Measurement of $\Delta\Gamma_d$ from $B^0 \to J/\psi K_s^0$ and $B^0 \to J/\psi K^{*0}$ decay channels

MSc Thesis Presentation

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20 April 2026

[1] A. Lenz and U. Nierste, Numerical updates of lifetimes and mixing parameters of B mesons, in CKM unitarity triangle (2010).
[2] Particle Data Group collaboration, Particle listings, B0, page 6 (2025).

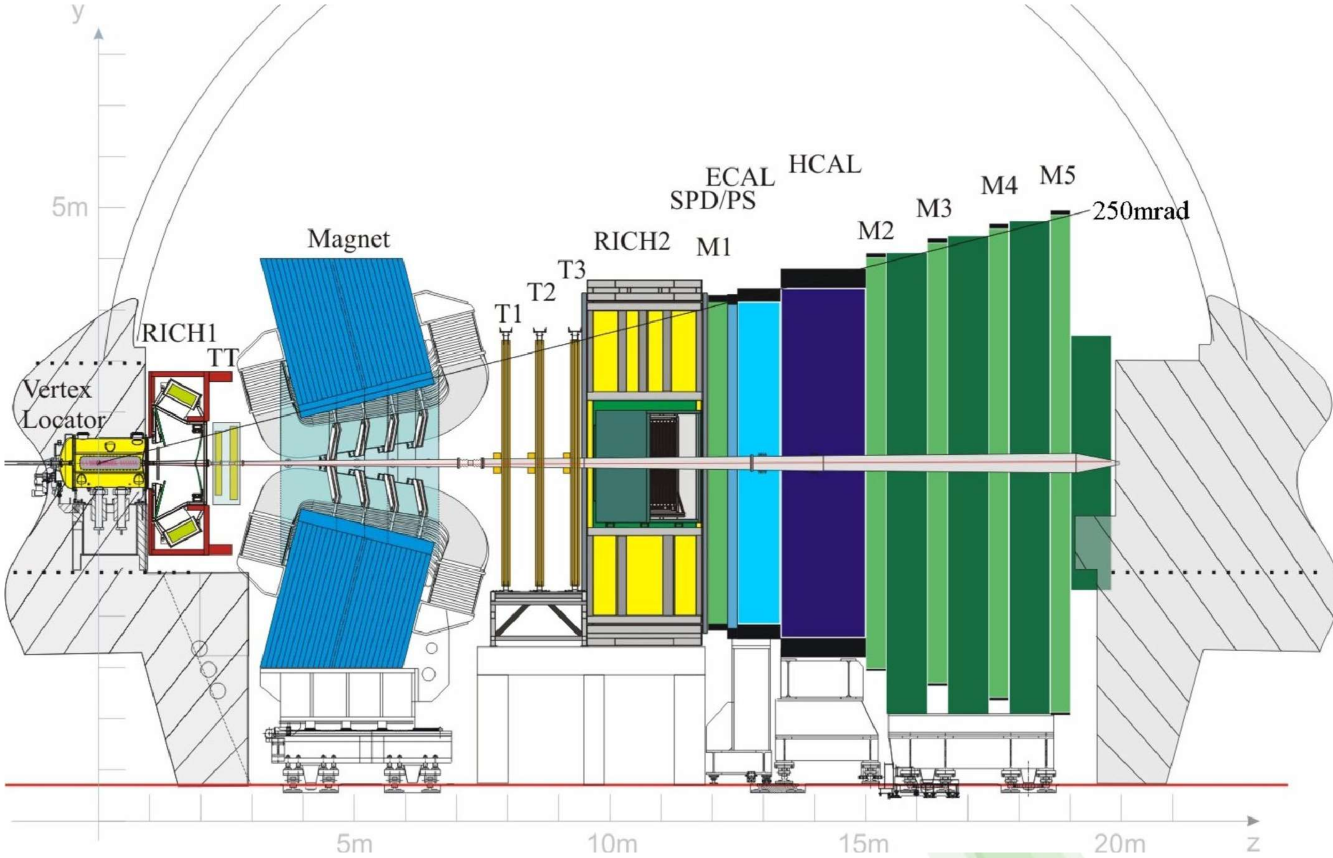
Goal of the thesis

- Measure $\Delta\Gamma_d$: difference in decay times between B_d^0 mass eigenstates
- Independent, stringent test on SM

- SM prediction: $\frac{\Delta\Gamma_d}{\Gamma_d} = (0.42 \pm 0.08) \times 10^{-2}$ [1]
- World average measurement: $\frac{\Delta\Gamma_d}{\Gamma_d} = (0.1 \pm 1.0) \times 10^{-2}$ [2]
- Very large uncertainty!

LHCb detector

- b-physics triggering
- time resolution and vertexing
- particle identification



Where to extract $\Delta\Gamma_d$ from?

- Method: Compare decay time distributions of
  - $B^0 \to J/\psi K_s^0$ (CP eigenstate)
  - $B^0 \to J/\psi K^{*0}$ (flavour-specific)

- Perform simultaneous fit to cancel out systematic uncertainties with LHCb Run2 data

Neutral meson mixing

- Effective Hamiltonian: $\mathbf{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$
- Define eigenstates of Hamiltonian as:

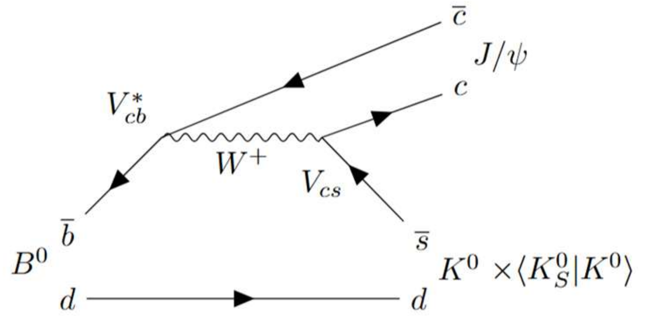
$$|B_H\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$
$$|B_L\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$
$$\rightarrow \Gamma_d = \frac{\Gamma_H + \Gamma_L}{2} \text{ and } \Delta\Gamma_d = \Gamma_L - \Gamma_H$$

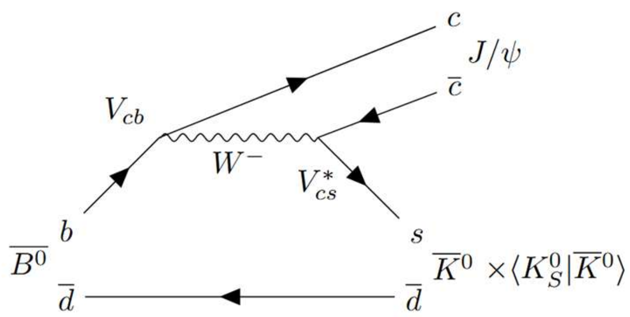
- Particle interaction as flavour states, but propagation as eigenstates of effective Hamiltonian
- Time evolution:

$$|B_H(t)\rangle = e^{-im_H t - \frac{1}{2}\Gamma_H t}|B_H(0)\rangle$$
$$|B_L(t)\rangle = e^{-im_L t - \frac{1}{2}\Gamma_L t}|B_L(0)\rangle$$

Channel specific decay rates

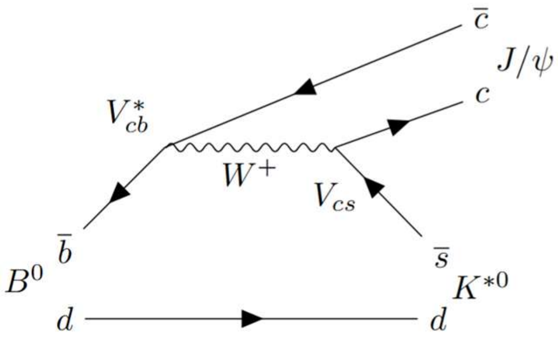
$$\Gamma_{B^0/\overline{B^0}\to J/\psi\,K^0_S}(t) = |A_{J/\psi\,K^0_S}|^2 e^{-\Gamma t}$$
$$\left(\left(1+\left|\frac{p}{q}\right|^2\right)\cosh\left(\frac{\Delta\Gamma t}{2}\right)+\left(1+\left|\frac{p}{q}\right|^2\right)\cos(2\beta)\sinh\left(\frac{\Delta\Gamma t}{2}\right)-\left(1-\left|\frac{p}{q}\right|^2\right)\sin(2\beta)\sin(\Delta m t)\right)$$

