(Heavy) Flavor Physics - Theory

- Flavor Physics: about, status
- Beyond-the-SM Flavor: concepts, constraints, predictions; susy
- Direct and indirect tests at hadron colliders

Gudrun Hiller, Dortmund

The Standard Model of Particle Physics

renormalizable quantum field theory + local symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{em}$$

$$\mathcal{L}_{\mathcal{SM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi} i \not{D} \psi + \frac{1}{2}(D\Phi)^2 - \underbrace{\bar{\psi} Y \Phi \psi}_{Yukawa\, interact.} + \underbrace{\mu^2\Phi^2 - \lambda\Phi^4}_{Higgs\, potential}$$

ψ: fermions (quarks and leptons)

$F_{\mu\nu}$: gauge bosons g, γ, Z, W

Φ: Higgs boson (not observed to date)

Known fundamental matter comes in generations $\psi \to \psi_i$, $i = 1, 2, 3$.

Flavor physics$=$ investigations on generational structure of fermions (and partners)

The Standard Model of Particle Physics: Flavor

fields in representations under the SM group $SU(3)_C \times SU(2)_L \times U(1)_Y$

Higgs: $\Phi(1, 2, 1/2)$ hypercharge $Y = Q - T^3$

quarks: $Q_L(3, 2, 1/6)_i$, $D_R(3, 1, -1/3)_i$, $U_R(3, 1, 2/3)_i$

leptons: $L_L(1, 2, -1/2)_i$, $E_R(1, 1, -1)_i$ L: doublet, R:singlet under $SU(2)_L$

$$\mathcal{L}_{SM} = \sum_{\psi=Q,U,D,L,E} \bar{\psi}_i i \not{D} \psi_i$$

$$-\bar{Q}_{L_i}(Y_u)_{ij}\Phi^C U_{R_j} - \bar{Q}_{L_i}(Y_d)_{ij}\Phi D_{R_j} - \bar{L}_{L_i}(Y_e)_{ij}\Phi E_{R_j}$$

$$+\mathcal{L}_{higgs} + \mathcal{L}_{gauge}$$

Y_u, Y_d, Y_e: Yukawa matrices (3×3, complex). After diagonalization, there are $6+3$ Dirac masses and 4 parameters in the quark mixing matrix $V_{CKM} \equiv V$ left. These are the only sources of flavor in the SM.

$$
\begin{aligned}
Y_u &\sim \begin{pmatrix} 10^{-5} & -0.002 & 0.008 + i\,0.003 \\ 10^{-6} & 0.007 & -0.04 \\ 10^{-8} + i\,10^{-7} & 0.0003 & 0.94 \end{pmatrix} \\
Y_d &\sim \mathrm{diag}\left(10^{-5}, 5 \cdot 10^{-4}, 0.025\right) \quad (\cdot \frac{\langle H_u \rangle}{\langle H_d \rangle}) \\
Y_e &\sim \mathrm{diag}\left(10^{-6}, 6 \cdot 10^{-4}, 0.01\right) \quad (\cdot \frac{\langle H_u \rangle}{\langle H_d \rangle})
\end{aligned}
$$

Very peculiar pattern.

Mismatch between gauge and mass basis allows quarks to mix and change flavor. This happens only thru charged (weak) currents, with strength $V_{ij} = V_{u_i\, d_j}$. Wolfenstein parameter $\lambda \simeq 0.22$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & +\lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & +A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

With 3 generations there are 10 param. in quark flavor $\&$ CP sector:
6 masses, 3 angles and 1 phase in CKM-matrix unitary, complex, hierarchical, known
with accuracy: $|V_{us}| = 0.225$ (permille), $|V_{cb}| = 42 \cdot 10^{-3}$ (percent), $|V_{ub}| = 4 \cdot 10^{-3}$ (ten percent), $\sin 2\beta(\text{measured}) = 0.67$ (percent)

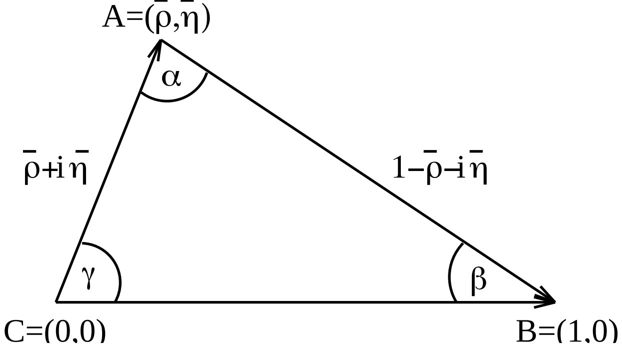
PS: enormous progress from B-factories over past decade. PPS: still improving precision.

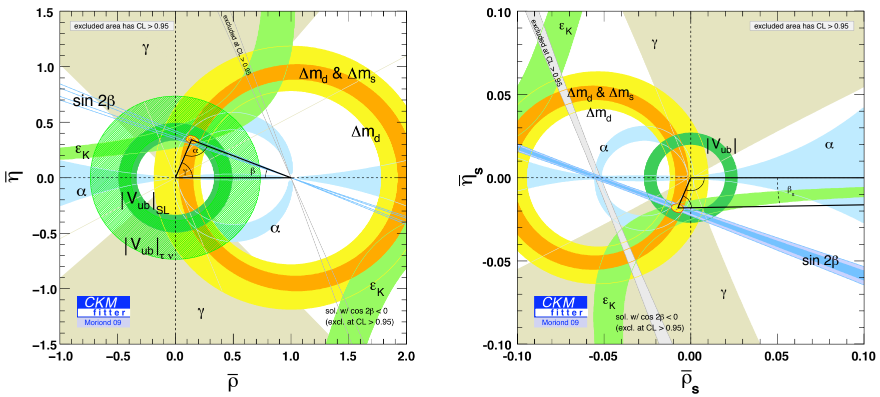
- The third generation is decoupled from the first two.
- The CP violating phase is order one.
- SM quark flavor violation is entirely described by 10 parameters.
- With these parameters better and better known, one can look for

(even small) deviations from SM/CKM-induced flavor and CP violat.

the unitarity triangle

$$V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0$$



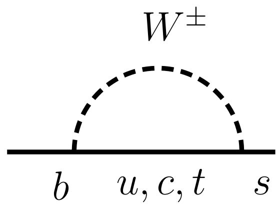


$\sum_j V_{ji}V_{jk}^* = \delta_{ik}$

the next unitarity triangle $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$

Flavor Changing Neutral Currents

generic SM $b \to s$ amplitude



quantum loop effect $\mathcal{A}(b \to s) = \underbrace{V_{ub}V_{us}^*}_{\mathcal{O}(\lambda^4)} A_u + \underbrace{V_{cb}V_{cs}^*}_{\mathcal{O}(\lambda^2)} A_c + \underbrace{V_{tb}V_{ts}^*}_{\mathcal{O}(\lambda^2)} A_t$

with unitarity $VV^\dagger = 1$:

