Robustness of theoretical model predictions

Michael Ratz

TECHNISCHE UNIVERSITÄT MÜNCHEN

NuFact, Virginia, July 27, 2012

Based on:

- T. Araki, T. Kobayashi, J. Kubo, S. Ramos–Sánchez, M.R. & P. Vaudrevange Nucl. Phys. B 805, 124–147 (2008)
- M.–C. Chen, M. Fallbacher, M.R. & C. Staudt, to appear

Origin of mass hierarchies and mixing

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- ☞ Standard model: $\mathcal{O}(20)$ physical quantities which seem unrelated
- ? Are there testable relations?
- ☞ Symmetries may relate the parameters and thus reduce their number

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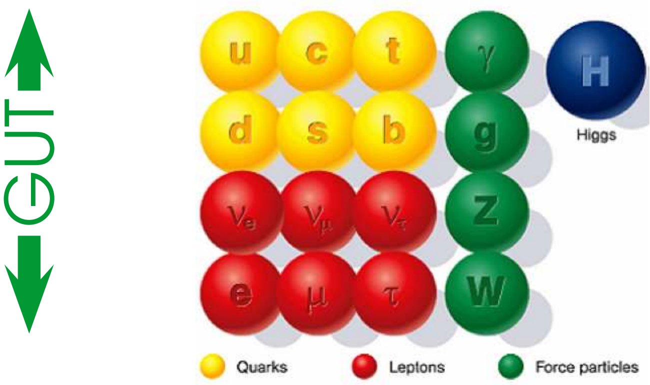

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- Quarks & leptons reside in the same GUT multiplets
- One set of Yukawa coupling for a given GUT multiplet
  $\curvearrowright$ intra–family relations

Family symmmetries

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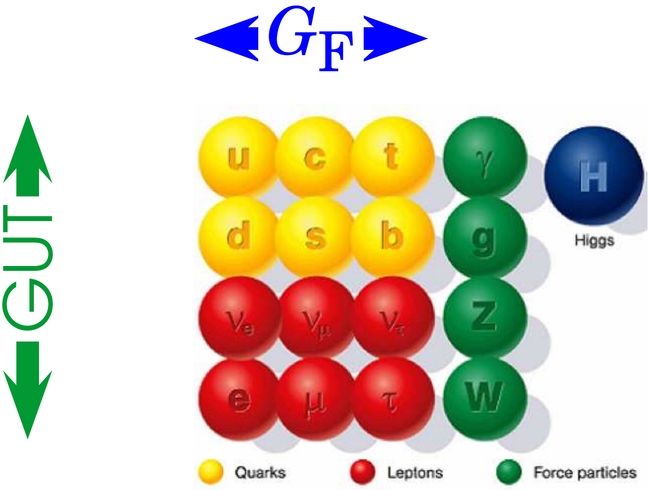
  ↷ inter–family relations



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- Plethora of models
- Attractive scheme: GUT symmetry $\times$ family symmetry G_F

Non–Abelian discrete flavor symmetries

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☞ Recently strong model building activities based on discrete family symmetry groups:

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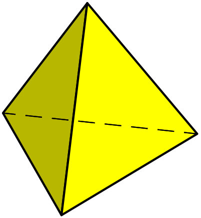

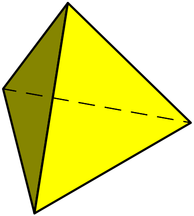

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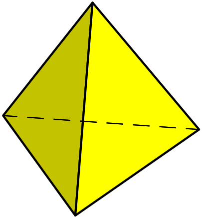

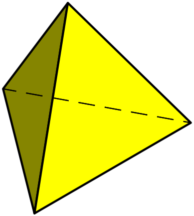

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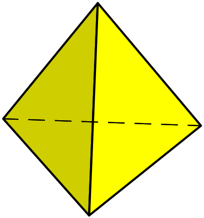

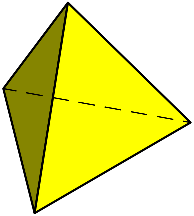

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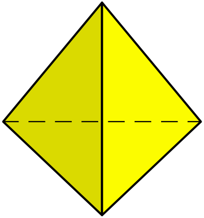

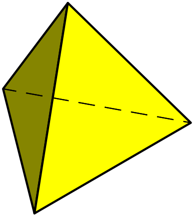

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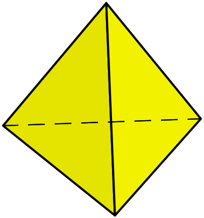

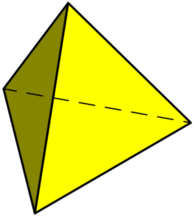

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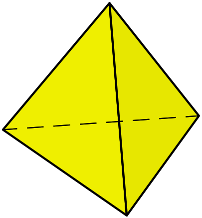

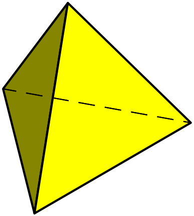

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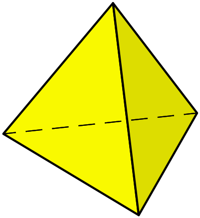

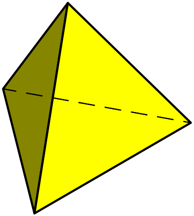

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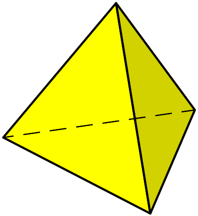

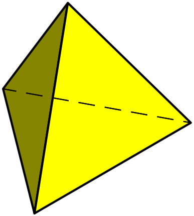

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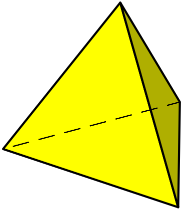

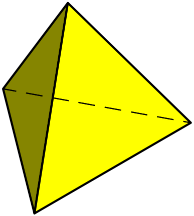

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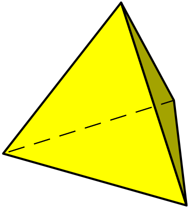

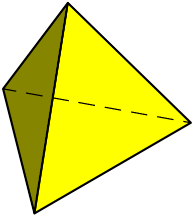

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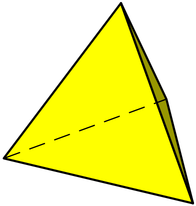

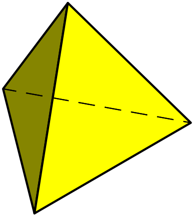

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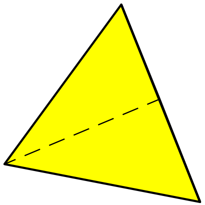

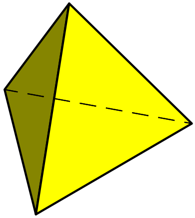

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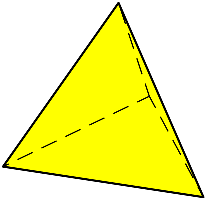

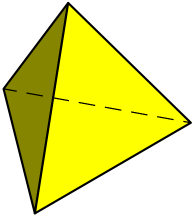

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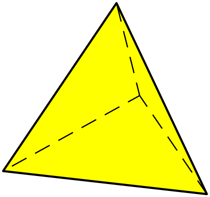

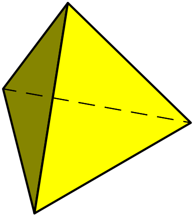

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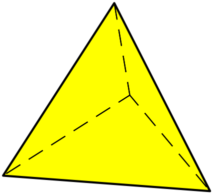

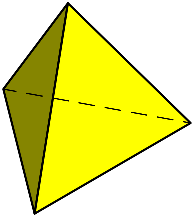

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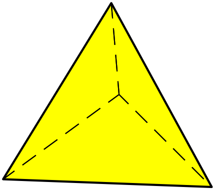

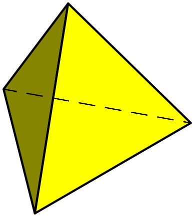

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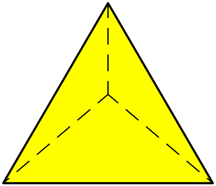

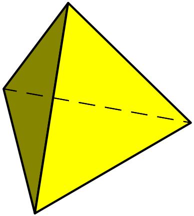

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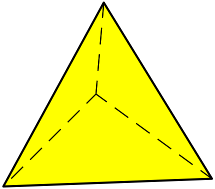

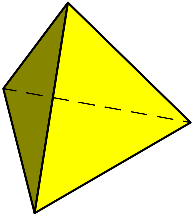

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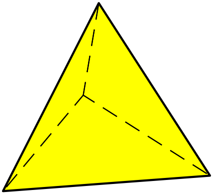

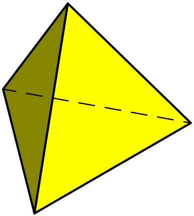

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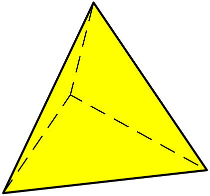

