LHCb requirements for γ from quantum-correlated threshold data

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IHEP, Beijing, 8/2/18

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- Requirements with future LHCb data sets
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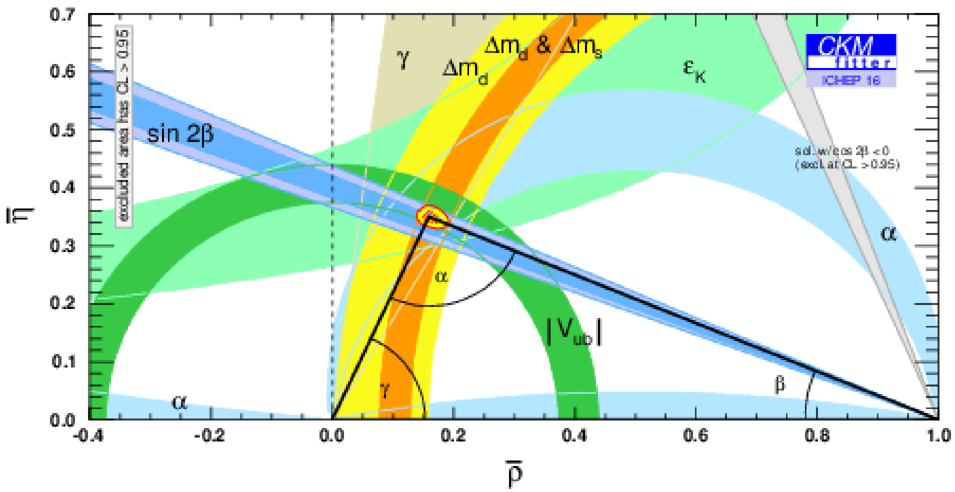
CKM γ – the beautiful obsession

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→u and b→c interference in B→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).

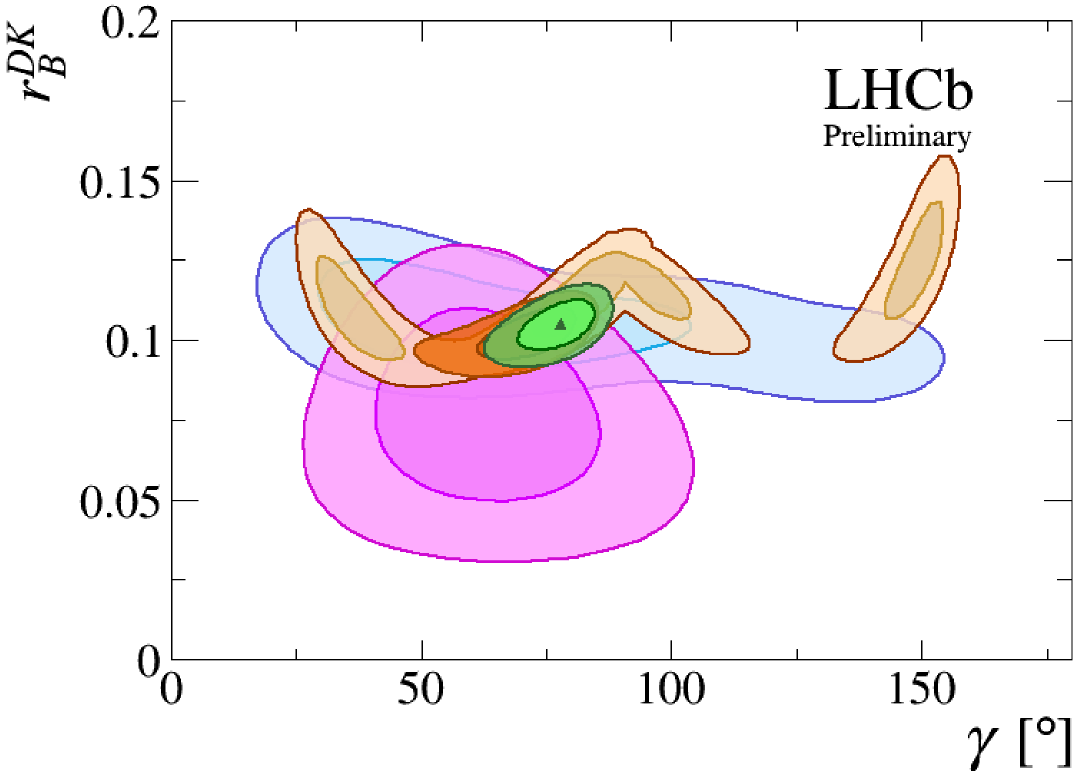
Hence our challenge is to:

- Measure CPV observables in many D modes in B→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.*)

→ Hence the need for quantum-correlated (Q.C.) charm threshold data !

