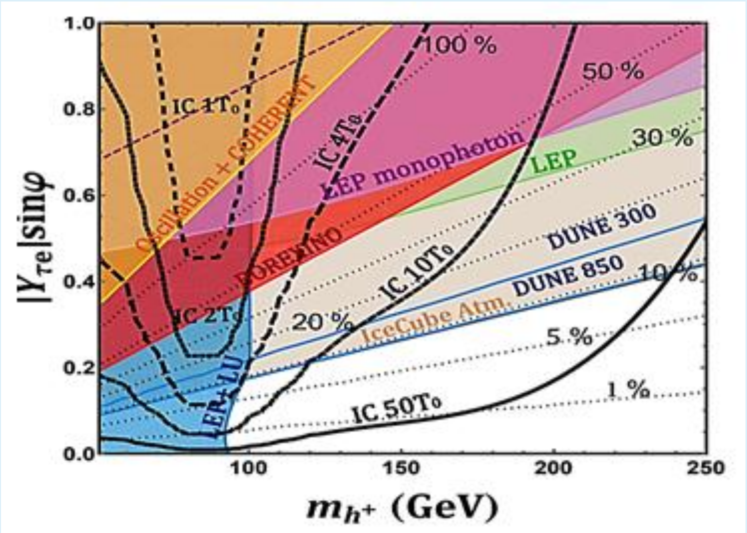
- Ultra High Energy neutrinos at IceCube can probe NSI in the Zee model
- $\overline{\nu_e} + e^- \to W^- \to$ anything has a resonant enhancement at

$$E_\nu = \frac{m_W^2}{2m_e} = 6.3\,\mathrm{PeV} \quad \text{Glashow resonance}$$

- Since $h^\pm$ and $H^\pm$ in Zee model are allowed to be as light as 100 GeV, $\overline{\nu}_\alpha + e^- \to h^- \to$ anything is resonantly enhanced

$$E_\nu = \frac{m_h^2}{2m_e} \simeq 9.3\,\mathrm{PeV} \quad \text{“Zee burst”}$$

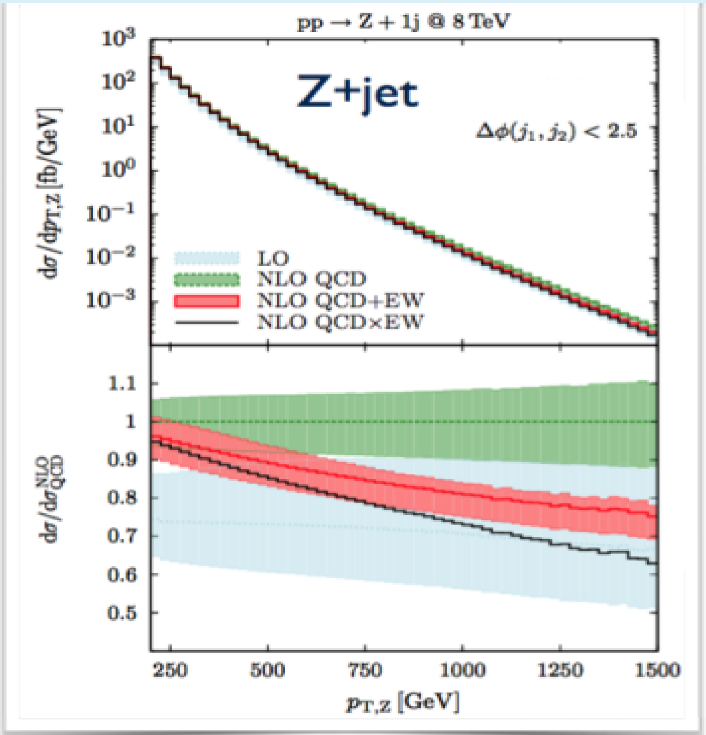
- We have analyzed this possibility of “Zee burst”



Babu, Dev, **SJ** , Sui **(PRL’ 2019)**


Thank you!

