Aspects of 3rd Generation Physics @ the LHC

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Z. Ligeti, M. Papucci, GP & J.Zupan (10); C. Delaunay, O. Gedalia, S.J. Lee & GP (10).

Capri 2010 7/1/10 10:39 PM

3rd Workshop on Theory, Phenomenology $\&$ Experiments in Heavy Flavour Physics, Capri 2010

♦ Introduction: importance of 3rd generation.

 \blacklozenge Introduction: importance of 3rd generation.

Implications of D0 & CDF results related to CPV $\in B_s - B_s$.

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Implications of D0 & CDF results related to $\text{CPV} \in B_s - B_s$.

Basics of GMFV (general minimal flavor violation).

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Basics of GMFV (general minimal flavor violation).

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♦ Deviation from SM predictions can be easily probed or severe bounds on new physics (NP) obtained.

Backups Flavor Changing & CP Violating Physics

News from the Tevatron

Dø reports 3.2σ in dimuon asymmetry; CDF improves $\Delta\Gamma_s$ vs. $S_{\psi\phi}$?? the dimunity of ω dimuon charge assumments in semi- 2σ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ *N* ++ *^b* + *N* −− *b n* asymmetry; where *N* ++ *^b* is the number of *^b*¯*^b* [→] *^µ*⁺*µ*⁺*^X* events (and

► **DO result:**
$$
a_{\text{SL}}^b = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = -(9.57 \pm 2.51 \pm 1.46) \times 10^{-3},
$$

_{1005.2757.}

where *N* ++ *^b* is the number of *^b*¯*^b* [→] *^µ*⁺*µ*⁺*^X* events (and **ON** $a_{\text{SL}}^b = (0.506 \pm 0.043) a_{\text{SL}}^d + (0.494 \pm 0.043) a_{\text{SL}}^s$. correlates $B_d \leftrightarrow B_s$ M = Construction of the Grossman et al. 06. The above results show that all shows that G results are all α . fragmentation

The above result showledge result showledge in conjunction $\mathcal{L}_\mathcal{D}$ is a conjunction of $\mathcal{L}_\mathcal{D}$

SL ⁼ [−](4*.*⁷ *[±]* ⁴*.*6) [×] ¹⁰−³ [3]; (ii) the flavor

¹*.*5) [×] ¹⁰−³ [4]; and (iii) the measurements of ∆Γ*^s* and

 $S_{\rm{H}}$ (the CP-even part of the CP-even part of the \sim even part of the \sim

final state) [5–8]. Here ∆Γ*^s* = Γ*^L* − Γ*H*, is the width

difference of the heavy and light *B^s* mass eigenstates. If

CP violation is negligible in the relevant tree-level decays,

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specific asymmetry measured in the time dependence of

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SL

, (1)

fs = −(1*.*7*±*9*.*1*±*

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*B*⁰ *s*

[→] *^µ*⁺*D*[−]

ad

SL and *a^s*

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SL and *a^s*

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$$
a_{\rm SL}^s = -\frac{|\Delta\Gamma_s|}{\Delta m_s}\,S_{\psi\phi}\,/\sqrt{1-S_{\psi\phi}^2}\,, \quad \ \ \text{Ligeti et al. (06);} \quad \ \ \text{Grossman et al. (09).}
$$

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Correlation with ∆Γ^s vs. *S*ψφ SL ⁼ [−](4*.*⁷ *[±]* ⁴*.*6) [×] ¹⁰−³ [3]; (ii) the flavor specific asymmetry measured in the time ℓ fs = −(1*.*7*±*9*.*1*±* $\mathbf{1}$ is defined by data, our fit below can be defined by data, our fit below can be defined by data, $\mathbf{1}$ done independent of the theoretical calculation of ∆Γ*s*, the accuracy of which can be questioned \mathcal{I} . Using the accuracy of which can be questioned \mathcal{I}

◆ D0 result can be written as: $\frac{1}{2}$ $|$ ◆ レ

$$
-|\Delta\Gamma_s| \simeq \Delta m_s \big(2.0\, a_{\rm SL}^b - 1.0\, a_{\rm SL}^d\big)\, \sqrt{1 - S_{\psi\phi}^2\, /\, S_{\psi\phi}}\,.
$$

where ∆*m^s* ≡ *m^H* −*mL*. Since all quantities in this rela-

Ligeti, Papucci, GP, Zupan.

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difference of the heavy and light *B^s* mass eigenstates. If

CP violation is negligible in the relevant tree-level decays,

the Tevatron experiments [9–11]. If the evidence for the

sizable dimuon charge asymmetry, Eq. (1), is confirmed

SL. The SM predictions for the asymmetries

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 $S^2_{\psi\phi} \, \big/ \, S_{\psi\phi} \, .$

Ligeti, Papucci, GP, Zupan.

For simplicity we do not display the *O* (10%) uncertain- $\mathbf{u}_1 \bullet \mathbf{u}_2$ for the two numerical factors. A global fit with all $\mathbf{u}_1 \bullet \mathbf{u}_2$ ♦ Tevatron experiments also measure:

 \overline{a} \overline{b} \overline{c} \overline{c} 948 Tuesday, July 6, 2010

Correlation with ∆Γ^s vs. *S*ψφ SL ⁼ [−](4*.*⁷ *[±]* ⁴*.*6) [×] ¹⁰−³ [3]; (ii) the flavor specific asymmetry measured in the time ℓ fs = −(1*.*7*±*9*.*1*±* $\mathbf{1}$ is defined by data, our fit below can be defined by data, our fit below can be defined by data, $\mathbf{1}$ done independent of the theoretical calculation of ∆Γ*s*,

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Allow for consistency check or making indep' $\Delta\Gamma_s$ fit (robustly bound NP)! the measured values of ∆*m^s* and *ab,d* SL , we find

It is extracted under the assumption that the assumption that the assumption that the width difference \mathcal{L}_max

¹²) the dispersive (absorptive) part

♦ Consistency check: *[|]*∆Γ*s[|]* [∼] !

Ligeti, Papucci, GP, Zupan.

$$
(a_{\rm SL}^b)_{\rm D\emptyset} : \qquad |\Delta\Gamma_s| \sim (0.28 \pm 0.15) \sqrt{1 - S_{\psi\phi}} / S_{\psi\phi} \,\text{ps}^{-1}
$$

$$
(S_{\psi\phi})_{\rm CDF+D\emptyset} : \qquad (\Delta\Gamma_s, S_{\psi\phi}) \sim (0.15 \,\text{ps}^{-1}, \quad 0.5)
$$

¹² (Γ*^q*

We denote by *M^q*

◆ Consistency check: value, ∆Γ*^s* [≈] ⁰*.*2 ps−¹, we find *^S*ψφ [≈] ⁰*.*⁸⁵ *[±]* ⁰*.*12, which *[|]*∆Γ*s[|]* [∼] !

 $\mathsf{C}\mathsf{k}$: input parameters where we use the most fit parameters $\mathsf{C}\mathsf{k}$:

further investigation, and hence we do not use it investigation, and hence we do not use it in the investigation, α

Beauty2009 CKMfitter input values [?], except for the

^s satisfies

recent experimental data. In Fig. (??) we show the re-

vs. *S*ψφ result. JZ: we need to change the above

plot in the *h^d* − σ*^d* plane is shown in Fig. ??; in this case $\mathcal{O}(\log n)$ is consistent with no new physics contributions contributions contributions contributions contributions of $\mathcal{O}(\log n)$

To interpret the pattern of the pattern of the current experimental $\mathcal{L}_\mathbf{r}$

data in terms of NP models, one should investigate if NP

models that respect the SM approximate *SU*(2)*^q* symme-

try are favored (in the SM this is due to the SM this is due to the smallness of the

the masses in the first two generations and the smallness

of the mixing with the mixing with the third generation α

in *^B^d* [−] *^B*¯*^d* mixing (*h^d* = 0) below the 2^σ level.

$$
(a_{\text{SL}}^b)_{\text{D}\emptyset}
$$
: $|\Delta\Gamma_s| \sim (0.28 \pm 0.15) \sqrt{1 - S_{\psi\phi}}/S_{\psi\phi} \text{ps}^{-1}$
 $(S_{\psi\phi})_{\text{CDF+D}\emptyset}$: $(\Delta\Gamma_s, S_{\psi\phi}) \sim (0.15 \text{ps}^{-1}, 0.5)$

♦ Clean NP interpretation: $(\Delta\Gamma_s \text{ is taken from the fit} \rightarrow \text{not theory involved})$ *^q* [−] *^B*¯⁰ *^q* mixing amplitude and SM superscripts denote the $M^{d,s} = \ell M^c$ here, see \mathbf{r} . This model is the \mathbf{r} \mathbf{r} \mathbf{r} \mathbf{r} \mathbf{r} \mathbf{r} \mathbf{r} $\begin{bmatrix} \mathbf{M} & \mathbf{I} & \mathbf{$ $\left. M^{d,s}_{12}\right. =\left. \left(M^{d,s}_{12}\right)^{\text{SM}}\left(1+h_{d,s}\,e^{2i\sigma_{d,s}}\right) \right|$ $\frac{1}{\sqrt{1+\frac{1$ $\mathop{\text{the }}$ $\mathop{\text{int}}$ \rightarrow $\mathop{\text{not }}$ theory involved. ¹² (Γ*^q* ¹²) the dispersive (absorptive) part previous data on ∆Γ*^s* and *S*ψφ, which by themselves have bretation: $M_{12}^{u,s} = (M_{12}^{u,s})^{S_{111}} (1 + h_{d,s} e^{2i\sigma_{d,s}})$ found consistency between different measurements is not a significant measurements in \mathcal{L} $\left(\Delta t g$ is vanted from the presence of physics between $\frac{1}{\sqrt{2\pi}}$ and $\frac{1}{\sqrt{2\pi}}$ and $\frac{1}{\sqrt{2\pi}}$ and $\frac{1}{\sqrt{2\pi}}$ and $\frac{1}{\sqrt{2\pi}}$ interpretation: $M_{12}^{m} = (M_{12}^{m}) \quad (1 + h_{d,s} e^{2i\omega})$ neutral meson mixing.

tb)*/*(*VcsV* [∗]

¹² (Γ*^q*

cb)] = (1*.*04 *±*

It is extracted under the assumption that the assumption that the assumption that the width difference \mathcal{L}_max

¹²) the dispersive (absorptive) part

$$
\Delta m_q = \Delta m_q^{\text{SM}} \left| 1 + h_q e^{2i\sigma_q} \right|,
$$

\n
$$
\Delta \Gamma_s = \Delta \Gamma_s^{\text{SM}} \cos \left[\arg \left(1 + h_s e^{2i\sigma_s} \right) \right],
$$

\n
$$
A_{\text{SL}}^q = \text{Im} \left\{ \Gamma_{12}^q / \left[M_{12}^{q, \text{SM}} \left(1 + h_q e^{2i\sigma_q} \right) \right] \right\},
$$

\n
$$
S_{\psi K} = \sin \left[2\beta + \arg \left(1 + h_d e^{2i\sigma_d} \right) \right],
$$

\n
$$
S_{\psi \phi} = \sin \left[2\beta_s - \arg \left(1 + h_s e^{2i\sigma_s} \right) \right].
$$

ψφ = arg[−(*VtsV* [∗]

We denote by *M^q*

Global fit's results

Ligeti, Papucci, GP, Zupan.

