Aspects of charm theory

Roman Zwicky
Edinburgh University

aims of charm physics:

- test the Standard Model (**new physics** search)
- over-**constrain CKM**-matrix (reduce uncertainties B,K-physics)
- **quantitative** and **qualitative description** of nature

- charm theory for this talk means study of decay of D-mesons $\bar{c}q$
- SM-flavour governed CKM-elements from where we learn the two major points:

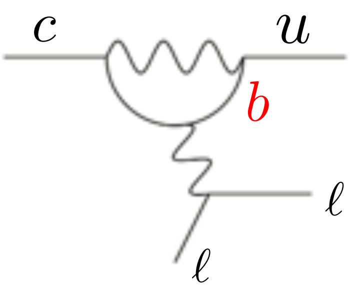
$$|V_{\mathrm{CKM}}| = \uparrow\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |\underline{V_{cd}}| & |\underline{V_{cs}}| & |\underline{V_{cb}}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

Cabibbo-angle
$\lambda \approx 0.23$

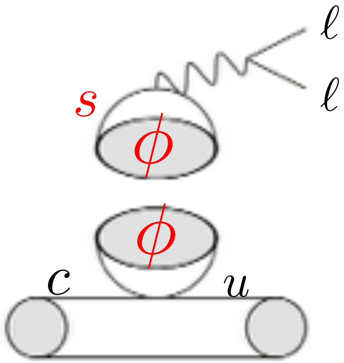
c→u,d,s governed by the **two light** generations

A. CP-violation small: O(λ^4). **Null test for SM**
B. **dominance of long distance** (LD) over short distance (different B-physics). opportunity **test long distance tools**

e.g. $c \to u\ell\ell$



short distance O(λ^5)



long distance O(λ)

Overview

(A) **basics** of D-physics [5 slides]

- CP-violation null-test and long distance dominance (done)
- decay types: leptonic, semi-leptonic, non-leptonic
- D-mixing

(B) **non-leptonic** modes (CP-violation) [4 slides]

- approaches to non-leptonic D modes
- flavour symmetries $SU(3)_F$,Iso,U,V-spin
- direct CP-asymmetry D→2-body
- D→3,4-body decays

theory: difficult
use isospin, U-spin
$SU(3)_F$-symetries

(C) **rare decays** (potential for future) [4 slides]

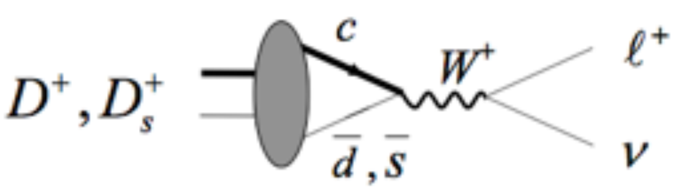
- $D \to V\gamma$
- issue of colour suppression
- $D \to V,P\ ll$ — master resonances

theory: under
developed
(potential!)

decay-types

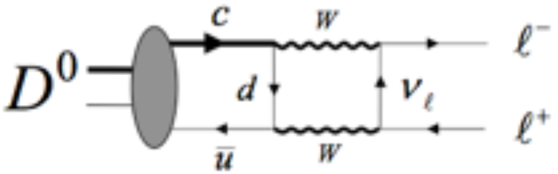
a) leptonic

tree



$$\mathcal{B}(D_q^+ \to \ell^+\nu) \simeq 5 \cdot 10^{-2} \left| \frac{m_\ell V_{\rm cq} f_{D_q}^+}{m_\tau V_{\rm cs} f_{D_q}^+} \right|^2$$

rare(FCNC)

