The Basis Invariant Flavor Puzzle

Andreas Trautner

based on:

arXiv:2308.00019 JHEP 01 (2024) 024 w/ Miguel P. **Bento** and João P. **Silva**

arXiv:1812.02614 JHEP 05 (2019) 208

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Workshop on the Standard Model and Beyond

30.08.24

MAX-PLANCK-GESELLSCHAFT

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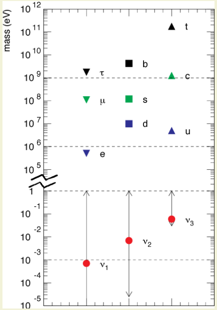
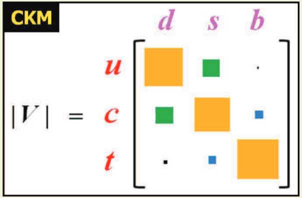
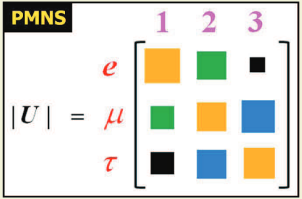
The Standard Model Flavor Puzzle

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







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

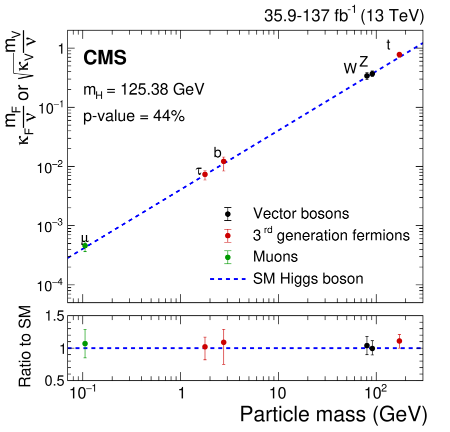
Parametrization independent measure of CP violation:

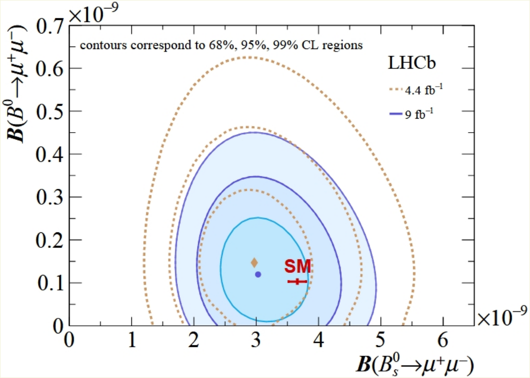
[Greenberg '85, Jarlskog '85]

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

The Standard Model Flavor Puzzle

Often underappreciated: Direct confirmation of SM FP at the LHC





And: No signs of physics beyond the Standard Model.

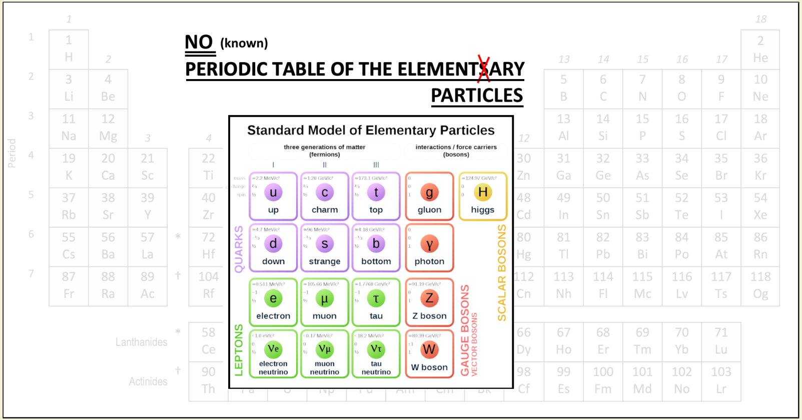
The Standard Model Flavor Puzzle

PERIODIC TABLE OF THE ELEMENTS

Period	1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc		22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y		40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	†	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

Lanthanides *	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides †	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

