Flavour physics after the first run of the LHC: status and perspectives

based on 1402.6677 with R. Barbieri, F. Sala and D. Straub, 1408.0728, and 1503.02693 with A. J. Buras, J. Girrbach and R. Knegjens

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Naturalness (in one slide)

• The Standard Model alone has **no hierarchy problem**

$$\frac{d m_h^2(\mu)}{d \log \mu} = \frac{3m_h^2}{8\pi^2} \left(2\lambda + y_t^2 - \frac{3g_2^2}{4} - \frac{g_Y^2}{4}\right)$$

running Higgs mass

• Generic new particles at a scale M higher than the EW scale, coupled to the Higgs boson, generate large corrections to the Higgs mass



The CKM picture of flavour



Remarkable accuracy (~ 20%) of the CKM picture of flavour changing interactions

 Explore the highest energies indirectly testable, assuming generic flavour effects: in several cases up to 10^{4÷5} TeV

2. Physics at the TeV scale must have a very peculiar structure: symmetries

EFT approach: only a limited set of effective operators is present, size controlled by the CKM matrix V $(\xi_{ij} = V_{ti}^* V_{tj})$

 $\xi_{ij}^2 (\bar{d}_L^i \gamma_\mu d_L^j)^2 \qquad \xi_{ij} (\bar{d}_L^i \gamma_\mu d_L^j) \mathcal{O}^\mu_\alpha \qquad \xi_{ij} m_j (\bar{d}_L^i \sigma_{\mu\nu} d_R^j) \mathcal{O}^{\mu\nu}_\beta$

How to get a flavour scenario close to CKM, beyond the SM?

