Charm Physics

Jure Zupan
u. of cincinnati

The landscape of Flavour Physics towards the high intensity era, Dec 9 2014, Pisa

OUTLINE

- the aim of this talk: give a status of charm physics at the end of 2014
  - what is the present exp. precision on CPV
    - CPV in D^0-$\bar{D}^0$ mixing, direct CPV
  - how large can it be in the SM
  - how to know if NP

INDIRECT CPV

D-Dbar mixing

- CP violation in D system CKM suppressed
  - using CKM unitarity can always rewrite amplitudes not to depend on λ_s

$$\lambda_d + \lambda_s + \lambda_b = 0 \qquad \lambda_q = V_{cq} V_{uq}^*$$

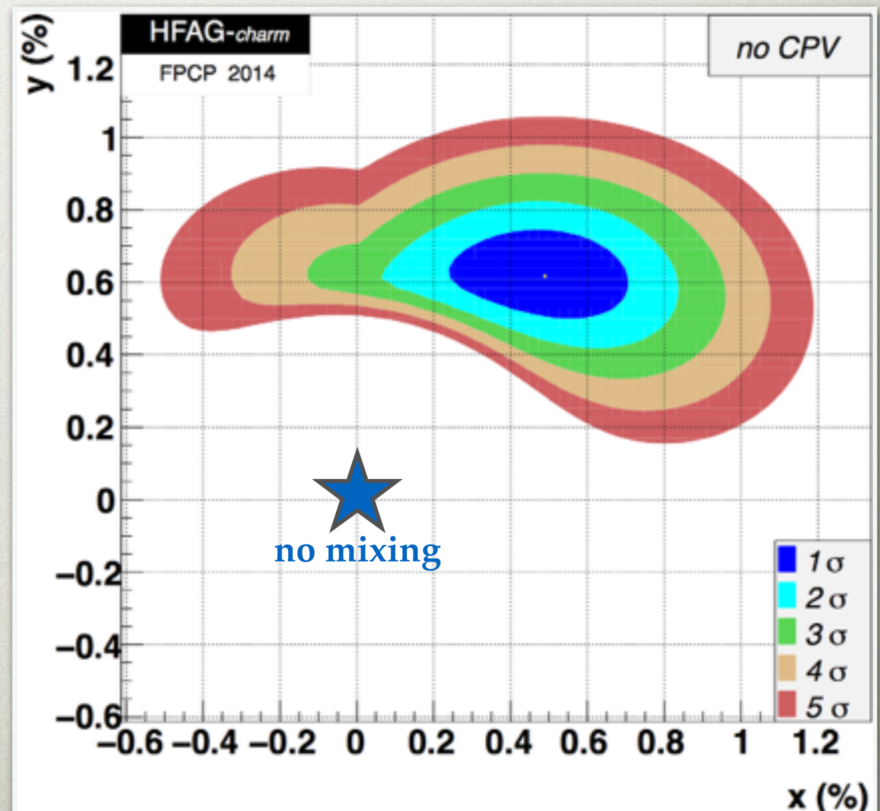
  - CPV thus suppressed by $Im[\lambda_b/\lambda_d] \sim 6.2 \times 10^{-4}$
- to a very good approximation D^0-$\bar{D}^0$ mixing is real in the SM
  - given by two CP conserving parameters

$$x = \frac{m_2 - m_1}{\Gamma}, \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

CONSTRAINED FIT

- with present precision a justifiable approx.
  - leads to a constrained fit by HFAG
  - *x,y~O(1%)*

x (%)	$0.49\,^{+0.14}_{-0.15}$
y (%)	0.62 ± 0.08



NEW PHYSICS

- CPV in D^0-$\bar{D}^0$ mix. at present precision would mean NP
- viable NP very likely off-shell in D^0-$\bar{D}^0$ mixing
  - would contribute to M_{12} (dispersive ampl.) not to Γ_{12} (absorptive ampl.)

$$\langle D^0|H|\overline{D^0}\rangle = M_{12} - \frac{i}{2}\Gamma_{12}\,, \quad \langle\overline{D^0}|H|D^0\rangle = M_{12}^* - \frac{i}{2}\Gamma_{12}^*$$