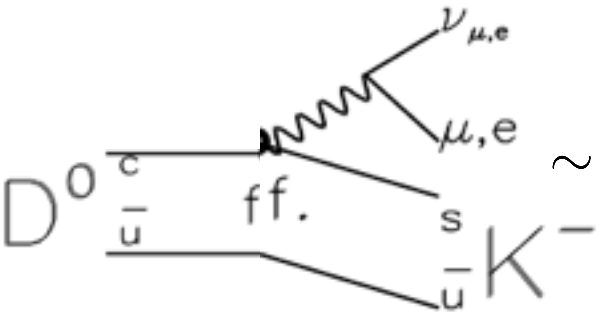


$$\mathcal{B}(D^0 \to \ell\ell) \sim O(10^{-11} \left| \frac{m_\ell}{m_\tau} \right|^2)$$

additional suppression: 1. GIM 2. loop

BSM down to 10^{-6}

b) semi-leptonic



$$\sim |V_{\rm cq} f_+(q^2)|^2$$

$$\mathcal{B}(D^0 \to \pi^- e^+ \nu) \simeq 1.6 \cdot 10^{-3}$$

form factor and no helicity (m_ℓ) suprression

$$D \to V\gamma\ , \quad D \to P, V\ell\ell$$

- long distance dominated (contrary B-decays)
- rich observables (later)

interplay extraction prediction of $|V_{\rm cq}|$ and *computable* f_D, $f_+(q^2)$

e.g. talk Ma

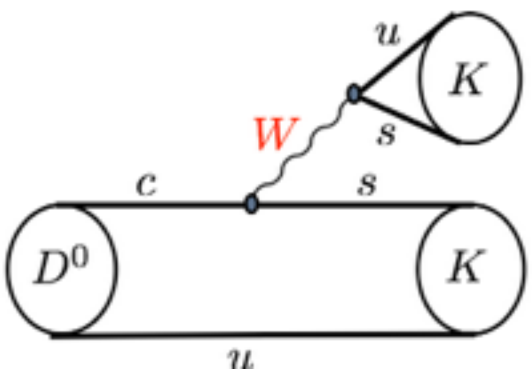
partly computable (LD)
BSM-search

c) non-leptonic

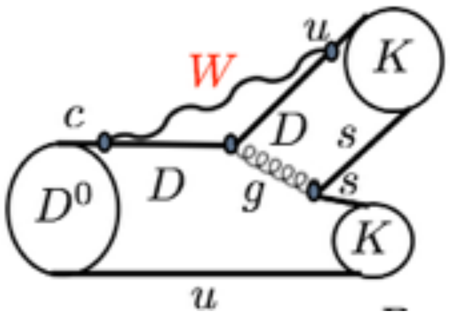
$D \to PP, PV, VV$ *very hard to compute* *(later)*

example topologies: $D^0 \to KK$

Tree T_s



Penguin P



- **Δs-Rule:** c→Δs=(1,0,-1) amplitude O($\lambda^0, \lambda^1, \lambda^2$)
Cabibbo allowed (CA), single C suppressed (SCS), double C suppressed (DCS)

$$\mathcal{B} \simeq 10^{-2} \qquad \simeq 10^{-3} \qquad \simeq 10^{-4}$$

- Copious decay modes → test CP-violation (BSM-signal)

D-Mixing
of importance for CP-violation

- D^0 and D^0 can decay same state ⟹ **D-mixing**

$$i\frac{d}{dt}\begin{pmatrix}|D(t)\rangle\\|\bar{D}(t)\rangle\end{pmatrix}=\left(M-i\frac{\Gamma}{2}\right)\begin{pmatrix}|D(t)\rangle\\|\bar{D}(t)\rangle\end{pmatrix}$$

long-distance

$$7-\text{numbers}\overset{\text{CPT}}{\rightarrow}5-\text{numbers}$$

$$\boxed{\begin{array}{lll} M_{\mathrm{L}} & \Delta M = M_H - M_L & \delta_{\mathrm{CP}} = |p|^2 - |q|^2 \\ \Gamma_{\mathrm{L}} & \Delta\Gamma = \Gamma_H - \Gamma_L & \end{array}}$$

flavour to mass eigenstate: $|D_{H,L}\rangle = p|D^0\rangle \mp q|\bar{D}^0\rangle$

