What have we learned about flavor from experiment

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DPF 2013, Santa Cruz

many thanks to Sebastian Jaeger, Jorge Camalich, Gilad Perez and Jure Zupan for sharing unpublished results with me
Standard Model Higgs, vacuum metastability

- we are faced with a renormalizable theory, metastable vacuum
  no clear indication for $M_{np} < M_{pl}$

- $\lambda$ never gets too negative: tunneling probability to true vacuum longer than age of universe

- from Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia ’13
• The traditional role of flavor physics - provide effective theories scales of new physics

• weak scale (V-A), charm quark mass ($K - \bar{K}$ mixing), top mass ($B - \bar{B}$ mixing)

• where do we stand today in the search for the next scale of new physics
Low $p_T$
\[ \bar{B}_d \rightarrow \bar{K}^{*0} \rightarrow K^- \pi^+ \ell^+ \ell^- \]

- semileptonic operators: SM dominated by the electroweak penguin operators

\[ Q_{7\gamma} = \frac{e}{16\pi^2} \hat{m}_b \bar{s}\sigma_{\mu\nu} P_R F^{\mu\nu} b \]

\[ Q_{9V} = \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l) \]

\[ Q_{10A} = \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu \gamma^5 l) \]

- with NP could have operators with opposite chirality, (pseudo)scalar, tensor currents,...
  eg: \( Z' \), susy loops, new Higgs penguins,.....
• The lepton pair and $K^*$ can have three helicities

$$\lambda = \pm 1, 0$$

The decay amplitudes given in terms of products of leptonic and hadronic amplitudes

hadronic amplitudes have three possible helicities $H(\lambda)$
correspondence with leptonic currents

$$\bar{\ell} \gamma_{\mu} \ell \rightarrow H_V(\lambda), \quad \ell \gamma_{\mu} \gamma_5 \ell \rightarrow H_A(\lambda), \ldots$$

$H_{V,A,..}(\lambda)$ depend on $q_{\ell \ell}^2$, Wilson coefficients $C_{7V}, C_{9V}, C_{10A}, \ldots$, form factors, factorizable, and non-factorizable effects (power corrs)

• SM V-A structure $H^+ << H^-, H^0$
• A lot of information in the angular dependence of the decays:
  The four-fold differential spectrum

\[
\frac{d^{(4)}\Gamma}{dq^2 \, d(\cos \theta_i) \, d(\cos \theta_k) \, d\phi} = \frac{9}{32 \pi} \left( I_1^s \sin^2 \theta_k + \ldots \right)
\]

contains 12 angular coefficients \( I_i \) (notn. of Jaeger, Camalich ’12)

related to well known \( A_{FB} \)

\[
\begin{align*}
I_6^s &\propto \text{Re} \left[ H_V^- (H_A^-)^* - H_V^+ (H_A^+)^* \right] \\
I_3 &\propto \text{Re} \left[ H_V^+ (H_V^-)^* \right] + (V \rightarrow A) \\
I_5 &\propto \text{Re} \left[ (H_V^- - H_V^+)(H_A^0)^* \right] + (V \leftrightarrow A)
\end{align*}
\]

related to \( P_5^f \)

\[
I_3 \approx 0 \quad \text{in SM due to H+ suppression - tests for RH currents}
\]
“Clean” observables

• new generation of observables $P_i^{(i)}$ with reduced form factor
dependence at large recoil, $0.1 < q^2 < 8 \text{ GeV}^2$, due to cancelations
with denominators

Descotes-Genon, Hurth, Matias, Virto ’13; Matias, Mescia, Ramon, Virto ’12; Becirevic, Schneider ’11;
Bobeth, Hiller, van Dyk ’10; Altmanshofffer, Ball, Bharucha, Buras, Straub ’08

• numerators and denominators are CP averaged integrals over
bins of $q^2$, eg.

