

# Neutrinos in Muon Collisions

Dr Innes Bigaran || Virginia Tech

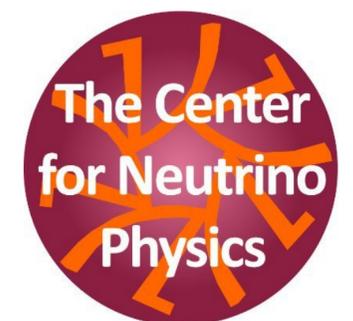
*Based on [IB, de Gouvêa, Han, Low, Ma, Tabrizi & Xie], In progress*



# Neutrinos in Muon Collisions

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# Lepton physics at a Neutrino Collider

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# Overview

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1. Lepton flavour physics
2. Electroweak Radiation
3.  $\nu$  complementarity in SMEFT

# Overview

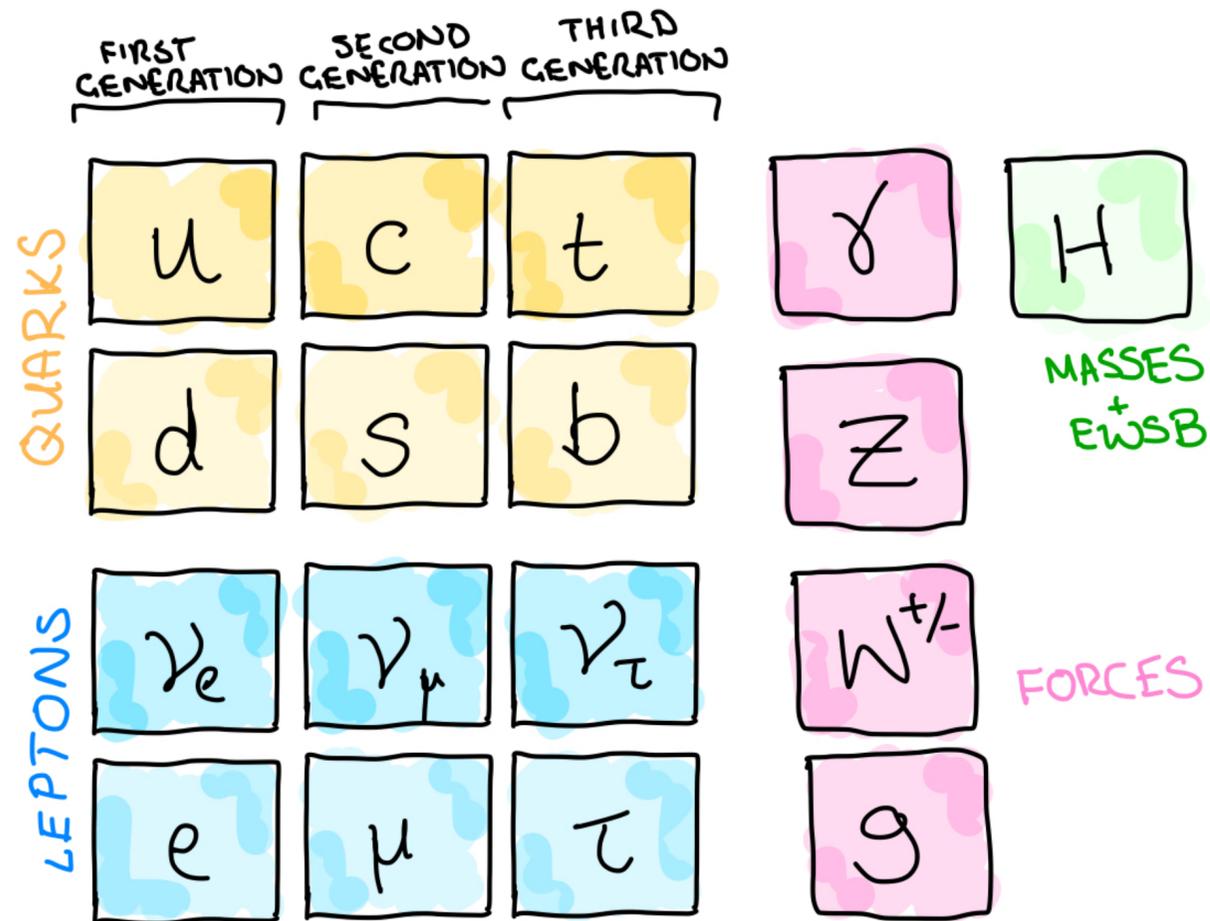
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# Why study flavor?



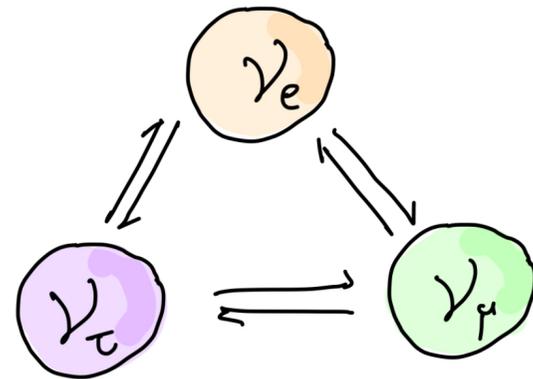
- The SM is a semi-empirical theory. Requires experimental input to fix  $\sim 27$  free parameters to fully prescribe it

Gauge	Force interactions	3 gauge couplings
Higgs	EWSB and W/Z masses	2 Higgs-potential couplings
Flavour	Quark and lepton masses and	$\sim 22$ free parameters

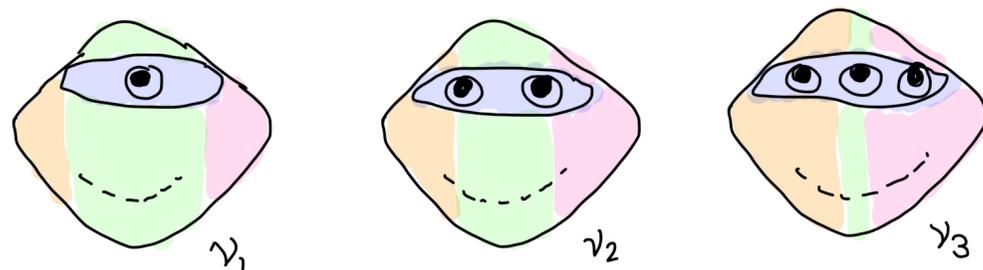
- We need experimentalists to measure these parameters. Can we understand the underlying symmetries that guide them?

