Standard Model Fermion Masses and Mixing Angles generated in a 3HDM

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in collaboration with Alejandro Ibarra

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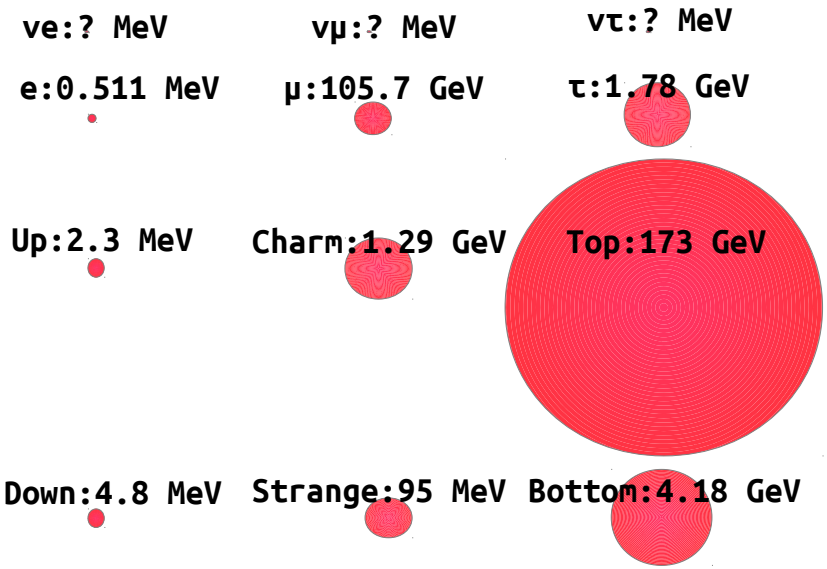
Outline

Introduction

- **Motivation:** Hierarchy for masses and mixing angles in the Standard Model. $\Rightarrow$ **New Physics?**



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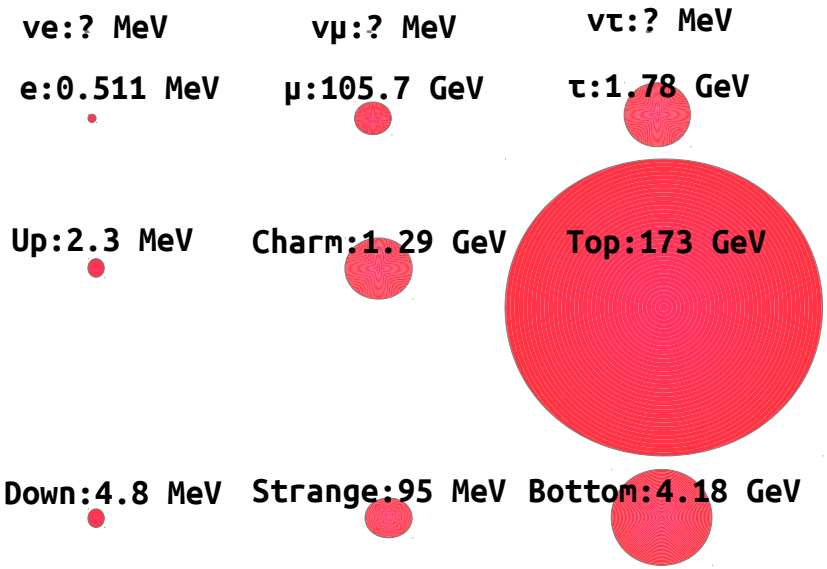

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- **Our goal:** Reproduce masses and mixing angles.

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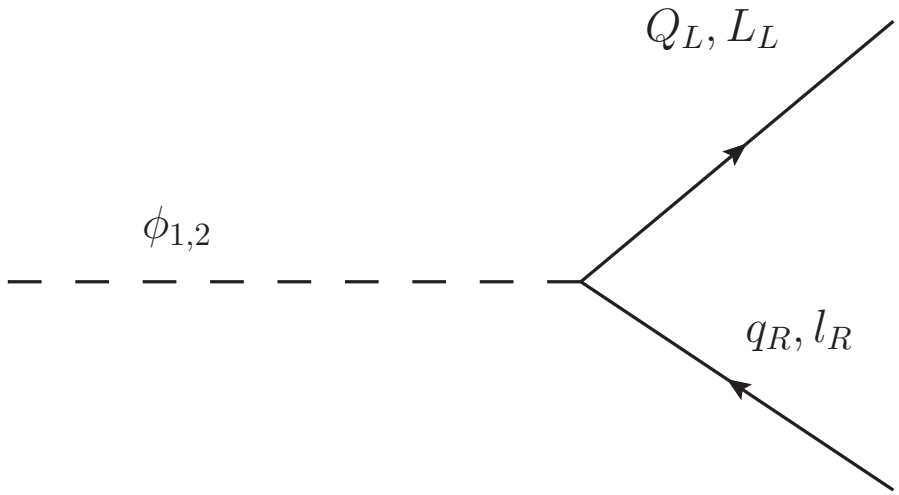

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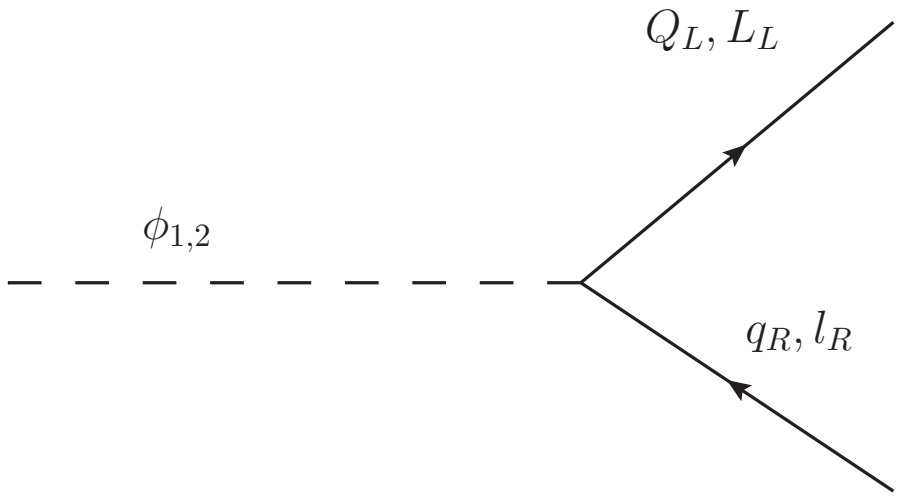

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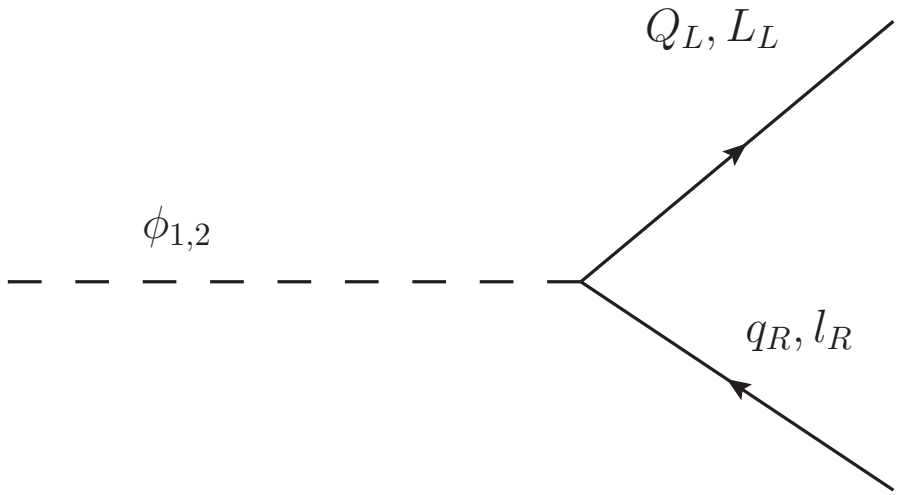

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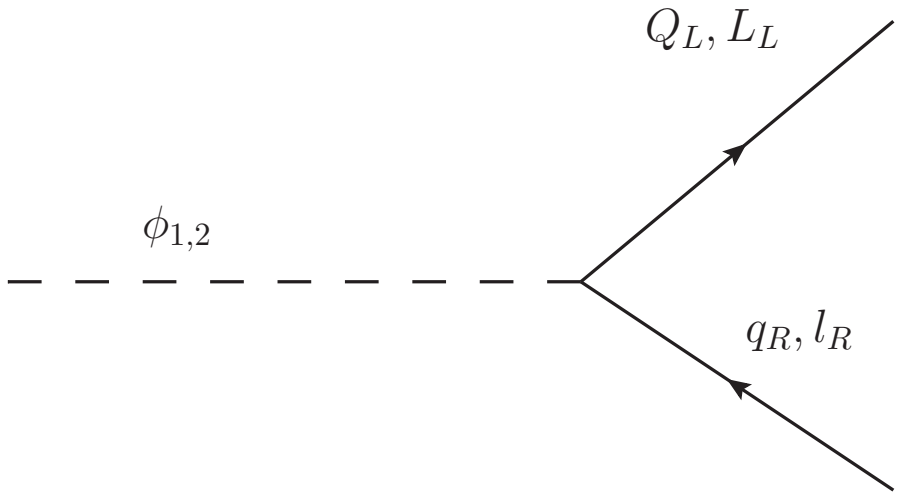

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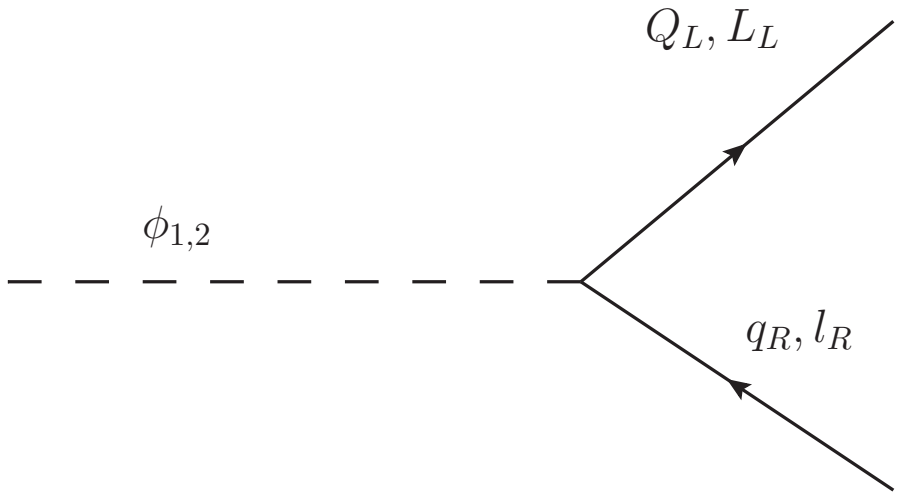

