First measurements of $B_s^0 \to J/\psi\phi$ at LHCb

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IoP NPPD 2011, Glasgow

Introduction

- This talk will focus on one of the flagship channels at LHCb: $B_s^0 \to J/\psi\phi$
- I will present results from the $36pb^{-1}$ collected at 7 TeV throughout 2010
- See Ailsa's slides for a description of LHCb

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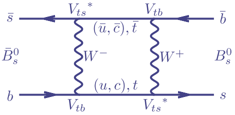
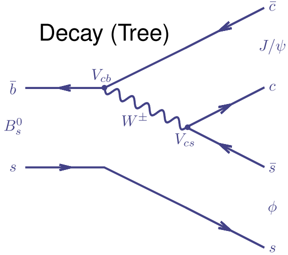
CP Violation in $B_s^0 \to J/\psi\phi$

Mixing



Decay (Tree)

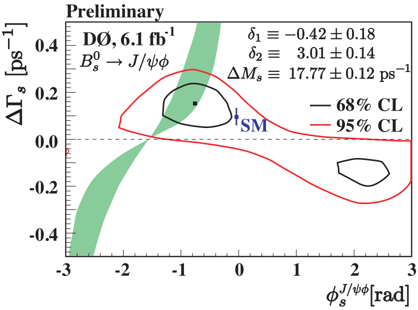


- B_s^0 and $\overline{B}_s^0$ **mix**: States oscillate as a function of time
- Both can **decay** to $J/\psi\phi$ as it's a CP eigenstate
- CP Violating weak phase difference between the interfering amplitudes, $\phi_s = \phi_{\rm mix} - 2\phi_{\rm decay}$
- ϕ_s precisely predicted in the SM: $\phi_s = -2\beta_s = -0.036 \pm 0.002$ rad (excluding penguin pollution)
- $\phi_{\rm decay}$ is dominated by SM contribution, but new physics can alter $\phi_{\rm mix}$
- This can also affect the decay width difference, $\Delta\Gamma_s$

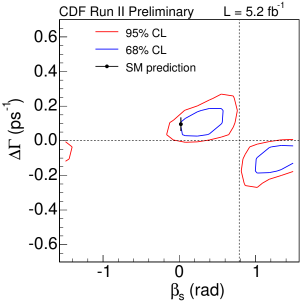
Hints of New Physics?

- Both Tevatron experiments have measured ϕ_s, originally finding a combined $\sim 2\sigma$ deviation from $-2\beta_s$
- Since then this deviation has decreased with higher statistics, but the errors are still large

DØ Conf Note 6093



CDF Public Note 10206



- LHCb is in a unique position to make the most precise measurement of ϕ_s in $B_s^0 \to J/\psi\phi$
- We can also boost sensitivity with our latest observation: $B_s^0 \to J/\psi f_0(980)$

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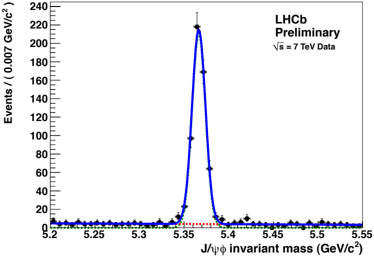
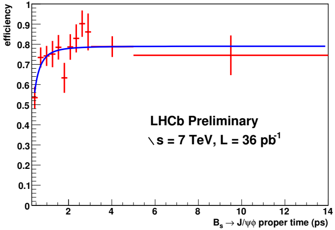
Trigger and Selection

- We use a common selection for $B_s^0 \to J/\psi\phi$ and control channels
- All samples are selected with $\tau > 0.3$ ps to reduce prompt J/ψ background
- Two trigger types used: lifetime "unbiased" and "biased".
- After selection, 757 ± 28 signal candidates





- "unbiased" sample gets a small correction determined from MC: $\epsilon_R(t) \propto 1 + \beta t$ with $\beta = -0.0250 \pm 0.0016$ ps^{-1}
- "biased" sample acceptance determined from data: $\epsilon_B(t) \propto \epsilon_R(t) \cdot (a \cdot t)^c / (1 + (a \cdot t)^c)$