“Standard Model Flavor Puzzle”

# Why study lepton flavor?



Mass eigenstates are linear combinations of flavor eigenstates



- In the SM, neutrinos are *massless* particles and lepton **flavor symmetry** is conserved

$$\mathcal{G}_L = U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau$$

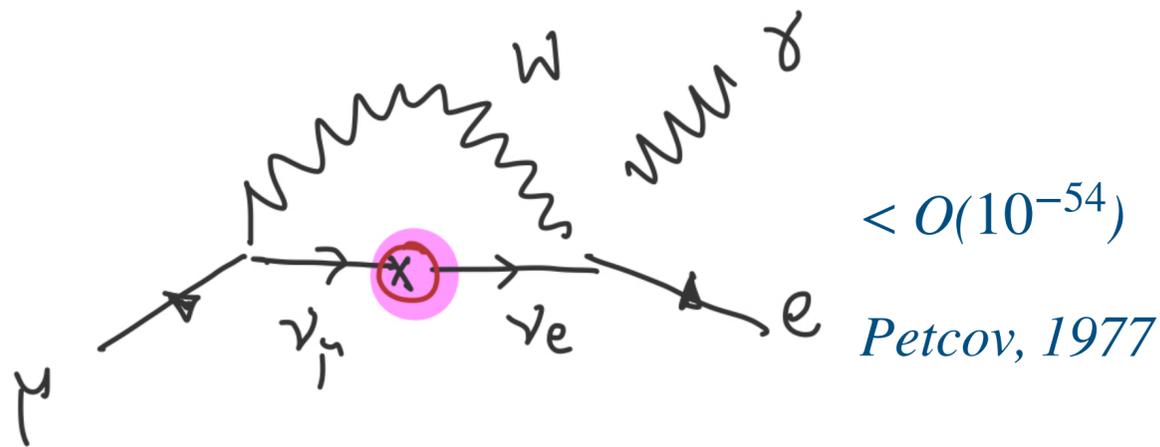
- Flavored lepton number is conserved in SM interactions, thus also total lepton number

$$L = L_\mu + L_e + L_\tau$$

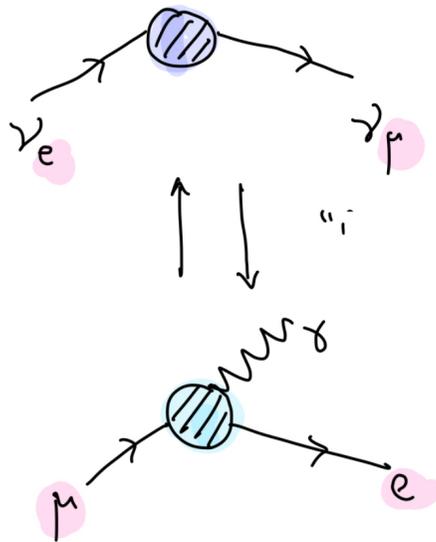
But neutrinos aren't massless, so this symmetry must be broken!

Neutrino masses are BSM physics!

# Where else do we look for flavor violation?



Many models for  
neutrino mass  
introduce other new  
sources of LFV...



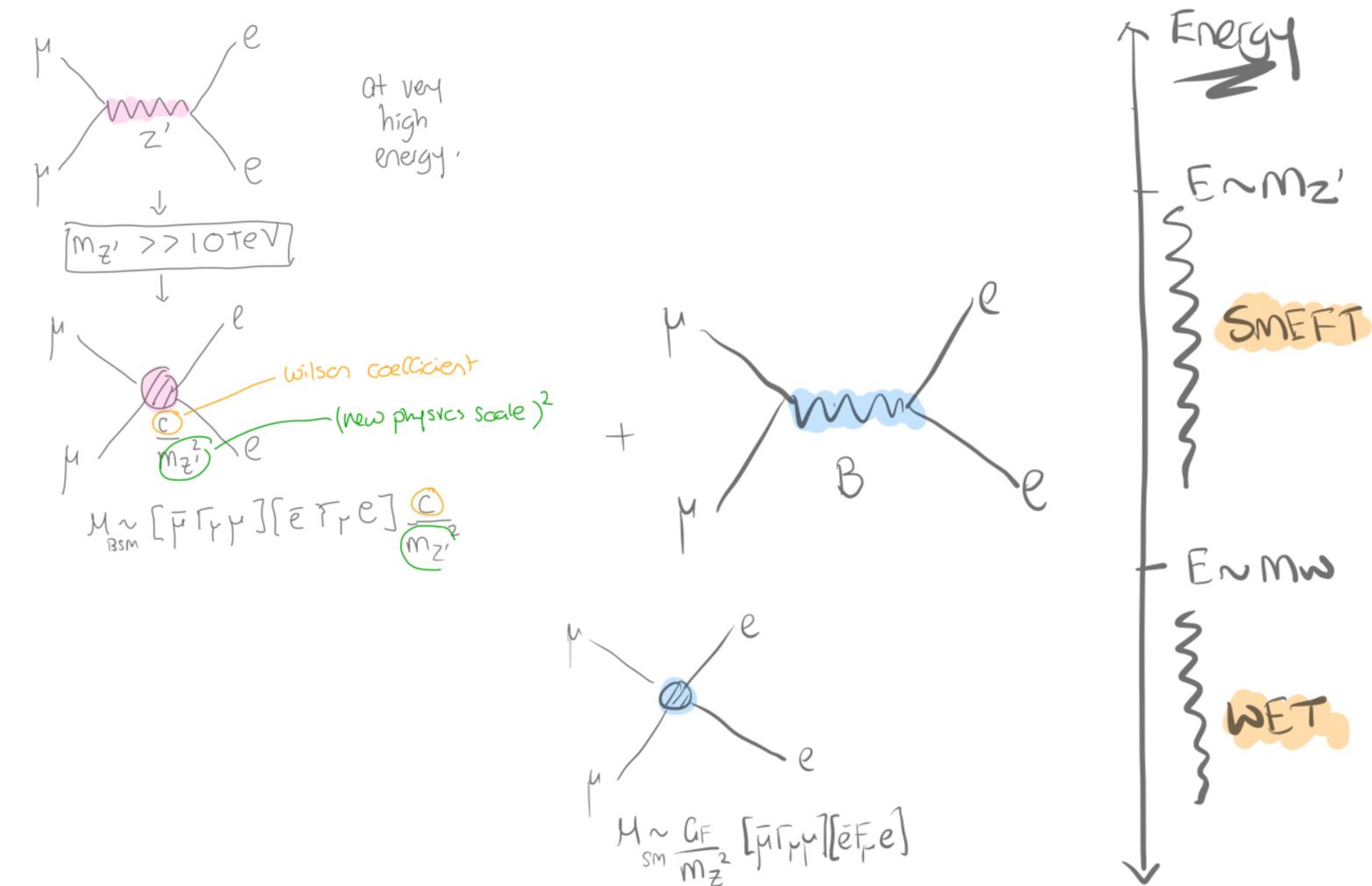
- Neutrinos and charged-leptons are part of the same SU(2) doublet
- Flavor-violation in neutrinos should “bleed into” the charged-lepton sector
- Adding just neutrino masses as a parameter for size of flavor-violation, the projected very small effects
- **Observing charged-lepton flavor violation (CLFV) is a sign of new physics beyond just neutrino masses**

$$L_L \sim \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

**Genuine signal of new physics!**

# LFV at Low and High E

Excellent overview in the context of a MuC [Asadi, Bagherian, Fraser, Homiller, Lu] [2509.22771](#)



