Time-dependent amplitude analysis of $B_s \to D_s K \pi \pi$ at LHCb

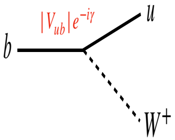
Physics at the Terascale Workshop, DESY Hamburg

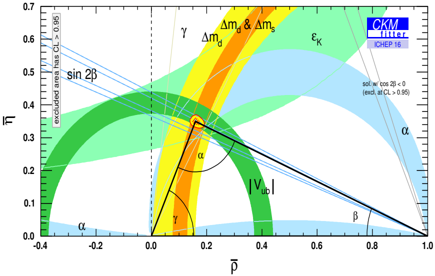
P. d'Argent[1]

[1]Physikalisches Institut Heidelberg

26.11.2018

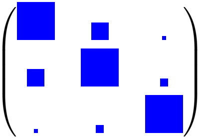
CKM Matrix



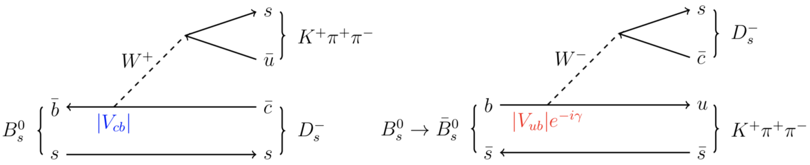


- Quark transitions are described by CKM matrix
- Complex elements are **only** source of CPV in SM
- **Key test** of the SM: Verify unitarity

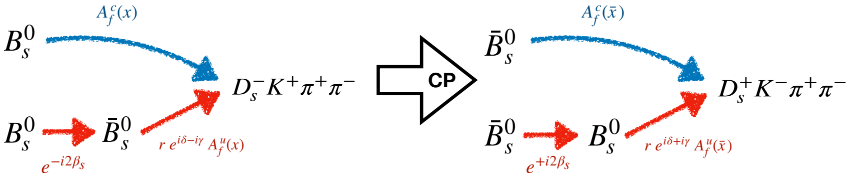
$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} =$$



CKM γ from $B_s \to D_s K\pi\pi$



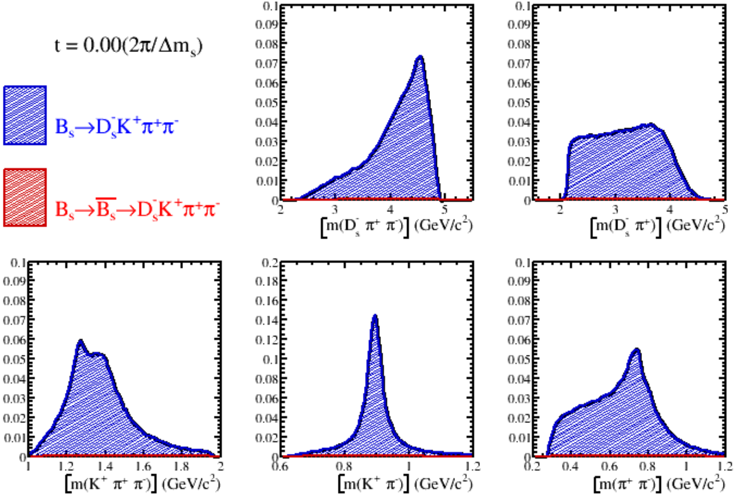
- Close sensitivity gap:
  Direct measurement: $\gamma = (73.5^{+4.3}_{-5.7})^\circ$
  Indirect measurement: $\gamma = (65.3^{+1.0}_{-2.5})^\circ$ (CKM fit)
- Exploit interference between $b \to c$ and $b \to u$ transitions achieved through $B_s - \bar{B}_s$ mixing
- Both processes are similar suppressed $\Rightarrow$ Expect large interference !



