Super γ: sensitivity with future experiments.

Anton Poluektov

The University of Warwick, UK,
Budker Institute of Nuclear Physics, Novosibirsk, Russia

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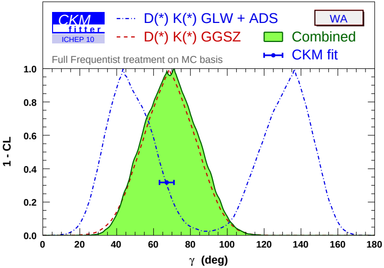
In many cases, the answer given by the experiment does not really match the question asked by theory.

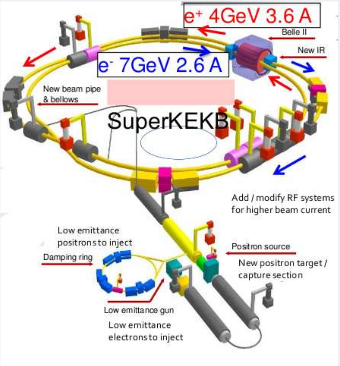
> "They say the Ultimate Answer or whatever is Forty-two, how am I supposed to know what the question is?"
>
> *Douglas Adams*
> *The Hitchhiker's Guide to the Galaxy*

This is not the case for γ (up to 10^{-6} precision).

And by the way, $\gamma = 42^{\circ}$ is not ruled out yet...



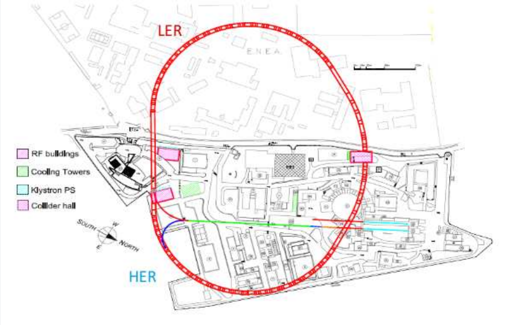
Super B factories



SuperKEKB and Belle II

$L = 8 \times 10^{35}$ cm^{-2}s^{-1}

$\int L dt = 50$ ab^{-1}



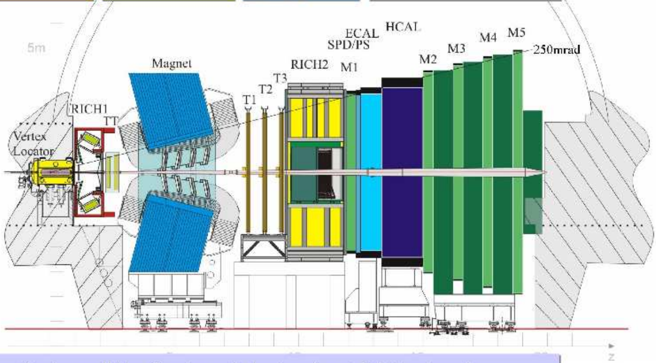
SuperB project

$L = 10^{36}$ cm^{-2}s^{-1}

$\int L dt = 75$ ab^{-1}

Will refer to both projects as SuperB.

VELO	TRACKING	RICH	CALO + MUON
New pixel system	New TT and IT	New photon detector	Remove M1



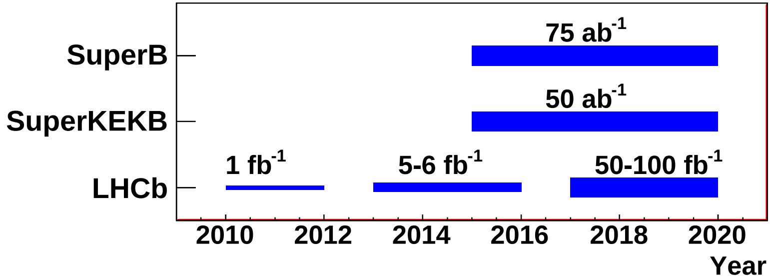
Replace all the front-end electronics + DAQ network

Luminosity 2×10^{33} cm^{-2}s^{-1}

$\int Ldt = 50 - 100$ fb^{-1}

Increased hadronic trigger efficiency ($\times 2 - 3$).