The Standard Model Flavor Puzzle



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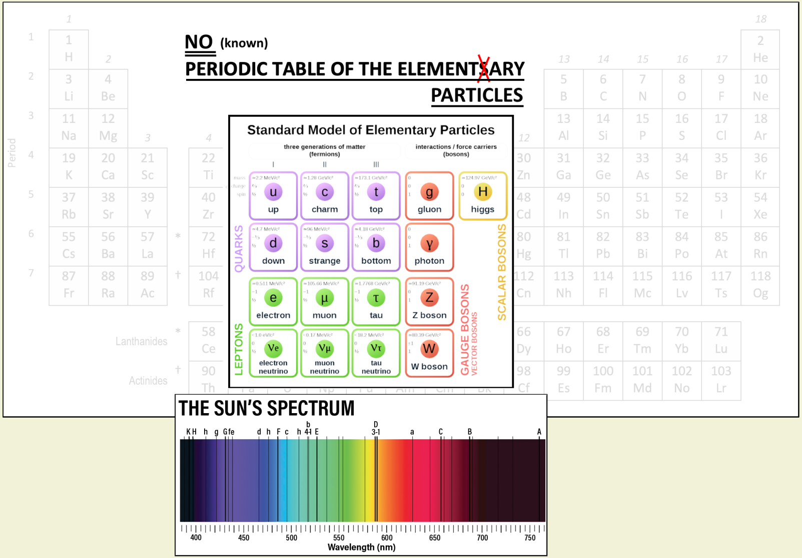


Why use Basis Invariants **(B.I.'s)**?

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

  . . . and BSM: Multi-scalar 2/3/NHDM, SM+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], . . .

The quantitative, basis invariant analysis opens a new perspective on the flavor puzzle!

Why hasn't it been done? Technically challenging:

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

Outline

- Motivation

  Disclaimer: I will focus entirely on the quark sector here.

- Standard Model quark sector **flavor co̲variants**
- Construction of the **complete ring** of *orthogonal* **basis in̲variants**
- Determine the basis invariants from experimental data

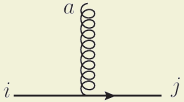
⇒ An entirely basis invariant picture of the quark flavor puzzle.

- CP transformation of invariants & comments

SM Quark Sector Flavor Invariants – Systematic Construction

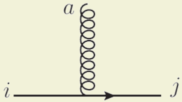
Birdtrack diagrams / "Colorflow" / ... / $\mathrm{SU}(N)$ tensors

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



$$\left[t^a, t^b\right] \;=\; \mathrm{i} f^{abc} t^c \,, \qquad \mathrm{Tr}\left(t^a\, t^b\right) \;=\; T_{\boldsymbol{r}}\, \delta^{ab}$$

Birdtrack diagrams / "Colorflow" / ... / $\mathrm{SU}(N)$ tensors

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

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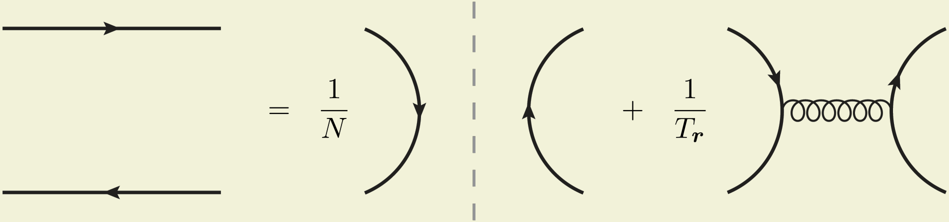
$$\overline{\boldsymbol{N}} \otimes \boldsymbol{N} = \boldsymbol{1} \oplus \boldsymbol{adj}$$

$$\delta^i_n \delta^j_m = \frac{1}{N}\, \delta^i_m \delta^j_n + \frac{1}{T_{\boldsymbol{r}}}\, (t^a)^i_{\ m}\, (t^a)^j_{\ n}$$



References for introduction to Birdtracks: [Cvitanovic Book '08, Keppeler and Sjödahl '13, Keppeler '17]

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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of $\mathrm{SU}(3)_{Q_\text{L}} \otimes \mathrm{SU}(3)_{u_\text{R}} \otimes \mathrm{SU}(3)_{d_\text{R}}$

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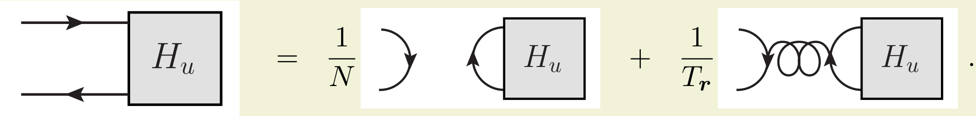
$$\overline{\mathbf{3}} \otimes \mathbf{3} \quad = \quad \mathbf{1} \quad \oplus \quad \mathbf{8}\,.$$