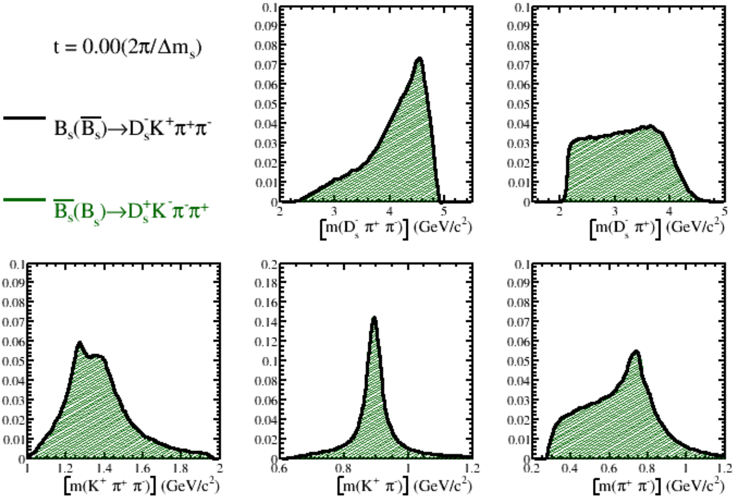
Full time-dependent amplitude PDF:

$$\begin{aligned}\frac{d\Gamma(x,t)}{e^{-\Gamma_s t}\, dt\, d\Phi_4} \propto & \left(|\mathcal{A}_f^c(x)|^2 + r^2\, |\mathcal{A}_f^u(x)|^2\right) \cosh\left(\frac{\Delta\Gamma_s\, t}{2}\right) \\ & + q\, f\, \left(|\mathcal{A}_f^c(x)|^2 - r^2\, |\mathcal{A}_f^u(x)|^2\right) \cos\left(\Delta m_s\, t\right) \\ & - 2\mathrm{Re}\left(\mathcal{A}_f^c(x)^*\, r\, \mathcal{A}_f^u(x)\, e^{i\delta - if(\gamma - 2\beta_s)}\right) \sinh\left(\frac{\Delta\Gamma_s\, t}{2}\right) \\ & - 2\, q\, f\, \mathrm{Im}\left(\mathcal{A}_f^c(x)^*\, r\, \mathcal{A}_f^u(x)\, e^{i\delta - if(\gamma - 2\beta_s)}\right) \sin\left(\Delta m_s\, t\right)\end{aligned}$$

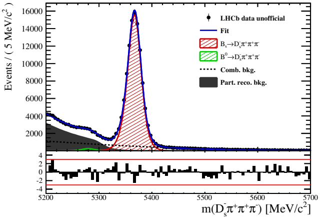
$q = +1, 0, -1$ for a B_s^0, no-, $(\bar{B}_s^0)$ tag
$f = +1(-1)$ for $D_s^- K^+ \pi\pi$ $(D_s^+ K^- \pi\pi)$ final states.

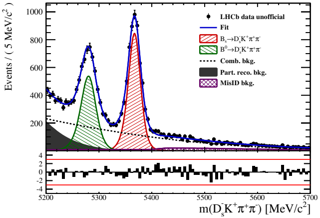


t = 0.00(2π/Δm_s)
B_s→D_s^- K^+π^+π^-
B_s→B̄_s→D_s^- K^+π^+π^-
[m(D_s^- π^+ π^-)] (GeV/c^2)
[m(D_s^- π^+)] (GeV/c^2)
[m(K^+ π^+ π^-)] (GeV/c^2)
[m(K^+ π^-)] (GeV/c^2)
[m(π^+ π^-)] (GeV/c^2)



t = 0.00(2π/Δm_s)
B_s(B̄_s)→D_s^- K^+π^+π^-
B̄_s(B_s)→D_s^+ K^-π^-π^+
[m(D_s^- π^+ π^-)] (GeV/c^2)
[m(D_s^- π^+)] (GeV/c^2)
[m(K^+ π^+ π^-)] (GeV/c^2)
[m(K^+ π^-)] (GeV/c^2)
[m(π^+ π^-)] (GeV/c^2)





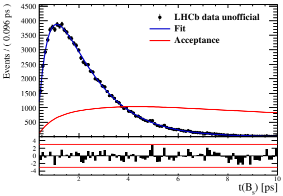
- Using Run-1 and 15/16/17 LHCb data ($\approx 7\ \text{fb}^{-1}$)
- Reconstruct three D_s final-states: $KK\pi$, $\pi\pi\pi$ and $K\pi\pi$
- Have selected 5k signal events (100k calibration events)

