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# How To Kill a Penguin

# Next 15<sup>+</sup> minutes ...\*

- **Setting stage:** MFV & CMFV
- **Introducing theme:**  $Z \rightarrow d_{iL} \bar{d}_{jL}$  vs.  $Z \rightarrow b_L \bar{b}_L$
- **General observation:** small momentum expansion of Z-vertex form factor
- **Model calculations:** 2HDM, CMFV MSSM, mUED & LHT
- **Grand final:** Killing Z-penguin, lower & upper bounds on rare decays

\*done in collaboration with Andreas Weiler; still preliminary results

# Minimal Flavor Violation (MFV)

In limit of vanishing Yukawa couplings  $Y_{D,U}$  SM acquires a global symmetry  $G_F = U(3)^5 \supset SU(3)_Q \times SU(3)_U \times SU(3)_D$

$$\mathcal{L}_{\text{Yukawa}} = \bar{Q}_L Y_D D_R \phi + \bar{Q}_L Y_U U_R \phi_c + \text{h.c.}$$

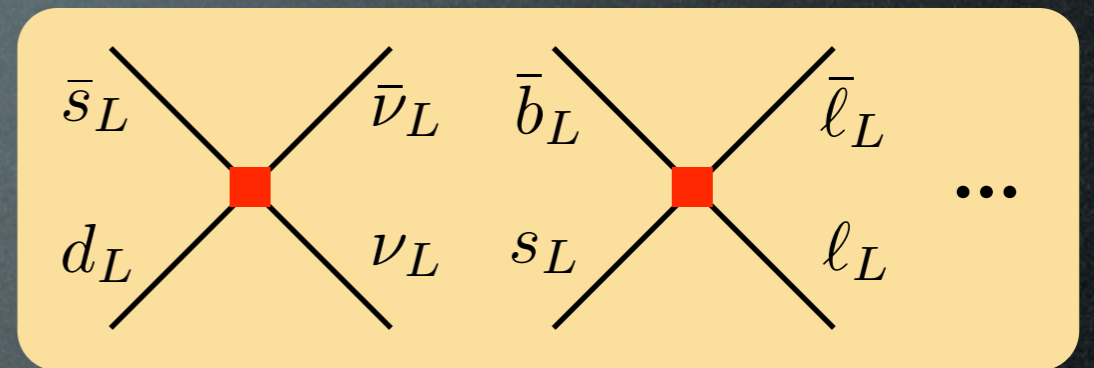
If Yukawa couplings  $Y_{D,U}$  transform as  $Y_D \sim (3, 1, \bar{3})$  &  $Y_U \sim (3, \bar{3}, 1)$  global symmetry  $G_F$  is restored

MFV = “effective theory constructed from SM fields & Yukawa couplings  $Y_{D,U}$  that is invariant under  $G_F$ ”\*

\*D'Ambrosio et al. '02

# Typical FCNC D=6 Operator

$$(\bar{Q}_L^i (Y_U Y_U^\dagger)_{ij} Q_L^j) (\bar{L}_L L_L)$$



$$(Y_U Y_U^\dagger)_{ij} = V^\dagger \text{diag}(y_u^2, y_c^2, y_t^2) V \approx y_t^2 V_{ti}^* V_{tj}$$

$y_t^2 V_{ti}^* V_{tj}$  is effective coupling ruling all FCNCs with external down-type quarks:  $K \rightarrow \pi \nu \bar{\nu}$ ,  $\bar{B} \rightarrow X_s \gamma$ ,  $\bar{B} \rightarrow X_s l^+ l^-$ , ...

Only flavor-independent magnitude of FCNC amplitudes can be modified by NP contributions to  $D \leq 6$  operators\*

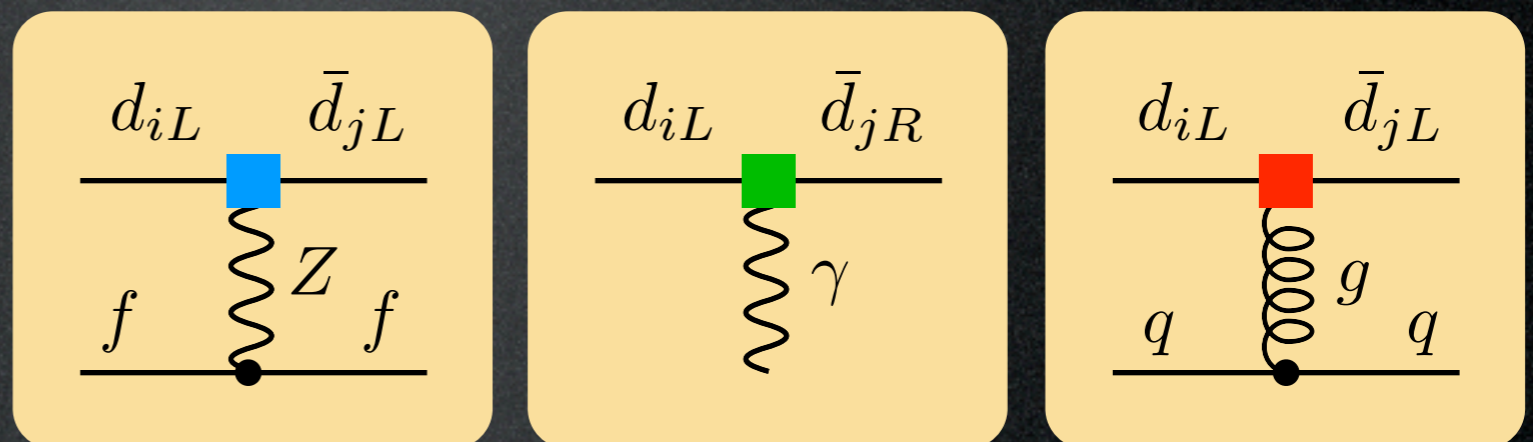
\*phase measurements  $a(B \rightarrow \psi K_s)$ ,  $\Delta M_{B_s}/\Delta M_{B_d}$ , ... unaffected in MFV

# Constrained MFV (CMFV)

CMFV = “MFV & no other operators beyond SM ones”\*

CMFV  $\equiv$  MFV under assumption of single  $\phi$  doublet;  
large  $\tan\beta$  effects in 2HDM/MSSM not covered by CMFV

- D=4 effective FCNC Z-vertex:  $C = C_{\text{SM}} + \Delta C$
- D=5 (chromo)magnetic operators:  $C_7^{\text{eff}} = C_{7,\text{SM}}^{\text{eff}} + \Delta C_7^{\text{eff}}, \dots$
- D=6 subleading penguins and EW boxes:  $E = E_{\text{SM}} + \Delta E, \dots$



\*Buras et al. '00, ...

# CMFV parameters

$K$ - $\bar{K}$  mixing ( $|\epsilon_K|$ )

$B_{d,s}$ - $\bar{B}_{d,s}$  mixing ( $\Delta M_{B_{d,s}}$ )

$K \rightarrow \pi \nu \bar{\nu}, \bar{B} \rightarrow X_{d,s} \nu \bar{\nu}$

$K_L \rightarrow \mu^+ \mu^-, B_{d,s} \rightarrow \mu^+ \mu^-$

$K_L \rightarrow \pi^0 \ell^+ \ell^-$

$\epsilon'/\epsilon, |\Delta S| = 1$

non-leptonic  $|\Delta B| = 1$

$\bar{B} \rightarrow X_s \gamma$

$\bar{B} \rightarrow X_s g$

$\bar{B} \rightarrow X_s \ell^+ \ell^-$

$S(v)$

$S(v)$

$X(v)$

$Y(v)$

$Y(v), Z(v), E(v)$

$X(v), Y(v), Z(v), E(v)$

$X(v), Y(v), Z(v), E(v), E'(v)$

$D'(v), E'(v)$

$E'(v)$

$Y(v), Z(v)$

$E(v)$

$D'(v), E'(v)$

$$X(v) = C(v) + B^{\nu\nu}(v)$$

$$Y(v) = C(v) + B^{\ell\ell}(v)$$

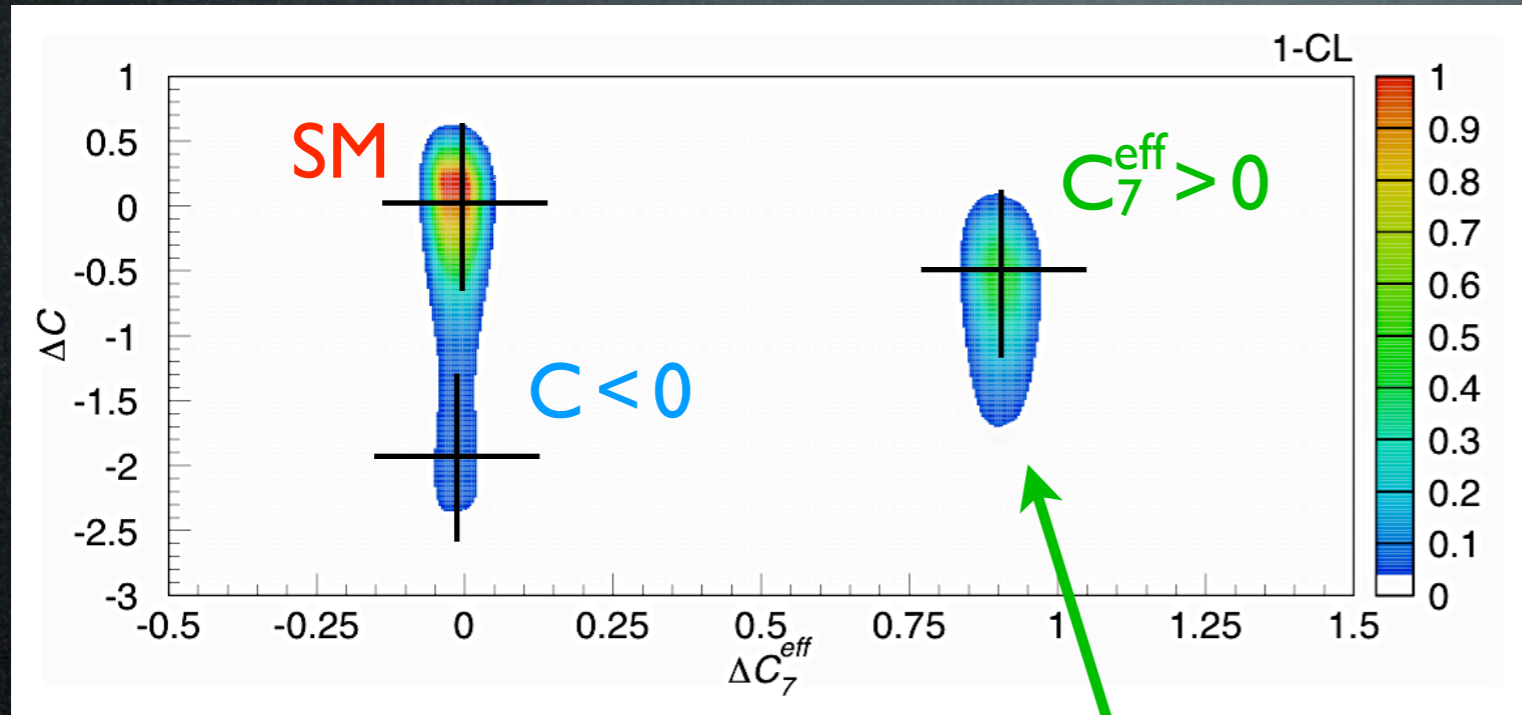
$$Z(v) = C(v) + \frac{1}{4}D(v)$$

drop as  $\mathcal{O}(10^{-2})$

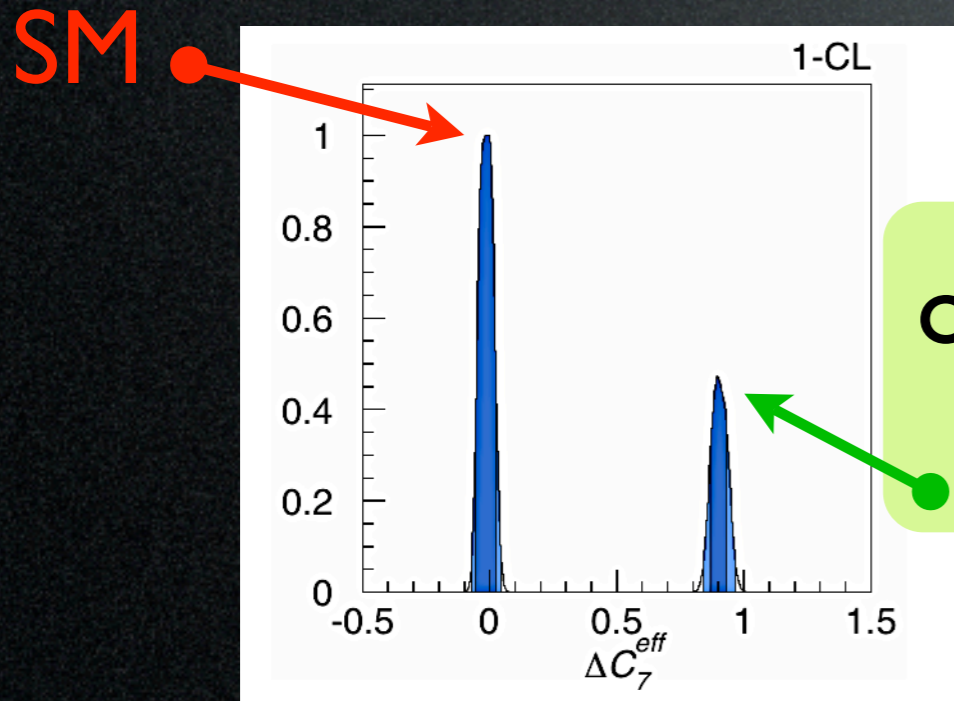
dominated by Z-penguin

trade for  $C_7^{\text{eff}}(\mu_b)$

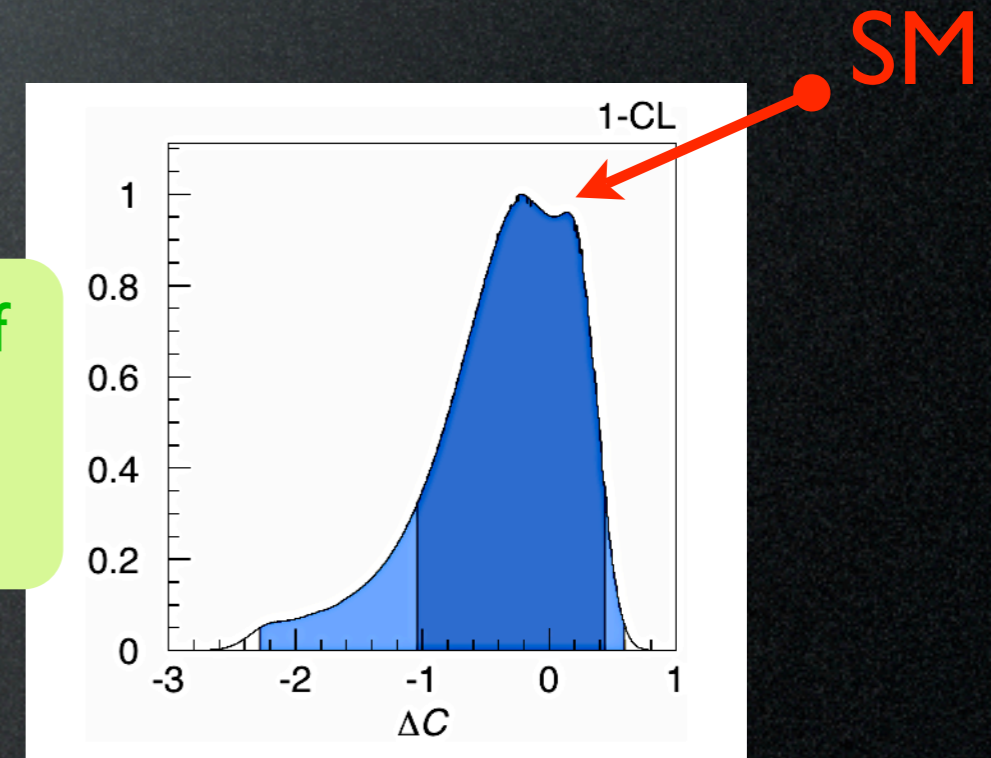
# $\Delta C_7^{\text{eff}}$ vs. $\Delta C$ from $\bar{B} \rightarrow X_s \gamma, l^+ l^-$ & $K^+ \rightarrow \pi^+ \nu \bar{\nu}$



results depend on  
assumptions  $\Delta B = 0$   
&  $|\Delta D| \leq |D_{\text{SM}}|$

