γ measurements in $B_s^0 \to D_s^\mp K^\pm$ and other tree-level decays

Manuel Schiller

Nikhef

August 12th, 2014

image: CERN

image: CERN

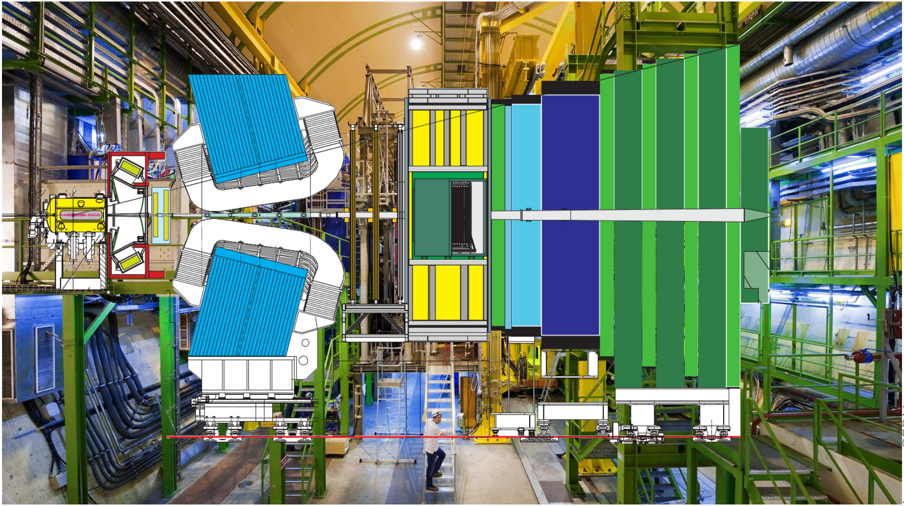
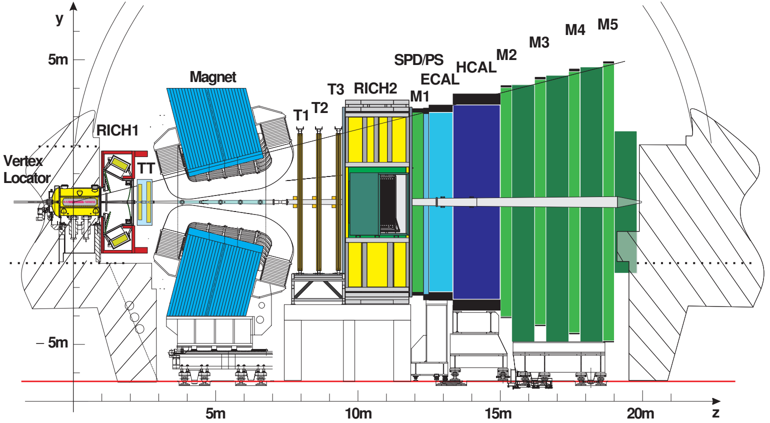


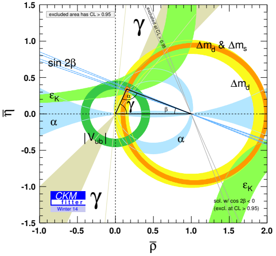
image: CERN

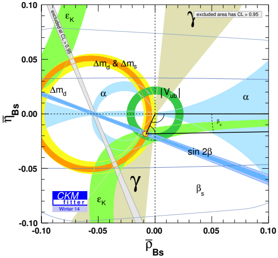


- key features:
  - excellent vertexing (25 tracks: $\sigma_{x,y} = 13\mu$m, $\sigma_z = 71\mu$m)
  - excellent momentum resolution dp/p (from 0.4% to 0.6% at 100 GeV$/c^2$)
  - excellent particle identification capabilities

constraining the CKM matrix at LHCb

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$





[CKMFitter, Moriond 2014]

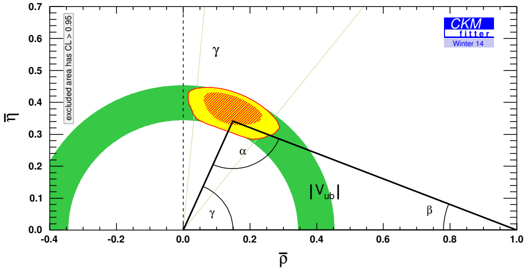
- LHCb is all about B mesons; naturally we measure Δm_d, Δm_s
- LHCb is especially competitive in angles:
  - β_s from $b \to c\bar{c}s$ transitions
    - e.g. $B_s^0 \to J/\psi\phi, J/\psi KK, J/\psi\pi\pi$ (well, $\phi_s = -2\beta_s$ really)

      [Phys. Rev. D 87, 112010 (2013)] [Physics Letters B, 736, (2014) 186]
  - $\sin(2\beta)$ from $B^0 \to J/\psi K_S^0$ [Phys. Lett. B 721 (2013) 24-31]
  - γ from tree-level decays
    - time-integrated: $B \to DX$-type measurements (ADS/GLW & GGSZ methods)
    - time-dependent: $B^0 \to D\pi$, $B_s^0 \to D_s K$

γ measurements

γ measurements

γ measurements: the present



[CKMFitter, Moriond 2014]

- γ is least well measured angle in unitarity triangle
  - needed for New Physics predictions, SM value can be measured from tree-level decays
  - avg. from dir. meas.: $\gamma = (70.0^{+7.7}_{-9.0})^\circ$ (Moriond 2014, prel.)
  - without dir. measurements in fit: $\gamma = (66.4^{+1.2}_{-3.3})^\circ$

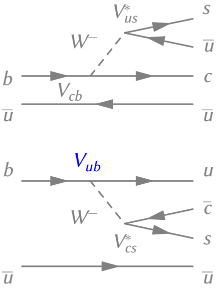
  $\Rightarrow$ still some way to go to bridge "sensitivity gap"

γ measurements from tree decays

- involve measuring interference between two decay paths, one involves V_{ub}, since $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- e.g. “workhorse” of time-integrated γ measurements: $B^- \longrightarrow f_{D^0} K^-$



$$B^- \xrightarrow{A_B} D^0 K^- \xrightarrow{A_D} f_{D^0} K^-$$

$$B^- \xrightarrow{A_B r_B e^{i(\delta_B - \gamma)}} \overline{D^0} K^- \xrightarrow{A_D r_D e^{i\delta_D}} f_{D^0} K^-$$

A_B, A_D: (magnitude of) amplitude(s)

r_B, r_D: suppression factor(s)

δ_B, δ_D: strong phase difference(s)

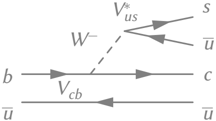
γ from trees: main methods

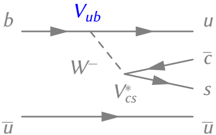
- time-integrated measurement methods
  - GLW ($B^- \rightarrow D^0 h^-$, $D^0 \rightarrow 2-$body CP-eigenstate)
    Gronau, London, Wyler, [Phys. Lett. B 253, 483 (1991), Phys. Lett. B 265, 172 (1991)]
  - ADS ($B^- \rightarrow D^0 h^-$, $D^0 \rightarrow 2-$body CP-non-eigenstate)
    Atwood, Dunietz, Soni [Phys. Rev. Lett. 78, 3257 (1997), Phys. Rev. D 63, 036005 (2001)]
  - GGSZ/Dalitz plot ($B^- \rightarrow D^0 h^-$, $D^0 \rightarrow$ 3-body state)
    Giri, Grossman, Soffer, Zupan [Phys. Rev. D. 68, 054018 (2003)]
    A. Bondar, Proceedings of BINP special analysis meeting on Dalitz analysis, 24.–26. Sep, 2002. Unpublished.
- time-dependent measurement methods, e.g. $B_s \rightarrow D_s K$
  Aleksan, Dunietz, Kayser [Z. Phys. C, 54 (1992), p. 653], Fleischer [Nucl.Phys. B671 (2003) 459-482]

time-integrated γ

time-integrated γ

GGSZ/Dalitz plot method: $D^0 \longrightarrow K^0_S \pi^+ \pi^-$

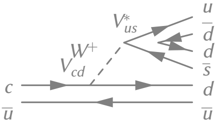


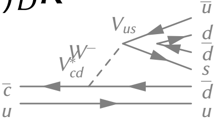


$$B^- \xrightarrow{A_B} D^0 K^- \searrow^{f(m^2_+, m^2_-)}$$

$$(K^0_S \pi^+ \pi^-)_D K^-$$

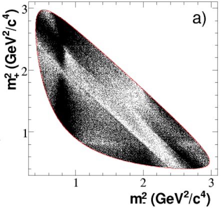
$$B^- \xrightarrow{A_B r_B e^{i(\delta_B - \gamma)}} \overline{D^0} K^- \nearrow_{f(m^2_-, m^2_+)}$$