- We can search for LFV in low-energy processes, such as  $\mu \rightarrow e\gamma$ , but also in high-energy lepton collisions
- Lepton vs. proton collisions: fundamental, “clean”
- **Running and matching** and running between SMEFT (SM EFT,  $E \ll \Lambda_{NP}$ ) and WET (Wilson Effective Theory,  $E \ll m_W \ll \Lambda_{NP}$ ) to contrast these constraints

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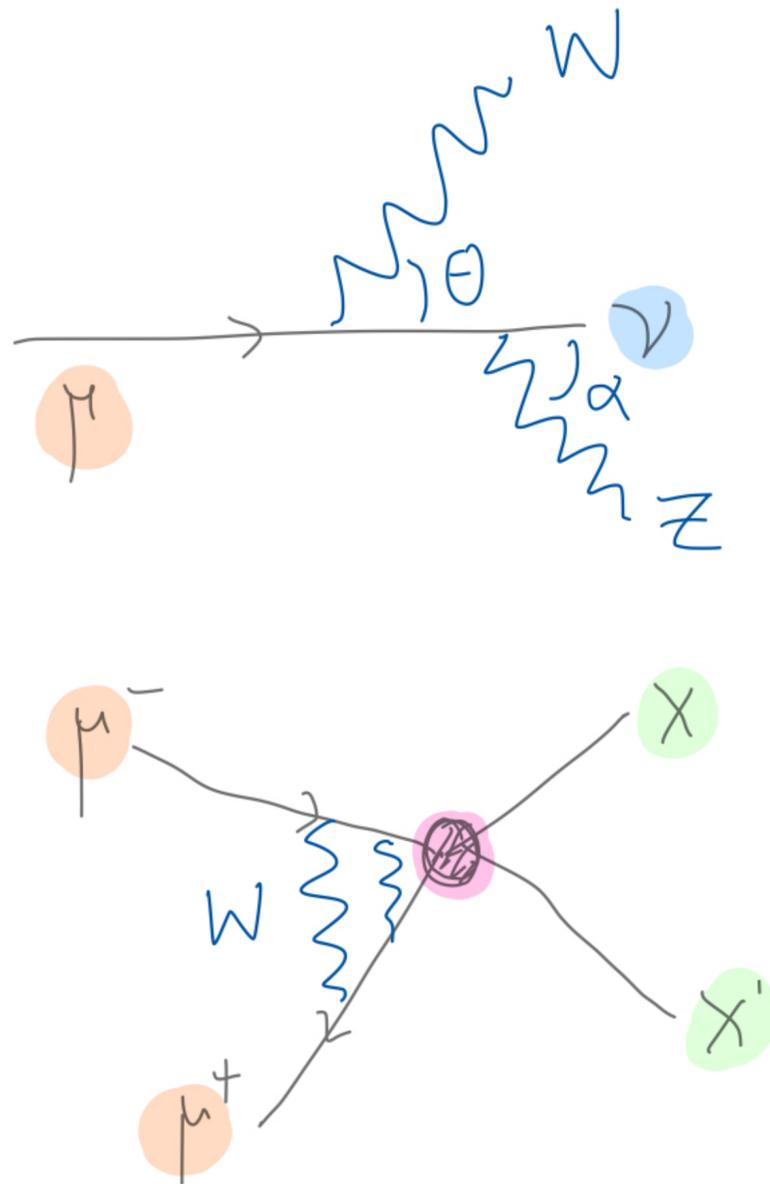
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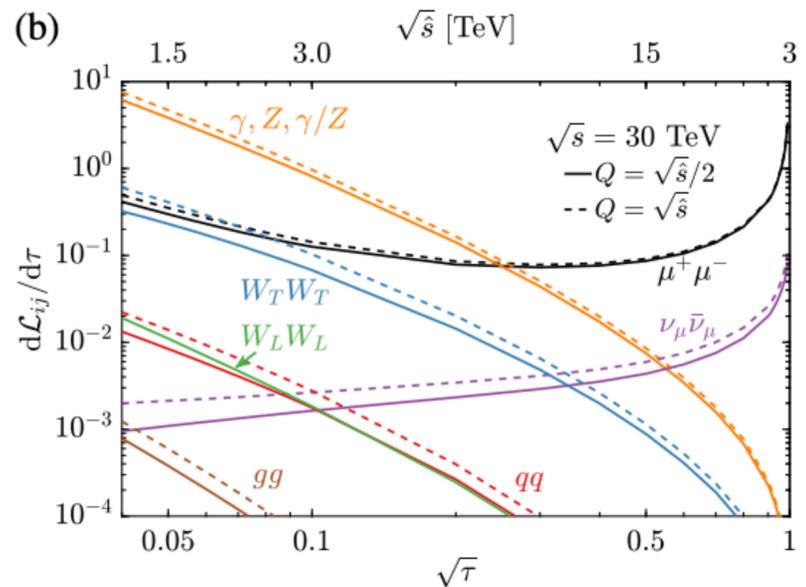
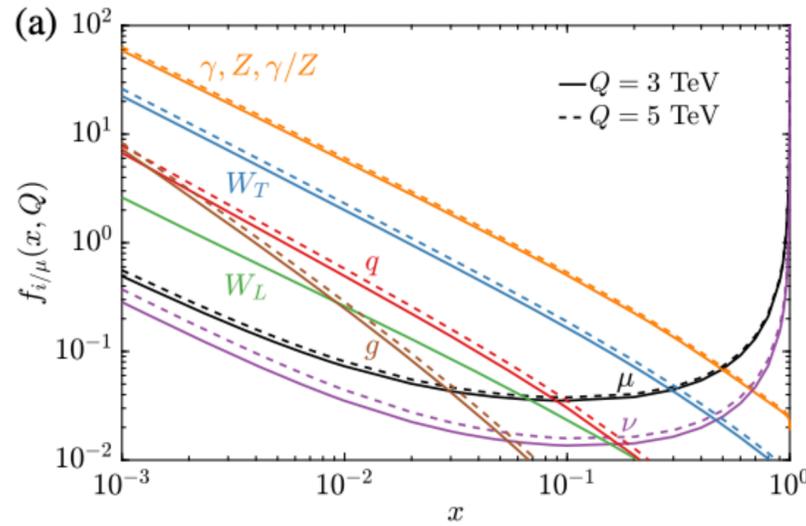
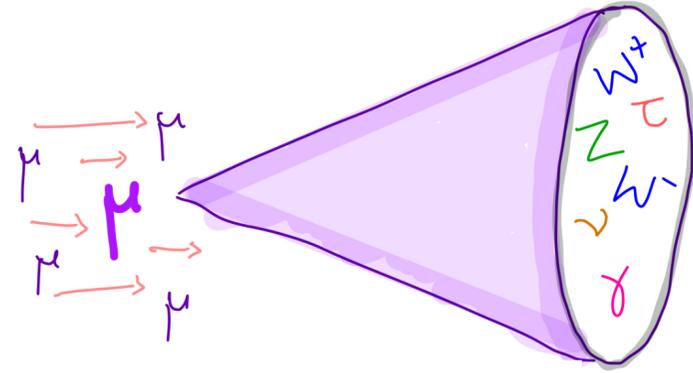
# EW radiation and neutrino physics