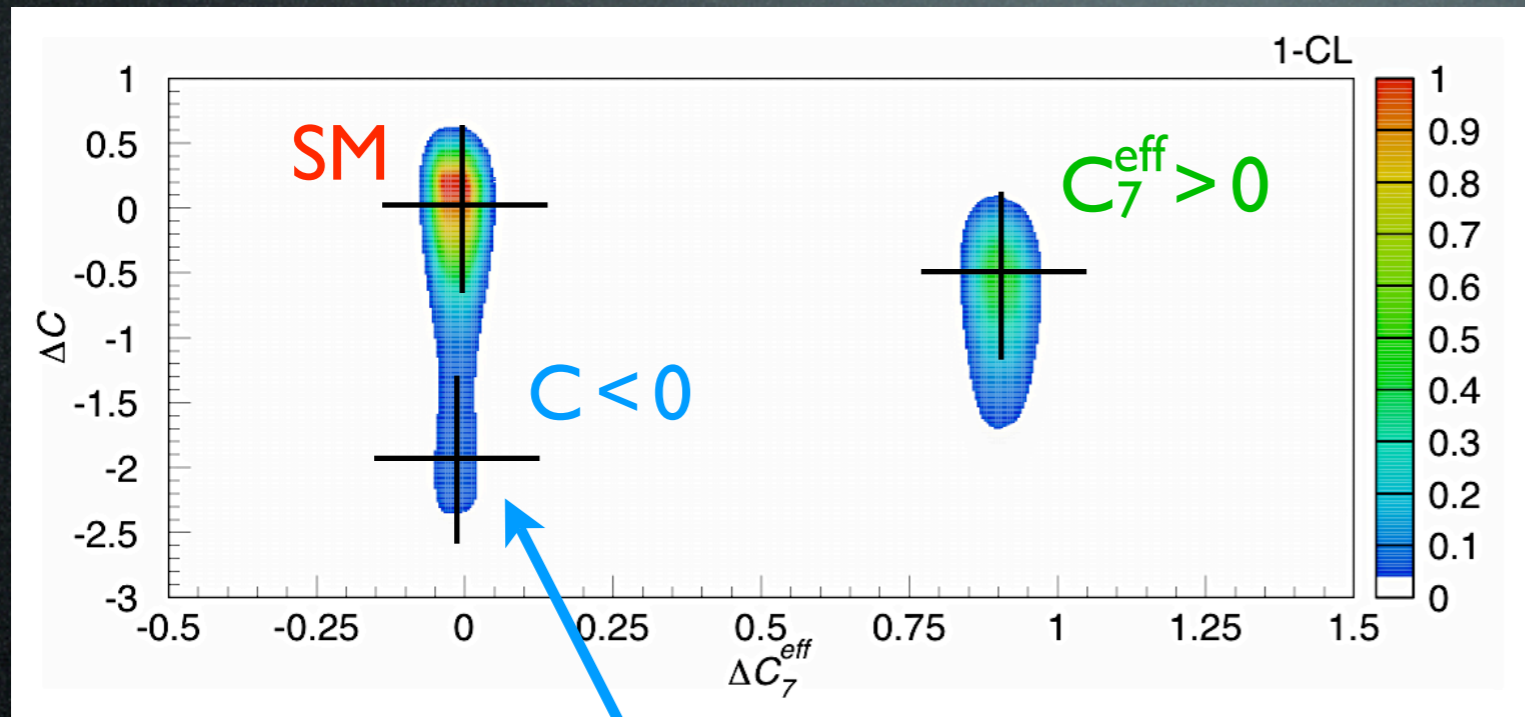


opposite sign  $C_7^{\text{eff}}$   
less likely\*

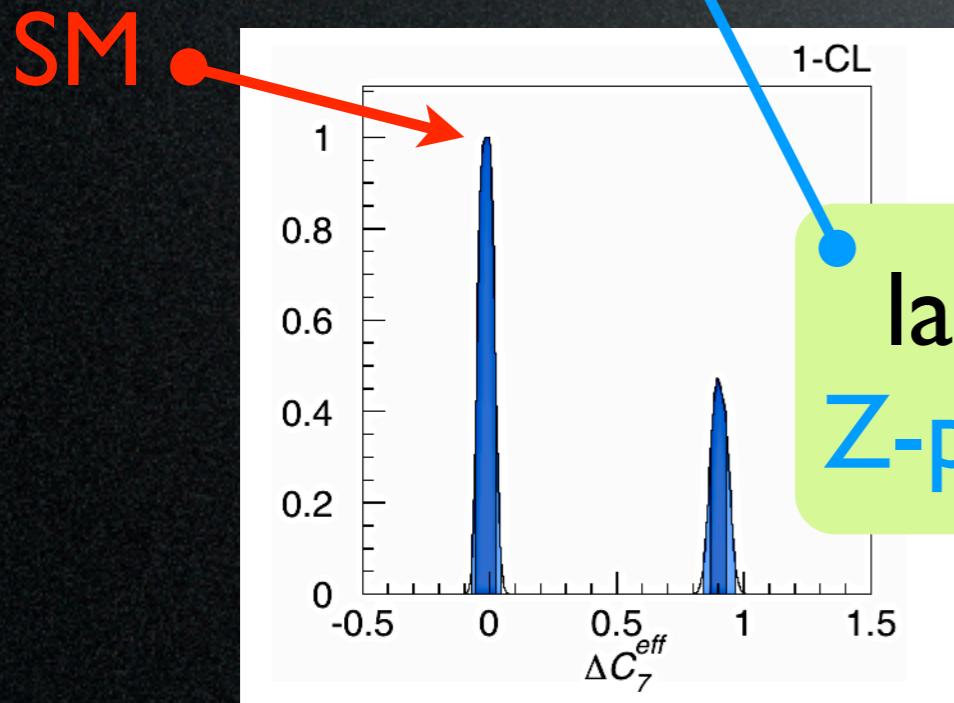


\*Gambino, UH, Misiak '04

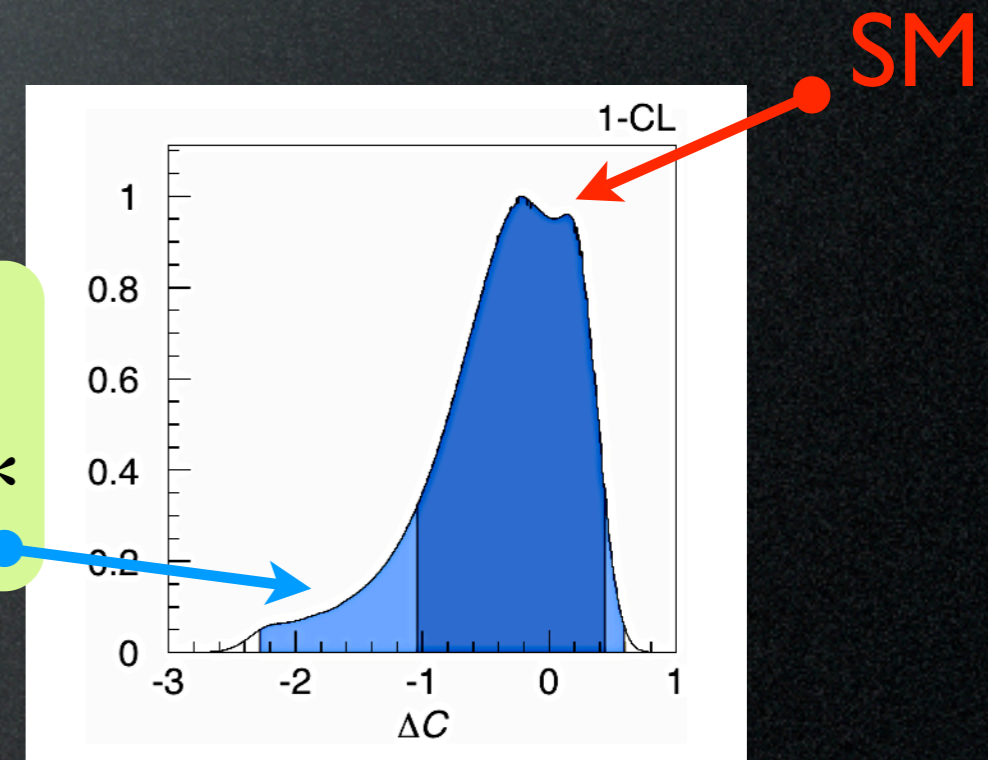
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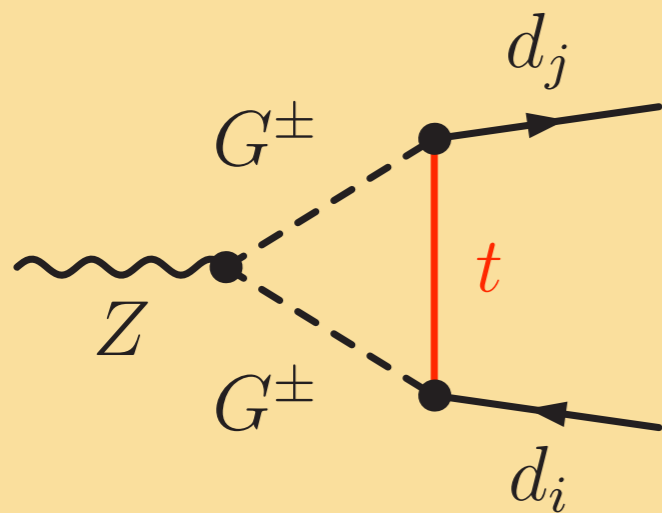


large destructive  
**Z-penguin** allowed\*



\*Bobeth et al. '05

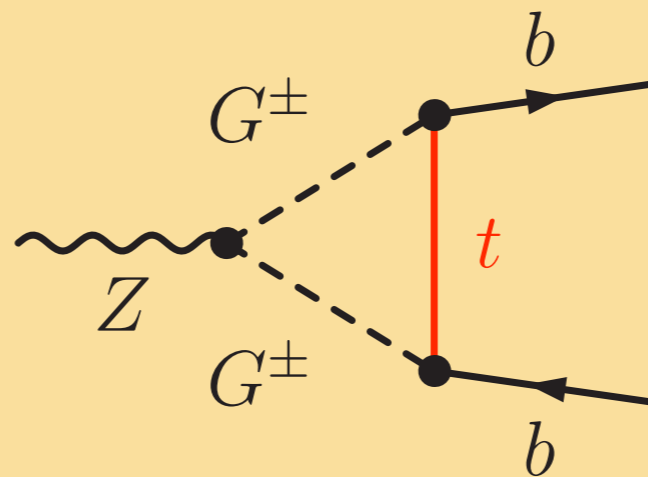
Idea:  $Z \rightarrow d_{iL} \bar{d}_{jL} \equiv Z \rightarrow b_L \bar{b}_L$



universal  
Z-penguin:

$C$

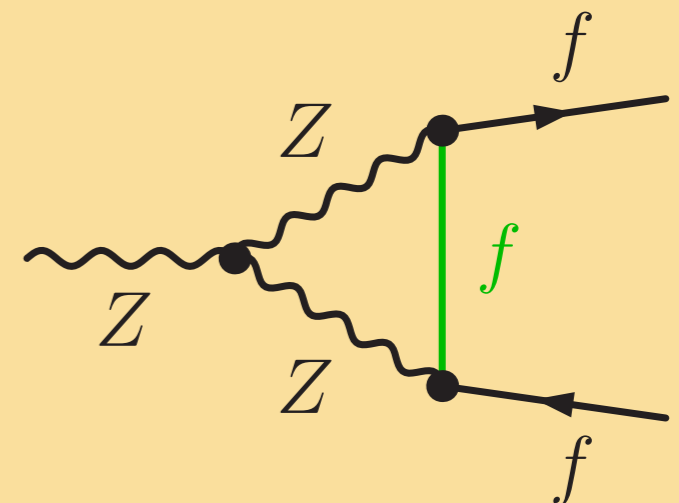
$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}), \dots$



non-universal  
corrections:

$\epsilon_b^*$

$R_b^0, A_b$  &  $A_{FB}^{0,b}$

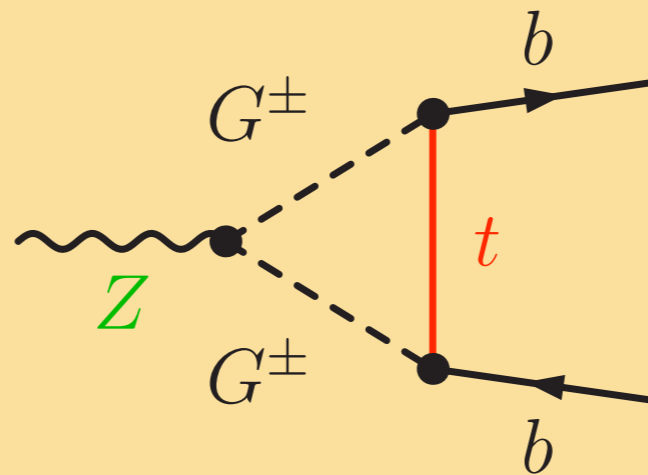
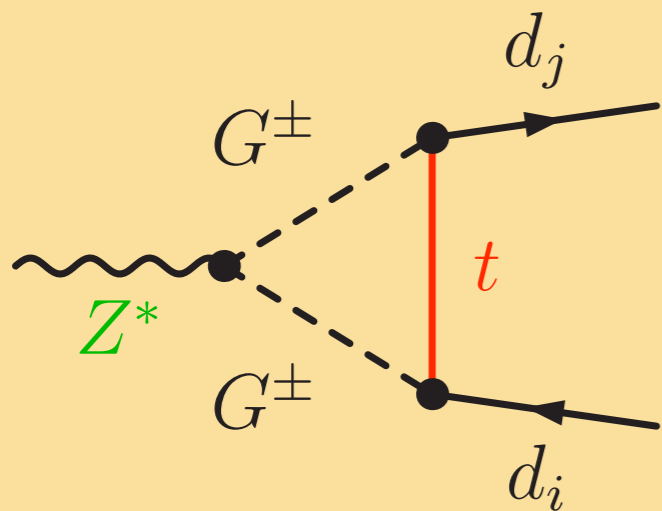


universal  
corrections:

$\rho_f$  &  $\sin^2 \theta_{eff}^f$

$A_f, A_{LR}^0, R_c^0, \dots$

Idea:  $Z \rightarrow d_{iL} \bar{d}_{jL} \equiv Z \rightarrow b_L \bar{b}_L$



$$\Gamma_{ji} \propto V_{tj}^* V_{ti} C(q^2) \bar{d}_{jL} Z d_{iL}$$

$$\delta C = 1 - \frac{\text{Re } C(q^2 = 0)}{\text{Re } C(q^2 = M_Z^2)}$$

$$Z \rightarrow d_{iL} \bar{d}_{jL} : C(q^2 = 0)$$

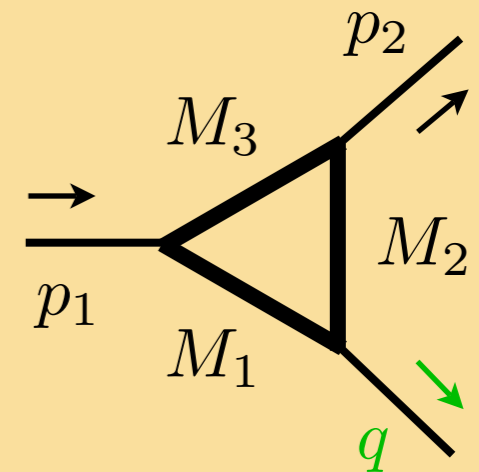
$$Z \rightarrow b_L \bar{b}_L : C(q^2 = M_Z^2)$$

is there a general argument that shows that  $\delta C$  is small?