Direct searches

A	TLAS SUSY Sea	arches	s* - 95	5% (CL L	ower Limits	ATLA	AS Preliminary
Sta	atus: SUSY 2013						$\int \mathcal{L} dt = (4.6 - 22.9) \text{ fb}^{-1}$	\sqrt{s} = 7, 8 TeV
	Model	e, μ, τ, γ	Jets	E ^{miss} T	∫£ dt[fb	^{b-1}] Mass limit	-	Reference
Inclusive Searches	$ \begin{array}{l} \text{MSUGRA/CMSSM} \\ \text{MSUGRA/CMSSM} \\ \overline{q} \bar{a}, \overline{q} \rightarrow \overline{q} \tilde{v}_{1}^{0} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{x}_{1}^{0} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{0} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{v}_{1}^{0} \\ \overline{g} \bar{s}, \overline{g} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{v}_{1}^{0} \\ \overline{g} \bar{s}, \overline{g} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{v}_{1}^{0} \\ \overline{g} \bar{s}, \overline{g} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{v}_{1}^{0} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{v}_{1}^{0} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{v}_{1}^{0} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{v}_{1}^{0} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{v}_{1}^{0} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{v}_{1}^{0} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{v}_{1}^{0} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{v}_{1}^{0} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{v}_{1}^{0} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{v}_{1}^{1} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{s} \tilde{v}_{1}^{1} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{s} \tilde{v}_{1}^{1} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{s} \tilde{v}_{1}^{1} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{s} \tilde{v}_{1}^{1} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q W^{+} \overline{s} \tilde{v}_{1}^{1} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \\ \overline{g} \bar{s}, \overline{s} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \rightarrow q \overline{s} \tilde{v}_{1}^{1} \\ \overline{g} \bar{s} \bar{s} \bar{s} \bar{s} \bar{s} \bar{s} \bar{s} s$	$\begin{matrix} 0 \\ 1 \ e, \mu \\ 0 \\ 0 \\ 1 \ e, \mu \\ 2 \ e, \mu \\ 2 \ e, \mu \\ 1.2 \ \tau \\ 2 \ \gamma \\ 1 \ e, \mu + \gamma \\ \gamma \\ 2 \ e, \mu (Z) \\ 0 \end{matrix}$	2-6 jets 3-6 jets 2-6 jets 2-6 jets 3-6 jets 3-6 jets 0-3 jets 0-2 jets - 1 b 0-3 jets mono-jet	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 4.7 20.7 4.8 4.8 4.8 4.8 5.8 10.5	4.8 1.7 TeV 8 1.2 TeV 8 1.1 TeV 9 740 GeV 8 1.1 TeV 8 1.1 TeV 8 1.1 TeV 8 1.18 TeV 8 1.12 TeV 8 1.2 TeV 8 900 GeV 8 900 GeV 8 619 GeV 8 600 GeV 8 600 GeV 8 645 GeV	(m(ā)=m(ā) any m(ā) ary m(ā) m(t ²)=0.GeV m(t ²)=0.GeV m(t ²)=0.GeV m(t ²)=0.GeV tan/c+15 tan/c+15 tan/c +15 tan/c +15	ATLAS-CONF-2013-047 ATLAS-CONF-2013-062 1308.1841 ATLAS-CONF-2013-047 ATLAS-CONF-2013-047 ATLAS-CONF-2013-047 ATLAS-CONF-2013-047 ATLAS-CONF-2013-026 1209.0753 ATLAS-CONF-2012-144 1211.1167 ATLAS-CONF-2012-144 1214.2147
3 rd gen. ĝ med.	$\begin{array}{l} \tilde{g} \rightarrow b \bar{b} \tilde{\chi}_{1}^{0} \\ \tilde{g} \rightarrow t \bar{t} \tilde{\chi}_{1}^{0} \\ \tilde{g} \rightarrow t \bar{t} \tilde{\chi}_{1}^{0} \\ \tilde{g} \rightarrow b \bar{t} \tilde{\chi}_{1}^{+} \end{array}$	0 0 0-1 e, µ 0-1 e, µ	3 b 7-10 jets 3 b 3 b	Yes Yes Yes Yes	20.1 20.3 20.1 20.1	š 1.2 TeV š 1.1 TeV š 1.3 TeV š 1.3 TeV	$\begin{array}{l} m(\tilde{v}_1^0){<}600~\text{GeV} \\ m(\tilde{v}_1^0){<}350~\text{GeV} \\ m(\tilde{v}_1^0){<}400~\text{GeV} \\ m(\tilde{v}_1^0){<}300~\text{GeV} \end{array}$	ATLAS-CONF-2013-061 1308.1841 ATLAS-CONF-2013-061 ATLAS-CONF-2013-061
3 rd gen. squarks direct production	$ \begin{array}{l} \tilde{b}_{1} \tilde{b}_{1} - \tilde{b}_{1}^{*0} + \tilde{b}_{1}^{*0} \\ \tilde{b}_{1} \tilde{b}_{1} - \tilde{b}_{1}^{*1} + \tilde{b}_{1}^{*1} \\ \tilde{b}_{1} \tilde{b}_{1} - \tilde{b}_{1}^{*1} + \tilde{b}_{1}^{*0} \\ \tilde{t}_{1} \tilde{t}_{1} (light), \tilde{t}_{1} \rightarrow b \tilde{b}_{1}^{*1} \\ \tilde{t}_{1} \tilde{t}_{$	$\begin{array}{c} 0\\ 2\ e,\mu\ (SS)\\ 1-2\ e,\mu\\ 2\ e,\mu\\ 2\ e,\mu\\ 0\\ 1\ e,\mu\\ 0\\ 1\ e,\mu\\ 0\\ 3\ e,\mu\ (Z) \end{array}$	2 b 0-3 b 1-2 b 0-2 jets 2 jets 2 b 1 b 2 b nono-jet/c-ta 1 b 1 b	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.1 20.7 4.7 20.3 20.3 20.1 20.7 20.5 20.3 20.7 20.7	b₁ 100-620 GeV b₁ 275-430 GeV t₁ 110-167 GeV t₁ 130-220 GeV t₁ 225-525 GeV t₁ 200-610 GeV t₁ 200-610 GeV t₁ 200-610 GeV t₁ 90-200 GeV t₁ 90-200 GeV t₁ 90-200 GeV t₁ 90-200 GeV	$\begin{split} m(\tilde{\xi}_{1}^{0})90 \ GeV \\ m(\tilde{\xi}_{1}^{0})92 \ m(\tilde{\xi}_{1}^{0}) \\ m(\tilde{\xi}_{1}^{0})55 \ GeV \\ m(\tilde{\xi}_{1}^{0})m(\tilde{\xi}_{1}^{0})m(\tilde{\chi}_{1}^{0})6V \\ m(\tilde{\xi}_{1}^{0})0 \ GeV \\ m(\tilde{\xi}_{1}^{0})10 \ GeV \\ m(\tilde{\xi}_{1}^{0})150 \ GeV \\ m(\tilde{\xi}_{1}^{0}).+180 \ GeV \end{split}$	1308.2631 ATLAS-CONF-2013-007 1208.4305,1209.2102 ATLAS-CONF-2013-065 1308.2631 ATLAS-CONF-2013-065 ATLAS-CONF-2013-068 ATLAS-CONF-2013-068 ATLAS-CONF-2013-025 ATLAS-CONF-2013-025
