Past, present, and future of CP violation

Ulrich Nierste

Karlsruhe Institute of Technology
Institute for Theoretical Particle Physics

Karlsruhe Institute of Technology

Federal Ministry of Education and Research

Flavour Physics Conference
XIII$^{\text{th}}$ Rencontres du Vietnam

1964: Discovery of CP violation in $K \to \pi\pi$ decays. The size of the effect is governed by the mass of the top quark (of which no one had a clue at the time).

$$m_t \approx 350 \times m_K$$

CP violating quantities probe mass scales far above the energy of the experiment!

1964: Discovery of CP violation in $K \to \pi\pi$ decays. The size of the effect is governed by the mass of the top quark (of which no one had a clue at the time).

$$m_t \approx 350 \times m_K$$

CP violating quantities probe mass scales far above the energy of the experiment!

Enough of the past,…

…the rest of the talk is about present and future.

Could history repeat itself?

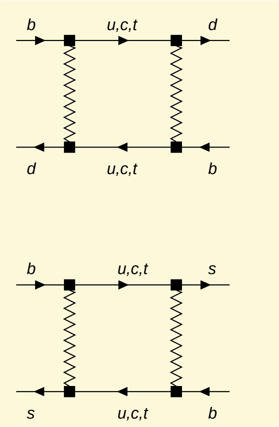
Why CP asymmetries may reveal virtual effects of new particles in the (multi-)TeV range:

- suppression of FCNC transitions by small CKM factors like $|V_{td}V_{tb}| \sim 9 \cdot 10^{-3}$, $|V_{td}V_{ts}| \sim 3 \cdot 10^{-4}$, is artifact of the Standard Model (SM) and absent in generic models of new physics,
- only one CP phase in Yukawa sector $\Rightarrow$ SM is very predictive,
- poorly calculable hadronic effects drop out from many CP asymmetries or can be eliminated by combining measurements.

Time-dependent CP asymmetries
(for $q = d$ or s):

$$A_{\rm CP}^{B_q\to f}(t) = \frac{S_f \sin(\Delta m_q t) - C_f \cos(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2) + A^f_{\Delta\Gamma_q} \sinh(\Delta\Gamma_q t/2)}$$

Δm_q: mass difference
$\Delta\Gamma_q$: width difference



The coefficients S_f, C_f, and $A^f_{\Delta\Gamma_q}$ encode the information on the decay amplitudes $A_f \equiv A(B_q \to f)$ and $\overline{A}_f \equiv A(\overline{B}_q \to \overline{f})$.

Golden mode: B decay into a CP eigenstate $f = f_{\rm CP}$ which only involves a single CKM factor ($\Rightarrow |A_{f_{\rm CP}}| = |\overline{A}_{f_{\rm CP}}|$ and $|\lambda_f| = 1$).

$$CP|f_{\rm CP}\rangle = \eta_{f_{\rm CP}}|f_{\rm CP}\rangle \qquad \text{with } \eta_{f_{\rm CP}} = \pm 1.$$

Time-dependent CP asymmetry:

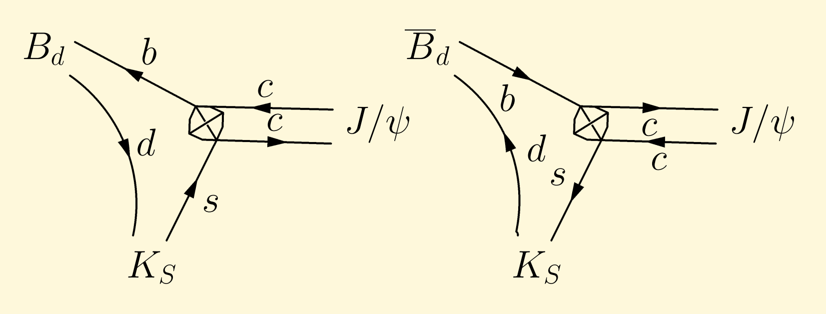
$$a_{f_{\rm CP}}(t) = -\frac{\mathrm{Im}\,\lambda_f \sin(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2) - \mathrm{Re}\,\lambda_f \sinh(\Delta\Gamma_q t/2)},$$

$\mathrm{Im}\,\lambda_f$ quantifies the CP violation in the interference between mixing and decay:

$$\begin{array}{ccc} B & \xrightarrow{q/p} & \bar{B} \\ A_f \searrow & & \swarrow \overline{A}_f \\ & f & \end{array}$$

Recall: $\lambda_f = \dfrac{q}{p}\dfrac{\overline{A}_f}{A_f}$

$B_d \to J/\psi K_S \quad \Rightarrow \quad |\bar{f}\rangle = -|f\rangle$ (CP-odd eigenstate)

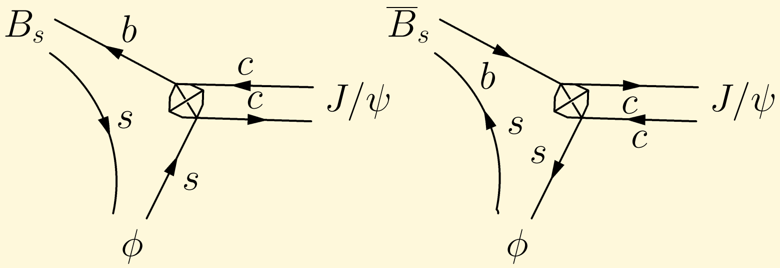


$$a_{J/\psi K_S}(t) \simeq -\sin(2\beta)\sin(\Delta m_d t),$$

where
$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

golden mode to measure the angle β of the unitarity triangle

$B_s \to (J/\psi\phi)_{L=0} \qquad \Rightarrow \qquad |\overline{f}\rangle = |f\rangle$ (CP-even eigenstate)



$$a_{(J/\psi\phi)_{L=0}}(t) = -\frac{\sin(2\beta_s)\sin(\Delta m_s t)}{\cosh(\Delta\Gamma_s t/2) - \cos(2\beta_s)\sinh(\Delta\Gamma_s t/2)},$$

where
$$\beta_s = \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right] \simeq \lambda^2\overline{\eta}$$

The decay amplitudes $A(B_{d,s} \to J/\psi X)$ are dominated by the CKM structure $V_{cb}V_{cs}^*$, but have a small contribution with $V_{ub}V_{us}^*$, called penguin pollution.