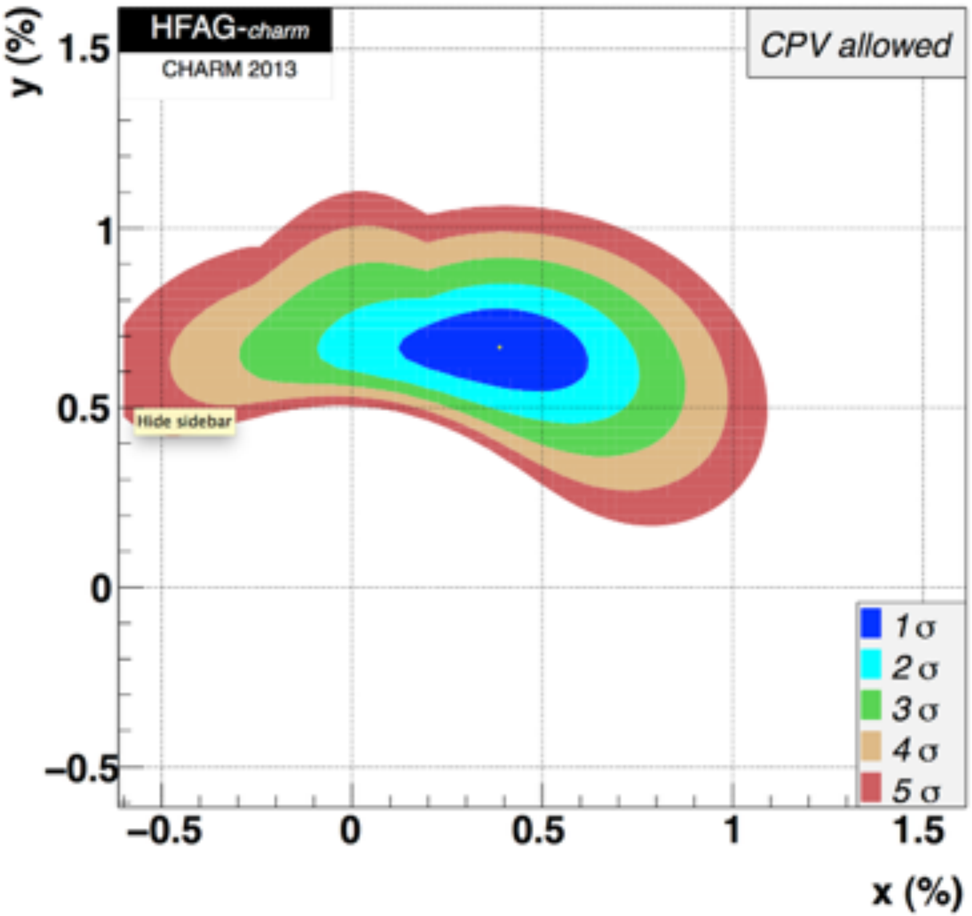
- **mixing established** 2007 combined CDF, BaBar and Belle
  2013 LHCb individual 9.1σ PRL 110 (2013)

- oscillation parameters $x \equiv \frac{\Delta M}{\Gamma}$, $y \equiv \frac{\Delta\Gamma}{2\Gamma}$ hard to compute (LD)

$$x, y|_{\text{SM}} \sim \lambda^2 \cdot SU(3)_F^{\text{break}} = 0.04^{m_s^2/m_c^2}_{m_K^2/m_D^2} \simeq \begin{matrix} 4{\cdot}10^{-4} \\ 1{\cdot}10^{-2} \end{matrix}$$

Δs-rule & GIM

- HFAG (experiment)



- spectrum of theory predictions
  - OPE 1/m$_c$ (partons)

    LO term GIM cancellation x(y)~$10^{-5(7)}$

    6-quark GIM relieved x(y)~10^{-3}

    Georgi, Ohl et al, Bigi, Uraltsev ca 92-93

    need m-elements (lattice)

    cannot exclude y ~10^{-2} Bobrowwsli et al 10

    bag-parameters missing (lattice)
  - hadrons

    x~10^{-2} dispersion relation Falk et al ‘04

    saturation D→PP,PV states x(y)~10^{-3}

    Cheng et al 10

    y~10^{-3} phase space effects Falk et al ’02 …

- comparison with three other neutral mesons that mix

	x	y	δ_{CP}
K^0	0.474	0.997	$3.32(6)10^{-3}$
B^0	$0.774(6)$	< 0.01	~ 0
B_s	$26.85(13)$	$7.5(12) \cdot 10^{-2}$	~ 0
D^0	$< 10^{-2}$	$8.66(155) \cdot 10^{-3}$	~ 0

