Future flavour: inputs from charm threshold and interplay with LHCb

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- How to measure strong phases *etc.*
  and current and future threshold data sets
- Important inputs from charm threshold (at present)
- Current status of LHCb measurement
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- Impact and requirements of new strategies
- Beyond γ
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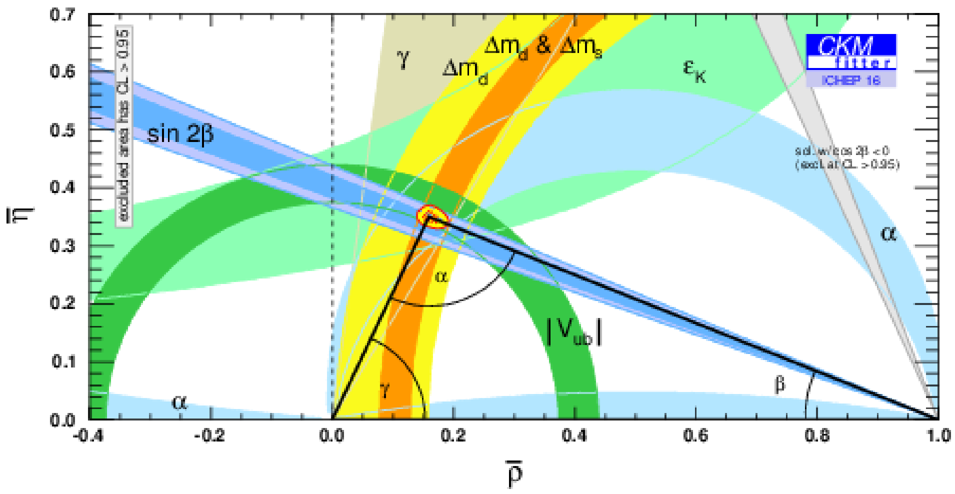
CKM γ – the beautiful obsession

The angle γ has a special place in CP-violation studies:

- It can be measured with negligible theoretical uncertainty; a clean observable *par excellence,* whose knowledge is limited by experiment alone.

- Moreover this measurement comes through tree-level processes ($b \to u$ and $b \to c$ interference in $B \to DK$ decays), and hence rather immune to New Physics effects. → provides a SM benchmark against which other observables can be compared !



Current direct measurement error ~5°.
Indirect prediction has current uncertainty of 1-2 degrees, but this will steadily improve (lattice QCD).

Hence our challenge is to:

- Measure CPV observables in many D modes in $B \to DK$ decays.

- Strive for ***model-independence*** wherever possible, most notably in the hadronic parameters of the D decays (*e.g.* strong phases, coherence factors *etc.*)

→ These must be measured, but how ?

How to measure strong-phases *etc.*

1) Double-tagged events at $\Psi(3770)$

e.g. probe strong-phase distribution of multibody decays…

$D^{*+} \rightarrow D^0 \pi^+$

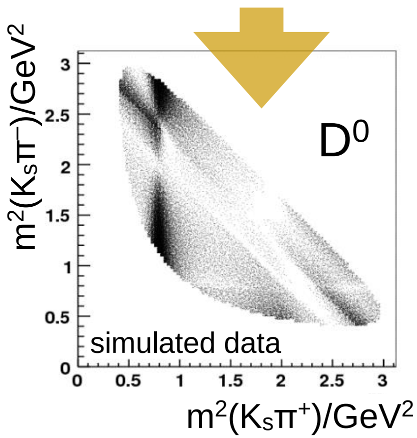
$D^0 \rightarrow K_S\pi^+\pi^-$

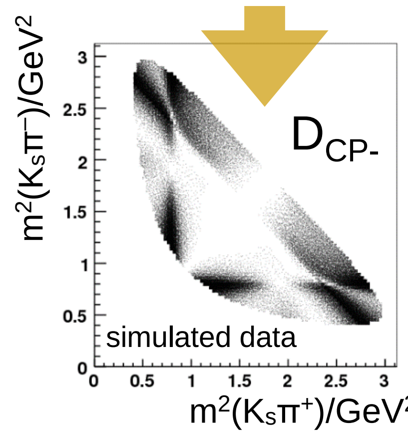
$\psi'' \rightarrow D_a D_b$

$D_a \rightarrow KK$ eg. CP+

$D_b \rightarrow K_S\pi^+\pi^-$

Flavour tagged Distribution ~ $|D^0|^2$ or $|\bar{D}^0|^2$





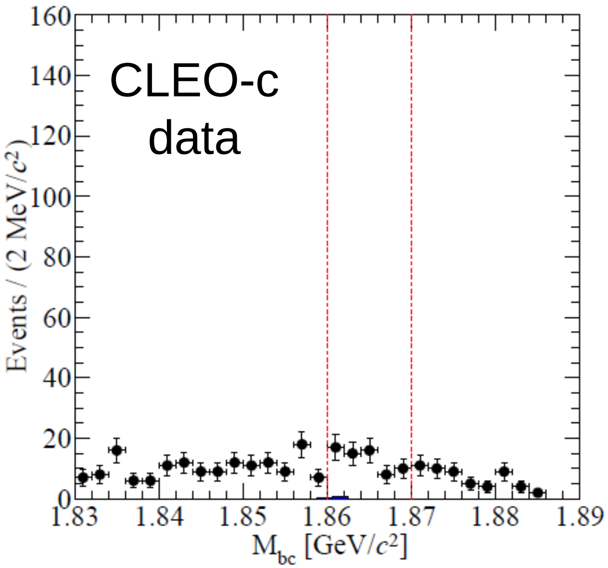
CP-tagged ~ $|D^0|^2 + |\bar{D}^0|^2 \pm 2\, D^0\bar{D}^0 \cos\delta$

