The Basis Invariant Flavor Puzzle

Andreas Trautner

based on:

arXiv:2308.00019 with Miguel P. **Bento** and João P. **Silva**

arXiv:1812.02614 JHEP 1905 (2019) 208

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1920

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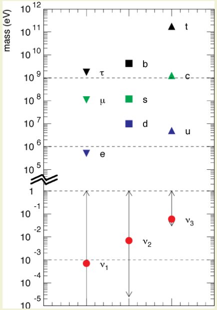
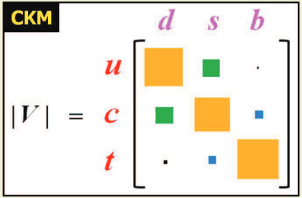
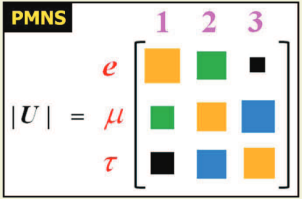
The Standard Model Flavor Puzzle

- **Why** *three* generations of matter Fermions?
- **Why** *hierarchical* masses of Fermions?
- **Why** *small* transition probabilities for $q_i^{\rm up} \to q_{j\neq i}^{\rm down}$? $\left(\propto |V_{ij}^{\rm CKM}|^2\right)$
- **Why** *large* transition probabilities for $\ell_i \to \nu_j$? $\left(\propto |U_{ij}^{\rm PMNS}|^2\right)$







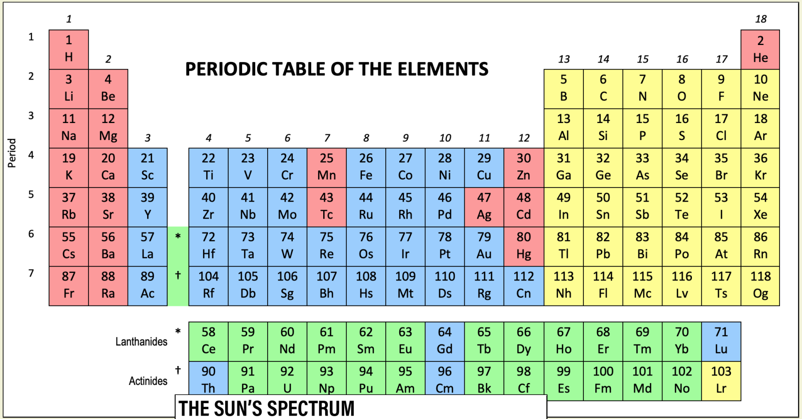
- **Why** CP violation *only* in combination with *flavor violation*?

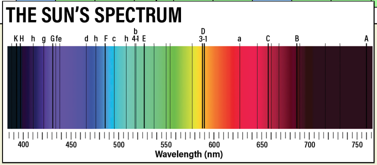
Parametrization independent measure of CP violation:

[Greenberg '85, Jarlskog '85]

$$J_{33} \;=\; \det\left[M_u\, M_u^\dagger, M_d\, M_d^\dagger\right] \;\propto\; \boldsymbol{Im}\left[V_{ud}^* V_{cs}^* V_{us} V_{cd}\right] \;=\; 3.08^{+0.15}_{-0.13} \times 10^{-5}\;.$$

The Standard Model Flavor Puzzle





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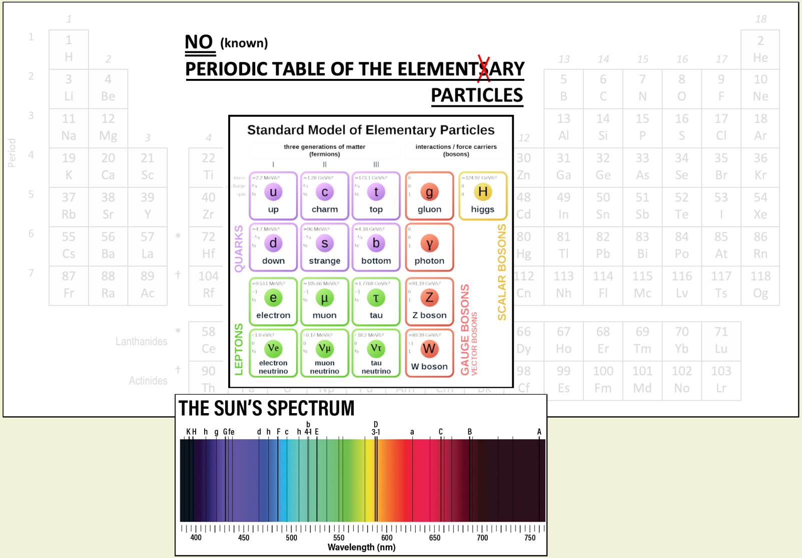

Why use Basis Invariants (BIs)?

- Physical observables <u>must</u> be given as function of BIs.
- Flavor puzzle is *plagued* by ***unphysical*** choice of basis and parametrization.
- BI necessary and sufficient conditions for **CPV** in SM. . . . [Greenberg '85; Jarlskog '85]

  . . . and BSM: Multi-scalar 2/3/NHDM, 4th gen., Dirac vs. Majorana ν's, . . .

  [Bernabeau et al. '86], [Branco, Lavoura, Rebelo '86], [Botella, Silva '95], [Davidson, Haber '05], [Yu, Zhou '21],. . .
- BIs and their relations, incl. CP-even BIs, allow to detect symmetries in general.

  [Ivanov, Nishi, Silva, AT '19], [de Meideiros Varzielas, Ivanov '19], [Bento, Boto, Silva, AT '20]
- BI formulation simplifies RGE's, RGE running, and derivation of RGE invariants.

  [Harrison, Krishnan, Scott '10], [Feldmann, Mannel, Schwertfeger '15], [Chiu, Kuo '15], [Bednyakov '18], [Wang, Yu, Zhou '21], . . .

