D - $\bar{D}$ Mixing, Charm CP Violation and New Physics

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D-$\bar{D}$ Mixing and New Physics

D^0 - $\bar{D}^0$ Mixing Basics

Schrödinger equation describing D^0 - $\bar{D}^0$ mixing:

$$i\partial_t \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(M + \frac{i}{2}\Gamma \right) \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

Three physical mixing parameter:

$$|M_{12}| \ , \ \ |\Gamma_{12}| \ , \ \ \phi_{12} = -\text{arg}\left(\frac{M_{12}}{\Gamma_{12}} \right)$$

Eigenstates D_1 and D_2 are linear combinations of D^0 and $\bar{D}^0$

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \quad , \quad \frac{q}{p} = \sqrt{\frac{{M_{12}}^* - \frac{i}{2}{\Gamma_{12}}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \quad , \quad \phi = \text{Arg}(q/p)$$

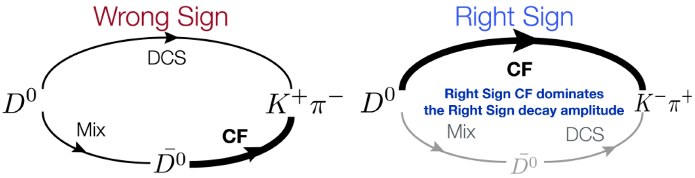
If CP is conserved, then $\phi = 0$ and $|q/p| = 1$

CP Conserving Observables

- normalized mass and width differences

$$x = \frac{\Delta M_D}{\Gamma_D} = 2\tau_D \,\mathrm{Re}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right] \,,\quad y = \frac{\Delta\Gamma_D}{2\Gamma_D} = -2\tau_D \,\mathrm{Im}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right]$$

- experimentally accessible through the
  time dependent ratio of wrong sign to right sign decay rates



$$R(t) \simeq R_D + \sqrt{R_D}\, y' \frac{t}{\tau_D} + \frac{1}{4}(x'^{\,2} + y'^{\,2})\frac{t^2}{\tau_D^2} \,,$$

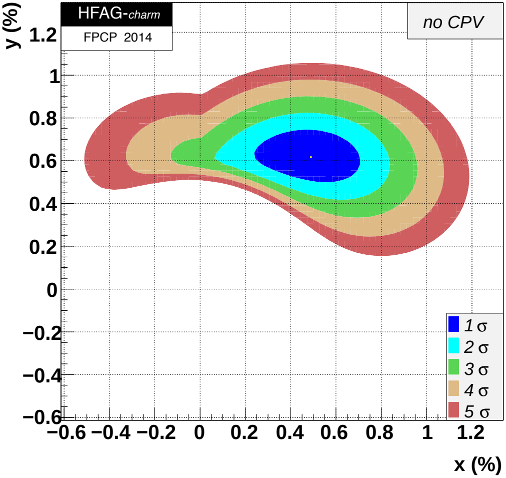
$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x' \\ y' \end{pmatrix}$$

- no mixing hypothesis $x = y = 0$ is excluded by $\gg 10\sigma$

- HFAG result for the mixing parameters

$$x = \left(0.49^{+0.14}_{-0.15}\right)\ \%$$

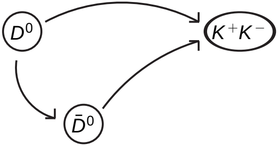
$$y = (0.62 \pm 0.08)\ \%$$



CP Violating Observables (example)

- effective lifetime differences in decays to final CP eigenstates f

$$\Gamma(D^0 \to f) \propto \exp\left[-\hat{\Gamma}_{D^0\to f}\, t\right] \quad , \quad \Gamma(\bar{D}^0 \to f) \propto \exp\left[-\hat{\Gamma}_{\bar{D}^0\to f}\, t\right]$$



$$A_\Gamma = \frac{1}{2\Gamma_D}\left(\hat{\Gamma}_{D^0\to f} - \hat{\Gamma}_{\bar{D}^0\to f}\right)$$

$$\eta_f^{CP} A_\Gamma \simeq \frac{x}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\phi - \frac{y}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\phi \; + \; \text{small contribution from direct CPV}$$