# Small Momentum Expansion of $C_0$

$$C_0 = \frac{M_3^2}{i\pi^2} \int \frac{d^4 l}{D_1 D_2 D_3} = \sum_{n=0}^{\infty} a_n \left( \frac{q^2}{M_3^2} \right)^n$$

$$D_i = (l + p_i)^2 - M_i^2, \quad p_3 = 0$$



\*

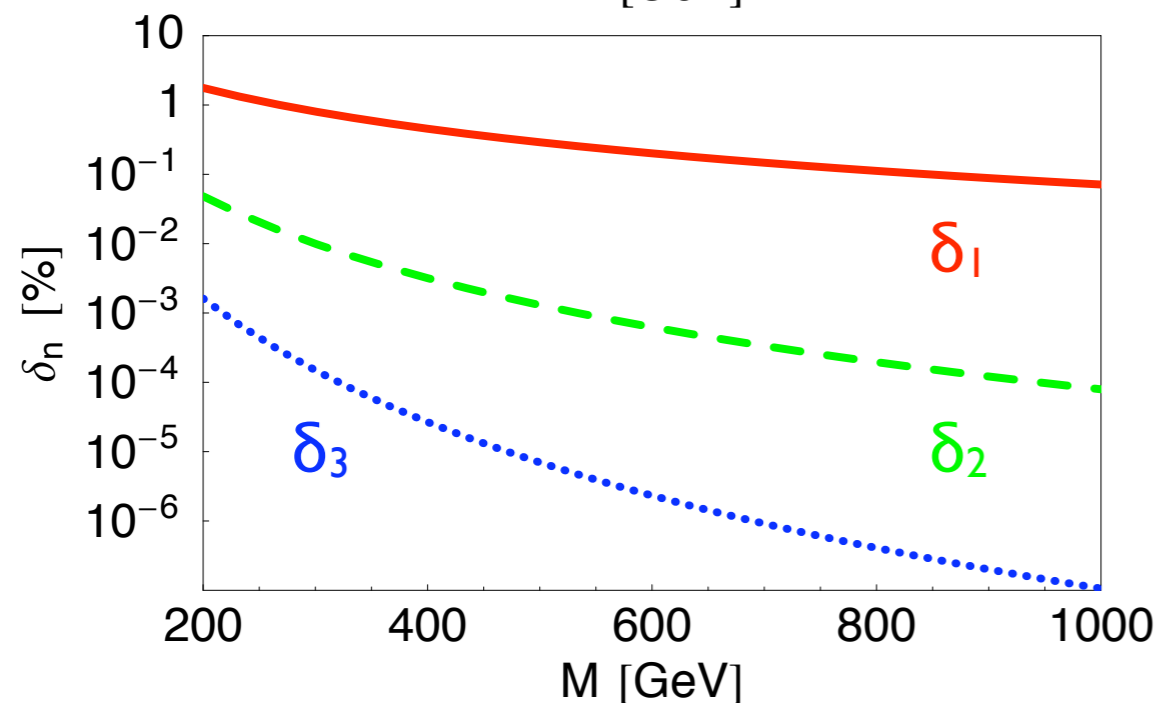
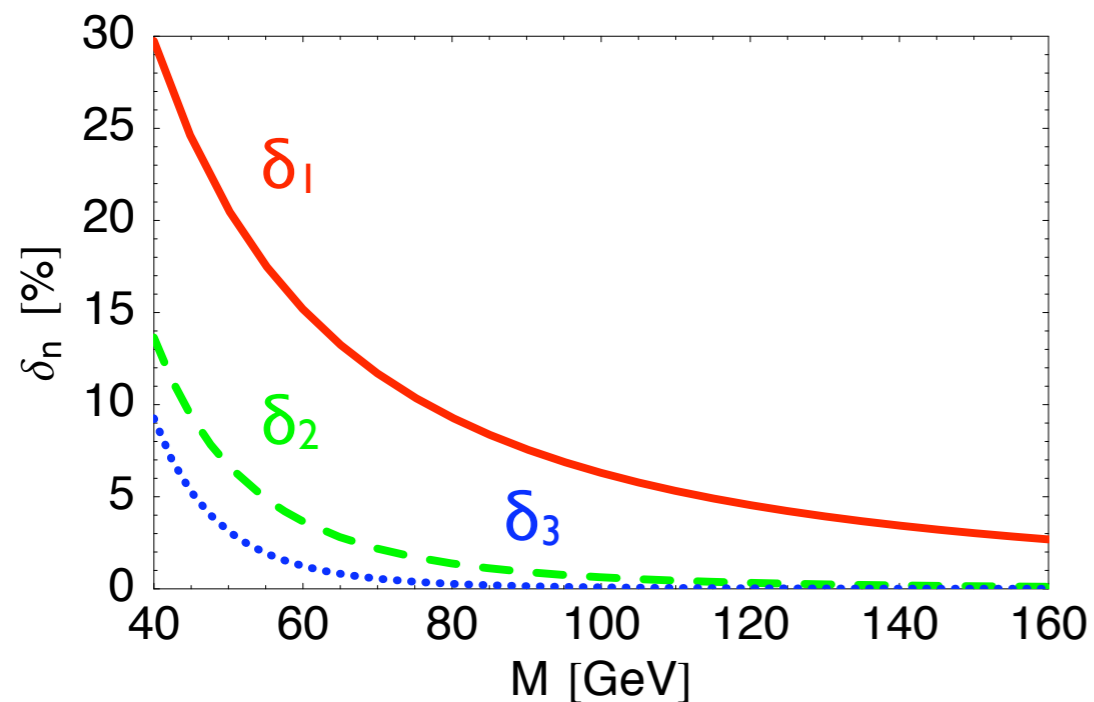
$$a_n = \frac{(-1)^n}{(n+1)!} \sum_{l=0}^n \binom{n}{l} x_1^l \frac{\partial}{\partial x_1^l} \frac{\partial}{\partial x_2^n} g(x_1, x_2)$$

$$g(x_1, x_2) \stackrel{\dagger}{=} \frac{1}{x_1 - x_2} \left( \frac{x_1 \ln x_1}{1 - x_1} - \frac{x_2 \ln x_2}{1 - x_2} \right)$$

$$\dagger \quad M_3 \neq 0, \quad p_{1,2}^2 = m_{1,2}^2 = 0, \\ q^2 = (p_1 - p_2)^2 = -2p_1 \cdot p_2$$

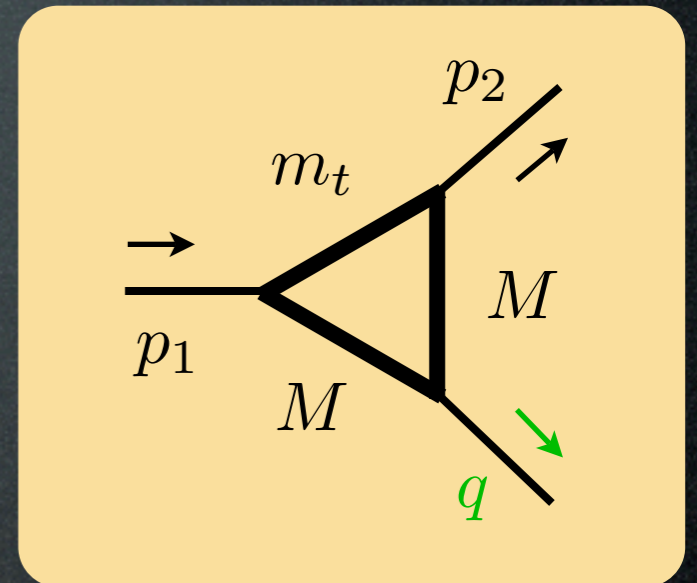
$$\ddagger \quad x_i = M_i^2 / M_3^2$$

# Small Momentum Expansion of $C_0$



$$M_{1,2} = M$$

$$M_3 = m_t$$



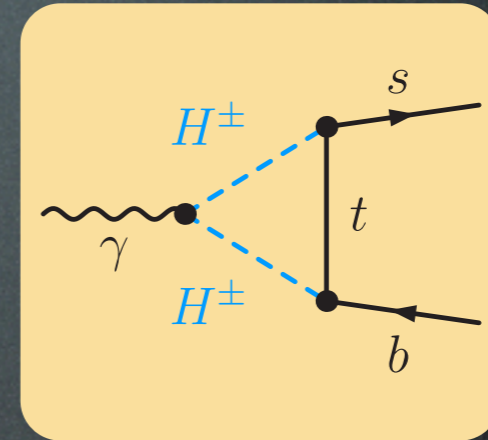
$$\delta_n = a_n \left( \frac{M_Z^2}{m_t^2} \right)^n \left( \sum_{l=0}^{n-1} a_l \left( \frac{M_Z^2}{m_t^2} \right)^l \right)$$

suggests that  $\delta C$  is small if internal masses are  $\geq 100$  GeV\*

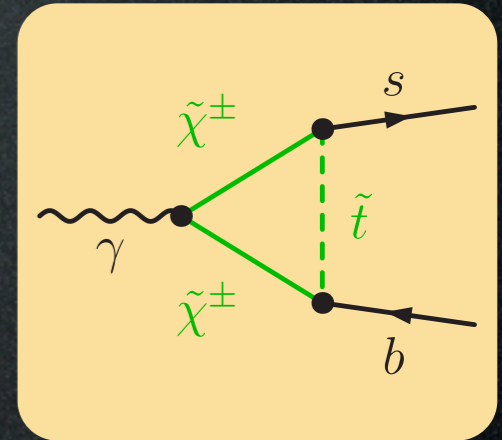
\*applies also to case of  $Z \rightarrow b_R \bar{b}_R$ ; argument doesn't rely on MFV assumption!

# Assortment of MFV models

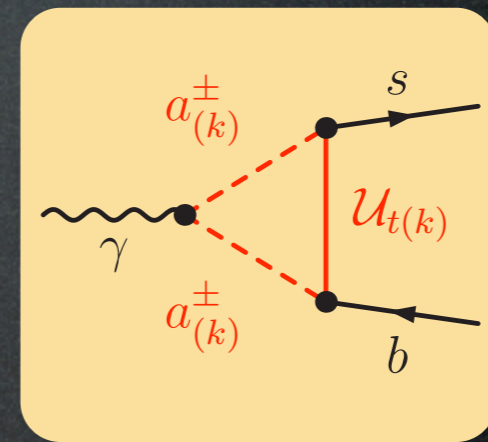
- 2-Higgs-Doublet-Model (2HDM)
- MSSM with universal squark mass & diagonal tri-linear terms\* (MFV MSSM)
- SM with one flat universal extra dimension (mUED)
- Littlest Higgs model with T-parity & degenerate mirror quarks (LHT)



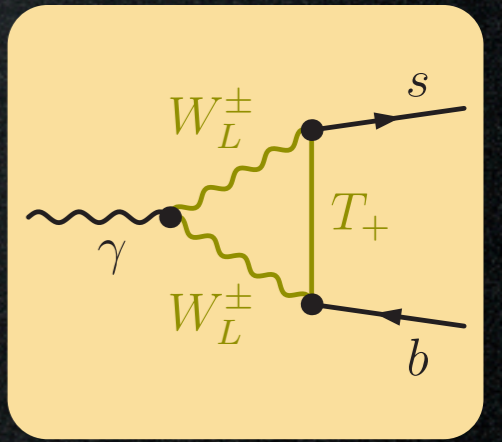
(2HDM)



(MFV MSSM)



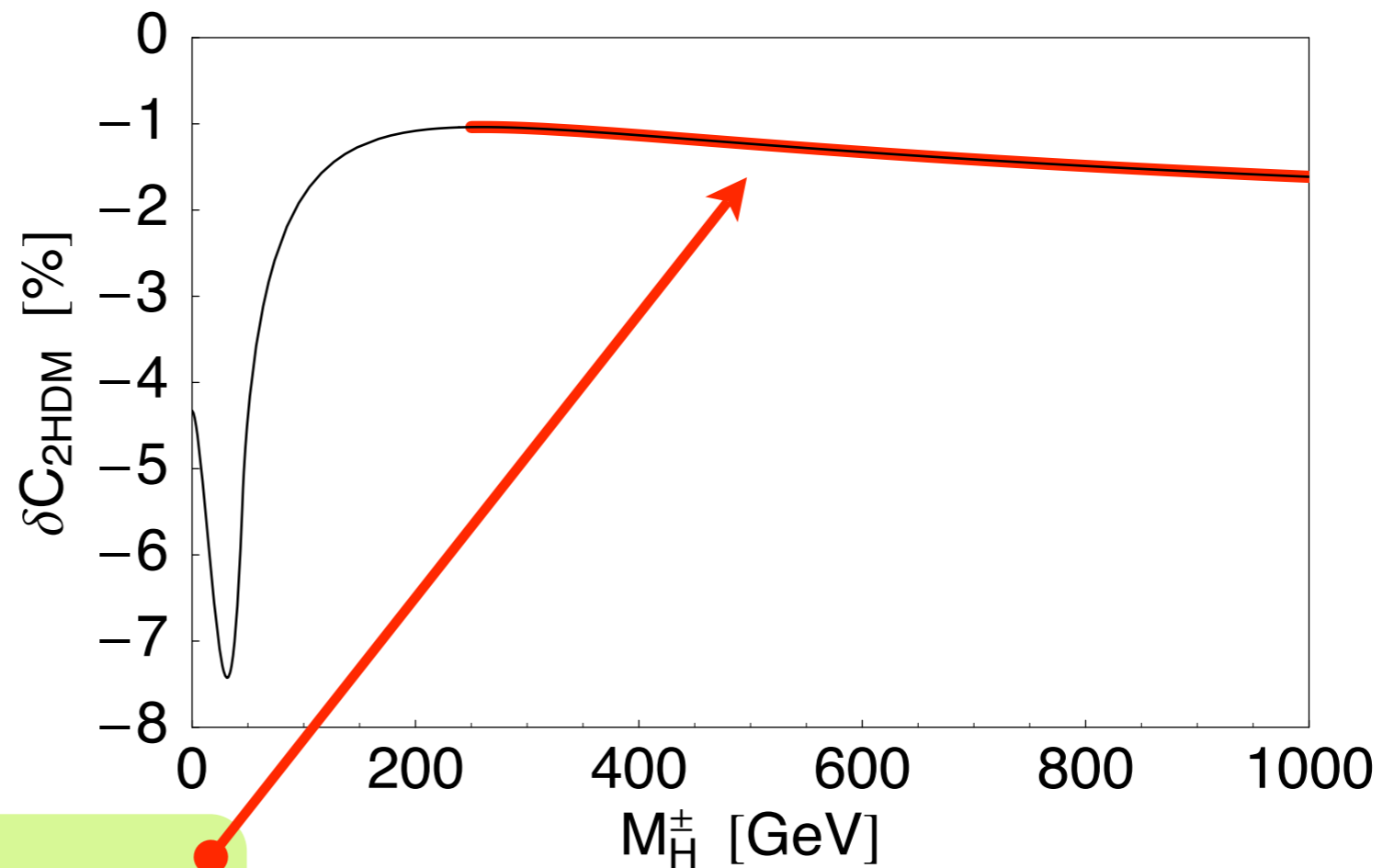
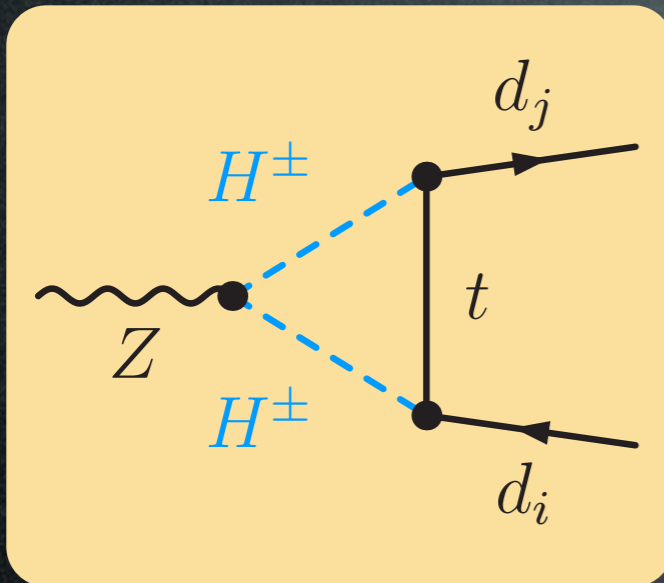
(mUED)



