Next to Minimal Flavor Violation

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Outline

- Introduction + Motivation.
- NMFV (next to minimal flavor violation).
- Ex.: Randall-Sundrum I (RS1).
- Signals: $\Delta F = 2, 1$ & correlations.
- Top FCNC & direct LHC signals.
- 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.

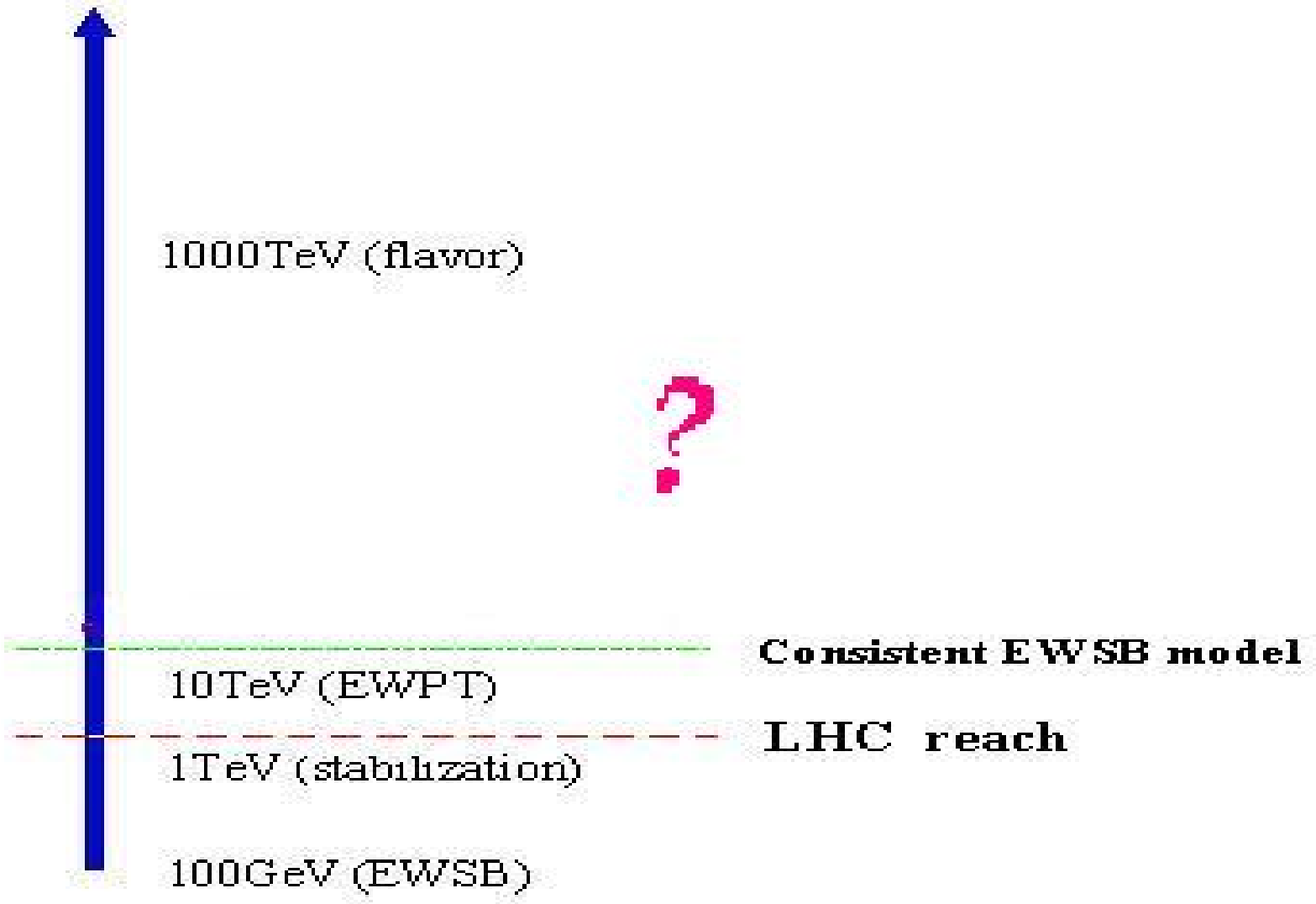
EW desert & flavor desert

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.

Requirements from a viable theory

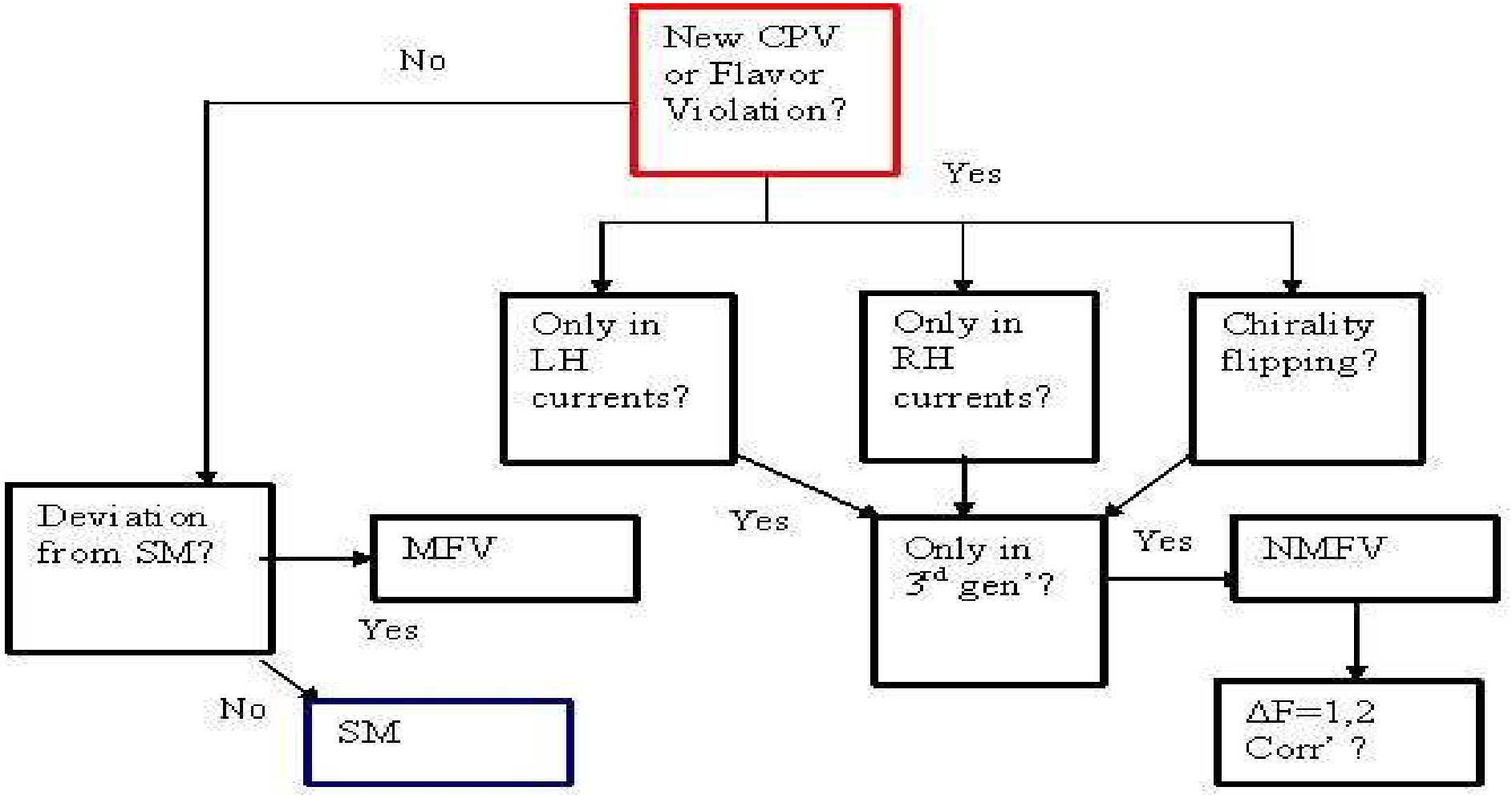


Elimination will be required

Degeneracies

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

Degeneracies & Classification



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: (non-SUSY) 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 bottom-up study

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

(Agashe, Papucci, GP & Pirjol)

N M F V


NEXT...
YOU'RE TOO SCREWED UP— NEXT PATIENT, PLEASE.
PSYCHIATRIST
CALLAHAN

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 $\Delta F = 2$:

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

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

$$\Downarrow$$

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

$$\Downarrow$$

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

(M)NMFV, Typical Structure

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

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

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

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

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

Ex.: RS1 - Flavor Violation

The RS1 model

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

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

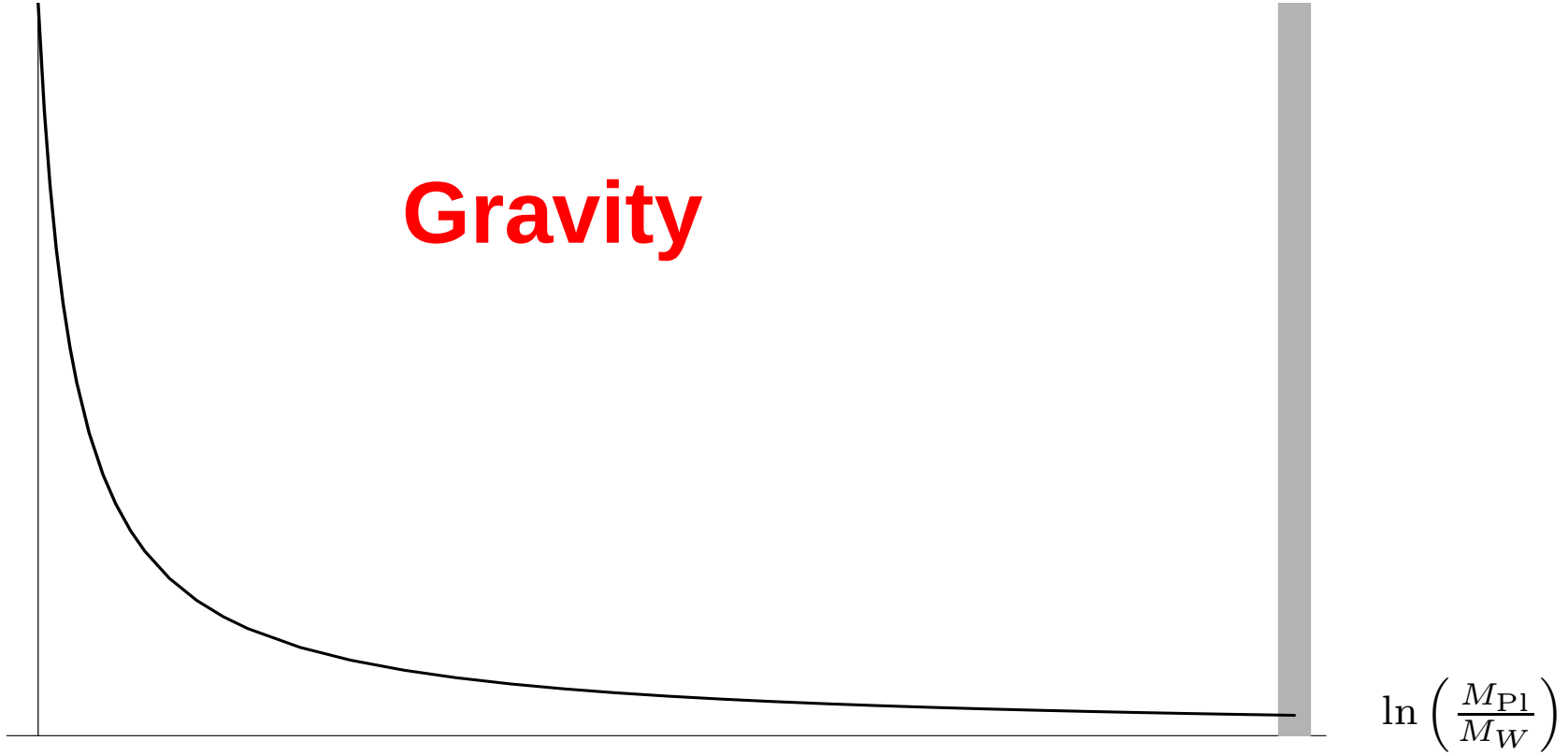
- $kr_c \sim \mathcal{O}(10) \Rightarrow$

natural low EWSB:

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

RS1 & the Hierarchy Problem

Higgs

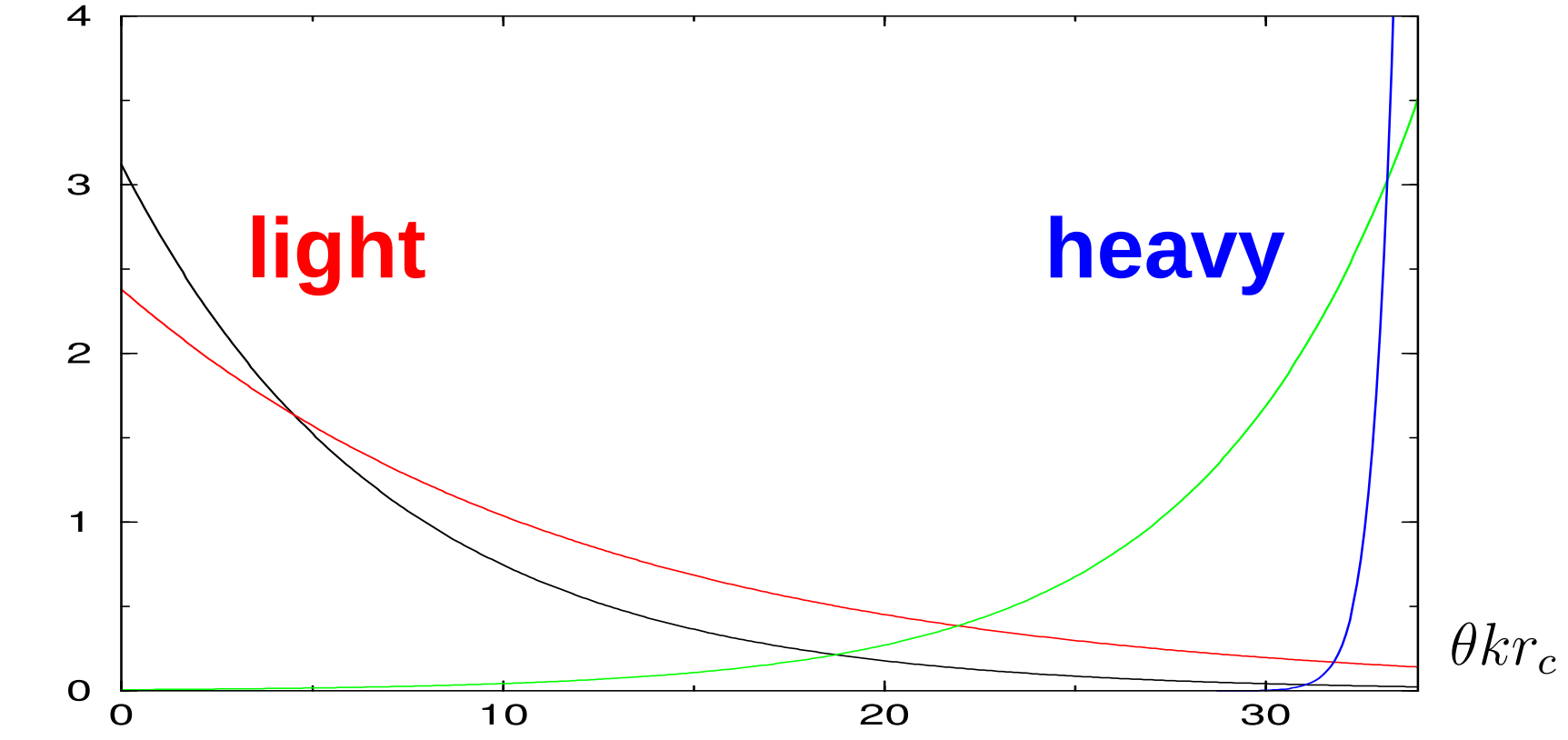


5D Lagrangian & Flavors (Agashe, GP & Soni)

- $\mathcal{L}_f = \sqrt{G}k \left[C_Q \bar{Q} Q + C_d \bar{d} d + C_u \bar{u} u + h\bar{Q} \left(Y_u u + Y_d d \right) \Big|_{\rm TeV} \right]$
- 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'): $c \Rightarrow \text{diag}\left(C_{Q,u,d}\right)$

  $f_\psi \Rightarrow \text{diag}\left(F_{Q,u,d}\right)$

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	$\frac{m_t}{v f_{u^3}} \sim \frac{1}{3}$	$\mathcal{O}\left(\frac{5}{6}\right)^*$	$\frac{m_b}{m_t f_{u^3}} \sim 6 \times 10^{-3}$

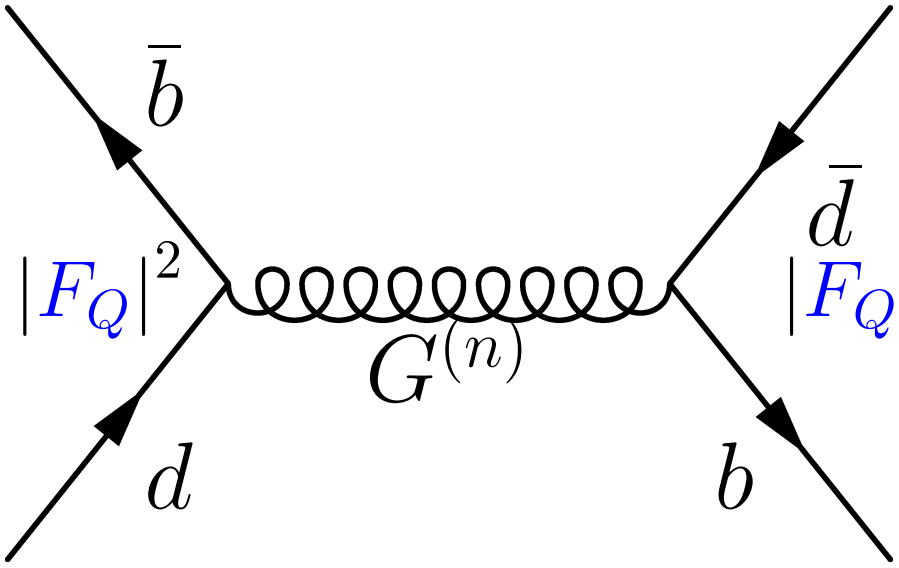
* Determined by m_t & EWPM, $Z \to b\bar{b}$.