  - mixing parametrized with three parameters

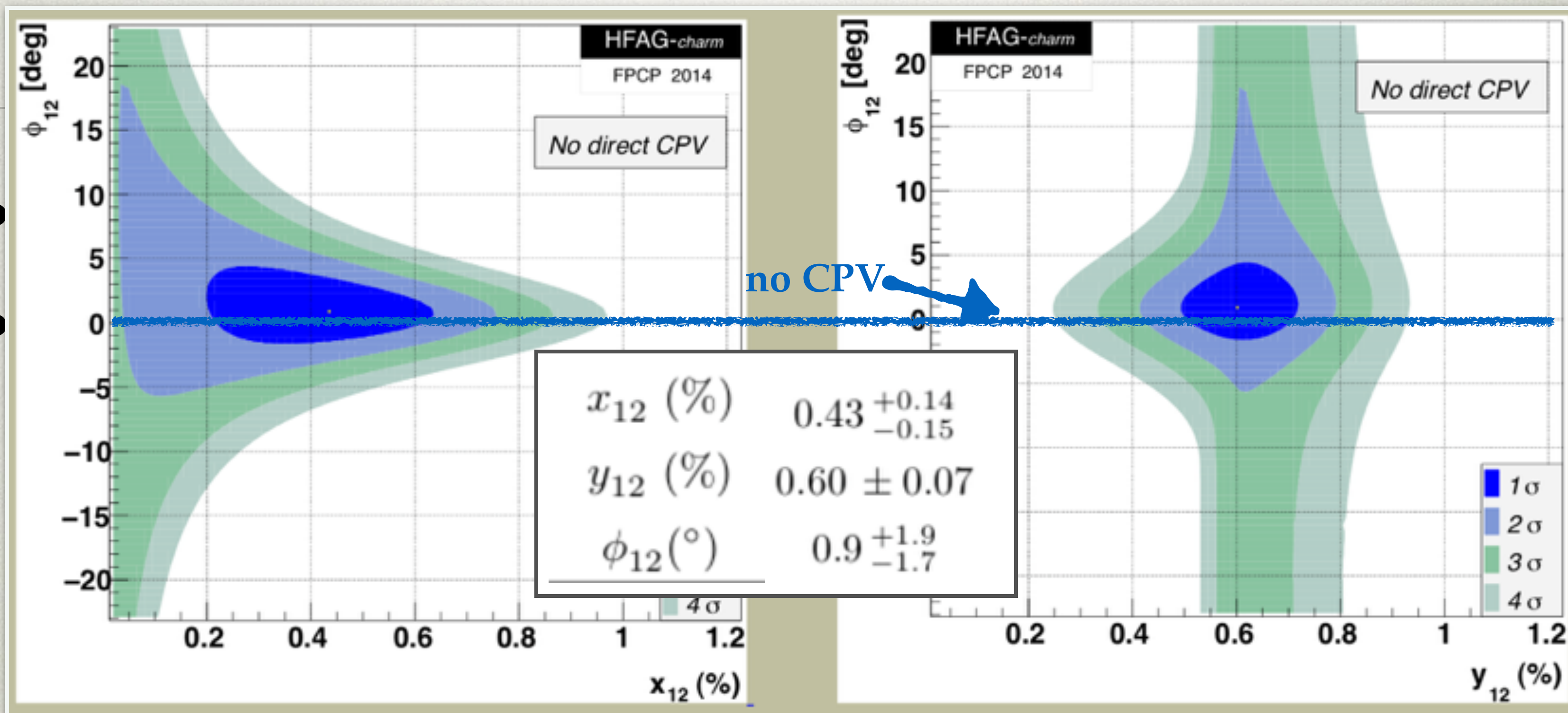
$$x_{12} \equiv 2|M_{12}|/\Gamma, \quad y_{12} \equiv |\Gamma_{12}|/\Gamma, \quad \phi_{12} \equiv \arg(M_{12}/\Gamma_{12})$$

  - this is the *superweak approximation*

Kagan, Sokoloff, 0907.3917;
Ciuchini et al, hep-ph/0703204;
Grossman et al, 0904.0305

- note: x_{12}, y_{12} related to x, y

$$|x| = x_{12} + O(\text{CPV}^2), \quad |y| = y_{12} + O(\text{CPV}^2)$$



x_{12} (%)	$0.43^{+0.14}_{-0.15}$
y_{12} (%)	0.60 ± 0.07
$\phi_{12}(^\circ)$	$0.9^{+1.9}_{-1.7}$