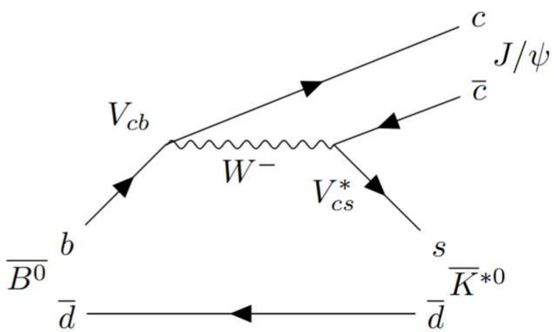




Channel specific decay rates

$$\Gamma_{B^0/\overline{B^0}\to J/\psi\, K^{*0}/\overline{K}^{*0}}(t) = \left|\overline{A}_{J/\psi\,\overline{K}^{*0}}\right|^2 \frac{e^{-\Gamma t}}{2}\left(\left(\left(2+\left|\frac{p}{q}\right|^2+\left|\frac{q}{p}\right|^2\right)\cosh\left(\frac{\Delta\Gamma t}{2}\right)+\left(2-\left|\frac{p}{q}\right|^2-\left|\frac{q}{p}\right|^2\right)\cos(\Delta m t)\right)$$





$$\left|\frac{q}{p}\right|^2 \approx 1$$

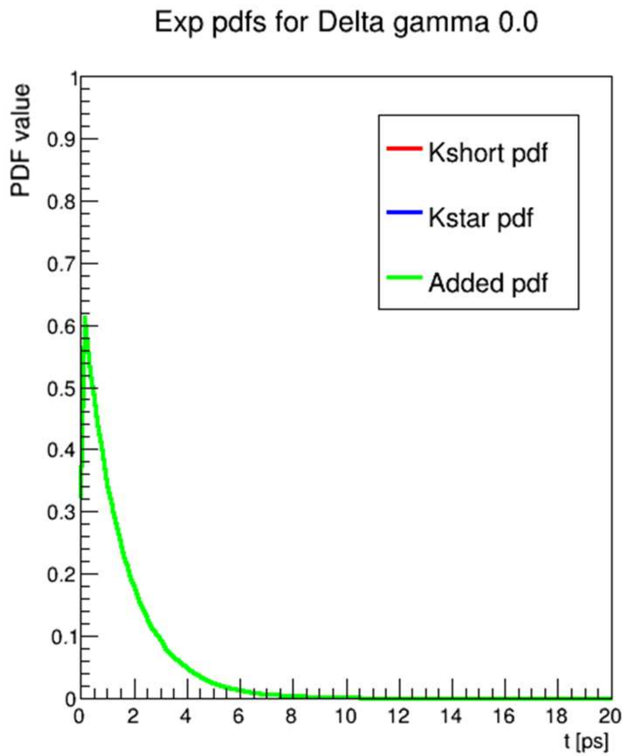
Channel specific decay rates

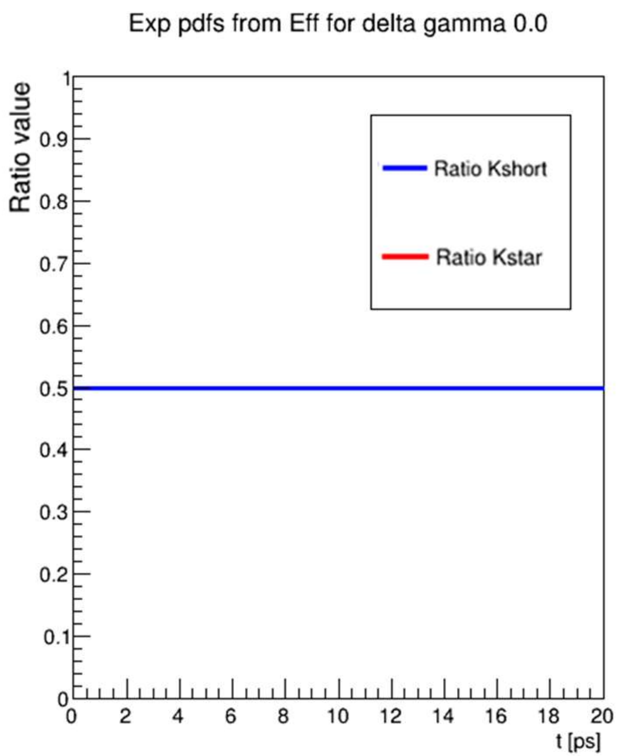
$$\Gamma_{B^0/\overline{B^0}\to J/\psi\, K_S^0}(t) = |A_{J/\psi\, K_S^0}|^2\; 2\, e^{-\Gamma t}\left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) + \cos(2\beta)\sinh\left(\frac{\Delta\Gamma t}{2}\right)\right)$$

$$\Gamma_{B^0/\overline{B^0}\to J/\psi\, K^{*0}/\overline{K}^{*0}}(t) = \left|\overline{A}_{J/\psi\, \overline{K}^{*0}}\right|^2 2e^{-\Gamma t}\cosh\left(\frac{\Delta\Gamma t}{2}\right)$$

Feasibility study

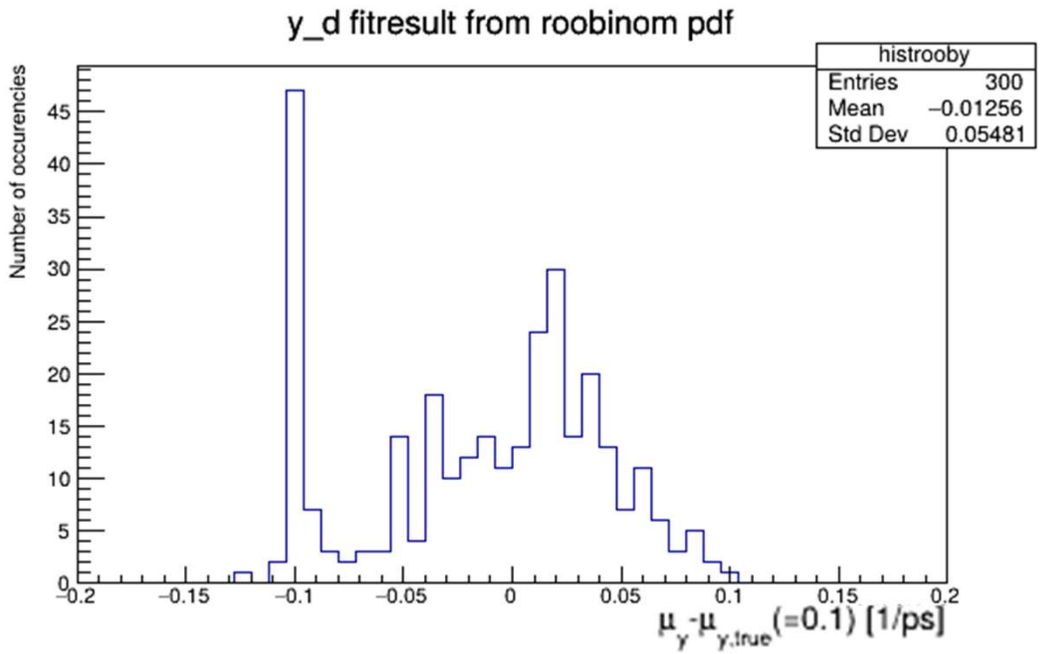
- Toys showing dependency of channel ratios on $\Delta\Gamma_d$
- $\text{ratio Kshort} = \dfrac{\text{Kshort events}}{\text{total events}}$