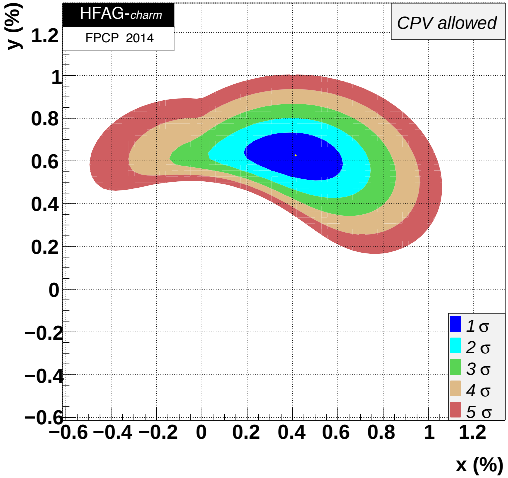
CPV in interference — CPV in mixing

Experimental Status

- no mixing hypothesis $x = y = 0$ is excluded by $\gg 10\sigma$
- HFAG results

$$x = \left(0.41^{+0.14}_{-0.15}\right)\ \%$$

$$y = \left(0.63^{+0.07}_{-0.08}\right)\ \%$$



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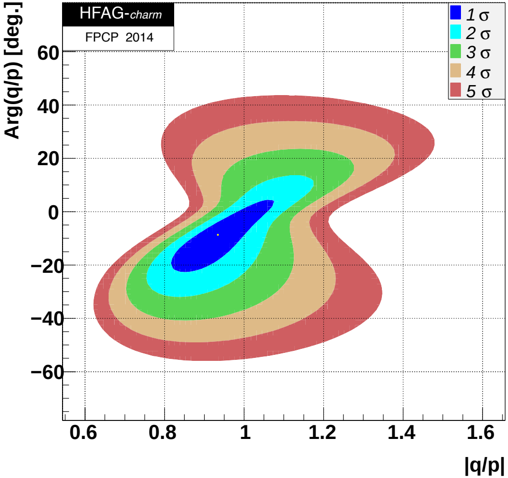
$$x = \left(0.41^{+0.14}_{-0.15}\right)\ \%$$

$$y = \left(0.63^{+0.07}_{-0.08}\right)\ \%$$

- no evidence for CPV
- $|q/p| = 1$ and $\phi = 0$ is consistent with the data

$$1 - |q/p| = 0.07^{+0.08}_{-0.09}$$

$$\phi = \text{Arg}(q/p) = -8.7^\circ\ {}^{+8.7^\circ}_{-9.1^\circ}$$

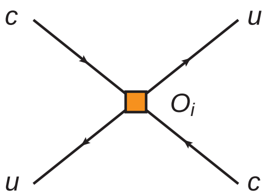


allowing for direct CPV in DCS decays

Contributions from short distance new physics can be described by an effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = \sum_{i=1}^{5} \frac{C_i}{\Lambda_{\text{NP}}^2} O_i + \sum_{i=1}^{3} \frac{\tilde{C}_i}{\Lambda_{\text{NP}}^2} \tilde{O}_i$$

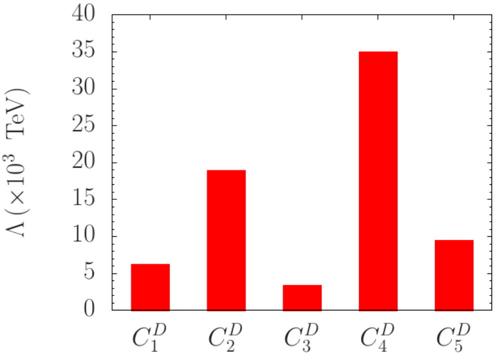
$$O_1 = (\bar{u}_\alpha \gamma_\mu P_L c_\alpha)(\bar{u}_\beta \gamma^\mu P_L c_\beta)$$
$$O_2 = (\bar{u}_\alpha P_L c_\alpha)(\bar{u}_\beta P_L c_\beta)$$
$$O_3 = (\bar{u}_\alpha P_L c_\beta)(\bar{u}_\beta P_L c_\alpha)$$
$$O_4 = (\bar{u}_\alpha P_L c_\alpha)(\bar{u}_\beta P_R c_\beta)$$
$$O_5 = (\bar{u}_\alpha P_L c_\beta)(\bar{u}_\beta P_R c_\alpha)$$