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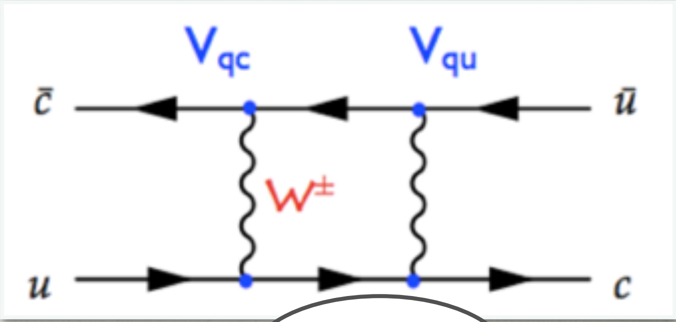
Kagan, talk at KEK-FF 2014; Silvestrini, talk at CKM2014

BEYOND SUPERWEAK



- what is the leading correction to the super-weak approximation?
- what is the size of ϕ_{12} in the SM?
- in the SM both M_{12} and Γ_{12} have the structure

O(ε)

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

O(ε²)

  - $\phi_{12}^{\Gamma} \equiv arg(\Gamma_{12})$ and $\phi_{12}^{M} \equiv arg(M_{12})$ enhanced by ~$O(1/\varepsilon)$
- note: no such enhancement for each individual direct CP asymmetry
- the parametrization of D mixing that is leading in SU(3) breaking is thus in terms of four parameters

$$x_{12}, y_{12}, \phi_{12}^M, \phi_{12}^\Gamma$$

Grossman, Kagan, Ligeti, Perez, Petrov, Silvestrini, unpublished;
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SM value

- from this also estimate for SM size of the weak mixing phase

$$\phi_{12}^{\Gamma} \sim \phi_{12}^{M} \sim \mathrm{Im}\left(\frac{\lambda_{\rm b}}{\lambda_{\rm d}}\right)\frac{1}{\epsilon} \sim 3 \times 10^{-3}$$

  - using for SU(3) breaking ε~0.2
  - more detailed estimates using sums over exclusive decay mode in agreement with this
- current fits: $\sigma(\phi_{12}^{\Gamma})\sim 10^{o}$, $\sigma(\phi_{12}^{M})\sim 3^{o}$

	$\lvert q/p\rvert - 1$	$\phi[^\circ]$	$\phi_\Gamma[\mathrm{rad}]$	$\phi_M[\mathrm{rad}]$
superweak fit	$(1.5 \pm 1.9)10^{-2}$	-0.4 ± 0.6	0	0.033 ± 0.047
two-parameter fit	$(4.6 \pm 0.7)10^{-2}$	3.2 ± 7.1	-0.09 ± 0.17	0.024 ± 0.06

- the parametrization of mixing with universal four parameters x_{12}, y_{12}, ϕ_{12}^{Γ}, ϕ_{12}^{M} valid for some NP
  - e.g., NP dominated by QCD peng., but not for EW peng.

SEARCHING FOR NP

- four parameter fit valid for the precision of the next generation of *B*-factories

Kagan, talk at KEK-FF 2014

Fit results for future scenarios

	ϕ_Γ [rad]		ϕ_M [rad]	
	input	fit	input	fit
LHCb/BelleII	0	0.0 ± 0.019	0	0.0 ± 0.007
extreme	0	0.0 ± 0.002	0	0.0 ± 0.0007

100x more data → extreme

- $\phi_{12}^{\Gamma} \gg 0.003$ or $\phi_{12}^{M} \gg 0.003$ would indicate NP
- $\phi_{12}^{M} \gg \phi_{12}^{\Gamma}$ would indicate NP