$$-\frac{A_{T_{\text{Re}}}}{2} \sim P_2 \sim \frac{\int I_6^s dq^2}{\int \sqrt{F_T F_L} dq^2}, \quad P_5' \sim \frac{\int I_5 dq^2}{\int \sqrt{F_T F_L} dq^2}$$

$F_L =$ longitudinal pol. fraction; $F_T = 1 - F_L =$ transverse pol. fraction

$P_2$ is the ‘normalized’ $A_{FB}$ (forward-backward asymmetry of $\mu^-$)
SM theory predictions show good overall agreement with recent LHCb measurements

some speculation about ‘anomalies’ at low $q^2$ in $P'_5$, $P_2$

Descotes-Genon, Matias, Virto; Altmanshoffer, Straub; Gauld, Goertz, Hasich

relative to SM theory errors in eg, Descotes-Genon, Hurth, Matias, Virto ’13

from Serra, EPS ’13:

$P_2$ is the evolved version of $A_{FB}$, but, they play a complementary role.
It magnifies a tiny tension in the second bin of $A_{FB}$. ” - from Matias, EPS ’13
Results for new observables

- Discrepancy with respect to SM predictions (arXiv:1303.5794) at low $q^2$
- 3.7 sigma discrepancy in the region $4.3 < q^2 < 8.68$ GeV$^2$/c$^4$
- 0.5% probability (2.8 sigma) to observe such a deviation considering 24 independent measurements
- 2.5 sigma discrepancy in the region $1.0 < q^2 < 6.0$ GeV$^2$/c$^4$

N.B.: Jaeger-Camelich (arXiv:1212.2263) have predictions in the region $1.0 < q^2 < 6.0$ GeV$^2$/c$^4$ with much larger theoretical error and small shift in the central value (QCD factorization breaking + ccbar loop)

*slide from N. Serra EPS 2013
treatment of $O(\Lambda/m_b)$ power correction uncertainties is ad-hoc - insufficient to claim the existence of anomalies

e.g., in Descotes-Genon, Hurth, Matias, Virto ’13 helicity amplitudes parametrized as

$$H_i^\lambda = (H_i^\lambda)^0 [1 + C_i e^{i\theta_i}]$$

the $C_i, \theta_i$ varied independently in the ranges

$$C_i \in [-0.1, 0.1], \quad \theta_i \in [-\pi, \pi]$$

For each observable,

$$1\sigma \text{ uncertainty} = \text{interval containing 66\% of scatter about median}$$
Theory uncertainties  
Jaeger, Camalich ’12

- leading power hadronic params: soft form factors, decay constants, light cone distribution amps,...

- $O(\Lambda/m_b)$ power corrections to heavy quark / large energy limit form factor relations: surveyed their violation in calculations which automatically include power corrections, (LCSR, QCDSR, DSE)

- $O(\Lambda/m_b)$ non-factorizable power corrections, mainly ‘charm loops’ from current-current operators: estimated in LCSR approach

eg.,

For each observable, the full scatter ranges obtained in each category are added in quadrature
- O(TeV) NP, e.g., $Z'$ exchange contributions to $C_{9V}$, $C'_{9V}$, could be lurking in the data Descotes-Genon, Matias, Virto; Altmanshoffer, Straub

- However, the dedicated assessment of power correction uncertainties by Jaeger, Camalich + recent LHCb measurements significant theoretical improvements will probably be required, in order to have a window to NP based solely on CP conserving observables in $B \rightarrow K^* \mu^+ \mu^-$ at low $q^2$ (with the exception of the lowest bin)
\[ B_s \rightarrow \mu^+\mu^-, \quad B_d \rightarrow \mu^+\mu^- \]

- **semileptonic effective operators**

SM+NP: \[ Q_{10A} = \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu\gamma^5 l) \]

NP: \[ Q_S(P) = \frac{\alpha_{em}}{4\pi} [\bar{s}P_R b][\bar{\ell}(\gamma^5)\ell] \]