- D decay amplitude $f(m^2_+, m^2_-)$ depends only on Dalitz variables $m^2_\pm = (p^\mu_{K^0_S} + p^\mu_{\pi^\pm})^2$
- $\Gamma(B^- \longrightarrow (K^0_S\pi^+\pi^-)_D K^-) \sim |f(m^2_+, m^2_-) + r_B e^{i(\delta_B - \gamma)} f(m^2_-, m^2_+)|^2$

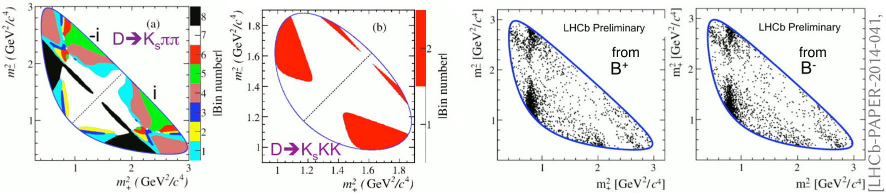
$\Longrightarrow$ need D decay model or measurement of density and phase over Dalitz plot (charm factories)



[Phys.Rev.D78:034023,2008]

- fit for $x_\pm = r_B \cos(\gamma \pm \delta_B)$, $y_\pm = r_B \sin(\gamma \pm \delta_B)$

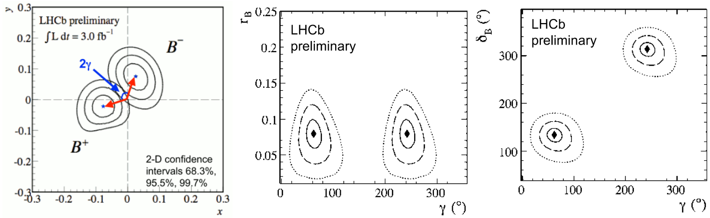
GGSZ: 3 fb^{-1} analysis of $B^- \to D^0(K^0_S hh)K^-$ $(h = \pi, K)$



- get D strong phase in bins from CLEO (c_i, s_i)
- count events in each Dalitz bin ($N_i^{\pm}$)
- check fraction of D in bin i with $B^0 \to D^{*-}\mu^+\nu$ on data, correct with ratio $B^- \to D^0(K^0_S hh)K^- / B^0 \to D^{*-}\mu^+\nu$ from simulation ($f_{\pm i}$)

$$N_i^{\pm} \sim f_{\pm i} + {r_B}^2 f_{\mp i} + 2\sqrt{f_{\pm i} f_{\mp i}}(x_{\pm} c_i \pm y_{\pm} s_i)$$

GGSZ: $3\,\mathrm{fb}^{-1}$ analysis of $B^- \to D^0(K^0_S hh)K^-$ $(h = \pi, K)$



Projection of contours onto 1-D gives 68.3, 95.5,99.7 % CL

Preliminary

[LHCb-PAPER-2014-041, in preparation]

$$x_+ = (-7.7 \pm 2.4 \pm 1.0 \pm 0.4) \cdot 10^{-2} \qquad y_+ = (-2.2 \pm 2.5 \pm 0.4 \pm 1.0) \cdot 10^{-2}$$

$$x_- = (2.5 \pm 2.5 \pm 1.0 \pm 0.5) \cdot 10^{-2} \qquad y_- = (7.5 \pm 2.9 \pm 0.5 \pm 1.4) \cdot 10^{-2}$$

$$r_B = 0.080^{+0.019}_{-0.021} \qquad \gamma = (62^{+15}_{-14})^\circ \qquad \delta_B = (134^{+14}_{-15})^\circ$$

preliminary

- single $3\mathrm{fb}^{-1}$ LHCb measurement as good as B factories or $1\mathrm{fb}^{-1}$ combination of LHCb! BaBar $\gamma = (69^{+17}_{-16})^\circ$, [arXiv:1301.3283]; Belle: $\gamma = (68^{+15}_{-14})^\circ$, [arXiv:1301.2033]; $1\mathrm{fb}^{-1}$ LHCb $B \to DK$ combination: $\gamma = (72^{+15}_{-16})^\circ$, [Phys. Lett. B726 (2013) 151]
- will supersede result with $1\,\mathrm{fb}^{-1}$: $\gamma = (44^{+43}_{-38})^\circ$ (same method, [PLB 718 (2012) 43-55])
- sensitivity: $\sigma(\gamma) \approx 25^\circ\sqrt{\mathrm{fb}^{-1}}$

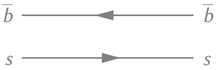
(late breaking news: $1\mathrm{fb}^{-1}$ model-dependent GGSZ: [arXiv:1407.6211])

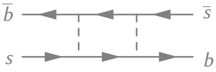
time-dependent γ

time-dependent γ

time-dependent $B_s \longrightarrow D_s K$: basics

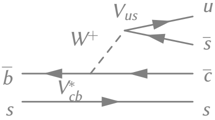
- interference between mixing and decay:

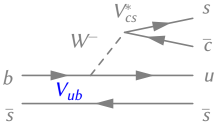




$$B_S^0 \xrightarrow{1} B_S^0 \xrightarrow{A_B} D_S^- K^+$$

$$B_S^0 \xrightarrow[e^{-i\phi m}]{} \overline{B_S^0} \xrightarrow[A_B r_{B_s} e^{i(\delta-\gamma)}]{} D_S^- K^+$$





- not colour-suppressed, both diagrams $\mathcal{O}(\lambda^3_{CKM})$
  $\Rightarrow$ large interference
- weak phases γ, ϕ_m (mixing), strong phase δ
- sensitive to $\gamma + \phi_m$, but ϕ_m small effect [Phys. Rev. D 87, 112010 (2013)]
- measure 4 decay rates:
  $\Gamma_{B_s^0 \longrightarrow D_s^- K^+}(t)$, $\Gamma_{B_s^0 \longrightarrow D_s^+ K^-}(t)$, $\Gamma_{\overline{B_s^0} \longrightarrow D_s^- K^+}(t)$, $\Gamma_{\overline{B_s^0} \longrightarrow D_s^+ K^-}(t)$

$B_s \longrightarrow D_s K$ decay rate equations

- work out decay of B_s^0, $\bar{B}_s^0$ to final states $f(D_s^- K^+)$, $\bar{f}(D_s^+ K^-)$[1]:

$$\lambda_{D_s^- K^+} = \frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*} \frac{V_{ub} V_{cs}^*}{V_{cb}^* V_{us}} \left|\frac{A_{\bar{f}}}{A_f}\right| e^{i\delta} = |\lambda_{D_s^- K^+}| e^{i(\delta-(\gamma+\phi_m))}$$

$$1/\lambda_{D_s^+ K^-} = \frac{V_{tb} V_{ts}^*}{V_{tb}^* V_{ts}} \frac{V_{ub}^* V_{cs}}{V_{cb} V_{us}^*} \left|\frac{A_{\bar{f}}}{A_f}\right| e^{i\delta} = |\lambda_{D_s^- K^+}| e^{i(\delta+(\gamma+\phi_m))}$$

$$C_f = \frac{1-|\lambda_{D_s^- K^+}|^2}{1+|\lambda_{D_s^- K^+}|^2} \qquad A_f^{\Delta\Gamma} = \frac{-2\Re\lambda_{D_s^- K^+}}{1+|\lambda_{D_s^- K^+}|^2} \qquad S_f = \frac{2\Im\lambda_{D_s^- K^+}}{1+|\lambda_{D_s^- K^+}|^2}$$

$$C_{\bar{f}} = \frac{1-|\lambda_{D_s^+ K^-}|^2}{1+|\lambda_{D_s^+ K^-}|^2} \qquad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2\Re\lambda_{D_s^+ K^-}}{1+|\lambda_{D_s^+ K^-}|^2} \qquad S_{\bar{f}} = \frac{2\Im\lambda_{D_s^+ K^-}}{1+|\lambda_{D_s^+ K^-}|^2}$$

$$\frac{d\Gamma_{B_s^0\to f}(t)}{dt\, e^{-\Gamma t}} \sim |A_f|^2(1+|\lambda_f|^2) \left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma t}{2}\right) + C_f\cos(\Delta m t) - S_f\sin(\Delta m t)\right)$$

$$\frac{d\Gamma_{\bar{B}_s^0\to f}(t)}{dt\, e^{-\Gamma t}} \sim |A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2) \left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma t}{2}\right) - C_f\cos(\Delta m t) + S_f\sin(\Delta m t)\right)$$