EW direct	$ \begin{array}{c} \tilde{\ell}_{L,R} \tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_{1}^{0} \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\ell} \nu(\ell \tilde{r}) \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{2}^{-}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{r} \nu(r \tilde{r}) \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{2}^{0} \rightarrow \tilde{\ell}_{L} \nu \tilde{\ell}_{L} \ell(\tilde{r} \nu), \ell \tilde{\tau} \tilde{\ell}_{L} \ell(\tilde{r} \nu) \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{1}^{0} \delta Z \tilde{\chi}_{1}^{0} \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{1}^{0} h \tilde{\chi}_{1}^{1} \end{array} $	2 e, μ 2 e, μ 2 τ 3 e, μ 3 e, μ 1 e, μ	0 0 - 0 2 b	Yes Yes Yes Yes Yes Yes	20.3 20.3 20.7 20.7 20.7 20.7 20.3		$\begin{array}{l} m(\tilde{r}_{1}^{0})=0 \mbox{ GeV } \\ m(\tilde{r}_{1}^{0})=0 \mbox{ GeV } m(\tilde{r}, \tilde{\gamma})=0.5(m(\tilde{r}_{1}^{0})+m(\tilde{r}_{1}^{0})) \\ m(\tilde{r}_{1}^{0})=0 \mbox{ GeV } m(\tilde{r}, \tilde{\gamma})=0.5(m(\tilde{r}_{1}^{0})+m(\tilde{r}_{1}^{0})) \\ m(\tilde{r}_{2}^{0}),m(\tilde{r}_{1}^{0})=0,m(\tilde{r}, \tilde{\gamma})=0.5(m(\tilde{r}_{1}^{0})+m(\tilde{r}_{1}^{0})) \\ m(\tilde{r}_{1}^{0})-m(\tilde{r}_{2}^{0}),m(\tilde{r}_{1}^{0})=0.5sptons decoupled \\ m(\tilde{r}_{1}^{0})-m(\tilde{r}_{2}^{0}),m(\tilde{r}_{2}^{0})=0.5sptons decoupled \\ \end{array}$	ATLAS-CONF-2013-049 ATLAS-CONF-2013-049 ATLAS-CONF-2013-028 ATLAS-CONF-2013-035 ATLAS-CONF-2013-035 ATLAS-CONF-2013-033
Long-lived particles	Direct $\tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}$ prod., long-lived $\tilde{\chi}_{1}^{\pm}$ Stable, stopped \tilde{g} R-hadron GMSB, stable $\tilde{\tau}, \tilde{\chi}_{1}^{0} \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu})_{+}\tau(e_{1}, \tilde{\mu})_{+}\tau$	Disapp. trk 0 e, μ) 1-2 μ 2 γ 1 μ, displ. vtz	1 jet 1-5 jets - -	Yes Yes Yes	20.3 22.9 15.9 4.7 20.3	x1 270 GeV ž 832 GeV x1 475 GeV x1 230 GeV q 1.0 TeV	$\begin{array}{l} m(\tilde{\chi}_{1}^{2})\!+\!m(\tilde{\chi}_{1}^{0})\!=\!160 \; \text{MeV}, \tau(\tilde{\chi}_{1}^{*})\!=\!0.2 \; \text{ns} \\ m(\tilde{\chi}_{1}^{0})\!=\!100 \; \text{GeV}, 10 \; \mu \text{s}\!<\!\tau(\tilde{g})\!<\!1000 \; \text{s} \\ 10 \cdot \text{tan} \beta \!<\!50 \\ 0.4 \! <\!\tau(\tilde{\chi}_{1}^{0})\!<\!2 \; \text{ns} \\ 1.5 <\!cr\!<\!156 \; \text{cm}, \; \text{BR}(\mu)\!=\!1, \; m(\tilde{\chi}_{1}^{0})\!=\!108 \; \text{GeV} \end{array}$	ATLAS-CONF-2013-069 ATLAS-CONF-2013-057 ATLAS-CONF-2013-058 1304.6310 ATLAS-CONF-2013-092
RPV	$ \begin{array}{l} LFV \ pp \rightarrow \tilde{v}_{\tau} + X, \ \tilde{v}_{\tau} \rightarrow e + \mu \\ LFV \ pp \rightarrow \tilde{v}_{\tau} + X, \ \tilde{v}_{\tau} \rightarrow e(\mu) + \tau \\ \tilde{v}_{\tau} \rightarrow e(\mu) + \tau \\ \tilde{v}_{\tau} \tilde{v}_{\tau} \rightarrow NF^{0}_{\tau}, \ \tilde{x}_{\tau}^{1} \rightarrow NF^{0}_{\tau}, \ \tilde{x}_{\tau}^{0} \rightarrow e\tilde{v}_{\mu}, e\mu\tilde{v} \\ \tilde{x}_{\tau}^{1} \tilde{x}_{\tau}, \ \tilde{x}_{\tau}^{1} \rightarrow NF^{0}_{\tau}, \ \tilde{x}_{\tau}^{1} \rightarrow NF^{0}_{\tau}, \ \tilde{x}_{\tau}^{1} \rightarrow NF^{0}_{\tau}, e\mu\tilde{v} \\ \tilde{x}_{\tau}^{1} \tilde{x}_{\tau}, \ \tilde{x}_{\tau}^{1} \rightarrow NF^{0}_{\tau}, \ \tilde{x}_{\tau}^{1} \rightarrow NF^{0}_{\tau}, e\mu\tilde{v} \\ \tilde{g} \rightarrow qq \\ \tilde{g} \rightarrow \tilde{t}_{1}, \ \tilde{t}_{\tau} \rightarrow bs \end{array} $	$\begin{array}{c} 2 \ e, \mu \\ 1 \ e, \mu + \tau \\ 1 \ e, \mu \\ \tau \\ \phi_{e} \\ 4 \ e, \mu \\ \phi_{\tau} \\ 3 \ e, \mu + \tau \\ 0 \\ 2 \ e, \mu \left(\text{SS} \right) \end{array}$	7 jets 6-7 jets 0-3 <i>b</i>	Yes Yes Yes Yes	4.6 4.6 4.7 20.7 20.7 20.3 20.7	\$\vec{v}_r\$ 1.61 TeV \$\vec{v}_r\$ 1.1 TeV \$\vec{v}_e\$ 1.1 TeV \$\vec{v}_e\$ 1.2 TeV \$\vec{v}_1\$ 760 GeV \$\vec{v}_1\$ 350 GeV \$\vec{v}_2\$ 916 GeV \$\vec{v}_2\$ 880 GeV	$\begin{array}{l} \lambda_{111}'=0.10, \lambda_{112}'=0.05\\ \lambda_{111}'=0.10, \lambda_{1(2)13}=0.05\\ m(\tilde{q})=m(\tilde{g}), cr_{LS}<1 mm\\ m(\tilde{q}_1^{(1)})=0.05\\ m(\tilde{\chi}_1^{(1)})>300 GeV, \lambda_{122}>0\\ m(\tilde{\chi}_1^{(1)})>300 GeV, \lambda_{123}>0\\ BR(t)=BR(b)=BR(c)=0\% \end{array}$	1212.1272 1212.1272 ATLAS-CONF-2013-036 ATLAS-CONF-2013-036 ATLAS-CONF-2013-036 ATLAS-CONF-2013-091 ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon $\rightarrow q\bar{q}$ Scalar gluon pair, sgluon $\rightarrow t\bar{t}$ WIMP interaction (D5, Dirac χ)	0 2 e, μ (SS) 0	4 jets 1 <i>b</i> mono-jet	- Yes Yes	4.6 14.3 10.5	sgluon 100-287 GeV 800 GeV ggluon 800 GeV M" scale 704 GeV	incl. limit from 1110.2693 m(χ)<80 GeV, limit of<687 GeV for D8	1210.4826 ATLAS-CONF-2013-051 ATLAS-CONF-2012-147
	$\sqrt{s} = 7 \text{ TeV}$ full data p	$\sqrt{s} = 8 \text{ TeV}$	√s = 8 full c	B TeV data		10 ⁻¹ 1	Mass scale [TeV]	-