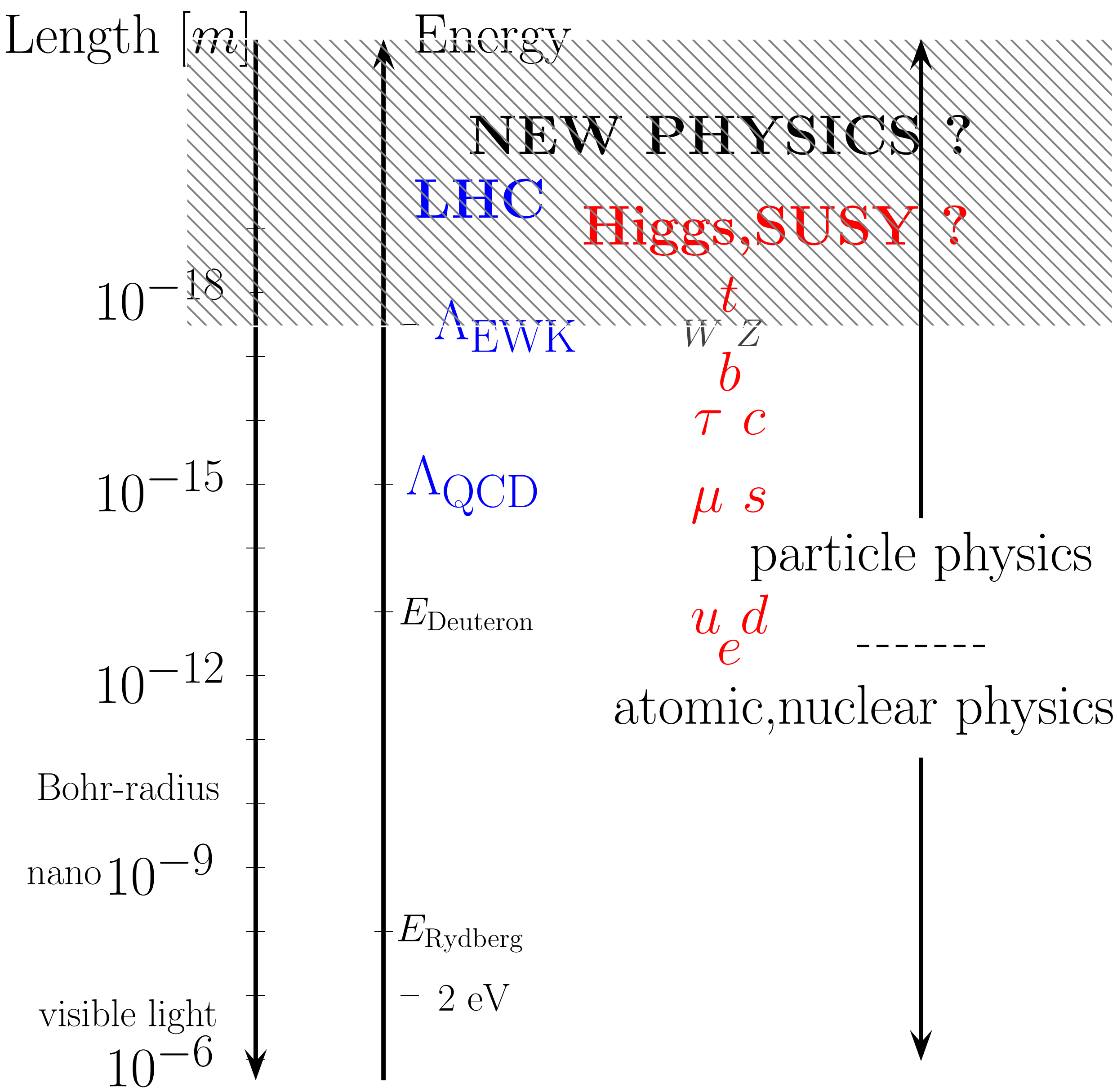
$$\mathcal{A}(b \to s) = V_{tb}V_{ts}^*(A_t - A_c) + V_{ub}V_{us}^*(A_u - A_c) = V_{tb}V_{ts}^*(A_t - A_c) + \mathcal{O}(\lambda^4)$$

$\ast$ GIM suppression inactive $\frac{m_t^2 - m_c^2}{m_W^2} \sim \mathcal{O}(1)$

$\ast$ direct CP violation $b \to s$ small: $|\mathcal{A}(b \to s)| = |\mathcal{A}(\bar{b} \to \bar{s})|(1 + \mathcal{O}(\lambda^2))$

$\ast$ $c \to u$, top FCNCs: GIM and CKM suppressed in SM.

Exploring Physics at Highest Energies

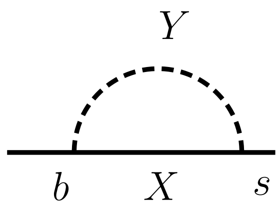


Flavor Physics at Highest Energies

Modulo ”hints” all flavor changing data† are currently ok with the SM within uncertainties.

(but no explanation for flavor/hierarchies in masses and mixing)

What is the flavor structure of the electroweak physics beyond the SM?



†Not every relevant observable is measured or measured with sufficient accuracy.

Flavor Violation beyond the SM

$\mathcal{A}_{\mathrm{SM}}(b \to q) \sim V_{tb}V_{tq}^* \cdot \frac{g^2}{16\pi^2} \cdot \frac{(m_t^2 - m_c^2)}{m_W^2}$

$\mathcal{A}_{\mathrm{NP}}(b \to q) \sim f_{bq} \cdot$ (loop or tree) $\cdot \frac{(m_{\tilde{t}}^2 - m_{\tilde{c}}^2)}{\Lambda^2}$

$f_{AB} = \tilde{V}_{iA}\tilde{V}_{Bi}^\dagger$: New Physics flavor mixing $\quad$ Λ: scale of NP

$*$ Data on FCNC suggest that – if $\Lambda \sim \sqrt{s_{LHC}} \sim \Lambda_{EWK}$ – it is very natural that the suppression of flavor changing transitions is similar to the one in the SM

$f \sim f_{\mathrm{SM}} + \epsilon$ and $f_{\mathrm{SM}} = \lambda^n$, $\lambda \simeq \sin\Theta_C \simeq 0.2$.

$*$ Flavor suppression as in the SM ($\epsilon = 0$):

Minimal Flavor Violation (MFV)

Chivukula, Georgi '87; d'Ambrosio et al '02 non-symmetry based definitions: Ali,London '99; Buras^2 '00

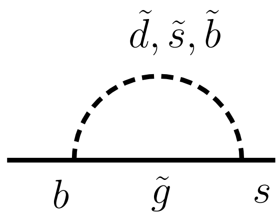
$\ast$ The superpotential ($N = 1$, unbroken R-parity) is MFV:

$$W_{MSSM} = Q_L Y_u H_u U_R + Q_L Y_d H_d D_R + L_L Y_e H_d E_R + \mu H_d H_u$$

$\ast$ Without further input there can be arbitrarily large and CP-violating intergenerational mixing among the scalar partners of the SM fermions from the SUSY breaking:

$$\mathcal{L}_{soft} = -\tilde{Q}^\dagger_{Li} (\tilde{m}^2_Q)_{ij} \tilde{Q}_{Lj} + \ldots$$

This is ruled out by FCNC data for TeV-scale SUSY partners.



* The off-diagonal squark mass terms ”mass insertions” $\delta^Q_{ij} = (\tilde{m}^2_Q)_{ij}/\tilde{m}^2_{ave}\,, i \neq j$, induce FCNCs, and are constrained by data.

	$\sqrt{\lvert\Re(\delta^d_{12})^2_{\mathrm{LL}}\rvert}$		$\sqrt{\lvert\Im(\delta^d_{12})^2_{\mathrm{LL}}\rvert}$	
x	TREE	NLO	TREE	NLO
0.3	1.4×10^{-2}	2.2×10^{-2}	1.8×10^{-3}	2.9×10^{-3}
1.0	3.0×10^{-2}	4.6×10^{-2}	3.9×10^{-3}	6.1×10^{-3}
4.0	7.0×10^{-2}	1.1×10^{-1}	9.2×10^{-3}	1.4×10^{-2}
	$\sqrt{\lvert\Re(\delta^d_{12})_{\mathrm{LL}}(\delta^d_{12})_{\mathrm{RR}}\rvert}$		$\sqrt{\lvert\Im(\delta^d_{12})_{\mathrm{LL}}(\delta^d_{12})_{\mathrm{RR}}\rvert}$	
x	TREE	NLO	TREE	NLO
0.3	1.8×10^{-3}	8.6×10^{-4}	2.3×10^{-4}	1.1×10^{-4}
1.0	2.0×10^{-3}	9.6×10^{-4}	2.6×10^{-4}	1.3×10^{-4}
4.0	2.8×10^{-3}	1.3×10^{-3}	3.7×10^{-4}	1.8×10^{-4}
	$\sqrt{\lvert\Re(\delta^d_{12})^2_{\mathrm{LR}}\rvert}$		$\sqrt{\lvert\Im(\delta^d_{12})^2_{\mathrm{LR}}\rvert}$	
x	TREE	NLO	TREE	NLO
0.3	3.1×10^{-3}	2.6×10^{-3}	4.1×10^{-4}	3.4×10^{-4}
1.0	3.4×10^{-3}	2.8×10^{-3}	4.6×10^{-4}	3.7×10^{-4}
4.0	4.9×10^{-3}	3.9×10^{-3}	6.5×10^{-4}	5.2×10^{-4}

Table 1: Maximum allowed values for $\lvert\Re\left(\delta^d_{12}\right)_{AB}\rvert$ and $\lvert\Im\left(\delta^d_{12}\right)_{AB}\rvert$, with $A, B = (L, R)$ for an average squark mass $m_{\tilde{q}} = 500$ GeV and for different values of $x = m^2_{\tilde{g}}/m^2_{\tilde{q}}$. The bounds are given at tree level in the effective Hamiltonian and at NLO in QCD corrections as explained in the text. For different values of $m_{\tilde{q}}$ the bounds scale roughly as $m_{\tilde{q}}/500$ GeV.