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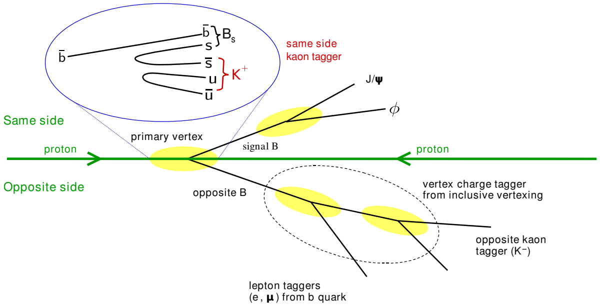
Flavour tagging

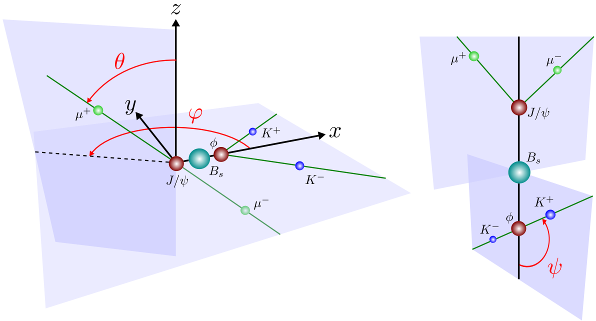
- To measure ϕ_s we need to know the B_s^0 flavour at the production vertex
- B_s^0 flavour is determined by **tagging** algorithms:
  - Opposite Side **(OS)**: Decay products of the other b-meson
  - Same Side **(SS)**: particles produced in fragmentation alongside signal B



- At present we only use OS tagging. This is optimised and calibrated on control channels
  $\epsilon_{eff}(J/\psi\phi) = \epsilon(1-2\omega)^2 = 2.66 \pm 0.12\%$ determined from $B^+ \to J/\psi K^+$
- Per-event mistag probability (η) treated in the fit, Gaussian constraints on P_0, P_1:
  $\omega = P_0 + P_1(\eta - <\eta>)$

Measurement by angular analysis

- $B_s^0 \to J/\psi\phi$ is a pseudoscalar to vector vector decay
- Three polarisation amplitudes and phases:
  - $|A_0|^2, |A_\parallel|^2\ \delta_0, \delta_\parallel$ (CP-even)
  - $|A_\perp|^2, \delta_\perp$ (CP-odd)
- S-wave component introduces another amplitude and phase: $|A_s|^2, \delta_s$
- These must be extracted by angular analysis
- LHCb uses the transversity basis to define the angles θ, φ, ψ:



Untagged Analysis

- The untagged analysis is an interim step on the way to measuring ϕ_s
- Permits extraction of Γ_s and $\Delta\Gamma_s$ as well as two amplitudes.
- This is still a complicated fit!
  - Uses the full ϕ_s PDF with $\phi_s = 0$, without tagging information
  - Only lifetime-unbiased events are used
    - **Observables**: $\theta,\ \varphi,\ \psi,\ t,\ m_{B_s^0}$
    - **Physics parameters**: $\Gamma_s,\ \Delta\Gamma_s,\ \Delta m_s,\ \delta_{\parallel},\ |A_0|^2,\ |A_{\perp}|^2$
    - **Detector parameters**: time, mass resolutions, angular acceptances, etc
- Two separate fitting strategies, three fitters independently verified:
  - All strategies show excellent agreement