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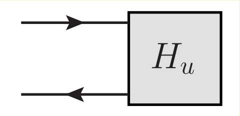
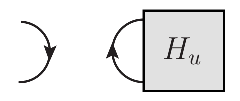
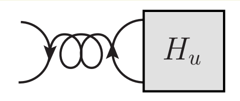


$= \frac{1}{N}$



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



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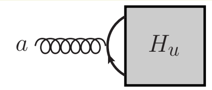
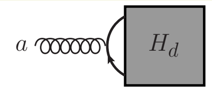
$\boldsymbol{u}^a = \mathrm{Tr}\left[t^a H_u\right] =$



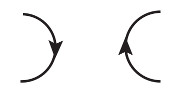
$\boldsymbol{d}^a = \mathrm{Tr}\left[t^a H_d\right] =$



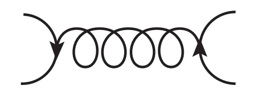
Orthogonal Covariant Projection Operators

What does orthogonal mean here?

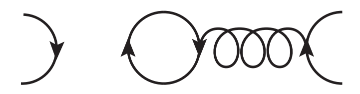
Orthogonality on the level of **projection operators**!



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



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



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

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

Orthogonality: $P_i \cdot P_j = 0$.

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

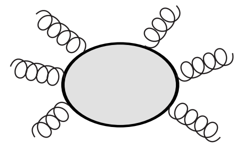
What is necessary to construct **Basis Invariants**

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

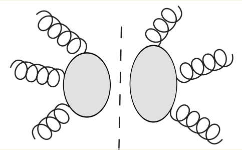
Singlet projection operators:

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

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)

Number and structure of invariants

- **How to find the number of primary / secondary invariants?**
- **How to find their structure in terms of covariants?**

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Answer: ***Hilbert series (HS)*** and ***Plethystic Logarithm (PL)***.

[Noether 1916; Getzler & Kapranov '94]

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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):

linear	$(\boldsymbol{u})$	$(\boldsymbol{d})$		
quadratic	$\boldsymbol{u}^2$	$\boldsymbol{d}^2$	$\boldsymbol{ud}$	
cubic	$\boldsymbol{u}^3$	$\boldsymbol{d}^3$	$\boldsymbol{u}^2\boldsymbol{d}$	$\boldsymbol{ud}^2$
quartic	$\boldsymbol{u}^2\boldsymbol{d}^2$			

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

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- 1 secondary invariant of structure: $\boldsymbol{u}^3\boldsymbol{d}^3$. (Jarlskog invariant)
- 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 $\mathrm{SU}(3)_{Q_\mathrm{L}}$)

[AT '18]

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

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$\delta^{ab} =$  .

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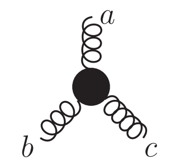
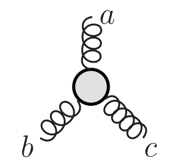


$= \mathrm{i}\, f^{abc}$ and



$= d^{abc}$.

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

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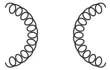
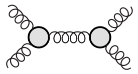
- $\mathbf{8}^{\otimes 2} \to \mathbf{1}$
- $\mathbf{8}^{\otimes 3} \to \mathbf{1}$
- $\mathbf{8}^{\otimes 4} \to \mathbf{1}$

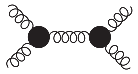
$\mathbf{1}$:



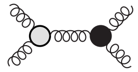
$\mathbf{8}_\mathrm{S}$:



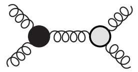
$\mathbf{8}_\mathrm{A}$:

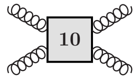


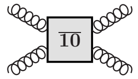
$\mathbf{8}_{\mathrm{A}\to\mathrm{S}}$:

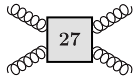


$\mathbf{8}_{\mathrm{S}\to\mathrm{A}}$:









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Can understand the different contraction channels from

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

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

[AT '18]

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

- $\mathbf{8}^{\otimes 2} \to \mathbf{1}$
- $\mathbf{8}^{\otimes 3} \to \mathbf{1}$
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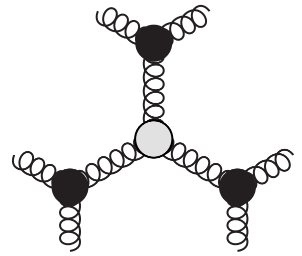
- $\mathbf{8}^{\otimes 6} \to \mathbf{1}$

