COMMENTS ON CP-VIOLATION IN CHARM

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OUTLINE

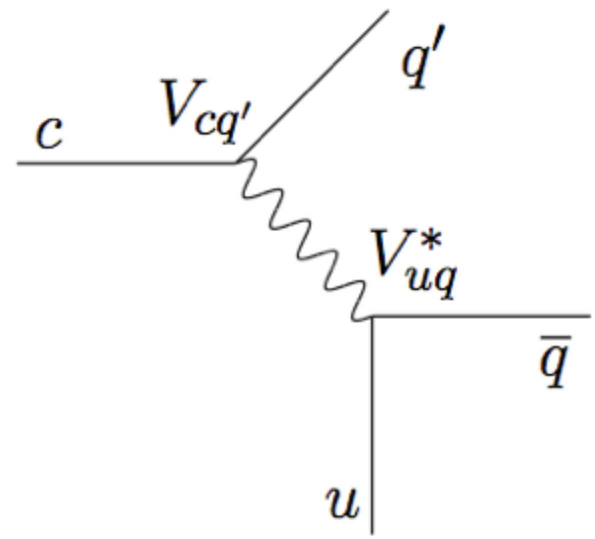
- the aim of this talk:

for indirect CPV see talk by A. Kagan on Thursday

- direct CP violation in charm decays
  - how large can it be in the SM
  - how to know if NP

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

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

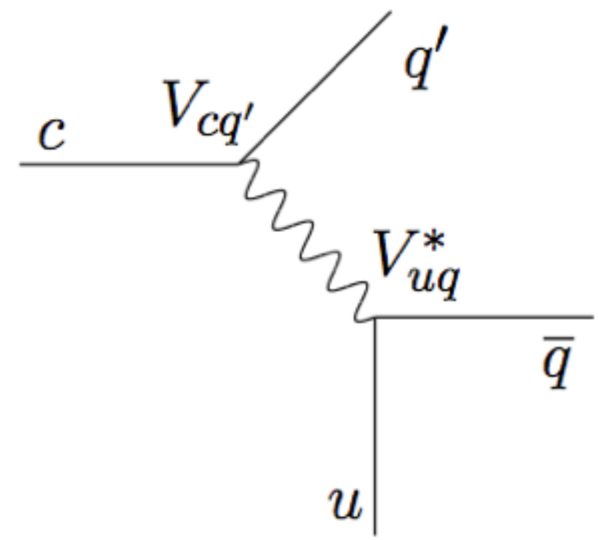
- A_f^T - tree ampl., r_f - relative "penguin" contrib., δ_f - strong phase

- direct CP asymmetry

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

  - $\sin\gamma$~0.9, so for δ_f~$O(1)$

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



$q, q' = s, d$

CP VIOLATION IN CHARM

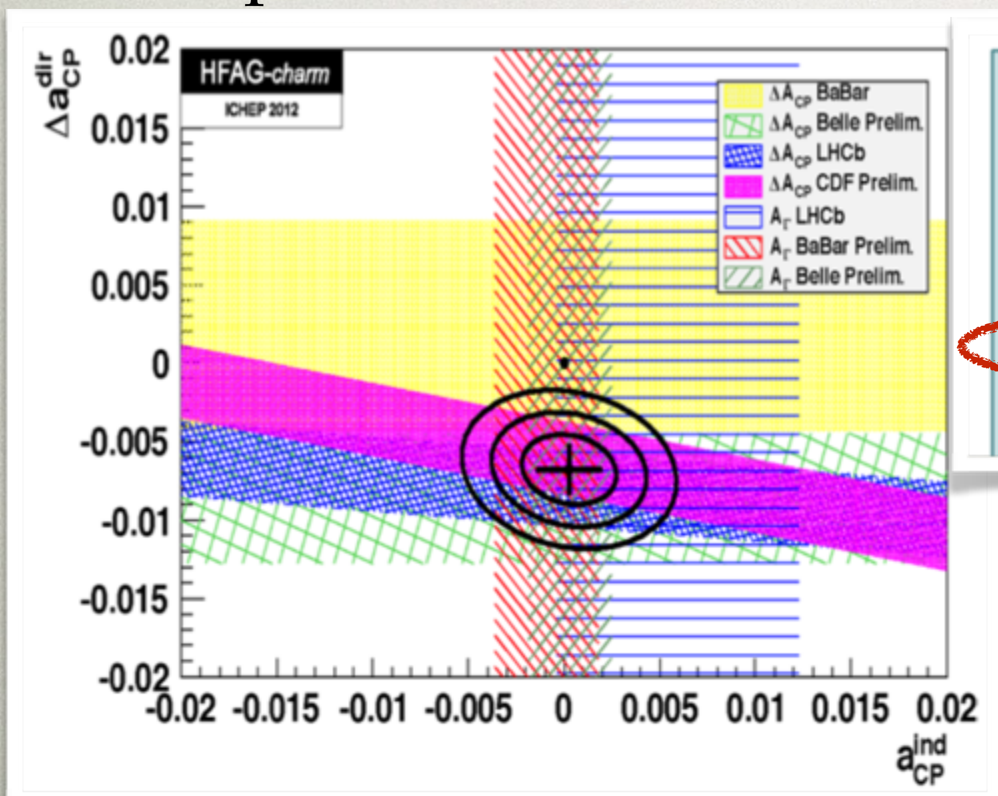
- in charm physics the first 2 gen. dominate
  - $\Rightarrow$ CP conserving to a good approximation in the SM
- CPV is parametrically suppressed
  - in mixing it enters as $\boxed{\mathcal{O}\big(V_{cb}V_{ub}/V_{cs}V_{us}\big) \sim 10^{-3}}$
  - direct CPV in SCS as $\boxed{\mathcal{O}([V_{cb}V_{ub}/V_{cs}V_{us}]\alpha_s/\pi) \sim 10^{-4}}$
- is it possible that it is significantly larger?

