Impact of Charm physics to CKM fit

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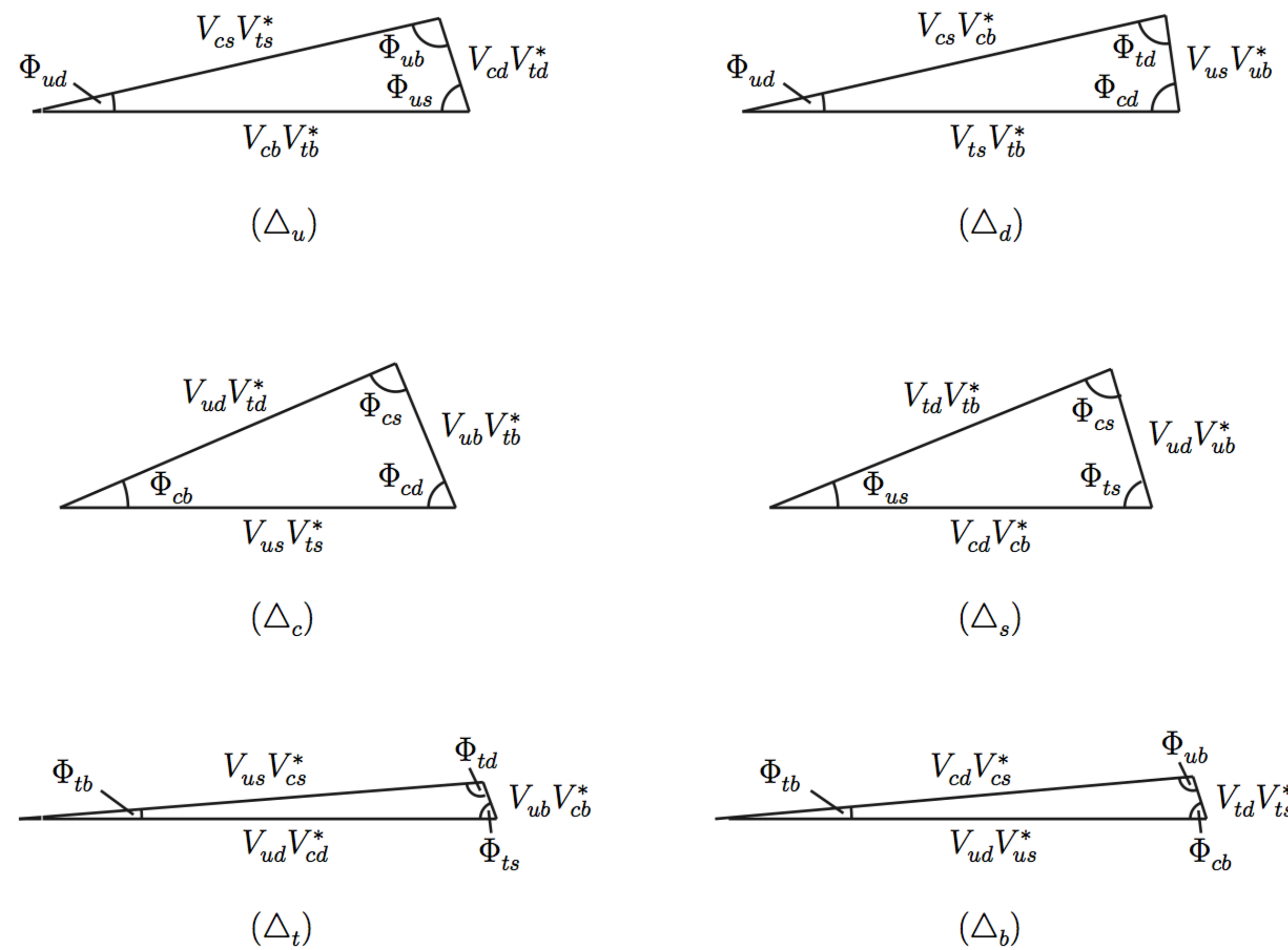
Outline and Motivation

Charm is a quite rare guest in the slides of a fitter group speaker.

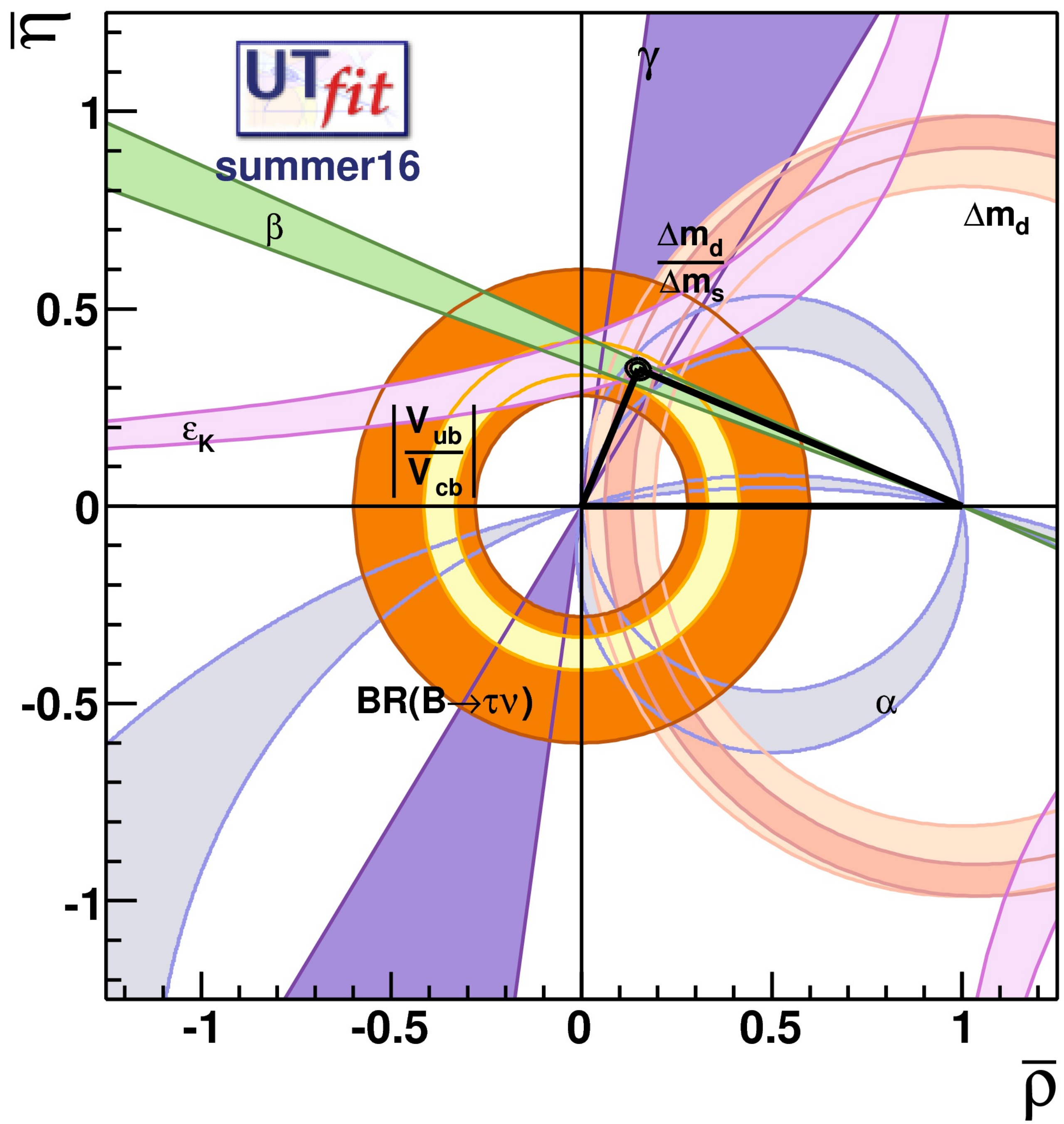
Explanations are:

- The effects are small .
- The measurements were not as precise to be sensitive to interesting effects.
- Long distance effects may interfere.



However, charm already plays an important role in the Unitarity fits.
With new data arriving, this role will only increase.

Unitarity Triangle Status



The main global effect of charm measurements can be felt in the CKM angle gamma.