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



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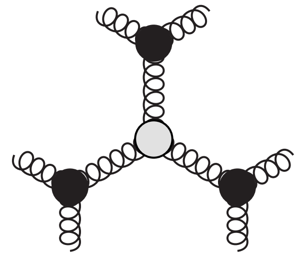
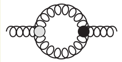
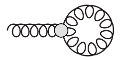
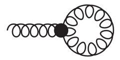


 $= 0$

 $= 0$

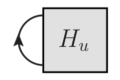
 $= 0$

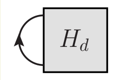
All of these operators are **orthogonal** to each other.

$\curvearrowright$ We use them to construct the **orthogonal** invariants.

Orthogonal Invariants

The 10 *algebraically independent* and orthogonal invariants are given by: $I_{\#\text{u's},\#\text{d's}}$

$I_{10} \propto$ 

and $I_{01} \propto$ 

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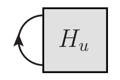
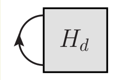
$I_{10} \propto$ 

and $I_{01} \propto$ 

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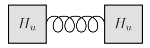
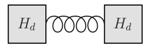
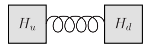
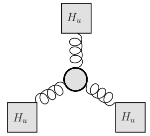
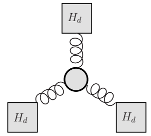
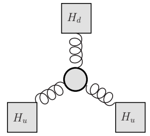
$I_{20} \propto$ 

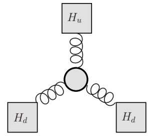
$I_{02} \propto$ 

$I_{11} \propto$ 

$I_{30} \propto$ 

$I_{03} \propto$ 

$I_{21} \propto$ 

$I_{12} \propto$ 

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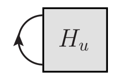
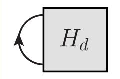
$I_{10} \propto$ 

and $I_{01} \propto$ 

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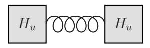
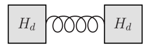
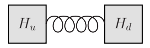
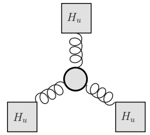
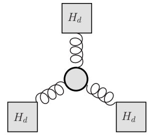
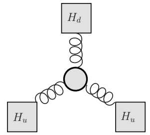
$I_{20} \propto$ 

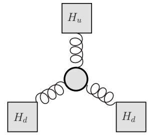
$I_{02} \propto$ 

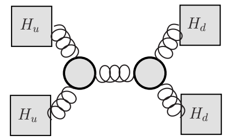
$I_{11} \propto$ 

$I_{30} \propto$ 

$I_{03} \propto$ 

$I_{21} \propto$ 

$I_{12} \propto$ 

$I_{22} \propto$ 

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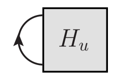
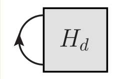
$I_{10} \propto$ 

and $I_{01} \propto$ 

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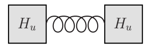
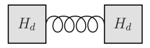
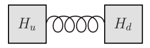
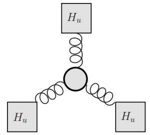
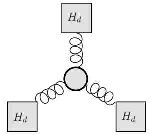
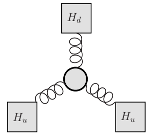
$I_{20} \propto$ 

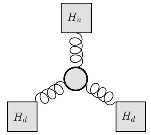
$I_{02} \propto$ 

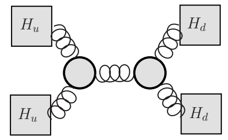
$I_{11} \propto$ 

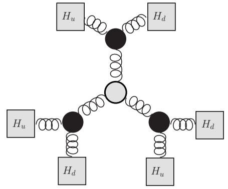
$I_{30} \propto$ 

$I_{03} \propto$ 

$I_{21} \propto$ 

$I_{12} \propto$ 

$I_{22} \propto$ 

Secondary invariant: $J_{33} \propto$ 

Orthogonal Invariants

By chance all 10 algebraically independent and orthogonal invariants are traces:

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

Here, $\widetilde{H}_u \equiv Y_u Y_u^\dagger$, $\widetilde{H}_d \equiv Y_d Y_d^\dagger$. Define $H_{u,d} := \widetilde{H}_{u,d} - \mathbb{1}\,\mathrm{Tr}\frac{\widetilde{H}_{u,d}}{3}$, then:

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

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

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

"Traces of traceless matrices"

Secondary invariant: exactly the Jarlskog invariant,

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

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).