Global fit's results

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Allowed regions in the B_s & B_d systems.

The allowed ranges of h_s , σ_s (left) and h_d , σ_d (right) from the combined fit to all four NP parameters.

plitude. As is well known, the set of these processes are highly processes are highly processes are highly processes

Universal case: $h_d = h_s$, $\sigma_d = \sigma_s$ still make the following general statements: ersal case: $n_d = n_s \, , \ \ \sigma_d = \sigma$

our discussion to a specific model, we can specific model, we can specific model, we can specific model, we can

mentally. Universality is expected in a large class of well

motivated models with approximate *SU*(2)*^q* invariance,

for instance when flavor transitions are mediated by the

 $\mathcal{O}(\mathcal{C})$ for $\mathcal{C}(\mathcal{C})$ and $\mathcal{C}(\mathcal{C})$ and $\mathcal{C}(\mathcal{C})$

tributions are *SU*(2)*^q* universal (see Eq. (8) and Fig. 3)

is also quite generically obtained in the minimal flavor

 $v_{\rm{max}}$ framework \sim

 $v_{\rm c}$ iolating phases are present μ

org approach such a contribution may arise from the four-

 $\mathcal{L}^{\mathcal{L}}(\mathcal{L}^{\mathcal{L}})$ is contral value of the measurement in Eq. (1) is con-

firmed, this inequality would be computed by

that the suppression from the bottom Yukawa, *yb*, is

 $n_{\rm eff}$ into account into account in Δ

this case requires requires requires \mathcal{L}_c

 Y ukawa coupling $[2, 3]$. In general the presence of \mathbb{Z}

vor diagonal phases could contribute to the neutron elec-

tric dipole moment $\mathcal{Z}(\mathcal{Z})$

and different class of operators and requires a separate in-

vestigation. Another interesting aspect of these flavor di-

agonal phases is that there are examples where the there are examples where the canonical canonical α

contribute to the generation of matter-antimatter asym-

metry, another issue which deserves further investigation.

^L, suppressed by scales ΛMFV;1*,*2*,*3, re-

¹ ⁼ ¯*b*^α

spectively. We find that the data require

^ΛMFV;1*,*2*,*³ *>*[∼] *{*8*.*8*,* ¹³ *^yb,* ⁶*.*⁸ *^yb}*

The allowed h_b , σ_b range assuming $SU(2)$ universality.

Lessons from the data, model indep' the new contributions to *B^d* and *B^s* transition are simdata but are not the most preferred scenarios experience **F**IGRADES **FIGARA** the data me

♦ SU(2)q approximate universality can accommodate data, त्र limit of many models, where NP effects are via 3rd gen'. $_{27}^{43-1}$ X.: general MinmalFlavorViolation (GMFV): MFV+flavor diag' phases. *Colangelo, et al. (09); Kagan, et al. (09).* tribute mainly to ∆*F* = 2 processes via the mixing am- $\frac{45}{27}$ X.: general MinmalFlavorViolation (GMFV): MFV+flavor di 73 $\mathbf{C}^{\mathbf{X}}$ 2)_q approximate universality can accommoda ζ is the new diagonal contraction of ζ of many models, where the effects are via or $\mathcal{C}[\|(\mathcal{I})\|]$ approximate universality can accommod σ α approximate diversancy can accomm mit of many models where NP effects are v motivativativate models with a process α , β in α for instance when flavor transitions are mediated by the the general MinmalFlavor Violation (GMFV): MFV+11av . t Colangelo,

$$
\Lambda_{\rm MFV;1,2,3} \gtrsim \{8.8,~13\,y_b,~6.8\,y_b\}\,\sqrt{0.2/h_b}~\rm TeV\,.
$$

$$
O^{bq}_1=\bar{b}^\alpha_L\gamma_\mu q_L^\alpha\,\bar{b}^\beta_L\gamma_\mu q_L^\beta,\, O^{bq}_2=\bar{b}^\alpha_R q_L^\alpha\,\bar{b}^\beta_R q_L^\beta,
$$

^L, suppressed by scales ΛMFV;1*,*2*,*3, re-

 $W_{\rm eff}$ interpreting to interpreting the above results, as

suming that the dimuon asymmetry is indeed providing

evidence for deviation from the \sim

out restricting our discussion to a specific model, we can

sources of CP violation are present and that they con-

 $\overline{}$

 \overline{a}

 $\overline{}$

 \vdash

 \vert

 $\left\lvert \cdot \right\rvert$

tribute mainly to ∆*F* = 2 processes via the mixing am-

Lessons from the data, model indep' #2

 \blacklozenge What models naturally yield $h_s \gg h_d$??

Lessons from the data, model indep' #2 $\frac{1}{2}$ \mathbf{g} and up an n the data, model indep $\,$ \pm $\,$ $\,$

approximate SU(2)*^q symmetry without being excluded by*

 \blacklozenge What models naturally yield $h_s \gg h_d$?? are equally important. The above set of operator α

Surprisingly: GMFV models dominated by (=> others as well):

 \mathcal{L} to *b* → *s* transition and *n*ot to *b* → *d* transition, because Buras, et al. (10); Dobrescu, et al. (10); Jung, et al. (10); Ligeti, et. al. (10).

rithms or large anomalous dimensions. Consequently, the

Heiko Lacker and Yossi Nir for useful discussions. GP

is the Shlomo and Michla Tomarin career development

chair; GP is supported by the Israel Science Foundation

 $(1087)^2$

and the Peter & Patricia Gruber Award. The work of

 $\mathcal{M}_{\rm{S}}$

 0.74

of the U.S. Department of Energy under contract DE-

[1] V. M. Abazov *et al.* [D0 Collaboration], arXiv:1005.2757.

 \mathcal{L}

[3] E. Barberio *et al.* [Heavy Flavor Averaging Group],

[4] V. M. Abazov *et al.* [D0 Collaboration], arXiv:0904.3907.

 \mathcal{F} the alleged \mathcal{F}

AC02-05CH11231.

$$
O_4^{\text{NL}} = \frac{c}{\Lambda_{\text{MFV};4}^2} \left[\bar{Q}_3 (A_d^m A_u^n Y_d)_{3i} d_i \right] \left[\bar{d}_3 (Y_d^\dagger A_d^{l,\dagger} A_u^{p,\dagger})_{3i} Q_i \right].
$$

 Λ _i $\Lambda_{\rm MFV;4} \gtrsim 13.2 \, y_b\, \sqrt{m_s/m_b}\, \, \text{TeV} = 2.9 \, y_b\, \text{TeV}\, ,$

Thus, remarkably, *h^s* \$ *h^d* can arise in MFV models

with flavor diagonal C violating phase, where large chi- α violating phase, where large chi-base, where lar

rality flipping sources exist at the TeV scale. Such models

have not been studied in great detail, but possible inter-

esting examples are supersymmetric extension of the SM

1 We adopt here for simplicity a linear formulation where α linear formulation where the re- α

Lessons from the data, model indep' #2 $\frac{1}{2}$ generation eigenvalues is required (both for the up and up an n the data, model indep $\,$ \pm $\,$ $\,$

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Surprisingly: GMFV models dominated by (=> others as well):

 \mathcal{L} to *b* → *s* transition and *n*ot to *b* → *d* transition, because Buras, et al. (10); Dobrescu, et al. (10); Jung, et al. (10); Ligeti, et. al. (10).

זה למעלה משלושה עשורים עמלים מאות פיזיקאים ברחבי

מושג שהוצע לראשונה על-ידי אינשטיין ב,1917- ונועד להסביר את מצבו היציב של היקום: מדוע הוא אינו קורס, מצד אחד, או "מתפרק" ונעלם, מצד שני. פועל בכיוון הפוך לכוח הכבידה, ורק גודל מסוים שלו מאפשר את קיום היקום שלנו. אחד מארבעת כוחות היסוד בטבע. משפיע על היווצרות חלקיקים אלמנטריים ועל האינטרקציה ביניהם.

החלש קשורה לאינטרקציה מיקרוסקופית בין חלקיקים במרחקים זעירים של מאית–טריליונית המילימטר (כמאית מגודלו של הפרוטון). לשתי התעלומות הללו יש מאפיין משותף: **כוונון עדין**. רק קבוע קוסמולוגי בגודל זעיר מעבר לכל דמיון מאפשר את היווצרות היקום המוכר לנו, ולכאורה, רק כוח חלש במידה הנכונה מאפשר היווצרות חומר וחיים. התעלומה היא, כיצד התייצבו כוחות אלה על הגודל

rithms or large anomalous dimensions. Consequently, the

Heiko Lacker and Yossi Nir for useful discussions. GP

is the Shlomo and Michla Tomarin career development

chair; GP is supported by the Israel Science Foundation

 $(1087)^2$

and the Peter & Patricia Gruber Award. The work of

 $\mathcal{M}_{\rm{S}}$

 0.74

of the U.S. Department of Energy under contract DE-

[1] V. M. Abazov *et al.* [D0 Collaboration], arXiv:1005.2757.

 \mathcal{L}

[3] E. Barberio *et al.* [Heavy Flavor Averaging Group],

[4] V. M. Abazov *et al.* [D0 Collaboration], arXiv:0904.3907.