e.g., 0711.2903

$*$ MFV implies squark flavor-mixing given by quark-Yukawa matrices

$$\tilde{m}_Q^2 \quad = \quad \tilde{m}^2(a_1\mathbf{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger) \quad \text{etc.}$$

$Y_u = \mathrm{diag}(y_u, y_c, y_t), \qquad Y_d = V \cdot \mathrm{diag}(y_d, y_s, y_b)$ (up mass basis)

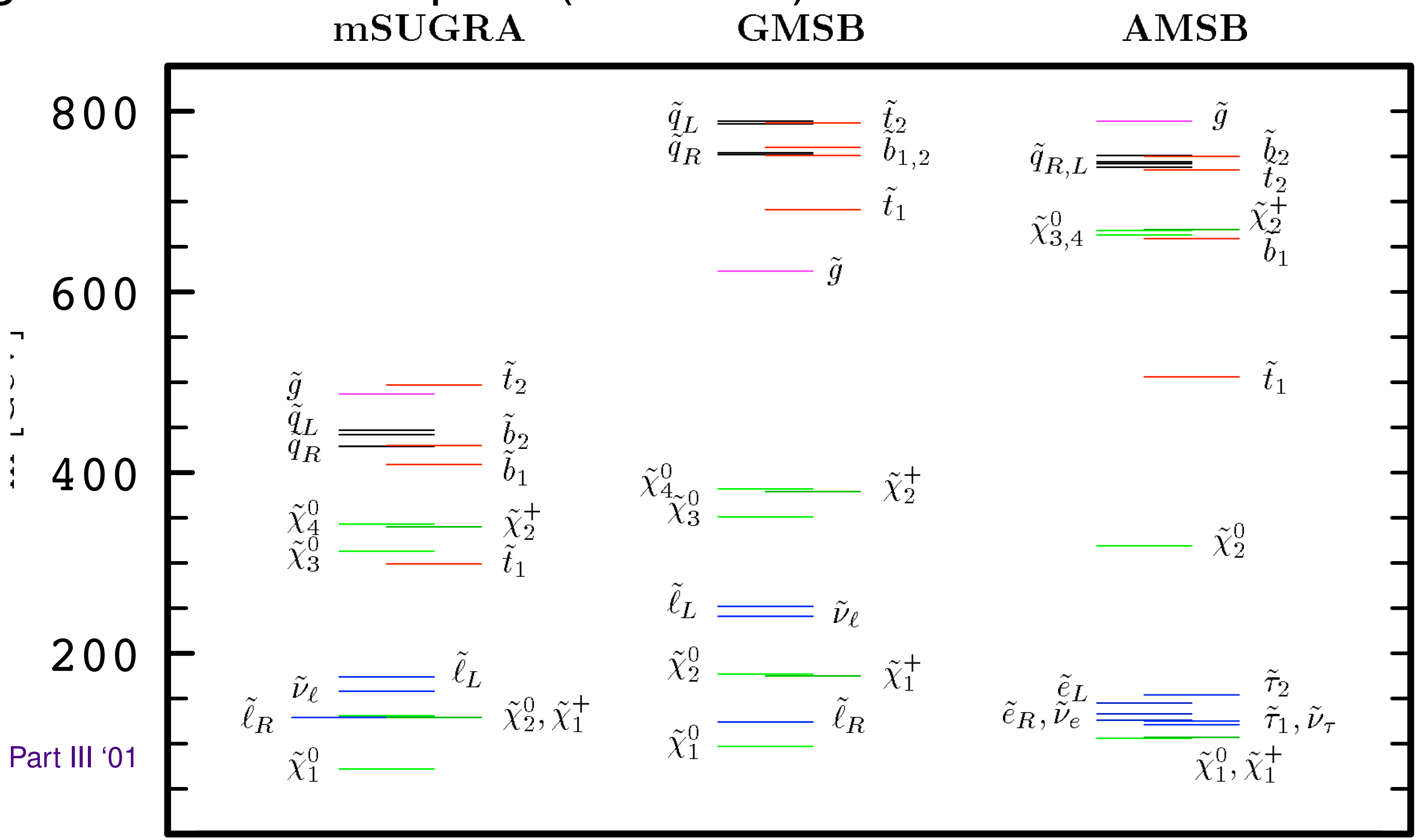
Controlled departure from flavor-blind SUSY breaking.

$*$ $\mathcal{O}(1)$ deviations possible in MFV-MSSM from SM in rare processes if $\tan\beta$ is large.

$*$ Anomaly mediation, gauge mediation and CMSSM/mSUGRA (by construction) are MFV.

$*$ MFV coefficients also induced by RG-evolution.

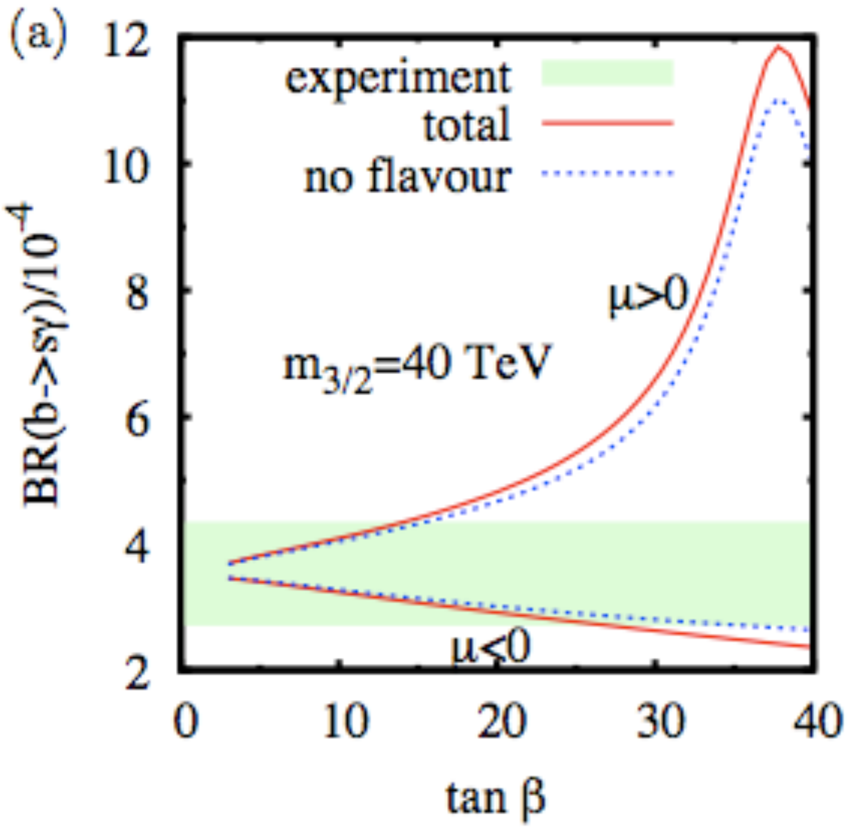
* Highly degenerate squarks of 1st and 2nd generation:
$\Delta m/m_0 \sim \lambda_c^2/2; \qquad \Delta m < 1$ GeV
* 3rd generation decoupled (via CKM).