No quantitative BI analysis of the flavor puzzle exist.

$\curvearrowright$ This allows an entirely new perspective on the flavor puzzle!

Why hasn't it been done? Technically challenging:

How to construct BI's? **When** to stop?

general answers and technique based on example of 2HDM [AT '18]

Outline

- Motivation

I will focus entirely on the quark sector here!

- Standard Model quark sector **flavor <u>co</u>variants**
- Construction of the **complete ring** of quark sector *orthogonal* **basis <u>in</u>variants**
- Determine the invariants from experimental data

⇒ This gives an entirely basis invariant picture of the quark flavor puzzle.

- CP transformation of invariants & comments

Standard Model Quark Sector Flavor **Covariants**

$$-\mathcal{L}_{\text{Yuk.}} = \overline{Q}_{\text{L}}\,\widetilde{H}\,\boldsymbol{Y_u}\,u_{\text{R}} + \overline{Q}_{\text{L}}\,H\,\boldsymbol{Y_d}\,d_{\text{R}} + \text{h.c.}\,,$$

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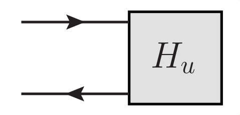
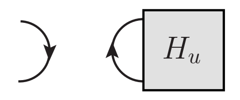
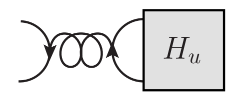
$$\overline{\mathbf{3}} \otimes \mathbf{3} = \mathbf{1} \oplus \mathbf{8}\,.$$



$= \dfrac{1}{N}$

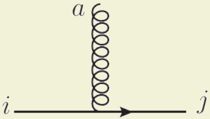


$+ \dfrac{1}{T_{\boldsymbol{r}}}$



.

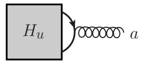
$(t^a)^i_{\ j} =$



$$(H_u)_{\mathbf{1}} = \mathrm{Tr}\,H_u$$

$$(H_u)_{\mathbf{8}} = H_u - \mathbb{1}\,\mathrm{Tr}\,\frac{H_u}{3}$$

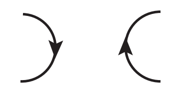
$\boldsymbol{u}^a = \mathrm{Tr}\left[t^a H_u\right] =$



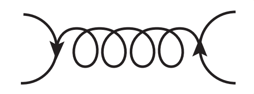
Orthogonal Covariant Projection Operators

What does orthogonal mean here?

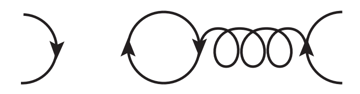
Orthogonality on the level of **projection operators**!



$P_{(\mathbf{1})}$



$P_{(\mathbf{8})}$


.

$P_{(\mathbf{1})} \cdot P_{(\mathbf{8})} = 0 \quad (\propto \operatorname{Tr} t^a)$

Projection operators: $P_i^2 = P_i, \quad \operatorname{Tr} P_i = \dim(\boldsymbol{r}_i)$,

Orthogonality: $P_i \cdot P_j = 0$.

Using orthogonal **singlet** projectors we find invariants that are ortogonal to each other!

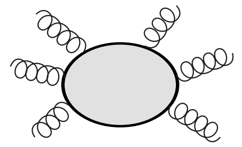
What is necessary to construct **Basis Invariants**

$$\mathbf{8}_u \otimes \mathbf{8}_u \otimes \ldots \mathbf{8}_d \otimes \mathbf{8}_d \otimes \cdots = \mathbf{8}_u^{\otimes k} \otimes \mathbf{8}_d^{\otimes \ell} = \sum_{\oplus} \boldsymbol{r}_i$$

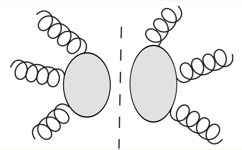
Singlet projection operators:

$$\mathbf{8}_u^{\otimes k} \otimes \mathbf{8}_d^{\otimes \ell} \supset \mathbf{1}_{(1)} \oplus \mathbf{1}_{(2)} \oplus \ldots$$

Singlet projection operators are characterized by ***factorization***. For example:



$$\mathbf{8}^{\otimes 3} \to \mathbf{8}^{\otimes 3}$$



$$\Leftrightarrow \quad \mathbf{8}^{\otimes 3} \supset \mathbf{1}$$

How many ***independent*** singlets exist? (here: in contractions $\mathbf{8}_u^{\otimes k} \otimes \mathbf{8}_d^{\otimes \ell}$ **for all** k, ℓ)

Jargon of invariant theory

- *Algebraic* **(in-)dependence:**

  Invariants $\mathcal{I}_1, \mathcal{I}_2, \mathcal{I}_3, \dots$ are ***algebraically dependent*** if and only if

$$\exists \quad \text{Polynomial}\,(\mathcal{I}_1, \mathcal{I}_2, \mathcal{I}_3, \dots) = 0\ .$$

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- ***Generating set*** of invariants $\equiv$ all **primary + *<u>secondary</u>*** invariants.

