Opportunities for Run II
(for CP violation measurements in B decays)

Tim Gershon
University of Warwick

Implications of LHCb Measurements and Future Prospects

15th October 2014

Outline

- For each of four main areas:
  - (i) $a_{sl}^{d,s}$ from semileptonic decays; (ii) γ from $B \to DK$; (iii) $2\beta_{(s)}$ from $b \to c\bar{c}s$; (iv) γ and $2\beta_{(s)}$ from charmless decays

  consider
  - current status
  - prospects to reduce experimental uncertainty
  - other aspects: assumptions in the analyses; data-driven ways to reduce “theory uncertainty”

Run I and Run II

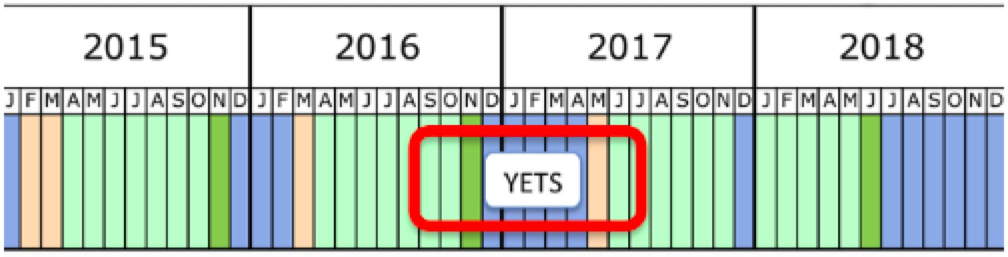
- Run I
  - 2011: 1/fb recorded at $\sqrt{s}$ = 7 TeV
  - 2012: 2/fb recorded at $\sqrt{s}$ = 8 TeV
  - L0Hadron: typically 1:1 TOS:TIS for $B \to DX$ decays
- Some key measurements not yet on full data set, e.g.
  - 1/fb: a_{sl}^{s}, γ (GLW/ADS), sin(2β), $B_s \to K^+K^-$
  - 3/fb: a_{sl}^{d}, γ (GGSZ), $2\beta_s$, $B_s \to \varphi\varphi$
- Improvement is not just $\sqrt{\int L dt}$, nor $\sqrt{(\int L dt \times \sigma)}$
  - better S/B separation, better flavour tagging, etc.
  - but in future stocks could go down as well as up ...

Examples

- $2\beta_s$ (aka ϕ_s) from $B_s \to J/\psi\phi$
  - 1/fb (LHCb-PAPER-2013-002) → 3/fb (LHCb-PAPER-2014-059)
  - Signal yield: 27,500 → 95,000
  - Tagging (εD^2): 3.1% → 3.7%
  - Stat. error: 0.09 → 0.049
- γ from B → DK GGSZ
  - 1/fb (LHCb-PAPER-2012-027) → 3/fb (LHCb-PAPER-2014-041)
  - Signal yield: 650 → 2250
  - Stat. error (r_B): 0.04 → 0.02

Run I and Run II

- Run I
  - 2011: 1/fb recorded at √s = 7 TeV
  - 2012: 2/fb recorded at √s = 8 TeV
  - L0Hadron: typically 1:1 TOS:TIS for B→DX decays
- Run II