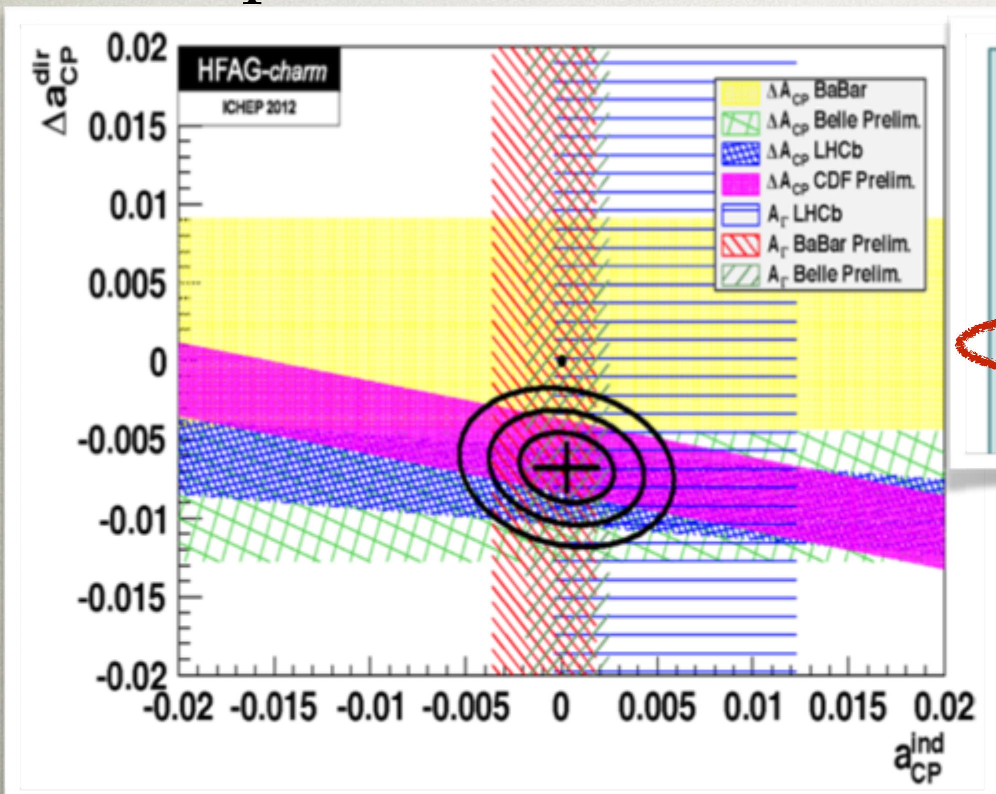
DIRECT CPV

THE PROBLEM

- lots of excitement caused by

$$\Delta A_{CP} = A_{CP}(D \to K^+K^-) - A_{CP}(D \to \pi^+\pi^-)$$

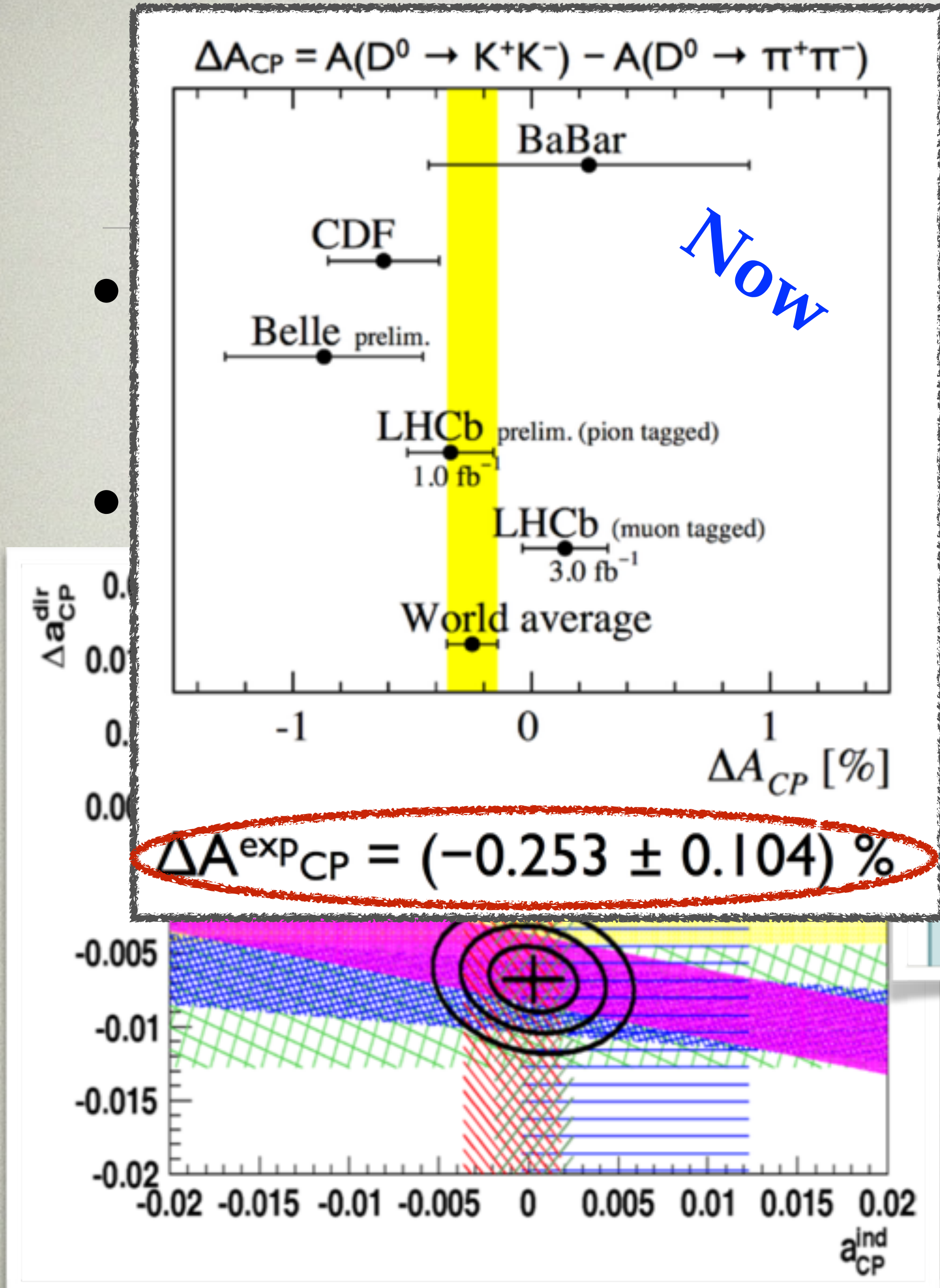
- experimental situation two years ago



HFAG ICHEP 2012
with Belle preliminary,
No CPV hypothesis : 1.98×10^{-5}
$\Delta a_{CP}(dir)=(-0.678\pm0.147)\%$
$a_{CP}(ind)=(-0.027\pm0.163)\%$

BLEM

- by
  $A_{CP}(D\to\pi^+\pi^-)$
- o years ago



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THE LESSONS

- the experimental anomaly went away