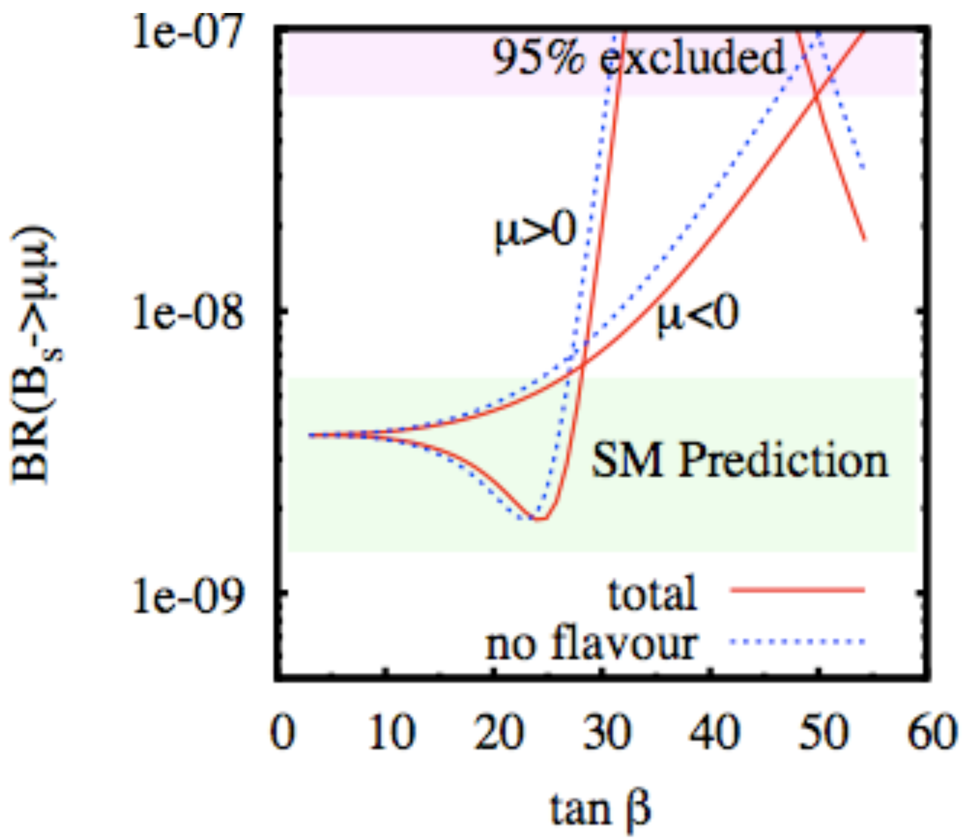


TESLA TDR Part III '01

Predictivity and large Effects in FCNC Loops

$\ast$ Predictive $\mathcal{O}(1)$ effects within MFV models if $\tan\beta$ largish. many works
Here, AMSB ($m_{3/2} = 40$ TeV)





Analytical expressions for the full flavor structure, that is, a_i, b_j or $(\delta^q)_{ij}$, within mAMSB 0902.4880 .

Summary BSM Flavor

$*$ MFV models are flavor-safe and predictive; like the SM, they do not address the origin of the Yukawas.

$*$ Realistic and viable non-MFV models can be constructed, which access the origin of flavor (symmetry vs anarchy) (0812.051, 1001.1513 [hep-ph]).

$*$ The larger the departure from MFV, the larger the potential NP effects due to larger mixing and/or mass splitting between generations.

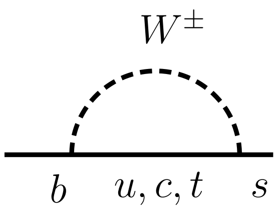
$*$ Existing flavor data leave large room for strong non-MFV signals to show up in branching ratios, decay shapes, angular distributions and CP-asymmetries. Esp.: B_s-mixing, D^0-mixing, $B \to K^{(*)}ll$, photon helicity in $b \to q\gamma_{L,R}$, and in

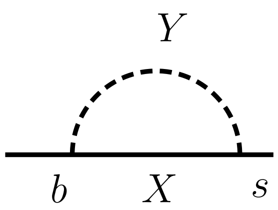
$$R_{\mu\mu} = \frac{\mathcal{B}(B_s \to \mu^+\mu^-)}{\mathcal{B}(B_d \to \mu^+\mu^-)}\,, \qquad R_{\mu\mu}^{SM,MFV} = \frac{m_{B_s} f_{B_s}^2 \tau_{B_s}}{m_{B_d} f_{B_d}^2 \tau_{B_d}} r_{\text{ps}} \times \frac{|V_{ts}|^2}{|V_{td}|^2}\,.$$

Testing Quark Flavor Violation at Colliders

* indirectly: b phyiscs
* directly: (s)top physics

Penguins and Effective Theory





add $A = \gamma, g, Z, h^0, \ldots$. Thats an $=$"A"-penguin.

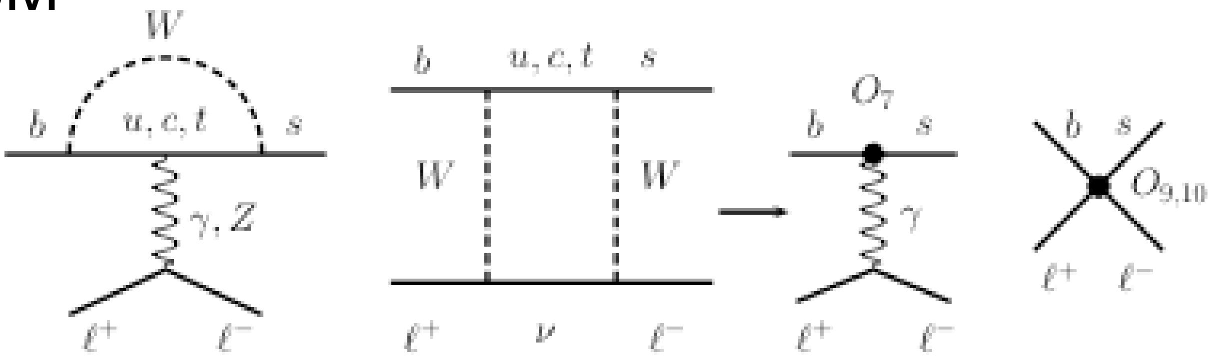
construction of weak low energy effective theory valid $\mu \lesssim \mu_W = \Lambda$

$$\mathcal{L}_{\text{eff}} = \sum_i C_i(\mu) \frac{O_i(\mu)}{\Lambda^2} + \mathcal{O}(\frac{p^4}{\Lambda^4})$$

O_i: dim 6 operators out of light degrees of freedom, originate from penguins and boxes

C_i: Wilson coefficients: contain info on high scales $\gtrsim \mu_W$ e.g., hep-ph/9806471
$C_i(m_W)$: matching of effective onto full theory. $\rightarrow$ RG-running
C_i: known up to NNLO in SM for QCD, and NLO for EWK corr.

diagrams in SM



$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum C_i(\mu) O_i(\mu)$$

dipole operators $O_7 \propto \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$ $O_8 \propto \bar{s}_L \sigma_{\mu\nu} b_R G^{\mu\nu}$

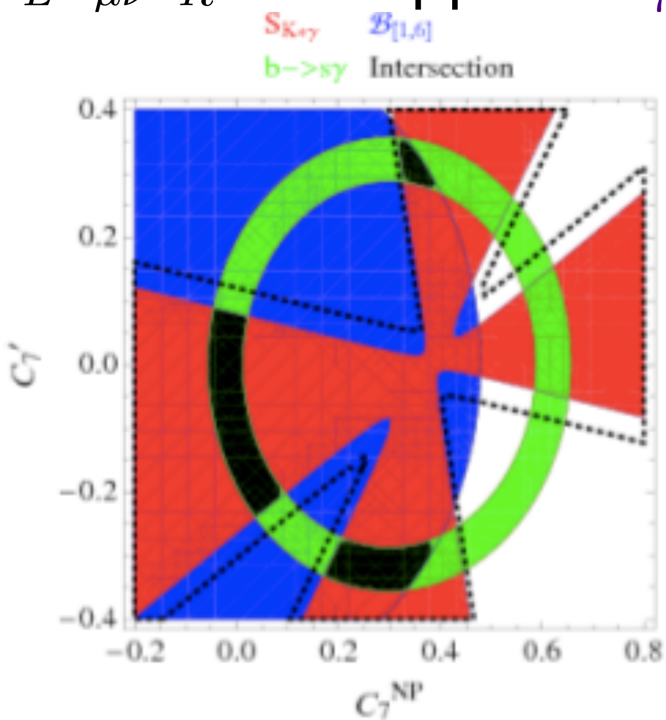
4-Fermi operators $O_9 \propto (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$ $O_{10} \propto (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$

NP in Wilson coefficients $C_i = C_i^{SM} + C_i^{NP}$ or new operators

model-independent analysis: Br's, $A_{CP}, A_{FB} = f(C_i) \to$ fit! hep-ph/9408213

FCNC Photon Couplings Model-independently

dipole operators $O_7 \propto \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$ "flipped" $O_7' \propto \bar{s}_R \sigma_{\mu\nu} b_L F^{\mu\nu}$ 0805.2525



green ring: $Br(B \to X_s \gamma) \sim |C_7|^2 + |C_7'|^2 \sim |C_7^{SM}|^2$

red cross: time-dependent CP-asymmetry $B \to (K^{*0} \to K_S^0 \pi^0)\gamma$

blue area: $Br(B \to X_s ll)$ data favor sign(C_7) to be SM like.

- Penguin bounds: (at $\mu \simeq m_b$, assuming no BSM operators)

  $$bsZ : |C_{10}| \lesssim (1-2)|C_{10}|_{\rm SM}\,, \quad bs\gamma : C_7 \simeq C_{7\,\rm SM}\,, \quad bsg : |C_8| \lesssim 5|C_8|_{\rm SM}\,.$$

- Todays best bound on MSSM Higgs-penguins from Tevatron $\mathcal{B}(B_s \to \mu^+\mu^-)$

- $b \to d$ beginning to be probed, MFV-link with $b \to s$ to come: CP-phases and helicity.

