Flavor physics beyond SUSY

FLAVOUR in the ERA of the LHC

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Outline

- Introduction + Motivation.
- Specific vs. model ind' approach.
- NMFV (next to minimal flavor violation).
- Signals: $\Delta F = 2, 1$ & correlations.
- Conclusions.

Introduction

Why LHC?

Origin of EWSB. (electroweak sym' breaking)

Stable hierarchy $\Leftrightarrow$ $M_W^2 / M_{\rm Pl}^2 \sim 10^{-32}$

$\Downarrow$

Physics $\sim$ EWSB scale, M_W.

EW desert & flavor desert

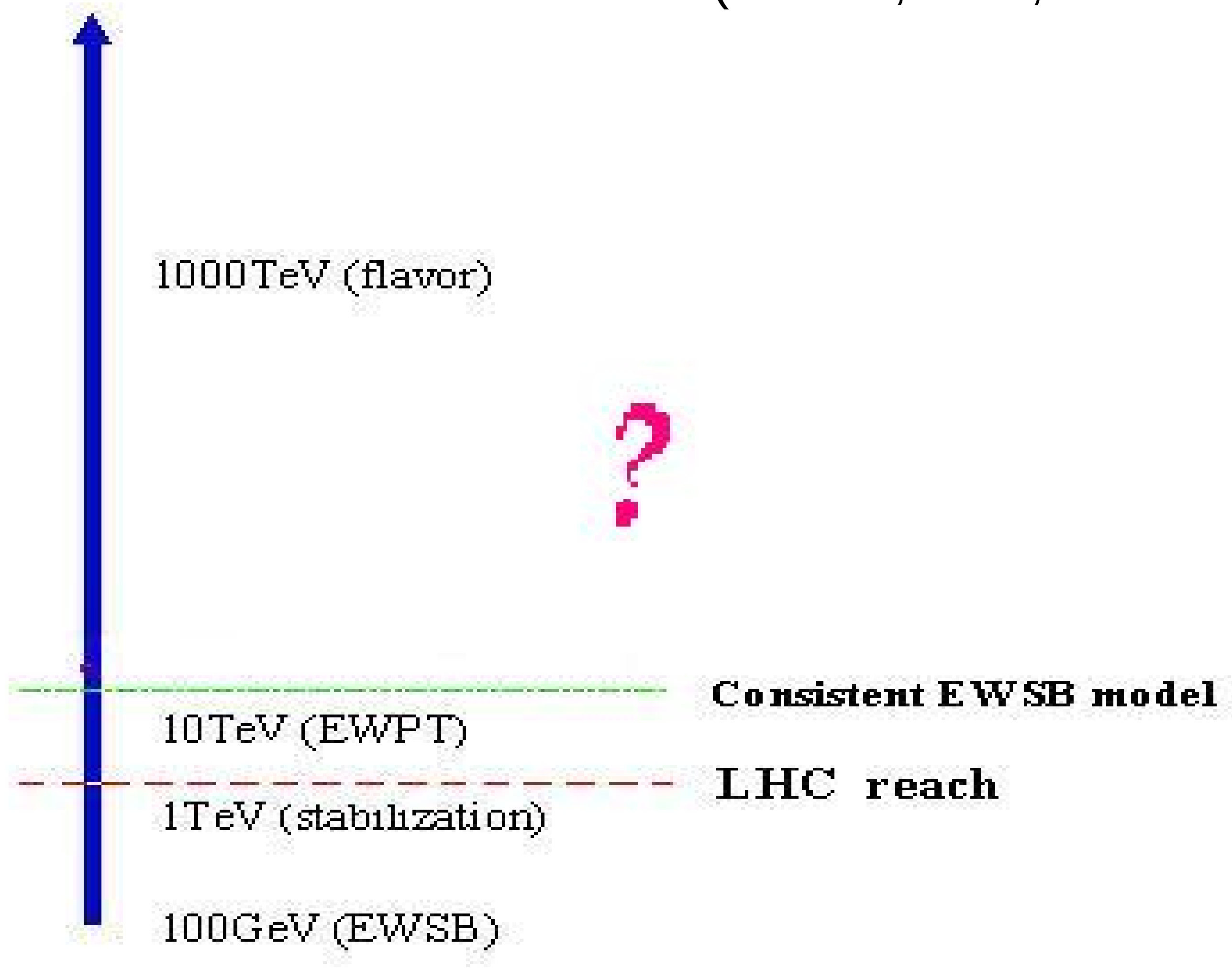
Indirect data favor SM to a high scale.

Observable	Operator	Λ_X^2 in GeV ^{2}
EWSB scale	M_W^2	$\sim (10^2)^2$
EWPT	$\frac{1}{\Lambda_{\rm EW}^2}\left(\bar{f}f\right)^2$	$\gtrsim (10^4)^2$
FCNC	$\frac{1}{\Lambda_F^2}\left(\bar{d}s\right)^2$	$\gtrsim (10^6)^2$

- EWPT (S) $\Rightarrow$ little hier', no sym'!
- FCNC (ε_K) $\Rightarrow$ flavor hier', flavor sym.

Missing info': flavor implicit phys.

Minimalism (Little H, UED, Twins Higgs, 2HDM ...)

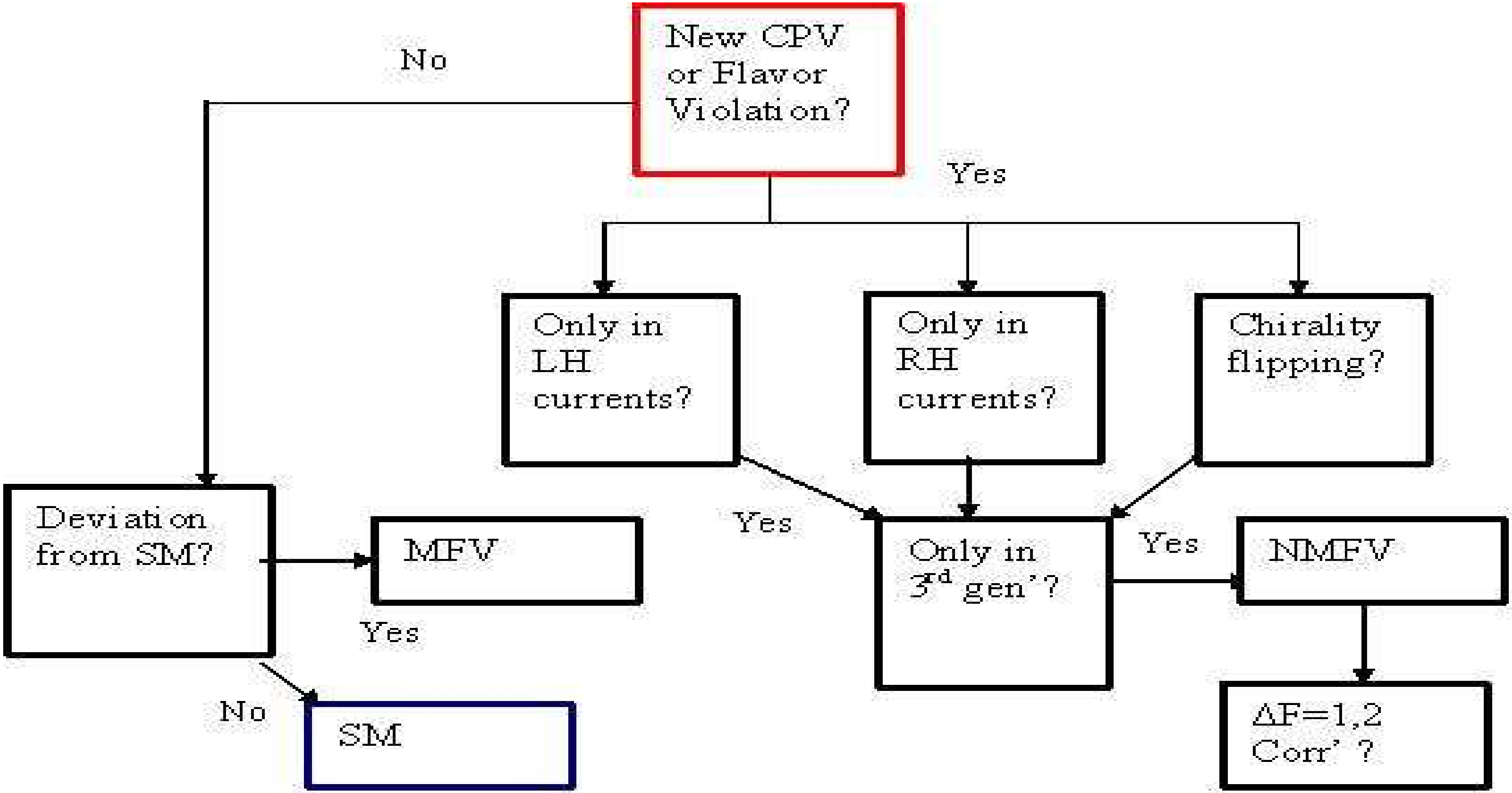


Elimination will be required

Degeneracies

- LHC data will not be conclusive.
- Can flavor phys. give guidelines?
- Partially, through classification.

Degeneracies & Classification



Degeneracies

- Frameworks have same subclasses.
- Some are unclassifiable.

Framework	MFV	LR flavor viol'	NMFV(next to MFV)
SUSY	$\surd$	$\surd$	$\surd$
RS (Randall-Sundrum)	$\surd$	$\surd$	$\surd$
UED (universal xtra dim')	$\surd$	X ?	X ?
Little H	?	?	?

How to proceed ?

Model dep'

- Analyse specific models with minimal (flavor) content: (must assume MFV!)

  UED, (*e.g.* Agashe, Deshpande & Wu; Buras, Spranger & Weiler)

  Little H (Lee; Buras, Poschenrieder & Uhlig; Choudhury *et. al*) ...

How to proceed ?

Top-down, model indep' (too wide?)

- MFV [Only $Y_{u,d}$ (Buras *el. al*; D'Ambrosio *el. al*)]

  See Buras, Isidori & Stocchi's talks.

- Or look for more hints ...

Hints: EW breaking & flavor phys'

- Largest H divergency is from the top.
- nonSUSY $\longrightarrow$ strong dynamics $\longleftrightarrow$ top.
- EW sym' breaking $\Rightarrow$ top $\longleftrightarrow$ NP.

  (*e.g.* Little H, RS, Comp' Higgs, SUSY ...)
- TeV nonuniversal NP? (tension with Λ_F)

Hints: Solutions to the tension

Look @ EW models + consistent UV phys.:

(Agashe, GP & Soni; Burdman)

e.g. RS, Composite Higgs (Georgi, Kaplan; Agashe, Contino, Pomarol, Nomura),

Little H on AdS (Thaler & Yavin), Comp' little H (Katz *et. al*).

