RECENT PROGRESS IN CHARM PHYSICS

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- Introduction
- CP violation in charm mixing
  - present status
  - future prospects
- CP violation in charm decays
  - VIA matrix elements, penguins & $\Delta I=1/2$
- Conclusions

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INTRODUCTION

- Charm physics in the SM is almost a two-generations story:
  - long-distance dominated
  - no CPV

$\Rightarrow$ excellent place to look for CPV NP!

- Charm mixing 2nd only to ε_K in NP sensitivity
- We are reaching the point in which the word almost becomes important

D MIXING

- D mixing is described by:
  - Dispersive $D \to \bar{D}$ amplitude M_{12}
    - SM: long-distance dominated, not calculable
    - NP: short distance, calculable w. lattice
  - Absorptive $D \to \bar{D}$ amplitude Γ_{12}
    - SM: long-distance, not calculable
    - NP: negligible
  - Observables: $|M_{12}|$, $|\Gamma_{12}|$, $\Phi_{12}=\arg(\Gamma_{12}/M_{12})$

D-mixing discussion based on Grossman, Kagan, Ligeti, Perez, Petrov & L.S., in preparation

GIM ⇔ SU(3) (U-spin)

- Use CKM unitarity

  $V_{cd}V_{ud}^{*} + V_{cs}V_{us}^{*} + V_{cb}V_{ub}^{*} = \lambda_d + \lambda_s + \lambda_b = 0$

- eliminate λ_d and take λ_s real (all physical results convention independent)

- imaginary parts suppr. by $r = \mathrm{Im}\, \lambda_b/\lambda_s = 6.5\ 10^{-4}$

- M_{12}, Γ_{12} have the following structure:

  $\lambda_s^2\, (f_{dd}+f_{ss}-2f_{ds}) + 2\lambda_s\lambda_b\, (f_{dd}-f_{ds}-f_{db}+f_{sb}) + O(\lambda_b^2)$

GIM $\Leftrightarrow$ SU(3) (U-spin)

- Write long-distance contributions to M_{12} and Γ_{12} in terms of U-spin quantum numbers:

  $\lambda_s^2\ (\Delta U=2) + \lambda_s\lambda_b\ (\Delta U=2 + \Delta U=1) + O(\lambda_b^2)$

  $\sim \lambda_s^2\ \varepsilon^2 + \lambda_s\lambda_b\varepsilon$

- CPV effects at the level of $r/\varepsilon \sim 2\ 10^{-3} \sim 1/8°$ for "nominal" SU(3) breaking $\varepsilon \sim 30\%$

"REAL SM" APPROXIMATION

- Given present experimental errors, it is perfectly adequate to assume that SM contributions to both M_{12} and Γ_{12} are real
- all decay amplitudes relevant for the mixing analysis can also be taken real
- NP could generate a nonvanishing phase for M_{12}

"REAL SM" APPROXIMATION II

- Define $|D_{S,L}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$ and $\delta=(1-|q/p|^2)/(1+|q/p|^2)$. All observables can be written in terms of $x=\Delta m/\Gamma$, $y=\Delta\Gamma/2\Gamma$ and δ, with

$$\sqrt{2}\,\Delta m = \mathrm{sign}(\cos\Phi_{12})\sqrt{4|M_{12}|^2-|\Gamma_{12}|^2+\sqrt{(4|M_{12}|^2+|\Gamma_{12}|^2)^2-16|M_{12}|^2|\Gamma_{12}|^2\sin^2\Phi_{12}}}\,,$$

$$\sqrt{2}\,\Delta\Gamma = 2\sqrt{|\Gamma_{12}|^2-4|M_{12}|^2+\sqrt{(4|M_{12}|^2+|\Gamma_{12}|^2)^2-16|M_{12}|^2|\Gamma_{12}|^2\sin^2\Phi_{12}}}\,,$$

$$\delta = \frac{2|M_{12}||\Gamma_{12}|\sin\Phi_{12}}{(\Delta m)^2+|\Gamma_{12}|^2}\,, \qquad (7)$$