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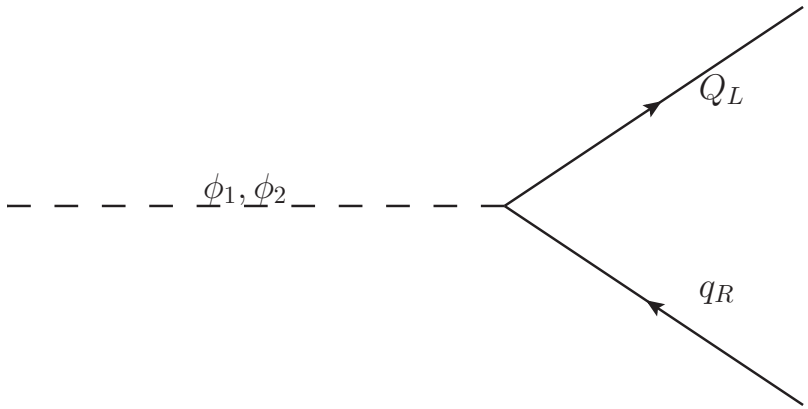
- Basis $\langle \Phi_1^0 \rangle = v/\sqrt{2}$, $\langle \Phi_2^0 \rangle = 0$
- Yukawa interaction (rank-1):



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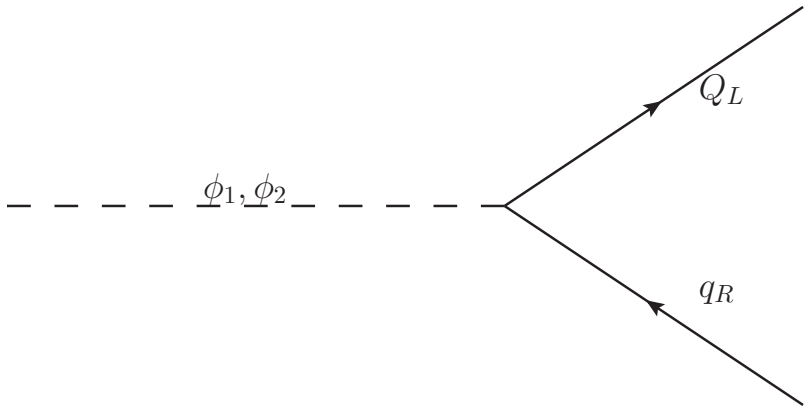

$$-\mathcal{L}^{\text{Yuk}} = (Y_u^{(1)})_{ij} \bar{q}_{Li} u_{Rj} \tilde{\Phi}_1 + (Y_d^{(1)})_{ij} \bar{q}_{Li} d_{Rj} \Phi_1 + \text{h.c.} \,,$$

$$Y_{u,d}^{(1,2)}|_{\text{tree}} = |y_{u,d_L}^{(1,2)}\rangle \langle y_{u,d_R}^{(1,2)}|$$

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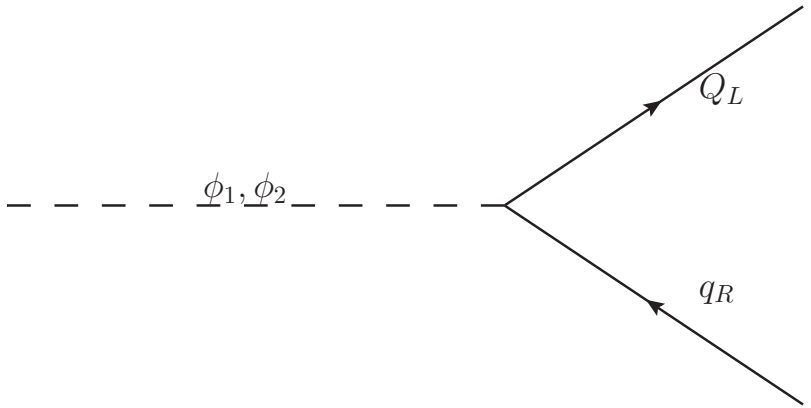

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@ tree level

$$\Rightarrow \begin{cases} m_t \\ m_b \end{cases}$$

$$Y_u^{(2)}|_{\text{tree}} = |y_{u_L}^{(2)}\rangle\langle y_{u_R}^{(2)}|, \qquad Y_d^{(2)}|_{\text{tree}} = |y_{d_L}^{(2)}\rangle\langle y_{d_R}^{(2)}|$$

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- Parametrize:

$$|y_{u_L}^{(2)}\rangle = \sqrt{y_u^{(2)}} \begin{pmatrix} e^{i\rho_{u_L}} \sin\theta_{u_L} \sin\omega_{u_L} \\ e^{i\xi_{u_L}} \sin\theta_{u_L} \cos\omega_{u_L} \\ \cos\theta_{u_L} \end{pmatrix}$$

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- Neglect phases.
- Assume for simplicity $\mathrm{y_u^{(1)}}, \mathbf{y_u^{(2)}} >> \mathrm{y_d^{(1)}}, \mathbf{y_d^{(2)}}$

$$V_u = \begin{pmatrix} \mathbf{u_L} & \mathbf{c_L} & \mathbf{t_L} \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad V_d = \begin{pmatrix} \mathbf{d_L} & \mathbf{s_L} & \mathbf{b_L} \\ 0.974 & 0.225 & 0.0035 \\ 0.225 & 0.973 & 0.041 \\ 0.0087 & 0.04 & 0.999 \end{pmatrix}$$

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$$|\text{strange}_\text{L}\rangle \simeq \sin\theta_c |\text{up}_\text{L}\rangle + \cos\theta_c |\text{charm}_\text{L}\rangle = \begin{pmatrix} \sin\theta_c \\ \cos\theta_c \\ 0 \end{pmatrix}$$

$$|\text{down}_\text{L}\rangle \simeq \cos\theta_c |\text{up}_\text{L}\rangle - \sin\theta_c |\text{charm}_\text{L}\rangle = \begin{pmatrix} \cos\theta_c \\ -\sin\theta_c \\ 0 \end{pmatrix}$$

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$$|V_{ub}|^2 + |V_{cb}|^2 \ll 1 \Rightarrow \ \boldsymbol{\epsilon \to 0}$$

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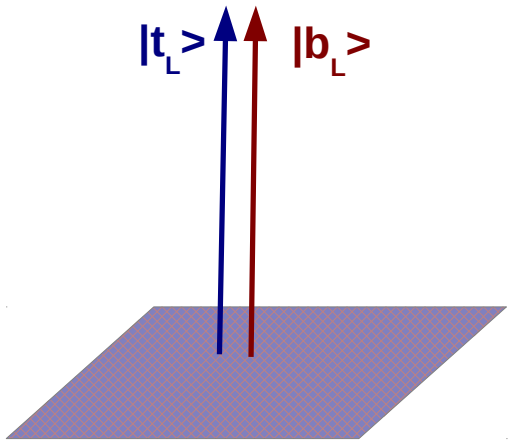
$$\Rightarrow V_{CKM} = \begin{pmatrix} ? & ? & 0 \\ ? & ? & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



- 1-loop from β function:

$$Y^{(1)}_{u,d}|_{1-\text{loop}} \simeq Y^{(1)}_{u,d}|_{\text{tree}} + \frac{1}{16\pi^2}\beta^{(1)}_{u,d}\log\frac{\Lambda}{M_{\phi 2}}$$

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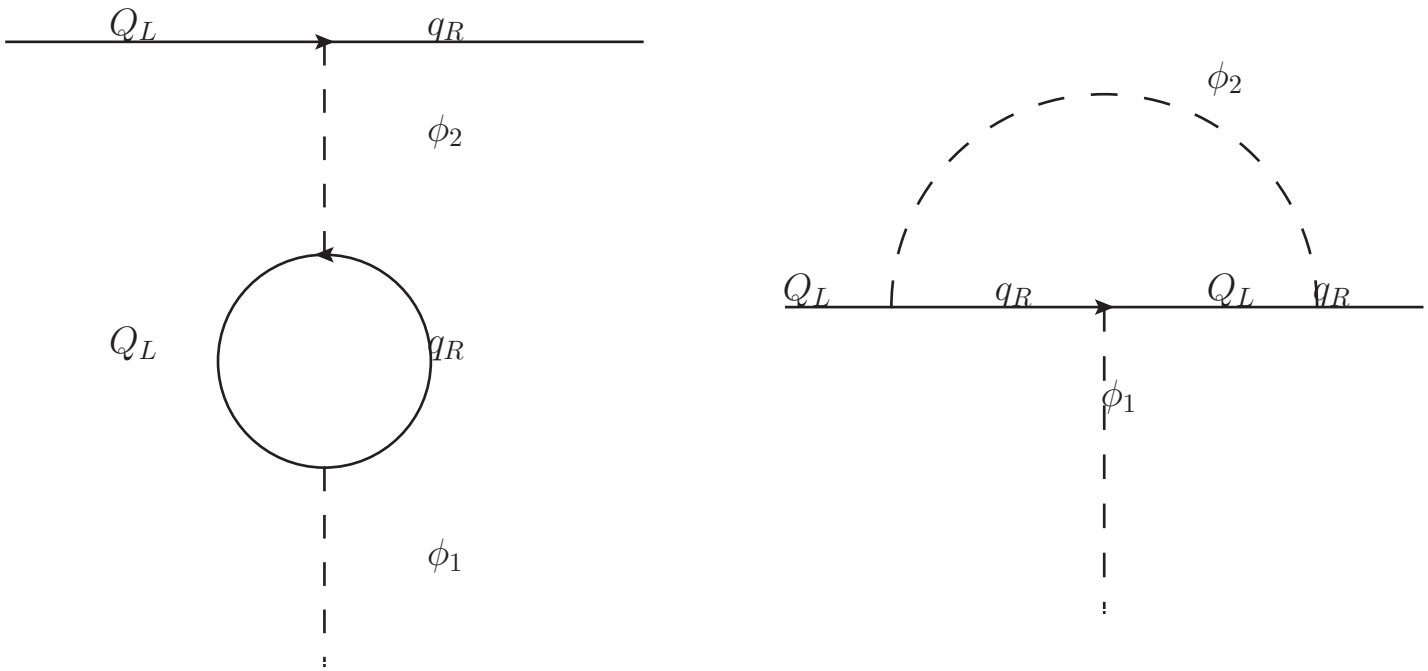
- 1-loop diagram (generate 2nd mass):



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Mass hierarchy for the quarks:

$$\frac{y_c}{y_t} \simeq \left(\frac{1}{16\pi^2} \log \frac{\Lambda}{M_H} \right) \frac{3}{4} (y_u^{(2)})^2 \times \text{mixing angles}$$

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- First generation massless.