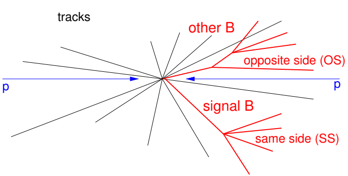
$$\frac{d\Gamma_{\bar{B}_s^0\to \bar{f}}(t)}{dt\, e^{-\Gamma t}} \sim |\bar{A}_{\bar{f}}|^2(1+|\bar{\lambda}_{\bar{f}}|^2) \left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) + A_{\bar{f}}^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma t}{2}\right) - C_{\bar{f}}\cos(\Delta m t) + S_{\bar{f}}\sin(\Delta m t)\right)$$

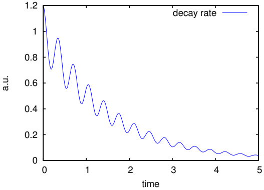
$$\frac{d\Gamma_{B_s^0\to \bar{f}}(t)}{dt\, e^{-\Gamma t}} \sim |\bar{A}_{\bar{f}}|^2\left|\frac{q}{p}\right|^2(1+|\bar{\lambda}_{\bar{f}}|^2) \left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) + A_{\bar{f}}^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma t}{2}\right) + C_{\bar{f}}\cos(\Delta m t) - S_{\bar{f}}\sin(\Delta m t)\right)$$

[1] use convention where $\Delta m_s = m_H - m_L > 0$ and $\Delta\Gamma = \Gamma_L - \Gamma_H > 0$

$B_s \longrightarrow D_s K$ basics

- five parameters in decay rate equations:
  - $A_f^{\Delta\Gamma}$, $A_{\bar{f}}^{\Delta\Gamma}$: sensitive to Γ_s, $\Delta\Gamma_s$, time-dependent efficiency
  - C_f, S_f, $S_{\bar{f}}$: sensitive to oscillations
- need to know flavour at production: to B_s or not to $\overline{B_s}$?
  - b quarks are produced in pairs

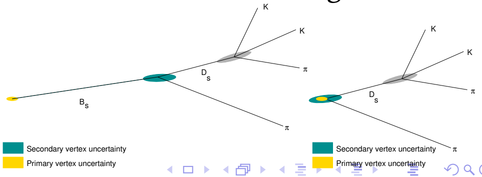




- can tag in $\epsilon_{tag} = 68\%$ of $D_s K$ events, tag wrong in $\langle\eta\rangle = 36\%$

$\rightarrow$ stat. "power" of sample reduced to $\epsilon_{eff.} = \epsilon_{tag}(1-2\eta)^2 = 5.1\%$

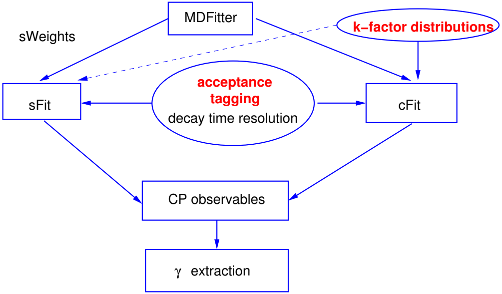
- even more difficult: decay time resolution ”smears out“ signal
- get decay time error estimate from decay time fit
- can check by how much the estimate is "off" in data: "fake B_s candidates"
- have to scale error estimate up by 1.37 ± 0.10



selecting $B_s \to D_s K / D_s \pi$

- hardware trigger: muons or sufficient energy in calorimeter clusters
- software trigger:
  - reconstruct full event (fast reconstruction for the trigger)
  - select significantly displaced 2, 3, 4-prong vertices with high $\sum p_T$
  - use MVA methods to identify b decay vertices
- build decays $D_s^- \to K^- K^+ \pi^-$, $K^- \pi^+ \pi^-$, $\pi^- \pi^+ \pi^-$
- combine with charged K (π) to for B_s
- use a gradient boosted decision tree (BDTG) to suppress combinatorial background
- different D_s decay modes reconstructed with tuned selection cuts to remove/suppress specific physics backgrounds

$B_s^0 \to D_s K$: strategy

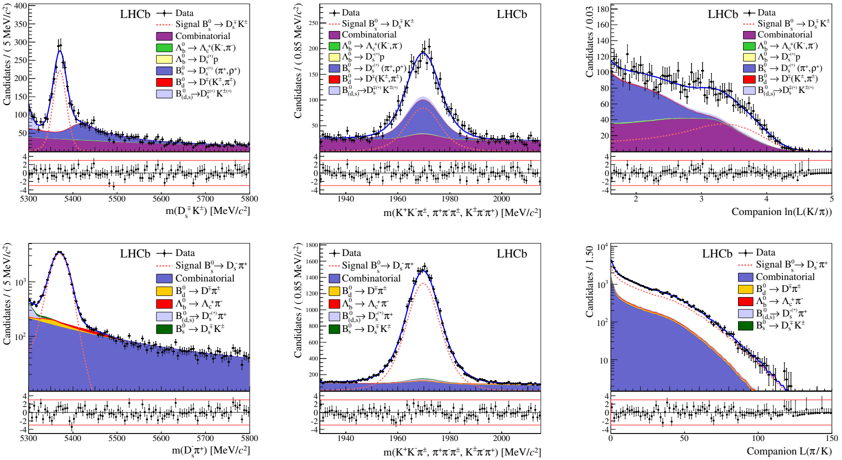


- disentangle signal and background with multidimensional fit (MDFitter, m_{B_s}, m_{D_s}, PID of K)
- two fitter frameworks for the time-dependent part (time, time error, mistag)
  - sFit: uses sWeights to subtract background on a statistical basis
  - cFit: classical fit, all BG described with full physics PDF

$B_s \to D_s K (D_s \pi)$ mass fits

- disentangle signal and background better: use m_{B_s}, m_{D_s}, particle ID

$\rightarrow$ signal yield: 1809 ± 52 $B_s^0 \to D^s K$ candidates in $1\,\mathrm{fb}^{-1}$

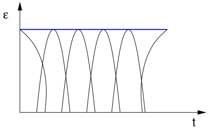


$D_s K$, [arXiv:1407.6127]

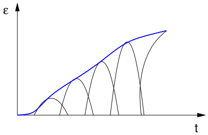
$D_s \pi$, [arXiv:1407.6127]

acceptance

- trigger introduces time-dependent efficiency ("acceptance")
- model it with splines
  - piecewise polynomial, continuous 1st and 2nd derivatives
  - consists of "base" polynomials ("knots"), form partition of unity: $\sum_i b_i(t) = 1$



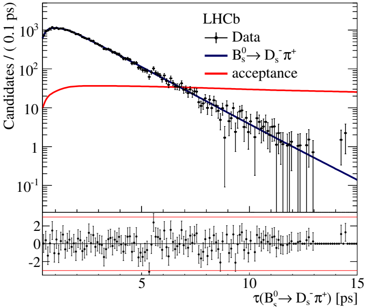
  - varying coefficients allows to approximate arbitrary functions: $\sum_i c_i b_i(t) \approx \epsilon(t)$



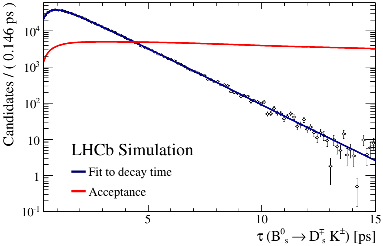
- numerically and technically "well-behaved" (low correlations among c_i)

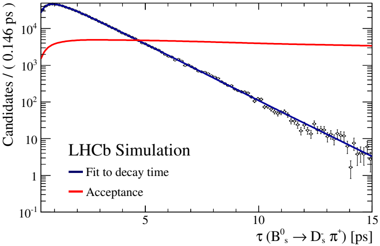
acceptance

- splines to describe acceptance function: analytical integrals make fit fast! [arXiv:1407.0748]
- acceptance from $B_s^0 \to D_s\pi$ control channel
- $D_sK/D_s\pi$ acceptance ratio: use large MC statistics much reduced acceptance systematics!