(LHT)

\*corrections to universality  $\sim (Y_U Y_U^\dagger)_{ij}$  induced by RGE

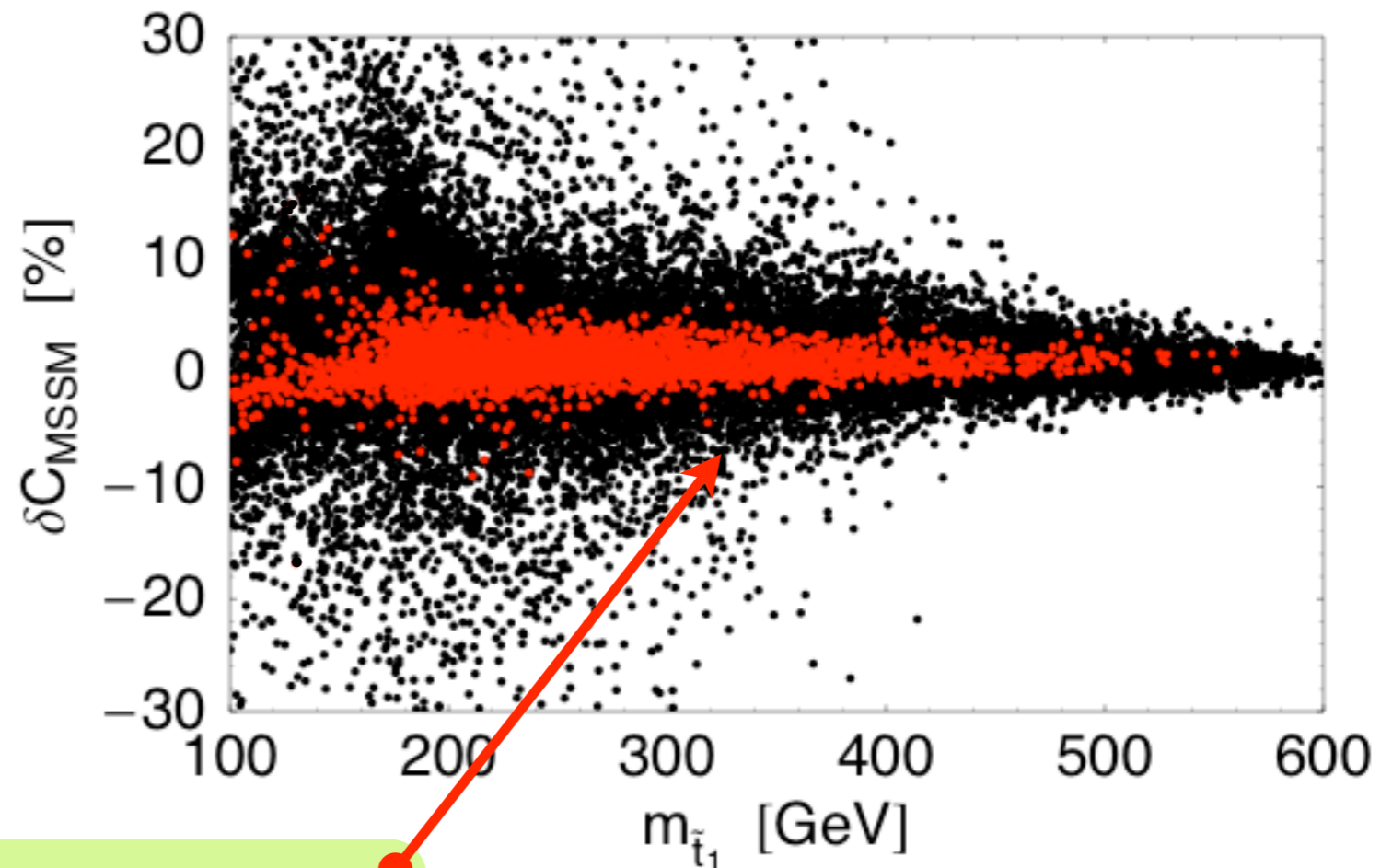
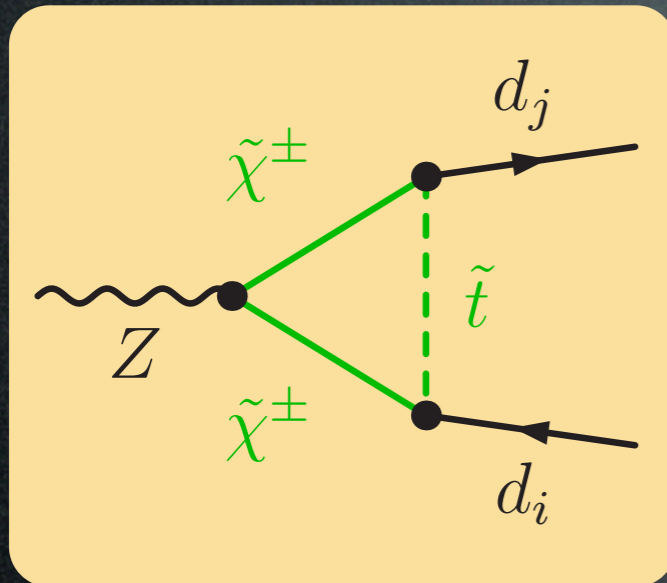
# $\delta C$ in 2HDM Type II & low $\tan\beta = v_U/v_D$



bound  $M_H^\pm > 250$  GeV  
from  $\bar{B} \rightarrow X_s \gamma^*$

general argument  
applies to 2HDM:  
 $|\delta C_{2HDM}| \lesssim 2\%$

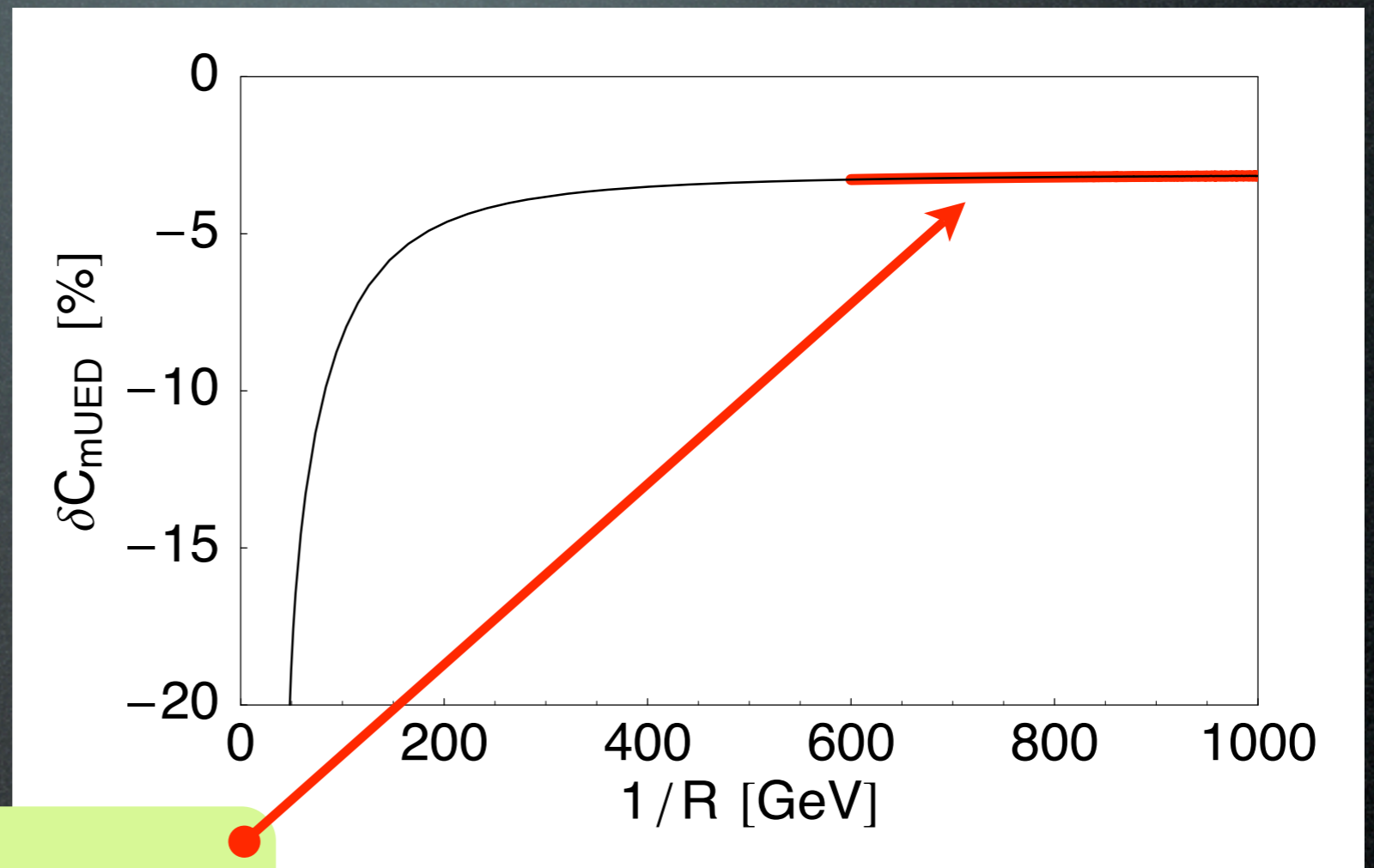
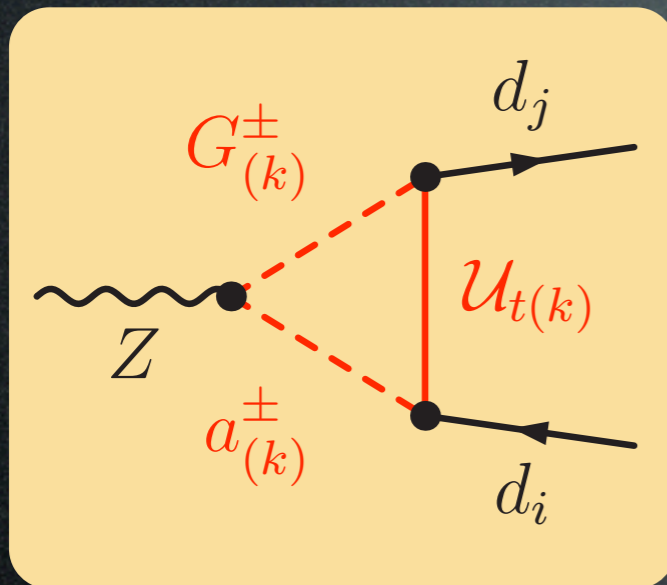
# $\delta C$ in CMFV MSSM & low $\tan\beta$



red points satisfy SUSY mass bounds,  $m_h > 114.4$  GeV, EW precision & flavor constraints

general argument applies to CMFV MSSM:  
 $|\delta C_{\text{MSSM}}| \lesssim 10\%$

# $\delta C$ in mUED Model

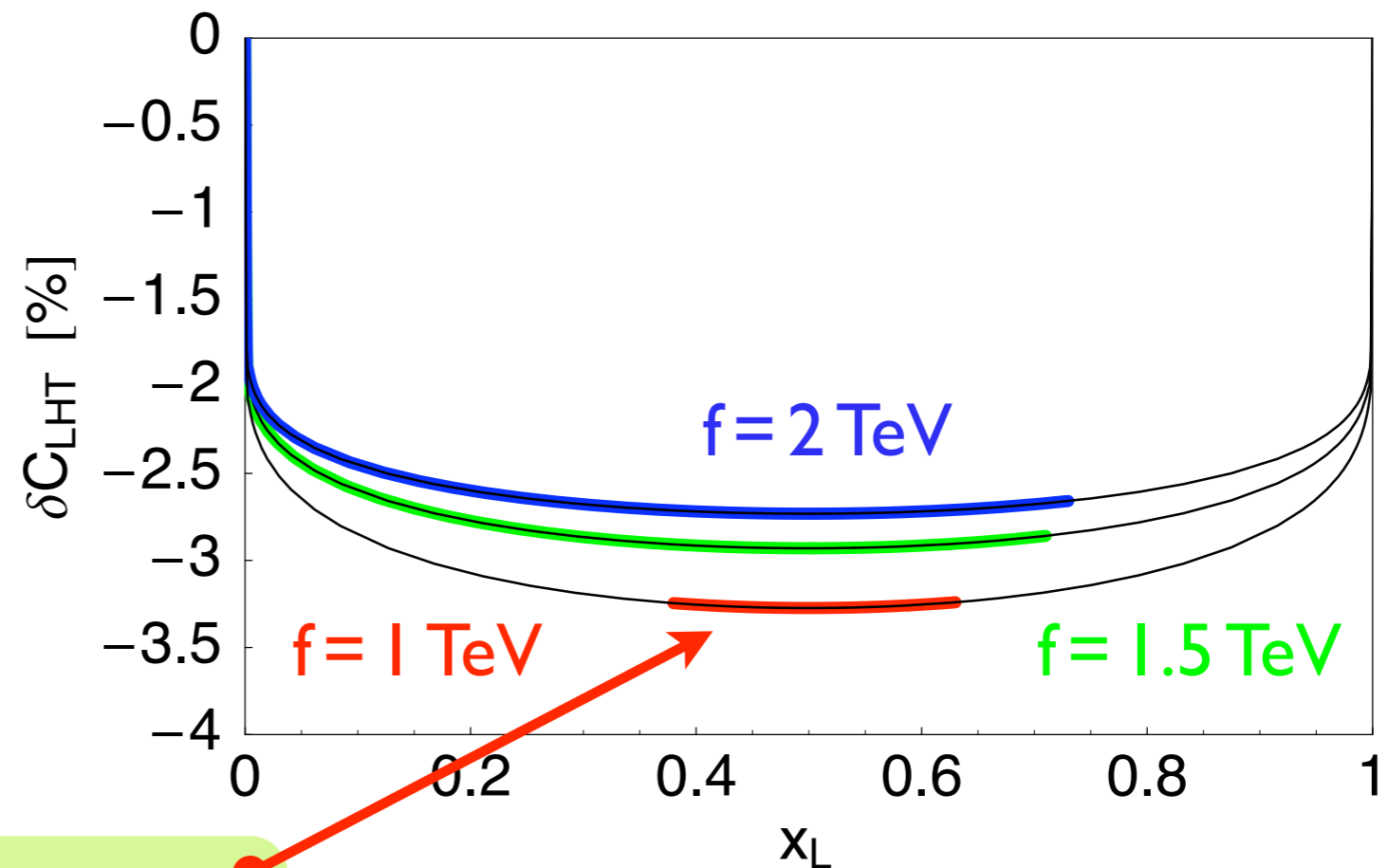
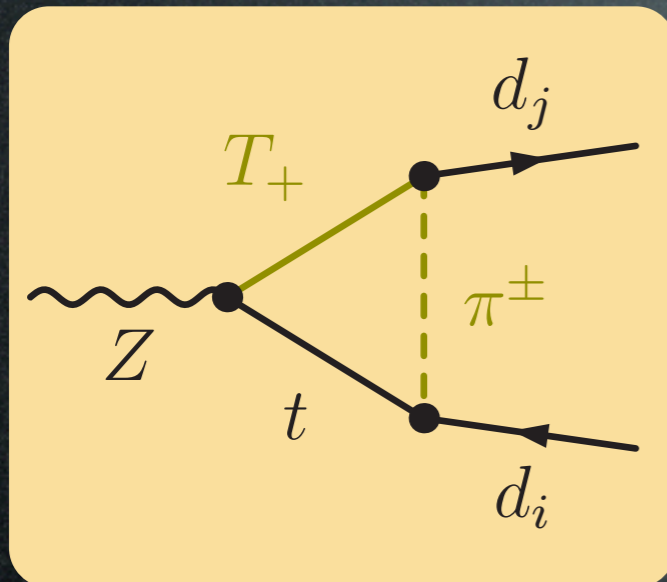


bound  $1/R > 600 \text{ GeV}$   
from  $\bar{B} \rightarrow X_s \gamma^*$

general argument applies  
to mUED model:

$$|\delta C_{\text{ACD}}| < 5\%$$

# $\delta C$ in CMFV version of LHT Model\*



colored bands allowed  
by EW precision  
constraints

general argument  
applies to LHT model:  
 $|\delta C_{\text{LHT}}| < 4\%$

\*i.e. assuming degenerate mirror quarks; no left over UV pole in Z-penguin after GIM