How to measure strong-phases *etc.*

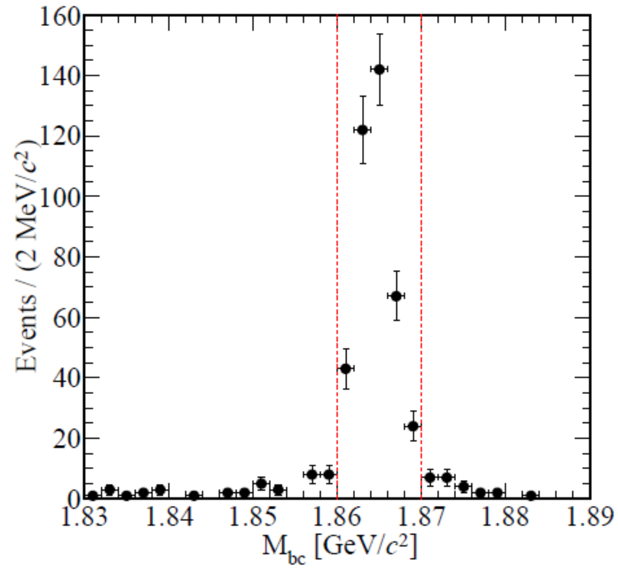
1) Double-tagged events at Ψ(3770)

…or measure overall CP content.

$D\to\pi\pi\pi^0$ decays tagged with a CP-even eigenstate



$D\to\pi\pi\pi^0$ decays tagged with a CP-odd eigenstate



[M. Nayak *et al.*, PLB 740 (2015) 1]

Hence $D\to\pi\pi\pi^0$ is overwhelmingly CP even.

How to measure strong-phases *etc.*

1) Double-tagged events at Ψ(3770)

These are what have been used until now as inputs to γ determination, based on measurements from CLEO-c data (see later).

2) LHCb B and D data

- Global fit to all B→DK analyses is overconstrained, & allows validity of charm inputs to be tested, provided that observables' dependence on these inputs is kept explicit in results (*e.g.* currently true for D→K3π, but not for D→K_Sππ).
- Fits to charm mixing data have sensitivity to strong phases etc. *i.e.* HFLAV fit to Kπ strong phase much more precise than CLEO result. Some discussion on this later.
- B→DK data themselves will soon be sensitive to fit strong phase information in individual channels, when overconstrained. Anton will show us that for D→K_Sπππ this approach could be very powerful (next talk).

How to measure strong-phases *etc.*

1) Double-tagged events at Ψ(3770)

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  i … puts is
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- F
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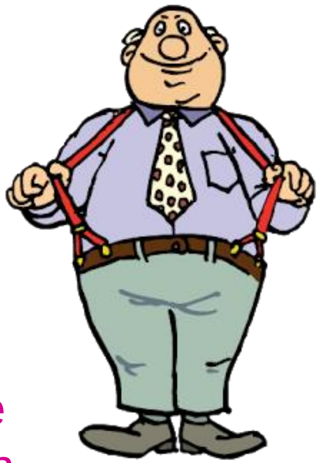
- B … ation
  i … for
  D

Difficult in assess respective importance of threshold data and LHCb data as we move through the Upgrade I and II eras.

Suspicion is that both will play a vital role in achieving ultimate precision.

More reliable measurements will be those where we have redundant measurements of required precision from both sources – the belt-and-braces scenario.

In what follows I shall assess what we need from threshold data assuming it is the only source of input – the belt-only scenario. (But as Anton will show us, the braces will be available.)



Past, current and future sources of Ψ(3770) threshold data

Source		Comment
CLEO-c (finished)	0.8 fb^{-1}	Thoroughly exploited
BES III (on tape)	2.9 fb^{-1}	Flagship analyses still to be published
BES III (under discussion)	10-20 fb^{-1}	Collaboration discussing future running schedule. Some additional threshold running is rather likely, but enthusiastic support of wider flavour community would be very helpful !
Super tau-charm factory	~1 ab^{-1}	Proposals exist for machine in Novosibirsk [A. Bondar *et al.* , Phys. Atom. Nucl. 76 (2013) 1072] and in China [*e.g.* Zhengguo Zhao, LP 2017], either of which could operate at luminosities of 1 x 10^{35} $cm^{-2}s^{-1}$, *i.e.* 100x higher than BEPCII

Q.C. D-decay measurements in existence

(earlier papers on some channels not listed)

Measurements with CLEO-c data (* indicates legacy-data publication)