+ opposite chirality ops

- **SM predictions** Buras, et al.'13

\[
\begin{align*}
\text{Br}(B_s \rightarrow \mu^+\mu^-)_{\text{SM}} &= (3.56 \pm 0.18) \times 10^{-9} \\
\text{Br}(B_d \rightarrow \mu^+\mu^-)_{\text{SM}} &= (1.03 \pm 0.07) \times 10^{-10}
\end{align*}
\]

largest uncertainties from CKM, 5% from higher order EWK corrections

- **LHCb /CMS averages** Serrano CERN seminar

- Several methods used, giving compatible results

\[
\begin{align*}
\text{BR}(B_s^0 \rightarrow \mu^+\mu^-) &= (2.9 \pm 0.7) \times 10^{-9} \\
\text{BR}(B^0 \rightarrow \mu^+\mu^-) &= (3.6^{+1.6}_{-1.4}) \times 10^{-10}
\end{align*}
\]

Observation!!

Not statistically significant
$B_s \to \mu^+ \mu^- \text{ vs } B_d \to \mu^+ \mu^-$

"Golden" MFV relation: Buras '03; Hurth, Isidori, Kamenik, Mescia '08

\[
\frac{\text{Br}(B_d \to \mu^+ \mu^-)}{\text{Br}(B_s \to \mu^+ \mu^-)} \sim \frac{f_{B_d}^2}{f_{B_s}^2} \frac{\tau_{B_d}}{\tau_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2} \sim 0.03
\]

holds for SM, MFV, $U(2)^3$ flavor symmetry

- experimental ratio
  (assuming SM time integration for $B_s$)

\[
\frac{\text{Br}(B_d \to \mu^+ \mu^-)_{\text{exp}}}{\text{Br}(B_s \to \mu^+ \mu^-)_{\text{exp}}} \sim 0.14 \pm 0.06
\]

interesting future flavor symmetry diagnostic!

* slide adopted from Altmanshofer, Snowmass Argonne Intensity Frontier workshop
CP violation in $D - \bar{D}$ mixing

CP violation (CPV) in charm provides a unique probe of New Physics (NP)

- sensitive to NP in the up sector
- SM charm physics is CP conserving to first approximation (2 generation dominance)
- In the SM, CPV in mixing enters at $O(V_{cb}V_{ub}/V_{cs}V_{us}) \sim 10^{-3}$

In view of the consensus that can be obtained in the SM $\Delta A_{CP} \leq O(\text{few} \times 10^{-3})$

D mixing is probably the only open window for NP in charm CPV, at least in the absence of future precision lattice data on charm direct CPV
The “theoretical” mixing parameters

\[ x_{12} \equiv 2|M_{12}|/\Gamma, \quad y_{12} \equiv |\Gamma_{12}|/\Gamma, \quad \phi_{12} \equiv \arg(M_{12}/\Gamma_{12}) \]

\( M_{12} \) is dispersive mixing: due to long-distance exchange of off-shell intermediate states (dominates in SM), and short-distance effects (NP)

\( \Gamma_{12} \) is absorptive mixing: due to long distance exchange of on-shell intermediate states
• $\phi_{12}$ is a CP violating phase: responsible for CP violation in pure mixing

  e.g., a non-vanishing semileptonic CP asymmetry, $a_{SL}$

$$\Gamma(D^0(t) \to \ell^- X) \neq \Gamma(\bar{D}^0(t) \to \ell^+ X)$$

• $\phi_{12}$ is solely responsible for CPV in the interference between decays with and without mixing (time dependent CP asymmetries), in the limit that non-trivial weak phases in decay are neglected

• excellent approximation given current exp sensitivity to $\phi_{12}$

Example: SCS decays to CP eigenstates, $D^0 \to K^+ K^- , \pi^+ \pi^-$

$$\Gamma(D^0(t) \to f) \propto \exp[-\hat{\Gamma}_{D^0 \to f} t], \quad \Gamma(\bar{D}^0(t) \to f) \propto \exp[-\hat{\Gamma}_{\bar{D}^0 \to f} t]$$