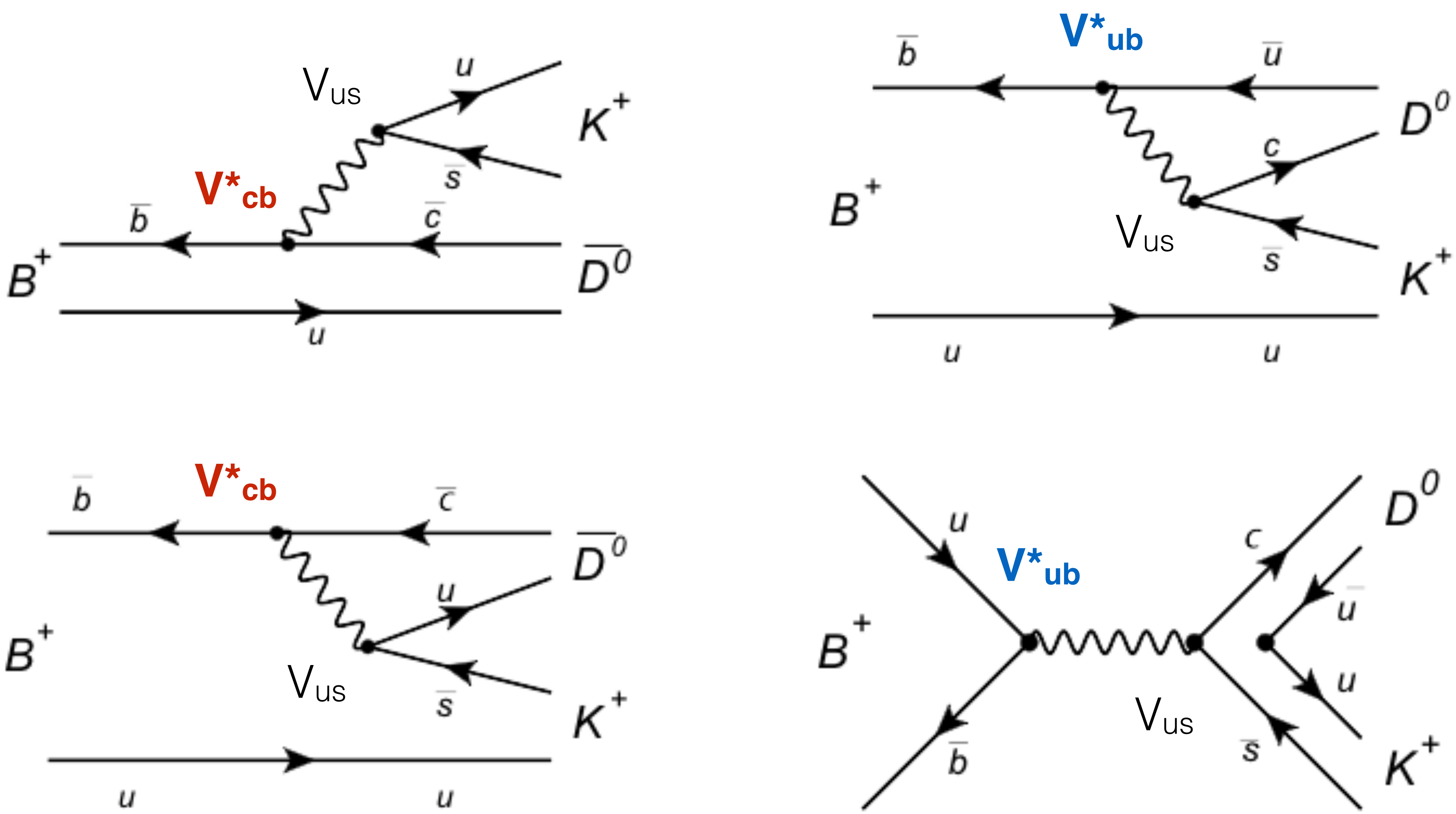
$$\gamma \equiv \arg\left[-V_{ud}V_{ub}{}^{*}/V_{cd}V_{cb}{}^{*}\right]$$

Gamma:

- relatively easily accessible at tree-level
- still not well-known
- in general, theoretically quite clean
- together with |Vub| provides a SM benchmark for other loop-mediated measurements

Gamma measurements

$$\gamma \equiv \arg\left[-V_{ud}V_{ub}{}^{*}/V_{cd}V_{cb}{}^{*}\right]$$

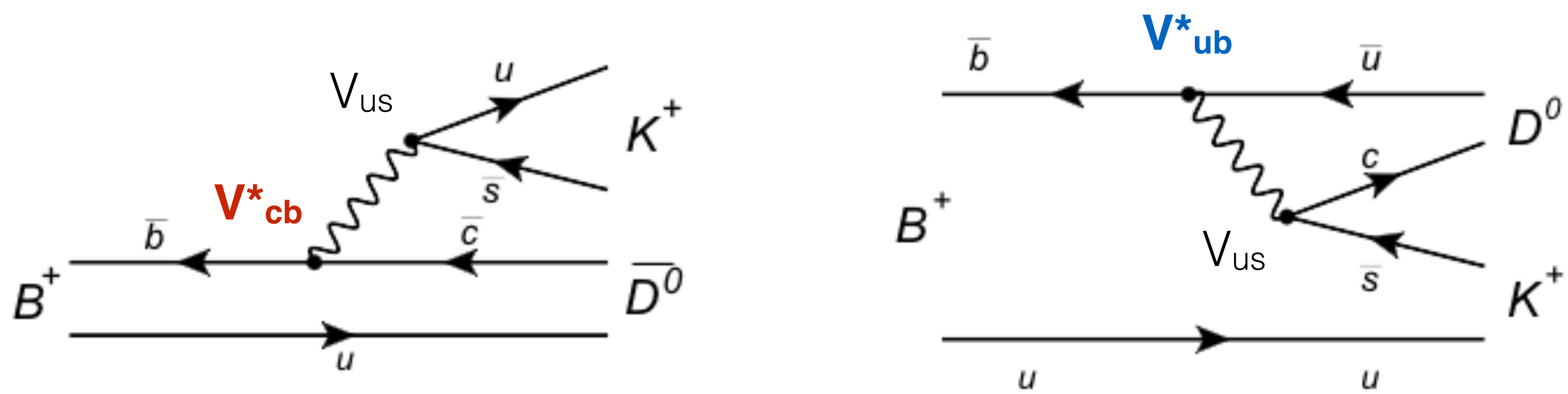


The best channel to get the value of gamma is $B^+ \rightarrow DK^+$:

- it can proceed through both Vub and Vcb transitions;
- it has got a relatively high Branching fraction.

Gamma measurements

$$\gamma \equiv \arg\left[-V_{ud}V_{ub}{}^{*}/V_{cd}V_{cb}{}^{*}\right]$$



This measurement is theoretically very clean, the precision is ~10^{-6}

Thus the NP scale that can be probed is ~100-1000 TeV

Jure Zupan, arXiv:1101.0134

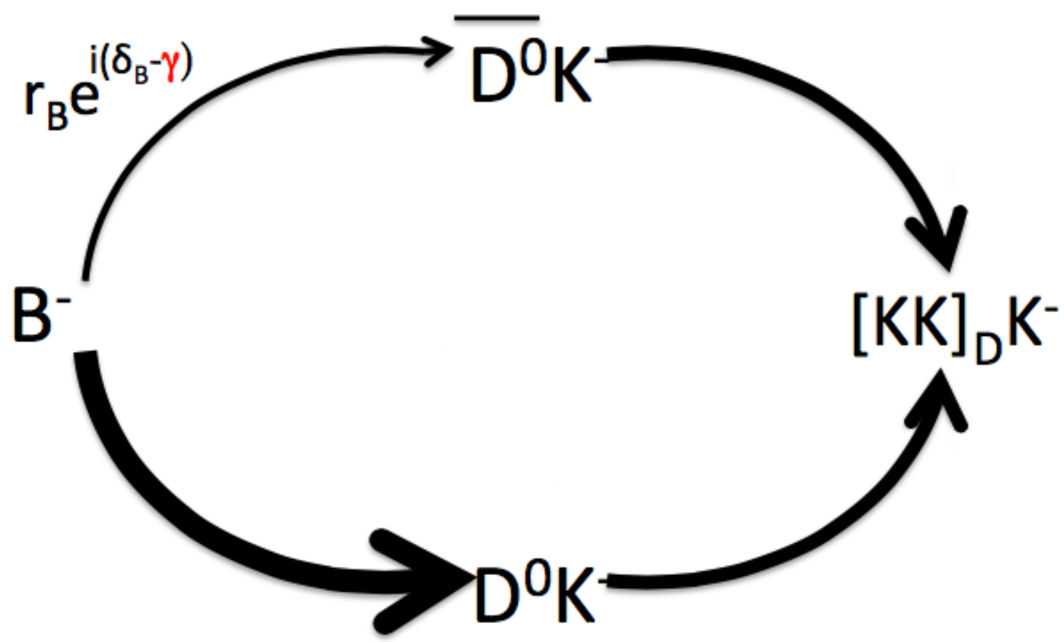
Two additional hadronic parameters are determined alongside with gamma:

- relative strong phase δ_B;
- amplitude ratio, r_B (magnitude drives the precision on gamma).

We just need to choose the D^0 final state that will provide interference of the final state.

Gronau London Wyler method

Choose D^0 decaying to (quasi) two-body *CP* eigenstate



One can choose several decay modes:

$$CP+: D^0 \to K^+K^-, \pi^+\pi^-$$
$$CP-: D^0 \to K_S^0\pi^0, K_S^0\omega, K_S^0\phi, (K_S^0\eta)$$

B decay rate is given by:

$$\Gamma(B^- \to D[\to f_D]K^-) \propto A_c^2(1 + r_B^2 \pm 2r_B\cos(\delta_B - \gamma))$$

Decay amplitude of the process (cancelled in ratio)

