CP violation in the charm system

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CP violation in charm: an unique probe

- Processes involving K and B mesons have always been regarded as the most interesting probe of flavor and CP violation

- In the SM, the largest flavor and CP violating effects appear in the down sector, since the top mass is the main source of flavor violation and charged-current loops are needed to communicate symmetry breaking, in agreement with the GIM mechanism

- While these properties hold in the SM, there is no good reason for them to be true if NP is present at the electroweak scale

    - In particular, it is quite plausible that NP contributions affect mostly the up-type sector, possibly in association with the mechanism responsible for the large top mass. Examples are classes of models in which the flavor hierarchies are explained without invoking the MFV hypothesis [Giudice, Gripaios, Sundrum ‘11]

- D-meson decays represent a unique, complementary, probe of NP flavor effects

What/where to look for?

- "Golden" measurements in up-flavor physics:

  - Direct CP violation in singly-Cabibbo-suppressed decays
  - CPV in neutral D mesons mixing
  - Hadronic EDMs

  Low-energy flavor physics

  - FCNC top decays
  - FB asymmetry in $t\bar{t}$ production

  High-p_T physics

Time-integrated CP asymmetries in $D^0 \rightarrow h^+h^-$

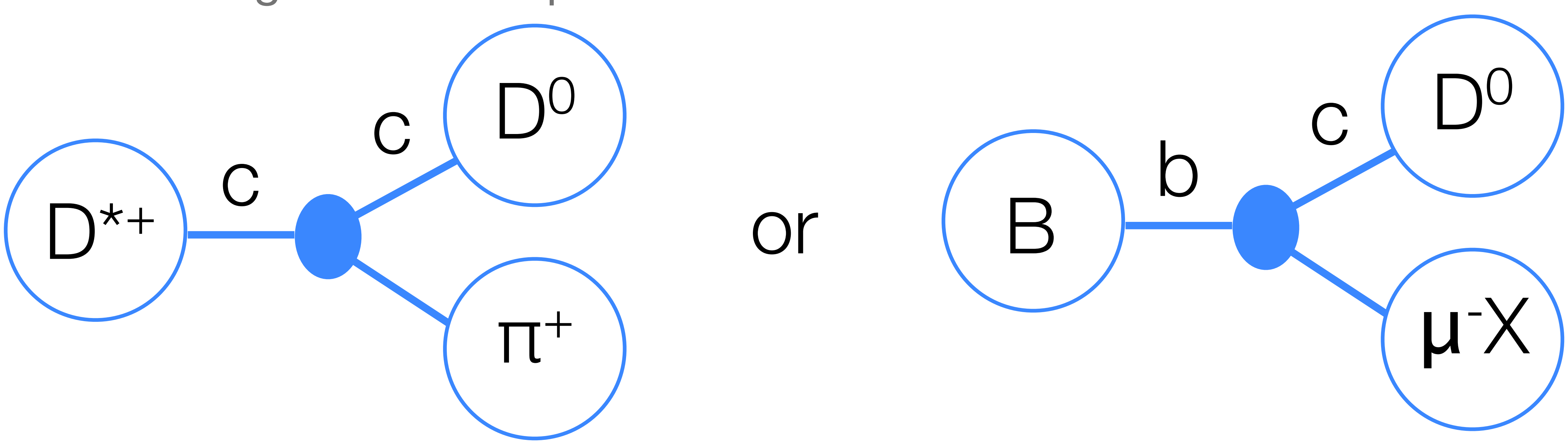
- Two-body decays of neutral D into charged hadrons (experimentally easy)

- Sensitive to both direct and indirect (mixing induced) CPV

$$A_{CP}(h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\bar{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) - \Gamma(\bar{D}^0 \to h^+h^-)}$$

$$\approx a_{CP}^{\mathrm{dir}}(h^+h^-) + \frac{\langle t \rangle}{\tau} a_{CP}^{\mathrm{ind}}$$

- Need to tag D^0 flavor at production time



Experimental method

- Observed (raw) asymmetries suffer from instrumental and production effects

$$\frac{N(D^0 \to h^+h^-) - N(\bar{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\bar{D}^0 \to h^+h^-)}$$

$$A(h^+h^-) = A_{CP}(h^+h^-) + A_D + A_P$$

The CP asymmetry you want to measure

Detection asymmetry of tagging track (π^+ or μ^-)

Production asymmetry of parent hadron (D^* or B)

- Difference of raw asymmetries to cancel unwanted effect and is robust against systematic uncertainties

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

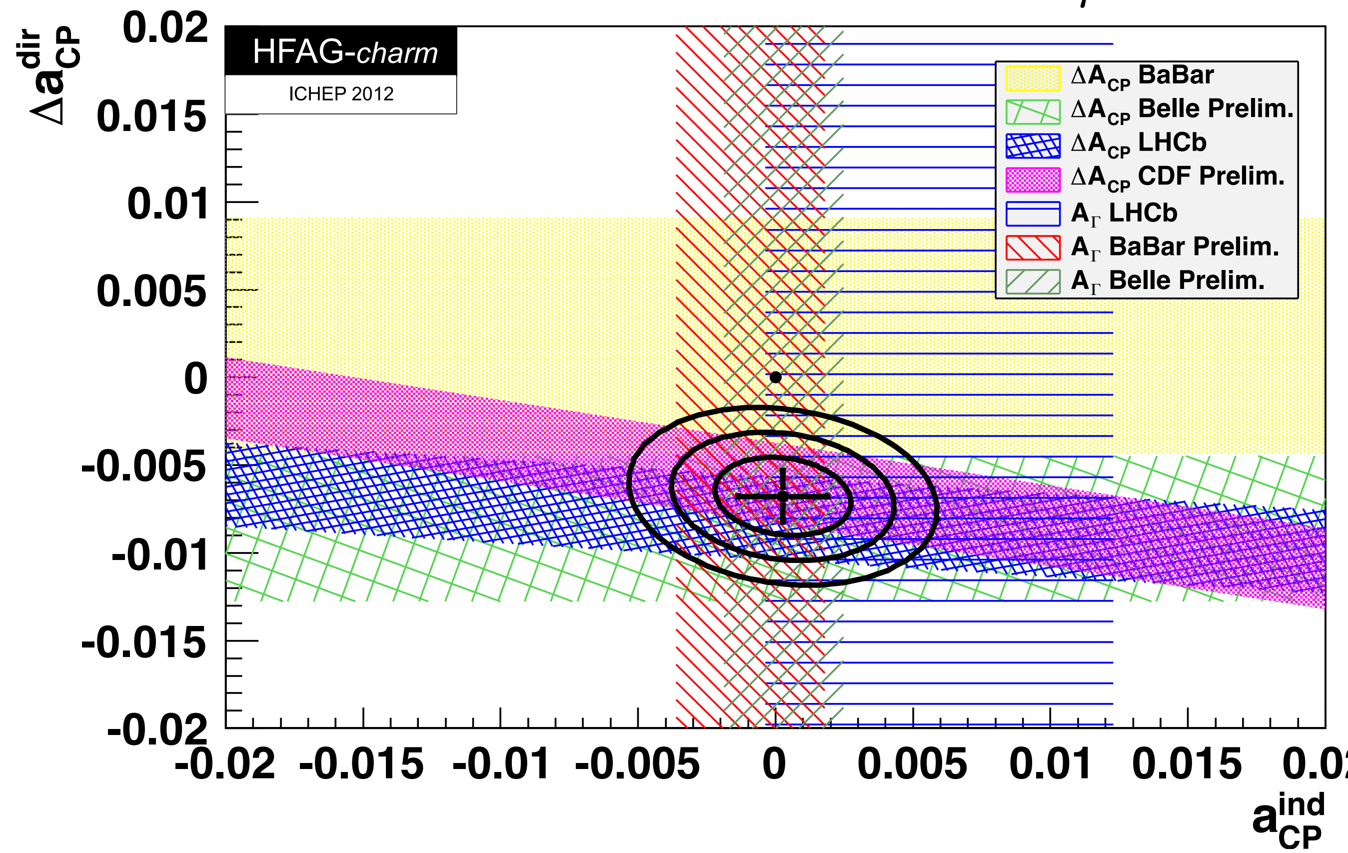
- Different tagging methods suffer from independent sources of systematic uncertainties

Status pre-Moriond 2013

- Available measurements of ΔA_{CP} [PRL 108 (2012) 111602, PRL 109 (2012) 111801, arXiv:1212.1975, PRL 100 (2008) 061803]

$$\Delta A_{CP}(\text{LHCb}) = (-0.82 \pm 0.21 \pm 0.11)\%$$
$$\Delta A_{CP}(\text{CDF}) = (-0.62 \pm 0.21 \pm 0.10)\%$$
$$\Delta A_{CP}(\text{Belle}) = (-0.87 \pm 0.41 \pm 0.06)\%$$
$$\Delta A_{CP}(\text{BaBar}) = (+0.24 \pm 0.62 \pm 0.26)\%$$

$$\Delta A_{CP} \approx \Delta a_{CP}^{\text{dir}}(h^+h^-) + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\text{ind}}$$



- HFAG average [ICHEP '12] gives strong evidence for direct CPV in charm

$$\Delta a_{CP}^{\text{dir}} = (-0.68 \pm 0.15)\%$$
$$a_{CP}^{\text{ind}} = (+0.02 \pm 0.16)\%$$

- This results sparked controversy: is it possible Δa_{CP} @ % in the SM? [Golden, Grinstein '89; Brod et al. '12; Pirtskhalava et al. '12; Cheng et al. '12; Bhattacharya et al. '12; Feldmann et al. '12; Li et al. '12; Franco et al. '12]