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: $g_Q^{(00)} \propto |f_Q|^2 g^{5D}$.



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

NMFV, Intermediate Summary

(M)NMFV, Typical Structure

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

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

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

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

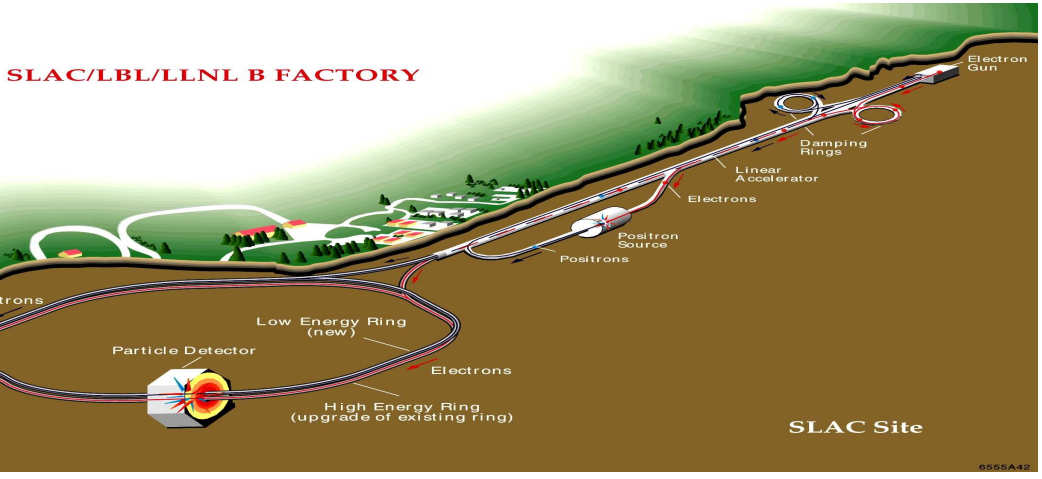
$$M^{b\to s}_{12} \to M^{b\to s}_{12} \left[1 + h_s \exp\left(2i\sigma_s\right)\right];$$

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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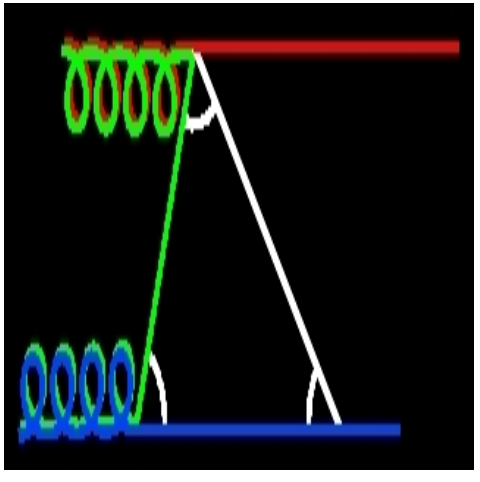


Main Points

- $\Delta F = 2$ processes (03,05).
- $\Delta F = 1$ transitions ($S_{\phi,\eta' K_S}$, $B \to K\pi$)
- 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. $\epsilon_K, \Delta m_d, S_{\psi K}, A_{\rm SL}, V_{ub}$.

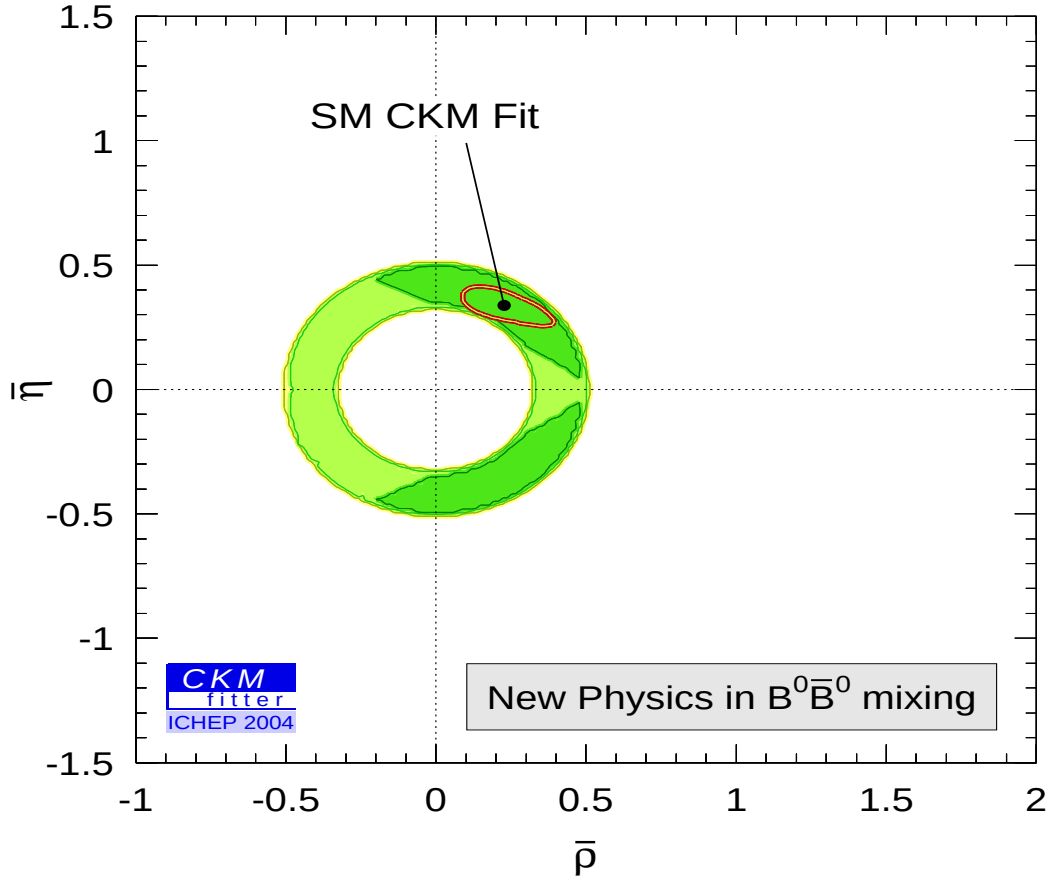
How big is the NP, $h_{K,d,s}$?

Compare ranges for ρ, η, $h_{K,d,s}$ (03,05).

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

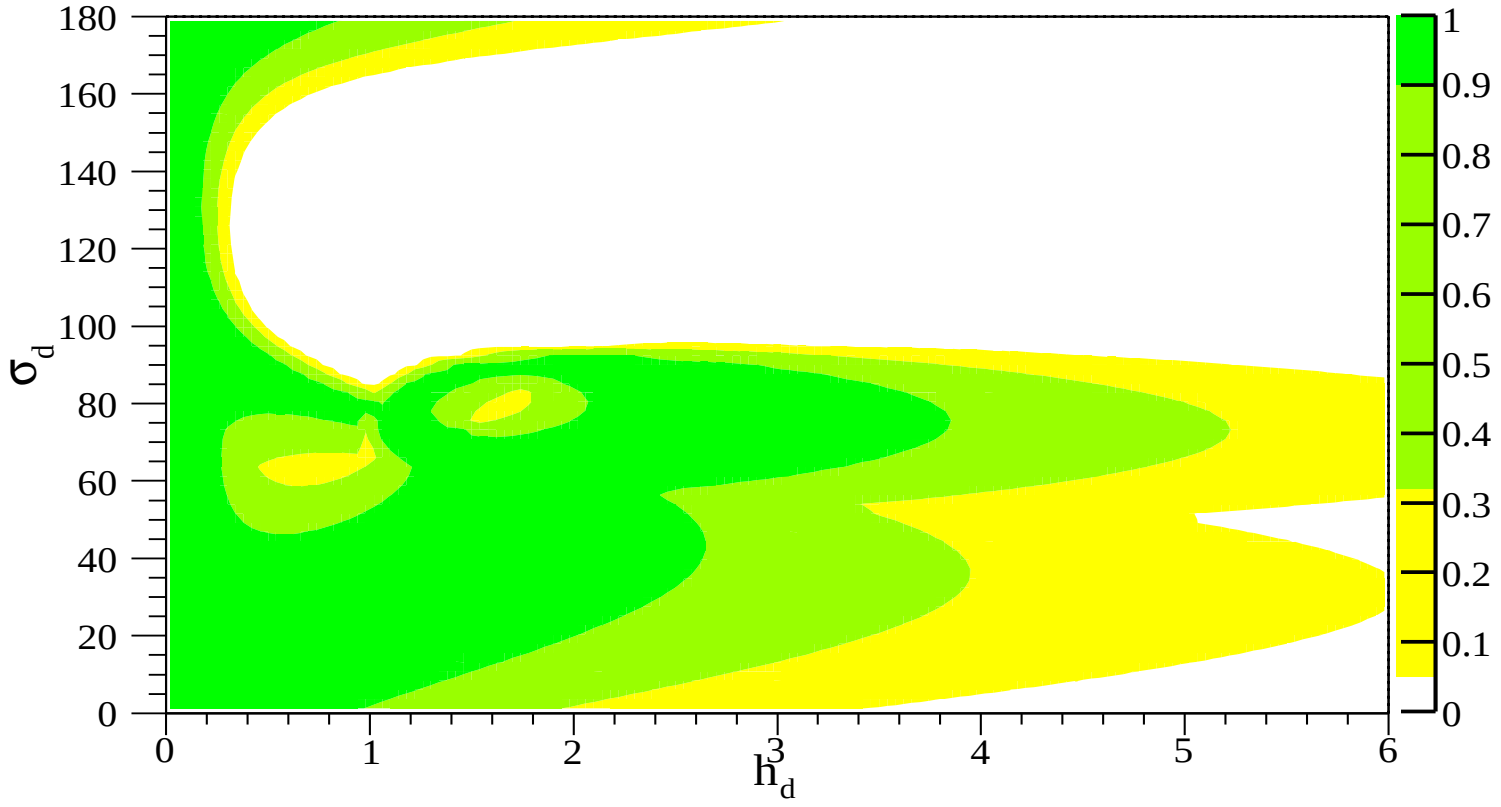
ρ, η from $\Delta m_d, S_{\psi K_S}, V_{ub}$. ($h_d, \sigma_d$-scanned)