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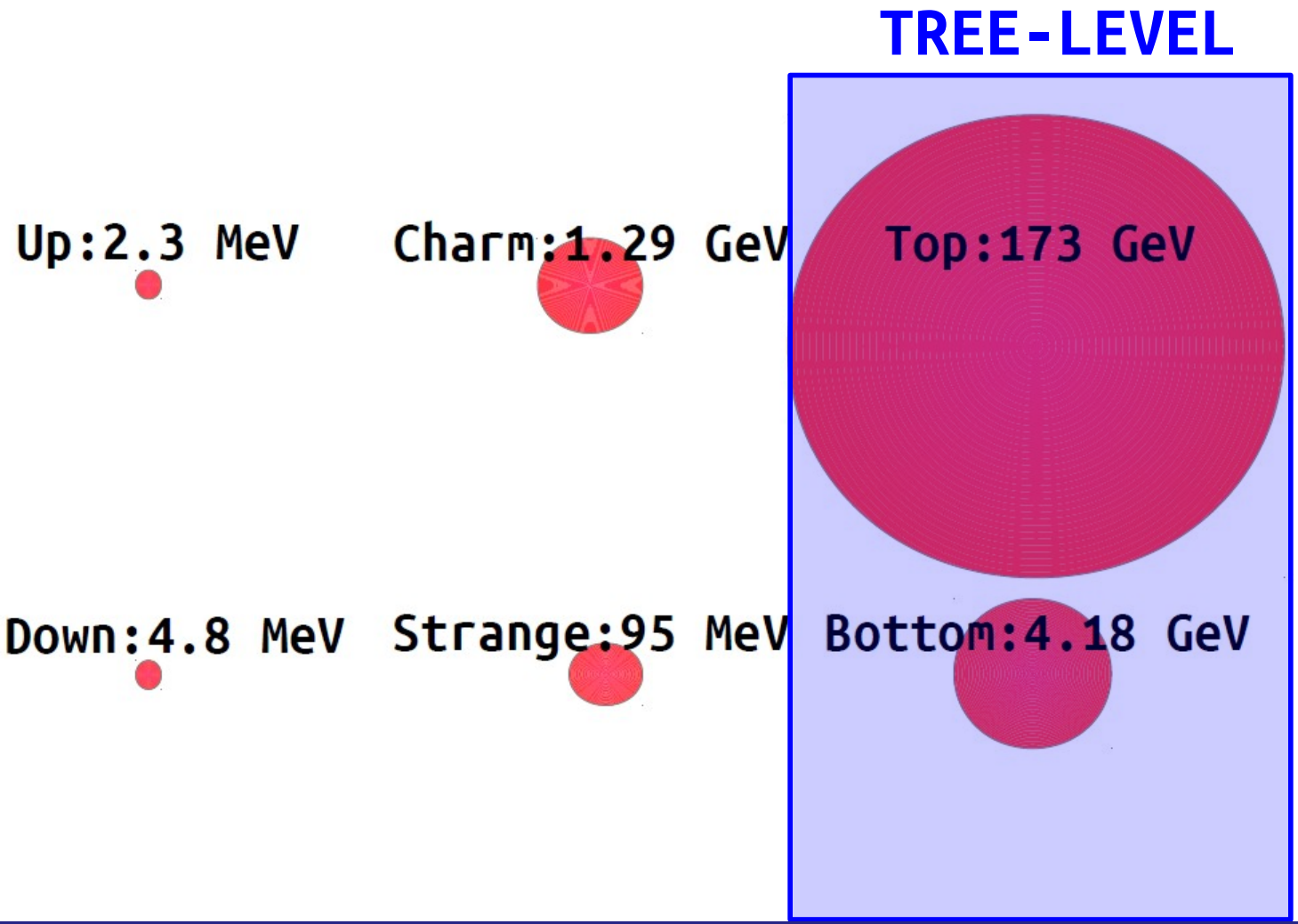

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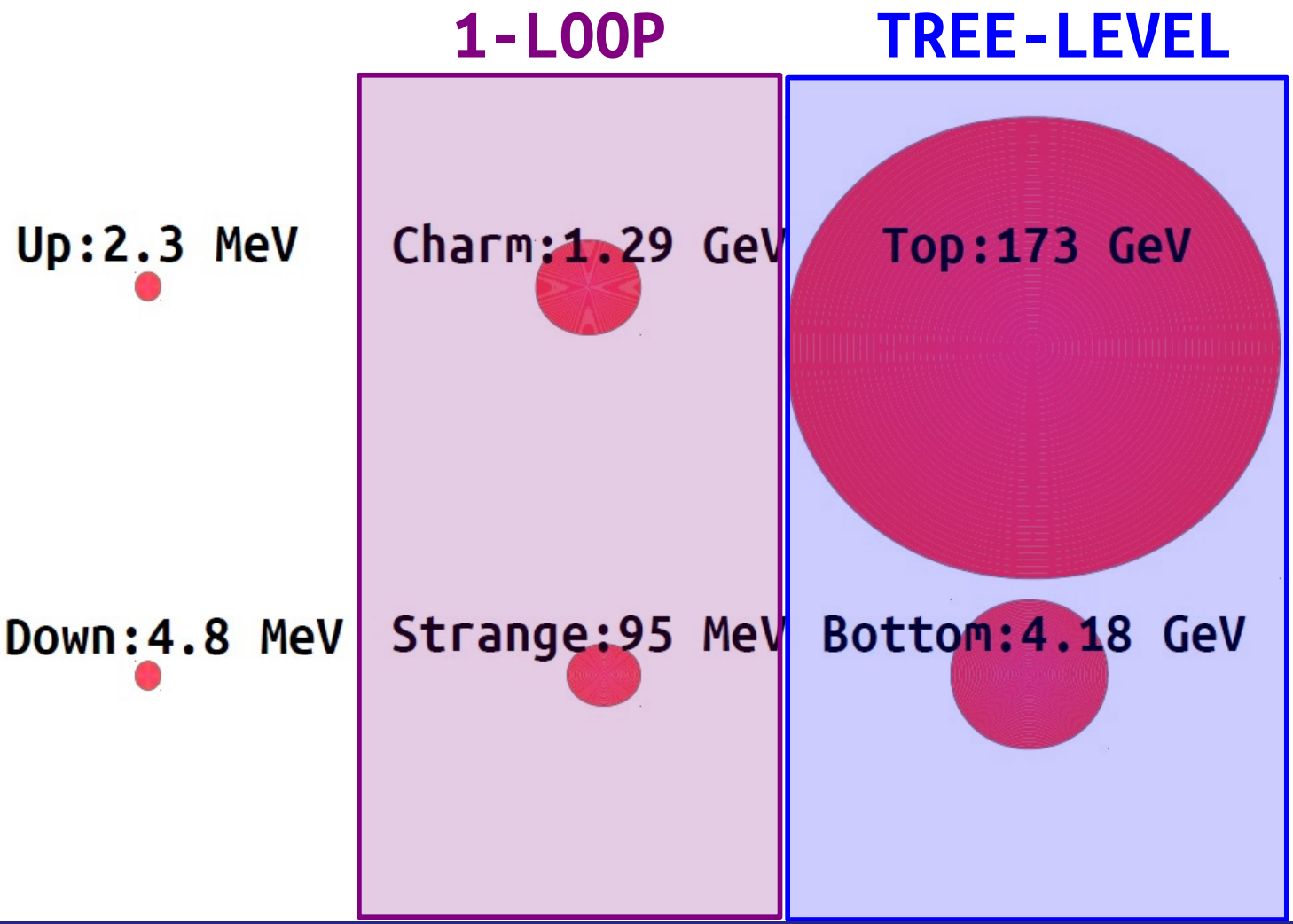

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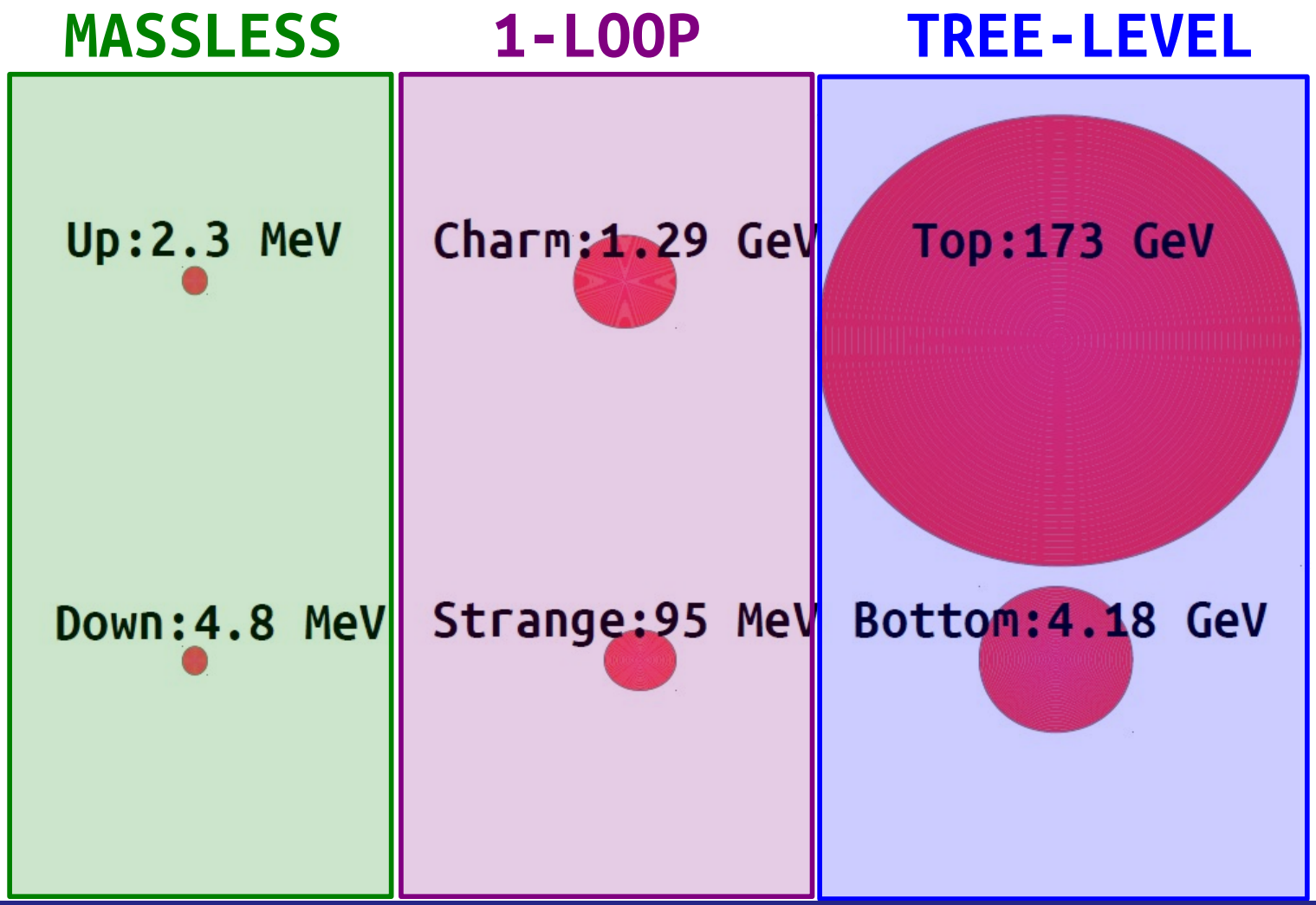