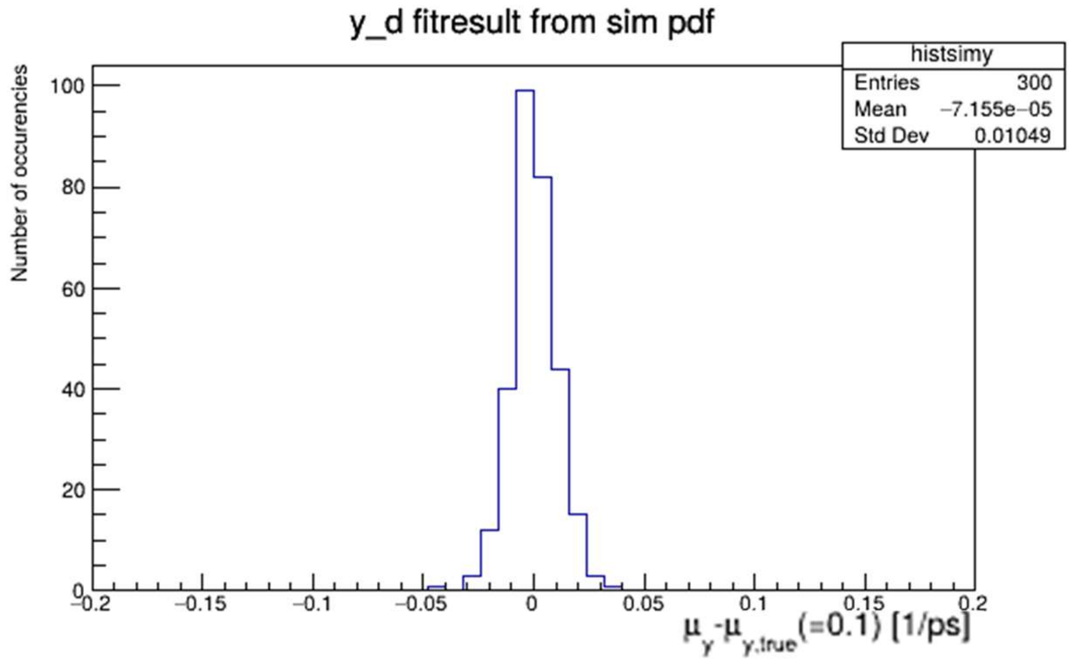




Feasibility study

- Compare two ways of fitting simultaneously: new model directly using ratio of the two samples and RooSimultaneous
- RooSimultaneous is best after all





Simultaneous fit to reduce uncertainties

- Simultaneous fit of $B^0 \to J/\psi K_s^0$ and $B^0 \to J/\psi K^{*0}$ Run 2 LHCb data 5.57 fb^{-1}
- Suppress common systematics (trigger, resolution, production asymmetry)
- Fit parameters: $\tau = \frac{1}{\Gamma_d}$ and $y = \frac{\Delta\Gamma_d}{2\Gamma_d}$ and a fraction of events in K^{*0} vs K_s^0 sample

$$\to \Gamma_d = \frac{\Gamma_H + \Gamma_L}{2} \text{ and } \Delta\Gamma_d = \Gamma_L - \Gamma_H$$

Analysis triggers

Description	Requirement
HLT1	Jpsi_Hlt1DiMuonHighMassDecision_TOS
	Bd_Hlt1TrackMuonMVADecision_TOS
	Bd_Hlt1TwoTrackMVADecision_TOS
HLT2	Jpsi_Hlt2DiMuonDetachedJPsiDecision_TOS

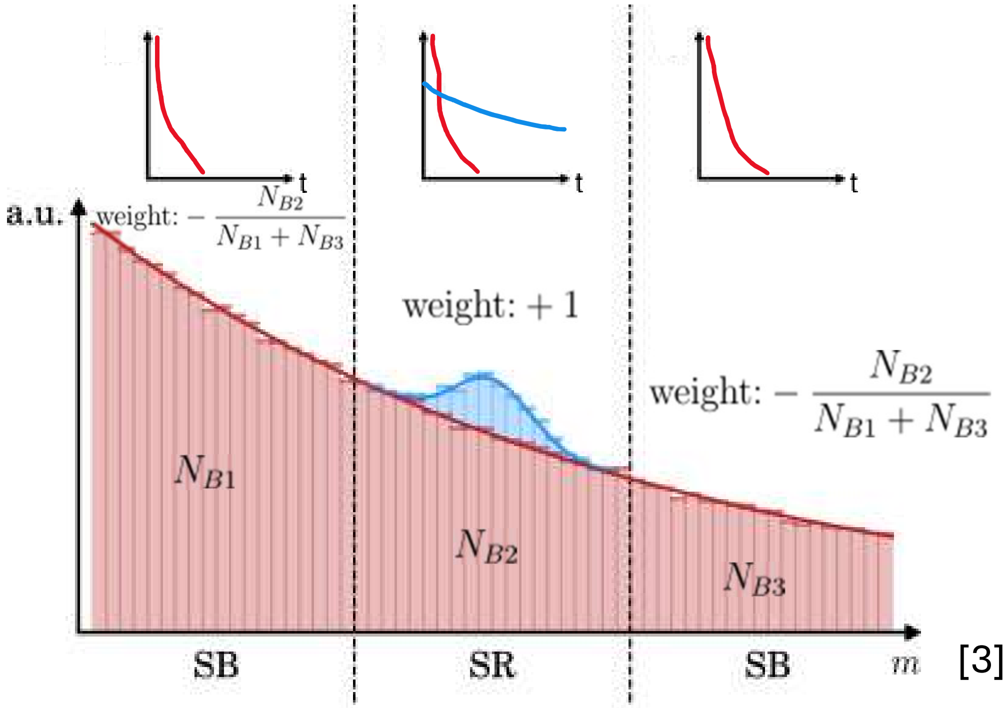
Decay time unbiased trigger

Decay time biased trigger

Account for with acceptance!

Analysis method: background subtraction

- Trigger, stripping, BDT selection on MC and data
- Create data sets with *sWeights*: sideband subtraction



[3]

Analysis method: resolution modelling

- RooSimultaneous of two extended RooBDecay PDFs convoluted with resolution model and cubic spline acceptance model:

$$\mathcal{P}(t\,|\,\sigma_t) = \varepsilon(t)\,[\mathcal{P}_{\text{true}}(t') \otimes \mathcal{R}(t-t'\,|\,\sigma_t)]$$

- $B^0 \to J/\psi K_s^0$: triple gaussian resolution model:

$$\mathcal{R}(t-t'-\mu_{\text{bias}}|\sigma_t) = \Sigma_{g=1}^{3} f_g \cdot G(t-t'-\mu_{\text{bias}};\sigma'_{g,t}),\ \sigma'_{g,t} = c_g\sigma_t + b_g$$ [4]

- $B^0 \to J/\psi K^{*0}$: effective single gaussian resolution model:

$$\mathcal{R}(t-t'-\mu_{\text{bias}}|\sigma_t) = G(t-t'-\mu_{\text{bias}};\sigma'_{\text{eff},t}),\ \sigma'_{\text{eff},t} = d\,\sigma_t^2 + c\,\sigma_t + b$$ [5]

[4] LHCb collaboration, Measurement of CP violation in B0 → ψ(→ ℓ+ℓ−)K0S (→ π+π−) decays, Phys. Rev. Lett. 132 (2024) 021801, arXiv:2309.09728

[5] LHCb collaboration, Observation of CP violation in B0 → J/ψρ(770)0 decays, arXiv:2601.15646, Submitted to Phys. Rev. Lett.