 \mathcal{F} the alleged \mathcal{F}

AC02-05CH11231.

$$
O_4^{\text{NL}} = \frac{c}{\Lambda_{\text{MFV};4}^2} \big[\bar{Q}_3 (A_d^m A_u^n Y_d)_{3i} d_i \big] \big[\bar{d}_3 (Y_d^\dagger A_d^{l,\dagger} A_u^{p,\dagger})_{3i} Q_i \big].
$$

 Λ _i $\Lambda_{\rm MFV;4} \gtrsim 13.2 \, y_b\, \sqrt{m_s/m_b}\, \, \text{TeV} = 2.9 \, y_b\, \text{TeV}\, ,$

Thus, remarkably, *h^s* \$ *h^d* can arise in MFV models

with flavor diagonal C violating phase, where large chi- α violating phase, where large chi-base, where lar

esting examples are supersymmetric extension of the SM

1 We adopt here for simplicity a linear formulation where α linear formulation where the re- α

generation eigenvalues is required (both for the up and up an
The up and u \blacksquare What is \blacksquare (general MFV) ?? \sqrt{h} \mathbf{v} and been in \mathbf{v} (generativity): What is GMFV (general MFV) ?? העולם, על פיצוח שתי בעיות בסיסיות בחזית הפיזיקה התיאורטית. הראשונה היא גודלו (או נכון יותר, קטנותו) של הקבוע הקוסמולוגי \mathbf{r} \blacksquare \blacksquare \boldsymbol{v} repertion in \boldsymbol{v} \sim 10 \sim 7

 0.85 ± 0.000 and 0.000 and 0.000 and 0.000 and 0.000 and 0.000 and 0.000

GMFV: LinearMFV vs NonLMFV

Kagan, GP, Volansky & Zupan (09); 2 x Gedalia, Mannelli, GP (10).

What defines MFV (minimal flavor violation) Pheno'?

• Is CPV is broken only by the Yukawa or flavor diag' phase are present?

◆ Is the down type flavor group is broken "strongly"?

♦ Is the up type flavor group is broken "strongly"?

Linear MFV vs. non-linear MFV (NLMFV) Linear MFV vs. non-linear MFV (NLMFV) VQYu,dV †

HuQ, (4) HoQ, (4)

Kagan, GP, Volansky & Zupan (09). u,d, while the fundamental representations are in the fundamental representations, $\frac{1}{2}$ and $\frac{1}{2}$ are $\frac{1}{2}$ and $\frac{1}{2}$ are $\frac{1}{2}$ and $\frac{1}{2}$ are $\frac{1}{2}$ and $\frac{1}{2}$ are $\frac{1}{2}$ and $\frac{1}{2}$ are models are then of the MFV class if they are formally invariant under ^GSM, when treating the SM Yukawa couplings

Huddham + HdQ, (4)

 $E_{\rm eff}$ are \sim low energy supersymmetric models in which large tan B effects need to be resummed (large tan B

 d , and models obeying $M_{\rm{H}}$ at a UV scale μ log(μ) are generated from sizable from sizable

anomalous dimensions in the renormalization group $[5]$. Another example is warped extra dimension models in \mathbb{R}

In this letter we show that even in NLMFV there is a systematic expansion in small α

quark masses, while resumming in yt, y^b ∼ O(1). This is achieved via a non-linear σ-model–like parametrization.

 $N_{\rm eff}$ in the limit of vanishing weak gauge coupling (or \sim), U(3) \sim

theory is described by a $[U(3)]$ non-linear original to the misalignment of $U(3)$ non-linear originment of $U(3)$

with all 6 , in cases where right handed up-quark currents are subdominant. The subdominant α

two groups are broken down to U(2) \times U(2) \times U(2) \times U(1) by large third generation eigenvalues in \times

The top Yukawa is large (possibly also bottom one) no justification to treat it perturbatively. as and the lop runawa is large (possibly also bottom one) invariant under the low energy flavor of the materia that only connected insertions of Yustinication to treat it perturbatively. $\log \sup$ yallowed insertions of \log eat it perturbatively. The above definition of MFV is only useful if flavor invariant operators such as Qf

"LO" MFV expansion valid only for $\frac{1}{2}$ ^D(Y^U ^Y † ^U)nQ are not. "LO" MFV expansion valid only for $\bar Qf(\epsilon_u Y_U, \epsilon_d Y_D)Q$ $\epsilon_{u,d}\,\ll\, 1$ in powers of Y u, In the large tan β limit both β $\epsilon_{u,d}~\ll~ 1$

 $\mathcal{L}_{\mathcal{M}}(\mathcal{M}_{\mathcal{M}})$: $\mathcal{L}_{\mathcal{M}}(\mathcal{M}_{\mathcal{M}})$ and the dominant flavor breaking effects are captured by the dominant flavor breaking effects are captured by the lowest order order order order order order order o

• Non-linear MFV (NLMFV): !u,d ∼ O(1), higher powers of Yu,d are important, and a truncated expansion in yt,b

Examples of NLMFV are: low energy supersymmetric models in which large tan β effects need to be resummed (large

!d), and models obeying MFV at a UV scale ΛF \$ µW , where large !u,d « log(μW /ΛF) are generated from sizabl
Στην αναφέρει το μεγαλύτερο με το μεγαλύτερο μεγαλύτερο μεγαλύτερο μεγαλύτερο μεγαλύτερο μεγαλύτερο μεγαλύτερ

anomalous dimensions in the renormalization group running [5]. Another example is warped extra dimension models

 Γ argo \mathcal{V} the size of \mathcal{V} are \mathcal{V} and \mathcal{V} and \mathcal{V} are \mathcal{V} and \mathcal{V} are \mathcal{V} ω, ω Large "logs" or anomalous dim' $\Rightarrow \epsilon_{u,d} = \mathcal{O}(1)$

u,d, while the quark fields are in the fundamental representations, (Q!

Linear MFV vs. non-linear MFV (NLMFV) Linear MFV vs. non-linear MFV (NLMFV) VQYu,dV † NP to a⇒ 104 TeV. Therefore, Tev scale NP which stabilizes the electroweak scale and is accessible and is accessible at the LHC has the L to hingar MFV non generic flavor structure. The structure is a highly non generic flavor structure in the structure \sim \blacksquare The tension is related in the SM \blacksquare

HuQ, (4) HoQ, (4)

Kagan, GP, Volansky & Zupan (09). even in the fundamental representations, in the presentations of the presentations of the presence of the presence of the presence of α and α and α are α ar models are then of the MFV class if they are formally invariant under ^GSM, when treating the SM Yukawa couplings $\mathcal{S}(\mathcal{M})$. Sometimes additional assumptions are made $\mathcal{S}(\mathcal{M})$ the only the

Huddham + HdQ, (4)

 $E_{\rm eff}$ are \sim low energy supersymmetric models in which large tan B effects need to be resummed (large tan B

theory is described by a $[U(3)]$ non-linear original to the misalignment of $U(3)$ non-linear originment of $U(3)$

The top Yukawa is large (possibly also bottom one) no justification to treat it perturbatively. as and the lop runawa is large (possibly also bottom one) invariant under the low energy flavor of the materia that only connected insertions of Yustinication to treat it perturbatively. $\log \sup$ yallowed insertions of \log intertional such a treat it perturbatively. The above definition of MFV is only useful if flavor invariant operators such as Qf \blacksquare The ton Yukawa is large (possibly also bottom c \mathcal{A} is the cop randival is farge \mathcal{A} (possibil) and boccommone, include \mathcal{A}

source of CP violation (CPV), e.g. in [1], or that NP does not change the Lorentz structure of the effective weak

"LO" MFV expansion valid only for $\frac{1}{2}$ ^D(Y^U ^Y † ^U)nQ are not. "LO" MFV expansion valid only for $\bar{Q}f(\epsilon_u Y_U,\epsilon_d Y_D)Q$ $\epsilon_{u,d}\,\ll\, 1$ in powers of Y u, In the large tan β limit both β $\epsilon_{u,d}~\ll~ 1$ $\mathcal{H} = \frac{1}{2}$

> as spurions. Similarly, the low energy flavor observables are formally invariant under ^GSM. Practically, this means that only certain insertions of Yukawa couplings are allowed in the quark bilinears. For example, in \mathcal{A}

 I_{area} $\mathcal{V}_{\text{base}}$ $\mathcal{V}_{\text{base}}$ are promoted to $\mathcal{V}_{\text{base}}$ are promoted to spurions that transform as $\mathcal{O}(1)$ ω, ω Large "logs" or anomalous dim' $\Rightarrow \epsilon_{u,d} = \mathcal{O}(1)$. models are the MFV class if the MFV class if they are formally invariant under GSM, when treating the SM Yukawa
The SM Yukawa coupling the SM Yukawa couplings the SM Yukawa couplings the SM Yukawa couplings the SM Yukawa c Large "logs" or anomalous dim' $\Rightarrow \epsilon_{u,d} = \mathcal{O}(1)$

We distinguish between 2 cases LMFV & NLMFV: and \mathbf{S} . Another extra dimensions \mathbf{S} . Another extra dimension models is warped extra dimension models in \mathbf{S} . We distinguish between 2 cases LMFV & NLMFV: given by the size of \mathbb{R}^n , we distinguish between two limiting cases of \mathbb{R}^n

 $\mathcal{L}_{\mathcal{M}}(\mathcal{M}_{\mathcal{M}})$: $\mathcal{L}_{\mathcal{M}}(\mathcal{M}_{\mathcal{M}})$ and the dominant flavor breaking effects are captured by the dominant flavor breaking effects are captured by the lowest order order order order order order order o

- polynomials of $Y_{u,d}$. with all groups where right handed up-quark currents are subdominant. The subdominant subdominant subdominant α • Linear MFV (LMFV): $\epsilon_{u,d} \ll 1$ and the dominant flavor breaking effects are captured by the lowest order polynomials of V_{th} polynomials of $Y_{u,d}$.
- Non-linear MFV (NLMFV): $\epsilon_{u,d} \sim O(1)$, higher powers of $Y_{u,d}$ are important, and a truncated expansion in $y_{t,b}$ is not possible. $\frac{1}{\sqrt{5}}$ another extra dimensions in the renormalization group $\frac{1}{\sqrt{5}}$. Another extra dimension models is warped to $\frac{1}{\sqrt{5}}$. q_s of V one important, and \circ this pathology in ω • Non-linear MFV (NLMFV): $\epsilon_{u,d} \sim O(1)$, higher powers of $Y_{u,d}$ are important, and a truncated expansion in $y_{t,b}$ is not possible. two groups are broken down to U(2) \times U(2) \times U(2) \times U(1) by large third generation eigenvalues in \times is not possible.