B hadronic parameters

Gronau & London, PLB 253 (1991) 483, Gronau & Wyler PLB 265 (1991) 172

Gronau London Wyler method

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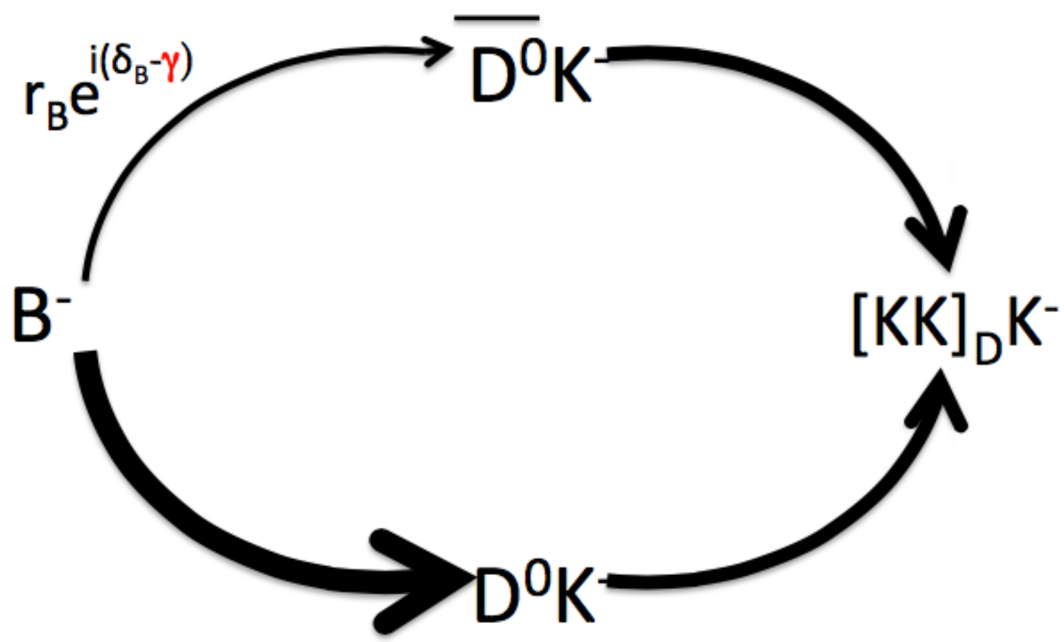


One can choose several decay modes:

$$CP+: D^0 \to K^+K^-, \pi^+\pi^-$$
$$CP-: D^0 \to K_S^0\pi^0, K_S^0\omega, K_S^0\phi, (K_S^0\eta)$$

Typical observables are:

$$R_{CP^\pm} = \frac{\Gamma(B^+ \to D_\pm^0 K^+) + \Gamma(B^- \to D_\pm^0 K^-)}{\Gamma(B^+ \to D^0 K^+) + \Gamma(B^- \to \bar{D}^0 K^-)} = 1 + r_B^2 \pm 2r_B \cos\gamma\cos\delta_B,$$
$$A_{CP^\pm} = \frac{\Gamma(B^+ \to D_\pm^0 K^+) - \Gamma(B^- \to D_\pm^0 K^-)}{\Gamma(B^+ \to D_\pm^0 K^+) + \Gamma(B^- \to D_\pm^0 K^-)} = \frac{\pm 2r_B \sin\gamma\sin\delta_B}{R_{CP^\pm}}.$$

The charm mesons introduce complications.

Gronau & London, PLB 253 (1991) 483, Gronau & Wyler PLB 265 (1991) 172

D^0 *CP* asymmetry

The first suspect to introduce corrections into the *CP* violation measurement is the *CP* violation brought by the presence of charm.

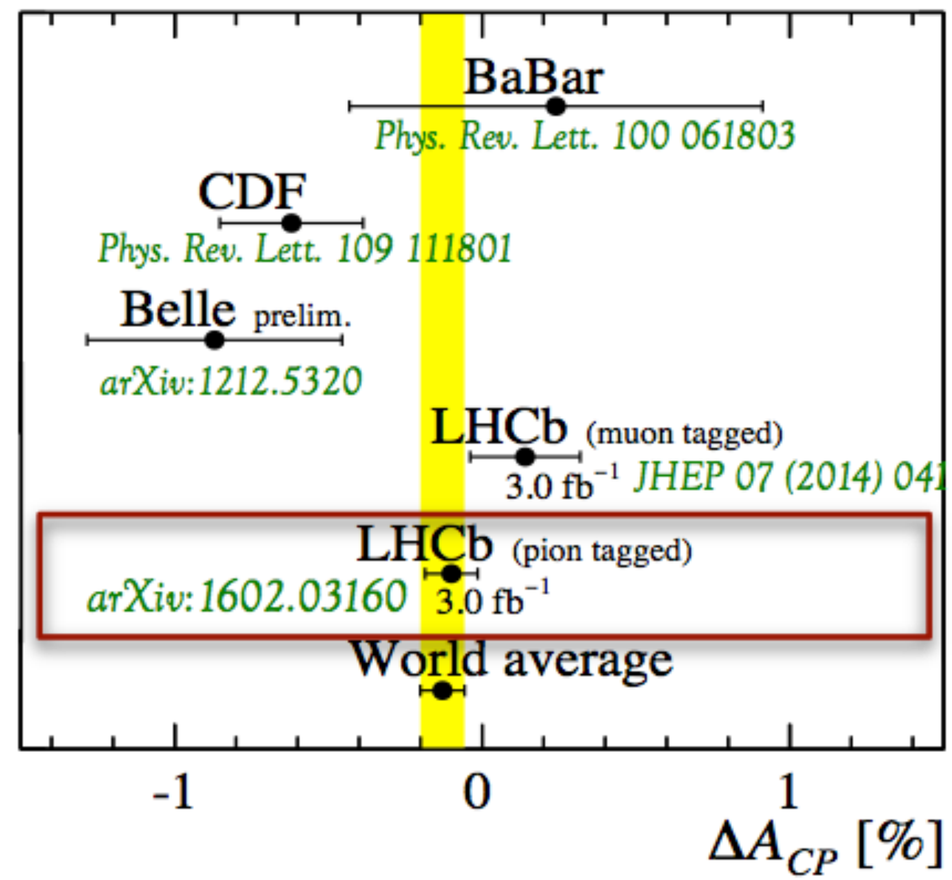
Naïve weighted average (neglecting indirect CPV contribution) gives:

$$\Delta A_{CP} = (-0.129 \pm 0.072)\%.$$

This value should be linearly added to a difference of Acp(KK) and Acp(pipi).

With a typical value of asymmetries (and their uncertainties):

LHCb KK $\int L dt = 3\ \mathrm{fb}^{-1}$	0.087 ± 0.020 ± 0.008
LHCb pipi $\int L dt = 3\ \mathrm{fb}^{-1}$	0.128 ± 0.037 ± 0.012

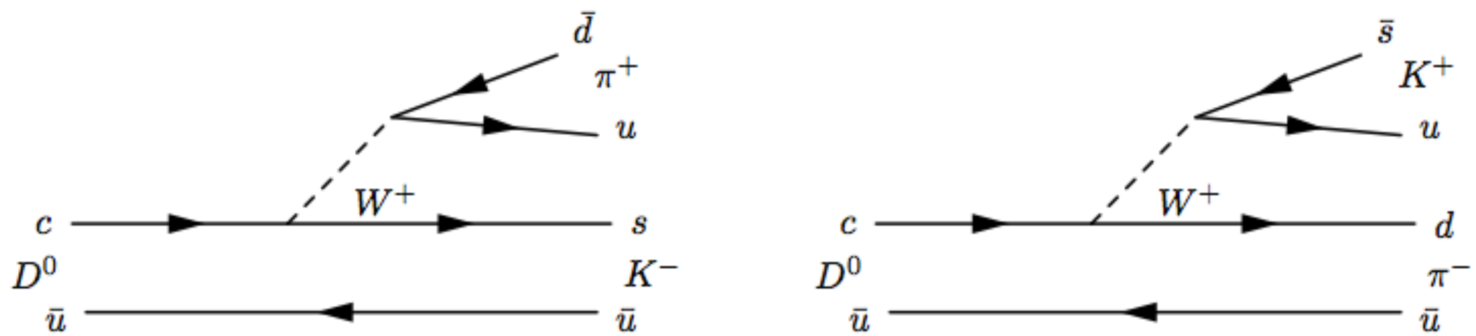


LHCb Physics Letters B 760 (2016)

The influence is currently **quite small**. However, with new data arriving, we can expect it to bring an **additional constraint to gamma**.

Charm doubly Cabibbo suppressed decays

Another approach would be to use the interference between Cabibbo allowed and doubly Cabibbo suppressed decays.

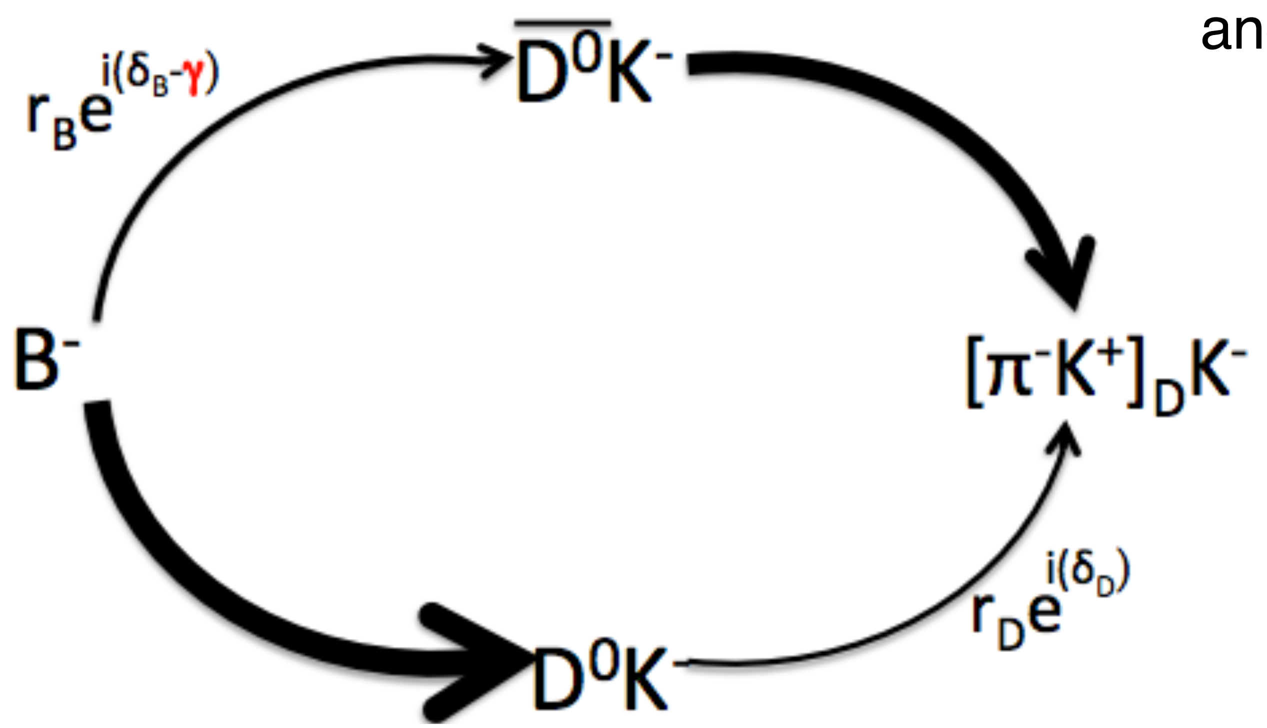


We first need to introduce parameters of the system:

$$r_d = \left| A_{K^+\pi^-} / \bar{A}_{K^+\pi^-} \right| = \left| \bar{A}_{K^-\pi^+} / A_{K^-\pi^+} \right|$$

and a relative strong phase δ_{D}.