Analysis method: acceptance

- RooSimultaneous of two extended RooBDecay PDFs convoluted with resolution model and cubic spline acceptance model:

$$\mathcal{P}(t \mid \sigma_t) = \varepsilon(t)\,[\mathcal{P}_{\text{true}}(t') \otimes \mathcal{R}(t - t' \mid \sigma_t)]$$

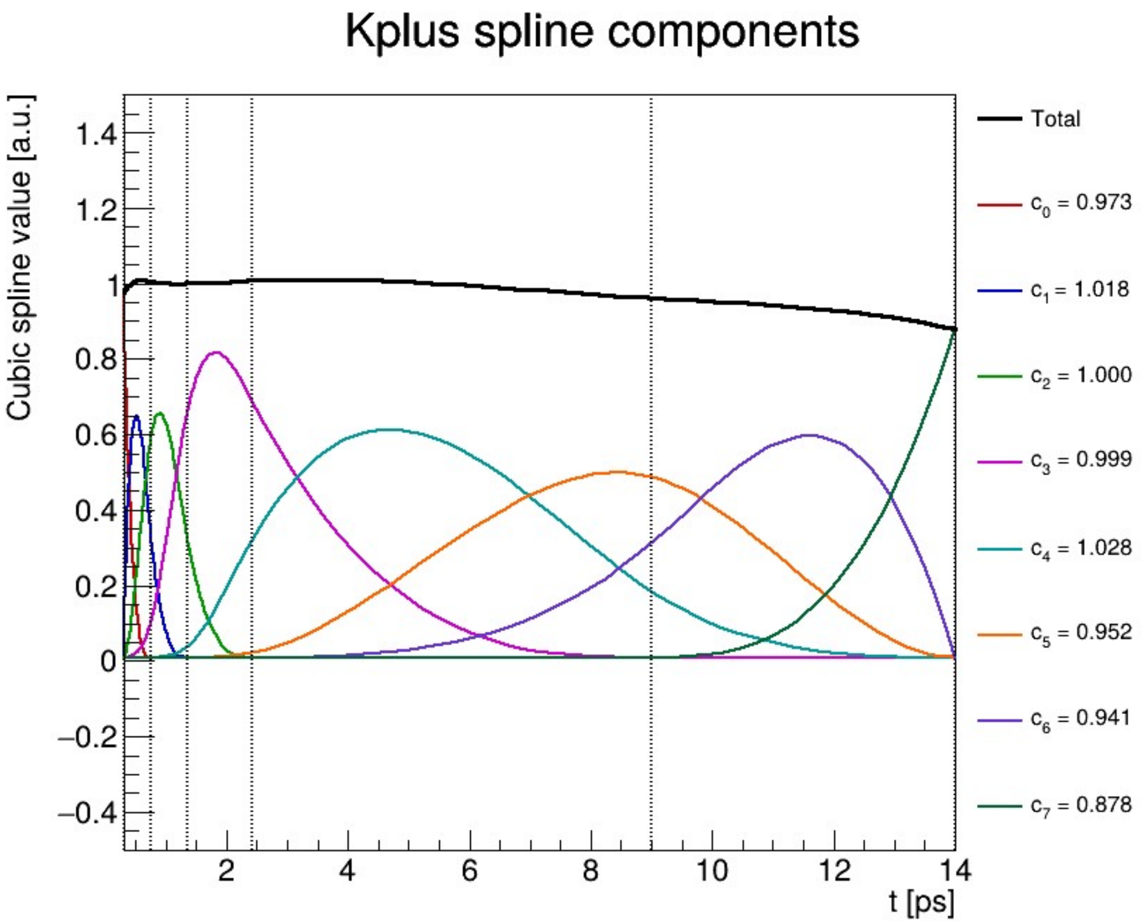
- Fit MC splines for $B^0 \to J/\psi K_s^0$, $B^0 \to J/\psi K^{*0}$ and control channel $B^+ \to J/\psi K^+$, then get $B^0 \to J/\psi K_s^0$ and $B^0 \to J/\psi K^{*0}$ splines for data with:

$$\varepsilon^{data}_{B^0 \to J/\psi K}(t) = \frac{\varepsilon^{MC}_{B^0 \to J/\psi K}(t)}{\varepsilon^{MC}_{B^+ \to J/\psi K^+}(t)} \cdot \varepsilon^{data}_{B^+ \to J/\psi K^+}(t)$$

- Snakemake pipeline for the analysis

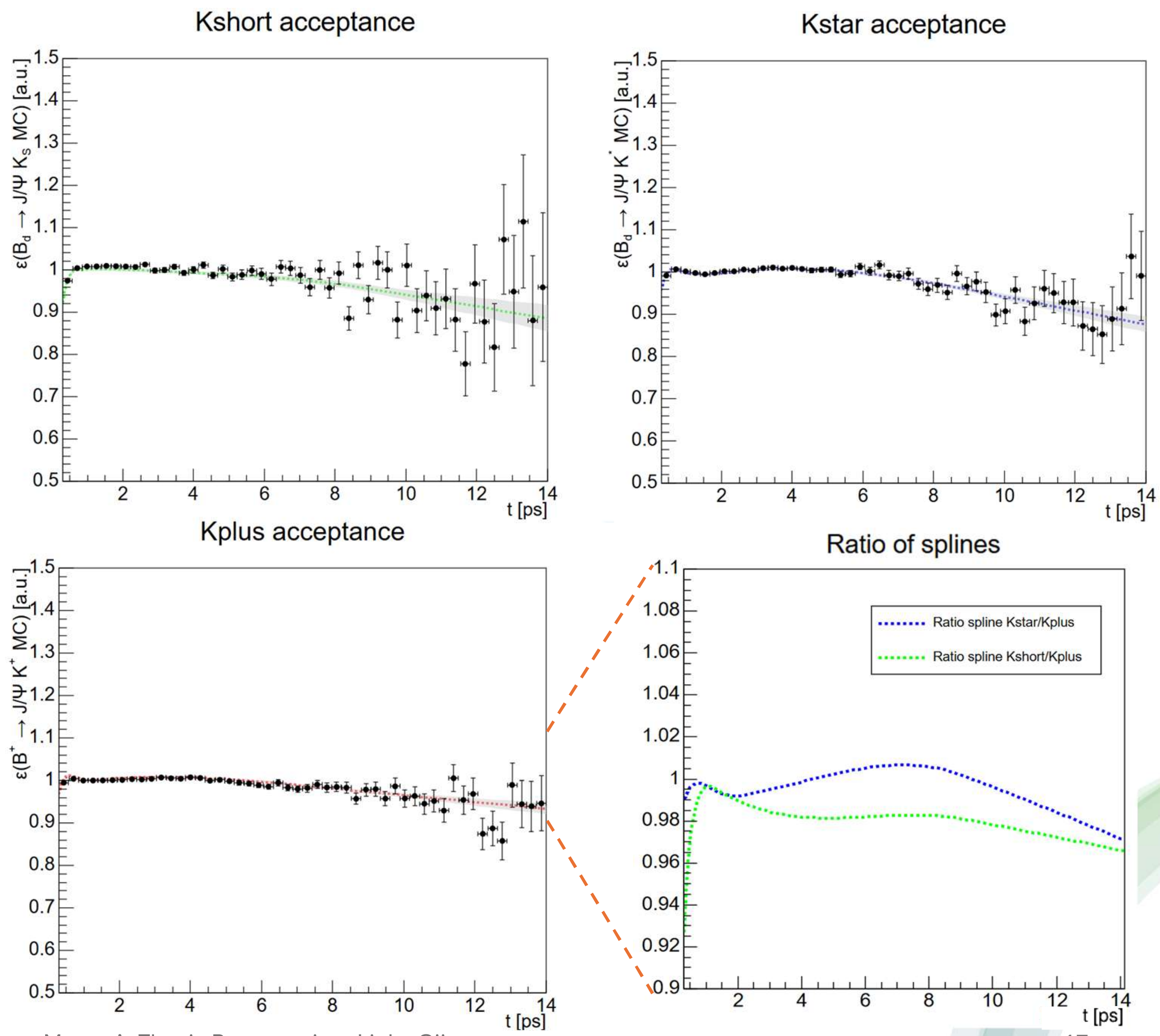
Acceptance

- Acceptance described by cubic spline
- Piecewise smooth function built from 3rd-order polynomials
- $S(t) = \sum_i \beta_i \, s_{i,m}(t)$
- Resistant to boundary conditions



Acceptance

- Described by cubic spline
- Cut events for t < 0.3 ps
- Equipopulated knots at [0.30, 0.75, 1.36, 2.42, 9.00] ps
- After final knot: linear function
- Fix basic spline at ~1-2 ps for normalisation
- Plots for unbiased trigger, 2018



