# A measurement of the $CP$-violating phase $\phi_s$ in the decay $\overline{B}^0_s \to D_s^+ D_s^-$

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On behalf of the LHCb collaboration

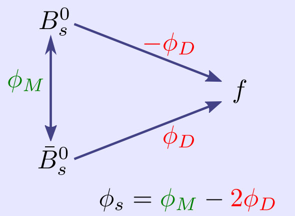
8th International Workshop on the CKM Unitarity Triangle
Wien, Österreich

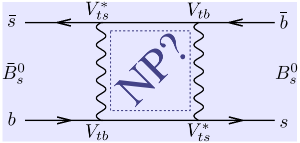
# Introduction

- $CP$ violating weak phase $\phi_s$ parameterises interference between mixing and decay to $CP$ eigenstate $f$
- In $b \to c\bar{c}s$ transitions $\phi_s$ predicted to be small with high precision: PRD 84 033005 (2011)

$$\phi_s^{\mathrm{SM}} \simeq -2\beta_s \equiv -2\arg\left(-\frac{V_{ts}V_{tb}{}^*}{V_{cs}V_{cb}{}^*}\right) = -36.3^{+1.6}_{-1.5}\,\mathrm{mrad}$$

- New Physics entering the $\bar{B}_s^0$-$B_s^0$ mixing can influence the measured value of $\phi_s$.
- 'Golden Modes' for $\phi_s$ in $b \to c\bar{c}s$: $f = J/\psi\, K^+K^-, J/\psi\, \pi^+\pi^-$
- See talk on Tuesday by W. Kanso for LHCb measurements



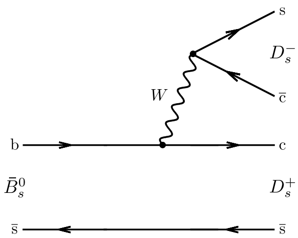



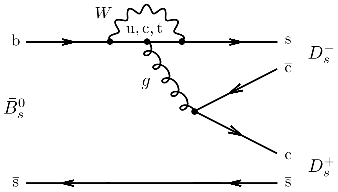
# The penguins


- $\phi_s = -2\beta_s$ only in the absence of penguin pollution
- Expected to be small in $J/\psi K^+K^-$, $J/\psi \pi^+\pi^-$ but experimental precision is increasing.
  - See talks by R. Knegjens and P. Frings on Tuesday, S. Schacht this session.
- Measurements of $\phi_s$ in additional modes with different penguin amplitudes are a valuable input

# $\phi_s$ from $D_s^+ D_s^-$

- $\overline{B}_s^0 \to D_s^+ D_s^-$ is a $b \to c\bar{c}s$ transition:




- Disadvantage: Lower yield compared to $J/\psi\, hh$
- Advantage: Angular analysis not necessarry
- Analysies using $\overline{B}_s^0 \to D_s^+ D_s^-$ at LHCb already:
  - $\overline{B}_s^0 \to D_s^+ D_s^-$ Effective lifetime PRL 112 111802 (2014)
  - $\overline{B}_s^0 \to D_s^+ D^-$ First observation: PRD 87 092007 (2013)
- Today I present the First measurement of $\phi_s$ in $\overline{B}_s^0 \to D_s^+ D_s^-$

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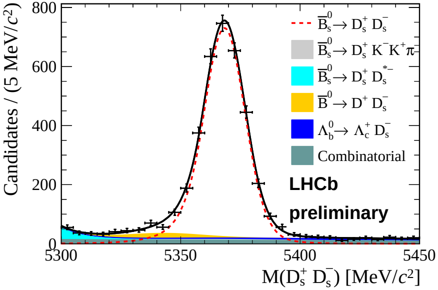
# Data sample

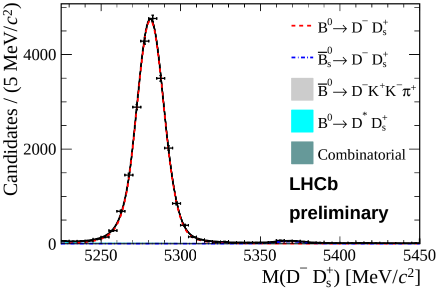
- Analysis uses full LHCb Run 1 dataset
- $D_s^+ D_s^-$ candidates are reconstructed in 4 final states:
  - $K^+K^-\pi^+$ vs. $K^-K^+\pi^-$
  - $K^+K^-\pi^+$ vs. $K^-\pi^+\pi^-$
  - $K^+K^-\pi^+$ vs. $\pi^-\pi^+\pi^-$
  - $\pi^-\pi^+\pi^-$ vs. $\pi^-\pi^+\pi^-$
- $B^0 \to D^- D_s^+$ control channel