first unquenched lattice QCD results
for the hadronic matrix elements are now available

(Carrasco et al. '14)

$\mathrm{Im}(C_i) = 1$



Carrasco et al. '14

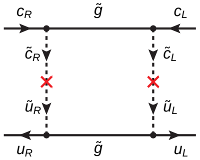
(assuming SM contribution is negligible)

the experimental results on CP violation in $D - \bar{D}$ mixing can set bounds on the scale Λ_{NP} of generic new physics with O(1) up-charm mixing at the level of several 10,000 TeV

$\rightarrow$ New Physics Flavor Problem

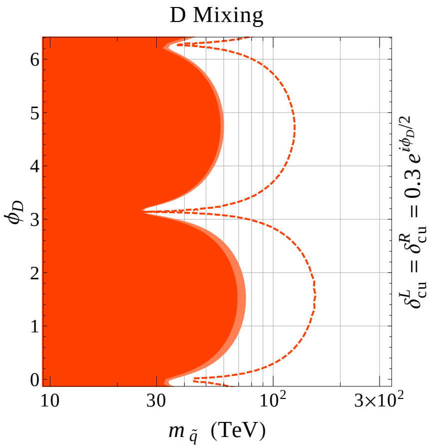
Implications for the MSSM

Example: Mini-Split SUSY framework: $m_{\text{sfermions}} \sim 16\pi^2 m_{\text{gauginos}}$



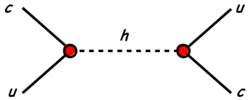
$$M_{12}^D \propto \frac{\alpha_s^2}{m_{\tilde{q}}^2} \, (\delta_{cu}^L \delta_{cu}^R)$$

- contributions depend to an excellent approximation only on the squark masses
- scales of O(50 TeV) can be probed for O(1) phases
- experimental bounds on CPV in charm mixing can still improve (LHCb and Belle II)



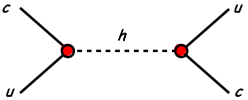
WA, Harnik, Zupan ’13

many NP models contain flavor violating Higgs couplings: $\mathcal{L}_{\text{eff}} \supset c_{ij} \bar{u}_L^i u_R^j \, h$



Operator	Eff. couplings	95% C.L. Bound		Observables
		$\lvert c_{\rm eff}\rvert$	$\lvert{\rm Im}(c_{\rm eff})\rvert$	
$(\bar s_R\, d_L)(\bar s_L d_R)$	$c_{sd}\ c_{ds}^*$	1.1×10^{-10}	4.1×10^{-13}	$\Delta m_K;\ \epsilon_K$
$(\bar s_R\, d_L)^2,\ \ (\bar s_L d_R)^2$	$c_{ds}^2,\ \ c_{sd}^2$	2.2×10^{-10}	0.8×10^{-12}	
$(\bar c_R\, u_L)(\bar c_L u_R)$	$c_{cu}\ c_{uc}^*$	0.9×10^{-9}	1.7×10^{-10}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar c_R\, u_L)^2,\ \ (\bar c_L u_R)^2$	$c_{uc}^2,\ \ c_{cu}^2$	1.4×10^{-9}	2.5×10^{-10}	
$(\bar b_R\, d_L)(\bar b_L d_R)$	$c_{bd}\ c_{db}^*$	0.9×10^{-8}	2.7×10^{-9}	$\Delta m_{B_d};\ S_{B_d\to\psi K}$
$(\bar b_R\, d_L)^2,\ (\bar b_L d_R)^2$	$c_{db}^2,\ \ c_{bd}^2$	1.0×10^{-8}	3.0×10^{-9}	
$(\bar b_R\, s_L)(\bar b_L s_R)$	$c_{bs}\ c_{sb}^*$	2.0×10^{-7}	2.0×10^{-7}	Δm_{B_s}
$(\bar b_R\, s_L)^2,\ (\bar b_L s_R)^2$	$c_{sb}^2,\ \ c_{bs}^2$	2.2×10^{-7}	2.2×10^{-7}	