[arXiv:1407.6127]

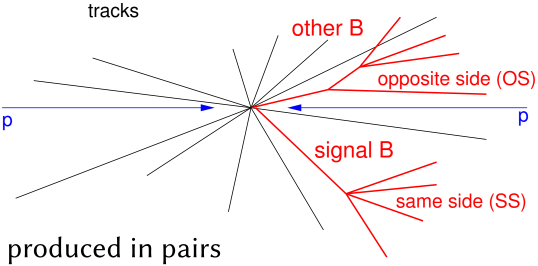




supplementary material for [arXiv:1407.6127]

flavour tagging

- need to know flavour at production: B_s or $\overline{B_s}$?



- b quarks are produced in pairs
- can learn something from other B in the event, or fragmentation: opposite side tagging/same side tagging
  - can "guess" initial flavour $\epsilon_{tag} = 67.5\%$ of $D_s K$ events
  - guess wrong in about $\omega = 36.3\%$ of cases on average
  - effective tagging power $\epsilon(1-2\omega)^2 = 5.07\%$

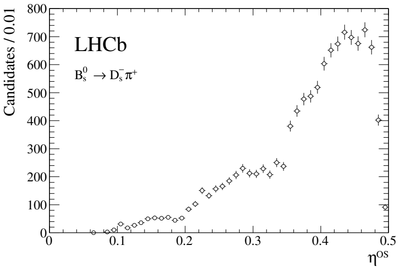
  - use event-by-event mistag prediction to increase sensitivity

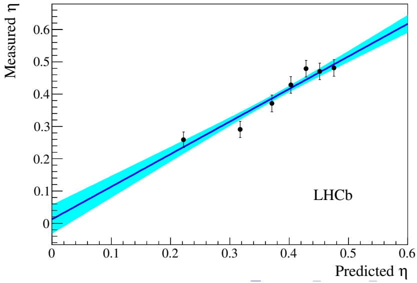
flavour tagging: opposite side tagging

- uses the "other B" in the event (e.g. charged, semileptonic B decays, …)
- tagger estimates mistag rate η for every candidate
- need to calibrate to get true mistag ω:

$$\omega = p_0 + p_1(\eta - \langle\eta\rangle)$$

- use flavour specific/self-tagging modes
- calibration constants p_0, p_1 portable across modes





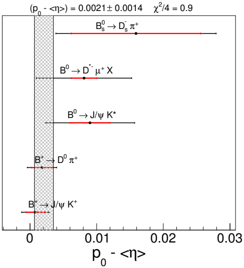
$B_s^0 \to D_s\pi$ candidates
supplementary material for [arXiv:1407.6127]

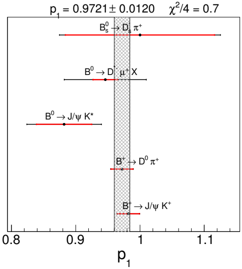
flavour tagging: opposite side tagging

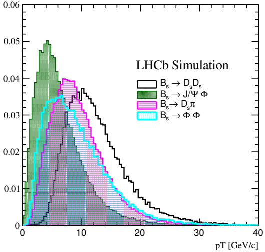
- there are many modes with various amounts of statistics

→ average $p_0 - \langle\eta\rangle$, p_1 across modes

- but: mistag depends on p_T ($nTracks$, azimuthal angle ϕ) of B candidate
  - reweight $P(\eta)$ to p_T distributions of different channels, recalibrate
  - largest difference gives systematic error







flavour tagging: opposite side tagging

- result:
  - vastly improved understanding of opposite side tagger performance
  - smaller stat. error on calibration
  - obtain $\epsilon(1-2\omega)^2 = 2.7\%$

Control channel	$\langle\eta\rangle$	$p_0 - \langle\eta\rangle$	p_1
$B^+ \to J/\psi K^+$	0.3919	$0.0008 \pm 0.0014 \pm 0.0015$	$0.982 \pm 0.017 \pm 0.005$
$B^+ \to \bar{D}^0 \pi^+$	0.3836	$0.0018 \pm 0.0016 \pm 0.0015$	$0.972 \pm 0.017 \pm 0.005$
$B^0 \to J/\psi K^{*0}$	0.390	$0.0090 \pm 0.0030 \pm 0.0060$	$0.882 \pm 0.043 \pm 0.039$
$B^0 \to D^{*-} \mu^+ \nu_\mu$	0.3872	$0.0081 \pm 0.0019 \pm 0.0069$	$0.946 \pm 0.019 \pm 0.061$
$B_s^0 \to D_s \pi$	0.3813	$0.0159 \pm 0.0097 \pm 0.0071$	$1.000 \pm 0.116 \pm 0.047$
Average	0.3813	$0.0021 \pm 0.0014 \pm 0.0040$	$0.972 \pm 0.012 \pm 0.035$

[arXiv:1407.6127]

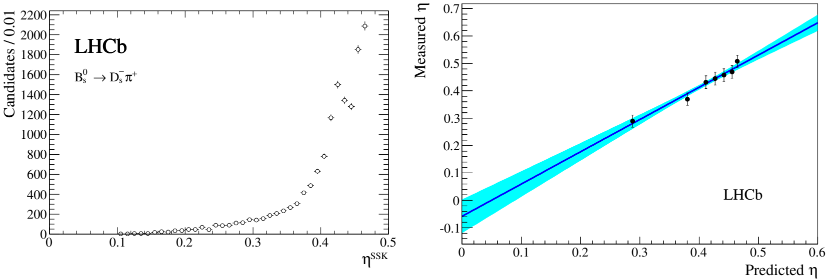
flavour tagging: same side kaon tagging

- use the fragmentation of the other strange quark in the $s\bar{s}$ quark pair that makes the B_s^0

$\rightarrow$ additional tagger added to analysis

- new development: use two neural nets (NNet):
  - first NNet provides fragmentation track candidate(s)
  - second NNet gives mistag estimate η
- $\epsilon = 47.7\%$, $\epsilon(1-2\omega)^2 = 2.1\%$

$\Longrightarrow$ combine OS + SSK taggers: $\varepsilon_{comb.} = 67.5\%$, $\epsilon(1-2\omega)^2 = 5.07\%$



$B_s^0 \to D_s\pi$ candidates

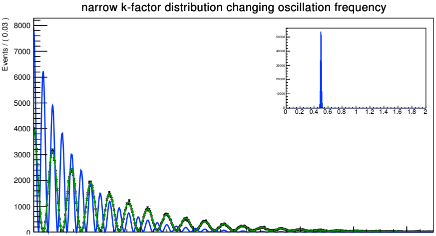
supplementary material for [arXiv:1407.6127]

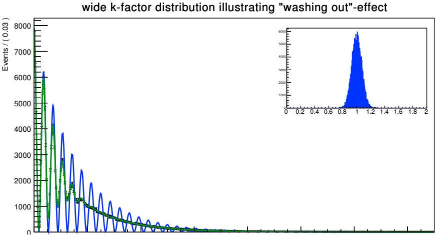
k-factors (1/2)