- Topological b-hadron trigger: displaced $n$-body vertices
- Particle ID & mass vetoes to suppress part. reco and mis-ID backgrounds
- Boosted decision tree trained on simulation and sidebands in data

$\overline{B}_s^0 \to D_s^+ D_s^-$




$B^0 \to D^- D_s^+$




$3345 \pm 62$ $\overline{B}_s^0 \to D_s^+ D_s^-$, $21\,320 \pm 148$ $B^0 \to D^- D_s^+$ in $3\,\text{fb}^{-1}$ (PRELIMINARY)

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# Decay rates

- $\phi_s$ is measurable through the time-evolution of the $\overline{B}^0_s$,$B^0_s$ mesons
- Decay rates of $B^0_s$ ($\overline{B}^0_s$) decaying to a $CP$ eigenstate:

$$\Gamma(\hat{t}) = \mathcal{N} e^{-\Gamma_s \hat{t}} \left[ \cosh\left(\frac{\Delta\Gamma_s}{2}\hat{t}\right) - \frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2} \sinh\left(\frac{\Delta\Gamma_s}{2}\hat{t}\right) + \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m_s \hat{t}) - \frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}\sin(\Delta m_s \hat{t}) \right],$$

$$\bar{\Gamma}(\hat{t}) = \left|\frac{p}{q}\right|^2 \mathcal{N} e^{-\Gamma_s \hat{t}} \left[ \cosh\left(\frac{\Delta\Gamma_s}{2}\hat{t}\right) - \frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2} \sinh\left(\frac{\Delta\Gamma_s}{2}\hat{t}\right) - \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m_s \hat{t}) + \frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}\sin(\Delta m_s \hat{t}) \right],$$

- Complex parameter $\lambda = (q/p)(\bar{A}_f/A_f)$. $\phi_s = -\arg(\lambda)$
- Magnitude of $\lambda$ quantifies $CP$ violation in decay

# Procedure

- $\overline{B}_s^0/B_s^0$ rates contribute with different sign: Performant flavor tagging needed to determine initial flavor
- $\Delta m_s$ is fast: excellent time resolution needed to distinguish oscillations
- *sPlot* technique is used to statistically subtract background NIM A555 (2005). Signal-only PDF:

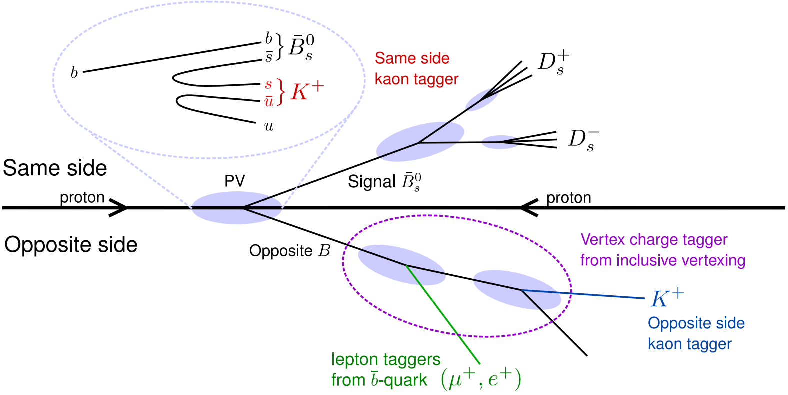
$$P(t,q,\eta,\delta) = R(\hat{t},q,\eta) \otimes G(t-\hat{t},\delta) \times \epsilon_{\text{data}}^{\text{D}_\text{s}\text{D}_\text{s}}(t)$$

- $R(\hat{t},q,\eta)$ is the rate including flavor tagging
- $G(t-\hat{t},\delta)$ is the per-event decay time resolution
- $\epsilon_{\text{data}}^{\text{D}_\text{s}\text{D}_\text{s}}(t)$ is the decay time acceptance
- The fundamental quantity we measure is:

$$\sin(\phi_s) \times [1-2\omega] \otimes G(\hat{t}-t|\delta) \times \sin(\Delta m_s t)$$

