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Radiative Generation of Quark Masses and Mixing Angles in the 2HDM

[arXiv:1403.2382]

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in collaboration with Alejandro Ibarra

Technische Universität München & Max-Planck-Institut für Physik

FLASY 2014, Brighton





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Introduction	The 2HDM	The Quark Sector	The Lepton Sector	Conclusions
Introduct	tion			
► N Sta	lotivation: Hierar andard Model. \Rightarrow	chy for masses an New Physics?	d mixing angles in the	
ve:? Me e:0.511	V vµ:? MeV MeV µ:105.7 GeV	vt:? MeV t:1.78 GeV		
Up:2.3 /	MeV Charm:1-29 GeV	Top:173 GeV	$V_{CKM} = \begin{pmatrix} 0.974 & 0.225 \\ 0.225 & 0.973 \\ 0.0087 & 0.04 \end{pmatrix}$	5 0.0035 3 0.041 0.999
Down:4.8	MeV Strange:95 MeV Bo	ttom:4.18 GeV		

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Introduction	The 2HDM	The Quark Sect	or The Lepton Sector	Conclusions
Introd	uction			
•	Motivation: H Standard Model	ierarchy for masse \Rightarrow New Physic	es and mixing angles in s?	the
ve	e:? MeV vµ:? MeV	vt:? MeV		
e:	0.511 MeV µ:105.7 Ge	V T:1.78 GeV		
Up	2.3 MeV Charm 129 (ieV Top:173 GeV	$V_{CKM} = \begin{pmatrix} 0.974\\ 0.225\\ 0.0087 \end{pmatrix}$	$\begin{array}{c c} 0.225 & 0.0035 \\ \hline 0.973 & 0.041 \\ \hline 0.04 & 0.999 \end{array}$

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• Our goal: Reproduce masses and mixing angles.

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Radiative Generation of Quark Masses and Mixing Angles in the 2HDM

Down:4.8 MeV Strange:95 MeV Bottom:4.18 GeV

Introduction	The 2HDM	The Quark Sector	The Lepton Sector	Conclusions
Introduc	ction			
	Motivation: Hie	rarchy for masses a	and mixing angles in the	
S	standard Model.	⇒ New Physics?		
ve:?	MeV vµ:?MeV	ντ:? MeV		
e:0.5	11 MeV µ:105.7 GeV	τ:1.78 GeV		
	•.			
Up:2.3	3 MeV Charm:1.29 GeV	Top:173 GeV	$\begin{pmatrix} 0.974 & 0.225 \\ 0.974 & 0.225 \\ 0.974 & 0.225 \\ 0.974 & 0.974 \\ 0.974 & 0.$	



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- Our goal: Reproduce masses and mixing angles.
- How?: 2HDM (extra symmetries)

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The Two-Higgs Doublet Model

Standard Model + one extra Higgs doublet.

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- Standard Model + one extra Higgs doublet.
- Interactions with fermions:



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- Standard Model + one extra Higgs doublet.
- Interactions with fermions:



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Interactions with SM Higgs

The 2HDM	The Quark Sector	The Lepton Sector	Conclusions

- Standard Model + one extra Higgs doublet.
- Interactions with fermions:



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- Interactions with SM Higgs
- Self-interactions

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- Standard Model + one extra Higgs doublet.
- Interactions with fermions:



- Interactions with SM Higgs
- Self-interactions
- ► Decoupling limit $(M_{\phi 1} \sim 126 \text{ GeV}, M_{\phi 2} >> M_{\phi 1}) \Rightarrow \text{FENC}$ or LFV processes.

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- Standard Model + one extra Higgs doublet.
- Interactions with fermions:



- Interactions with SM Higgs
- Self-interactions
- ► Decoupling limit $(M_{\phi 1} \sim 126 \text{ GeV}, M_{\phi 2} >> M_{\phi 1}) \Rightarrow \text{FENC}$ or LFV processes.

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► Decoupling limit √SM vacuum.

