中国物理学会高能物理分会第十一届全国会员代表大会暨学术年会

Probing heavy Majorana neutrinos and the Weinberg operator through vector boson fusion processes at the LHC CMS Experiment

arXiv: 2206.08956

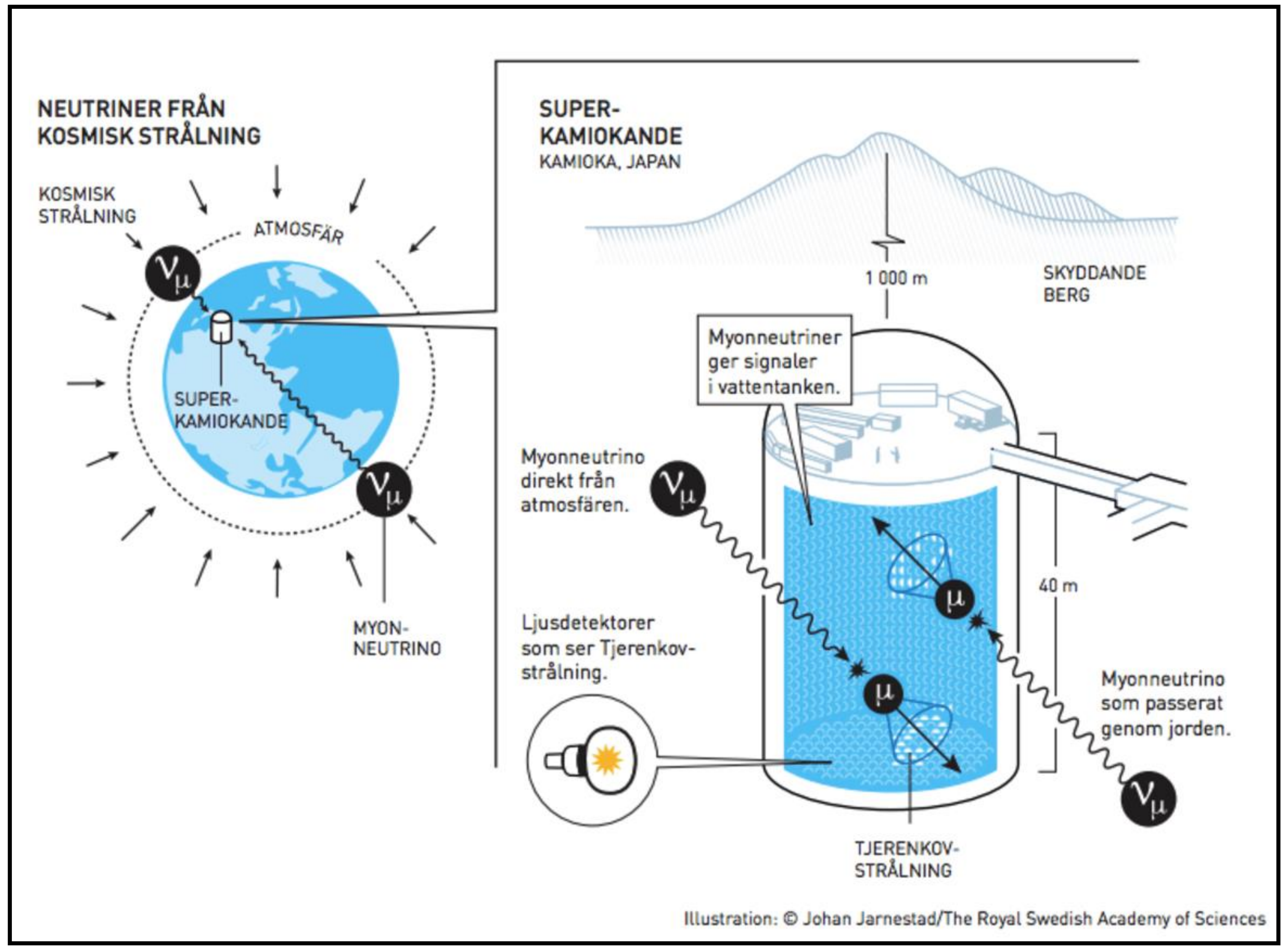
肖杰

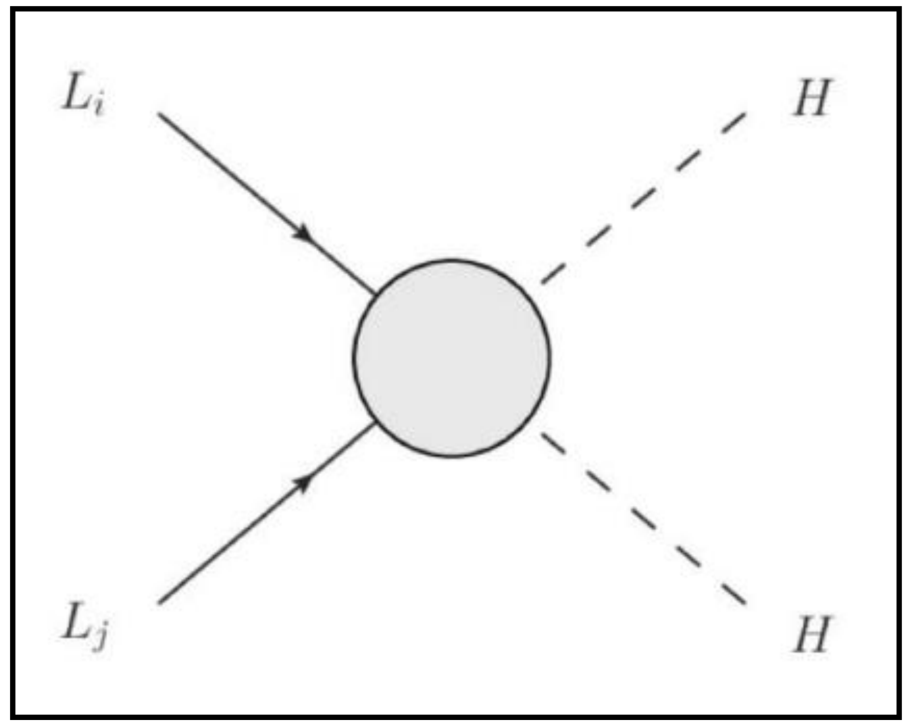
2022-08-10 大连

The dim-5 Weinberg operator

- The Standard Model **neutrino masses** are non-zero
- Why are neutrinos massless in the SM?
  - Renormalizability requires all SM operators with dimension = 4
  - $SU(2)_L \times U(1)_Y$ ElectroWeak symmetry
  - Only left-handed neutrino → No Dirac mass term
  - Only one neutral Higgs doublet → No Majorana mass term
- Masses of SM neutrinos call for an **extension** to the SM **Lagrangian**
  - An Effective Field Theory (**EFT**) solution:
    The dimension-5 Weinberg operator Weinberg ('79)

$$\mathcal{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda}\left[\Phi \cdot \overline{L}_\ell^c\right]\left[L_{\ell'} \cdot \Phi\right] + \text{H.c.}$$



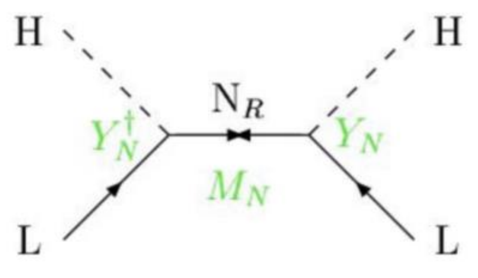


- Adding this operator will give SM neutrinos **Majorana masses**
- Result **lepton number violation (LNV)**
- **EFT** doesn't describe the new physics in detail. Need UV complete models.

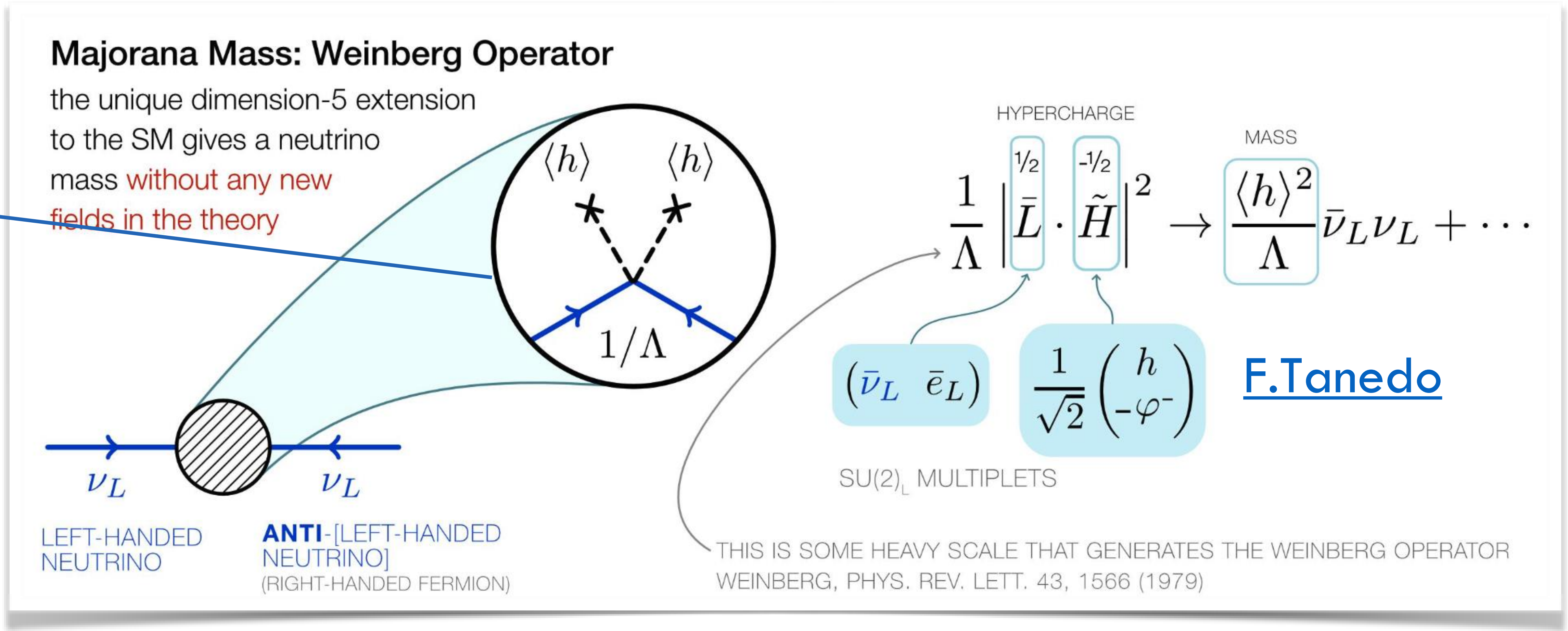
Seesaw Model

- Opening the black box of Weinberg operator requires a “seesaw”