- lifetime is calculated along the lines of $t = |\vec{x}_{SV} - \vec{x}_{PV}| \frac{m_{B_s}}{|\vec{p}|}$
- for partially reconstructed and misid'ed modes, we get $\frac{m_{B_s}}{|\vec{p}|}$ wrong
- idea: take correction factor from MC:

$$k = \frac{(m_{B_s}/|\vec{p}|)_{true}}{(m_{B_s}/|\vec{p}|)_{reco}}$$

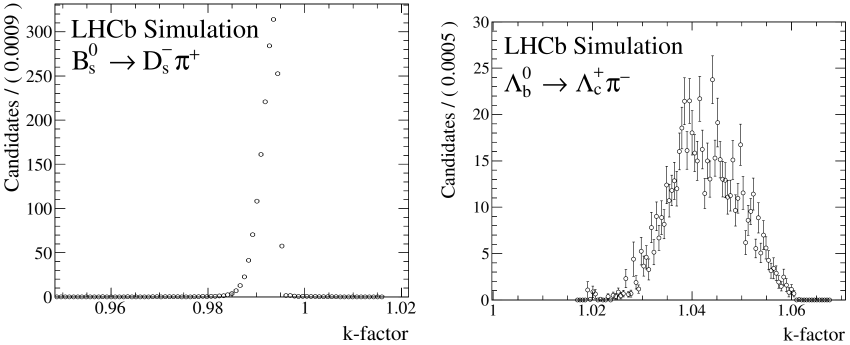
- can correct by substitution $t \longrightarrow k \cdot t$





toy simulation, demonstrating effect

k-factors (2/2)



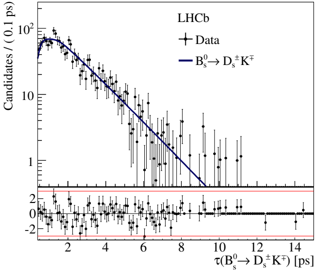
supplementary material for [arXiv:1407.6127]

- put into generator(s) for $D_s K/\pi$ (toy simulation)
- can also use it in cFit to get the BG description correct:

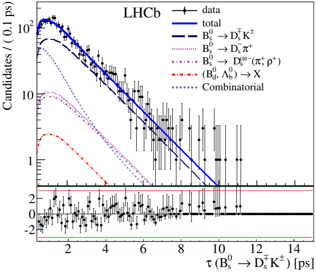
$$\frac{d\Gamma}{dt}(t; \Gamma, \Delta\Gamma, \Delta m) \longrightarrow \int k dk\, P(k) \cdot \frac{d\Gamma}{dt}(t; k\Gamma, k\Delta\Gamma, k\Delta m)$$

$B_s \to D_s K$ time fit

- for sFit: backgrounds subtracted with sWeights ($5300 < m_{B_s}/\text{MeV} < 5800$)
- for cFit: full description of partially reconstructed/misid. BGs ($5320 < m_{B_s}/\text{MeV} < 5420$)
  - use yields/shapes from MDFitter
  - reconstructed time off by $(m/p)_{reco}/(m/p)_{true}$)
  - use k-factor correction (from simulation)



sFit



cFit

[arXiv:1407.6127]

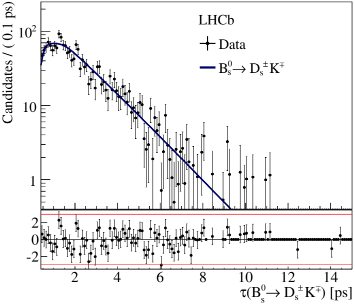
$B_s \to D_s K$ time fit

- fixed parameters:

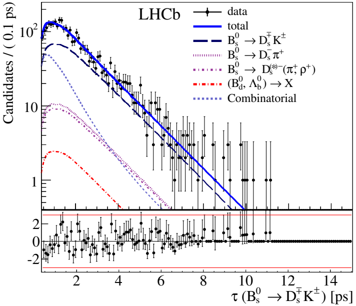
$$\Gamma_s = 0.661 \pm 0.007\,\text{ps}^{-1}\,, \qquad \Delta\Gamma_s = 0.106 \pm 0.013\,\text{ps}^{-1}$$
$$\rho(\Gamma_s, \Delta\Gamma_s) = -0.39\,,$$
$$\Gamma_{\Lambda_b} = 0.676 \pm 0.006\,\text{ps}^{-1}\,, \qquad \Gamma_d = 0.658 \pm 0.003\,\text{ps}^{-1}$$
$$\Delta m_s = 17.768 \pm 0.024\,\text{ps}^{-1}\,.$$

- constrained parameters (in cFit per signal/background component):
  - tagging calibration parameters
  - tagging asymmetries
  - detection/production asymmetries ($(1 \pm 0.5)\%/0 \pm 1\%$ (mesons), prod. $0 \pm 3\%$ for Λ_b)

$B_s \to D_s K$ time fit



sFit



cFit

[arXiv:1407.6127]

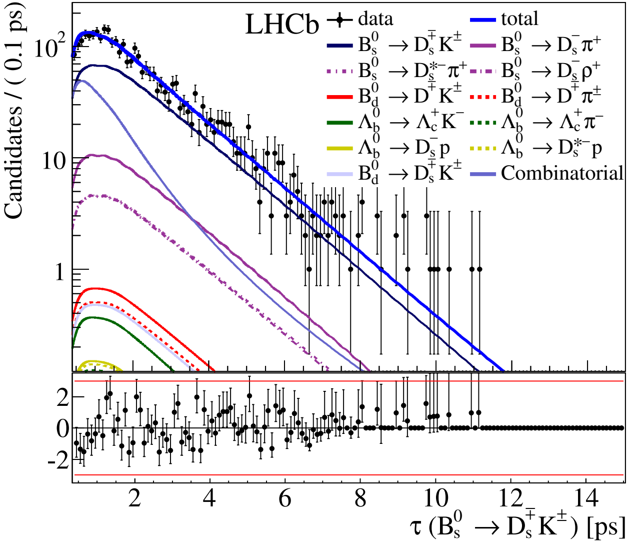
$$C_f = 0.52 \pm 0.25 \pm 0.04$$
$$A_f^{\Delta\Gamma} = 0.29 \pm 0.42 \pm 0.17$$
$$A_{\bar{f}}^{\Delta\Gamma} = 0.14 \pm 0.41 \pm 0.18$$
$$S_f = -1.09 \pm 0.31 \pm 0.06$$
$$S_{\bar{f}} = -0.36 \pm 0.34 \pm 0.06$$

$$C_f = 0.53 \pm 0.25 \pm 0.04$$
$$A_f^{\Delta\Gamma} = 0.37 \pm 0.42 \pm 0.20$$
$$A_{\bar{f}}^{\Delta\Gamma} = 0.20 \pm 0.41 \pm 0.20$$
$$S_f = -1.09 \pm 0.33 \pm 0.08$$
$$S_{\bar{f}} = -0.36 \pm 0.34 \pm 0.08$$

[arXiv:1407.6127]

$\Longrightarrow$ excellent agreement between both fitters

$B_s \to D_s K$ time cFit: all backgrounds



supplementary material for [arXiv:1407.6127]

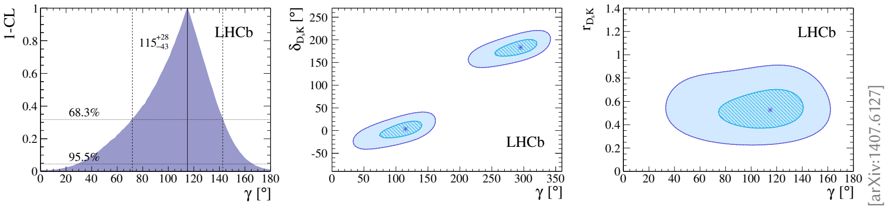
systematics

- fixed parameters, acceptance: from large scale studies with pseudo-experiments
- check also by splitting sample into:
  - magnet up/down
  - hardware trigger on signal/independent of signal
  - high/low BDT response
- expressed as fraction of stat. uncertainties

Parameter		C	$A_f^{\Delta\Gamma}$	$A_{\bar{f}}^{\Delta\Gamma}$	S_f	$S_{\bar{f}}$
cFit	Δm_s	0.068	0.014	0.011	0.131	0.126
	scale factor	0.131	0.004	0.004	0.101	0.103
	$\Delta\Gamma_s$	0.008	0.265	0.274	0.009	0.008
	Γ_s	0.049	0.395	0.394	0.048	0.042
	acceptance, Γ_s, $\Delta\Gamma_s$	0.050	0.461	0.464	0.050	0.043
	comb. bkg. lifetime	0.016	0.069	0.072	0.015	0.005
	sample splits	0.102	0.000	0.000	0.156	0.151
	total	0.187	0.466	0.470	0.234	0.226

[arXiv:1407.6127]

extracting γ from $B_s \to D_s K$



- extract γ based on cFit results

$$\gamma = (115^{+28}_{-43})^\circ \quad \delta = (3^{+19}_{-20})^\circ \quad r_{D_sK} = 0.53^{+0.17}_{-0.16}$$

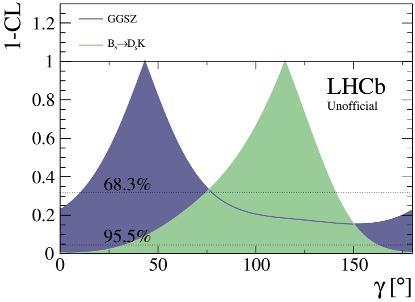
- sensitivity: $\sigma(\gamma) \approx 36^\circ \sqrt{\text{fb}^{-1}}$

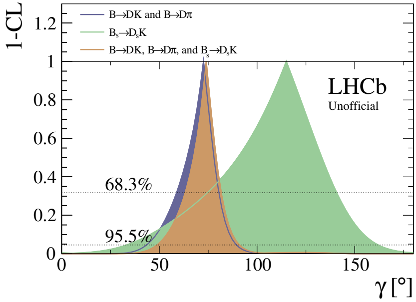
$\to$ competitive!