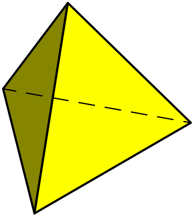

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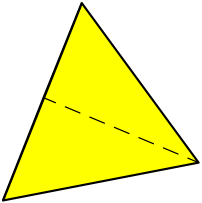

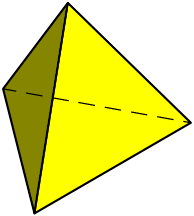

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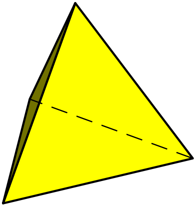

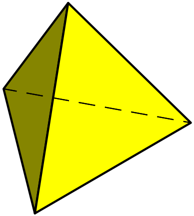

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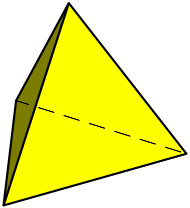

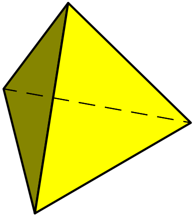

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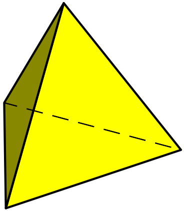

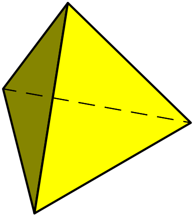

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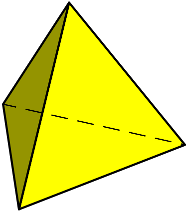

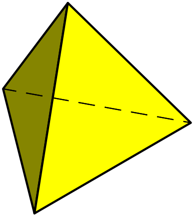

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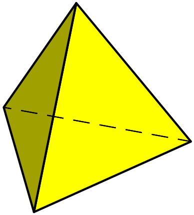

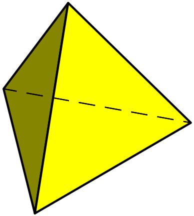

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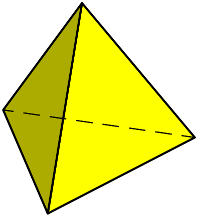

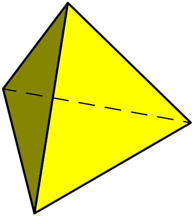

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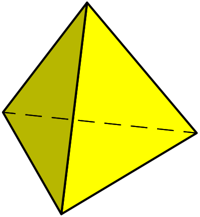

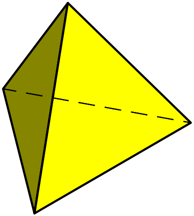

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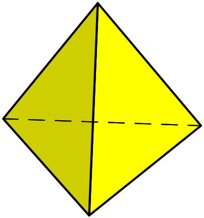

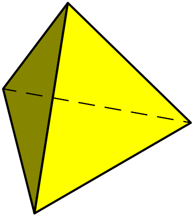

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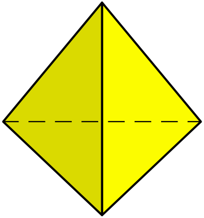

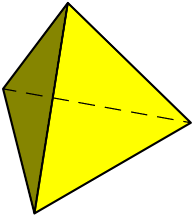

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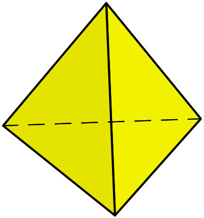

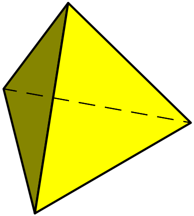

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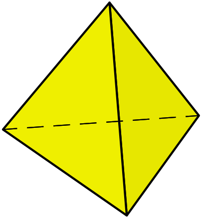

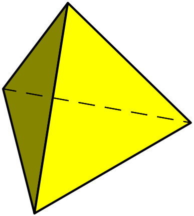

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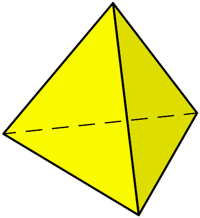

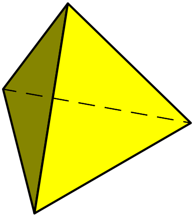

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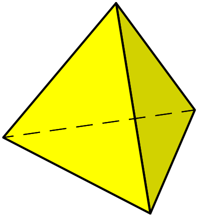

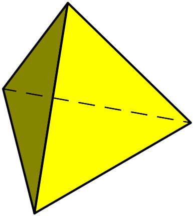

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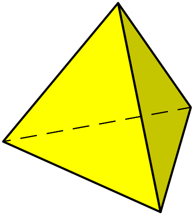

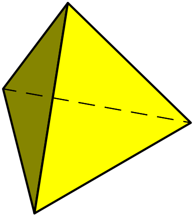

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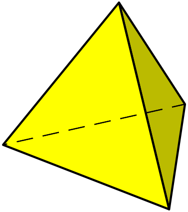

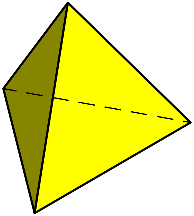

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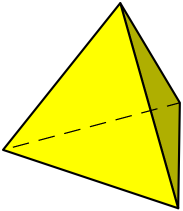

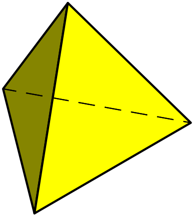

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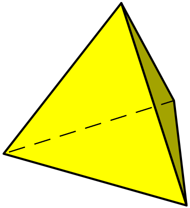

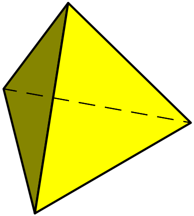

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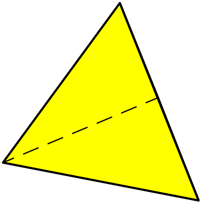

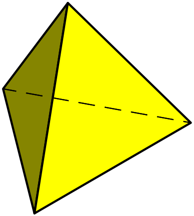

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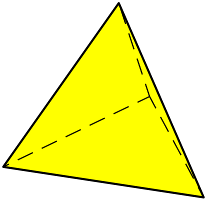

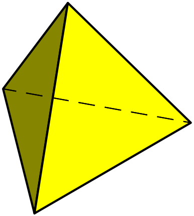

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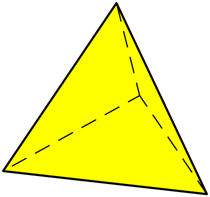

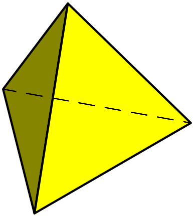

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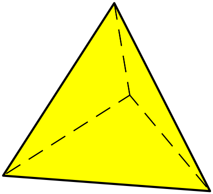

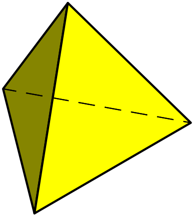

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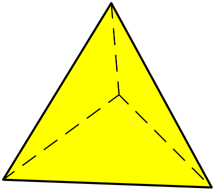

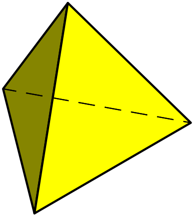

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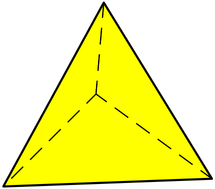

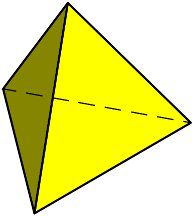

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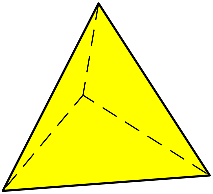

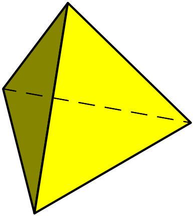

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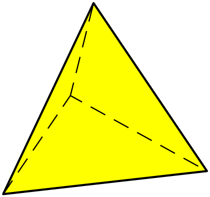

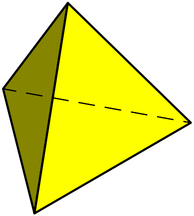

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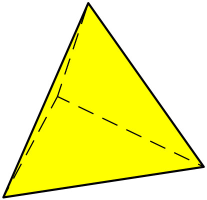

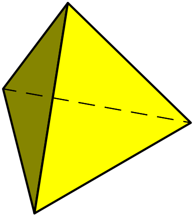

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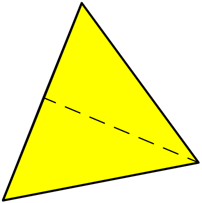

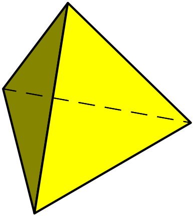

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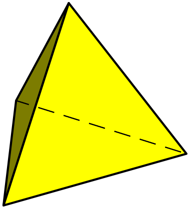