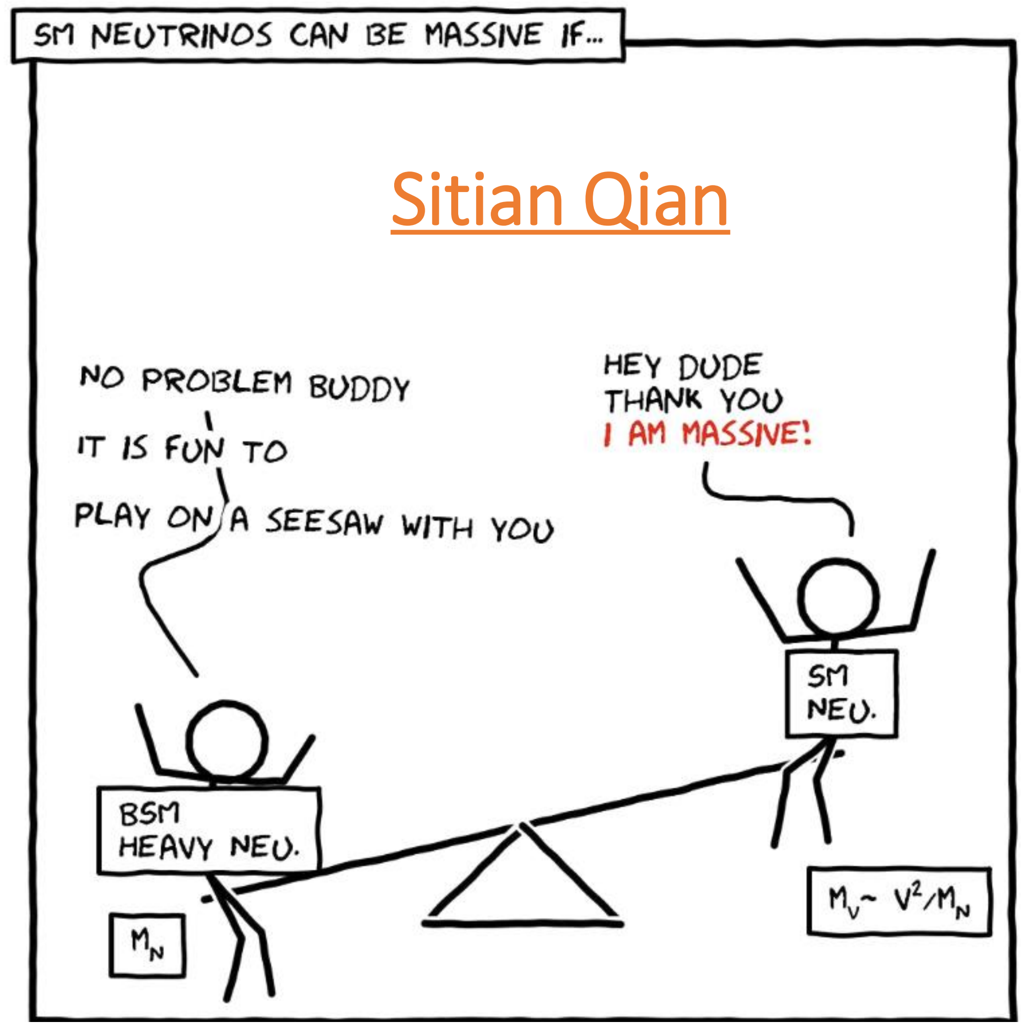
Right-handed singlet:
(type-I seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$



F.Tanedo



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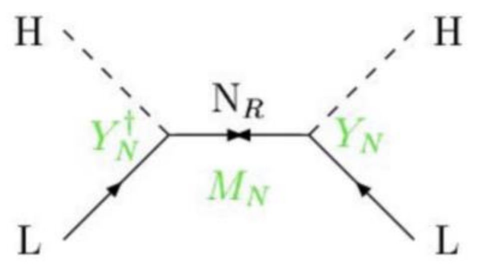
Heavier BSM particles lead to lighter SM neutrinos

Seesaw Model

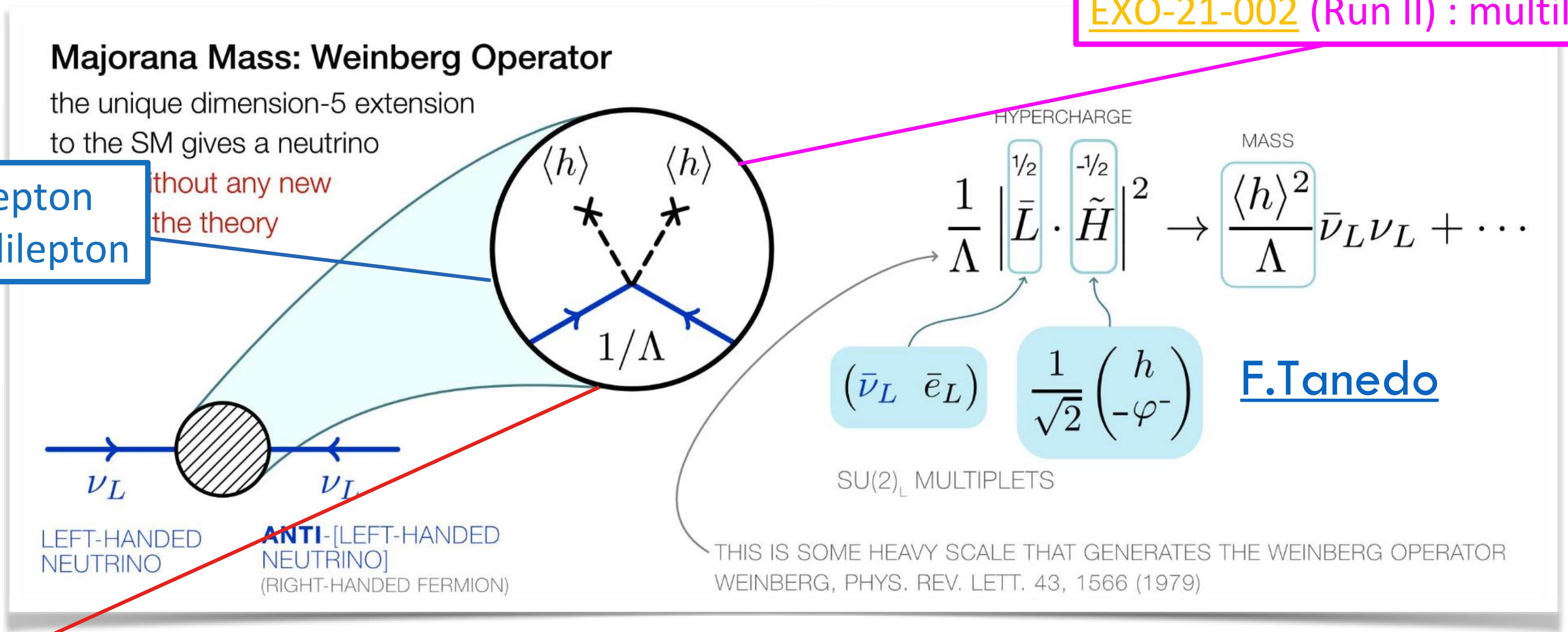
- Only three different kinds of realization at Born-level are allowed

Right-handed singlet: (type-I seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

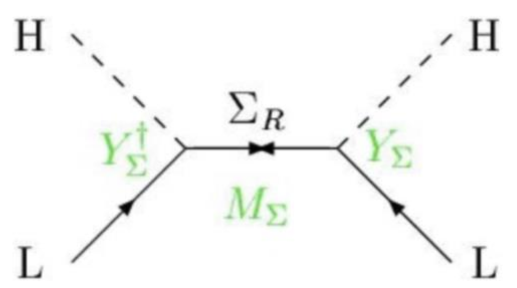
EXO-17-012: Trilepton
EXO-17-028: SS dilepton



F.Tanedo

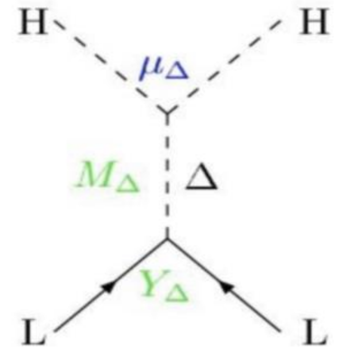
EXO-17-006 (16) : multilepton, cut-based
EXO-19-002 (Run II) : multilepton, cut-based
EXO-21-002 (Run II) : multilepton, MVA

Fermion triplet: (type-III seesaw)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Scalar triplet: (type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

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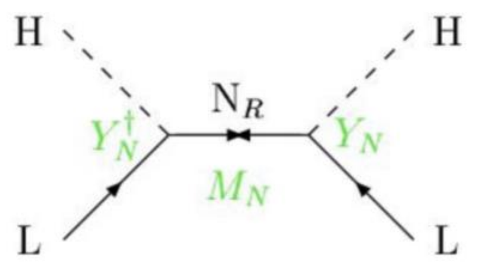

$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

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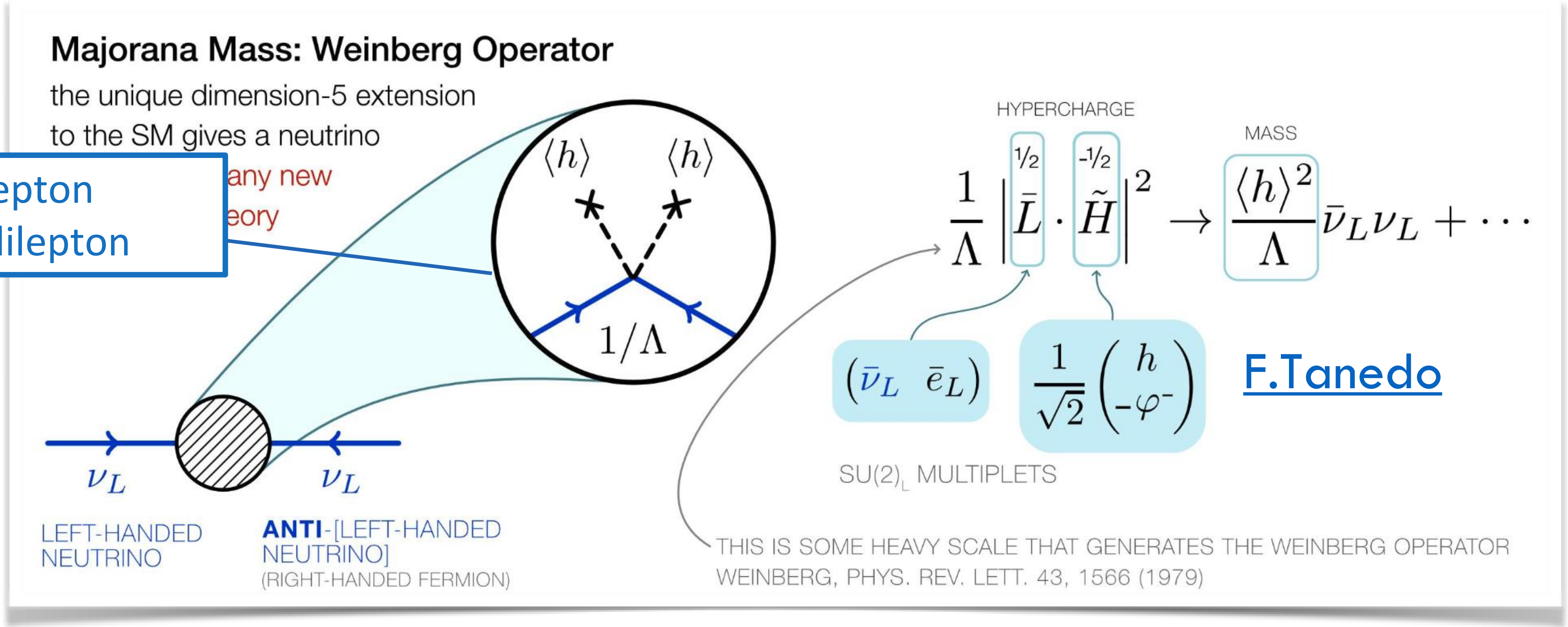
EXO-17-028: SS dilepton