Examples of NLMFV are: low energy supersymmetric models in which large tan β effects need to be resummed (large

insertions such as Q¯(Y^U Y †

VQYu,dV †

u,d, while the quark fields are in the fundamental representations, (Q!

General MFV, non-linear MFV (NLMFV) General MEV non-linear MEV (NII ME General MFV, non-linear MFV (NLMFV) di ^L ^gij 2 U \overline{y} , \overline{y} , \overline{y} jl glk

Idea: spearate the small (large) eigenvalues, expand linearly (non-linearly) small (large) flavor breaking. $Y_U \sim \text{diag}(0, 0, y_t)$ and $Y_D \sim \text{diag}(0, 0, y_b)$. breaking.

 $V_{CKM} = 1_3 + \mathcal{O}(\theta_{ud})$ $\theta_{ud} \sim \lambda^2$ $VCKM - 13 + O(v_{ud})$ vud V We thus use the parameterization $\theta_{ud} \sim \lambda^2$ $V_{\text{CKM}} = \mathbf{1}_3 + \mathcal{O}(\theta_{u d})$

¯

<u>William Communication</u>

broken generators

All Control

² d^k

L

Yu,d = eiρˆ^Q e±iχˆ/2Y˜u,de−iρˆu,d

1

 $\mathcal{L}_{\mathcal{A}}$

⁰ ^yt,b"

diag(1, 1, −2)

where the reduced Yukawa spurions, Yukawa spurions, Yukawa spurions, Yukawa spurions, Yukawa spurions, Yukawa
Waxaa siyaasii waxaa siyaasii waxaa siyaasii waxaa siyaasii waxaa siyaasii waxaa siyaasii waxaa siyaasii waxaa

General MFV, non-linear MFV (NLMFV) General MEV non-linear MEV (NII ME General MFV, non-linear MFV (NLMFV) di ^L ^gij 2 U \overline{y} , \overline{y} , \overline{y} Canaral MEV non-linear MEV (NII MEV) glk General MFV, non-linear MFV (NLMFV) in MFV: (i) extra CPV can only arise from flavor diagonal CPV sources in the UV theory; (iii) the extra CPV α

Introduction. Precision flavor and CP violation measurements provide very strong constraints on models of new

Idea: spearate the small (large) eigenvalues, expand linearly (non-linearly) small (large) flavor breaking. $Y_U \sim \text{diag}(0, 0, y_t) \text{ and } Y_D \sim \text{diag}(0, 0, y_b)$ inearly (non-linearly) small (large) flavor breaking. l dea: spearate the small (large) eigenvalues, expand
The study is model in order in order in the model in the model is model in the model in the model in the model $\begin{vmatrix} 1 & 1 \\ 1 & 1 \end{vmatrix}$ and the small (large) eigenvalues, expand and dea: spearate the small (large) eigenvalues, expand and can induce significant new CPV in the CPV in the CPV in the CPV value of \mathbf{V} $\alpha_I U \sim \text{diag}(0, 0, y_t)$ and $I_D \sim \text{diag}(0, 0, y_b)$ to have a highly non general structure.
The structure of the structure is a high structure. The tension of the tension included in the SM Yukawa matrices are the SM Yukawa matrices are the only source o $Y_U \sim \text{diag}(0,0,y_t) \text{ and } Y_D \sim \text{diag}(0,0,y_b)$ polynomials of Yu, and you
now that Indianally is not possible.

$$
V_{\text{CKM}} = \mathbf{1}_3 + \mathcal{O}(\theta_{ud}) \qquad \theta_{ud} \sim \lambda^2
$$
\nbroken generators

¯

<u>William Communication</u>

All Control

² d^k

in powers of Yu,d. In the large tan β limit both Yu and Yu an

L

diag(1, 1, −2)

$$
\mathcal{H}^{\rm SM} = U(2)_Q \times U(2)_U \times U(2)_D \times U(1)_3
$$

$$
\mathcal{G}^{\rm SM} = U(3)_Q \times U(3)_U \times U(3)_D
$$

 $\begin{pmatrix} 0 & \sqrt{2} & \sqrt{2} & \sqrt{2} \\ \end{pmatrix}$ The broken symmetry cenerators live in non-line
h collecti $\operatorname*{ar}\sigma\text{-model}.$
re breaking.) theory is described by a $[U(3)/U(2)\times U(1)]^2$ non-linear $\sigma\text{-model.}$ The broken symmetry generators live in $\mathcal{G}^{\rm SM}/\mathcal{H}^{\rm SM}$ cosets. $\begin{pmatrix} 1 & 1 & 1 & 1 \end{pmatrix}$ thus the parameterization of $\mathbf{I}^T(\mathbf{Q})$ (i.e. $\mathbf{I}^T(\mathbf{Q})$) (i.e. $\left(c f$. little Higgs models with collective breaking.) described by a $[U(3)/U(2) \times U(1)]^2$ non-linear σ -model. The broken symmetry generators live in $\mathcal{G}^{\text{SM}}/\mathcal{H}^{\text{SM}}$ cosets the broken symmetry generators nic in y //t = cosets. theory is described by a $[U(3)/U(2)\times U(1)]^2$ non-linear σ -model.

The formalism $T_{\rm{loc}}$ for the subset it down to $U_{\rm{loc}}$ The formalism
1996 cosets. It is useful to factor the Yukawa matrices. It is useful to factor them out of the Yukawa matrices. It is useful to factor the Yukawa matrices. It is useful to factor the Yukawa matrices. It is u properties given below Eq. (4). These flavor transformations are broken once the Yukawa couplings obtain their we the eigenvalues of the two matrices are approximately aligned. We then the parameterization and the parameterization of the two matrices are approximately aligned. We thus use the parameterization of the parameterizatio therefore take Y^U ∼ diag (0, 0, yt) and Y^D ∼ diag (0, 0, yb). The breaking of the flavor group is dominated by the top T_{ho} factors lies and can induce significant new CPV in the sensitive to LMFV in the sensitive to LMFV vs. NLMFV vs. NLMFV vs. N are also identified. Another non-linear parameterization of MFV was presented in \mathbb{Z} . We focus on exploiting the MFV was presented in \mathbb{Z} general control obtained by our formalism in order to study its model independent implications. A modification of Γ diag Γ diag Γ diag (0, 0, 0, 0, 0, 0, 0, 0, Γ dominated by the top the <u>read to the formalism</u> properties given below Eq. (4). These flavor transformations are broken once the Yukawa couplings obtain their therefore take Y^U ∼ diag (0, 0, yt) and Y^D ∼ diag (0, 0, yb). The breaking of the flavor group is dominated by the top properties given below Eq. (4). These flavor transformations are broken once the Yukawa couplings obtain their therefore take Y^U ∼ diag (0, 0, yt) and Y^D ∼ diag (0, 0, yb). The breaking of the flavor group is dominated by the top Formalism. To realize ^GSM non-linearly, we promote the Yukawa matrices to spurions, with the transformation properties and the formations are broken on the Yukawa couplings of the Yukawa couplings of the Yukawa coupling background values of the two matrices are higherarchical and the two matrices are approximately aligned. We have a set of the two matrices are approximately aligned. We have a set of the two matrices are approximately alig <u>YU & YAYA</u>

The broken symmetry generators live in GSM/HSM cosets. It is useful to factor them out of them out of the Yukawa
It is useful to factor them out of the Yukawa matrices. It is useful to factor them out of the Yukawa matrice

 $H_{\rm eff}$ \sim 2 \times 2 complex spurions, while \sim 3 \times 3

where χ are two dimensional vectors. The play two dimensional vectors and the play the role play the role

 2×10^{-11} transitions. Conversely, the correlation between C in the BS and Bd systems, α

Without loss of generality the Y 's can be written as: The broken symmetry in GSM called with the symmetry $\frac{1}{1}$ Without loss of generality the Y's can be written as: **Properties given below Eq. (4). These flavor transformations with the Yukawa concerned vertical transformations obtain the Yukawa concerned vertical transitions of Vulkawa couplings obtain the Yukawa coupling vertical th** background values. The eigenvalues of the latter are hierarchical and the two matrices are approximately aligned. We $\overline{}$ Without loss of generality the V 's can be written as: : loss of generality the Y 's can be written as: \overline{U} enerality the Y 's can be written as: therefore take YU ∼ diagnosis and YD ∼ diagnosis dominated by the flavor group is dominated by the flavor group
The breaking of the flavor group is dominated by the flavor group is dominated by the top the top the top the Without loss of generality the Y's The broken symmetry generators is useful to the IT is useful to the Vulle of the Yukawa matrices. Without loss of generality the *Y'*s can be written as:

$$
Y_{U,D}=e^{i\hat{\rho}_Q}e^{\pm i\hat{\chi}/2}\tilde{Y}_{U,D}e^{-i\hat{\rho}_{u,d}},
$$

 \sim

 $\ddot{}$

, if $\frac{1}{2}$

 $\mathcal{L}(\mathcal{G})$

, if $\mathcal{L} \subset \mathbb{R}^d$

, (5)

where the reduced Yukawa spurions, $\tilde{Y}_{U,D}$, are $\tilde{Y}_{U,D}$ = $\text{a spurious}, \, \tilde{Y}_{U,D}, \, \text{are} \,\,\, \tilde{Y}_{U,D} = \begin{pmatrix} \phi_{u,d} & 0 \ 0 & y_{t,b} \end{pmatrix}.$ where the reduced Tukawa sp $,\, \tilde{Y}_{U,D},$ are $\,\tilde{Y}_{U,D}\,$ $= \begin{bmatrix} \varphi_{u,d} & \mathbf{0} \end{bmatrix}$ $\frac{1}{\sqrt{2}}$ $\begin{pmatrix} 0 \\ 0 \end{pmatrix}$ $9t,b$) \qquad $\sqrt{2}$ \mathbf{U} where the relation \mathbb{P} arrows, $\mathbb{P}(y, y)$ are $\mathbb{P}(y, y) = \begin{pmatrix} 0 & y_{t,b} \end{pmatrix}$. . The contraction of the contra \sim

purions, while $\hat{\chi}$ as
 $\hat{\gamma} = \begin{pmatrix} 0_{2 \times 2} \end{pmatrix}$. (6) 0 years of the control of t Here $\phi_{u,d}$ are 2×2 complex spurions, while $\hat{\chi}$ and $\hat{\rho}_i$, $i = Q, U, D$, are the 3×3 matrices spanned by the broken generators. Explicitly, generators. Explicitly, Here $\phi_{u,d}$ are 2×2 complex spurions, while $\hat{\chi}$ and $\hat{\rho}_i$, $i = Q, U, D$, are the 3×3 matrices spanned by the broken $\sqrt{2}$ $\frac{1}{2}$ generators, where $\frac{1}{2}$ Here $\phi_{u,d}$ are 2×2 complex spurions, while $\hat{\chi}$ and $\hat{\rho}_i$, $i = Q, U, D$, are the 3×3 matrices spanned by the broken χ and ρ_l , φ $\frac{1}{2}$