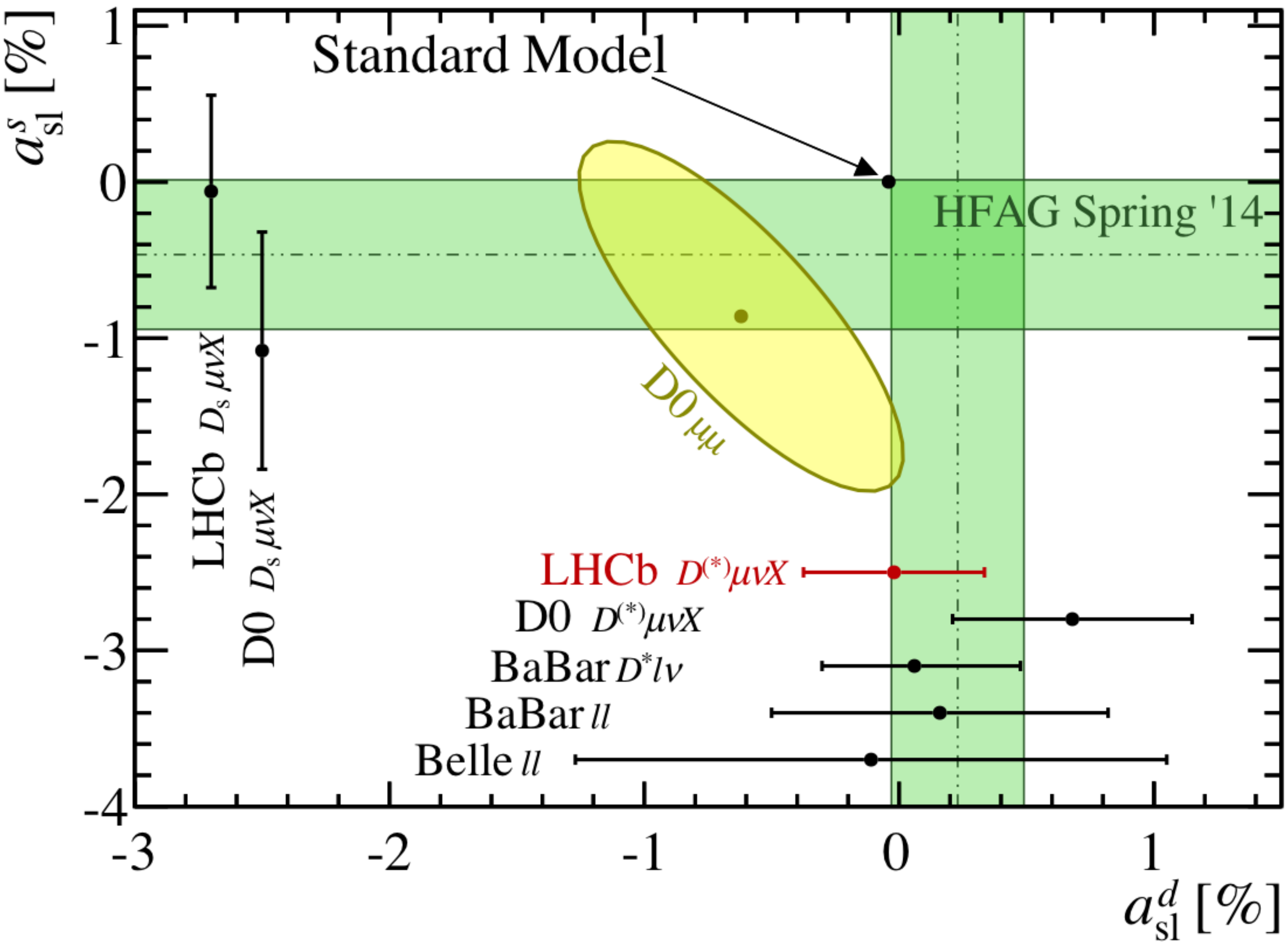


  - Expect 5-6/fb to be recorded at √s = 13 TeV
  - Trigger settings under discussion

Large increase in yields is coming, but …
not immediately and
not equally for all channels

$a_{sl}^{d,s}$ from semileptonic decays

$a_{sl}^{s} = (-0.06 \pm 0.50 \pm 0.36)\%$



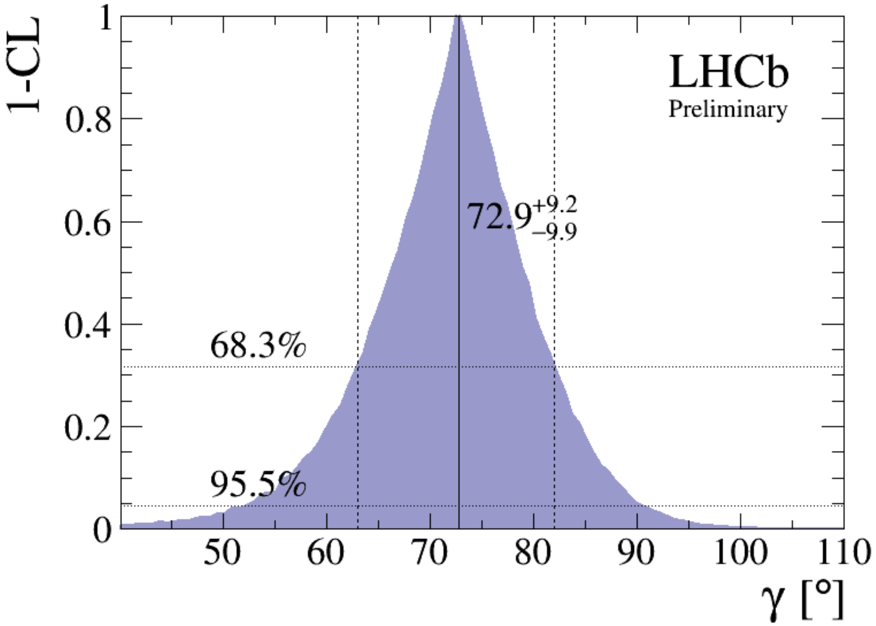
$a_{sl}^{d} = (-0.02 \pm 0.19 \pm 0.30)\%$