Perspectives



LHCb:

20×10^{12} produced $B\overline{B}$ pairs
detection efficiency $< 1\%$.
B/S typically $O(1)$

SuperB:

50×10^{9} produced $B\overline{B}$ pairs
detection efficiency $O(100\%)$
clean signals

e^+e^- vs hadron experiments

Benchmark modes

Mode	SuperB (50 ab^{-1})	LHCb (50 fb^{-1})
$B \to D(K\pi)K$ allowed	200K	4M
$B \to D(K_S\pi\pi)K$	100K	300K
$B_s \to D_s(KK\pi)K$	-	700K

- Main "golden" modes ($B \to DK$ with $D \to hh'$, $D \to K_S hh$) accessible to both LHCb and SuperB.
- SuperB can reconstruct modes with neutrals such as $K_S\pi^0$. Not possible or very hard at LHCb.
- B_s, B_c, Λ_b decays are available at LHCb.

Precision γ measurement

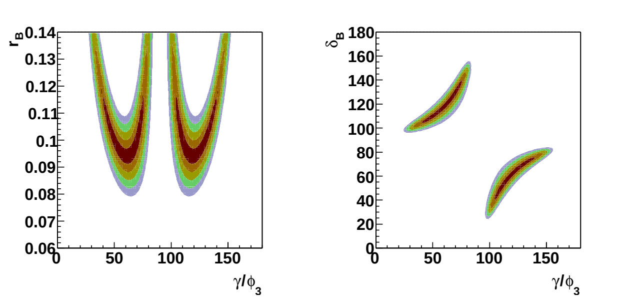
- Expect to reach $O(1^\circ)$ sensitivity with SuperB and LHCb.
- The methods used to extract γ need to have little or no theoretical uncertainty.
- Controlling experimental systematics can be tricky. Expect that most of it should also scale with statistics (depends on control samples).
- Statistical errors should be much easier to calculate: Gaussian regime.

Use simple likelihood estimates; compare SuperB and LHCb side-by-side.

Methods involving $D \to hh$: SuperB

$$R_{GLW\pm} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\gamma$$
$$A_{GLW\pm} = \pm 2r_B \sin\delta_B \sin\gamma / R_{GLW\pm}$$
$$R_{ADS} = r_B^2 \pm r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos\gamma$$
$$A_{ADS} = 2r_B r_D \sin(\delta_B + \delta_D)\sin\gamma / R_{ADS}$$

CP-even: $D \to hh$
CP-odd: $K_S\pi^0$, $K_S\omega$
6 observables
4 parameters:
$\gamma, r_B, \delta_B, \delta_D$



GLW alone, poor sensitivity in practice.

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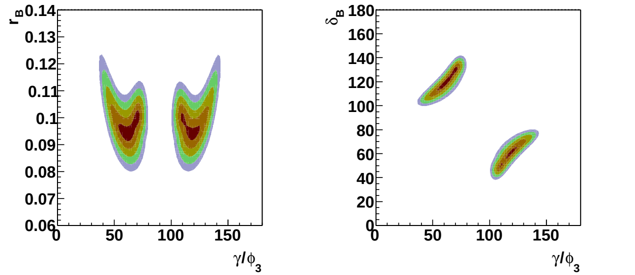

GLW+ADS, no δ_D constraint — still ambiguous, non-Gaussian tail

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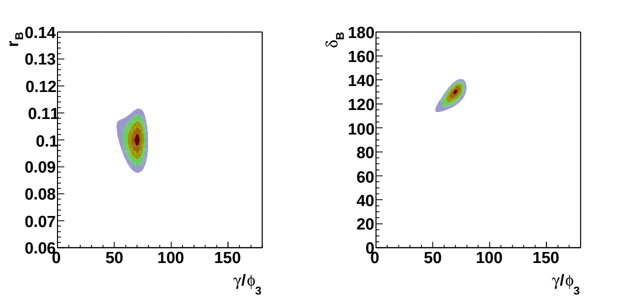

GLW+ADS, $\sigma(\delta_D) = 2^\circ$.

Sensitivity with
$r_B = 0.1$
$\gamma = 70^\circ$
$\delta_B = 130^\circ$
$\delta_D = 22^\circ - 180^\circ$:

$\sigma(\delta_D)$	$\sigma(\gamma)$
-	5.1°
11°	4.7°
1°	3.9°

$$R_{GLW\pm} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\gamma$$
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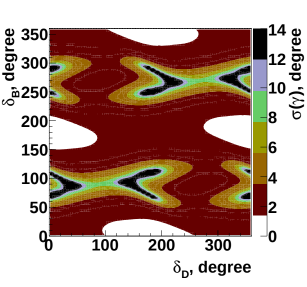