THE PROBLEM

- lots of excitement caused by

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

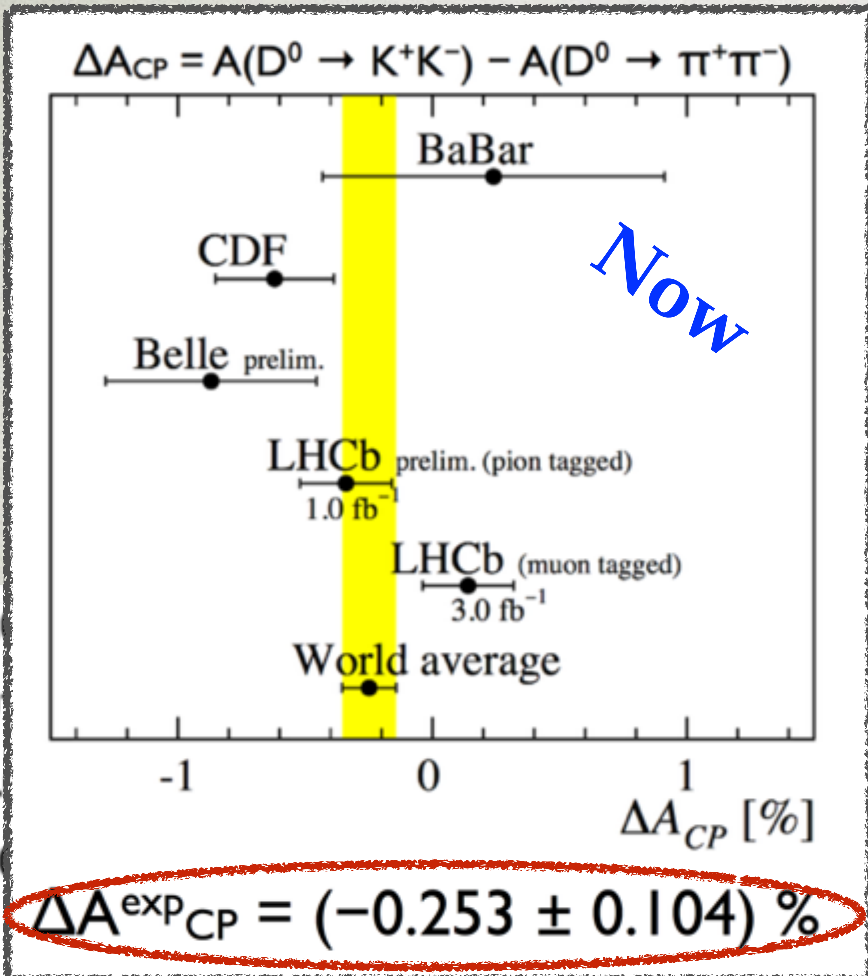
- experimental situation two years ago

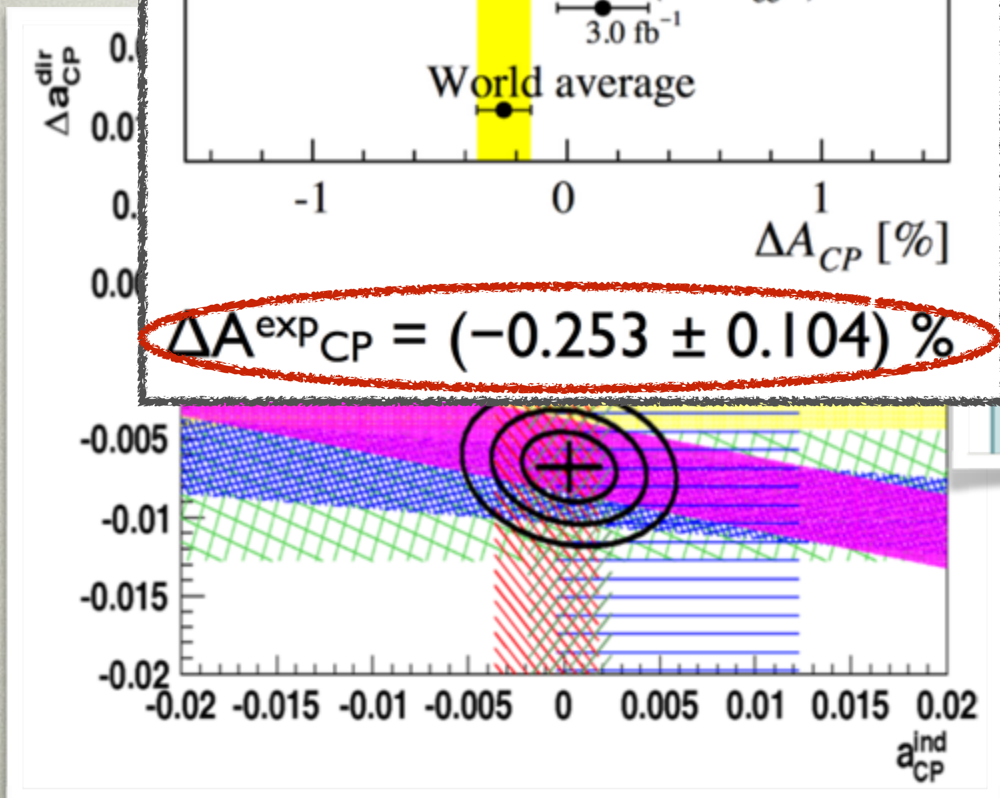


HFAG ICHEP 2012
with Belle preliminary,
No CPV hypothesis : 1.98×10^{-5}
$\Delta a_{CP}(\text{dir}) = (-0.678 \pm 0.147)\%$
$a_{CP}(\text{ind}) = (-0.027 \pm 0.163)\%$

BLEM

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





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a_{CP}(ind)=(-0.027±0.163)%