  Secondary invariants: all $\mathcal{I}$'s that *cannot* be written as polynomial of other invariants,

  $$\mathcal{I}_i \neq \text{Polynomial}\left(\mathcal{I}_j, \ldots\right) \; .$$

  $\Rightarrow$ *All* invariants can be written as a polynomial in the ***generating set*** of invariants,

  $$\mathcal{I} = \text{Polynomial}\left(\mathcal{I}_1, \mathcal{I}_2, \ldots\right) \; .$$

Number and structure of invariants

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- **How to find their structure in terms of covariants?**

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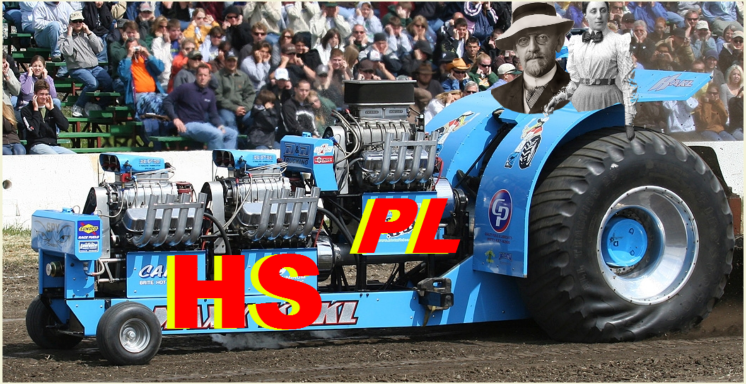

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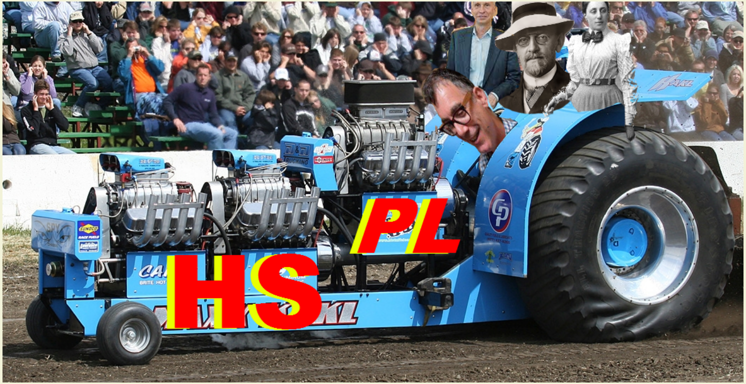

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- HS/PL input: covariants are $\mathbf{8}_u$ and $\mathbf{8}_d$ of $\mathrm{SU}(3)$.

↷ HS/PL output: [Jenkins & Manohar '09]

  - # of primary invariants and their sub-structure (covariant content):

$$\begin{array}{llll} (\boldsymbol{u}) & (\boldsymbol{d}) & & \\ \boldsymbol{u}^2 & \boldsymbol{d}^2 & \boldsymbol{ud} & \\ \boldsymbol{u}^3 & \boldsymbol{d}^3 & \boldsymbol{u}^2\boldsymbol{d} & \boldsymbol{ud}^2 \\ \boldsymbol{u}^2\boldsymbol{d}^2 & & & \end{array}$$

(10 primary invariants $\widehat{=}$ 10 physical parameters).

  - 1 secondary invariant of structure: $\boldsymbol{u}^3\boldsymbol{d}^3$.
  - Relation (***Syzygy***) of order $\boldsymbol{u}^6\boldsymbol{d}^6$ between primaries and the secondary.

Projection operators

Note: The HS/PL does **not** tell us ***how*** to construct the invariants or the relations.

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For this we use ***orthogonal projection operators***. (here in adjoint space of $\mathrm{SU}(3)_{Q_\mathrm{L}}$)

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- $\mathbf{8}^{\otimes 2} \to \mathbf{1}$

$\delta^{ab} =$  .

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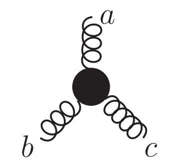
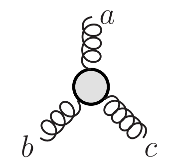
- $\mathbf{8}^{\otimes 3} \rightarrow \mathbf{1}$



$= \mathrm{i}\, f^{abc}$ and



$= d^{abc}$.

$$f^{abc} = \frac{1}{\mathrm{i}\, T_r} \operatorname{Tr}\left(\left[t^a, t^b\right] t^c\right) \qquad d^{abc} = \frac{1}{T_r} \operatorname{Tr}\left(\left\{t^a, t^b\right\} t^c\right)$$

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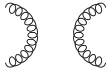
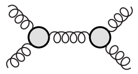
- $\mathbf{8}^{\otimes 4} \to \mathbf{1}$

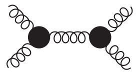
$\mathbf{1}$:



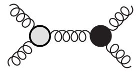
$\mathbf{8}_\mathrm{S}$:



$\mathbf{8}_\mathrm{A}$:



$\mathbf{8}_{\mathrm{A}\to\mathrm{S}}$:



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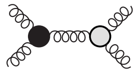

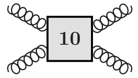

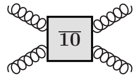

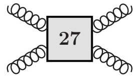

.

Can understand the different contraction channels from

$$\mathbf{8}^{\otimes 2} = \mathbf{1} \oplus \mathbf{8}_\mathrm{S} \oplus \mathbf{8}_\mathrm{A} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27}\ .$$

Projection operators

Note: The HS/PL does **not** tell us ***how*** to construct the invariants or the relations.

For this we use ***orthogonal projection operators***. (here in adjoint space of $\mathrm{SU}(3)_{Q_\mathrm{L}}$)

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Those can be constructed via ***birdtrack*** diagrams [Cvitanovic '76 '08, Keppeler and Sjödahl '13]

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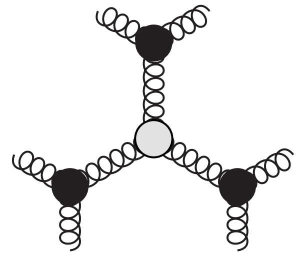
- $\mathbf{8}^{\otimes 3} \to \mathbf{1}$
- $\mathbf{8}^{\otimes 4} \to \mathbf{1}$
- $\mathbf{8}^{\otimes 6} \to \mathbf{1}$

many operators exist in $\mathbf{8}^{\otimes 6} \to \mathbf{1}$, we only need one:



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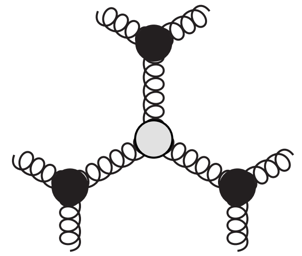
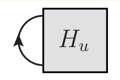
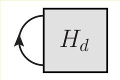


All of these operators are **orthogonal** to each other.
We now use them to construct the orthogonal invariants.