Here
$$
\phi_{u,d}
$$
 are 2×2 complex spurious, while $\hat{\chi}$ and $\hat{\rho}_i$, $i = Q, U, D$, are the 3×3 matrices spanned by the broken generators. Explicitly,

$$
\hat{\chi} = \begin{pmatrix} 0_{2 \times 2} & \chi \\ \chi^{\dagger} & 0 \end{pmatrix}, \qquad \hat{\rho}_i = \begin{pmatrix} 0_{2 \times 2} & \rho_i \\ \rho_i^{\dagger} & \theta_i \end{pmatrix},
$$

ⁱ , eiχˆ!

where χ are two dimensional vectors. The play two dimensional vectors and the play the role play the role

misalignment of the up and down Yukawa couplings and will therefore correspond to Vtd and Vts in the low energy

where χ are two dimensional vectors. The play two dimensional vectors and the play the role play the role play the role play the role play the play the play the role play the role play the role play the role play the r

02×² ρⁱ

misalignment of the up and down Yukawa couplings and will therefore correspond to Vtd and Vts in the low energy

ⁱ θⁱ

of spurion "Goldstone bosons". Thus the ρⁱ have no physical significance. χ, on the other hand, parametrizes the

 $\overline{}$ spurion "Goldstone bosons". Thus the physical significance. $\overline{}$

The ρ_i shift under the broken generators \Rightarrow
"Goldstone bosons", have no physical significance. The ρ_i shift under the broken generators \Rightarrow \rightarrow e bose , $\frac{1}{2}$, $\frac{1}{2}$ The ρ_i sum under the broken generators \Rightarrow
"Goldstone bosons", have no physical significance. , if $\mathcal{L} \subset \mathcal{L}$ $\overline{}$ The ρ_i shift under the broken generators \Rightarrow
"C 11" = " "Goldstone bosons", have no p

Under the flavor group the above spurions transform as,

eiρˆ!

, ρˆⁱ =

 $\mathcal{L}_{\mathcal{A}}$

Under the flavor group the above spurions transform as,

effective theory [see Eq. (14)].

misalignment of the up and down Yukawa couplings and will therefore correspond to Vtd and Vts in the low energy

Separating small & large spurions Eq. (7). Consequently ˆpin is shifted under GSM/HSM and can be set to a convenient value as discussed below. U **Separating small & large spurions** $\overline{}$, χ [ρi] are fundamentals of U(2)^Q [U(2)i] carrying charge −1 under the U(1)3, while φu,d are bi-fundamentals of As final step we also reduced the spurious spurious spurions", , \hat{p} are fundamentals of U(2) \hat{p} ian charge \hat{p} under the U(1)3, while \hat{p} are bi-fundamentals of U(1)3, while \hat{p} **Separation** As final step we also reduced the step we have the spurions of the spurions of the "Goddstone spurions", and the "Goddstone spurions", and the "Goddstone spurions", and the "Goddstone spurions", and the "Goddstone spurions YU YA MARA WA TARAFARA WA U , U , D Constating small 8. firso spurions Field on the broken generators and ^{on} the broken generators in the broken generators and ^{on th}e specified in the set of A s also redefine the quark fields by moding out the \bullet

Trick: flavor invariance is obtained by moding-out fields: $\,$ ce is obtained by moding-out fields: $\,$ \vert \vert d ieius. $\boxed{\text{Trick}}$ flavor invariance is obtained by moding-out fields: ef. Trick: Havor invariance is obtained by moding-out helds: $\frac{1}{\sqrt{2}}$

Introduction. Precision flavor and CP violation measurements provide very strong constraints on models of new

The tension with precision flavor tests is relaxed if the SM $_{\rm H}$ the only source of flavor breaking, σ

even in the presence of new particles and interactions [1–3]. This hypothesis goes under the name of Minimal Flavor

Violation (MFV). Sometimes additional assumptions are made — that the SM Yukawa couplings are also the only

source of CP violation (CPV), e.g. in [1], or that NP does not change the Lorentz structure of the effective weak

physics (NP) beyond the Standard Model (SM). For instance, #^K constrains the scale of maximally flavor violating

With the redefinitions above, invariance under the full flavor group is captured by the invariance under the unbro-

ken flavor subgroup ^HSM [8]. Thus, NLMFV can be described without loss of generality as a formally ^HSM–invariant

hamiltonian \mathcal{A} . We will not make the se assumptions, but will discuss the intervals of the intervals below.

to have a highly non-term in the structure flavor structure. The structure \mathcal{L}_max

The latter form reducible representations of ^HSM. Concentrating here and below on the down sector we therefore

 A lso φu,d (χ) form appropriate bi-fundamental ϕ fundamental) of H SM. The ϕ

With the redefinitions above, invariance under the full flavor group is captured by the invariance under the unbro-

ken flavor subgroup ^HSM [8]. Thus, NLMFV can be described without loss of generality as a formally ^HSM–invariant

 $\tilde u_L = e^{-i\hat\chi/2}e^{-i\hat\rho_Q}u_L,\quad \tilde d_L = e^{i\hat\chi/2}e^{-i\hat\rho_Q}d_L,\quad \tilde u_R = e^{-i\hat\rho_u}u_R,\quad \tilde d_R = e^{-i\hat\rho_d}d_R. \bigg[$ $\sum_{n=1}^{\infty} a_n \cdot \frac{1}{n} \cdot \frac{1}{n} \cdot \frac{1}{n} = \left(\tilde{d}^{(2)}_{\tau,n} \cdot \tilde{d$ Also $\phi_{u,d}$ (χ) form appropriate bi-fundamentals (fundeamental) of \mathcal{H}^{SM} . $\overline{\text{NLMFV}}$ described via re $_{\rm{2}}$ definition can be made for the up quarks. The reducible representations of \mathcal{H}^{SWI} , $d_{L,R} = (d_{L,R}^{(2)}, 0) + (0, b_{L,R}).$ d(2) definition can be made for the up quarks. described via requiring solely π ^{ord}-invariance: Also $\phi_{u,d}$ (χ) form appropriate bi-fundamentals (fundeamental) of \mathcal{H}^{SM} . $=$ $\overline{}$ τ definition can be made for the up τ With the redefinitions above, invariance \vert Species of $2\pi S M$ \tilde{j} α $(\tilde{j}^{(2)}, 0)$, $(0, \tilde{b})$ $I = \frac{1}{\sqrt{N}}$ \vert NLMFV described via requiring solely $\mathcal{H}^{\mathrm{out}}$ -invariance! \vert $i\hat{\chi}/2$ _c $-i\hat{\rho}_Q$ d_c $\tilde{\chi}_P = e^{-i\hat{\rho}_u}i\hat{\rho}_Q$ $\tilde{\lambda}_P = e^{-i\hat{\rho}_d}d\hat{\rho}_Q$ Form reducible representations of \mathcal{H}^{SM} , $\tilde{d}_{L,R} = (\tilde{d}_{L,R}^{(2)}, 0) + (0, \tilde{b}_{L,R}).$ $\overline{\Lambda}$ \mathbb{R}^2 $\overline{\mathcal{L}}$ $\overline{\text{MININ}}$ with the redefinition above, invariance under the full flavor group is captured by the unbro- $\left\{ \begin{array}{ll} \tilde u_L=e^{-i\hat\chi/2}e^{-i\hat\rho_Q}u_L,\hspace{0.5cm} \tilde d_L=e^{i\hat\chi/2}e^{-i\hat\rho_Q}d_L,\hspace{0.5cm} \tilde u_R=e^{-i\hat\rho_u}u_R,\hspace{0.5cm} \tilde d_R=e^{-i\hat\rho_Q}u_R, \end{array} \right.$ Form reducible representations of \mathcal{H}^{SM} , $\tilde{d}_{L,R} = (\tilde{d}_{L,R}^{(2)}, 0) + (0, \tilde{b}_{L,R}).$ $\left(\begin{array}{cccc} \text{Also } \varphi_{u,d} & (\chi) \text{ for all appropriate or-functions (tunderential) of } t \end{array} \right)$ NLMFV described via requiring solely \mathcal{H}^{SM} -invariance! $\begin{aligned} \mathcal{L}_L, \quad u_R &= e^{-\epsilon \cdot \mathcal{L}_L} u_R, \quad u_R &= e^{-\epsilon \cdot \mathcal{L}_L} u_R. \end{aligned}$ entals (fundeamental) of \mathcal{H}^{SM} . W_{max} above, invariance under the full flavor group is captured by the unbro-NLMFV described via requiring solely \mathcal{H}^{SM} -invariance! $\begin{aligned} \mathcal{L}_{q}^{(3)}(3) & \mathcal{L}_{q}^{(3)}(4) &$ Also $\phi_{u,d}$ (χ) form appropriate bi-fundamentals (fundeamental) of \mathcal{H}^{SW} .

∽ 104 TeV. Therefore, TeV scale NP which stabilizes the electroweak scale and is accessible and is accessible a
The electroweak scale and is accessible and is accessible at the LHC has accessible and is accessible and i

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ken flavor subgroup ^HSM [8]. Thus, NLMFV can be described without loss of generality as a formally ^HSM–invariant

The tension with precision flavor tests is relaxed if the SM Yukawa matrices are the only source of flavor breaking,

ken flavor subgroup ^HSM [8]. Thus, NLMFV can be described without loss of generality as a formally ^HSM–invariant

even in the presence of new particles and interactions [1–3]. This hypothesis goes under the name of Minimal Flavor

Violation (MFV). Sometimes additional assumptions are made — that the SM Yukawa couplings are also the only

source of CP violation (CPV), e.g. in [1], or that NP does not change the Lorentz structure of the effective weak

A useful language for discussing $M_{\rm eff}$ was introduced in σ vanishing σ vanishing σ

hamiltonian [4]. We will not make these assumptions, but will discuss their consequences below.

coupling the SM has an enhanced global symmetry. Focusing on the symmetry. Focusing on the quark sector this i
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[∼] ¹⁰⁴ TeV. Therefore, TeV scale NP which stabilizes the electroweak scale and is accessible at the LHC has

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U(2) and U(2)u,d. U(

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L,R, 0) + (0, ˜bL,R). Under flavor transformations ˜

to have a highly non generic flavor structure.