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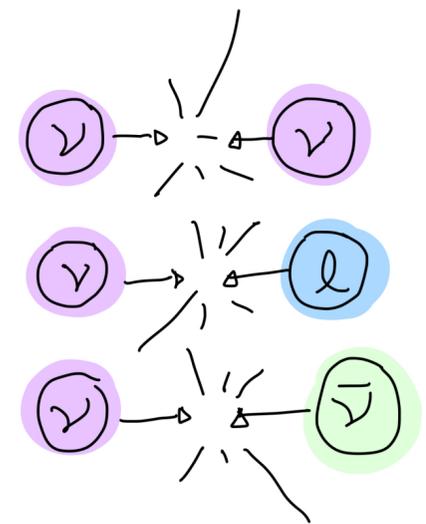
- Once we reach the 10 TeV energy scale, the hard-scattering scale of muon collisions is now significantly larger than the EW scale  $\sim 100$  GeV
- This makes virtual corrections, and real emissions, of **electroweak bosons** relevant for precision collision studies ( $\sim$ tens of percent correction)
- This radiation is unique from QCD and QED radiation relevant at other colliders: **SU(2) “charge” violation in radiation events**
- Connect back to lepton doublet: **neutrinos in contact interactions.**

# PDF from EW radiation

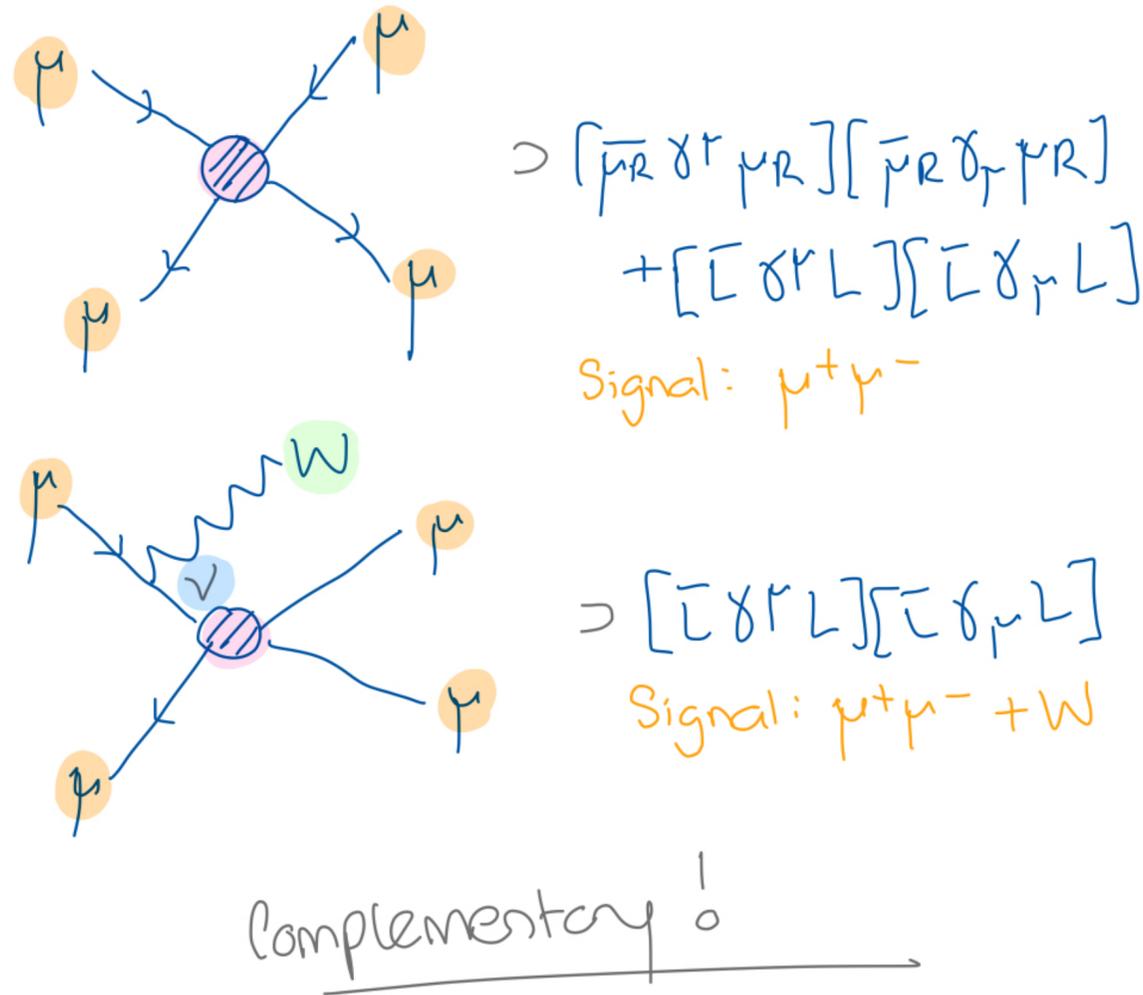


Han, Ma, Xie, [2007.14300](#)