Blankenburg, Ellis, Isidori ’12; Harnik, Kopp, Zupan ’12 many NP models contain flavor violating Higgs couplings: $\mathcal{L}_{\text{eff}} \supset c_{ij} \bar{u}_L^i u_R^j \, h$



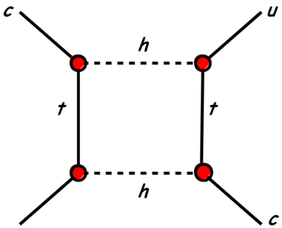
$D - \bar{D}$ mixing sets strong constraints

Operator	Eff. couplings	95% C.L. Bound		Observables
		$\|c_{\text{eff}}\|$	$\|\text{Im}(c_{\text{eff}})\|$	
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	$c_{sd}\ c_{ds}^*$	1.1×10^{-10}	4.1×10^{-13}	Δm_K; ϵ_K
$(\bar{s}_R d_L)^2$, $(\bar{s}_L d_R)^2$	c_{ds}^2, c_{sd}^2	2.2×10^{-10}	0.8×10^{-12}	
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	$c_{cu}\ c_{uc}^*$	0.9×10^{-9}	1.7×10^{-10}	Δm_D; $\|q/p\|, \phi_D$
$(\bar{c}_R u_L)^2$, $(\bar{c}_L u_R)^2$	c_{uc}^2, c_{cu}^2	1.4×10^{-9}	2.5×10^{-10}	
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	$c_{bd}\ c_{db}^*$	0.9×10^{-8}	2.7×10^{-9}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_R d_L)^2$, $(\bar{b}_L d_R)^2$	c_{db}^2, c_{bd}^2	1.0×10^{-8}	3.0×10^{-9}	
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	$c_{bs}\ c_{sb}^*$	2.0×10^{-7}	2.0×10^{-7}	Δm_{B_s}
$(\bar{b}_R s_L)^2$, $(\bar{b}_L s_R)^2$	c_{sb}^2, c_{bs}^2	2.2×10^{-7}	2.2×10^{-7}	

Blankenburg, Ellis, Isidori '12; Harnik, Kopp, Zupan '12

Implications for Higgs Couplings (II)

top-up-Higgs and top-charm-Higgs couplings can also lead to $D - \bar{D}$ mixing at the loop level



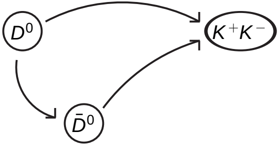
$$\sqrt{|\mathrm{Im}(Y_{tc}^* Y_{ut}^* Y_{tu} Y_{ct})|} \lesssim 4.1 \times 10^{-4}$$

(Gorbahn, Haisch '14)

Singly Cabibbo Suppressed D decays and New Physics

CPV in SCS D Decays: Basics

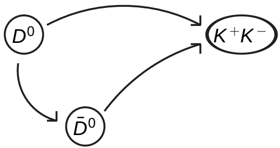
Time integrated CP asymmetries
in decays to final CP eigenstates



$$A_{\rm CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \simeq A_f^d + \frac{\langle t \rangle}{\tau_D} A_\Gamma$$