How golden are these modes?

$$S(B_q \to f) = \sin(\phi_q + \Delta\phi_q)$$

If one neglects $\lambda_u = V_{ub} V_{us}^*$ in the decay amplitude, $S(B_q \to f)$ measures ϕ_q with

$$\begin{aligned} B_d \to J/\psi K^0: &\qquad \phi_d = \ \ 2\beta \\ B_s \to J/\psi \phi: &\qquad \phi_s = -2\beta_s \end{aligned}$$

The penguin pollution $\Delta\phi_q$ is parametrically suppressed by $\epsilon \equiv \left| \frac{V_{us} V_{ub}}{V_{cs} V_{cb}} \right| = 0.02$.

$$\Delta S_{J/\psi K_S} = S_{J/\psi K_S} - \sin\phi_d, \qquad S_{J/\psi K_S} = \sin(\phi_d + \Delta\phi_d)$$

HFLAV 2016:

$2\beta + \Delta\phi_d = 43.8^\circ \pm 1.4^\circ$ dominated by $B_d \to J/\psi K_S$

$2\beta_s - \Delta\phi_s = 1.7^\circ \pm 1.9^\circ$ mainly from $B_s \to J/\psi\phi$ and $B_s \to J/\psi f_0$

Author	$\Delta S_{J/\psi K^0}$	$\Delta\phi_d$	Method
De Bruyn, Fleischer 2014	-0.01 ± 0.01	$-\left(1.1^\circ{}^{+0.70}_{-0.85}\right)^\circ$	SU(3) flavour
Jung 2012	$\lvert\Delta S\rvert \lesssim 0.01$	$\lvert\Delta\phi_d\rvert \lesssim 0.8^\circ$	SU(3) flavour
Ciuchini *et al.* 2011	0.00 ± 0.02	$0.0^\circ \pm 1.6^\circ$	U-spin
Faller *et al.* 2009	$[-0.05, -0.01]$	$[-3.9, -0.8]^\circ$	U-spin
Boos *et al.* 2004	$-(2 \pm 2) \cdot 10^{-4}$	$0.0^\circ \pm 0.0^\circ$	perturbative calculation

Extract penguin contribution from $b \to c\bar{c}d$ control channels such as $B_d \to J/\psi\pi^0$ or $B_s \to J/\psi K_S$, in which the penguin contribution is Cabibbo-unsuppressed.

Drawbacks:

- statistics in control channels smaller by factor of 20
- size of $SU(3)$ breaking in penguin contributions to $B_{d,s} \to J/\psi X$ decays unclear

$SU(3)$ breaking can be large, e.g. a b quark fragments into a B_d four times more often than into a B_s.

Extract penguin contribution from $b \to c\bar{c}d$ control channels such as $B_d \to J/\psi\pi^0$ or $B_s \to J/\psi K_S$, in which the penguin contribution is Cabibbo-unsuppressed.

Drawbacks:

- statistics in control channels smaller by factor of 20
- size of $SU(3)$ breaking in penguin contributions to $B_{d,s} \to J/\psi X$ decays unclear

$SU(3)$ breaking can be large, e.g. a b quark fragments into a B_d four times more often than into a B_s.

- SU(3) does not help in $B_s \to J/\psi\phi$, because ϕ is an equal mixture of octet and singlet.

Tree and Penguin

Define $\lambda_q = V_{qb} V_{qs}^*$ and use $\lambda_t = -\lambda_u - \lambda_c$.

Generic B decay amplitude:

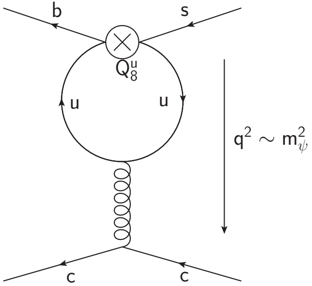
$$A(B \to f) = \lambda_c t_f + \lambda_u p_f$$

Terms $\propto \lambda_u = V_{ub} V_{us}^*$ lead to the penguin pollution.

Remark: One can include first-order SU(3) breaking in the extraction of t_f from control channels (Jung 2012).
This is not possible for p_f.

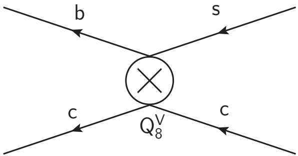
Idea: employ an operator product expansion,

to factorise the *u*-quark loop into a perturbative coefficient and matrix elements of local operators:



$q^2 \gg \Lambda^2_{QCD}$

$\longrightarrow$



$Q_{8V} = (\bar{s} T^a b)_{V-A} (\bar{c} T^a c)_V$

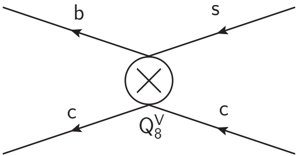
Perturbative approach is due to Bander Soni Silverman (1979) (BSS).
Boos, Mannel and Reuter (2004) applied this method to $B_d \to J/\psi K_S$.
Our study:

- Investigate soft and collinear infrared divergences to prove factorization.
- Analyse spectator scattering.
- Organise matrix elements by $1/N_c$ counting, no further assumptions on magnitudes and strong phases.

Operator product expansion works!

- Soft divergences factorise.
- Collinear divergences cancel or factorise.
- Non-factorisable spectator scattering is power-suppressed.

$\Rightarrow$ Up-quark penguin can be absorbed into a Wilson coefficient C_8^u!



$C_8^u Q_{8V}$

Local operators:

$$Q_{0V} \equiv (\bar{s}b)_{V-A}(\bar{c}c)_V \qquad Q_{0A} \equiv (\bar{s}b)_{V-A}(\bar{c}c)_A$$
$$Q_{8V} \equiv (\bar{s}T^a b)_{V-A}(\bar{c}T^a c)_V \qquad Q_{8A} \equiv (\bar{s}T^a b)_{V-A}(\bar{c}T^a c)_A$$

Results

$$A_{\rm CP}^{B_q\to f}(t) = \frac{S_f \sin(\Delta m_q t) - C_f \cos(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2) + A^f_{\Delta\Gamma_q} \sinh(\Delta\Gamma_q t/2)}$$

$$S_f = \pm \sin(2\beta_{(s)}) + \Delta S_f$$

B_d decays:

Final State:	$J/\psi K_S$	$\psi(2S) K_S$	$(J/\psi K^*)^0$	$(J/\psi K^*)^\parallel$	$(J/\psi K^*)^\perp$
$\max(\lvert\Delta\phi_d\rvert)$ [°]	0.68	0.74	0.85	1.13	0.93
$\max(\lvert\Delta S_f\rvert)$ [10^{-2}]	0.86	0.94	1.09	1.45	1.19
$\max(\lvert C_f\rvert)$ [10^{-2}]	1.33	1.33	1.65	2.19	1.80

…and more.

Ph. Frings, UN, M. Wiebusch, Phys.Rev.Lett. 115 (2015) 061802

Results

B_s decays:

Final State	$(J/\psi\phi)^0$	$(J/\psi\phi)^\parallel$	$(J/\psi\phi)^\perp$
$\max(\lvert\Delta\phi_s\rvert)$ [°]	0.97	1.22	0.99
$\max(\lvert\Delta S_f\rvert)$ [10^{-2}]	1.70	2.13	1.73
$\max(\lvert C_f\rvert)$ [10^{-2}]	1.89	2.35	1.92

Ph. Frings, UN, M. Wiebusch, Phys.Rev.Lett. 115 (2015) 061802

We can also constrain p_f/t_f in $b \to c\bar{c}d$ decays:

B_d decays:

Final State	$J/\psi\pi^0$	$(J/\psi\rho)^0$	$(J/\psi\rho)^\parallel$	$(J/\psi\rho)^\perp$
$\max(\lvert\Delta S_f\rvert)$ [10^{-2}]	18	22	27	22
$\max(\lvert C_f\rvert)$ [10^{-2}]	29	35	41	36

B_s decays:

Final State	$J/\psi K_S$
$\max(\lvert\Delta S_f\rvert)$ [10^{-2}]	26
$\max(\lvert C_f\rvert)$ [10^{-2}]	27

Ph. Frings, UN, M. Wiebusch, Phys.Rev.Lett. 115 (2015) 061802

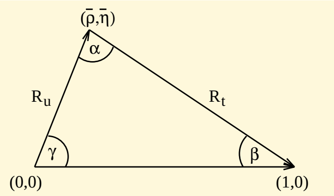
The $B_d - \overline{B}_d$ mixing amplitude is very sensitive to new physics, probing scales up to 100 TeV (depending on the model). Add new-physics contribution ϕ_d^{NP}:

$$2\beta + \Delta\phi_d + \phi_d^{NP} = 43.8^\circ \pm 1.4^\circ$$

$\Rightarrow$ To constrain ϕ_d^{NP} need β from elsewhere.