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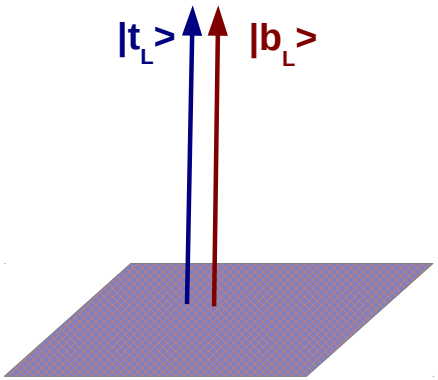

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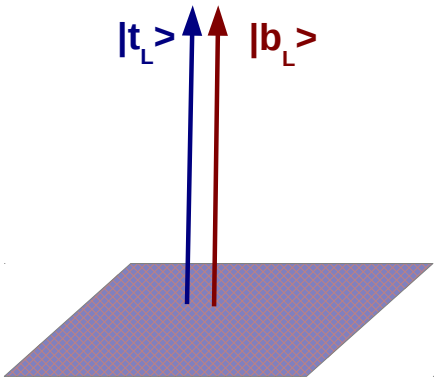

- Cabibbo angle @ 0-order in perturbation theory:

$$V_{us} \simeq -V_{cd} \simeq \frac{3 \sin\theta_{d_L} \cos\theta_{u_L} \sin(\omega_{d_L} - \omega_{u_L})}{N_d}$$

$$N_d = \left[9 \sin^2\theta_{d_L} \cos^2\theta_{u_L} + 4 \cos^2\theta_{d_L} \sin^2\theta_{u_L} - 3 \sin 2\theta_{d_L} \sin 2\theta_{u_L} \cos(\omega_{d_L} - \omega_{u_L})\right]^{1/2}$$

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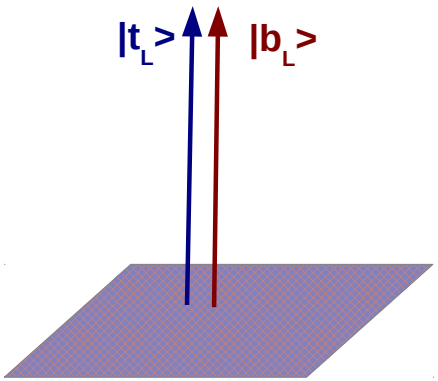

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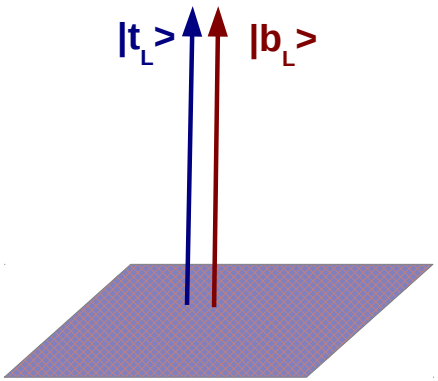

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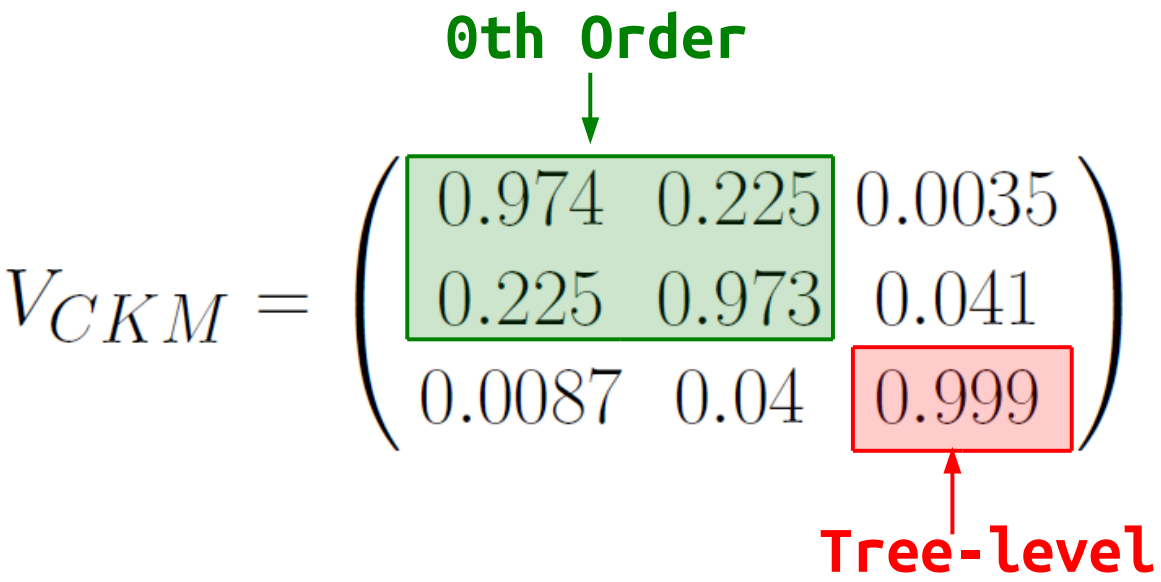
Tree-level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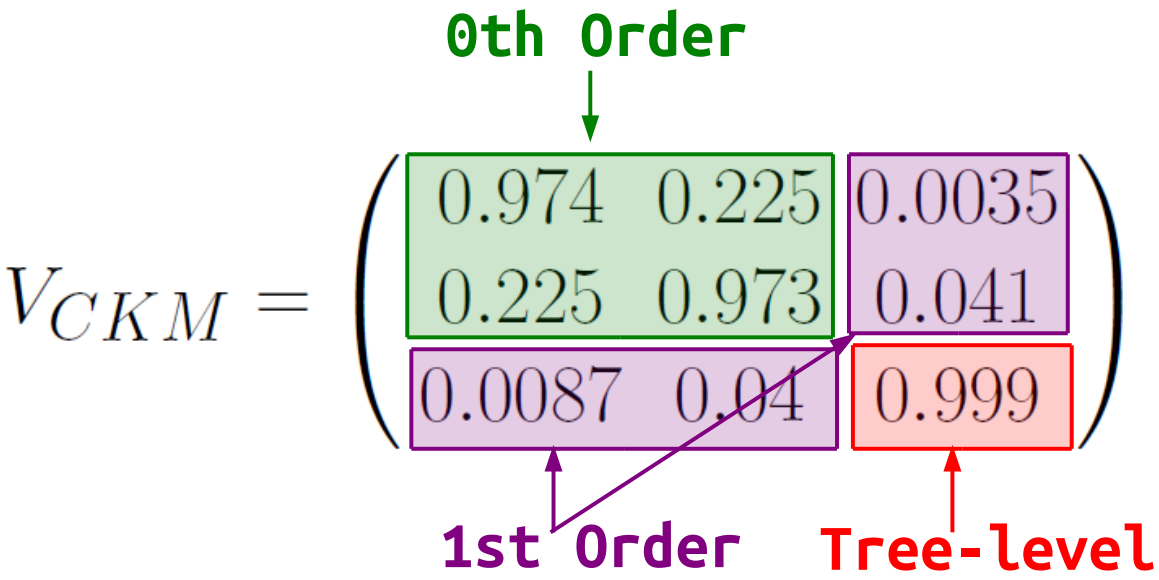
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$$U^{PMNS} = \begin{pmatrix} 0.822 & 0.574 & 0.156 \\ 0.355 & 0.704 & 0.614 \\ 0.443 & 0.452 & 0.774 \end{pmatrix}$$

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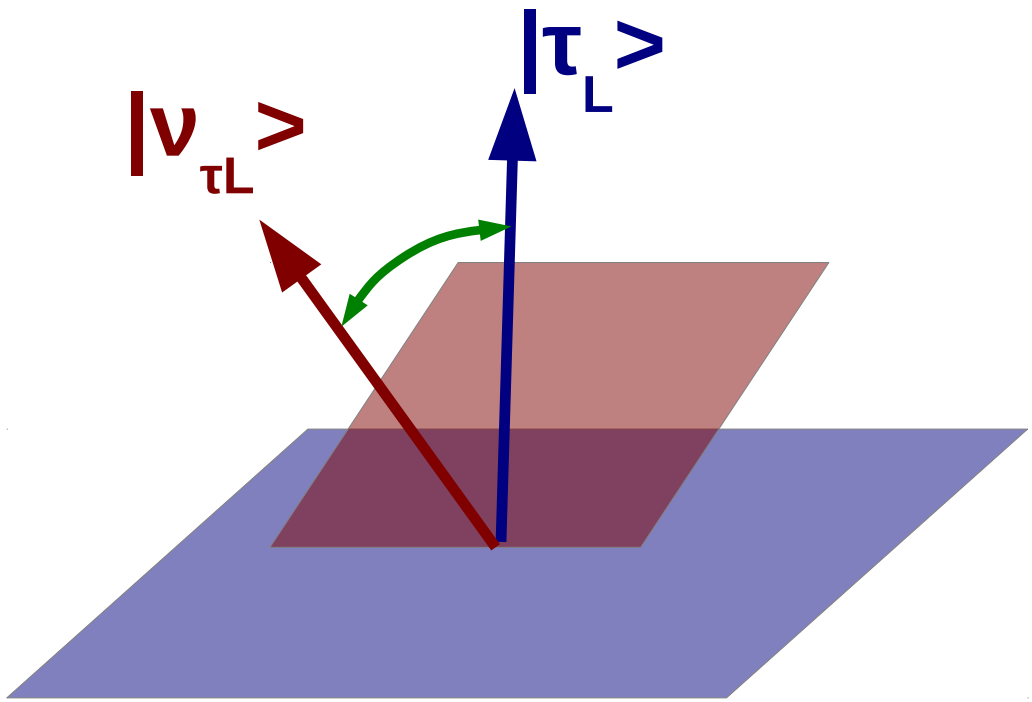