- plan to add more final states for 3fb^{-1}, also with neutrals like $B_s^0 \to D_s^*(D_s\gamma)K$

extracting γ from $B_s \to D_s K$

- how does this compare to other modes (for $1\,\mathrm{fb}^{-1}$ of data)?
- for illustration, will show some utterly unofficial plots (until the next LHCb-wide combination comes out)
- left: constraint on γ comparable to GGSZ, $D_s K$ is powerful
- right: utterly unofficial combination of $1\,\mathrm{fb}^{-1}$ results





conclusion

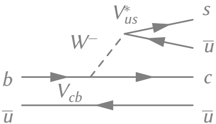
- LHCb offers a multitude of ways (and channels) to measure γ
- increasing precision of direct γ measurements provides ever more stringent tests of the Standard Model
- run 1 of the LHC was exciting, and many good results are out
  - first results for γ from the full 2011+2012 data set
  - first measurement $\gamma = (115^{+28}_{-43})^\circ$ from $B_s^0 \to D_s K$
- for the future:
  - more γ sensitive measurements will be updated to the full 3fb^{-1}
  - expect new LHCb γ combination in the coming months
  - improve sensitivity by adding new final states to analyses
  - run 2 and the LHCb upgrade are ahead!

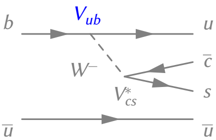
$\rightarrow$ LHCb is a versatile tool to constrain the CKM matrix, especially γ, and exciting times are ahead!

backup slides

backup slides

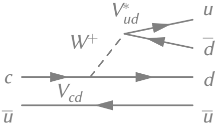
GLW method: D to CP eigenstate ($\pi^+\pi^-$ or K^+K^-)

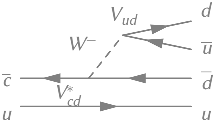




$$B^- \xrightarrow{A_B} D^0 K^- \xrightarrow{A_D} (\pi^+\pi^-)_{D^0} K^-$$

$$B^- \xrightarrow{A_B r_B e^{i(\delta_B - \gamma)}} \overline{D^0} K^- \xrightarrow{A_D} (\pi^+\pi^-)_{D^0} K^-$$

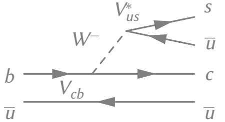


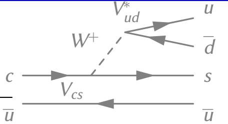


- $\Gamma(B^\mp \longrightarrow (\pi^+\pi^-)_{D^0} K^\mp) \sim 1 + r_B^2 + 2 r_B \cos(\delta_B \mp \gamma)$
- 2 observables:
  - $A_{CP+} = \frac{\Gamma(B^- \longrightarrow (\pi^+\pi^-)_{D^0} K^-) - \Gamma(B^+ \longrightarrow (\pi^+\pi^-)_{D^0} K^+)}{\Gamma(B^- \longrightarrow (\pi^+\pi^-)_{D^0} K^-) + \Gamma(B^+ \longrightarrow (\pi^+\pi^-)_{D^0} K^+)} = \frac{2 r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2 r_B \cos\delta_B \cos\gamma}$
  - $R_{CP+} = 2 \frac{\Gamma(B^- \longrightarrow (\pi^+\pi^-)_{D^0} K^-) + \Gamma(B^+ \longrightarrow (\pi^+\pi^-)_{D^0} K^+)}{\Gamma(B^- \longrightarrow D^0 K^-) + \Gamma(B^+ \longrightarrow \overline{D^0} K^+)} =$
    $1 + r_B^2 + 2 r_B \cos\delta_B \cos\gamma$
- 3 unknowns (r_B, δ_B, γ)

  $\Longrightarrow$ need to combine with other method(s)

ADS method: $D^0 \longrightarrow K\pi$



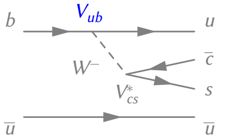


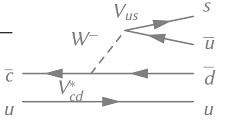
$$B^- \xrightarrow{A_B} D^0 K^- \xrightarrow{A_D} (K^-\pi^+)_D K^-$$

$A_D r_D e^{-i\delta_D^{K\pi}}$

$$B^- \longrightarrow \overline{D^0} K^- \longrightarrow (K^+\pi^-)_D K^-$$

$A_B r_B e^{i(\delta_B-\gamma)}$ $\quad A_D$





- 4 decay rates:
  - $\Gamma(B^\mp \longrightarrow (K^\mp\pi^\pm)_{D^0} K^\mp) \sim 1 + (r_B r_D)^2 + 2 r_B r_D \cos(\delta_B - \delta_D^{K\pi} \mp \gamma)$
  - $\Gamma(B^\mp \longrightarrow (K^\pm\pi^\mp)_{D^0} K^\mp) \sim r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D^{K\pi} \mp \gamma)$
- 2 observables:
  - $A_{ADS} = \frac{\Gamma(B^-\to(K^+\pi^-)_{D^0}K^-)-\Gamma(B^+\to(K^-\pi^+)_{D^0}K^+)}{\Gamma(B^-\to(K^+\pi^-)_{D^0}K^-)+\Gamma(B^+\to(K^-\pi^+)_{D^0}K^+)} = \frac{2r_Br_D\sin(\delta_B+\delta_D^{K\pi})\sin\gamma}{r_B^2+r_D^2+2r_Br_D\cos(\delta_B+\delta_D^{K\pi})\cos\gamma}$
  - $R_{ADS} = \frac{\Gamma(B^-\to(K^+\pi^-)_{D^0}K^-)-\Gamma(B^+\to(K^-\pi^+)_{D^0}K^+)}{\Gamma(B^-\to(K^-\pi^+)_{D^0}K^-)+\Gamma(B^+\to(K^+\pi^-)_{D^0}K^+)} = r_B^2+r_D^2+2r_Br_D\cos(\delta_B+\delta_D^{K\pi})\cos\gamma$
- 3 unknowns shared with GLW (r_B, δ_B, γ), 2 new ones $(r_D, \delta_D^{K\pi})$

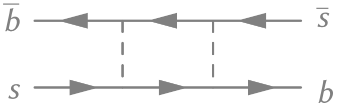
$\Longrightarrow$ need input on $r_D, \delta_D^{K\pi}$, and combine with other method(s)