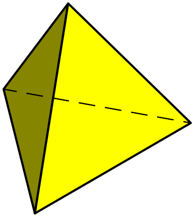

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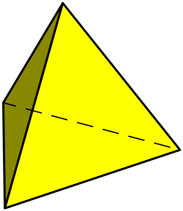

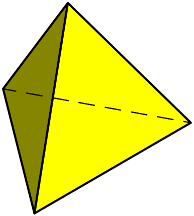

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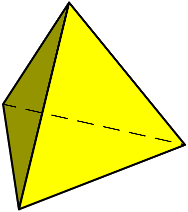

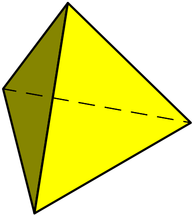

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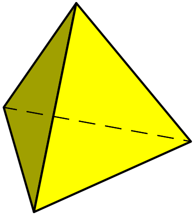

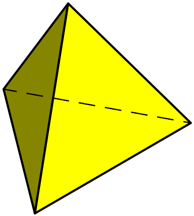

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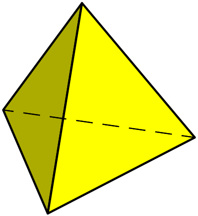

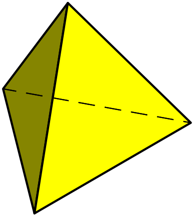

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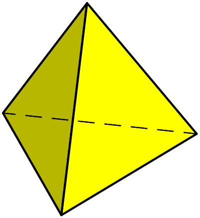

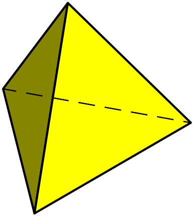

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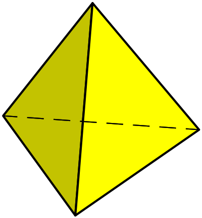

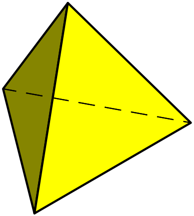

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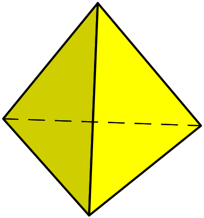

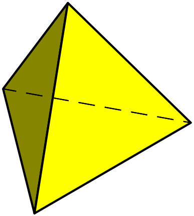

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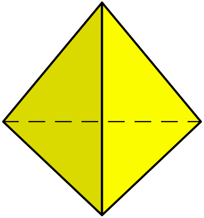

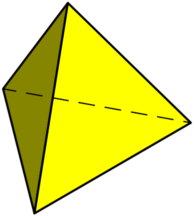

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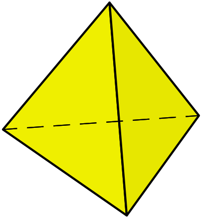

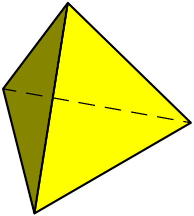

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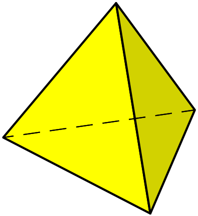

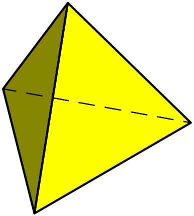

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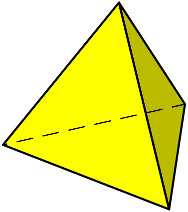

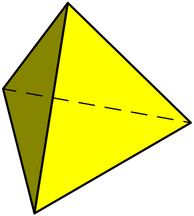

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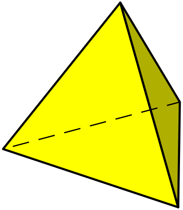

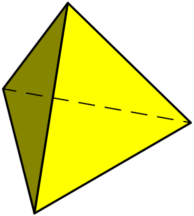

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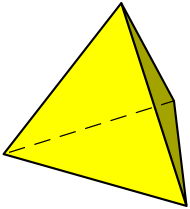

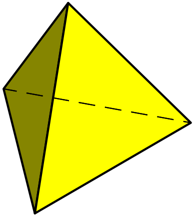

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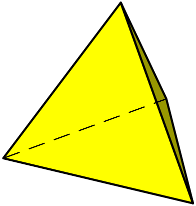

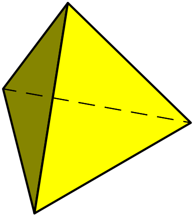

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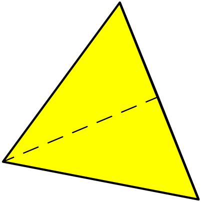

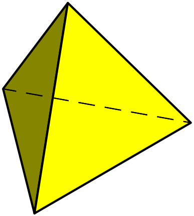

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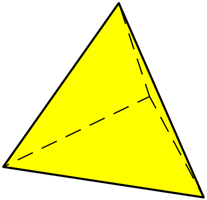

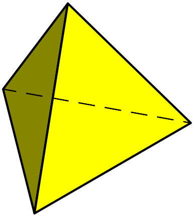

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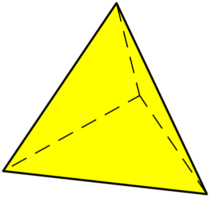

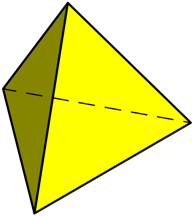

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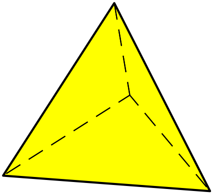

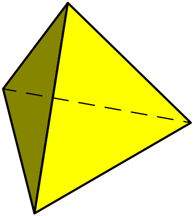

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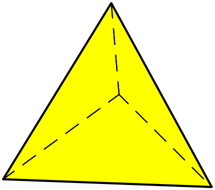

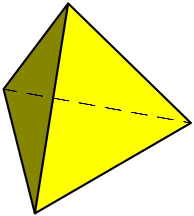

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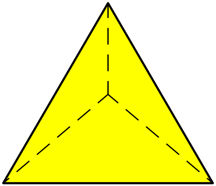

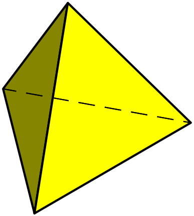

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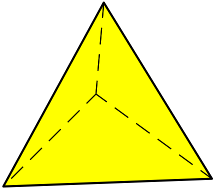

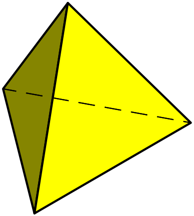

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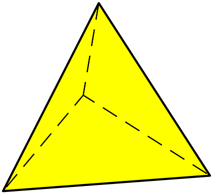

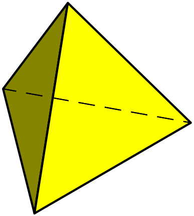

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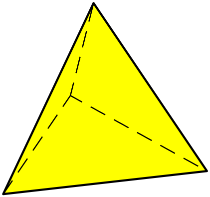

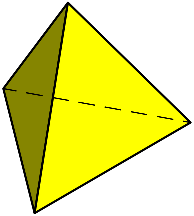

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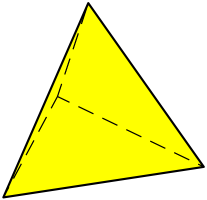

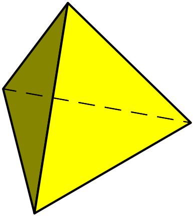

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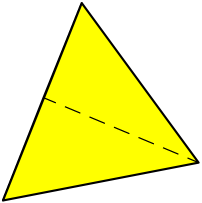

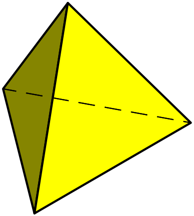

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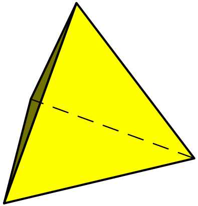

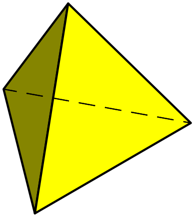

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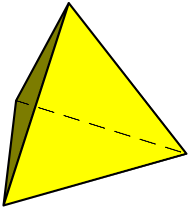

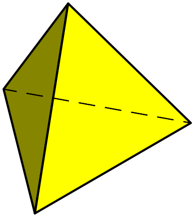

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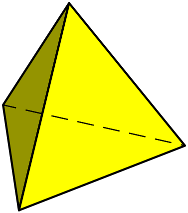

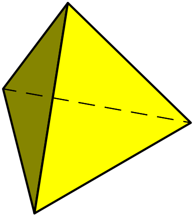

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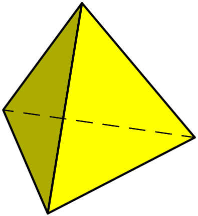

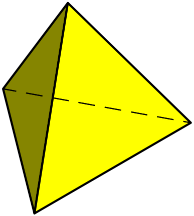

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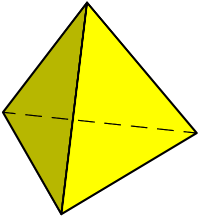