New LHCb results

- D*-tagged analysis (preliminary result) [LHCb-CONF-2013-003]

$$\Delta A_{CP} = (-0.34 \pm 0.15 \pm 0.10)\%$$

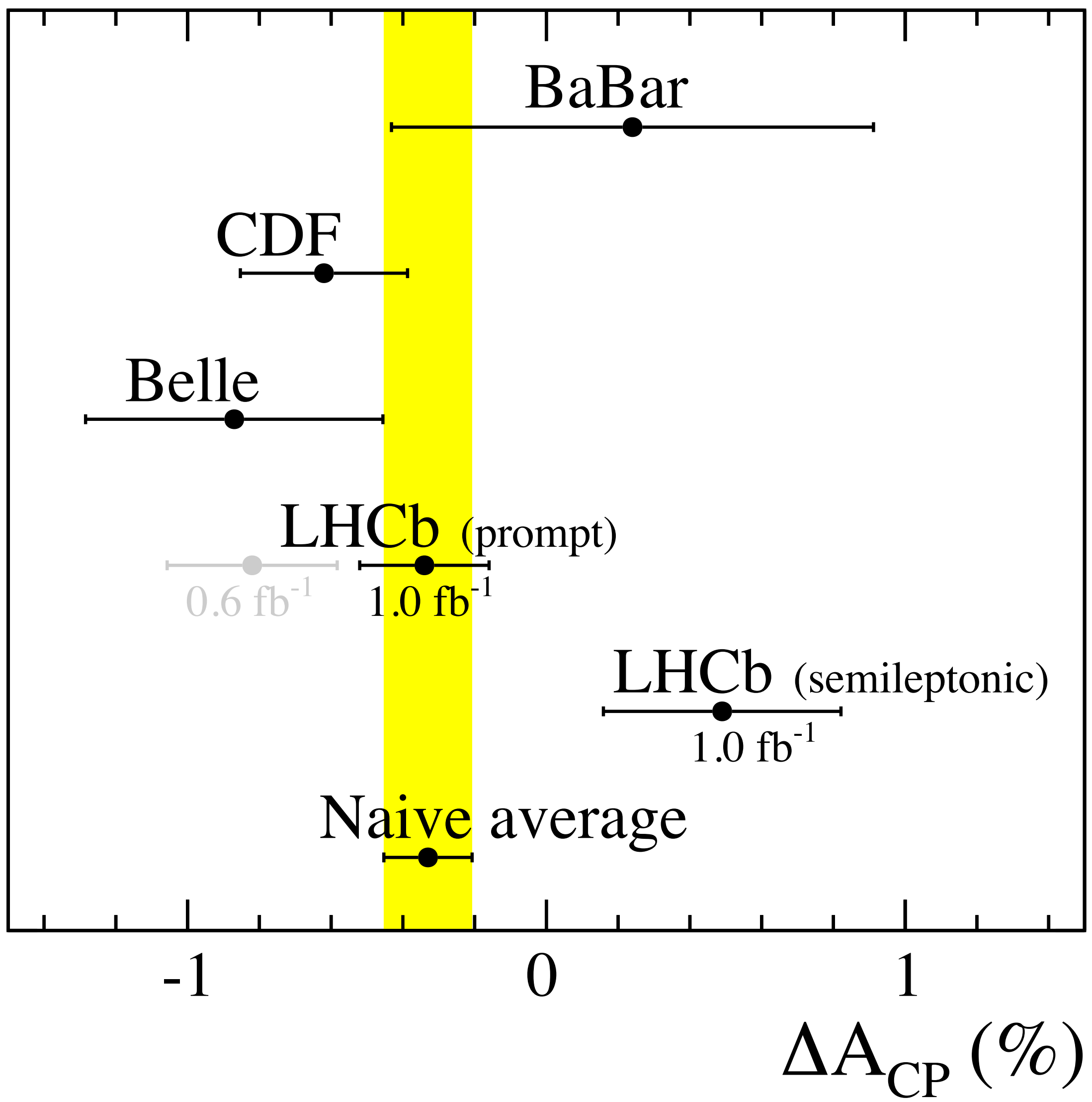
- Semileptonic B-tagged analysis [LHCb-PAPER-2013-003, arXiv:1303.2614]

$$\Delta A_{CP} = (+0.49 \pm 0.30 \pm 0.14)\%$$

- New HFAG average [March ‘13]

$$\Delta a_{CP}^{\rm dir} = (-0.33 \pm 0.12)\%$$

$$a_{CP}^{\rm ind} = (+0.01 \pm 0.16)\%$$



What does theory tell us?

- General effective Hamiltonian [Isidori, Kamenik, Ligeti, Perez '11]

$$\mathcal{H}^{\rm eff}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_{i=1,2,5,6} (C_i^q Q_i^q + C_i^{q\prime} Q_i^{q\prime}) + \sum_{i=7,8} (C_i Q_i + C_i' Q_i') + \text{h.c.}$$

$$Q_1^q = (\bar{u}q)_{V-A}\,(\bar{q}c)_{V-A}\,, \qquad Q_2^q = (\bar{u}_\alpha q_\beta)_{V-A}\,(\bar{q}_\beta c_\alpha)_{V-A}\,,$$

$$Q_5^q = (\bar{u}c)_{V-A}\,(\bar{q}q)_{V+A}\,, \qquad Q_6^q = (\bar{u}_\alpha c_\beta)_{V-A}\,(\bar{q}_\beta q_\alpha)_{V+A}\,,$$

$$Q_7 = -\frac{e}{8\pi^2}\, m_c\, \bar{u}\sigma_{\mu\nu}(1+\gamma_5)F^{\mu\nu}\, c\,, \qquad Q_8 = -\frac{g_s}{8\pi^2}\, m_c\, \bar{u}\sigma_{\mu\nu}(1+\gamma_5)T^a G_a^{\mu\nu} c$$

- Constraints from D⁰-D̄⁰ mixing and ε'/ε:

Best NP candidates because in D-mixing suppressed by $(m_c/m_W)^2$

Allowed	Ajar	Disfavored
$Q_{7,8}\,,\ Q'_{7,8}\,,$ $\forall f\ Q_{1,2}^{f\prime}\,,\ Q_{5,6}^{(c-u,b)\prime}$	$Q_{1,2}^{(c-u,8d,b,0)}\,,$ $Q_{5,6}^{(0)}\,,\ Q_{5,6}^{(8d)\prime}$	$Q_{1,2}^{s-d}\,,\ C_{5,6}^{(s-d)\prime}\,,$ $C_{5,6}^{s-d,c-u,8d,b}$

SM vs NP predictions

- Considering only the chromomagnetic operator as possible NP contribution

$$\Delta a_{CP}^{\rm dir} \approx \frac{-2}{\sin\theta_c}\left[{\rm Im}(V_{cb}^* V_{ub}){\rm Im}(\Delta R^{\rm SM}) + \sum_i {\rm Im}(C_i^{\rm NP}){\rm Im}(\Delta R^{{\rm NP}_i})\right]$$
$$= -(0.13\%){\rm Im}(\Delta R^{\rm SM}) - 9\sum_i {\rm Im}(C_i^{\rm NP})\,{\rm Im}(\Delta R^{{\rm NP}_i})$$

- $\Delta R^{SM} \approx \alpha_s(m_c)/\pi \approx 0.1$ in perturbation theory but a much larger non-perturbative effect is expected

- In SU(3) limit $a_{CP}(K^+K^-) = -a_{CP}(\pi^+\pi^-)$ which then should add constructively in Δa_{CP}

- In naive factorization $|{\rm Im}(\Delta R^{NP})| \approx 0.2$ [Grossman, Kagan, Nir '06] then

$$\Delta a_{CP}^{\rm NP} \approx 2\ {\rm Im}(C_8^{\rm NP} + C_8'^{\rm NP})$$

Other tests of direct CPV in charm

- If Δa_{CP} driven by the chromomagnetic opertator, then large direct CP asymmetries could show up in $D^0 \to V\gamma$ [Isidori, Kamenik '12; Lyon, Zwicky '12]

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

- SU(3)-flavor anatomy of non-leptonic decays taking into account SU(3)-breaking effects at the second order [Grossman, Robinson '12; Hiller, Jung, Schacht '12]
  - Correlations between CP asymmetries in different channels ($D_s^+ \to K_S\pi^+$ vs $D^+ \to K_S K^+$, $D^+ \to \pi^+\pi^0$, $D^0 \to \pi^0\pi^0$ and $D^0 \to K_S K_S$) allow to differentiate between different scenarios for the underlying dynamics, as well as between SM and various extensions

- Measurement of individual asymmetries rather than difference of asymmetries

$$A_{CP}(K^+K^-) = (-0.32 \pm 0.21)\%$$
$$A_{CP}(\pi^+\pi^-) = (+0.31 \pm 0.22)\%$$

[CDF 10784, arXiv:1208.2517]

CP Violation in $D^+ \to \phi\pi^+$ and $D_S^+ \to K_S\pi^+$

- Measure difference of raw asymmetries with respect to Cabibbo-favored decay (where CPV is assumed to be negligible)

$$A_{CP}(D^+ \to \phi\pi^+) = A(D^+ \to \phi\pi^+) - A(D^+ \to K_S\pi^+) + A(K^0/\bar{K}^0)$$

$$A_{CP}(D_s^+ \to K_S\pi^+) = A(D_s^+ \to K_S\pi^+) - A(D_s^+ \to \phi\pi^+) + A(K^0/\bar{K}^0)$$

Removes $D_{(s)}^+$ production asymmetry and π^+ detection asymmetry

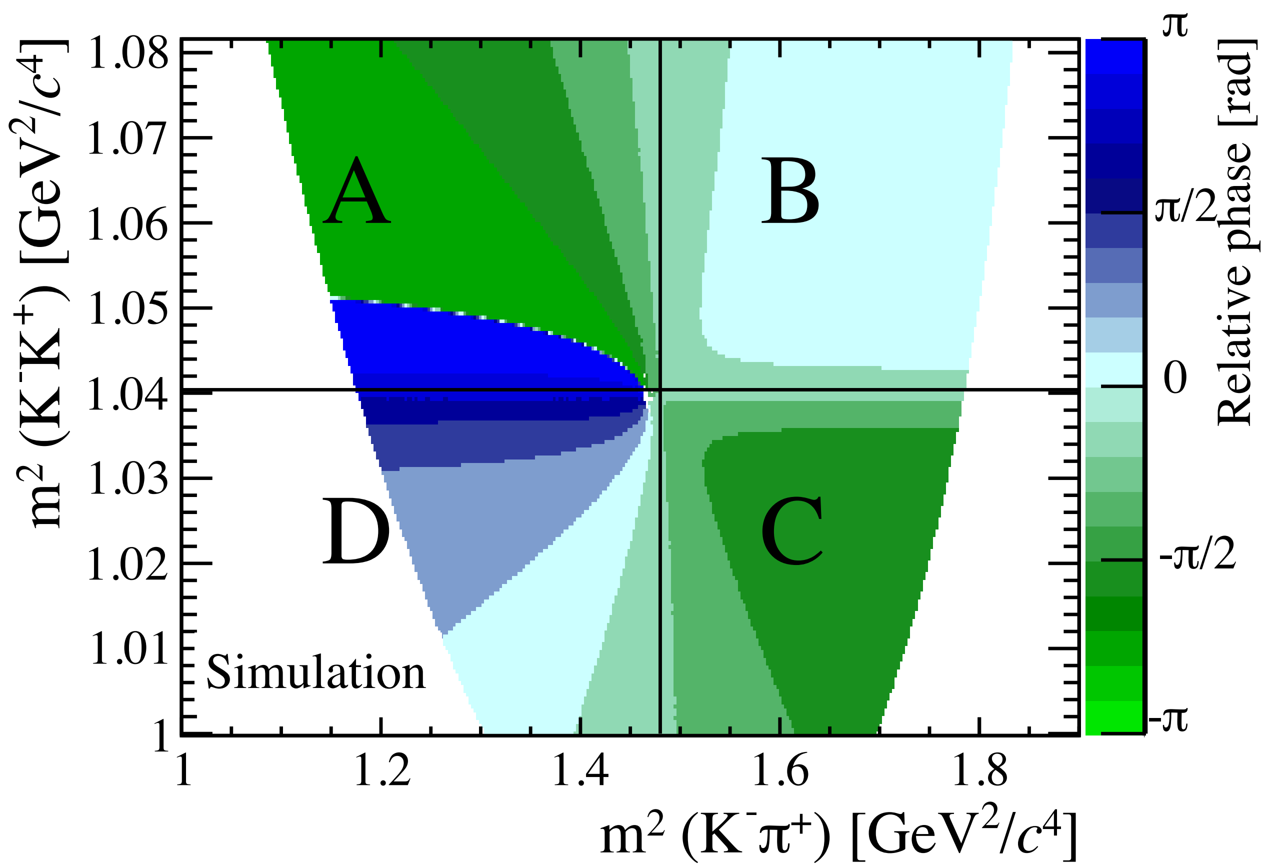
Correction for CPV in neutral kaon system and for different interaction with matter

