Measurement of the CP violating phase, ϕ_s, in Run 2 using $B_s^0 \to J/\psi K^+K^-$

Konstantin Gizdov

PPE Group, University of Edinburgh

On behalf of the LHCb Collaboration

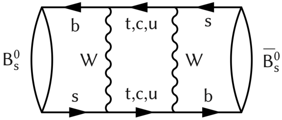
Joint APP and HEPP Annual Conference

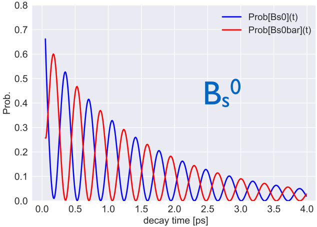
26^{th}-28^{th} Mar 2018

CP Violation

- CP Violation is a necessary condition for baryon asymmetry in the Universe
  [A. D. Sakharov, JETP Lett. 5, 24-27 (1967)]
- Present in the Standard Model, but too small by 10^{10} to explain asymmetry
- Heavy-quark hadrons are excellent place to search for new sources of CPV

$\|\mathrm{B}^0{}_{L,H}\rangle = p\|\mathrm{B}^0\rangle + q\|\overline{\mathrm{B}}^0\rangle$	Mass eigenstates
$\Delta m \equiv m_H - m_L$	Mixing frequency
$\Gamma \equiv \dfrac{(\Gamma_\mathrm{L} + \Gamma_\mathrm{H})}{2}$	Average decay width
$\Delta\Gamma \equiv \Gamma_\mathrm{H} - \Gamma_\mathrm{L}$	Width difference



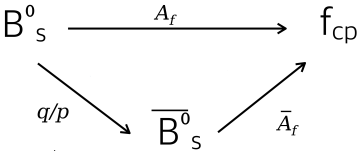


$$P(\mathrm{B}^0_\mathrm{s} \to \overline{\mathrm{B}}^0_\mathrm{s}) = \frac{\Gamma_\mathrm{s} e^{-\Gamma_\mathrm{s} t}}{2}[\cosh(\Delta\Gamma_\mathrm{s}/2) - \cos(\Delta m_s t)]|q/p|^2$$

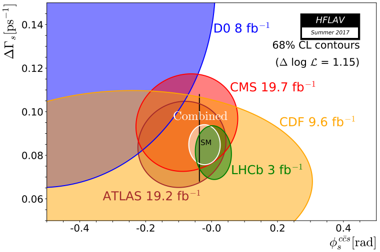
ϕ_s (CPV in interference of mixing and decay)

$$\mathcal{A}_{CP}(t) = \frac{\Gamma(\overline{B}^0_s \to f) - \Gamma(B^0_s \to f)}{\Gamma(\overline{B}^0_s \to f) + \Gamma(B^0_s \to f)} \approx \eta_f \sin\phi_s \sin(\Delta m_s t)$$

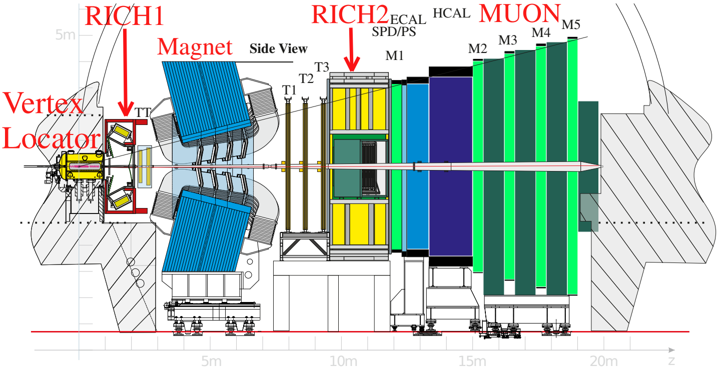
$$|B^0_s \to \overline{B}^0_s \to \overline{f}|^2 \neq |\overline{B}^0_s \to B^0_s \to f|^2$$