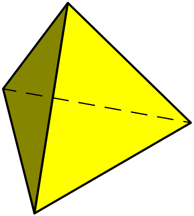

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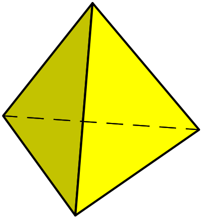

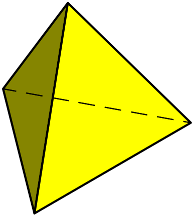

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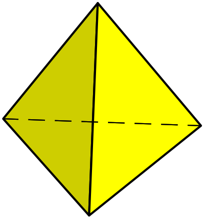

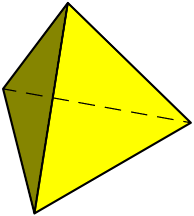

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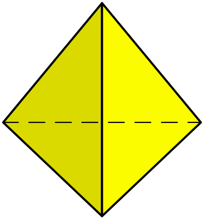

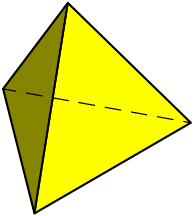

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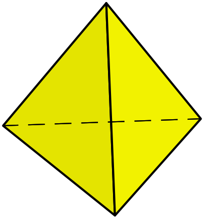

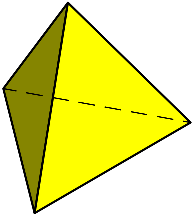

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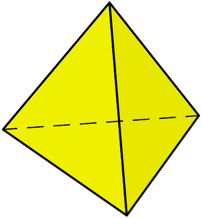

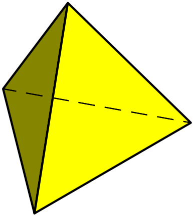

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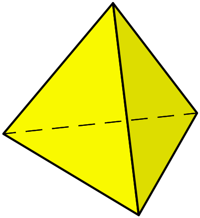

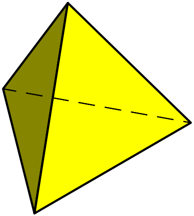

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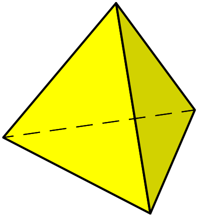

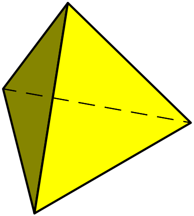

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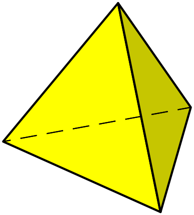

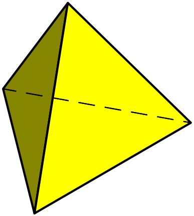

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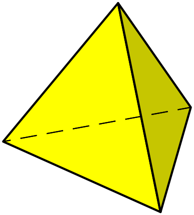

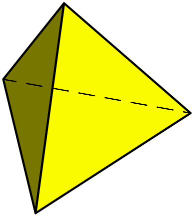

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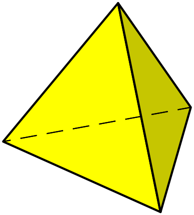

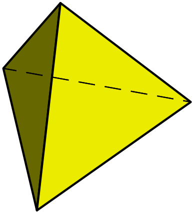

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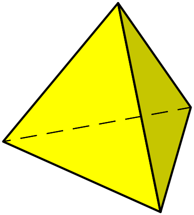

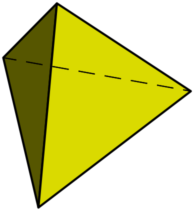

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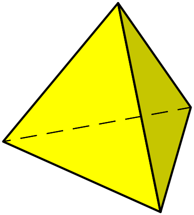

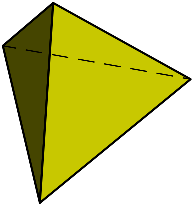

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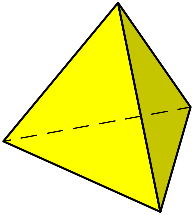

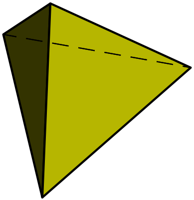

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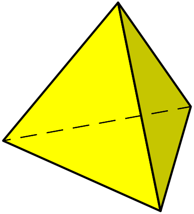

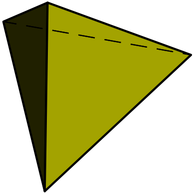

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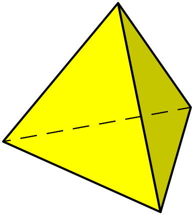

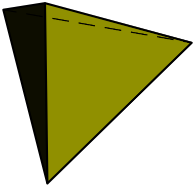

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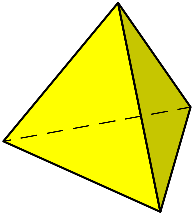

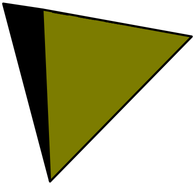

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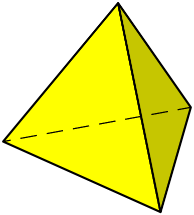

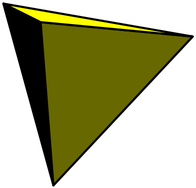

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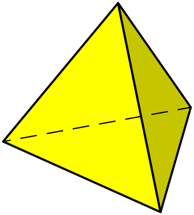

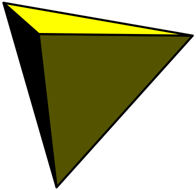

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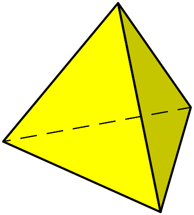

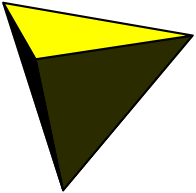

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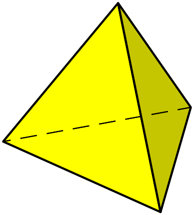

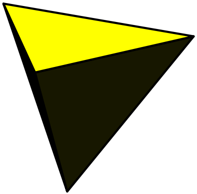

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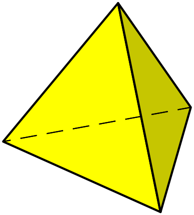

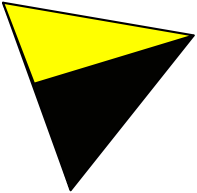

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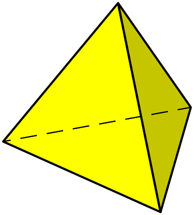

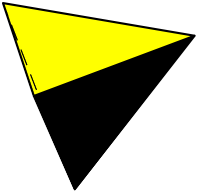

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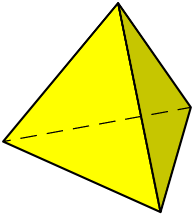

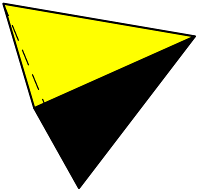

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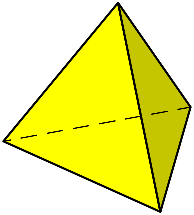

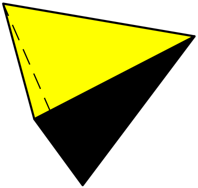

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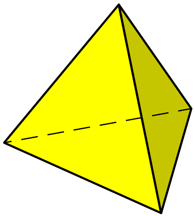

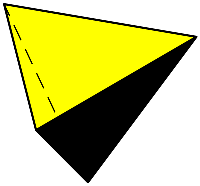

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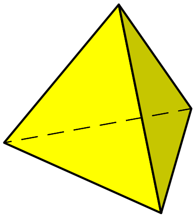

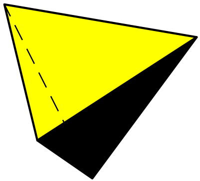

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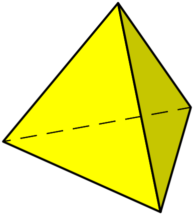

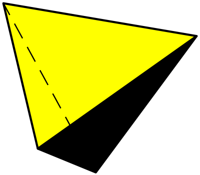

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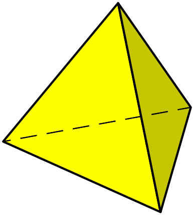

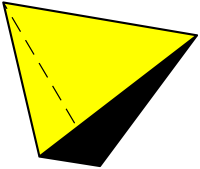

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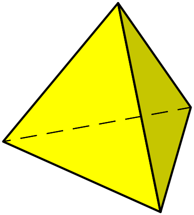

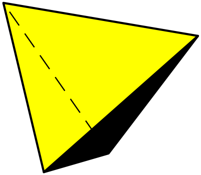

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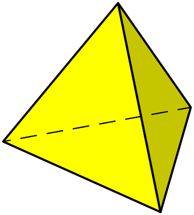