- still we have learned something
  - relatively easy to write down models to explain NP in charm at present precision
  - slight enhancement of penguins in SM could explain the effect
  - in the future: to be sure we are seeing NP need better observables

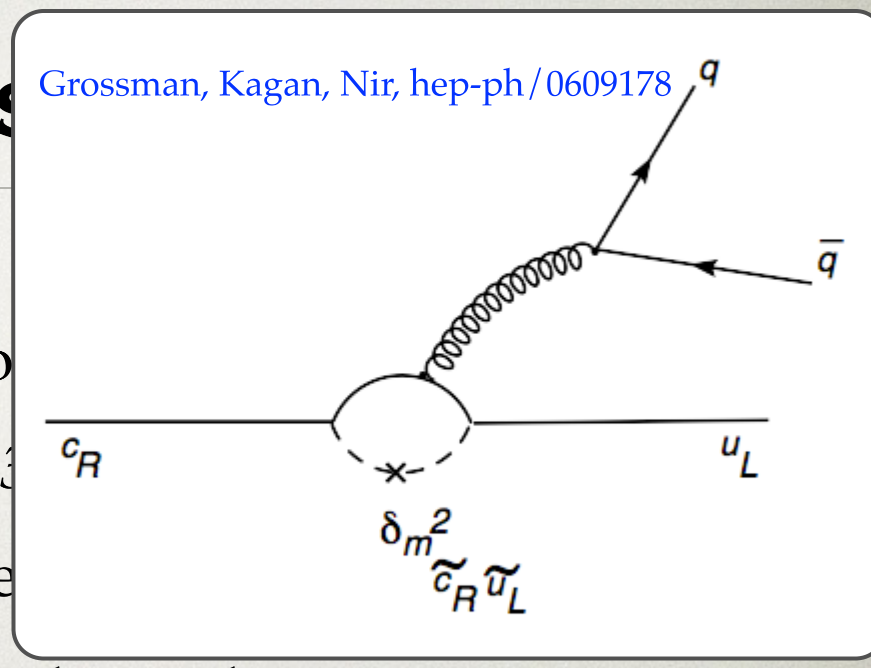
NP and isospin

- the isospin of SM contributions
  - tree ~$(\bar{d}c)(\bar{u}d)$, so both $\Delta I=3/2$ and $\Delta I=1/2$ components
  - penguins ~$(\bar{u}c)(\bar{q}q)$ so purely $\Delta I=1/2$
- NP models can be grouped in two sets
  - if they contribute only to $\Delta I=1/2$