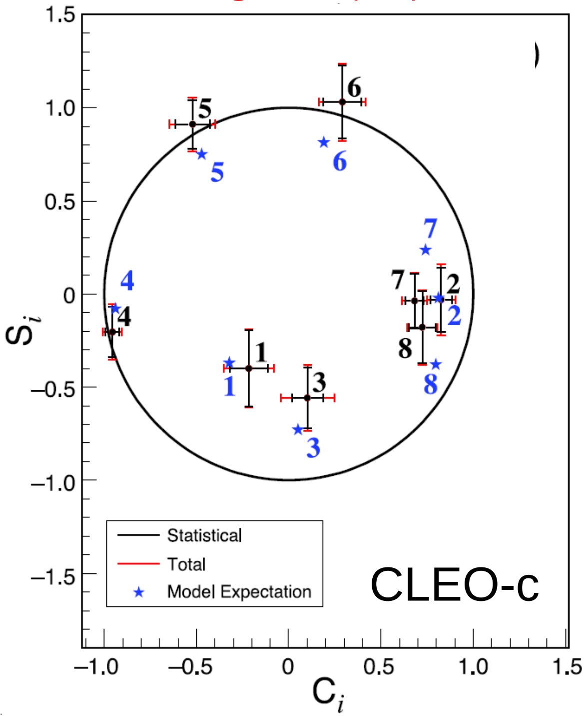
$K\pi$ strong phase	PRD 86 (2012) 112001, arXiv:1210.0939
$K_S\pi\pi$, K_SKK binned c_i, s_i	PRD 82 (2010) 112006, arXiv:1010.2817
$K3\pi$ and $K\pi\pi^0$ coherence factor & strong phase	PLB 757 (2016) 520, Corrigendum ibid. 765 (2017) 402, arXiv:1602.07430 *
$K_SK\pi$ coherence factor & strong phase	PRD 85 (2012) 092016, arXiv:1203.3804
$\pi\pi\pi^0$, $KK\pi^0$ CP-content	PLB 747 (2015) 9, arXiv:1504.05878 *
4π CP-content & binned c_i,s_i	JHEP 01 (2018) 144, arXiv:1709.03467 *
$K_S\pi\pi\pi^0$ c_i, s_i	JHEP 01 (2018) 982, arXiv:1710.10086 *

BESIII measurements

$K\pi$ strong phase	PLB 734 (2014) 227, arXiv:1404.4691
Measurement of y_{CP} with KK	PLB 744 (2015) 339, arXiv:1501.01378

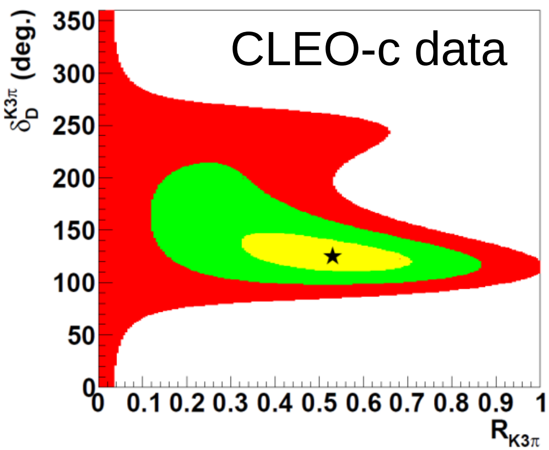
Most important current Q.C. inputs

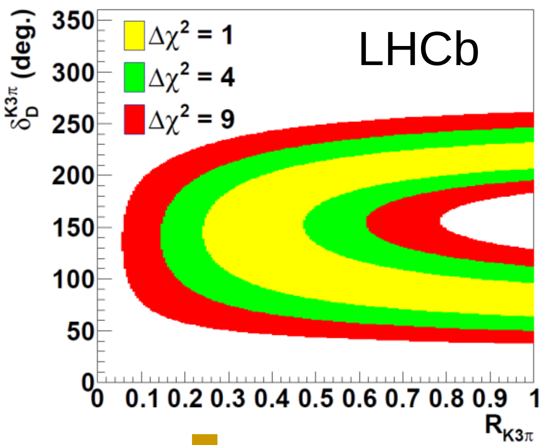
$K_S\pi\pi$ c_i, s_i

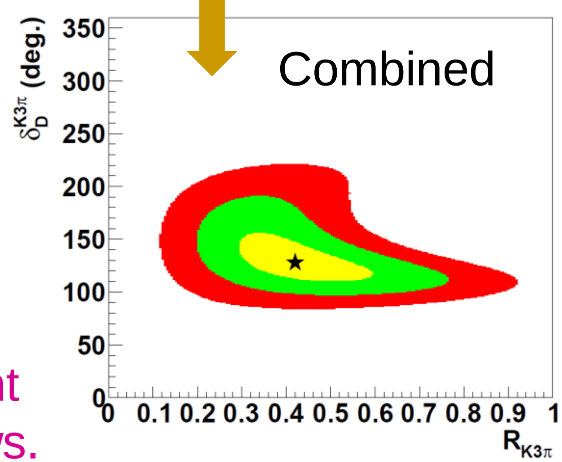


[PRD 82 (2010) 112006]

$K3\pi$ global coherence factor & strong-phase difference







[PLB 757 (2016) 520; Erratum PLB 765 (2017) 402]