Atwood Dunietz Soni method



Interplay between Doubly-Cabibbo-Suppressed and Cabibbo allowed D meson decay:

D^0 Modes:
$K^+\pi^-$,
$K^+\pi^-\pi^0$,
$K^+\pi^-\pi^+\pi^-$

Typical observables are:

D hadronic parameters

$$R_{ADS} = \frac{\Gamma([\bar{f}]K^-)+\Gamma([\bar{f}]K^+)}{\Gamma([f]K^-)+\Gamma([f]K^+)} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos\gamma$$

$$A_{ADS} = \frac{\Gamma([\bar{f}]K^-)-\Gamma([\bar{f}]K^+)}{\Gamma([f]K^-)+\Gamma([f]K^+)} = 2 r_B r_D \cos(\delta_B + \delta_D)\cos\gamma / R_{ADS}$$

B hadronic parameters

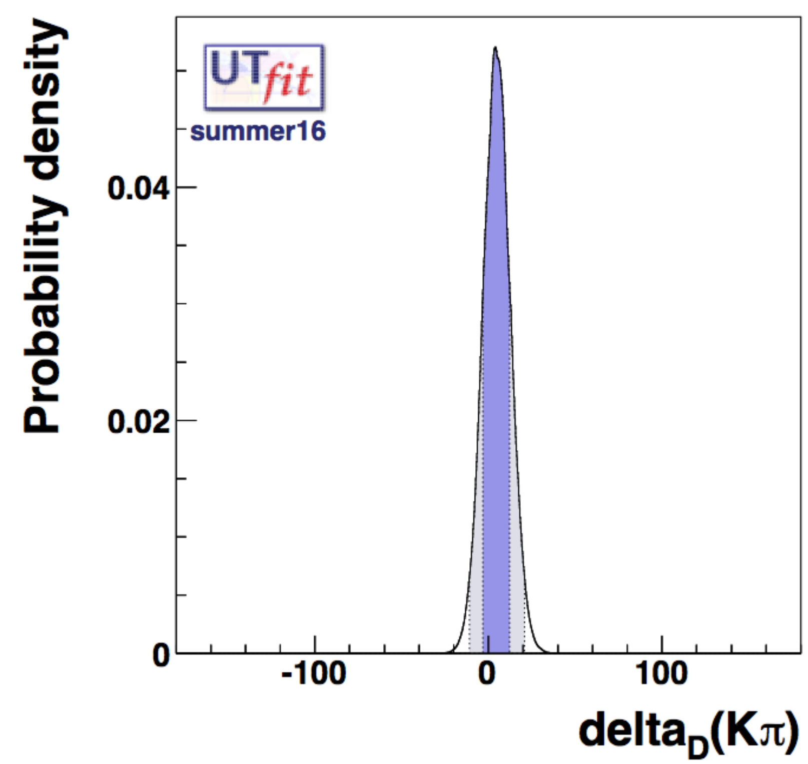
Two body strong phase

The $\delta_{D\to K\pi}$ can be measured using quantum correlations at charm factories or elsewhere. The current value is

$$\delta_{D\to K\pi} = (2.2 \pm 12.4)^\circ$$

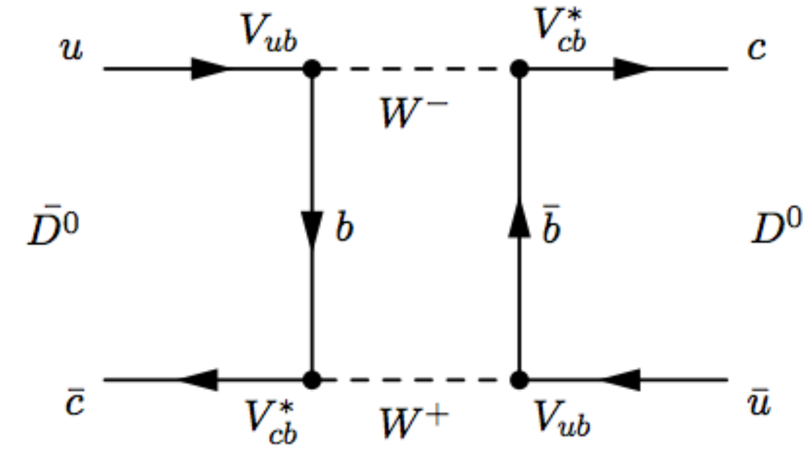
In fact, the precision of gamma measurement is so good, that we are able to "measure" the strong phase $\delta_{D\to K\pi}$. The results are consistent with our mixing studies.

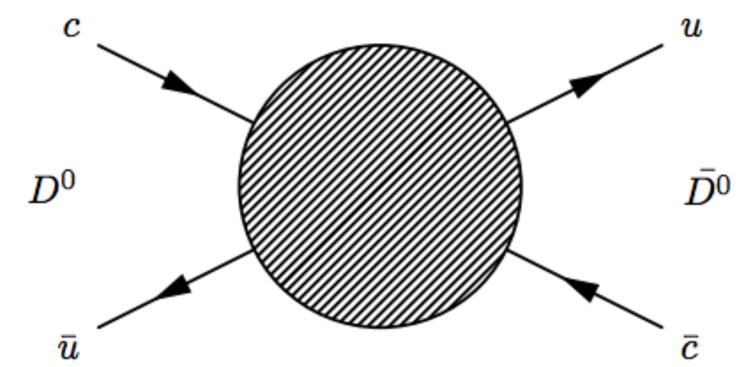
at 68.27% prob [-3.2,12.3]°
at 95.45% prob [-10.9,20.7]°



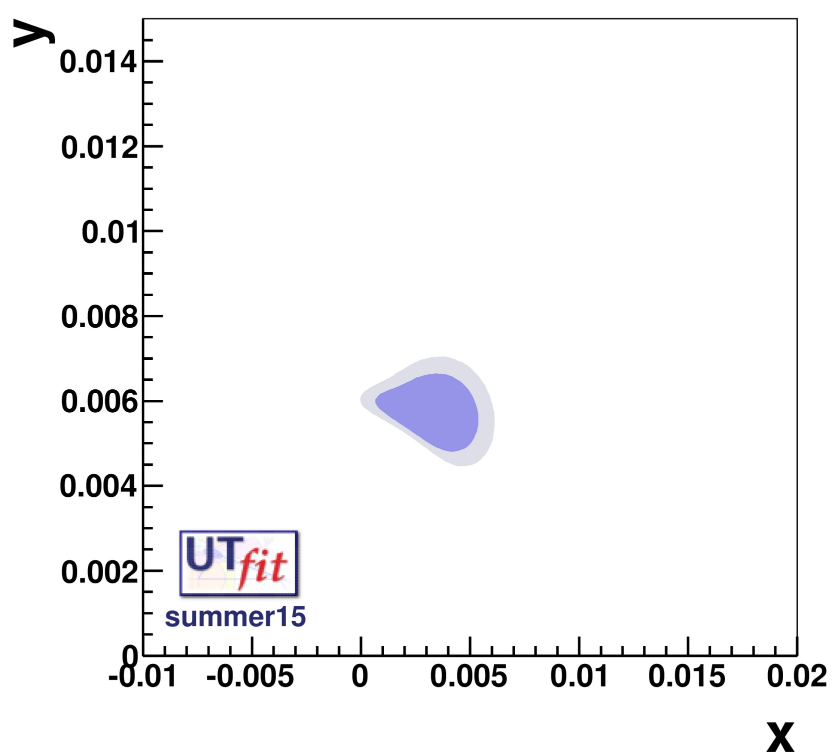
D^0 mixing

(Un)fortunately D^0's mix.
For gamma combination we do not care about the nature of mixing: long distance or short distance,
what we care is the magnitude of mixing