CP Violation in $D^+ \to \phi\pi^+$

[LHCb-PAPER-2012-052, arXiv:1303.4906]

- Variations of the strong phase difference across the φ resonance could cancel out the effect of a constant CPV asymmetry

$$A_{CP} \propto \mathrm{Im}\left(\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*}\right) R\sin\delta_S$$



- Define a new observable, which carries additional information with respect to A_{CP}, to enhance sensitivity to CPV

$$A_{CP|S} = \frac{1}{2}\left(A^A + A^C - A^B - A^D\right)$$

- Examples:

Type of CPV	Mean A_{CP} (%)	Mean $A_{CP}\|_S$ (%)
3° in ϕ phase	-0.01 (0.1σ)	-1.02 (5.1σ)
0.8% in ϕ amplitude	-0.50 (2.5σ)	-0.02 (0.1σ)
4° in $K_0^*(1430)^0$ phase	0.52 (2.6σ)	-0.89 (4.5σ)
4° in $K_0^*(800)$ phase	0.70 (3.5σ)	0.10 (0.5σ)

Results

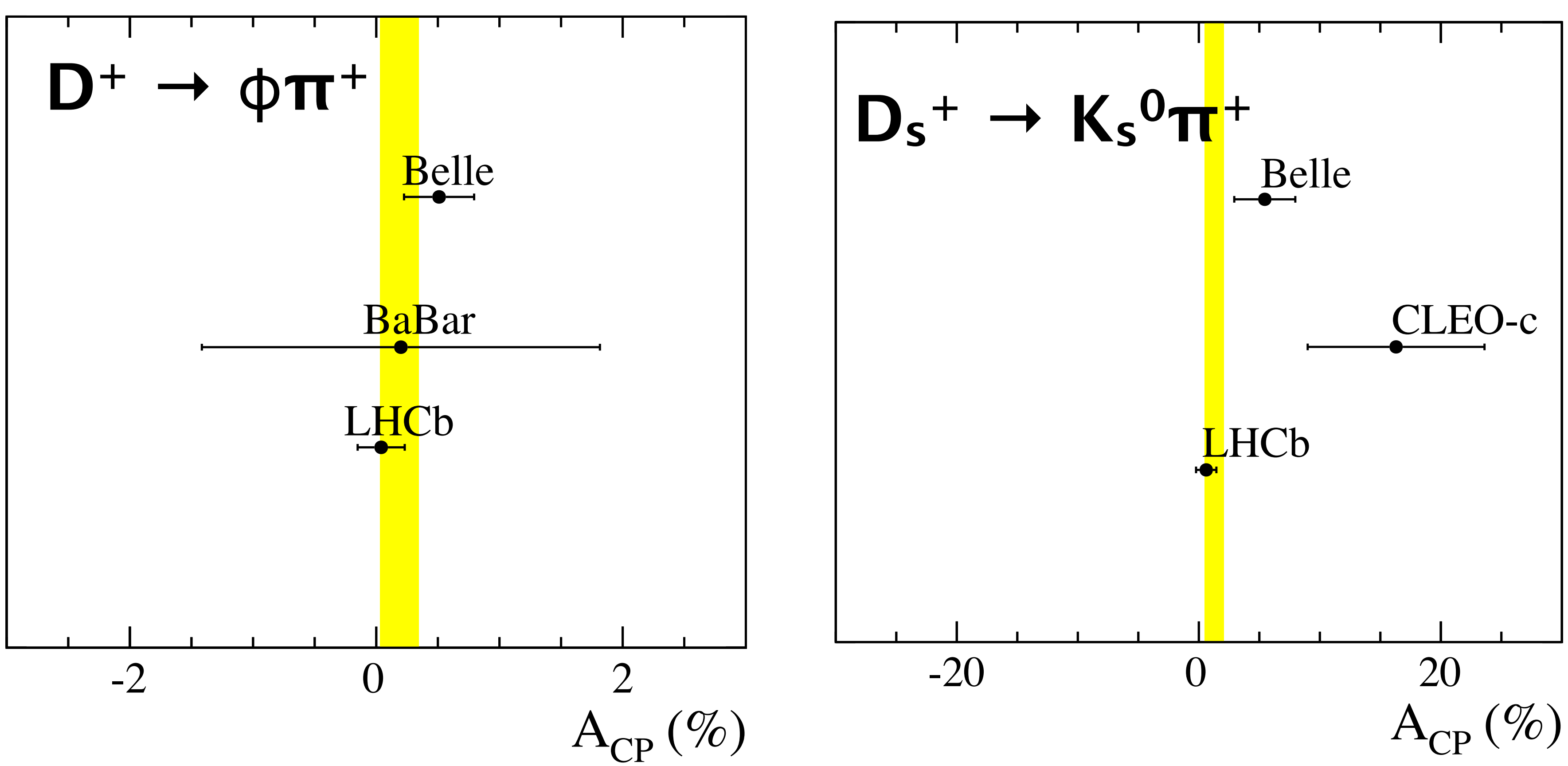
[LHCb-PAPER-2012-052, arXiv:1303.4906]

- Most precise measurements to date, but no hints of CPV

$$A_{CP}(D^+ \to \phi\pi^+) = (-0.04 \pm 0.14 \pm 0.13)\%$$

$$A_{CP|S}(D^+ \to \phi\pi^+) = (-0.18 \pm 0.17 \pm 0.18)\%$$

$$A_{CP}(D_s^+ \to K_S\pi^+) = (+0.61 \pm 0.83 \pm 0.16)\%$$



NP scenarios with direct CPV in charm

- On general grounds, models in which the primary source of flavor violation is linked to the breaking of chiral symmetry (left-right flavor mixing) are natural candidates to generate large direct CPV in charm

- Examples:

  - SUSY models with dominant flavor violation in the left-right squark sector: alignment models [Nir, Seiberg ‘93], disoriented A terms [Giudice, Isidori, PP ’12], partial compositeness [Rattazzi et al. ‘12], Gauge Mediation beyond MFV [Calibbi, PP, Ziegler ‘13]

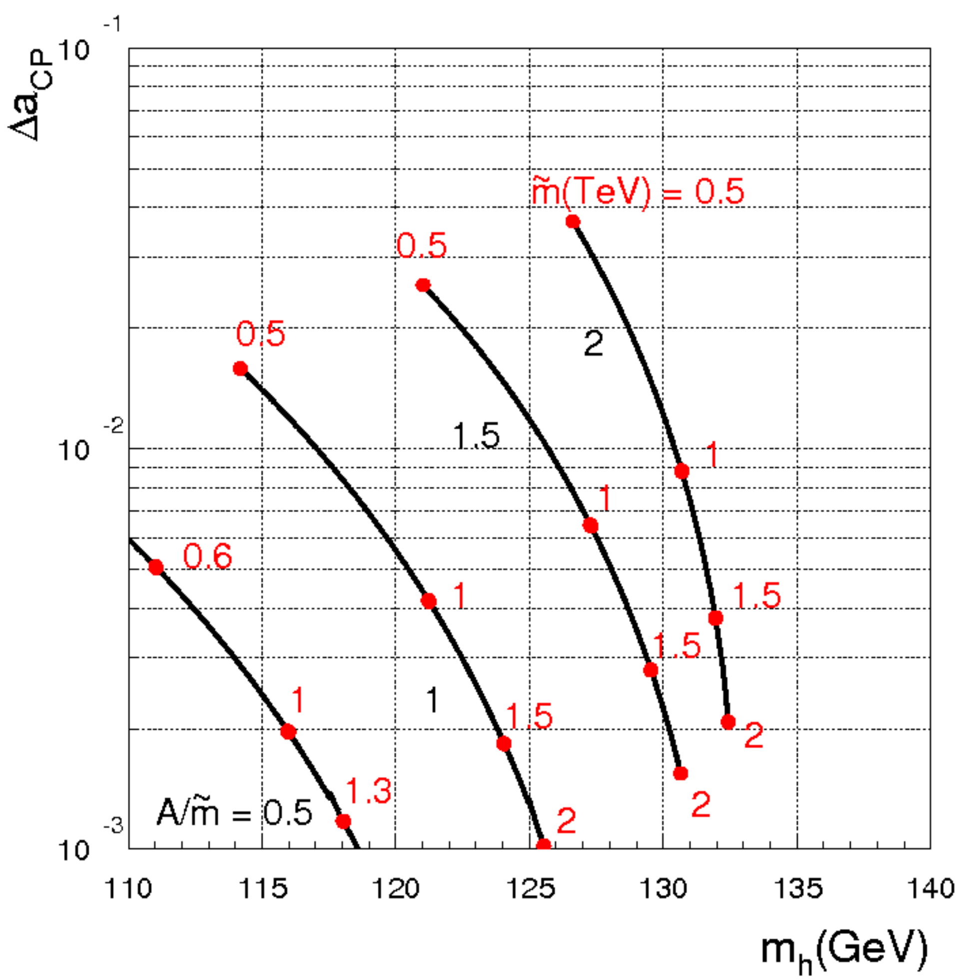
  - Models with partial compositeness [Rattazzi et al. ‘12] or Randall-Sundrum models [Randall et al. ‘12]

  - Z or scalar-mediated FCNC [Giudice, Isidori, PP ‘12]

SUSY

- **Disoriented A terms** [G.F.Giudice, G.Isidori, & P.P, '12]**, explicitly realized in Partial Compositeness frameworks** [Rattazzi et al., '12]

$$(\delta^q_{ij})_{LR} \sim \frac{A\theta^q_{ij} m_{q_j}}{\tilde{m}}, \qquad (\delta^q_{ij})_{LL} \sim (\delta^q_{ij})_{RR} \sim 0\ ,$$ [G.F.Giudice, G.Isidori, & P.P, '12]



[G.F.Giudice, G.Isidori, & P.P, '12]

$$\left(\delta^u_{12}\right)_{LR} \approx \frac{A m_c}{\tilde{m}}\,\theta_{12} \approx \frac{A}{3}\frac{\theta_{12}}{0.5}\frac{\mathrm{TeV}}{\tilde{m}} \times 10^{-3}\ ,$$

$$\left|\Delta a_{CP}^{\mathrm{SUSY}}\right| \approx 0.6\% \frac{\left|\mathrm{Im}\,(\delta^u_{12})_{LR}\right|}{10^{-3}} \left(\frac{\mathrm{TeV}}{\tilde{m}}\right)\ ,$$

- Down-quark FCNC under control thanks to the smallness of m_{down}.
- EDMs suppressed by $m_{u,d}$ yet close to the exp. bounds.
- Robust prediction: $|\Delta a_{CP}| \sim 1\%$ implies a heavy Higgs boson!