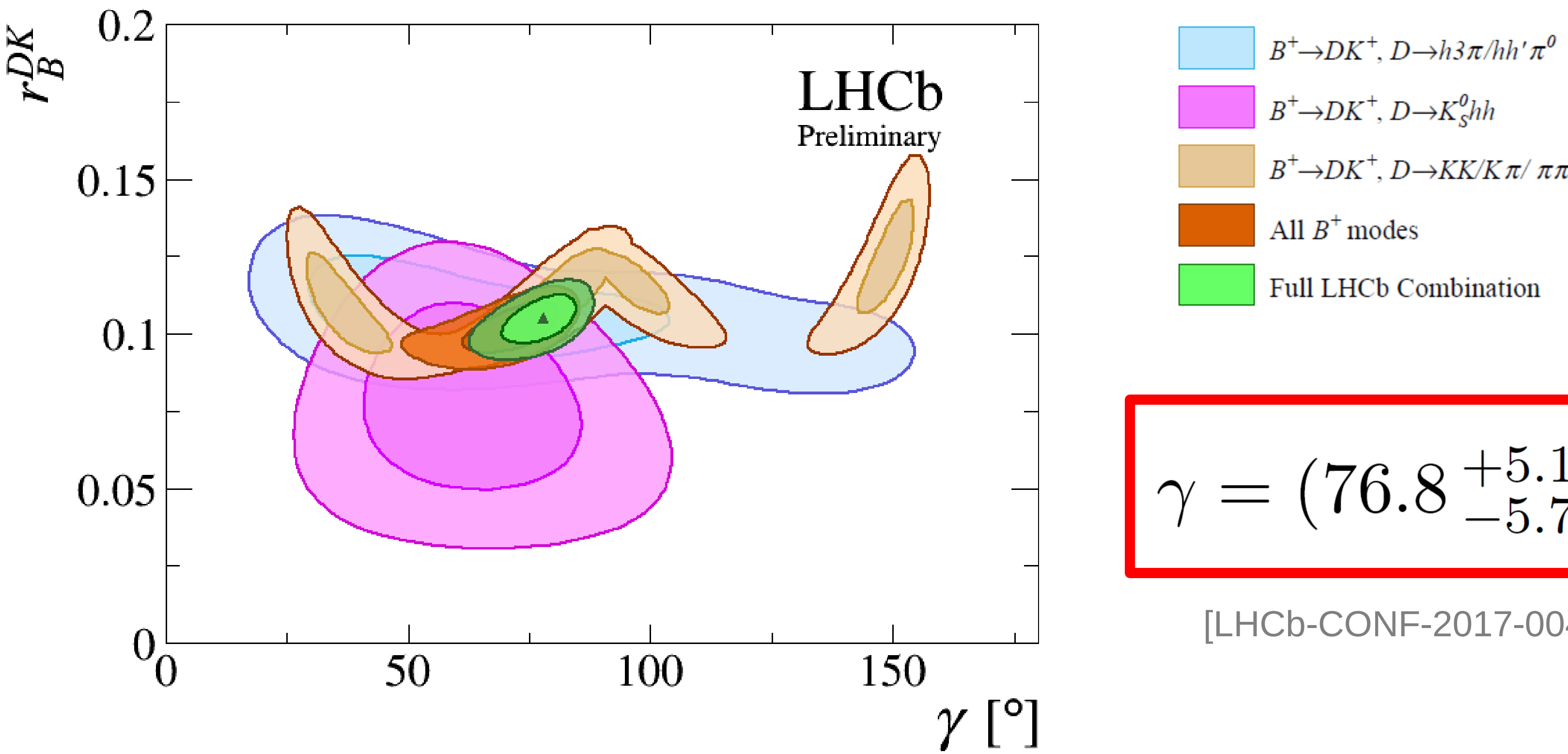
LHCb also uses CLEO-c inputs for other modes

K_SKK, $K_SK\pi$, 4π global, $K\pi\pi^0$, $\pi\pi\pi^0$, $KK\pi^0$

which will become important as statistical precision grows.

(Q.C. also used for $\delta_{K\pi}$ but here mixing inputs dominate)

Current sensitivity on γ from LHCb



$$\gamma = (76.8\,^{+5.1}_{-5.7})^\circ$$

[LHCb-CONF-2017-004]

Includes the final run-1 results for all the most dominant B→DK modes (*i.e.* D→hh, $K_S\pi\pi$, K3π global) and a little run-2 data for some analyses (*e.g.* D→KK), but is still missing several interesting modes of less weight (*e.g.* $B^+\to D^*K$, $D\to K_S\pi\pi$).

Unofficial GW exercise: assume ~5.5° to be run-1 sensitivity, notwithstanding the pinch of run-2 input.

Q.C. (CLEO-c) inputs contribute **~2°** to this [LHCb-PUB-2016-025]

Small, but not negligible !

Future LHCb data sets

Let us see how B statistics is growing in Run 2 and is expected to increase during upcoming Upgrade I, and would increase in future Upgrade II.

Run Period [E_{CM}]	Collected / Projected luminosity per run	Cumulative yield factor compared to Run 1	Year attained
Run 1 [7,8 TeV]	3 fb^{-1}	1	2012
Run 2 [13 TeV]	5 fb^{-1}	4	2018
LHCb phase-1 upgrade [14 TeV]	50 fb^{-1}	60	2030
LHCb phase-2 upgrade [14 TeV]	300 fb^{-1}	$\sim$400	2035(?)

Scaling *unofficial* Run-1 statistical error (assume ≈ current total error):

Run 1	Run 2
5.5^{o}	2.8^{o}

Of course there are also experimental systematics, but these are currently data driven, and we may hope (with a little optimism) this remains so.

So current CLEO-c based error of 2^{o} would compromise precision of Run-2 data. However, existing BESIII data set (4 x larger than CLEO-c) has capabilities to reduce this uncertainty to ~1^{o}, which would match well. ***Important input !***

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Scaling *unofficial* Run-1 statistical error (assume ≈ current total error):

Run 1	Run 2	Upgrade 1
5.5^{o}	2.8^{o}	0.71^{o}

Of course there are also experimental systematics, but these are currently data driven, and we may hope (with a little optimism) this remains so.