Global fit to unitarity triangle (UT): essentially $|V_{ub}|$ needed.

$\frac{|V_{ub}|}{|V_{cb}|}$ determines R_u, which drives the prediction of β.



1. CP asymmetry in flavour-specific B_d decays (e.g. $B_d \to X^- \ell^+ \nu$):

$$a_{\rm fs}^d = \left[(47 \pm 9) \cdot 10^{-4} \sin \phi_d^{\rm NP} - (4.0 \pm 0.6) \cdot 10^{-4} \cos \phi_d^{\rm NP} \right] \frac{\Delta m_d^{\rm SM}}{\Delta m_d}$$

$\Rightarrow$ enhancement factor $47/4 \sim 12$!

Other avenues to $\phi_d^{\rm NP}$

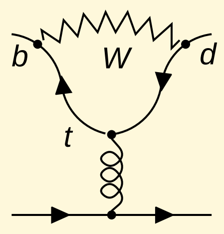
1. CP asymmetry in flavour-specific B_d decays (e.g. $B_d \to X^- \ell^+ \nu$):

$$a_{\rm fs}^d = \left[(47 \pm 9) \cdot 10^{-4} \sin \phi_d^{\rm NP} - (4.0 \pm 0.6) \cdot 10^{-4} \cos \phi_d^{\rm NP} \right] \frac{\Delta m_d^{\rm SM}}{\Delta m_d}$$

$\Rightarrow$ enhancement factor $47/4 \sim 12$!

2. CP asymmetries in $b \to d s \bar{s}$ penguins:

In the SM β cancels between $\rm B_d - \overline{B}_d$ mixing amplitude and the decay amplitude.
Examples: $B_d \to K_S K_S$, $B_d \to K_S K^{0*}$.



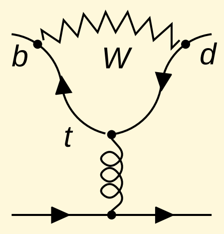
1. CP asymmetry in flavour-specific B_d decays (e.g. $B_d \to X^- \ell^+ \nu$):

$$a_{\rm fs}^d = \left[(47 \pm 9) \cdot 10^{-4} \sin \phi_d^{\rm NP} - (4.0 \pm 0.6) \cdot 10^{-4} \cos \phi_d^{\rm NP} \right] \frac{\Delta m_d^{\rm SM}}{\Delta m_d}$$

$\Rightarrow$ enhancement factor $47/4 \sim 12$!

2. CP asymmetries in $b \to d s \bar{s}$ penguins:

In the SM β cancels between $\mathrm{B_d} - \overline{\mathrm{B}}_\mathrm{d}$ mixing amplitude and the decay amplitude.
Examples: $B_d \to K_S K_S$, $B_d \to K_S K^{0*}$.



3. Determine the UT from $B(K_L \to \pi^0 \nu \bar{\nu}) \propto \bar{\eta}$ and either γ or $B(K^+ \to \pi^+ \nu \bar{\nu})$ (giving R_t) to find β.

Hadronic two-body weak decays of D^+, D^0, D_s^+ mesons:

$$D^+ \sim c\overline{d}, \qquad D^0 \sim c\overline{u}, \qquad D_s^+ \sim c\overline{s},$$

Examples: $D^+ \to \overline{K}^0\pi^+$, $D^0 \to \pi^+\pi^-$, $D^+ \to K^0\pi^+$.

Decays are classified in terms of powers of the Wolfenstein parameter

$$\lambda \simeq |V_{us}| \simeq |V_{cd}| \simeq 0.22.$$

$$\text{Amplitude } A \propto \begin{cases} \lambda^0 & \text{Cabibbo-favoured} \\ \lambda^1 & \text{singly Cabibbo-suppressed} \\ \lambda^2 & \text{doubly Cabibbo-suppressed} \end{cases}$$

In the SCS amplitudes three CKM structures appear:
$\lambda_d = V_{cd}^* V_{ud}$, $\lambda_s = V_{cs}^* V_{us}$, $\lambda_b = V_{cb}^* V_{ub}$ and CKM unitarity
$\lambda_d + \lambda_s + \lambda_b = 0$ is invoked to eliminate one of these.

Commonly used

$$\mathcal{A}^{\text{SCS}} \equiv \lambda_{sd} A_{sd} - \frac{\lambda_b}{2} A_b$$

with

$$\lambda_{sd} = \frac{\lambda_s - \lambda_d}{2} \qquad \text{and} \qquad -\frac{\lambda_b}{2} = \frac{\lambda_s + \lambda_d}{2}$$

In the SCS amplitudes three CKM structures appear:
$\lambda_d = V_{cd}^* V_{ud}$, $\lambda_s = V_{cs}^* V_{us}$, $\lambda_b = V_{cb}^* V_{ub}$ and CKM unitarity
$\lambda_d + \lambda_s + \lambda_b = 0$ is invoked to eliminate one of these.

Commonly used

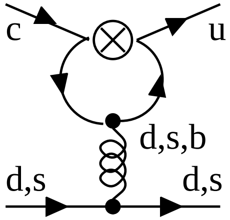
$$\mathcal{A}^{\mathrm{SCS}} \equiv \lambda_{sd} A_{sd} - \frac{\lambda_b}{2} A_b$$

with

$$\lambda_{sd} = \frac{\lambda_s - \lambda_d}{2} \qquad \text{and} \qquad -\frac{\lambda_b}{2} = \frac{\lambda_s + \lambda_d}{2}$$

In view of $|\lambda_b|/|\lambda_{sd}| \sim 10^{-3}$ only A_{sd} is relevant for branching ratios.

Direct CP asymmetries involve $\mathrm{Im}\,\dfrac{A_b}{A_{sd}}$.



Branching ratios of hadronic charm decays . . .

. . . are "dull" tree-level quantities dominated by a single CKM amplitude

Branching ratios of hadronic charm decays ...

...are "dull" tree-level quantities dominated by a single CKM amplitude

...and are therefore insensitive to new physics, but

Branching ratios of hadronic charm decays . . .

. . . are “dull” tree-level quantities dominated by a single CKM amplitude

. . . and are therefore insensitive to new physics, but

. . . are useful to test the calculational framework and

Branching ratios of hadronic charm decays . . .