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The 2HDM	The Quark Sector	The Lepton Sector	Conclusions

The Quark Sector

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Introduction	The 2HDM	The Quark Sector	The Lepton Sector	Conclusions
The Quark	Sector			
► E {'	Basis $\langle \Phi^0_1 angle = v_A \ \Phi^0_2 angle = 0$	/√2,	<u> </u>	QL
► Y	′ukawa interact	ion		q_R

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(rank-1):



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The Quark Sector
 Basis \$\langle \Phi_1^0 \rangle = v/\sqrt{2}\$, \$\langle \Phi_2^0 \rangle = 0\$ Yukawa interaction (rank-1): \$\langle q_R\$
$Y_{1}^{(1)} _{\text{tree}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, Y_{1}^{(1)} _{\text{tree}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & e^{(1)} \\ e^{(1)} \end{pmatrix}$

The Quark Sector

$$\begin{aligned} Y_{u}^{(1)}|_{\text{tree}} &= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_{u}^{(1)} \end{pmatrix} , \quad Y_{d}^{(1)}|_{\text{tree}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \overbrace{\epsilon y_{d}^{(1)}} \\ 0 & 0 & y_{d}^{(1)} \end{pmatrix} \\ & \left| V_{ub} \right|^{2} + \left| V_{cb} \right|^{2} \ll 1 \Rightarrow \ \epsilon \to \mathbf{0} \end{aligned}$$

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	The 2HDM	The Quark Sector	The Lepton Sector	Conclusions
The Qua	rk Sector			
•	Basis $\langle \Phi_1^0 \rangle = v$ $\langle \Phi_2^0 \rangle = 0$ Yukawa interac (rank-1):	$1/\sqrt{2}$, 	$- \frac{\phi_1, \phi_2}{\phi_1, \phi_2}$	Q _L
	$Y_u^{(1)} _{\text{tree}} = \begin{pmatrix} 0\\0\\0 \end{pmatrix}$	$egin{array}{ccc} 0 & 0 \ 0 & 0 \ 0 & y_u^{(1)} \end{array} ight) \;, \;\; Y_d^{(1)} _{ m tree}$	$\mathbf{e} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \underbrace{\epsilon y_d^{(1)}}_{0 & 0 & y_d^{(1)}} \end{pmatrix}$	
	$ V_{ub} $	$ ^2 + V_{cb} ^2 \ll 1 \Rightarrow$	$\epsilon ightarrow 0$	
► Y	$Y_u^{(1)} _{ ext{tree}} \& Y_d^{(1)} _{ ext{tree}}$	$t_{\text{tree}} \Rightarrow \left\{ egin{array}{c} m_t \ m_b \end{array} 0 \mathbf{t} ight.$	ree level	≣। ► ≣ <i>•</i>)q(
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	The 2HDM	The Quark Sector	The Lepton Sector	Conclusions
$Y_u^{(2)} _{\mathrm{tre}}$	$_{ m e} = U_L^{\dagger} \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 \\ 0 \\ y_u^{(2)} \end{pmatrix} U_R \;,\;\; Y_d^{(2)} _t$	$c_{\rm ree} = D_L^{\dagger} \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0\\ 0\\ y_d^{(2)} \end{pmatrix} D_R$

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$$\begin{split} & \text{The 2HDM} & \text{The Quark Sector} & \text{The Lepton Sector} & \text{Conclusions} \\ & Y_u^{(2)}|_{\text{tree}} = U_L^{\dagger} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_u^{(2)} \end{pmatrix} U_R \ , \ Y_d^{(2)}|_{\text{tree}} = D_L^{\dagger} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_d^{(2)} \end{pmatrix} D_R \end{split}$$

• $Y_{u,d}^{(2)}|_{\text{tree}}$ just depend on $U_{L3i}, U_{R3i}, D_{L3i}, D_{R3i}$. Parametrize:

$$\begin{aligned} (U_L)_{31} &= e^{i\rho_{u_L}} \sin \theta_{u_L} \sin \omega_{u_L} , \\ (U_L)_{32} &= e^{i\xi_{u_L}} \sin \theta_{u_L} \cos \omega_{u_L} , \\ (U_L)_{33} &= \cos \theta_{u_L} , \end{aligned}$$

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Neglect phases.