Entering Upgrade-I era we see uncertainty from current BESIII data set (~1^{o} ?) will be limiting systematic. Desirable to x(1/2 – 1/4) this contribution if possible. Also recall that Belle II will be performing a measurement of similar precision and this systematic will be largely in common – so it needs to be as small as possible.

Future LHCb data sets

Let us see how B statistics is growing in Run 2 and is expected to increase during upcoming Upgrade I, and would increase in future Upgrade II.

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Scaling *unofficial* Run-1 statistical error (assume ≈ current total error):

Run 1	Run 2	Upgrade 1	Upgrade 2
5.5^{o}	2.8^{o}	0.71^{o}	0.28^{o}

Of course there are also experimental systematics, but these are currently data driven, and we may hope (with a little optimism) this remains so.

More threshold data ***very desirable*** for Upgrade II ! Certainly possible to access some strong phases *etc.* in LHCb fits, but Q.C. data will remain vital and necessary.

Future LHCb data sets

Let us see how B statistics is growing in Run 2 and is expected to increase during upcoming Upgrade I, and would increase in future Upgrade II.

Run Period [E_{CM}]	Collected / Projected luminosity per run	Cumulative yield factor compared to Run 1	Year attained
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Scaling *unofficial* Run-1 statistical error (assume ≈ current total error):

Run 1	Run 2	Upgrade 1	Upgrade 2
5.5°	2.8°	0.71°	0.28°

Of course there are also experimental systematics, but these are currently data driven, and we may hope (with a little optimism) this remains so.

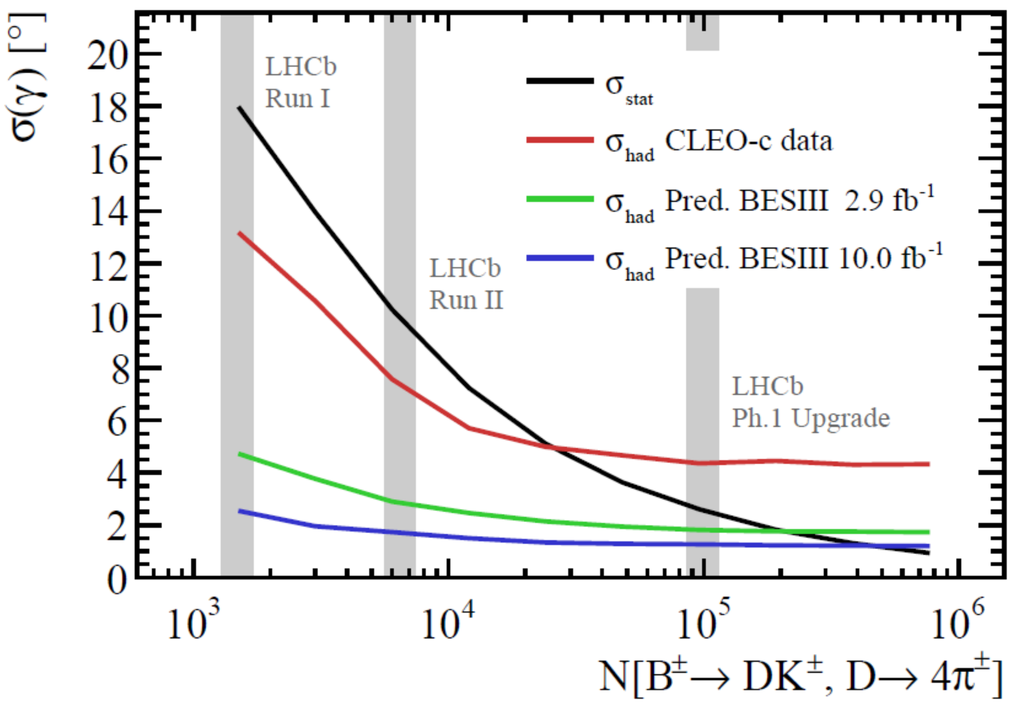
However, there is good reason to think that even these impressive numbers are conservative, as new strategies are being proposed that will can improve precision significantly – but role of Q.C. threshold data will remain central !

→ Let's look at three examples

New kids on the block $D \rightarrow 4\pi$

Extrapolations so far are based on existing analysis strategies, but there are new approaches being proposed which are very powerful; most need BESIII data!
(Benchmark: expected run-2 precision of ‘golden channel’, $K_S\pi\pi$ (+ K_SKK) ~ 7º.)

$D \rightarrow 4\pi$, already analysed globally, can also be studied in bins [S. Harnew *et al.*, JHEP 01 (2018) 144, arXiv:1709.03467]. Binning schemes proposed, & CLEO-c data already analysed.