- Tools in penguin-physics: multi-observable analyses and fits and SM-null tests.

How to calculate $A(B \to K^* \mu\mu)$

1. choose model, such as SM, MSSM etc. This is your ”full” theory.

2. Calculate the low energy effects ”Wilson coefficients” of this full theory within a ”generalized Fermi-theory”, the effective theory, H_{eff}.

3. Take the matrix element $A(B \to K^* \mu\mu) = \langle K^* \mu\mu | H_{eff} | B \rangle$. This needs input from non-pertubative QCD: form factors etc.

In full QCD, there are 7 form factors in $B \to K^*$:
$A_0, A_1, A_2, V, T_1, T_2, T_3$. see, e.g., ABHH,hep-ph/9910221
This simplifies for low dilepton mass to just 2: $\xi_\perp, \xi_{||}$. e.g., BFS hep-ph/0412400

4. Work out your observables/distributions.

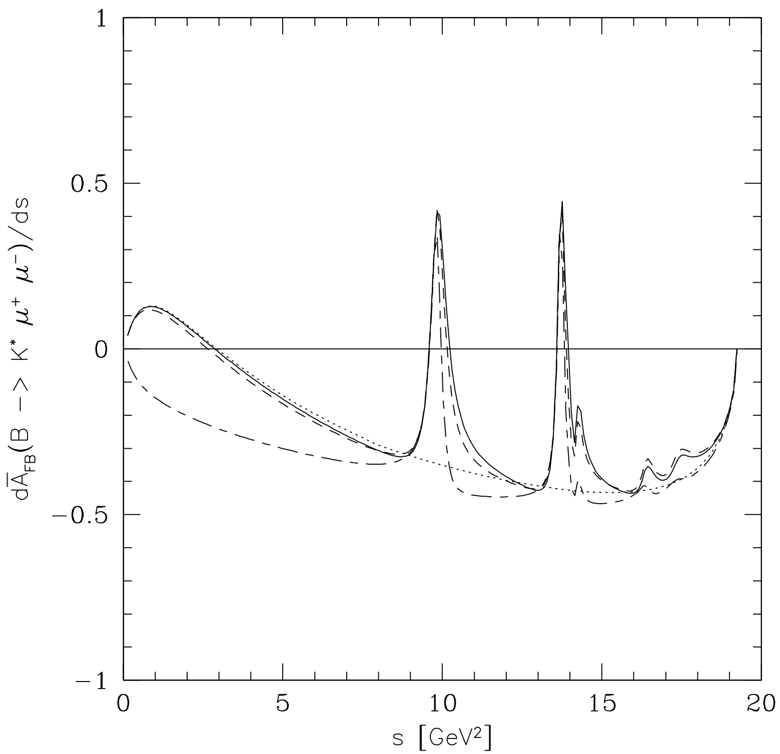
5. Employ cuts: Remove huge BGD from $B \to V_{cc} K^* \to \mu\mu K^*$; $V_{cc} = J/\Psi, \Psi', ..$ by cuts in dilepton invariant mass.

Observables in $\bar{B} \to K^* ll$

$d^2\Gamma/dq^2 d\cos\Theta$;   note: $\cos\Theta(\bar{B}l^+) = -\cos\Theta(\bar{B}l^-)$

A_{FB}: # forward - # backward ℓ^+ in dilepton CMS w.r.t. $\bar{B}$ (CP-odd)

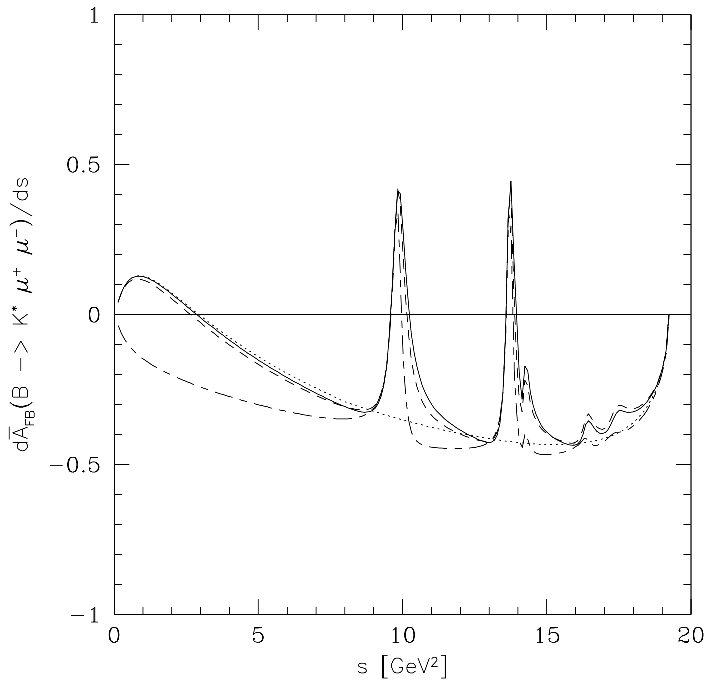
$$A_{FB}(\hat{s}) \equiv \int d\cos\Theta \mathrm{sign}(\cos\Theta) \frac{d\Gamma}{d\hat{s} d\cos\Theta} \sim -\mathrm{Re}\left[C_{10}^*(C_7^{\mathrm{eff}} + \beta(\hat{s}) C_9^{\mathrm{eff}})\right]$$



Exclusive $b \to (s,d)ll$ and New Physics Searches

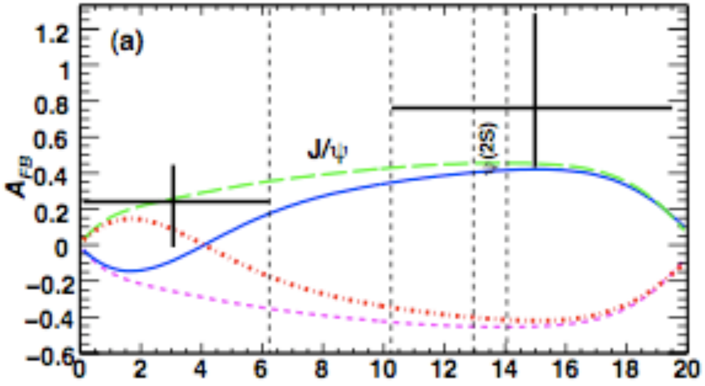
There is no unique rigorous framework available to describe exclusive $b \to sll$ decays in the whole kinematically accessible range. Theoretically preferred region: low dilepton mass below J/Ψ (QCDF); low recoil region also calculable. CUTS are important!

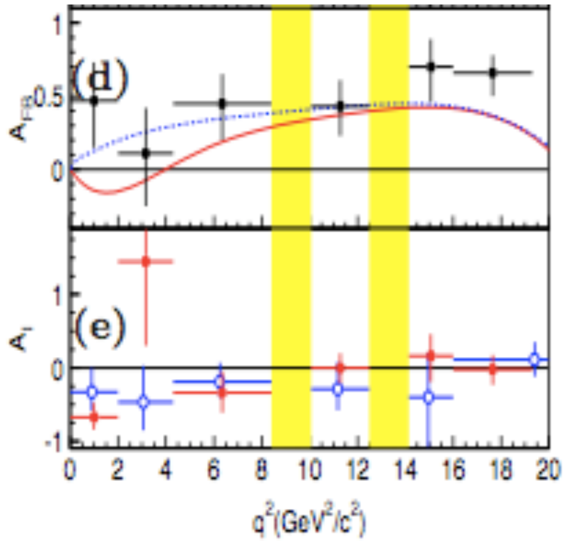
Whole q^2-region tests the SM; different regions are sensitive to different New Physics.

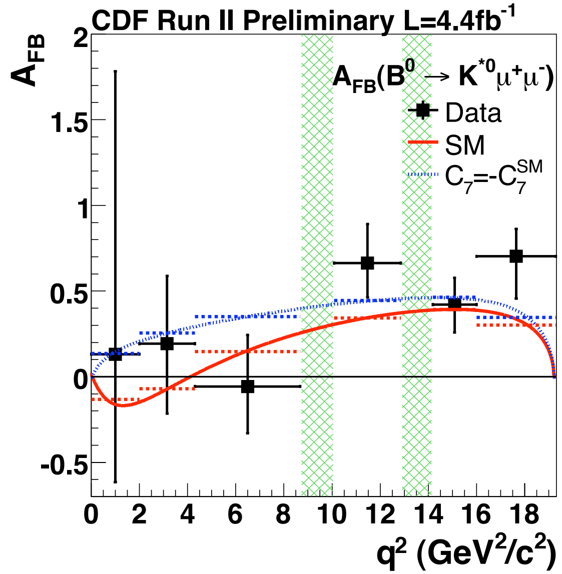


Forward-Backward Asymmetry

left: BaBar: 0804.4412 [hep-ex], mid: Belle 0904.0770 [hep-ex], right: CDF Public note 10047







Sign/zero of A_{FB} at low dilepton mass?