NP with Z-mediated FCNC

- **Effective Lagrangian for FCNC couplings of the Z-boson to fermions**

$$\mathcal{L}_{\rm eff}^{Z-\rm FCNC} = -\frac{g}{2\cos\theta_W} \bar{F}_i \gamma^\mu \left[(g_L^Z)_{ij} P_L + (g_R^Z)_{ij} P_R \right] q_j Z_\mu + \text{ h.c.}$$

  F can be either a SM quark ($F = q$) or some heavier non-standard fermion. If F is a SM fermion

$$(g_L^Z)_{ij} = \frac{v^2}{M_{\rm NP}^2} (\lambda_L^Z)_{ij} \qquad (g_R^Z)_{ij} = \frac{v^2}{M_{\rm NP}^2} (\lambda_R^Z)_{ij}$$

- **Direct CPV in charm**

$$\left| \Delta a_{CP}^{Z-\rm FCNC} \right| \approx 0.6\% \left| \frac{\mathrm{Im}\left[(g_L^Z)_{ut}^* (g_R^Z)_{ct} \right]}{2 \times 10^{-4}} \right| \approx 0.6\% \left| \frac{\mathrm{Im}\left[(\lambda_L^Z)_{ut}^* (\lambda_R^Z)_{ct} \right]}{5 \times 10^{-2}} \right| \left(\frac{1~\mathrm{TeV}}{M_{\rm NP}} \right)^4$$

- **Neutron EDM**

$$|d_n| \approx 3 \times 10^{-26} \left| \frac{\mathrm{Im}\left[(g_L^Z)_{ut}^* (g_R^Z)_{ut} \right]}{2 \times 10^{-7}} \right| e\,\mathrm{cm}$$

- **Top FCNC**

$$\mathrm{Br}(t \to cZ) \approx 0.7 \times 10^{-2} \left| \frac{(g_R^Z)_{tc}}{10^{-1}} \right|^2$$

NP with scalar-mediated FCNC

[Giudice, Isidori, PP '12]

- **Effective Lagrangian for FCNC scalar couplings to fermions**

$$\mathcal{L}_{\rm eff}^{h-{\rm FCNC}} = -\bar{q}_i \left[(g^h_L)_{ij}\, P_L + (g^h_R)_{ij}\, P_R \right] q_j\, h + \text{ h.c.} ,$$

$$(g^h_L)_{ij} = \frac{v^2}{M^2_{\rm NP}} (\lambda^h_L)_{ij} , \qquad (g^h_R)_{ij} = \frac{v^2}{M^2_{\rm NP}} (\lambda^h_R)_{ij} ,$$

- **Direct CPV in charm**

$$\left| \Delta a_{CP}^{h-{\rm FCNC}} \right| \approx 0.6\% \left| \frac{{\rm Im}\left[(g^h_L)^*_{ut} (g^h_R)_{tc} \right]}{2 \times 10^{-4}} \right| \approx 0.6\% \left| \frac{{\rm Im}\left[(\lambda^h_L)^*_{ut} (\lambda^h_R)_{ct} \right]}{5 \times 10^{-2}} \right| \left(\frac{1\ {\rm TeV}}{M_{\rm NP}} \right)^4 .$$

- **Neutron EDM**

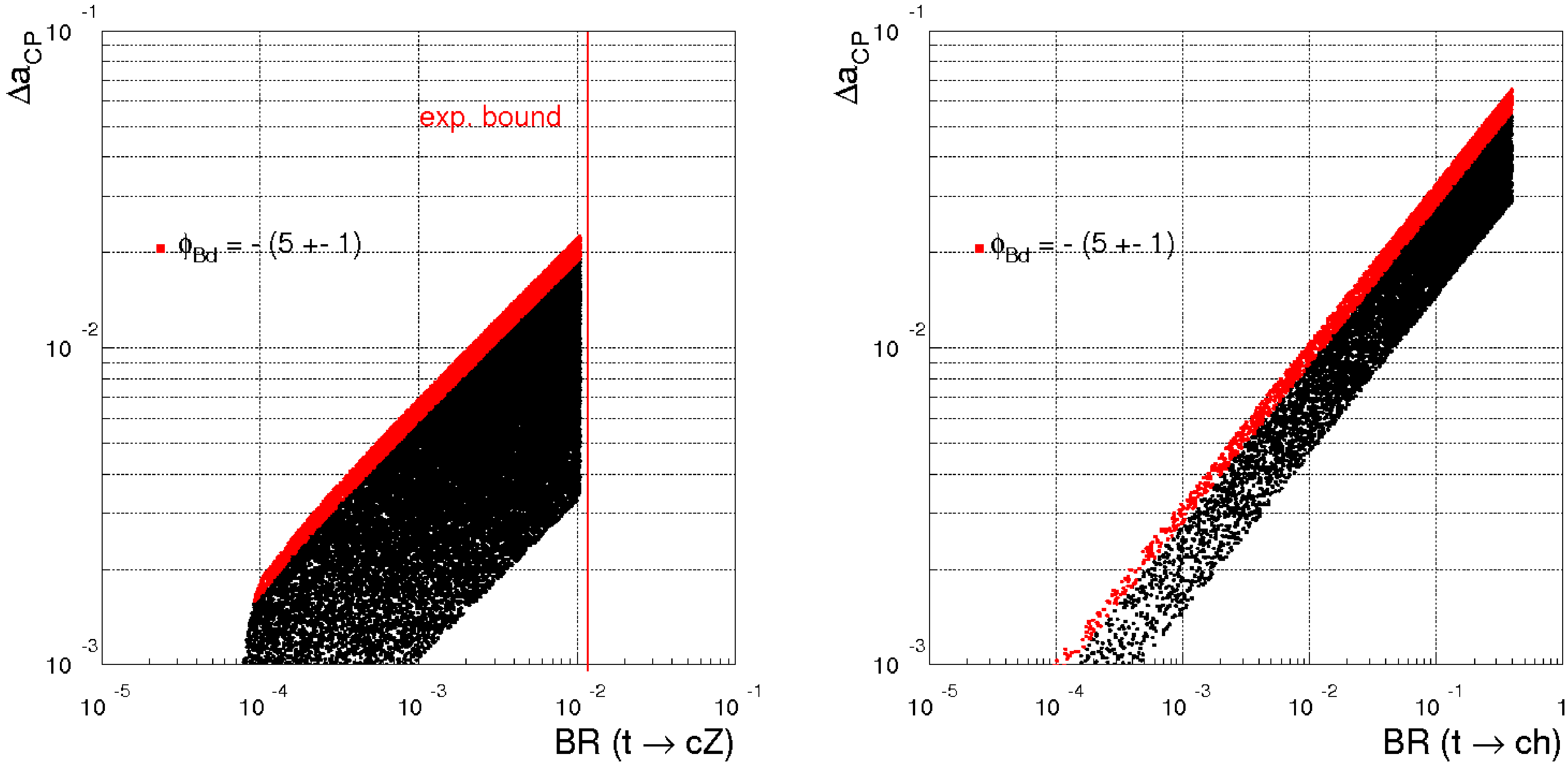
$$|d_n| \approx 3 \times 10^{-26} \left| \frac{{\rm Im}\left[(g^h_L)^*_{ut} (g^h_R)_{tu} \right]}{2 \times 10^{-7}} \right| e\,{\rm cm} ,$$

- **Top FCNC**

$${\rm Br}(t \to qh) \approx 0.4 \times 10^{-2} \left| \frac{(g^h_R)^{tq}}{10^{-1}} \right|^2 ,$$

Explicit realization of this setup in Partial Compositenes [Rattazzi & collaborators, '12] and Randall-Sundrum models [Delaunay, Kamenik, Perez, Randall, '12]

Δa_{CP} with Z- and scalar-mediated FCNC [Giudice, Isidori, PP '12]



Scan of $|(g_L^X)_{ut}|>10^{-3}$, $|(g_R^X)_{ct}|>10^{-2}$ with $\arg[(g_L^X)_{ut}]=\pm\pi/4$, $\arg[(g_R^X)_{ct}]=0$

Red regions solve the tension in the CKM fits through a non-standard phase in B_d–mixing

CPV in neutral D-meson mixing

- Formalism

[Nir et al.; Kagan et al.; Petrov et al.; Bigi et al.; Buras et al.; ...]

$$\langle D^0|\mathcal{H}_{\rm eff}|\bar{D}^0\rangle = M_{12} - \frac{i}{2}\Gamma_{12}, \qquad |D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}, \qquad \phi = \mathrm{Arg}(q/p)$$

$$x = \frac{\Delta m}{\Gamma} = 2\tau \mathrm{Re}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right], \qquad y = \frac{\Delta\Gamma}{2\Gamma} = -2\tau \mathrm{Im}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right]$$

- Observables

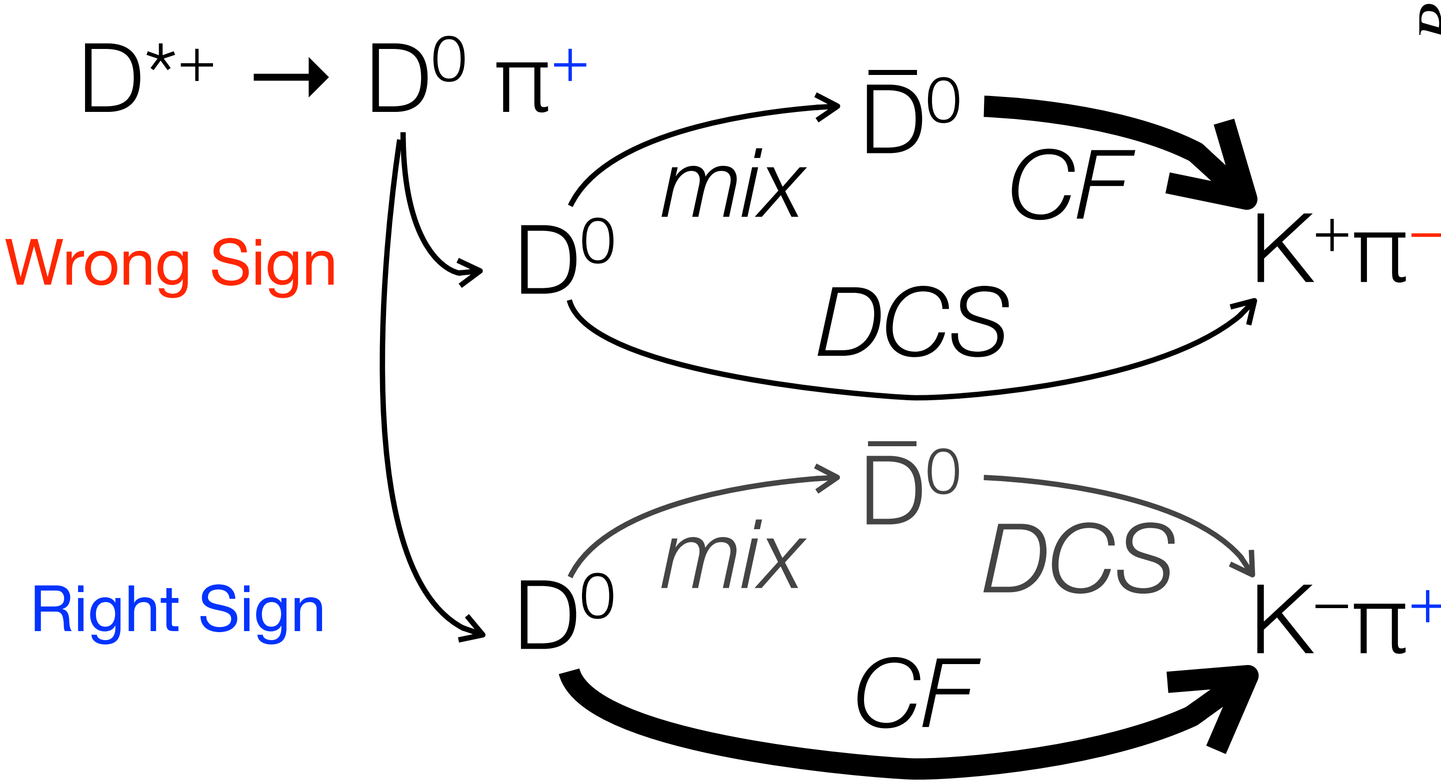
$$A_\Gamma = \frac{\hat{\tau}(\bar{D}^0 \to h^+h^-) - \hat{\tau}(D^0 \to h^+h^-)}{\hat{\tau}(\bar{D}^0 \to h^+h^-) + \hat{\tau}(\bar{D}^0 \to h^+h^-)} = -a_{CP}^{\rm ind}$$