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$$\Rightarrow \begin{cases} m_\tau = \frac{v}{\sqrt{2}} y_e^{(1)} \\ m_{\nu_\tau} = \frac{v^2}{2} \frac{{y_\nu^{(1)}}^2}{M_{Maj}} \end{cases}$$ **@ tree level**

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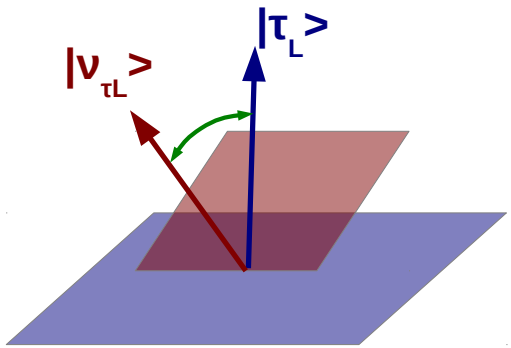
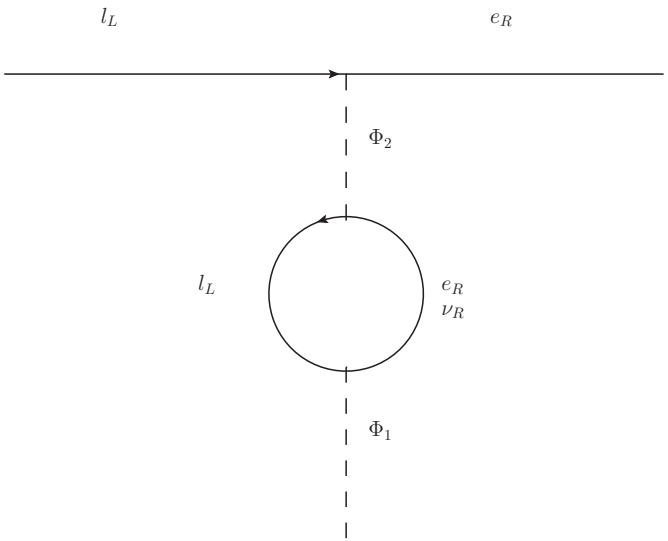
$$\Rightarrow U^{PMNS} = \begin{pmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & \cos\alpha \end{pmatrix}$$

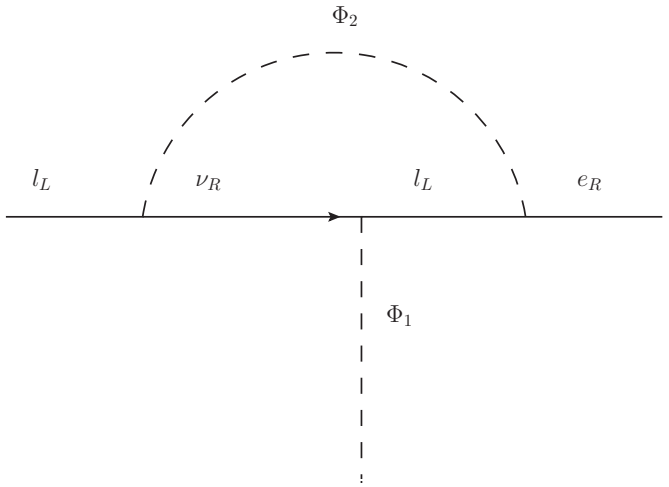


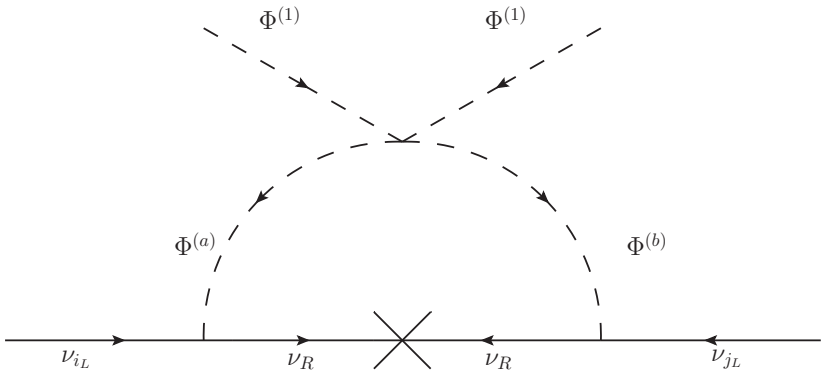
1-loop from β function:

$$Y^{(1)}_{e,\nu}|_{1-\text{loop}} \simeq Y^{(1)}_{e,\nu}|_{\text{tree}} + \frac{1}{16\pi^2}\beta^{(1)}_{e,\nu}\log\frac{\Lambda}{M_{\phi 2}}$$

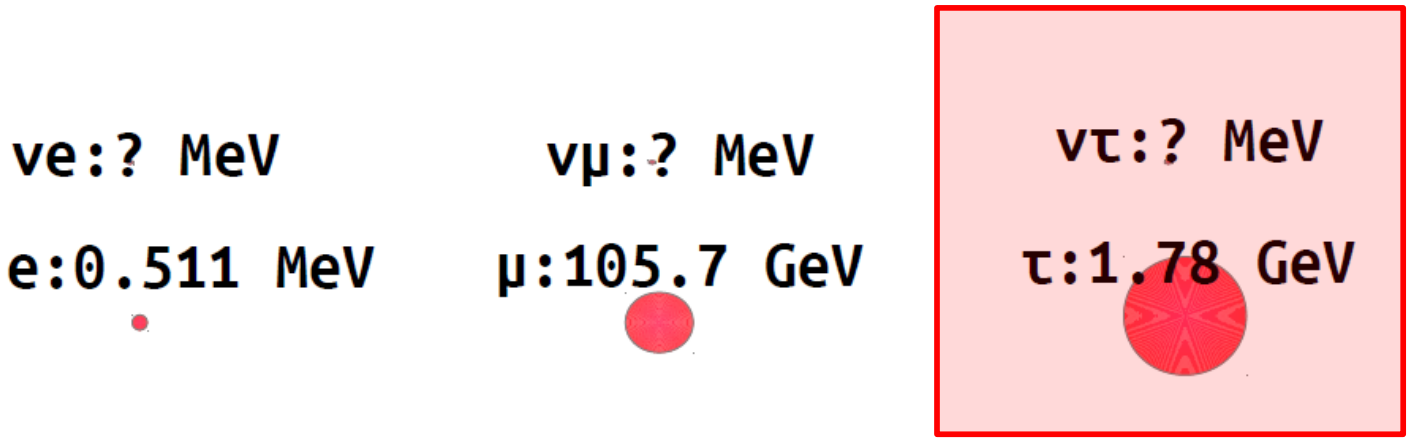
1-loop diagram (generate 2nd mass):