$a_{sl}^{d,s}$ from semileptonic decays

- Prospects for reduction of uncertainties
  - Statistical:
    - a_{sl}^{s} update to 3/fb, use more D_s decays
  - Systematic:
    - largest contribution due to detection asymmetries
    - related to size of control samples → expect reduction
- Other aspects:
  - assumptions that SL decays are (i) flavour-specific & (ii) CP conserving; also CPT assumed to be conserved (see e.g. arXiv:1407.1269)
    - shouldn't these be experimentally tested? [n.b. very hard to test (ii) @ LHCb]
  - contribution to D0 inclusive dimuon result if $\Delta\Gamma_d \neq 0$; important therefore to measure it (LHCb-PAPER-2013-065; 1/fb)

γ from $B \to DK$

- Sensitivity to γ from numerous channels
  - $B^+ \to DK^+$ ($D \to K_S hh$)
  - $B^+ \to DK^+$ ($D \to hh'$)
  - $B_s \to D_s K$
  - $B^0 \to DK^{*0}$ ($D \to hh'$)
    - $B^0 \to DK\pi$ ($D \to hh'$)
  - $B^+ \to DK^+$ ($D \to K_S K\pi$)
  - $B^+ \to DK^+$ ($D \to K3\pi$, 4h, $hh'\pi^0$)
  - $B^0 \to DK^{*0}$ ($D \to K_S hh'$)
  - $B^+ \to DK^+\pi\pi$ ($D \to hh'$, $K_S hh'$, etc.)
  - $B^+ \to D^*K^+$ ($D \to hh'$, $K_S hh'$, etc.) … and many, many more



Colour code: 3/fb; 1/fb; not yet

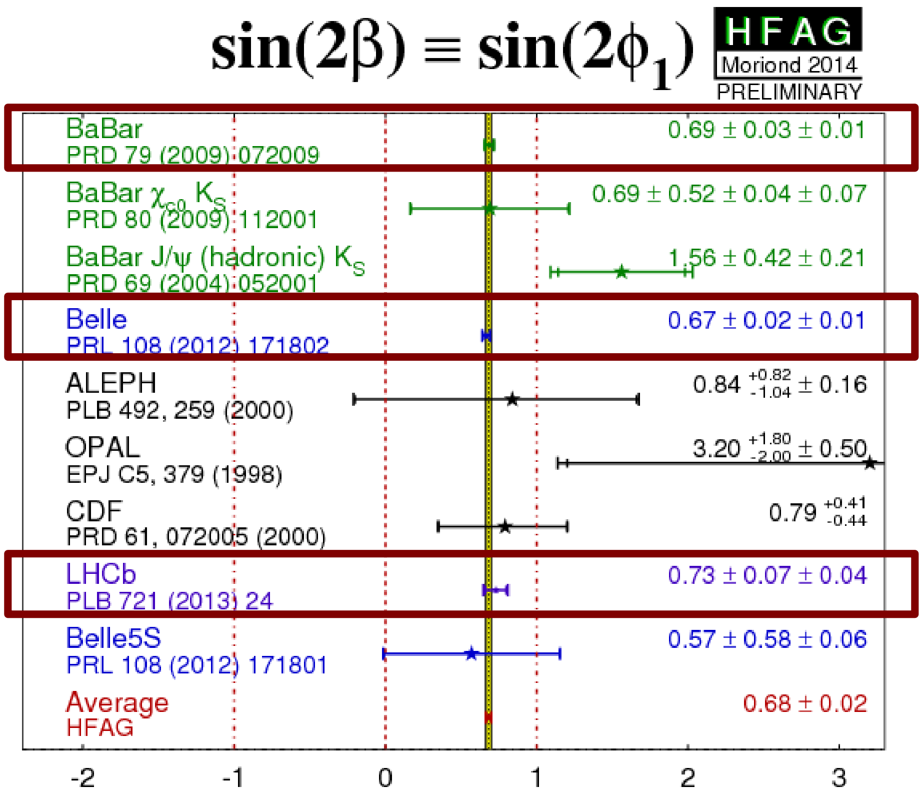
Which modes add most?