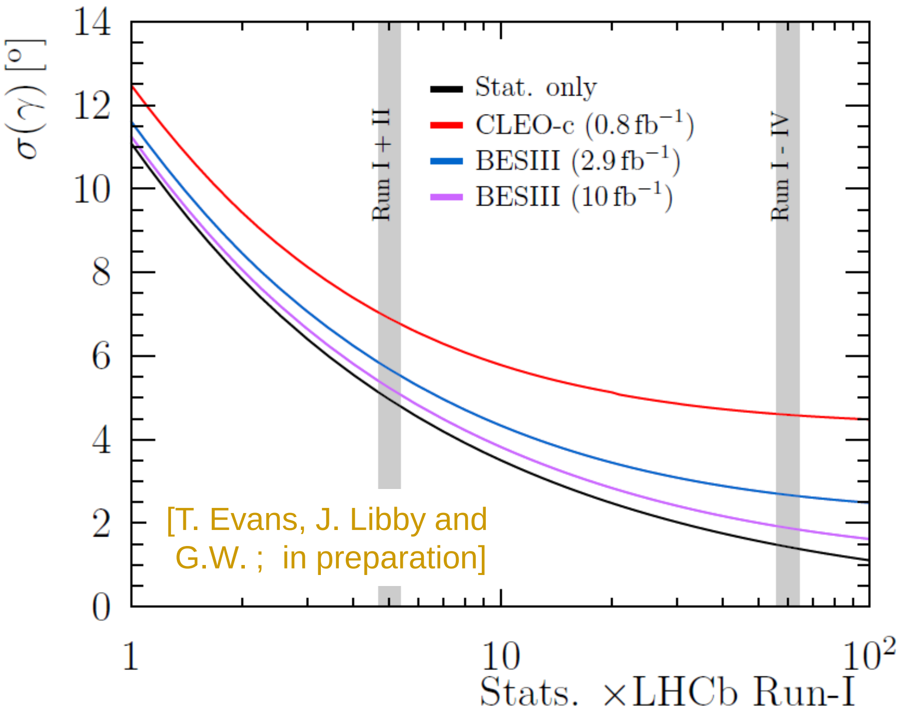


- Expected stat. precision after run 2 is ~10 degrees.
- Contribution from CLEO-c uncertainties ~7 degrees.
- BESIII input already very helpful now, and soon will become essential.
- Larger BESIII sample would benefit Upgrade I, and will be mandatory for Upgrade II.

New kids on the block D→K3π

Extrapolations so far are based on existing analysis strategies, but there are new approaches being proposed which are very powerful; most need BESIII data!
(Benchmark: expected run-2 precision of 'golden channel', $K_S\pi\pi$ (+ K_SKK) ~ 7°.)

D→K3π, already analysed globally, can also be studied in bins informed by recent LHCb amplitude models [arXiv:1712.08609] . Requires coherence factor and strong phase to be measured in each bin, by combination of threshold data and D-mixing studies.



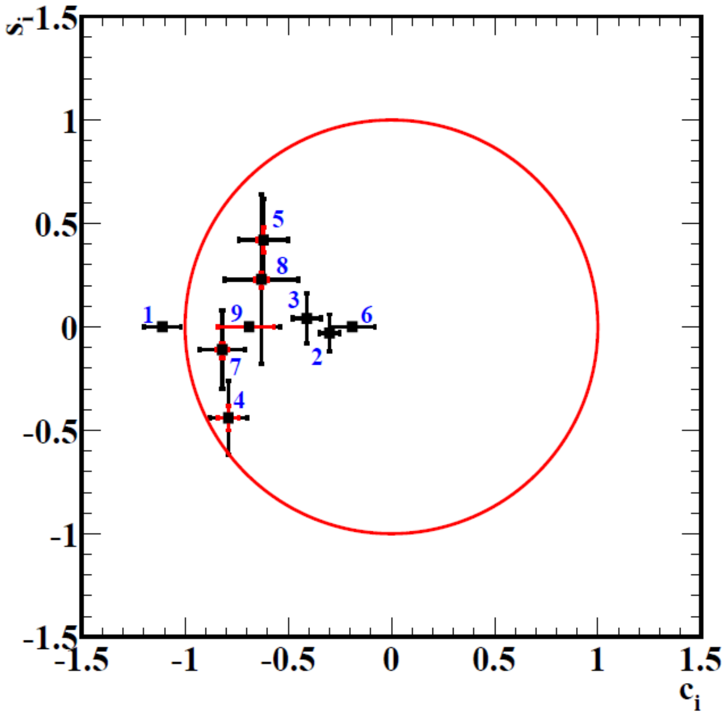
- Stat. precision after run 2 ~5.5°. Best sensitivity of any single mode !
- BESIII input urgently required.
- Larger BESIII samples needed for Upgrade era.

New kids on the block $D \to K_S \pi\pi\pi^0$

Extrapolations so far are based on existing analysis strategies, but there are new approaches being proposed which are very powerful; most need BESIII data!

(Benchmark: expected run-2 precision of 'golden channel', $K_S\pi\pi$ (+ $K_S KK$) ~ 7°.)

$D \to K_S \pi\pi\pi^0$ has a high B.R. & rich resonant structure. A naïve binning has already been proposed & CLEO data analysed [Resmi P.K. *et al.* JHEP 01 (2018) 082, arXiv:1710.10086] .



- No analysis of this channel yet performed on LHCb so hard to estimate sensitivity.
- Soft π^0 is challenging, but there may be workarounds, and future Upgrades may improve sensitivity here.
- With 60k decays (a lot!) a precision of 4.4° is estimated with current binning scheme. CLEO-c data contribute uncertainty of 1.5°.
- Better binning schemes could improve stat. sensitivity significantly… but also increase uncertainty from strong-phase inputs.

Beyond γ

There are other very important customers for threshold (+ Belle II) D meson results.