Monojets: systematic uncertainties



Lindert, Pozzorini, et al '17

- QCD corrections:
  Moderate and stable
  NLO uncert. 5-10%

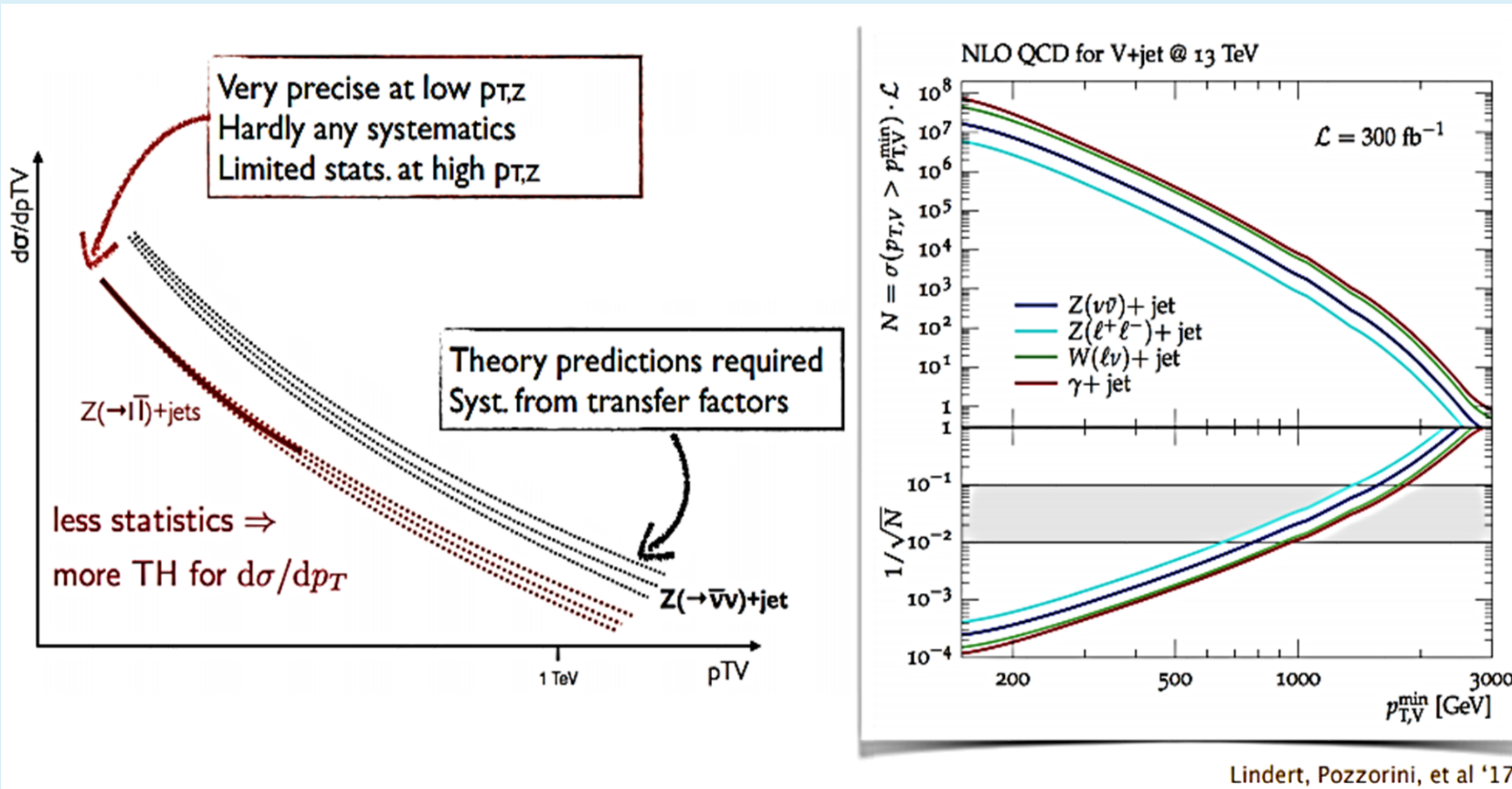
- EW corrections:
  EW corrections> QCD corrections for $p_{T,Z}$>350 GeV

→ Given that QCD and EW corrections are large, mixed QCD-EW corrections have to be considered

- State of the art of MC simulation: NNLO QCD + NLO EW
  "Simply" accounting for higher orders is not enough. Uncertainties O(5%)
  We need new ingredients to control the errors!

Slide courtesy: Dorival

Monojets: systematic uncertainties



Slide courtesy: Dorival