SM Quark Sector Flavor Invariants – Quantitative Analysis

Measuring the Invariants

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

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

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

1. **Explore the *possible* parameter space**: scan $\mathcal{O}(10^7)$ 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: $(m_{u,c}/\text{MeV}) \in 10^{[-1,\log(m_t/\text{MeV})]}$, $(m_{d,s}/\text{MeV}) \in 10^{[-1,\log(m_b/\text{MeV})]}$.

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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 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	$3.08(^{+0.16}_{-0.19}) \times 10^{-5}$		

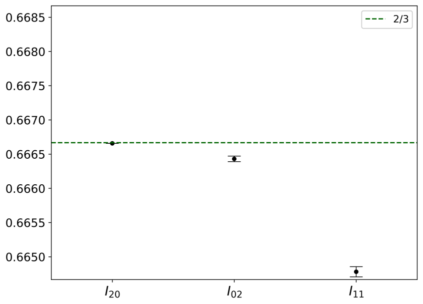
Table: Experimental values of the quark sector basis invariants evaluated using PDG data. Uncertainties are 1σ. Left: orthogonal invariants at face value. Right: the same invariants normalized to the largest Yukawa couplings.

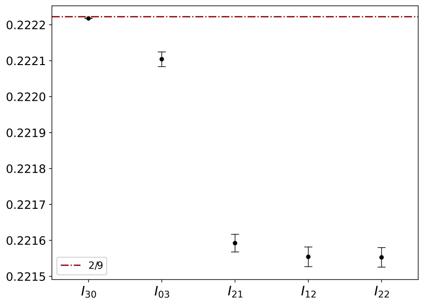
Experimental values of the Invariants

$$\hat{I}_{10} \approx \hat{I}_{01} \approx 1, \qquad \hat{I}_{11} \approx \hat{I}_{20} \approx \hat{I}_{02} \approx \frac{2}{3}\,,$$

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

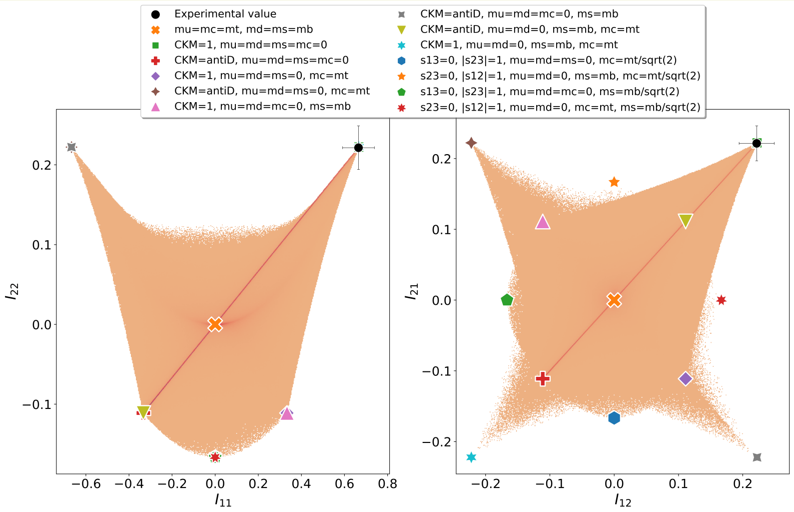
$$\left(\hat{I}_{ij} := \frac{I_{ij}}{\left(y_t^2\right)^i \left(y_b^2\right)^j}\,. \right)$$





