Probing heavy Majorana neutrinos and the Weinberg operator through $pp \rightarrow \mu^{\pm}\mu^{\pm}jj$ at CMS

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The dim-5 Weinberg operator

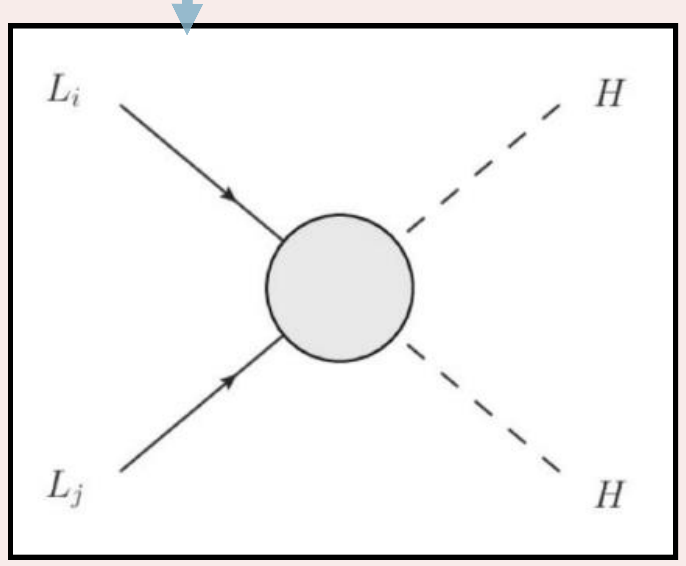
1957 — 1970s — 2002-2005

- Neutrino oscillation B. Pontecorvo ('57)

- An effective field theory (**EFT**) solution

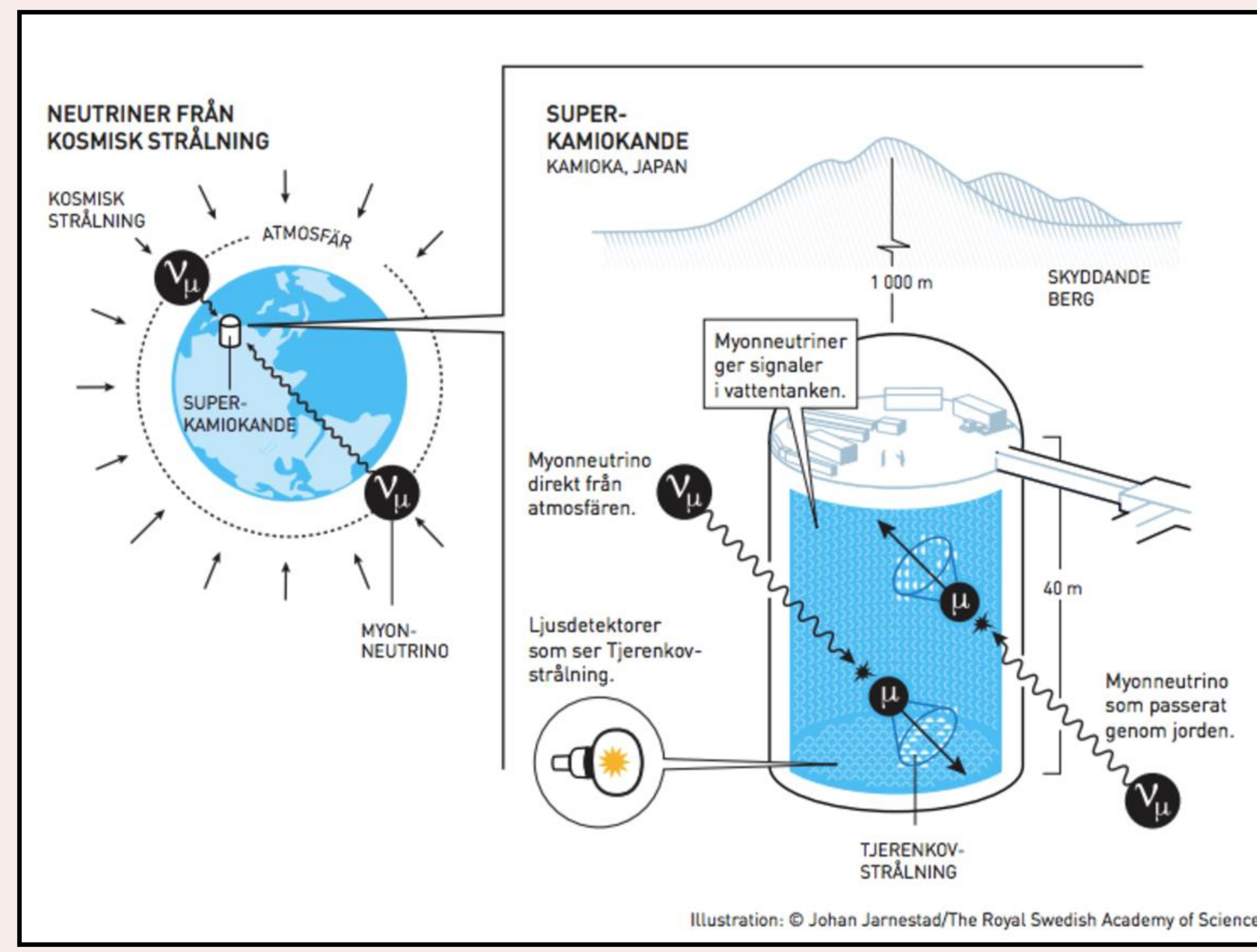
$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

The only gauge-invariant operator at dim-5
Weinberg Operator Weinberg ('79)



- Adding this operator will give SM neutrinos **Majorana masses**
- EFT doesn't describe the new physics in detail. Need UV complete models.

- **Observation** of neutrino oscillations
  - SNO: PhysRevLett.89.011301
  - Super-Kamiokande: PhysRevD.71.112005
- SM neutrino masses are **non-zero**



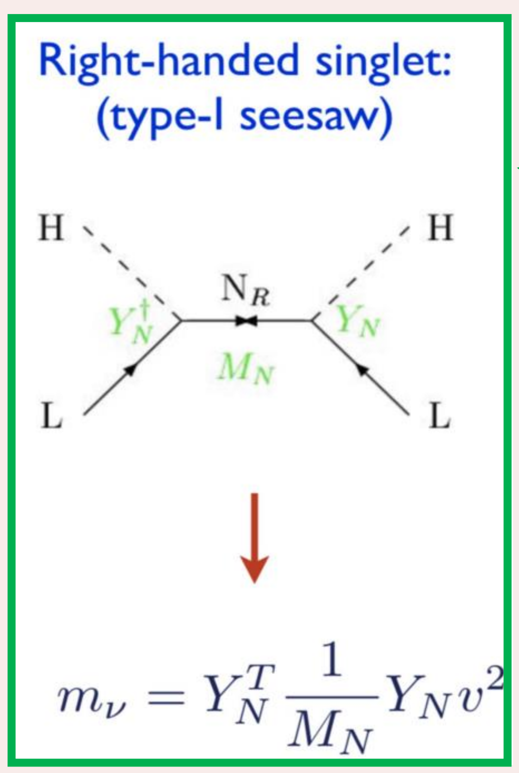
Seesaw models

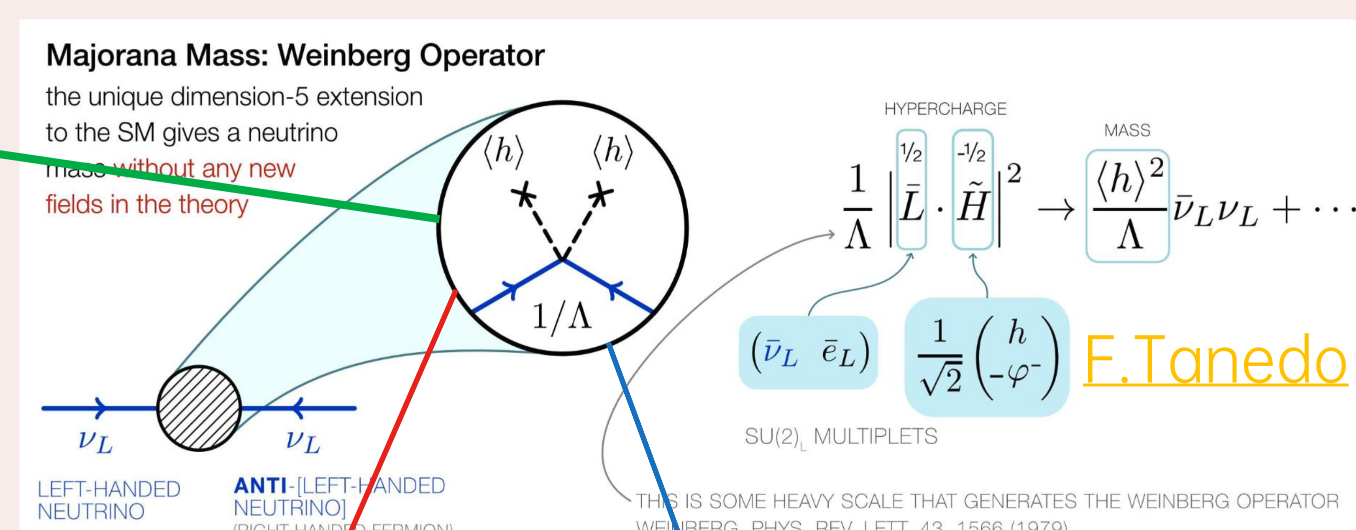
1937

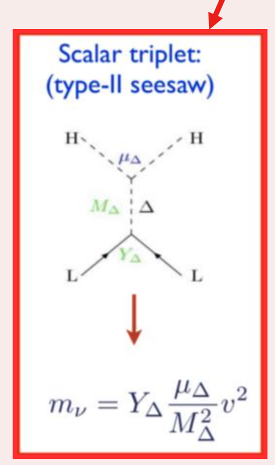
1970s

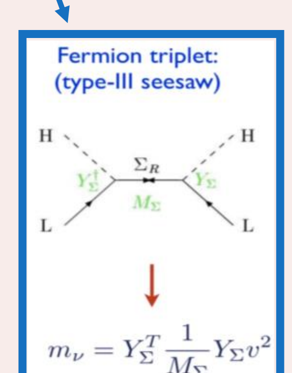
- ❑Majorana fermion E. Majorana ('37)
  - A fermion that is its own antiparticle