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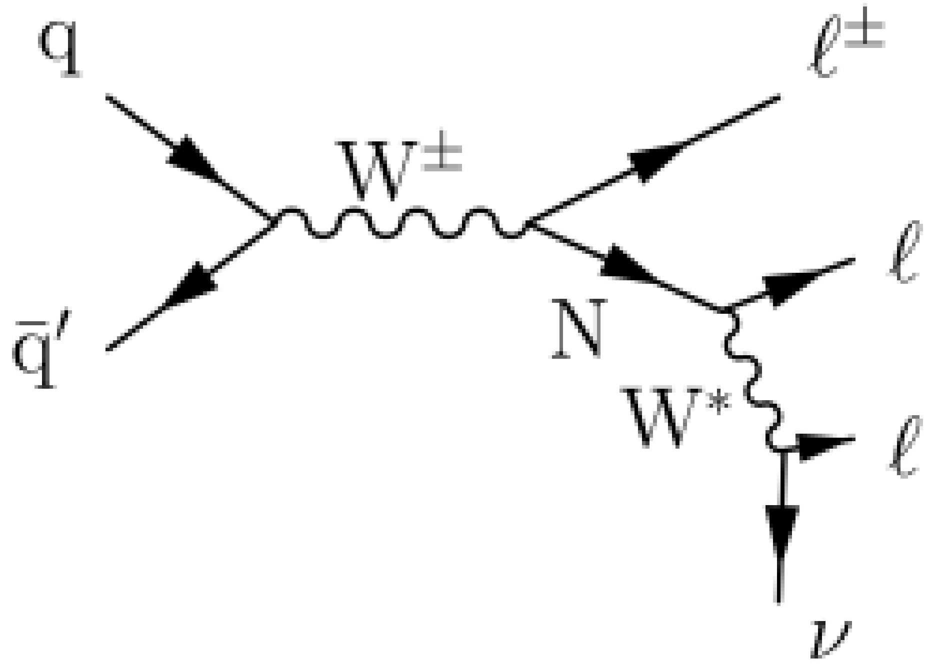
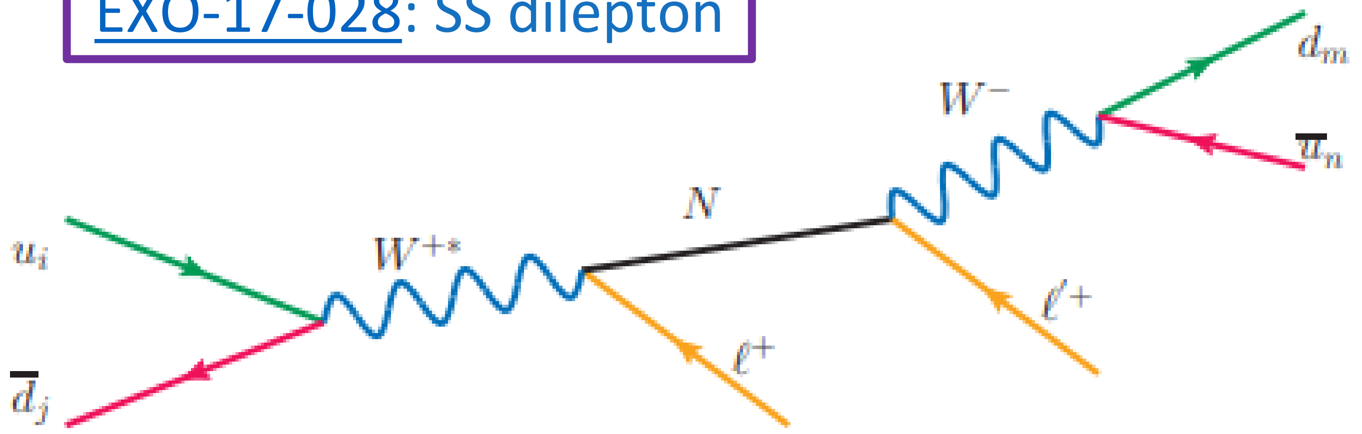
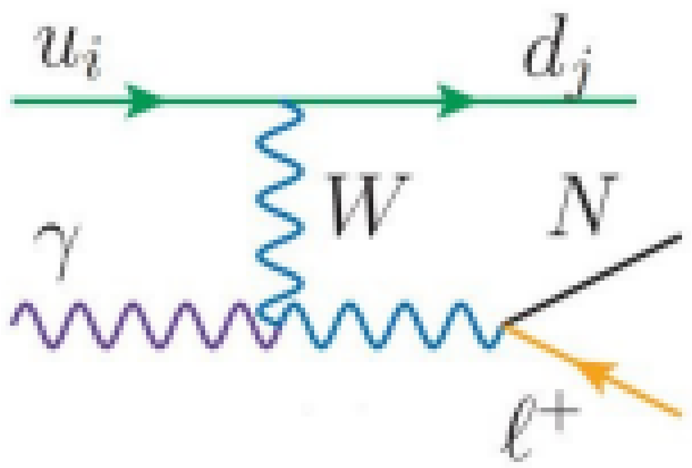
EXO-17-012: Trilepton



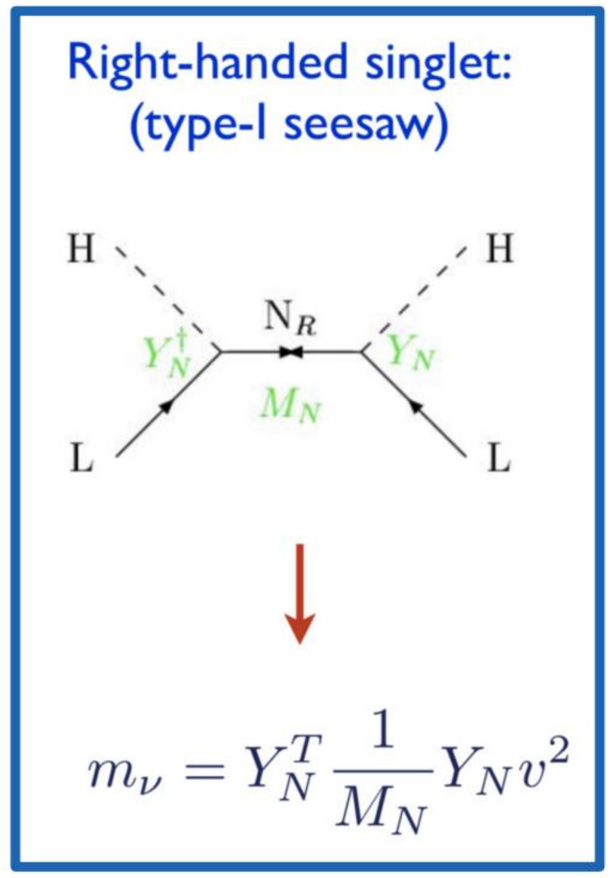
EXO-17-028: SS dilepton





Seesaw Model

- Opening the black box of Weinberg operator requires a “seesaw”



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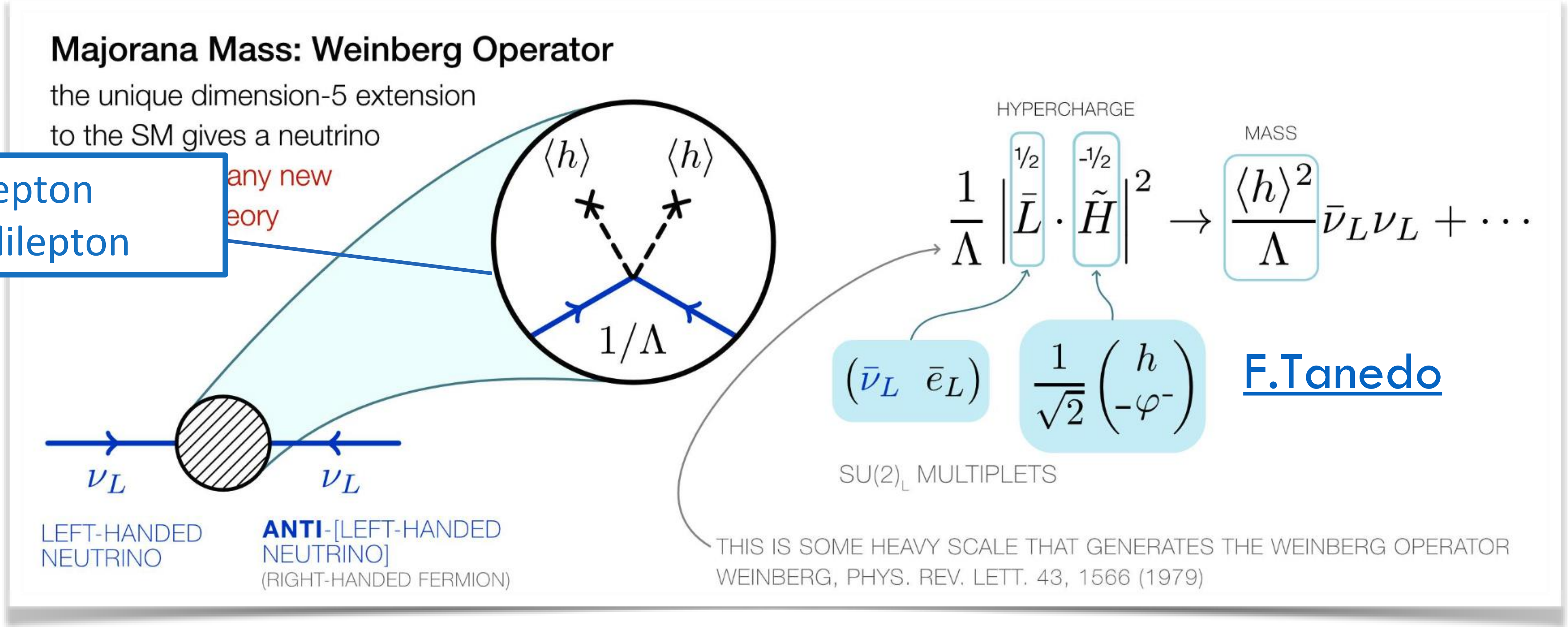
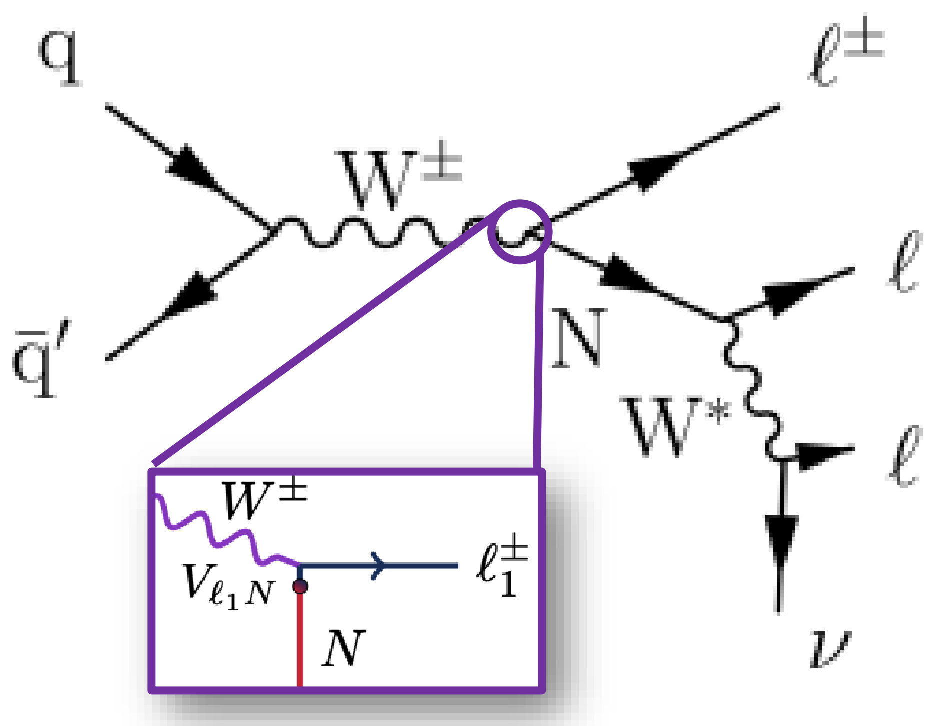
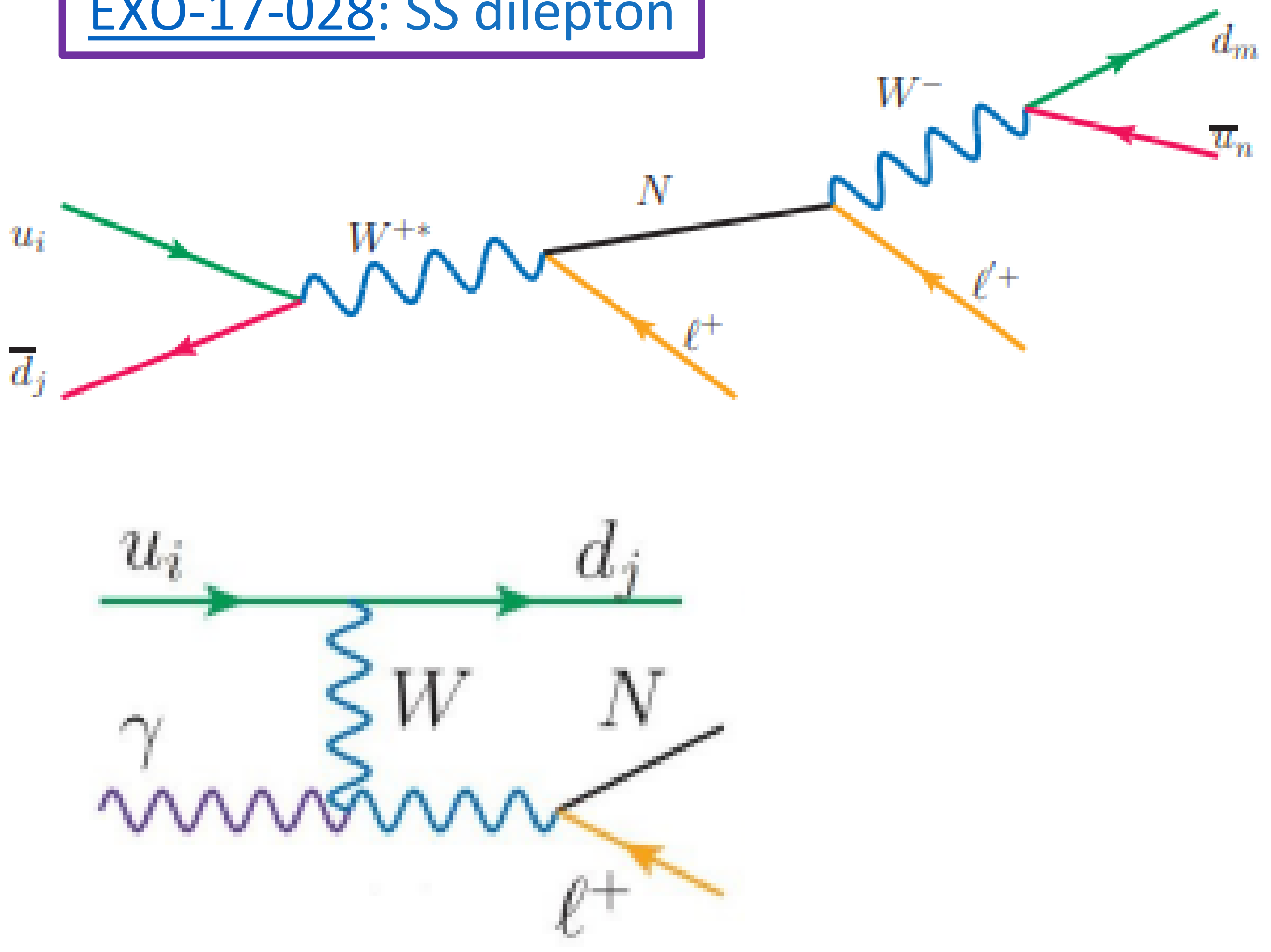
EXO-17-028: SS dilepton