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

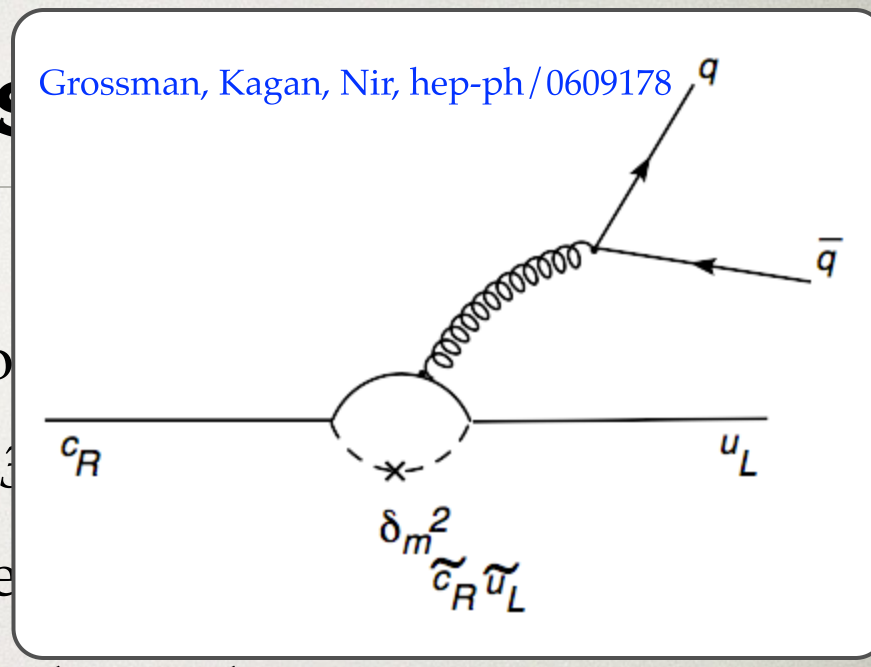
- the isospin of SM contributions
  - tree ~$(\bar{d}c)(\bar{u}d)$, so both ΔI=3/2 and ΔI=1/2 components
  - penguins ~$(\bar{u}c)(\bar{q}q)$ so purely ΔI=1/2
- NP models can be grouped in two sets
  - if they contribute only to ΔI=1/2

    Grossman, Kagan, Nir, hep-ph/0609178; Giudice, Isidori, Paradisi, 1201.6204, ...
    - an example: LR contribs. to Q_{8g} from MSSM
  - models that also have ΔI=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