$\Longrightarrow$

A. D^0-oscillation are slow

B. no evidence CP-violation in charm yet.

non-leptonic D-decays

A. amplitudes: hard to compute
B. CP-violation (quasi null test)

$\Longrightarrow$ to capitalise on B. for BSM-search
semi-quantitive knowledge A. seems necessary

delicate point

approaches to on-leptonic decays

- QCDF Λ/m_c -corrections too large (already sizeable Λ/m_b) - let alone FSI

- LCSR (not a Λ/m_c-expansion) could do à la Khodjamirian et al for B→ππ
  - Not yet explored.
  - Assume can compute "bare amplitude" (no FSI).
    Would FSI modify magnitude as well as phase? (like in K→ππ unlike B→ππ)

- Lattice proposal D→PP Hansen, Sharpe '12 following Lellouch-Lüscher K→ππ
  LL-works because single channel ππ
  HS generalised multichannel case PP = {KK,ππ}-system 2x2 rescattering

establishing (direct) charm CP-violation in SM

- 3 ingredients: 1) weak & 2) strong phase difference & 3) sizeable Δ

$$A_{\rm CP}^{\rm direct} = \frac{2\Delta \sin(\delta_{12}^{\rm strong}) \sin(\phi_{12}^{\rm weak})}{1+2\Delta \cos(\delta_{12}^{\rm strong}) \cos(\phi_{12}^{\rm weak})+\Delta^2}$$

$$\Delta \equiv \frac{A_2}{A_1}$$

likely sizeable D-decays
e.g. D→Kπ isospin analysis

looking for

largest in SCS in SM (MFV)

SCS benchmark value: $A_{CP} < 10^{-3}$
$D^0 \to K^+K^-, \pi^+, \pi^-, D_S^+ \to K_S, \pi + ..$

CA/DCS benchmark value:
untagged $A_{CP} < 10^{-3}\,\lambda^2$ $D^0 \to K^+\pi^-, ..$

- **ΔA_{CP}-excitement in 2011** — LHCb challenging benchmark (lots theory activity)

$$\Delta A_{\rm CP}^{\rm dir} = A_{\rm CP}^{K+K-} - A_{\rm CP}^{\pi+\pi-} = -0.82(21)(11) \cdot 10^{-2}$$

how large penguin be in SM?

$$\Delta A_{\rm CP}^{\rm dir}|_{\rm HFAG}^{2014} = -0.253(104) \cdot 10^{-2}$$

LHCb semileptonic tag

$\Longrightarrow$ current results less compelling — search for CP-violation charm continues

e.g. talk Carbone

Flavour symmetries

$SU(3)_F$

$m_u = m_d = m_s$
or $m_\pi = m_K (= m_\eta)$

$SU(2)-$subgroups

isospin $(u \leftrightarrow d)$

U-spin $(d \leftrightarrow s)$

V-spin $(u \leftrightarrow s)$

good symmetry

isospin analysis

(Grossman, Kagan, Zupan'12)

- e.g. penguin ΔI=1/2

$$D^+ \to \pi^+\pi^0|^{\rm SM}_{\Delta I=3/2}$$

$$A_{\rm CP}(D^+ \to \pi^+\pi^0) = 0$$

- sum rules
D→ρ(K*)π

large corrections

- an extreme example U-spin zero

$$\frac{|A(D^0 \to K^+K^-|}{|A(D^0 \to \pi^+\pi^-|} - 1 = 0.82(2)$$

- parameterise SU(3)$_F$ -breaking mass-spurion

⟹ proliferation of parameters (unless assumptions)

⟹ SU(3)-breaking ca 30% — penguin >> tree

back how large penguin be in SM?

CP-violation in 3-4 body final states

Bigi, Paul, ….