EXO-17-012: Trilepton



EXO-17-028: SS dilepton



$$\sigma(pp \rightarrow N\ell^\pm + X) \equiv |V_{\ell N}|^2 \times \sigma_0(pp \rightarrow N\ell^\pm + X)$$

Seesaw Model

Opening the black box of Weinberg operator requires a "seesaw"

Right-handed singlet:
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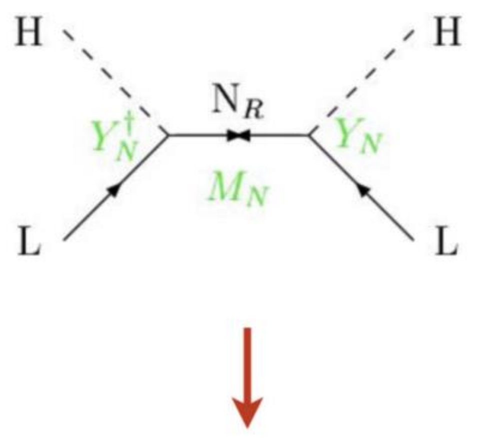

$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

EXO-17-012: Trilepton
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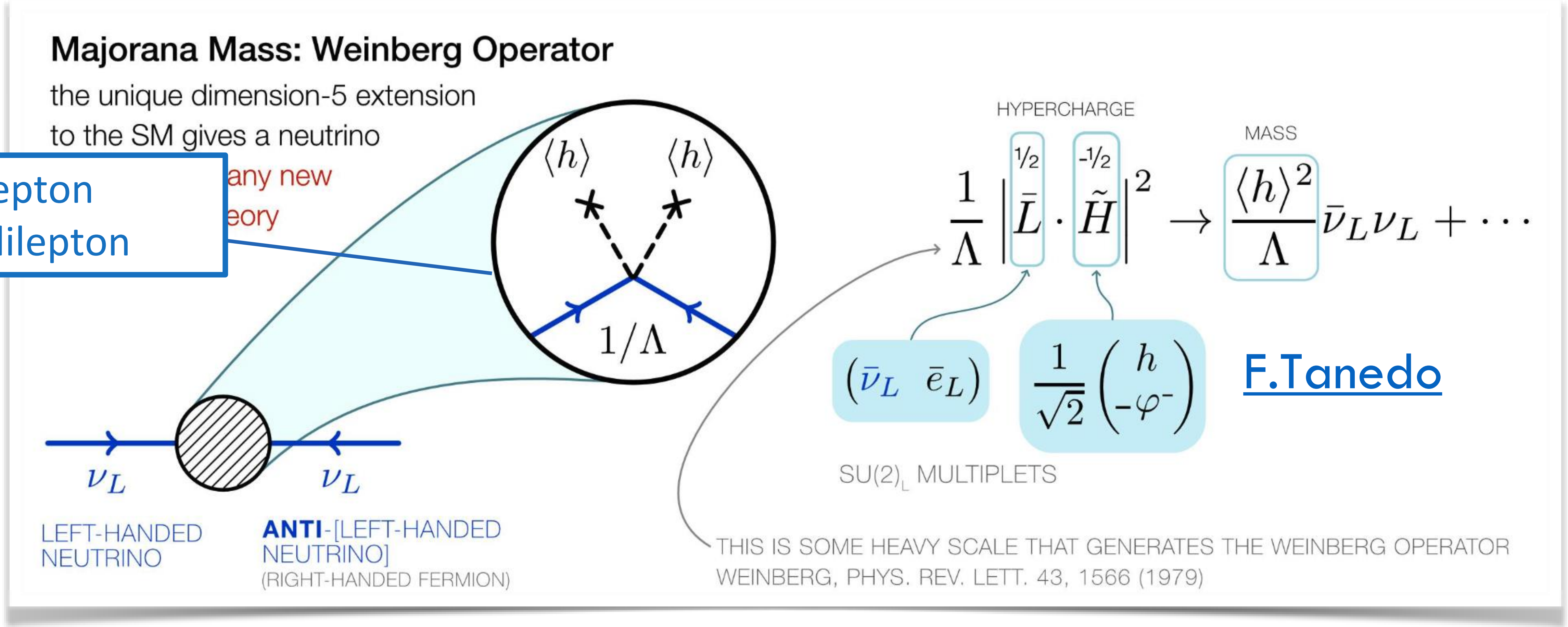

$$\frac{1}{\Lambda}\left|\bar{L}\cdot\tilde{H}\right|^2 \rightarrow \frac{\langle h\rangle^2}{\Lambda}\bar{\nu}_L\nu_L + \cdots$$

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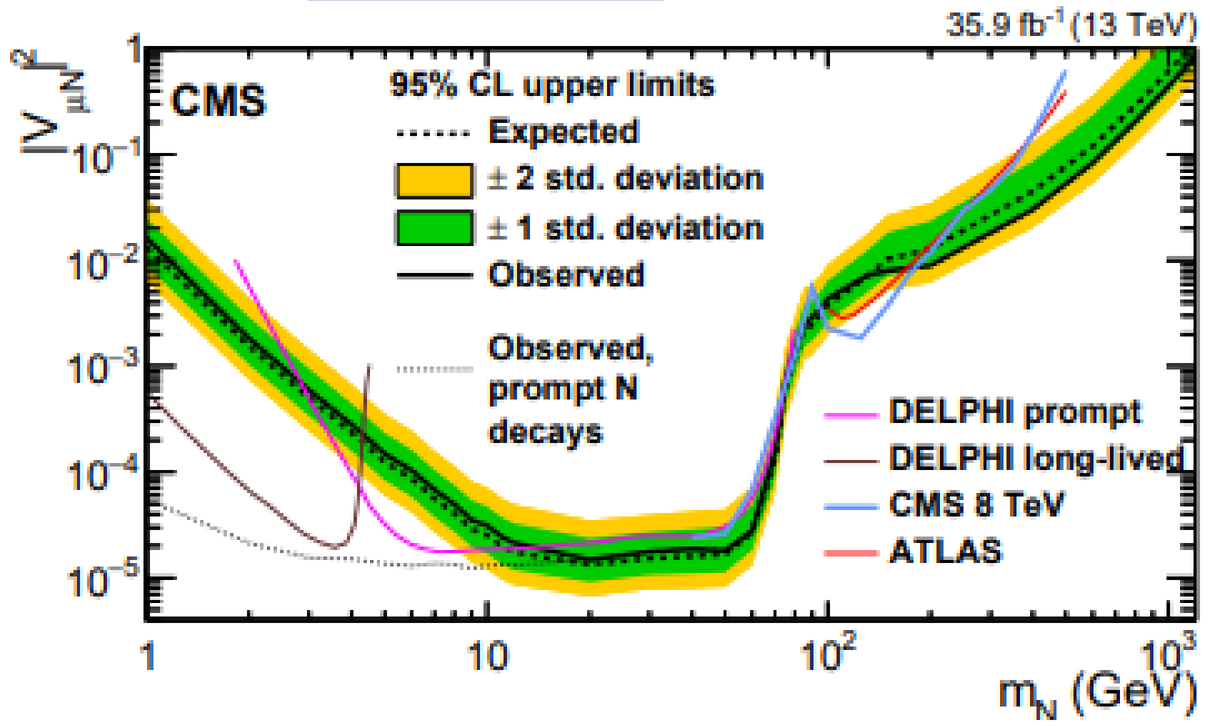
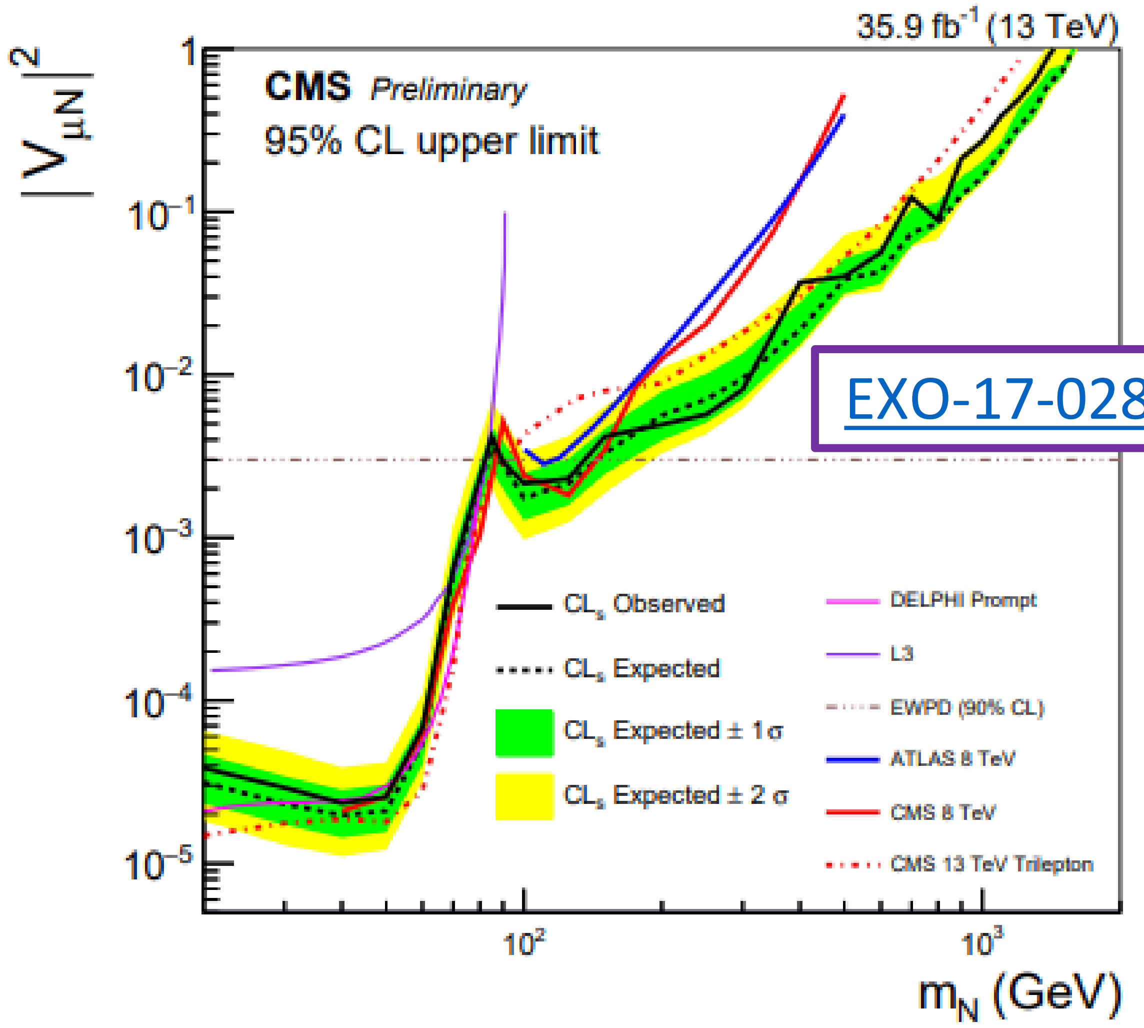
EXO-17-012