- ϕ_s : phase difference between amplitudes w/ and w/o oscillation in $b \to c\bar{c}s$ decays
- Sensitive probe of NP in B^0_s mixing and decay
- ${\phi_s}^{SM} = -0.0365 \pm 0.0013$ rad [CKMFitter]
- ${\phi_s}^{AVG} = -0.021 \pm 0.031$ rad [HFLAV Summer 2017]



LHCb Detector

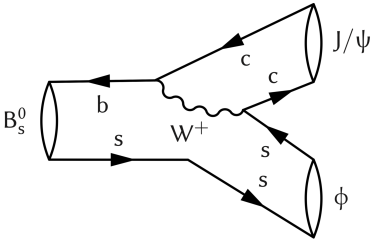


LHCb Detector Layout

- Interaction VErtex LOcator ($\varepsilon_{track} \approx 96\%$)
- Ring-Imaging Cherenkov ($\varepsilon_{PID}(K) \approx 95\%$) ($MisID(\mathrm{K} \to \pi) \approx 5\%$)
- High-granularity Muon ($\varepsilon_{PID}(\mu) \approx 97\%$) ($MisID(\mu \to \pi) \approx 3\%$)
- 4% of solid angle = 40% of heavy quark cross-section
- Decay time resolution: 45 fs
- Run 1: $\sim 3\,\mathrm{fb}^{-1}$
- Run 2 (2015 & 2016): $\sim 2\,\mathrm{fb}^{-1}$

Analysis strategy

For Run 2 ϕ_s with $B^0_s \to J/\psi\,\phi$



- $B^0_s \to J/\psi\,\phi$ is the **golden mode** for measuring ϕ_s
- Measure ϕ_s, $\Delta\Gamma_s$, $\Gamma_s - \Gamma_d$
- Final state is a mixture of CP-even/CP-odd, requires angular analysis to disentangle $CP|J/\psi\,\phi\rangle_\ell = (-1)^\ell|J/\psi\,\phi\rangle_\ell$
- Good tagging performance to resolve B^0_s flavour at production
- High decay-time resolution to see fast B^0_s oscillation and determine Δm_s
- Flavour-tagged time-dependent angular fit
- Robust understanding and modelling of background and acceptance effects

Event Selection

Run 2:

- Higher centre-of-mass energy means 2x the heavy quark cross-section
- More statistical power

MC Corrections:

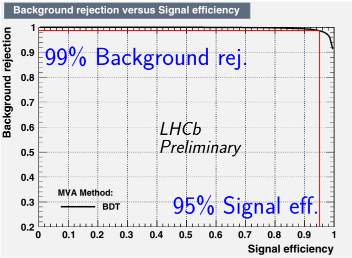
- Data-driven calibration of final-state Particle ID
- Multidimensional Gradient-Boosted Reweighting for Data-MC agreement

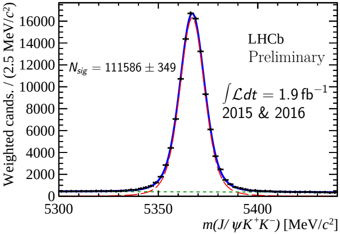
Selection:

- Multivariate analysis using Boosted Decision Tree
- Avoid variables that can bias angular or decay time distributions

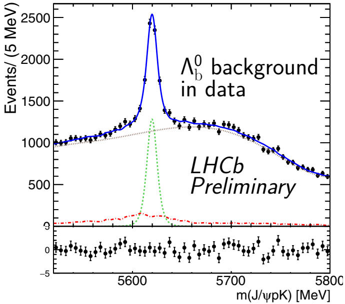
New Invariant Mass Model:

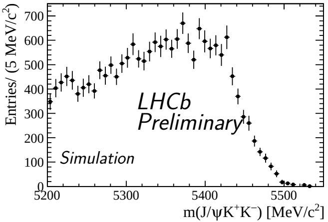
- Double-sided Crystal Ball function with per-event mass error as a conditional observable





Peaking Backgrounds





Negative weighted Λ_b^0 Monte-Carlo embedded to subtract remaining background

$\Lambda_b^0 \to J/\psi\, pK$:
- Veto event when $P(K \to p)_{max} > 0.7$ and consistent with $\Lambda_b^0 \pm$ 15MeV