# ZFITTER\* + CKMfitter†

ZFITTER includes SM purely **EW**, **QED** & **QCD** radiative effects needed to extract pseudo observables (POs)  $R_b^0$ ,  $A_b$  &  $A_{FB}^{0,b}$  in model-independent fashion

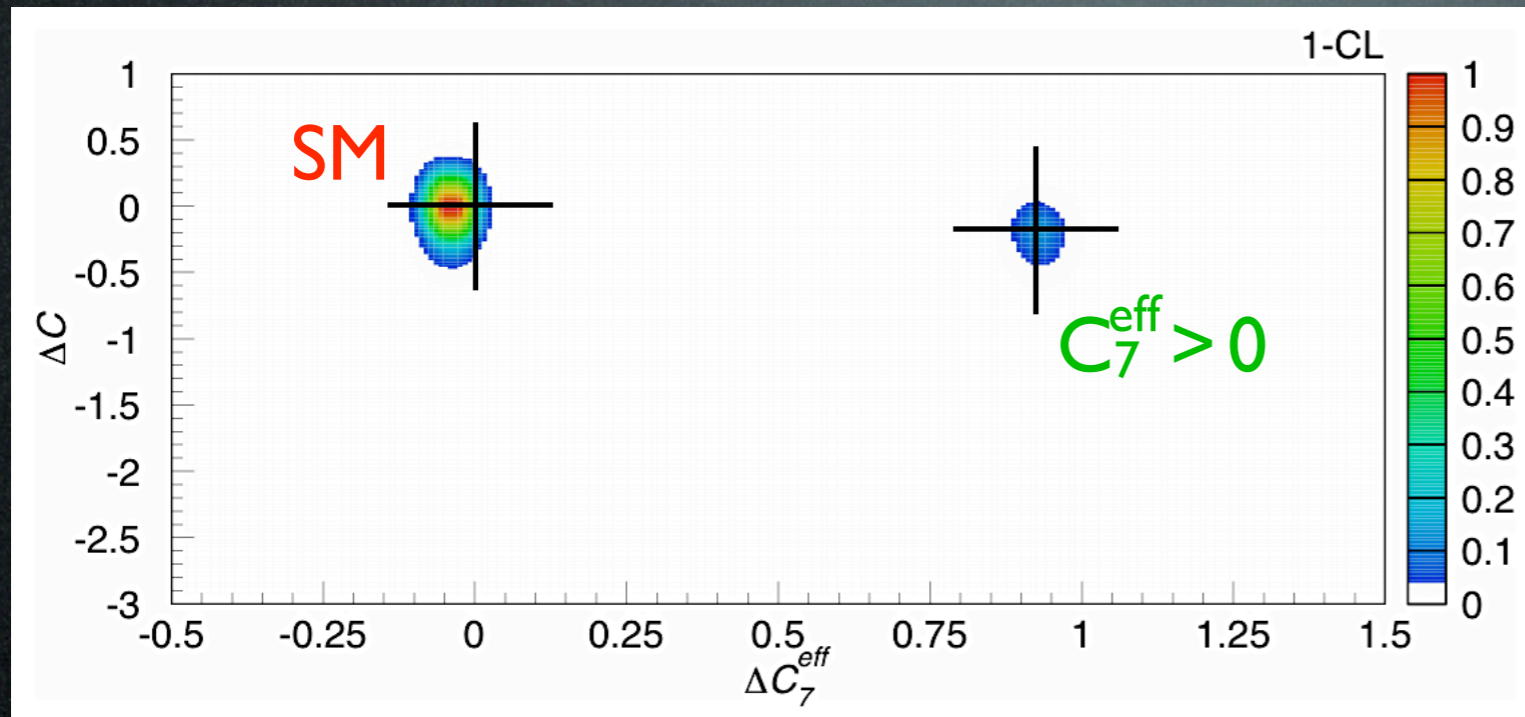
Routines for calculation of POs  $R_b^0$ ,  $A_b$ ,  $A_{FB}^{0,b}$ , &  $B(\bar{B} \rightarrow X_s \gamma)$ ,  $B(\bar{B} \rightarrow X_s l^+ l^-)$  called by CKMfitter to derive “personal believe unbiased” CLs using frequentist approach Rfit

meaning of experiment & theory remains distinct

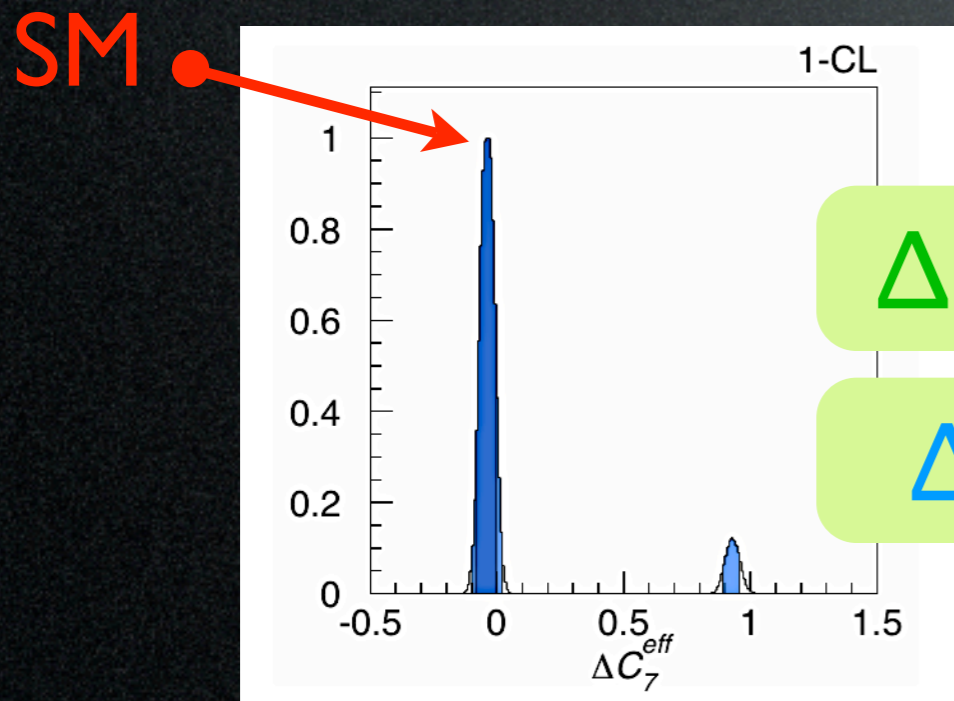
\*Bardin et al. '99, Arbuzov et al. '05

†Charles et al. '04

# $\Delta C_7^{\text{eff}}$ vs. $\Delta C$ from POs & $\bar{B} \rightarrow X_s \gamma, l^+ l^-$

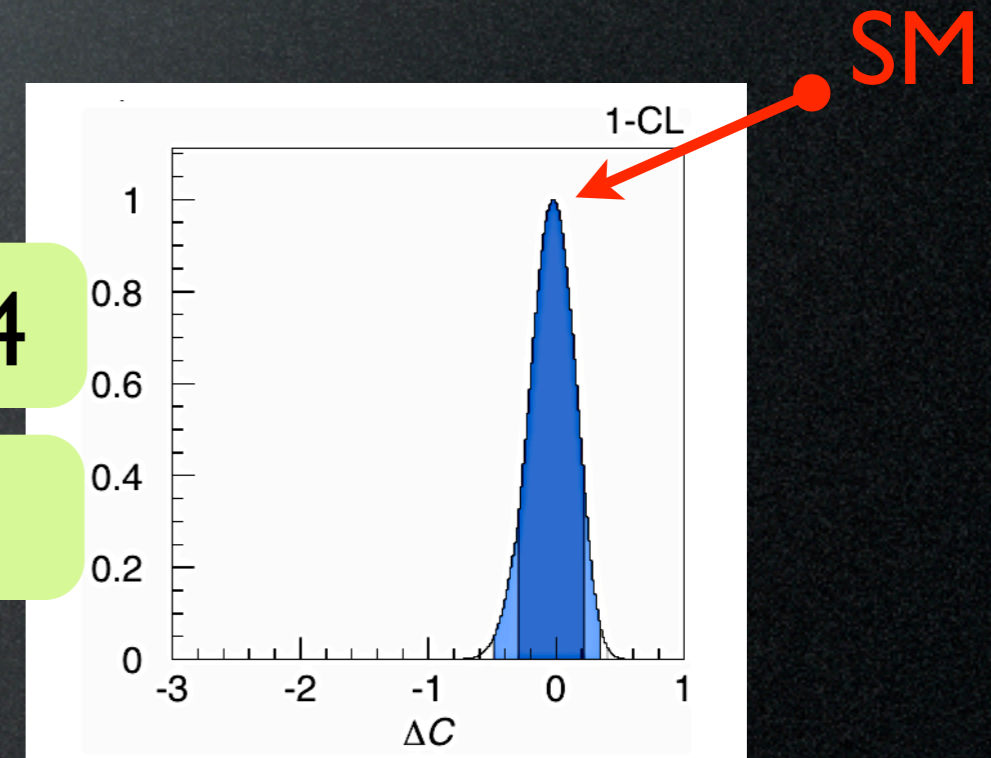


results don't depend  
on assumptions  $\Delta B$   
 $= 0$  &  $|\Delta D| \leq |D_{\text{SM}}|^*$



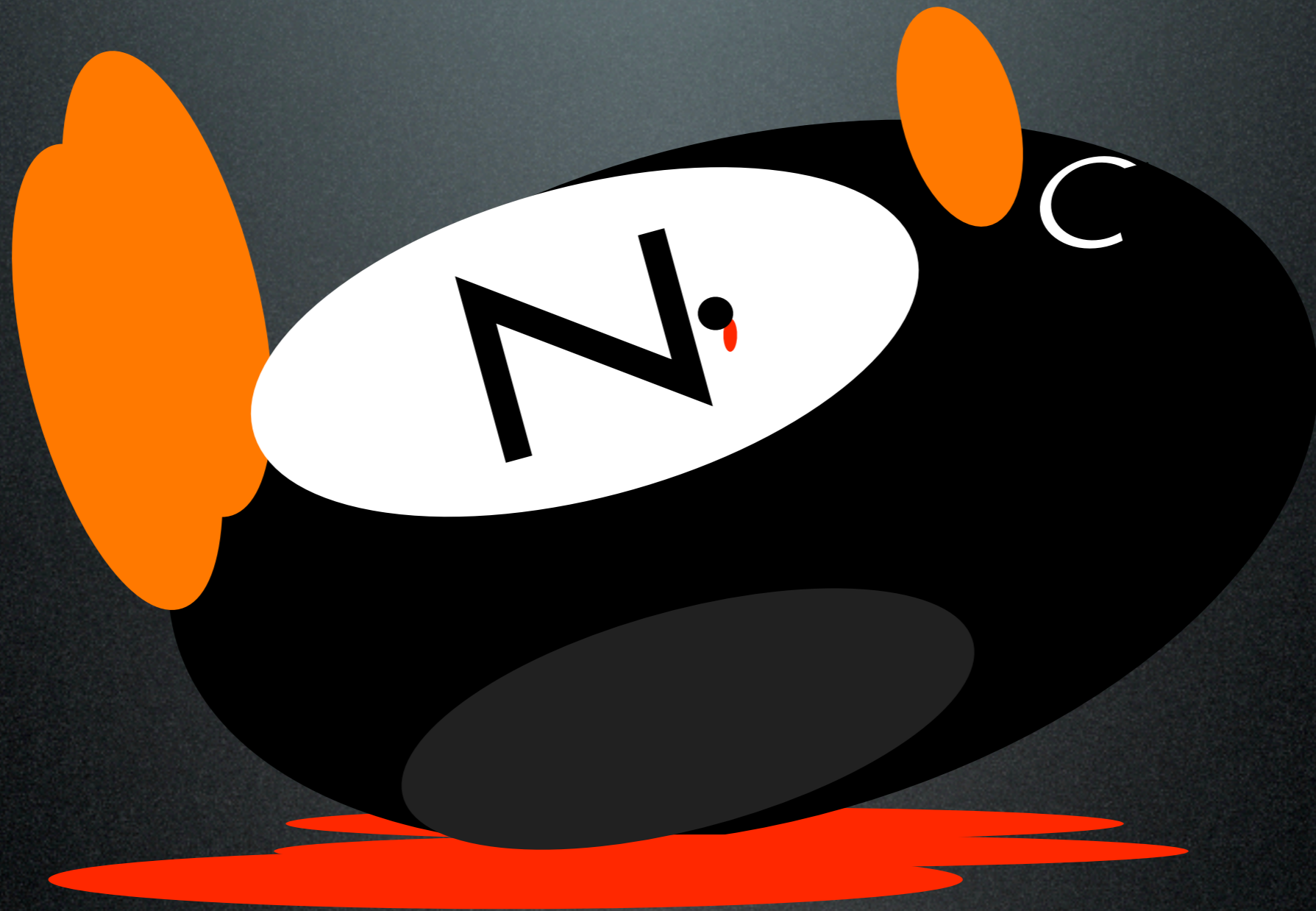
$$\Delta C_7^{\text{eff}} = -0.04 \pm 0.04$$