. . . are "dull" tree-level quantities dominated by a single CKM amplitude

. . . and are therefore insensitive to new physics, but

. . . are useful to test the calculational framework and

. . . experimentally determine $|A_{sd}|$, an important ingredient to predict CP asymmetries.

Branching ratios of hadronic charm decays ...

...are "dull" tree-level quantities dominated by a single CKM amplitude

...and are therefore insensitive to new physics, but

...are useful to test the calculational framework and

...experimentally determine $|A_{sd}|$, an important ingredient to predict CP asymmetries.

Branching ratios of hadronic charm decays ...

...are "dull" tree-level quantities dominated by a single CKM amplitude

...and are therefore insensitive to new physics, but

...are useful to test the calculational framework and

...experimentally determine $|A_{sd}|$, an important ingredient to predict CP asymmetries.

CP asymmetries of hadronic charm decays ...

...are proportional to $\mathrm{Im}\,\frac{\lambda_b}{\lambda_{sd}} = -6 \cdot 10^{-4}$ in the Standard Model

Branching ratios of hadronic charm decays ...

- ...are "dull" tree-level quantities dominated by a single CKM amplitude
  - ...and are therefore insensitive to new physics, but
    - ...are useful to test the calculational framework and
    - ...experimentally determine $|A_{sd}|$, an important ingredient to predict CP asymmetries.

CP asymmetries of hadronic charm decays ...

- ...are proportional to $\mathrm{Im}\,\frac{\lambda_b}{\lambda_{sd}} = -6 \cdot 10^{-4}$ in the Standard Model
  - ...and probe new physics in flavour transitions of up-type quarks,

Branching ratios of hadronic charm decays . . .

. . . are "dull" tree-level quantities dominated by a single CKM amplitude

. . . and are therefore insensitive to new physics, but

. . . are useful to test the calculational framework and

. . . experimentally determine $|A_{sd}|$, an important ingredient to predict CP asymmetries.

CP asymmetries of hadronic charm decays . . .

. . . are proportional to $\mathrm{Im}\,\frac{\lambda_b}{\lambda_{sd}} = -6 \cdot 10^{-4}$ in the Standard Model

. . . and probe new physics in flavour transitions of up-type quarks,

. . . are very difficult to predict in the Standard Model,

Branching ratios of hadronic charm decays ...

...are "dull" tree-level quantities dominated by a single CKM amplitude

...and are therefore insensitive to new physics, but

...are useful to test the calculational framework and

...experimentally determine $|A_{sd}|$, an important ingredient to predict CP asymmetries.

CP asymmetries of hadronic charm decays ...

...are proportional to $\mathrm{Im}\,\frac{\lambda_b}{\lambda_{sd}} = -6 \cdot 10^{-4}$ in the Standard Model

...and probe new physics in flavour transitions of up-type quarks,

...are very difficult to predict in the Standard Model,

...are not discovered yet!

Use the approximate SU(3)$_F$ symmetry of QCD: Owing to $m_{u,d,s} \ll \Lambda_{\text{QCD}}$ hadronic amplitudes are approximately invariant under unitary rotations of

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix}.$$

$\Rightarrow$ One can correlate various $D \to K\pi$ decays.

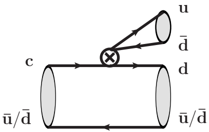
Example: In the limit of exact SU(3)$_F$ symmetry find

$$\mathcal{B}(D^0 \to \pi^+\pi^-) = \mathcal{B}(D^0 \to K^+K^-).$$

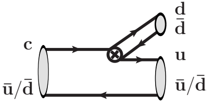
Data show $\mathcal{O}(30\%)$ SU(3)$_F$ breaking in the decay amplitudes.

Combine topological amplitudes (Chau 1980,1982; Zeppenfeld 1981) with linear $SU(3)_F$ breaking (Gronau 1995).

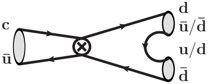
$SU(3)_F$ limit amplitudes contributing to A_{sd}:



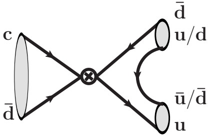
tree (T)



color-suppressed tree (C)



exchange (E)



annihilation (A)

Direct CP asymmetries in singly Cabibbo-suppressed decays:
With $\mathcal{A}^{\rm SCS} = \mathcal{A}$ write

$$\mathcal{A} = \lambda_{sd} A_{sd} - \frac{\lambda_b}{2} A_b,$$

CP-conjugate decay: $$\overline{\mathcal{A}} = -\lambda_{sd}^* A_{sd} + \frac{\lambda_b^*}{2} A_b.$$

Find

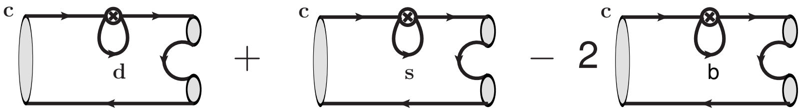
$$a_{CP}^{\rm dir} \equiv \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2} = \mathrm{Im}\,\frac{\lambda_b}{\lambda_{sd}}\,\mathrm{Im}\frac{A_b}{A_{sd}}.$$

Recall: $|A_{sd}|$ is fixed from measured branching ratios.

$\Rightarrow$ need $|A_b|$ and the phase of $\arg(A_b/A_{sd})$ to predict $a_{CP}^{\rm dir}$.

For CP asymmetries we need A_b:

In the SU(3)$_F$ limit usually penguin or penguin annihilation topologies contribute to A_b in addition to T,C,E,A.



Apparently data do not show order-of-magnitude enhancements of charm CP asymmetries over the SM expectation

$$a_{CP}^{\mathrm{dir}} = \mathrm{Im}\,\frac{\lambda_b}{\lambda_{sd}}\,\mathrm{Im}\,\frac{A_b}{A_{sd}} = -6 \cdot 10^{-4} \cdot \mathrm{Im}\,\frac{A_b}{A_{sd}}$$

Therefore the scientific goals to (a) discover charm CP violation and (b) falsify the SM require different strategies:

For (a) need decay modes with large SM predictions for a_{CP}^{dir}.
For (b) need decay modes with clean SM predictions for a_{CP}^{dir}.

This talk: focus on (a).

$$\mathcal{A}(D^0 \to K_S K_S) = \lambda_{sd} \mathcal{A}_{sd} - \frac{\lambda_b}{2} \mathcal{A}_b.$$

Special feature I:

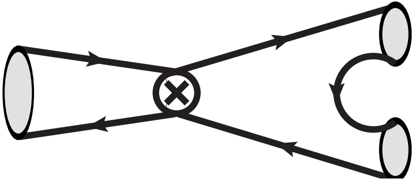
In the SU(3)$_F$ limit: $\mathcal{A}_{sd} = 0$ while $\mathcal{A}_b \neq 0$

$\Rightarrow$ suppressed $\mathcal{B}(D^0 \to K_S K_S) = (1.7 \pm 0.4) \cdot 10^{-4}$

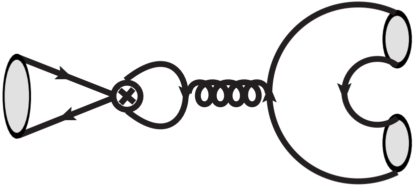
enhanced $a_{CP}^{\rm dir} \propto {\rm Im} \dfrac{A_b}{A_{sd}}$

Special feature II:

$a_{CP}^{\rm dir}(D^0 \to K_S K_S)$ receives contributions at tree level, from the (sizable!) exchange diagram:



exchange diagram



penguin annihilation diagram

Thus $a_{CP}^{\rm dir}(D^0 \to K_S K_S) \neq 0$, even if penguin topologies (which generate e.g. $a_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-)$ and $a_{CP}^{\rm dir}(D^0 \to K^+K^-)$) vanish!