Current sensitivity on γ from LHCb



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

[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.* $B^+ \to D^*K$, $D \to K_S\pi\pi$).

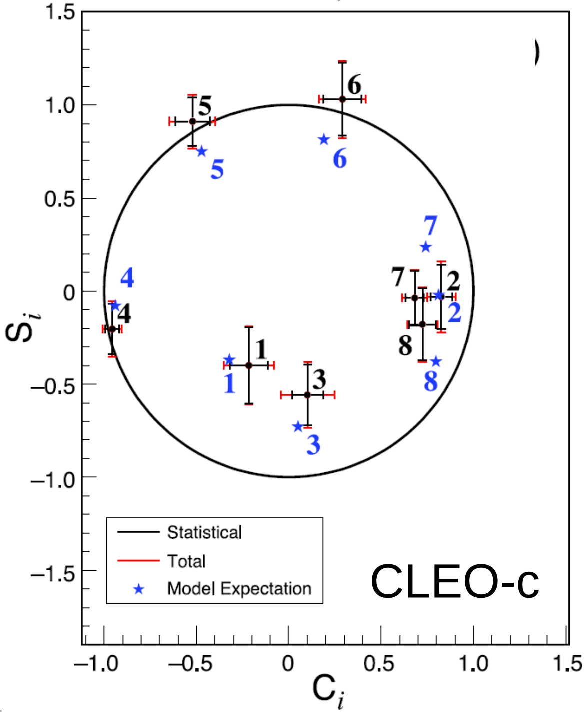
Reasonable to take ~5.5° as run-1 sensitivity (with current strategies).

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

Small, but not negligible !

Most important current Q.C. inputs

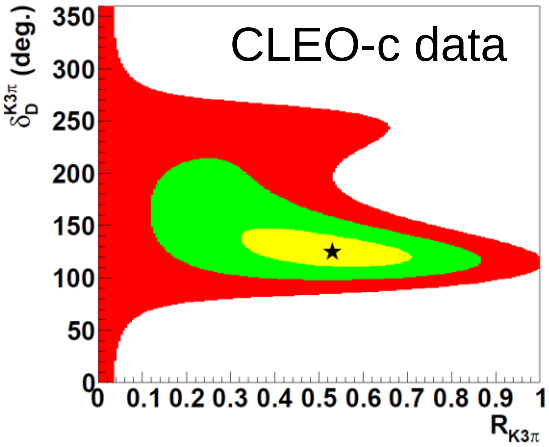
$K_S\pi\pi$ c_i, s_i

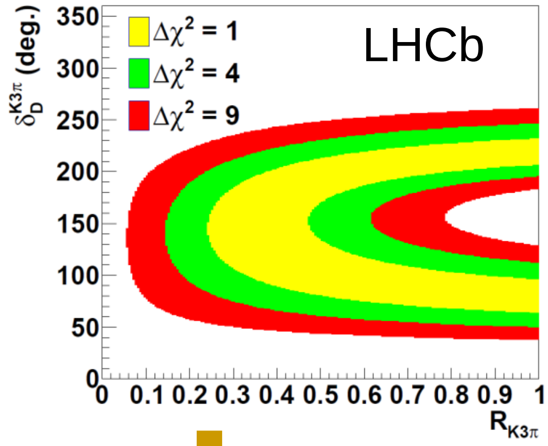


[PRD 82 (2010) 112006]