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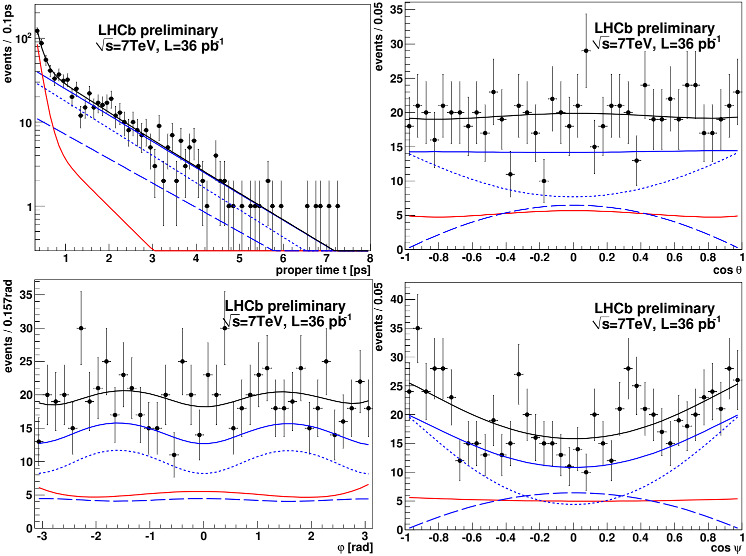
The Untagged Fit

- Untagged fit projections in time and angles



Signal CP-even: - - - CP-odd: · · · Background

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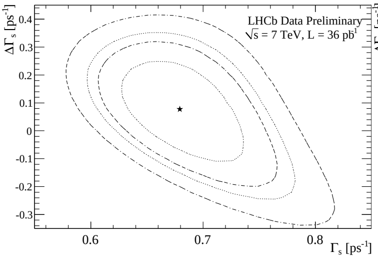
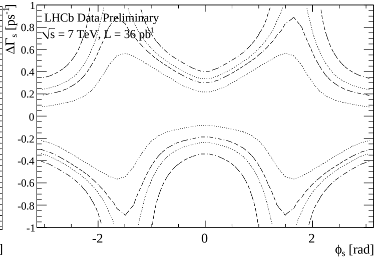
Untagged Results

		LHCb, 36pb^{-1}	CDF 5.2fb^{-1}
Γ_s	=	$0.679 \pm 0.036 \pm 0.027$ ps^{-1}	$0.654^{\dagger} \pm 0.016 \pm 0.008$ ps^{-1}
$\Delta\Gamma_s$	=	$0.077 \pm 0.119 \pm 0.021$ ps^{-1}	$0.075 \pm 0.035 \pm 0.01$ ps^{-1}
$\lvert A_\perp\rvert^2$	=	$0.263 \pm 0.056 \pm 0.014$	$0.245^{\dagger} \pm 0.014 \pm 0.015$
$\lvert A_0\rvert^2$	=	$0.528 \pm 0.040 \pm 0.028$	$0.524 \pm 0.013 \pm 0.015$

- Remarkable agreement between LHCb, CDF results!
- 68, 90, 95, 99% C.L. Contours:





- $\Gamma_s, \Delta\Gamma_s$ Profile Likelihood
- Central value denoted by $\star$
- $\phi_s, \Delta\Gamma_s$ Profile Likelihood
- Four-fold ambiguity.

† Parameters transformed from CDF note: $\Gamma_s = 1/c\tau_s$, $|A_\perp|^2 = 1 - |A_{||}|^2 - |A_0|^2$

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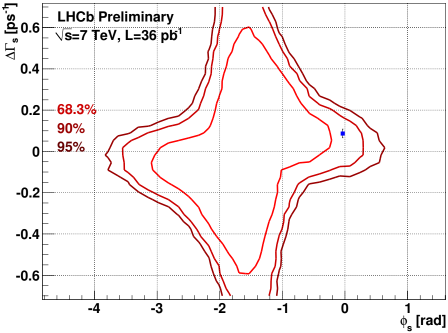
Tagged Analysis

- For the tagged analysis we make use of the tagging information and per-event mistag (η)
- To increase sensitivity we include the biased dataset
  - $\approx$ 30% more events
  - Simultaneous fit to both samples to extract physics parameters
- Additional parameters in the tagged fit: $\phi_s, \delta_\perp, \eta$, tag, mistag calibration
- As with the untagged analysis, several independent fitters and strategies
  - Results show good agreement

NEW! Tagged Results

- Presenting LHCb's first measurement of ϕ_s, simultaneously at Beauty '11
- Feldman-Cousins corrected C.L. contour, statistical uncertainties only
- SM value is in blue