- $\Gamma_X \overset{CPT}{=} \Gamma_{\bar{X}}$ $\Longrightarrow$ the more inclusive the less CP
- principal motivation for 3-4 body decays (differential distributions)

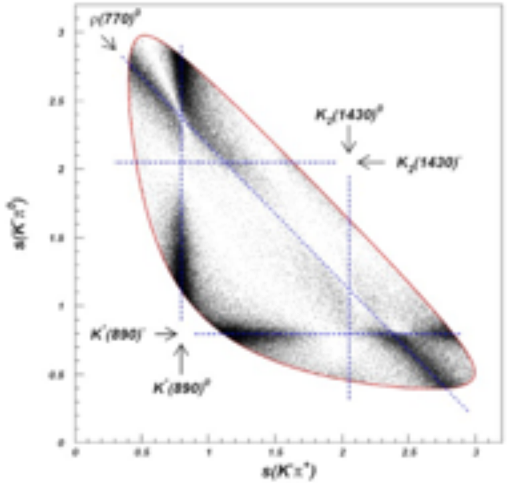
a) **3 scalars**: **Dalitz-plot** — 2 variable-PS

- e.g. resonance-region of CP-conj. channels
  Miranda-method (inspired astronomer techniques)

$$\Delta_{\rm CP}^{i{\rm bin}} = \frac{N_i - \bar{N}_i}{N_i + \bar{N}_i} \to \frac{N_i - \bar{N}_i}{\sqrt{N_i + \bar{N}_i}}$$

to look for signals in Dalitz-space

$D \to K^- \pi^+ \pi^0$



b) **polarised charm mesons** $\Lambda_c \to p\pi^+\pi^-$
beyond Dalitz more variables T-odd observables …

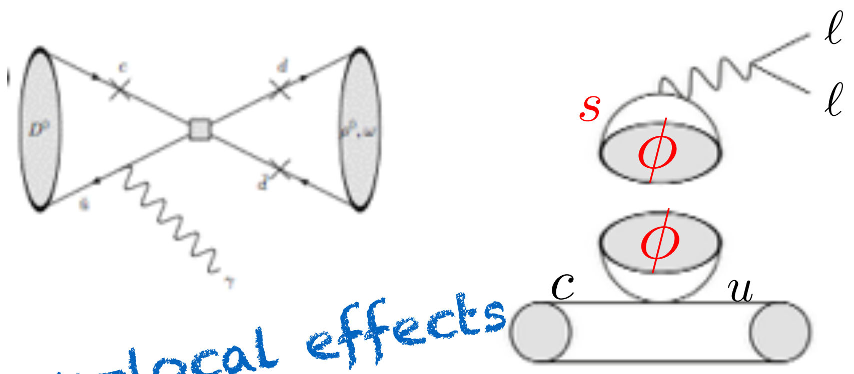
c) **4 body** decays aka $D^0 \to \pi\pi KK$ (à la angular analysis $B \to K^* ll$ at LHCb)
5 variable-PS $\Longrightarrow$ possibilities proliferate ….