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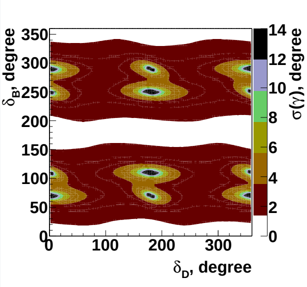
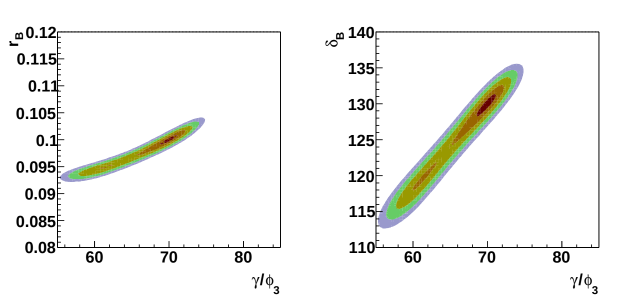


$\sigma(\gamma)$ depends on strong phases → external constraints on r_B help (*e. g.* from $B \to (K\pi\pi\pi)_D K$).

Methods involving $D \to hh$: LHCb

$$\frac{N(B^\pm \to D(K^\pm\pi^\mp)K^\pm) = N_{K\pi}[1 + r_B^2 r_D^2 + 2r_B r_D \cos(\delta_B - \delta_D \pm \gamma)]}{N(B^\pm \to D(K^\mp\pi^\pm)K^\pm) = N_{K\pi}[r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D \pm \gamma)]}$$
$$N(B^\pm \to D(h^+h^-)K^\pm) = N_{hh}[1 + r_B^2 + 2r_B \cos(\delta_B \pm \gamma)]$$

Only CP-even states are available at LHCb.
GLW+ADS modes provide enough constraints if $N_{K\pi}/N_{hh}$ is fixed.



$B \to D(hh')K$, no δ_D constraint.

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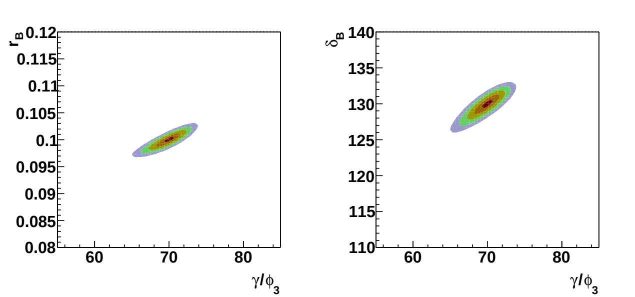

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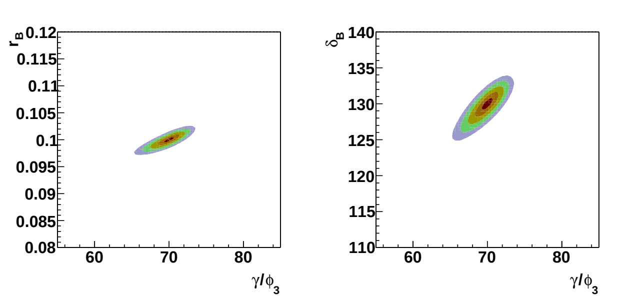


$B \to D(hh')K$, $B \to D(K\pi\pi\pi)K$, no δ_D constraint.

Methods involving $D \to hh$: summary

- Combination of both ADS and GLW modes is essential to reach a good γ precision.
- External δ_D constraint is necessary to resolve ambiguities and to reach optimal precision: need $\sigma(\delta_D) \sim 1^\circ$!
- Sensitivity strongly depends on strong phase values δ_D and δ_B. In some unlucky cases up to $\times 10$ worse and more. Additional constraints may help in most cases. SuperB looks safer since more modes with potentially different δ_D and δ_B can be used.

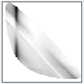
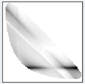
Sensitivity for $r_B = 0.1$, $\gamma = 70^\circ$, $\delta_B = 130^\circ$, $\delta_D = 22^\circ - 180^\circ$:

	SuperB (50 ab^{-1})	LHCb (50 fb^{-1})
$D \to hh$, $D \to K\pi$	5.1°	1.4°
$D \to hh$, $D \to K\pi$, $\sigma(\delta_D) = 1^\circ$	3.9°	1.0°
$D \to hh$, $D \to K\pi$, $D \to K\pi\pi\pi$	2.4°	0.8°

- Other modes available at SuperB: $B^\pm \to D^*(D\pi^0)K^\pm$, $B^\pm \to D^*(D\gamma)K^\pm$, $B^\pm \to DK^{*\pm}$ can double the precision.