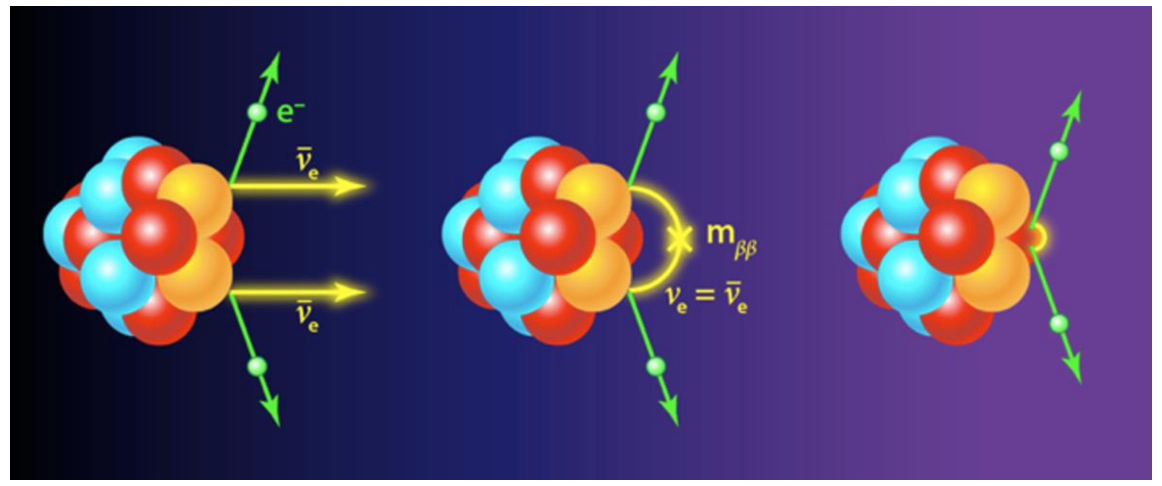




EXO-17-028

Heavy Majorana neutrinos in pp→μ±μ±jj

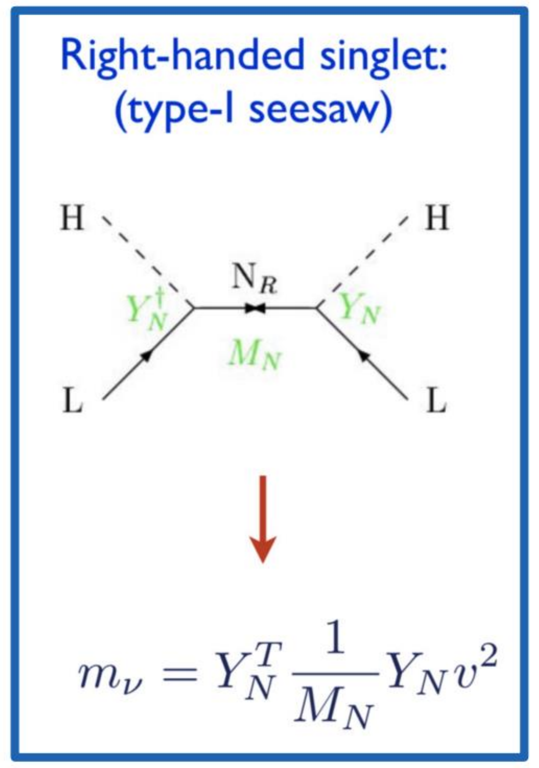
- If neutrinos are Majorana fermions (whose anti-particles are themselves)
  - A LHC version **0νββ,** lead to Lepton Number Violation (LNV))
  - At the LHC, we can probe **μ and τ sectors**

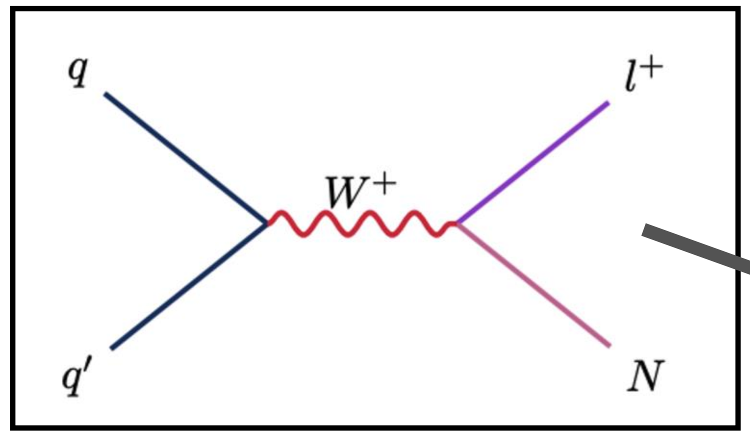


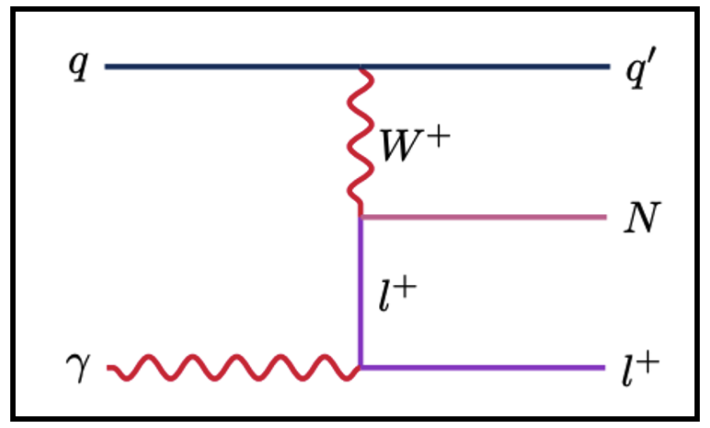
- Study the Type-I seesaw Heavy Majorana neutrino (HMN) in μ±μ±jj
  - Key parameters: $\boldsymbol{m_N}$ & **mixing** with SM neutrinos