(Ligeti)



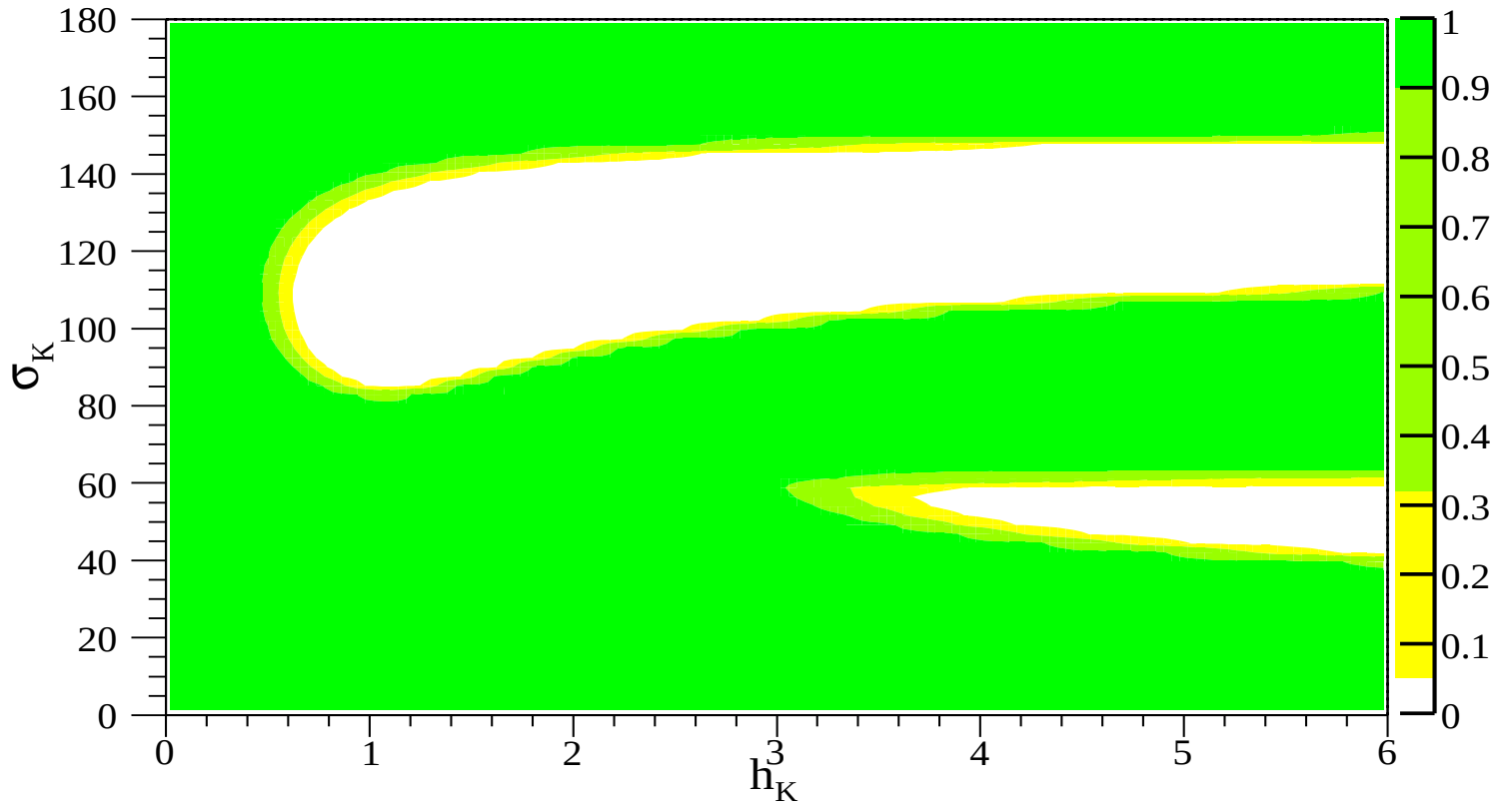
How large is h_d (03) ?

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



How large is NP in ϵ_K, h_K (03) ?

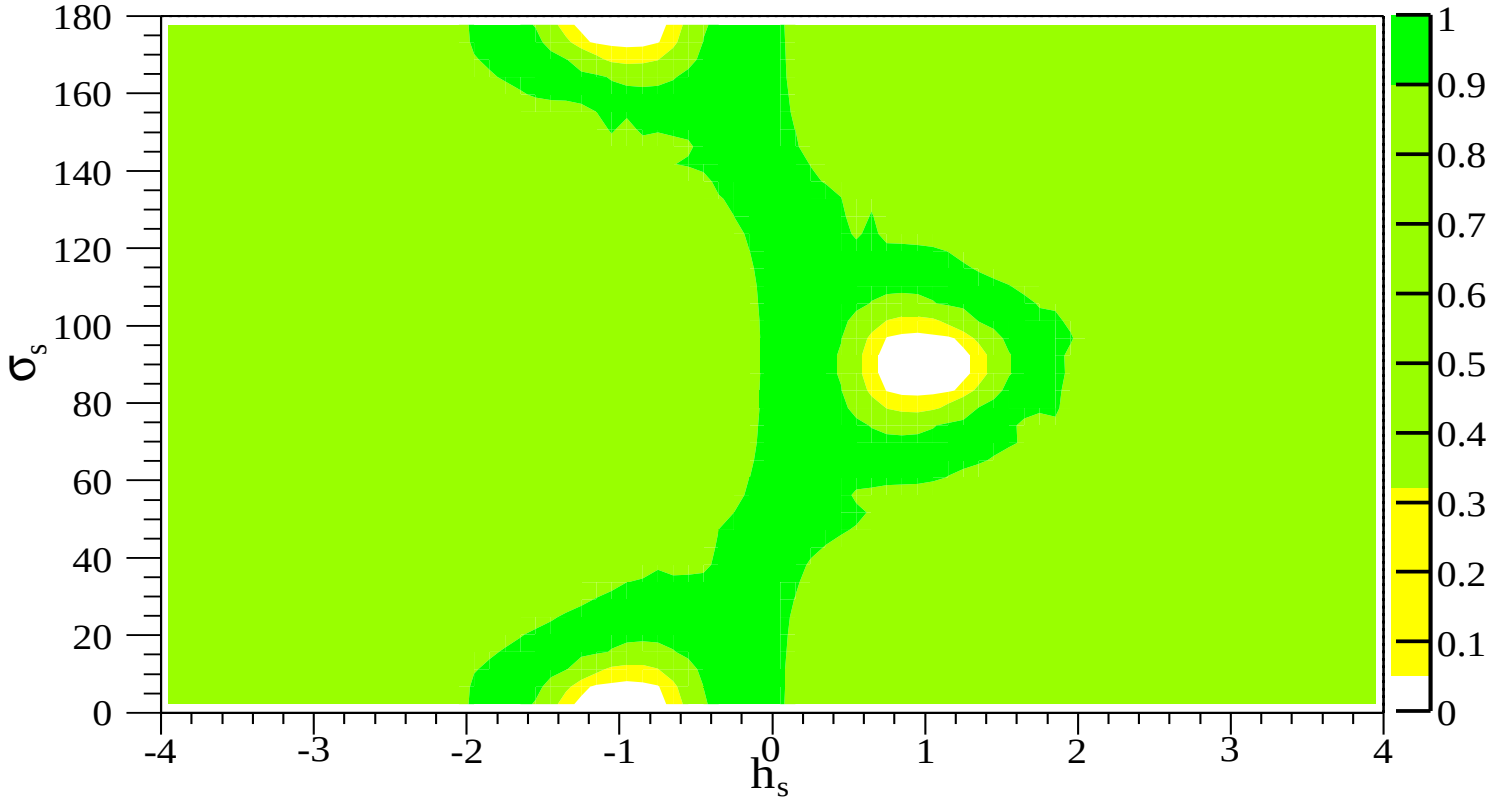
$$h_K \lesssim 6$$



How large is NP in Δm_s, h_s (03) ?