    Grossman, Kagan, Nir, hep-ph/0609178; Giudice, Isidori, Paradisi, 1201.6204, …
    - an example: LR contribs. to Q_{8g} from MSSM
  - models that also have $\Delta I=3/2$ contributions
    - an example: single scalar explains $A_{FB}(t\,\bar{t})$, but also ΔA_{CP} from annih. op. $(\bar{u}c)(\bar{u}u)$

    Hochberg, Nir, 1112.5268, …

NP and is



- the isospin of SM contributio
  - tree ~$(\bar{d}c)(\bar{u}d)$, so both ΔI=3
  - penguins ~$(\bar{u}c)(\bar{q}q)$ so pure
- NP models can be grouped in two sets
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    - an example: LR contribs. to Q_{8g} from MSSM
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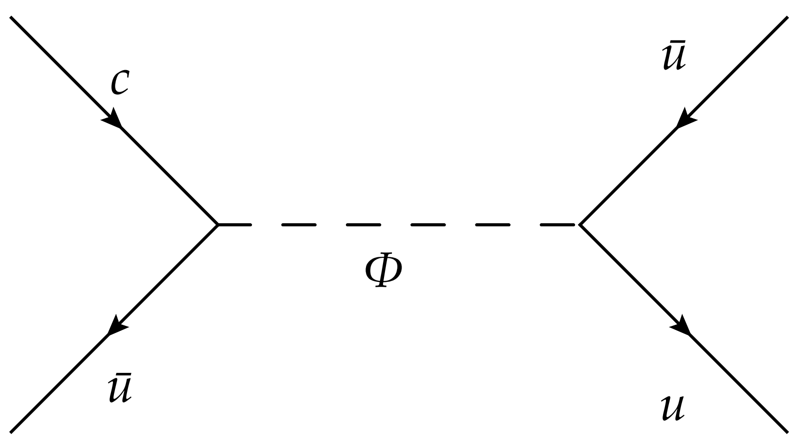

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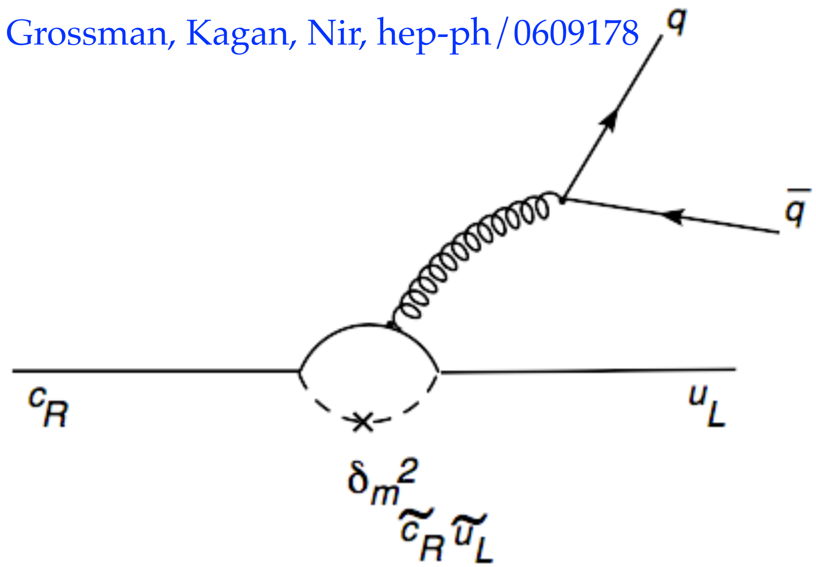

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TESTING FOR NP IN CHROMOMAGNETIC OP.

- chromomag. and electromag. ops mix under RG

Isidori, Kamenik, 1205.3164

$$Q_8 = \frac{m_c}{4\pi^2}\,\bar{u}_L\sigma_{\mu\nu}T^a g_s G_a^{\mu\nu} c_R \qquad Q_7 = \frac{m_c}{4\pi^2}\,\bar{u}_L\sigma_{\mu\nu}Q_u e F^{\mu\nu} c_R$$

- generally NP models that induce Q_{8G} also induce $Q_{7\gamma}$
- $Q_{7\gamma}$ with a weak phase can induce direct CPV in $D\to\rho\gamma,\omega\gamma$

$$|a_{(\rho,\omega)\gamma}|^{\max} = 0.04(1)\left|\frac{\mathrm{Im}[C_7(m_c)]}{0.4\times10^{-2}}\right|\left[\frac{10^{-5}}{\mathcal{B}(D\to(\rho,\omega)\gamma)}\right]^{1/2} \lesssim 10\%$$