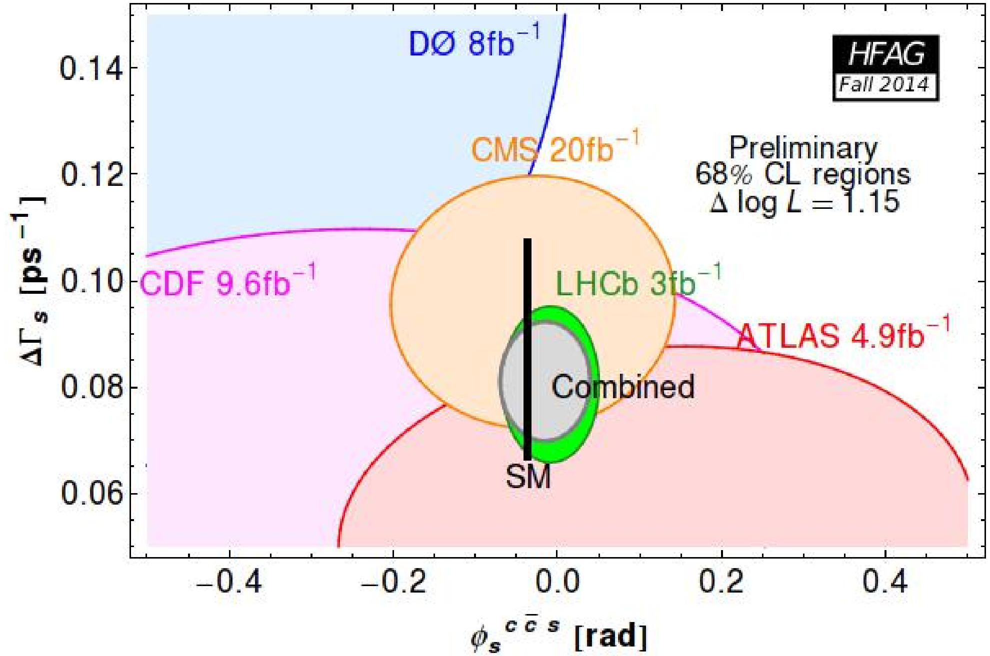
- Could save time & effort if we knew a priori which modes give the most γ sensitivity
- No golden rule, but we want
  - potentially large CP violation (large r_B)
  - large yield
    - high product branching fraction x efficiency [in practice: few final state particles]
  - reduced reliance on flavour tagging
  - enough observables to reduce ambiguities
- Several modes seem to have good potential, e.g.
  - $B^0 \to DK\pi$ Dalitz plot analysis
  - $B^+ \to DK^+$ ($D \to \pi\pi\pi^0$) [n.b. $\mathcal{B}(D \to \pi\pi\pi^0) \sim 10 \times \mathcal{B}(D \to \pi\pi)$]

Prospects for γ sensitivity

- Still much to come from Run I
  - Official projection is that we reach 7˚ sensitivity
- Run II data-doubling time will be years, not months
  - Will need to squeeze the most out of the data
- Other aspects:
  - Systematic uncertainties generally small
    - Must consider correlations between analyses in combination
  - Negligible theoretical uncertainty
  - Combination already considering sub-1˚ level effects
    - e.g. charm mixing & CP violation (see, e.g., arXiv:1307.4384)

$2\beta_{(s)}$ from $b \to c\bar{c}s$





3/fb update on sin(2β) from $B^0 \to J/\psi\, K_S$ will be close to world-leading

LHCb 3/fb results dominate world average of φ_s from $B_s \to J/\psi\ \{\varphi,\pi\pi\}$

Can we do (even) better on $2\beta_{(s)}$?