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

How do flavour measurements compare with direct searches at the LHC (e.g. in SUSY)?





1. The way of flavour symmetries

• $U(3)^3 \equiv U(3)_q \times U(3)_u \times U(3)_d$ broken by the SM Yukawa's

 $Y_u \sim (\mathbf{3}, \overline{\mathbf{3}}, \mathbf{1}), \quad Y_d \sim (\mathbf{3}, \mathbf{1}, \overline{\mathbf{3}})$

Chivukula, Georgi Hall, Randall D'Ambrosio *et al.*

- At leading order in the breaking parameters $\neq y_t$:
 - Quark bilinears:

$$\bar{q}_L \, I_3 \gamma_\mu \, q_L$$

$$\bar{q}_L I_3 Y_d \sigma_{\mu\nu} d_R$$

 $Y_u Y_u^{\dagger} \sim I_3 = \operatorname{diag}(0, 0, 1)$

Effective operators:

$$\Delta F = 2: \qquad c_{LL} \xi_{ij}^2 (\bar{d}_L^i \gamma_\mu d_L^j)^2$$

$$\Delta F = 1: \qquad c_{cc}^\alpha \xi_{ij} (\bar{d}_L^i \gamma_\mu d_L^j) \mathcal{O}_\mu^\alpha$$

$$(\xi_{ij} \equiv V_{ti}^* V_{tj})$$

 $\overline{c_{c}}^{\beta} e^{i\phi^{\beta}} \xi_{ij} m_j (\bar{d}_L^i \sigma_{\mu\nu} d_R^j)$

Minimal U(2)³

- $U(2)^3 \equiv U(2)_q \times U(2)_u \times U(2)_d$ broken by the spurions $\mathcal{V} \sim (\mathbf{2}, \mathbf{1}, \mathbf{1}), \quad \Delta_u \sim (\mathbf{2}, \mathbf{\overline{2}}, \mathbf{1}), \quad \Delta_d \sim (\mathbf{2}, \mathbf{1}, \mathbf{\overline{2}})$ $q_L = (\mathbf{q}_L, q_L^3), \quad d_R = (\mathbf{d}_R, b_R), \quad u_R = (\mathbf{u}_R, t_R)$
- At leading order in the breaking parameters:

Barbieri *et al.* '11 Barbieri, B, Sala, Straub '12

Quark bilinears:	$ar{q}_L q_L$	$ar{m{q}}_{m{L}} \mathcal{V} q_L^3$	$ar{q}_L^3 q_L^3$
	$ar{m{q}}_{m{L}}\Delta_dm{d}_{m{R}}$	$ar{m{q}}_{m{L}} \mathcal{V} b_R$	$ar{q}_L^3 b_R$
Effective operators:		$G_{\rm cb}^{\beta} e^{i\phi^{eta}} \xi_{ij} m_j (\bar{d}_L^i \sigma)$	$\sigma_{\mu u} d_R^j) \mathcal{O}^{eta}_{\mu u}$
$c^{\scriptscriptstyle K}_{\scriptscriptstyle LL}\xi^2_{ds}(ar d_L\gamma_\mu s_L)^2$	С	$\xi^{\scriptscriptstyle K,lpha}_{ m cc} \xi_{ds} (ar{d}_L \gamma_\mu s_L) {\cal C}$	\mathcal{O}^{lpha}_{μ}
$c^{\scriptscriptstyle B}_{\scriptscriptstyle LL} e^{i\phi_B} \xi^2_{ib} (ar d^i_L \gamma_\mu b$	$(L)^2$ c	$E^{\scriptscriptstyle B,lpha}_{\scriptscriptstyle m cc}e^{i\phi^lpha}\xi_{ib}(ar{d}^i_L\gamma_\mu b)$	$(\mathcal{O}_L)\mathcal{O}_\mu^lpha$

Minimal U(2)³

• Weakly broken: a good symmetry of the SM Yukawa sector



- Potentially more observable effects w.r.t. MFV
- Naturally arises from a minimum principle in the dynamical breaking of U(3)³
 Alonso et al. '13
- The only continuous symmetry along with U(3)³ which gives a near-CKM structure of flavour violation, <u>if no further assumptions</u> <u>on the underlying model</u> Barbieri, B, Sala, Straub '14

Are there other pictures naturally close to CKM?