Flavor eigenstate	Mass eigenstate
$\|D^0(\bar{c}u)>)$	$\|D^0(M_1, \Gamma_1)>)$
$\|\overline{D^0}(cu)>)$	$\|D^0(M_2, \Gamma_2)>)$



$$x = \frac{M_1 - M_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

See Marco Ciuchini's presentation for more detail

D^0 mixing in gamma combination

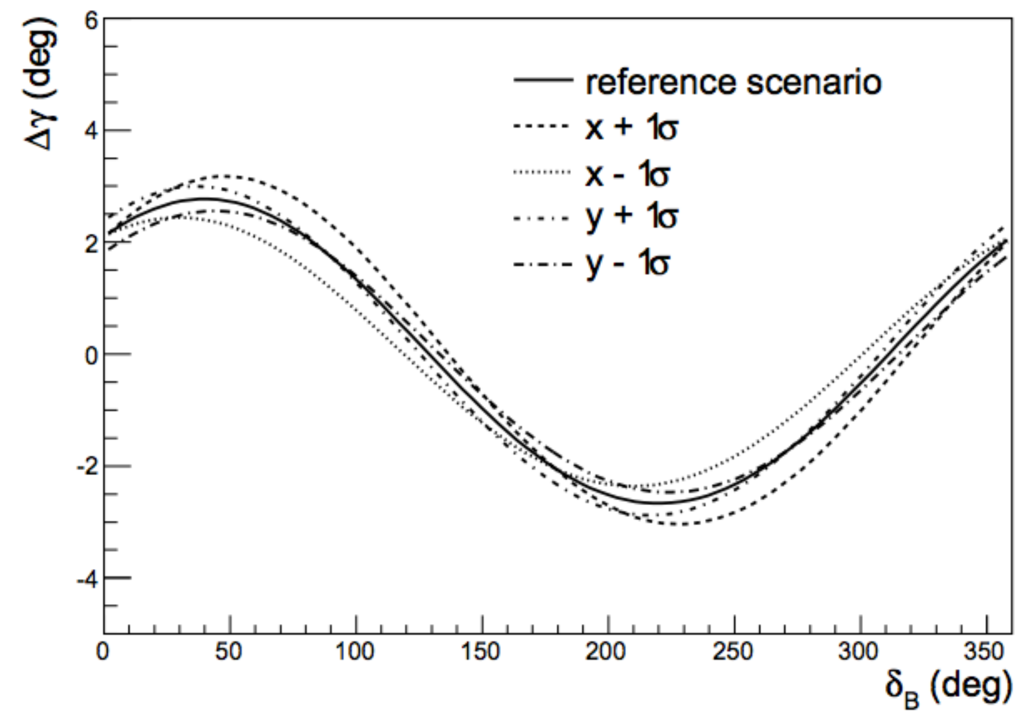
$$\Delta\gamma = \gamma_{\mathrm{true}} - \gamma_{\mathrm{reco}}$$

A simple non-mixing formulas have to be modified:

$$\Gamma(B^- \to [\bar{f}]_D K^-) \propto \left|A_D \bar{A}_f\right|^2 \Big[1 + r_f^2 r_B^2 + 2\, r_f r_B \cos(\delta_B - \gamma - \delta_f) \Big],$$

$$\Downarrow$$

$$\Gamma(B^- \to [\bar{f}]_D K^-) \propto \left|A_D \bar{A}_f\right|^2 \Big[1 + r_f^2 r_B^2 + 2\, r_f r_B \cos(\delta_B - \gamma - \delta_f) - y\, r_f \cos\delta_f - y\, r_B \cos(\delta_B - \gamma) - x\, r_f \sin\delta_f + x\, r_B \sin(\delta_B - \gamma) \Big],$$



	r_B	δ_B (deg)	$\Delta\gamma$ (deg)
$B^- \to D^0 K^-$	0.096 ± 0.006	115 ± 9	0.7 ± 0.7
$B^- \to D^{*0} K^-$	0.121 ± 0.019	-55 ± 14	-0.2 ± 0.6
$B^- \to D^0 K^{*-}$	0.140 ± 0.046	110^{+31}_{-42}	0.6 ± 1.1

Ignoring mixing **introduces bias** in the final combination, however, the current World Averages point to the fact that these corrections are quite small.

M. Rama, PRD89 (2014) 014021

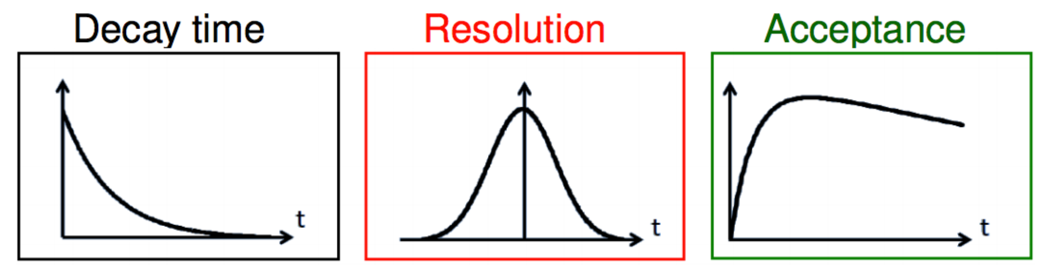
D^0 mixing in gamma combination

GLW method is almost not sensitive to D^0 mixing correction due to the choice of decay channels.
Other channels, however, may well be affected.

Currently, the precision does not give big difference.

However, in the future (~ statistics available after LHCb run 3 and Belle 2 data sample with a simple scaling of errors) the precision of mixing will become more important.

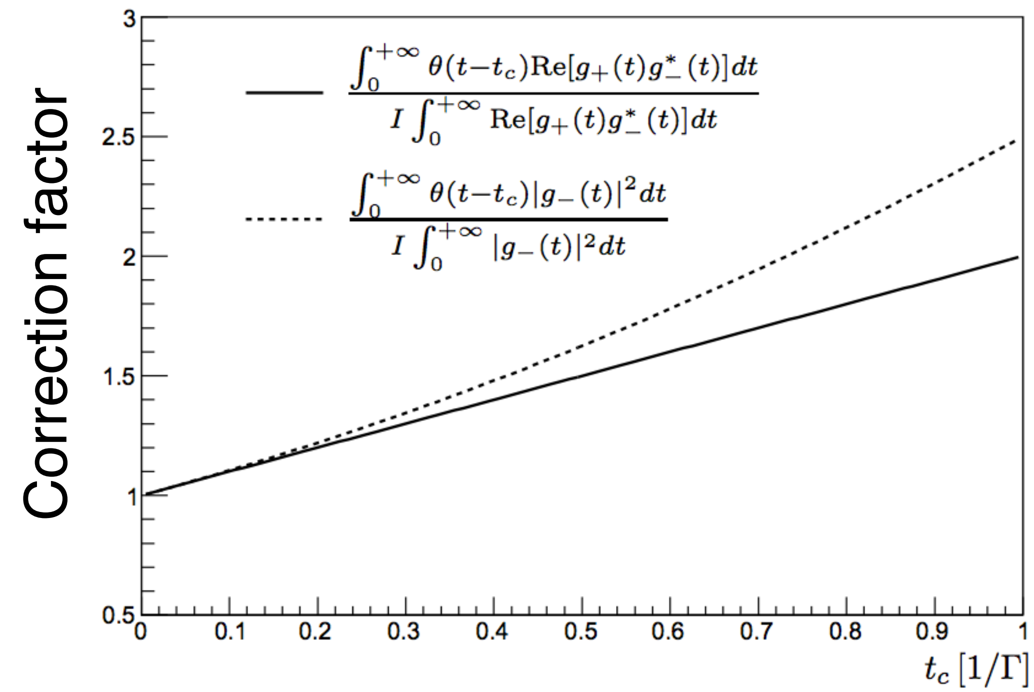
D^0 acceptance influence



$$\text{Measured distribution} = \left[e^{\frac{-t}{\tau}} \otimes \mathrm{Res}(t, t')\right] \cdot \mathrm{Acc}(t')$$

The difference is seen when the D^0 reconstruction efficiency is not flat:

- influenced by selection criteria or detector properties;
- can be quite complicated to account for in case of D^0 studies;
- affecting gamma analyses as one needs to get rid of fast decaying background.



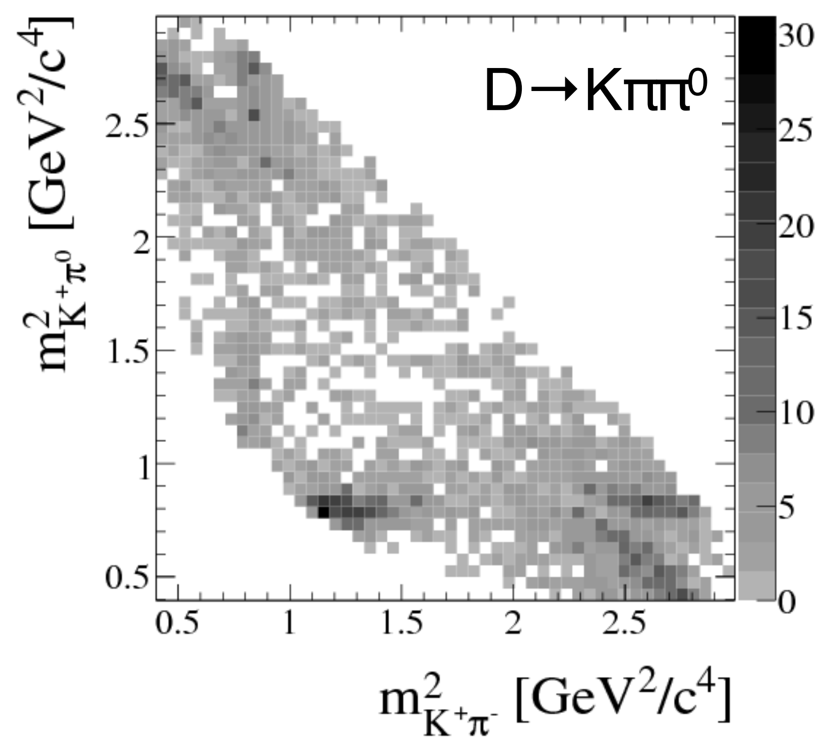
Gamma Uncertainty	No acceptance	Acceptance
Current	5.7	5.9

While acceptance almost doesn't bring any additional information, it can bring an additional bias up to 1 degree to a global combination.