# Flavour tagging

- Flavour tagging algorithms determine initial $\bar{B}_s^0/B_s^0$ flavour.
- Opposite Side (OS) algorithms use information from the other $b$-hadron decay
- Same-Side Kaon (SS) uses charge of fragmentation kaon coproduced with the $\bar{B}_s^0$




- Performance metrics:
  - Tagging efficiency, $\epsilon = N_{\text{tagged}}/(N_{\text{tagged}} + N_{\text{untagged}})$
  - Wrong-tag probability $\omega = N_{\text{wrong tag}}/N_{\text{tagged}}$
  - Effective tagging power, $\epsilon D^2 = \epsilon[1 - 2\omega]^2$

M. Dorigo, ICHEP 2014
LHCb-TALK-2014-169

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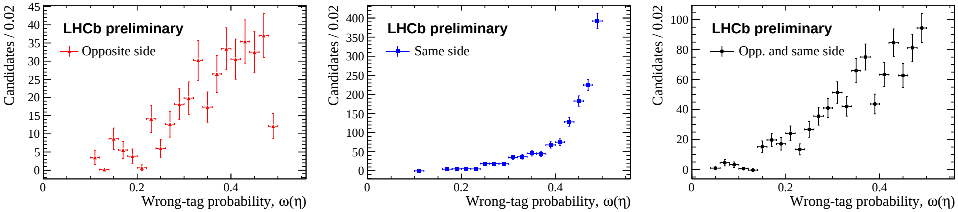
# Tagging Performance

- Fit uses estimated per-event wrong-tag probability, $\eta$
- Calibration performed for $\overline{B}{}^0_s$, $B^0_s$ using flavor specific final states: $\bar{\omega}(\eta)$, $\omega(\eta)$
- OS + SS taggers combined when both taggers make a decision:

$$R(\hat{t}, q^{\text{OS}}|\eta^{\text{OS}}, q^{\text{SS}}|\eta^{\text{SS}}) = \begin{array}{l}(1 + q^{\text{OS}}[1 - 2\omega^{\text{OS}}])(1 + q^{\text{SS}}[1 - 2\omega^{\text{SS}}])\Gamma(\hat{t}) + \\ (1 - q^{\text{OS}}[1 - 2\bar{\omega}^{\text{OS}}])(1 - q^{\text{SS}}[1 - 2\bar{\omega}^{\text{SS}}])\bar{\Gamma}(\hat{t}).\end{array}$$




| | OS only | SS only | OS + SS | Combined |
|---|---|---|---|---|
| $\epsilon$ [%] | $10.66 \pm 0.54$ | $40.02 \pm 0.86$ | $26.51 \pm 0.77$ | $77.2 \pm 1.3$ |
| $\epsilon D^2_{\text{eff}}$ [%] | $1.08 \pm 0.06 \pm 0.05$ | $1.42 \pm 0.46 \pm 0.36$ | $2.83 \pm 0.10 \pm 0.11$ | $5.33 \pm 0.18 \pm 0.17$ |

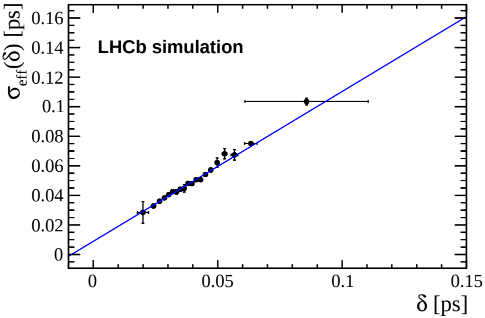
Similar performance to $B^0_s \to \phi\phi$: arXiv:1407.2222

# Resolution

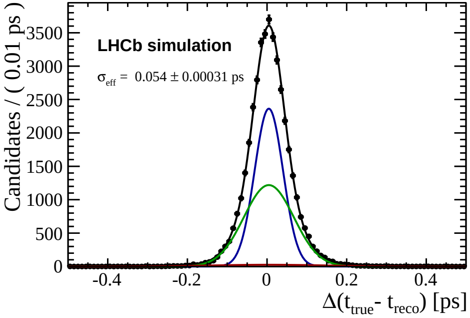
- Per-event resolution: decay time uncertainty $\delta$ from constrained vertex fit:

$$G(t-\hat{t}|\delta) \propto \frac{1}{\sigma(\delta)} e^{-\frac{1}{2}\left(\frac{t-\hat{t}}{\sigma(\delta)}\right)^2}$$