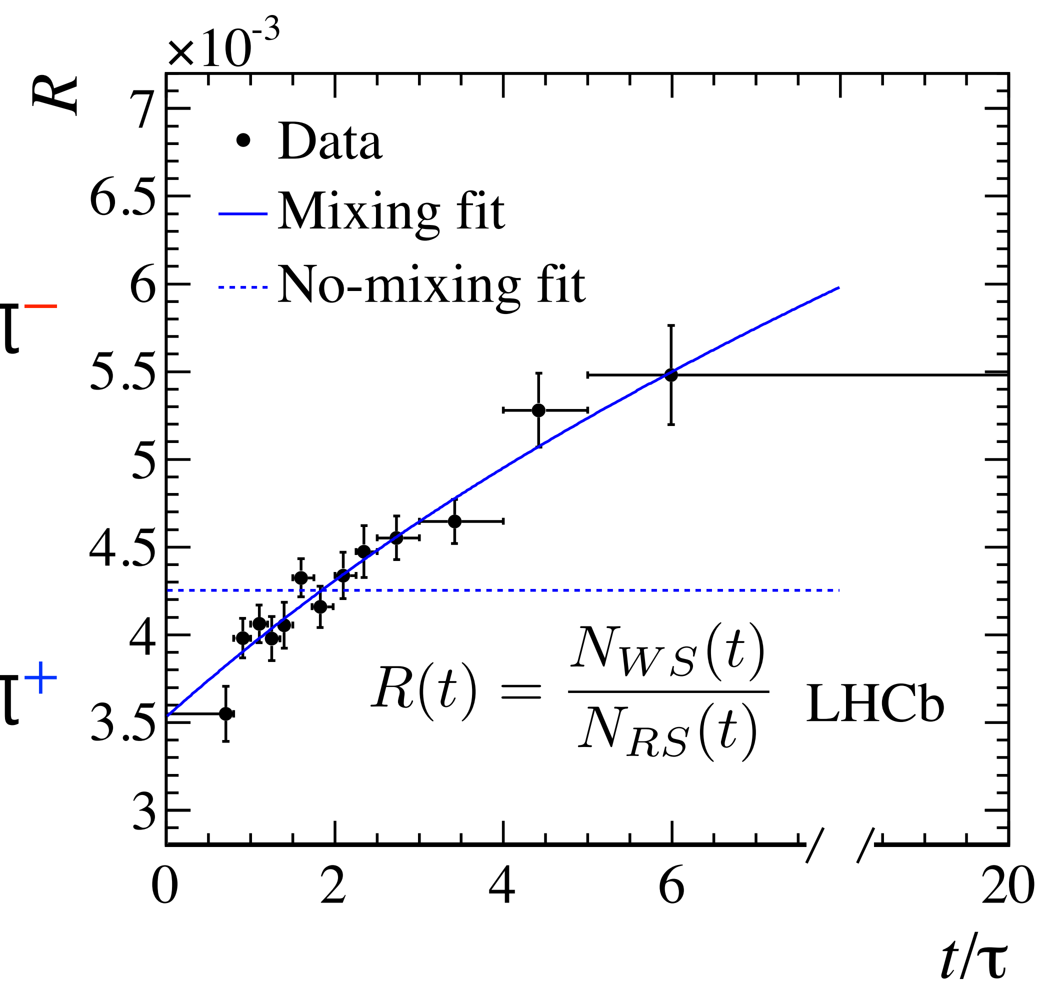
$$\approx \frac{y}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\phi - \frac{x}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\phi$$

$$a_{\rm SL} = \frac{\Gamma(D^0 \to h^+\ell^-\nu) - \Gamma(\bar{D}^0 \to h^-\ell^+\nu)}{\Gamma(D^0 \to h^+\ell^-\nu) + \Gamma(\bar{D}^0 \to h^-\ell^+\nu)} = \frac{|q|^4 - |p|^4}{|q|^4 + |p|^4}$$

Mixing in the charm system

- Mixing of neutral D mesons, as for K and $B_{(s)}$, is well established
- First observation from single measurement using 1/fb of LHCb data [PRL 110 (2013) 101802]