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$$\begin{split} & \text{Introduction} & \text{The 2HDM} & \text{The Quark Sector} & \text{The Lepton Sector} & \text{Conclusions} \\ & Y_u^{(2)}|_{\text{tree}} = U_L^{\dagger} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_u^{(2)} \end{pmatrix} U_R \ , \ Y_d^{(2)}|_{\text{tree}} = D_L^{\dagger} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_d^{(2)} \end{pmatrix} D_R \end{split}$$

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Neglect phases.

• Assume for simplicity $y_u^{(1)}, \mathbf{y_u^{(2)}} >> y_d^{(1)}, \mathbf{y_d^{(2)}}$

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The 2HDM	The Quark Sector	The

▶ 1-loop from β function:

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

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The 2HDM	The Quark Sector	The Lepton Sector	Conclusions

• 1-loop from β function:

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

1-loop diagram (generate 2nd mass):



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The 2HDM	The Quark Sector	The Lepton Sector	Conclusions

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	The 2HDM	The Quark Sector	The Lepton Sector	Conclusions
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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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Mass hierarchy for the quarks:

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

$$\frac{y_s}{y_b} \simeq \left(\frac{1}{16\pi^2}\log\frac{\Lambda}{M_H}\right) \frac{y_u^{(1)}y_u^{(2)}y_d^{(2)}}{y_d^{(1)}} \times \text{mixing angles}$$

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Mass hierarchy for the quarks:

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

$$rac{y_s}{y_b} \simeq \left(rac{1}{16\pi^2}\lograc{\Lambda}{M_H}
ight) rac{y_u^{(1)}y_u^{(2)}y_d^{(2)}}{y_d^{(1)}} imes$$
 mixing angles

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First generation massless.

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$$\blacktriangleright V_{CKM} = V_u^{\dagger} V_d$$



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- $\blacktriangleright V_{CKM} = V_u^{\dagger} V_d$
- ▶ $V_{tb} \sim 1$ @ tree-level.



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- $\blacktriangleright V_{CKM} = V_u^{\dagger} V_d$
- ▶ $V_{tb} \sim 1$ @ tree-level.
- Cabibbo angle @ 0-order in perturbation theory:

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

$$\begin{split} N_d &= \left[9\sin^2\theta_{d_L}\cos^2\theta_{u_L} + 4\cos^2\theta_{d_L}\sin^2\theta_{u_L}\right.\\ &-3\sin2\theta_{d_L}\sin2\theta_{u_L}\cos(\omega_{d_L} - \omega_{u_L})\right]^{1/2} \end{split}$$

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- $\blacktriangleright V_{CKM} = V_u^{\dagger} V_d$
- ▶ $V_{tb} \sim 1$ @ tree-level.
- Cabibbo angle @ 0-order in perturbation theory:

$$V_{us} \simeq -V_{cd} \simeq \mathsf{mixing}$$
 angles

- $\blacktriangleright V_{CKM} = V_u^{\dagger} V_d$
- ▶ $V_{tb} \sim 1$ @ tree-level.
- Cabibbo angle @ 0-order in perturbation theory:

$$V_{us} \simeq -V_{cd} \simeq \text{mixing angles}$$

Remaining off-diagonal terms @ 1st order in perturbation theory:

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

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The Quark Sector

The Lepton Secto

Quark Mixing Angles

$V_{CKM} = \begin{pmatrix} 0.974 & 0.225 & 0.0035 \\ 0.225 & 0.973 & 0.041 \\ 0.0087 & 0.04 & 0.999 \end{pmatrix}$

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The Quark Sector

The Lepton Sector

Quark Mixing Angles



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The Quark Sector

The Lepton Sector

Quark Mixing Angles



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Constraints from masses and CKM matrix:

$$\begin{split} \frac{y_s}{y_b} \frac{V_{us}}{V_{ub}} &\simeq \tan \theta_{d_R} \ , \\ \frac{y_c}{y_t} \frac{V_{us}}{V_{td}} &\simeq \frac{3 \sin 2\theta_{u_R}}{2 + 3 \cos 2\theta_{u_R}} \end{split}$$