- to get at the central value of ΔA_{CP}

$$|\mathrm{Im}[C_8^{\mathrm{NP}}(m_c)]| \approx \cancel{0.4}\times10^{-2}$$

0.1×10^{-2}

- the value in the SM parametrized to be

$$|a_f^{\mathrm{SM}}| \approx 2\xi\,\mathrm{Im}(R_f^{\mathrm{SM}}) \approx 0.13\%\times\mathrm{Im}(R_f^{\mathrm{SM}}) \qquad \xi \equiv |V_{cb}V_{ub}|/|V_{cs}V_{us}|$$

nonpert. parameter, O(1)?

TESTING FOR NP USING $\Delta I=3/2$

Y. Grossman, A. Kagan, JZ, 1204.3557

- the general idea:
  - in SM $\Delta I=3/2$ comes from tree operators (up to very small EWP)
    - it carries no weak phase
  - test if $\Delta I=3/2$ amplitude is CPV
    - if it is $\Rightarrow$ found NP!

THE IMPLEMENTATION

- we want to isolate ΔI=3/2 amplitudes
- for D^0 and D^+ decays this means identifying I=2 final state
  - so can use $D\to\pi\pi$, $\rho\pi$, $\rho\rho$ decays
  - but not $D\to KK$ decays
- for D_s^+ decays need to isolate I=3/2 final state
  - $D_s\to\pi K$,... decays
- need to be careful about isospin breaking
  - all sum rules valid to 2nd order in isospin breaking
  - corrections expected at O(10^{-4})
  - present experimental errors at O(10^{-2}) to O(10^{-3})

$D \to \pi\pi$ and $D \to \rho\rho$

- the isospin decomposition

$$\begin{aligned} A_{\pi^+\pi^-} &= -\sqrt{2}\mathcal{A}_3 + \sqrt{2}\mathcal{A}_1, \\ A_{\pi^0\pi^0} &= -2\mathcal{A}_3 - \mathcal{A}_1, \\ A_{\pi^+\pi^0} &= 3\mathcal{A}_3, \end{aligned}$$

- if $A_{CP}(\pi^+\pi^0) \neq 0$, then $\Rightarrow$ $\Delta I = 3/2$ New Physics
  - note: $A_{CP}(\pi^+\pi^0) = 0$, if strong phase between NP and SM $\Delta I = 3/2$ ampl. is zero
- exactly the same holds for $D \to \rho\rho$

FURTHER TESTS

- another test possible using $D(t)\to\pi^+\pi^-$
  - needs $D(t)\to\pi^0\pi^0$ or info from charm factor. on phases
- construct the isospin sum (and its CP conjugate)

$$\boxed{\frac{1}{\sqrt{2}}A_{\pi^+\pi^-}+A_{\pi^0\pi^0}+A_{\pi^+\pi^0}=A_{\text{break}}}$$

  - note: cannot use triangle construction from rates as in B physics due to isospin breaking
- the isospin breaking A_{break} is CP conserving
  - it cancels in the sum rule

$$\boxed{\begin{aligned}&\frac{1}{\sqrt{2}}A_{\pi^+\pi^-}+A_{\pi^0\pi^0}-\frac{1}{\sqrt{2}}\bar{A}_{\pi^+\pi^-}-\bar{A}_{\pi^0\pi^0}\\&=3\big(\mathcal{A}_3-\bar{\mathcal{A}}_3\big).\end{aligned}}$$

- r.h.s nonzero *only* if CPV ΔI=3/2 NP

NP test from $D \to \rho\pi$

- use $D \to \pi^+\pi^-\pi^0$ Dalitz plot
  - measure magn. and phases of $D \to \rho\pi$
- construct isospin sum rule

$$A_{\rho^+\pi^-} + 2A_{\rho^0\pi^0} + A_{\rho^-\pi^+} = -2\sqrt{3}\mathcal{A}_3.$$

- construct the CP difference

$$|A_{\rho^+\pi^-} + 2A_{\rho^0\pi^0} + A_{\rho^-\pi^+}|^2 - |\overline{A}_{\rho^+\pi^-} + 2\overline{A}_{\rho^0\pi^0} + \overline{A}_{\rho^-\pi^+}|^2$$