• $U(2)_q \times U(2)_u \times U(3)_d$, broken by $\Delta_u \sim (\mathbf{2}, \mathbf{\overline{2}}, \mathbf{1}), \ \Delta_d \sim (\mathbf{2}, \mathbf{1}, \mathbf{\overline{3}})$, and $\tilde{\Delta}_d \sim (\mathbf{1}, \mathbf{1}, \mathbf{\overline{3}})$, gives rise to MFV (*i.e.* has <u>the same effective</u> <u>operators</u>)

Are there other pictures naturally close to CKM?

- $U(2)_q \times U(2)_u \times U(3)_d$ gives rise to MFV
- Reducing the U(2)³ group:
 - Distinction between left- and right-handed fermions is essential (e.g. $U(2)_{q+u+d}$ has large non-CKM LR currents);
 - U(2)_L × U(2)_R broken by Δ_u ~ (2, 2), Δ_d ~ (2, 2), V ~ (2, 1), generates non-CKM chirality breaking op.s in ΔC = 1 and ΔS = 1: distinction between *u* and *d* quarks is needed;
 - $U(2)_L \times SU(2)_R \times U(1)_u \times U(1)_d$, broken by $\mathcal{V} \sim (\mathbf{2}, \mathbf{1})_{(0,0)}$, $\Delta_u \sim (\mathbf{2}, \mathbf{2})_{(-1,0)}, \ \Delta_d \sim (\mathbf{2}, \mathbf{2})_{(0,-1)}$, is equivalent to U(2)³ at leading order in the breaking parameters

Are there other pictures naturally close to CKM?

- $U(2)_q \times U(2)_u \times U(3)_d$ gives rise to MFV
- Reducing the U(2)³ group:
 - Distinction between left- and right-handed fermions is essential
 - Distinction between u and d quarks is needed;
 - $U(2)_L \times SU(2)_R \times U(1)_u \times U(1)_d$ is equivalent to U(2)³
- Alignment: e.g. $U(3)_d \times U(1)_{(q+u)_1} \times U(1)_{(q+u)_2} \times U(1)_{(q+u)_3}$ broken by $\Delta_1 \sim \mathbf{3}_{(1,0,0)}, \ \Delta_2 \sim \mathbf{3}_{(0,1,0)}, \ \Delta_3 \sim \mathbf{3}_{(0,0,1)}$ Barbieri *et al.* '10

gives rise to the bilinear $\left((c_3-c_1)\xi_{ij}+(c_2-c_1)V_{ci}^*V_{cj}\right)(\bar{d}_L^i\gamma_\mu d_L^j)$

Non CKM effects unless $c_2 \sim c_1$: this can work in specific contexts.

Fit of $\Delta F = 2$ observables

$$\Delta M_{s,d} = \Delta M_{s,d}^{\rm SM} \left| 1 + h_B e^{2i\sigma_B} \right| \qquad \epsilon_K = \epsilon_K^{\rm SM} + h_K \epsilon_K^{\rm SM,tt}$$
$$S_{\psi K_S} = \sin \left(2\beta + \arg(1 + h_B e^{2i\sigma_B}) \right)$$



Fit of $\Delta F = 2$ observables

$$\Delta M_{s,d} = \Delta M_{s,d}^{\rm SM} \left| 1 + \boldsymbol{h}_{B} e^{2i\boldsymbol{\sigma}_{B}} \right| \qquad \epsilon_{K} = \epsilon_{K}^{\rm S}$$
$$S_{\psi K_{S}} = \sin \left(2\beta + \arg (1 + \boldsymbol{h}_{B} e^{2i\boldsymbol{\sigma}_{B}}) \right)$$

$$\epsilon_K = \epsilon_K^{\rm SM} + h_K \epsilon_K^{\rm SM, tt}$$



Flavour and supersymmetry



- "Natural" spectrum with light stops and gluino, and heavy squarks of 1st & 2nd generation: compatible with U(2)³
- What is the impact on flavour physics of the direct bounds on s-particle masses from the LHC?

 $h_K \simeq F_{H^{\pm}} + |\xi_L|^4 F_{\tilde{g},1} + |\xi_L|^2 \delta F_{\tilde{g},2} + |\delta|^2 F_{\tilde{g},3} \xrightarrow{} \text{second-order effects}$ $h_B e^{2i\sigma_B} \simeq F_{H^{\pm}} + |\xi_L|^2 e^{2i\gamma_L} F_{\tilde{g},1} + |\xi_L \xi_R| e^{i(\gamma_L + \gamma_R)} F_{\tilde{g},4} \text{ (only for } B_s) \tag{gluino only}$



 $h_K \simeq F_{H^{\pm}} + |\xi_L|^4 F_{\tilde{g},1} + |\xi_L|^2 \delta F_{\tilde{g},2} + |\delta|^2 F_{\tilde{g},3} \xrightarrow{} \text{second-order effects}$ $h_B e^{2i\sigma_B} \simeq F_{H^{\pm}} + |\xi_L|^2 e^{2i\gamma_L} F_{\tilde{g},1} + |\xi_L \xi_R| e^{i(\gamma_L + \gamma_R)} F_{\tilde{g},4} \text{ (only for } B_s) \tag{gluino only}$