Moving to many body modes

Instead of using sometimes quite complicated models, one could use an effective (and efficient) approach: integrating over the Dalitz space.

$$k_D e^{i\delta_D} = \frac{\int A_D \overline{A}_D e^{i(\overline{\delta}(m)-\delta(m))} dm}{\sqrt{\int |A_D|^2 \, dm \int |\overline{A}_D|^2 \, dm}}$$



Typical observables would be modified:

$$R_{ADS} = \frac{\Gamma([\overline{f}]K^-) + \Gamma([\overline{f}]K^+)}{\Gamma([f]K^-) + \Gamma([f]K^+)} = r_B^2 + r_D^2 + 2k_D r_B r_D \cos(\delta_B + \delta_D)\cos\gamma$$

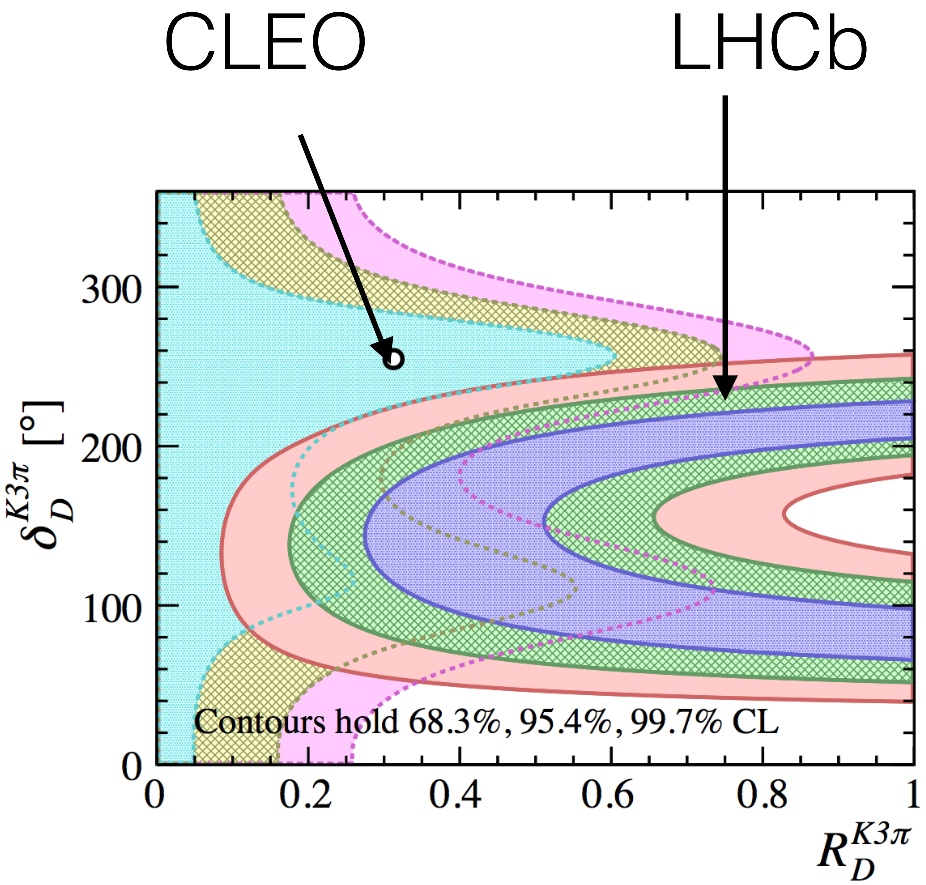
$$A_{ADS} = \frac{\Gamma([\overline{f}]K^-) - \Gamma([\overline{f}]K^+)}{\Gamma([f]K^-) + \Gamma([f]K^+)} = 2k_D r_B r_D \cos(\delta_B + \delta_D)\cos\gamma \,/\, R_{ADS}$$

PRL 103 (2009) 211801

Coherence factor and phase influence

The results can be obtained using:
- quantum correlated measurements (CLEO, BES)
- time-dependent decay rates

More quasi multibody D0 channels are analysed:
- $D^0 \to K_S K \pi$ (GLS method)
- $D^0 \to \pi\pi\pi\pi$ (quasi GLW method)

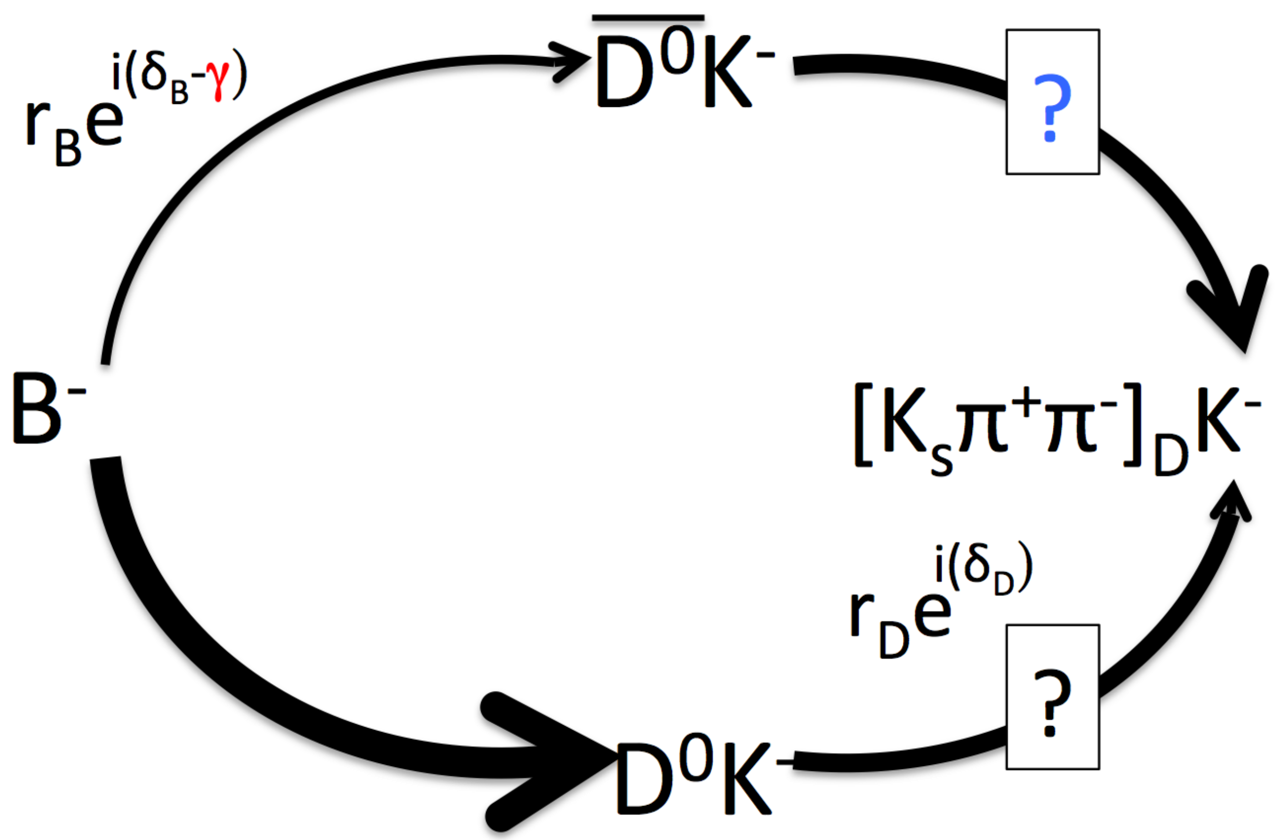


Gamma Uncertainty	with δ	without δ
Current	5.7	6.2

The result contributes significantly to current combination precision

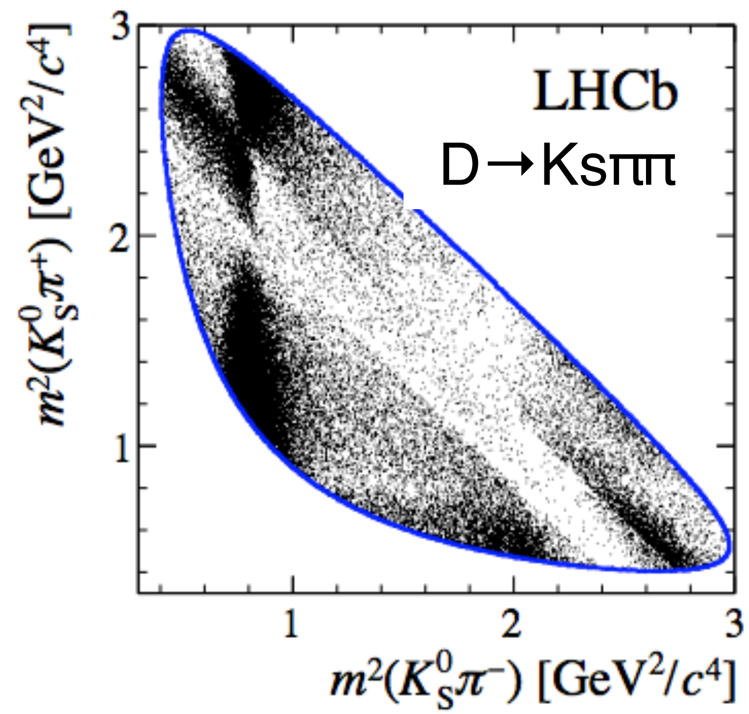
LHCB PRL 116 (2016) 241801

Giri Gronau Soffer Zupan method



Making the same trick as in GLW/ADS analyses leads to a significant loose of sensitivity.