- If AdS-CFT (70s) $\leftrightarrow$ SUSY (98) ...

Use features for top-down study

- Always find MFV $\longrightarrow$ high flavor scale.

  (anomalous dim'/5D mass mat' aligned with Yukawas)

- NMFV (next to MFV) $\longrightarrow$ low flavor scale.

  (Agashe, Papucci, GP & Pirjol)

NMFV (Agashe, Papucci, GP & Pirjol)

NMFV

- 3$^{\rm rd}$ gen' is special, $U(2)^3$ approx' sym'.
- Like $Y_u Y_u^\dagger \leftrightarrow Y_d Y_d^\dagger$, NP$\leftrightarrow$3$^{\rm rd}$ gen' int' $\Rightarrow$

  quasi-align, $D_L, U_L \sim \mathcal{O}(V_{\rm CKM})$.
- Ex., $U(2)_Q \times U(3)_d$ sym':

  int' basis, below $\Lambda_{\rm NMFV} \Rightarrow \frac{(\bar{Q}_3 Q_3)^2}{\Lambda^2_{\rm NMFV}}$.

Flavor violation in NMFV

In mass basis, down quarks $\Delta F = 2$:

$$(\bar{Q}_3 Q_3)^2 \Rightarrow (D_L^*)^2_{3i} (D_L)^2_{3j} \, (\bar{Q}_i Q_j)^2 \approx (V^*_{\rm CKM})^2_{3i} (V_{\rm CKM})^2_{3j} \, (\bar{Q}_i Q_j)^2$$

FCNC (Δm_d) $\Rightarrow (D_L)^2_{31} \frac{(\bar{Q}_3 Q_1)^2}{\Lambda^2{}_{\rm NMFV}} \sim \lambda_C^6 \frac{(\bar{Q}_3 Q_1)^2}{\Lambda^2{}_{\rm NMFV}}$

$$\Downarrow$$

$$\frac{M_{12}^{\rm NMFV}}{M_{12}^{\rm SM}} \sim \frac{16\pi^2 M_W^2 / g_2^4}{\Lambda^2{}_{\rm NMFV}}$$

$$\Downarrow$$

Given $\Lambda_{\rm NMFV} \sim \Lambda_{\rm EW} \sim 3\,{\rm TeV} \;\Rightarrow\; \frac{M_{12}^{\rm NMFV}}{M_{12}^{\rm SM}} = \mathcal{O}(1)\,!$

(M)NMFV, Typical Structure

- Assume LH currents ("support" by $S_{\phi\eta',K_S}$).
- 3 new weak phases (per transition):

  $s \longrightarrow d \Rightarrow \sigma_K$; $b \longrightarrow d, s \Rightarrow \sigma_{d,s}$.

- Affect both $\Delta F = 2$ & $\Delta F = 1$:

$$A^{b\to s}_{\Delta F=1} \longrightarrow A^{b\to s}_{\Delta F=1}\left[1 + \sum_i a_i h^1_s \exp\left(i\sigma_s\right)\right];$$

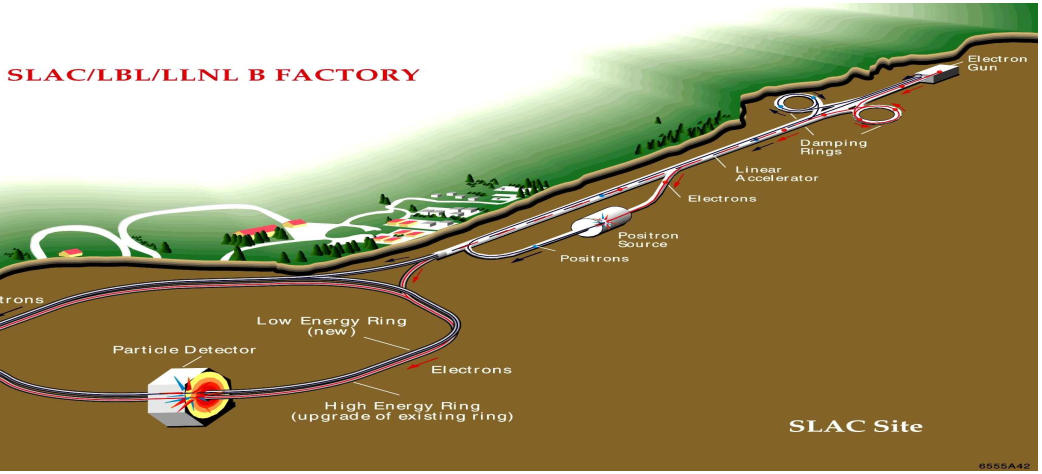
$$M^{b\to s}_{12} \longrightarrow M^{b\to s}_{12}\left[1 + h_s \exp\left(2i\sigma_s\right)\right];$$

Test of NMFV

Are $h_{d,s,K} \sim 1$ disfavored ??

Fine tune $\Leftrightarrow h_{d,s,K}, h^1_{d,s,K} \lesssim 10\%$. (arbitrary $\sigma_{K,d,s}$).

Tests & Signals



BELLE

BABAR™

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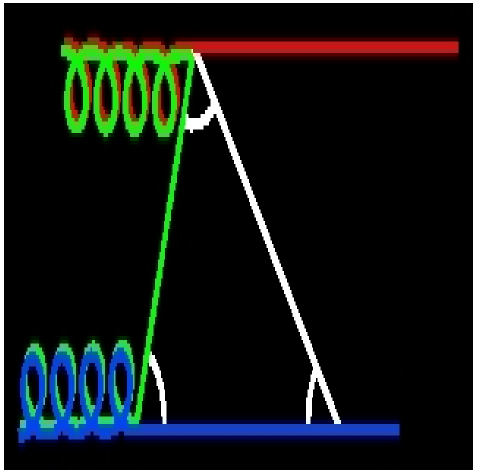


Main Points

- $\Delta F = 2$ processes (03,05).
- $\Delta F = 1$ transitions ($S_{\phi,\eta' K_S}\,,\ \ B \to K\pi$)

  see Papucci's talk.
- Correlations.

$\Delta F = 2$: What the bleep did we know (03)?

- $M_{12} = M_{12}^{\rm SM}\left(1 + h_i e^{2i\sigma_i}\right) \equiv M_{12}^{\rm SM} {r_i}^2 e^{2i\theta_i}$.
- $\Delta m_{d,s} \;=\; \Delta m_{d,s}^{\rm SM}\, {r_{d,s}}^2$.
- $S_{B\to\psi K_S} = \sin 2\left(\beta + \theta_d\right)$.
- $\epsilon_K \propto {\rm Im}\left[V_{td}^* V_{ts}\left(1 + h_K e^{2i\sigma_K}\right) + ...\right]$.
- Tree level unchanged V_{ub}.

03: $h_{K,d,s}, \sigma_{K,d,s}, \rho, \eta$ vs. $\epsilon_K, \Delta m_d, S_{\psi K}, A_{\rm SL}, V_{ub}$.

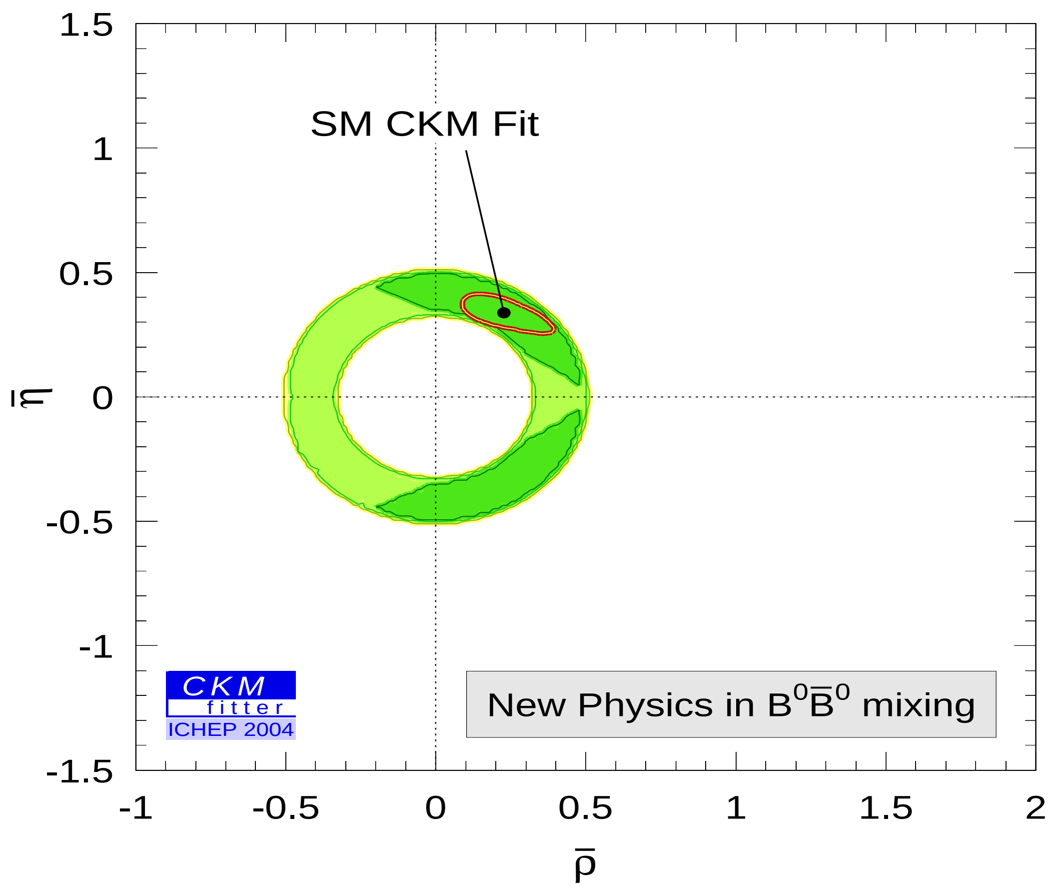
How big is the NP, $h_{K,d,s}$?

Compare ranges for $\rho, \eta,\ h_{K,d,s}$ (03,05).