Experimental challenges

$$\mathcal{P}(x, t, q_t) = [P(x, t', q_t) \otimes R(t, t')] \cdot \epsilon(t)$$

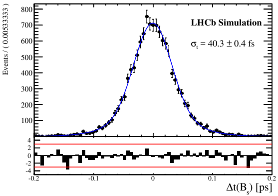
Time-Acceptance

Determined on $B_s \to D_s\pi\pi\pi$ data



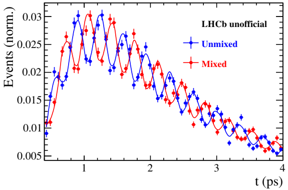
Time-Resolution

$\sigma_t = 40$ fs $\ll 2\pi/\Delta m_s \approx 350$ fs



Tagging: Identify initial state flavor

- Calibrated on $B_s \to D_s\pi\pi\pi$ ($\epsilon_{eff} \approx 5.5\%$)
- $\Delta m_s = (xx.xxx \pm 0.009(stat.))\text{ps}^{-1}$
  More presice than PDG average:
  $\Delta m_s = (17.757 \pm 0.021)\text{ps}^{-1}$



Amplitude model selection

Plenty of possible decay channels ! How to select them ?

Decay channel
$B_s \to D_s^- \, [K_1(1270)^+[S,D] \to \pi^+ \, K^*(892)^0]$
$B_s \to D_s^- \, [K_1(1270)^+ \to \pi^+ \, K^*(1430)^0]$
$B_s \to D_s^- \, [K_1(1270)^+[S,D] \to K^+ \, \rho(770)^0]$
$B_s \to D_s^- \, [K_1(1270)^+[S,D] \to K^+ \, \omega(782)]$
$B_s \to D_s^- \, [K_1(1400)^+[S,D] \to \pi^+ \, K^*(892)^0]$
$B_s \to D_s^- \, [K_1(1400)^+[S,D] \to K^+ \, \rho(770)^0]$
$B_s \to D_s^- \, [K(1460)^+ \to \pi^+ \, \kappa]$
$B_s \to D_s^- \, [K(1460)^+ \to K^+ \, \sigma]$
$B_s \to D_s^- \, [K(1460)^+ \to \pi^+ \, K^*(892)^0]$
$B_s \to D_s^- \, [K(1460)^+ \to K^+ \, \rho(770)^0]$
$B_s \to D_s^- \, [K^*(1410)^+ \to \pi^+ \, K^*(892)^0]$
$B_s \to D_s^- \, [K^*(1410)^+ \to K^+ \, \rho(770)^0]$
$B_s \to D_s^- \, [K_2^*(1430)^+ \to \pi^+ \, K^*(892)^0]$
$B_s \to D_s^- \, [K_2^*(1430)^+ \to K^+ \, \rho(770)^0]$
$B_s \to D_s^- \, [K^*(1680)^+ \to \pi^+ \, K^*(892)^0]$
$B_s \to D_s^- \, [K^*(1680)^+ \to K^+ \, \rho(770)^0]$
$B_s \to D_s^- \, [K_2(1770)^+ \to \pi^+ \, K^*(892)^0]$
$B_s \to D_s^- \, [K_2(1770)^+ \to K^+ \, \rho(770)^0]$
$B_s \to \sigma^0 (D_s^- K^+)_S$
$B_s[S,P,D] \to \rho(770)^0 \, (D_s^- K^+)_V$
$B_s \to K^*(892)^0 \, (D_s^- \pi^+)_S$
$B_s[S,P,D] \to K^*(892)^0 \, (D_s^- \pi^+)_V$
$B_s \to (D_s^- K^+)_S \, (\pi^+ \pi^-)_S$