Orthogonal Invariants

The 10 algebraically independent and orthogonal invariants are given by:

$I_{10} \propto$ 

and $I_{01} \propto$ 

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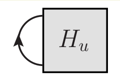
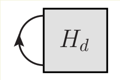
$I_{10} \propto$ 

and $I_{01} \propto$ 

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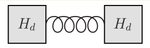
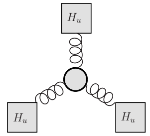
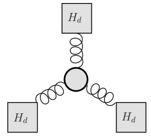
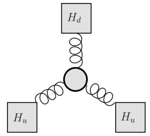
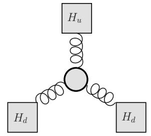
$I_{02} \propto$ 

$I_{11} \propto$ 

$I_{30} \propto$ 

$I_{03} \propto$ 

$I_{21} \propto$ 

$I_{12} \propto$ 

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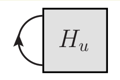
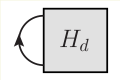
$I_{10} \propto$ 

and $I_{01} \propto$ 

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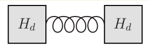
$I_{02} \propto$ 

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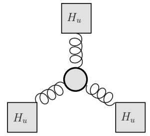
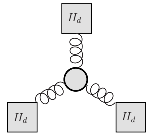
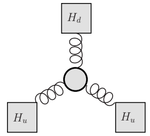
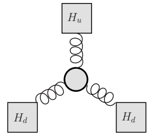
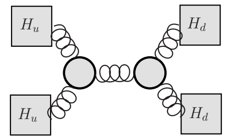
$I_{30} \propto$ 

$I_{03} \propto$ 

$I_{21} \propto$ 

$I_{12} \propto$ 

$I_{22} \propto$ 

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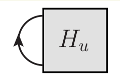
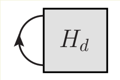
$I_{10} \propto$ 

and $I_{01} \propto$ 

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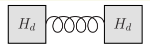
$I_{02} \propto$ 

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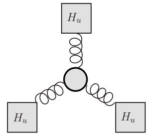
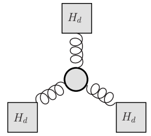
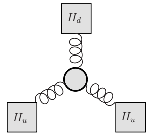
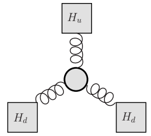
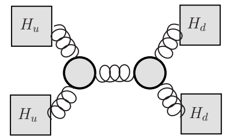
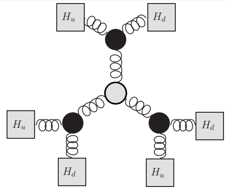
$I_{30} \propto$ 

$I_{03} \propto$ 

$I_{21} \propto$ 

$I_{12} \propto$ 

$I_{22} \propto$ 

Secondary invariant: $J_{33} \propto$ 

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The 10 algebraically independent and orthogonal invariants are given by:

$$I_{10} := \mathrm{Tr}\, \widetilde{H}_u \qquad \text{and} \qquad I_{01} := \mathrm{Tr}\, \widetilde{H}_d \;.$$

$$I_{20} := \mathrm{Tr}(H_u^2)\,, \quad I_{02} := \mathrm{Tr}(H_d^2)\,, \quad I_{11} := \mathrm{Tr}(H_u H_d)\,,$$

$$I_{30} := \mathrm{Tr}(H_u^3)\,, \quad I_{03} := \mathrm{Tr}(H_d^3)\,, \quad I_{21} := \mathrm{Tr}(H_u^2 H_d)\,, \quad I_{12} := \mathrm{Tr}(H_u H_d^2)\,,$$

$$I_{22} := 3\,\mathrm{Tr}(H_u^2 H_d^2) - \mathrm{Tr}(H_u^2)\,\mathrm{Tr}(H_d^2)\,.$$

Secondary invariant: exactly the Jarlskog invariant,

$$J_{33} := \mathrm{Tr}(H_u^2 H_d^2 H_u H_d) - \mathrm{Tr}(H_d^2 H_u^2 H_d H_u) \equiv \frac{1}{3}\,\mathrm{Tr}\,[H_u, H_d]^3 \;.$$

Note: Here $\widetilde{H}_u \equiv Y_u Y_u^\dagger$, $\widetilde{H}_d \equiv Y_d Y_d^\dagger$, and $H_{u,d} \equiv \widetilde{H}_{u,d} - \mathbb{1}\,\mathrm{Tr}\frac{\widetilde{H}_{u,d}}{3}$. **"Traces of traceless matrices"**

The Syzygy

With our orthogonal invariants, the syzygy is given by

$$
\begin{aligned}
(J_{33})^2 = &- \frac{4}{27} I_{22}^3 + \frac{1}{9} I_{22}^2 I_{11}^2 + \frac{1}{9} I_{22}^2 I_{02} I_{20} + \frac{2}{3} I_{22} I_{30} I_{03} I_{11} - \frac{2}{3} I_{22} I_{21} I_{12} I_{11} - \frac{1}{9} I_{22} I_{11}^2 I_{20} I_{02} \\
&+ \frac{2}{3} I_{22} I_{21}^2 I_{02} + \frac{2}{3} I_{22} I_{12}^2 I_{20} - \frac{2}{3} I_{22} I_{30} I_{12} I_{02} - \frac{2}{3} I_{22} I_{03} I_{21} I_{20} \\
&- \frac{1}{3} I_{30}^2 I_{03}^2 + I_{21}^2 I_{12}^2 + 2 I_{30} I_{03} I_{21} I_{12} - \frac{4}{9} I_{30} I_{03} I_{11}^3 \\
&+ \frac{1}{18} I_{30}^2 I_{02}^3 + \frac{1}{18} I_{03}^2 I_{20}^3 - \frac{4}{3} I_{30} I_{12}^2 - \frac{4}{3} I_{03} I_{21}^2 \\
&- \frac{1}{3} I_{30} I_{21} I_{11} I_{02}^2 - \frac{1}{3} I_{03} I_{12} I_{11} I_{20}^2 + \frac{2}{3} I_{30} I_{12} I_{11}^2 I_{02} + \frac{2}{3} I_{03} I_{21} I_{11}^2 I_{20} \\
&- \frac{2}{3} I_{21} I_{12} I_{20} I_{02} I_{11} - \frac{1}{108} I_{20}^3 I_{02}^3 + \frac{1}{36} I_{20}^2 I_{02}^2 I_{11}^2 + \frac{1}{6} I_{21}^2 I_{20} I_{02}^2 + \frac{1}{6} I_{12}^2 I_{02} I_{20}^2 \ .
\end{aligned}
$$