The $\rho - \eta$ Plane + NP (03)

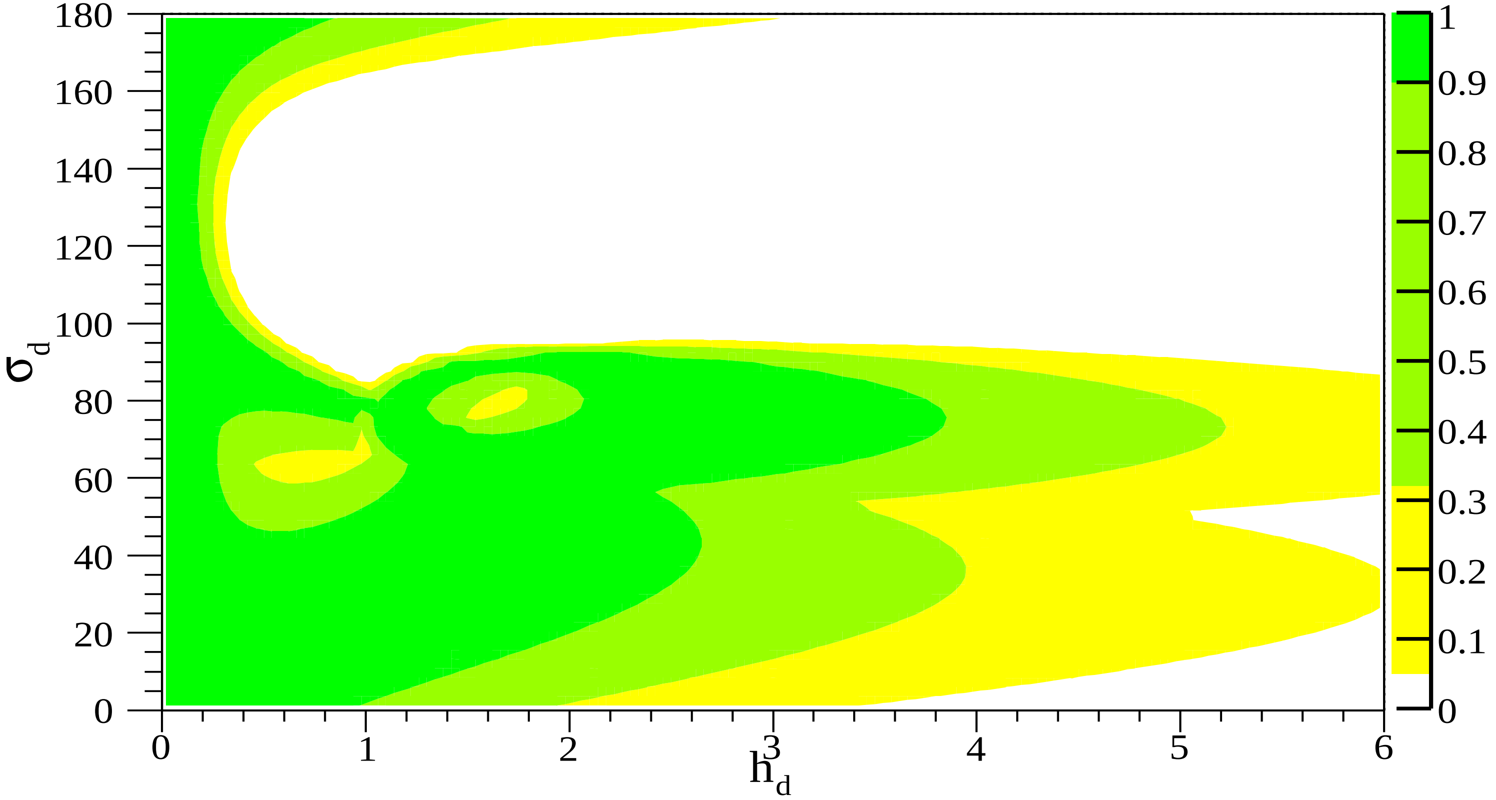
ρ, η from $\Delta m_d, S_{\psi K_S}, V_{ub}$. ($h_d, \sigma_d$-scanned)

(Ligeti)



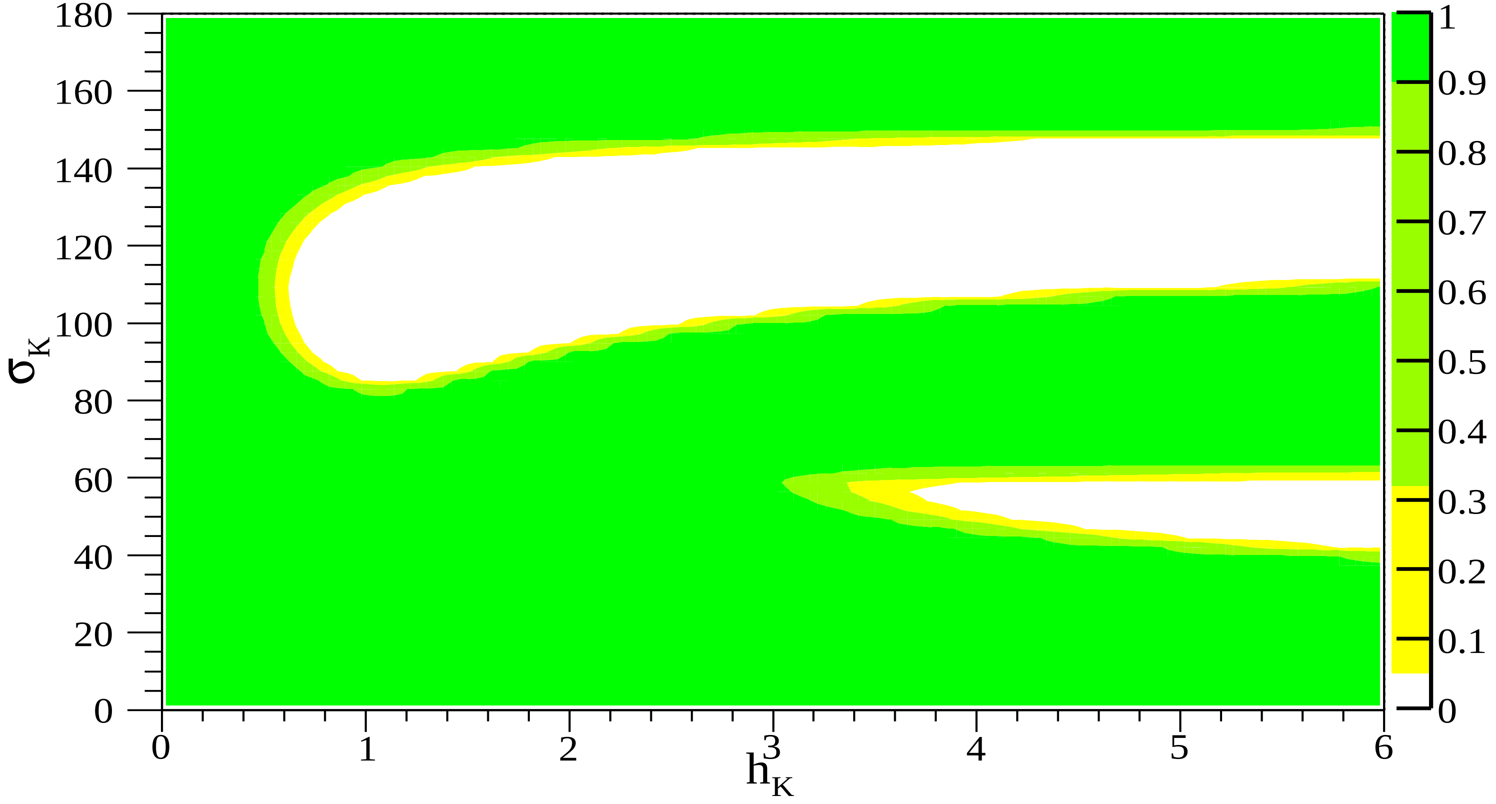
How large is h_d (03) ?

$$h_d \lesssim 5 \quad \text{(MFV} \leftrightarrow \sigma_d = 0, 90^o\text{)}$$



How large is NP in ϵ_K, h_K (03) ?

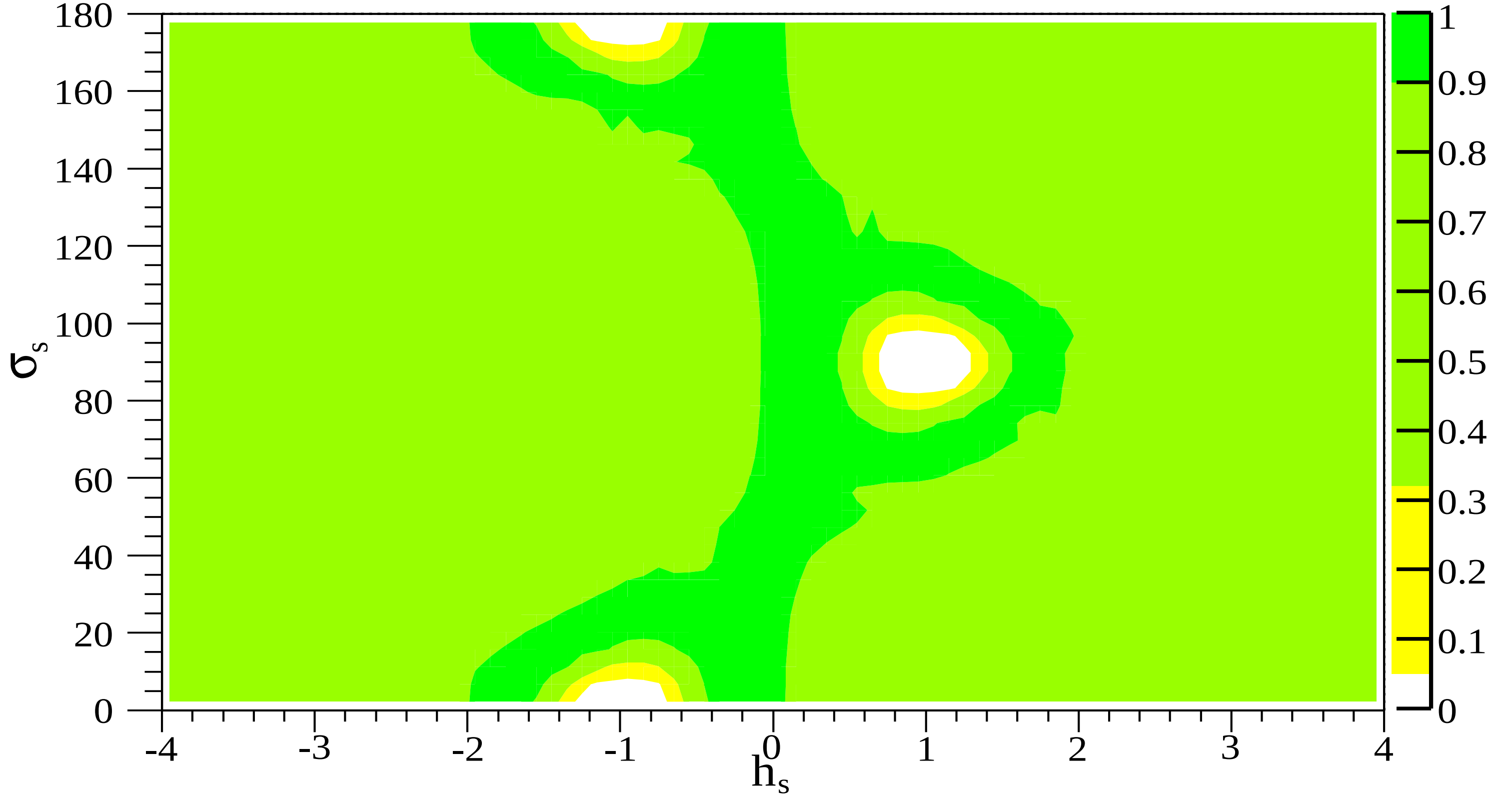
$$h_K \lesssim 6$$



How large is NP in Δm_s, h_s (03) ?