Sign of A_{FB} at large dilepton mass SM-like! 0805.2525 [hep-ph]

Full Angular Analysis in $B \to V(\to PP)\mu\mu$

full angular analysis hep-ph/9907386

$$d\Gamma^4 \sim J dq^2 d\cos\Theta_l d\cos\Theta_{K^*} d\Phi;\ J = \sum_{i=1}^9 J_i(q^2) f(\Theta_l, \Theta_{K^*}, \Phi)$$

$\Gamma \sim J_1 - J_2/3$, $A_{FB} \sim J_6$, $A_T^{(2)} \sim J_3$ hep-ph/0502060

$B \to K^{(*)} ll$ CP observables in angular analysis Bobeth,GH,Piranishvili 0805.2525

CP-asymmetries $A_i \propto J_i - \bar{J}_i$: SM: all doubly Cabbibo-suppressed

A_3, A_9 vanish in SM by helicity conservation: sens. to RH currents
$A_3, A_9, (A_6)$ can be extracted from single-diff distribution in $\Phi(\Theta_l)$
A_7, A_8, A_9: T-odd: no strong phase suppression; O(1) with NP
A_5, A_6, A_8, A_9: CP-odd: can be extracted without tagging from $\Gamma + \bar{\Gamma}$
Difference between $B_d \to K^*$ and $B_s \to \Phi$ probes predom. B_s mixing ($\Delta\Gamma_s$ and phase); $A_{5,6,8,9}$ without flavor-taging and time-integrated !

For $\bar{B} = (b\bar{q})$ decays:

$$
\begin{aligned}
J(q^2, \theta_l, \theta_{K^*}, \phi) = & \, J_1^s \sin^2\theta_{K^*} + J_1^c \cos^2\theta_{K^*} + (J_2^s \sin^2\theta_{K^*} + J_2^c \cos^2\theta_{K^*}) \cos 2\theta_l \\
& + J_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + J_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi + J_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi \\
& + J_6 \sin^2\theta_{K^*} \cos\theta_l + J_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi \\
& + J_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi + J_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi, \qquad (2.3)
\end{aligned}
$$

$J_i = J_i(q^2)$, $q = p_{l^+} + p_{l^-}$; J_i are functions of transversity amplitudes.

Θ_l: angle between l^- and $\bar{B}$ in dilepton CMS (warning: different conventions in literature)
Θ_{K^*}: angle between K and $\bar{B}$ in K^*-cms
Φ: angle between normals of the $K\pi$ and l^+l^- plane

For CP-conjugate B decays: $J_{1,2,3,4,7} \to \bar{J}_{1,2,3,4,7}$, $J_{5,6,8,9} \to -\bar{J}_{5,6,8,9}$

T-odd versus T-even CP Asymmetries

Here, what is meant by T is the naive T transformation, not time-reversal! Under naive T, the momenta and spins of all particles are flipped, but the initial and final states are not interchanged.

φ_W: weak, CP-violating phase; φ_S: strong, CP-conserving phase

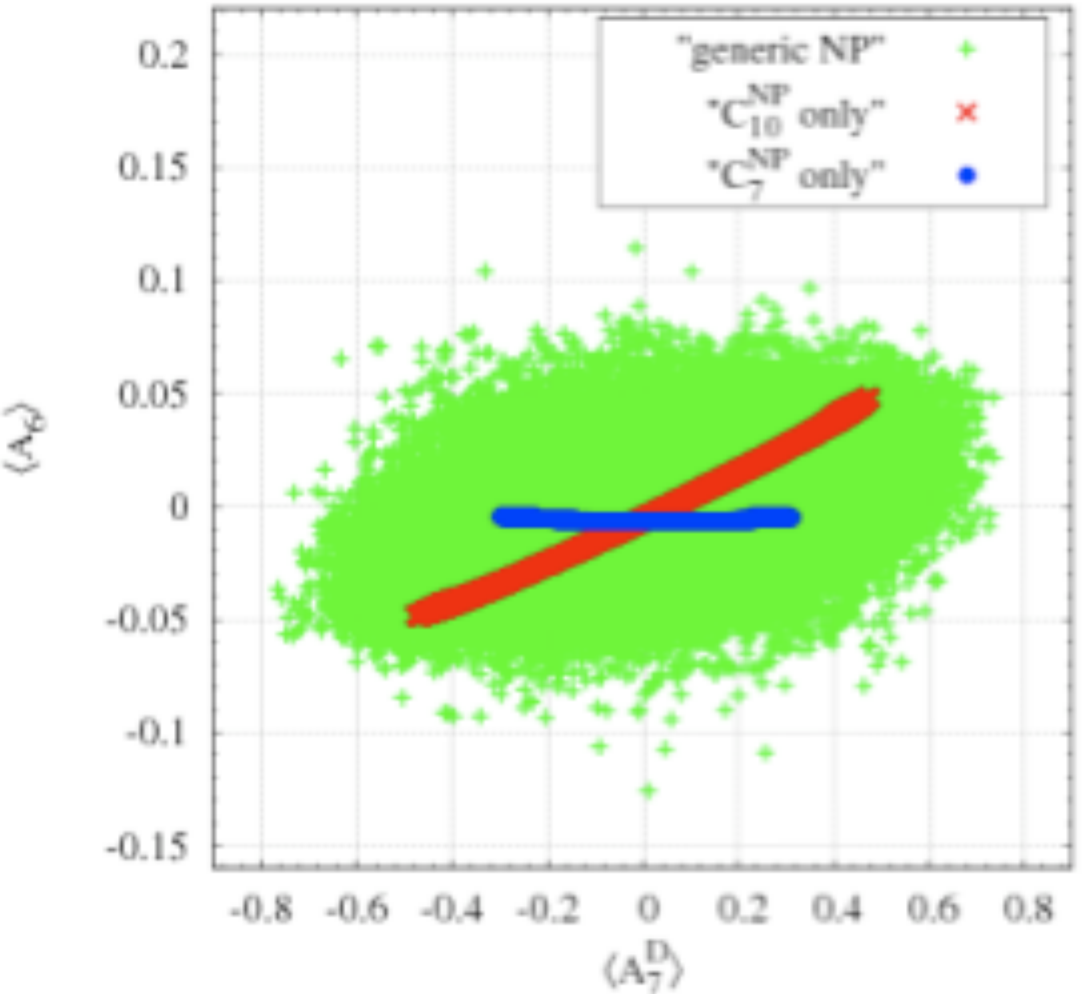
T-even CP asymmetries: $\propto \sin\varphi_W \sin\varphi_S$: small if QCD gives us only small strong phases despite a possible O(1) NP phase.

PS: this is exaclty what happens at low dilepton mass in $B \to K^{(*)} ll$ decays where QCDF predicts small φ_S

T-odd CP asymmetries: $\propto \sin\varphi_W \cos\varphi_S$ maximal for vanishing strong phase