h_s unconstrained

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



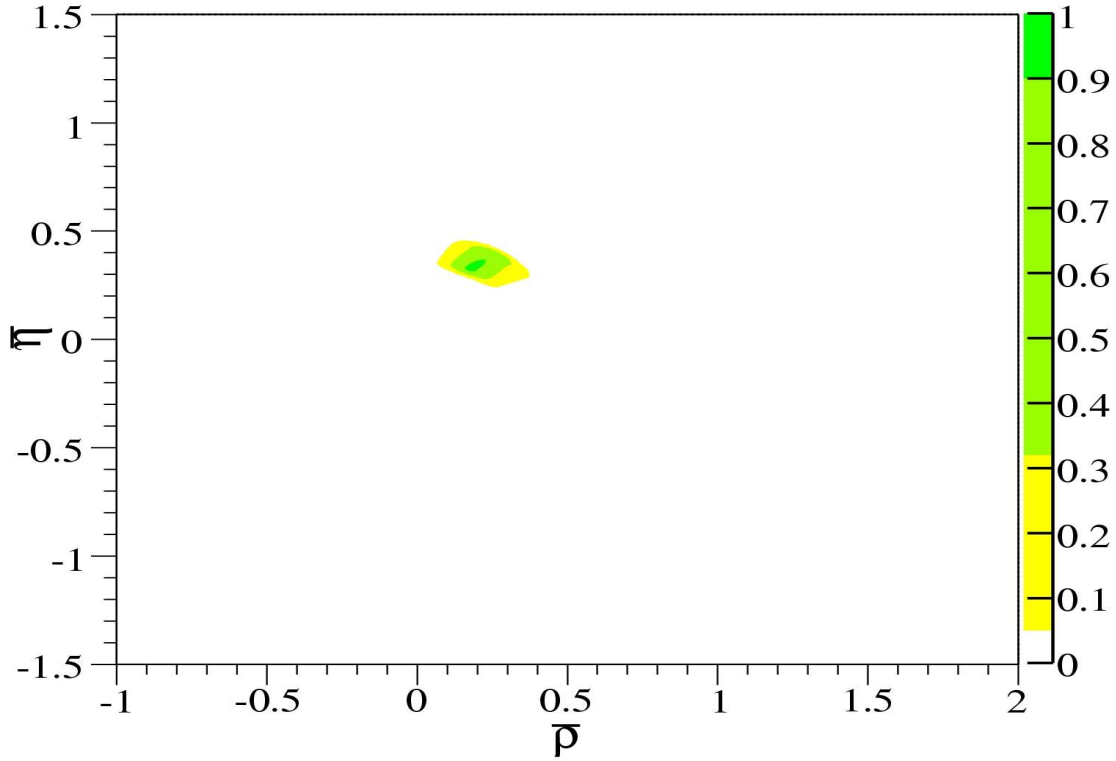
What do we know (05)

"Tree" level data. (statistical dominated.)

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

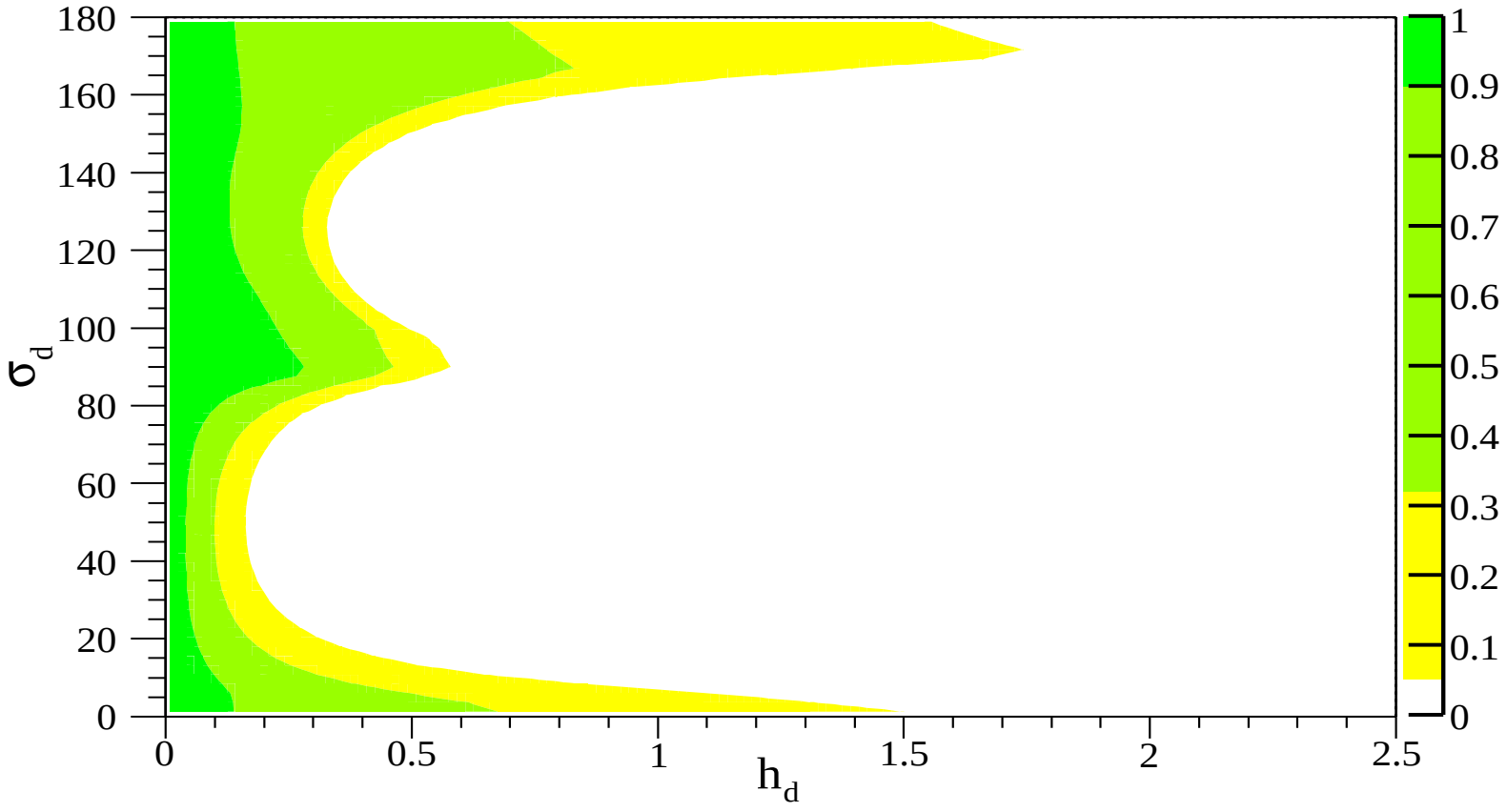
The $\rho - \eta$ Plane + NP (05)

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



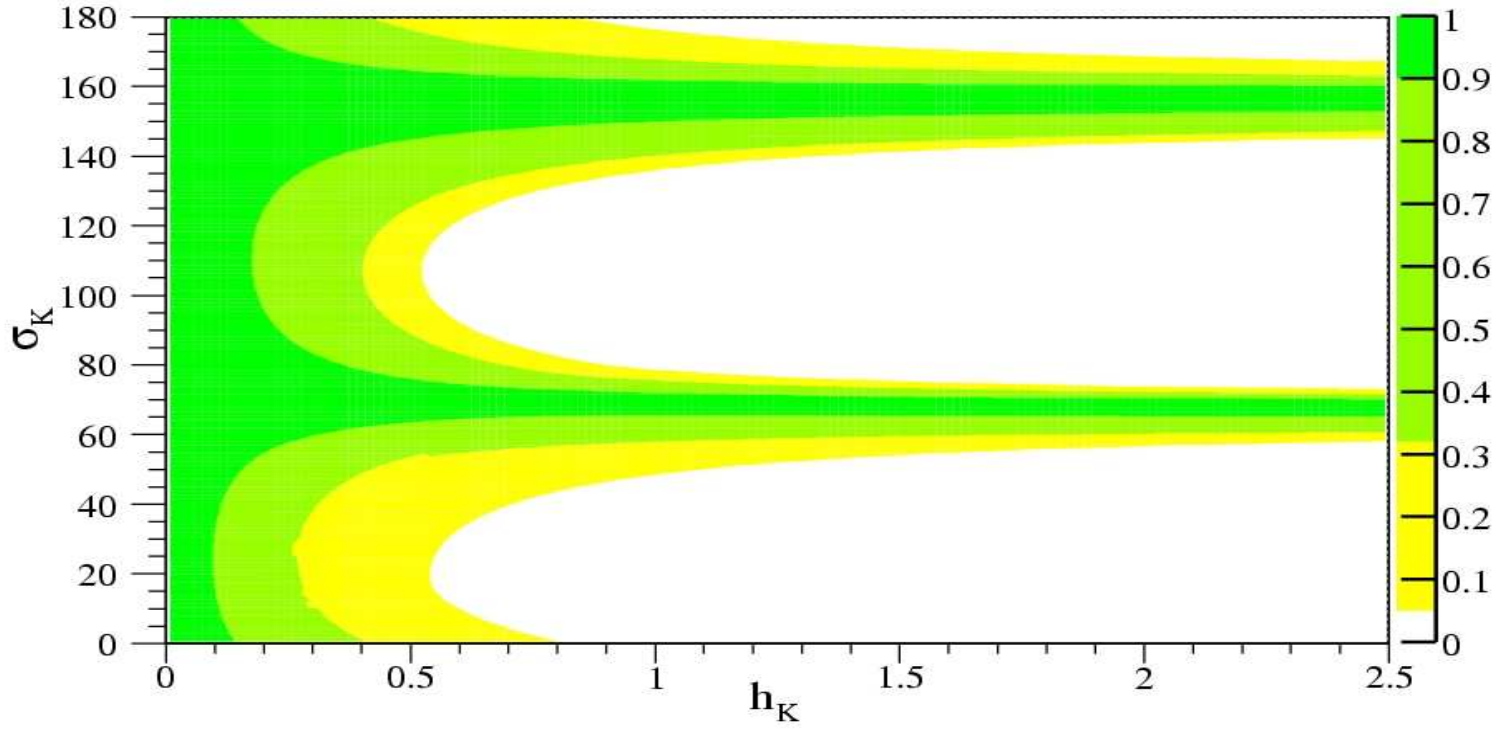
How big can h_d be (05) ?

$$h_d \lesssim 0.4$$



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: $S_{\psi K} - S_{\phi,\eta',\pi K} \ll 1$.
- 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.
- RS1,Z' (other models are covered...)