h_s unconstrained

[$h_s < 0 \rightarrow$ physical. (Larson, Murayama & GP)]



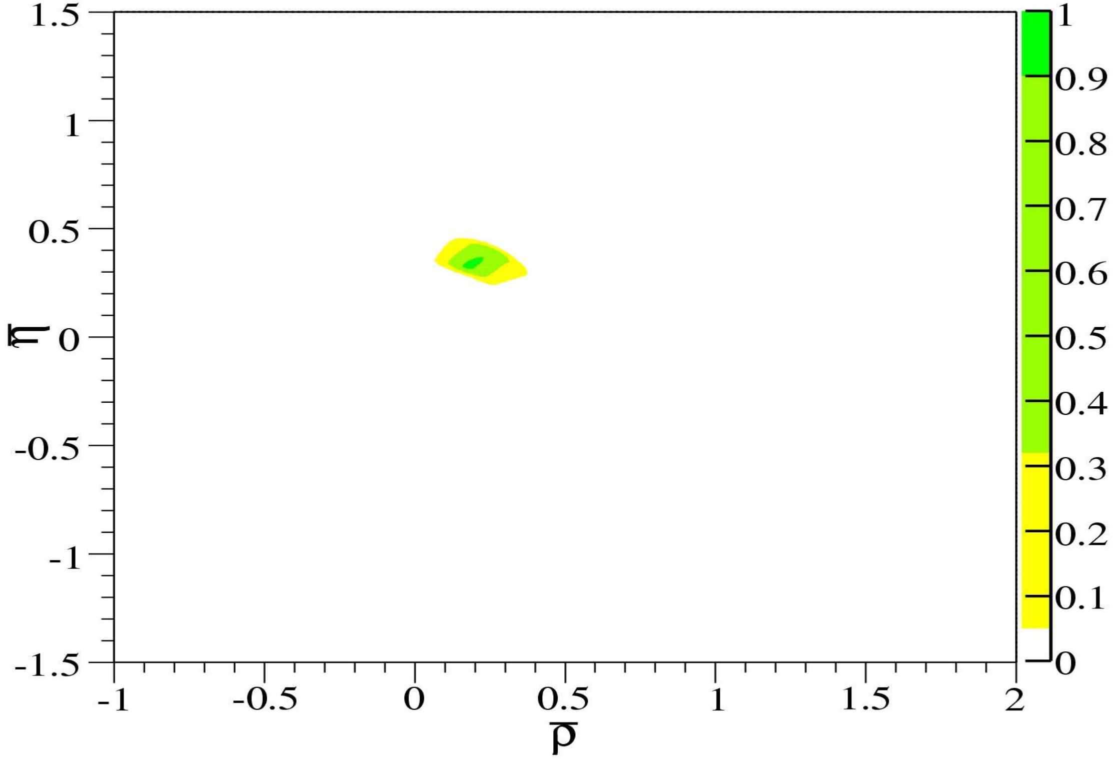
What do we know (05)

"Tree" level data. (statistical dominated.)

- We can constrain $\rho, \eta, h_d, \sigma_d$.
- $S_{\rho\rho,\pi\pi} \Rightarrow \sin(2\alpha + 2\theta_d)$ (isospin non-clean).
- $A_{DK^\pm} \Rightarrow \tan\gamma$.
- and $V_{ub}, \Delta m_d, S_{\psi K_S}, A_{\mathrm{SL}}$.

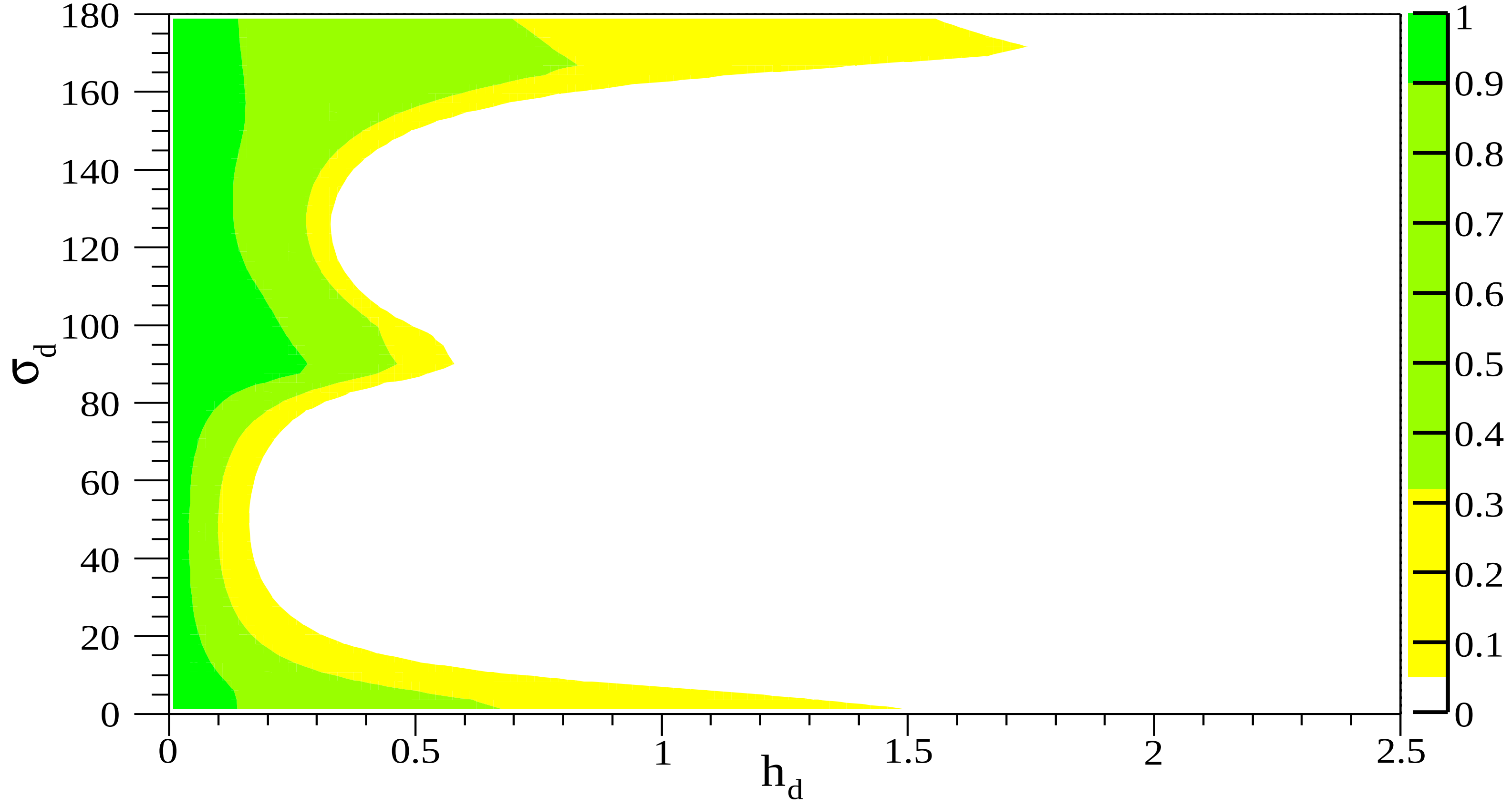
The $\rho - \eta$ Plane + NP (05)

Adding $S_{\pi\pi,\rho\rho}, A_{DK^{\pm}}$, ... ($h_d, \sigma_d$-scanned)



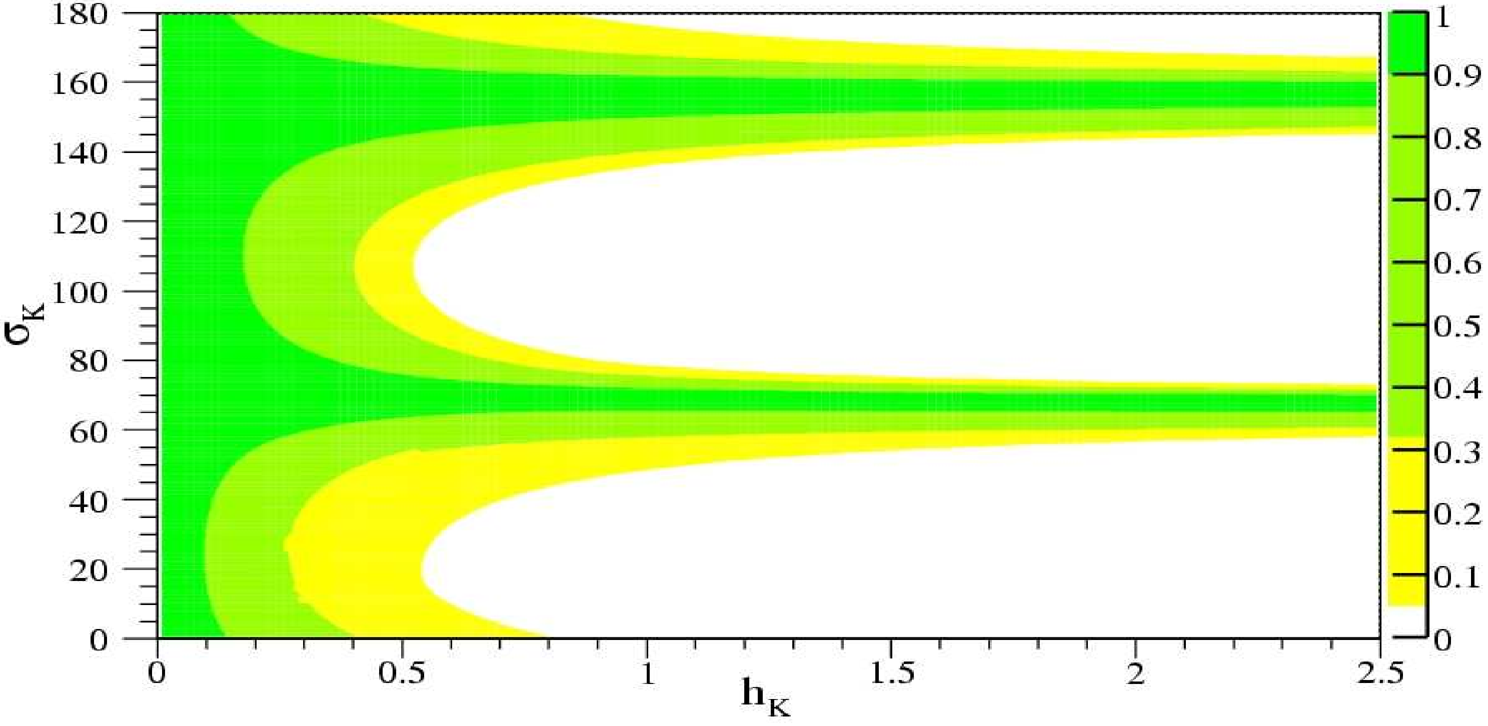
How big can h_d be (05) ?