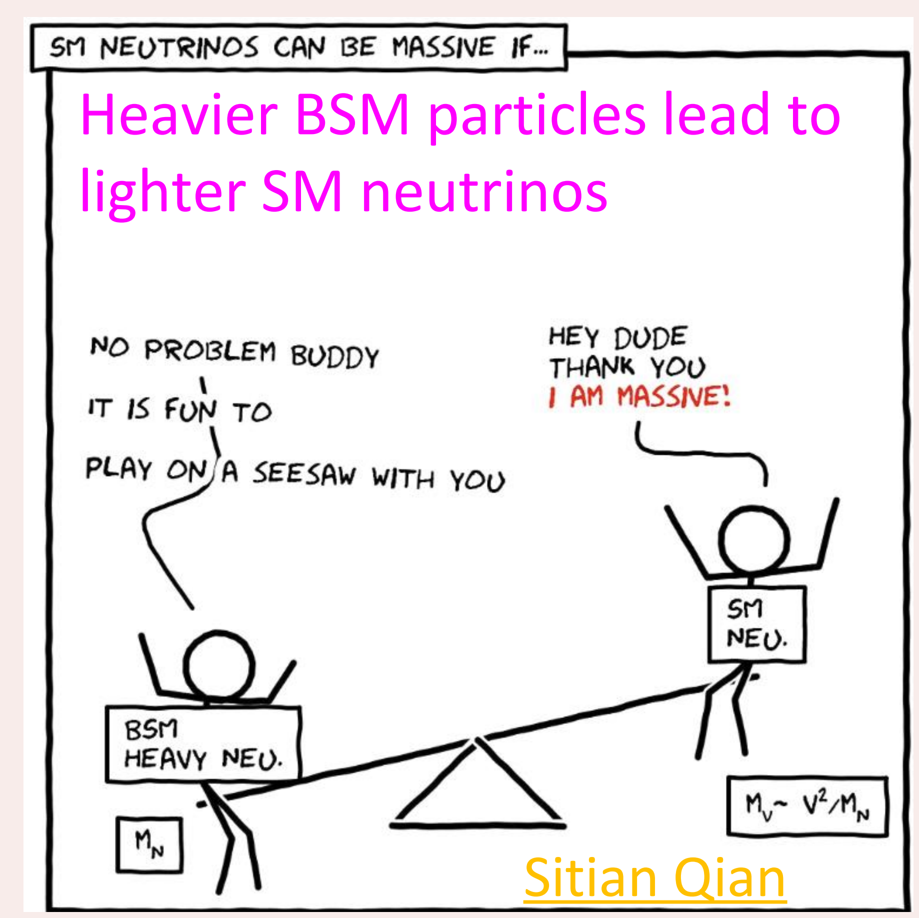
- ❑Seesaw mechanism
  - Opening the black box of Weinberg operator requires a "seesaw"
  - Only three different kinds of realization at Born-level are allowed







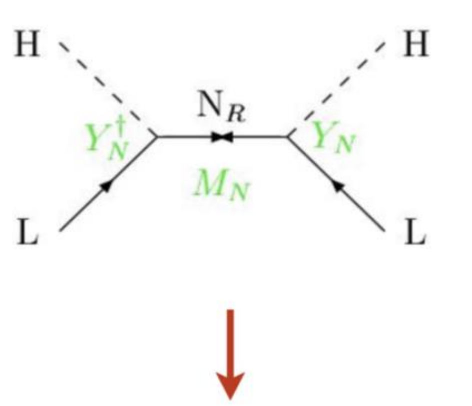




Analyses of the Type-I Seesaw Model

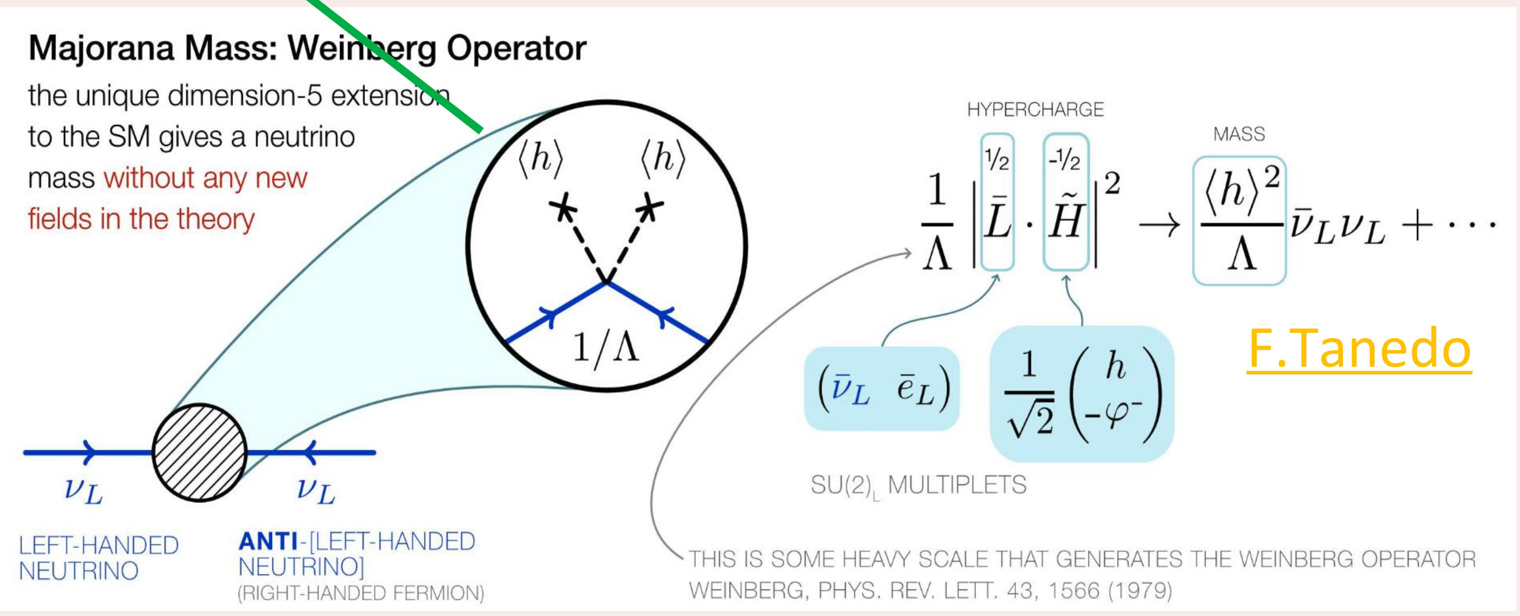
2018-2019

Right-handed singlet:
(type-I seesaw)



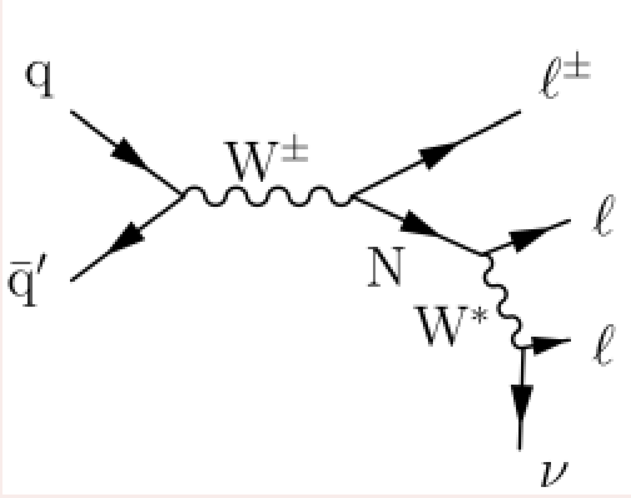
$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

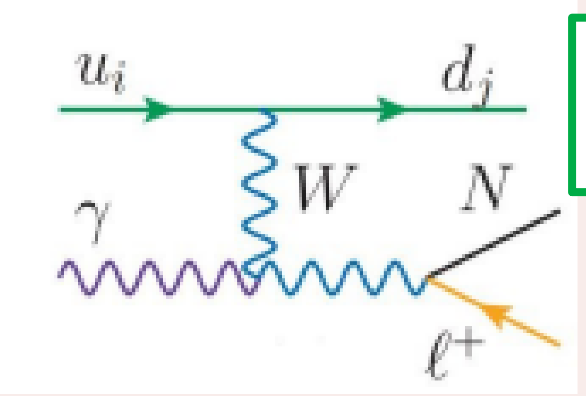
PhysRevLett.120.221801: Trilepton
JHEP01(2019)122: Same-sign dilepton



F.Tanedo

PhysRevLett.120.221801:
Trilepton





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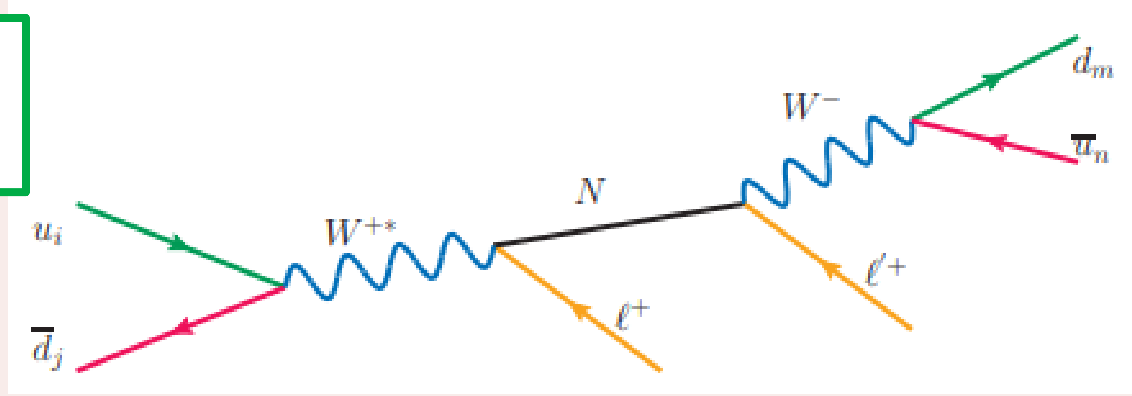

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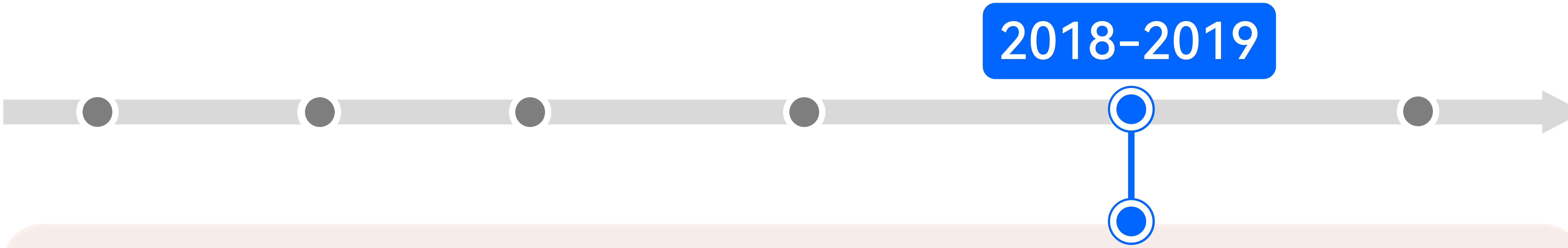