$$\Delta C = -0.04 \pm 0.27$$

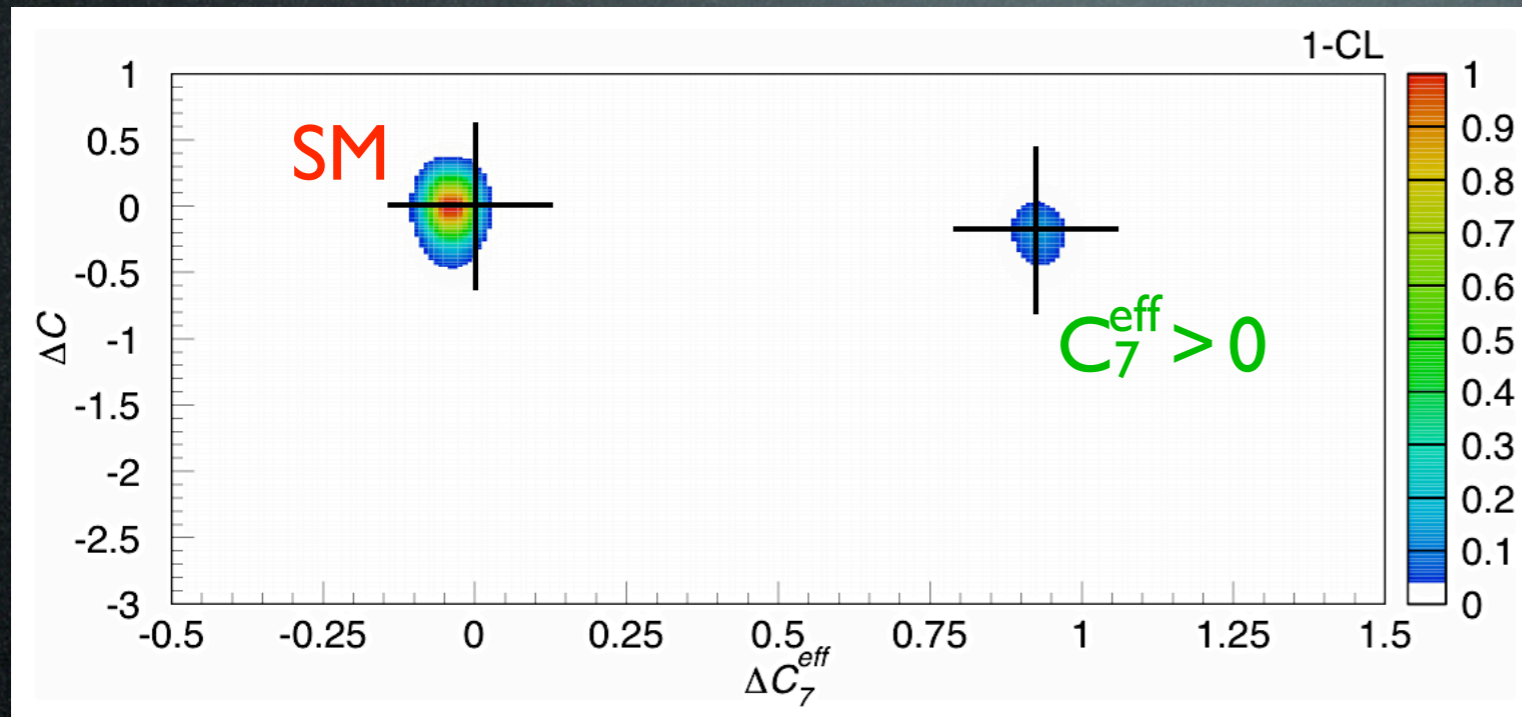


\*results obtained assuming  $\delta C = \pm 10\%$

R.I.P. Large Destructive CMFV Z-Penguin!



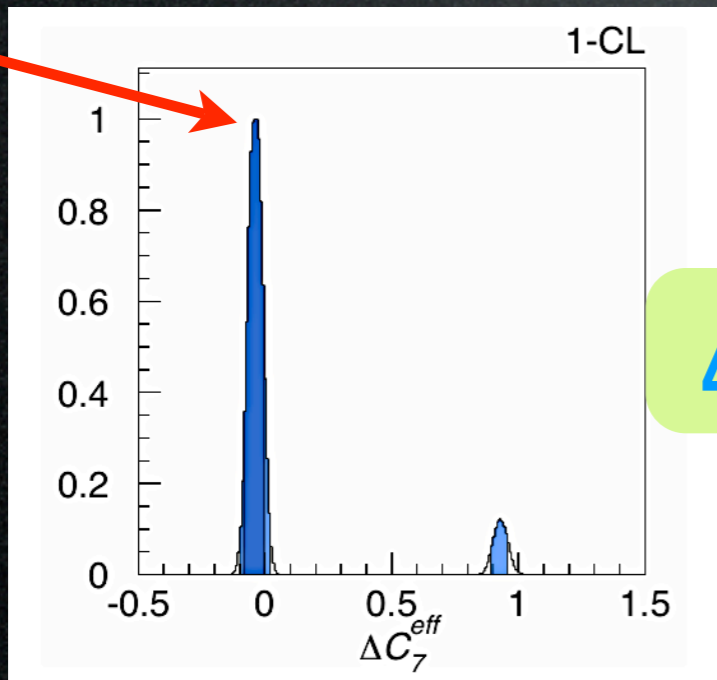
# 2007: $\Delta C$ from POs



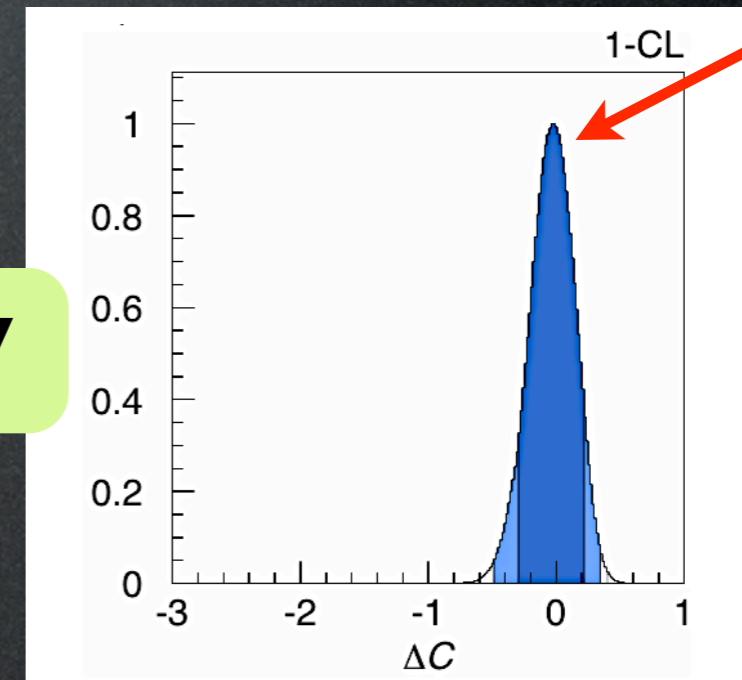
results **don't** depend  
on assumptions  $\Delta B$   
 $= 0$  &  $|\Delta D| \leq |D_{\text{SM}}|$

SM

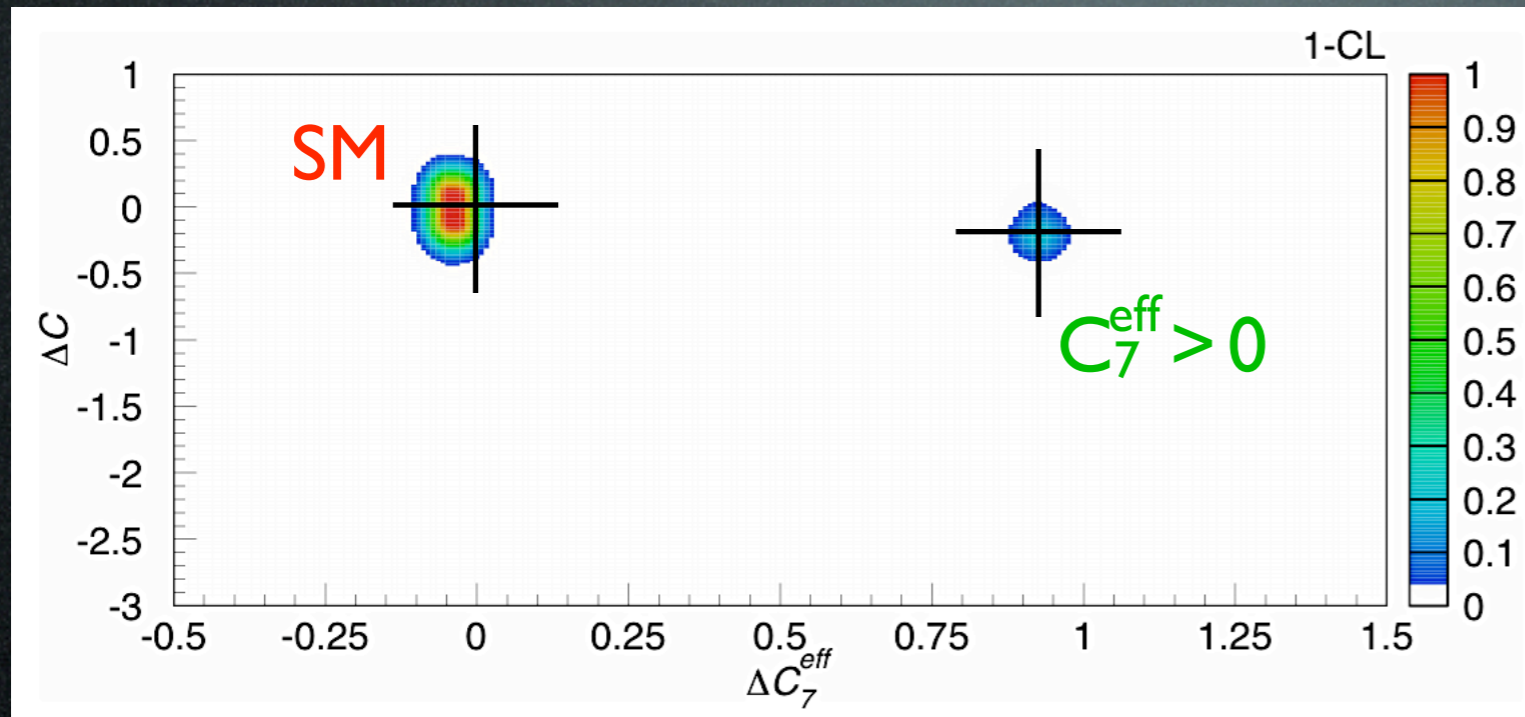
SM



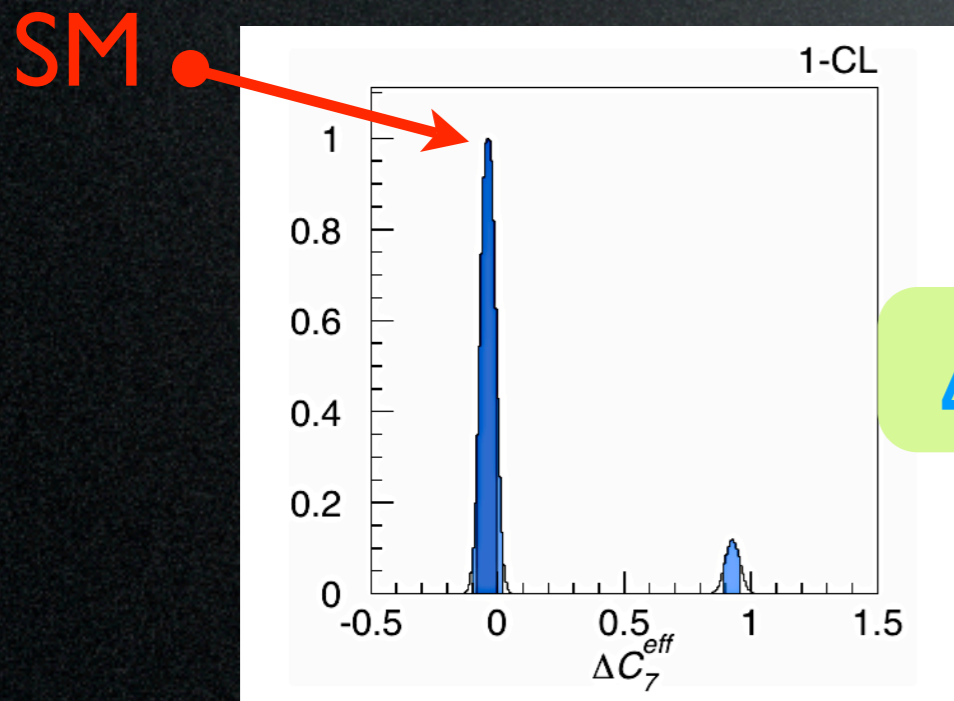
$$\Delta C = -0.04 \pm 0.27$$



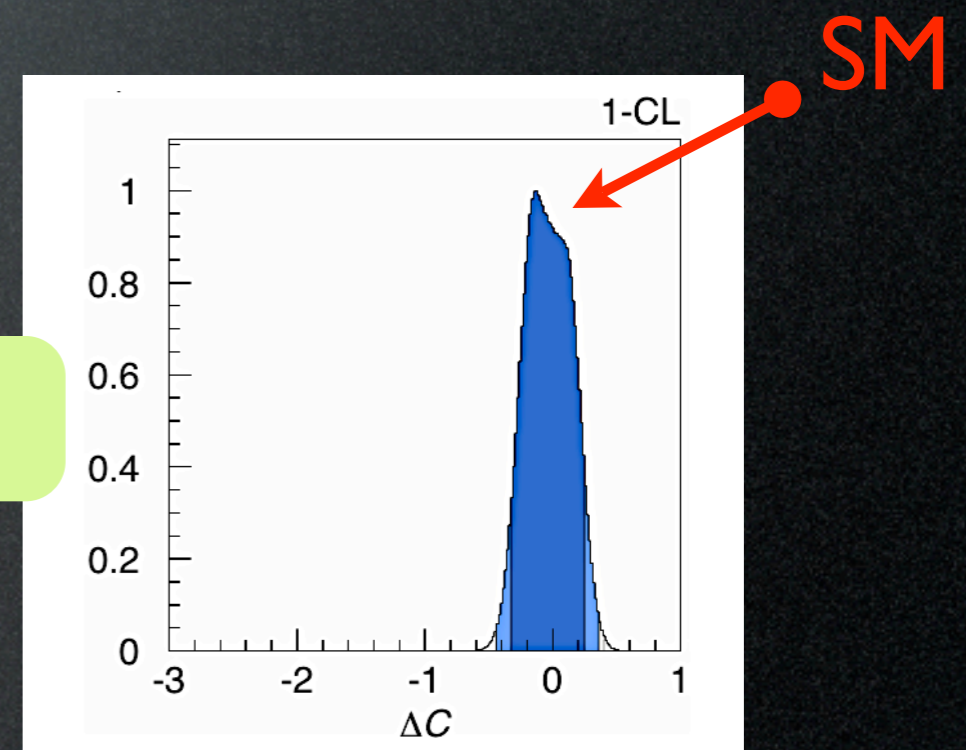
# 2015 (?): $\Delta C$ from $K^+ \rightarrow \pi^+ \nu \bar{\nu}^*$



results **do** depend  
on assumptions  $\Delta B$   
 $= 0$  &  $|\Delta D| \leq |D_{\text{SM}}|$



$$\Delta C = -0.03 \pm 0.29$$



\*assuming a 10% measurement of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  close to SM prediction

# Lower & Upper CMFV Bounds\*

Observable	CMFV (95% CL)	SM (95% CL)	Experiment
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \times 10^{11}$	[4.24, 11.09]	[5.46, 9.41]	$(14.7^{+13.0}_{-8.9})$
$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \times 10^{11}$	[1.56, 4.56]	[2.24, 3.59]	$< 2.1 \times 10^4$ (90% CL)
$\mathcal{B}(K_L \rightarrow \mu^+ \mu^-)_{\text{SD}} \times 10^9$	[0.30, 1.22]	[0.54, 0.88]	—
$\mathcal{B}(\bar{B} \rightarrow X_d \nu \bar{\nu}) \times 10^6$	[0.77, 2.00]	[1.24, 1.45]	—
$\mathcal{B}(\bar{B} \rightarrow X_s \nu \bar{\nu}) \times 10^5$	[1.88, 4.86]	[3.06, 3.48]	$< 64$ (90% CL)
$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) \times 10^{10}$	[0.36, 2.03]	[0.87, 1.27]	$< 3.0 \times 10^2$ (95% CL)
$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) \times 10^9$	[1.17, 6.67]	[2.92, 4.13]	$< 9.3 \times 10^1$ (95% CL)