Separating small & large spurions **Separating small & large spurions** expansion in \bullet straightforward generalization of the known effective field theory description of the known effective field theory description of the known effective field theory description of spon-Eq. (7). Consequently ˆpin is shifted under GSM/HSM and can be set to a convenient value as discussed below. U **Separating small & large spurions** $\overline{}$, χ [ρi] are fundamentals of U(2)^Q [U(2)i] carrying charge −1 under the U(1)3, while φu,d are bi-fundamentals of As final step we also reduced the spurious spurious spurions", , \hat{p} are fundamentals of U(2) \hat{p} ian charge \hat{p} under the U(1)3, while \hat{p} are bi-fundamentals of U(1)3, while \hat{p} **Separation** As final step we also reduced the step we have the spurions of the spurions of the "Goddstone spurions", and the "Goddstone spurions", and the "Goddstone spurions", and the "Goddstone spurions", and the "Goddstone spurions U , U , D Constating small 8. firso spurions Field on the broken generators and ^{on} the broken generators in the broken generators and ^{on th}e specified in the set of A s also redefine the quark fields by moding out the \bullet

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Trick: flavor invariance is obtained by moding-out fields: Since the background field values of the relevant space in the relevant space in the relevant in the spirit sp Γ \vert Then, have inivaliance is odealited by inountg-our neids. $\frac{1}{2}$ is a straightforward generalization of the known effective field theory of the known effective field theory of the known effective field theory description of the known effective field theory description of spon Trick: flavor invariance is obtained by moding-out fields: Since the background field values of the relevant spurions are small, we can expand in them. $\,$ ce is obtained by moding-out fields: $\,$ \vert \vert d ieius. $\boxed{\text{Trick}}$ flavor invariance is obtained by moding-out fields: ef. Trick: Havor invariance is obtained by moding-out helds: $\frac{1}{\sqrt{2}}$

 $\begin{vmatrix} \tilde{u}_L=e^{-i\hat{\chi}/2}e^{-i\hat{\rho}_Q}u_L, & \tilde{d}_L=e^{i\hat{\chi}/2}e^{-i\hat{\rho}_Q}d_L, & \tilde{u}_R=e^{-i\hat{\rho}_u}u_R, & \tilde{d}_R=e^{-i\hat{\rho}_d}d_R. \end{vmatrix}$ Form roducible representations of 2^{SM} , $\tilde{d}_{z} = -(\tilde{d}^{(2)}$, 0), (0) \tilde{h}_{z} FOITH TEQUCIDIE IEDIESEIRANDIIS OF \mathcal{T} , $a_{L,R} = (a_{L,R}, 0) + (0, o_{L,R})$. $\overline{}$ MFV described via requiring solely $\mathcal{H}^{\cup w}$ -invariance! \vert Γ in a position to write down the flavor structures of \tilde{I} Form requcible representations of π^{--} , $d_{L,R} = (d_{L,R}^+, 0) + (0, b_{L,R})$. Also $\phi_{u,d}$ (χ) form appropriate bi-fundamentals (fundeamental) of \mathcal{H}^{SM} . $\overline{\text{NLMIV}}$ described via re $W = \frac{1}{\sqrt{2\pi}}$ in a position to write down the flavor structures of $\frac{1}{\sqrt{2}}$ for $\frac{1}{\sqrt{2}}$ fo Form reducible representations of \mathcal{H}^{SWI} , $d_{L,R} = (d_{L,R}^{(2)}, 0) + (0, b_{L,R}).$ $t=e^{-\epsilon\cdot\alpha}u_R, \quad u_R=e^{-\epsilon\cdot\alpha}u_R.$ orm reducible representations of \mathcal{H}^{SM} $\tilde{d}_{L,R} = (\tilde{d}_{L,R}^{(2)}, 0) + (0, \tilde{b}_{L,R})$ $\tilde u_L = e^{-i\hat\chi/2}e^{-i\hat\rho_Q}u_L,\quad \tilde d_L = e^{i\hat\chi/2}e^{-i\hat\rho_Q}d_L,\quad \tilde u_R = e^{-i\hat\rho_u}u_R,\quad \tilde d_R = e^{-i\hat\rho_d}d_R. \bigg[$ \overline{V} described via requiring solely $\mathcal{H}^{\rm SM}$ invariance definition can be made for the up quarks. The reducible representations of \mathcal{H}^{SWI} , $d_{L,R} = (d_{L,R}^{(2)}, 0) + (0, b_{L,R}).$ d(2) described via requiring solely π ^{ord}-invariance: Also $\phi_{u,d}$ (χ) form appropriate bi-fundamentals (fundeamental) of \mathcal{H}^{SM} . $=$ $\overline{}$ τ definition can be made for the up τ With the redefinitions above, invariance \vert Species of $2\pi S M$ \tilde{j} α $(\tilde{j}^{(2)}, 0)$, $(0, \tilde{b})$ $I = \frac{1}{\sqrt{N}}$ \vert NLMFV described via requiring solely $\mathcal{H}^{\mathrm{out}}$ -invariance! \vert $i\hat{\chi}/2$ _c $-i\hat{\rho}_Q$ d_c $\tilde{\chi}_P = e^{-i\hat{\rho}_u}i\hat{\rho}_Q$ $\tilde{\lambda}_P = e^{-i\hat{\rho}_d}d\hat{\rho}_Q$ Form reducible representations of \mathcal{H}^{SM} , $\tilde{d}_{L,R} = (\tilde{d}_{L,R}^{(2)}, 0) + (0, \tilde{b}_{L,R}).$ $\overline{\Lambda}$ \mathbb{R}^2 $\overline{\mathcal{L}}$ $\overline{\text{MININ}}$ with the redefinition above, invariance under the full flavor group is captured by the unbro- $\left\{ \begin{array}{ll} \tilde u_L=e^{-i\hat\chi/2}e^{-i\hat\rho_Q}u_L,\hspace{0.5cm} \tilde d_L=e^{i\hat\chi/2}e^{-i\hat\rho_Q}d_L,\hspace{0.5cm} \tilde u_R=e^{-i\hat\rho_u}u_R,\hspace{0.5cm} \tilde d_R=e^{-i\hat\rho_Q}u_R, \end{array} \right.$ Form reducible representations of \mathcal{H}^{SM} , $\tilde{d}_{L,R} = (\tilde{d}_{L,R}^{(2)}, 0) + (0, \tilde{b}_{L,R}).$ $\left(\begin{array}{cccc} \text{Also } \varphi_{u,d} & (\chi) \text{ for all appropriate or-functions (tunderential) of } t \end{array} \right)$ NLMFV described via requiring solely \mathcal{H}^{SM} -invariance! $\begin{aligned} \mathcal{L}_L, \quad u_R &= e^{-\epsilon \cdot \mathcal{L}_L} u_R, \quad u_R &= e^{-\epsilon \cdot \mathcal{L}_L} u_R. \end{aligned}$ entals (fundeamental) of \mathcal{H}^{SM} . W_{max} above, invariance under the full flavor group is captured by the unbro-NLMFV described via requiring solely \mathcal{H}^{SM} -invariance! $\begin{aligned} \mathcal{L}_{q}^{(3)}(3) & \mathcal{L}_{q}^{(3)}(4) &$ Also $\phi_{u,d}$ (χ) form appropriate bi-fundamentals (fundeamental) of \mathcal{H}^{SW} .

d-type flavor violation is obtained by shifting to *d*-mass basis: $\frac{u}{\sqrt{2}}$ are diagonal in Eq. (12) are down-quark mass basis. $\boldsymbol{Y_U} = \boldsymbol{V_{\text{CKM}}^\dagger} \text{diag}(m_u, m_c, m_t), \, \boldsymbol{Y_D} = \text{diag}(m_d, m_s, m_b).$ spurions taking taking the background values puriously while flavor violations σ induced values σ induced values σ flavor violation is obtained by shifting to d -mass basis: $Y_U = V_{\text{CKM}}^{\dagger} \text{diag}(m_u, m_c, m_t), Y_D = \text{diag}(m_d, m_s, m_b)$ r violation is obtained by shifting to d -mass basis: λ k en flavor subgroup HSM \sim Thus, NSMFV can be described with loss of generality as a formal set of generality as a formally HSM d-type flavor violation is obtained by shifting to d-mass basis: even in the presence of new particles and interactions [1–3]. This hypothesis goes under the name of Minimal Flavor source of CP violation (CPV), e.g. in [1], or that NP does not change the Lorentz structure of the effective weak $\big|$ d-type flavor violatic d-type flavor violation is obtained by shifting to d-mass basis: ken flavor subgroup HSM [8]. Thus, NLMFV can be described with loss of generality as a formally HSM–invariant
And the description of generality as a formally HSM–invariant as a formally HSM–invariant as a formally HSM–in μ by μ between the Standard Model (SM). For instance, μ instance, μ to have a highly non generic flavor structure.

$$
\rho_Q = \chi/2, \,\hat{\rho}_{u,d} = 0, \,\phi_d = \text{diag}(m_d, m_s)/m_b,
$$

With the redefinitions above, invariance under the full flavor group is captured by the invariance under the unbro-

to have a highly non-term in the structure flavor structure. The structure \mathcal{L}_max

The latter form reducible representations of ^HSM. Concentrating here and below on the down sector we therefore

 A lso φu,d (χ) form appropriate bi-fundamental ϕ fundamental) of H SM. The ϕ

$$
\chi^{\dagger} = i(V_{td}, V_{ts}), \qquad \phi_u = V_{\text{CKM}}^{(2)\dagger} \text{ diag}\left(\frac{m_u}{m_t}, \frac{m_c}{m_t}\right). \quad \text{(} (\phi_u)_{12} \sim \lambda^5 \text{)}
$$

 Tuesday, July 6, 2010

coupling the SM has an enhanced global symmetry. Focusing on the symmetry. Focusing on the quark sector this i
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ken flavor subgroup ^HSM [8]. Thus, NLMFV can be described without loss of generality as a formally ^HSM–invariant

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GMFV Predictions top and both Yukawa couplings. Beginning with the left-left-left (LL) bilinears, to see order in \mathcal{L} \mathbb{R} in the background field values of the relevant spurions are small, we can expand in the m. \mathbb{R} We are now in a position to write down the flavor structures of $\mathbf G$ and $\mathbf H$ in a position which low energy flavor $\mathbf G$ observables can be constructed. We work to lead the spurions that break HSM, but to all orders in the spurions that break HSM, but to all orders in the spurions in the spurion order in the spurion order in the spurion orde

LO flavor violation comes from: (omitting gauge and Lorentz indices) acion comes nomil $\overline{}$ ^L , (12) top and bottom Yukawa couplings. Beginning with the left-left (LL) bilinears, to second order in χ, φu,d one finds $\overline{}$ LV

- Kaon phys. (no CPV): $\tilde{d}_L^{(2)} \phi_u \phi_u^{\dagger} \tilde{d}_L^{(2)}, \quad \tilde{d}_L^{(2)} \chi \chi^{\dagger} \tilde{d}_L^{(2)}$. $L^{(2)}$.
- \blacksquare Kaon: contributions from charm $\&$ top are decorrelated. \blacksquare basis the Yukawa couplings take the form Y^U = V † Kaon: contributions from charm & top are decorrelated.