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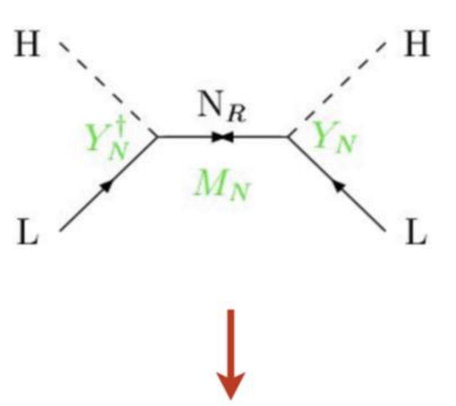

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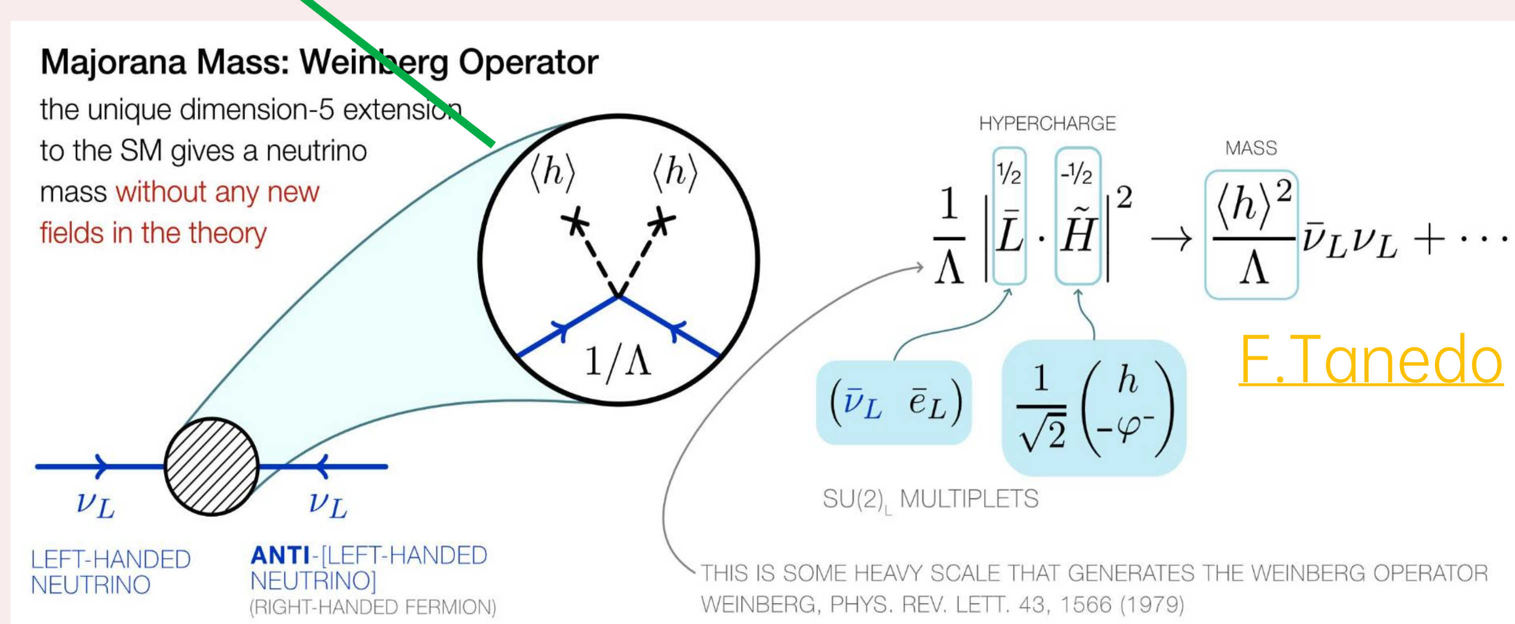

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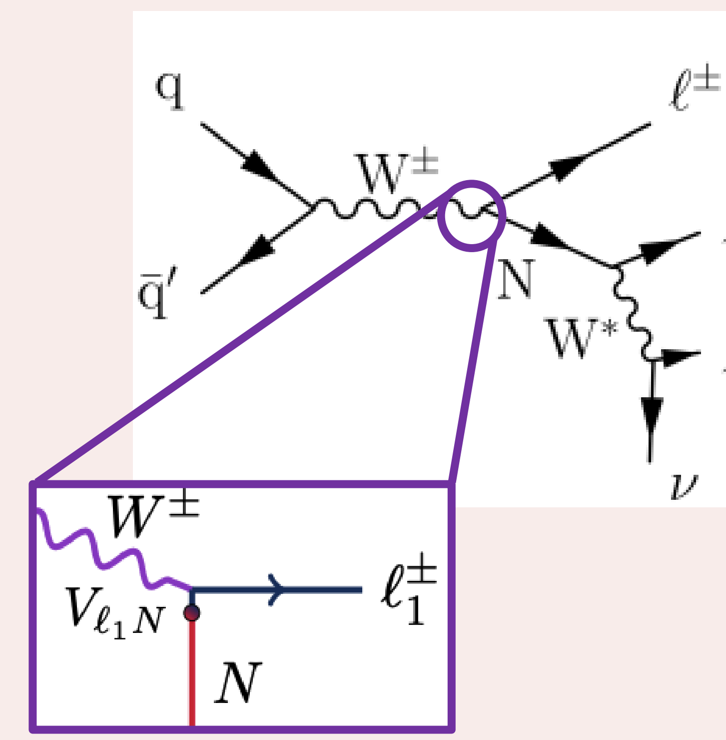
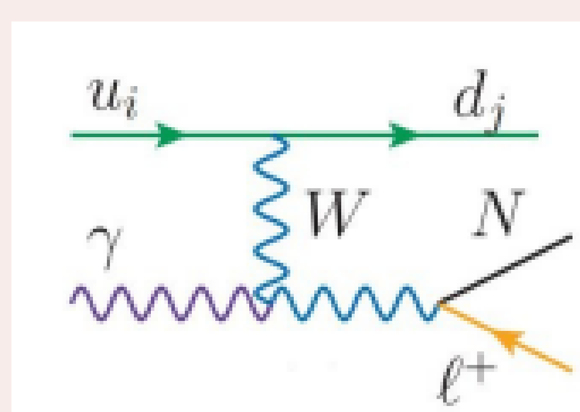


$$\sigma(pp \to N\ell^\pm + X) \equiv |V_{\ell N}|^2 \times \sigma_0(pp \to N\ell^\pm + X)$$



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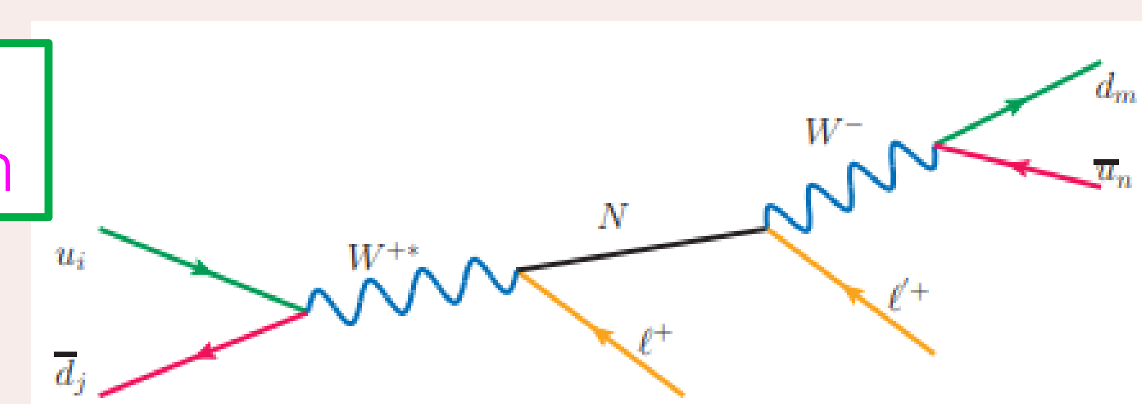

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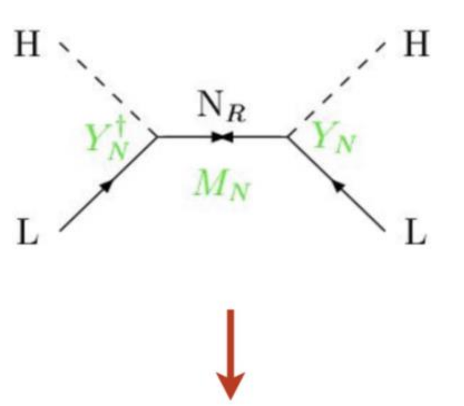

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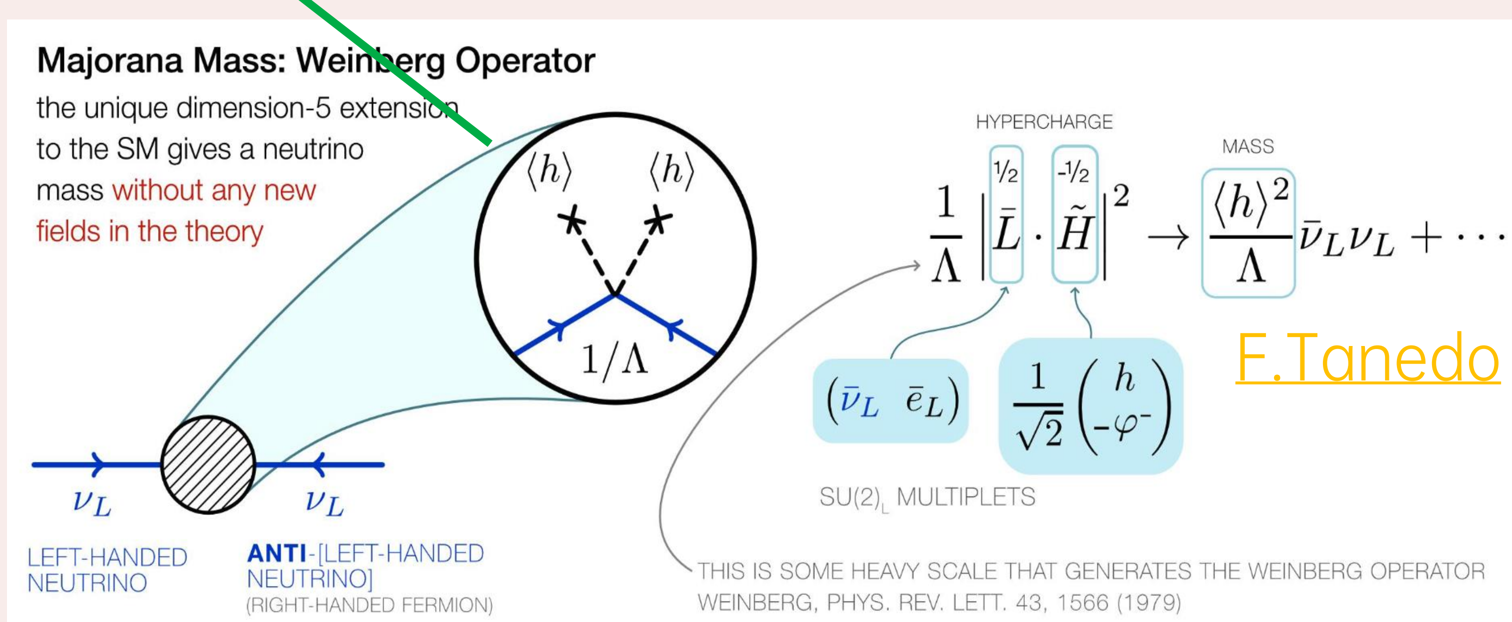