Many channels studied for $\sin(2\beta)$, not only $B^0 \to J/\psi\ K_S$

Mode	BaBar	Belle	Average
Charmonium:	N(BB)=465M	N(BB)=772M	
$J/\psi K_S$ ($\eta_{CP}=-1$) ☺ ☺ ☺	0.657 ± 0.036 ± 0.012	0.670 ± 0.029 ± 0.013	0.665 ± 0.024 (0.023 stat-only)
$J/\psi K_L$ ($\eta_{CP}=+1$)	0.694 ± 0.061 ± 0.031	0.642 ± 0.047 ± 0.021	0.663 ± 0.041 (0.037 stat-only)
$J/\psi K^0$	0.666 ± 0.031 ± 0.013	-	0.665 ± 0.022 (0.019 stat-only)
$\psi(2S)K_S$ ($\eta_{CP}=-1$) ☺ ☺	0.897 ± 0.100 ± 0.036	0.738 ± 0.079 ± 0.036	0.807 ± 0.067 (0.062 stat-only)
$\psi(nS)K^0$	-	-	0.676 ± 0.021 (0.018 stat-only)
$\chi_{c1}K_S$ ($\eta_{CP}=-1$) ☺ ☺	0.614 ± 0.160 ± 0.040	0.640 ± 0.117 ± 0.040	0.632 ± 0.099 (0.094 stat-only)
$\eta_c K_S$ ($\eta_{CP}=-1$) ☺	0.925 ± 0.160 ± 0.057	-	-
$J/\psi K^{*0}$ ($K^{*0} \to K_S \pi^0$) ($\eta_{CP}=1-2\vert A_\perp\vert^2$)	0.601 ± 0.239 ± 0.087	-	
All charmonium	0.687 ± 0.028 ± 0.012	0.667 ± 0.023 ± 0.012	0.677 ± 0.020 (0.018 stat-only)

☺ rating indicates favourability at LHCb

How about φ_s?

- Can (should) add $\psi(2S)\varphi$, $\chi_{c1}\varphi$, $\eta_c\varphi$, $J/\psi\ \eta'$, etc. but gain will be marginal
- More to gain in $B_s \to J/\psi\ KK$ at high m(KK)? [Also $J/\psi \to ee$ can be added]

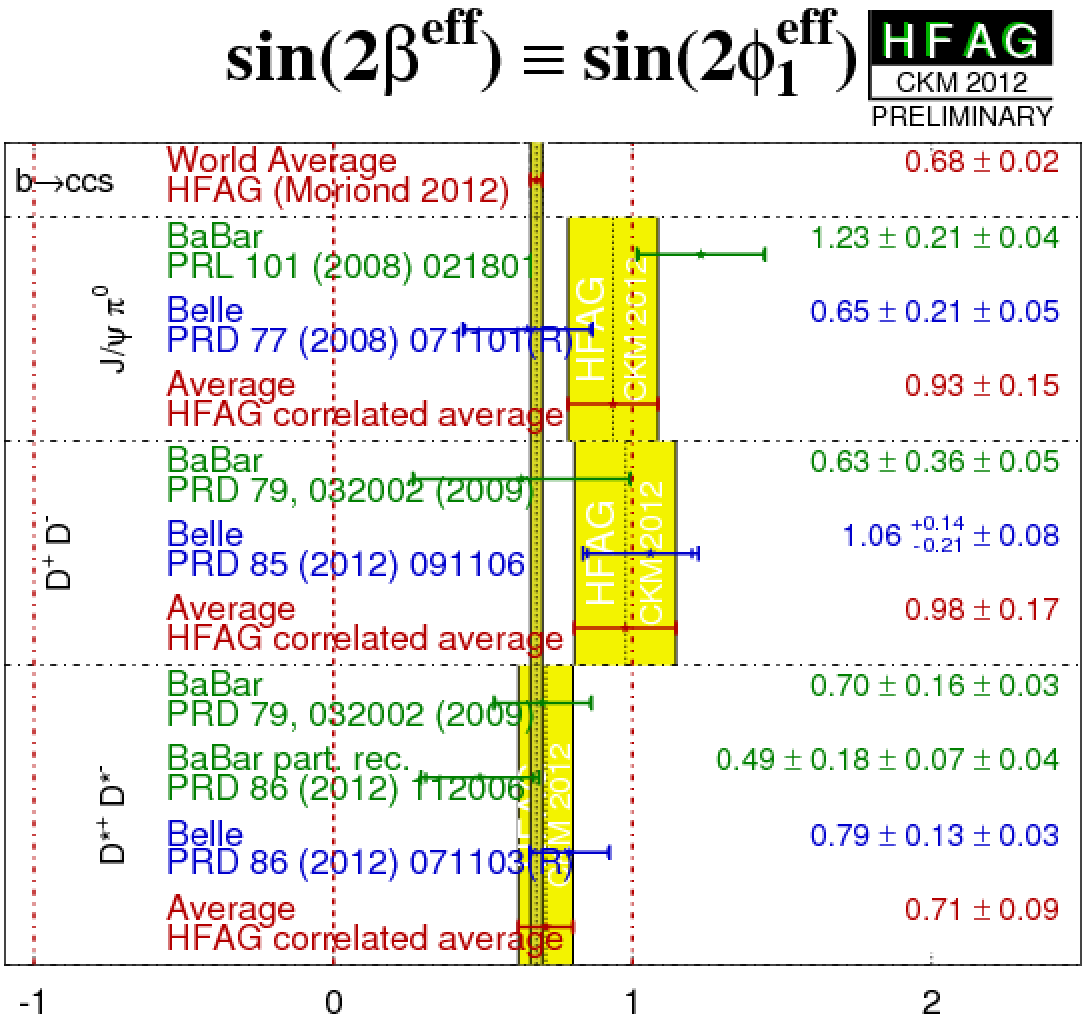
(and, always, trying to squeeze more out of the tagging)