- $\sigma(\delta)$ calibrated from linear fit in simulation:



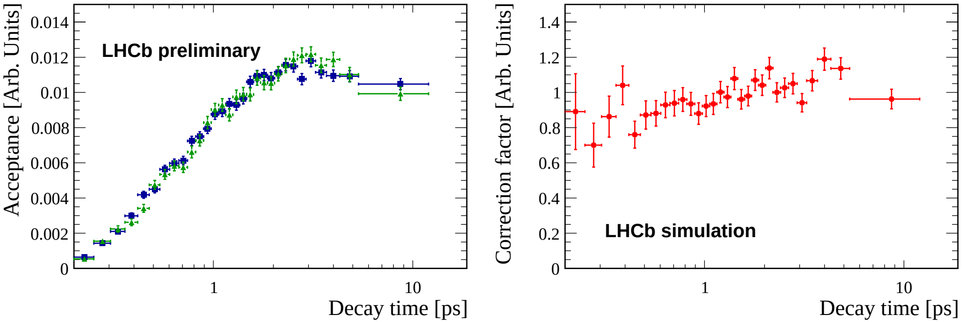

- Effective resolution: 54 fs:




- Calibration parameters constrained in the fit
- Comparable with calibration determined from $\overline{B}^0_s \to D^+_s \pi^-$ data New J. Phys. 15 (2013) 053021

# Decay time acceptance

- The trigger and selection impose decay-time biasing requirements to reduce backgrounds
- Data-driven acceptance model determined using $B^0 \to D^- D_s^+$ control channel:
  - Ratio of background subtracted $B^0 \to D^- D_s^+$ and known $B^0$ lifetime: $\varepsilon_{\rm data}^{D^- D_s^+}(t)$
  - Compared to simulation: $\varepsilon_{\rm sim}^{D^- D_s^+}(t)$




- Correction from ratios of $B^0 \to D^- D_s^+$, $\overline{B}{}_s^0 \to D_s^+ D_s^-$ acceptances in simulation

$\overline{B}{}_s^0 \to D_s^+ D_s^-$

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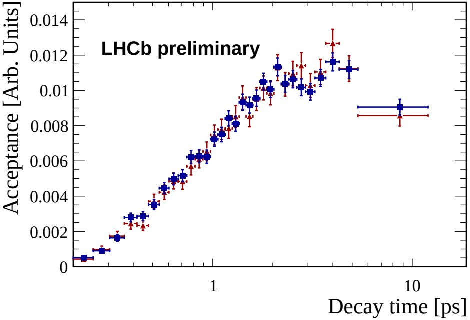
# Decay time acceptance

- Data-driven $D_s^+ D_s^-$ acceptance agrees well with simulation:

$$\varepsilon_{\text{data}}^{D_s^+ D_s^-}(t) = \varepsilon_{\text{data}}^{D^- D_s^+}(t) \cdot \frac{\varepsilon_{\text{sim}}^{D_s^+ D_s^-}}{\varepsilon_{\text{sim}}^{D^- D_s^+}}(t)$$




- Technique verified by fitting for the $B_s^0$ lifetime in data: Consistent with world average

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# External Constraints

- Parameters with limited sensitivity constrained in the fit
- Gaussian constraints incorporating both statistical and systematic uncertainties

- $\Gamma$, $\Delta\Gamma$ constrained to PRD 87 (2013) 112010, correlation included
- $\Delta m_s$ constrained to New J. Phys. 15 (2013) 053021
- Additional constraints applied to the flavor tagging and resolution calibration parameters

| Parameter | Constraint |
|---|---|
| $\Gamma$ | $0.661 \pm 0.007\ \mathrm{ps}^{-1}$ |
| $\Delta\Gamma$ | $0.106 \pm 0.013\ \mathrm{ps}^{-1}$ |
| $\Delta m_s$ | $17.768 \pm 0.024\ \mathrm{ps}^{-1}$ |