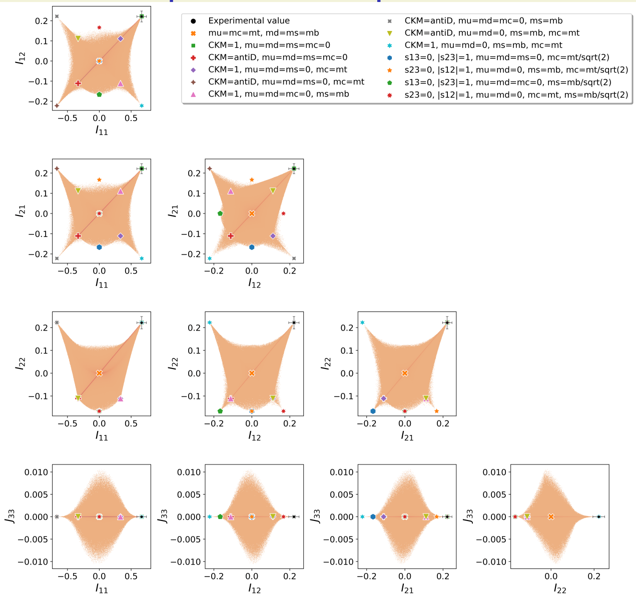
- Deviations from maximal possible values are significant.
- Deviations from each other, e.g. $\hat{I}_{21} - \hat{I}_{12} \neq 0$ and $\hat{I}_{12} - \hat{I}_{22} \neq 0$, are significant.

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.
- Small deviations from max. correspond to 1./2. gen. masses and mixings.
- Explaining the value of the invariants and their misalignment from maximal point amounts to solving the flavor puzzle in the language of invariants.

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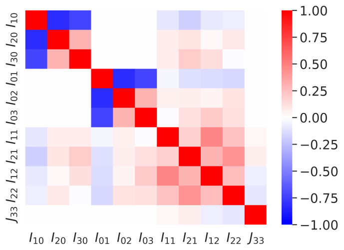
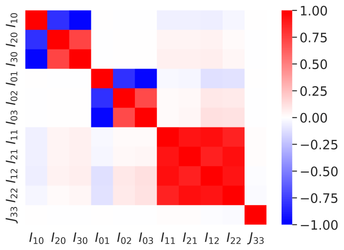
- Observed primary invariants are *very close to* maximal – with small but significant deviations.
- Small deviations from max. correspond to 1./2. gen. masses and mixings.
- Explaining the value of the invariants and their misalignment from maximal point amounts to solving the flavor puzzle in the language of invariants.
- 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.

CP transformation of covariants and invariants

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

$$\begin{aligned} \boldsymbol{u}^a &\mapsto -R^{ab}\,\boldsymbol{u}^b\,, \\ \boldsymbol{d}^a &\mapsto -R^{ab}\,\boldsymbol{d}^b\,, \end{aligned}$$

e.g. in Gell-Mann basis for the generators:
$R = \mathrm{diag}(-1, +1, -1, -1, +1, -1, +1, -1)$.

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

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

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

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$$\boldsymbol{u}^a \;\mapsto\; -R^{ab}\,\boldsymbol{u}^b\,,$$
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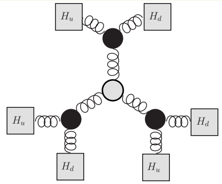
$\Rightarrow$ Only CP-odd in SM: $J_{33} \propto$



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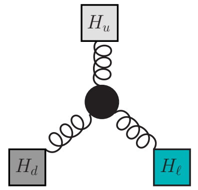
BSM: CPV at order 3 ?

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



CP trafo of invariants is easily read-off from birdtrack projection operator:

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

Remarks

- CPV requires interplay of 8 CP-even primary invariants (all besides trivial I_{10}, I_{01}). Non-trivial $\hat{I}_{ij}$'s being close to maximal forces the Jarlskog invariant to be ***small***.
- Maximization and strong correlation of invariants could point to possible **information theoretic** argument to set parameters!
  see e.g. [Bousso, Harnik, Kribs, Perez '07], [Beane, Kaplan, Klco, Savage '19], [Carena, Low, Wagner, Xiao '23]
- 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]
- Any reduction of # of parameters corresponds to relation between invariants.
- Investigation of $u \leftrightarrow d$ custodial flavor symmetry $\rightarrow$ should be done.
- General relation of BI's to observables $\rightarrow$ should be done.
- Our procedure is *completely general*, can be applied to other sectors and models.

Conclusion

- We have for the first time obtained a quantitative analysis of the flavor puzzle exclusively in terms of basis invariants.
- This uncovers an entirely new angle on the flavor puzzle.
- 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 the first step in an entirely new exploration of the (SM & BSM) flavor puzzle.

Thank You!