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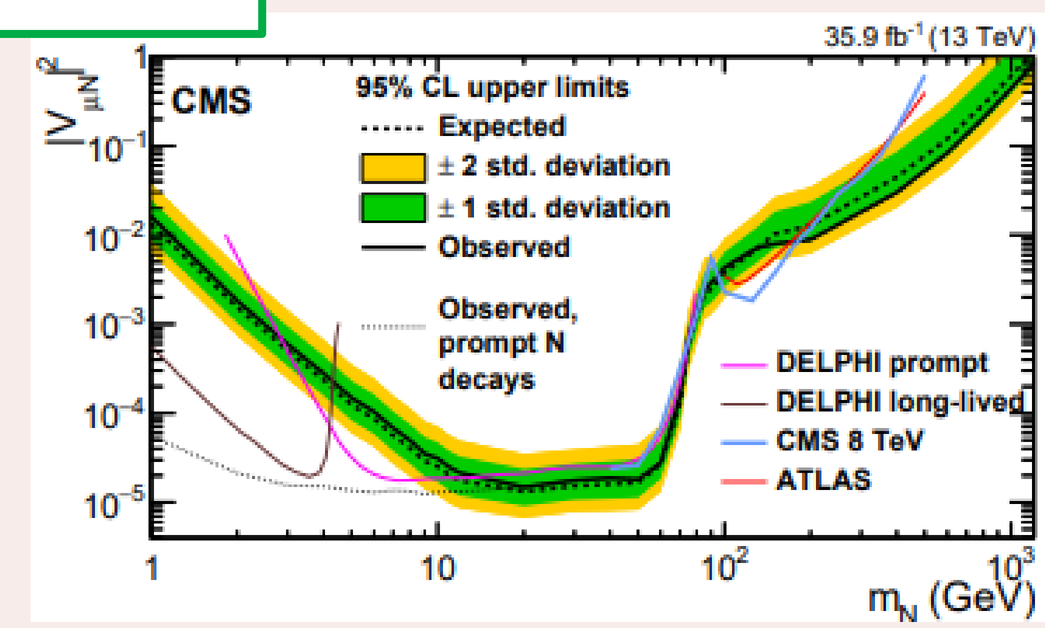

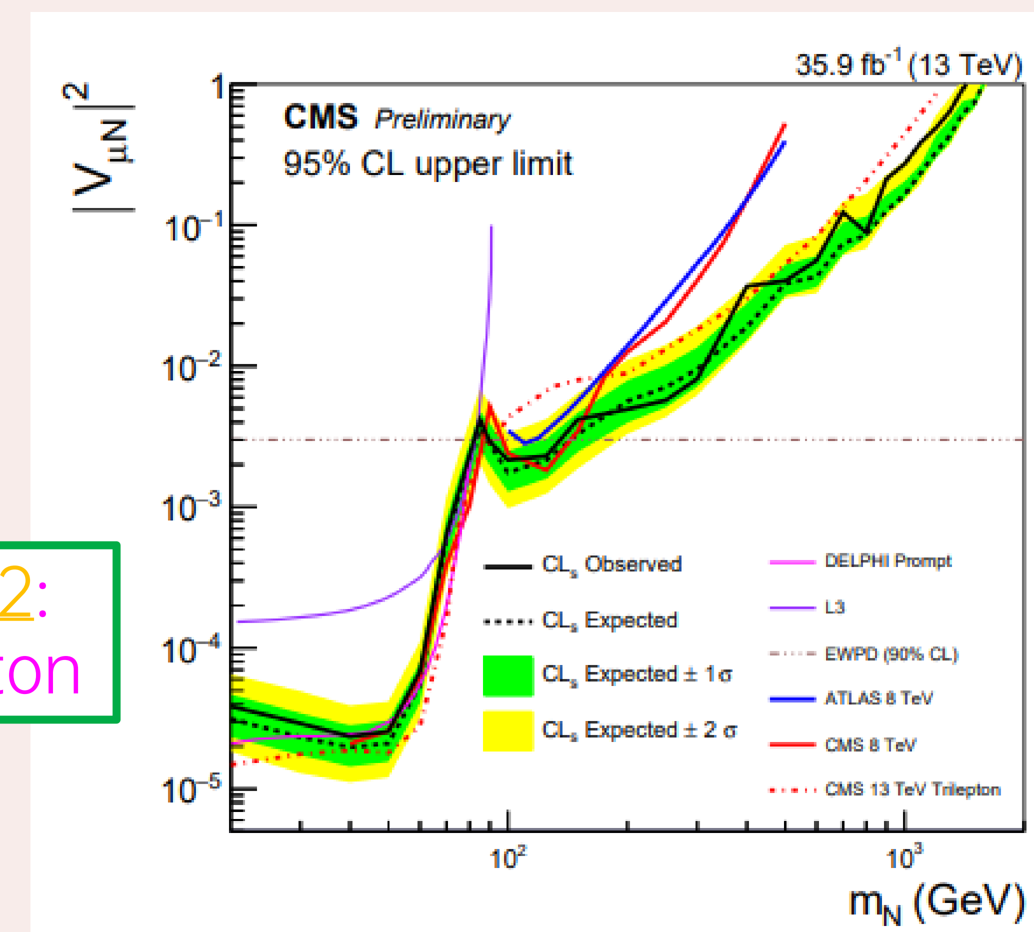

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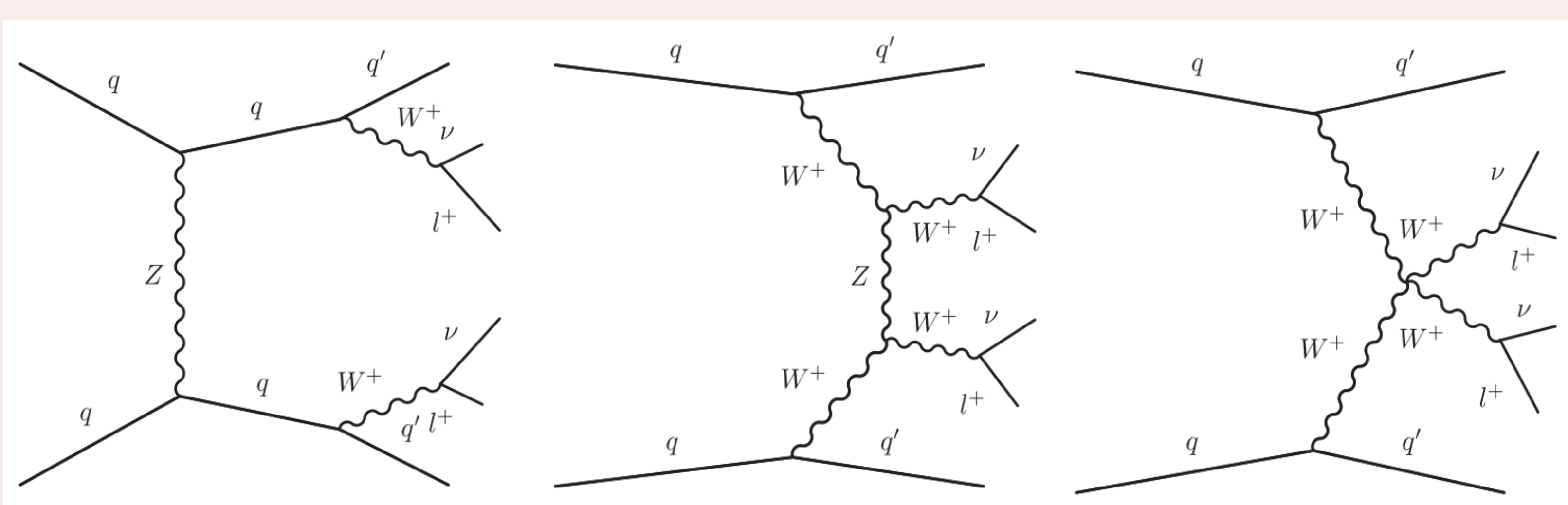
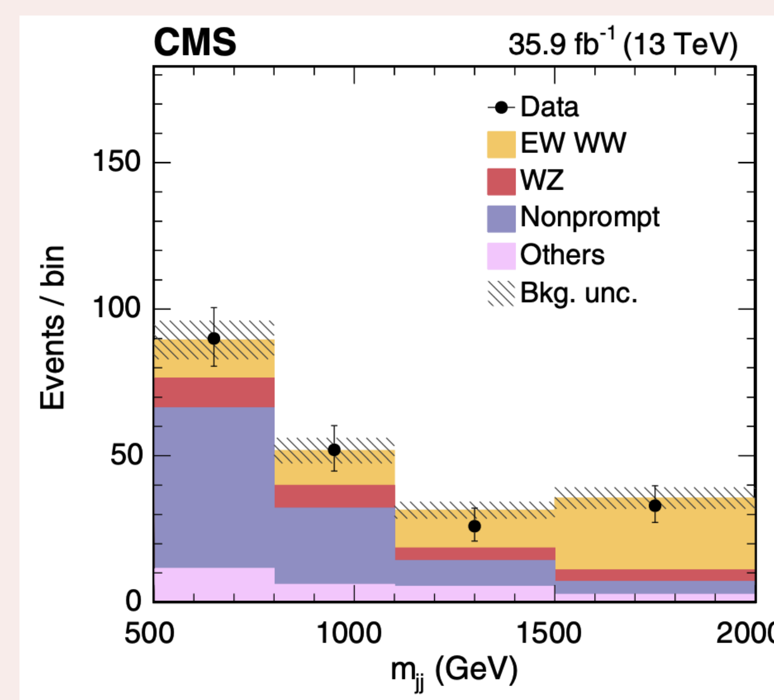
Introduction on same-sign WW scattering