This is the **shortest relation ever** expressed for the SM quark flavor ring and has 27 terms.

(this should be compared to result of [Jenkins&Manohar'09] with 241 terms using non-orthogonal invariants).

Measuring the Invariants

In order to evaluate the invariants, one can use *any* parametrization. We use PDG:

$$\widetilde{H}_u = \mathrm{diag}(\, y_u^2 \,,\, y_c^2 \,,\, y_t^2 \,)$$

and

$$\widetilde{H}_d = V_{\mathrm{CKM}}\, \mathrm{diag}(\, y_d^2 \,,\, y_s^2 \,,\, y_b^2 \,)\, V_{\mathrm{CKM}}^\dagger \,,$$

1. **Explore the *possible* parameter space**: scan $\mathcal{O}(10^7)$ uniform random points
   - $s_{12}, s_{13}, s_{23} \in [-1, 1]$ and $\delta \in [-\pi, \pi]$ together with:

   A) Linear measure: $y_{u,c} \in [0,1] y_t$, $y_{d,s} \in [0,1] y_b$.

   B) Log measure: $(m_{u,c}/\mathrm{MeV}) \in 10^{[-1, \log(m_t/\mathrm{MeV})]}$, $(m_{d,s}/\mathrm{MeV}) \in 10^{[-1, \log(m_b/\mathrm{MeV})]}$.

2. **"Measure" the parameter point realized in Nature.**

We use PDG data and errors and evaluate at the EW scale $\mu = M_Z$. see e.g. [Huang, Zhou '21]

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For convenience of the presentation we normalize the invariants as

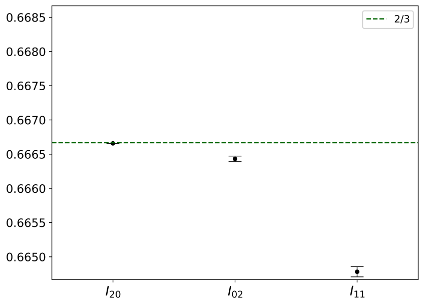
$$\hat{I}_{ij} := \frac{I_{ij}}{\left(y_t^2\right)^i \left(y_b^2\right)^j}\,.$$

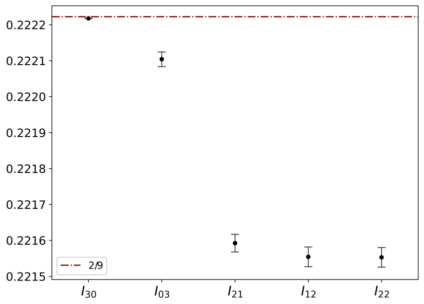
Experimental values

$$\hat{I}_{11} \approx \hat{I}_{20} \approx \hat{I}_{02} \approx \frac{2}{3}\,,$$

$$\hat{I}_{30} \approx \hat{I}_{03} \approx \hat{I}_{21} \approx \hat{I}_{12} \approx \hat{I}_{22} \approx \frac{2}{9}\,.$$

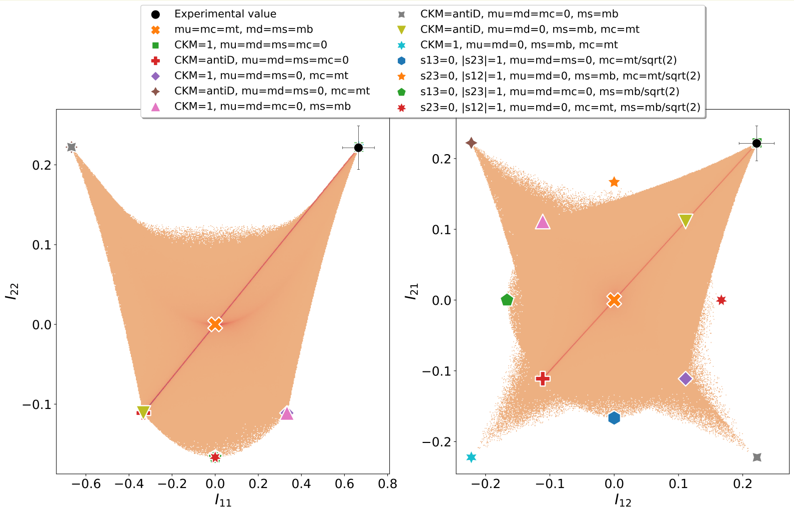
$$\left(\hat{I}_{ij} := \frac{I_{ij}}{\left(y_t^2\right)^i \left(y_b^2\right)^j}\,. \right)$$