Result: a_{CP}^{dir} can be large. We find:

$$|a_{CP}^{\mathrm{dir}}(D^0 \to K_S K_S)| \leq 1.1\% \qquad @95\%\ \text{C.L.}$$

The CP violation in $\mathrm{K}-\overline{\mathrm{K}}$ mixing is meant to be subtracted.

UN, St. Schacht, Phys.Rev.D92(2015) 054036

$a_{CP}^{\mathrm{dir}} = 1.1\%$ is found by maximising the the topological amplitudes found from a global fit to branching ratio data and varying the unknown strong phase A_b/A_{sd} between $-\pi$ and π. If the amplitudes obey the hierarchies expected from color counting, the limit becomes

$$|a_{CP}^{\mathrm{dir}}(D^0 \to K_S K_S)| \leq 0.6\%.$$

Experiment determines $$A_{CP} = a_{CP}^{\text{dir}} - A_\Gamma \frac{\langle t \rangle}{\tau},$$
where $\langle t \rangle$ is the average decay time and τ is the D^0 lifetime.

$$A_{CP}^{\text{CLEO 2001}} = -0.23 \pm 0.19$$

$$A_{CP}^{\text{LHCb 2015}} = -0.029 \pm 0.052 \pm 0.022$$

$$A_{CP}^{\text{Belle 2016}} = -0.0002 \pm 0.0153 \pm 0.0017$$

UN, St.Schacht, arXiv:1708.03572

New features of $a_{CP}^{\text{dir}}(D^0 \to K_S K^{0*})$ and $a_{CP}^{\text{dir}}(D^0 \to K_S \overline{K}^{0*})$ compared to $a_{CP}^{\text{dir}}(D^0 \to K_S K_S)$:

- Prompt decay $K^{0*} \to K^+\pi^-$ helps in the experiment, since K_S lives too long.
- No flavour tagging is needed: essentially undiluted untagged CP asymmetry

$$a_{CP}^{\text{dir}}(\overset{(-)}{D} \to K_S K^{0*}) \approx a_{CP}^{\text{dir}}(D^0 \to K_S K^{0*})$$

- In a Dalitz plot analysis one can explore the region of $K^+\pi^-$ invariant mass a bit away from the K^{0*} resonance to hunt for favourable strong phases (maximising a_{CP}^{dir}).

Subtracting Kaon CP violation we find:

$$|a_{CP}^{\text{dir}}(\overset{(-)}{D} \to K_S K^{0*})| \leq 0.3\%$$

CP violation in $K \to \pi\pi$

Combine decay amplitudes $A(K^0 \to \pi^+\pi^-)$ and $A(K^0 \to \pi^0\pi^0)$ into

$$A_0 \equiv A(K^0 \to (\pi\pi)_{I=0}) \qquad \text{and} \qquad A_2 \equiv A(K^0 \to (\pi\pi)_{I=2}),$$

where I denotes the strong isospin.

Combine decay amplitudes $A(K^0 \to \pi^+\pi^-)$ and $A(K^0 \to \pi^0\pi^0)$ into

$$A_0 \equiv A(K^0 \to (\pi\pi)_{I=0}) \qquad \text{and} \qquad A_2 \equiv A(K^0 \to (\pi\pi)_{I=2}),$$

where I denotes the strong isospin.

Indirect CP violation (from $\mathrm{K}-\overline{\mathrm{K}}$ mixing):

$$\epsilon_K \equiv \frac{A(K_L \to (\pi\pi)_{I=0})}{A(K_S \to (\pi\pi)_{I=0})} = (2.228 \pm 0.011) \cdot 10^{-3} \cdot e^{i(0.97\pm0.02)\pi/4}$$

discovered in 1964

CP violation in $K \to \pi\pi$

Combine decay amplitudes $A(K^0 \to \pi^+\pi^-)$ and $A(K^0 \to \pi^0\pi^0)$ into

$$A_0 \equiv A(K^0 \to (\pi\pi)_{I=0}) \qquad \text{and} \qquad A_2 \equiv A(K^0 \to (\pi\pi)_{I=2}),$$

where I denotes the strong isospin.

Indirect CP violation (from $\mathrm{K}-\overline{\mathrm{K}}$ mixing):

$$\epsilon_K \equiv \frac{A(K_L \to (\pi\pi)_{I=0})}{A(K_S \to (\pi\pi)_{I=0})} = (2.228 \pm 0.011) \cdot 10^{-3} \cdot e^{i(0.97 \pm 0.02)\pi/4}$$

discovered in 1964

Direct CP violation (from decay amplitude):

$$\epsilon_K' \simeq \frac{\epsilon_K}{\sqrt{2}} \left[\frac{\langle (\pi\pi)_{I=2} | K_L \rangle}{\langle (\pi\pi)_{I=0} | K_L \rangle} - \frac{\langle (\pi\pi)_{I=2} | K_S \rangle}{\langle (\pi\pi)_{I=0} | K_S \rangle} \right] = (16.6 \pm 2.3) \cdot 10^{-4} \cdot \epsilon_K$$

discovered in 1999

(i) theoretical control of ϵ_K increases steadily (hadronic matrix elements and NNLO QCD under good control, $\epsilon_K \propto |V_{cb}|^4$ issue improving),

(ii) ϵ'_K now tractable with lattice QCD,

(iii) upcoming measurements of theoretically clean branching ratios $B(K^+ \to \pi^+ \nu\bar{\nu})$ (by NA62) and $B(K_L \to \pi^0 \nu\bar{\nu})$ (by KØTØ),

(iv) no new particles found at LHC:
   $\Rightarrow$ weaker rationale for Minimal Flavour Violation (MFV)

If the flavour structure of new physics is unrelated to the SM Yukawa sector, one expects the largest effects in Kaon (and $\mu \to e$) FCNC processes.

Master equation for ϵ'_K:

$$\frac{\epsilon'_K}{\epsilon_K} = \frac{\omega_+}{\sqrt{2}|\epsilon_K^{\rm exp}|{\rm Re}A_0^{\rm exp}} \left\{ \frac{{\rm Im}A_2}{\omega_+} - \left(1 - \hat{\Omega}_{\rm eff}\right) {\rm Im}A_0 \right\}.$$

Here:

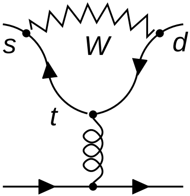
$$\omega_+ \simeq \frac{{\rm Re}A_2}{{\rm Re}A_0} = (4.53 \pm 0.02) \cdot 10^{-2}$$

$\hat{\Omega}_{\rm eff} = (14.8 \pm 8.0) \cdot 10^{-2}$ quantifies isospin breaking.