rare D-decays

focus D→Vɣ and D→V(→PP)ll

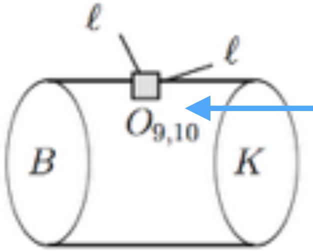
CKM-hierarchy

D-physics LD-dominated



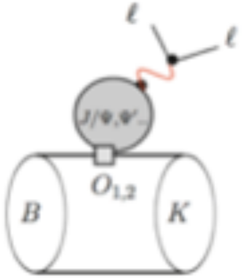
non-local effects

B-physics SD-dominated



local operator transition

Yet charm resonances (LD) matter! Lyon RZ'14

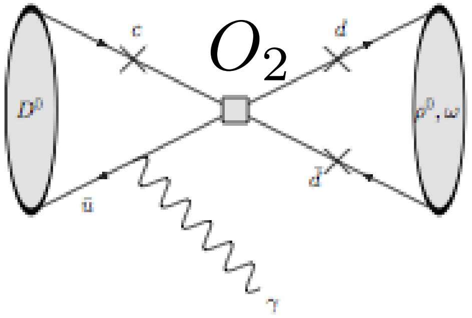


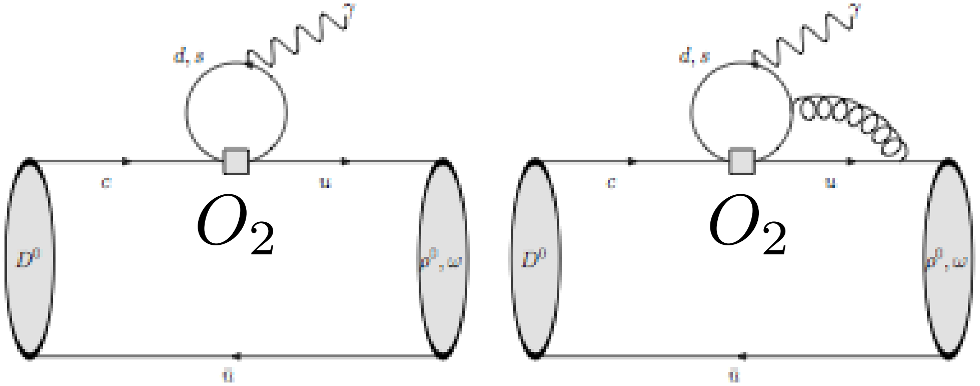
1. plausible candidate of B-K*ll-anomalies
2. on [4m$_D^2$,(m$_B$-m$_K$)^2] duality fails by roughly a factor of seven. new physics in b→ccs?

LD-predictions - D→Vɣ test-ground

- D→Vɣ only two BF measured $\Longrightarrow$ what dominates BF?
- our view Lyon RZ'12 weak annihilation (use LCSR *not rely on 1/m_h)*

A)





hadronic effects when on-shell cuts

weak annihilation (WA)

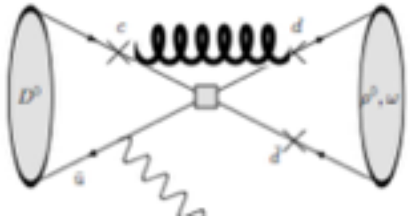
quarkloops (QL)

loops:	tree O(1)	1-loop: 0 gauge invariance	2-loop: O(10^{-2})
GIM supp.:	no	yes	yes

$\Longrightarrow$ weak annihilation dominates - yet an issue D^0-modes ….

colour-suppression

- tree-level WC $a_2 = (C_2/3+C_1)(m_D) \sim 0.1$ accidentally small (don't trust)
  - $a_2^{\text{eff}}|_{\text{non-leptonic}} \sim 0.5$ then $BF(D^0 \to K^*, \phi\gamma)$ well described
  - importance $O(\alpha_s)$-correction (hard task)