Other aspects related to $2\beta_{(s)}$

- $B_s \to J/\psi$ KK analysis now very sophisticated
  - KK S-wave handled model-independently
  - Different CP violation effects allowed in each polarisation amplitude
- Assumptions of $\Delta\Gamma_d = 0$ (sin(2β) analysis) and CPT conservation (both) can be tested in dedicated analyses
- Only(?) remaining concern is possible penguin pollution
  - Study $b \to c\bar{c}d$ modes related by flavour symmetries ($B^0 \to J/\psi\, \rho^0$; $J/\psi\, \omega$, $B_s \to J/\psi\, K_S$, $J/\psi\, K^{*0}$)
  - Related: exploit U-spin relation between $B^0 \to D^+D^-$ and $B_s \to D_s^+D_s^-$

How can we quantify effects of flavour-symmetry breaking?

Aside on b → c$\bar{c}$d

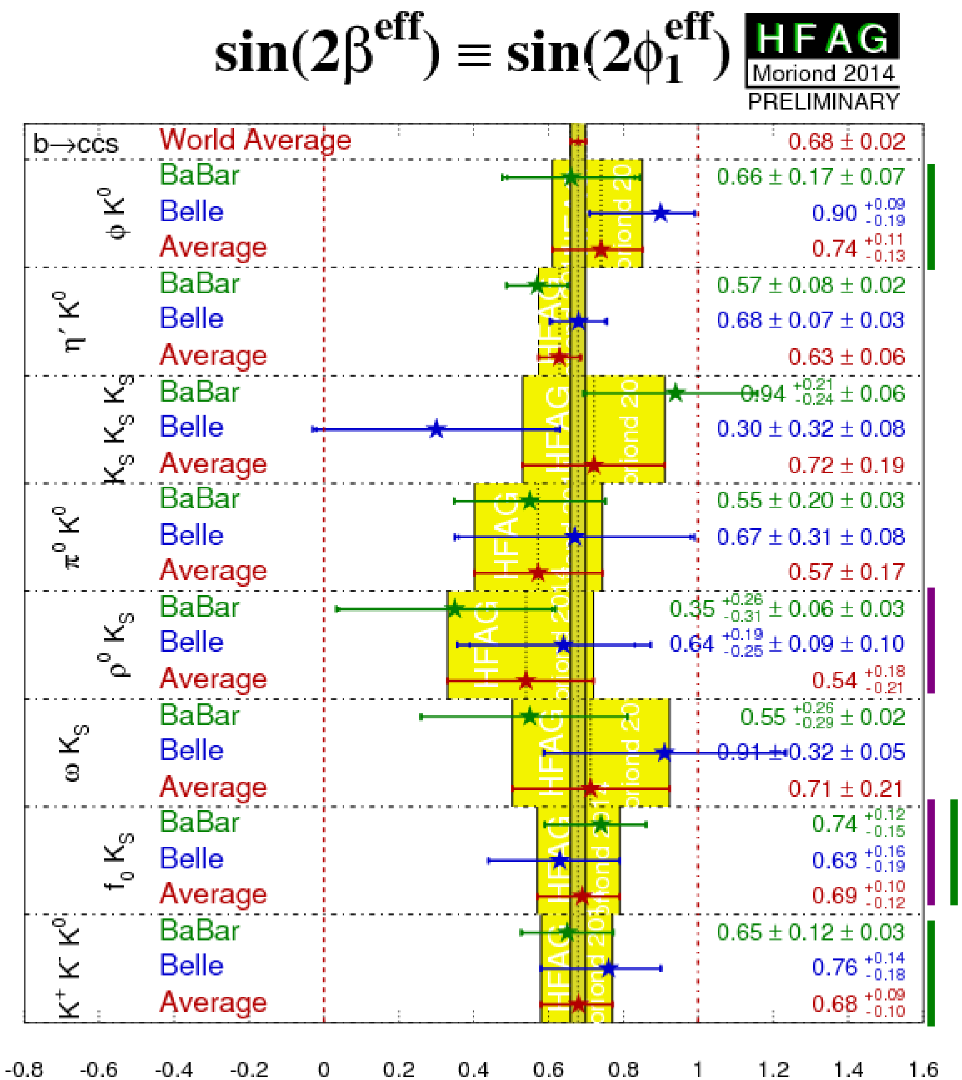


Currently no LHCb results on this plot, but will add results on $B^0 \to J/\psi\ \rho^0$ (LHCb-PAPER-2014-058) and expect to be competitive for D(*)D(*)

