Prospects of the Search for B_s^0 Oscillations with ATLAS at LHC

Armin NAIRZ

on behalf of the
Innsbruck ATLAS Group

CERN

and

Institute for Experimental Physics
University of Innsbruck, Austria

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Introduction

B_s^0 and $\bar{B}_s^0$ are superpositions of two mass eigenstates B_H , B_L .

Transitions (frequency $\propto \Delta m_s \equiv m_H - m_L$) between B_s^0 and $\bar{B}_s^0$ states occur due to **flavour non-conservation** in charged weak-current interactions.

Experimental status: (LEP B Oscillations WG $\longrightarrow$ PDG 2002)

- $B_s^0 - \bar{B}_s^0$ oscillations **not yet observed**
- **limits** from combined LEP and Tevatron measurements:
 - $\Delta m_s > 13.1 \text{ ps}^{-1}$ (@ 95% CL)
 - **sensitivity** (@ 95% CL) of 13.3 ps^{-1}
- $B_d^0 - \bar{B}_d^0$ oscillations **well measured**:
 - $\Delta m_d = 0.489 \pm 0.008 \text{ ps}^{-1}$ (world average)

Introduction II

Theoretical observations:

- $B_s^0 - \bar{B}_s^0$ oscillations in the SM: via **box diagrams**

$$q \equiv d, s$$

$$q_1, q_2 \equiv u, c, t$$

- t -quark contributions dominant

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$$\Delta m_d \propto |V_{td}|^2$$

(hadronic uncertainties)

$$\Delta m_s \propto |V_{ts}|^2$$

$$\Rightarrow \frac{\Delta m_s}{\Delta m_d} \propto \left| \frac{V_{ts}}{V_{td}} \right|^2 \Rightarrow |V_{td}|^2$$

Introduction III

- **limits** from fits to Standard Model:
 - $\Delta m_s < 20 \text{ ps}^{-1}$ (@ 95% CL)
 - “The SM cannot easily accomodate values of $\Delta m_s > 25 \text{ ps}^{-1}$.” (PDG)

Reference for this talk:

B. Epp, V.M. Ghete, A.N., “*Prospects for the measurement of B_s^0 oscillations with the ATLAS detector at LHC*”, Scientific Note SN-ATLAS-2002-015, an evaluation study of the capability of the ATLAS detector to measure B_s^0 oscillations, based on detailed detector simulation.

Event Selection

- **signal channels** considered: hadronic channels
 $B_s^0 \rightarrow D_s \pi$ and $B_s^0 \rightarrow D_s a_1$ from semileptonic events, with
 - $D_s \rightarrow \phi \pi$, followed by $\phi \rightarrow K^+ K^-$
 - $a_1 \rightarrow \rho^0 \pi$, followed by $\rho^0 \rightarrow \pi^+ \pi^-$
- **event simulation and reconstruction**
 - **generation** with PYTHIA 5.7
 - $b\bar{b}$ production in pp collisions at $\sqrt{s} = 14$ TeV (direct production, gluon splitting, flavour excitation)
 - b decays semileptonically, giving $\mu(p_T > 6 \text{ GeV}, |\eta| < 2.5)$
 - $\bar{b}$ forced to produce required B -decay channels
 - **ATLAS Inner Detector response** simulated with GEANT3-based DICE
 - **reconstruction** with Kalman-filter based algorithm (xKalman/ATRECON)

Event Selection II

- triggering procedure
 - Level-1: muon with $p_T > 6$ GeV, $|\eta| < 2.4$, from semileptonic b decay
 - Level-2: confirmation of muon from Level-1, reconstruction of D_s
 - Event Filter: uses set of loose offline cuts
- flavour tagging of B_s^0 meson
 - at the production point by the muon charge
 - at the decay vertex by the charge-sign of decay product D_s
- offline B_s^0 reconstruction
 - kinematical cuts on reconstructed tracks,
on B_s^0 decay products (D_s , a_1 , ϕ , ρ^0), and B_s^0 candidates
 - quality cuts on vertex fits

Signal and Background Channels

Analysed Channels and expected number of events for an integrated luminosity of 10 fb^{-1} (1 year @ $10^{33} \text{ cm}^{-2}\text{s}^{-1}$, “low luminosity”):

Signal channel	$B_s^0 \rightarrow D_s^- \pi^+$	2370	$B_s^0 \rightarrow D_s^- a_1^+$	870
Exclusive decay background	$B_d^0 \rightarrow D^- \pi^+$	3	$B_d^0 \rightarrow D^- a_1^+$	1
	$B_d^0 \rightarrow D_s^+ \pi^-$	< 400	$B_d^0 \rightarrow D_s^+ a_1^-$	< 340
	$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$	2	$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$	0
Combinatorial bg.	4 ch. tracks	1920	6 ch. tracks	1830

- charge-conjugate channels implicitly taken into account
- **combinatorial background** study based on 1.1 million $b\bar{b} \rightarrow \mu X$ events
- **trigger efficiencies**: 63% Level-2 D_s ,
82% muon efficiency (Level-1/offline combined)

B_s^0 Mass Distributions

B_s^0 candidates selected within $2\sigma_{B_s^0}$ of the nominal B_s^0 mass.