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

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

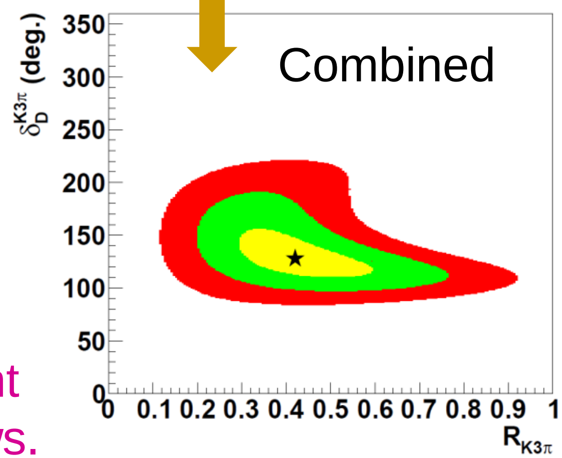




LHCb also uses CLEO-c inputs for other modes

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.



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

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 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. ***Essential input !***

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LHCb phase-2 upgrade [14 TeV]	300 fb^{-1}	~400	2035(?)

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

Run 1	Run 2	Upgrade 1
5.5°	2.8°	0.71°

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° ?) 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

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Scaling 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 ***essential*** for Upgrade II ! Becomes possible to access 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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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 !

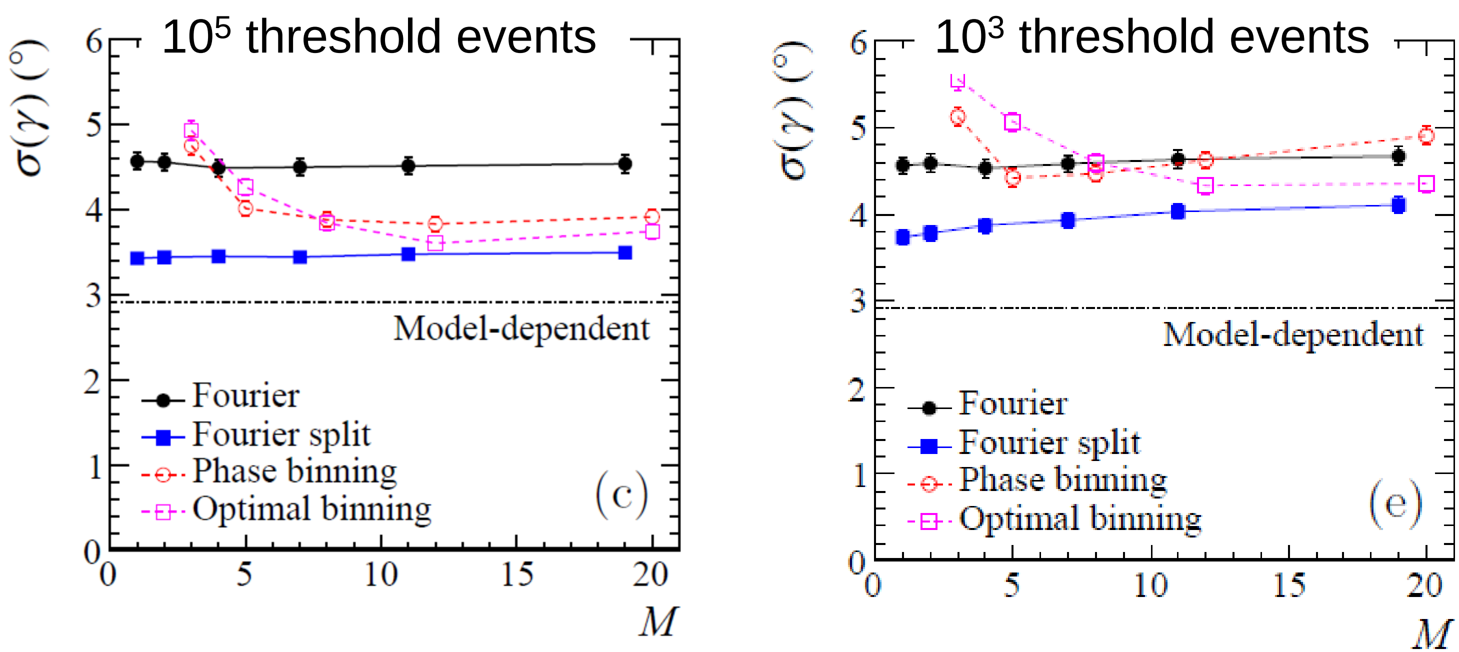
New kids on the block

$D \to K_S \pi\pi$ 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.