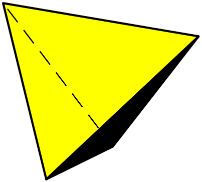

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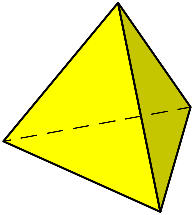

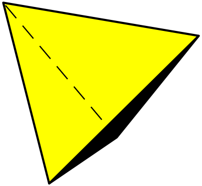

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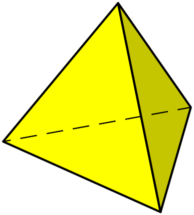

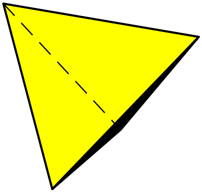

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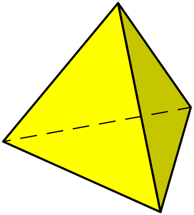

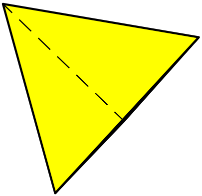

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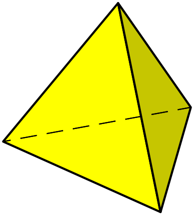

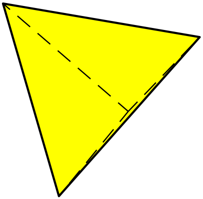

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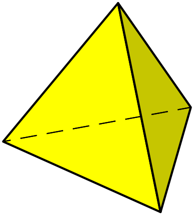

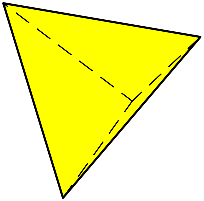

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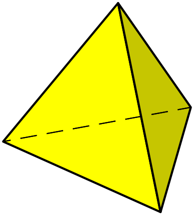

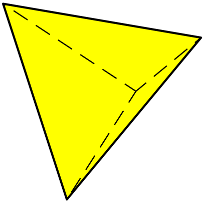

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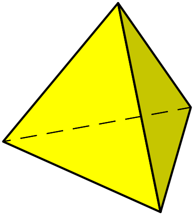

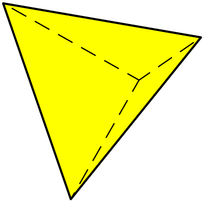

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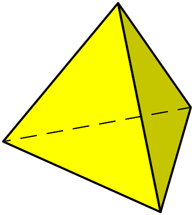

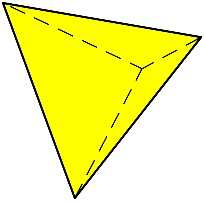

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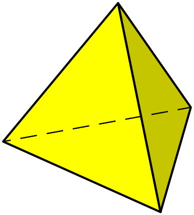

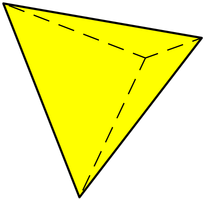

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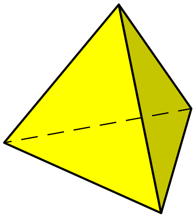

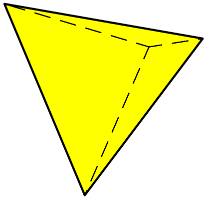

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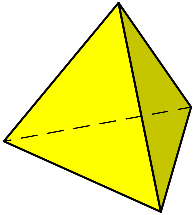

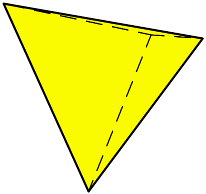

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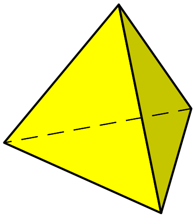

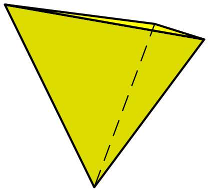

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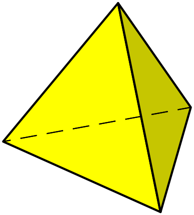

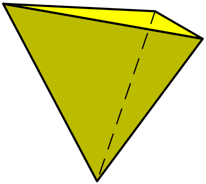

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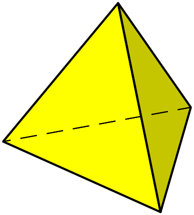

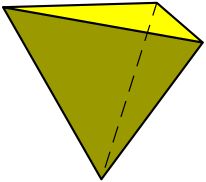

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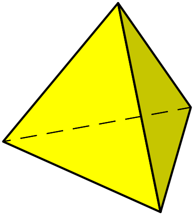

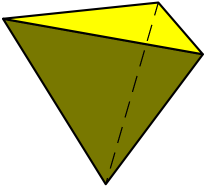

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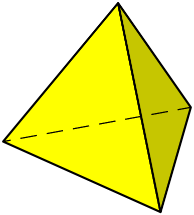

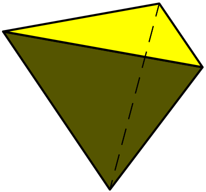

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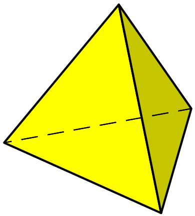

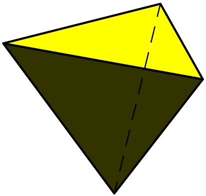

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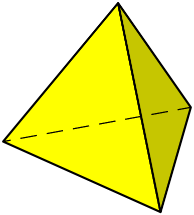

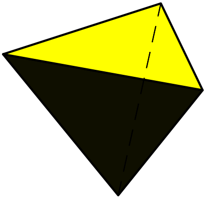

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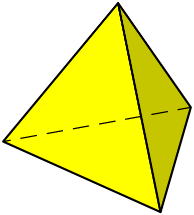

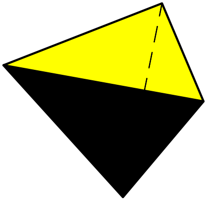

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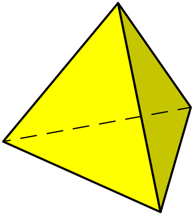

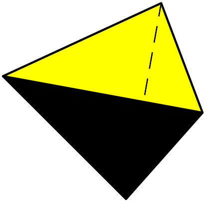

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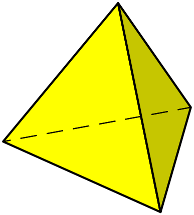

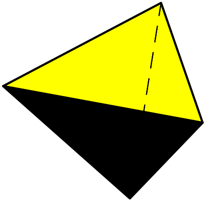

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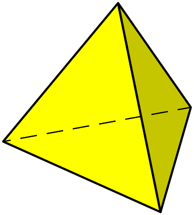

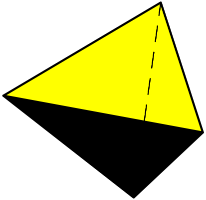

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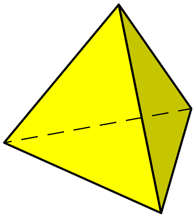

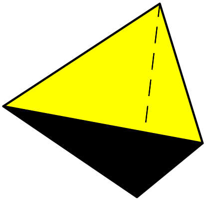

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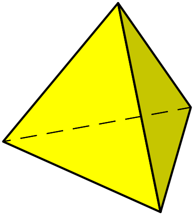

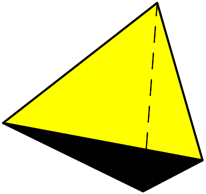

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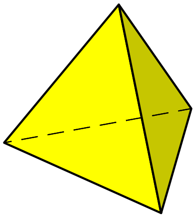

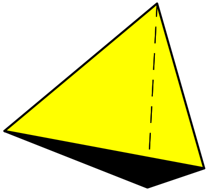

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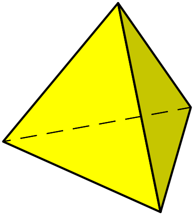

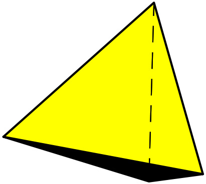

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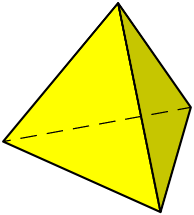

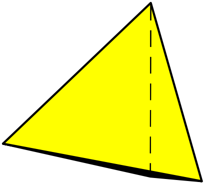

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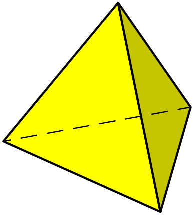

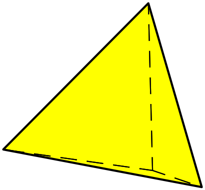

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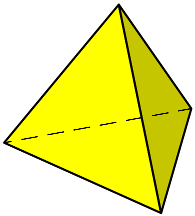