# Validation

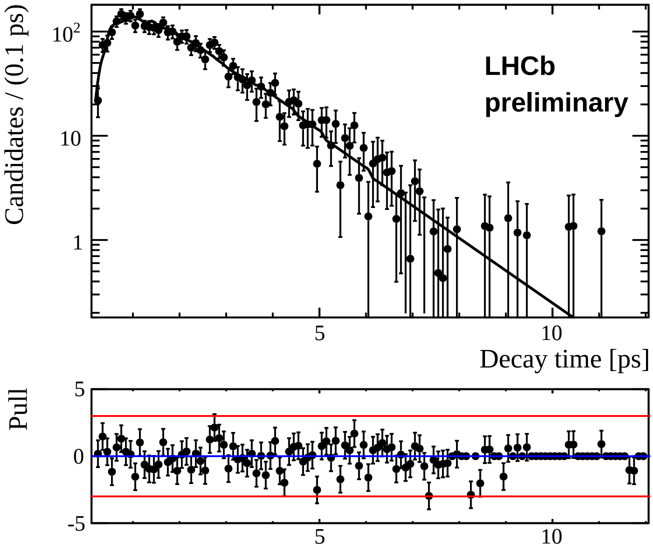
- Pseudoexperiments and simulation are used to validate the fit procedure
  - Fit is found to be without bias for both $\phi_s$ and $|\lambda|$
  - Expected sensitivity from pseudoexperiments: $\sigma(\phi_s) = 0.18\ \mathrm{rad}$, $\sigma(|\lambda|) = 0.17$
- Systematic uncertainties:

| Systematic uncertainty | $\phi_s$ ($\|\lambda\| = 1$) | $\phi_s$ | $\|\lambda\|$ |
|---|---|---|---|
| Resolution | $\pm 0.098\ \sigma$ | $\pm 0.094\ \sigma$ | $\pm 0.100\ \sigma$ |
| Acceptance (model) | $\pm 0.022\ \sigma$ | $\pm 0.027\ \sigma$ | $\pm 0.027\ \sigma$ |
| Acceptance (stat.) | $\pm 0.013\ \sigma$ | $\pm 0.013\ \sigma$ | $\pm 0.014\ \sigma$ |
| Mass | $\pm 0.044\ \sigma$ | $\pm 0.043\ \sigma$ | $\pm 0.010\ \sigma$ |
| Background subtraction | $\pm 0.0092\ \sigma$ | $\pm 0.0077\ \sigma$ | $\pm 0.046\ \sigma$ |
| Total | $\pm 0.11\ \sigma$ | $\pm 0.11\ \sigma$ | $\pm 0.11\ \sigma$ |

- Largest systematic uncertainty comes from resolution calibration: Differences between $\bar{B}_s^0 \to D_s^+ D_s^-$ simulated and $\bar{B}_s^0 \to D_s^+ \pi^-$ data-driven model
- Systematic uncertainties are small (11%) compared to statistical uncert.

# Time fit in data

- $\overline{B}^0_s \to D_s^+ D_s^-$ Decay time distribution in $3\,\mathrm{fb}^{-1}$







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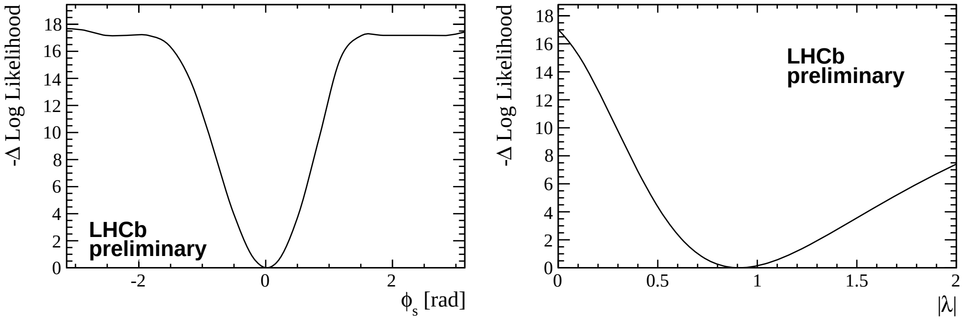
# Results

- Fitting to data with $|\lambda|$ as a free parameter:



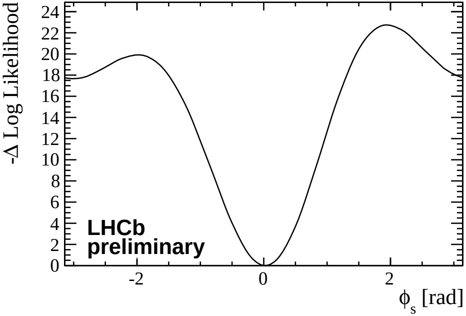

PRELIMINARY

$$\phi_s = 0.02 \pm 0.17\,(\text{stat}) \pm 0.02\,(\text{syst})\,\text{rad}, \qquad |\lambda| = 0.91\,^{+0.18}_{-0.15}\,(\text{stat}) \pm 0.02\,(\text{syst})$$