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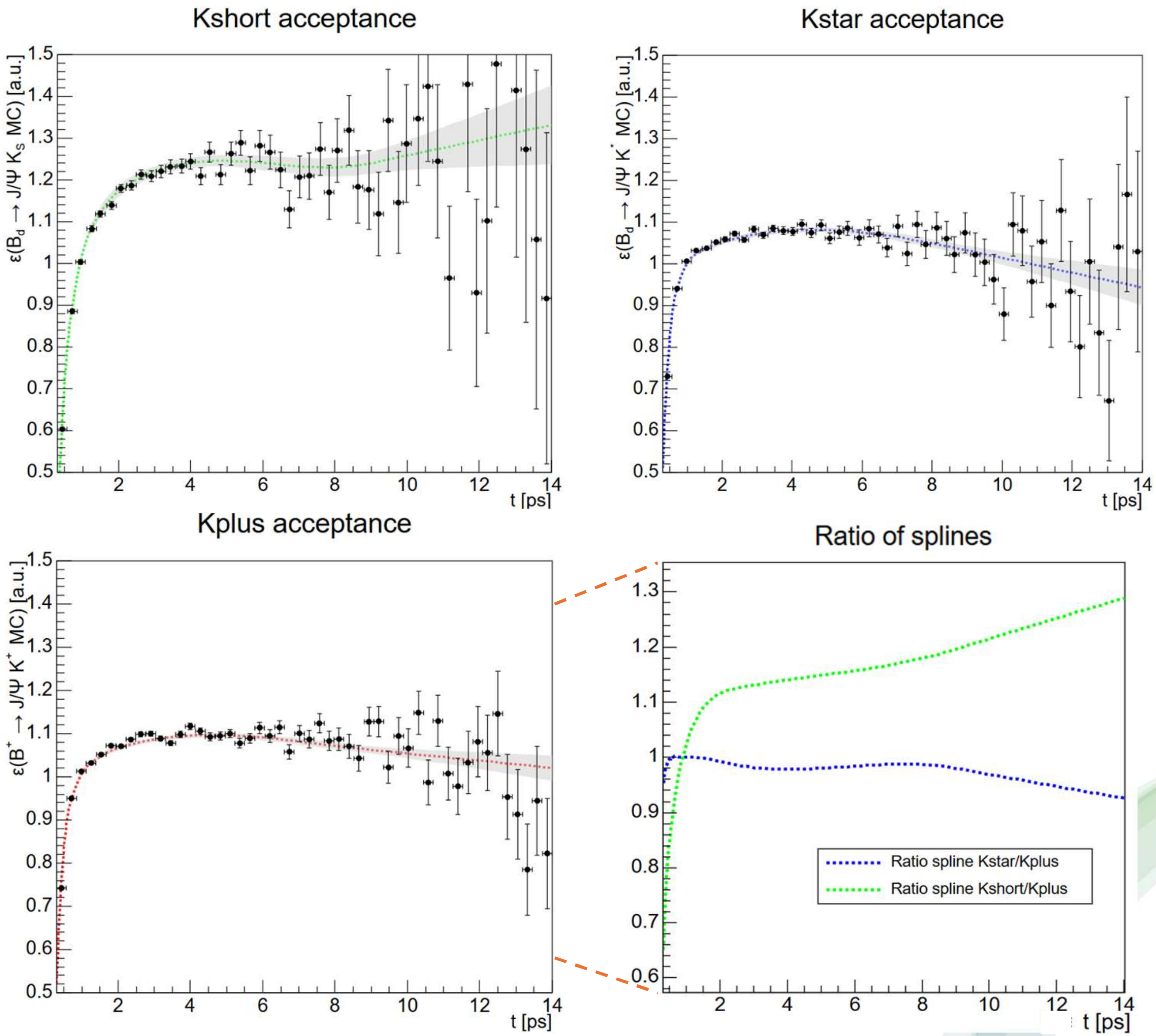
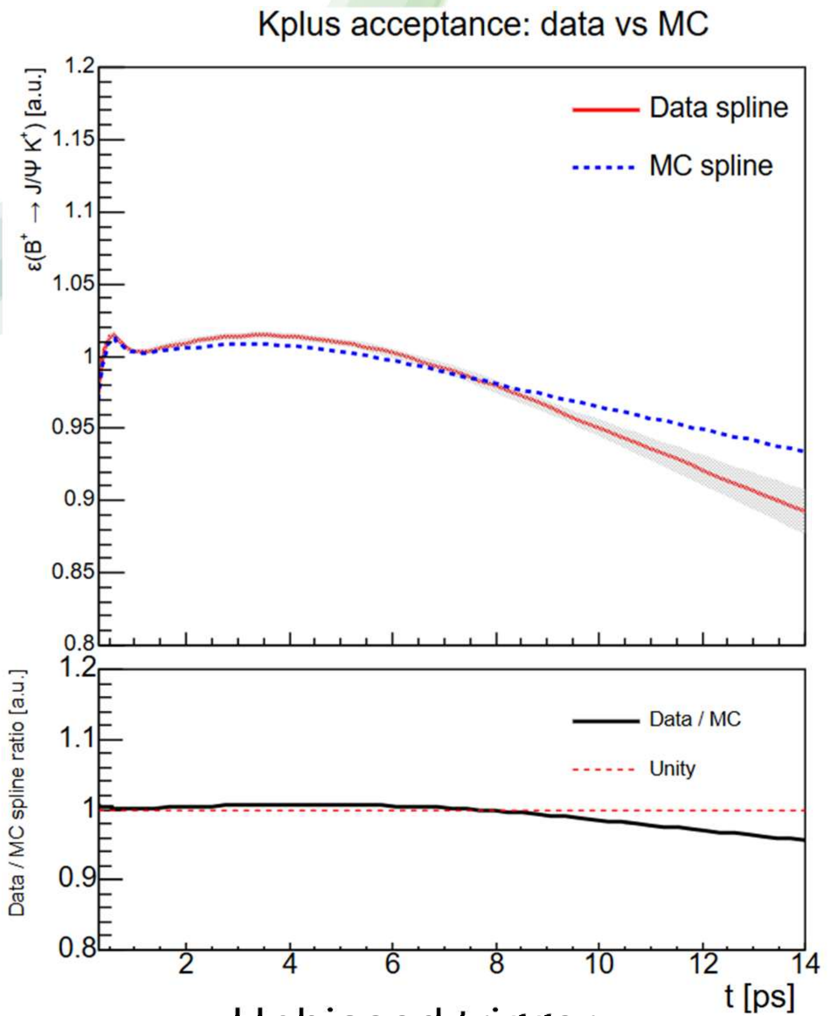
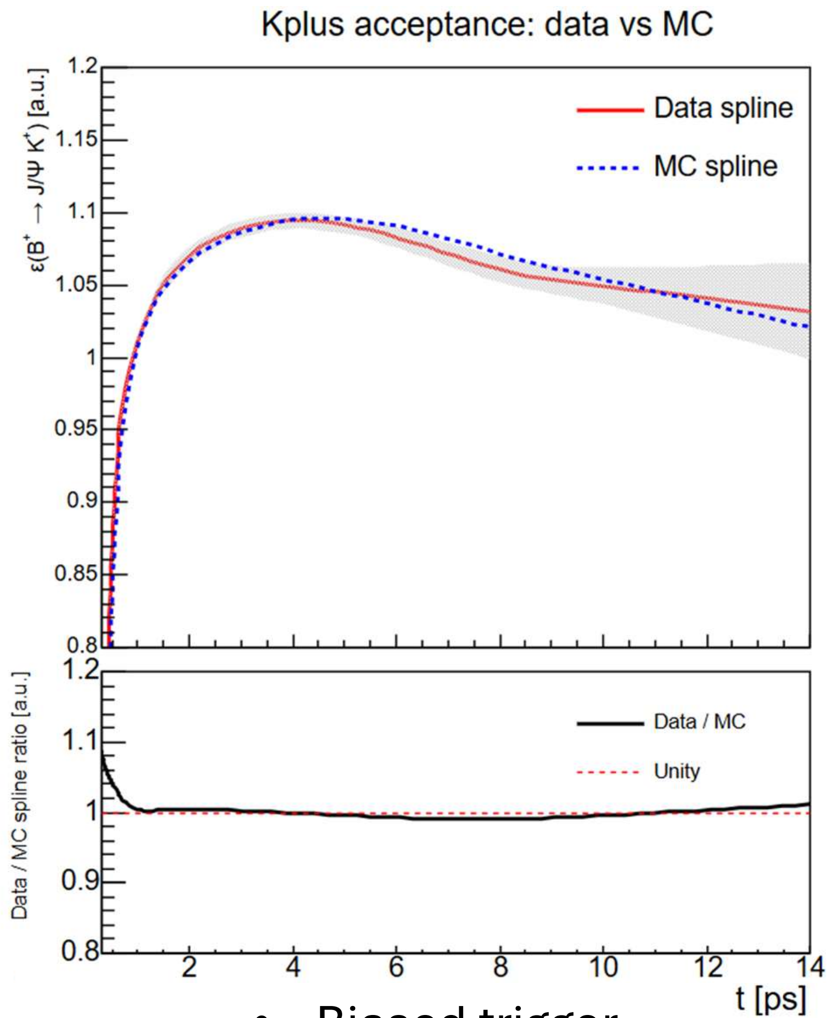