$$h_d \lesssim 0.4$$



How big can h_K be (05) ?

$$h_K \lesssim 0.6$$



Summary of constraints $h_{K,d,s}$ (05)

- $h_K \lesssim 0.6$.
- $h_d \lesssim 0.4$.
- h_s unconstrained.
- Unconstrained phases $\sigma_{K,d,s}$.

$\Delta F = 1$ transitions yield more info'

- Contribution due to $\sigma_{K,d,s}, h^1_{K,d,s}$.
- Analysis is more complicated.
- Extra assumptions required.
- $d \to s \Rightarrow K \to \pi\nu\bar{\nu}, l\bar{l}$, exp'?.
- $b \to d \Rightarrow$ subleading (bound ?).

$b \to s$ **transition &** h_s^1, σ_s

- SM penguin dominated: $B \to \phi, \eta', \pi K$ sensitive to h_s^1, σ_s.
- SM: $S_{\psi K} - S_{\phi,\eta',\pi K} \ll 1\,.$ (Nir's talk)
- Exp: $S_{\psi K} \simeq 0.7, S_{\phi K} \simeq 0.5 \pm 0.2, S_{\eta' K} \simeq 0.5 \pm 0.1,$ $S_{\pi K} \simeq 0.3 \pm 0.3 \Rightarrow S_{\psi K} - \langle S_{xK} \rangle \geq 0.$
- Parity $\Rightarrow$ LH currents are favored!

Kagan; Endo, Mishima & Yamaguchi.

$B \to \phi, \eta', \pi K$ & NMFV

- Xtra assumptions are required.

  (Papucci's talk)

- RS1,Z' (other models are covered...)

$$\Rightarrow C^Z(M_W) \to C^Z(M_W)\left(1 + h_s^1 e^{i\sigma_s}\right) .$$

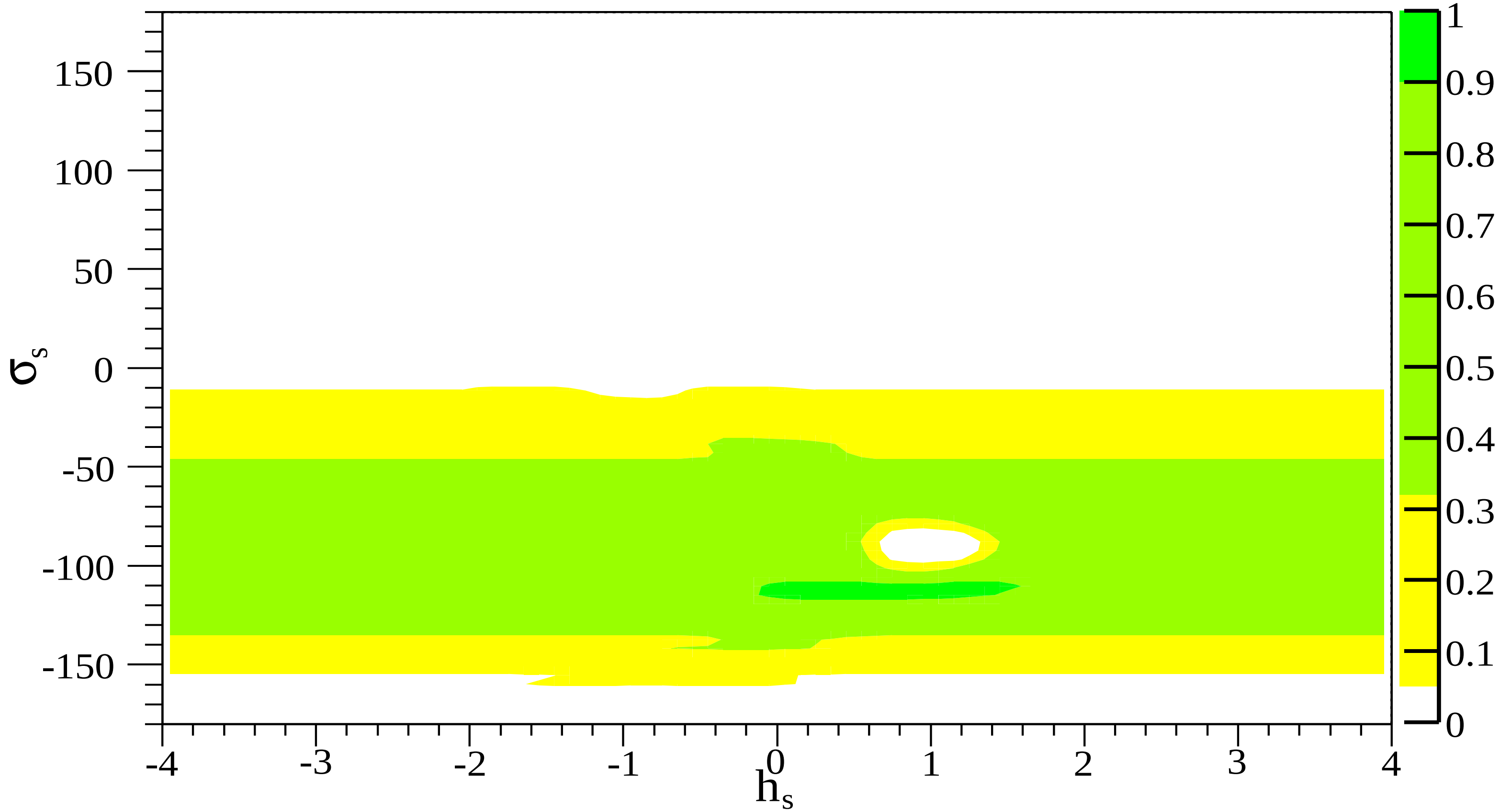
- $S_{\phi,\eta' K} \Rightarrow$ naive factorization, BBNS.
- $B \to \pi K \Rightarrow$ SU(3), BBNS.

Correlation: $S_{\phi,\eta',\pi K}$ & $\Delta m_s,\ S_{B_s\to\psi\phi}$

- $S_{\phi,\eta' K} \sim \sin\left[2\beta + f\left(h_s^1, \sigma_s\right)\right]$.
- $S_{B_s\to\psi\phi} \propto \mathcal{I}m\left(1 + h_s e^{2i\sigma_s}\right)$!
- $\Delta m_s \propto \left|1 + h_s e^{2i\sigma_s}\right| \geq \Delta m_s^{\rm Exp}$!
- $\left(\epsilon_K\ ,\ \ K \to \pi\nu\nu...\right)$

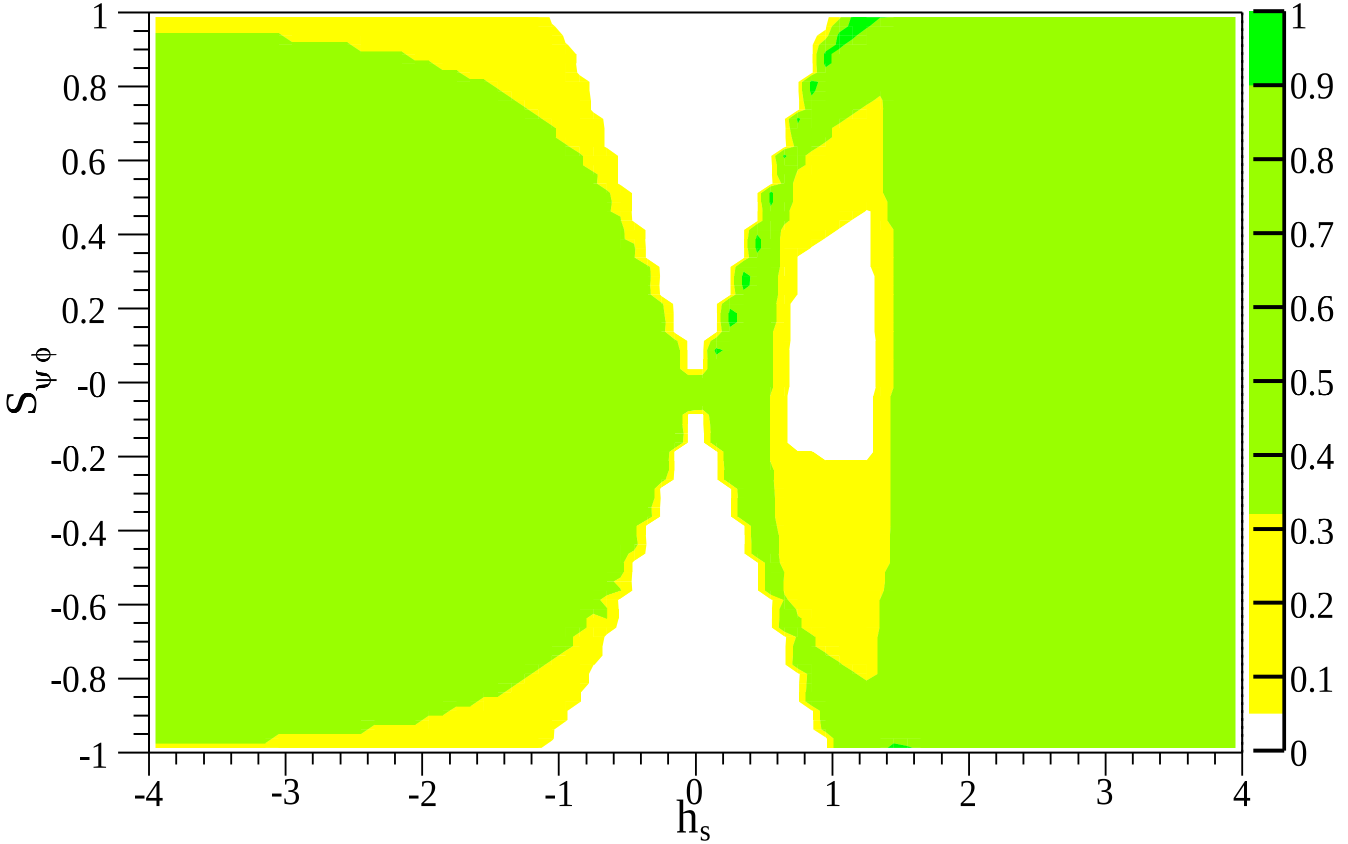
$\Delta m_s(\sigma_s)$ **from** $S_{\phi,\eta' K}, B \to K\pi(\sigma_s)$