- Collinear splitting pre-collision yields a “PDF” picture for the muon
- One can define EW boson content of the muon, “Electroweak Boson Collider”
- Flipping this splitting on it’s head, we could also define neutrino content of the muon
- Collision of neutrinos at a MuC?
- Unprecedented opportunity

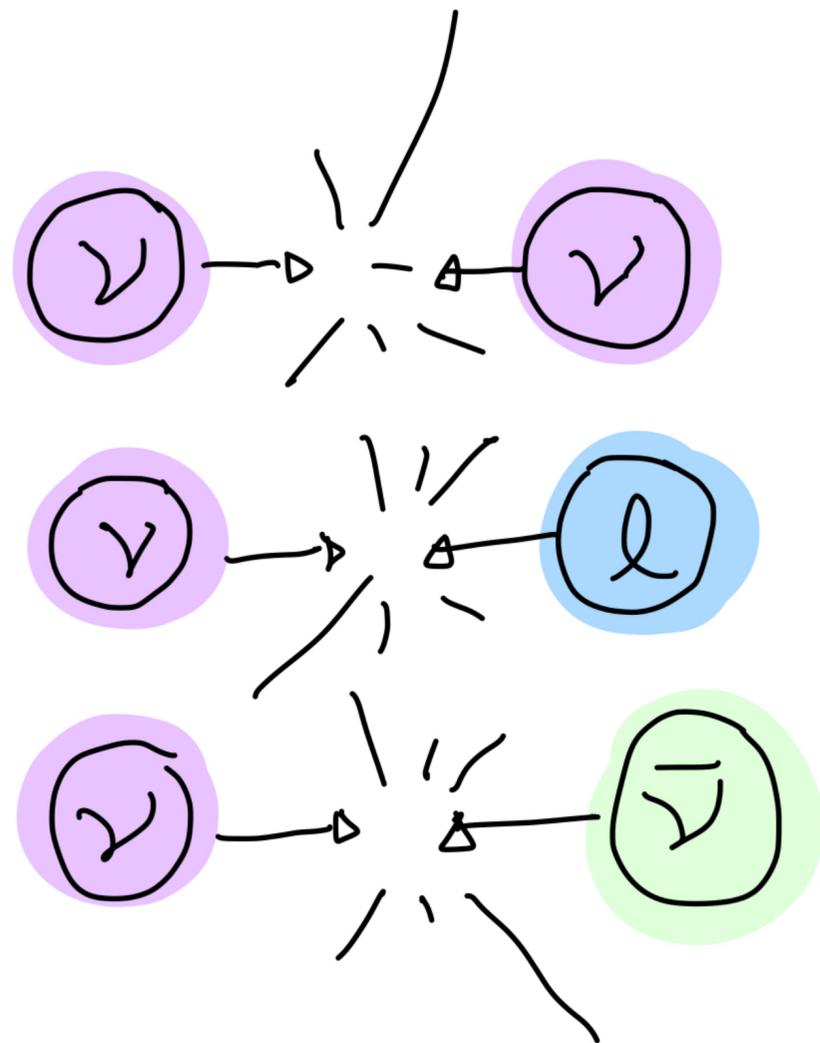


# Complementarity from neutrino contact



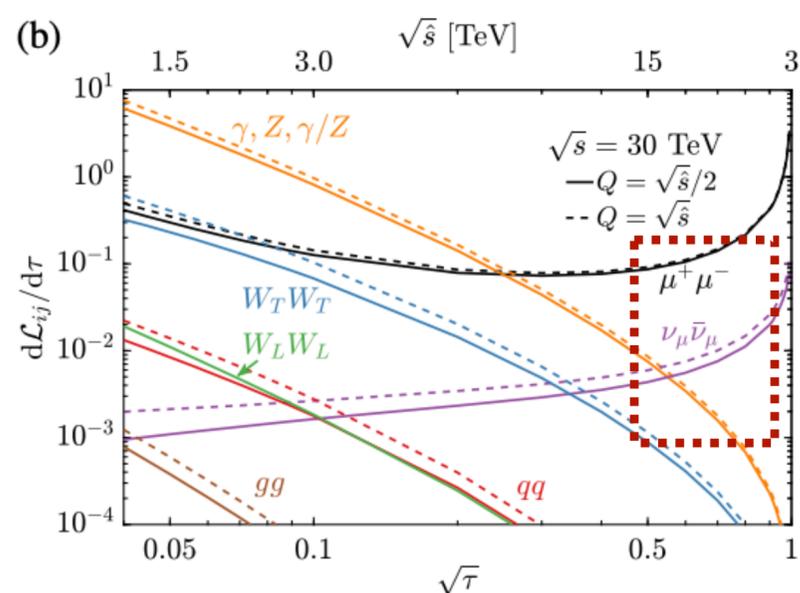
PDFs are alternate to calculation in  
 [Glioti, Marzocca, Wulzer] [2509.08132](#)

- Consider: probing **contact interactions** at a high-energy MuC
- With EW boson emissions, you are probing different contact interactions at high energy in the hard scattering process. This may be folded into PDFs.
- In a regime where EW symmetry is approximately restored - unprecedented in such a clean environment



# Opportunities from nu PDF

- Lepton Flavour violation?
- Lepton Number violation?
- Complementarity: b/w  $\nu$  facilities and the path to a MuC



*We pay the price for “parton” luminosity, but with large amounts of data this remains large!*