- Now possible to investigate CPV in mixing with unprecedented precision

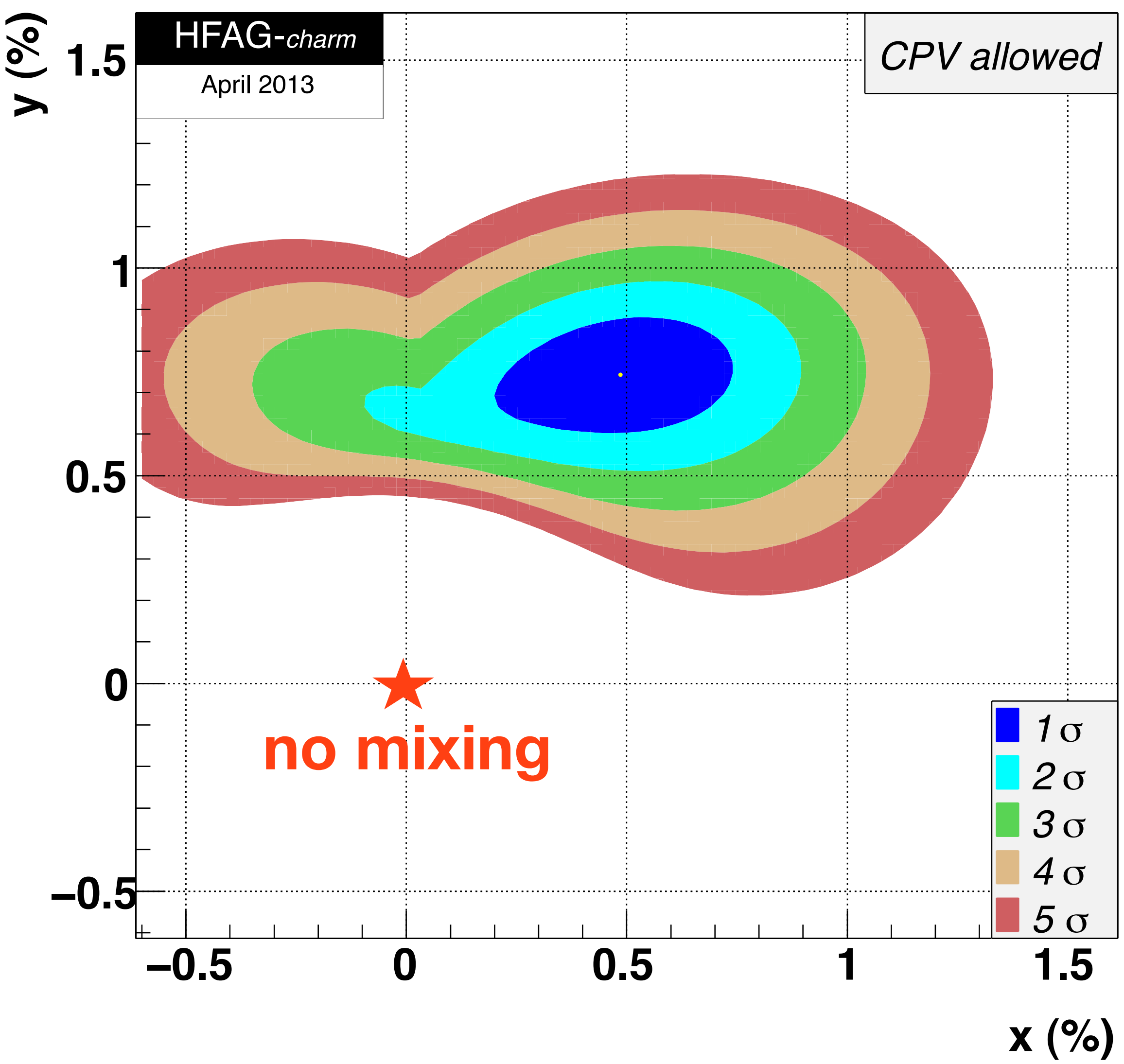
Experimental status

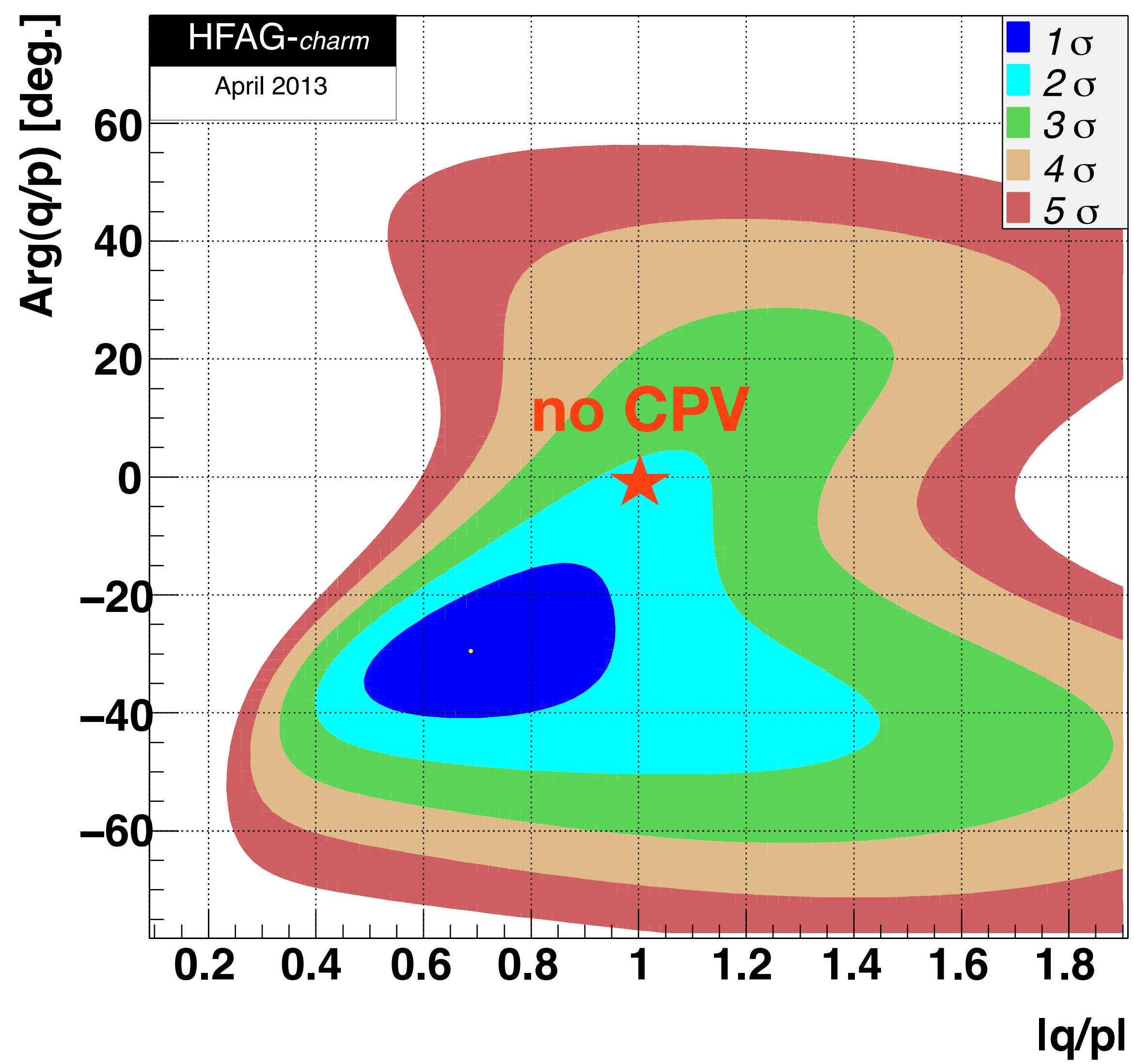
$$x = (0.49^{+0.17}_{-0.18})\%$$

$$y = (0.74 \pm 0.09)\%$$

$$|q/p| = (0.69^{+0.17}_{-0.14})\%$$

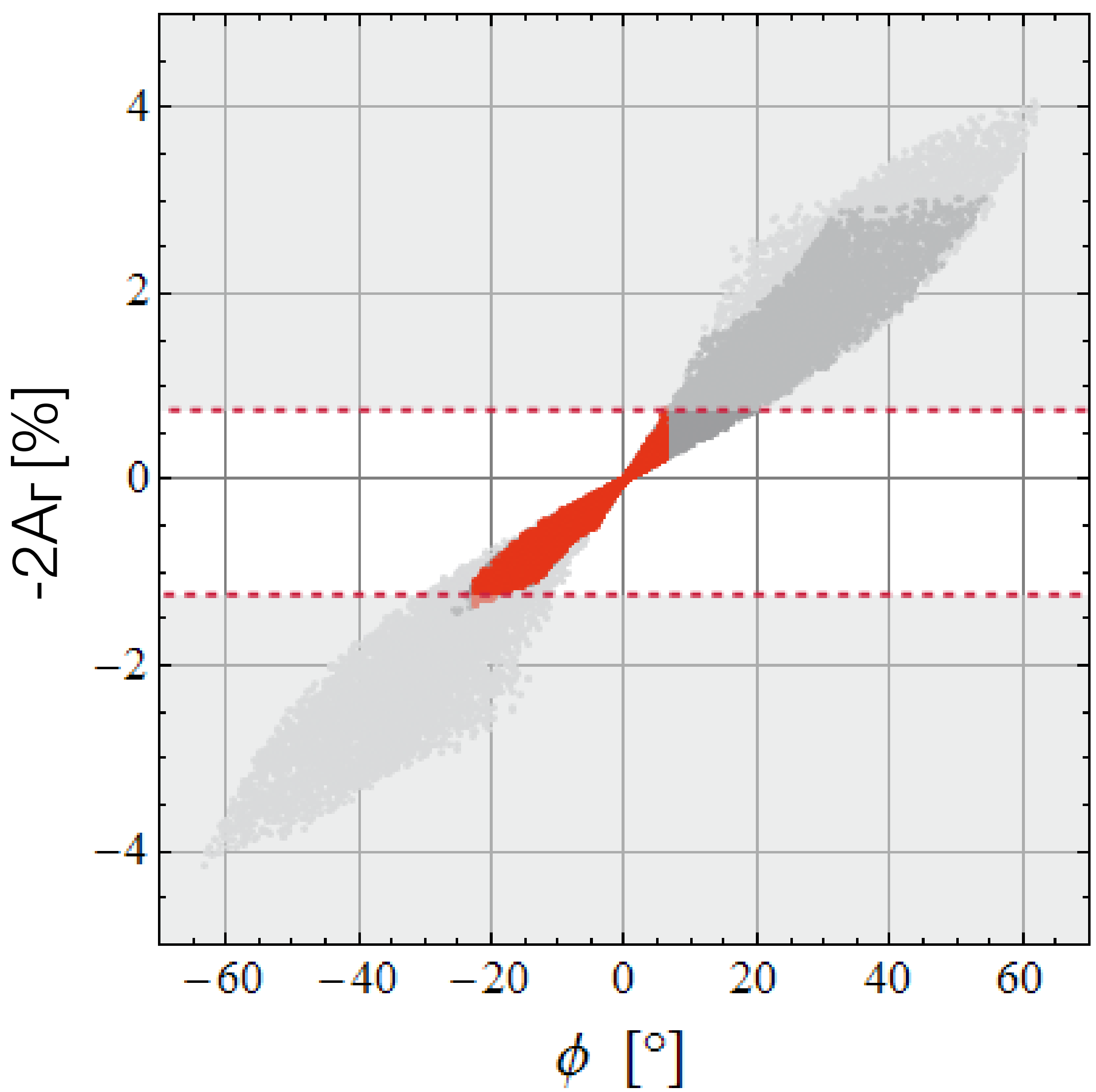
$$\phi = (-29.6^{+8.9}_{-7.5})^\circ$$

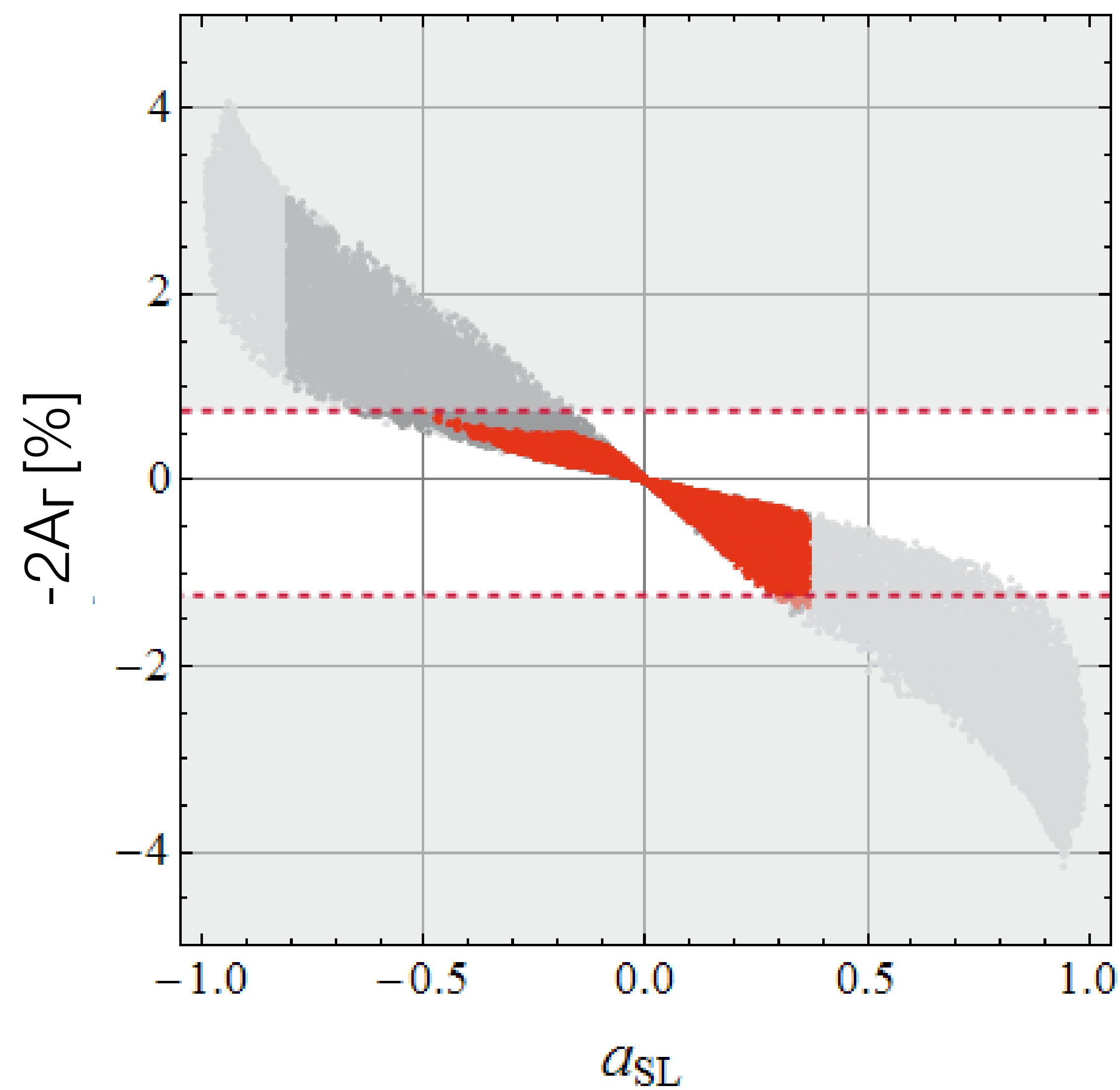




Model independent CPV in mixing

[Altmannshofer, Buras, PP '10]





- light gray satisfies x∈[0.46,1.46]% and y∈[0.51,1.15]%
- darker gray further satisfies |q/p|∈[0.57,1.21]
- red is compatible with all above constraints plus ϕ∈[-22.5,6.3]°
- the dashed lines stand for the resulting allowed range for A_Γ