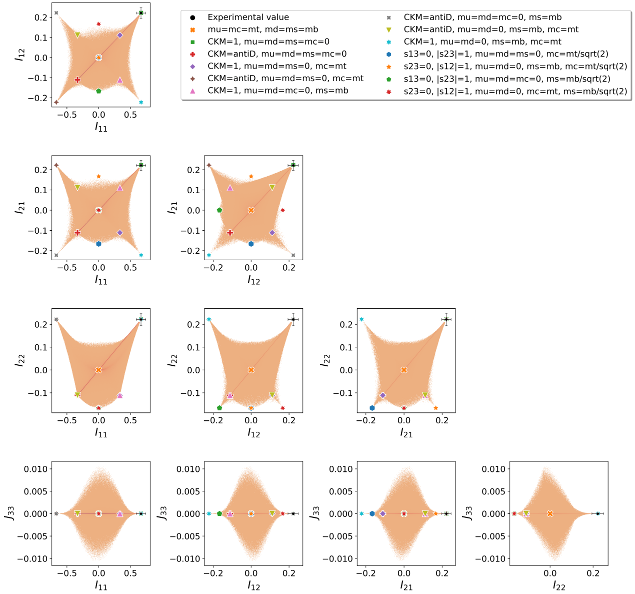
- Deviations from maximal values are significant.
- Deviations from each other, e.g. $\hat{I}_{21} - \hat{I}_{12} \neq 0$ and $\hat{I}_{12} - \hat{I}_{22} \neq 0$, are significant.

Parameter space and experimental values



Error bars: $1\sigma \times 1000$

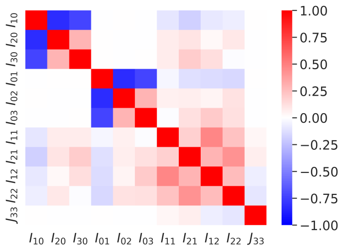
Parameter space and experimental values



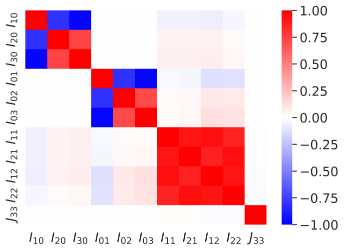
Results and empirics

- Observed primary invariants are *very close to* maximal – with small but significant deviations.
- Explaining the value of the invariants and their misalignment from maximal point amounts to solving the flavor puzzle in the language of invariants.
- Exact maximization would correspond to $\mathrm{SU}(2)_{Q_\mathrm{L}}$ flavor symmetry.
- Small deviations from max. correspond to 1/2nd gen. masses and mixings.
- The invariants are ***strongly correlated*** (for the observed hierarchical parameters).

linear scan:



log scan:



This is **not** true for anarchical parameters, or points with increased symmetry.

Comments

- I_{01}, I_{02}, I_{03}, I_{10}, I_{20}, I_{30} correspond to masses.
- CP-even I_{11}, I_{21}, I_{12}, I_{22} correspond to mixings.
- CPV requires interplay of 8 CP-even primary invariants (all besides the "trivial" invariants I_{10}, I_{01}).
- Non-trivial $\hat{I}_{ij}$'s being close to maximal forces the Jarlskog invariant to be ***small***.
- **Any** explanation of the flavor structure will have to explain the value of the invariants.
- Any reduction of # of parameters corresponds to relation between invariants.
- **All** flavor observables can be expressed as

$$\mathcal{O}_{\text{flavor}} = \text{Polynomial}_1(I_{ij}) + J_{33} \times \text{Polynomial}_2(I_{ij})\,.$$

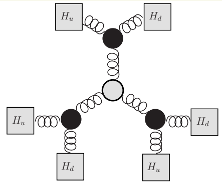
This is guaranteed since our primary and secondary invariants form a "Hironaka decomposition" of this ring.

CP transformation of covariants and invariants

CP is trafo under $\mathrm{Out}\,(\mathrm{SU}(N)) = \mathbb{Z}_2$.
Covariants:

$$\boldsymbol{u}^a \;\mapsto\; -\,R^{ab}\,\boldsymbol{u}^b\,,$$
$$\boldsymbol{d}^a \;\mapsto\; -\,R^{ab}\,\boldsymbol{d}^b\,,$$

$\Rightarrow$ Only CP-odd in SM: $J_{33} \propto$

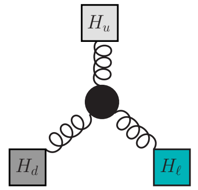


$\mathrm{SU}(3)$ tensors (projection ops.):

$$f^{abc} \;\mapsto\; R^{aa'}\,R^{bb'}\,R^{cc'}\,f^{a'b'c'} \;=\; f^{abc}\,,$$
$$d^{abc} \;\mapsto\; R^{aa'}\,R^{bb'}\,R^{cc'}\,d^{a'b'c'} \;=\; -\,d^{abc}\,.$$

$R = \mathrm{diag}(-1,+1,-1,-1,+1,-1,+1,-1)$ (GM basis).

BSM: CPV at order 3 ?



$$\mathrm{i}f^{abc}\;\mathrm{Tr}[t^a\,H_u]\,\mathrm{Tr}[t^b\,H_d]\,\mathrm{Tr}[t^c\,\boldsymbol{H_\ell}]$$

CP trafo of invariants is easily read-off:

Invariants are **CP even** / **CP odd** iff their projection operator contains and **even** / **odd # of f tensors**.

Outlook

- Ambiguity in choice of I_{22} needs to be clarified. Contributions to different contraction channels could be very relevant to decipher flavor puzzle.
- Relative alignments of 8-plet covariants are in 1:1 relation with invariant relations.
  see other examples [Merle, Zwicky '12], [Bento, Boto, Silva, AT '20]
- Maximization and strong correlation of invariants could point to possible **information theoretic** argument to set parameters!
  see e.g. [Carena, Low, Wagner, Xiao '23] and talk by **Carena**.
- Extension to lepton sector with **orthogonal** invariants.
  for HS/PL and non-orthogonal invariants see [Hanany, Jenkins, Manhoar, Torri '10], [Wang, Yu, Zhou '21], [Yu, Zhou '21].
- Our invariants provide easy targets for fits of any BSM model to SM flavor structure.
- Our procedure is *completely general*, can be applied to all BSM scenarios.