Important theoretical ingredients: ${\rm Im}A_0$ and ${\rm Im}A_2$, calculated from the effective $|\Delta S| = 1$ hamiltonian describing $s \to d q \overline{q}$ decays.

The enhanced sensitivity to $\Delta I = 3/2$ transitions (such as electroweak penguins and boxes) is a special feature of ϵ'_K.

$\mathrm{Im}A_0$ is dominated by gluon penguins:



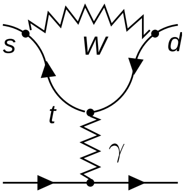
Operator: $Q_6 = \bar{s}^j_L \gamma_\mu d^k_L \sum_q \bar{q}^k_R \gamma^\mu q^j_R$

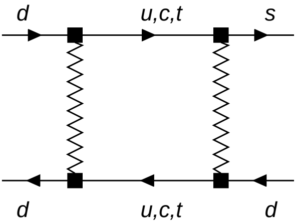
Matrix element: $\langle (\pi\pi)_{I=0} | Q_6 | K^0 \rangle$

$\mathrm{Im}A_2$ is dominated by photon penguin and box diagrams:

Operator: $Q_8 = \frac{3}{2} \bar{s}^j_L \gamma_\mu d^k_L \sum_q e_q \bar{q}^k_R \gamma^\mu q^j_R$

Matrix element: $\langle (\pi\pi)_{I=2} | Q_8 | K^0 \rangle$





$$\frac{\epsilon'_K}{\epsilon_K} = (16.6 \pm 2.3) \times 10^{-4} \qquad \text{(experiments: NA62, KTeV)}$$

$$\frac{\epsilon'_K}{\epsilon_K} = \left(1.1 \pm 4.7_{\text{lattice}} \pm 1.9_{\text{NNLO}} \pm 0.6_{\text{isosp. br.}} \pm 0.2_{m_t}\right) \times 10^{-4} \qquad \text{(SM)}$$

Kitahara,UN,Tremper, JHEP 1612 (2016) 078

The prediction uses the lattice-QCD results from RBC-UKQCD, Phys. Rev. Lett. **115** 212001 (2015).

Discrepancy with a significance of 2.8σ!

Our prediction uses the methodology of Buras et al. (JHEP 1511 (2015) 202) (taking $\mathrm{Re}A_{0,2}$ from data), NLO formulae from Buras et al., and a new formula for the RG evolution.

Buras, Jäger, Jamin, Gorbahn (JHEP 1511 (2015) 202) find a 2.9σ deviation:

$$\frac{\epsilon'_K}{\epsilon_K} = (1.9 \pm 4.5) \times 10^{-4} \qquad \text{(SM)}$$

Sensitivity to new physics

Standard Model:

Cabibbo-Kobayashi-Maskawa (CKM) factor:

$$\tau = -\frac{V_{td} V_{ts}^*}{V_{ud} V_{us}^*} \sim (1.5 - 0.6i) \cdot 10^{-3}$$

$$\epsilon_K'^{\,\mathrm{SM}} \propto \mathrm{Im}\,\tau \qquad \text{and} \qquad \epsilon_K^{\mathrm{SM}} \propto \mathrm{Im}\,\tau^2.$$

Generic loop-induced new physics:

some flavour-violating parameter δ with $|\delta| \gg |\tau|$ to compensate for suppression from heavy new-physics mass:

$$\epsilon_K'^{\,\mathrm{NP}} \propto \mathrm{Im}\,\delta \qquad \text{and} \qquad \epsilon_K^{\mathrm{NP}} \propto \mathrm{Im}\,\delta^2.$$

$\Rightarrow$ If $\epsilon_K'^{\,\mathrm{NP}} \sim \epsilon_K'^{\,\mathrm{SM}}$, expect $\epsilon_K^{\mathrm{NP}} \gg \epsilon_K^{\mathrm{SM}}$.

$\Rightarrow$ Need clever ideas to suppress ϵ_K^{NP}.

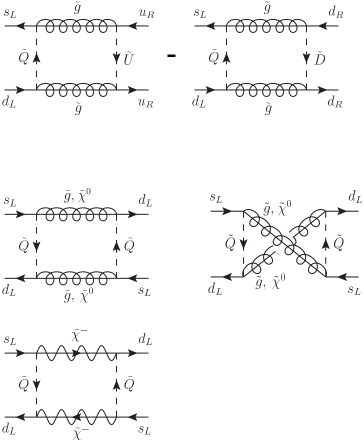
Supersymmetry

The MSSM has a mechanism

- to enhance $\mathrm{Im}\, A_2$, because it permits strong-isospin violation through splittings between right-handed up-squark and down-squark masses (Trojan penguins),

  Grossman, Kagan, Neubert 1999.

- to suppress the $\mathrm{K}-\overline{\mathrm{K}}$ mixing amplitude thanks to the Majorana nature of the gluinos, with negative interference of two box diagrams. Crivellin, Davidkov 2010

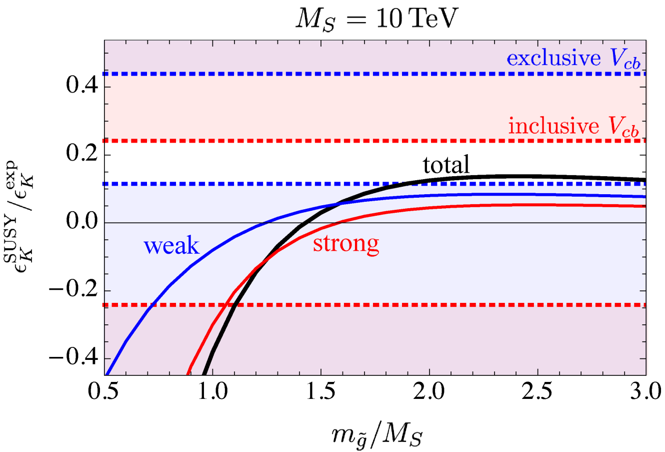


The second feature makes the MSSM contribution to $\mathrm{K}-\overline{\mathrm{K}}$ mixing vanish for $M_{\tilde{g}} \sim 1.5 M_{\tilde{q}}$, it stays small for $M_{\tilde{g}} > 1.5 M_{\tilde{q}}$.