Giri, Grossman, Soffer, Zupan, PRD 68, 054018 (2003)
Bondar, Belle Dalitz analysis meeting (2002)

Observable — D decay Dalitz plot density (different for B^+ and B^-):

$$p(m_+^2, m_-^2) = |A_\pm|^2 = \Bigg|$$  $$+\, r_B e^{i\delta_B \pm i\gamma}$$  $$\Bigg|^2$$

Convenient fit parameters: $x_\pm + iy_\pm = r_B e^{i(\delta_B \pm \gamma)}$.
Model-dependent analysis — a few degree model error. Binned model-independent approach is a solution:

$$M_i^\pm = h\{K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(x_\pm c_i - y_\pm s_i)\},$$

$c_i = \langle\cos(\Delta\delta_D)\rangle$, $s_i = \langle\sin(\Delta\delta_D)\rangle$ obtained by CLEO-c.
In the binned fit, can reach $\sim 90\%$ precision compared to the unbinned by choosing proper binning. With increased charm data — finer binning, closer to the unbinned precision.

$B^+ \to DK^+$, $D \to 3$ body Dalitz analysis

- Sensitivity practically independent of δ_B and γ.
- Errors scale proportional to $1/r_B$. Expect Gaussian errors with high statistics.
- In LHCb, $B/S \sim 1$ is expected $\Rightarrow$ suppression of sensitivity.

	Event sample	$\sigma(\gamma)$
SuperB (50 ab^{-1})	100K	$1.5 - 2^\circ$
LHCb (50 fb^{-1})	300K	$1 - 1.5^\circ$

- CLEO-c error of c_i, s_i translates to $2 - 3^\circ$ error in γ.
- There is a slight model assumption in CLEO-c analysis due to use of $K_L\pi\pi$ tags. To *completely* avoid model assumptions, use only $\sim 1/3$ of statistics $\Rightarrow$ expect $3 - 5^\circ$ error.
- Reducing the model error to $\sim 1^\circ$ requires $\sim 10 - 20$ fb^{-1} of $e^+e^- \to \psi(3770)$ data.
- Other D modes can be used $K_S KK$, $KK\pi\pi$ (SuperB, LHCb), $\pi\pi\pi^0$, $K_S\pi\pi\pi^0$, $K\pi\pi^0$ (SuperB, LHCb?).

Time-integrated B^0 analyses

$B^0 \to DK^{*0}$ can be used in the same way as $B \to DK$ for ADS, GLW analyses.

$$\left.\begin{array}{l}\text{Smaller } \mathcal{B} \text{ by factor 4–5} \\ \text{Larger } r_B = 0.3 \ (0.1 \text{ for } B \to DK).\end{array}\right\} \text{Expect similar sensitivity}$$

Additional complication: other states in $B \to DK\pi$ amplitude.
Turns out to be an advantage: simultaneous Dalitz analysis of $B \to D(K\pi)K\pi$ and $B \to D_{CP}(hh)K\pi$ decays provides additional sensitivity and resolution of ambiguities.

T. Gershon, M. Williams, PRD 08 092002 (2009), arXiv:0909:1495

Inherent model dependence — can be limiting with $\sim 1^\circ$ precision.
Using binned analysis with the addition of $B \to D(K_S\pi\pi)K\pi$ state to the combined analysis allows to avoid model uncertainties. Correlations constrain $B \to DK\pi$ amplitude from $D \to K_S\pi\pi$.

T. Gershon, A.P., PRD 81 014025 (2010), arXiv:0910:5437

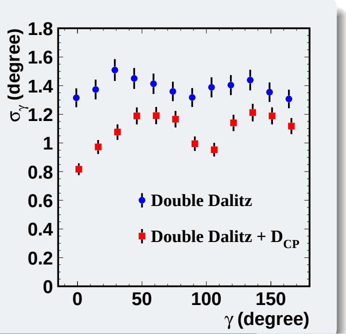
Time-integrated B^0 analyses

The amplitude of the $B^0 \to D(K_S\pi^+\pi^-)K^+\pi^-$ is $A = \overline{A}_B\overline{A}_D + e^{i\gamma}A_BA_D$ and thus the Dalitz plots $B^0 \to DK^+\pi^-$ and $D \to K_S\pi^+\pi^-$ are correlated (4D analysis!).
Binning ($M_{\alpha i}$: double Dalitz, N_α: $B^0 \to D_{fl}K^+\pi^-$, K_i: $D^0 \to K_S\pi\pi$):