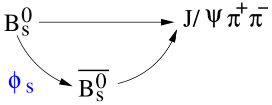
ADS/GLW/GGSZ measurements at LHCb

- LHCb has a wide variety of ADS/GLW measurements:
  - classic ADS/GLW: $B^- \to D^0 h^-$ ($h = \pi, K$, $D^0 \to K^+K^-, \pi^+\pi^-, K^\mp\pi^\pm$) [1203.3662]
  - ADS $B^- \to D^0 h^-$ ($h = \pi, K$, $D^0 \to K^\pm\pi^\mp\pi^+\pi^-, \pi^\pm K^\mp\pi^+\pi^-$) [1303.4646]
  - ADS/GLW $B^0 \to D^0 K^{*0}$ ($D^0 \to K^+K^-, K^\mp\pi^\pm$) [1212.5205]
  - ADS/GLW $B^- \to D^0 K^-\pi^+\pi^-$ ($D^0 \to K^-\pi^+, K^+K^-, \pi^+\pi^-$) [LHCb-CONF-2012-021]
  - ADS/GLW $B^- \to D^0 h^-\pi^+\pi^-$ ($h = K, \pi$, $D^0 \to K^+K^-, \pi^+\pi^-, K^\mp\pi^\pm$) (in preparation)
- GGSZ measurement efforts are gaining momentum, too…
  - classic $B^- \to D^0(K^0_s h^+h^-)K^-$ ($h = K, \pi$) [1209.5869], [LHCb-CONF-2013-004]
  - $B^- \to D^0(K^0_s h^+h^-)h^-\pi^+\pi^-$ ($h = K, \pi$) (in preparation)

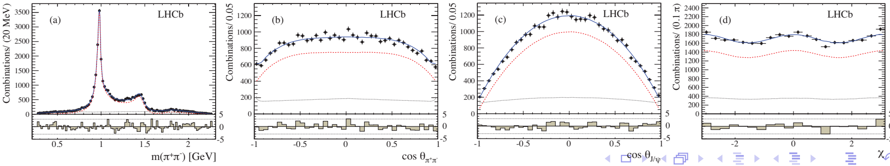
news from β_s

- took $3\,\text{fb}^{-1}$ of data during run 1, results becoming available
- example: $B_s^0 \to J/\psi\pi^+\pi^-$ [arXiv:1405.4140]



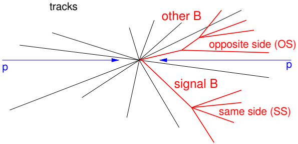


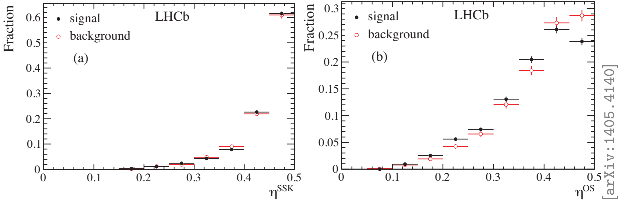
- sensitive to mixing phase ϕ_s — assuming no penguin pollution, $\phi_s = -2\beta_s$
- fully tagged analysis
- $\pi^+\pi^-$ spectrum contains different contributions, so need
  - modelling in $m_{\pi^+\pi^-}$
  - full angular analysis to disentangle different angular momentum contributions

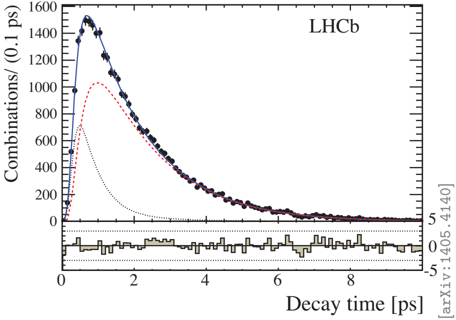


[arXiv:1405.4140]

news from β_s







- improved tagging:
  - ϵ =tagged canditates/all = (68.68±0.33)%
  - mistag rate η, dilution $D = 1 - 2\eta$
  - ⇒ OS+SSK combined give $\epsilon D^2 = (3.89 \pm 0.25)\%$
- $\phi_s = (70 \pm 68 \pm 8)$ mrad (allowing for direct CPV)
- eager to see $B_s^0 \to J/\psi\phi$ (to be released in the coming months)

γ combination: $B^\pm \to DK^\pm$ incl. 2012 data

LHCb γ combination:
$B^\pm \to DK^\pm$ combination
including 2012 data

γ combination: approach

- use various (fit) parameters α_i:

$B^{\pm} \to Dh^{\pm}$	CP-violating weak phase	γ
	$\Gamma(B^- \to D^0 K^-)/\Gamma(B^- \to D^0 \pi^-)$	R_{cab}
$B^{\pm} \to D\pi^{\pm}$	$A(B^- \to \overline{D^0}\pi^-)/A(B^- \to D^0\pi^-) = r_B^{\pi} e^{i(\delta_B^{\pi} - \gamma)}$	$r_B^{\pi}, \delta_B^{\pi}$
$B^{\pm} \to DK^{\pm}$	$A(B^- \to \overline{D^0}K^-)/A(B^- \to D^0 K^-) = r_B e^{i(\delta_B - \gamma)}$	r_B, δ_B
$D \to K^{\pm}\pi^{\mp}$	$A(D^0 \to \pi^- K^+)/A(D^0 \to K^-\pi^+) = r_{K\pi} e^{-i\delta_{K\pi}}$	$r_{K\pi}, -\delta_{K\pi}$
$D \to K^{\pm}\pi^{\mp}\pi^+\pi^-$	amplitude ratio and effective strong phase diff.	$r_{K3\pi}, -\delta_{K3\pi}$
	coherence factor	$\kappa_{K3\pi}$
direct CP	in $D \to K^+K^-$	$A_{CP}^{D\to KK}$
asymmetries	in $D \to \pi^+\pi^-$	$A_{CP}^{D\to\pi\pi}$
Other D system	D mixing	x_D, y_D
parameters	Cabibbo-favoured rates	$\Gamma(D \to K\pi)$
		$\Gamma(D \to K\pi\pi\pi)$

- frequentist approach:
  - express various observables $\vec{A}_i$ in terms of fit parameters
  - use a χ^2-derived likelihood contribution f_i for the various measurements

$$f_i \propto \exp\left(-\chi^2\right) \propto \exp\left(-(\vec{A}_i(\vec{\alpha}_i) - \vec{A}_{i,\text{obs}})^T V_i^{-1} (\vec{A}_i(\vec{\alpha}_i) - \vec{A}_{i,\text{obs}})\right)$$

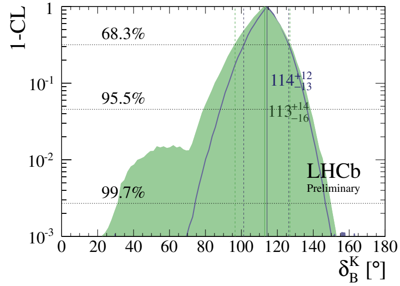
  - then combine:

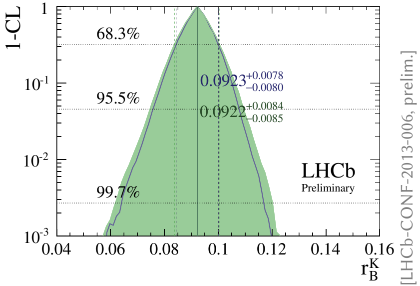
$$\mathcal{L}(\vec{\alpha}) = \prod_i f_i(\vec{A}_i^{\text{obs}} | \vec{A}_i(\vec{\alpha}_i))$$

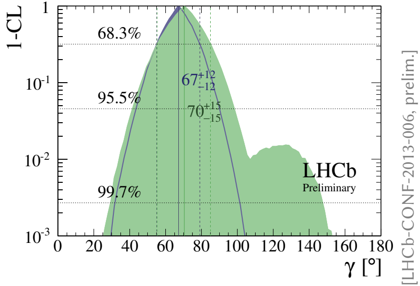
inputs

- LHCb GGSZ model-independent measurement $B^{\pm} \to DK^{\pm}$ with $D \longrightarrow K^0_S h^+ h^-$ ($1\,\text{fb}^{-1}$, 2011) [Phys. Lett. B 718 (2012) 43-55]
  - strong phase of D decay over Dalitz plane taken from CLEO [arXiv:0903.1681]
  - inputs: $x_{\pm}$, $y_{\pm}$
- GLW/ADS modes $B^{\pm} \to DK^{\pm}$ with $D \longrightarrow h^+ h^-$ ($1\,\text{fb}^{-1}$, 2011) [Phys. Lett. B712 (2012) 203] [arXiv:1203.3662]
  - inputs: $A_K^{K\pi}$, A_K^{KK}, $A_K^{\pi\pi}$, R_K^-, R_K^+
- ADS modes $B^{\pm} \to DK^{\pm}$ with $D \longrightarrow K^{\pm}\pi^{\mp}\pi^+\pi^-$ ($1\,\text{fb}^{-1}$, 2011) [LHCb-CONF-2012-030]
  - strong phase variation over D phase space absorbed in coherence factor $\kappa_{K3\pi}$
  - inputs: $A_K^{K3\pi}$, $R_{K-}^{K3\pi}$, $R_{K+}^{K3\pi}$
- LHCb GGSZ model-independent measurement $B^{\pm} \to DK^{\pm}$ with $D \longrightarrow K^0_S h^+ h^-$ ($2\,\text{fb}^{-1}$, 2012) [LHCb-CONF-2013-004]