- $\phi_s$, $|\lambda|$ correlated at +3%

# Results, $|\lambda| = 1$

- Requiring that $|\lambda| = 1$:

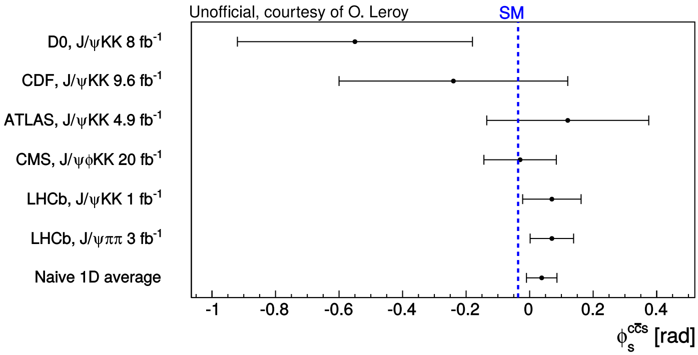



PRELIMINARY

$$\phi_s = 0.02 \pm 0.17\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})\,\mathrm{rad}$$

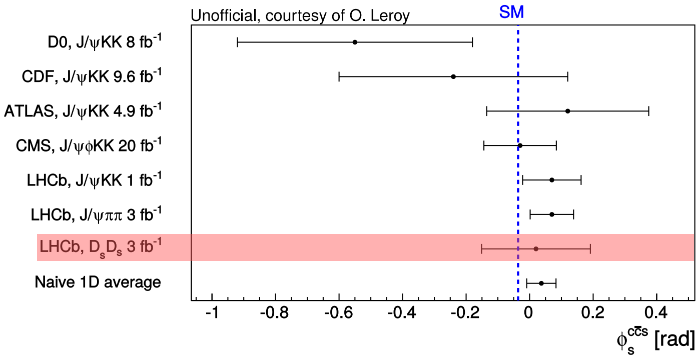
# Comparison to $J/\psi hh$

- SM and meaurements of $\phi_s$ in $J/\psi\pi\pi$, $J/\psi KK$



# Comparison to $J/\psi hh$

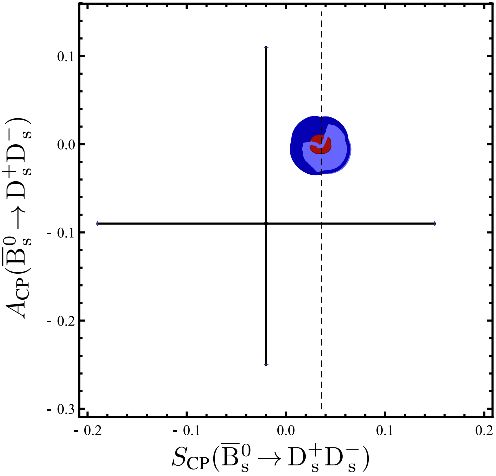
- SM and meaurements of $\phi_s$ in $J/\psi\pi\pi$, $J/\psi KK$




- This result is consistent with SM and $J/\psi hh$ measurements
- Still statistically limited: Prospects in LHCb run 2 are good.

# Stop press!

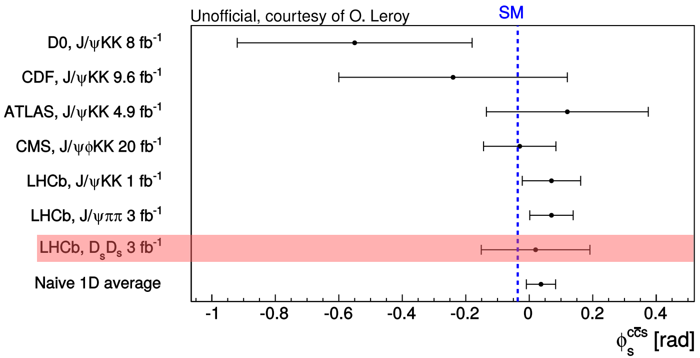
- Preliminary penguin predicitons previously presented:




- Figure courtesy of S. Schacht & M. Jung: Looking forward to their paper
- Preliminary LHCb result overlaid

# Summary

- In this talk I have presented for the first time a measurement of the *CP*-violating phase $\phi_s$ in the decay $\bar{B}^0_s \to D_s^+ D_s^-$




- $|\lambda|$ consistent with 1: No *CP* violation in decay.
- $\phi_s$ consistent with$J/\psi hh$ measurements and SM
- This result to be submitted to PRL.