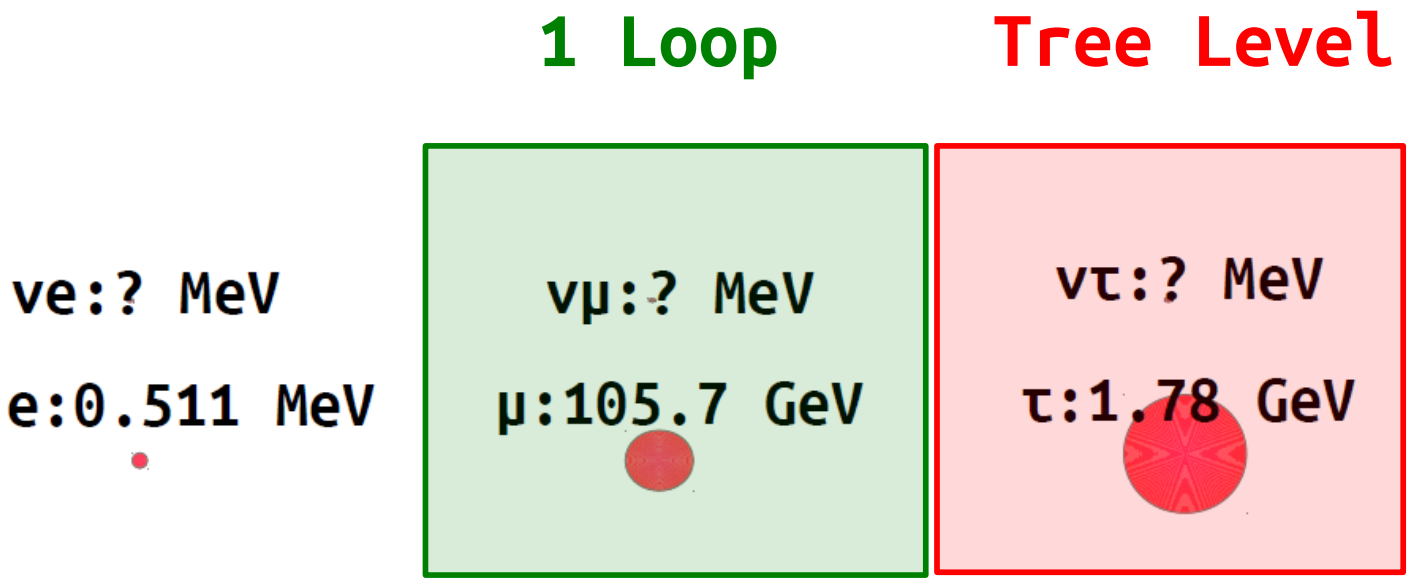


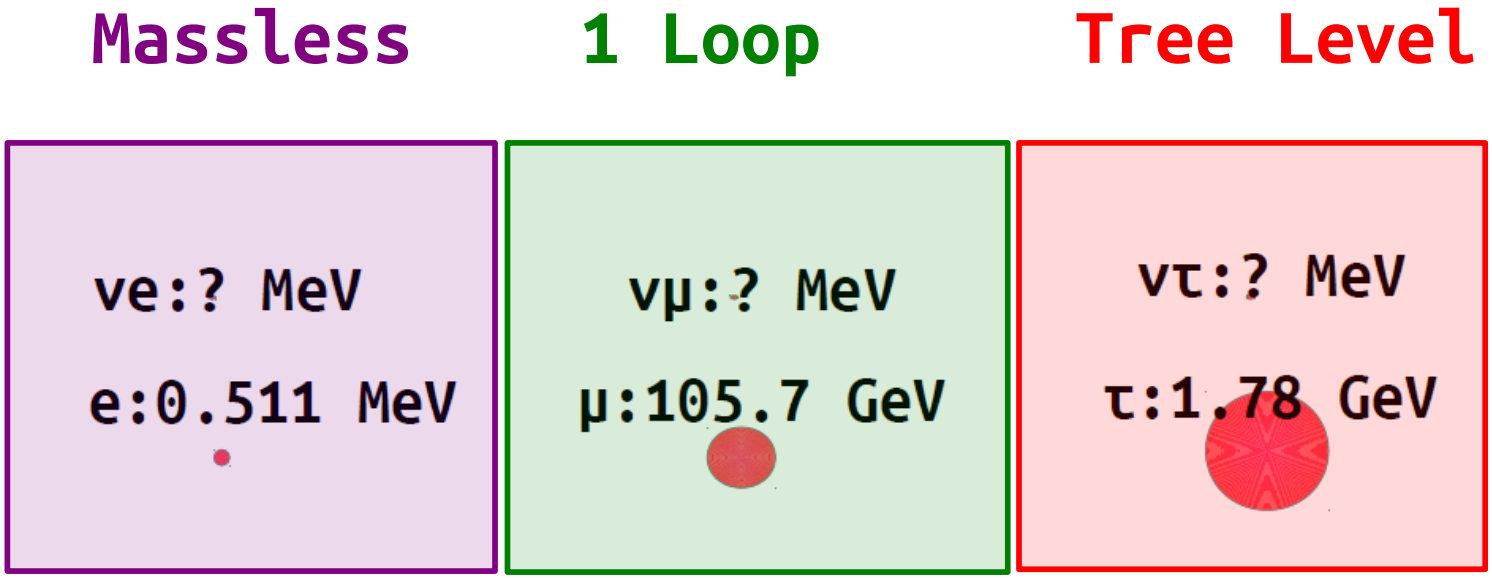




Tree Level




1 Loop
Tree Level
νe:? MeV
e:0.511 MeV
νμ:? MeV
μ:105.7 GeV
ντ:? MeV
τ:1.78 GeV


Massless
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Tree Level
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PMNS Matrix

$$\left|U^{PMNS}\right| = \begin{pmatrix} 0.822 & 0.574 & 0.156 \\ 0.355 & 0.704 & 0.614 \\ 0.443 & 0.452 & 0.774 \end{pmatrix}$$

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0-Order Tree-Level

3HDM

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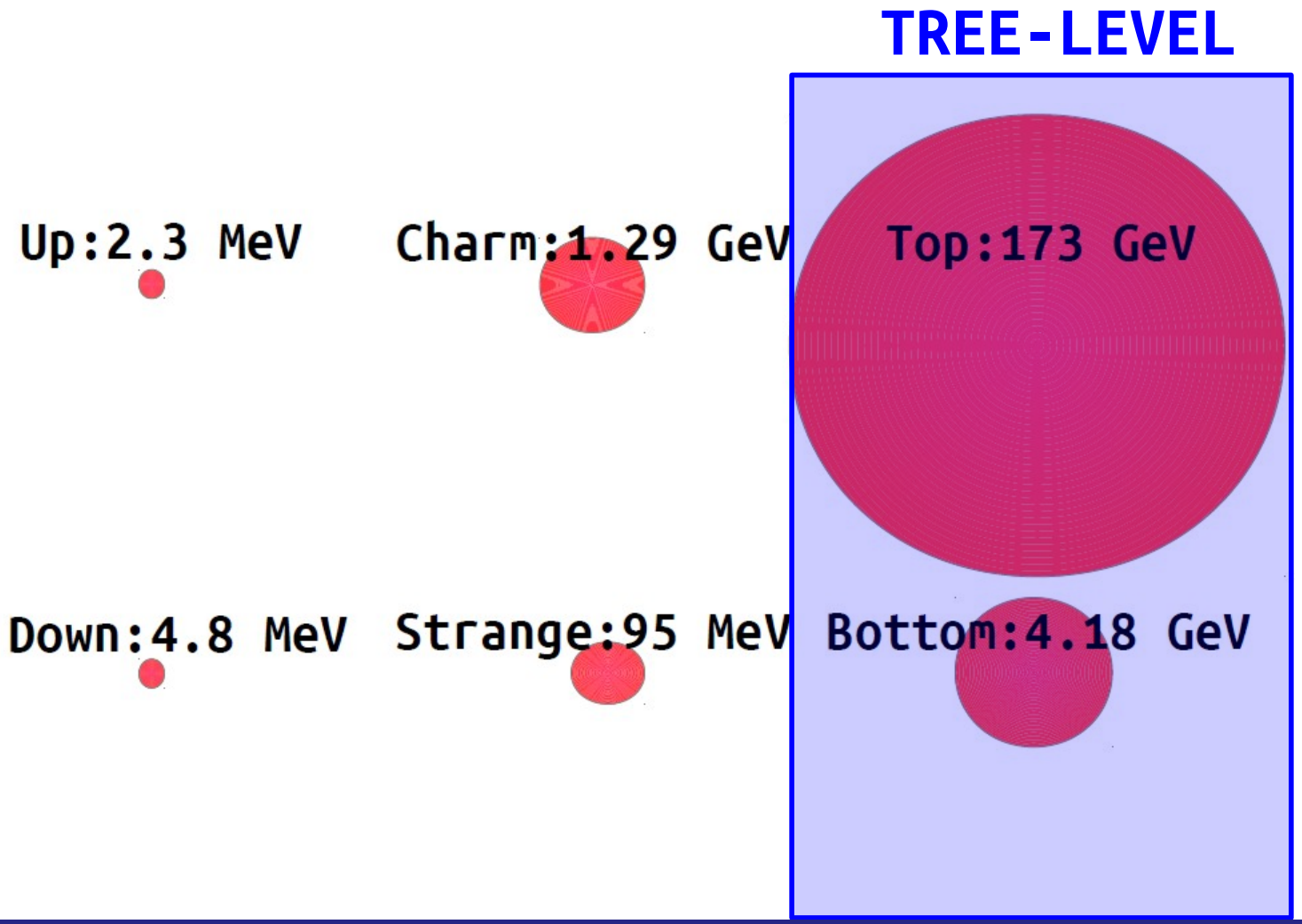
Quark Masses



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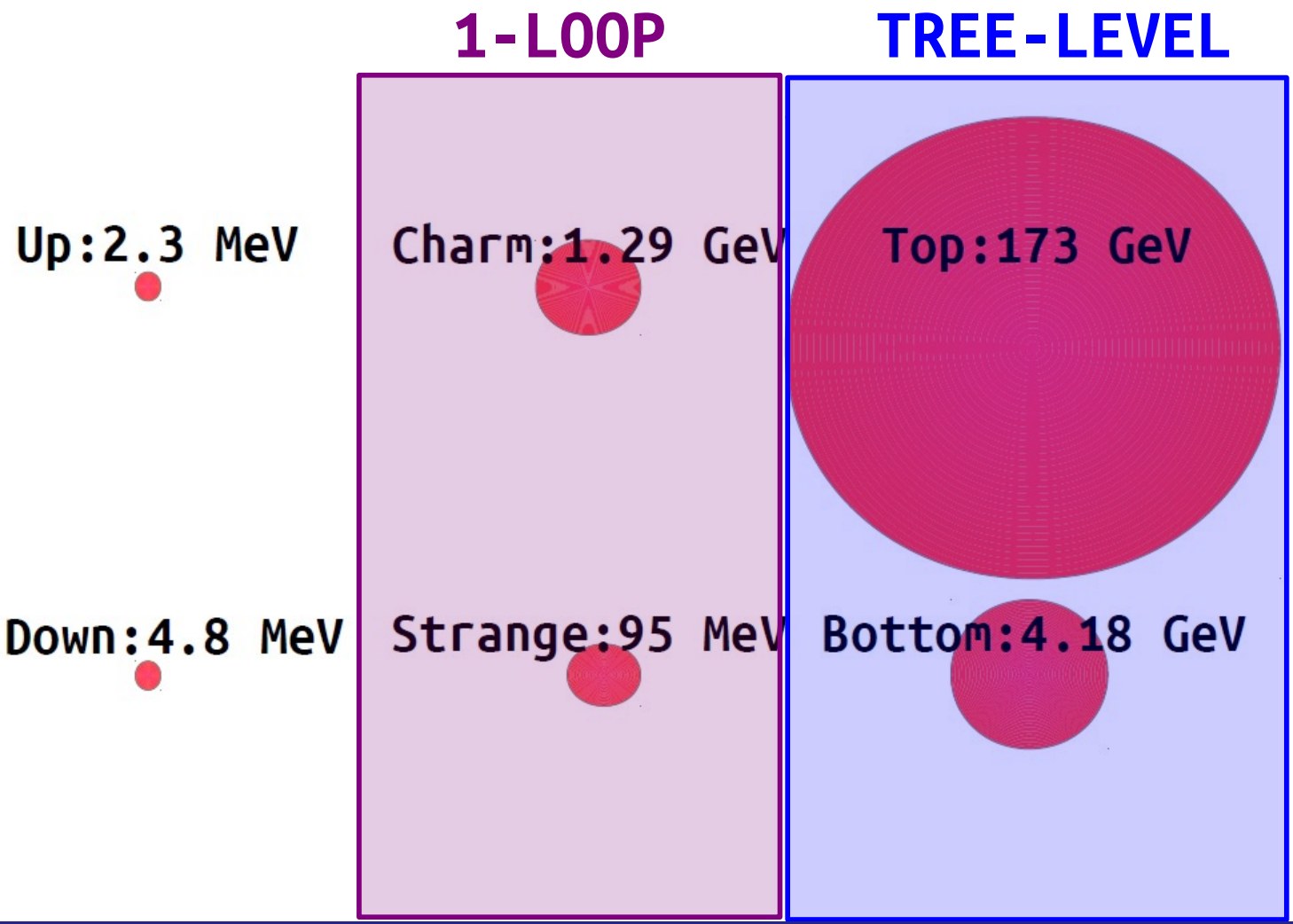