 $h_K \simeq F_{H^{\pm}} + |\xi_L|^4 F_{\tilde{g},1} + |\xi_L|^2 \delta F_{\tilde{g},2} + |\delta|^2 F_{\tilde{g},3} \xrightarrow{\text{second-order effects}}$ $h_B e^{2i\sigma_B} \simeq F_{H^{\pm}} + |\xi_L|^2 e^{2i\gamma_L} F_{\tilde{g},1} + |\xi_L \xi_R| e^{i(\gamma_L + \gamma_R)} F_{\tilde{g},4} \quad \text{(only for } B_s) \quad \text{(gluino only)}$



observable deviations from the SM only for large values of ξ_L

 $h_K \simeq F_{H^{\pm}} + |\xi_L|^4 F_{\tilde{g},1} + |\xi_L|^2 \delta F_{\tilde{g},2} + |\delta|^2 F_{\tilde{g},3} \xrightarrow{} \text{second-order effects}$ $h_B e^{2i\sigma_B} \simeq F_{H^{\pm}} + |\xi_L|^2 e^{2i\gamma_L} F_{\tilde{g},1} + |\xi_L \xi_R| e^{i(\gamma_L + \gamma_R)} F_{\tilde{g},4} \text{ (only for } B_s) \tag{gluino only}$



- Consider all the contributions. Many free parameters: scan Crivellin over the parameter space (analysis with **SUSY FLAVOR**) Rosiek
- ATLAS and CMS mass bounds:



• Scan ranges: $\xi_{\alpha} \in [1/3, 3]$

 $\tilde{m}_3 \in [0.1, 1.5] \text{ TeV}, \quad m_{\tilde{q}} \in [0.1, 3] \text{ TeV},$ $m_{\tilde{\chi}} \in [0.1, 0.8] \text{ TeV}, \quad \tan \beta \in [1, 5]$



heavy spectrum
compressed spectrum
excluded by $b \to s\gamma$

★ SM
 ◯ U(2)³ fit
 ◯ generic fit





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 ◯ generic fit



Rare B decays

- Main $\Delta B = 1$ effects in U(2)³ arise from (chromo-)magnetic dipole operators
- Higgsino and charged Higgs contributions MFV-like, constrained by $B \to X_s \gamma$
- Gluino (and Wino) contributions, Secontribute to the CP asymmetries: angular asymmetry A₇ in $B \rightarrow K^* \mu^+ \mu^-$ at low $\mu\mu$ invariant mass



• $B_{d,s} \rightarrow \mu^+ \mu^-$ not relevant for moderate tan ß (get tan ß enhanced contributions from scalar operators)

A different example: composite Higgs models

- In composite Higgs models large flavour effects are generated by the strongly interacting dynamics.
- In general, the bounds from flavour are stronger than the direct constraints on composite resonances.

Direct bounds: $m_{\psi} \gtrsim 700, \text{GeV}$

	doublet	triplet	bidoublet							
\bigotimes	4.9^{\dagger}	1.7^\dagger	$1.2^{*\dagger}$							
$U(3)^3_{ m LC}$	6.5	6.5	5.3							
$U(3)^3_{ m RC}$	-	-	3.3							
$U(2)^3_{ m LC}$	4.9^{\ddagger}	0.6^{\ddagger}	0.6^{\ddagger}							
$U(2)^3_{ m RC}$	-	-	1.1^{*}							
		Barbieri, B,	Sala, Straub 2013							

Minimal fermion resonance mass [TeV]

* f > 500 GeV and $g_{\psi} \approx 2.5$ † excluding ε_{K} , up to $\mathcal{O}(1)$ factors ‡ $r_{b} = 0.2$

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 Only a few models can accommodate a 125 GeV composite Higgs with light top partners.

* f > 500 GeV and $g_{\psi} \approx 2.5$ \dagger excluding ε_{K} , up to $\mathcal{O}(1)$ factors $\ddagger r_b = 0.2$

Conclusions (part 1)

- Precision measurements in the flavour sector require a <u>near-CKM</u> picture of flavour-changing interactions.
- Two possible scenarios, <u>based on symmetries only</u>: U(3)³, U(2)³
- Updated fit of meson mixings in U(2)³ (improved measurement of CP asymmetries in B decays and new lattice results)
- SUSY: direct bounds on s-particle masses are becoming competitive with flavour constraints
- Still <u>room for observable deviations</u> from SM in meson mixings, if s-particles in the reach of LHC14

2. High-scale flavour physics

What are the highest scales testable through rare decays?