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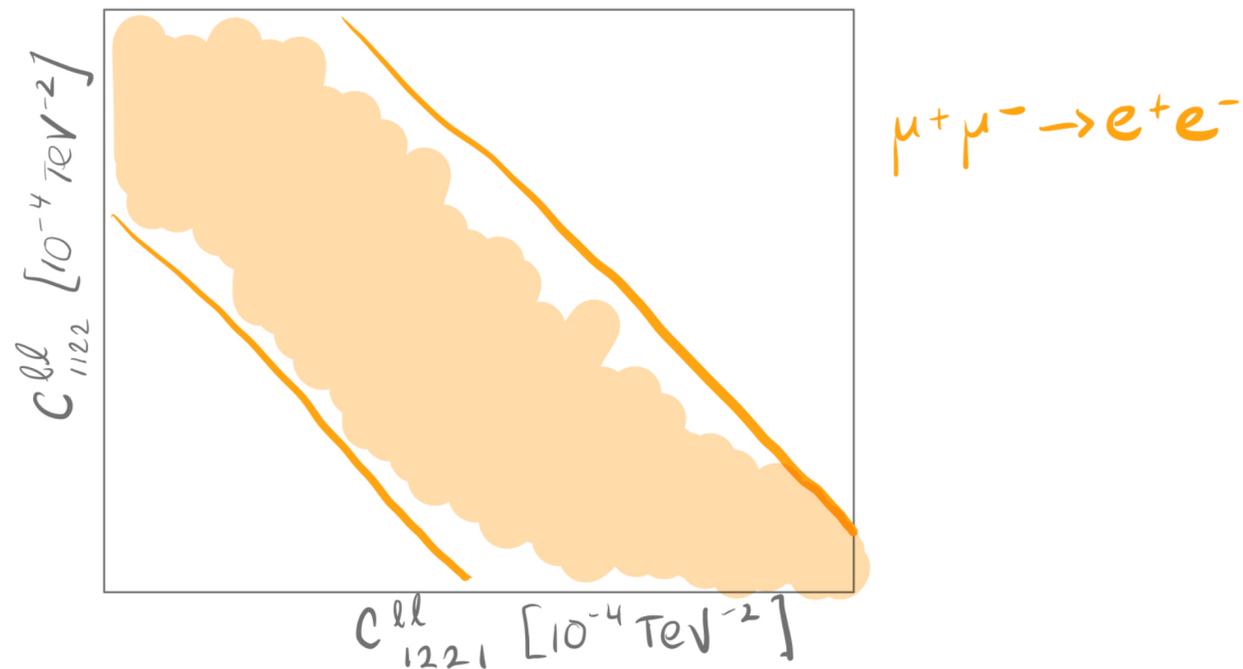
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# With and without a EW emission

An “illustrative example”

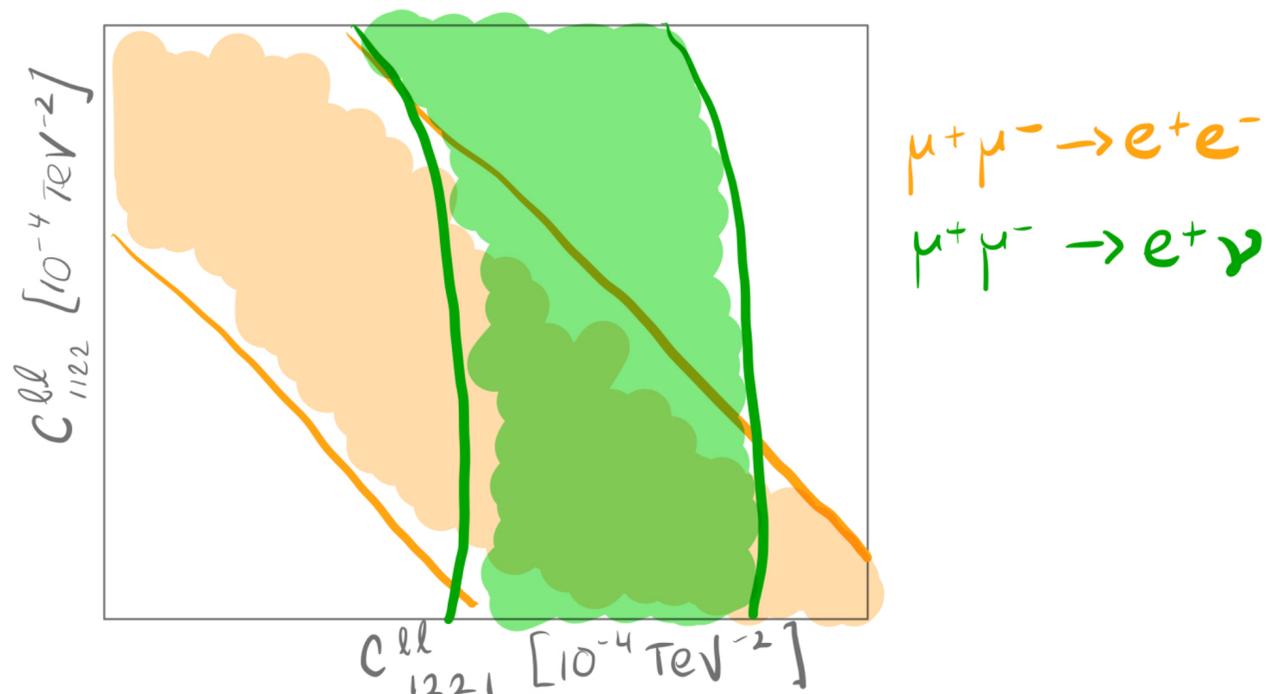


$$\mathcal{L} \supset C_{ijkl}^{ll} (\bar{L}_i \gamma^\mu L_j) (\bar{L}_k \gamma_\mu L_l)$$

- Useful even for flavour-universal processes:  
 $\mu^+\mu^- \rightarrow \mu^+\mu^-, \mu^+\mu^- \rightarrow e^+e^- \text{ \& } \mu^+\mu^- \rightarrow \tau^+\tau^-,$
- Approximate EW radiation effects: Sudakov double-log factors for loop-corrections [Exclusive] and for W radiation emission [Semi-inclusive]  
*[Glioti, Marzocca, Wulzer] [2509.08132](#)*
- Alternatively use PDF picture. and **final states with MET** as additional signals which “appear” to violate charge.