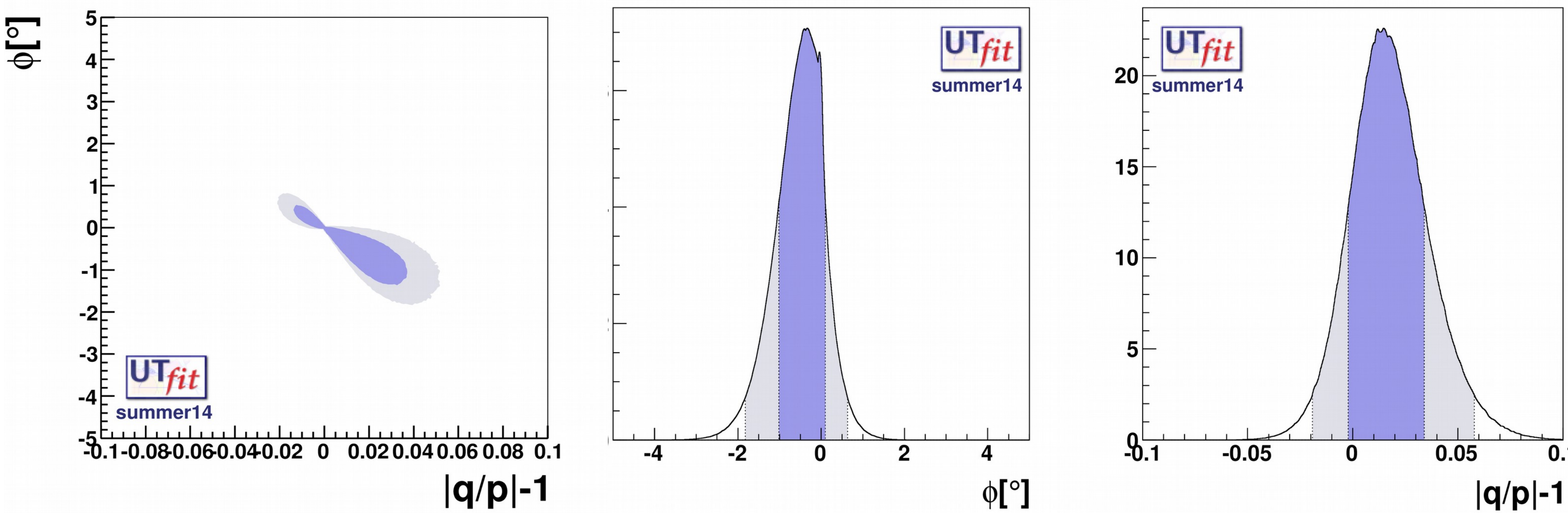
- Notice that $\phi=\arg(q/p)=\arg(y+i\delta x)$ - ~~$\arg\Gamma_{12}$~~
- $|q/p|\neq 1 \Leftrightarrow \phi\neq 0$ clear signals of NP

Ciuchini et al; Kagan & Sokoloff

CPV IN MIXING TODAY

- latest UTfit average (HFAG very similar):

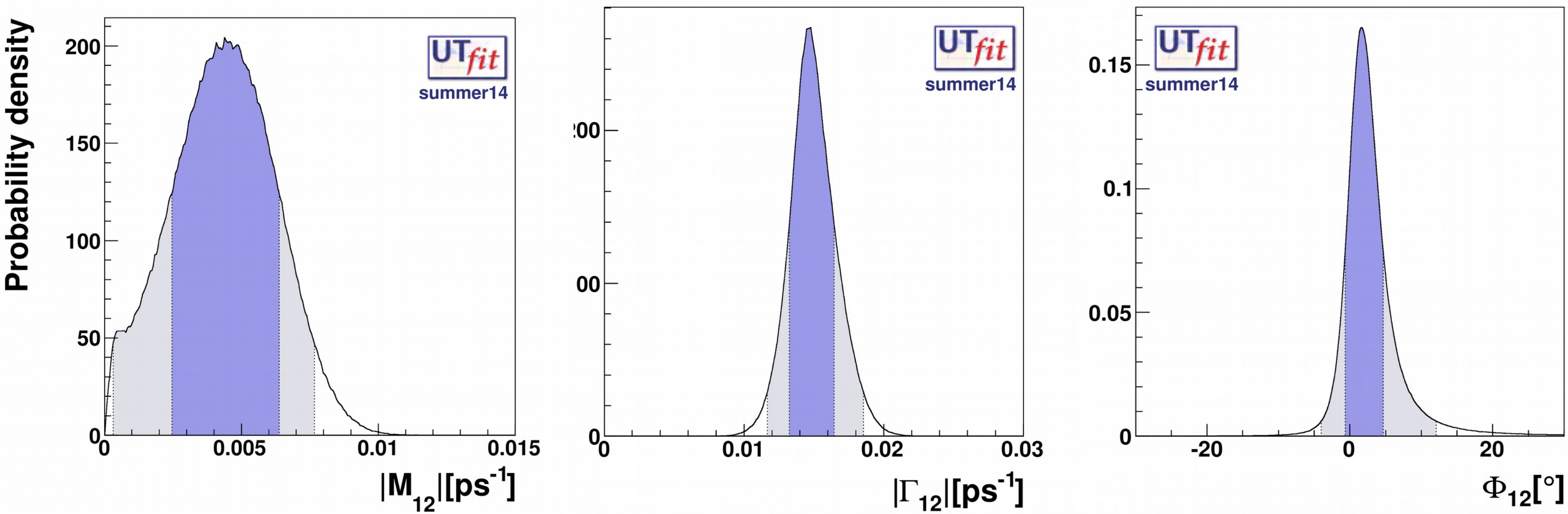
$$x = (3.6 \pm 1.6)\ 10^{-3},\ y = (6.1 \pm 0.6)\ 10^{-3},$$
$$|q/p|-1 = (1.6 \pm 1.8)\ 10^{-2},$$
$$\phi = \arg(q/p) = (0.45 \pm 0.56)^\circ$$