Acceptance

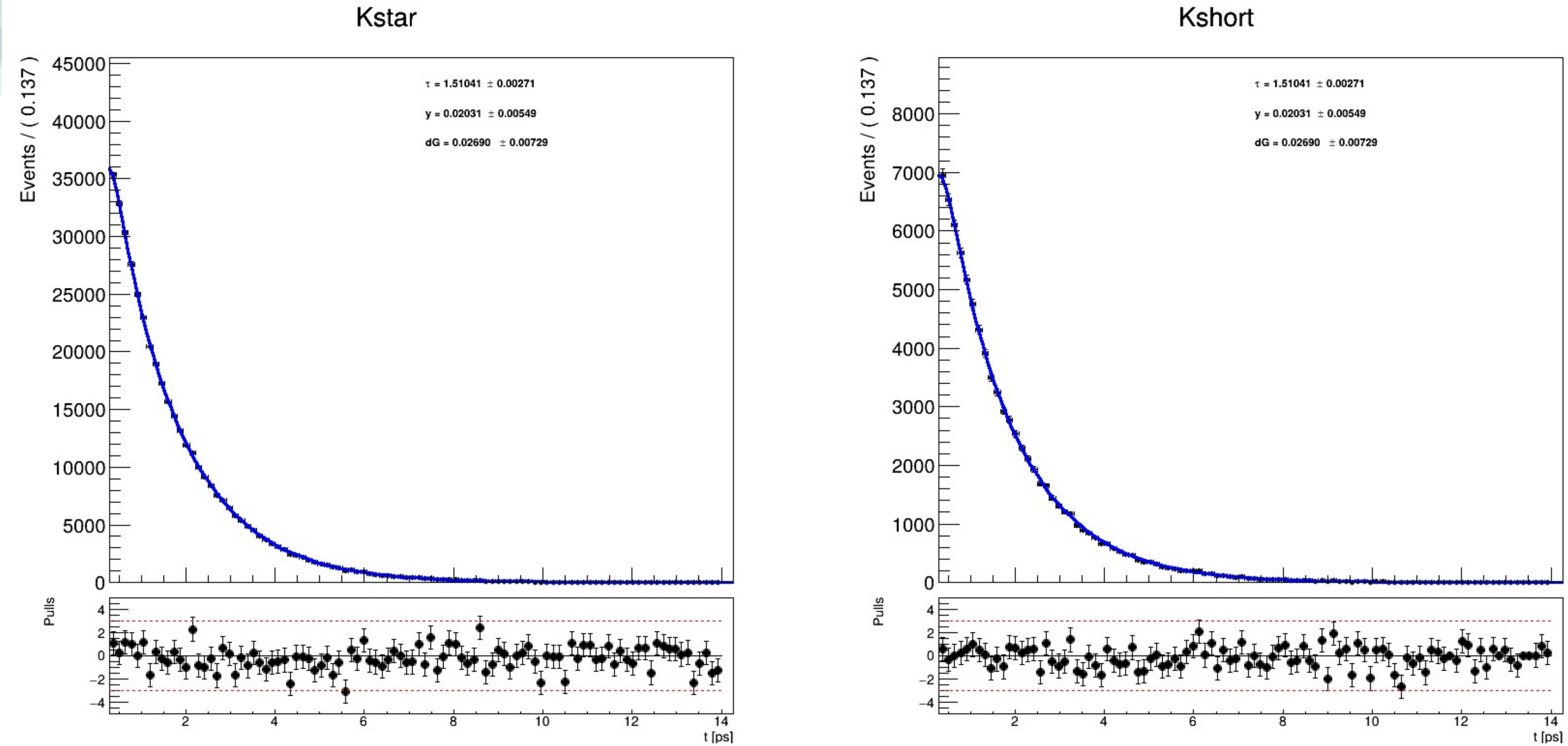




- Unbiased trigger
- Biased trigger

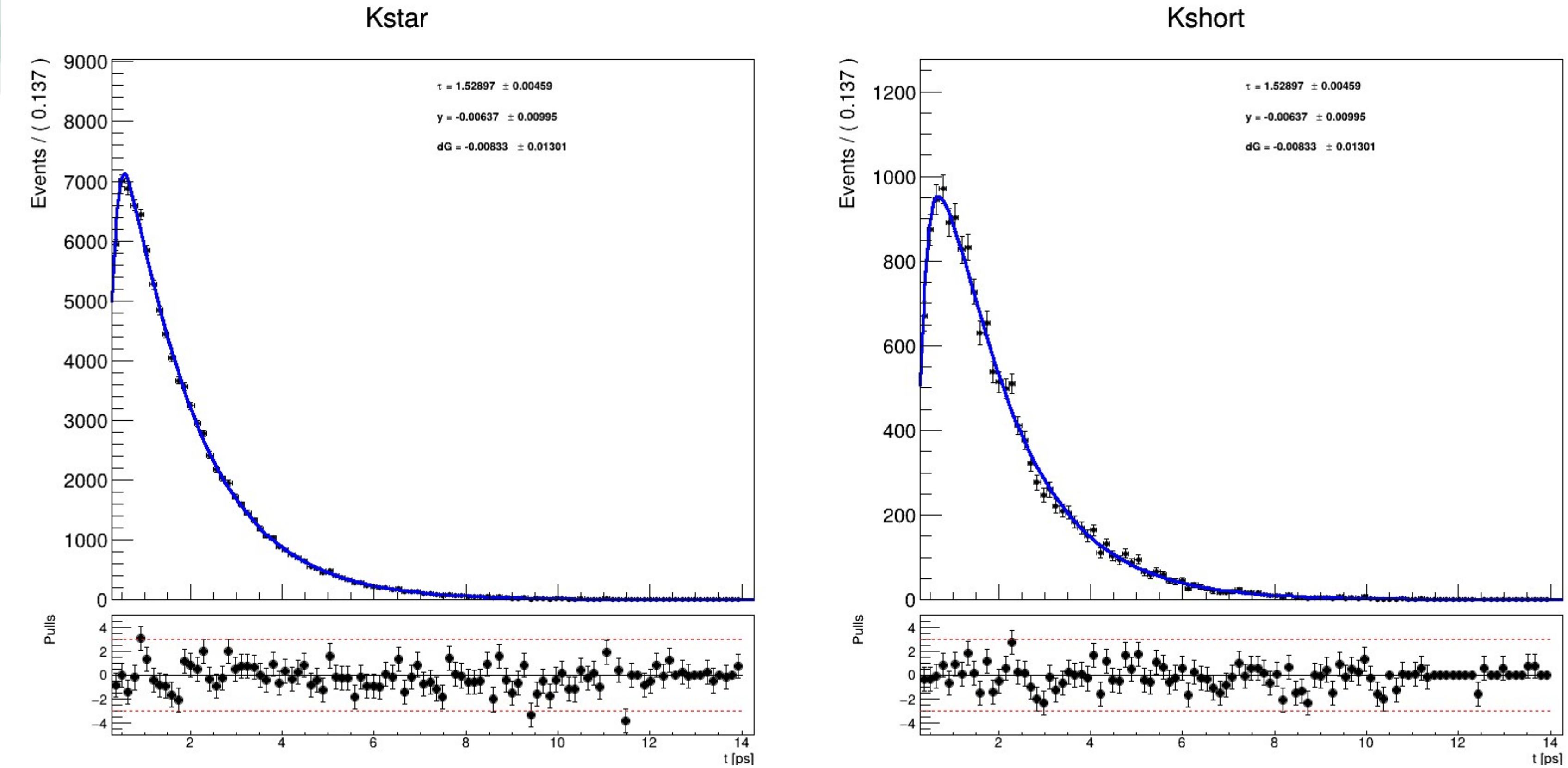
Simultaneous fit

- Final result, plot shows 2018 fit result
- Unbiased trigger result $\frac{\Delta\Gamma_d}{\Gamma_d} = (2.43 \pm 0.66) \times 10^{-2}(\text{stat.})$; $\tau = 1.5150 \pm 0.0016(\text{stat.})\text{ps}$