 Heavy vector resonance with flavour-changing quark couplings: a toy model to mimic FCNC



• All the 4-fermion amplitudes depend only on the ratios



Projections for the coming years

Ob	servable		2014	:		20	19	2024	2030
$\mathcal{B}(K^+$	$ \to \pi^+ \nu \bar{\nu})$	(17.3]	$\left(\begin{array}{c} +11.5 \\ -10.5 \end{array} \right) \times 10$	-11	[32]	10%	[33]	5% [34]	
$\mathcal{B}(K_{\mathrm{I}})$	$\Delta \to \pi^0 \nu \bar{\nu})$	< 2.6	$\times 10^{-8}$ (9	$0\% \mathrm{CI}$	(35]			5% [34]	
$\mathcal{B}(B^+)$	$\rightarrow K^+ \nu \bar{\nu})$	$< 1.3 \times 10^{-5} \ (90\% \mathrm{CL})[36]$					30%[37]		
$\mathcal{B}(B^0_d)$	$\to K^{*0} \nu \bar{\nu})$	< 5.5	$\times 10^{-5}$ (9	$0\% \mathrm{CI}$	(-1)[38]			35%[37]	
$\overline{\mathcal{B}}(B_s)$	$\rightarrow \mu^+ \mu^-)$	$(2.9 \pm$	$(0.7) \times 10$	$^{-9}$ [3]	9-41]	15%[4	[2, 43]	12%[42]	10-12%[42,43]
$\mathcal{B}(B_d$	$\to \mu^+\mu^-)$	(3.6^{+1}_{-1})	$^{1.6}_{1.4}$ × 10 ⁻¹	^{LO †} [3	9-41]	66%	[42]	45%[42]	$18\% \ [42]$
$\mathcal{B}(B_d \to \mu^+ \mu^-)$	$(B_s \to \mu^+ \mu^-)$					71%	[42]	47%[42]	21 - 35% [42, 43]
	2014		2019)	202	24	2030		
F_{B_s}	$(227.7 \pm 4.5) \text{ MeV}$	/ [44]	< 1%	[45]					
F_{B_d}	$(190.5 \pm 4.2) \text{ MeV}$	7 [44]	< 1%	[45]					
$F_{B_s}\sqrt{\hat{B}_{B_s}}$	$(266 \pm 18) \text{ MeV}$	[44]	2.5%	[45]	< 1%	6 [46]			
$F_{B_d}\sqrt{\hat{B}_{B_d}}$	$(216 \pm 15) \text{ MeV}$	[44]	2.5%	[45]	< 1%				
$\dot{\hat{B}_K}$	0.766 ± 0.010	[44]	< 1%	[45]					
$ V_{ub} _{\text{incl}}$	$(4.40 \pm 0.25) \times 10$	$^{-3}[44]$	5%	[37]	3%	[37]			
$ V_{ub} _{\text{excl}}$	$(3.42 \pm 0.31) \times 10$	$^{-3}[44]$	12% ^{††}	[37]	5% †	[†] [37]			
$ V_{cb} _{ m incl}$	$(42.4 \pm 0.9) \times 10^{-1}$	$^{-3}$ [47]	1%	[48]	< 1%				
$ V_{cb} _{ m excl}$	$(39.4 \pm 0.6) \times 10^{-1}$	$^{\cdot 3}$ [44]	1%	[48]	< 1%				
γ $(70.1 \pm 7.1)^{\circ \dagger}$		[49]	6%	[37]	1.5%	$\left[37\right]$	1.3%[4	3]	
$\phi_d^{\rm SM} = 2\beta$	$(43.0^{+1.6}_{-1.4})^{\circ}$	[50]	$\sim 1^{\circ \ddagger} [51]$	1, 52]					
$\phi_s^{\rm SM} = -2\beta_s$	$(0 \pm 4)^{\circ}$	[50]	1.4°	[43]	$\sim 1^{\circ}$	[‡] [53]			

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How far can we go with $\Delta F = 1$ measurements?

- Assume for now only LH (or only RH) couplings to quarks
- $\Delta F = 2$ alone would constrain only the ratio $\Delta_{ij}/M_{Z'}...$
- $\Delta F = 1$ has a different mass/coupling dependence: we can constrain mass and couplings separately

$$C_{\Delta F=2} \propto \frac{\Delta_{ij}^2}{M_{Z'}^2} \qquad \qquad C_{\Delta F=1} \propto \frac{\Delta_{ij} \Delta_{\ell \bar{\ell}}}{M_{Z'}^2}$$

$$\implies C_{\Delta F=1} \propto \sqrt{C_{\Delta F=2}} \frac{\Delta_{\ell\bar{\ell}}}{M_{Z'}}$$

does not depend on the FC coupling

• If nothing is seen in $\Delta F = 2$, rare decays are more effective at low mass and small couplings...

How far can we go with rare B decays?



How far can we go with rare K decays?



Removing the $\Delta F = 2$ constraint by tuning

- Of course, you can complicate the model at will, and get rid of the $\Delta F = 2$ bounds by tuning the parameters...
- If e.g. both LH and RH flavour-changing couplings are present: $(M_{12}^*)^{ij} = \frac{1}{2M_{Z'}^2} \Big[\big((\Delta_L^{ij})^2 + (\Delta_L^{ij})^2 \big) \langle \hat{Q}_1^{VLL} \rangle^{ij} + 2\Delta_L^{ij} \Delta_R^{ij} \langle \hat{Q}_1^{LR} \rangle^{ij} \Big]$



• For the largest possible flavour violation, compatibly with perturbativity (all couplings = 3):

 $M_{Z'}^{\max}(K) \approx 2000 \text{ TeV}$ $M_{Z'}^{\max}(B_{s,d}) \approx 160 \text{ TeV}$

Buras, B, Girrbach, Knegjens '14

3. $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$ in the SM

- Two golden modes that will be precisely measured in this decade
- Theoretically very clean prediction of the BR's in the SM

$$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = \kappa_+ (1 + \Delta_{\rm EM}) \cdot \left[\left(\frac{{\rm Im}\lambda_t}{\lambda^5} X_t \right)^2 + \left(\frac{{\rm Re}\lambda_c}{\lambda} P_c + \frac{{\rm Re}\lambda_t}{\lambda^5} X_t \right)^2 \right]$$

$$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) = \kappa_L \cdot \left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X_t\right)^2,$$