Backup slides

Jargon of invariant theory

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

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

$$\exists \quad \mathrm{Polynomial}\,(\mathcal{I}_1, \mathcal{I}_2, \mathcal{I}_3, \ldots) = 0 \; .$$

(⇔ $\mathcal{I}_1, \mathcal{I}_2, \mathcal{I}_3, \ldots$ are algebraically <u>in</u>dependent iff $\nexists \mathrm{Pol}$)

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- ***Generating set*** of invariants $\equiv$ all ***primary*** **+** ***secondary*** invariants.

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

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

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

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

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

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

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

Möbius function $\mu(n) = \begin{cases} \overset{+}{(-)}1, & \text{if } n \text{ is square free with even(odd) \# number of prime factors,} \\ 0, & \text{else.} \end{cases}$

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

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

RGE running of invariants

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

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

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

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

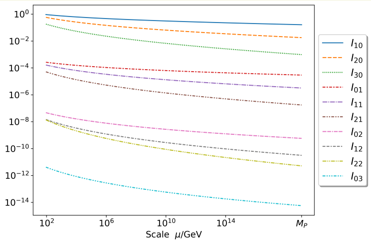
$$t_{udl} := 3\,\mathrm{Tr}\tilde{H}_u + 3\,\mathrm{Tr}\tilde{H}_d + \mathrm{Tr}\tilde{H}_\ell\,.$$

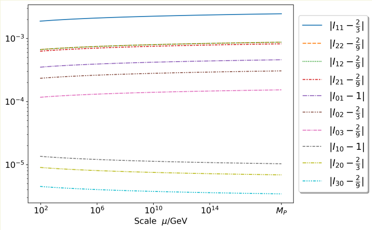
$$\mathcal{D}\tilde{H}_u = 2\left(a_\Delta + t_{udl}\right)\,\tilde{H}_u + 3\,\tilde{H}_u^2 - \frac{3}{2}\left(\tilde{H}_d\tilde{H}_u + \tilde{H}_u\tilde{H}_d\right)\,,$$

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

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

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





Explicit expressions for Invariants in physical basis

In "physical parameters" of SM the normalized invariants can be approximated using the (empirically observed) parametric hierarchies $y_t \gg y_{c,u}$, $y_b \gg y_{s,d}$ and $\lambda \ll 1$,

$$\hat{I}_{20} = \frac{2}{3} - 2\frac{y_c^2 + y_u^2}{y_t^2} + \text{h.o.}\,,$$

$$\hat{I}_{30} = \frac{2}{9} - \frac{y_c^2 + y_u^2}{y_t^2} + \text{h.o.}\,,$$

$$\hat{I}_{11} = \frac{2}{3} - A^2\lambda^4 - \frac{y_c^2 + y_u^2}{y_t^2} - \frac{y_s^2 + y_d^2}{y_b^2} + \text{h.o.}\,,$$

$$3\,\hat{I}_{21} = \frac{2}{3} - A^2\lambda^4 - 2\frac{y_c^2 + y_u^2}{y_t^2} - \frac{y_s^2 + y_d^2}{y_b^2} + \text{h.o.}\,,$$

$$3\,\hat{I}_{12} = \frac{2}{3} - A^2\lambda^4 - \frac{y_c^2 + y_u^2}{y_t^2} - 2\frac{y_s^2 + y_d^2}{y_b^2} + \text{h.o.}\,,$$

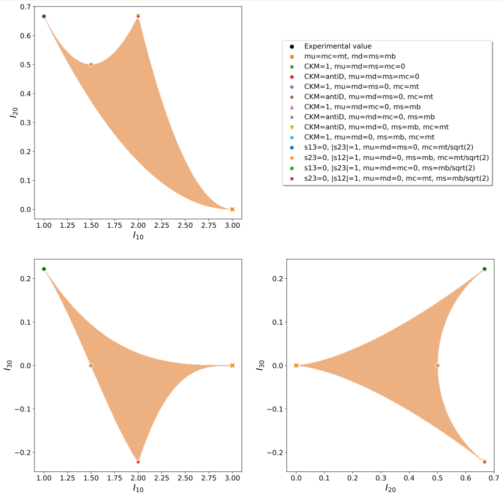
$$3\,\hat{I}_{22} = \frac{2}{3} - A^2\lambda^4 - 2\frac{y_c^2 + y_u^2}{y_t^2} - 2\frac{y_s^2 + y_d^2}{y_b^2} + \text{h.o.}\,.$$