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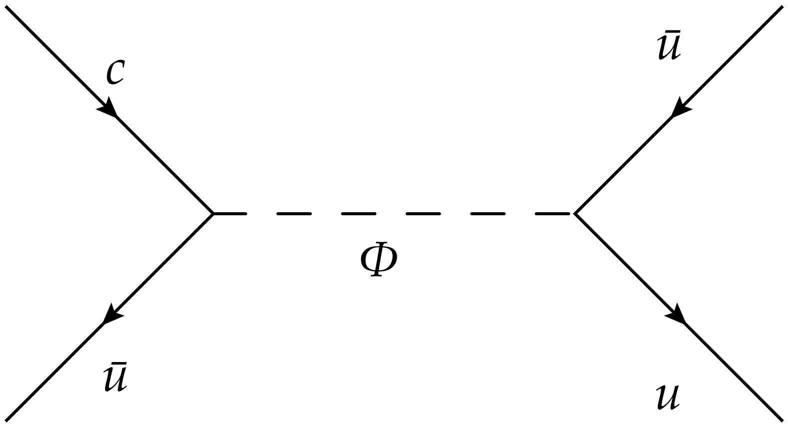
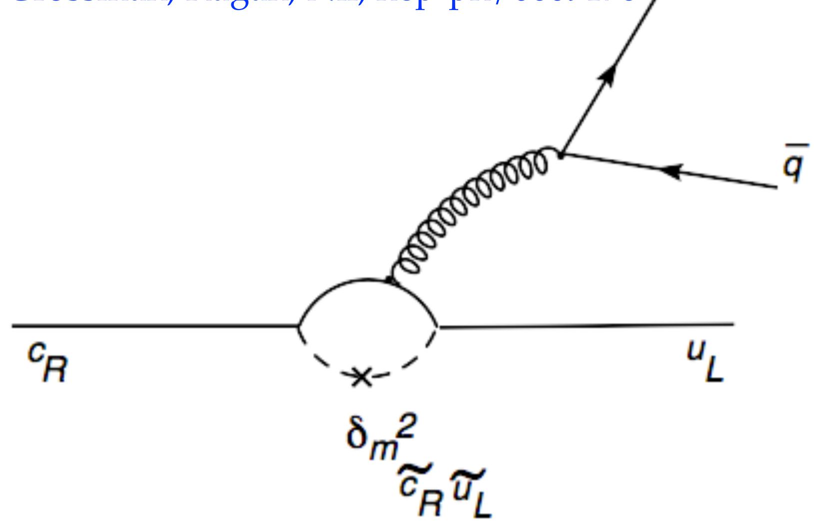


Grossman, Kagan, Nir, hep-ph/0609178



- NP models can be grouped in two sets
  - if they contribute only to $\Delta I=1/2$
    - an example: LR contribs. to Q_{8g} from MSSM

Grossman, Kagan, Nir, hep-ph/0609178;
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  - 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, …

HOW TO KNOW IF NEW PHYSICS

- several tests devised
  - if NP due to Q_{8g} then also in $Q_7 \Rightarrow$ look for CPV in radiative $D \to V\gamma$ decays
  - if ΔI=3/2 NP $\Rightarrow$ use isospin sum rules
  - find consistency in direct CPV using SU(3) expansion

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 $D\to\rho\gamma,\omega\gamma$

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

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

$$|\mathrm{Im}[C_8^{\mathrm{NP}}(m_c)]| \approx \cancel{0.4} \times 10^{-2}$$

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 $\Delta I=3/2$ 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

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

- 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

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

- r.h.s nonzero *<u>only</u>* if CPV $\Delta I=3/2$ 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

$$\boxed{\begin{aligned} A_{\rho^+\pi^-} + A_{\rho^-\pi^+} + 2A_{\rho^0\pi^0} - \\ \big(\bar{A}_{\rho^+\pi^-} + \bar{A}_{\rho^-\pi^+} + 2\bar{A}_{\rho^0\pi^0}\big) = \\ \dots.\big(\mathcal{A}_3 - \bar{\mathcal{A}}_3\big). \end{aligned}}$$

- 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

SU(3) tests

see also talks by S. Schacht on Thu, A. Paul on Tue

- in principle can devise SU(3) tests of direct CPV
  - for instance in SU(3) limit

Grossman, Robinson, 1211.3361;
Hiller, Jung, Schacht, 1211.3734

$$\Sigma a_{CP}^{dir}(K^+K^-, \pi^+\pi^-) = 0\,,$$
$$\Sigma a_{CP}^{dir}(\bar{K}^0K^+, K^0\pi^+) = 0\,,$$

- as isospin sum rules can only test $\Delta I=3/2$ NP
  - because NP in QCD penguin has the same SU(3) property as SM penguin
- crucial to measure as many modes as possible
  - to establish that $\varepsilon_{SU(3)}$ expansion works
  - need to face the description of η, η' and ω, ϕ states

CONCLUSIONS

- discussed possible tests for NP using direct CPV in *D* decays
- radiative decays, isospin sum rules, SU(3) tests

BACKUP SLIDES

SUSY?