- Tagging reduces the 4-fold ambiguity to a 2-fold one
- Coverage-corrected confidence interval for ϕ_s, statistical uncertainties only:

$$\phi_s \in [-2.7;\ -0.5]\text{rad at } 68\%\text{ CL}$$
$$\phi_s \in [-3.5;\ 0.2]\text{rad at } 95\%\text{ CL}$$
$$1.2\sigma \text{ deviation from SM}$$

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Conclusions

- With the first 36pb^{-1} LHCb finds good agreement with Tevatron results
- 1fb^{-1} is expected this year: $\approx 25k$ signal events
- The analysis is in excellent shape, ready for this data
- Extrapolated **conservative** sensitivity with this years' data: $\sigma\phi_s = 0.12$ rad excluding SS tagger
- With it we will be able to make the single most precise measurement of ϕ_s in $B_s^0 \to J/\psi\phi$
- We will also measure ϕ_s in other channels

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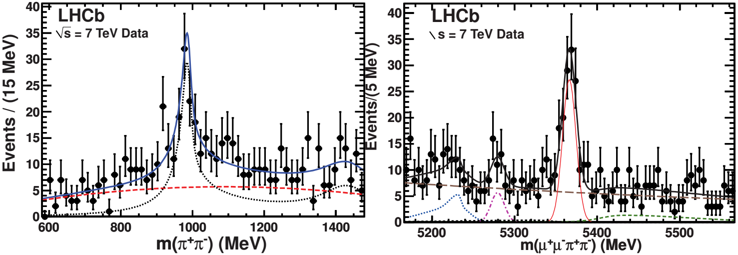
First Observation of $B_s^0 \to J/\psi f_0(980)$

- $B_s^0 \to J/\psi f_0(980)$ is a single CP-odd eigenstate. No need for angular analysis as with $B_s^0 \to J/\psi \phi$
- This simplifies the extraction of ϕ_s
- LHCb has made the first observation of $B_s^0 \to J/\psi f_0(980)$! arxiv:1102.0206v2 [hep-ex]



- 111 ± 14 signal events within $m_{B_s^0} \pm 30$ MeV (33pb^{-1})

Systematics

- In general, systematics are very small. This analysis will benefit greatly from larger statistics this year

Effect	Abs. deviation for parameter				
	Γ_s	$\Delta\Gamma_s$	$\lvert A_\perp\rvert^2$	$\lvert A_\parallel\rvert^2$	$\delta_\parallel$
Lifetime resolution	0.0001	-	-	-	-
Angular acceptance	-	-	-	0.0007	-
Acceptance parametrization	0.0002	0.001	0.0017	0.0013	-
Lifetime acceptance	**0.0272**	0.001	0.0003	0.0002	-
S-wave	0.003	0.003	**0.013**	**0.028**	**0.13**
Background description	0.0002	**0.02**	0.0016	0.0012	-
Mass model	0.0004	0.004	0.0032	0.0006	-
Σ (quadrature)	0.0274	0.0206	0.0136	0.0281	0.13

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Selection

- Selection optimised to minimise bias on propertime
- Common to $J/\psi\ \phi$ and control channels

Decay mode	Cut parameter	Stripping value	Selection value
$J/\psi \to \mu^-\mu^+$	$\Delta_{LL}(\mu^\pm - \pi^\pm)$	> 0	> 0
	$\chi^2_{track}/nDoF(\mu^-)$	< 5	< 4
	$min(p_T(\mu^-), p_T(\mu^+))$	-	> 0.5 GeV/c
	$\chi^2_{vtx}/nDoF(J/\psi)$	< 16	< 11
	$\lvert M(\mu^-\mu^+) - M(J/\psi)\rvert$	< 60 MeV/c^2	< 60 MeV/c^2
$\phi \to K^+K^-$	$\Delta_{LL}(K^\pm - \pi^\pm)$	> -2	> 0
	$\chi^2_{track}/nDoF(K^\pm)$	< 5	< 4
	$p_T\ (\phi)$	$>$ 1GeV/c	$>$ 1 GeV/c
	$M(\phi)$	$\in$ [980, 1050] MeV/c^2	$\in$ [1008, 1032] MeV/c^2
	$\chi^2_{vtx}/nDoF(\phi)$	< 16	< 16
$B_s^0 \to J/\psi\,\phi$	$M(B_s^0)$	$\in$ [5100, 5550] MeV/c^2	$\in$ [5200, 5550] MeV/c^2
	$\chi^2_{vtx}/nDoF(B_s^0)$	< 10	< 10
	$\chi^2_{DTF(B+PV)}/nDoF(B_s^0)$	-	< 5
	$IP\chi^2(B_s^0)$	-	< 25