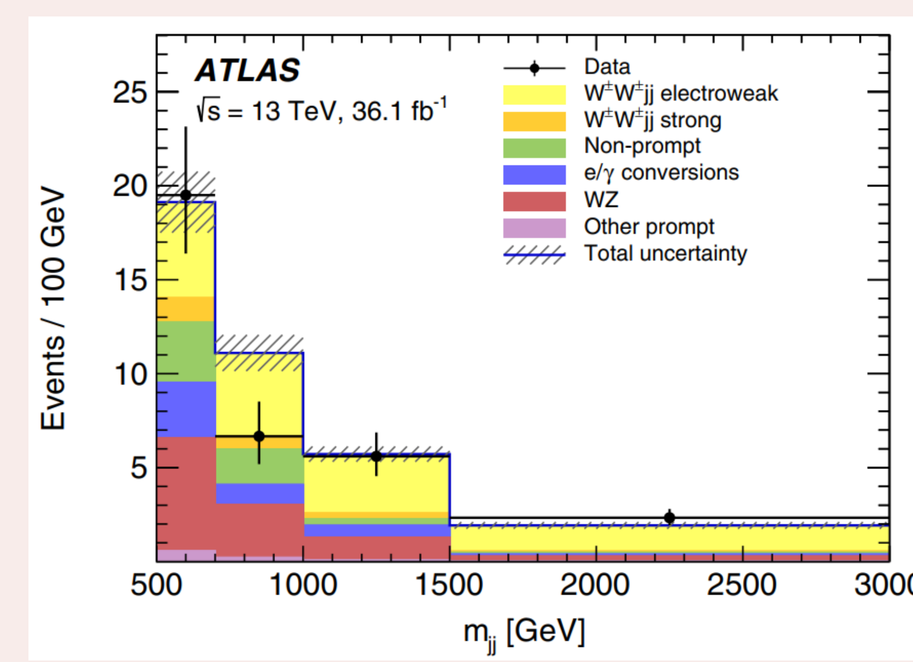
2018-2019

❑Large Boson Collider

- EW production of $W^{\pm}W^{\pm}jj$: Through Vector Boson Scattering (VBS)
  - VBS processes are the key to reveal the nature of Electroweak Symmetry Breaking (EWSB)
- EW production of $W^{\pm}W^{\pm}jj$ has its own advantages:
  - Dominant EW production over QCD
  - Clear event topology: two same-sign leptons + back-to-back VBS dijet







❑The first observed VBS process: same-sign WW scattering

- CMS: PhysRevLett.120.081801
- ATLAS: PhysRevLett.123.161801

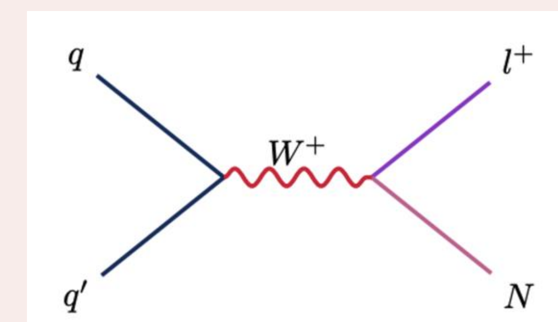
Heavy Majorana neutrinos in pp→μ±μ±jj

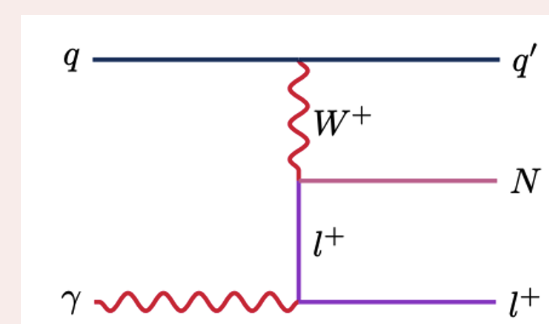
2021

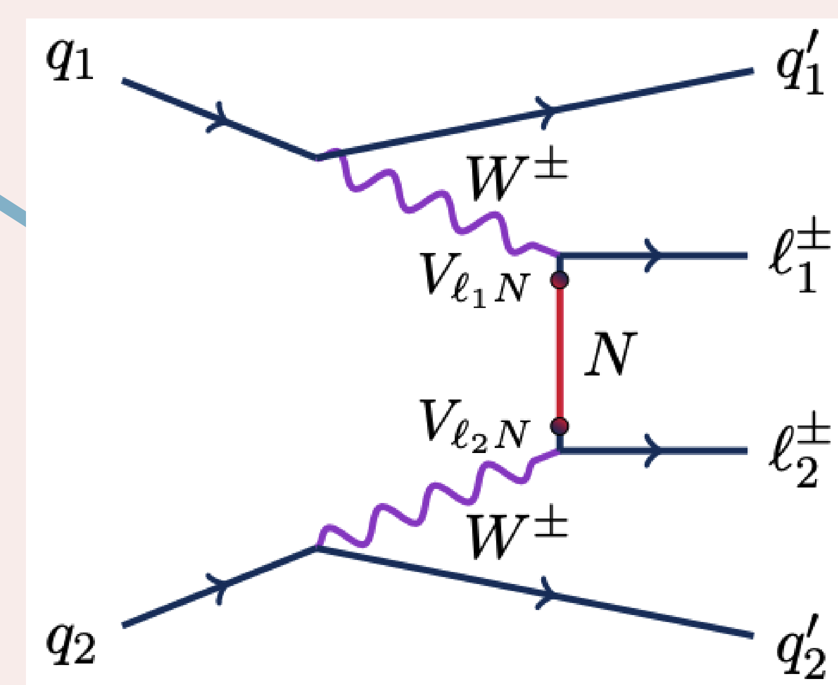
- T-channel exchange of a heavy Majorana neutrino PhysRevD.103.055005
- The "**neutrinoless double-β decay**" version of the LHC
- Consider the **dimuon** channel

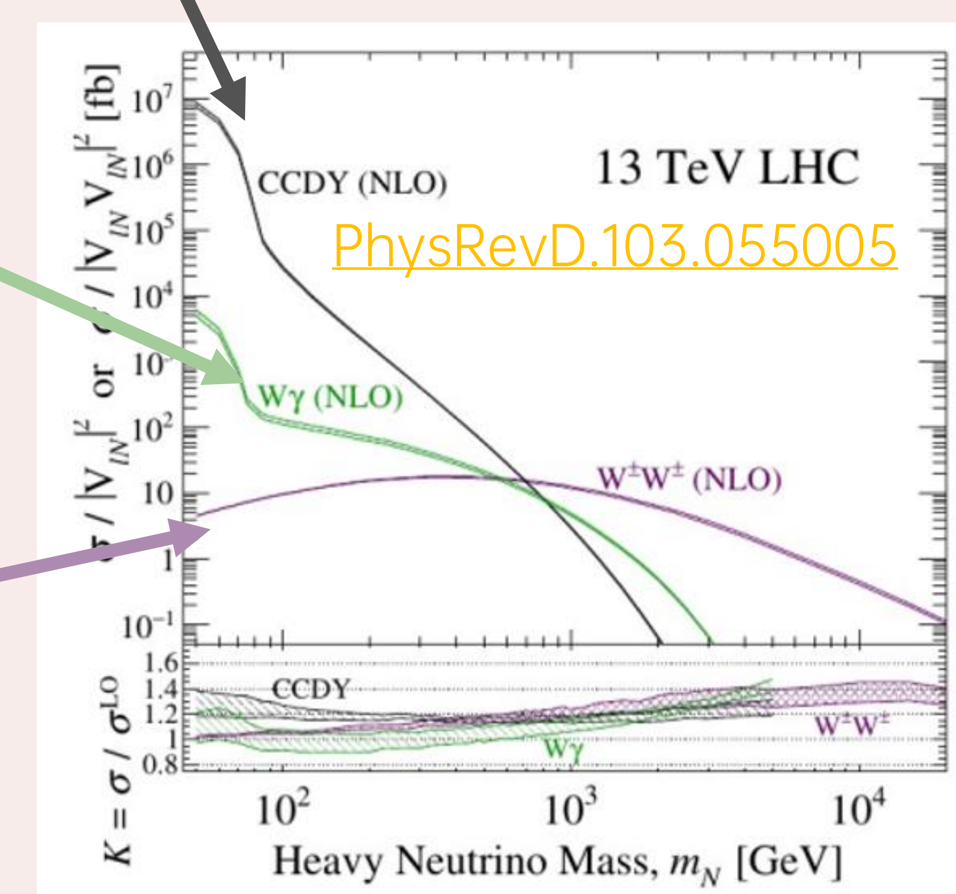
$$V_{lN} = \begin{pmatrix} V_{eN_1} & V_{eN_2} & V_{eN_3} \\ V_{\mu N_1} & V_{\mu N_2} & V_{\mu N_3} \\ V_{\tau N_1} & V_{\tau N_2} & V_{\tau N_3} \end{pmatrix}$$

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









- T-channel process extends the probing mass range to ~20 TeV

Probing heavy Majorana neutrinos and the Weinberg operator through pp→μ±μ±jj at CMS arXiv: 2206.08956

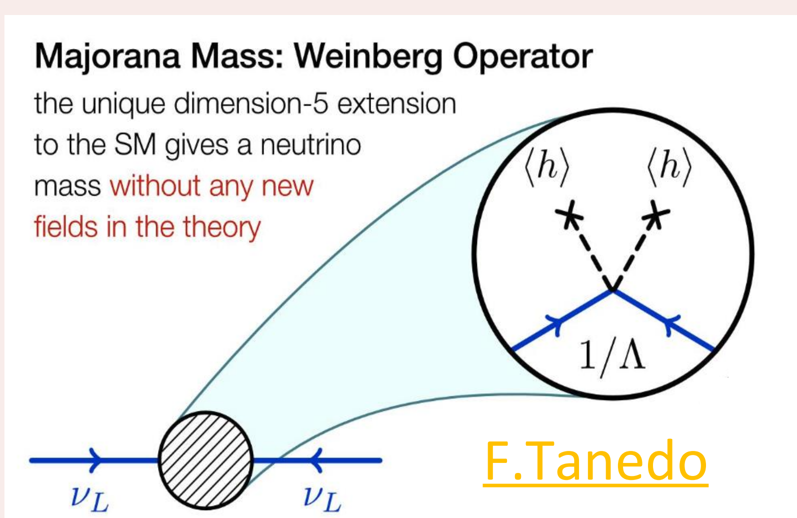
Weinberg operator in pp→μ±μ±jj

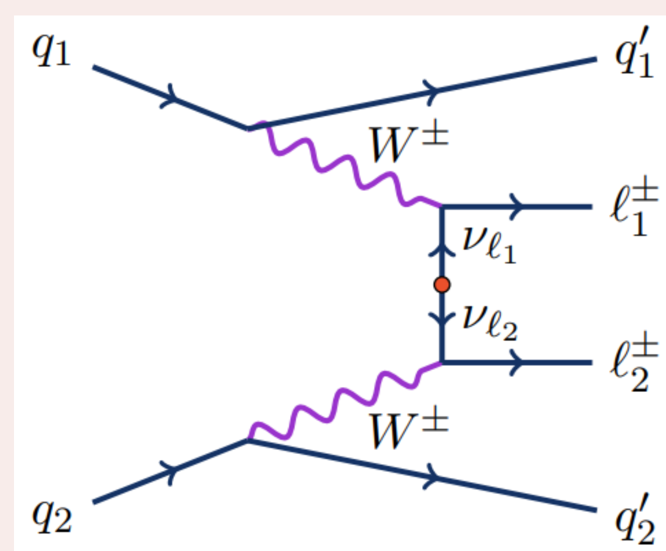
2021

- Take an EFT approach:

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

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





Wilson Coefficients

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

SM Higgs Doublet

SM Lepton

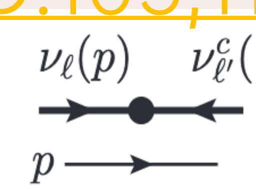
EFT Scale

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

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

Effective Majorana Mass

PhysRevD.103,115014



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

$$\sigma \sim |m_{\ell\ell'}|^2 \propto \left|C_5^{\ell\ell'}/\Lambda\right|^2$$

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

Signal simulation

- Generator: Madgraph5_aMC@NLO
- Focus on same-sign dimuon channel: pp → $\mu^{\pm}\mu^{\pm}$jj
- Heavy Majorana neutrino process
  - UFO model: SM_HeavyN_NLO

```
import model SM_HeavyN_NLO
define p = g u c d s u~ c~ d~ s~
define j = p
generate p p > mu+ mu+ j j QED=4 QCD=0 $$ w+ w- / n2 n3 [QCD]
add process p p > mu- mu- j j QED=4 QCD=0 $$ w+ w- / n2 n3 [QCD]
```

- HMN: Parameters refer to PhysRevD.103.055005
  - Only consider lightest HMN N1
  - Additional heavy mass eigenstates are decoupled $m_{N2}=m_{N3}=10^{10}$ GeV
  - Only mixing element $|V_{\mu N1}|^2=1$

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

- Weinberg op. process
  - UFO model: SMWeinbergNLO

- Weinberg op. : Parameters refer to PhysRevD.103,115014
  - Focus on $c^5_{\mu\mu}$= 1 and Λ = 200 TeV

```
import model SMWeinbergNLO
generate p p > mu+ mu+ j j QED=4 QCD=0 $$ w+ w- [QCD]
add process p p > mu- mu- j j QED=4 QCD=0 $$ w+ w- [QCD]
```

- Generator Cuts $p_T^j > 20$ GeV and $|\eta^j| < 5.5$

Background estimation

Category	Estimation
W±W± EW	From MC simulation
W±W± QCD	
WW DPS	
WZ/γ* QCD	
WZ EW	
Tribosons & ttV	
ZZ	
Non-prompt muon	From data-driven

❑Main backgrounds

- Non-prompt muon
- SM W±W±jj

❑Non-prompt muon

- Heavy flavor decayed leptons, misidentified charge pions, etc.
- A data-driven approach based on matrix method

p_1: probability for a **real** lepton passes the loose selection to also pass the tight selection

m_{XY} — X: # real leptons; Y: # fake leptons

$$\begin{pmatrix} m_{20} \\ m_{11} \\ m_{02} \end{pmatrix} = \frac{p_2 - p_1}{-(p_1-p_2)^3} \begin{pmatrix} p_2^2 & -p_2(1-p_2) & (1-p_2)^2 \\ -2p_2p_1 & p_1(1-p_2)+p_2(1-p_1) & -2(1-p)(1-p_2) \\ p^2 & -p_1(1-p_1) & (1-p_1)^2 \end{pmatrix} \begin{pmatrix} n_{20} \\ n_{11} \\ n_{02} \end{pmatrix}$$

n_{XY} — X: # tight leptons; Y: # loose-but-not-tight leptons

p_2: probability for a **fake** lepton passes the loose selection to also pass the tight selection

p_2= Numerator/Denominator

Dijet control region

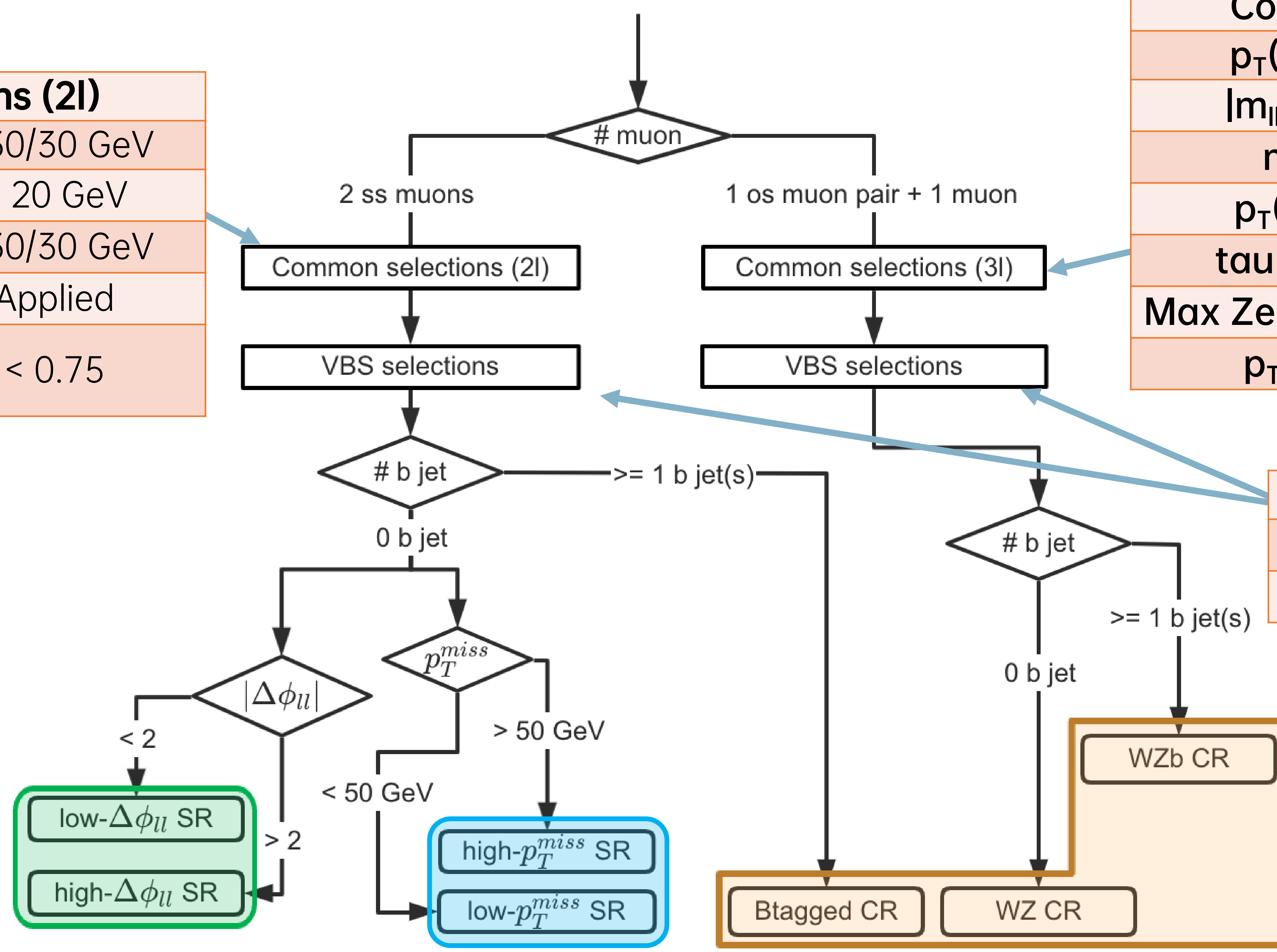
- Denominator Events with loose muon
- Numerator With tight muon

- n_{20}, n_{11}, n_{02} are observed yields measured in control regions
- p_1, p_2 are probabilities of interest measured in Z mass and QCD enriched dijet control regions respectively
- m_{20}, m_{11}, m_{02} are thus calculated based on measured n_{20}, n_{11}, n_{02} and p_1, p_2

Event selection

- 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
p_T^{miss}	> 30 GeV

VBS selections	
m_{jj}	> 750 GeV
$\|\Delta\eta_{jj}\|$	> 2.5

- Low-$\Delta\phi_{ll}$ SR and high-$\Delta\phi_{ll}$ SR are used for heavy Majorana neutrino processes
- High-p_T^{miss} SR and low-p_T^{miss} SR are used for Weinberg op. process

Fit Strategy

- Via a simultaneous fit of signal regions and control regions
  - Sub signal regions ($\Delta\phi_{ll}/p_{\mathrm{T}}^{miss}$) are considered
  - The fitted distribution is $\boldsymbol{H_T/p_{\mu 1}}$ where $H_{\mathrm{T}} = \sum p_{\mathrm{T}}^{i}(jet), (i \in p_{\mathrm{T}}(jet) > 30\mathrm{GeV})$

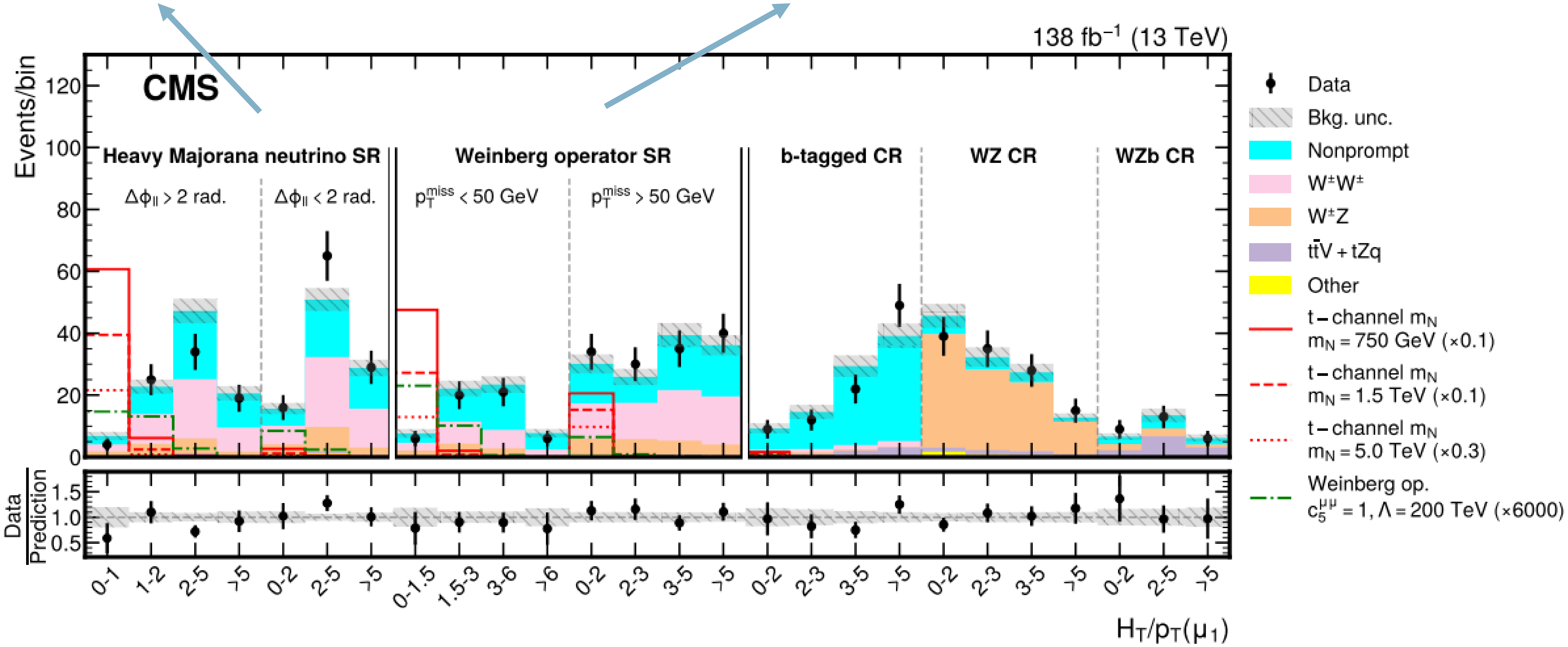
Region	Variable	variable binning
high $\Delta\phi_{\ell\ell}$ bin in W±W± SR	$H_{\mathrm{T}}/p_{\mathrm{T}}^{\ell 1}$	[0, 1, 2, 5, ∞]
low $\Delta\phi_{\ell\ell}$ bin in W±W± SR	$H_{\mathrm{T}}/p_{\mathrm{T}}^{\ell 1}$	[0, 2, 5, ∞]
b-tagged CR	$H_{\mathrm{T}}/p_{\mathrm{T}}^{\ell 1}$	[0, 2, 3, 5, ∞]
WZ CR	$H_{\mathrm{T}}/p_{\mathrm{T}}^{\ell 1}$	[0, 2, 3, 5, ∞]
WZb CR	$H_{\mathrm{T}}/p_{\mathrm{T}}^{\ell 1}$	[0, 2, 5, ∞]