- Present bounds: $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$ $\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu})_{exp} \le 2.6 \cdot 10^{-8}$
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CKM matrix elements

$$\begin{split} \lambda_t &= V_{ts} V_{td}^*, \quad \lambda_c = V_{cs} V_{cd}^*, \\ \lambda &= V_{us} \end{split}$$

CKM matrix elements from tree-level decays

• Tree-level measurements can safely be assumed to be free of BSM physics effects. They determine the CKM matrix elements V_{ub} , V_{cb} , V_{us} , and γ :

$$V_{us} = 0.2252(9) \qquad \gamma = (73.2^{+6.3}_{-7.0})^{\circ}$$

- Discrepancy between inclusive and exclusive determinations $|V_{ub}|_{incl} = (4.40 \pm 0.25) \times 10^{-3}, \qquad |V_{cb}|_{incl} = (42.21 \pm 0.78) \times 10^{-3}.$ $|V_{ub}|_{excl} = (3.72 \pm 0.14) \times 10^{-3}, \qquad |V_{cb}|_{excl} = (39.36 \pm 0.75) \times 10^{-3}.$
- The full CKM matrix is fixed once these parameters are known $\operatorname{Re} \lambda_t = |V_{ub}| |V_{cb}| \cos \gamma (1 - 2\lambda^2) + (|V_{ub}|^2 - |V_{cb}|^2) \lambda \left(1 - \frac{\lambda^2}{2}\right) + \cdots$ $\operatorname{Im} \lambda_t = |V_{ub}| |V_{cb}| \sin \gamma + \cdots \qquad \operatorname{Re} \lambda_c = -\lambda \left(1 - \frac{\lambda^2}{2}\right) + \cdots$

CKM matrix elements from tree-level decays



 $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$

• The main uncertainy at present comes from the CKM matrix



CKM matrix elements from tree-level decays



• Using an average of the previous values one gets:

$$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$

• The main uncertainy at present comes from the CKM matrix



CKM matrix from loop processes

• Performing a fit to the loop-level observables $\varepsilon_K, \Delta M_s, \Delta M_d, S_{\psi K_S}$ a more precise determination of the CKM matrix is obtained (assuming that all those observables are SM-like)



 $|V_{ub}| = (3.61 \pm 0.14) \times 10^{-3},$ $|V_{cb}| = (42.4 \pm 1.2) \times 10^{-3},$ $\gamma = (69.5 \pm 5.0)^{\circ}.$

> using the projected lattice errors from 1412.5097:

$$|V_{cb}| = (42.0 \pm 0.9) \times 10^{-3},$$

 $\gamma = (70.8 \pm 2.3)^{\circ}.$

Buras, B, Girrbach, Knegjens

 $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}, \quad \mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) = (3.00 \pm 0.31) \times 10^{-11}$

Correlation between $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L \to \pi^0 \nu \bar{\nu}$

In all models that do not change the phase of X_t (e.g. in MFV)

$$B_{+} = B_{L} + \left[\frac{\operatorname{Re}\lambda_{t}}{\operatorname{Im}\lambda_{t}}\sqrt{B_{L}} - \left(1 - \frac{\lambda^{2}}{2}\right)P_{c}\operatorname{sgn}(X_{t})\right]$$









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Conclusions (part 2)

- Precision measurements of rare meson decays can be used to probe high energy scales, otherwise directly unaccessible.
- In a simple Z' toy model, K decays can probe scales as high as 100 TeV, while B decays can reach only 15 – 20 TeV. (scales of 2000 and 200 TeV are reached tuning the parameters)
- Lattice calculations of hadronic parameters are improving quickly. Many errors are already dominated by CKM uncertainties.
- $K \to \pi \nu \bar{\nu}$ decays will be measured very precisely: stay tuned!
- Precise SM predictions and several correlations among observables can be used to constrain BSM physics.

Electric dipole moment of the electron

- New bound: $|d_e| < 8.7 \times 10^{-29} \, e \, {\rm cm}$
- One loop chargino-sneutrino contribution:

 $m_{\tilde{\nu}_1} > 17 \, \text{TeV} \times (\sin \phi_\mu \tan \beta)^{\frac{1}{2}}$

• Two loop Barr-Zee type contributions



Flavour effects in composite Higgs models

	(b)	$U(3)^3_{ m LC}$	$U(3)^3_{ m RC}$	$U(2)^3_{\rm LC}$	$U(2)^3_{ m RC}$
$\epsilon_K, \Delta M_{d,s}$	*	0	*	*	*
$\Delta M_s / \Delta M_d$	*	0	0	0	0
$\phi_{d,s}$	*	0	0	*	0
$\phi_s - \phi_d$	*	0	0	0	0
C_{10}	*	0	0	*	0
C_{10}^{\prime}	*	0	0	0	0
$pp \rightarrow jj$	0	*	*	0	0
$pp \rightarrow q'q'$	*	0	0	*	*

★ effect could show up in future measurements

Correlation with B -> $\mu\mu$



CKM fit: more plots



different fits

isolines of $\boldsymbol{\gamma}$