Conclusion

- We have for the first time obtained a quantitative analysis of the flavor puzzle in terms of basis invariants.
- This uncovers an entirely new angle on the flavor puzzle that must (and will) be explored in the future.
- The (quark) flavor puzzle in invariants amounts to explaining:
  - **Why** are the invariants very close to maximal?
  - **What** explains their tiny deviations from the maximal values?
  - **Why** are the (*orthogonal, a priori independent*) invariants so strongly correlated?
- **Any** explanation of the flavor structure will have to answer these questions.

This is just the beginning of an entirely new exploration of the flavor puzzle.

Thank You!

Backup slides

General Procedure / Algorithm

for the construction of basis invariants.

Three steps:

1. Construction of *basis covariant* objects: “building blocks”.
   - Determine CP transformation behavior of the building blocks.
2. Derive Hilbert series & Plethystic logarithm.
   - $\Rightarrow$ # and order of primary invariants.
   - $\Rightarrow$ # and structure of generating set of invariants.
   - $\Rightarrow$ interrelations between invariants ($\equiv$ syzygies).
3. Construct all invariants and interrelations explicitly.

Application here:
Characterize SM flavor sector invariants.

Hilbert Series and Plethystic Logarithm

Covariant building blocks as **input** for the ring:

$$\mathbf{8}_u \;\widehat{=}\; u\,, \quad \mathbf{8}_d \;\widehat{=}\; d.$$

From input, compute Hilbert series (HS) and Plethystic logarithm (PL):

$$\mathfrak{H}(u,d) = \int_{\mathrm{SU}(3)} d\mu_{\mathrm{SU}(3)}\, \mathrm{PE}\left[z_1, z_2; u; \mathbf{8}\right] \mathrm{PE}\left[z_1, z_2; d; \mathbf{8}\right]\,,$$

$$\mathrm{PL}\left[\mathfrak{H}\left(u,d\right)\right] := \sum_{k=1}^{\infty} \frac{\mu(k)\,\ln \mathfrak{H}\left(u^k, d^k\right)}{k}\,.$$

introduced in math: [Getzler, Kapranov '94], physics [Benvenuti, Feng, Hanany, He '06]

$$\mathfrak{H}(u,d) = \frac{1 + u^3 d^3}{(1-u^2)(1-d^2)(1-ud)(1-u^3)(1-d^3)(1-ud^2)(1-u^2d)(1-u^2d^2)}\,.$$

$$\mathrm{PL}\left[\mathfrak{H}(u,d)\right] = u^2 + ud + d^2 + u^3 + d^3 + u^2 d + ud^2 + u^2d^2 + u^3d^3 - u^6d^6\,.$$

CKM in PDG parametrization

$V_{\mathrm{CKM}} := V_{u,\mathrm{L}}^{\dagger} V_{d,\mathrm{L}}$ is the Cabibbo-Kobayashi-Maskawa (CKM) matrix. In PDG parametrization

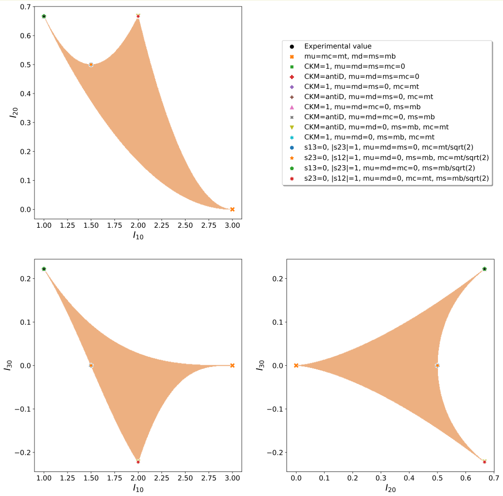
$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-\mathrm{i}\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{\mathrm{i}\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} ,$$

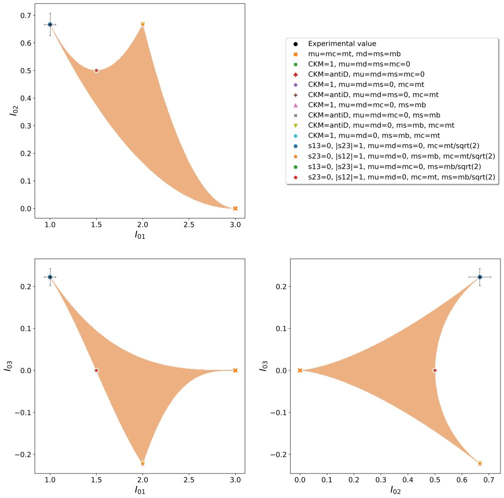
Experimental values of the invariants

Invariant	best fit and error	Normalized invariant	best fit and error
I_{10}	$0.9340(83)$	$\hat{I}_{10}$	$1.00001358(^{+85}_{-88})$
I_{01}	$2.660(49)\times 10^{-4}$	$\hat{I}_{01}$	$1.000351(^{+63}_{-71})$
I_{20}	$0.582(10)$	$\hat{I}_{20}$	$0.66665761(^{+59}_{-57})$
I_{02}	$4.71(17)\times 10^{-8}$	$\hat{I}_{02}$	$0.666432(^{+47}_{-42})$
I_{11}	$1.651(45)\times 10^{-4}$	$\hat{I}_{11}$	$0.664783(^{+91}_{-87})$
I_{30}	$0.1811(48)$	$\hat{I}_{30}$	$0.22221769(^{+29}_{-28})$
I_{03}	$4.18(23)\times 10^{-12}$	$\hat{I}_{03}$	$0.222105(^{+24}_{-21})$
I_{21}	$5.14(^{+18}_{-19})\times 10^{-5}$	$\hat{I}_{21}$	$0.221593(^{+30}_{-29})$
I_{12}	$1.463(^{+65}_{-68})\times 10^{-8}$	$\hat{I}_{12}$	$0.221555(^{+38}_{-36})$
I_{22}	$1.366(^{+73}_{-76})\times 10^{-8}$	$\hat{I}_{22}$	$0.221554(^{+38}_{-36})$
J_{33}	$4.47(^{+1.23}_{-1.58})\times 10^{-24}$	$\hat{J}_{33}$	$2.92(^{+0.74}_{-0.93})\times 10^{-13}$
J	$3.08(^{+0.16}_{-0.19})\times 10^{-5}$		