$\Longrightarrow$ please measure D^+-modes crucial in validating theory

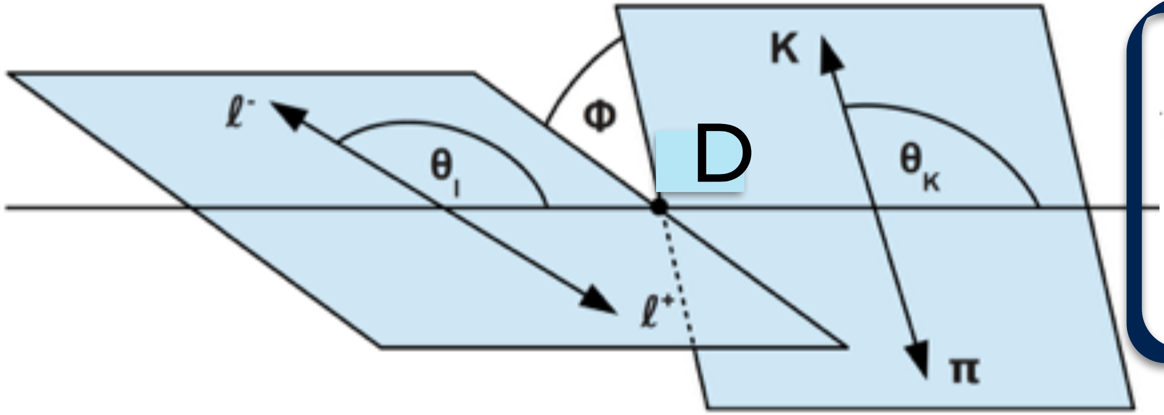
decay	FCNC-type	transition	Cab.	c.s.	$\mathcal{B}(D \to V\gamma)$
$D^0 \to (\rho^0, \omega)\gamma/ll$	$c \to u$	$c\bar{u} \to d\bar{d}$	λ^1	yes	$6 \cdot 10^{-6}(a_2/0.5)^2$ LZ'12
$D^0 \to \phi\gamma/ll$	$c \to u$	$c\bar{u} \to s\bar{s}$	λ^1	yes	$2.70(35)10^{-5}$ PDG
$D^0 \to \bar{K}^{0,*}\gamma/ll$	no	$c\bar{u} \to s\bar{d}$	λ^0	yes	$3.27(32)10^{-4}$ PDG
$D^+_{(d,s)} \to (\rho, K^*)^+\gamma/ll$	$c \to u$	$c\bar{d}(\bar{s}) \to u\bar{d}(\bar{s})$	λ^1	no	$(0.7, 1.3)10^{-6}$ LZ'12
$D^+_s \to \rho^+\gamma/ll$	no	$c\bar{s} \to u\bar{d}$	λ^0	no	$1.3 \cdot 10^{-5} \simeq 0.7 \cdot 10^{-6}/\lambda^2$

- once validate theory charged modes, test cuqq-operators in FCNC …

D →P,Vll

“wrt D→Vγ highlight three aspects”

- D→V(→PP)ll get helicity amplitudes from angular distribution as currently done B→K*(→Kπ)ll at LHCb



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = (J_{1s} + J_{2s}\cos 2\theta_\ell + J_{6s}\cos\theta_\ell)\sin^2\theta_K$$
$$+ (J_{1c} + J_{2c}\cos 2\theta_\ell + J_{6c}\cos\theta_\ell)\cos^2\theta_K$$
$$+ (J_3\cos 2\phi + J_9\sin 2\phi)\sin^2\theta_K\sin^2\theta_\ell$$
$$+ (J_4\cos\phi + J_8\sin\phi)\sin 2\theta_K\sin 2\theta_\ell$$
$$+ (J_5\cos\phi + J_7\sin\phi)\sin 2\theta_K\sin\theta_\ell\,,$$