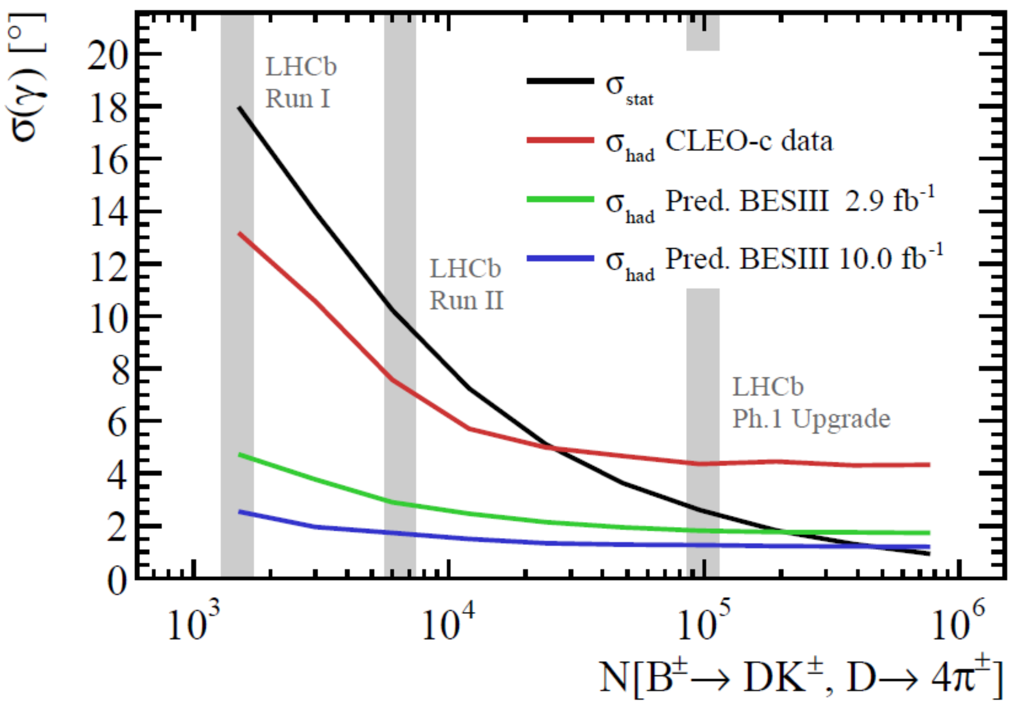


See Anton Poluektov talk and arXiv:1712.08326.

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

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.)