Radiative Generation of Quark Masses and Mixing Angles in the 2HDM



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Constraints from masses and CKM matrix:

$$\frac{y_s}{y_b} \frac{V_{us}}{V_{ub}} \simeq \tan \theta_{d_R} ,$$
$$\frac{y_c}{y_t} \frac{V_{us}}{V_{td}} \simeq \frac{3 \sin 2\theta_{u_R}}{2 + 3 \cos 2\theta_{u_R}}$$

$$\Rightarrow \theta_{u_R} \approx 0.16, \ \theta_{d_R} \approx 1.06$$

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Degeneracy for other parameters:

Constraints from masses and CKM matrix:

$$\frac{y_s}{y_b} \frac{V_{us}}{V_{ub}} \simeq \tan \theta_{d_R} ,$$
$$\frac{y_c}{y_t} \frac{V_{us}}{V_{td}} \simeq \frac{3 \sin 2\theta_{u_R}}{2 + 3 \cos 2\theta_{u_R}}$$

$$\Rightarrow \theta_{u_R} \approx 0.16, \ \theta_{d_R} \approx 1.06$$

Degeneracy for other parameters:

✓ All masses and angles can be reproduced (example: $y_u^{(2)} \approx 1.04$, $y_d^{(2)} \approx 0.02$, $\theta_{d_L} \approx 0.61$, $\theta_{u_L} \approx 0.51$, $\omega_{d_L} - \omega_{u_L} \approx 0.10$)

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Rank-1 Yukawa interaction.

Radiative Generation of Quark Masses and Mixing Angles in the 2HDM



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- Rank-1 Yukawa interaction.
- Include one right-handed neutrino.

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Radiative Generation of Quark Masses and Mixing Angles in the 2HDM



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Radiative Generation of Quark Masses and Mixing Angles in the 2HDM



The 2HDM	The Quark Sector	The Lepton Sector	Conclusions

Lepton Masses







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Lepton Masses





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PMNS Matrix

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

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PMNS Matrix



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The 2HDM	The Quark Sector	The Lepton Sector	Conclusions

Conclusions

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	The 2HDM	The Quark Sector	The Lepton Sector	Conclusions
Conclusions	;			

• Extend the SM with and extra Higgs doublet.

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Radiative Generation of Quark Masses and Mixing Angles in the 2HDM



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	The 2HDM	The Quark Sector	The Lepton Sector	Conclusions
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	The 2HDM	The Quark Sector	The Lepton Sector	Conclusions
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	The 2HDM	The Quark Sector	The Lepton Sector	Conclusions
Conclusio	ons			

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	The 2HDM	The Quark Sector	The Lepton Sector	Conclusions
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	The 2HDM	The Quark Sector	The Lepton Sector	Conclusions
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Radiative Generation of Quark Masses and Mixing Angles in the 2HDM

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	The 2HDM	The Quark Sector	The Lepton Sector	Conclusions
Backup slid	les			



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How to calculate eigenstates (@ 0-order) and the corresponding eigenvectors (@ 1st order):

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• Hamiltonian $H = H^{(0)} + \lambda W$

How to calculate eigenstates (@ 0-order) and the corresponding eigenvectors (@ 1st order):

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- Hamiltonian $H = H^{(0)} + \lambda W$
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How to calculate eigenstates (@ 0-order) and the corresponding eigenvectors (@ 1st order):

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- W⁽ⁿ⁾ is the perturbation in subspace $\perp \left| t^{(0)}
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How to calculate eigenstates (@ 0-order) and the corresponding eigenvectors (@ 1st order):

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- $\mathsf{H}^{(0)}$ of rank-1 determines 1-eigenstate ($\left|t^{(0)}\right\rangle$)
- W $^{(n)}$ is the perturbation in subspace $\perp \left| t^{(0)}
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- ► Eigenstates and eigenvalues of \u03c8W⁽ⁿ⁾ are eigenstates (0-order) and eigenvalues (1st-order) of H from the subspace \u03c4 |t⁽⁰⁾\u03c8.

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