D mixing and indirect CPV studies

- $D \rightarrow K_S \pi\pi$ is a golden channel for these studies, just as much as for γ.
- The sample sizes at Upgrade II will be ***ginormous*** ! Several billion decays will give statistical sensitivity to *e.g.* φ_{CP} to $<10^{-2}$ degrees.
- Once again, a model independent approach will be mandatory.
- Studies still underway, but indication (in agreement with Thomas & Wilkinson JHEP 10 (2012) 185, arXiv:1209.0172) that CLEO c_i, s_i results become limiting early in Upgrade I era. BES III inputs will therefore be essential.
- Acceptance effects will become a concern. Therefore necessary to investigate potential of fitting these parameters from LHCb charm data themselves.

Branching ratios

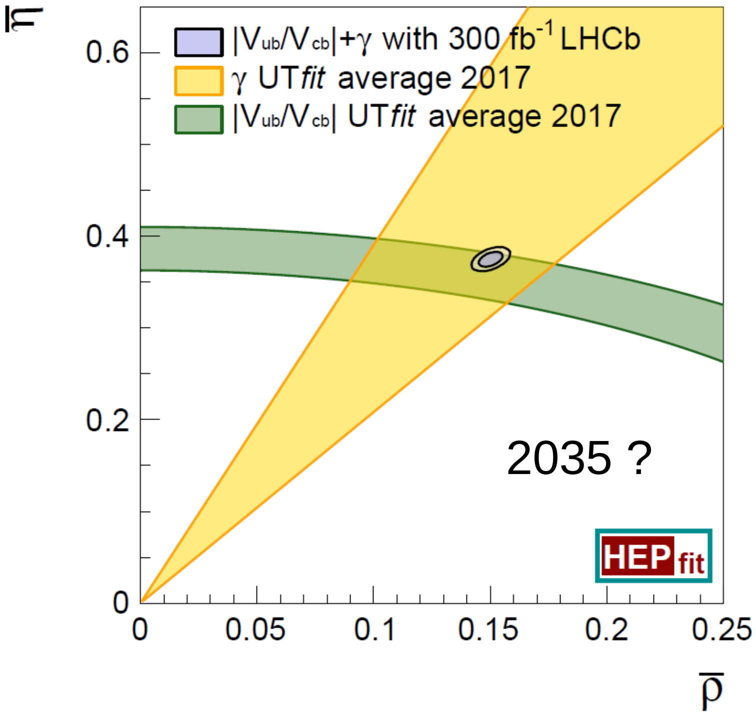
- Current and future B-physics measurements require ever improving knowledge of charm BRs, for both normalisation modes & backgrounds.

Conclusions

- We have an obligation to measure γ with the highest possible precision.
- Model independence essential – so all $B \rightarrow DK$, $D \rightarrow$multibody analyses require measurements of strong-phases, coherence factors *etc.*
- Charm threshold data (so far all from CLEO-c) play a very important role in current LHCb γ determination. The corresponding uncertainty arising from the finite precision of the CLEO-c inputs is ~2^{o}, is not *yet* limiting…
- …but it will start to become so with the analysis of the full run-2 data set. Hence essential that BESIII starts to contribute ! Size of current BESIII $\Psi(3770)$ sample is well matched to LHCb's immediate needs.
- But with the much larger samples anticipated at Upgrade-I, more threshold data will for sure be required. Argument even stronger for further future. Another 10-20 fb-1 of $\Psi(3770)$ will be very helpful, whatever the potential of floating these 'nuisance' parameters in the very large LHCb data sets.
- New strategies have potential to improve precision on γ even more, but almost all of these will place the same demands on external Q.C. inputs.
- Similar arguments apply for charm mixing and CPV searches.

Synergy – an opportunity

The γ determination represents a great opportunity for synergy between facilities.



Sub-degree precision is attainable – but only if LHCb and BESIII work together !
More Ψ(3770) data are required to exploit fully the very large future samples at LHCb.