- if nonzero then there is $\Delta I = 3/2$ NP

NP test from $D \to \rho\pi$

- no strong phase needed if time dependent Dalitz plot is measured
- from $D(t) \to \pi^+ \pi^- \pi^0$ all amplitudes (and phases) measured can construct

$$\boxed{\begin{aligned} &A_{\rho^+\pi^-} + A_{\rho^-\pi^+} + 2A_{\rho^0\pi^0} - \\ &\left(\bar{A}_{\rho^+\pi^-} + \bar{A}_{\rho^-\pi^+} + 2\bar{A}_{\rho^0\pi^0}\right) = \\ &\qquad \ldots.\left(\mathcal{A}_3 - \bar{\mathcal{A}}_3\right). \end{aligned}}$$

- l.h.s. is nonzero for CPV $\Delta I = 3/2$ NP

TEST USING D_s DECAYS

- isospin sum-rule

$$\sqrt{2}A(D_s^+ \to \pi^0 K^{*+}) + A(D_s^+ \to \pi^+ K^{*0}) = 3\mathcal{A}_3.$$

- the relative phase can be measured in $D_s^+ \to K_S \pi^+ \pi^0$ Dalitz plot

- if the following sum rule nonzero

$$|\sqrt{2}A(D_s^+ \to \pi^0 K^{*+}) + A(D_s^+ \to \pi^+ K^{*0})|^2 -$$
$$|\sqrt{2}A(D_s^- \to \pi^0 K^{*-}) + A(D_s^- \to \pi^- \overline{K^{*0}})|^2 \neq 0$$

  - then there is $\Delta I = 3/2$ NP

CONCLUSIONS

- discussed possible tests for NP using indirect CPV in *D*-mixing and direct CPV in *D* decays
- ~O(10) window for NP with present precision

BACKUP SLIDES

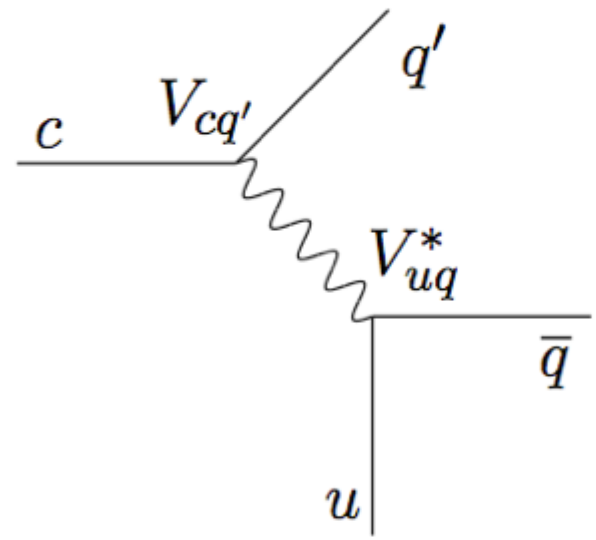
SETTING UP THE STAGE

- three classes of D decays
  - Cabibbo allowed
    - example: $D^0 \to K^- \pi^+$

      $\boxed{A_T \sim V_{cs} V_{ud} \sim 1}$
  - singly Cabibbo suppressed (SCS)
    - example: $D^0 \to K^- K^+$, $D^0 \to \pi^- \pi^+$

      $\boxed{A_T \sim V_{cd} V_{ud}, V_{cs} V_{us} \sim \lambda}$
  - doubly Cabibbo suppressed
    - example: $D^0 \to \pi^- K^+$

      $\boxed{A_T \sim V_{cd} V_{us} \sim \lambda^2}$



$q, q' = s, d$

DIRECT CPV

- focus on SCS *D* decays in the SM

$$\boxed{\begin{aligned} A_f(D \to f) &= A_f^T[1 + r_f e^{i(\delta_f - \gamma)}], \\ \overline{A}_{\overline{f}}(\bar{D} \to \bar{f}) &= A_f^T[1 + r_f e^{i(\delta_f + \gamma)}], \end{aligned}}$$

- A_f^T - tree ampl., r_f - relative “penguin” contrib., δ_f - strong phase
- direct CP asymmetry

$$\boxed{\mathcal{A}_f^{\rm dir} \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2} = 2r_f \sin\gamma \sin\delta_f}$$

  - sinγ~0.9, so for δ_f~*O(1)*

$$\boxed{\mathcal{A}_f^{\rm dir} \sim 2r_f}$$