T-odd versus T-even CP Asymmetries

Both A_7 and A_6 are sensitive to Z-penguins ($\sim C_{10}$) Fig. from 0805.2525

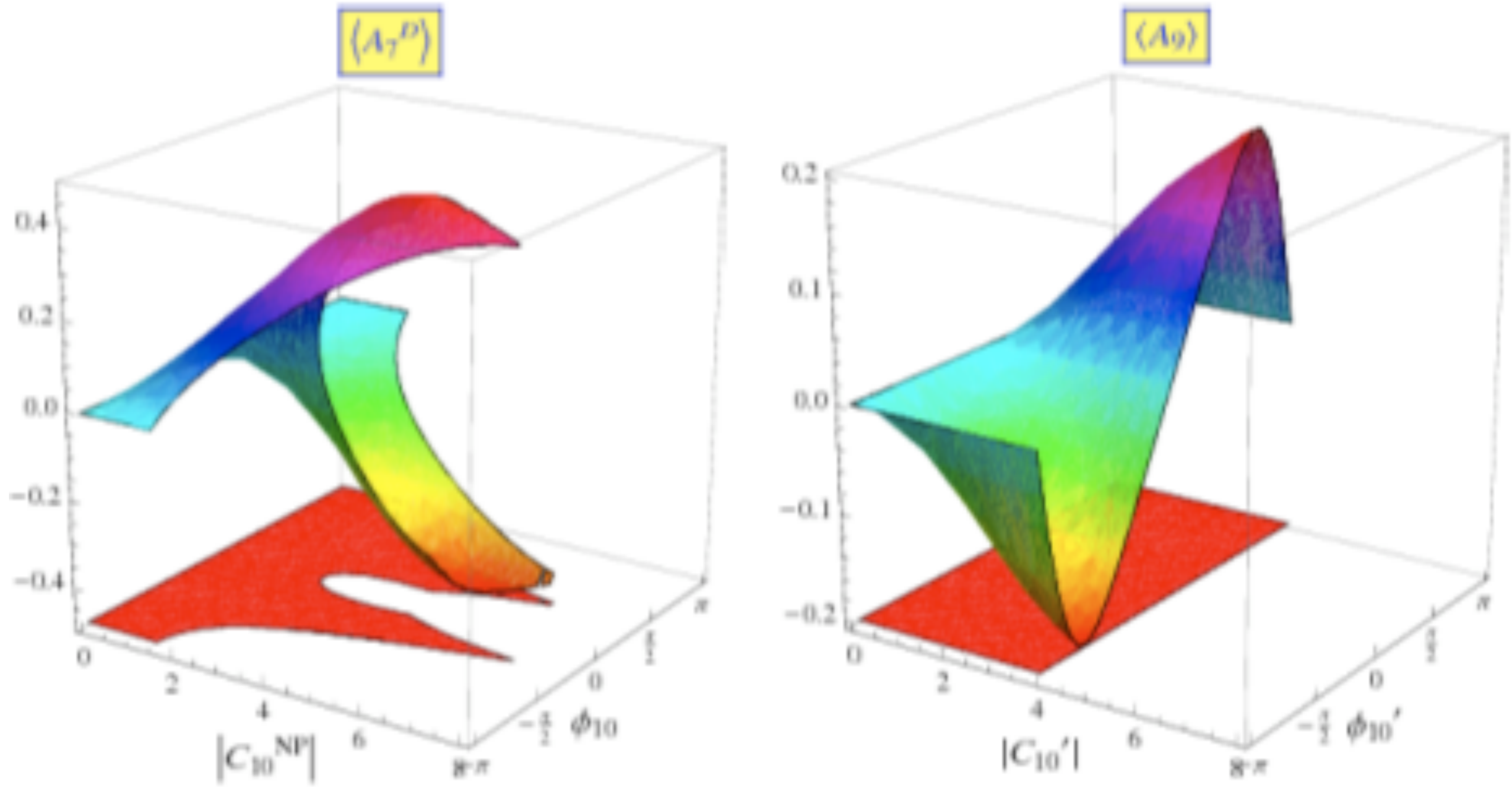


T-odd versus T-even CP Asymmetries

A_7, A_8, A_9 are T-odd and can be order one with NP Tab. from 0805.2525

	generic NP	$C_{10}^{\rm NP}$ only	$C_{10}^{\prime\rm NP}$ only	$C_9^{\rm NP}$ only
$\langle A_{\rm CP}\rangle$	$[-0.12, 0.10]$	$[3, 8]\cdot 10^{-3}$	SM-like	$[-0.02, 0.02]$
$\langle A_3\rangle$	$[-0.08, 0.08]$	SM-like	SM-like	SM-like
$\langle A_4^D\rangle$	$[-0.04, 0.04]$	$[-4, -1]\cdot 10^{-3}$	$[-3, -1]\cdot 10^{-3}$	$[-0.01, 0.01]$
$\langle A_5^D\rangle$	$[-0.07, 0.07]$	$[-0.04, 0.04]$	$[-0.02, 0.04]$	$[5, 9]\cdot 10^{-3}$
$\langle A_6\rangle$	$[-0.13, 0.11]$	$[-0.05, 0.05]$	$[-9, -3]\cdot 10^{-3}$	SM-like
$\langle A_7^D\rangle$	$[-0.76, 0.76]$	$[-0.48, 0.48]$	$[-0.38, 0.38]$	SM-like
$\langle A_8^D\rangle$	$[-0.48, 0.48]$	$[2, 7]\cdot 10^{-3}$	$[-0.28, 0.28]$	$[-0.17, 0.17]$
$\langle A_9\rangle$	$[-0.62, 0.60]$	SM-like	$[-0.20, 0.20]$	SM-like
$\mathcal{B}(\bar B_s \to \bar\mu\mu)$	$< 1.4\cdot 10^{-8}$	$< 6.3\cdot 10^{-9}$	$< 1.3\cdot 10^{-8}$	SM

A_7, A_8, A_9 are T-odd and can be order one with NP Fig. from 0805.2525



Angular Analysis in $B \to Kll$, $l = e$ vs μ

$B \to Kll$, $l = e, \mu$ angular analysis 0709.4174 [hep-ph]

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\Theta_l} = \frac{3}{4}(1 - F_H^l)(1 - \cos^2\Theta_l) + F_H^l/2 + A_{FB}^l \cos\Theta_l$$

information in F_H^l and A_{FB}^l beyond $d\Gamma^l/dq^2$ (in general: lepton flavor dependence)

F_H^l can be correlated with $R_K = \mathcal{B}(B \to K\mu\mu)/\mathcal{B}(B \to Kee)$

In SM: $R_K - 1$, F_H^l and A_{FB}^l (and $\mathcal{B}(B \to ll)$) are suppressed by lepton mass. hep-ph/0310219

Probe of Higgs-exchanges, lepto-quarks, R-parity violation etc.

Model-independently w. scalar/tensor couplings (for low q^2):

$$|A_{FB}^e| < 13\%, \quad |A_{FB}^\mu| < 15\%, \quad R_K - 1 = \mathcal{O}(1), \quad F_H^{e,\mu} < O(0.5)$$

- With the rich final state and many orthogonal observables, $b \to qll$ processes are powerful probes of BSM physics. At hadron colliders in particular exclusive decays into muons can be studied. Inclusive decays and those with $l = e$ or invisibles, i.e., $l = \tau$ or ν are favorable to e^+e^- super flavor machines.
- While the Br is observed, and first data on A_{FB}, R_K etc are available, $B \to K^{(*)} l\bar{l}$ has great potential to test the SM, search for NP and classify it (CP, right-handed currents, Higgs effects,..).
- Ideally, measure everything: the full angular distributions, and final states $l = e, \mu, \tau$ and ν (Z-penguins).
  $Br(B \to K^{(*)}\mu\mu)/Br(B \to K^{(*)}ee)$ tests lepton non-universality.
  Also $b \to d$.

Flavor physics in direct searches at hadron colliders usually means top physics. Further opportunities exist: Lepton flavor violation (sleptons): 0712.0674, 0712.2074, 0802.2582, but also quark flavor physics. The latter is difficult because there is no particle ID; its just top, bottom and all the others. However, some info is possible, e.g., from Higgs production and decay, or squark processes e.g., 0512315,0708.0940,0801.1800, if the third generation is involved. These studies are complementary to the ones performed indirectly.

I want to discuss here one idea: the possibility of observing a light, long-lived stop. 0802.0916

Measuring MFV Mixing at Colliders

In MFV, mixing between third and other generations is suppressed:

$$\tilde{M}_Q^2 = \tilde{m}^2(a_1 \mathbf{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger)$$

$$(\tilde{M}_Q^2)_{23}/\tilde{m}^2 \sim \lambda_b^2 V_{cb} V_{tb}^* \sim 10^{-5} \tan\beta^2$$

Such a tiny coupling can indeed be probed if $\tilde{t} \to c\chi^0$ is the dominant decay & sufficiently suppressed rate. 0802.0916[hep-ph]

Then, the lifetime of the stop is long:

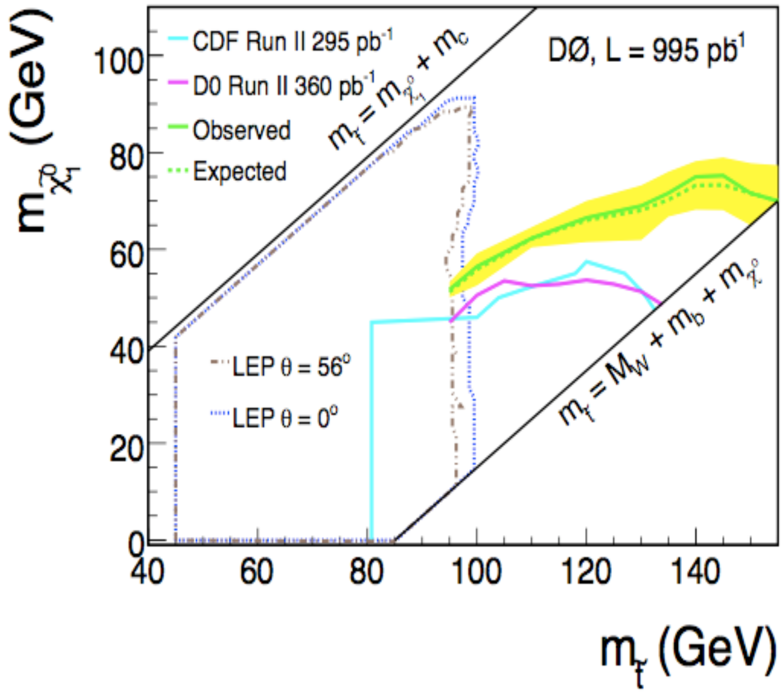
$\tau_{\tilde{t}} \sim \;\mathrm{ps}\; \left(\frac{100\ \mathrm{GeV}}{m_{\tilde{t}}}\right)\left(\frac{0.03}{\Delta m/m_{\tilde{t}}}\right)^2\left(\frac{10^{-5}}{Y}\right)^2$ where $\Delta m = m_{\tilde{t}} - m_{\chi^0}$, $Y_{\mathrm{MFV}} \sim \lambda_b^2 V_{cb}$.

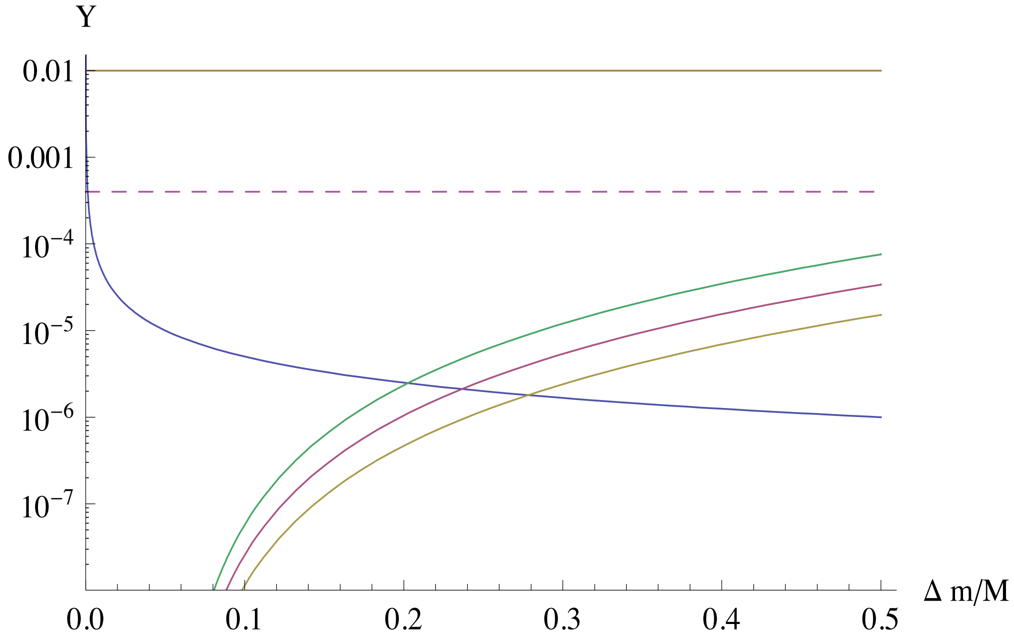
Yields a macroscopic decay length of a few hundred microns (or even larger), which is a way to "measure V_{cb}" with stops.

Long Live the Stop

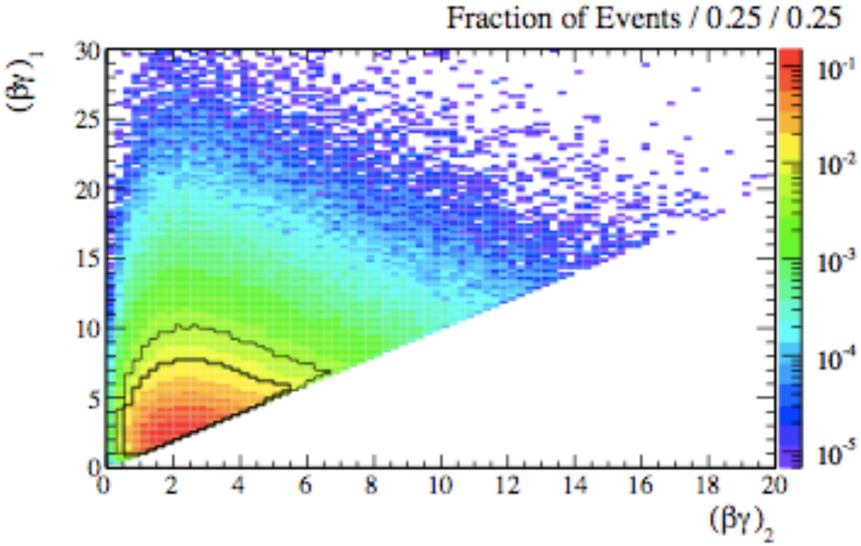
$Y_{MFV} \sim \lambda_b^2 V_{cb} V_{tb}^* \sim 10^{-5} \tan\beta^2$; $Y \sim V_{cb}\lambda_c$ (alignement).
Works for $m_{\tilde{t}} - m_\chi$ smallish.

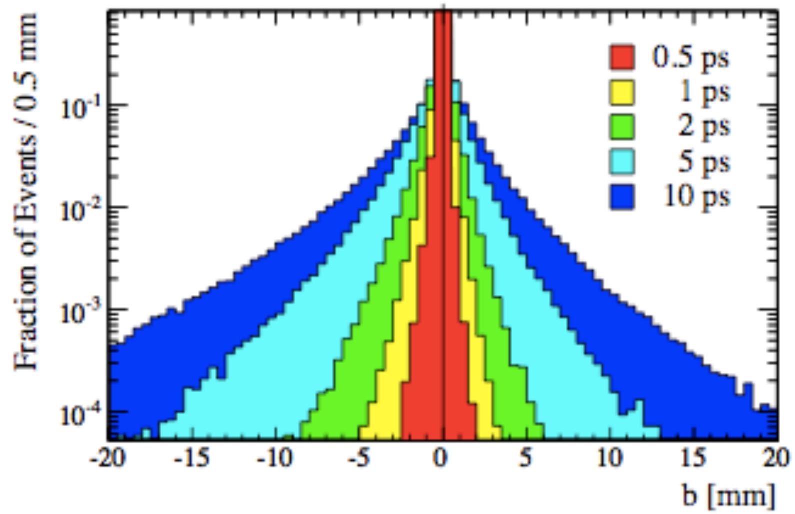
left: 0803.2263 [hep-ex], right: 0802.0916[hep-ph],0905.0327 [hep-ph]





Light stops are produced with low BGD in association with like-sign tops $pp \to \tilde{t}^*\tilde{t}^*tt, \tilde{t}\tilde{t}\bar{t}\bar{t}$ Kraml, Raklev '05; $\sigma \sim \mathrm{few\,pb}$ for 100 GeV stop and 500 GeV gluino.





$\gamma\beta \sim O(1)$, b: transverse impact parameter

0910.2124[hep-ph] Up to 10 events with 1 fb^{-1} (no detector effects, 14TeV).

Summary

* The LHC will explore for the first time the scale of electroweak symmetry breaking. What are the flavor quantum numbers of new particles/SM partners ?
* Already strong constraints: Either TeV-BSM accidentally small in measured K, D, B-observables, or there is an organizing principle such as MFV; or, we havent looked good enough at relevant observables yet $\rightarrow$ LHC(b), super flavor factories.
* Info can be obtained from indirect and direct collider searches. (see stop decay length measurement as one new example for the latter.)

Outlook

What can we learn from flavor physics?

Find out whether TeV-physics has more flavor violation than the SM.

The observation of non-MFV couplings could point towards the origin of generational mixing and hierarchies, i.e., flavor.

Some $B \to K^{(*)}ll$ Theory References

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more recent works on angular observables: U. Egede, T. Hurth, J. Matias, M. Ramon and W. Reece, JHEP **0811**, 032 (2008) [arXiv:0807.2589 [hep-ph]].
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