Thanks for listening!

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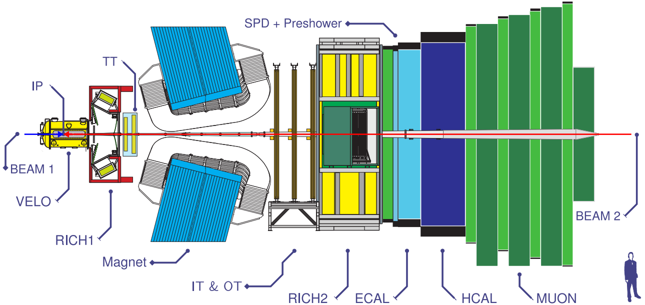
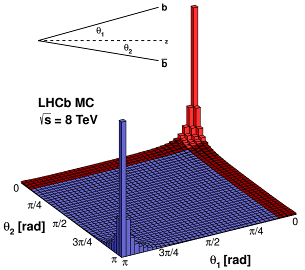
# backups

# The LHCb Experiment

- LHCb is a single-arm ($2 < \eta < 5$) spectrometer at the LHC
  - Precision beauty and charm physics: *CP* violation measurements, rare decays, heavy flavor production
  - Exploits the correlated production of $b\bar{b}$ pairs in the LHC environment




- Time-dependent analyses require good time resolution: $\sim 40$ fs (VELO)
- Flavor tagging, final state discrimination needs excellent particle ID: (RICH)
- Rare decays and extremely small asymmetries require pure data samples with high signal efficiency: (Trigger)

# Preselection

- $\overline{B}_s^0$ candidates:

| Cut | Value |
|---|---|
| $\chi^2_{IP}$ | $< 20$ |
| $\chi^2_{vtx}/ndf$ | $< 8$ |
| $\chi^2_{\text{vert. signif}}/ndf$ | $> 100$ |
| DIRA | $> 0.99994$ |

- Charm: Several invariant mass vetoes to reject $K/\pi$ mis-ID candidates
- $\mathrm{D}_s^+$ reconstructed through $\phi\pi$, $\mathrm{K}^*K$, nonresonant.
- Final-state specific ProbNN requirements + mass windows/vetos

- On charm:

| Cut | Value |
|---|---|
| Mass | $\pm 25\ \mathrm{MeV}/c^2$ |
| $K\ DLL_{K-\pi}$ | $> 0$ |
| $\pi\ DLL_{K-\pi}$ | $< 10$ |
| $z_D - z_B$ | $> 0$ |
| $\chi^2_{\text{vert. signif}}$ | $> 2.0$ WRT $B$ (except $\phi\ \pi$) |
| $\chi^2_{\text{vert. signif}}$ | $> 6.0$ WRT $B$ ($3\pi$ only) |
| $\tau$ | $< 1.0\,\mathrm{ps}$ ($\mathrm{D}^+$ only) |

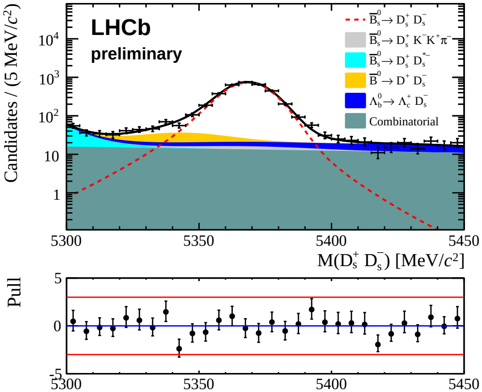
# Selection

- BDT used to improve B/S
  - Trained on signal MC and WS sidebands above 5.2 $\mathrm{GeV}/c^2$
  - Input variables from $B$: $\chi^2_{vtx}$, $\chi^2_{IP}$, DOCA, $\chi^2_{\text{vert. signif}}$, $p_{\mathrm{T}}$, $p_{\mathrm{T}}$ asymmetry.
  - Input variables from charm: $\chi^2_{IP}$, DOCA, Flight. dist. signif.
  - charm daughters: $p_{\mathrm{T}\,min}$, $\chi^2_{IPmin}$, $\chi^2_{IPmax}$
- Several variables reweighted in MC to match data