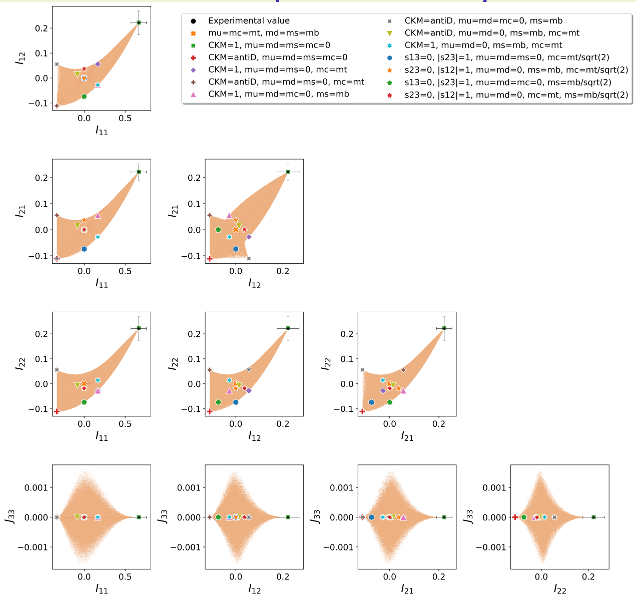
Tabelle: Experimental values of the quark sector basis invariants evaluated using PDG data. Uncertainties are 1σ. Left: orthogonal invariants at face value. Right: the same invariants normalized to the largest Yukawa couplings.

Correlation of “mass” invariants $I_{10}, I_{20}, I_{30}, I_{01}, I_{02}, I_{03}$





Parameter space and experimental values



Arguably even "more basis invariant" alternative choice of normalization:

$$\hat{I}_{ij}^{\text{alt}} := \frac{I_{ij}}{I_{10}^{i}\, I_{01}^{j}} \,.$$

RGE running of invariants

$$\mathcal{D} := 16\pi^2 \mu \frac{\mathrm{d}}{\mathrm{d}\mu} ,$$

$$a_\Delta := -8\, g_s^2 - \frac{9}{4} g^2 - \frac{17}{12} g'^2 ,$$

$$a_\Gamma := -8\, g_s^2 - \frac{9}{4} g^2 - \frac{5}{12} g'^2 ,$$

$$a_\Pi := -\frac{9}{4} g^2 - \frac{15}{4} g'^2 ,$$

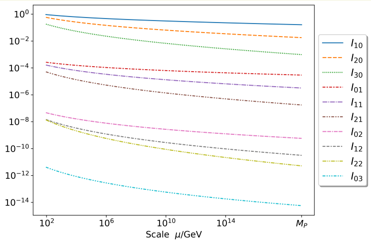
$$t_{udl} := 3\,\mathrm{Tr}\tilde{H}_u + 3\,\mathrm{Tr}\tilde{H}_d + \mathrm{Tr}\tilde{H}_\ell .$$

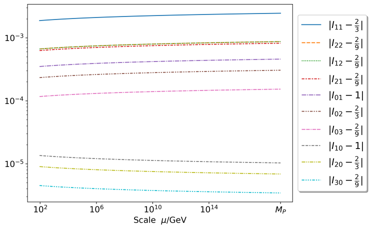
$$\mathcal{D}\tilde{H}_u = 2\,(a_\Delta + t_{udl})\; \tilde{H}_u + 3\,\tilde{H}_u^2 - \frac{3}{2}\left(\tilde{H}_d\tilde{H}_u + \tilde{H}_u\tilde{H}_d\right) ,$$

$$\mathcal{D}\tilde{H}_d = 2\,(a_\Gamma + t_{udl})\; \tilde{H}_d + 3\,\tilde{H}_d^2 - \frac{3}{2}\left(\tilde{H}_d\tilde{H}_u + \tilde{H}_u\tilde{H}_d\right) ,$$

$$\mathcal{D}\tilde{H}_\ell = 2\,(a_\Pi + t_{udl})\; \tilde{H}_\ell + 3\,\tilde{H}_\ell^2 ,$$

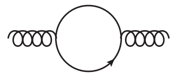
$$\mathcal{D}g_s = -7\, g_s^3 , \qquad \mathcal{D}g = -\frac{19}{6} g^3 , \qquad \mathcal{D}g' = \frac{41}{6} g'^3 .$$

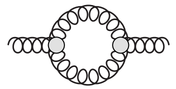


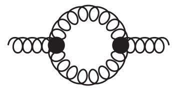


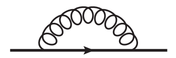
Birdtrack Identities

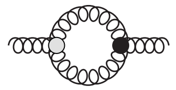
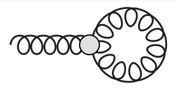
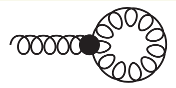
We mostly use the conventions of [Keppeler '17] with the following identities

 $= T_{\boldsymbol{r}}$  with $T_{\boldsymbol{r}}\delta^{ab} = \mathrm{Tr}[t^a t^b]$,

 $= C_D$  with $C_D = \dfrac{N^2-4}{N}$,

 $= C_A$  with $C_A = 2T_{\boldsymbol{r}}N$.

 $= C_F$  with $C_F = T_{\boldsymbol{r}}\dfrac{N^2-1}{N}$,

 $=$  $=$  $= 0$