$$-180^o \lesssim \sigma_s \lesssim 0^o \, .$$



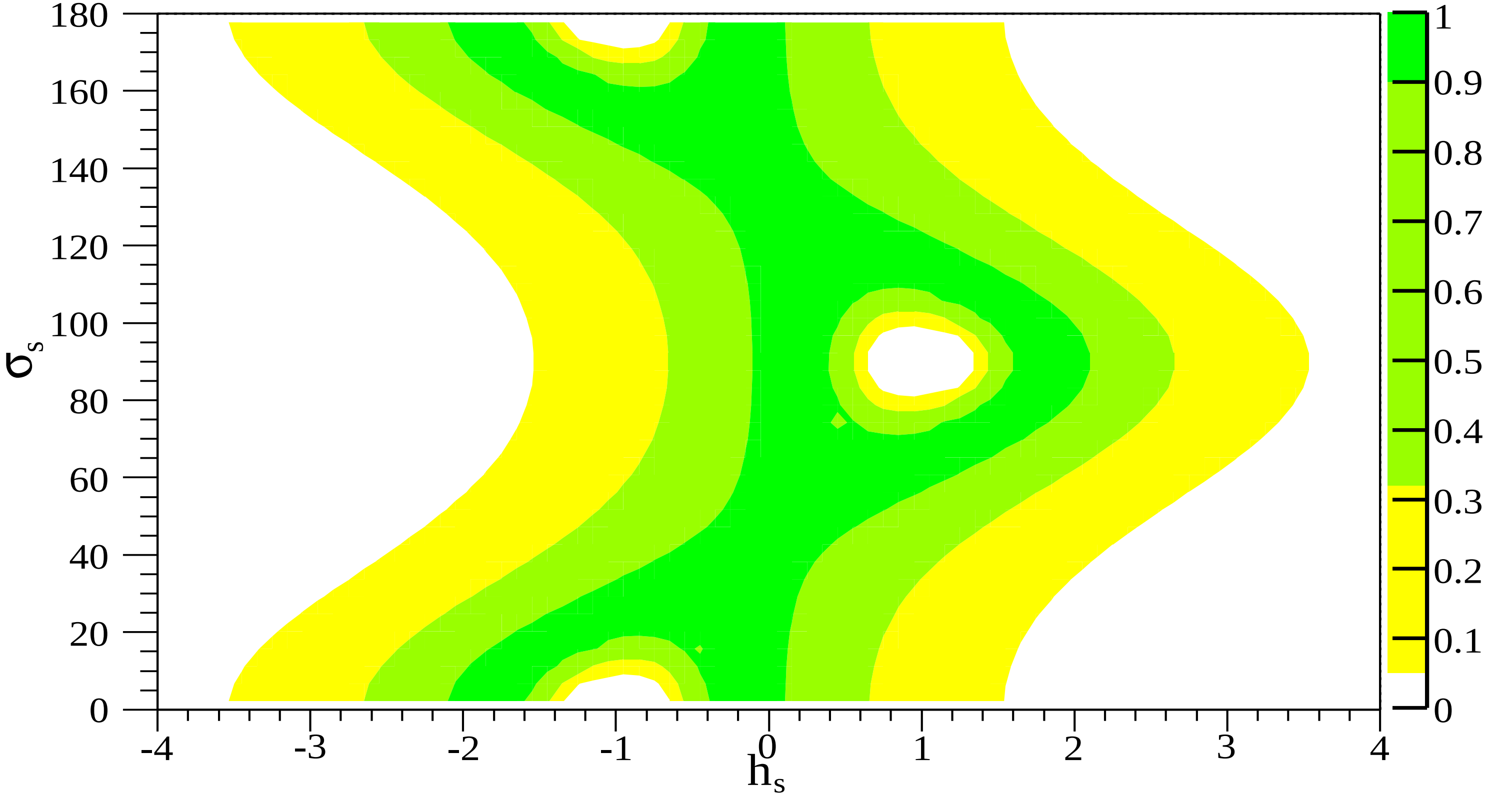
$S_{\psi\phi}(\sigma_s)$ from $\Delta m_s, S_{\phi,\eta' K}, B \to K\pi(\sigma_s)$

$$-180^o \lesssim \sigma_s \lesssim 0^o \,.$$

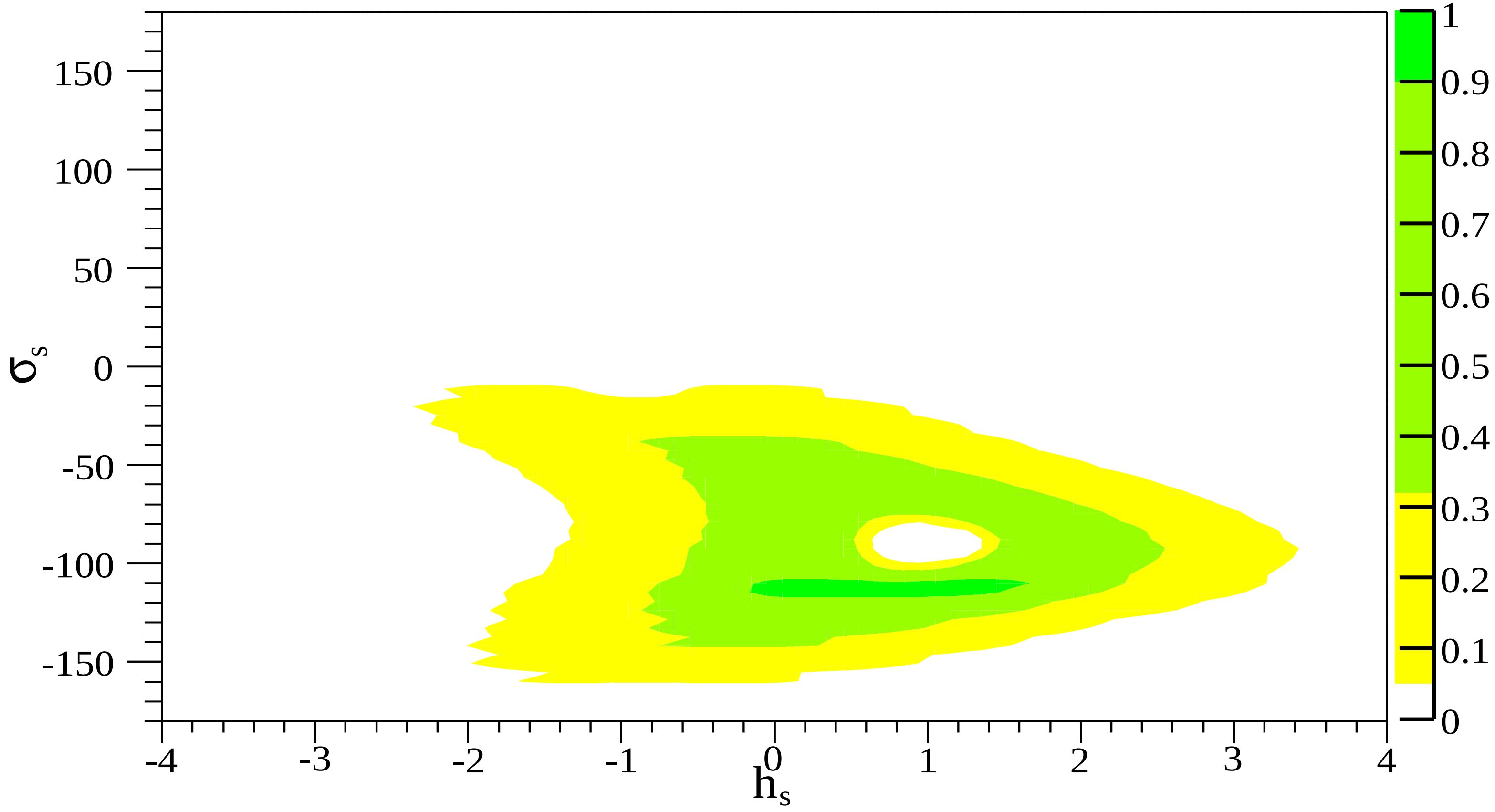


Fut': h_s, $\Delta m_s(\sigma_s) = 18.3 \pm 0.3 \mathrm{ps}^{-1}$ (SM) ?