CPV: $\hat{\Gamma}_{D^0 \to f} \neq \hat{\Gamma}_{\bar{D}^0 \to f}$
Fits of $\phi_{12}, x_{12}, y_{12}$ to data yield

HFAG fit (April 2013): $\phi_{12} (^\circ) = 4.8^{+9.2}_{-7.4}$

UTfit (Silvestrini, Beauty 2013): $\phi_{12} (^\circ) = 2 \pm 11$
Weak phases in decay

In general, $\phi_{12}$ consists of a dispersive part $\phi_{12}^M$, and a long-distance absorptive part $\phi_{12}^\Gamma$.

They can be consistently defined relative to the phases of decay amplitudes, e.g., $D \rightarrow K^{\pm}\pi^{\mp}$, with

$$\phi_{12} = \phi_{12}^M - \phi_{12}^\Gamma$$

In the SM: $\phi_{12}^\Gamma$ and the long-distance part of $\phi_{12}^M$ are due to the weak phase $\gamma$ in the penguin amplitudes of the singly Cabibbo suppressed intermediate states, and

- the short distance contribution to $\phi_{12}^M$ is negligible.
• SM U-spin based analysis  \( \text{(Grossman, Ligeti, Perez, Petrov, Silvestrini, AK)} \)

\[
\phi_{12}^\Gamma \leq O(0.01)
\]

• expect similar result for \( \phi_{12}^M \), related to \( \phi_{12}^\Gamma \) via dispersion relations

Current exp. sensitivity

\[
> O(10) \text{ window for NP in } \phi_{12}
\]

LHCb/Belle II or tau/charm factory could measure \( \phi_{12}^\Gamma \), thus isolating short distance NP in \( \phi_{12}^M \)
High $p_T$
Higgs couplings

- if NP then Higgs couplings could be modified
- if EFT description valid
  \[ \Delta \mathcal{L}_Y = -\frac{\chi_{ij}}{\Lambda^2} (\bar{f}_L^i f_R^j) H (H^\dagger H) + h.c. + \cdots \]
- therefore, in general
  \[ \mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij} (\bar{f}_L^i f_R^j) h + h.c. + \cdots \]
- new neutral currents
  - flavor diagonal @LHC
  - flavor violating @Belle2 and LHC
- both are important diagnostics

*slide on loan from Zupan, Snowmass Seattle
• what is a reasonable aim for precision on $Y_{ij}$?

• if off-diagonals are large $\Rightarrow$ spectrum in general not hierarchical

• no tuning, if $|Y_{\tau\mu}Y_{\mu\tau}| \lesssim \frac{m_{\mu} m_{\tau}}{v^2}$

Cheng, Sher, 1987

• different flavor models give

Dery, Efrati, Hochberg, Nir, 1302.3229

<table>
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<th>$R_{\tau+\tau-}$</th>
<th>$X_{\mu+\mu-}/(m_{\mu}^2/m_{\tau}^2)$</th>
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<td>0</td>
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<td>$1 - 4bm_{\tau}^2/\Lambda^2$</td>
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<td>$1 + \mathcal{O}(v^2/\Lambda^2)$</td>
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<td>GL</td>
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<td>25/9</td>
<td>$\mathcal{O}(X_{\mu+\mu-})$</td>
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*slide on permanent loan from Zupan
**FLAVOR VIOLATING HIGGS COUPLINGS**

- **B-factories:** the best sensitivity for FV higgs couplings to light quarks
- **LHC:** best constraints on $h-tc, h-tu$ and $h \rightarrow \tau\mu, \tau e$

*from the Zupan collection*
Bounds on CP violating Higgs-top coupling from EDMs

Brod, Haisch, Zupan in prep

Left: Bar-Zee contributions to electron and quark EDMs, quark chromo-EDMs.
Right: contribution to Weinberg’s operator