In addition, should get best results on CP violation in decay in $B^+ \to J/\psi\ \pi^+$, $\bar{D}^0 D^+$ and $B_s \to J/\psi\ K^{*0}$

A lot still to do!

$\sin(2\beta^{eff})$ from $b \rightarrow q\bar{q}s$ decays



Also no LHCb results on this plot (yet). Modes studied in $B^0 \rightarrow K_s hh$ Dalitz plot analyses are accessible in high yields

$K_s\pi^+\pi^-$, $K_sK^+K^-$

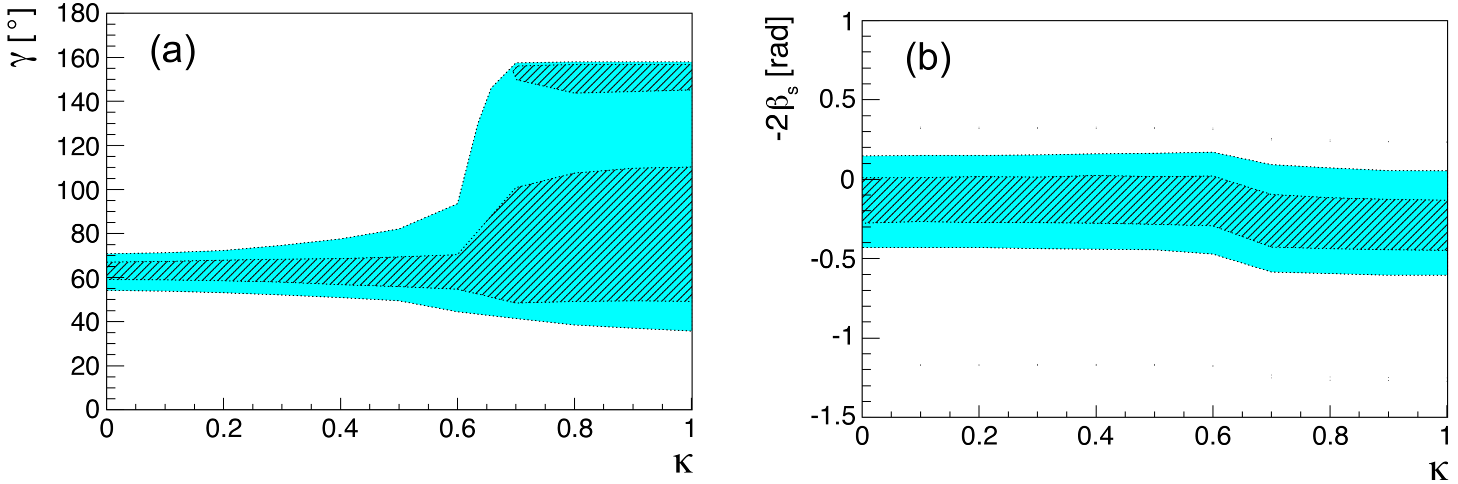
Sensitivity generally better for B_s modes (more convenient final states; better flavour-tagging; $\Delta\Gamma_s \neq 0$)

Done: $B_s \rightarrow K^+K^-$ (1/fb), $\phi\phi$ (3/fb)

To come: $B_s \rightarrow K^{*0}\overline{K}^{*0}$, $K_SK\pi$

Flavour symmetries in $b \to q\bar{q}s$ decays

- Possibility to study both B^0 and B_s decays opens many opportunities for studies based on flavour symmetries
  - e.g. relation between $B_s \to K^+K^-$ and $B^0 \to \pi^+\pi^-$
    - LHCb-PAPER-2014-045 following PL B459 (1999) 306, EPJ C52 (2007) 267, EPJ C71 (2011) 1532 and JHEP 10 (2012) 029