CPV IN MIXING TODAY II

- The corresponding results on fundamental parameters are

$$|M_{12}| = (4 \pm 2)/fs,\ |\Gamma_{12}| = (15 \pm 2)/fs$$
$$\text{and } \Phi_{12} = (2 \pm 3)^\circ$$



IMPLICATIONS ON NP SCALE

	95% upper limit (GeV^{-2})	Lower limit on Λ (TeV)
$\mathrm{Im}\, C_1^D$	$[-0.9, 2.5] \cdot 10^{-14}$	$6.3 \cdot 10^3$
$\mathrm{Im}\, C_2^D$	$[-2.8, 1.0] \cdot 10^{-15}$	$1.9 \cdot 10^4$
$\mathrm{Im}\, C_3^D$	$[-3.0, 8.6] \cdot 10^{-14}$	$3.4 \cdot 10^3$
$\mathrm{Im}\, C_4^D$	$[-2.7, 8.0] \cdot 10^{-16}$	$3.5 \cdot 10^4$
$\mathrm{Im}\, C_5^D$	$[-0.4, 1.1] \cdot 10^{-14}$	$9.5 \cdot 10^3$

$\sqrt{\left\vert \mathrm{Im}\, (\delta_{12}^u)^2_{LL,RR} \right\vert}$	$\sqrt{\left\vert \mathrm{Im}\, (\delta_{12}^u)^2_{LR,RL} \right\vert}$	$\sqrt{\left\vert \mathrm{Im}\, (\delta_{12}^u)^2_{LL=RR} \right\vert}$
0.019	0.0025	0.0011

1 TeV squark & gluino

Carrasco et al.

BEYOND THE "REAL SM"

- Belle II and LHCb upgrade will considerably improve the sensitivity to CPV in charm mixing
- Should critically re-examine the statement of negligible CPV in the SM:
  - Could CPV amplitudes be dynamically enhanced?
  - Is the SU(3)/U-spin argument reliable?

BEYOND THE "REAL SM" II

- Relax the assumption of real Γ_{12}, introduce $\phi_{\Gamma 12} = \arg \Gamma_{12}$
- The relation between ϕ, x, y and δ is modified as follows:
  - $\phi = \arg(q/p) = \arg(y+i\delta x) - \phi_{\Gamma 12}$
- Can we extract $\phi_{\Gamma 12}$ from experimental data?
- How large can $\phi_{\Gamma 12}$ be in the SM?

BEYOND THE "REAL SM" III

- In principle, if decay amplitudes are not real, they affect the extraction of ϕ:

  $\phi \to \phi + \delta\phi_f$, with $\delta\phi_f = \arg(\bar{A}_f / A_f)$ (f CP eig.)