contributions from direct CPV and indirect CPV

Time integrated CP asymmetries
in decays to final CP eigenstates



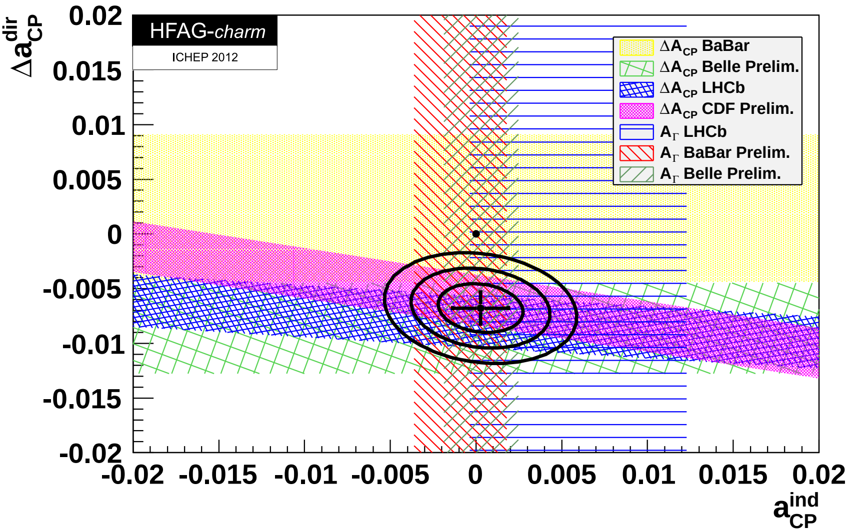
$$A_{\rm CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \simeq {\color{blue} A_f^d} + \frac{\langle t \rangle}{\tau_D} {\color{red} A_\Gamma}$$

contributions from direct CPV and indirect CPV

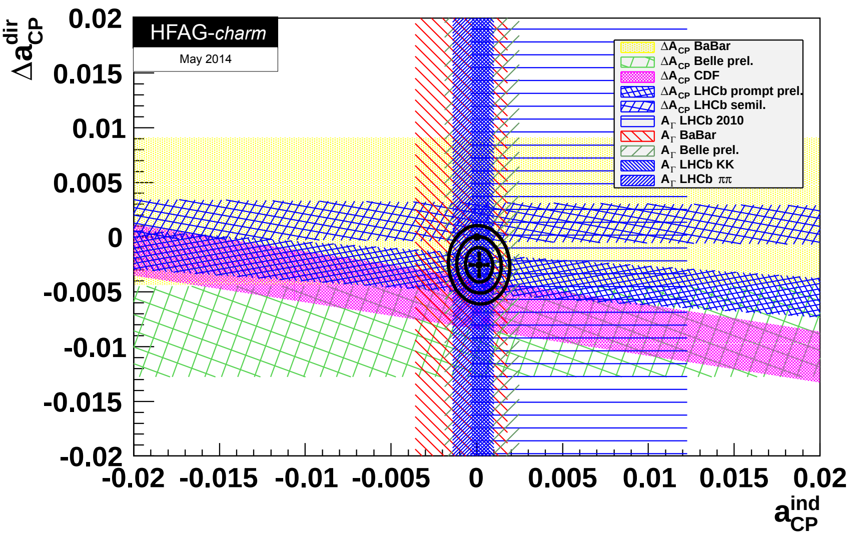
$$\Delta A_{\rm CP} = A_{\rm CP}(KK) - A_{\rm CP}(\pi\pi) \simeq A^d_{KK} - A^d_{\pi\pi} + \frac{\Delta\langle t \rangle}{\tau_D} A_\Gamma$$

indirect component (and experimental systematics!)
cancel to large extent in the difference of K^+K^- and $\pi^+\pi^-$ modes

Experimental Status (2012)



Experimental Status (2014)



Standard Model?

the latest HFAG average for direct CP violation reads

$$\Delta A_{\rm CP}^{\rm exp} = (-0.253 \pm 0.104)\%$$

(compatible with 0 at 2.5σ)

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naive SM estimate

$$\Delta A_{\rm CP}^{\rm SM} \sim \frac{\alpha_s}{\pi} \frac{V_{ub} V_{cb}^*}{V_{us} V_{cs}^*} \sim 10^{-4}$$

values as large as

$$\Delta A_{\rm CP}^{\rm SM} \sim \text{few} - \text{several} \times 10^{-3}$$

cannot be excluded in the SM

(Brod, Kagan, Zupan ’11; ...)