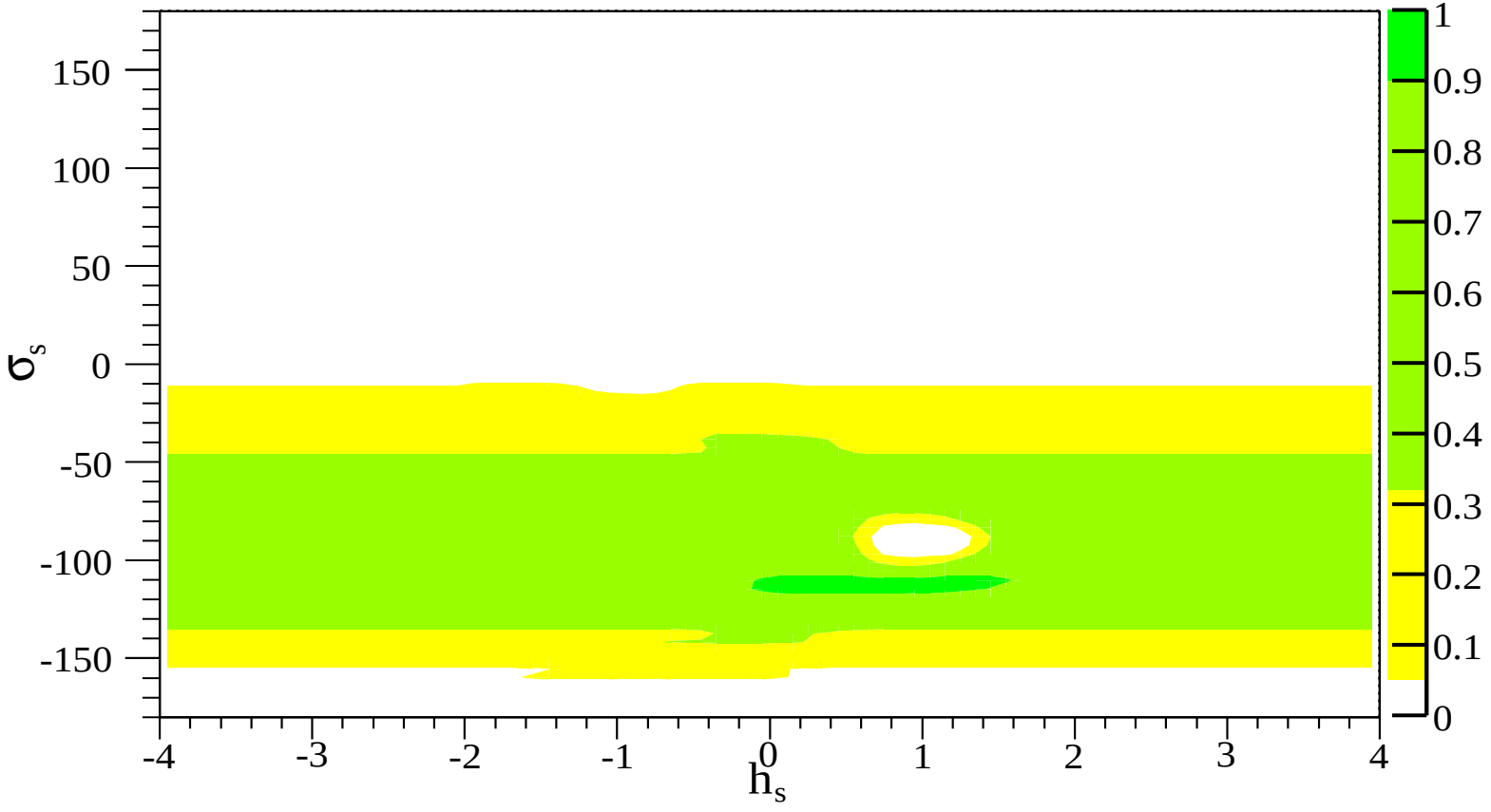
  $\Rightarrow C^Z(M_W) \to C^Z(M_W)\left(1 + h_s^1 e^{i\sigma_s}\right)$.
- $S_{\phi,\eta' K} \Rightarrow$ naive factorization, BBNS.
- $B \to \pi K \Rightarrow$ SU(3), BBNS.

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

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

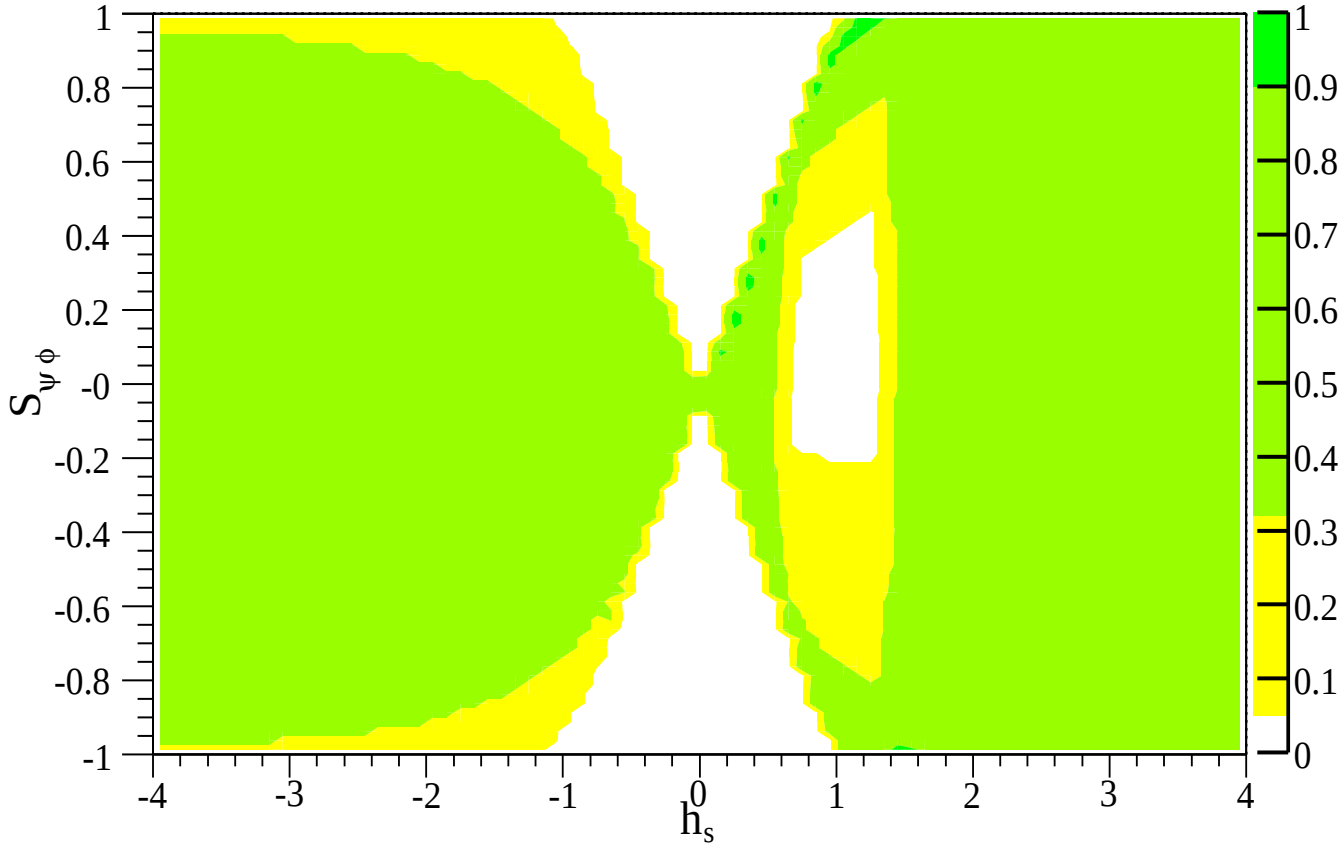
$\Delta m_s(\sigma_s)$ **from** $S_{\phi,\eta' K}, B \to K\pi(\sigma_s)$