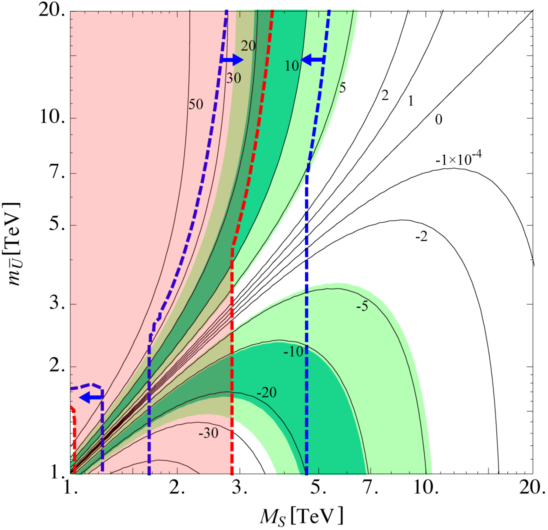
Teppei Kitahara, UN, Paul Tremper, Phys. Rev. Lett. 117 (2016) 091802

Choose:

Sparticle masses $M_S \sim 10$ TeV, $M_{\tilde{g}} > 1.5 M_S$, flavour mixing in down-squark mass matrix only with $\arg \Delta_{sd}^{LL} = \pi/4$.



Explain ϵ'_K



x-axis: generic sparticle mass, $M_{\tilde{g}} = 1.5 M_S$

y-axis: right-handed up-squark mass

red region: excluded by ϵ_K if $|V_{cb}|$ from inclusive decays is correct

blue dashes: delimit allowed region, if $|V_{cb}|$ from exclusive decays is correct

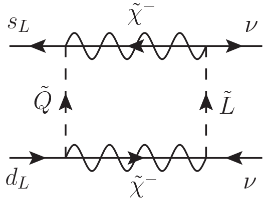
The (near) future of Kaon physics:

$$B(K^+ \to \pi^+\nu\bar{\nu}) \stackrel{\text{SM}}{=} (8.3 \pm 0.3) \cdot 10^{-11}$$ for NA62 (CERN)

$$B(K_L \to \pi^0\nu\bar{\nu}) \stackrel{\text{SM}}{=} (2.9 \pm 0.2) \cdot 10^{-11}$$ for KØTØ (J-PARC)

These branching ratios are theoretically extremely clean.

In our MSSM scenario:
Contributions from wino-like chargino box:



Giancarlo D'Ambrosio, Andreas Crivellin, Teppei Kitahara, UN, 1703.05786

If you allow for at most 10% (fine-)tuning in ϵ_K, you find (for GUT relations between $M_{1,2,3}$):

$$\frac{B(K^+ \to \pi^+\nu\bar{\nu})}{B(K^+ \to \pi^+\nu\bar{\nu})_{\rm SM}} \leq 1.1 \qquad \text{and} \qquad \frac{B(K_L \to \pi^0\nu\bar{\nu})}{B(K_L \to \pi^0\nu\bar{\nu})_{\rm SM}} \leq 1.2.$$

$\longrightarrow$ need upgrade KØTØ–step2, aiming at $\mathcal{O}(100)$ events.

Furthermore: if the new-physics contribution to ϵ'_K is positive (as indicated by present data), find

$$\mathrm{sgn}\left[B(K_L \to \pi^0\nu\overline{\nu}) - B^{\mathrm{SM}}(K_L \to \pi^0\nu\overline{\nu})\right] = \mathrm{sgn}\left(m_{\overline{U}} - m_{\overline{D}}\right)$$

Here $\overline{U}$ and $\overline{D}$ denote the right-handed up and down squarks, respectively.

Could collider experiments ever achieve this?

- OPE works for the penguin pollution in $B_{d,s}$ decays to charmonium, defining the "BSS mechanism" for the up-quark loop.
- No mysterious long-distance enhancement of up-quark penguins: $|\Delta\phi_d(B_d \to J/\psi K_S)| \leq 0.68^\circ$, $|\Delta\phi_s(B_s \to (J/\psi\phi)^0)| \leq 0.97^\circ$.
- New feature compared to $SU(3)_F$ method: Constrain the larger penguin pollution in $b \to c\bar{c}d$ channels, e.g. $|S_f(B_d \to J/\psi\pi^0) + \sin(2\beta)| \leq 0.18$.

Summary D

- Within the Standard Model the direct CP asymmetry in the charm decay in $D^0 \to K_S K_S$ can be as large as 1.1%. $a_{CP}^{\rm dir}(D^0 \to K_S K_S)$ is dominated by the exchange diagram, which involves no loop suppression. $D^0 \to K_S K_S$ may therefore be a discovery channel for charm CP violation.
- No tagging is required for $a_{CP}^{\rm dir}(D^0 \to K_S K^{0*})$ with

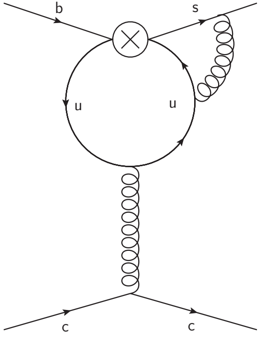
$$|a_{CP}^{\rm dir}(\overset{(-)}{D} \to K_S K^{0*})| \leq 0.3\%.$$

This is probably the best charm CP discovery channel.

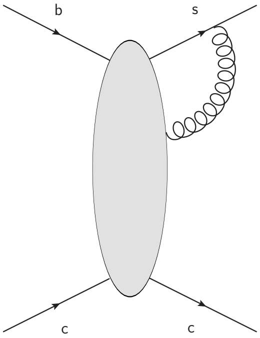
- The new lattice results for the matrix element $\langle(\pi\pi)_{I=0}|Q_6|K^0\rangle$ from RBC-UKQCD points to a tension between the experimental value of ϵ'_K and the Standard-Model prediction.
- If new physics enters through loops, a sizable effect in ϵ'_K requires a new source of flavour violation which is much larger then the CKM factor $\mathrm{Im}\,\dfrac{V_{td}V_{ts}^*}{V_{ud}V_{us}^*} \sim 6 \cdot 10^{-4}$. But then the effect on ϵ_K will typically be too big.
- In the MSSM one can simultaneously enhance ϵ'_K and suppress the new-physics contributions to ϵ_K. This requires flavour mixing among left-handed squarks, masses of right-handed up-type squarks different from those of the down-type squarks, and a gluino mass above 1.5 times the mass of the left-handed squarks.
- $B(K \to \pi\nu\overline{\nu})$ data will test our scenario. $B(K_L \to \pi^0\nu\overline{\nu})$ can determine, whether the right-handed up squark is heavier or lighter than the right-handed down squark.

Backup slides

Collinear divergent diagrams



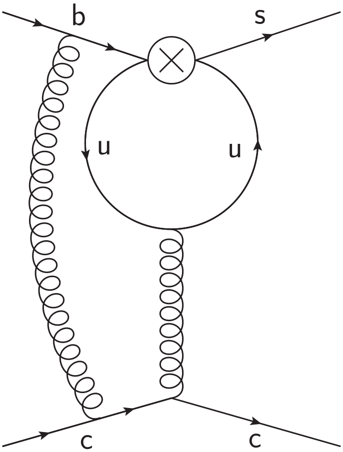
are infrared-safe if summed over



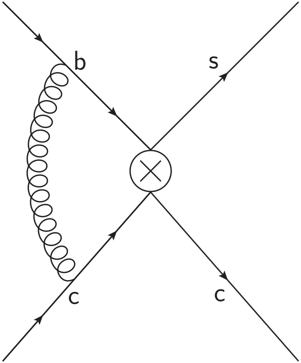
or are individually infrared-safe if considered in a physical gauge.

Soft divergent diagrams ...