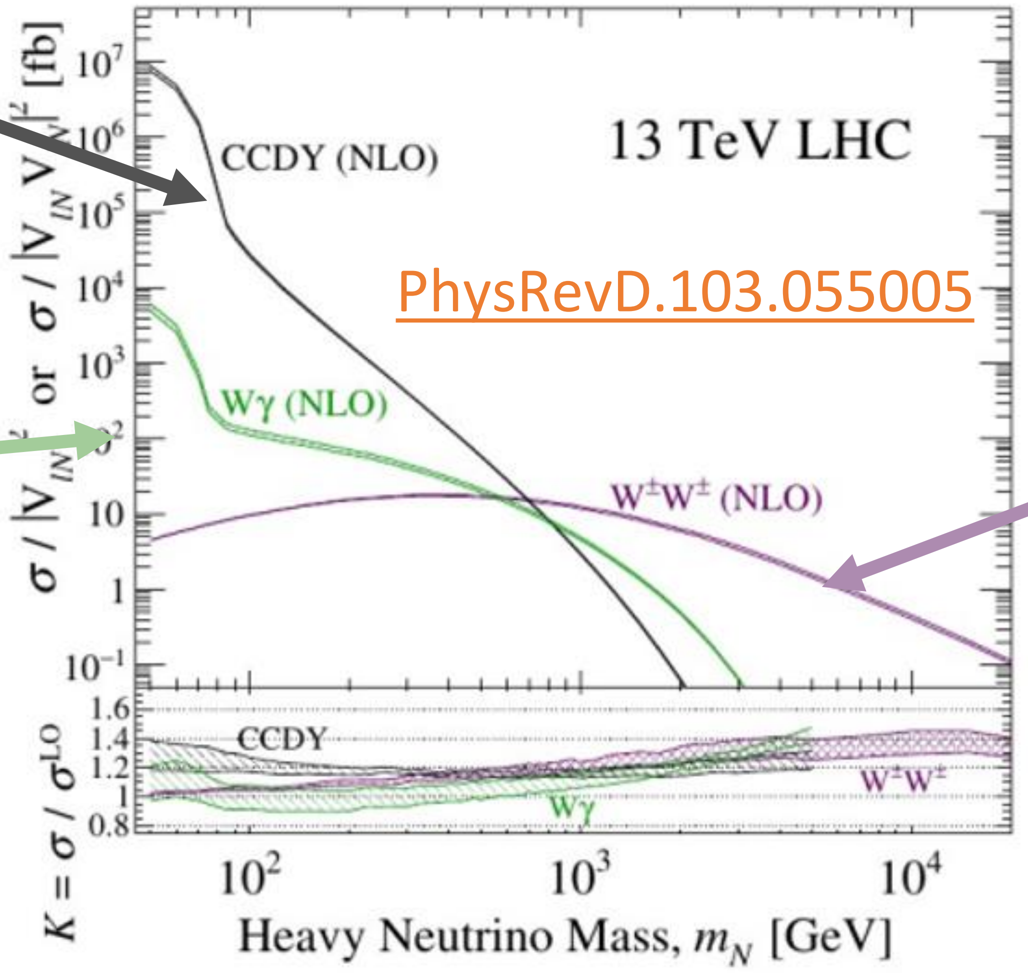
Mixing matrix

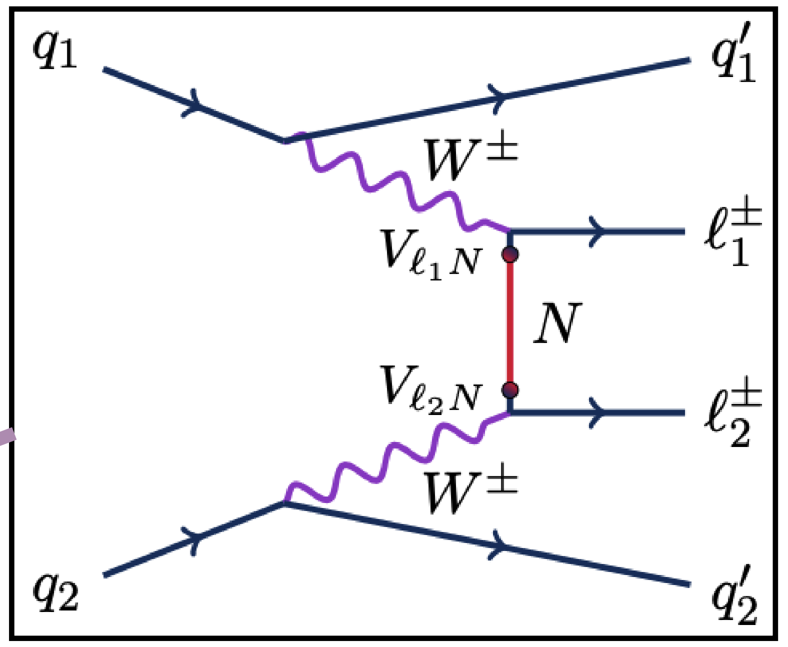
$$V_{lN} = \begin{pmatrix} V_{eN_1} & V_{eN_2} & V_{eN_3} \\ V_{\mu N_1} & V_{\mu N_2} & V_{\mu N_3} \\ V_{\tau N_1} & V_{\tau N_2} & V_{\tau N_3} \end{pmatrix}$$











Type-I Seesaw HMN

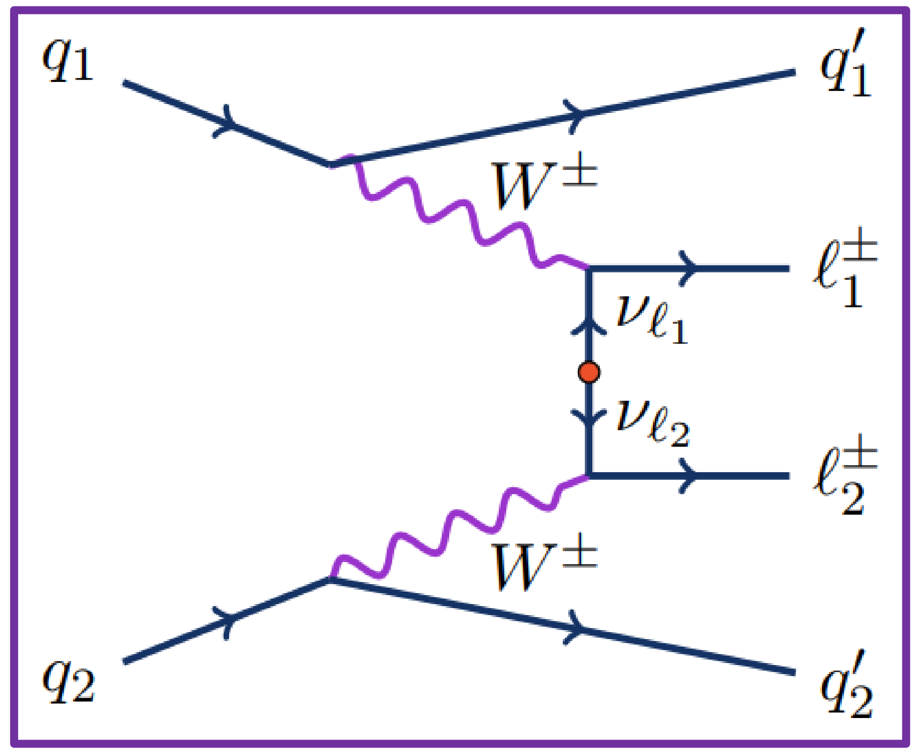
$$\sigma^{\ell\ell'}(s) \equiv \left|V_{\ell N} V^*_{\ell' N}\right|^2 \times \sigma_0^{\ell\ell'}(s)$$

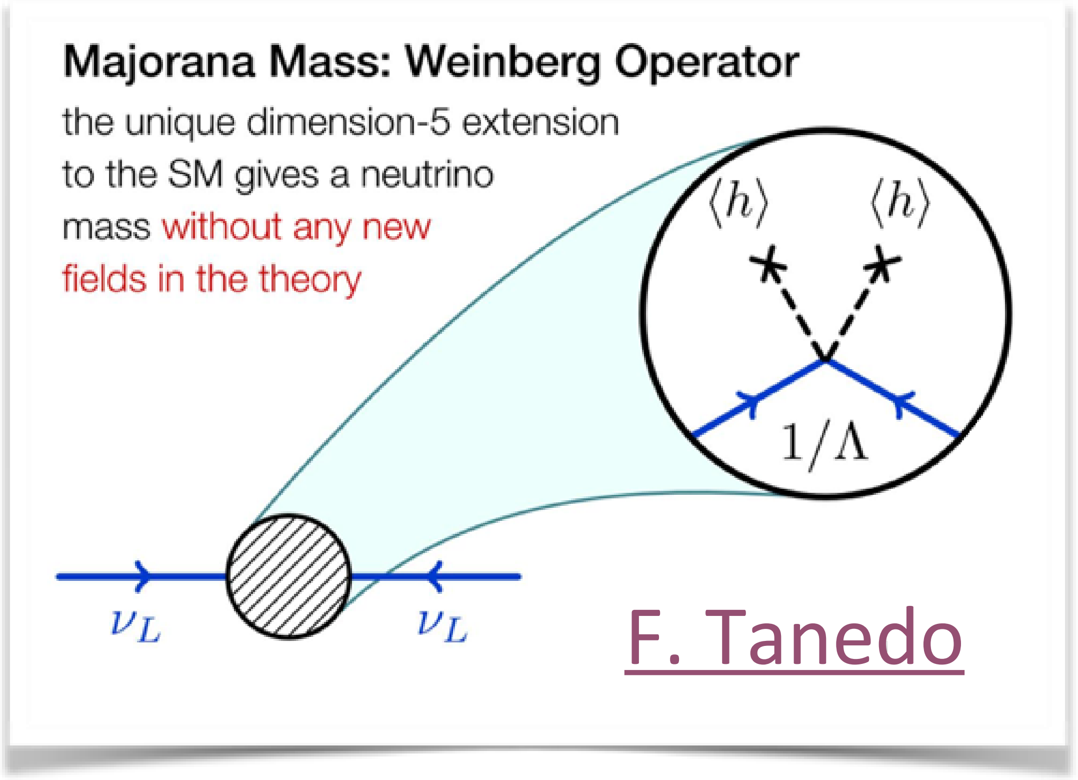
Weinberg operator in pp→μ±μ±jj

- Take an EFT approach:

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

- The Weinberg operator is the only gauge-invariant operator at dimension-5: Weinberg ('79)





Wilson Coefficients

$$\mathcal{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda}\left[\Phi\cdot\overline{L}_\ell^c\right]\left[L_{\ell'}\cdot\Phi\right] + \text{H.c.}$$

SM Higgs Doublet

SM Lepton

EFT Scale

$v = \sqrt{2}\langle\Phi\rangle \approx 246\ \text{GeV}$ Higgs vev

$$m_{\ell\ell'} = C_5^{\ell\ell'} v^2/\Lambda$$

Effective Majorana Mass

0νββ @ GERDA [2009.06079]
$|m_{ee}| < 79 - 180$ meV at 90% C.L.

Weinberg operator in pp→μ±μ±jj

- Take an EFT approach:

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

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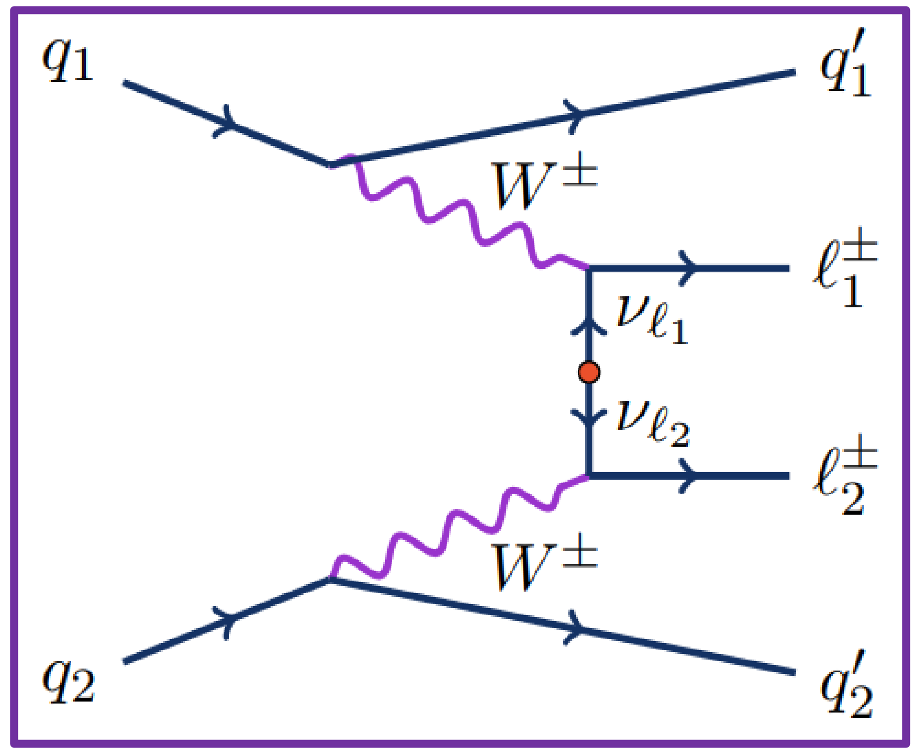
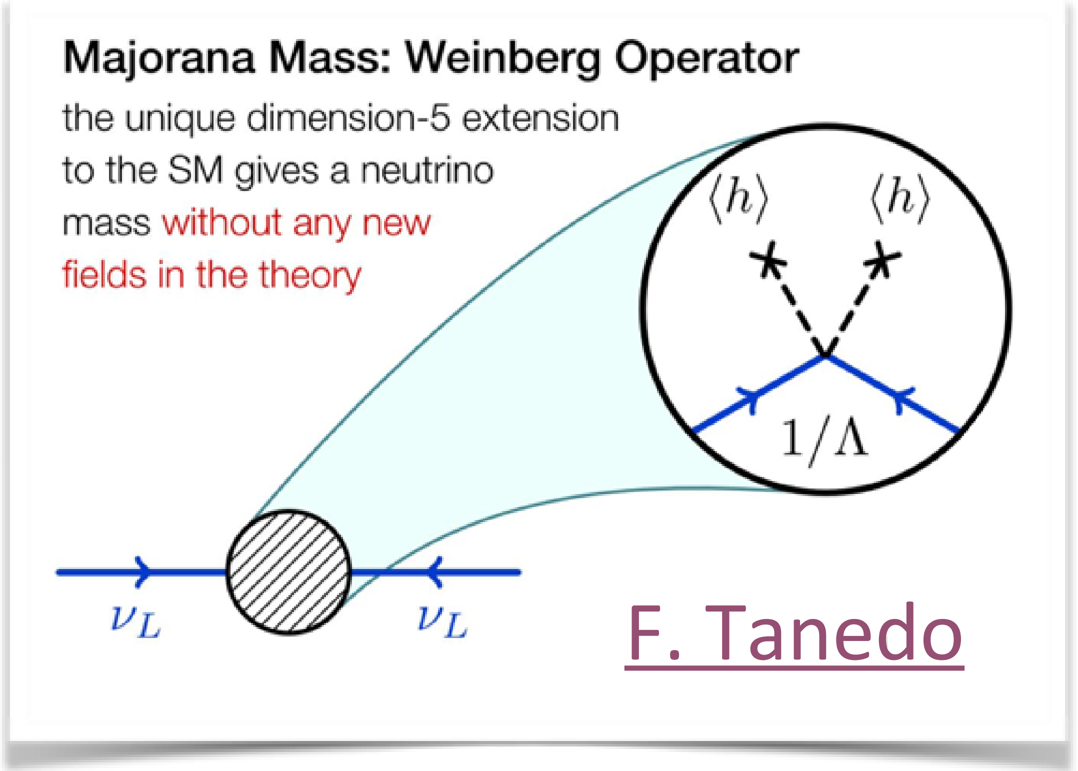