- $\square$ $B_s^0 \rightarrow D_s^- \pi^+$ signal
- $\blacksquare$ $B_d^0 \rightarrow D_s^+ \pi^-$ background
- $\blacksquare$ fake B_s^0 (in signal sample)

No comb. backgr. plotted.

$$\sigma_{B_s^0} = 42.4 \text{ MeV}$$

- $\square$ $B_s^0 \rightarrow D_s^- a_1^+$ signal
- $\blacksquare$ $B_d^0 \rightarrow D_s^+ a_1^-$ background
- $\blacksquare$ fake B_s^0 (in signal sample)

No comb. backgr. plotted.

$$\sigma_{B_s^0} = 32.3 \text{ MeV}$$

B_s^0 Proper-Time Resolution

Definition: $t = \frac{d_{xy} M_{B_s^0}}{cp_T} =: d_{xy} g$

with: $g := M_{B_s^0}/(cp_T)$,

d_{xy} ... transverse decay length,

p_T ... transverse momentum,

t/t_0 ... reconstructed/true proper time

Parameterisation: sum of two Gaussian functions

$\text{Res}(t|t_0) =$

$$f_1 \frac{1}{\sigma_1 \sqrt{2\pi}} \exp\left(-\frac{(t-t_0)^2}{2\sigma_1^2}\right) + f_2 \frac{1}{\sigma_2 \sqrt{2\pi}} \exp\left(-\frac{(t-t_0)^2}{2\sigma_2^2}\right)$$

α	$B_s^0 \rightarrow D_s^- \pi^+$		$B_s^0 \rightarrow D_s^- a_1^+$	
	Fraction f_α	Width σ_α	Fraction f_α	Width σ_α
1	59.65%	51.50 fs	62.51%	51.56 fs
2	40.35%	107.30 fs	37.49%	92.82 fs

Likelihood Function

- probability density function ($j = d, s$)

$$p_j(t_0, \mu_0) = \frac{\Gamma_j^2 - \left(\frac{\Delta\Gamma_j}{2}\right)^2}{2\Gamma_j} e^{-\Gamma_j t_0} \left(\cosh \frac{\Delta\Gamma_j t_0}{2} + \mu_0 \cos \Delta m_j t_0 \right)$$

- $\mu_0 = -1$: probability that a B_j^0 decays after time t_0 as a $\bar{B}_j^0$
- $\mu_0 = +1$: probability that a B_j^0 decays after time t_0 as a B_j^0
- $\Delta\Gamma_j = \Gamma_{\text{H}}^j - \Gamma_{\text{L}}^j$ ($\Delta\Gamma_d \simeq 0$, $\Delta\Gamma_s$ possibly sizeable)
- $p_j(t_0, \mu_0)$ modified through experimental effects

$$q_j(t, \mu_0) = N \int_{t_{\min}}^{\infty} p_j(t_0, \mu_0) \text{Res}_j(t | t_0) dt_0$$

(t ...reconstructed time, N ...normalisation, $t_{\min} = 0.4$ ps...offline cut)

Likelihood Function II

- considering wrong-tag fraction ω_j

$$q_j(t, \mu) = (1 - \omega_j)q_j(t, \mu) + \omega_j q_j(t, -\mu)$$

- adding pdf's from oscillating sources and combinatorial background with fractions f_j^k ($j = d, s, \text{comb. bg. } cb$)

$$\text{pdf}_k(t, \mu) = \sum_{j=s,d,cb} f_j^k [(1 - \omega_j)q_j(t, \mu) + \omega_j q_j(t, -\mu)]$$

where $k = 1 \dots B_s^0 \rightarrow D_s \pi$, $k = 2 \dots B_s^0 \rightarrow D_s a_1$

$\Rightarrow$ likelihood of the total sample:

$$\mathcal{L}(\Delta m_s, \Delta \Gamma_s) = \prod_{k=1}^{N_{\text{ch}}} \prod_{i=1}^{N_{\text{ev}}^k} \text{pdf}_k(t_i, \mu_i)$$

($N_{\text{ev}}^k \dots$ the total number of events of type k , $N_{\text{ch}} = 2$)

Δm_s Measurement Limits and Accuracy

... estimated using simplified Monte-Carlo model

Amplitude-fit method: (for B_s^0)