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GMFV Predictions top and both Yukawa couplings. Beginning with the left-left-left (LL) bilinears, to see order in \mathcal{L} \mathbb{R} in the background field values of the relevant spurions are small, we can expand in the m. \mathbb{R} We are now in a position to write down the flavor structures of $\mathbf G$ and $\mathbf H$ in a position which low energy flavor $\mathbf G$ observables can be constructed. We work to lead the spurions that break HSM, but to all orders in the spurions that break HSM, but to all orders in the spurions in the spurion order in the spurion order in the spurion orde

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GMFV Predictions top and both Yukawa couplings. Beginning with the left-left-left (LL) bilinears, to see order in \mathcal{L} \mathbb{R} in the background field values of the relevant spurions are small, we can expand in the m. \mathbb{R} The latter of GMFV Predictions of the down sector which low energy flavor which low energy flavor which low energy flavor we the down sector observables can be constructed. We work to lead the spurions that break HSM, but to all orders in the spurions that break HSM, but to all orders in the spurions in the spurion order in the spurion order in the spurion orde $\overline{}$, $\overline{}$ (0, $\overline{}$, $\overline{\phantom{a$ T COICCIONS d

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LO flavor violation comes from: (omitting gauge and Lorentz indices) acion comes nomil $\overline{}$ ^L , (12) top and bottom Yukawa couplings. Beginning with the left-left (LL) bilinears, to second order in χ, φu,d one finds $\overline{}$ LV \bigcup \sim 1 decret 20 de ratio 20 de ratio 20 de ratio 20 de ratio 20 de rat spurions taking the background values ρ^Q = χ/2, ˆρu,d = 0, φ^d = diag (md, ms)/mb, while flavor violation is induced L

Kaon phys. (no CPV): $\tilde{d}_L^{(2)} \phi_u \phi_u^{\dagger} \tilde{d}_L^{(2)}, \quad \tilde{d}_L^{(2)} \chi \chi^{\dagger} \tilde{d}_L^{(2)}$. $L^{(2)}$. k en flavor subgroup $\overline{\chi(2)}$ can be described without loss of $\overline{\chi(2)}$ and $\overline{\chi(2)}$ and $\overline{\chi(2)}$ **Examplys. (no CPV):** $\tilde{d}_L^{(2)} \phi_u \phi_u^{\dagger} \tilde{d}_L^{(2)}$, $\tilde{d}_L^{(2)} \chi \chi^{\dagger} \tilde{d}_L^{(2)}$. $\mathbf{v} = \mathbf{v} + \mathbf{v}$

 \blacksquare Kaon: contributions from charm $\&$ top are decorrelated. \blacksquare basis the Yukawa couplings take the form Y^U = V † ontributions from charm & top are decorrelated taneous symmetry breaking \mathcal{S} . The only difference is that YU,D are not aligned, as manifested by $\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal{S}=\mathcal$ \blacksquare Kaon: contributions from charm $\&$ top are deco We are now in a position to write down the flavor structures of Γ and Γ and Γ low energy function Γ (10) From charm & top are decorrelated. . (14) Kaon: contributions from charm & top are decorrelated.

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Hard to detect: Buras, Guadagnoli & Isidori (10), d_{max} declares choice of spuriton background values.

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 $\frac{1}{\sqrt{2}}$

χ† = i(Vtd, Vts), φ^u = V (2)†

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 $\mathcal{L}_{\mathcal{L}}$ can be complex for the SM phase beyond the SM phase beyond the SM phase. The leading flavor $\mathcal{L}_{\mathcal{L}}$

basis the Yukawa couplings take the form Y^U = V † CKMdiag (mu, mc, mt), Y^D = diag (md, ms, mb). This corresponds to Γ mixing impliestions. in following treppersons, Γ $\overline{ }$ $\overline{ }$ indixing $\overline{ }$, \overline{p} , coincide with the mass-eigenstate with the mass- \mid D mixing implications in following transp The left-right-right-right-right-right-right (RR) bilinears which contribute to flavor mixing are in turn (at leading order α $\mathbf{f}_{\mathbf{a}}$ left-right (RR) bilinears which contribute to flavor mixing are in turn (at leading order $\mathbf{f}_{\mathbf{a}}$ D mixing implications in following transparency.

 B phys.: $\overline{\widetilde{d}^{(2)}_L}\chi\widetilde{b}_L,$ $\overline{\widetilde{d}^{(2)}_L}\chi\widetilde{b}_R,$ & possibly $(B_s$ only) from $\widetilde{d}^{(2)}_R\phi_d^{\dagger}\chi\widetilde{b}_{R}$

 T first two bilinears in the down-quark mass basis and down-quark mass basis and do not induce flavor violation. In this case of induce flavor violation. In this case of induce flavor violation. In this case of induce f B: RH currents are non-Hermitians allows for new CPV. \mathbf{r} $\overline{}$ To make contact with the more familiar MFV notation, consider down quark flavor violation from LL bilinears. We To make contact with the more familiar MFV notation, consider down quark flavor violation from LL bilinears. We B: RH currents are non-Hermitians allows for new CPV.

(SUSY: Colangelo et. al., 0807.0801[ph]) $\frac{1}{2}$ $\begin{bmatrix} 1 & 1 \end{bmatrix}$

 $\mathsf{y}, \mathsf{C} \mathsf{r}$ in $\mathsf{D}_\mathcal{S}$ bounds on in D_d system. Generically, CPV in B_s bounds on in B_d system.

+ ··· , (17) d). Following the discussion in the Introduction, the Internet of LMFV limit corresponds to \mathcal{L} discussion in the α (without light RH currents they are fully correlated) $\big|$

can then expand in the Yukawa couplings,

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in χ, φu,d spurions),

TMEV_D in MEV₀ could arise formation **be end over the SM expectations by constant of the SM expectations of the SM expectations in SM expectations** GMFV vs. LMFV & CPV in $D^0 - \bar{D}^0$ mixing

An enhancement of both *B^s* → #⁺#[−] and *B^d* → #⁺#[−] respecting the MFV relation Γ(*B^s* → **f** *m*^{*t*}/m^{*b*} a^{*n*}/m^{*b*}, *n*^{*n*}/m^{*b*} a^{*n*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/*m*^{*i*}/*m*^{*i*}/*m*^{*i*}/*m*^{*i*}/*m*^{*i*}/*m*^{*i*}/*m*^{*i*}/*m*^{*i*}/*m*^{*i*}/*m* Kagan, et. al (09) ; Gedalia, et. al (09) .

 S is to top $F(\mathcal{S})$ for all \mathcal{S} for all \mathcal{S} emergency for a MFV scale tan \mathcal{S}

of ∼ 1 TeV, this can lead to *Br*(*t* → *cX*) ∼ *O*(10−⁵) [40], which may be within the reach of

The breaking of the *G*SM flavor group and the breaking of the discrete CP symmetry are not necessarily related, and we can add flavor diagonal CPV phases to generic MFV models [60,

 $61, 125$. Because of the experimental constraints on electric dipole moments (EDMs), which moments (EDMs), whi

are generally sensitive to such flavor diagonal phases \mathbb{F}_q , in this more general case the bounds \mathbb{F}_q

on the NP scale are substantially higher with respect to the "minimal" case, where the Yukawa α

couplings are assumed to be the only breaking sources of both symmetries [37].

♦ Comparable NP contributions from strange & bottom (unlike SM) **A** Comparable NP contributions from strange & bottom (unlike SM) \sum Compo contribution from the strange and bottom quarks does not apply for a strange and bottom quarks does not apply f ζ¹ = *e*²*i*^γ + 2*rsbeⁱ*^γ + *r*² *sb* ∼ 1*.*7*i* + *r*GMFV [2*.*4*i* − 1 − 0*.*7 *r*GMFV (1 + *i*)] *,*

$$
C_1^{cu} \propto \left[y_s^2 \left(V_{cs}^{\text{CKM}} \right)^* V_{us}^{\text{CKM}} + \left(1 + r_{\text{GMFV}} \right) y_b^2 \left(V_{cb}^{\text{CKM}} \right)^* V_{ub}^{\text{CKM}} \right]^2
$$

$$
C_1^{cu} \propto \left[y_s^2 \left(V_{cs}^{\text{CKM}} \right)^* V_{us}^{\text{CKM}} + \left(1 + r_{\text{GMFV}} \right) y_b^2 \left(V_{cb}^{\text{CKM}} \right)^* V_{ub}^{\text{CKM}} \right]^2
$$

$$
V_{\text{GMFV} \text{ result of}}^{\text{r} \text{symmation}} \sum_n y_b^n
$$

TMEV_D in MEV₀ could arise formation **be end over the SM expectations by constant of the SM expectations of the SM expectations in SM expectations** GMFV vs. LMFV & CPV in $D^0 - \bar{D}^0$ mixing

An enhancement of both *B^s* → #⁺#[−] and *B^d* → #⁺#[−] respecting the MFV relation Γ(*B^s* → **f** *m*^{*t*}/m^{*b*} a^{*n*}/m^{*b*}, *n*^{*n*}/m^{*b*} a^{*n*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/m^{*i*}/*m*^{*i*}/*m*^{*i*}/*m*^{*i*}/*m*^{*i*}/*m*^{*i*}/*m*^{*i*}/*m*^{*i*}/*m*^{*i*}/*m*^{*i*}/*m* Kagan, et. al (09) ; Gedalia, et. al (09) .