CMFV deviations now strongly bounded from both sides

Violation of **lower** & **upper** bounds could signal additional flavor & CP violation || new operators || sizable box effects

\*assuming  $\Delta B^{\nu\nu} = \Delta B^{\text{ll}} = 0$

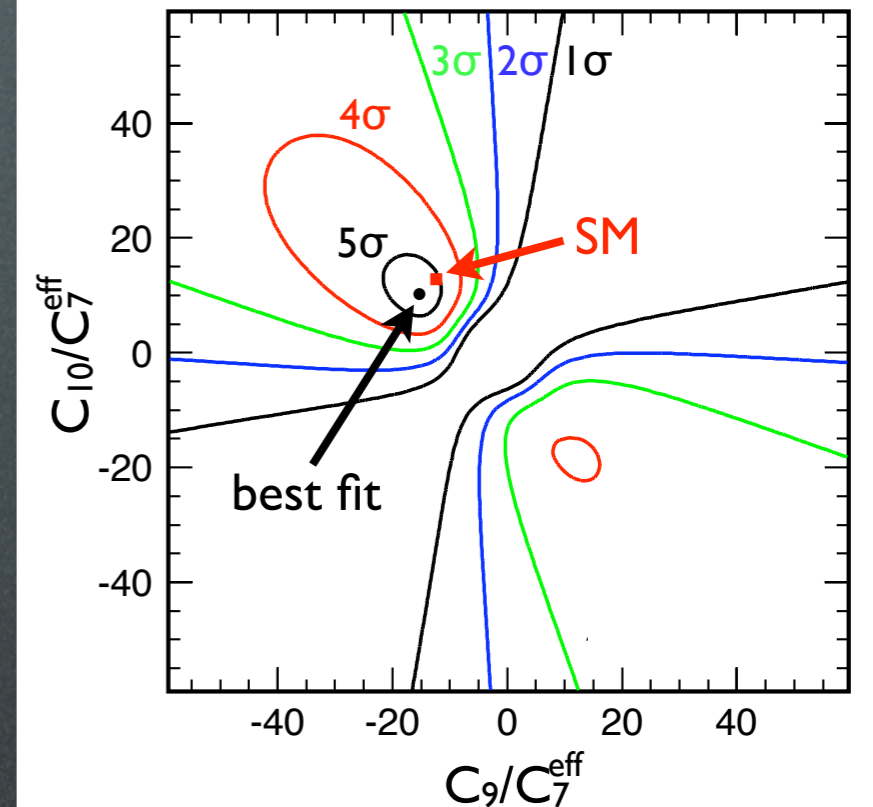
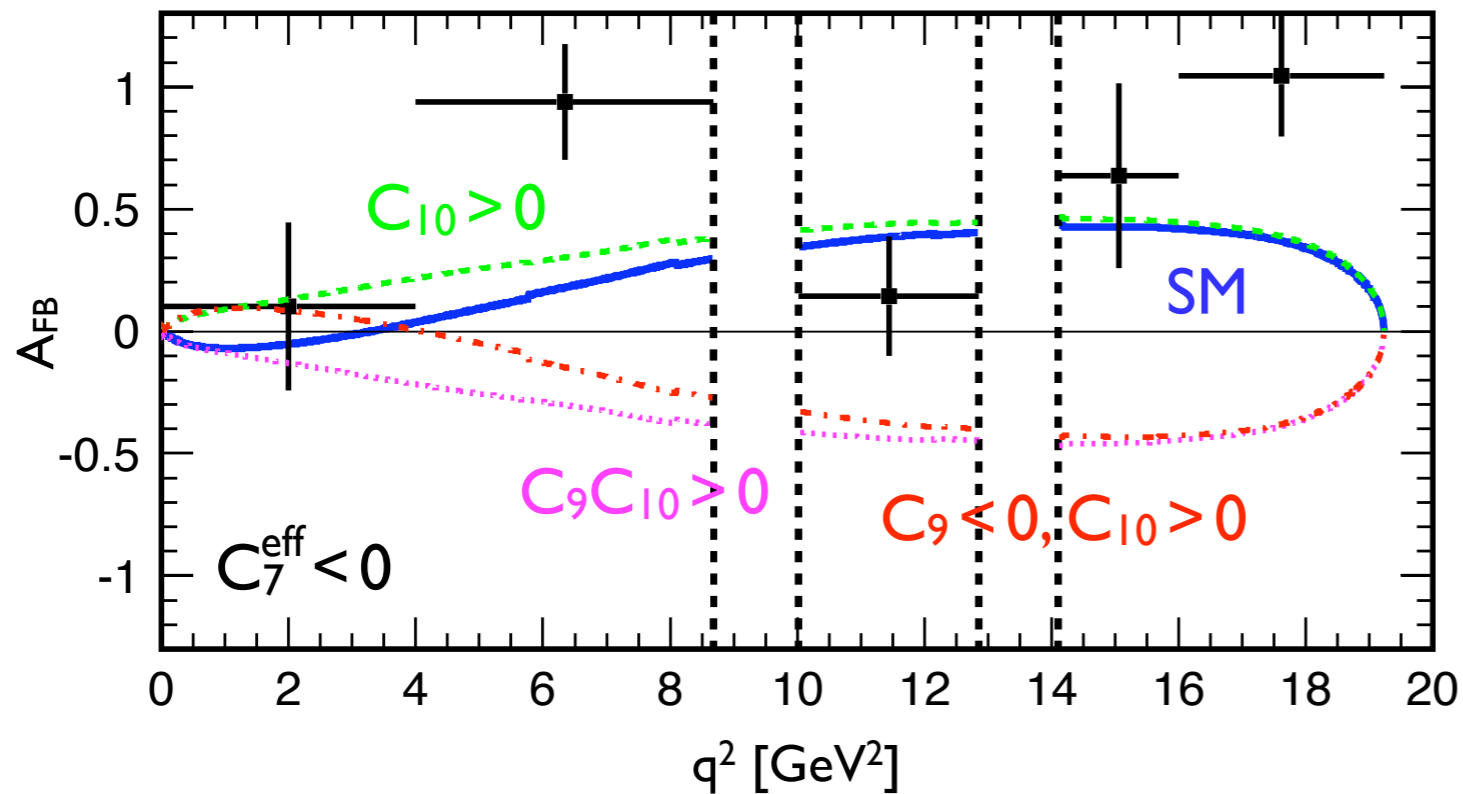
# Conclusions & Outlook

- Large CMFV contributions to  $Z \rightarrow d_{iL} \bar{d}_{jL}$  excluded by LEP and SLC measurements of POs  $R_b^0, A_b$  &  $A_{FB}^{0,b}$
- Are there other correlations in quark sector?  
 $b \rightarrow s\gamma$  vs.  $b \rightarrow b\gamma^*, \dots$
- Are there correlations in lepton sector assuming minimal lepton flavor violation?  
 $\mu \rightarrow e\gamma$  vs.  $(g-2)_\mu^*, \dots$
- Despite 5 meetings @ CERN<sup>†</sup> interplay between flavor & collider physics largely unexplored

\*these probably don't work

<sup>†</sup><http://mlm.home.cern.ch/mlm/FlavLHC.html>

# $\Delta C$ from $\bar{B} \rightarrow K^* l^+ l^-$



- FB asymmetry in  $\bar{B} \rightarrow K^* l^+ l^-$  excludes  $C_9 C_{10} > 0$  at 95% CL\*

- Hints towards exclusion of large destructive Z-penguin:  $|\Delta C| \lesssim 1.5$

# $\Delta C_7^{\text{eff}}$ vs. $\Delta C$ : Fit Input

\*

Observable	Result	$R_b^0$	$\mathcal{A}_b$	$A_{\text{FB}}^{0,b}$
$R_b^0$	$0.21629 \pm 0.00066$	1.00	$-0.08$	$-0.10$
$\mathcal{A}_b$	$0.923 \pm 0.020$		1.00	0.06
$A_{\text{FB}}^{0,b}$	$0.0992 \pm 0.0016$			1.00

†

Observable	Experiment
$\mathcal{B}(\bar{B} \rightarrow X_s \gamma) \times 10^4$	$3.55 \pm 0.26$
$\mathcal{B}(\bar{B} \rightarrow X_s l^+ l^-) \times 10^6$	$1.60 \pm 0.51$

\*S. Schael et al. '06

†HFAG '06

# Quick Estimate: $\Delta C$ from $\epsilon_b$

\*

$$\Gamma_{\mu}^{Zb\bar{b}} = \left( \sqrt{2} G_F M_Z^2 \right)^{\frac{1}{2}} \left( g_V^b \gamma_{\mu} - g_A^b \gamma_{\mu} \gamma_5 \right)$$

$$\frac{g_V^b}{g_A^b} = \left( 1 - \frac{4s_d^2}{3} + \epsilon_b \right) (1 + \epsilon_b)^{-1}, \quad g_A^b = g_A^b (1 + \epsilon_b)$$

$$\Gamma_{\mu}^{Zb\bar{b}} = \frac{G_F}{\sqrt{2}} \frac{M_Z^2}{\pi^2} \frac{ec_W}{s_W} \gamma_{\mu} P_L C$$

$$\epsilon_b = -\frac{G_F}{\sqrt{2}} \frac{M_Z^2}{\pi^2} 2c_W^2 \text{Re } C$$

$$\Delta\epsilon_b = (4 \pm 25) \times 10^{-3}{}^{\dagger}$$



$$\Delta C \approx -0.04 \pm 0.26$$

$$\delta C = \pm 10\%$$

\*Altarelli, Barbieri & Caravaglios '93

<sup>†</sup>S. Schael et al. '06; experimental & theory error added linearly

# 68% CL SM Bounds on Rare Decays

Observable	SM (68% CL)	Experiment
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \times 10^{11}$	$7.32 \pm 1.38$	$(14.7_{-8.9}^{+13.0})$
$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \times 10^{11}$	$2.86 \pm 0.36$	$< 2.1 \times 10^4$ (90% CL)
$\mathcal{B}(K_L \rightarrow \mu^+ \mu^-)_{\text{SD}} \times 10^9$	$0.70 \pm 0.11$	—
$\mathcal{B}(\bar{B} \rightarrow X_d \nu \bar{\nu}) \times 10^6$	$1.34 \pm 0.05$	—
$\mathcal{B}(\bar{B} \rightarrow X_s \nu \bar{\nu}) \times 10^5$	$3.27 \pm 0.11$	$< 64$ (90% CL)
$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) \times 10^{10}$	$1.06 \pm 0.16$	$< 3.0 \times 10^2$ (95% CL)
$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) \times 10^9$	$3.51 \pm 0.50$	$< 9.3 \times 10^1$ (95% CL)

# Mini Review: 2HDM

FCNCs naturally suppressed by imposing  $Z_2$  symmetries

$$\phi_I \rightarrow -\phi_I^* \text{ \& } D_R \rightarrow -D_R$$

$$\mathcal{L}_{\text{Yukawa}}^{2\text{HDM}} = \bar{Q}_L Y_D D_R \phi_1 + \bar{Q}_L Y_U U_R (\phi_2)_c + \text{h.c.}$$

Type I ( $U_R \rightarrow -U_R$ ):

$$\phi_D = \phi_1 = \phi_2$$

$$\frac{y_b}{y_t} = \frac{m_b}{m_t}$$

Type II ( $U_R \rightarrow +U_R$ ):

$$\phi_D = \phi_1 \neq \phi_2 = \phi_U$$

$$\frac{y_b}{y_t} = \frac{m_b}{m_t} \frac{v_U}{v_D}$$

†

\*softly broken in  $V(\phi_1, \phi_2)$

†realized in MSSM

# Mini Review: MFV MSSM

Soft mass & tri-linear terms that are invariant under  $G_F$

$$\begin{aligned}\tilde{m}_{Q_L}^2 &= \tilde{m}^2 \left( a_1 \mathbf{1} + b_1 Y_U Y_U^\dagger + b_2 Y_D Y_D^\dagger + \dots \right) \\ \tilde{m}_{U_R}^2 &= \tilde{m}^2 \left( a_2 \mathbf{1} + b_5 Y_U Y_U^\dagger \right), \quad \tilde{m}_{D_R}^2 = \tilde{m}^2 \left( a_3 \mathbf{1} + b_6 Y_D Y_D^\dagger \right) \\ A_U &= A \left( a_4 \mathbf{1} + b_7 Y_D Y_D^\dagger \right) Y_U, \quad A_D = A \left( a_5 \mathbf{1} + b_8 Y_U Y_U^\dagger \right) Y_D\end{aligned}$$

For  $\tan\beta$  not too large terms in  $Y_D Y_D^\dagger$  can be dropped

Assumption of universality of soft mass and proportionality of tri-linear terms corresponds to  $b_i = 0^\dagger$

# Mini Review: MFV MSSM cont'd

Physical 6×6 squark masses after EW symmetry breaking

$$\tilde{M}_U^2 = \begin{pmatrix} \tilde{m}_{Q_L}^2 + Y_U Y_U^\dagger v_U + D_U^{LL} & (A_U - \mu Y_U \cot \beta) v_U \\ (A_U - \mu Y_U \cot \beta)^\dagger v_U & \tilde{m}_{U_R}^2 + Y_U Y_U^\dagger v_U + D_U^{RR} \end{pmatrix}$$
$$\tilde{M}_D^2 \stackrel{*}{=} \begin{pmatrix} \tilde{m}_{Q_L}^2 + D_D^{LL} & (A_D - \mu Y_D \tan \beta) v_D \\ (A_D - \mu Y_D \tan \beta)^\dagger v_D & \tilde{m}_{D_R}^2 + D_D^{RR} \end{pmatrix}$$

For  $b_i = 0^\dagger$  (s)quark mass matrices can be diagonalized simultaneously & tree-level FCNCs governed by CKM matrix appear only in chargino couplings (CMFV MSSM)

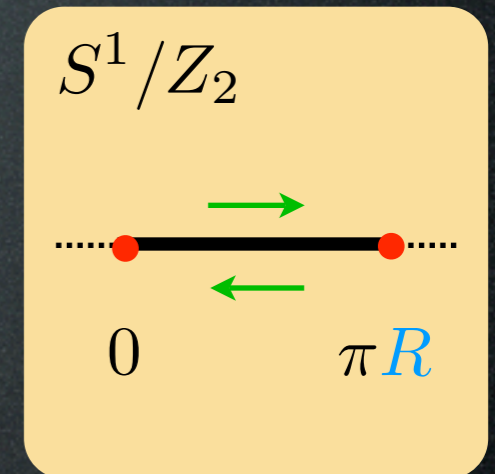
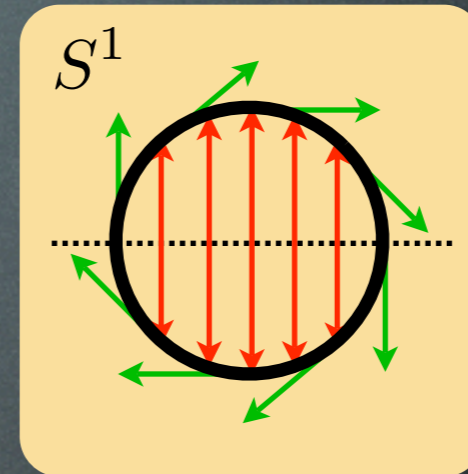
\* $Y_D Y_D^\dagger$  terms neglected