- SUSY contribs. to QCD penguin particularly interesting

Grossman, Kagan, Nir, hep-ph/0609178
Chang et al.,1201.2565
Giudice, Isidori, Paradisi, 1201.6204
Hiller, Hochberg, Nir, 1204.1046

  - LR mixing in squark matrices

$$\boxed{\frac{m_c}{m_W^2} \to \frac{v}{\tilde{m}^2}}$$

$$\boxed{Q_8 = \frac{m_c}{4\pi^2}\bar{u}_L \sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_R}$$

$$\boxed{Q_8 = \frac{1}{4\pi^2}(\bar{Q}_L H)\sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_R}$$

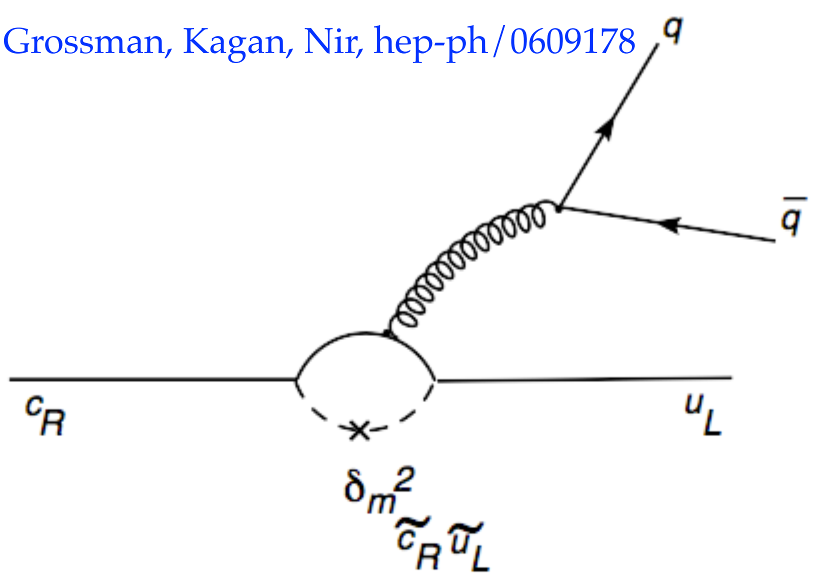
  - for v~m_{susy} the op. Q_8 is secretly dim=5

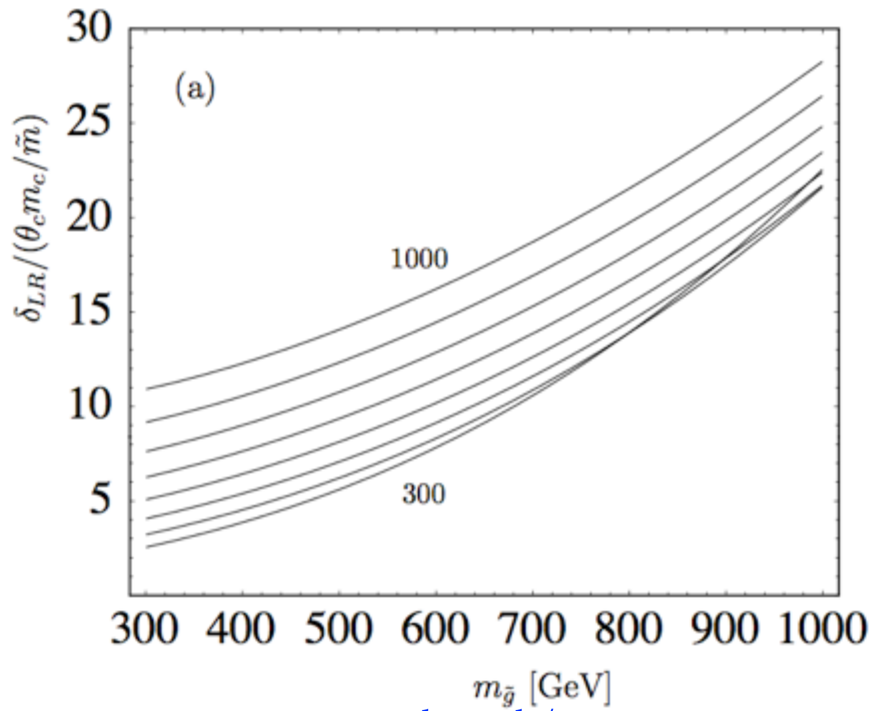
- *D-Dbar* mixing operators are dim=6

$$\boxed{Q_2^{cu} = \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta}$$

  - SUSY contributions are parametrically smaller

Grossman, Kagan, Nir, hep-ph/0609178





Grossman, Kagan, Nir, hep-ph/0609178

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- for $v \sim m_{susy}$ the op. Q_8 is secretly dim=5