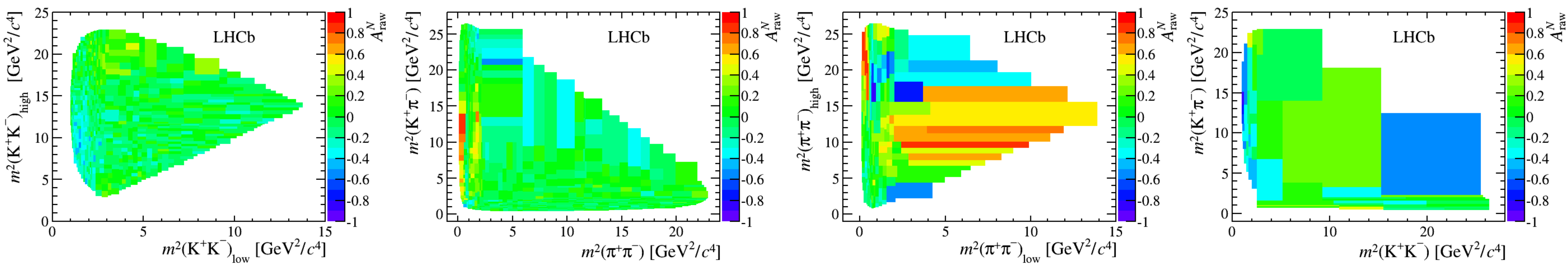
How can we control the maximum allowed U-spin breaking (κ)?

Will be important for many analyses

Hadronic effects in in $b \to q\bar{q}s$ decays

- Further challenges from hadronic effects in three-body decays
  - Striking CP violation effects observed
  - What is best approach to understand their origin? Model-independent or model-dependent approach?
  - Interpretation in terms of resonant contributions (φ, ρ, K*, etc.) needs model-dependent Dalitz plot fits – very challenging!

$B^+ \to K^+K^-K^+$ | $B^+ \to \pi^+\pi^-K^+$ | $B^+ \to \pi^+\pi^-\pi^+$ | $B^+ \to K^+K^-\pi^+$



Possibility for similar analyses to search for CP violation in b baryon decays – even more challenging!

Summary

- Over 200 papers published on Run I data ...
  - … but still many important analyses to be done
- Run II data will allow significant improvements in precision for almost all observables (for CP violation in B decays)
  - Very few channels with limiting systematics
  - Some limitations in interpretation (e.g. flavour symmetry breaking effects)
- Opportunities to improve beyond $\sqrt{(\int \mathcal{L} dt \times \sigma)}$ in most modes
  - but not guaranteed … plenty of hard work ahead

The infamous table

Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming $5\,\text{fb}^{-1}$ recorded during Run 2) and for the LHCb Upgrade ($50\,\text{fb}^{-1}$). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

	Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
☺ ☺ (☺)	B^0_s mixing	$\phi_s(B^0_s \to J/\psi\,\phi)$ (rad)	0.050	0.025	**0.009**	~ 0.003
☺ ☺		$\phi_s(B^0_s \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
☺		$A_{\rm sl}(B^0_s)$ (10^{-3})	2.8	1.4	**0.5**	0.03
☺ ☺	Gluonic penguin	$\phi^{\rm eff}_s(B^0_s \to \phi\phi)$ (rad)	0.15	0.10	**0.023**	0.02
☺		$\phi^{\rm eff}_s(B^0_s \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
☺		$2\beta^{\rm eff}(B^0 \to \phi K^0_S)$ (rad)	0.30	0.20	**0.04**	0.02
	Right-handed currents	$\phi^{\rm eff}_s(B^0_s \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
		$\tau^{\rm eff}(B^0_s \to \phi\gamma)/\tau_{B^0_s}$	5%	3.2%	**0.8%**	0.2 %
	Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
		$q^2_0\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
		$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
		$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
	Higgs penguin	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
		$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
☺ (☺ ☺)	Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
☺		$\gamma(B^0_s \to D^{\mp}_s K^{\pm})$	17°	11°	**2.4°**	negligible
☺ (☺ ☺)		$\beta(B^0 \to J/\psi\, K^0_S)$	1.7°	0.8°	**0.31°**	negligible
	Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
		ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

☺ ☺ ☺ – exceeded Run I expectation;
☺ ☺ – matched expectation; ☺ – on track