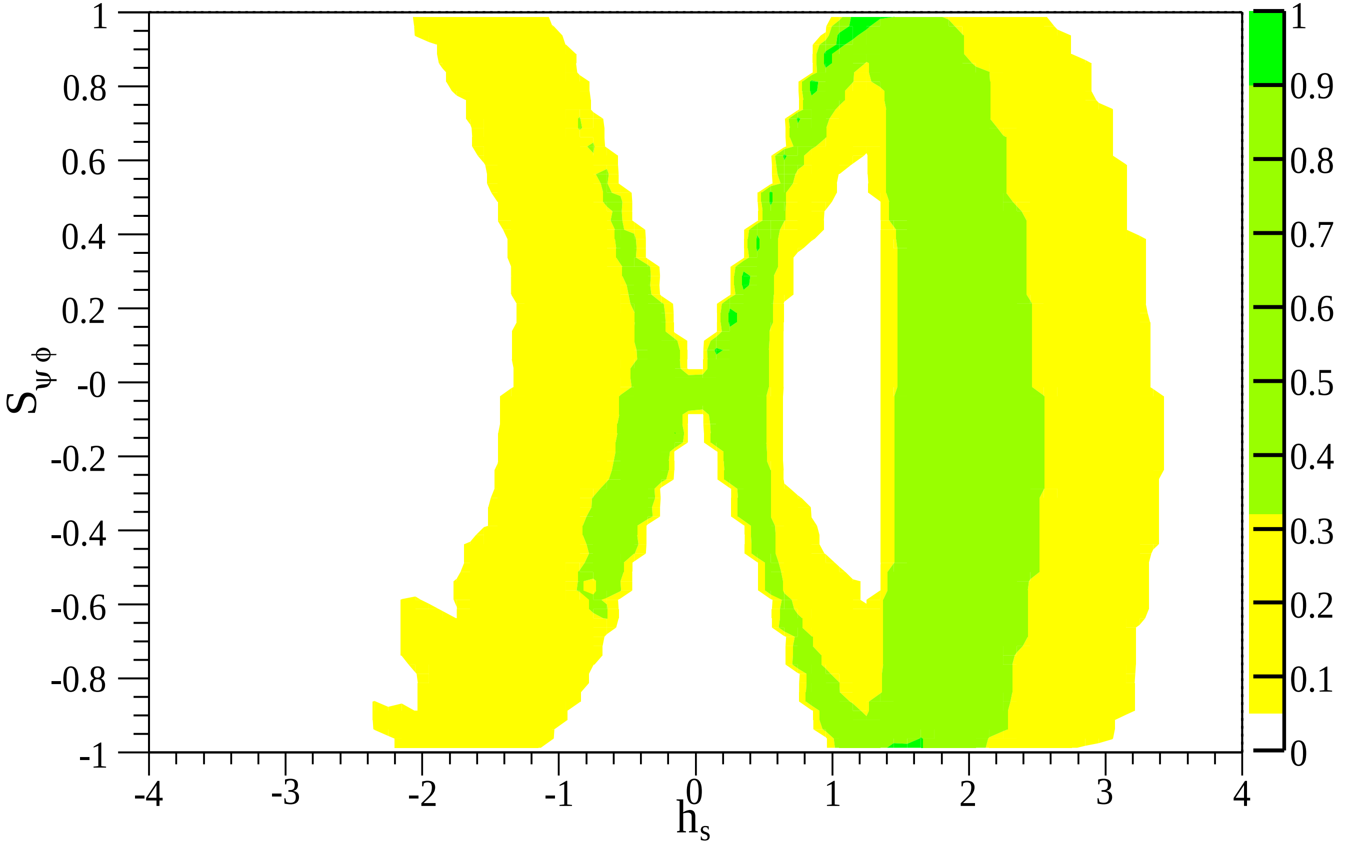
$$|h_s| \lesssim 2$$



Fut': $\Delta m_s(h_s - \sigma_s)$(SM) & all the above

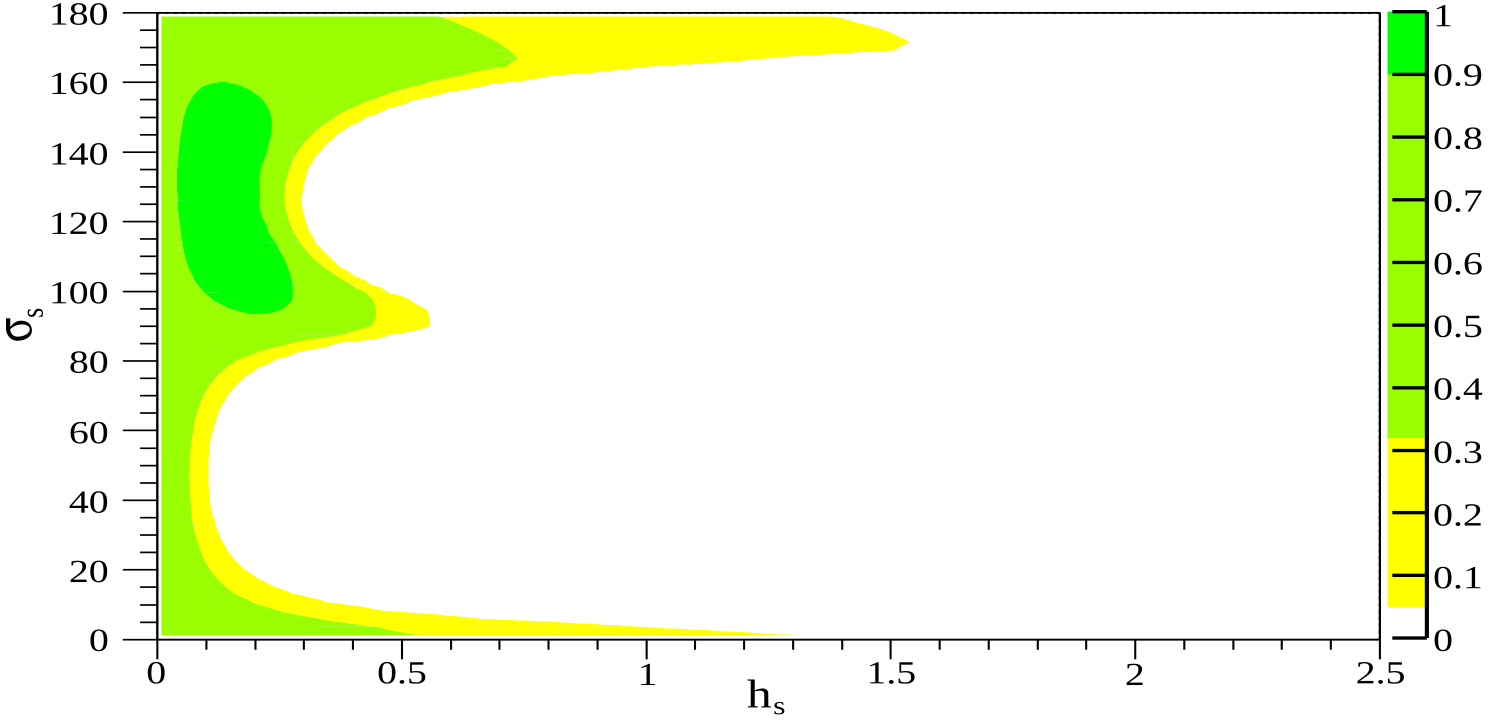


Fut': $S_{\psi\phi}(\sigma_s)$



Can we improve on h_d?

Preliminary



Conclusions

- Minimalist models $\Rightarrow$ flavor implicit.
- Models flow to NMFV, 3 Xtra phases.
- $\Delta F = 2$ probe NMFV $\Rightarrow$ not there!
- More info': $\Delta F = 1$; $\Delta F = 2 \leftrightarrow 1$ cor'.
- $K \to \pi\nu\bar{\nu}$ @ 10% may be enough; B_s?
- Top FCNC @ Atlas & CMS.
- FCNC $\leftrightarrow$ EWPT !

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Backups


ORIGINAL GLAZED
MAPLE ICED
GLAZED CINNAMON
GLAZED CRULLER
GLAZED BLUEBERRY CAKE
GLAZED SOUR CREAM
GLAZED DEVIL'S FOOD CAKE
CHOCOLATE ICED GLAZED
CHOCOLATE ICED CRULLER
CHOCOLATE ICED GLAZED WITH SPRINKLES
CHOCOLATE ICED CREME FILLED
CHOCOLATE ICED CUSTARD FILLED
CINNAMON APPLE FILLED
GLAZED CREME FILLED
POWDERED STRAWBERRY FILLED
GLAZED RASPBERRY FILLED
GLAZED LEMON FILLED

Flavor structure of NMFV

$$\frac{(\bar{Q}_3 Q_3)^2}{\Lambda^2_{\rm NMFV}}, \qquad \frac{\bar{Q}_3 Q_3 (\bar{Q},\bar{d},\bar{u})_i (Q,d,u)_i}{\Lambda^2_{\rm NMFV}}, \quad (i=1,2)$$

	Generic	No LR	Only L (R)
No. of phases	5	4	2

CP phases: 3 NMFV types. Only the down sector is considered.

Relation among the h_is

If vertices factorize $\longrightarrow$ specific relations found (RS):

$$\sqrt{\frac{h_s}{h_d}\frac{h_d^1}{h_s^1}} = 1\,, \quad \sqrt{\frac{h_s}{h_K}\frac{h_K^1}{h_s^1}} = k\,, \quad \sqrt{\frac{h_d}{h_K}\frac{h_K^1}{h_d^1}} = k\,.$$

The RS1 model

- $$(ds)^2 = e^{-2kr_c|\theta|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\theta^2$$

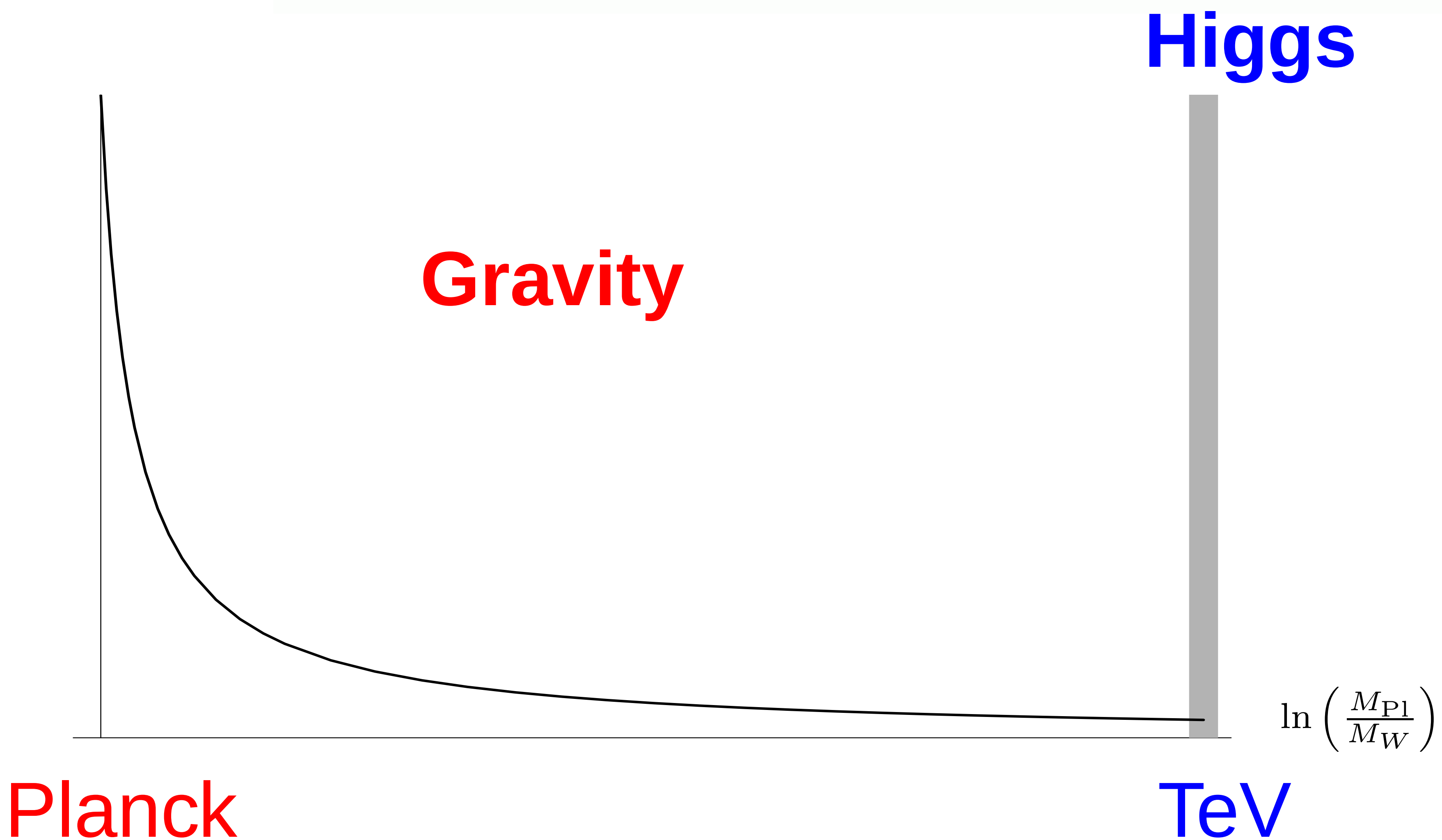
  $$k \sim M_{\rm Pl} \quad \theta = 0..\pi.$$