- *D-Dbar* mixing operators are dim=6

$$Q_2^{cu} = \bar{u}_R^{\alpha} c_L^{\alpha} \bar{u}_R^{\beta} c_L^{\beta}$$

- SUSY contributions are parametrically smaller

OTHER EXAMPLES

- SUSY: typically some tuning needed for EDMs   Giudice, Isidori, Paradisi, 1201.6204
- other examples for Q_8 oper.
  - W' at 1-loop Q_8 Altmannshofer, Primulando, Yu, Yu, 1202.2866
    - too large $B \to D$, $B \to \pi$
  - RS from KK fermions+higgs loop   Delaunay, Kamenik, Perez, Randall, 1207.0474
- tree level exchanges   Altmannshofer, Primulando, Yu, Yu, 1202.2866
  - if vectors (Z, Z′, G′) safest if FV in coupl. to u_R, c_R
    - typically still problems with *D-Dbar* mixing
    - same EDM challenge as SUSY
  - scalars
    - 2HDM with MFV (but very large *tanβ*)   Altmannshofer, Primulando, Yu, Yu, 1202.2866
      - gives only $A_{CP}(K^+K^-)$ from tree level H^+ exchange
    - diquarks   Chen et al., 1202.3300
    - scalar doublet that can simultaneously explain $A_{FB}^{t\bar{t}}$ Hochberg, Nir, 1112.5268

D-Dbar mixing

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

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

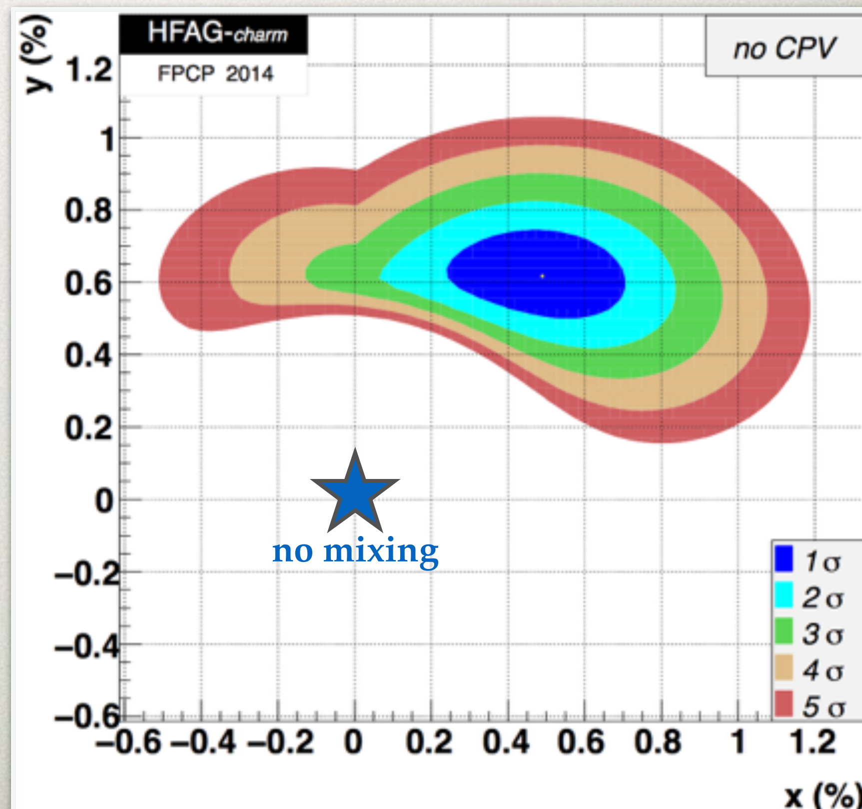
  - CPV thus suppressed by $Im[\lambda_b/\lambda_d] \sim 6.2 \times 10^{-4}$
- to a very good approximation D^0-$\bar{D}^0$ mixing is real in the SM
  - given by two CP conserving parameters