$^\dagger$  assumed here @ EW scale

# Mini Review: mUED Model\*

All SM fields promoted to bulk  
in  $D=4+1=5$

Compactify  $D=1$  to orbifold  
 $S^1/Z_2$  to allow for  $\psi_{L,R}$  in  $D=4$



Under  $y \rightarrow -y$  one has  $A^\mu(-y) = A^\mu(y)$  &  $A^5(-y) = -A^5(y)$

$$A^\mu(x, y) = A_{(0)}^\mu(x) + \sum_{k=1}^{\infty} A_{(k)}^\mu(x) \cos \frac{ky}{R}$$

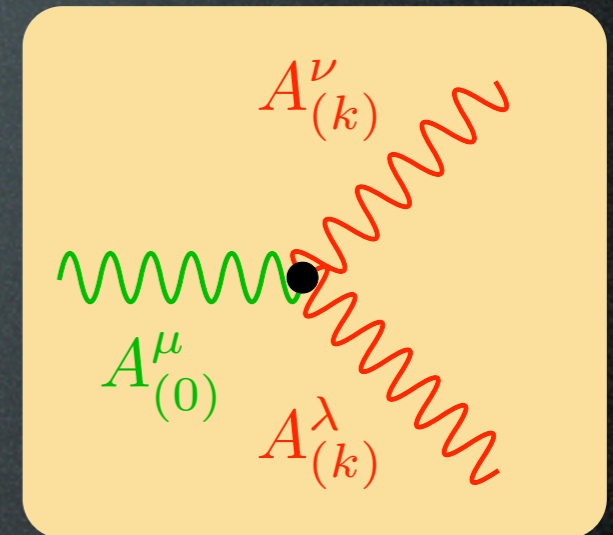
$$A^5(x, y) = \sum_{k=1}^{\infty} A_{(k)}^5(x) \sin \frac{ky}{R}$$

m	$A^\mu$	$A^5$
3/R	<u>k=3</u>	<u>k=3</u>
2/R	<u>k=2</u>	<u>k=2</u>
1/R	<u>k=1</u>	<u>k=1</u>
0	<u>k=0</u>	

\*Appelquist, Cheng & Dobrescu '01

# Mini Review: mUED Model cont'd

Translation invariance in  $y$  broken at fix points: remnant  $y \rightarrow y + \pi R$  leads to  $KK^*$ -parity  $(-1)^k$



Many similarities to MSSM:

$KK$ - vs.  $s$ particles,  $KK$ - vs.  $R$ -parity,  $LKP$  vs.  $LSP$ , bosonic extra  $D$  vs. fermionic extra  $D$ , ...

But:

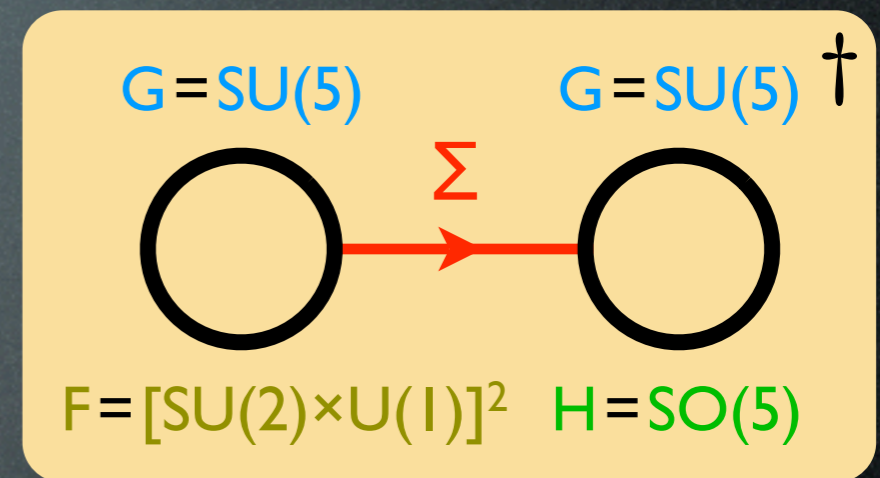
degenerate towers of  $KK$ -modes, same spin, only effective theory, UV completion needed for  $\Lambda \gg 1/R, \dots^\dagger$

\*Kaluza '21, Klein '26

$^\dagger$  boundary terms receive divergent radiative corrections

# Mini Review: LH Model

Higgs is pseudo Goldstone of spontaneously broken global symmetry  $G \rightarrow H$  at  $f \sim 1 \text{ TeV}^*$



Gauge couplings of  $F \rightarrow \text{SU}(2)_L \times \text{U}(1)_Y$  break  $G$  explicitly &  $V(\phi)$  generated radiatively

Higgs mass protected by collective symmetry breaking @ 1-loop, i.e., both gauge couplings of  $F$  need to be  $\neq 0$

Quadratic divergences cancelled by new heavy partners of SM particles:  $A_H, Z_H, W_H^\pm, T, \dots$

\*Arkani-Hamed, Cohen & Georgi '01

$^\dagger$ Arkani-Hamed et al. '02

# Mini Review: LHT Model

In LH  $SU(2)_c$  broken @ tree-level & large corrections to  $\rho$  parameter and POs arise implying  $f \gtrsim 2-4 \text{ TeV}$

$T$ -parity = “discrete symmetry exchanging two gauge factors of  $[SU(2) \times U(1)]^2$ ”\*

SM particles & top partner  $T_+$  are  $T$ -even,  $A_H, Z_H, W_H^\pm, \dots$  are  $T$ -odd; fermion spectrum has to be doubled<sup>†</sup>:  $T_-, u_H, \dots$

Again similarities to MSSM,  $T$ - vs.  $R$ -parity, LTP vs. LSP, ..., but only non-linearly realized effective theory valid up to  $\Lambda \sim 4\pi f \sim 10 \text{ TeV}$

\*Cheng & Low '03, Low '04

<sup>†</sup>to avoid large 4-fermion operators

# CMFV Hunting Strategy\*

determination of universal unitarity triangle from angles &  $\Delta M_{B_s}/\Delta M_{B_d}$

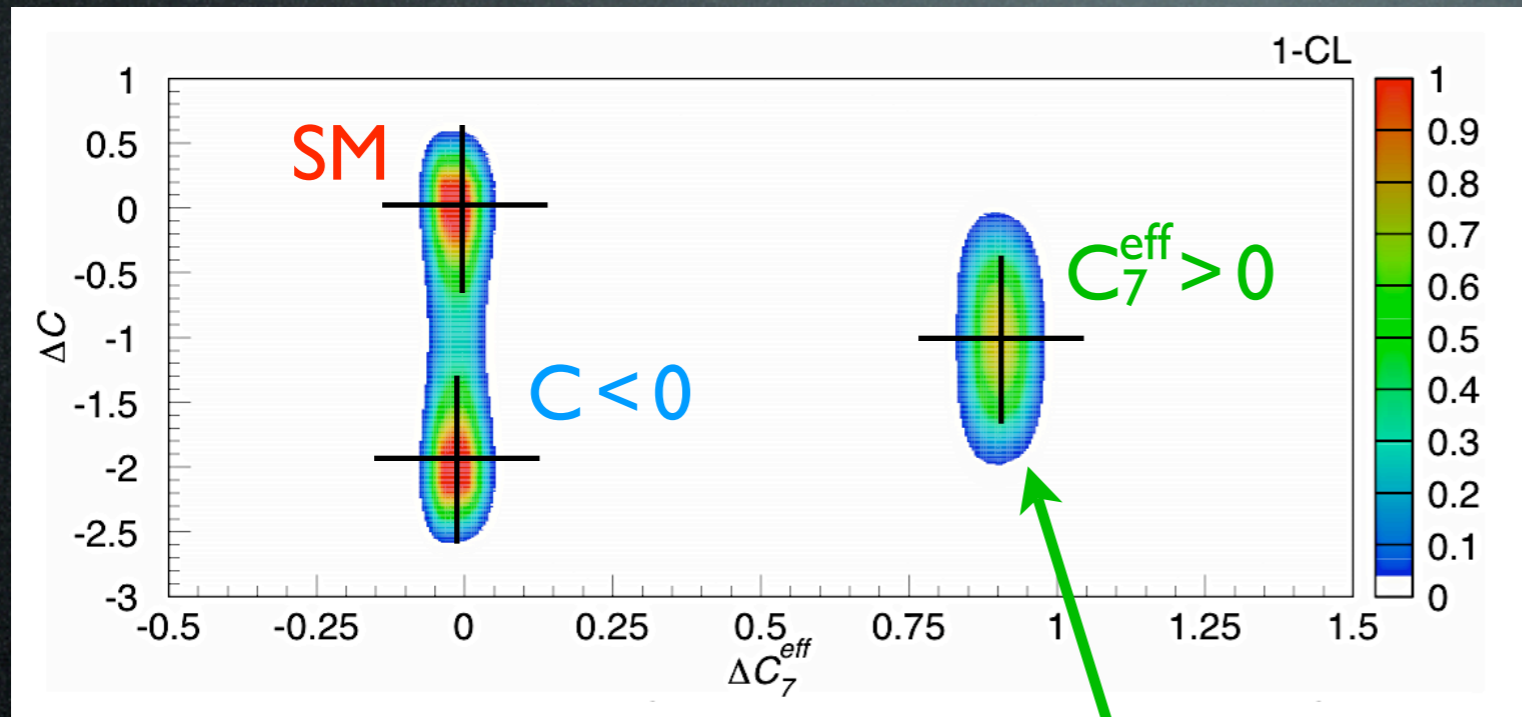
$$B(\bar{B} \rightarrow X_s \gamma) \propto |C_7^{\text{eff}}(\mu_b)|^2, B(\bar{B} \rightarrow X_s l^+ l^-) = f(C_7^{\text{eff}}(\mu_b), C_9(\mathbf{C}), C_{10}(\mathbf{C})) \text{ \& } B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = g(\mathbf{C})$$

bounds on  $\Delta C_7^{\text{eff}}(\mu_b)$  &  $\Delta \mathbf{C}$  from  $\bar{B} \rightarrow X_s \gamma$ ,  $\bar{B} \rightarrow X_s l^+ l^-$  &  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  data

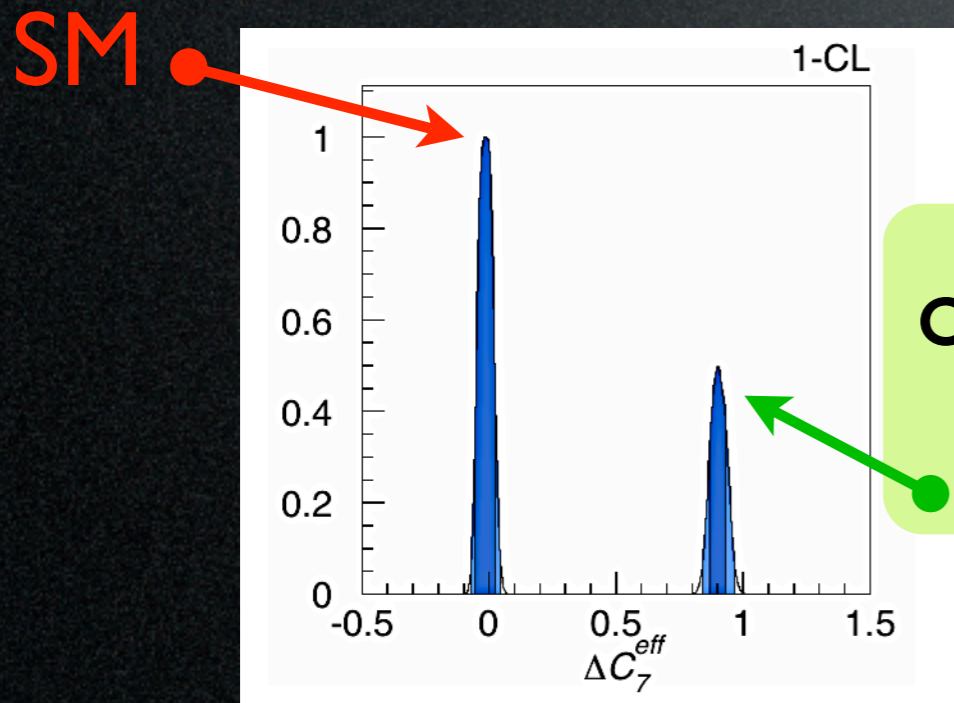
$$\begin{aligned} B(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{CMFV}} &< \dots \\ B(K_L \rightarrow \pi^0 \nu \bar{\nu})_{\text{CMFV}} &< \dots \\ B(K_L \rightarrow \mu^+ \mu^-)_{\text{CMFV}}^{\text{SD}} &< \dots \\ B(\bar{B} \rightarrow X_{d,s} \nu \bar{\nu})_{\text{CMFV}} &< \dots \\ B(B_{d,s} \rightarrow \mu^+ \mu^-)_{\text{CMFV}} &< \dots \end{aligned}$$

upper bounds!

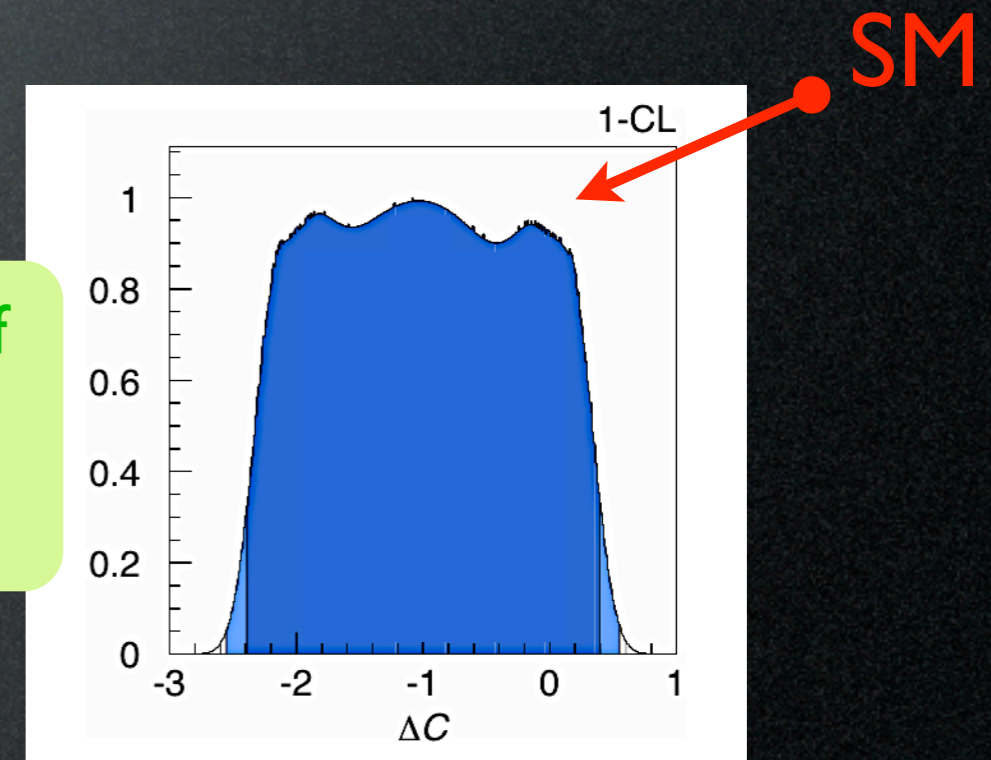
# $\Delta C_7^{\text{eff}}$ vs. $\Delta C$ from $\bar{B} \rightarrow X_s \gamma$ & $\bar{B} \rightarrow X_s l^+ l^-$



results depend on  
assumptions  $\Delta B = 0$   
&  $|\Delta D| \leq |D_{\text{SM}}|$



opposite sign  $C_7^{\text{eff}}$   
less likely\*



\*Gambino, Misiak & UH '04