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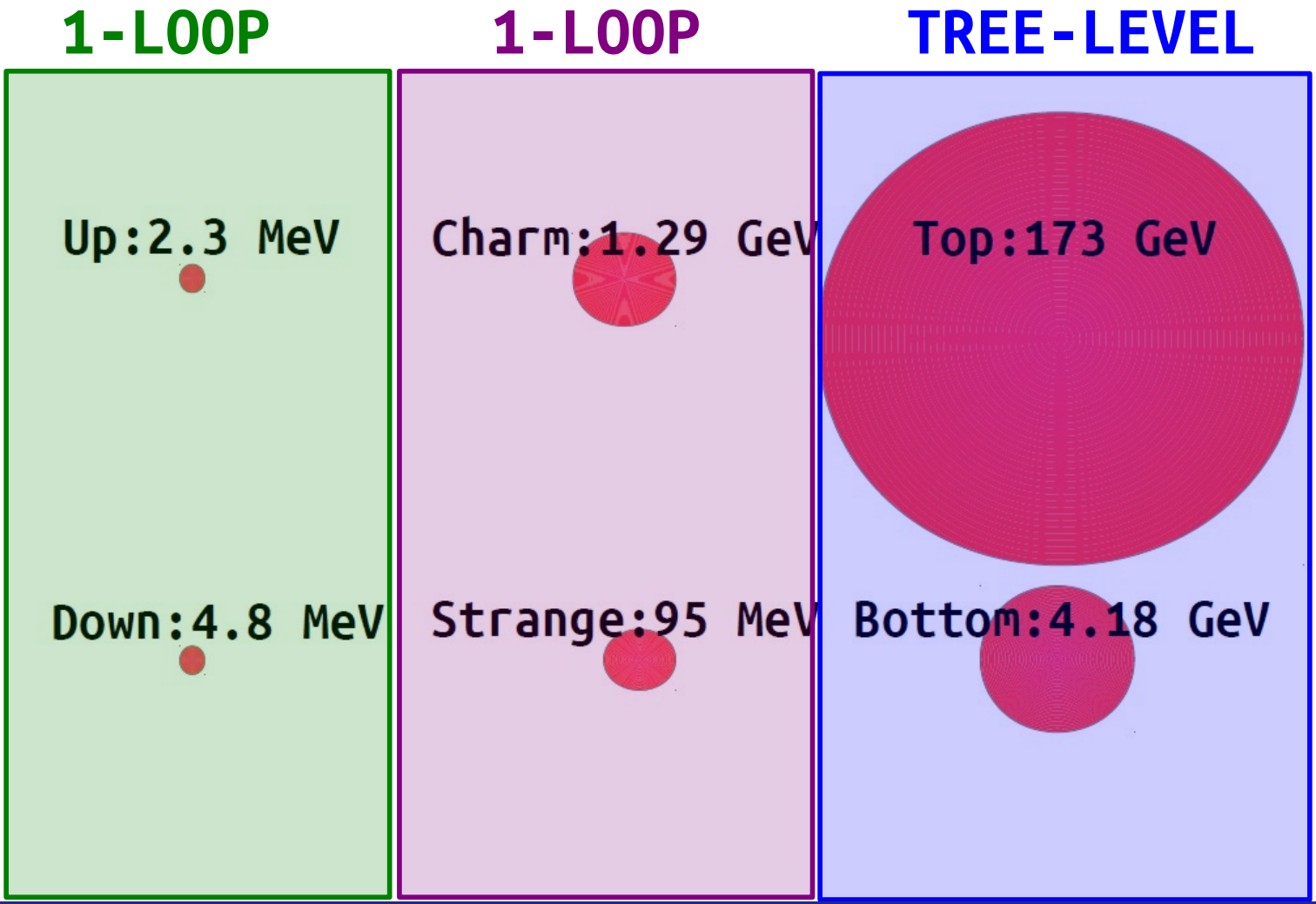

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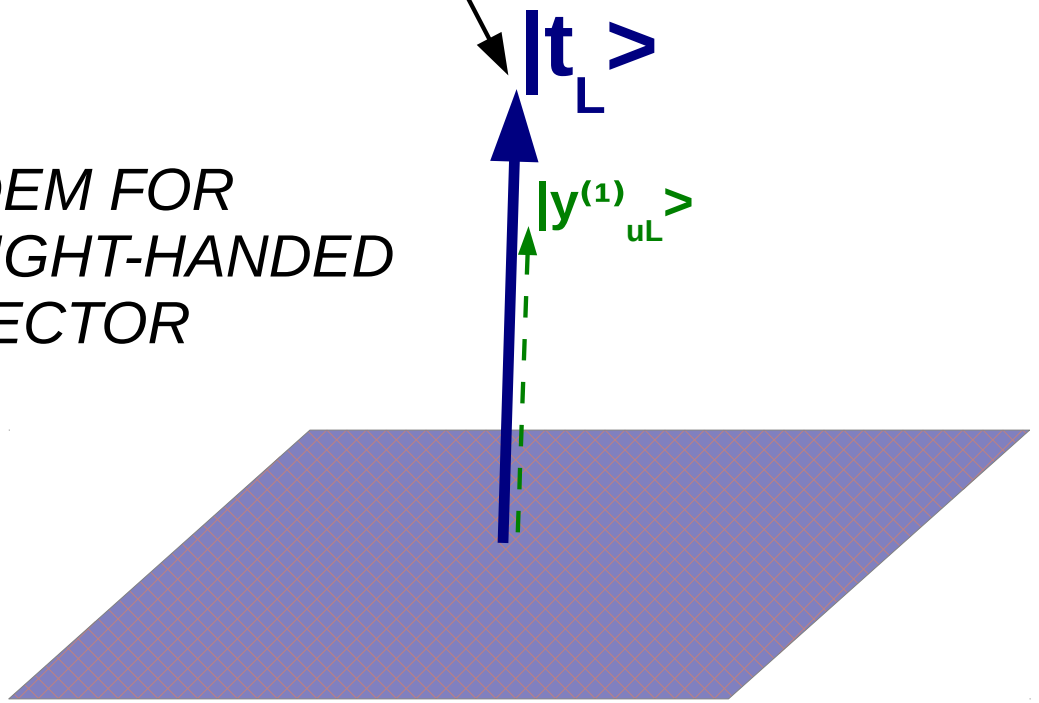

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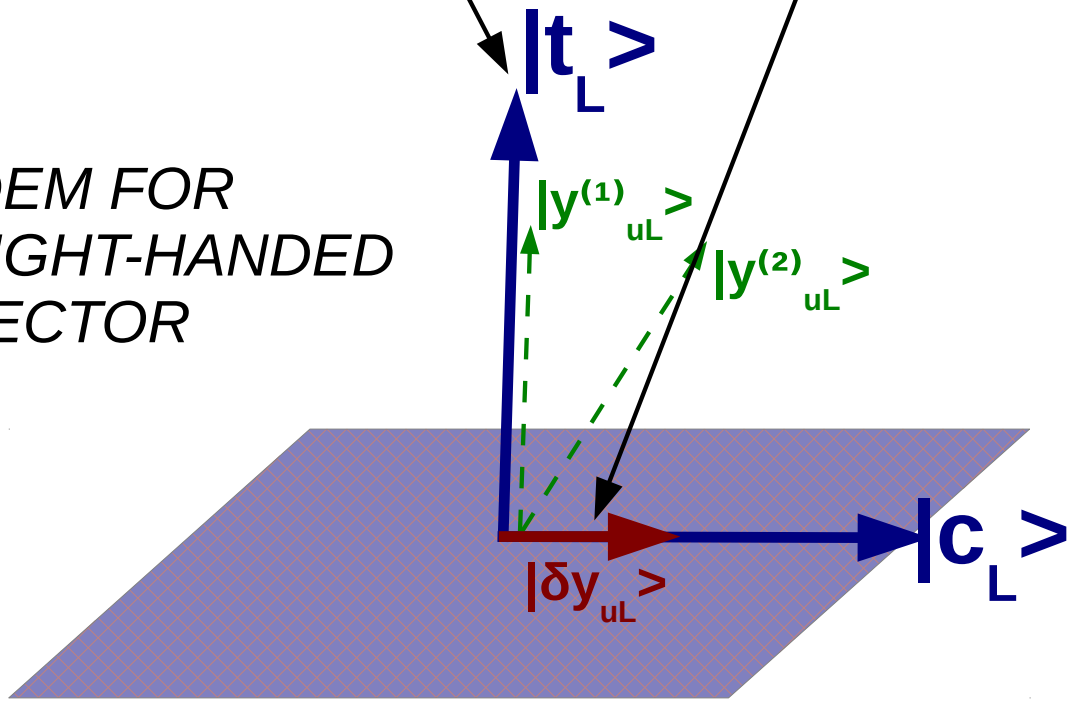