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

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

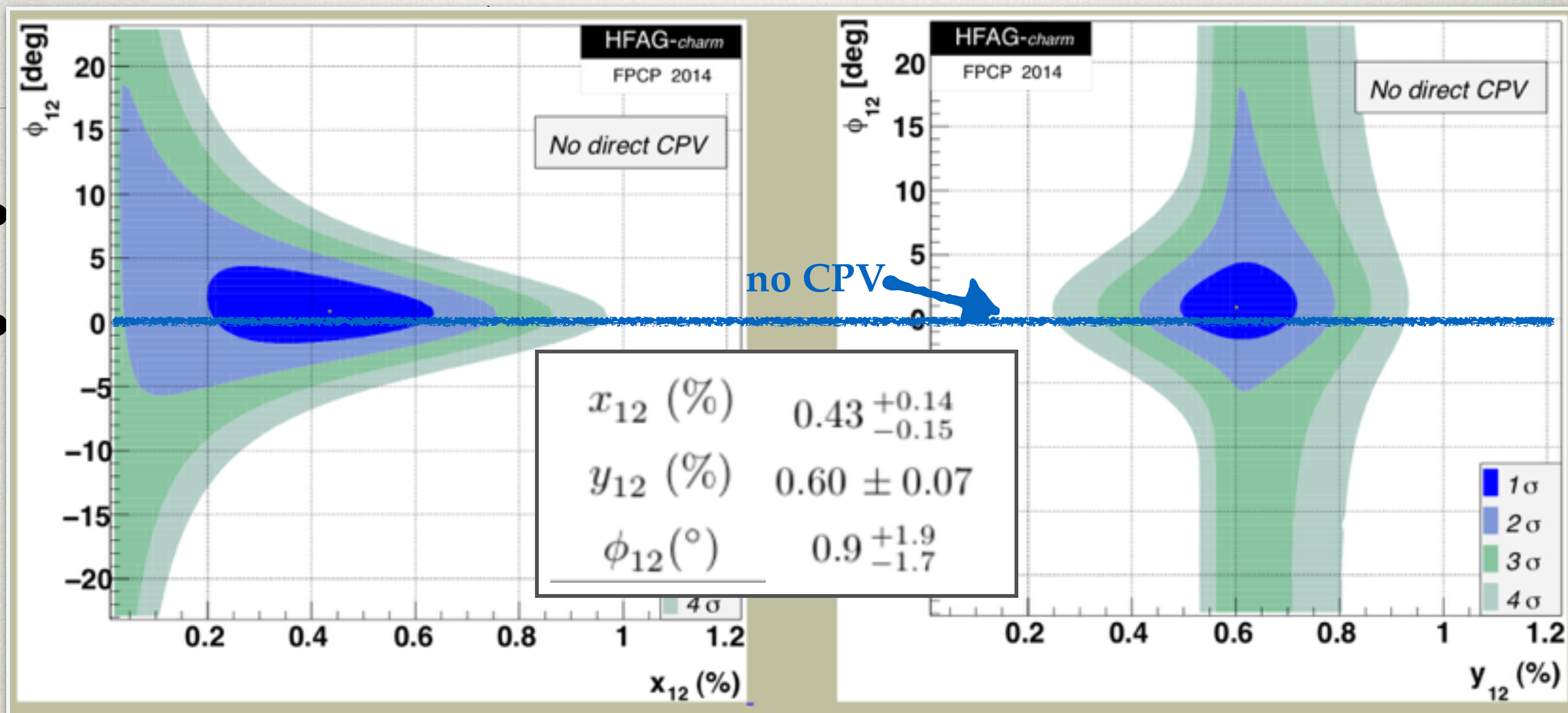
$$x_{12} \equiv 2|M_{12}|/\Gamma, \quad y_{12} \equiv |\Gamma_{12}|/\Gamma, \quad \phi_{12} \equiv \arg(M_{12}/\Gamma_{12})$$

  - 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

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



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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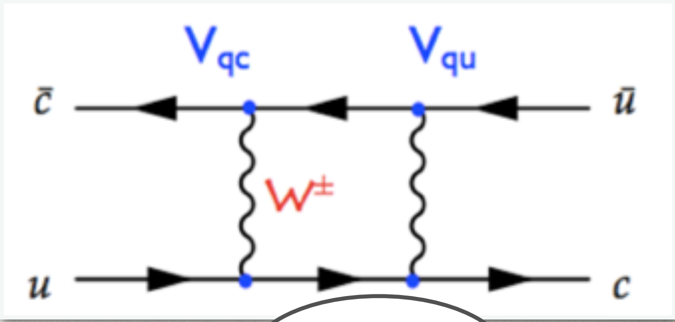
Grossman, Kagan, Ligeti, Perez, Petrov, Silvestrini, unpublished;
Kagan, talk at KEK-FF 2014; Silvestrini, talk at CKM2014

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 $\sim O(1/\varepsilon)$

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

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 $\varepsilon \sim 0.2$
  - 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