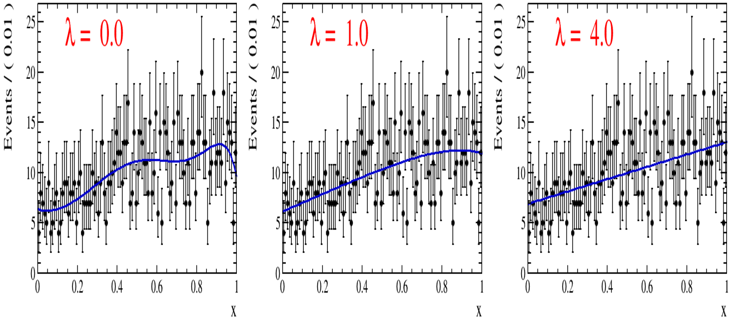
Amplitude model selection

- Overwhelmingly high number of possible amplitudes
- Adding more fit parameters will describe **this** data better
  $\Rightarrow$ **Overfitting**

- **LASSO:** Data-driven method for model selection
  [M. Williams, arXiv:1505.05133]
- Include "all" amplitudes, but penalize complexity in the likelihood:

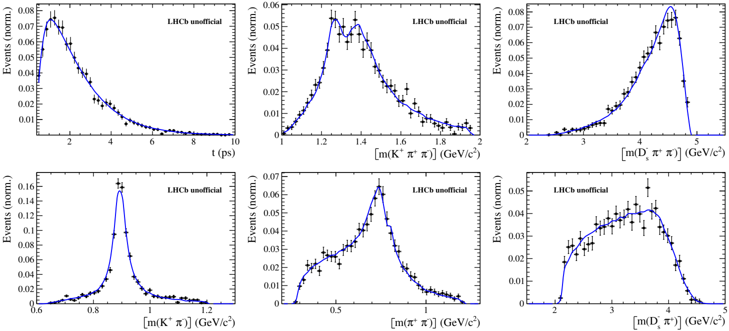
LASSO: Toy experiment

- Generated: pdf $= 1 + x$
- Fitted pdf $= 1 + \sum_{i=1}^{10} c_i\, x^i$
- $-2\cdot\log(L) \rightarrow -2\cdot\log(L) + \lambda \cdot \sum_i |c_i|$



Time-dependent Amplitude Fit

Full time-dependent amplitude fit with LASSO model



Selected 7 $b \to c$ and 7 $b \to u$ amplitudes

Selected LASSO amplitudes

Decay Channel	F^c [%]	F^u [%]
$B_s \to D_s\,(K_1(1270) \to K^*(892)\,\pi)$	6.3 $\pm$ 1.6	14.9 $\pm$ 4.5
$B_s \to D_s\,(K_1(1270) \to K\,\rho(770))$	12.3 $\pm$ 1.4	29.1 $\pm$ 6.1
$B_s \to D_s\,(K_1(1270) \to K_0^*(1430)\,\pi)$	3.4 $\pm$ 0.5	8.0 $\pm$ 2.1
$B_s \to D_s\,(K_1(1400) \to K^*(892)\,\pi)$	48.3 $\pm$ 4.5	17.2 $\pm$ 8.6
$B_s \to D_s\,(K^*(1410) \to K^*(892)\,\pi)$	15.5 $\pm$ 1.0	
$B_s \to D_s\,(K^*(1410) \to K\,\rho(770))$	6.7 $\pm$ 0.6	
$B_s \to D_s\,(K(1460) \to K^*(892)\,\pi)$		21.0 $\pm$ 4.6
$B_s \to (D_s\,\pi)_P\;K^*(892)$	6.8 $\pm$ 1.5	36.0 $\pm$ 8.0
$B_s \to (D_s\,K)_P\;\rho(770)$		9.7 $\pm$ 4.0
Sum	99.3 $\pm$ 4.7	135.9 $\pm$ 12.9

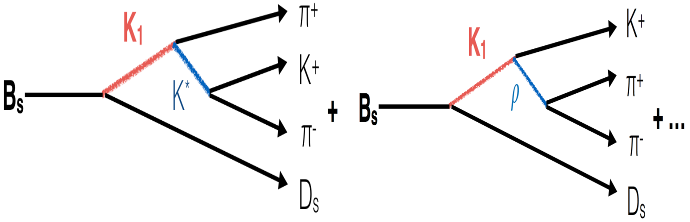
Fit parameter	Value
r	xx.xx $\pm$ 0.04
$\delta\,[^\circ]$	xx.xx $\pm$ 16
$\gamma - 2\beta_s\,[^\circ]$	xx.xx $\pm$ 16

Preliminary results !