We thus need to analyse the Dalitz plot



Each point on the Dalitz plot represents a different value of r_D and δ_D

PRD 68 (2003) 054018

GGSZ analysis structure

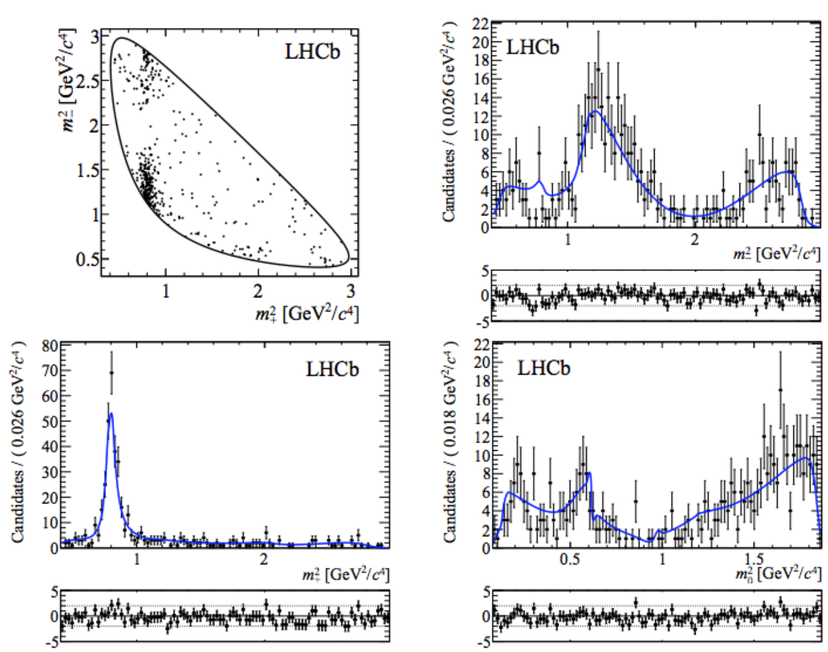
- D Dalitz plot from B decay will be a superposition of D^0 and D^0
- Differences are related to r_B δ_B and γ. Two ways to deal with the varying r_D, δ_D

Model dependent

r_D and δ_D determined from flavour tagged decays via amplitude model

No interference, no direct access to phase information

Systematic uncertainties due to model hard to quantify

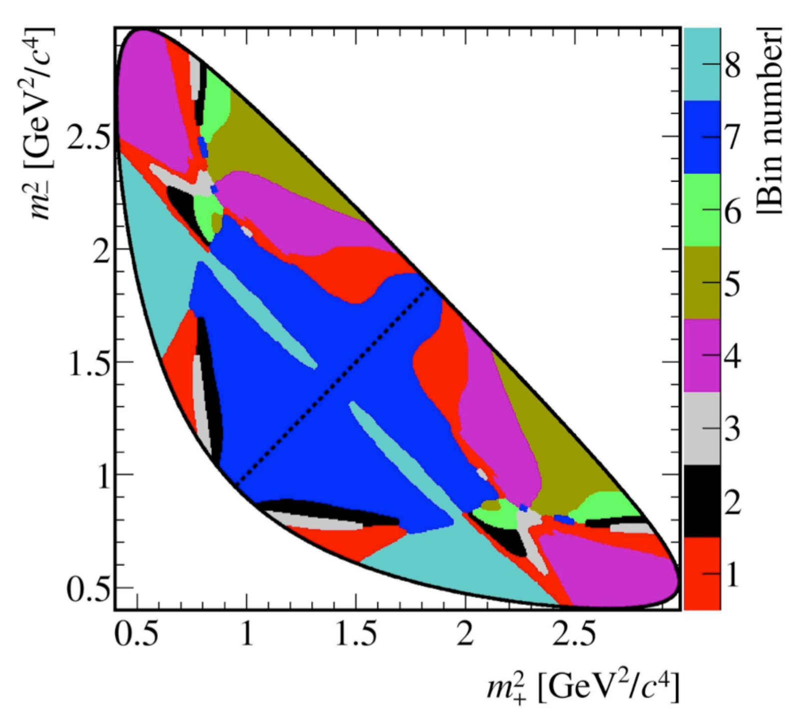


Model independent

Use charm factories data to measure average values of r_D and δ_D in bins

Some loss in statistical precision

Direct phase information, uncertainties on which are easily propagated



GGSZ Model independent Future Development

If we fix all current results and scale the uncertainty of GGSZ model independent with luminosity and charm factories input.

Gamma Uncertainty (global combination)	CLEO data	Perfect charm
GGSZ Current	5.7	5.5
GGSZ LHCb run 2	4.5	3.8
GGSZ LHCb run 3 + Belle 2	3.8	2.8

Currently, the precision of CLEO $D^0 \rightarrow K_S\pi\pi$ study is sufficient, however, already after LHCb run 2, we will need a more precise study (hope for BES III result, which is under way).

Charm input summary

Charm studies provide important input for the gamma combination:

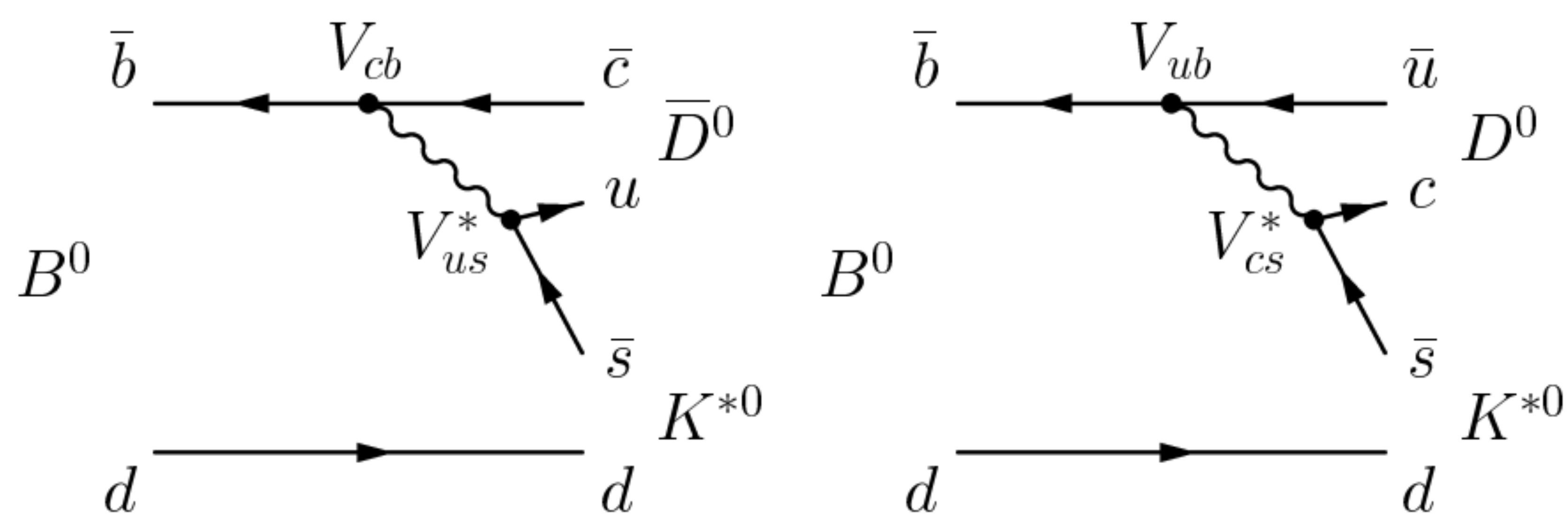
Charm mixing
CPV and strong information in $D \to hh$
κ_D, δ_D: $D \to K\pi\pi\pi$, $D \to K\pi\pi^0$
κ_D, δ_D : $D \to K_S K\pi$
CP fraction $D \to 4\pi$, $D \to hh\pi^0$
Strong phase information for $D \to K_S hh$

The most important part of these measurements is obtained using quantum correlation (and now also by LHCb). In the absence of this method, gamma would be 4 degrees less precise (current precision is 5.7 degrees).