Wilson Coefficients

$$\mathcal{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda}\left[\Phi\cdot\overline{L_\ell^c}\right]\left[L_{\ell'}\cdot\Phi\right] + \mathrm{H.c.}$$

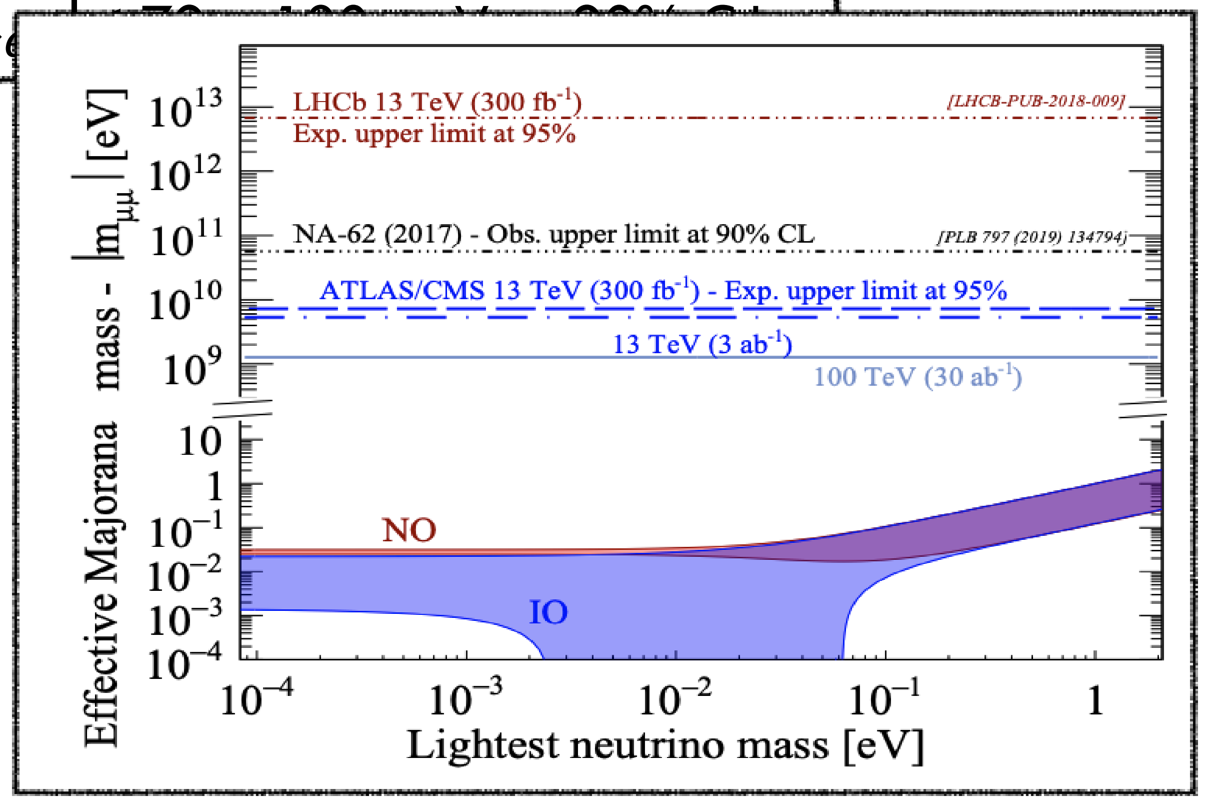
SM Higgs Doublet; SM Lepton; EFT Scale

$v = \sqrt{2}\langle\Phi\rangle \approx 246~\mathrm{GeV}$ Higgs vev

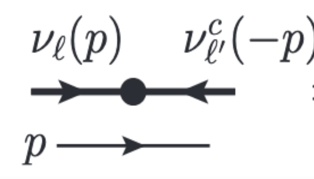
$$m_{\ell\ell'} = C_5^{\ell\ell'} v^2/\Lambda$$

Effective Majorana Mass

0νββ @ GERDA [2009.06079]



- **Head-on neutrino** lines appear and make it hard for the MC generation.
- Newly proposed solution Phys. Rev. D 103, 115014
  - Approximate head-on lines with a Majorana fermion line



$$= \frac{i\not{p}}{p^2}\,\frac{-iC_5^{\ell\ell'}v^2}{\Lambda}\,\frac{i\not{p}}{p^2} = \frac{i m_{\ell\ell'}}{p^2}$$

$$\hat{\sigma}(W^+W^+\to\ell^+\ell'^+) = \frac{(2-\delta_{\ell\ell'})}{2\pi 3^2}\left|\frac{C_5^{\ell\ell'}}{\Lambda}\right|^2 + \mathcal{O}\left(\frac{m_W^2}{M_{WW}^2}\right) \longrightarrow \sigma \sim |m_{\ell\ell'}|^2 \propto \left|C_5^{\ell\ell'}/\Lambda\right|^2$$

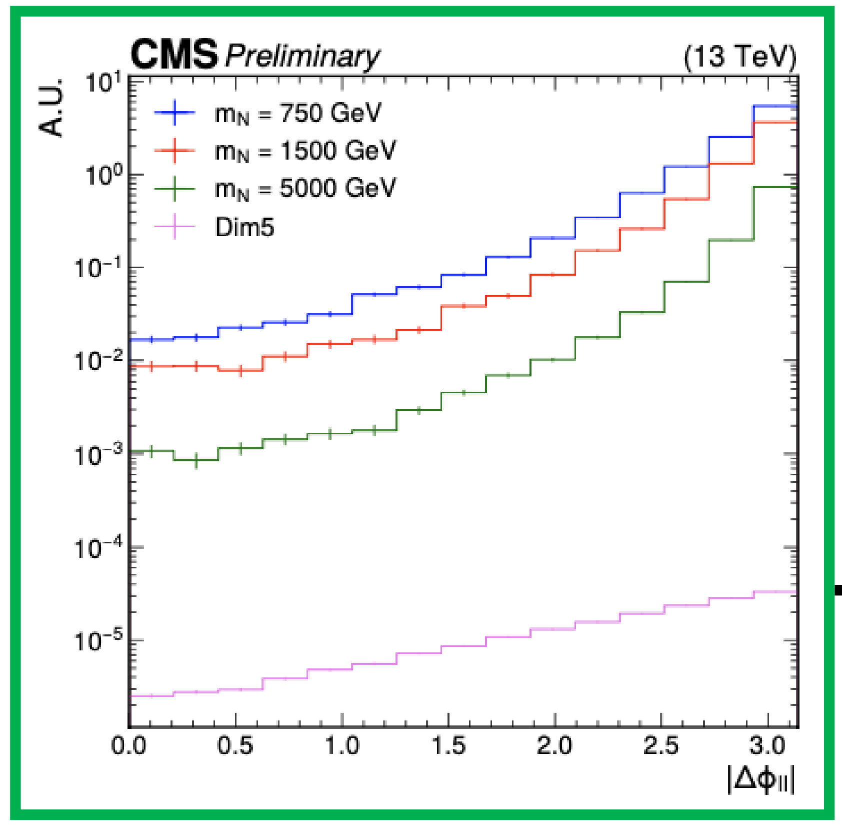
Event selections

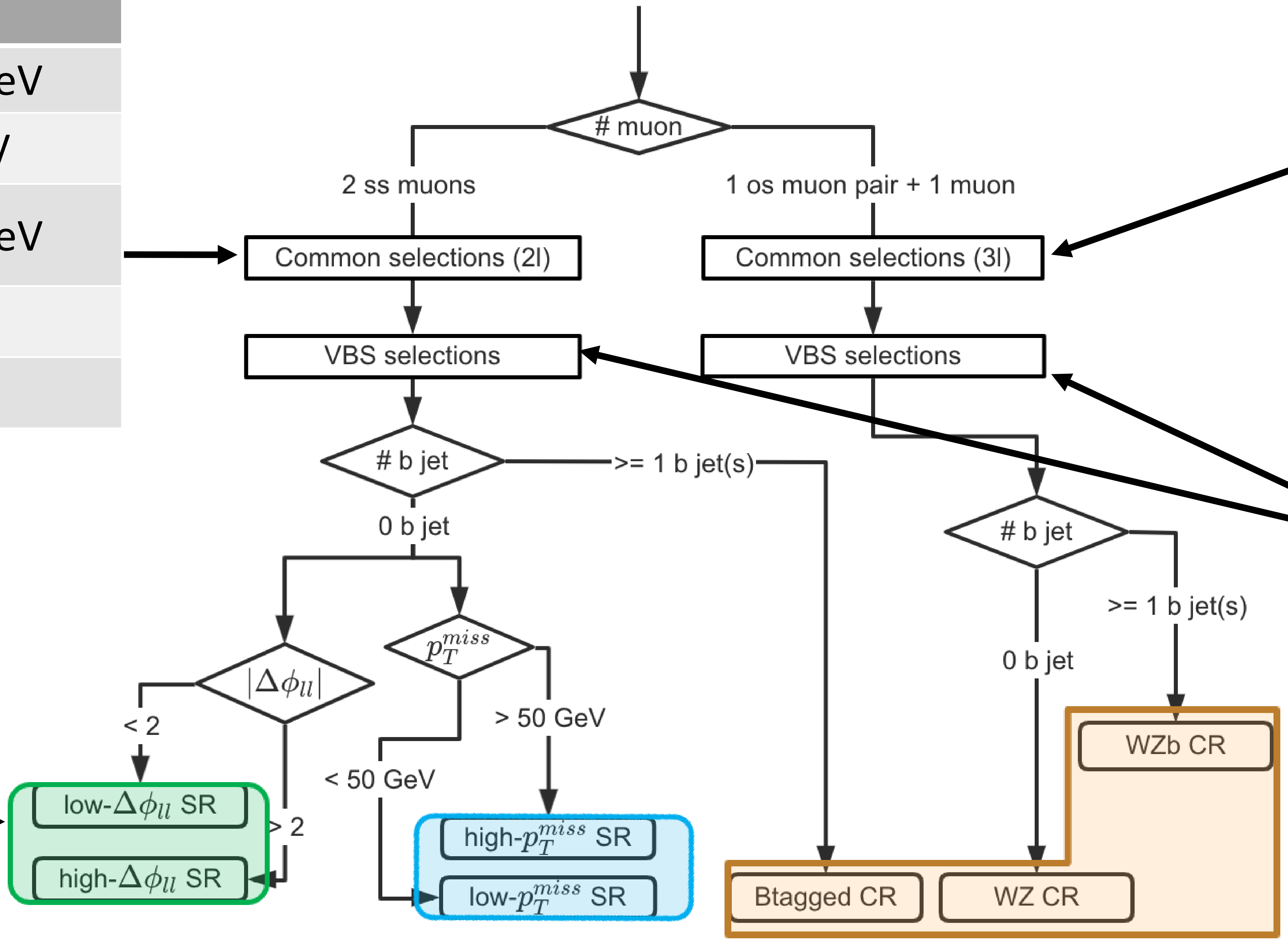
- Signal regions and background enriched control region selections are defined