- for CA and DCS decays, $\delta\phi_f$ negligible
- for SCS decays, $\delta\phi_f = A_{CP}^{dir}(D \to f) \cot \delta_f$ (δ_f strong phase difference, expected O(1))
- present data on DCPV imply $\delta\phi_f \sim 10^{-3}$

BEYOND THE "REAL SM" IV

- CPV contributions to $\phi_{\Gamma 12}$ are enhanced by $1/\varepsilon$, while this is not the case for $\delta\phi_f$
- can go beyond the "real SM" approximation by adding one universal phase $\phi_{\Gamma 12}$ and fitting for ϕ_{12} and $\phi_{\Gamma 12}$ or, equivalently, for ϕ_{M12} and $\phi_{\Gamma 12}$

CHARM CPV @ LHCb UPGRADE

- Expected errors w. LHCb upgrade:
  - δx=1.5 10^{-4}, $\delta y=10^{-4}$, $\delta|q/p|=10^{-2}$, $\delta\phi=3°$ (from $K_s\pi\pi$); $\delta y_{CP}=\delta A_\Gamma$=4 10^{-5} (from K^+K^-)
- Allows to experimentally determine $\phi_{\Gamma 12}$ with a reach on CPV @ the degree level:
  - $\delta\phi_{M12} = \pm 1°$ (17 mrad) and $\delta\phi_{\Gamma 12} = \pm 2°$ (34 mrad) @ 95% prob.
  - $\Lambda > 10^5$ TeV

CHARM CPV @ HI-LUMI

- "Extreme" flavour experiment (LHCb upgrade L x 100)

  see e.g. talk by G. Punzi @ 1st Future Hadron Collider Workshop

- Naïve extrapolation, scaling LHCb upgrade estimates:
  - δx=1.5 10^{-5}, δy=10^{-5}, $\delta|q/p|$=10^{-3}, $\delta\phi$=.3° (from $K_s\pi\pi$); δy_{CP}=δA_Γ=4 10^{-6} (from K^+K^-)
  - $\delta\phi_{M12}$ = ± 0.1° (1.7 mrad) and $\delta\phi_{\Gamma 12}$ = ± 0.2° (3.4 mrad) @ 95% prob.
  - Λ>3 10^5 TeV, close to the bound from ε_K

CAN WE ESTIMATE $\phi_{\Gamma 12}$ IN SM?

- $\Gamma_{12} = \Gamma_{12}^{0} + \delta\Gamma_{12} = \lambda_s^2\,(\Delta U=2) + \lambda_s\lambda_b\,(\Delta U=2 + \Delta U=1) + O(\lambda_b^2) \sim \lambda_s^2\,\Gamma_5 + \lambda_s\lambda_b\,\Gamma_3$
- Γ_5 changes Uspin by two units, arises @ $O(\varepsilon^2)$
- Γ_3 changes Uspin by one unit, arises @ $O(\varepsilon)$
- Trade Γ_{12}^{0} for $y\Gamma$, get
  $\phi_{\Gamma 12} \sim \mathrm{Im}\,\lambda_s\lambda_b/y\;\Gamma_3/\Gamma \sim 5\;10^{-3}\,\Gamma_3/\Gamma$

ESTIMATING Γ_3/Γ

- Γ_3 generated by SCS decay amplitudes
- two-body decays account for 75% of hadronic D decays, with PP~VV~AP~PV/3
- use exp data on BR's and DCPV to perform SU(3) analysis and estimate Γ_3, using e.g. the general parameterization of U-spin amplitudes in SCS decays by Brod, Kagan, Grossman & Zupan

ESTIMATING Γ_3/Γ II

- analysis of U-spin amplitudes suggests that currently $\Gamma_3/\Gamma \sim 1$ is plausible, and also that $\phi_{\Gamma 12}/\delta\phi_f \sim 4$, as previously argued, yielding

  $$\phi_{\Gamma 12} \sim 5 \text{ mrad } (0.3°)$$

  and leaving plenty of room for NP
- more data, in particular for PV SCS decays, would allow for a better estimate of $\phi_{\Gamma 12}$
- ϕ_{M12} might be estimated via dispersion rel.

CPV IN SCS D DECAYS

- CPV in SCS D decays suppressed by $r = \mathrm{Im}\, \lambda_b/\lambda_s = 6.5\ 10^{-4}$. Can it be dynamically enhanced?