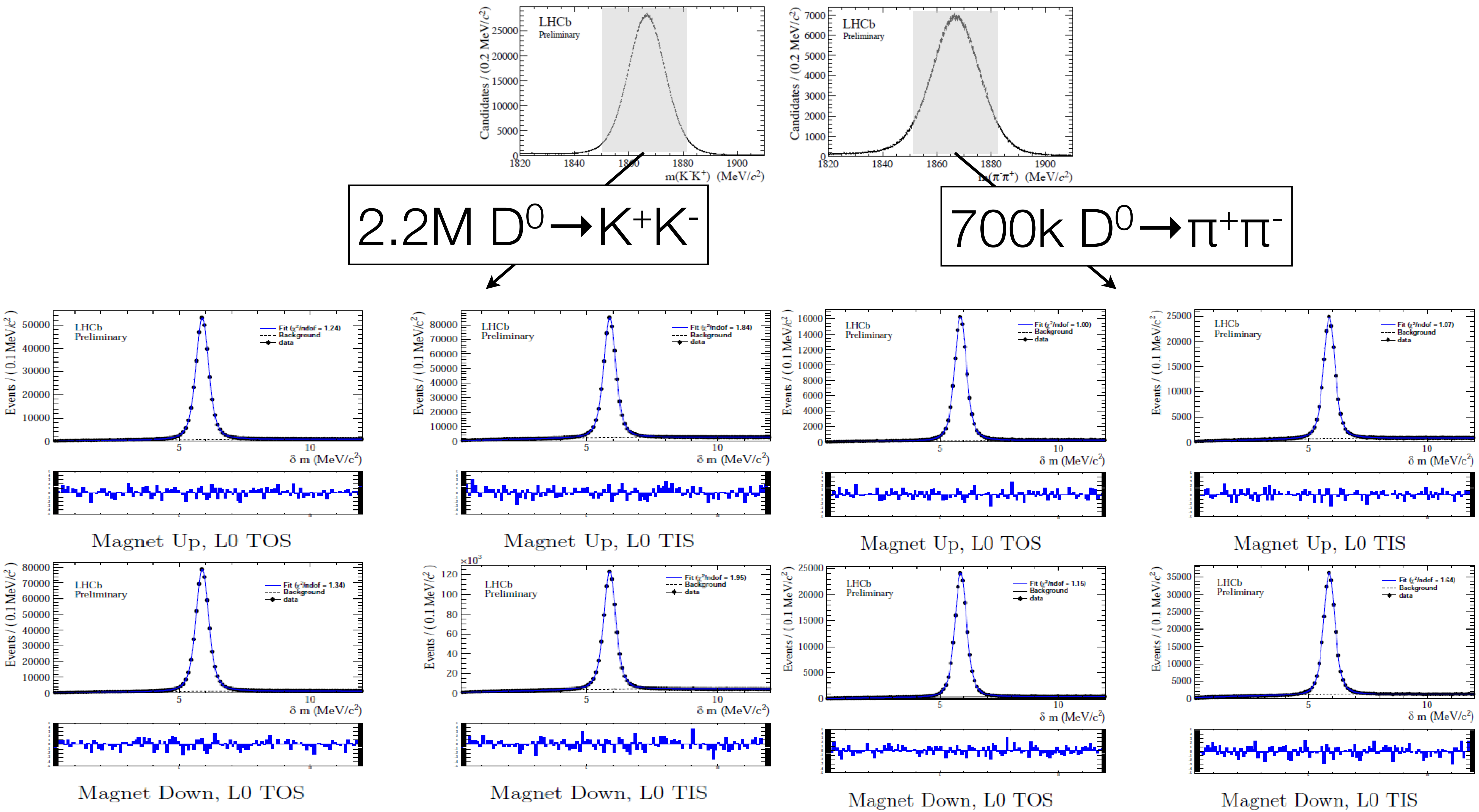
Conclusions

- It is quite plausible that NP contributions affect mostly the up sector
- CP/flavor violation in D mesons is a unique probe of NP flavor effects, quite complementary to tests in K and B systems
- Experimental evidence for large direct CPV in charm by LHCb, even if recently not confirmed, has stimulated new ideas and the construction of models departing in a controlled way from the MFV paradigm [Giudice, Isidori, PP ‘12; Rattazzi et al. ‘12; Calibbi, PP, Ziegler ‘13] which have a much broader (and hopefully testable) impact on low and high-p_T phenomenology
- Full LHCb Run I dataset still to be analyzed, additional investigations of the charm sector with more precise results are about to come
- The synergy of low-energy flavor data with the high-p_T part of the LHC program will teach us a lot about NP at the TeV scale (if any) with the upcoming 14 TeV LHC run

Backup

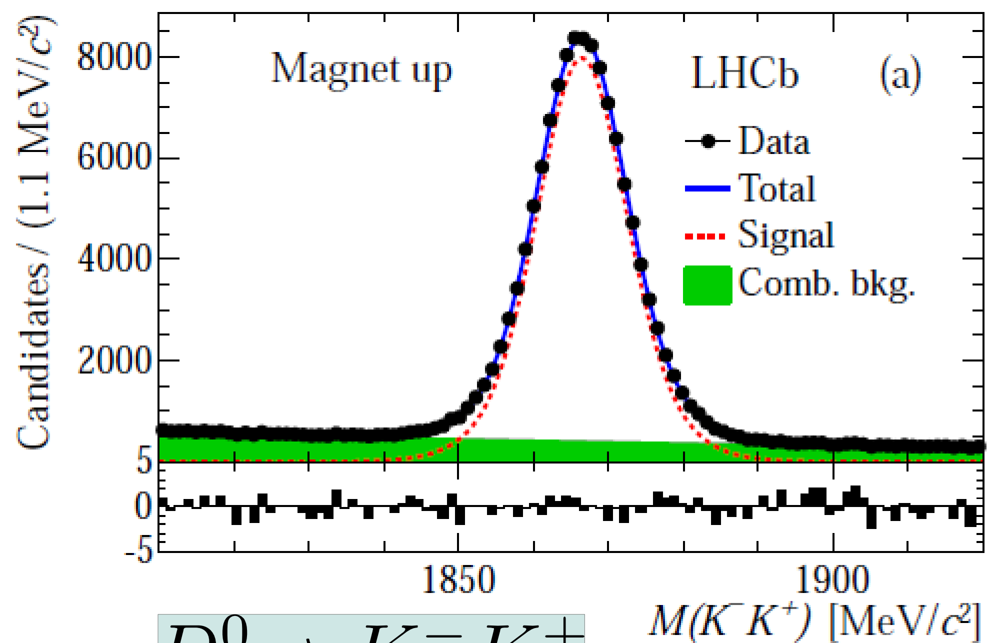
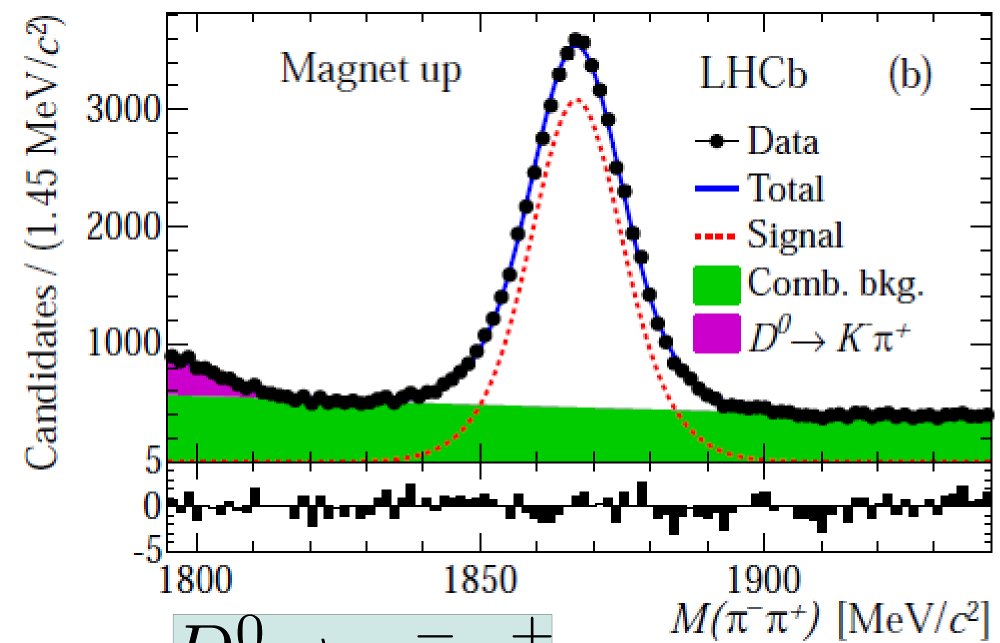
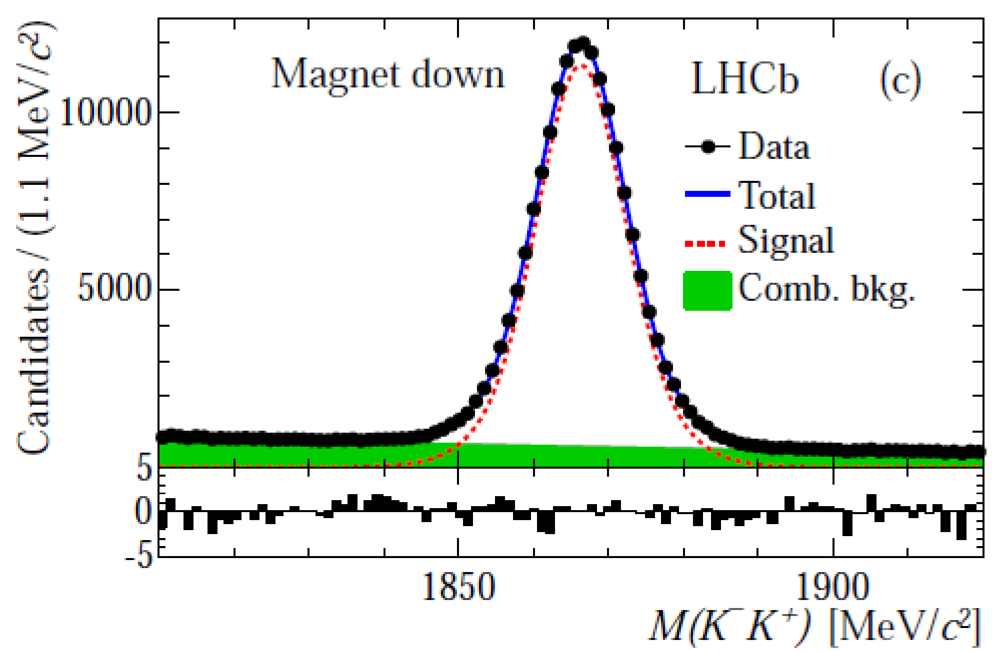
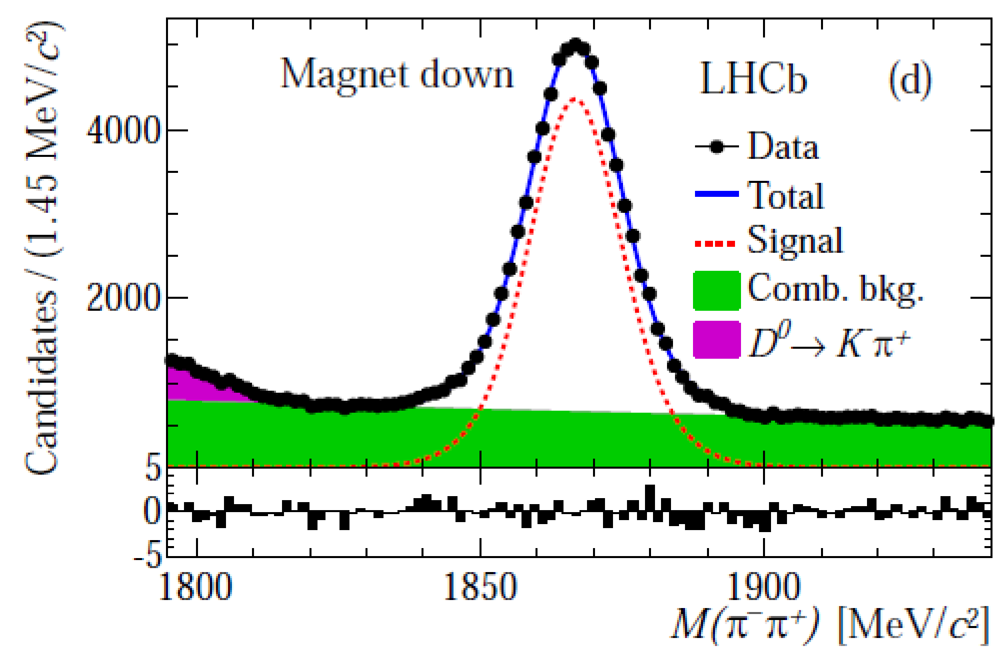
D*-tagged yield