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



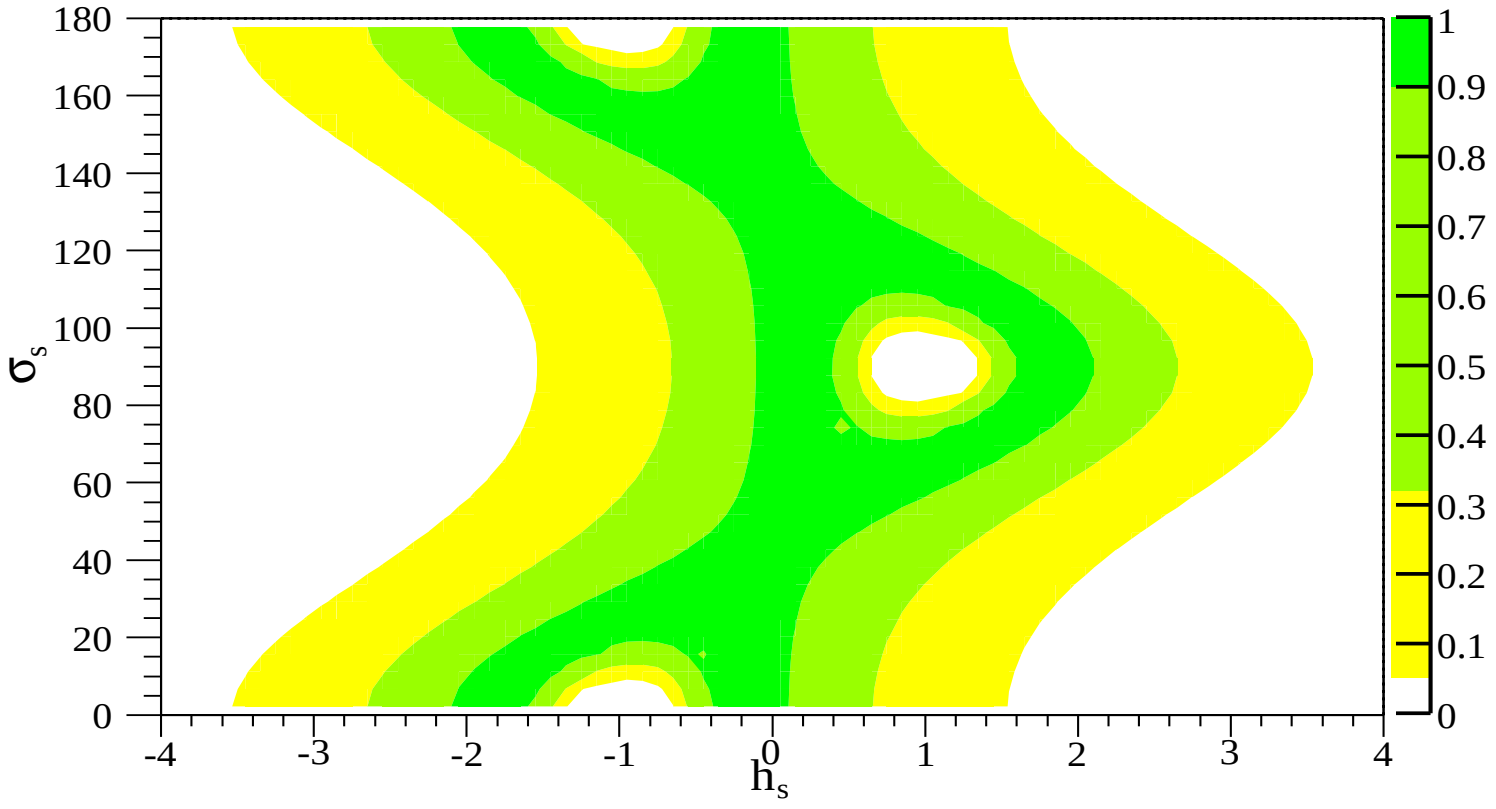
$S_{\psi\phi}(\sigma_s)$ **from** $\Delta m_s, S_{\phi,\eta' K}, B \to K\pi(\sigma_s)$

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

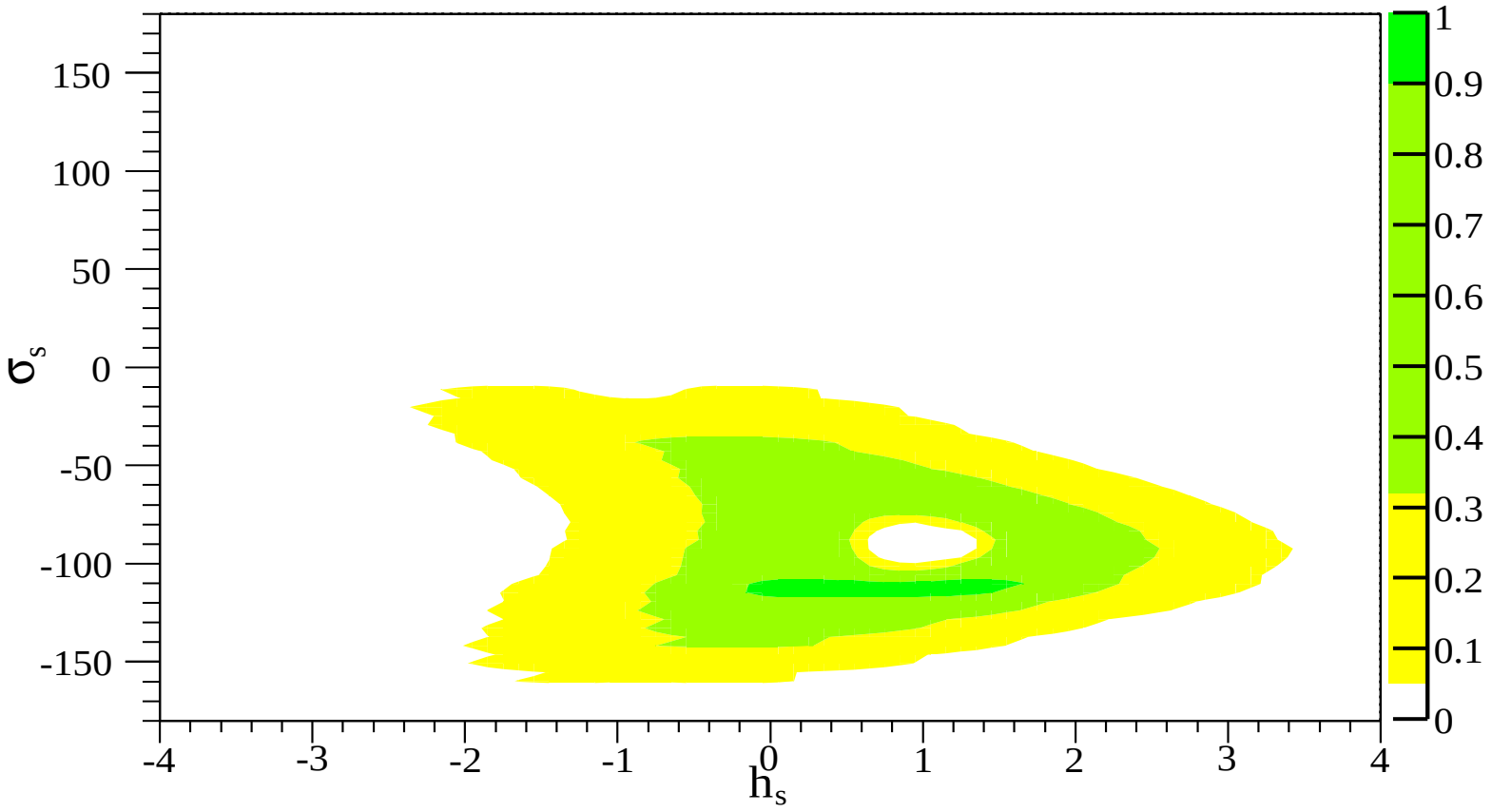


Fut': h_s, $\Delta m_s(\sigma_s) = 18.3 \pm 0.3 \mathrm{ps}^{-1}$ (SM) ?