Backups

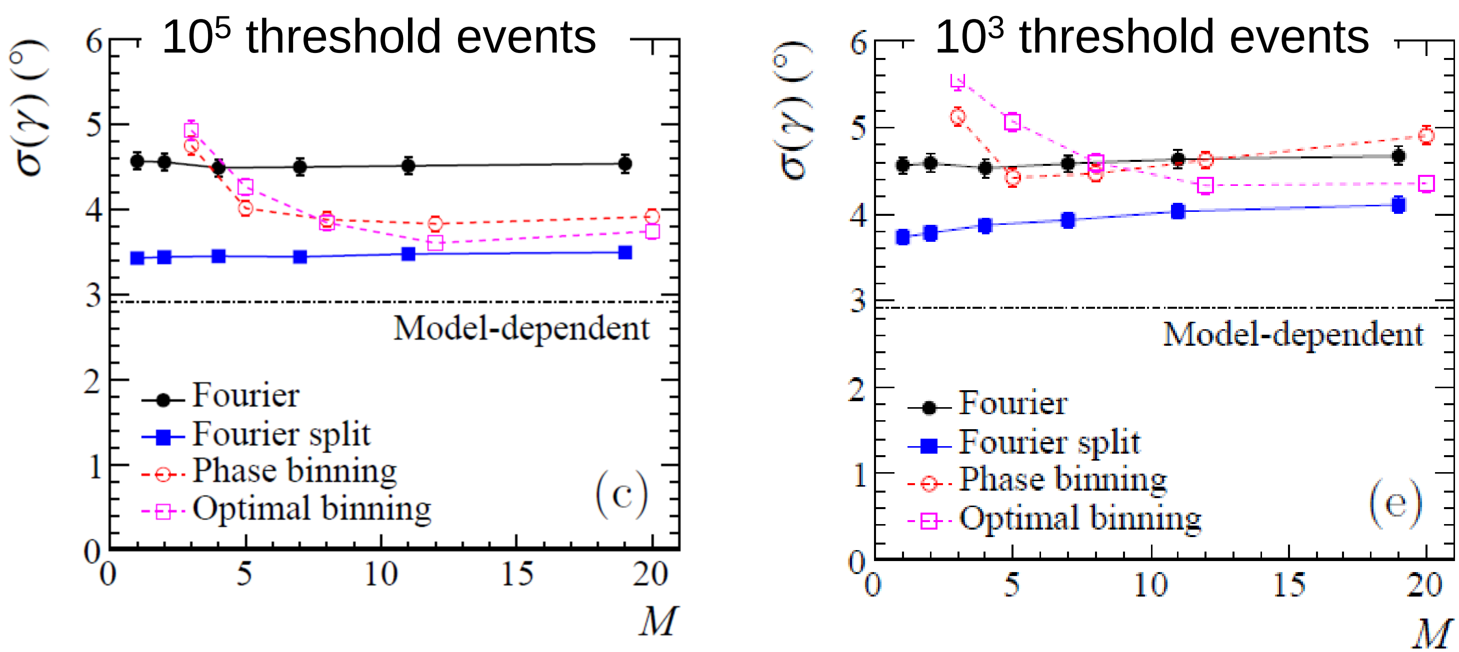
New kids on the block

$D \to K_S\pi\pi$ unbinned

Extrapolations so far are based on existing analysis strategies, but there are new approaches being proposed which are very powerful; most need BESIII data!

(Benchmark: expected run-2 precision of 'golden channel', $K_S\pi\pi$ (+ K_SKK) ~ 7º.)

Model-independent unbinned $D \to K_S\pi\pi$ analysis can squeeze almost all information from B data, but has essentially identical requirements on D inputs from threshold.



See Anton Poluektov talk and arXiv:1712.08326.

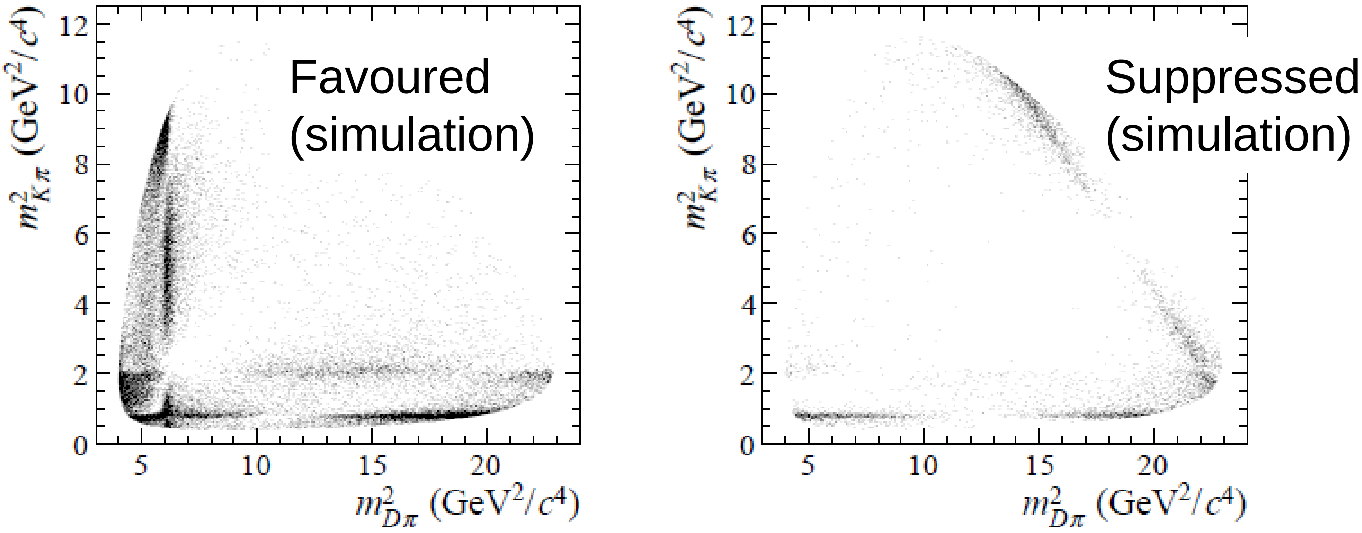
New kids on the block

$B^0 \to DK\pi$, $D \to K_S\pi\pi$ **'double Dalitz'**

Extrapolations so far are based on existing analysis strategies, but there are new approaches being proposed which are very powerful; most need BESIII data!

(Benchmark: expected run-2 precision of 'golden channel', $K_S\pi\pi$ (+ K_SKK) ~ 7°.)

Simultaneous analysis of $B^0 \to DK\pi$ and $D \to K_S\pi\pi$ phase space appears very promising [Craik et al.,arXiv:1712.0853] and again requires c_i, s_i inputs.



- Sensitivities of ~8° and ~2° achievable after run-2 and Upgrade-I.
- Interesting internal sensitivity to c_i, s_i with high statistics, but external inputs will always be essential to validate measurement.