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

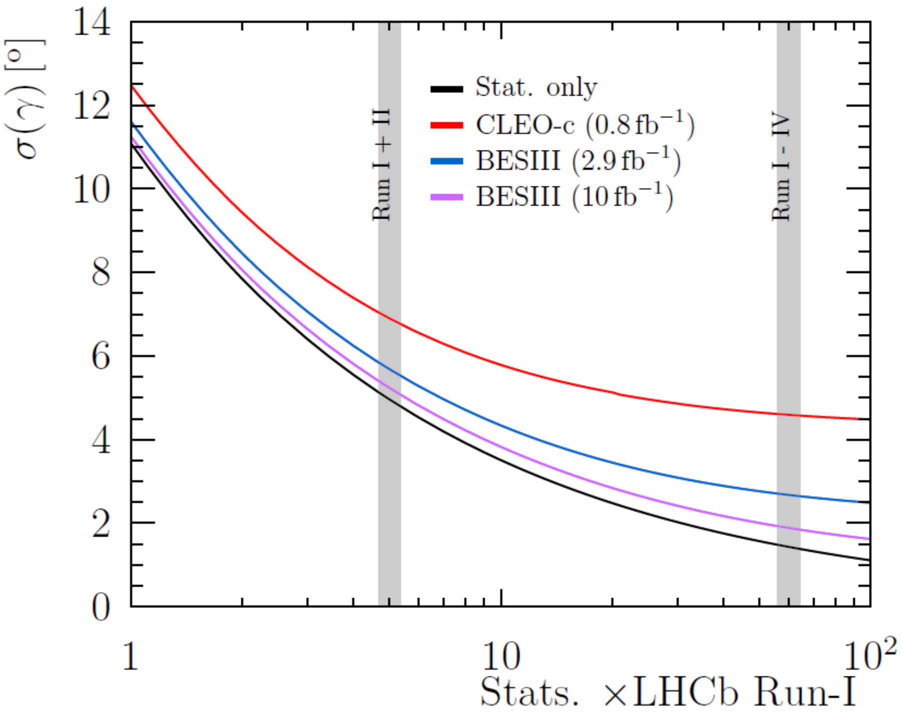


- Expected stat. precision after run 2 is ~10 degrees.
- Contribution from CLEO-c uncertainties ~7 degrees.
- BESIII input already very helpful now, and soon will become essential.
- Larger BESIII sample would benefit Upgrade I, and will be mandatory for Upgrade II.

New kids on the block $D\to K3\pi$

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.)

$D\to K3\pi$, already analysed globally, can also be studied in bins informed by LHCb amplitude model (see talk of Tim Evans). Requires coherence factor and strong phase to be measured in each bin, by combination of threshold data and D-mixing studies.



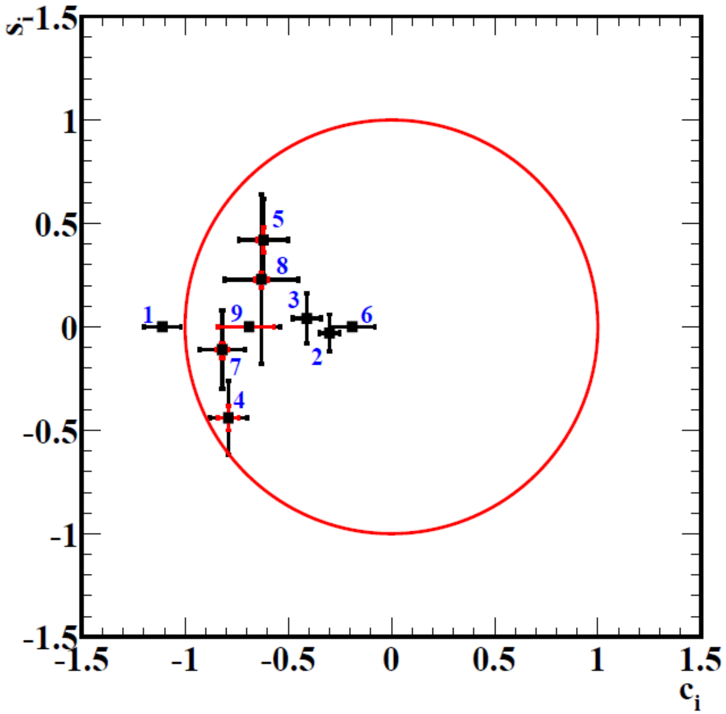
- Stat. precision after run 2 ~5.5º. Best sensitivity of any single mode !
- BESIII input urgently required.
- Larger BESIII samples needed for Upgrade era.

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_SKK) ~ 7°.)

$D \to K_S\pi\pi\pi^0$ has a high B.R. and rich resonant structure. A naïve binning scheme has already been proposed & CLEO data analysed [Resmi P.K. *et al.* JHEP01 (2018) 082] .



- 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.