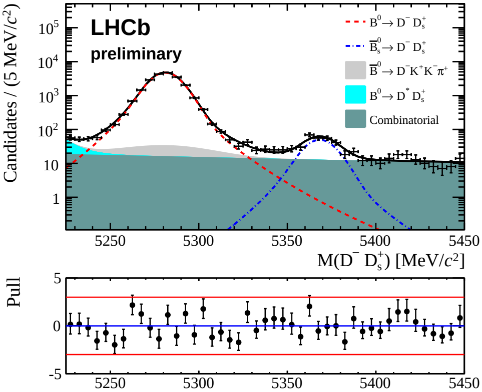
# Mass fits

- Both signal and background models are similar to those used in PRD 87 092007
- For signal and the control channel the mass shape is modelled with a double crystal ball:
  - Parameterisation from MC, with weighted averages for the means and widths according to the expected yields for each final state
  - In fits to data, increase in width ($\sim 4.5\ \mathrm{MeV}/c^2$) and CB tail ($\sim 15\%$) WRT MC taken from control channel
- Background includes several varieties of peaking and non peaking components:
  - Partially reconstructed, eg: $B \to \mathrm{D_s^* D_s}$ with $\mathrm{D_s^*} \to \mathrm{D_s}\gamma$ or $\mathrm{D_s^*} \to \mathrm{D_s}\pi^0$
  - Mis-ID, eg: $\mathrm{B_s^0} \to \mathrm{D^+ D_s^-}$ or $\Lambda_\mathrm{b} \to \Lambda_\mathrm{c}^+ \mathrm{D_s^-}$ reconstructed as $\mathrm{B_s^0} \to \mathrm{D_s D_s}$
  - Combinatorial: Determined from wrong-sign data
- In the fits to produce the decay time *sPlot*, all yields are free except $B^0_{(s)} \to D^-_{(s)} K^+ K^- \pi^+$ decays: Fixed to be 1% of the signal, determined from $D_{(s)}$ mass sidebands.

# Mass fits

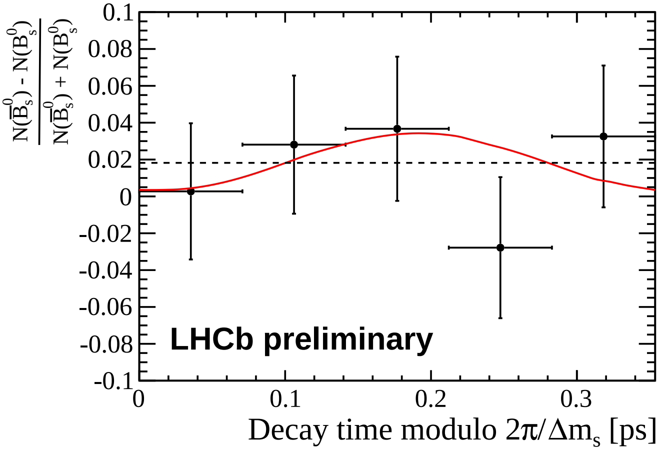


LHCb
preliminary
$\overline{B}_s^0 \to D_s^+ D_s^-$
$\overline{B}_s^0 \to D_s^+ K^- K^+ \pi^-$
$\overline{B}_s^0 \to D_s^+ D_s^{*-}$
$\overline{B}^0 \to D^+ D_s^-$
$\Lambda_b^0 \to \Lambda_c^+ D_s^-$
Combinatorial
Candidates / (5 MeV/$c^2$)
M($D_s^+ D_s^-$) [MeV/$c^2$]
Pull

LHCb
preliminary
$B^0 \to D^- D_s^+$
$\overline{B}_s^0 \to D^- D_s^+$
$\overline{B}^0 \to D^- K^+ K^- \pi^+$
$B^0 \to D^* D_s^+$
Combinatorial
Candidates / (5 MeV/$c^2$)
M($D^- D_s^+$) [MeV/$c^2$]
Pull

# Raw asymmetry




- Tagging asymmetry consistent with 0