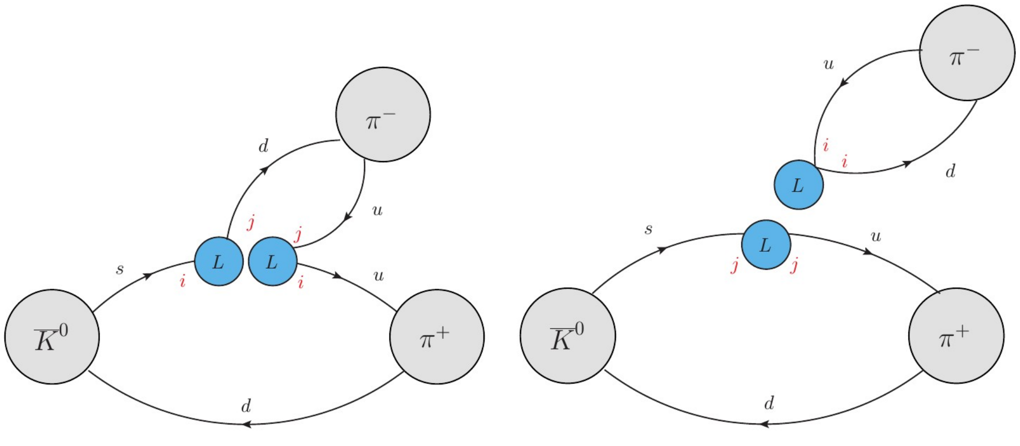
Brod, Kagan & Zupan '11; Pirtskhalava & Uttayarat '11; Bhattacharya, Gronau & Rosner '12; Cheng & Chiang '12; Brod, Grossman, Kagan & Zupan '12

- Can anything analogous to the $\Delta I = 1/2$ rule take place in SCS charm decays?

Golden & Grinstein, '89

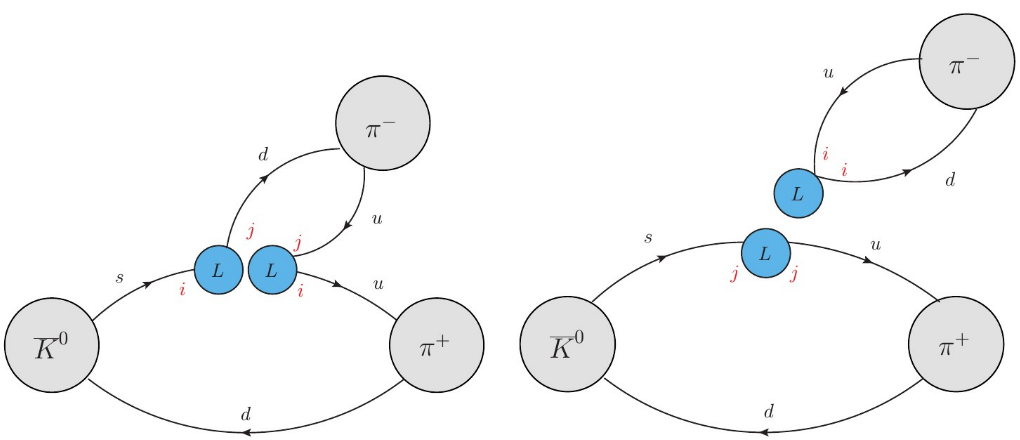
PENGUINS FROM K TO B

- What is the origin of the ΔI=1/2 rule in K decays? RBC-UKQCD lattice studies suggest a cancellation between connected and disconnected emission contributions to ΔI=3/2 amplitudes, which instead add up in the ΔI=1/2 case. Penguins play a minor role.



(a) *"Connected"* (b) *"Disconnected"*

- This corresponds to a maximal violation of VIA: the connected contribution has opposite sign in full QCD (cfr. large-N model estimate by Bardeen, Buras & Gérard)
- Is there a connection between the $\Delta I=1/2$ rule and the validity of naïve factorization for emission topologies?