General Yukawa coupling for fermion $f$ (in the SM $\kappa_f = 1$, $\tilde{\kappa}_f = 0$)

$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}} (\kappa_f \bar{f} f + i \tilde{\kappa}_f \bar{f} \gamma_5 f) h$$

A top quark CP violating coupling $\tilde{\kappa}_t$ would induce contributions to the charged lepton and neutron EDMs via the above diagrams.
left: current constraints on $\kappa_t$, $\tilde{\kappa}_t$ from the electron, mercury, and neutron EDM bounds, and Higgs physics

right: projected future constraints, for 1000 $\times$ improvement in electron EDM bound, 300 $\times$ improvement in neutron EDM bound, and expected Higgs production sensitivity with 3000 fb at LHC

will be interesting to compare with sensitivity of direct measurements of $\tilde{\kappa}_t$, eg via CPV triple products

(above plots assume SM Higgs couplings to electron, light quarks; weaker EDM bounds follow from Weinberg’s operator alone)
In new ATLAS search for stop decay to charm + neutralino ($\tilde{t} \rightarrow c + \chi^0$), charm jet tagging has been employed for the first time at LHC

 ATLAS-CONF-2013-068

charm jets identified by combining “information from the impact parameters of displaced tracks and topological properties of secondary and tertiary decay vertices” using multivariate techniques

‘medium’ operating point: c-tagging efficiency = 20%, rejection factor of 5 for b jets, 140 for light jets. 
#’s obtained for simulated $tt$ events for jets with $30 < p_T < 200$, and calibrated with data
Significance of charm tagging for flavor physics:

- increased sensitivity to flavor violating $\text{(s)top} + \text{(s)charm}$ production, or flavor violating $t - c$ couplings in top decay

- perhaps provide tests for horizontal flavor symmetries at high $p_T$, e.g. discriminate between $\text{SU}(2)$ vs. $\text{U}(1)$ horizontal symmetries?

- charm squark vs up squark masses?

- $t + c$ production vs. $\bar{t} + \bar{c}$ production?

- analogous sensitivities in models with partially composite quarks: charm partners, charm partners vs. up partners?
Flavor, naturalness, and the LHC
naturalness of the weak scale

new fields with large couplings to the Higgs, introduced to stabilize the Higgs mass, should have $\lesssim O(\text{TeV})$ masses, eg. stops, LH sbottom

pre LHC:

FCNC + naturalness $\rightarrow$ horizontal flavor symmetries

The motivation was model-dependent: certain dynamics can automatically yield flavor blind NP to very good approx, eg. supersymmetry breaking via gauge or anomaly mediation

today:

LHC bounds on NP + naturalness $\rightarrow$ horizontal flavor symmetries
two strategies for flavor symmetries were introduced in context of supersymmetry: non-Abelian and Abelian

non-Abelian (2+1) structure: first two families are doublets of an SU(2) horizontal symmetry, the third family is a singlet

Dine, Leigh, AK ’93; Pomarol, Tomassini ’95

SU(2) squarks / sleptons of first two families approximately degenerate. if their masses also >> stop masses, FCNC, eg $\epsilon_K, \mu \rightarrow e\gamma$ are OK, and maintain naturalness, evade LHC squark bounds

effective susy, or natural susy spectrum;

Cohen, Kaplan, Nelson ’96

could yield observable $\mu \rightarrow e\gamma$, neutron EDMs in future experiments. CPV in D mixing is small

can be extended to explain fermion mass hierarchies

- most recently, see Dudas, Gersdorff, Pokorski, Ziegler ’13
Abelian U(1)’s: with appropriate charge assignments can explain quark mass hierarchy and obtain alignment of the down squark and down quark mass eigenstates in flavor space.