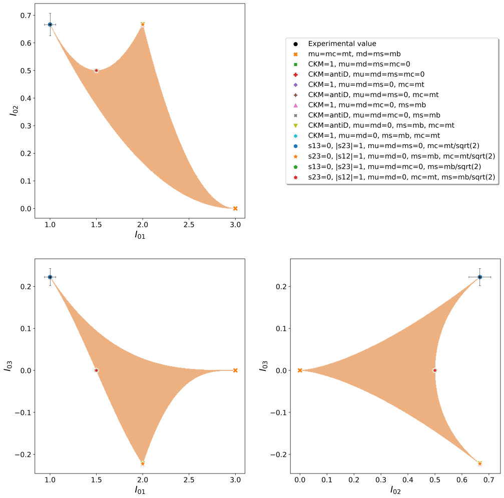
$$\hat{I}_{02} = \frac{2}{3} - 2\frac{y_s^2 + y_d^2}{y_b^2} + \text{h.o.}\,,$$

$$\hat{I}_{03} = \frac{2}{9} - \frac{y_s^2 + y_d^2}{y_b^2} + \text{h.o.}\,,$$

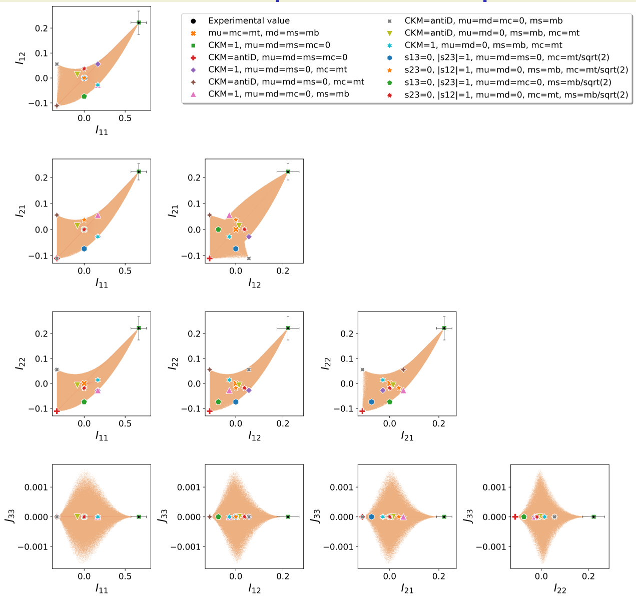
h.o. here refers to higher order corrections in λ or higher powers of the Yukawa coupling ratios. This shows that the values $2/3$ and $2/9$'ths become exact in the limit of zero mixing and zero 1st and 2nd-generation fermion masses.

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





Parameter space and experimental values

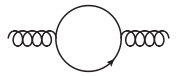


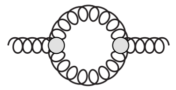
Arguably even "more basis invariant" alternative choice of normalization:

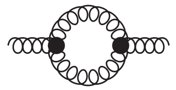
$$\hat{I}_{ij}^{\text{alt}} := \frac{I_{ij}}{I_{10}^{i}\, I_{01}^{j}} \; .$$

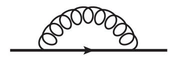
Birdtrack Identities

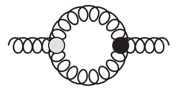
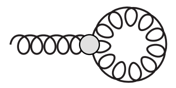
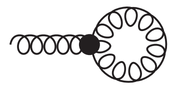
We mostly use the conventions of [Keppeler '17] with the following identities

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

 $=$  $=$  $= 0$

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 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 the ring.

- 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.

Future directions

- 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! $\rightarrow$ should be done.
  see e.g. [Bousso, Harnik, Kribs, Perez '07], [Beane, Kaplan, Klco, Savage '19], [Carena, Low, Wagner, Xiao '23]
- Extension to lepton sector with **orthogonal** invariants $\rightarrow$ should be done.
  for HS/PL and non-orthogonal invariants see [Hanany, Jenkins, Manhoar, Torri '10], [Wang, Yu, Zhou '21], [Yu, Zhou '21].
- Using orthogonal BIs in $\mathrm{SU}(3)_{Q_\mathrm{L}}$ fundamental space $\rightarrow$ should be done.
- RGE's directly in terms of invariants $\rightarrow$ should be done.
- Investigation of $u \leftrightarrow d$ custodial flavor symmetry $\rightarrow$ should be done.
- General relation of BI's to observables $\rightarrow$ should be done.