$B^{\pm} \to DK^{\pm}$ results: r_B, δ_B, γ





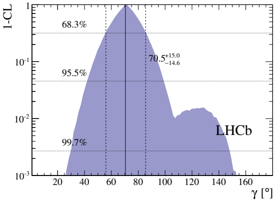


	best fit	68% CL	95% CL
δ_B	114.3°	[101.3, 126.3]°	[88.7, 136.3]°
r_B	0.09223	[0.0843, 0.1001]	[0.0762, 0.1075]
γ	67.2°	[55.1, 79.1]°	[43.9, 89.5]°

- 2011 $B^{\pm} \to DK^{\pm}$ combination
- 2011+2012 $B^{\pm} \to DK^{\pm}$ combination

$\Longrightarrow \gamma = (67 \pm 12)^{\circ}$

plug-in method



[LHCb-PAPER-2013-020, in prep.]

- evaluating confidence level for a parameter (e.g. γ), we use $\chi^2(\vec{\alpha}) = -2\log\mathcal{L}(\vec{\alpha})$
- call best fit point $\vec{\alpha}_{\text{min}}$, $\chi^2_{\text{min}} = \chi^2(\vec{\alpha}_{\text{min}})$
- call best fit point $\vec{\alpha}'_{\text{min}}(\gamma_0)$ with γ fixed to $\gamma = \gamma_0$
  - get profile LH $\hat{\mathcal{L}}(\gamma_0) = \exp(-\chi^2(\vec{\alpha}'_{\text{min}})/2)$
- for each value of γ_0, get p-value (1-CL) with a MC procedure:
  1. calculate test statistic $\Delta\chi^2 = \chi^2(\vec{\alpha}'_{\text{min}}) - \chi^2(\vec{\alpha}_{\text{min}}) \geq 0$ for data
  2. generate a set of toys $\vec{A}_{\text{toy}}$ with parameters set to $\vec{\alpha}'_{\text{min}}$
  3. for each toy, calculate $\Delta\chi^{2'}$ as in step 1
  4. $1 - CL = N(\Delta\chi^2 < \Delta\chi^{2'})/N_{\text{toy}}$

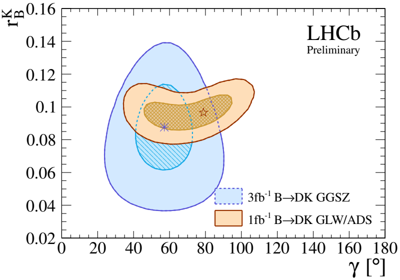
systematic uncertainties

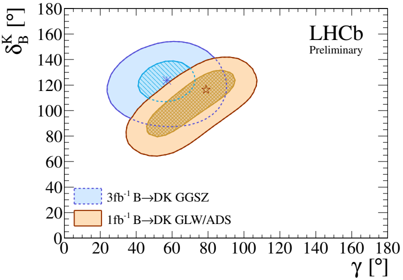
- plots and confidence limits above need to be corrected for
  - undercoverage
    - plug-in method does not guarantee coverage
    - evaluate actual coverage using toys: determine conf. intervals in toys, count how often the true value is inside

α	1σ ($\eta = 0.6827$)	2σ ($\eta = 0.9545$)	3σ ($\eta = 0.9973$)
$DK^{\pm}$ only	0.6646 ± 0.0067	0.9453 ± 0.0032	0.9911 ± 0.0013
$D\pi^{\pm}$ only	0.6532 ± 0.0048	0.9492 ± 0.0022	0.9912 ± 0.0009
$DK^{\pm}$ & $D\pi^{\pm}$	0.6616 ± 0.0067	0.9586 ± 0.0028	0.9958 ± 0.0009

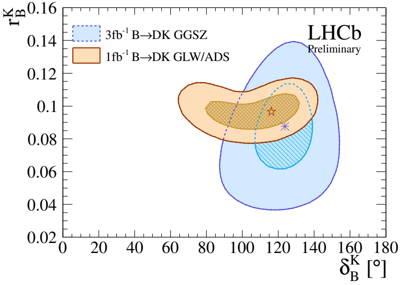
    - scale up conf. intervals in data by η/α
  - correlations in systematic uncertainties for 2/4-body GLW/ADS modes
    - plots below assume zero correlations
    - need to correct by running toys with random correlation matrices
    - $B^{\pm} \to DK^{\pm}$ unaffected, $B^{\pm} \to D\pi^{\pm}$ largely affected
    - full combination needs confidence intervals scaled by a factor 1.07 (1.04 for second best intervals)

$B^\pm \to DK^\pm$: contours





[LHCb-CONF-2013-006, prelim.]



[LHCb-CONF-2013-006, prelim.]

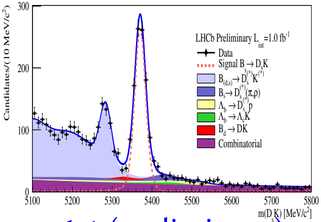
- blue: GGSZ ($3\,\text{fb}^{-1}$)
- orange: ADS/GLW ($1\,\text{fb}^{-1}$)
- stars, crosses: local minima

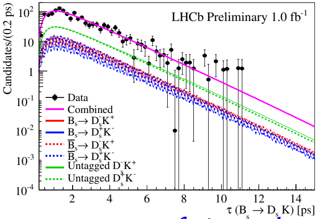
time-dependent $B_s \to D_s K$

time-dependent $B_s \to D_s K$

$B_s^0 \to D_s K$: results from 2012 CONF

- to get things right, you need to understand:
  - backgrounds
  - acceptance $\epsilon(t)$: else $A_f^{\Delta\Gamma}$, $A_{\bar{f}}^{\Delta\Gamma}$ biased
  - decay time resolution σ_t: else C_f, S_f, $S_{\bar{f}}$ biased
  - flavour tagging (produced as $B_s^0/\overline{B}_s^0$): else C_f, S_f, $S_{\bar{f}}$ biased
- here's our preliminary result (2011 data, $1\,fb^{-1}$)





$$C_f = 1.01 \pm 0.50 \pm 0.23$$
$$S_f = -1.25 \pm 0.56 \pm 0.24$$
$$S_{\bar{f}} = -0.08 \pm 0.68 \pm 0.28$$
$$A_f^{\Delta\Gamma} = 1.33 \pm 0.60 \pm 0.26$$
$$A_{\bar{f}}^{\Delta\Gamma} = 0.81 \pm 0.56 \pm 0.26$$

[LHCb-CONF-2012-029]

- 1st (preliminary) measurement of time-dependent CP parameters in $B_s \to D_s K$
- if you were to extract γ, you'd get $\sigma_\gamma \sim 60^\circ$ (don't do it, you need both stat. and syst. correlations, and even we don't have the syst. ones!)

systematics

- fixed parameters, acceptance: from large scale studies with pseudo-experiments
- check also by splitting sample into:
  - magnet up/down
  - hardware trigger on signal/independent of signal
  - high/low BDT response
- expressed as fraction of stat. uncertainties

Parameter		C	$A_f^{\Delta\Gamma}$	$A_{\bar{f}}^{\Delta\Gamma}$	S_f	$S_{\bar{f}}$
sFit	Δm_s	0.062	0.013	0.013	0.104	0.100
	scale factor	0.104	0.004	0.004	0.092	0.096
	$\Delta\Gamma_s$	0.007	0.261	0.286	0.007	0.007
	Γ_s	0.043	0.384	0.385	0.039	0.038
	acceptance, Γ_s, $\Delta\Gamma_s$	0.043	0.427	0.437	0.039	0.038
	sample splits	0.124	0.000	0.000	0.072	0.071
	total	0.179	0.427	0.437	0.161	0.160

[arXiv:1407.6127]