Region	Variable	variable binning
low $p_{\mathrm{T}}^{\mathrm{miss}}$ bin in W±W± SR	$H_{\mathrm{T}}/p_{\mathrm{T}}^{\ell 1}$	[0, 1.5, 3, 6, ∞]
high $p_{\mathrm{T}}^{\mathrm{miss}}$ bin in W±W± SR	$H_{\mathrm{T}}/p_{\mathrm{T}}^{\ell 1}$	[0, 2, 3, 5, ∞]
b-tagged CR	$H_{\mathrm{T}}/p_{\mathrm{T}}^{\ell 1}$	[0, 2, 3, 5, ∞]
WZ CR	$H_{\mathrm{T}}/p_{\mathrm{T}}^{\ell 1}$	[0, 2, 3, 5, ∞]
WZb CR	$H_{\mathrm{T}}/p_{\mathrm{T}}^{\ell 1}$	[0, 2, 5, ∞]

- Inverted signal regions
- Control non-prompt
- Control WZ
- Control tZq

HMN Fitting Strategy

Weinberg Op. Fitting Strategy



Result on Upper limits: Heavy Majorana Neutrinos

❑Interpretations of limits

- Parameter of interest (POI) in fit: signal strength $\hat{\mu}$
  - Can be converted to upper limits on cross section: $\hat{\sigma} = \sigma_{benchmark} \times \hat{\mu}$

For HMN:
Unit mixing only for muon:

$$|V_{\mu N}|^2 = 1,$$
$$|V_{eN}|^2 = |V_{\tau N}|^2 = 0$$

❑For VBF production of HMN

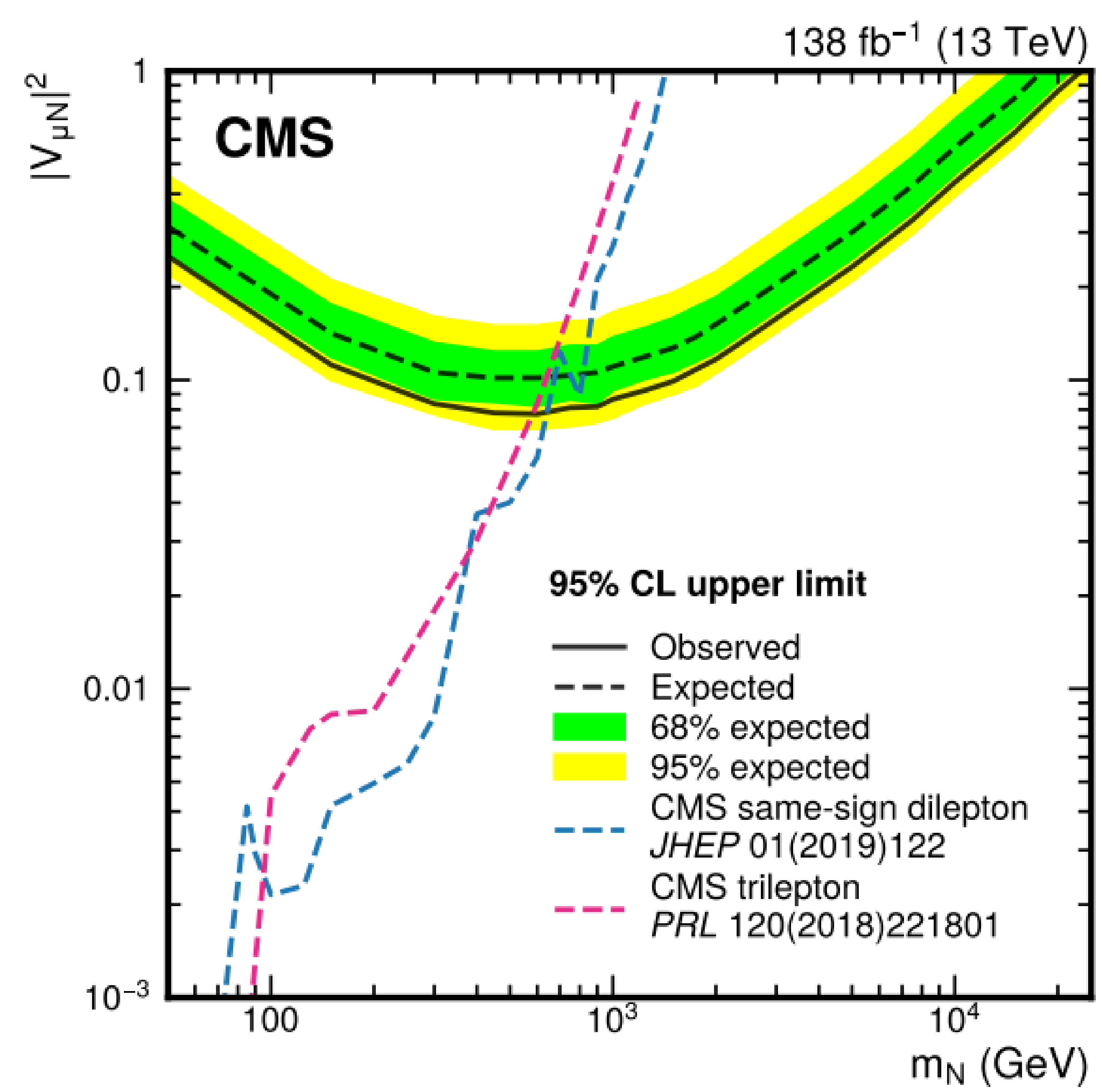
- The cross section dependence reads:

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

- Upper limits on signal strength can be translated to the squared mixing element $|V_{\mu N}|^2 = \sqrt{\hat{\mu}}$

❑Better constraints on $|V_{\mu N}|^2$ for $m_N \gtrsim 650$ GeV

❑Probing m_N up to 23 TeV



Result on Upper limits: Weinberg operator

❑Interpretations of limits

- POI in fit: signal strength $\hat{\mu}$
  - Can be converted to upper limits on cross section:

$\hat{\sigma} = \sigma_{benchmark} \times \hat{\mu}$

For Weinberg op. :
Unit Wilson Coefficient only for dimuon:
$|C_5^{\mu\mu}|^2 = 1$, others = 0
And EFT Scale $\Lambda = 200$ GeV

❑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 $m_{\mu\mu} = v^2|C_5^{\mu\mu}|/\hat{\Lambda}$

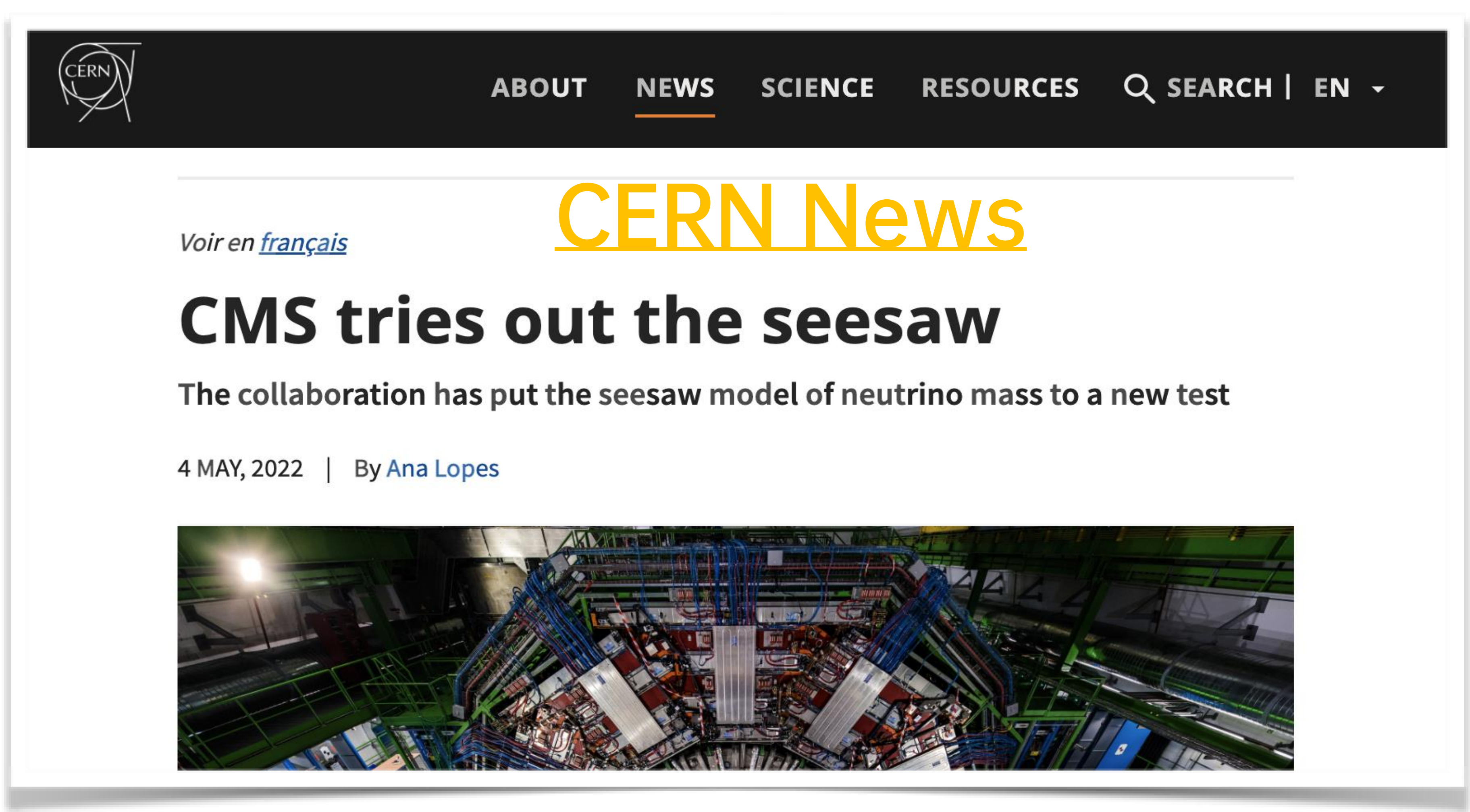
❑Results

- Observed (expected) lower bond on **EFT scales Λ**: 5.6 (4.7) TeV (assuming $C_5^{\mu\mu} = 1$)
- Observed (expected) upper limit of **effective Majorana mass $|m_{\mu\mu}|$**: 10.8 (12.8) GeV