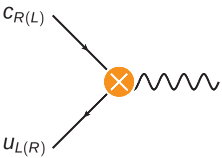
New Physics?

at the moment, new physics is not required by the data
(because the data is compatible with 0 at 2.5σ ...)

but new physics contributions are of course possible

most plausible candidate
for sizable NP contribution:
chromo-magnetic dipole
with $\Lambda_{\text{NP}} \sim 10$ TeV

$$\mathcal{H}_{\text{eff}} \supset \frac{m_c}{16\pi^2} \frac{1}{\Lambda_{\text{NP}}^2} (\bar{u}\sigma G P_{R/L} c)$$



Isidori, Kamenik, Ligeti, Perez ’11; ...

only weakly constrained by other flavor transitions
(in particular D-$\bar{D}$ mixing, ϵ'/ϵ, ...)

would also affect radiative D decays $D \to \rho\gamma$, $D \to \omega\gamma$, $D \to P^+P^-\gamma$
(Isidori, Kamenik ’12; Fajfer, Kosnik ’12; Lyon, Zwicky ’12)

ΔA_{CP} in New Physics Models

a large chromo-magnetic dipole can arise in various
motivated new physics scenarios

Supersymmetric models with flavor violation beyond MFV

(Giudice, Isidori, Paradisi '12; Hiller, Hochberg, Nir '12; Sala '13)

$$\Delta A_{CP}^{SUSY} \simeq 0.3\% \times \left(\frac{\text{Im}(A)}{3\tilde{m}} \right) \left(\frac{\theta_{12}}{0.3} \right) \left(\frac{1\text{TeV}}{\tilde{m}} \right)^2$$

Randall-Sundrum models or models with partial compositness

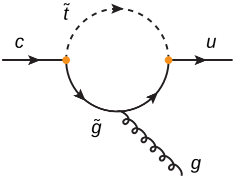
(Keren-Zur et al. '12; Delauney, Kamenik, Perez, Randall '12; Konig, Neubert, Straub '14)

$$\Delta A_{CP}^{RS} \simeq 0.6\% \times \left(\frac{\mathcal{O}_\beta}{0.1} \right) \left(\frac{Y_5}{4} \right)^2 \left(\frac{3\text{TeV}}{m_{KK}} \right)^2$$

effects of few$-$several $\times 10^{-3}$ can be obtained
with new physics at the TeV scale and
without the need for non-perturbative enhancements

Constraints on New Physics

bounds on squark mixing angles
in SUSY models with split families,
assuming stops and gluinos at 1TeV
and mixing of LH squarks CKM like



$$|W^R_{tu}| \lesssim 0.2$$

(neutron EDM gives slightly stronger bounds)

Sala '13

Constraints on New Physics

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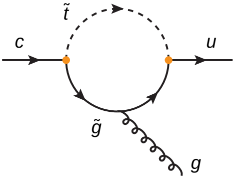
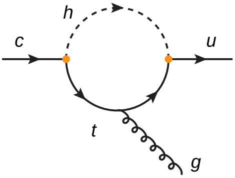
bounds on flavor violating
Higgs couplings





$$|W^R_{tu}| \lesssim 0.2$$

$$|\mathrm{Im}(Y^*_{ut} Y_{tc})| \lesssim 4 \times 10^{-4}$$

(neutron EDM gives slightly stronger bounds)

Sala '13

Gorbahn, Haisch '14

Summary

- charm mixing and decays are
  highly sensitive probes of New Physics
- combining the latest experimental results on charm mixing with the recent lattice results on the hadronic matrix elements allows to probe scales as high as 35,000 TeV
- translates e.g. into strong constraints on SUSY models or on flavor changing Higgs couplings
- ΔA_{CP} at the 1% level is possible in well motivated New Physics models, but experimental value is now compatible with 0 ...