Signal Yields

- All events:

	all	($t > 0.3$)	signal yield	signal yield ($t > 0.3$)
unbiased-only	38225	250	230 ± 53	161 ± 13
biased-only	653	345	208 ± 16	196 ± 15
both	1123	521	398 ± 22	400 ± 20
total	40001	1116	836 ± 60	757 ± 28

- Only tagged events:

	all	($t > 0.3$)	signal yield	signal yield ($t > 0.3$)
unbiased-only	7443	58	52 ± 24	36 ± 6
biased-only	150	83	56 ± 9	52 ± 8
both	315	136	111 ± 12	115 ± 11
total	7908	277	219 ± 28	203 ± 15

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Differential Decay rates

- Differential Decay rates for $\overline{\mathrm{B}}_s^0$, highlighted signs flip for B_s^0

$$|\bar{A}_0(t)|^2 = |\bar{A}_0(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\phi_s \sin(\Delta m_s t)\right]$$

$$|\bar{A}_\parallel(t)|^2 = |\bar{A}_\parallel(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\phi_s \sin(\Delta m_s t)\right]$$

$$|\bar{A}_\perp(t)|^2 = |\bar{A}_\perp(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\phi_s \sin(\Delta m_s t)\right]$$

$$\Im\mathfrak{m}\{\bar{A}_\parallel^*(t)\bar{A}_\perp(t)\} = |\bar{A}_\parallel(0)||\bar{A}_\perp(0)|e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_\parallel)\sin\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right.$$
$$\left. - \sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t) + \cos(\delta_\perp - \delta_\parallel)\cos\phi_s \sin(\Delta m_s t)\right]$$

$$\Re\mathfrak{e}\{\bar{A}_0^*(t)\bar{A}_\parallel(t)\} = |\bar{A}_0(0)||\bar{A}_\parallel(0)|e^{-\Gamma_s t}\cos\delta_\parallel\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right.$$
$$\left. - \sin\phi_s \sin(\Delta m_s t)\right]$$

$$\Im\mathfrak{m}\{\bar{A}_0^*(t)\bar{A}_\perp(t)\} = |\bar{A}_0(0)||\bar{A}_\perp(0)|e^{-\Gamma_s t}\left[-\cos\delta_\perp \sin\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right.$$
$$\left. - \sin\delta_\perp \cos(\Delta m_s t) + \cos\delta_\perp \cos\phi_s \sin(\Delta m_s t)\right]$$

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S-wave

- S-wave introduces additional amplitude and phase, A_S, δ_S:

$$
\begin{aligned}
|A_S(t)|^2 &= |A_S|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\phi_s \sin(\Delta m_s t)\right] \\
\Re\mathfrak{e}\,\{A_S^*(t)A_\parallel(t)\} &= |A_S||A_\parallel| e^{-\Gamma_s t}\left[-\sin(\delta_\parallel - \delta_S)\sin\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right. \\
&\quad \left. + \cos(\delta_\parallel - \delta_S)\cos(\delta m_s t) - \sin(\delta_\parallel - \delta_S)\cos\phi_s \sin(\Delta m_s t)\right] \\
\Im\mathfrak{m}\{A_S^*(t)A_\perp(t)\} &= |A_S||A_\perp| e^{-\Gamma_s t}\sin(\delta_\perp - \delta_S)\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right. \\
&\quad \left. - \sin\phi_s \sin(\Delta\Gamma_s t)\right] \\
\Re\mathfrak{e}\,\{A_S^*(t)A_0(t)\} &= |A_S||A_0| e^{-\Gamma_s t}\left[-\sin(\delta_0 - \delta_S)\sin\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right. \\
&\quad \left. + \cos(\delta_0 - \delta_S)\cos(\Delta m_s t) - \sin(\delta_0 - \delta_S)\cos\phi_s \sin(\Delta m_s t)\right]
\end{aligned}
$$