Common selections (2l)	
p_T(lep)	> 30/30 GeV
m_{ll}	> 20 GeV
p_T(jet)	> 30/30 GeV
tau veto	Applied
Max Zeppenfeld	< 0.75

Common selections (3l)	
p_T(lep)	> 25/10/25 GeV
$\|m_{ll}-m_Z\|$	< 15 GeV
m_{lll}	> 100 GeV
p_T(jet)	> 30/30 GeV
tau veto	Applied
Max Zeppenfeld	< 1.0
Max p_T^{miss}	> 30 GeV

VBS selections	
mjj	> 750 GeV
|Δηjj|	> 2.5





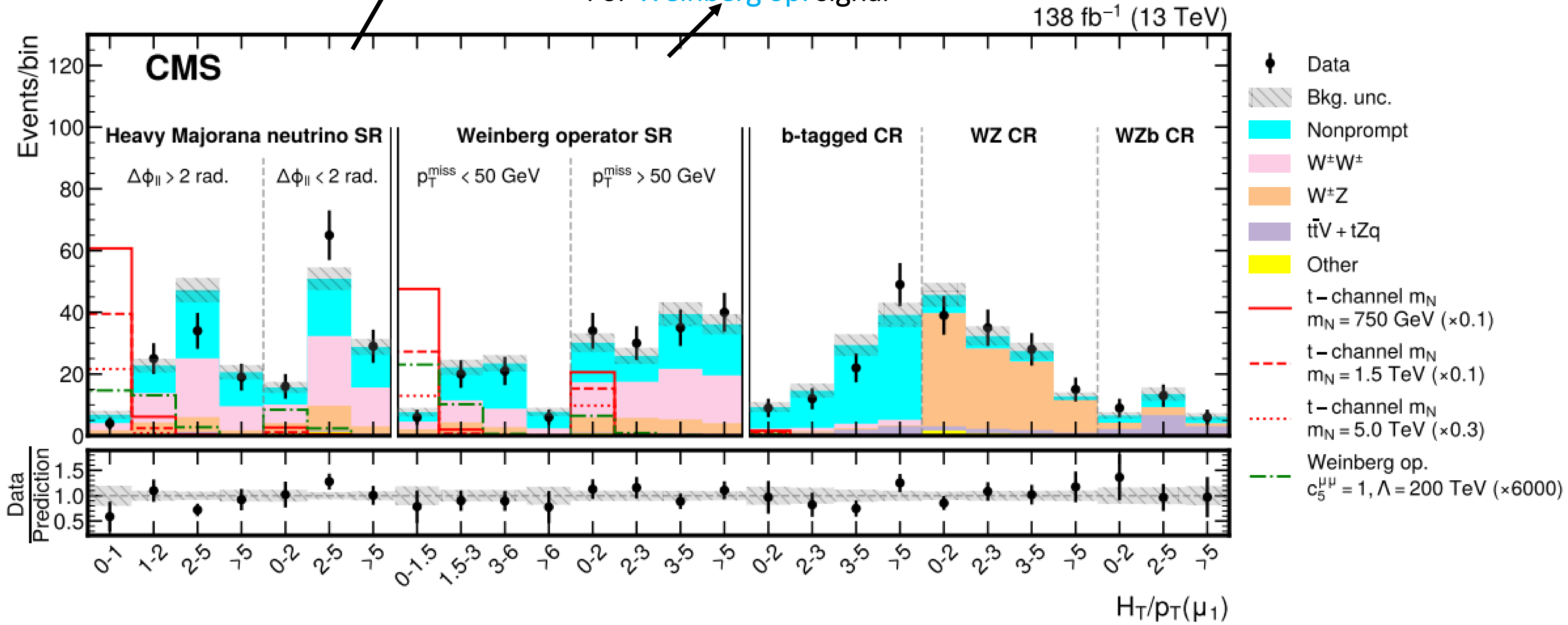
- low-$\Delta\phi_{ll}$ SR and high-$\Delta\phi_{ll}$ SR are used for HMN processes
- high-p_T^{miss} SR and inverted low-p_T^{miss} SR are used for Weinberg op. process

Post-fit Data vs. Expectation

- Simultaneously fit the signal and control regions.
  - The fitted distribution is $\boldsymbol{H_T/p_{\mu 1}}$ where $H_\mathrm{T} = \sum p_\mathrm{T}^i(jet), (i \in p_\mathrm{T}(jet) > 30\mathrm{GeV})$

For HMN signals

For Weinberg op. signal

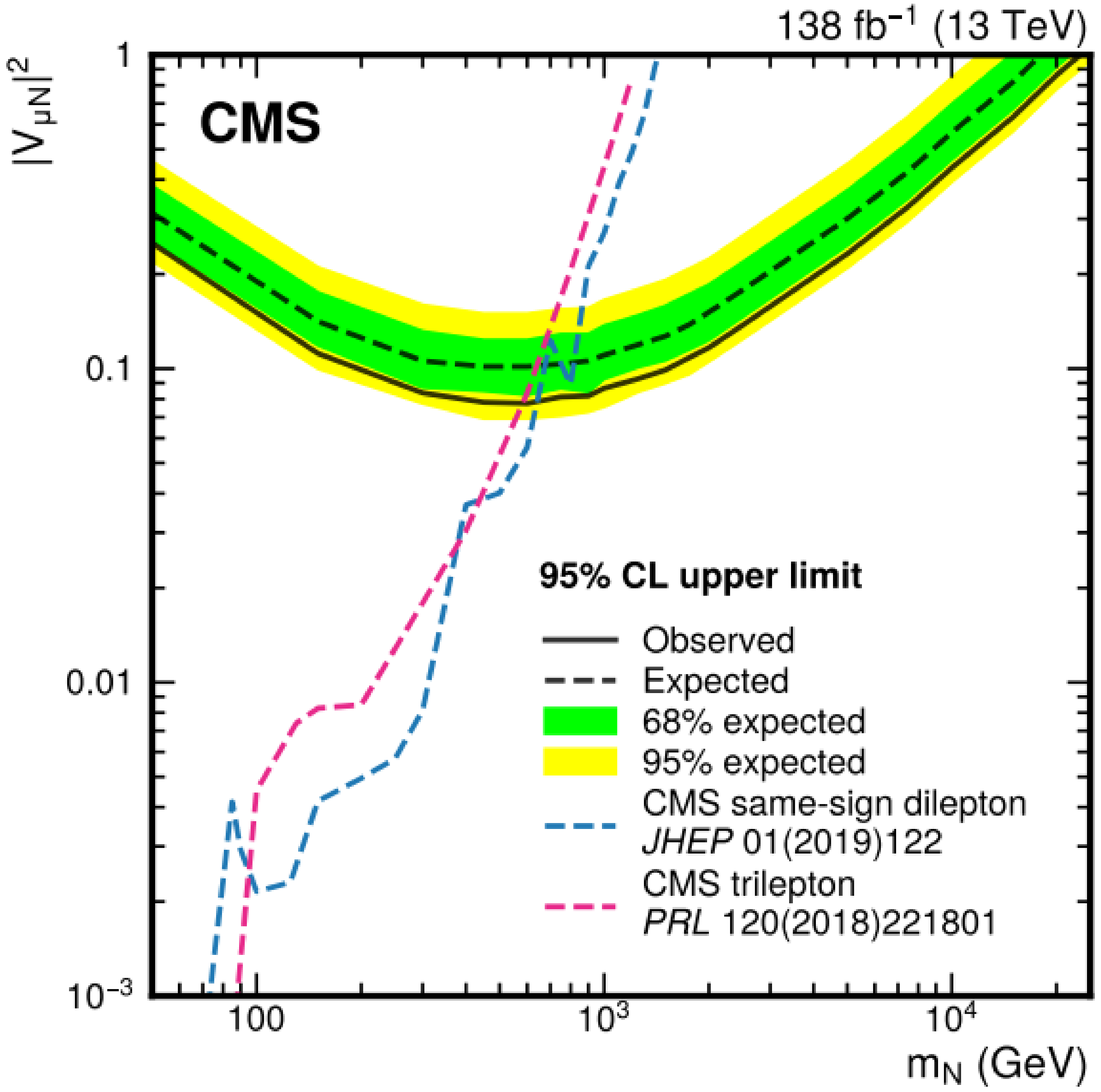


Signal extraction: Heavy Majorana Neutrinos

- Interpretations of limits
  - Parameter of interest (POI) in fit: signal strength $\hat{\mu}$
- For VBF production of HMN
  - The cross section dependence reads:

$$\sigma(pp \rightarrow \ell_i^{\pm}\ell_j^{\pm} + X) \equiv \left|V_{\ell_i N} V_{\ell_j N}\right|^2 \times \sigma_0\left(pp \rightarrow \ell_i^{\pm}\ell_j^{\pm} + X\right)$$

  - Upper limits on signal strength can be translated to the squared mixing element $|V_{\mu N}|^2 = \sqrt{\hat{\mu}}$
- m_N up to around **23 TeV** is excluded
- Better constraints on $|V_{\mu N}|^2$ for $m_N \gtrsim$ **650 GeV**



Signal extraction: Weinberg op.

- Interpretations of limits
  - POI in fit: signal strength $\hat{\mu}$
- For Weinberg op. processes
  - The cross-section dependence reads: $\hat{\sigma}(W^+W^+ \to \ell^+\ell'^+) = \frac{(2-\delta_{\ell\ell'})}{2\pi 3^2}\left|\frac{C_5^{\ell\ell'}}{\Lambda}\right|^2 + \mathcal{O}\left(\frac{m_W^2}{M_{WW}^2}\right)$
  - Effective Majorana Mass is given by: $m_{\ell\ell'} = C_5^{\ell\ell'} v^2/\Lambda$
  - Interpretation: translate to EFT scale limit with Wilson coefficient fixed to unit, thus $\hat{\Lambda} = 200 \times \hat{\mu}^{-\frac{1}{2}}$ **GeV**, and translate to effective Majorana mass limit $m_{\mu\mu} = \nu^2 |C_5^{\mu\mu}|/\hat{\Lambda}$
- Results
  - Observed (expected) lower bond on **EFT scales Λ: 5.6 (4.7) TeV** (assuming $C_5^{\mu\mu} = 1$)
  - Observed (expected) upper limits of **effective Majorana mass $m_{\mu\mu}$: 10.8 (12.8) GeV**

Summary

- Performed analysis on **VBF** production of **same-sign muon pairs** associated with two jets
  - Heavy Majorana neutrino from Type-I Seesaw Model
    - Upper limits on $|V_{\mu N}|^2$ for m_N up to around **23 TeV**
    - Better constraints on $|V_{\mu N}|^2$ for $\boldsymbol{m_N} \gtrsim$ **650 GeV**
  - First direct search at collider on dimension-5 Weinberg operator
    - Upper limit of effective Majorana mass $|\boldsymbol{m_{\mu\mu}}|$, observed (expected): **10.84 (12.84) GeV**
- arXiv: 2206.08956 submitted to PRL and will be accepted soon