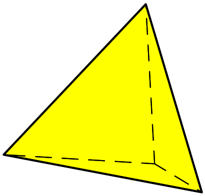

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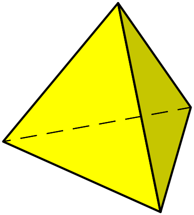

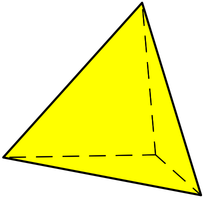

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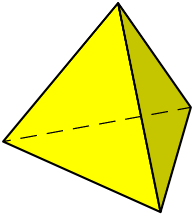

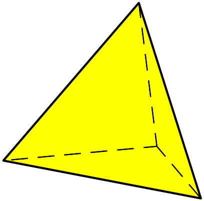

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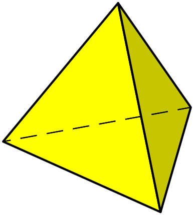

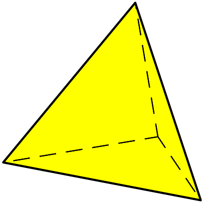

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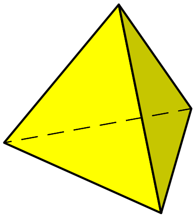

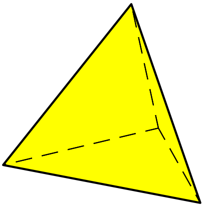

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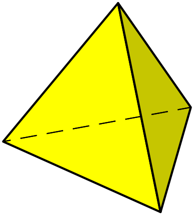

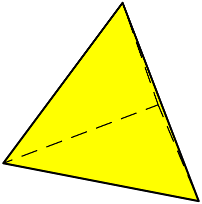

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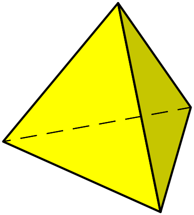

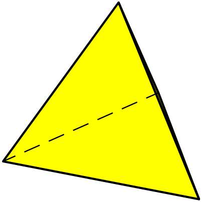

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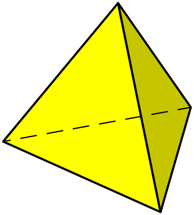

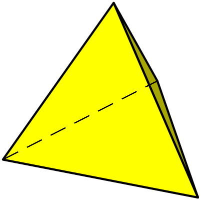

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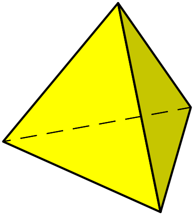

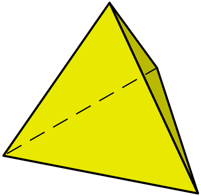

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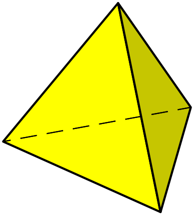

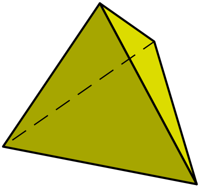

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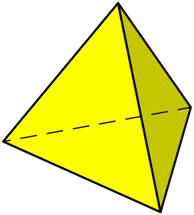

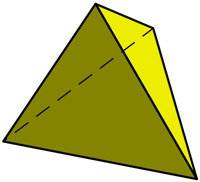

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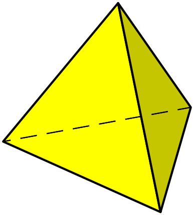

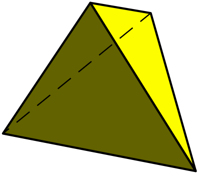

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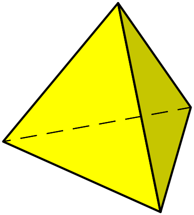
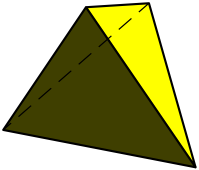
- A_4 (tetrahedron)





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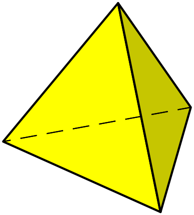

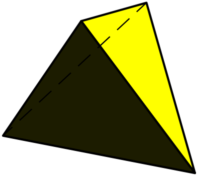

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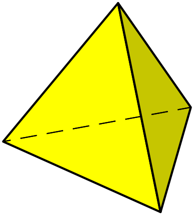

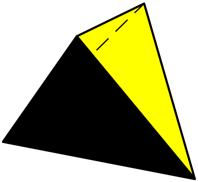

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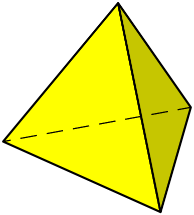

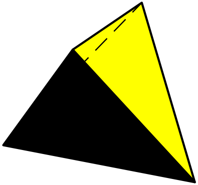

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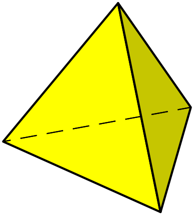

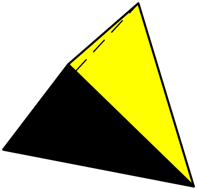

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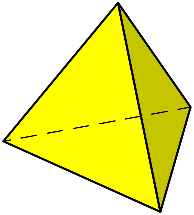

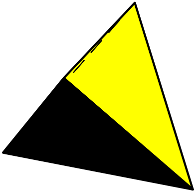

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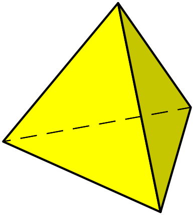

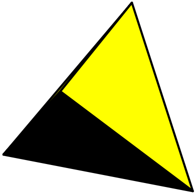

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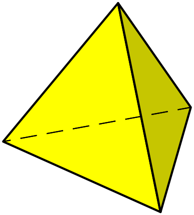

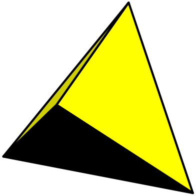

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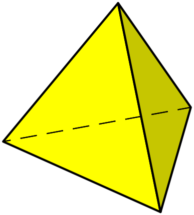

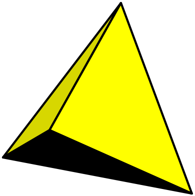

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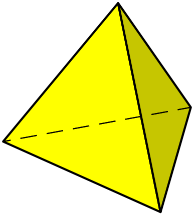

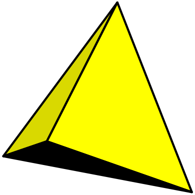

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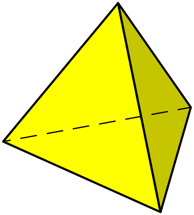

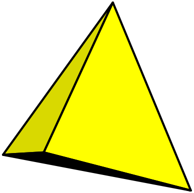

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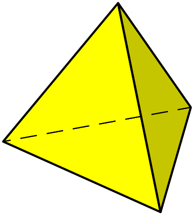

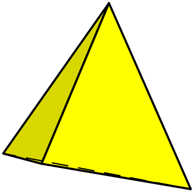

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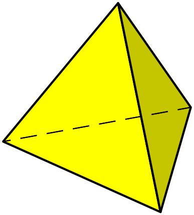

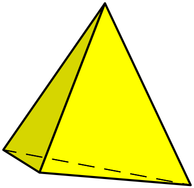

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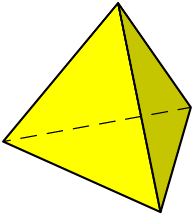

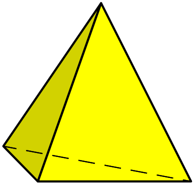

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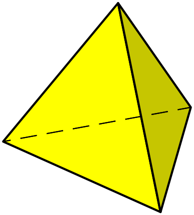

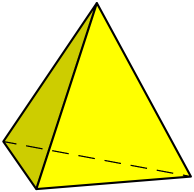

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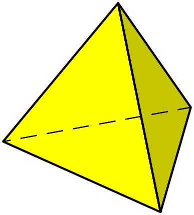

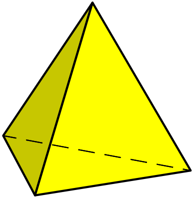

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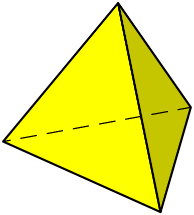

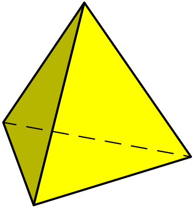

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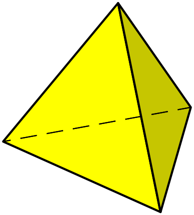

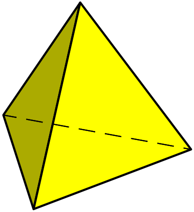

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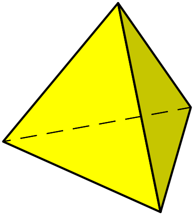

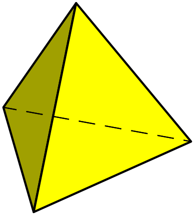

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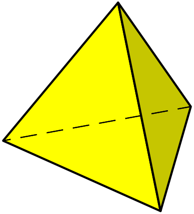