Simultaneous fit

- Final result, plot shows 2018 fit result
- Biased trigger result $\frac{\Delta\Gamma_d}{\Gamma_d} = (1.65 \pm 1.25) \times 10^{-2}(\text{stat.})$; $\tau = 1.5247 \pm 0.0030(\text{stat.})\,\text{ps}$



Simultaneous fit

- Unbiased trigger result: $\frac{\Delta\Gamma_d}{\Gamma_d} = (2.43 \pm 0.66) \times 10^{-2}(\text{stat.})$; $\tau = 1.5150 \pm 0.0016(\text{stat.})\text{ps}$
- Biased trigger result: $\frac{\Delta\Gamma_d}{\Gamma_d} = (1.65 \pm 1.25) \times 10^{-2}(\text{stat.})$; $\tau = 1.5247 \pm 0.0030(\text{stat.})\text{ps}$
- Combined trigger result: $\frac{\Delta\Gamma_d}{\Gamma_d} = (2.19 \pm 0.57) \times 10^{-2}(\text{stat.})$; $\tau = 1.5169 \pm 0.0014(\text{stat.})\text{ps}$

Systematic uncertainties

- Tested:
  - Spline knots independent
  - Time range independent
  - Constants independent
  - Resolution model: in progress
  - Spline parameters: in progress

Summary & outlook

- My result: $\frac{\Delta\Gamma_d}{\Gamma_d} = (2.19 \pm 0.57) \times 10^{-2}(\text{stat.})$
- SM prediction: $\frac{\Delta\Gamma_d}{\Gamma_d} = (0.42 \pm 0.08) \times 10^{-2}$ [1]
- World average: $\frac{\Delta\Gamma_d}{\Gamma_d} = (0.1 \pm 1.0) \times 10^{-2}$ [2]
- Better than world average!

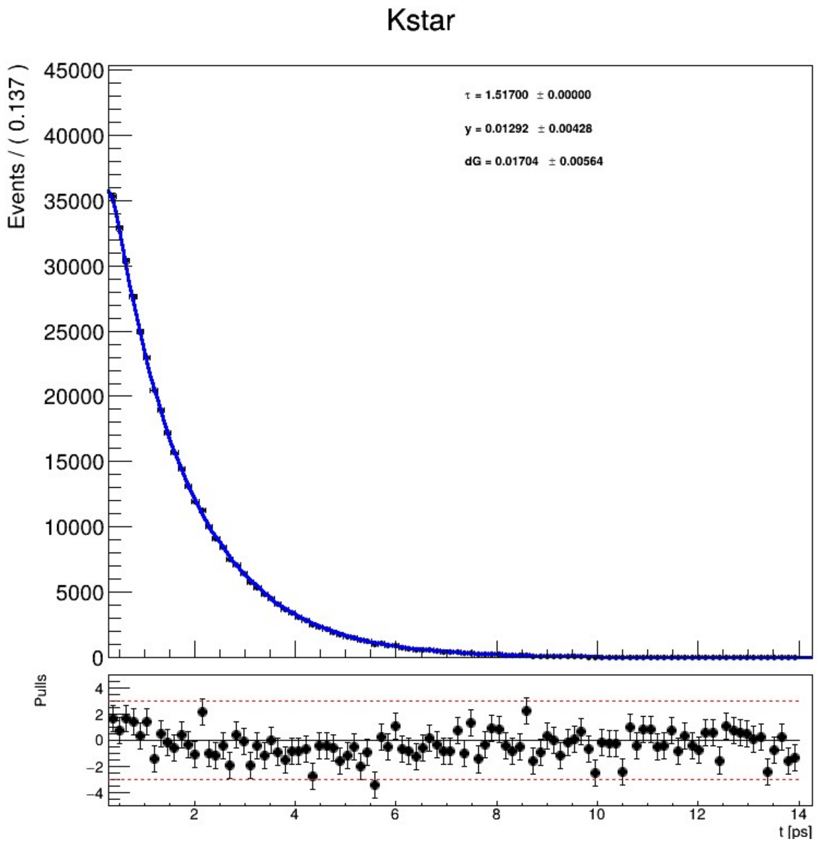
Summary & outlook

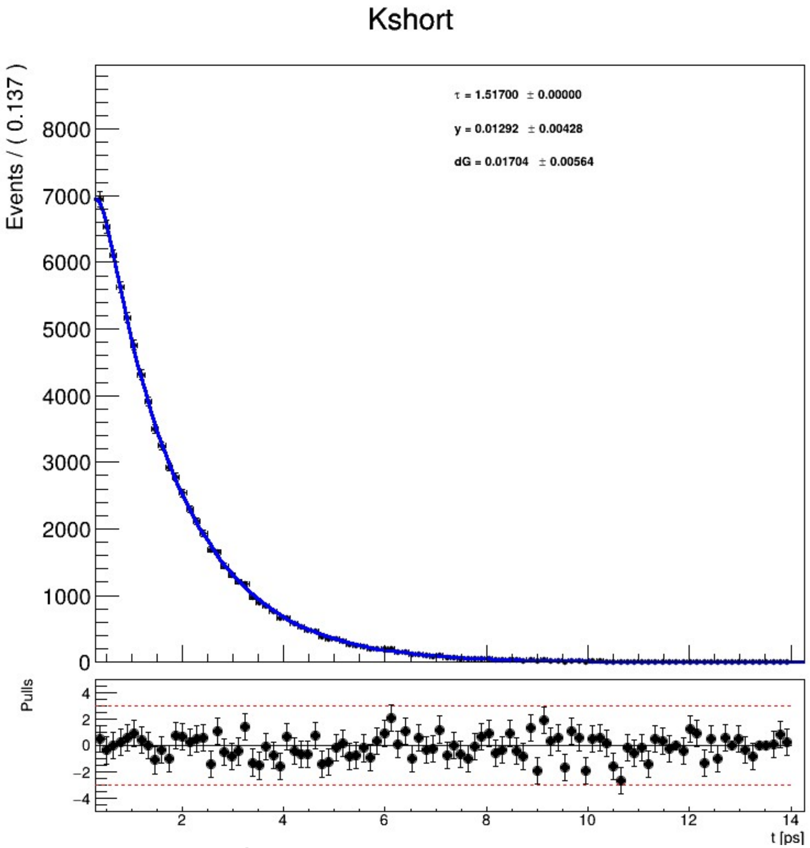
- RooSimultaneous better than 2 separate fits
- Kplus control mode for acceptance model
- Fitted Kshort and Kstar simultaneously
- Tested systematics
- Future work: resolution model for this analysis

Backup

Simultaneous fit

- Unbiased trigger result with fixed τ to PDG value of 1.517 ps -> assign systematic for this
- Final result: $\frac{\Delta\Gamma_d}{\Gamma_d} = (2.18 \pm 0.50) \times 10^{-2}(\text{stat.})$





Why use CP-eigenstate and flavour-specific state?