Other channels

Measurement of other tree-like channels is available:

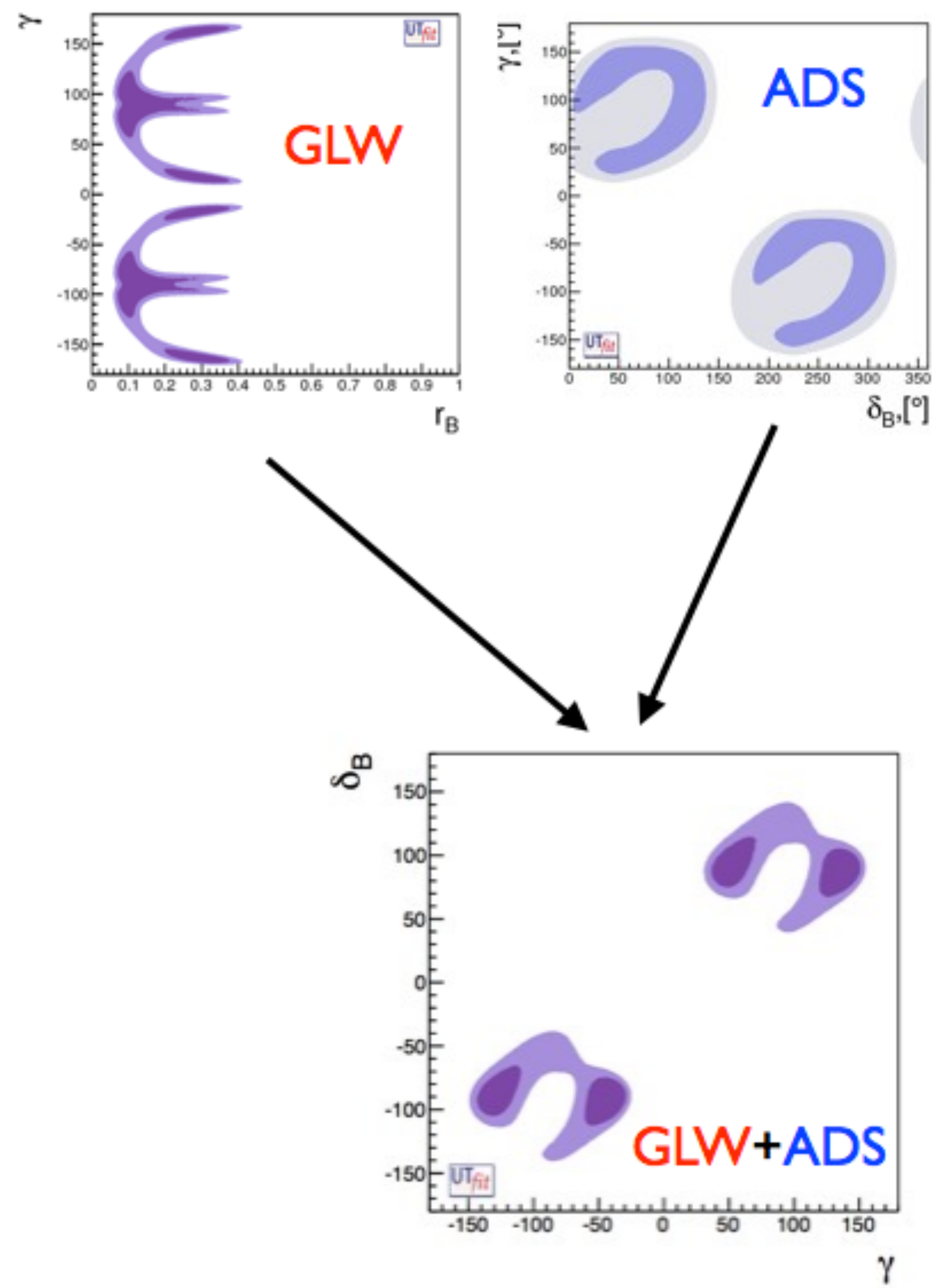
- $B_d \to DK^{*0}$ (r_B~0.25)
- $B_u \to D\pi$ (r_B~0.01)



The discussion of charm effects here stays the same, however, the lower rB the more pronounced the D effects are.

Combination method

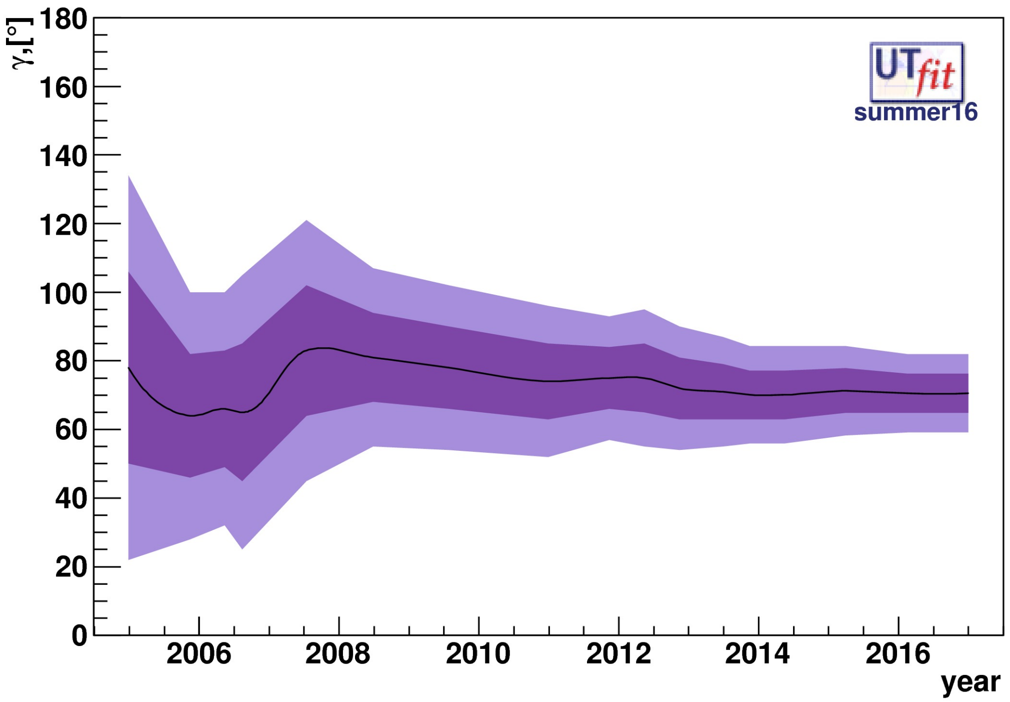
We use the Bayesian statistics to obtain the most probable values and credibility intervals from the current data.

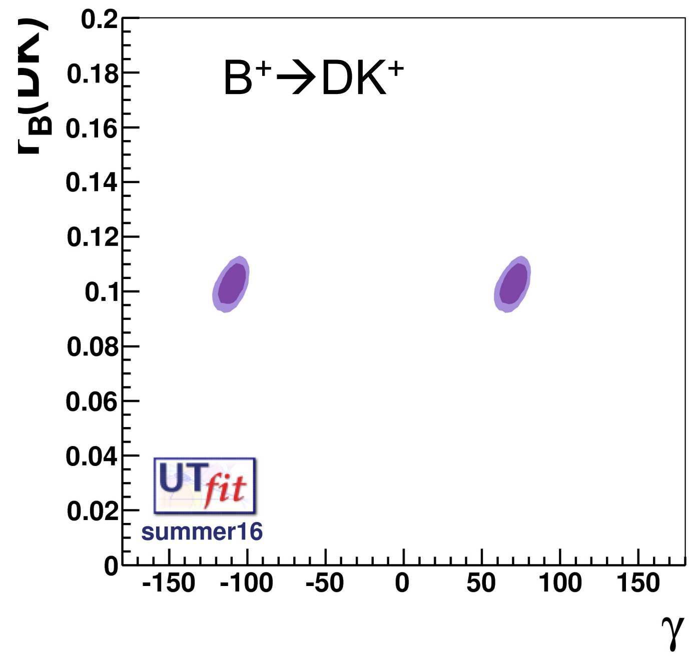


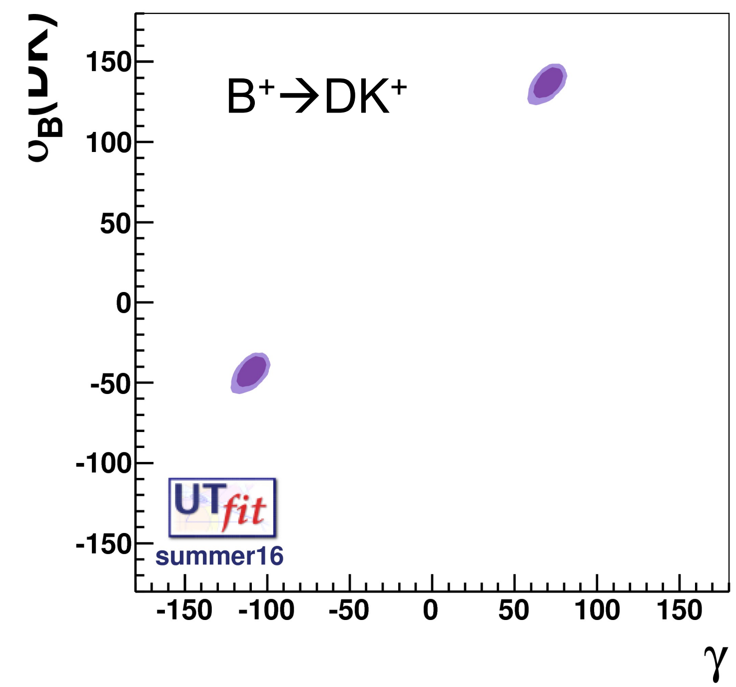
We use results from 4 experiments (BaBar, Belle, CDF, LHCb), overall ~140 input observables are used (coming from charm and beauty meson studies).

Other gamma combination analysis exist, by:
CKMfitter (http://ckmfitter.in2p3.fr/),

Final Combination







γ_{all} = (70.5 ±5.7)°

compatible with SM predictions γ_{SM} = (65.3 ± 2.0)°

	DK	D	DK	DK
δ	(137±6)°	(-48±12)°	(128±33)°	(-163 ±21)°
r	(0.103±0.005)	(0.12±0.02)	(0.13±0.06)	(0.23±0.03)

https://www.utfit.org/foswiki/bin/view/UTfit/GammaFromTrees

Conclusions

Charm inputs are of great importance to the gamma combination and thus to the search of NP effects.

With new analyses coming from LHCb and, subsequently, from Belle 2, new measurement from charm sector are needed to tackle more and more important corrections.

In order to take into account correlations between experiments, fitters groups need more information about analyses (selection, acceptance).