- $\epsilon_K$ is sufficiently small

- residual misalignment between up squark and up quark mass eigenstates in flavor space, $(u,c)$ vs $(\bar{u},\bar{c})$

- $\phi_{12} = O(10\%)$ CP violation in $D - \bar{D}$ mixing is possible

- $\mu \to e\gamma$, neutron EDMs could be observed in future experiments
3rd strategy: flavor symmetries which yield controlled violations of R parity (rather than ad-hoc assumption that it holds)
- sufficient suppression of proton decay, and
  - eliminates standard SUSY missing $E_T$ (MET)
signature: substantially weakens squark, gluino mass bounds
  - eliminates dangerous FCNC

- can follow from imposing MFV SM flavor symmetry $U(3)^3$
  - Smith, '08; Csaki, Grossman, Heidenreich, '11; Bhattacharjee et al, '13

- could follow from $U(1)$ Abelian models -
  which also yield quark/squark alignment
  - Montheaux '13
alignment and naturalness at the LHC

squark masses of same order but highly non-degenerate, eg,

\[ m_{\tilde{u}} \neq m_{\tilde{c}}, \quad m_{\tilde{u}}, m_{\tilde{c}} > m_{\tilde{t}} \]

stop can be light → naturalness

Mahbubani, Papucci, Perez, Ruderman, Weiler '12
Mahbubani, Papucci, Perez, Ruderman, Weiler ’12

sea vs. valence

\[ \tilde{m}_{\text{sea}} \gtrsim 600 \text{ GeV} \]

\[ \tilde{m}_{\text{valence}} \gtrsim 1.2 \text{ TeV} \]

\[ m_{\tilde{u}_{L,R}} = m_{\tilde{d}_{L,R}} \] [GeV]

\[ m_{\tilde{c}_{L,R}} = m_{\tilde{s}_{L,R}} \] [GeV]

\[ \Delta m_D \]

\[ \sigma / \sigma_{\text{lim}} \]

\[ g \]

*from G Perez “Flavorful naturalness and the top charm frontier” La Sapienza 2013

See also: Heikinheimo, Kellerstein & Sanz (11); Kribs & Martin (12),
Sea LH squarks vs. valence RH squarks

Adding flavor constraints ($\Delta m_D$) for LH squarks:

$$\delta_{Q}^{12} \equiv \frac{m_{\bar{Q}_2} - m_{\bar{Q}_1}}{m_{\bar{Q}_2} + m_{\bar{Q}_1}}$$

alignment: new upper bound on CP violation (CPV) in $D$-phys.:

$$\text{CPV in } D - \bar{D} : \frac{\delta_{\epsilon K}}{2\lambda_C} \delta_{Q}^{12} \lesssim 10\% \times \left(\frac{0.3}{\delta_{Q}^{12}}\right)$$

($$\delta_{\epsilon K} \sim 1\%$$)

LHCb soon start testing alignment paradigm!

$O(10\%)$ CPV

*adapted from G Perez “Flavorful naturalness and the top charm frontier” La Sapienza 2013
Summary

phenomenal progress in flavor measurements

- theoretical progress probably required on SM predictions for $B \rightarrow K^* \mu^+ \mu^-$ CP conserving observables at low $q^2$ (with exception of lowest bin)

- observation of $B_s \rightarrow \mu^+ \mu^-$ entering an exciting time in which can test for SU(2) based symmetry structure via comparison to $B_d \rightarrow \mu^+ \mu^-$

- $O(10)$ window for new physics in D mixing CP violation to be probed in the coming years

- tests for new physics in flavor violating Higgs decays are becoming interesting
naturalness + FCNC+ LHC bounds suggest the existence of flavor symmetries

- possibility to evade LHC bounds on 1st two generation squarks via light “sea” squarks (charm, strange squarks) in Abelian alignment models- they can be relatively light

- new charm jet tagging capability could help to test this scenario further

- similar in spirit search strategies for composite Higgs with partially composite quarks
  - Fraille, Flacke, Delauney, Lee, Perez in prep

- alignment models could lead to O(10%) CPV in D mixing

In abelian and non-abelian models \(\mu \rightarrow e\gamma\) and neutron EDM could be at observable levels in future experiments