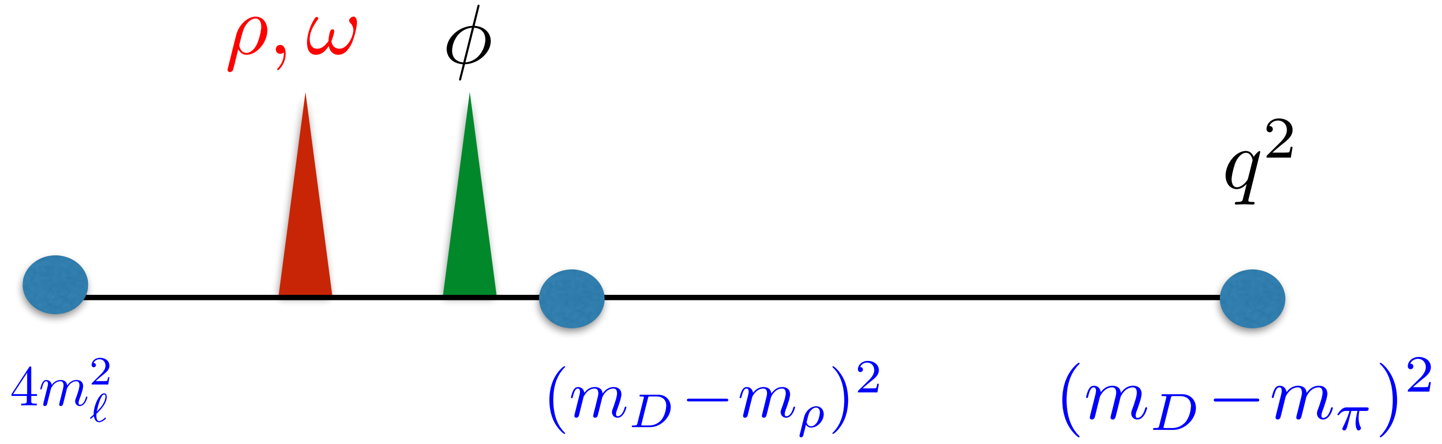
- Z-penguins tiny in SM

$$O_9 \sim (\bar{\ell}\gamma^\mu \ell)(\bar{u}\gamma_\mu(1-\gamma_5)c)$$
$$O_{10} \sim (\bar{\ell}\gamma^\mu \gamma_5 \ell)(\bar{u}\gamma_\mu(1-\gamma_5)c)$$

⟹ observables depending on O$_{10}$ are (quasi) null-test of the SM (no need for precise predictions there)

e.g. Burdman et al’ 01
Bigi, Paul, Recksiegel ‘11

- prominent resonances D→π(ρ→ll) through quark loops (become important!)



One benefit of H→Pll is q^2-dependence ⟹ need control resonances

- perform same program as for B→K(Ψ→ll)

$$A(D \to \pi \ell\ell)|_{q^2 \simeq m_\rho^2} \sim \frac{r_\rho}{q^2 - m_\rho^2 + i m_\rho \Gamma_\rho(q^2)} + \text{interference}$$

$$r_\rho \sim \underset{\substack{\uparrow \\ \text{fit}}}{e^{i\delta_\rho}} \, |A(D \to \rho\pi)||A(\rho \to \ell\ell)|$$

fit respective branching fractions

Summary main points

- **CP-violation** in **charm not** yet been **established**
- smallness of **CP in charm O(λ^4)** attractive **SM null-test**
  e.g. in D→PP,PV,VV yet SM-CP hard to predict by itself since

- do **not** (yet) have **quantitative approach** to
  non-leptonic D-decays (notorious problem FSI)

- **rare decays:** underdeveloped *(potential in my view)*
  - more control over matrix elements (than typically thought)
  - can be tested in non-FCNC decays
  - largely avoids FSI (problematic in non-leptonic)
  - for D→Vll lots of observables — need control ρ,ϕ-reson.

The End -- Thank You

apologies for omitted topics (backup)

BACKUP

topics not covered

- constraints from D-mixing on BSM-operators

  e.g. Gedalia, Grossman, Nir, Perez
  Golowich, Hewett, Pakvasa, Petrov'07

- more details on SU(3)F-fits e.g. Grossman Robinson, Hiller, Schacht, Jung, Gronau, Rosner…'12,13
- rare decays: details work of Faijfer, Singer, Zupan'01 …

  e.g. $\mathcal{B}(D^0 \to \gamma\gamma) \simeq 10^{-8} \quad (< 2.4 \cdot 10^{-6})_{\rm exp}$

  N.B. SD 10^{-12} Bigi, Paul Recksigel '11 …

- constraints between mixing and rare decays

  Golowich, Hewett, Pakvasa, Petrov'09

- untagged CP asymmetries Petrov'04

More on D→Vɣ $A_{CP}(t)$ LZ’12

$$A_{\mathrm{CP}}(D \to V\gamma)[t] = \frac{S\sin(\Delta m_D t) - C\cos(\Delta m_D t)}{\cosh(\frac{\Delta\Gamma_D}{2}t) - H\sinh(\frac{\Delta\Gamma_D}{2}t)}$$

$$H[S] \simeq \frac{2l_L l_R}{l_L^2 + l_R^2} \cdot (-\xi\cos[\sin](\phi_D))$$

$\xi = \pm 1$ is the CP-eigenvalue

$l_{L,R} =$ Weak annihilation

Left-Right polarisation of γ

$$H[D^0 \to (\rho^0,\omega)\gamma] \simeq -0.5(1)\cos(\phi_D)\,, \qquad S[D^0 \to (\rho^0,\omega)\gamma] \simeq -0.5(1)\sin(\phi_D)$$