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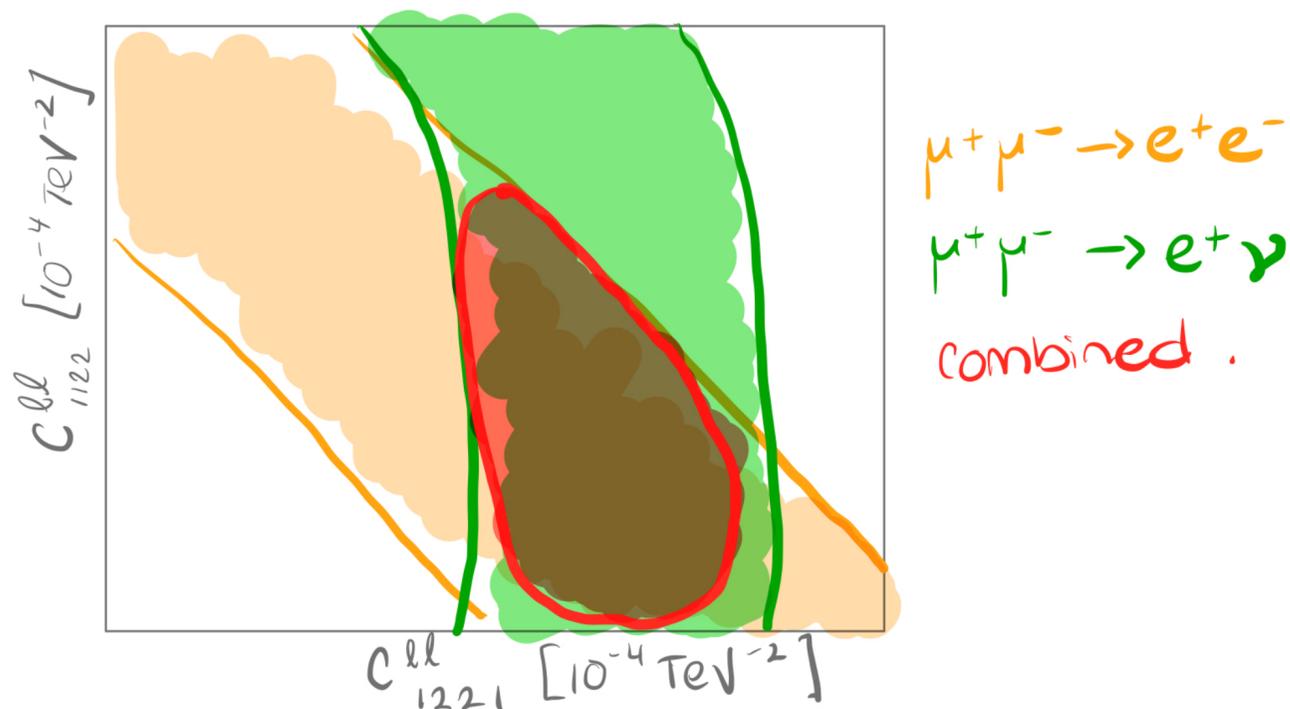


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# Useful even with flavor conserved

WC	Constraint [ $10^{-4}\text{TeV}^{-2}$ ]	Unitless [ $10^{-4}$ ]	Observable
$C_{2222}^{ee}$	0.1232	0.00745	$\mu^+\mu^- \rightarrow \mu^+\mu^-$
$C_{2222}^{le}$	0.2748	0.01663	$\mu^+\mu^- \rightarrow \mu^+\mu^-$
$C_{2222}^{ll}$	0.1252	0.00758	$\mu^+\mu^- \rightarrow \mu^+\mu^-$

Assumes: 10 TeV collider COM energy **\*\*Preliminary\*\***

[To do: No detection efficiencies considered, Born-level. No PDFs]

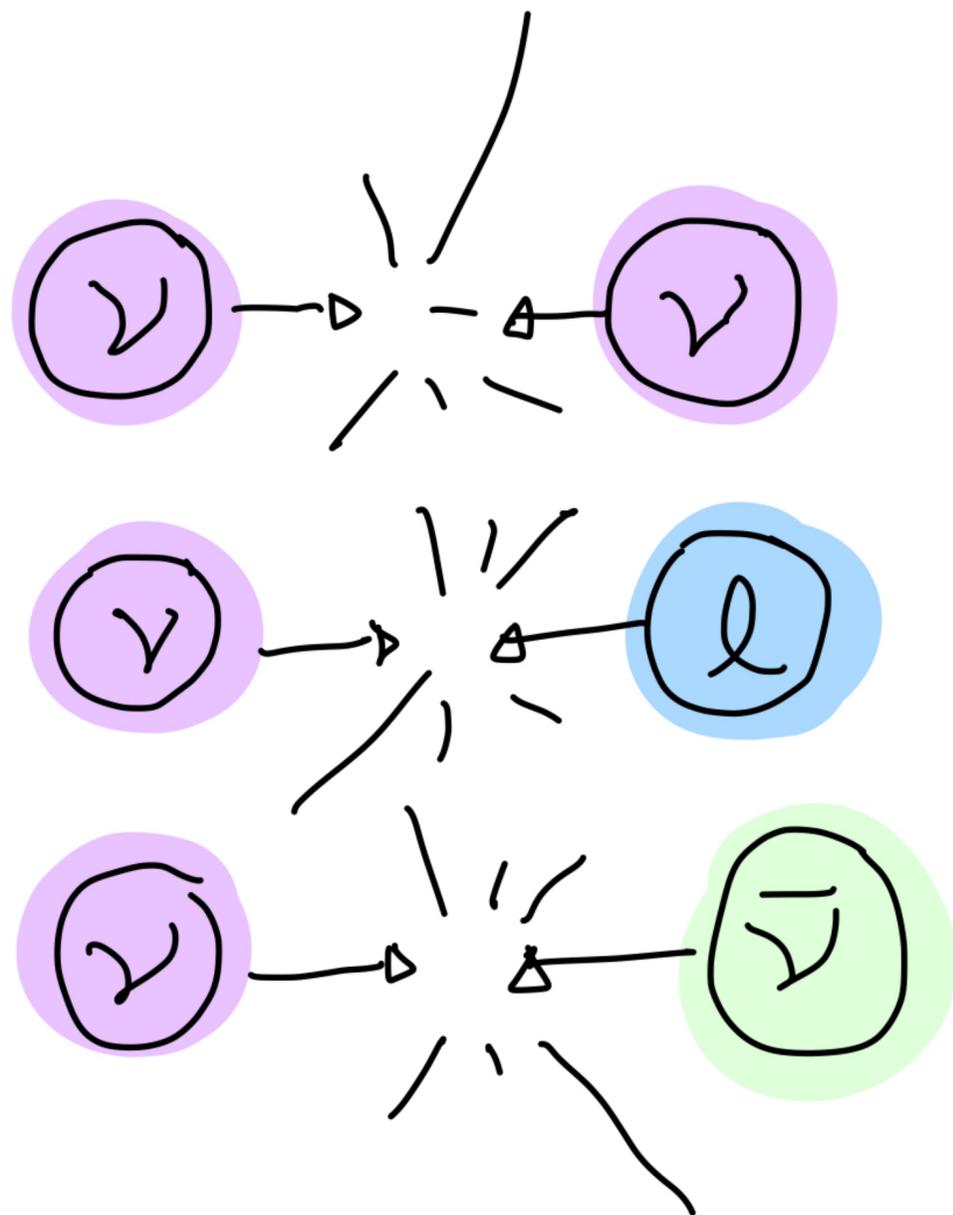
Coefficient	$\Delta$ (current)	$\Delta$ (no sys.)	$\Delta$ (0.1% sys.)	$\Delta$ (1% sys.)	$\Delta$ (w/o DUNE)
$\delta g_L^{We}$	3.5	0.37	2.5	3.4	3.5
$\delta g_L^{Z\mu}$	3.7	0.18	1.1	3.5	3.7
$\delta g_L^{Zu}$	1.9	0.34	1.4	1.5	1.5
$\delta g_R^{Zu}$	9.5	0.57	2.0	2.3	2.3
$\delta g_L^{Zd}$	1.9	0.28	1.4	1.6	1.6
$\delta g_R^{Zd}$	9.7	1.1	3.0	3.1	3.1
$\delta g_R^{Wq_1}$	1.9	0.36	1.7	1.9	1.9
$[c_{\ell\ell}]_{1122}$	28	2.6	2.6	21	28
$[c_{\ell e}]_{2211}$	45	3.1	3.1	27	45
$[c_{\ell\ell}]_{2222}$	2100	310	310	310	2100
$[c_{\ell e}]_{2222}$	6300	970	970	970	6300
$[c_{\ell q}^{(3)}]_{1111}$	1.9	0.36	1.7	1.9	1.9
$[c_{\ell q}^{(3)}]_{2211}$	12	1.8	10	12	12
$[c_{\ell q}]_{2211}$	210	3.0	30	180	210
$[c_{\ell u}]_{2211}$	190	1.2	9.5	85	190
$[c_{\ell d}]_{2211}$	370	2.4	19	170	370