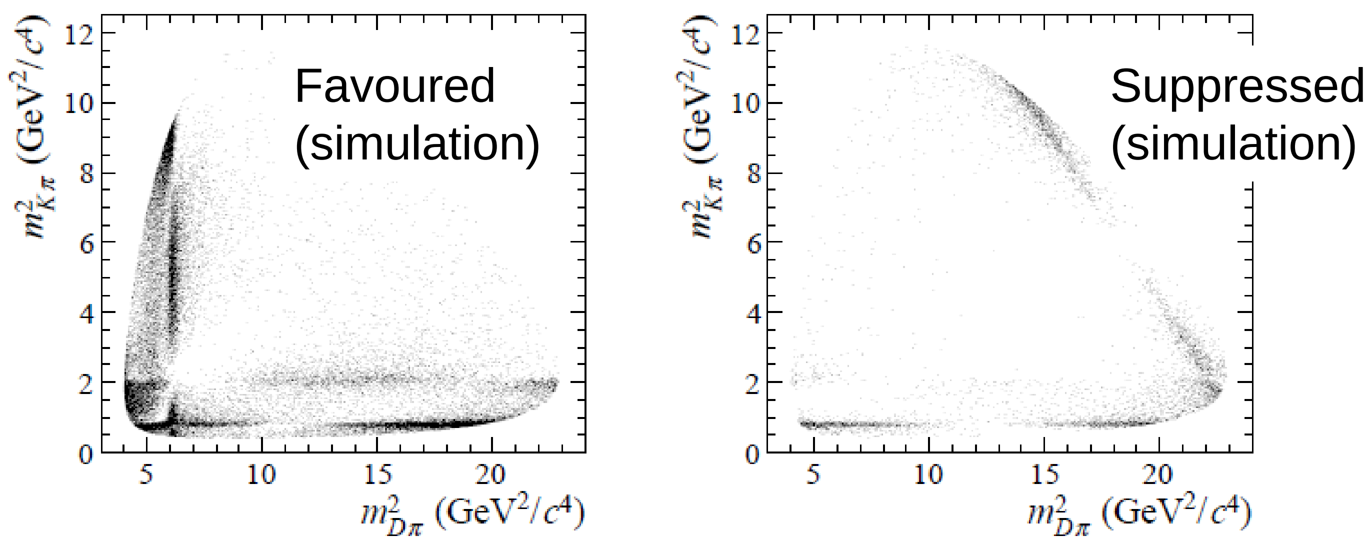
New kids on the block

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



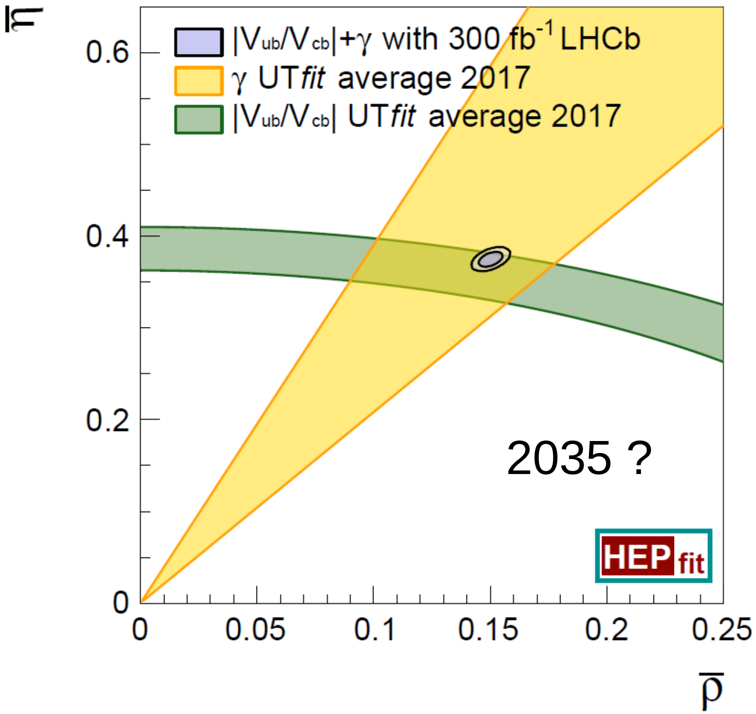
- Sensitivities of ~8° and ~2° achievable after run-2 and Upgrade-I.
- Interesting internal sensitivity to c_i, s_i with high statistics, but external inputs will always be essential to validate measurement.

Conclusions

- We have an obligation to measure γ with the highest possible precision.
- Model independence essential – so all $B \to DK$, $D \to$ multibody analyses require direct 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 $\sim 2^o$, 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.
- 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.

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 $\Psi(3770)$ data are required to exploit fully the very large future samples at LHCb.