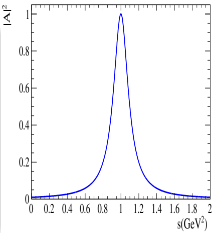
Summary

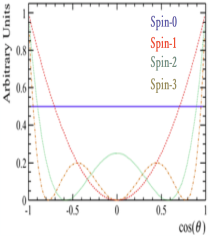
- First measurement of γ using $B_s \to D_s K\pi\pi$ decays on its way
- Statistical precision: $\sigma(\gamma) = 16^\circ$ (7fb^{-1})
- World average: $\sigma(\gamma) = 5.6^\circ$
- $B^\pm \to DK^\pm, D \to K_s hh$: $\sigma(\gamma) = 10^\circ$ (LHCb, 5fb^{-1})
- $B_s \to D_s K$: $\sigma(\gamma) = 20^\circ$ (LHCb, 3fb^{-1})

Backup: Amplitude description



- Single channel amplitudes:
  $A_1(x) \approx BW_{K_1} \cdot BW_{K^*} \cdot S_f$
  $A_2(x) \approx BW_{K_1} \cdot BW_{\rho} \cdot S_f$
- Total amplitudes:
  $A^c(x) = \sum_i a_i^c A_i(x)$
  $A^u(x) = \sum_i a_i^u A_i(x)$

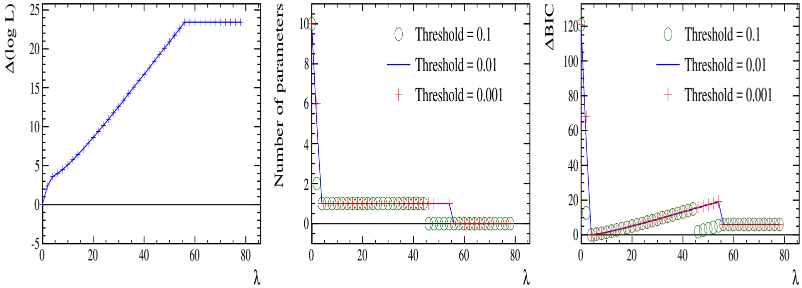




Backup: LASSO optimization

How to choose λ ?

- $\text{BIC}(\lambda) = -2 \cdot \log(L) + r \cdot \log(N_{events})$
  r = Number of parameters with: $|c_i| >$ threshold
- Balances **gain in fit quality vs. complexity**
- Optimal value $\lambda \approx 4$



Backup: Phasespace-integrated PDF

$$\begin{aligned}
\int P(x,t,q,f)\mathrm{d}x \propto & \left[\cosh\left(\frac{\Delta\Gamma\, t}{2}\right)\right. \\
& + qf\left(\frac{1-r^2}{1+r^2}\right)\cos\left(m_s\, t\right) \\
& - 2\left(\frac{\kappa\, r\cos(\delta - f(\gamma - 2\beta_s))}{1+r^2}\right)\sinh\left(\frac{\Delta\Gamma\, t}{2}\right) \\
& - 2qf\left(\frac{\kappa\, r\sin(\delta - f(\gamma - 2\beta_s))}{1+r^2}\right)\left.\sin\left(m_s\, t\right)\right]e^{-\Gamma t} \\
& = \left[\cosh\left(\frac{\Delta\Gamma\, t}{2}\right) + qf\,\mathbf{C}\cos\left(m_s\, t\right)\right. \\
& - \mathbf{D}_f\sinh\left(\frac{\Delta\Gamma\, t}{2}\right) - q\,\mathbf{S}_f\left.\sin\left(m_s\, t\right)\right]e^{-\Gamma t}
\end{aligned}$$

$$r \equiv \frac{\sqrt{\int |\bar{A}(x)|^2 \mathrm{d}x}}{\sqrt{\int |A(x)|^2 \mathrm{d}x}},\ \kappa\, e^{i\delta} \equiv \frac{\int A(x)^* \bar{A}(x)\mathrm{d}x}{\sqrt{\int |A(x)|^2\mathrm{d}x}\sqrt{\int |\bar{A}(x)|^2\mathrm{d}x}}$$