- Large difference in terms containing DGd, good statistics, reduced systematics
- Could use suppressed and favoured channels:
  - B0 -> $D(*)^{\pm}\pi^{\mp}$
  - Tagged analysis
  - Less statistics because less clean signal
- Could use CP-even CP-odd channels:
  - J/ψK0s / J/ψK0L
  - Have to disentangle CP-eigenvalues through angular analysis: less statistics
  - Or disentangle CP-eigenvalues with Dalitz plot analysis (which needs tagged analysis): lower statistics and systematic errors from Dalitz model
- Why not only use CP-eigenstate channel? -> large systematic uncertainties

Neutral meson mixing

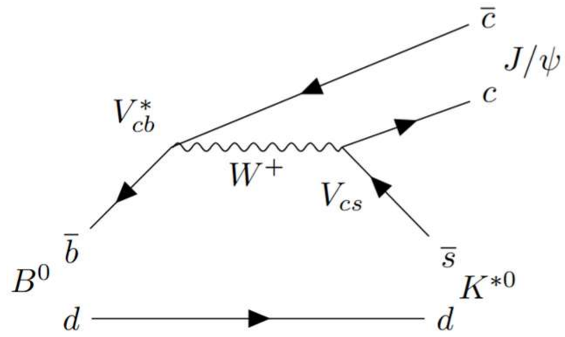
- $A_f = \langle f|T|B^0\rangle$; $\overline{A}_f = \langle f|T|\overline{B}^0\rangle$; $\Gamma_{B^0\to f}(t) = |\langle f|T|B^0(t)\rangle|^2$
- Gives master equations:

$$\Gamma_{B^0\to f}(t) = |A_f|^2 \frac{e^{-\Gamma t}}{2}\left(\left(1+|\lambda_f|^2\right)\cosh\left(\frac{\Delta\Gamma t}{2}\right) + 2\Re(\lambda_f)\sinh\left(\frac{\Delta\Gamma t}{2}\right) + \left(1-|\lambda_f|^2\right)\cos(\Delta m t) - 2\Im(\lambda_f)\sin(\Delta m t)\right)$$

$$\Gamma_{\overline{B}^0\to f}(t) = |A_f|^2 \left|\frac{p}{q}\right|^2 \frac{e^{-\Gamma t}}{2}\left(\left(1+|\lambda_f|^2\right)\cosh\left(\frac{\Delta\Gamma t}{2}\right) + 2\Re(\lambda_f)\sinh\left(\frac{\Delta\Gamma t}{2}\right) - \left(1-|\lambda_f|^2\right)\cos(\Delta m t) + 2\Im(\lambda_f)\sin(\Delta m t)\right)$$

- $\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}$

Where is A_p?

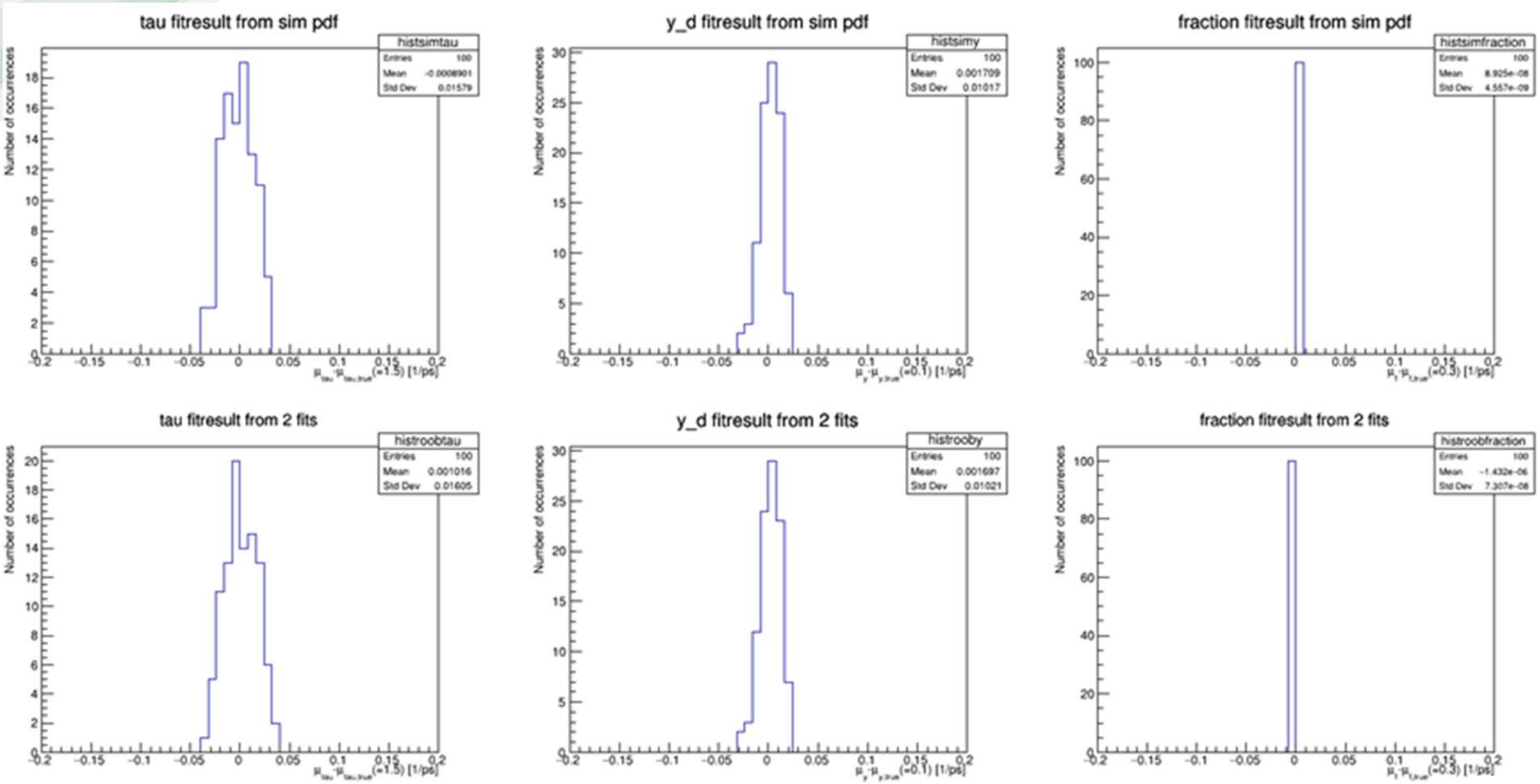


$$\Gamma_{B^0/\overline{B^0}\to J/\psi\, K^{*0}/\overline{K}^{*0}}(t) = \left|\overline{A}_{J/\psi\,\overline{K}^{*0}}\right|^2 \frac{e^{-\Gamma t}}{2}$$
$$\left(\left(2+(1+A_p)\left|\frac{p}{q}\right|^2+(1-A_p)\left|\frac{q}{p}\right|^2\right)\cosh\left(\frac{\Delta\Gamma t}{2}\right)+\left(2-(1+A_p)\left|\frac{p}{q}\right|^2-(1-A_p)\left|\frac{q}{p}\right|^2\right)\cos(\Delta m t)\right)$$

$$\Gamma_{B^0/\overline{B^0}\to J/\psi\, K^{*0}/\overline{K}^{*0}}(t) = \left|\overline{A}_{J/\psi\,\overline{K}^{*0}}\right|^2 \frac{e^{-\Gamma t}}{2}\left(\left(2+\left|\frac{p}{q}\right|^2+\left|\frac{q}{p}\right|^2\right)\cosh\left(\frac{\Delta\Gamma t}{2}\right)+\left(2-\left|\frac{p}{q}\right|^2-\left|\frac{q}{p}\right|^2\right)\cos(\Delta m t)\right)$$

Feasibility study

- Compared RooSimultaneous to an analysis which fits two separate lifetimes



Why simultaneous fit and not separate fits?

- Find all systematic uncertainties -> then later a lot of systematics cancels out, so a lot of work for nothing.
- Also it is not trivial in what way the systematic uncertainties cancel out -> complicated to get the systematic uncertainty from separate fits at all.

What was the new pdf?

- Calculate ratio of the samples as a function of the pdfs for those samples and the fraction of events in them
- Make efficiency pdf from this ratio
- Total model: two exponentials combined, but samples split by efficiency pdf:

```
model = ROOT.RooProdPdf("model", "model", {total_exps}, Conditional = ({effPdf_long}, {cut_sim}))
```

- What was wrong: efficiency was normalised, RooProdPdf wants efficiency to be normalised (shouldn't be)