$B^0 \to J/\psi\, K^*(K\pi)$:
- Veto event when $P(K \to K)_{max} < 0.35$, $P(K \to \pi)_{max} > 0.7$ and consistent with $B^0 \pm$ 15MeV

Year	$\Lambda_b^0 \to J/\psi\, pK$		$B^0 \to J/\psi\, K^*$	
	before veto	after veto	before veto	after veto
2015	4.3%	1.3%	0.2%	0.1%
2016	4.3%	1.2%	0.3%	0.1%

Remaining Λ_b^0 background is statistically subtracted to avoid biasing effect in angular distributions

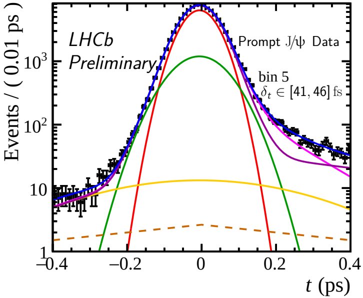
Decay Time Resolution

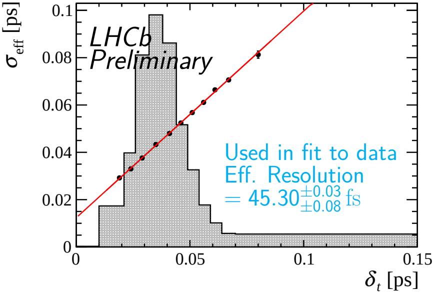
Extract the detector resolution from a sample of promptly produced J/ψ mesons from the PV

Resolution Model: Dirac-delta function and two exponentials convolved with a triple Gaussian with common mean + additional component to account for events reconstructed from wrong primary vertex

Calibration: Using single effective Gaussian computed from the dilution of the triple Gaussian

Dilution in bins of δ_t : $D = \sum_{i=1}^{3} f_i e^{-\sigma_i^2 \Delta m_s^2/2}$ Effective Gaussian width $\sigma_{eff} = \sqrt{(-2/\Delta m_s^2)\ln D}$





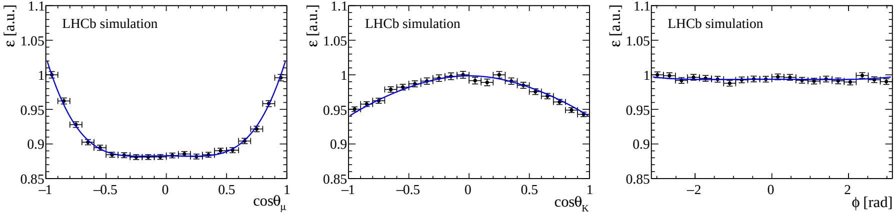
Angular Acceptance

Angular acceptance effect is modelled with normalisation weights in the resultant PDF for each individual polarisation state

Angles are computed from a re-fit of fully reconstructed events - resolution improved by 40%

Procedure:

- Normalisation weights from fully simulated signal events
- Iterative procedure to correct MC/Data kinematic difference



Projections of angular acceptances for 3 helicity angles

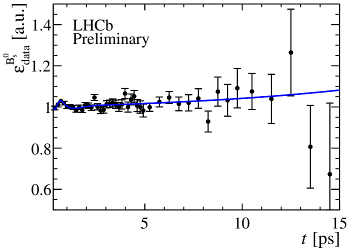
Decay Time Acceptance

New Strategy for Acceptance

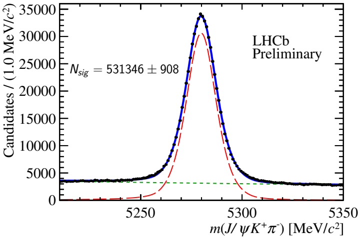
Method: Using a high-yield channel with well-know lifetime for data control sample

- Select $\mathrm{B}^0 \to \mathrm{J}/\psi\,\mathrm{K}^*(\to \mathrm{K}^+\pi^-)$ control the same way as signal channel $\mathrm{B}^0_s \to \mathrm{J}/\psi\,\phi$
- Obtain acceptance of B^0 from data using known lifetime
- Correct for difference in B^0_s and B^0 using MC ratio:

$$\epsilon^{\mathrm{B}^0_s}_{data}(t) = \epsilon^{\mathrm{B}^0}_{data}(t) \times \frac{\epsilon^{\mathrm{B}^0_s}_{sim}(t)}{\epsilon^{\mathrm{B}^0}_{sim}(t)}$$