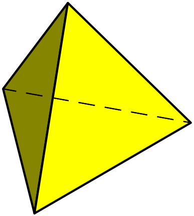

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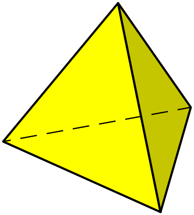

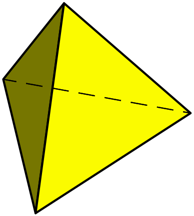

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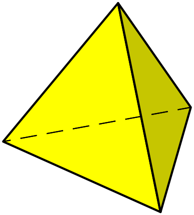

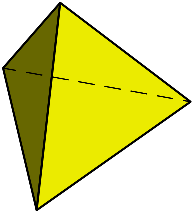

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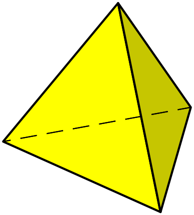

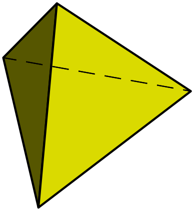

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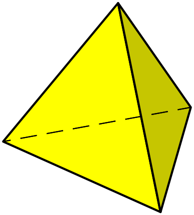

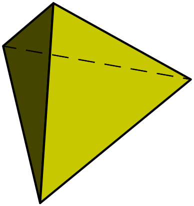

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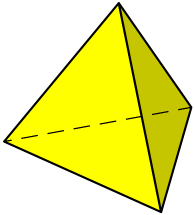

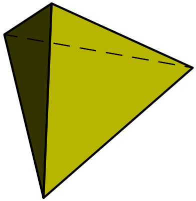

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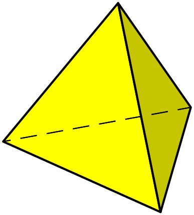

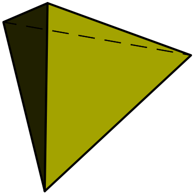

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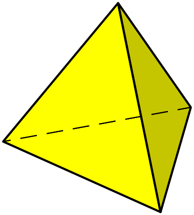

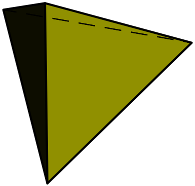

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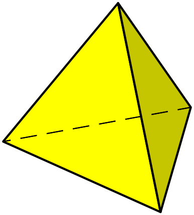

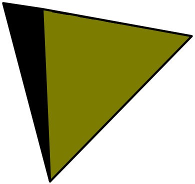

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- T' (double tetrahedron)
  complex CG coefficients ↷ geometrical origin of ~~CP~~

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VEV misalignment

- Interplay between the symmetry breaking patterns in two sectors lead to lepton mixing (BM, TBM, . . .)

VEV misalignment

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- Symmetry breaking achieved through flavon VEVs

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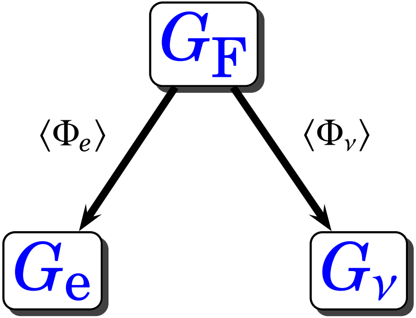

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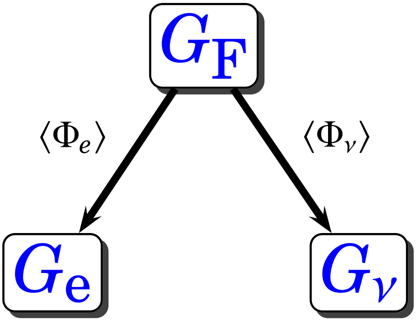

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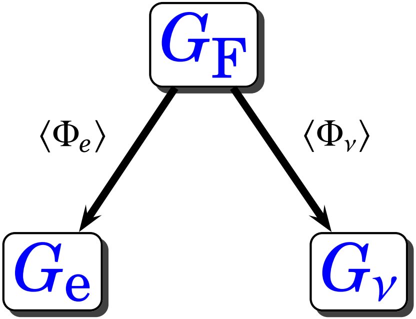

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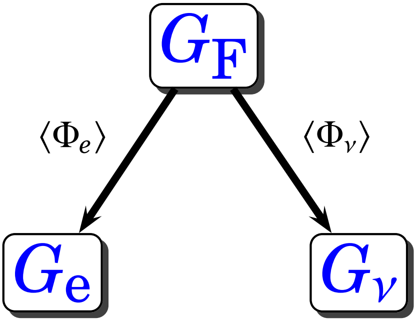

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question:

how robust are such predictions?

An example: A_4

Altarelli and Feruglio (2005)

- Superpotential couplings

$$\mathscr{W}_\nu = \frac{\lambda_1}{\Lambda\,\Lambda_\nu}\left\{\left[(L\,H_u)\times(L\,H_u)\right]_{\mathbf{3}}\times\Phi_\nu\right\}_{\mathbf{1}} + \frac{\lambda_2}{\Lambda\,\Lambda_\nu}\left[(L\,H_u)\times(L\,H_u)\right]_{\mathbf{1}}\,\xi$$

left–handed lepton doublets transform as A_4 triplet $L=(L_e,L_\mu,L_\tau)^T$

u–type Higgs

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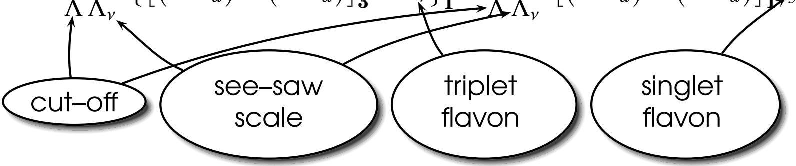

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triplet contraction

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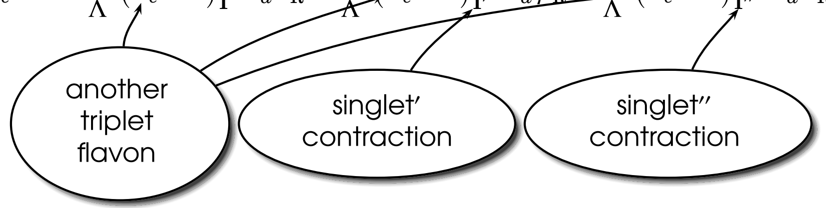
$$\mathscr{W}_e = \frac{h_e}{\Lambda}\left(\Phi_e\times L\right)_{\mathbf{1}}\,H_d\,e_{\mathrm{R}} + \frac{h_\mu}{\Lambda}\left(\Phi_e\times L\right)_{\mathbf{1}'}\,H_d\,\mu_{\mathrm{R}} + \frac{h_\tau}{\Lambda}\left(\Phi_e\times L\right)_{\mathbf{1}''}\,H_d\,\tau_{\mathrm{R}}$$



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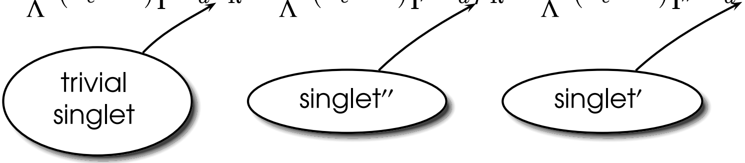

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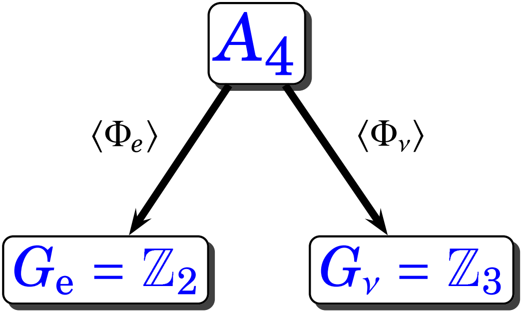

☞ A_4 symmetry broken by VEVs of flavons

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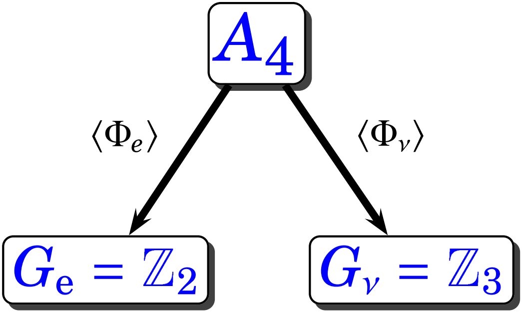

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➥ Tri–bi–maximal mixing (TBM)

Structure lepton masses

Altarelli and Feruglio (2005)

- After inserting the flavon VEVs

$$\mathscr{W}_\nu = \left(L_e H_u, L_\mu H_u, L_\tau H_u\right) \begin{pmatrix} a+2d & -d & -d \\ -d & 2d & a-d \\ -d & a-d & 2d \end{pmatrix} \begin{pmatrix} L_e H_u \\ L_\mu H_u \\ L_\tau H_u \end{pmatrix}$$

$$a = 2\lambda_1 \lambda_2 \frac{w}{\Lambda} \frac{1}{\Lambda_\nu}$$

$$d = \frac{\lambda_1}{3} \frac{v}{\Lambda} \frac{1}{\Lambda_\nu}$$

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$$\mathcal{W}_e = (L_e, L_\mu, L_\tau) \begin{pmatrix} y_e & 0 & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{pmatrix} \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix} H_d$$

$$y_{e,\mu,\tau} = h_{e,\mu,\tau}\, v' / \Lambda$$

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☞ After inserting the electroweak VEVs

$$\mathscr{W}_\nu \xrightarrow{H_u \to (0, v_u)^T} \frac{v_u^2}{2} (\nu_e, \nu_\mu, \nu_\tau) \begin{pmatrix} a+2d & -d & -d \\ -d & 2d & a-d \\ -d & a-d & 2d \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Tri–bi–maximal mixing (TBM)

Harrison et al. (2002)

- ☞ Structure of neutrino masses (in the basis in which the charged lepton masses are diagonal)

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? Conceptual question: how predictive are such models?