[LHCb-CONF-2013-003]



Semileptonic-tagged yields

[LHCb-PAPER-2013-003, arXiv:1303.2614]

	600k	200k
Magnet up		
	$D^0 \to K^- K^+$	$D^0 \to \pi^- \pi^+$
Magnet down		

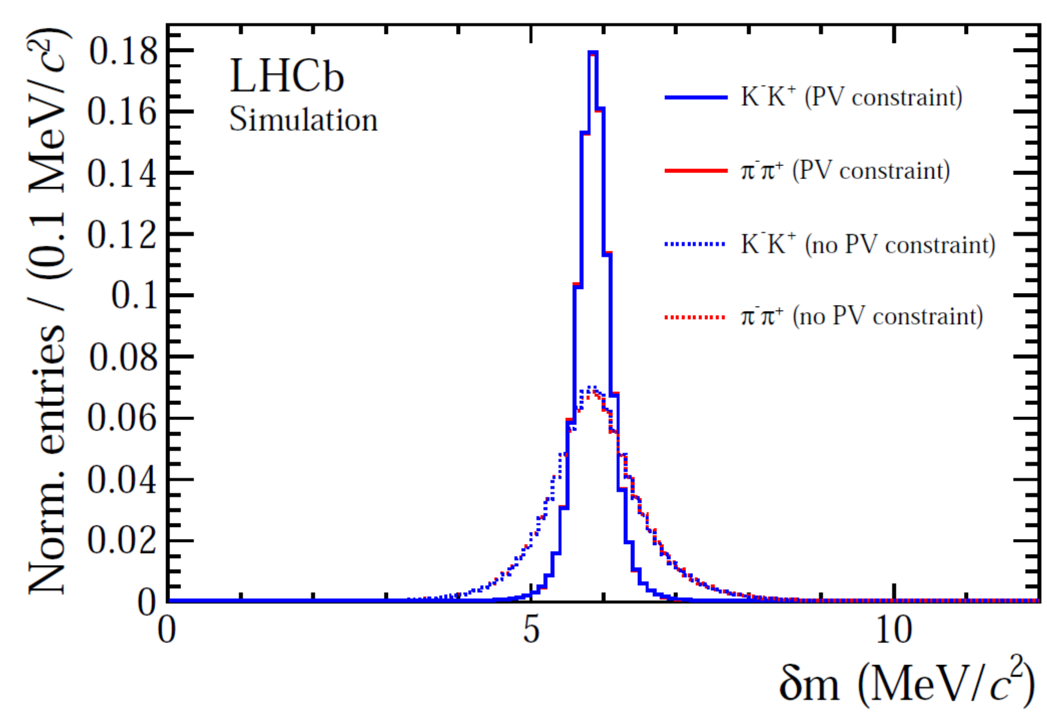
D*-tagged ΔA_{CP} evolution

[LHCb-CONF-2013-003]

Changes	ΔA_{CP} (%)
Old result (0.6/fb)	-0.82±0.11
New reconstruction (0.6/fb)	-0.55±0.21
Adding extra 0.4/fb	-0.28±0.26
Total 1/fb	-0.45±0.16
Adding PV constraint	-0.34±0.15

- 15/14% of KK/ππ not selected by new reco: ΔA_{CP} in overlapping sample is (-0.78±0.23)%

- new reco also selects additional 17/34% of KK/ππ events with ΔA_{CP} = (-0.28±0.46)%



Detailed ΔA_{CP} results

- Semileptonic analysis [LHCb-PAPER-2013-003, arXiv:1303.2614]

	up [%]	down [%]	mean [%]
$A_{\mathrm{raw}}(K^-K^+)$	-0.39 ± 0.23	-0.20 ± 0.19	-0.29 ± 0.15
$A_{\mathrm{raw}}(\pi^-\pi^+)$	-1.25 ± 0.40	-0.29 ± 0.34	-0.77 ± 0.26
$\Delta A_{CP}^{\mathrm{raw}}$	0.86 ± 0.46	0.09 ± 0.39	0.48 ± 0.30

  - Up and down compatible also in individual asymmetries
  - Final result arithmetic mean of both polarities
- Prompt analysis [LHCb-CONF-2013-003]

Quantity	Magnet polarity	Hardware trigger decision	Observed value [%]
$A_{\mathrm{raw}}(K^-K^+)$	Up	TOS	-1.35 ± 0.18
$A_{\mathrm{raw}}(K^-K^+)$	Down	TOS	-0.45 ± 0.15
$A_{\mathrm{raw}}(\pi^-\pi^+)$	Up	TOS	-0.73 ± 0.31
$A_{\mathrm{raw}}(\pi^-\pi^+)$	Down	TOS	-0.08 ± 0.26
$A_{\mathrm{raw}}(K^-K^+)$	Up	TIS	-1.72 ± 0.15
$A_{\mathrm{raw}}(K^-K^+)$	Down	TIS	$+0.12\pm0.12$
$A_{\mathrm{raw}}(\pi^-\pi^+)$	Up	TIS	-1.43 ± 0.26
$A_{\mathrm{raw}}(\pi^-\pi^+)$	Down	TIS	$+0.34\pm0.22$
ΔA_{CP}	Up	TOS	-0.62 ± 0.36
ΔA_{CP}	Down	TOS	-0.36 ± 0.30
ΔA_{CP}	Up	TIS	-0.30 ± 0.30
ΔA_{CP}	Down	TIS	-0.22 ± 0.25

Up and down differences in asymmetries

→ ΔA_{cp} very stable

Final result weighted average of independent samples

$$\Delta A_{CP} = (-0.34 \pm 0.15)\ \%$$

Systematics for ΔA_{CP}

[LHCb-PAPER-2013-003, arXiv:1303.2614]
[LHCb-CONF-2013-003]

- Semileptonic analysis
  - Low decay time backgrounds
  - Weighting procedure
  - Fit model

Source of uncertainty	Absolute uncertainty
Production asymmetry:	
Difference in b-hadron mixture	0.02%
Difference in B decay time acceptance	0.02%
Production and detection asymmetry:	
Different weighting	0.05%
Background from real D^0 mesons:	
Mistag asymmetry	0.02%
Background from fake D^0 mesons:	
D^0 mass fit model	0.05%
Low-lifetime background in $D^0 \to \pi^-\pi^+$	0.11%
Λ_c^+ background in $D^0 \to K^-K^+$	0.03%
Quadratic sum	0.14%

- Prompt analysis
  - Impact parameter cut on tagging pion
  - Peaking backgrounds
  - Fit model

Source	Uncertainty
Fiducial cut	0.02%
Peaking background	0.04%
Fit model	0.03%
Multiple candidates	0.01%
Reweighting	0.01%
Soft pion IPχ^2	0.08%
Total	0.10%

Independent systematics in both analyses.

Systematics for $D^{+}_{(s)}$ asymmetries

[LHCb-PAPER-2012-052, arXiv:1303.4906]

Source	$A_{CP}\ (D^+)$ [%]	$A_{CP}\ (D_s^+)$ [%]	$A_{CP}\|_S$ [%]
Triggers	0.114	0.114	n/a
D_s^+ control sample size	n/a	n/a	0.169
Kaon asymmetry	0.031	0.002	0.009
Binning	0.035	0.035	n/a
Resolution	0.007	0.006	0.056
Fitting	0.033	0.033	n/a
Kaon CP violation	0.028	0.028	n/a
Fiducial effects	0.022	0.022	n/a
Backgrounds	0.008	n/a	0.007
D from B	0.003	0.015	0.003
Regeneration	0.010	0.010	n/a
Total	0.133	0.130	0.178

D-mixing: HFAG average

Parameter	No CPV	No direct CPV	CPV-allowed	CPV-allowed 95% C.L.
x (%)	$0.49\,^{+0.17}_{-0.18}$	$0.46\,\pm 0.18$	$0.49\,^{+0.17}_{-0.18}$	$[0.10, 0.81]$
y (%)	$0.66\,\pm 0.09$	$0.67\,\pm 0.09$	$0.74\,\pm 0.09$	$[0.56, 0.92]$
δ (°)	$10.8\,^{+10.3}_{-12.3}$	$11.4\,^{+10.5}_{-12.7}$	$19.5\,^{+8.6}_{-11.1}$	$[-9.6, 35.4]$
R_D (%)	$0.347\,\pm 0.006$	$0.347\,\pm 0.006$	$0.350\,^{+0.007}_{-0.006}$	$[0.337, 0.362]$
A_D (%)	–	–	$-2.6\,\pm 2.2$	$[-6.9, 1.7]$
$\|q/p\|$	–	$1.04\,^{+0.07}_{-0.06}$	$0.69\,^{+0.17}_{-0.14}$	$[0.44, 1.07]$
ϕ (°)	–	$-1.6\,^{+2.4}_{-2.5}$	$-29.6\,^{+8.9}_{-7.5}$	$[-44.6, -7.5]$
$\delta_{K\pi\pi}$ (°)	$21.3\,^{+23.4}_{-23.8}$	$22.9\,^{+23.7}_{-24.0}$	$25.1\,^{+22.3}_{-23.0}$	$[-20.6, 69.2]$
A_π	–	–	$0.16\,\pm 0.21$	$[-0.25, 0.57]$
A_K	–	–	$-0.16\,\pm 0.20$	$[-0.56, 0.23]$
x_{12} (%)	–	$0.46\,\pm 0.18$	–	$[0.10, 0.80]$
y_{12} (%)	–	$0.67\,\pm 0.09$	–	$[0.50, 0.85]$
ϕ_{12}(°)	–	$4.8\,^{+9.2}_{-7.4}$	–	$[-11.7, 35.9]$

D-mixing: HFAG average