- At present not possible to fit for this small amplitude.
- We include the CDF upper limit ($|A_S|^2 < 0.067$ 95% C.L.) as a systematic by studying the bias introduced into toys when neglecting the presence of such a component

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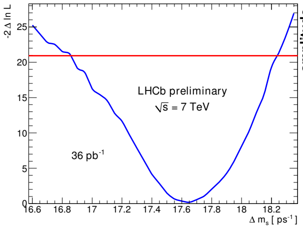
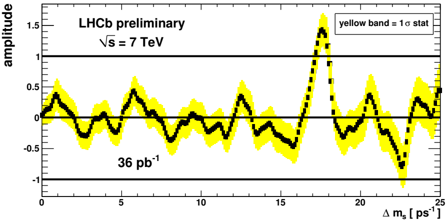
Δm_s

- For the present analysis we apply a gaussian constraint to Δm_s at the CDF measured value:

$$\text{CDF: } \Delta m_s = 17.77 \pm 0.10 \text{ (stat.) } \pm 0.07 \text{ (syst.) ps}^{-1}$$

- However, LHCb has made a competitive measurement of Δm_s in the mode $B_s^0 \to D_s^-(3)\pi$:

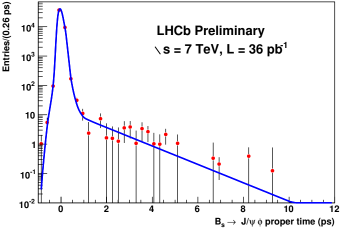




LHCb: $\Delta m_s = 17.63 \pm 0.11 \text{ (stat.) } \pm 0.04 \text{ (syst.) ps}^{-1}$

Propertime resolution

- Good propertime resolution is vital for time-dependent analyses
- LHCb was specifically designed with this in mind:
  - The VELO provides positional information on primary and secondary vertices with high resolution
- The propertime PDF is convolved with a sum of 3 Gaussians determined from the prompt J/ψ candidate lifetime distribution:



Resolution (ps^{-1})	Fraction
0.0337	0.527
0.0646	0.456
0.183	0.017

- This is in agreement with MC predictions of $\approx$ 50fs^{-1}

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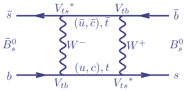
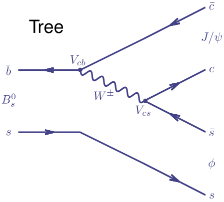
More Theory

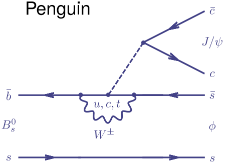
Mixing



Tree



Penguin



- Mixing phase: $\phi_{mix} = \arg(V_{ts}V_{tb}^*)^2$
- $B_s^0 \to J/\psi\phi$ is a $b \to c\bar{c}s$ transition, Tree (T) and Penguin (P_q) terms:

$$\begin{aligned} A_{c\bar{c}s} &= V_{cs}V_{cb}^*(T + P_c) + V_{us}V_{ub}^*P_u + V_{ts}V_{tb}^*P_t \\ &= V_{cs}V_{cb}^*(T + P_c - P_t) + V_{us}V_{ub}^*(P_u - P_t) \end{aligned}$$

- $V_{us}V_{ub}^*$ suppressed by O(λ^2) WRT $V_{cs}V_{cb}^*$ so $(P_u - P_t)$ penguin pollution (δP) small
- This leaves $\phi_{decay} = \arg(V_{cs}V_{cb}^*)$

$$\begin{aligned} \phi_s &= \phi_{mix} - 2\phi_{decay} = \arg(V_{ts}V_{tb}^*)^2 - 2\arg(V_{cs}V_{cb}^*) + \delta P \\ &= 2\arg\left[\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right] = -2\beta_s = -2\eta\lambda^2 - \eta\lambda^4 - O(\lambda^6) \end{aligned}$$

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