- $kr_c \sim \mathcal{O}(10) \Rightarrow$

  natural low EWSB:

  $$M_W \sim R_{\rm RS}^{-1} \sim ke^{-k\pi r_c}\,.$$

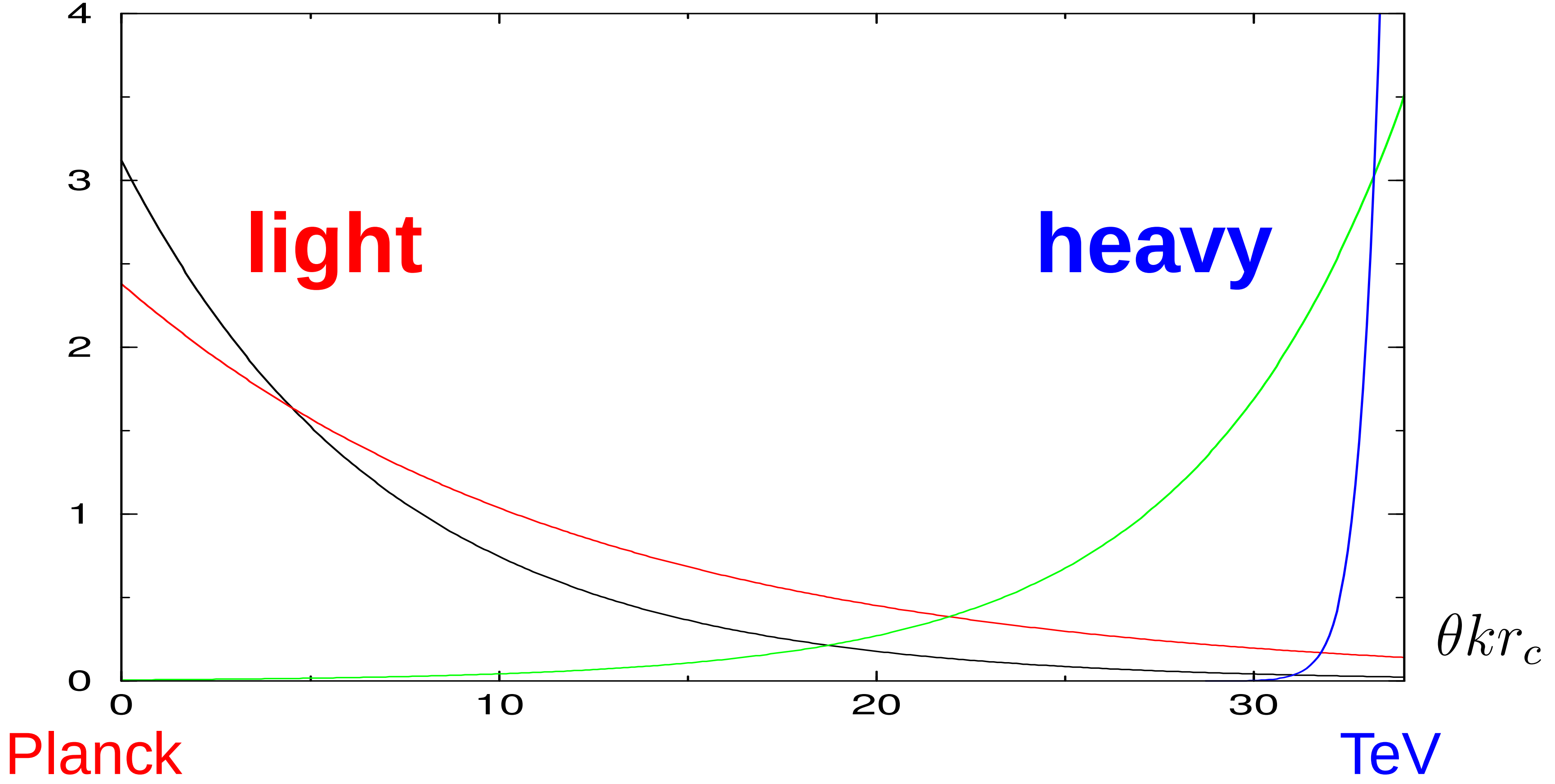
RS1 & the Hierarchy Problem



5D Lagrangian & Flavors

- $$\mathcal{L}_f = \sqrt{G}k\left[C_Q\bar{Q}Q + C_d\bar{d}d + C_u\bar{u}u + h\bar{Q}\left(Y_u u + Y_d d\right)\Big|_{\mathrm{TeV}}\right]$$
- Quarks: $f_\psi \propto e^{\left(\frac{1}{2}-c\right)\sigma}, \ \ \sigma \equiv k\pi r_c\theta\,.$
- Heavy [light] quarks $\Rightarrow c \gtrless \frac{1}{2}\,.$
- SM (3gen'): $c \Rightarrow$ diag$(C_{Q,u,d})$
  $f_\psi \Rightarrow$ diag$(F_{Q,u,d})$

Bulk RS1 - Fermion profiles



Determining the flavor parameters

Model independently -

$$Y_{u,d}^{4D} \propto \left(F_Q Y_{u,d}^{5D} F_{u,d}\right)\Big|_{\rm TeV}\ .$$

Assumption:

- Anarchic $Y_{u,d}^{5D} \Rightarrow m_{u,d}^{i} \propto f_{Q^i} f_{u^i,d^i}\ ,$

  where $f_{Q^i,u^i,d^i} = \text{diag}\left(F_{Q,u,d}\right)\ .$

$$\Downarrow$$

$$V_{\rm CKM} \sim f_{Q^i}/f_{Q^j}\ ,$$

Flavor parameters

Flavor	f_Q	f_u	f_d
I	$\lambda^3 f_{Q^3} \sim 4 \times 10^{-3}$	$\frac{m_u}{m_t}\frac{\lambda^3}{f_{u^3}} \sim 10^{-3}$	$\frac{m_d}{m_b}\frac{\lambda^3}{f_{d^3}} \sim 10^{-3}$
II	$\lambda^2 f_{Q^3} \sim 2 \times 10^{-2}$	$\frac{m_c}{m_t}\frac{\lambda^2}{f_{u^3}} \sim 5 \times 10^{-1}$	$\frac{m_s}{m_b}\frac{\lambda^2}{f_{d^3}} \sim 3 \times 10^{-3}$
III	$\frac{m_t}{v f_{u^3}} \sim \frac{1}{3}$	$\mathcal{O}\left(\frac{5}{6}\right)^*$	$\frac{m_b}{m_t f_{u^3}} \sim 6 \times 10^{-3}$

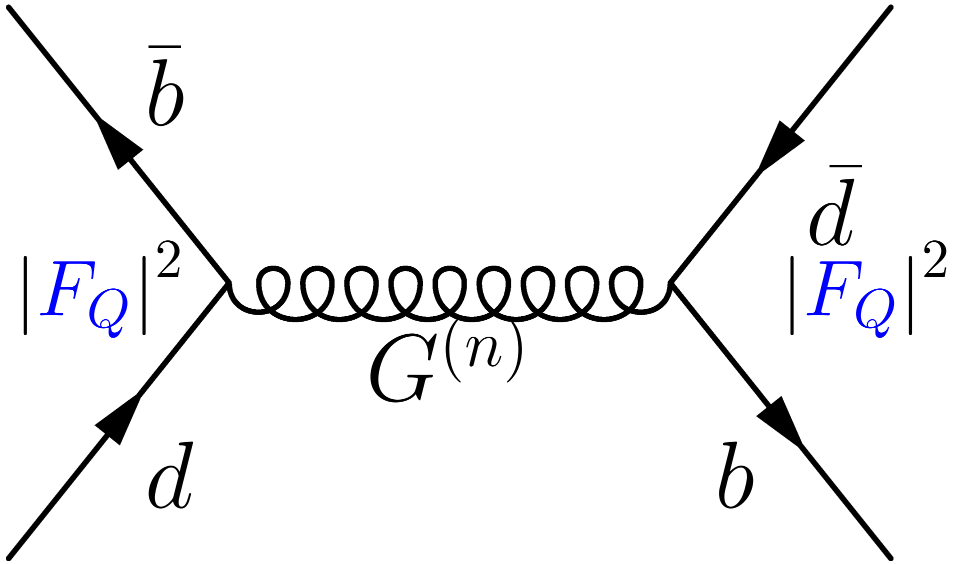
* Determined by m_t & EWPM, $Z \to b\bar{b}$.

Note that: $f_{1,2} \ll 1$.

Flavor violation - KK Gluon ($\tilde{G}$)

KK's "live" on the TeV brane ($\tilde{m}^2 \lesssim$TeV^2)**!**

- quarks (squark) KK-Gluon (gluino) coupling: $g_Q^{(00)} \propto |f_Q|^2 g^{5D}$.



$\Rightarrow \quad \left(\bar{b}\gamma^\mu d\right)^2$

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