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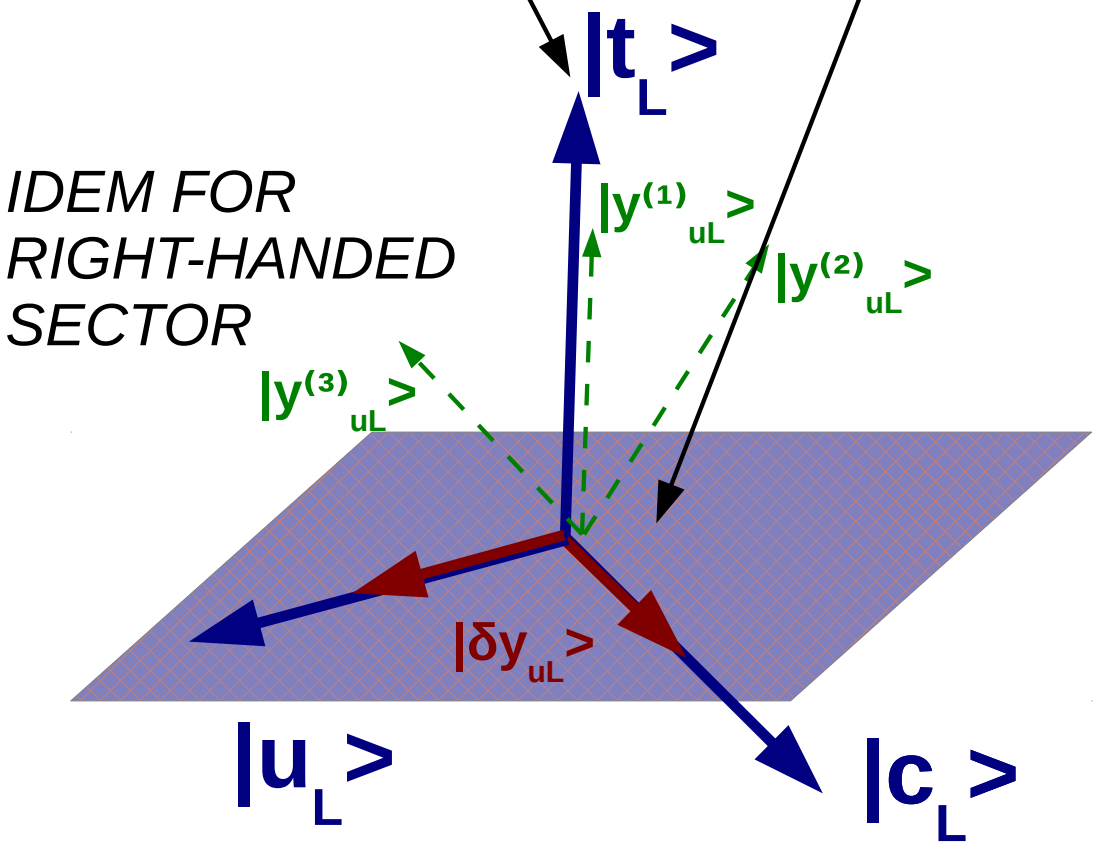
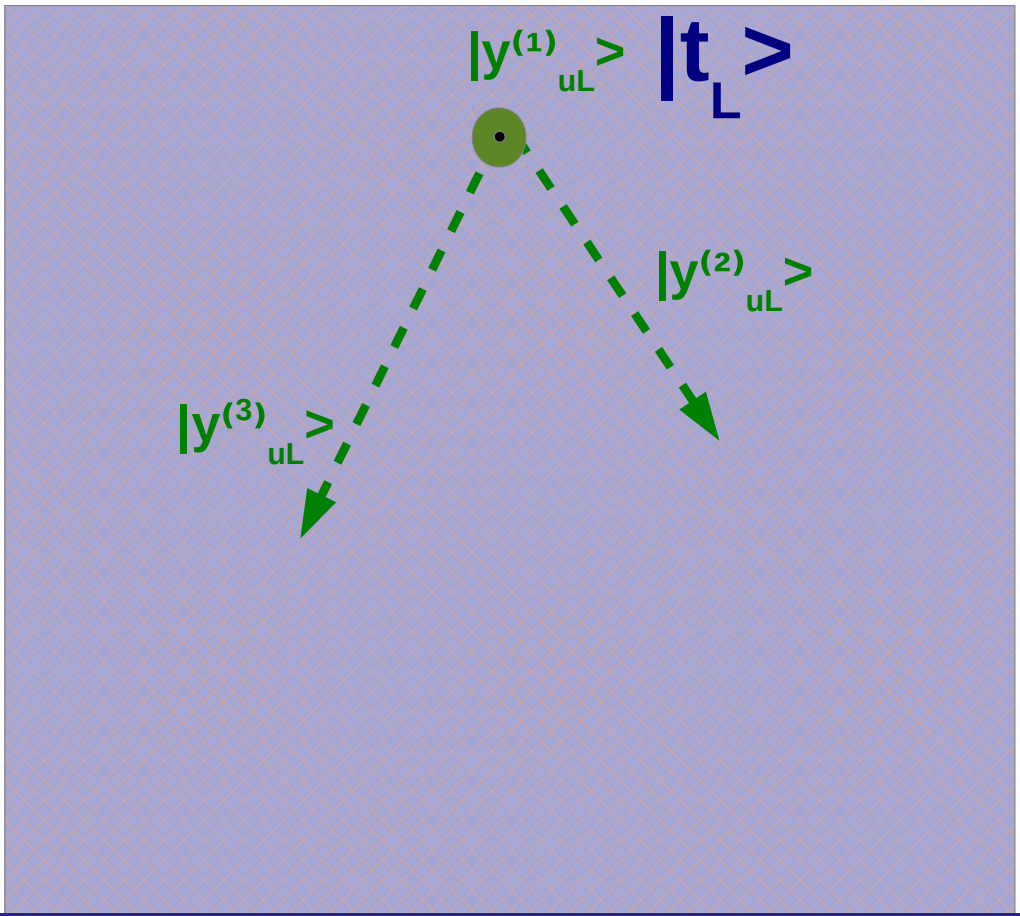


Hierarchy 1st and 2nd generation

IDEM FOR RIGHT-HANDED SECTOR



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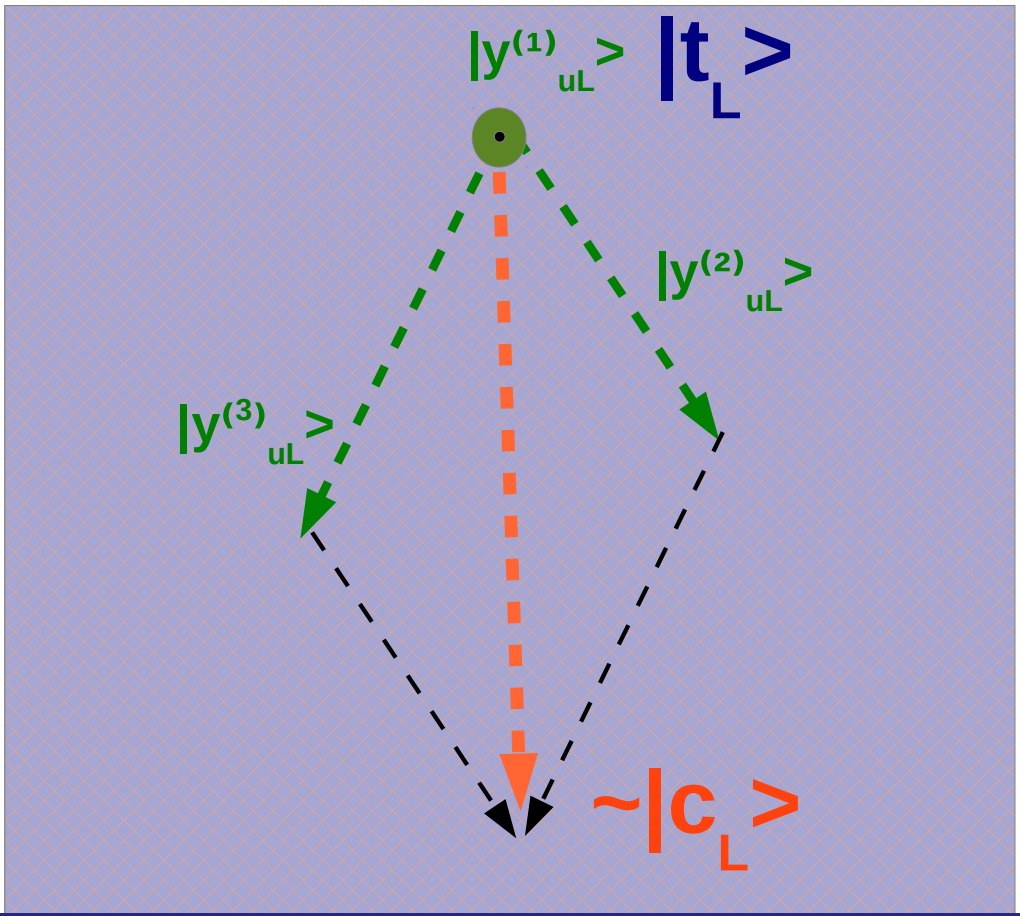

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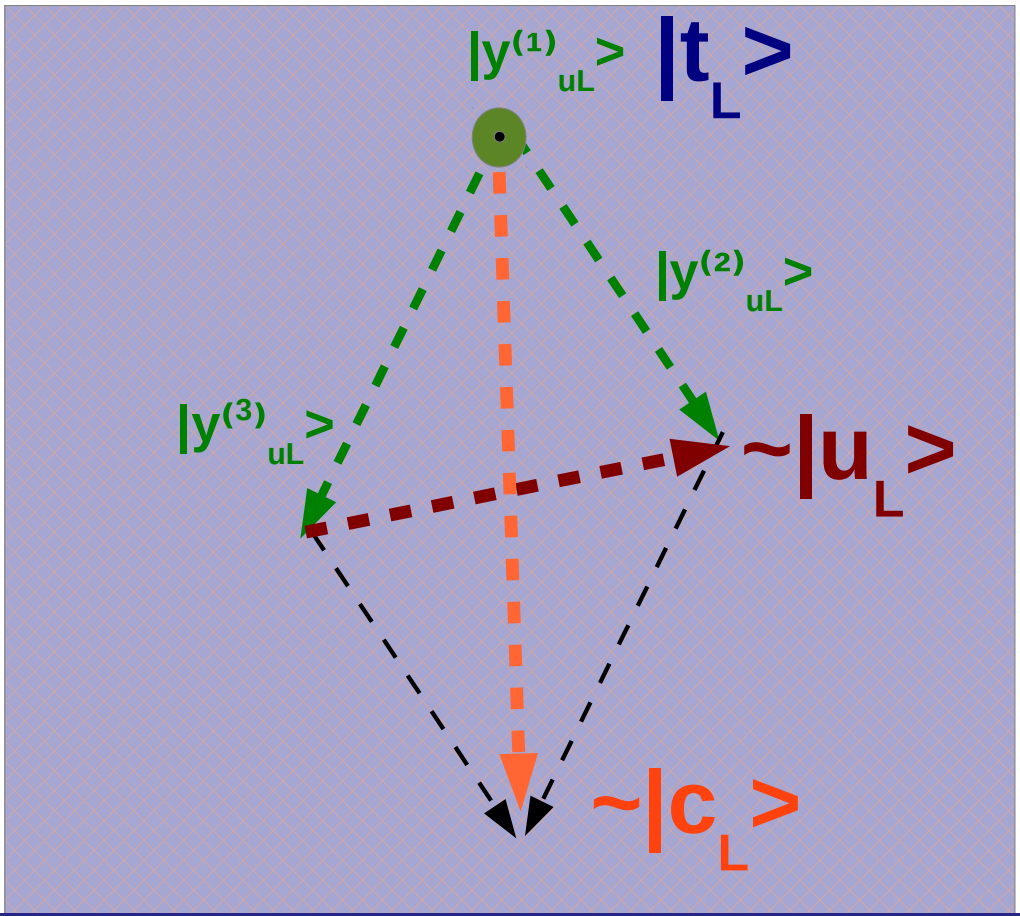

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