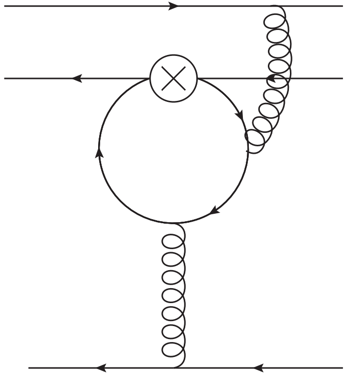
... factorise.



$\longrightarrow$



Spectator scattering diagrams…



$\longrightarrow$ …factorise up to power-suppressed contributions.

$1/N_c$ counting

For example: $B_d \to J/\psi K^0$

$$V_0 = \langle J/\psi K^0 | Q_{0V} | B_d \rangle = 2 f_\psi m_B p_{cm} F_1^{BK} \left[1 + \mathcal{O}\left(\frac{1}{N_c^2} \right) \right]$$

$1/N_c$ counting for $V_8, A_8 \equiv \langle J/\psi K^0 | Q_{8V,8A} | B_d \rangle$:

- Octet matrix elements are suppressed by $1/N_c$ w.r.t. singlet V_0
- Motivated by $1/N_c$ counting set the limits: $|V_8|, |A_8| \leq V_0/3$

For example: $B_d \to J/\psi K^0$

$$V_0 = \langle J/\psi K^0 | Q_{0V} | B_d \rangle = 2 f_\psi m_B p_{cm} F_1^{BK} \left[1 + \mathcal{O}\left(\frac{1}{N_c^2} \right) \right]$$

$1/N_c$ counting for $V_8, A_8 \equiv \langle J/\psi K^0 | Q_{8V,8A} | B_d \rangle$:

- Octet matrix elements are suppressed by $1/N_c$ w.r.t. singlet V_0
- Motivated by $1/N_c$ counting set the limits: $|V_8|, |A_8| \leq V_0/3$

Does the $1/N_c$ expansion work?

$$\frac{BR(B_d \to J/\psi K^0)|_{\text{th}}}{BR(B_d \to J/\psi K^0)|_{\text{exp}}} = 1 \quad \Rightarrow \quad 0.06|V_0| \leq |V_8 - A_8| \leq 0.19|V_0|$$

Strategy: Build combinations out of several CP asymmetries containing only those topological amplitudes which can be extracted from the global fit to the branching ratios.

$\rightarrow$ sum rules among CP asymmetries.

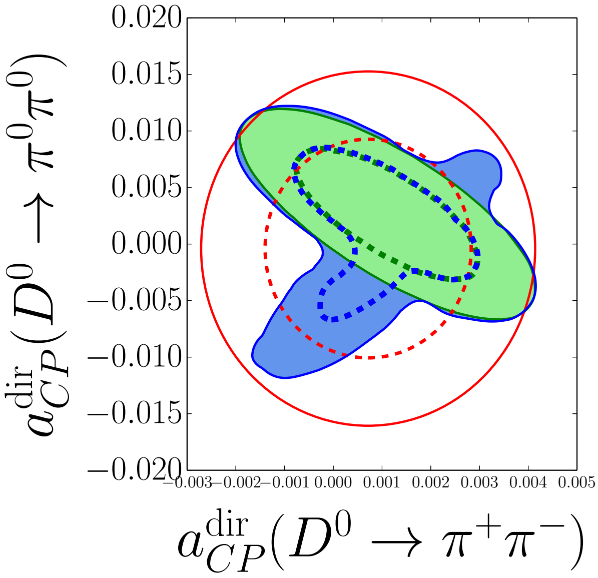
Our finding: Two sum rules each correlating three direct CP asymmetries in

I $D^0 \to K^+ K^-$, $D^0 \to \pi^+ \pi^-$, and $D^0 \to \pi^0 \pi^0$, and

II $D^+ \to \overline{K}^0 K^+$, $D_s^+ \to K^0 \pi^+$, and $D_s^+ \to K^+ \pi^0$.

Theoretical accuracy of new-physics tests only limited by the assumed size of $\mathrm{SU}(3)_F$ breaking; great progress compared to the $\mathcal{O}(1000\%)$ spread of past predictions.

S. Müller,UN,St. Schacht, Phys.Rev.Lett.115(2015) 251802.



Red solid:
95% CL measurement
Red dashed:
68% CL measurement

Present data:
Light blue:
95% CL from global fit
Dark blue dashed:
68% CL from global fit

Future scenario:
assume $\sqrt{50}$ better branching ratios, but $a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-)$ as today.

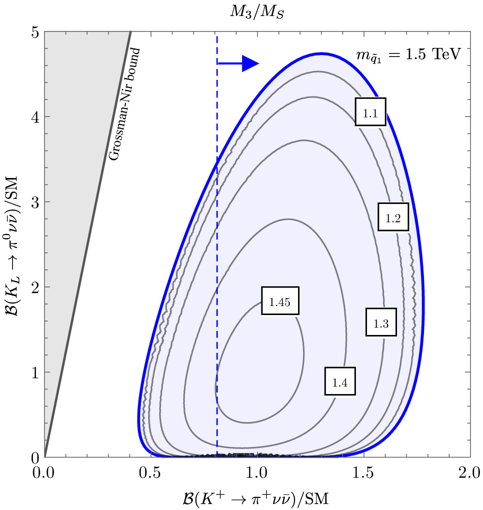
Light green:
95% CL from global fit
Dark green dashed:
68% CL from global fit

Our MSSM scenario makes falsifiable predictions for $B(K^+ \to \pi^+\nu\bar{\nu})$ and $B(K_L \to \pi^0\nu\bar{\nu})$:

Allowed region for the two branching ratios:

$m_{\tilde{q}_1} = 1.5\,\text{TeV}$ is the mass of the lightest ($\tilde{s}_L$–$\tilde{d}_L$–mixed) squark,
M_3 is the gluino mass, GUT relations for $M_{1,2}$,
M_S is the mass of all other sparticles.

The number in the squares show the value for M_3/M_S needed to cancel the MSSM contribution to ϵ_K.



In order to exhaust the bounds on $B(K^+ \to \pi^+\nu\bar{\nu})$ and $B(K_L \to \pi^0\nu\bar{\nu})$, one must fine-tune M_3 or the CP phase $\arg \Delta_{sd}^{LL}$: For $\arg \Delta_{sd}^{LL} = \pm\pi/2$ the MSSM contribution to ϵ_K vanishes, while ϵ'_K is maximised.

If you allow for at most 10% fine-tuning in ϵ_K, you find (for GUT relations between $M_{1,2,3}$):

$$\frac{B(K^+ \to \pi^+\nu\bar{\nu})}{B(K^+ \to \pi^+\nu\bar{\nu})_{\rm SM}} \leq 1.1 \qquad \text{and} \qquad \frac{B(K_L \to \pi^0\nu\bar{\nu})}{B(K_L \to \pi^0\nu\bar{\nu})_{\rm SM}} \leq 1.2.$$

$\longrightarrow$ need upgrade KØTØ–step2, aiming at $\mathcal{O}(100)$ events.