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TMEV_D in MEV₀ could arise formation GMFV vs. LMFV & CPV in $D^0 - \bar{D}^0$ mixing **be end over the SM expectations by constant of the SM expectations of the SM expectations in SM expectations f** *m*^{*t*}/m^{*b*}, *n*^{*n*} An enhancement of both *B^s* → #⁺#[−] and *B^d* → #⁺#[−] respecting the MFV relation Γ(*B^s* → Kagan, et. al (09) ; Gedalia, et. al (09) . **A** Comparable NP contributions from strange & bottom (unlike SM) contribution from the strange and bottom quarks does not apply for a strange and bottom quarks does not apply f ◆ Comparable NP contributions from strange & bottom (unlike SM) \sum Compo ζ¹ = *e*²*i*^γ + 2*rsbeⁱ*^γ + *r*² *sb* ∼ 1*.*7*i* + *r*GMFV [2*.*4*i* − 1 − 0*.*7 *r*GMFV (1 + *i*)] *,* $\sum_{x_i = y_s^2} \left| \frac{V_{us}^{\text{CKM}} V_{cs}^{\text{CKM}}}{v_s} \right| \sim 0.5$! ! y_s^2 $V_{us}^{\rm CKM}V_{cs}^{\rm CKM}$ | | $r_{sb} \equiv$ $\vert \sim 0.5$ *,* | y_b^2 $V_{ub}^{\text{CKM}}V_{cb}^{\text{CKM}}$ operator to *D* − *D* mixing is given by | where *γ ≈ 670o is the relevant phase of the unitarity* triangle. We thus learn that MFV models were that MFV models $V_{\rm FV}({V_{cb}^{\rm CKM}})^* \, V_{ub}^{\rm CKM} \big]^2 \quad ,$ $C_1^{cu} \propto \left[y_s^2\right]$ $\left(V_{cs}^{\text{CKM}}\right)^*$ V_{us}^{CKM} $r_{us}^\mathrm{CKM} + (1 \mid r_\mathrm{GMFV}) y_b^2$ [∼] ³ [×] ¹⁰−⁸ assuming a V_{cb} for the CPV part of the CPV ϵ compared to the CP conserving part , and can provide a measurable signal. In Fig. 9 we show in Fig. 9 we sho $|x_{12}^{NP}/x|$ pink (yellow) the range predicted by the range predicted by the LMFV (GMFV) class of models. The GMFV yellow $\mathcal{L}_{\mathcal{A}}$ 35 band is obtained by scanning the range *r*GMFV ∈ (−1*,* +1) (but keeping the magnitude of *Ccu r*_{FV} result of $\lim_{n \to \infty} \sum_{n} y_b^n$ Size able contributions to top FCNC can also emergency Determining what "phase" of ∼ 1 TeV, this can lead to *Br*(*t* → *cX*) ∼ *O*(10−⁵) [40], which may be within the reach of describes nature yield microscopic info'. Well beyond the LHC reach! The **GSM flavor** group and the breaking of the discrete CP symmetry and the discrete CP symmetry are not the discrete CP sy necessarily related, and we can add flavor diagonal CPV phases to generic MFV models [60, 61.68 and 61.68 constraints on 2.68 constraints on 2.68 constraints (EDMs), which moments (EDMs), which are generally sensitive to such $\sin 2\sigma_D$ -1.0 -0.5 0.5 substantially higher with respect to the 1.0

couplings are assumed to be the only breaking sources of both symmetries [37].

Gedalia, et. al (09).

♦ Even in 2-gen' case (with flavor diag' CPV) one gets MFV-CPV:

The SM basic vectors: $\mathcal{A}_u \equiv (Y_u Y_u^{\dagger})_{\mathsf{t}^k}$, $\mathcal{A}_d \equiv (Y_d Y_d^{\dagger})_{\mathsf{t}^k}$.

Define a covariant CPV direction $\hat{J} \propto [\mathcal{A}_u, \mathcal{A}_d]$

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The 2-gen' "Jarlskog": $X^J \propto \text{tr}(X_Q[\mathcal{A}_d, \mathcal{A}_u]) \neq 0$, $\begin{matrix} J \\ J \\ J \end{matrix}$

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If $X^{\text{NP}} \propto [\mathcal{A}_u, \mathcal{A}_d] \Rightarrow \text{new CPV (GMFV)!}$

Underlying physics of GMFV & $h_s \gg h_s$?

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(11)

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contributions of higher powers of the Yukawa couplings ble interesting examples are supersymmetric extensions Next: other interesting way + insight on EW physics! (LLRR) of the SM at large tan \mathcal{S} \mathcal{S} \mathcal{S} \mathcal{S} \mathcal{S} \mathcal{S} \mathcal{S} or \mathcal{S} $\mathcal{S$

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The contribute dominantly and may contribute dominantly and may contribute dominantly and may contribute domin

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Warped Exra Dimension

Randall Sundrum (RS)

RS1 & the Hierarchy Problem

Randall-Sundrum, PRL (99)

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$Fields$ (quarks) \Rightarrow bulk

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The RS "little" CP problem

◆ Combination of ϵ_K & ϵ'/ϵ_K ⇒ $M_{KK} = \mathcal{O}(10 \text{ TeV})$

UTFit; Davidson, Isidori & Uhlig (07); Blanke et al.; Casagrande et al.; Csaki, Falkowski & Weiler; Agashe, Azatov & Zhu (08)

 \blacklozenge Contributions to EDM's are $O(20)$ larger than bounds.

Agashe, GP & Soni (04)

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Severe tuning problem or fine tuning problem & null LHC pheno'.

Ultra natural warped model from flavor triviality or Sweet spot RS

C. Delaunay, O. Gedalia, S.J. Lee & GP (10)

5D MFV & Shining

What if we give up on solving the flavor puzzle? Rattazzi & Zaffaroni (00), Cacciapaglia, Csaki, Galloway, Marandella, Terning & Weiler (07)

♦ Rattazzi-Zaffaroni's (RZ) model: excellent & elegant protection

but no solution for the little hierarchy problem?

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♦ Rattazzi-Zaffaroni's (RZ) model: excellent & elegant protection but no solution for the little hierarchy problem?

Solution: Hierarchic 5D MFV (bulk RZ)

 $\blacklozenge Y_{u,d}$ => 5D Yukawa the only source of flavor breaking.

Fitzpatrick, GP & Randall (07) Csaki, et al. (09)

Also, bulk masses are functions of same spurions:

$$
C_{u,d} = Y_{u,d}^{\dagger} Y_{u,d} + \dots, \ C_Q = Y_u Y_u^{\dagger} + Y_d Y_d^{\dagger} + \dots,
$$

Ultra naturalness is observed that such a low scale is a low scale in the light for relatively flat light fermions, contribute the set of th from cancellation of the S parameter. Moreover, we show in Fig. 6, as a function of the light

 $M_{\rm KK}\lesssim 2\,{\rm TeV}$

Contours of mKK are for {1.6, 1.7, 1.8, 2, 2.2} TeV from dark to lighter blue. Contours of Y^t = 7, 3

are shown in red solid and red dashed respectively. Right: Lower bound on the KK scale at the

sweet spot cQ³ " 0.1, c^t " 0.48 as a function of ci. On the same plot the 95% CL bound on

 \mathcal{N}_{M} or 3 other cases: c \mathcal{N}_{M} = 0.37, cb = 0.37, cb = 0.37, cb = 0.37, cb = 0.38, cb = 0.38, cb = 0.37, cb = 0.38, c

and complete α = 0.37, ch α = case α = case α = 0.6 (dashed). For the lower bound is around is arou

 $\begin{array}{|c} 0.5 \end{array}$

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\blacklozenge New type of LHC pheno', flavor gauge bosons.

Csaki, Lee, GP, Weiler, in progress.

 1.9 TeV. We use diagonally top mass of multipliers of multipliers of multipliers of multipliers of \sim Tuesday, July 6, 2010

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What are model's flavor predictions?

♦ Since the bulk masses are in the exponent => GMFV.

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What are model's flavor predictions? m KK ! 1.5 TeV, consistent with EWPT3. In a case with EWPT3. In a case where consistent with handle right hand
In a case with the right handle T_{A} \mathbf{v} vitat and models haven predictions.

1.5 − c^x

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stronger than for Bd, but still weaker than the one from Q1. Note that the Q¹ contribution

¹ [−] ²

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\n- **8.4 system:**
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\left. \frac{C_4}{C_1} \right|_{2\text{TeV}} \approx 40 \frac{m_d}{m_b} \cdot \frac{(\delta f_{D^{31}}^2)}{(\delta f_{Q^{31}}^2)}
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from Q¹ and Q⁴ are C. Delaunay, O. Gedalia, S.J. Lee & GP (10)

relation between the contributions of Q⁴ and Q¹ to B^d mixing:

side of Eq. (15) becomes 2.4 1−2 cQ3 1−2 cQ3 1−2 cQ3 1−2 cQ3 2.4 1−2 cQ3 2.4 1−2 cQ3

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\n→ $\frac{O_1 \& O_4 \text{ decouple.}}{(\delta \text{ in the image})}$
\n**6** By a system: $\frac{C_4}{C_1}\Big|_{2\text{TeV}} \approx 39 \frac{m_s}{m_b} \cdot \frac{(\delta f_{D^{32}}^2)}{(\delta f_{Q^{32}}^2)}$
\n→ $\frac{(\text{ii}) \text{ Universal one}}{(\text{iii}) B_s \text{ dominated}}$

¹ [−] ²

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 $O_1 \& O_4$ decouple. Interpolate: (i) no NP $\frac{D^{31}}{Q^{31}}$ \longrightarrow $\frac{U_1 \alpha U_4}{\alpha U_1 \alpha U_2}$ accoupic

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from Q¹ and Q⁴ are

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Summary

♦ Assuming no direct CPV, data robustly tests SM prediction, almost no assumptions on long dist' QCD are made (exp' test).

◆ Data is consistent with NP interpretation favors large Bs contributions but not robustly.

```
♦ Can be accounted for by MFV.
```
♦ Ultra natural warped models => GMFV => can explain the data via KK gluon exchange, via LLRR operators.

\blacklozenge Low KK scale => soon tested \oslash LHC+flavor gauge bosons.