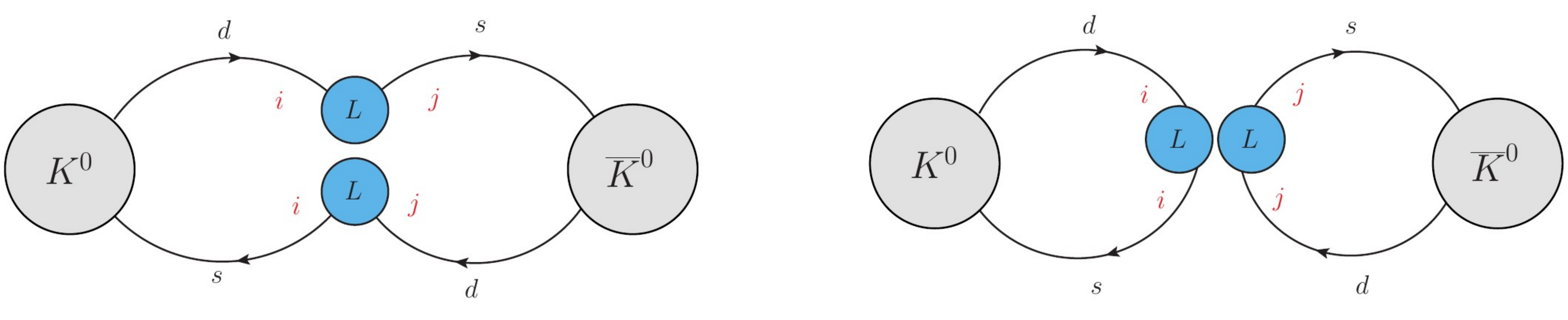


(a) *"Connected"* (b) *"Disconnected"*

- K physics: maximal deviation from the VIA, large suppression of $\Delta I=3/2$ amplitude
- D physics: sizable deviations from naïve factorization ($1/N \sim 0$), comparable $\Delta I=1/2$ and $\Delta I=3/2$ amplitudes with large phases
- B physics: factorization holds in the infinite mass limit and gives a good description of data once enhanced corrections taken into account, small phases

VIA VIOLATIONS IN ΔF=2

- Same violation of VIA seen in Δs=2: indeed the K-K and K→ππ matrix elements are proportional in the chiral limit
- Interesting to check whether the deviation from the VIA decreases for heavier mesons



(a) *"Connected"* (b) *"Disconnected"*

VIA VIOLATIONS IN $\Delta F=2$

	K	D_s	B_s	static limit
R^{λ}_{VV+AA}	-1.90(07)	-0.64(02)	-0.46(06)	-0.38(09)
R^{λ}_{VV-AA}	4.3(2)	0.60(05)	0.12(05)	-0.03(05)
R^{λ}_{SS-PP}	-0.13(03)	-0.11(03)	-0.07(03)	-0.05(03)
R^{λ}_{SS+PP}	-0.27(06)	-0.21(04)	-0.15(03)	-0.12(04)
$R^{\lambda}_{SS+PP-TT/2}$	4.04(16)	1.40(07)	0.81(06)	0.61(06)

Carrasco, Lubicz & L.S.

- R^{λ} is the octect matrix element, which vanishes in the VIA, normalized by the singlet matrix element

BACK TO CPV IN SCS DECAYS

- A consistent picture seems to emerge from lattice studies of $K \to \pi\pi$ and $\Delta F=2$:
  - suppression of 3/2 and enhancement of ½ amplitude in K decays due to emission diagrams; no penguin enhancement
  - deviations from VIA less dramatic but sizable in D decays; no reason to expect large penguins
- No compelling arguments for enhanced SM CPV in SCS D decays

CONCLUSIONS

- Given present experimental errors, SM contributions to CPV in mixing-related observables can be safely neglected, yielding a constrained three-parameter fit (M_{12}, Γ_{12}, ϕ_{12}) which allows to probe NP at the % level
- future experimental improvements will however go well below the %, reaching a level in which SM CPV contributions might be non-negligible

CONCLUSIONS II

- Given the SU(3) structure of $\Delta c=1$ and $\Delta c=2$ amplitudes, CPV contributions to Γ_{12} are parametrically enhanced over CPV contributions to decay amplitudes
- Moreover, the latter are already constrained to lie below the future sensitivity in ϕ, and essentially vanish in the SM
- Generalizing the fit introducing $\phi_{\Gamma 12}$ captures dominant SM effects

CONCLUSIONS III

- Belle II/LHCb upgrade will probe ϕ_{M12} and $\phi_{\Gamma 12}$ at the level of 1°, while an "extreme" flavour experiment might reach the 0.1° level
- $\phi_{\Gamma 12}$ can be estimated using fits of SCS decay amplitudes (in particular PV ones)
- at present $\phi_{\Gamma 12}$ at the 0.3° level is plausible, but more data needed to refine this estimate; may also estimate ϕ_{M12} via disp. rel.

CONCLUSIONS IV

- Lattice QCD starts providing a consistent picture of deviations from the VIA in K, D and B physics
- If confirmed by the full computation of $\Delta I=1/2$ rule, would exclude large penguin matrix elements
- Excluding large penguins, SM contributions to CPV in SCS D decays can be kept under control