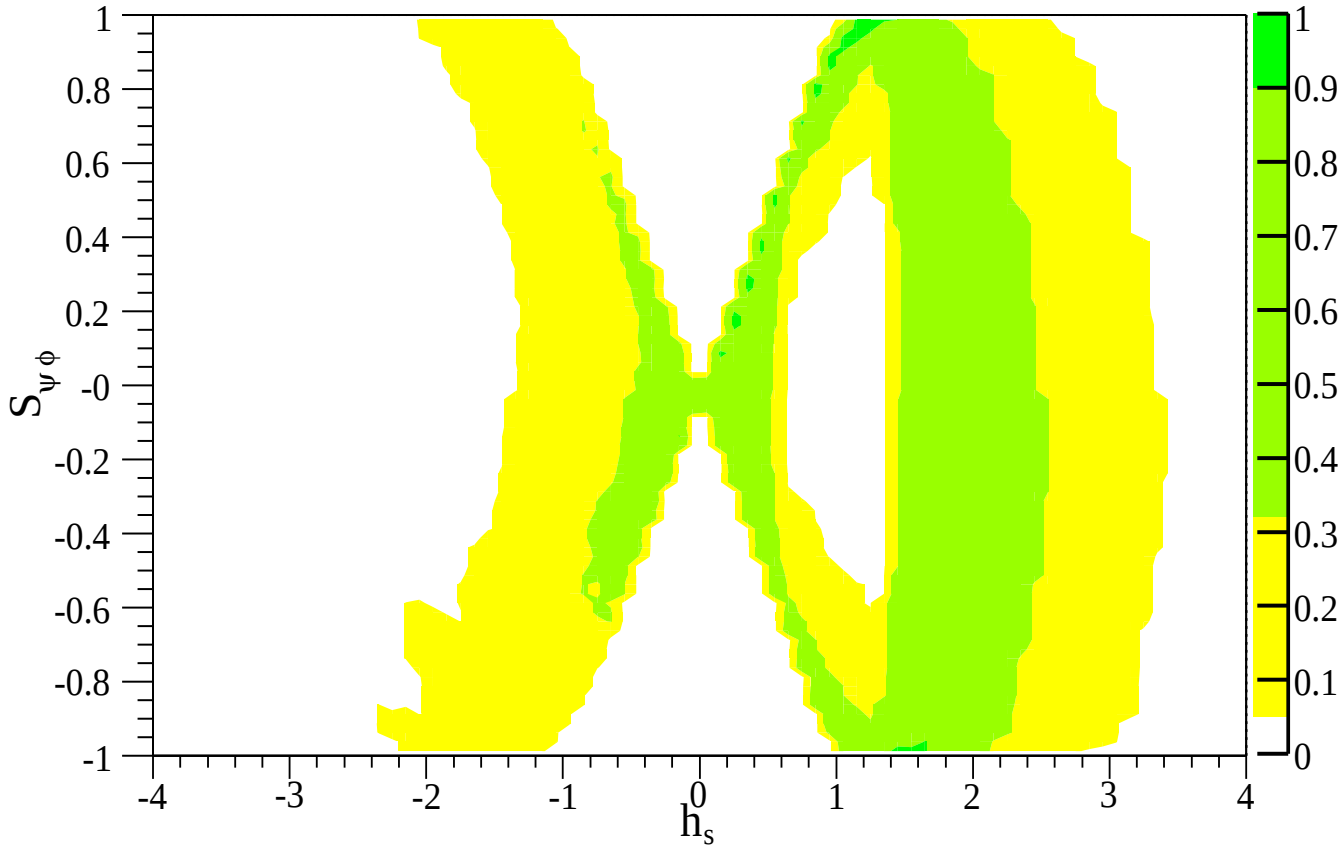
$$|h_s| \lesssim 2$$



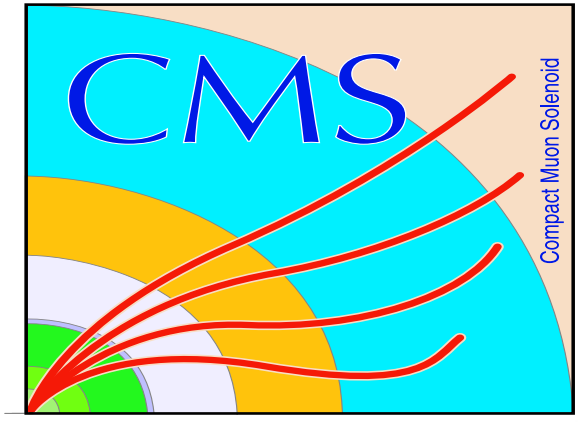
Fut': $\Delta m_s(h_s - \sigma_s)$(SM) & all the above



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



LHC & Top Phys'



LHC is a top machine

- $10^5 - 10^6$ tops/year $\longrightarrow$ test top coupling.
- Top FCNC $\longrightarrow t \longrightarrow c\,Z, \gamma, G$.
- SM $\longrightarrow BR(t \longrightarrow cZ, \gamma, G) \sim 10^{-12}$.
- ATLAS/CMS: $BR(t \longrightarrow cZ, \gamma) \gtrsim 10^{-5}$.
- Direct production signals.

2 main questions

- $BR(t \to cZ) \sim 10^{-5} \Leftrightarrow$ B phys'?

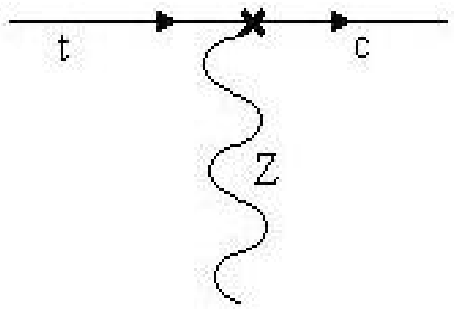
Requires model indep' study. (Fox, Ligeti, Papucci, GP & Schwartz)

- Can NP yield such enhancement?

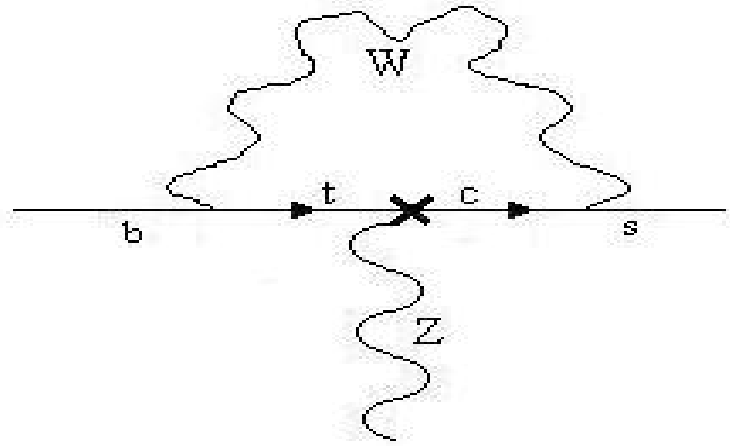
Possible within the NMFV framework. (Agashe, GP & Soni)

Is the LHC window closed?

- $t \to c\gamma, Z$: SM + Dim' 6 Op' @ m_t.
- $(LL^u)_{23} \leftrightarrow \bar{Q}_3 H^\dagger \not{D} H Q_2$,
  $(LR^u)_{23}, (RL^u)_{23}, (RR^u)_{23}$.
- Confront with $b \to s, c$ data.

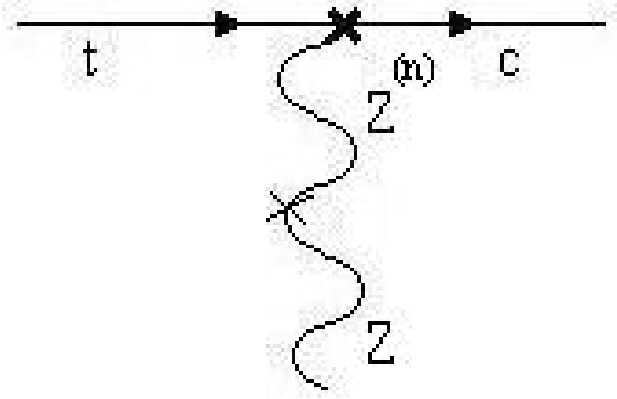


$\Rightarrow$



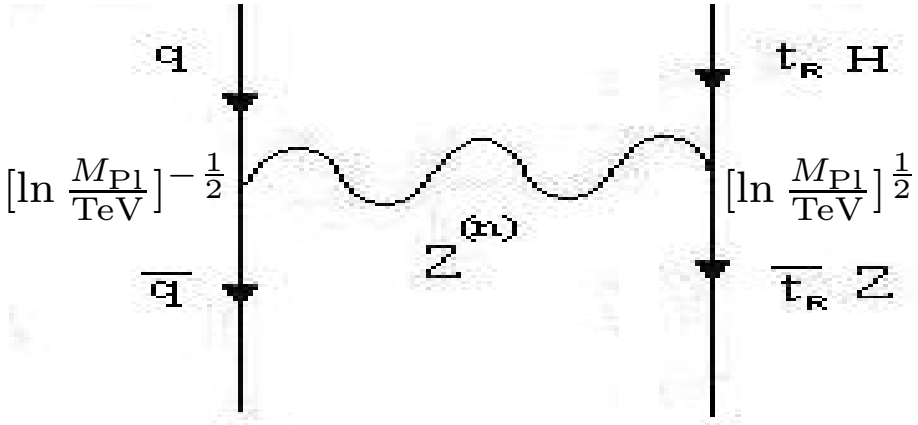
Huge enhancement in RS1

- After EWSB Z mix with the KK states.
- Tree level Z FCNC via mixing with KK states.
- $BR(t \to cZ) \propto |F_u|_{23} \times \delta g_Z \sim 10^{-5}$.



Direct RS1 signal ?

- KK states $\gtrsim$ 3TeV!
- Anom' coupling only to 3rd gen'.
- $Z^{(1)}$: Drell-Yan prod' $t_R\bar{t}_R$, HZ.
- $G^{(1)}$: $q\,\bar{q}$ fusion $\longrightarrow$ $t_R\bar{t}_R$ (asym').



Conclusions

- 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'.
- Top FCNC @ Atlas & CMS.
- FCNC $\leftrightarrow$ EWPT !
- Direct signal via 3rd gen' anom' coup'.

NMFV (next to minimal flavor violation)

Gilad Perez