Kähler corrections

e.g. Leurer et al. (1994)

- Superpotential: holomorphic, e.g.

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$$\begin{aligned}
\mathscr{W}_\nu &= \frac{1}{2}\left(L'\cdot H_u\right)^T \kappa_\nu\, L'\cdot H_u \\
&\simeq \frac{1}{2}\left[\left(\mathbb{1} + x\,P\right)\,L\cdot H_u\right]^T \kappa_\nu\, \left[\left(\mathbb{1} + x\,P\right)\,L\cdot H_u\right] \\
&\simeq \frac{1}{2}\left(L\cdot H_u\right)^T \kappa_\nu\, L\cdot H_u + x\,\left(L\cdot H_u\right)^T \left(P^T\kappa_\nu + \kappa_\nu P\right)\,L\cdot H_u
\end{aligned}$$

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➥ Differential equation

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Kähler vs. RG corrections

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cf. Antusch et al. (2003)

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- However, size of Kähler corrections can be substantially larger (no loop suppression)

Back to the A_4 example

☞ Kähler potential may contain

$$\Delta K_{\Phi}^{\text{linear}} \supset \sum_{i=1}^{2} \frac{1}{\Lambda} \kappa_{\Phi,\text{linear}}^{(i)} L^{\dagger} \left(L\Phi\right)_{\mathbf{3}_i} + \text{h.c.}$$

one of the triplet flavons

triplet contractions from

$$\mathbf{3} \times \mathbf{3} = \mathbf{1} + \mathbf{1}' + \mathbf{1}'' + \mathbf{3}_1 + \mathbf{3}_2$$

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- However, such terms may be forbidden by additional symmetries

A_4 example continued

☞ 'Quadratic' Kähler corrections

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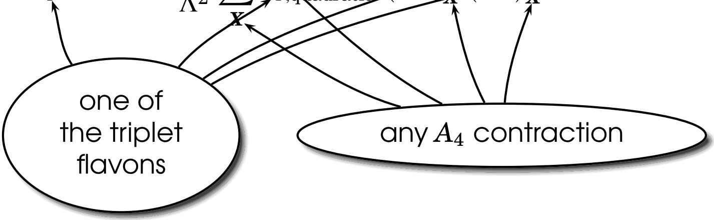

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➥ Kähler corrections when flavon fields attain their VEVs

- Additional parameters $\kappa_{\Phi}^{\boldsymbol{X}}$ reduce the predictivity of the scheme

Linear independent flavon corrections

☞ From $\langle \Phi_e \rangle$

$$P_{\mathrm{I}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} , \quad P_{\mathrm{II}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$P_{\mathrm{III}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

☞ From $\langle \Phi_\nu \rangle$

$$P_{\mathrm{IV}} = \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix} , \quad P_{\mathrm{V}} = \begin{pmatrix} 0 & \mathrm{i} & -\mathrm{i} \\ -\mathrm{i} & 0 & \mathrm{i} \\ \mathrm{i} & -\mathrm{i} & 0 \end{pmatrix}$$

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- Consider change induced by P_{V} correction

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- The analytic formula evaluated at tri–bi–maximal mixing reads ($m_e \ll m_\mu \ll m_\tau$)

$$\Delta\theta_{13} = \kappa_{\mathrm{V}} \cdot \frac{v^2}{\Lambda^2} \cdot 3\sqrt{\frac{3}{2}}\left(\frac{2m_1}{m_1+m_3} + \frac{m_e^2}{m_\mu^2 - m_e^2} + \frac{m_e^2}{m_\tau^2 - m_e^2}\right)$$

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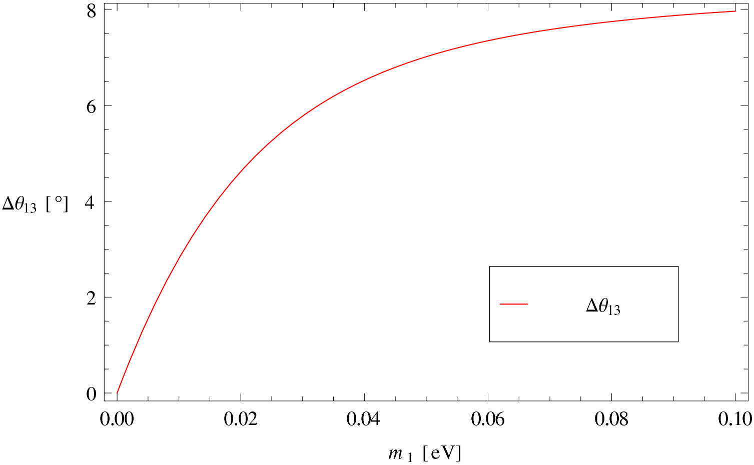
- Complex P matrix $\curvearrowright$ $\not{CP}$ is induced: $\delta \approx \pi/2$

Change of θ_{13}

☞ $\Delta\theta_{13}$ for Kähler coefficient $\kappa_V = 1$, $v/\Lambda = 0.2$



For comparison: change of θ_{12}

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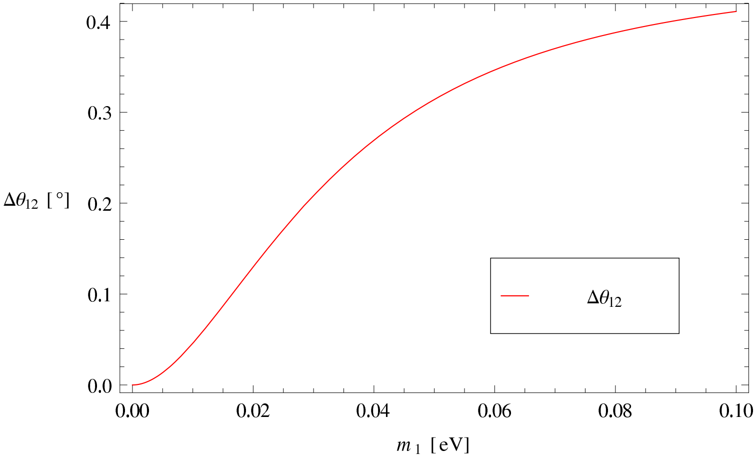
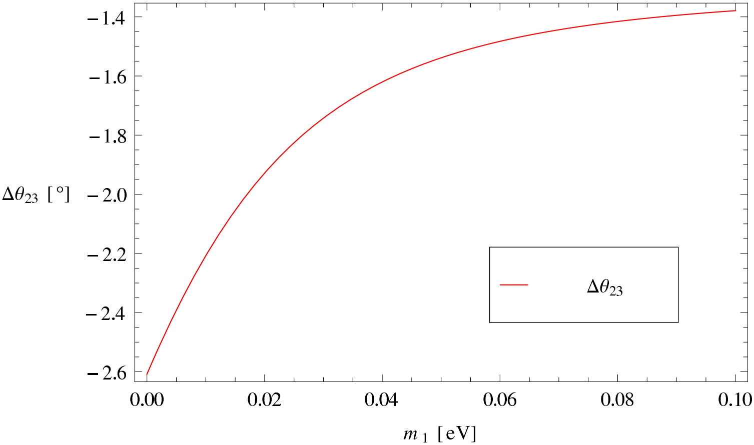


For comparison: change of θ_{23}

☞ $\Delta\theta_{23}$ for Kähler coefficient $\kappa_V = 1$, $v/\Lambda = 0.2$



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- However, such corrections are loop–suppressed

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- Example: realistic θ_{13} from tri–bi–maximal mixing scheme

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- In certain schemes (such as string compactifications) one may compute the coefficients of the higher order terms in the Kähler potential
- More effort both on theoretical and experimental side required to attack the **flavor problem**

Thank you very much!

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