Probing heavy Majorana neutrinos and the Weinberg operator through pp→$\mu^\pm\mu^\pm$jj at CMS arXiv: 2206.08956

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 $m_N \gtrsim 650$ GeV
  - First search at collider on dimension-5 Weinberg operator
    - Upper limit of effective Majorana mass $|m_{\mu\mu}|$, observed (expected): 10.8 (12.8) GeV
- ❑ arXiv: 2206.08956 accepted by PRL as an Editors' Suggestion



Backup

Cross sections of signal samples

- Cross sections of HMN processes
  - Cross sections from around 0.1 to 18 fb

m_N (GeV)	50	150	300	450	600	750	900	1000	1250
XS(fb)	4.606	13.57	17.99	18.20	16.91	15.47	13.86	12.84	10.67
m_N (GeV)	1500	1750	2000	2500	5000	7500	10000	15000	20000
XS (fb)	8.918	7.612	6.425	4.811	1.598	0.7736	0.4480	0.2052	0.1165

- Cross sections of Weinberg op. processes
  - Focus with benchmark inputs: $c^5_{\mu\mu}$ = 1 and Λ = 200 TeV

$$\sigma \sim |m_{\ell\ell'}|^2 \propto \left|C_5^{\ell\ell'}/\Lambda\right|^2$$

EFT scale Λ (TeV)	10	100	200	400
Effective Majorana mass (GeV)	6	0.6	0.3	0.15
Cross Section (pb)	1.33×10^{-4}	1.50×10^{-4}	3.74×10^{-7}	9.35×10^{-8}

Systematics Uncertainties

❑Theoretical uncertainties:

- **QCD scale** uncertainties and **PDF** uncertainties considered for signal processes (HMN & WO) and $W^{\pm}W^{\pm}jj$ process
  - Renormalization and factorization QCD scale uncertainties
  - PDF uncertainties: standard deviation of PDF variations in sample production
- NLO corrections are considered for $W^{\pm}W^{\pm}jj$ and $W^{\pm}Zjj$ process

❑Data-Driven non-prompt muon background

- Two major sources of uncertainty:
  - Statistical uncertainty for non-prompt rate measurement: by most 5%
  - Flavor composition discrepancies of faking lepton jets between measurement region and signal region: estimated from varying p_T of "away-side" jets, by most 7%
  - The estimation approaches are however conservative, thus a 30% total uncertainty for non-prompt muon modeling is applied in addition.

❑Common experimental uncertainties

- Integrated luminosity
- Jet Energy Scale
- …

❑Sample statistical uncertainties

- Barlow-Beeston-lite method

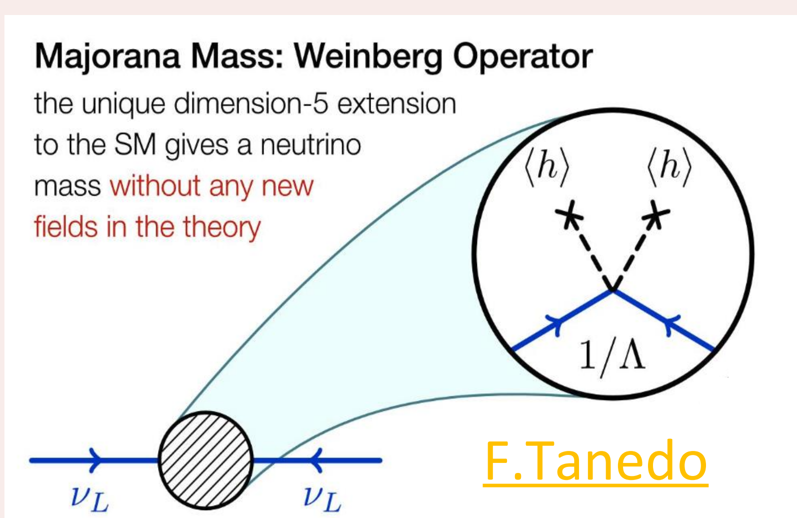
Weinberg operator in pp→μ±μ±jj

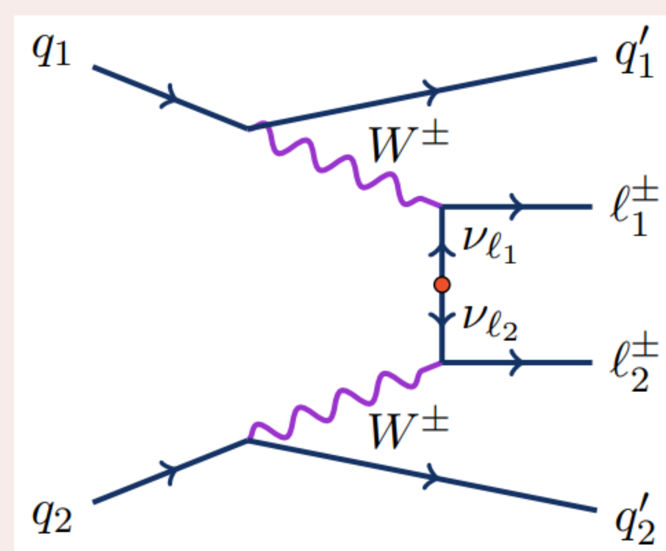
2021

- Take an EFT approach:

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

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





Wilson Coefficients

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

SM Higgs Doublet

SM Lepton

EFT Scale

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

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

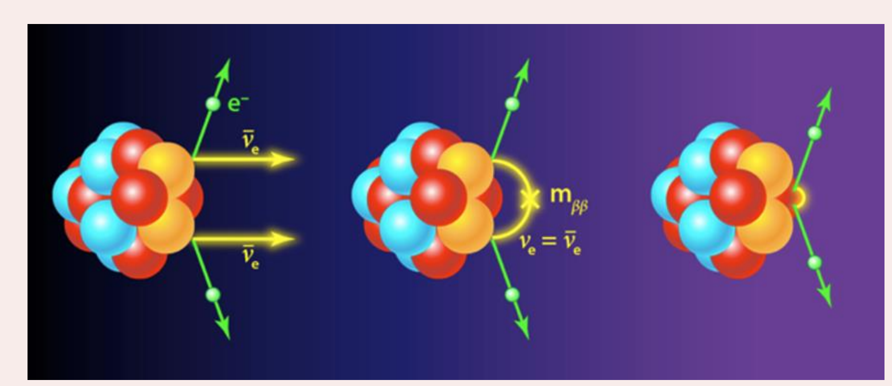
Effective Majorana Mass

PhysRevD.103,115014

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

$$\sigma \sim |m_{\ell\ell'}|^2 \propto \left|C_5^{\ell\ell'}/\Lambda\right|^2$$

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



0νββ @ GERDA [2009.06079]

$|m_{ee}|$< 79 – 180 meV at 90% C.L.

Probing heavy Majorana neutrinos and the Weinberg operator through pp→μ±μ±jj at CMS arXiv: 2206.08956

Weinberg operator in pp→μ±μ±jj

2021

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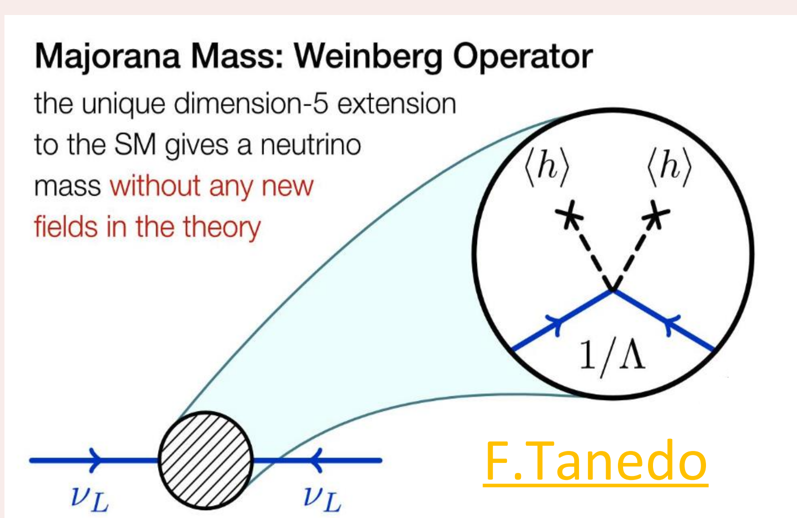

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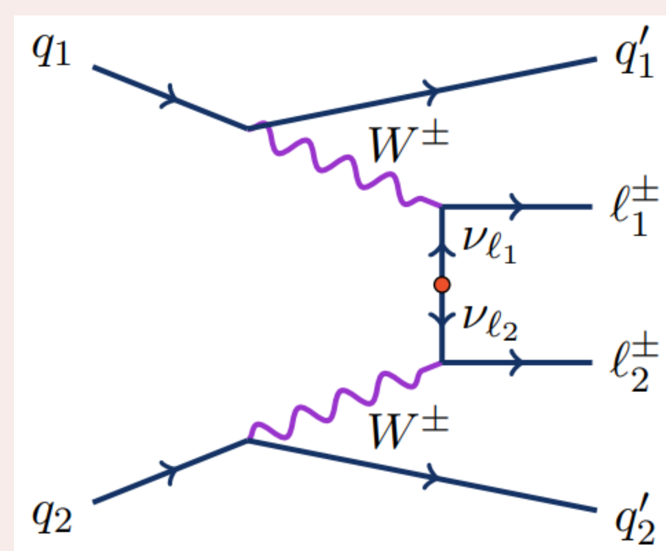

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Effective Majorana Mass

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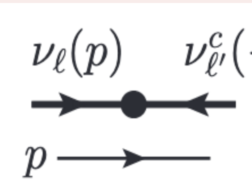

$$= \frac{i\not{p}}{p^2}\frac{-iC_5^{\ell\ell'}v^2}{\Lambda}\frac{i\not{p}}{p^2} = \frac{i m_{\ell\ell'}}{p^2}$$

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