For contrast: 1802.08296 [Falkowski, di Cortona, Tabrizi]

Compare with the “unitless” column above. Tridents.

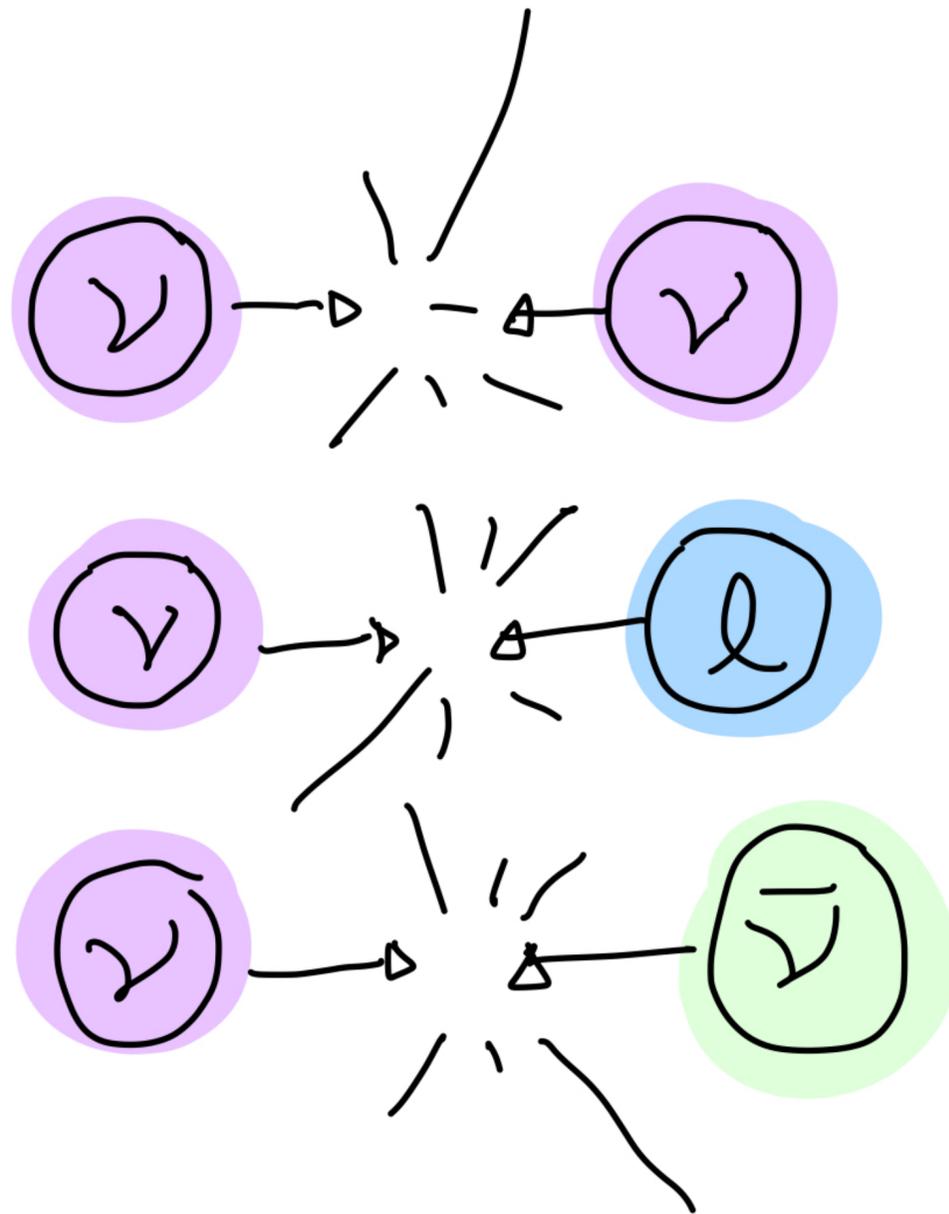
- Muon: present constraints from muon tridents  $\mathcal{O}(1000)$  in unitless constraints,  $\mathcal{O}(100)$  with DUNE, then with MuC orders of magnitude improvements!
- Consider for example the tau contact interactions: presently there are no low-energy muon-tau constraints from neutrino physics, because of lack of tau scattering
- Constrain contact interactions which we have not had precision access to before.

# Flavour-universal with $\nu$ PDFs



- Folding in partonic luminosity for neutrino initial states: at these energies, the left handed muon and muon neutrino interactions same
- Reduction of constraints by a few orders of magnitude by lumi, only constraining the left-handed interactions from  $\nu$  content
- Further reduction in flat-directions in WC space.
- Work in progress. Also extension to LFV, (LNV?)

# Conclusions



*“Lepton Physics at a Neutrino Collider”*

*[IB, de Gouvêa, Han, Low, Ma, Tabrizi & Xie]*

*2512.xxxx*

- Lepton collisions complement the present neutrino scattering programs
- Neutrino content of the muon provide “flat-direction” breaking to EFT constraints: with both real radiation + PDF treatment
- Useful for flavour-conserving and flavor-violating processes, perhaps even for lepton number violating. Access to as-yet unconstrained WCs.
- May be translated to model-specific constraints