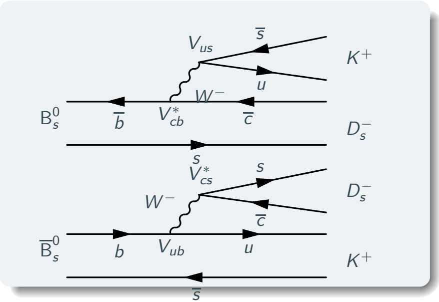
$$M_{\alpha i} = h\{\overline{N}_\alpha K_i + N_\alpha K_{-i} + 2\sqrt{N_\alpha K_i \overline{N}_\alpha K_{-i}} \times [(\varkappa_\alpha c_i - \sigma_\alpha s_i)\cos\gamma - (\varkappa_\alpha s_i + \sigma_\alpha c_i)\sin\gamma]\}.$$

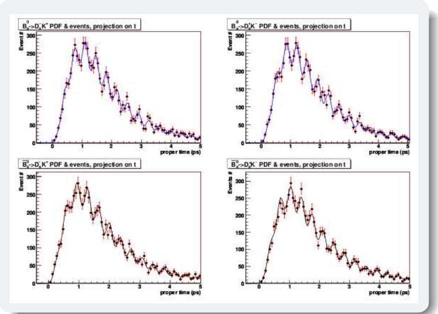
Phase parameters: c_i, s_i from charm data, $\varkappa_\alpha$ and σ_α — free parameters.

Very naive estimates for the sample $\sim$ 50 fb^{-1} at LHCb (and without background)
Amplitude is unknown, sensitivity may vary significantly.



Time-dependent analyses: $B_s \to D_s K$





Measurement unique to LHCb: sensitive to $\phi_s + \gamma$.

Looking at the time-dependent distributions for flavour-tagged $B_s \to D_s^{\pm} K^{\mp}$.

No external inputs needed except for ϕ_s (to be measured). Δm_s, mistag rate enter in the free parameters.

Sensitivity of 10° with 2 fb^{-1} at LHCb is expected $\Rightarrow$ scale to $\sim 1.5 - 2^\circ$ with 50 fb^{-1} at SuperLHCb, but limiting systematic uncertainties still need to be understood.

Influence of D mixing

In the modes with neutral D (time-integrated measurement), ignoring D mixing with $(x_D, y_D) \sim 1\%$ can affect a precision measurement.

- If the charm parameters (r_D, K_i, etc.) are extracted taking mixing into account, the mixing correction is linear and significant ($O(1^\circ)$).
  Silva, Soffer, PRD 61, 112001 (2000)
- If mixing is ignored in both charm and B parameters, mixing correction is of 2nd order in (x_D, y_D) $\Rightarrow$ can safely ignore. True for ADS, model-dependent Dalitz.
  Grossman, Soffer, Zupan, PRD 72, 031501 (2005)
- In model-independent Dalitz, c_i and s_i are extracted from correlated $D\overline{D}$ data with $\mathcal{C} = -1$ $\Rightarrow$ appear to be unaffected by mixing after integration over time. In that case, mixing corrections are linear, but suppressed by additional factors (incl. r_B). $\Delta\gamma \simeq 0.2^\circ$. Can be corrected. Bondar, AP, Vorobiev, PRD 82, 034033 (2010)
- Interestingly, in correlated $D\overline{D}$ decays produced with $\mathcal{C} = -1$, mixing effects are enhanced $\Rightarrow$ allows to measure x_D, y_D in time-integrated analysis at DD^* threshold.

Conclusion

- Various independent methods should allow for $\sim 1-3^\circ$ measurement with SuperB and upgraded LHCb:
  - ADS + GLW modes
  - $B \to D(K_S\pi\pi)K$ Dalitz analysis
  - Self-tagging $B^0 \to DK\pi$ modes
  - $B_s \to D_s K$ (LHCb only)
- Overall, LHCb sensitivity with 50 fb^{-1} potentially looks better than that of SuperB, but higher backgrounds can reduce it. SuperB is more stable against "unlucky" parameter combinations when the sensitivity can be significantly reduced.
- Having a large ($\sim$ 10-20 fb^{-1}) sample at charm threshold is desirable for an efficient use of B data:
  - Significant fraction of BES-III sample.
  - Dedicated charm-tau factory.
  - SuperB operated at low energy.