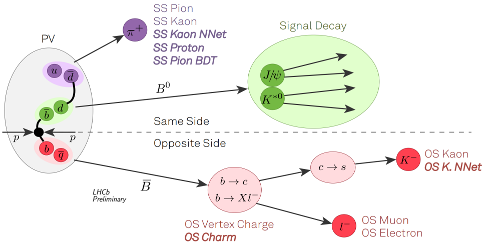


Cubic-spline product; final B^0_s acceptance

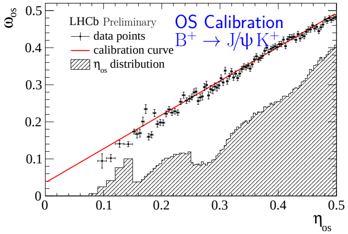


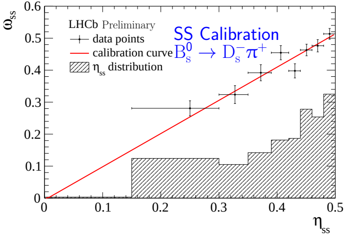
$\mathrm{B}^0 \to \mathrm{J}/\psi\,\mathrm{K}^*$

Flavour Tagging



- Crucial to tag B_s^0 flavour at production
- Taggers are Neural Nets optimized for Run 1
- Calibration works well with Run 2 data

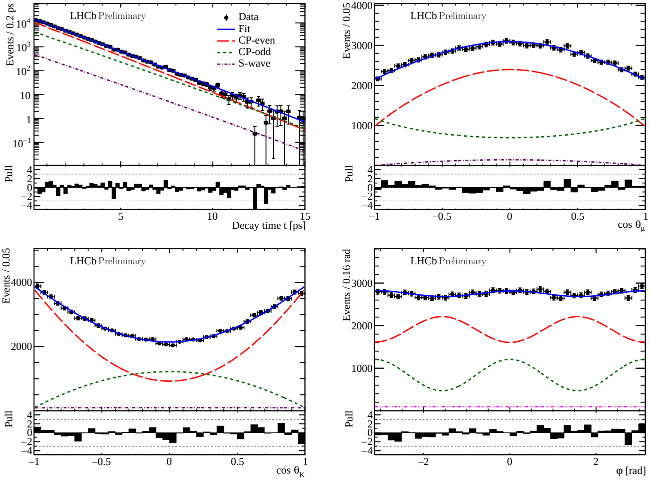




Tagging performance: $\varepsilon D^2 = 4.04 \pm 0.39\%$

Results

Data Fit Projections



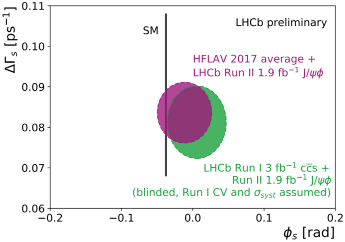
Summary

To do:

- Finalize systematics
- Unblind results

Expected statistical precision:

- $\sigma(\phi_s) = 0.042$ rad (Run 1: 0.049 rad)
- $\sigma(\Delta\Gamma_s) = 0.008\,\mathrm{ps}^{-1}$ (Run 1: $0.0091\,\mathrm{ps}^{-1}$)
- $\sigma(\Gamma_s - \Gamma_d) = 0.005\,\mathrm{ps}^{-1}$ (HFLAV: 0.004)



Thank you

Backup

Event Selection
MVA

Correct MC before training with:

- PIDCalib
- Gradient Boosted Reweighting to sWeighted data

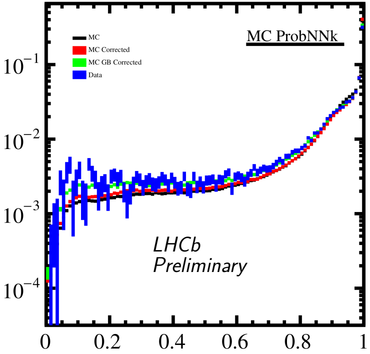
Avoid vars that introduce effects difficult to correct:

- IP$\chi^2(\mathrm{K}, \mu)$: angular/time correlation, could impact uniformity of decay time efficiency
- DIRA(B_s^0): large decay time acceptance effect
- $P_T(\mathrm{K}, \mu)$: large angular acceptance effect

- max Tr $\chi^2/\mathrm{ndf}(\mathrm{K})$
- min Log ProbNNk(K)
- max Tr $\chi^2/\mathrm{ndf}(\mu)$
- min Log ProbNNmu(μ)
- Log ENDVERTEX $\chi^2/\mathrm{ndf}(\mathrm{J}/\psi)$
- $P_T(\phi)$
- ENDVERTEX $\chi^2/\mathrm{ndf}(\mathrm{B}_s^0)$
- Log DTF $\chi^2/\mathrm{ndf}(\mathrm{B}_s^0)$
- Log IP$\chi^2/\mathrm{ndf}(\mathrm{B}_s^0)$
- $P_T(\mathrm{B}_s^0)$

MC Corrections

PID Correction



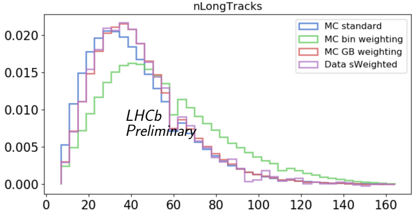
ProbNNk resampled and compared to sWeighted data

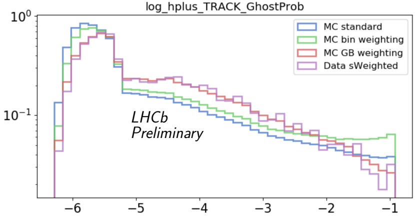
Resample MC PID distributions (ProbNN) with PIDCalib:

- ProbNNk/mu (K, μ)
- Also correlate ProbNNk(K) to ProbNNpi/p(K) to later use for vetos
- Resample based on P, P_T and nTracks.

MC Corrections

GB Reweighting

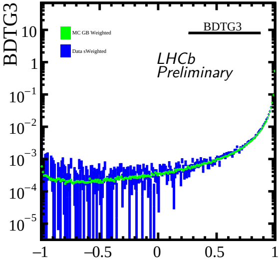


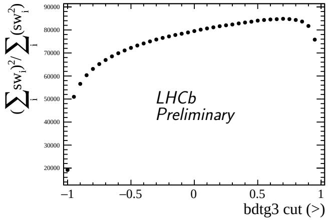


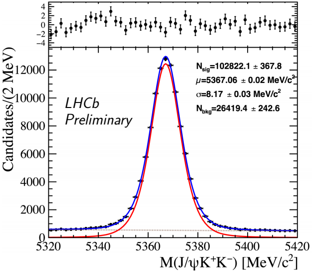
Gradient Boosted Reweighting:

- Uses iterative chain of decision trees to equalise unbinned multi-dimensional distributions
- Reweight on $P_T(\mathrm{B_s^0})$, $\eta(\mathrm{B_s^0})$, GhostProb(K, μ), nLongTracks
- Binned reweighter struggles to match all inputs

Optimizing MVA cut







$$FOM = \frac{(\sum_i sw_i)^2}{\sum_i (sw_i^2)}$$

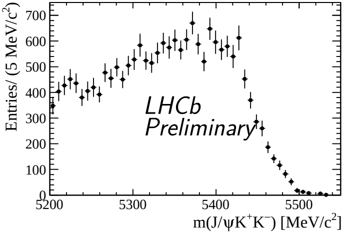
- $F_{max} = 89206$
- F_{max} at BDTG3 $= 0.78$
- Sig - 102822, Bkg - 26419

Double-sided Ipatia with Exponential bkg

After veto we expect 1192.0 ± 82.8 Λ_b^0 in $m(\mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-) \in [5200, 5550]$MeV

Procedure to subtract with negative weights:

- Reweight Λ_b^0 MC phase space to match the resonant structure in $\Lambda_b^0 \to \mathrm{J}/\psi\,\mathrm{p}\mathrm{K}$ pentaquark analysis
- Resample tagging information from data, missing in Λ_b^0 MC
- Normalize negative weights to -1181 Λ_b^0
- Merge with Data



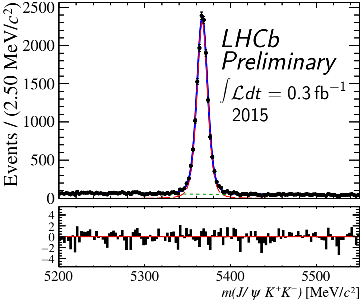
$\Lambda_b^0 \to \mathrm{J}/\psi\,\mathrm{p}\mathrm{K}$ Monte-Carlo reconstructed as $\mathrm{B}_s^0 \to \mathrm{J}/\psi\,\phi$

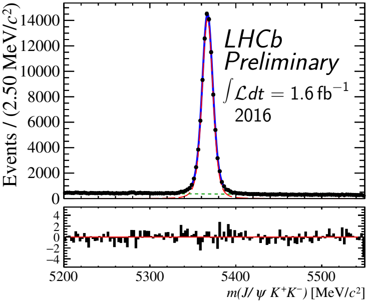
Invariant Mass Model

Signal Model: Double-sided Crystal Ball function (CB2) with per-event mass error as a conditional observable, quadratic dependence in mass error: $\sigma = s_1\sigma_i + s_2\sigma_i^2$
Background Model: Exponential for combinatorial and Gaussian distribution for $B^0 \to J/\psi K^+K^-$ contribution

Procedure to statistically subtract background with negative weights:

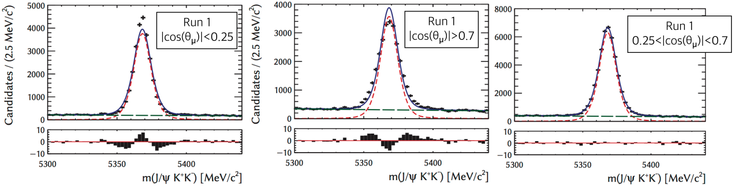
- Fix tails of CB2 with Gradient Boosted reweighted MC
- Fit to $m(J/\psi K^+K^-)$ with a Primary Vertex constraint
- Fit in 6 $m(KK)$ bins - [990, 1008, 1016, 1020, 1024, 1032, 1050] MeV

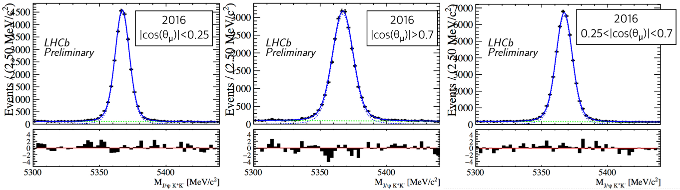




New Model takes care of the $m(\mathrm{B_s^0})$ and helicity angle correlations

Projections of the mass fit in 3 bins of $\cos(\theta_\mu)$





Iterative reweighting

- calculate normalisation weights
- perform the final fit to data to obtain parameter estimates
- reweigh the simulated sample, with event weights defined by $\epsilon = PDF(\Omega)/PDF_{gen}$
- reweigh simulated events such that the distributions of $p(\mathrm{K}^+)$ and $p(\mathrm{K}^-)$ match those in background subtracted data
- stop if $\Delta_p/\sigma_p < 0.01$ for all physics parameters, p, continue with step 1., otherwise

Flavour Tagging

Table: Overall tagging performance.

Category	Faction(%)	$\varepsilon_{\rm tag}$(%)	$\mathcal{D}^2$	$\varepsilon_{\rm tag}\mathcal{D}^2$(%)
OS-only	14.31	10.19	0.086	0.87±0.03
SSK-only	59.60	42.41	0.031	1.32±0.37
OS&SSK	26.09	18.57	0.099	1.85±0.14
Total	100.00	71.17	0.057	4.04±0.39

B_s^0 oscillation