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

DIRECT CPV

- focus on SCS D decays in the SM

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

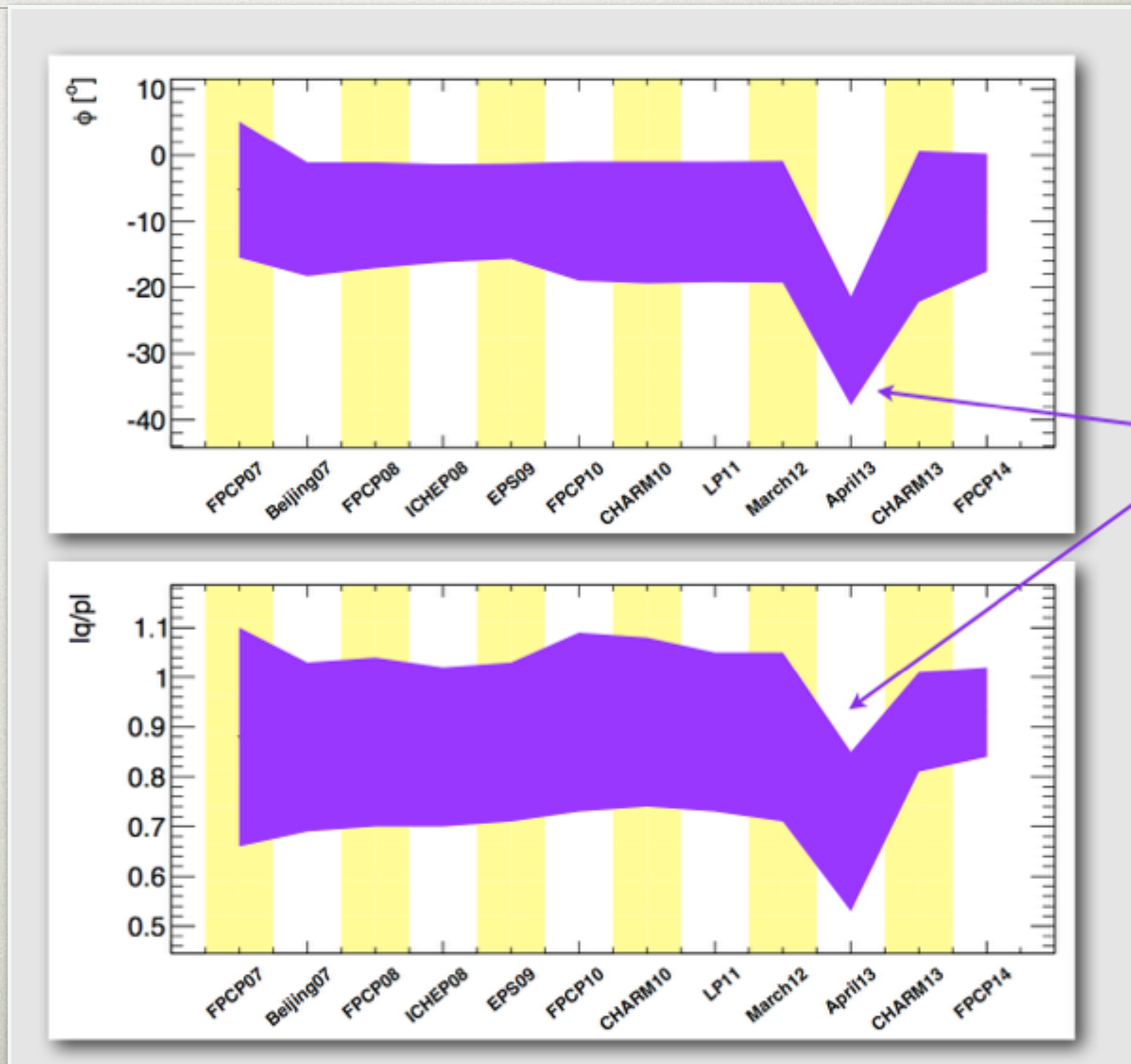
- A_f^T - tree ampl., r_f - relative “penguin” contrib., δ_f - strong phase
- direct CP asymmetry

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

  - $\sin\gamma \sim 0.9$, so for $\delta_f \sim O(1)$

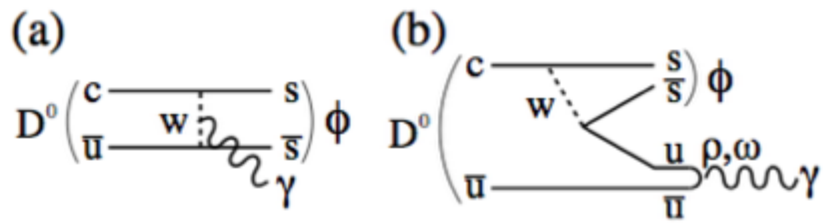
$$\boxed{\mathcal{A}_f^{\rm dir} \sim 2 r_f}$$

- show p.



φ [°]
10
0
-10
-20
-30
-40
FPCP07
Beijing07
FPCP08
ICHEP08
EPS09
FPCP10
CHARM10
LP11
March12
April13
CHARM13
FPCP14
|q/p|
1.1
1
0.9
0.8
0.7
0.6
0.5

Direct CPV in $D^0 \to \phi\gamma, \rho^0\gamma$



- Direct CPV in radiative decays can be enhanced to exceed 1% (G. Isidori and J. F. Kamenik, PRL 109, 171801 (2012))
  - $D^0 \to \phi\gamma$: A_{CP} up to 2%
  - $D^0 \to \rho^0\gamma$: A_{CP} up to 10%
- $D^0 \to \phi\gamma$: first observation by Belle with 78 fb^{-1} (PRL 92, 101803 (2004))
  - measured yield: $27.6^{+7.4+0.5}_{-6.5-1.0}$
    $\Rightarrow$ relative error on yield 25% (as would be the error on A_{CP})
- A_{CP} sensitivity at 50 ab^{-1}: $\approx 1\%$