- $p_s(t_0, \mu_0) \longrightarrow p_s(t_0, \mu_0, \mathcal{A}) = p_s(t_0, \mu_0 \mathcal{A})$
 $\implies \mathcal{L}(\Delta m_s, \Delta \Gamma_s) \longrightarrow \mathcal{L}(\Delta m_s, \Delta \Gamma_s, \mathcal{A}) \longrightarrow \text{minimise } \mathcal{L} \text{ as a function of } \mathcal{A}$
- statistical significance of an oscillation signal: $S \approx 1/\sigma_{\mathcal{A}}$

Measurement limits: set using the amplitude-fit method

- 5σ limit defined as: $S = 1/\sigma_{\mathcal{A}} = 5$
- 95% CL limit defined as: $\text{data} + 1.645\sigma_{\mathcal{A}} = 1$
- 95% CL sensitivity defined as: $S = 1/\sigma_{\mathcal{A}} = 1.645$

Accuracy: determined for values less than the measurement limits, using the log-likelihood method

Systematic Uncertainties

Systematic uncertainties on the B_s^0 oscillation amplitude $\sigma_{\mathcal{A}}^{\text{syst}}$:

$$\sigma_{\mathcal{A}}^{\text{syst}} = \Delta\mathcal{A} + (1 - \mathcal{A}) \frac{\Delta\sigma_{\mathcal{A}}^{\text{stat}}}{\sigma_{\mathcal{A}}^{\text{stat}}}$$

($\Delta\mathcal{A}$... difference between values for $\mathcal{A}$ obtained in analysis with changed single parameter and analysis with nominal sets of parameters; $\Delta\sigma_{\mathcal{A}}^{\text{stat}}$ similar)

Contributions to the systematic uncertainty:

- relative error of 5% on the **wrong-tag fraction** for both B_s^0 and B_d^0
- widths of the Gaussian functions from the parameterisation of the **proper-time resolution** varied by $\pm 1\sigma$
- fraction $f_{B_s^0} = BR(\bar{b} \rightarrow B_s^0)$, the B_s^0 **lifetime** and the Δm_d **value** varied separately by the uncertainty given in PDG 1998
- uncertainty of 5% on the (exponential) **decay time** τ_{cb} of the combinatorial background

Results

Dependence of amplitude and its statistical and systematic errors on Δm_s : (In the generation, the value of Δm_s was $\Delta m_s = \infty$.)

Δm_s	0 ps ⁻¹	10 ps ⁻¹	20 ps ⁻¹	30 ps ⁻¹	40 ps ⁻¹
A	0.045	0.189	0.042	-0.291	-0.541
σ_A^{stat}	± 0.048	± 0.090	± 0.167	± 0.357	± 0.930
σ_A^{syst}	+0.097 -0.084	+0.130 -0.096	+0.180 -0.142	+0.298 -0.226	+0.364 -0.259

With **“projected” systematic errors:**

(estimated systematic uncertainties at time of ATLAS data taking)

Δm_s	0 ps ⁻¹	10 ps ⁻¹	20 ps ⁻¹	30 ps ⁻¹	40 ps ⁻¹
σ_A^{syst}	+0.049 -0.049	+0.060 -0.048	+0.085 -0.066	+0.137 -0.117	+0.175 -0.150

Dominant contributions to the systematic error from $f_{B_s^0}$ fraction and from the parameterisation of the proper-time resolution.

Results II

For integrated luminosity 10 fb^{-1} :

16.0 ps^{-1} / 21.0 ps^{-1} 5 σ measurement limit (actual/projected)
 34.5 ps^{-1} / 35.5 ps^{-1} 95% CL sensitivity (actual/projected)

Dependence on Experimental Quantities

Examples (statistical uncertainties only):

Luminosity (fb^{-1})	5σ limit (ps^{-1})	95% CL sensitivity (ps^{-1})
5	17.5	32.0
10	22.5	36.0
20	27.0	39.0
30	29.5	41.0

$\Delta\Gamma_s/\Gamma_s$ (%)	5σ limit (ps^{-1})	95% CL sensitivity (ps^{-1})
0	29.5	41.0
30	29.0	41.0
40	29.0	40.5
80	27.0	39.0
100	25.5	38.0

Accuracy of Δm_s Measurement

Luminosity (fb ⁻¹)	Δm_s^{gen} (ps ⁻¹)	$\Delta m_s^{\text{rec}} \pm \sigma_{\text{stat}}^{\Delta m_s} \pm \sigma_{\text{syst}}^{\Delta m_s}$ (ps ⁻¹)	Obs.
5	17.5	$17.689 \pm 0.083 \pm 0.002$	$5\sigma_{\text{stat}}$ limit
10	15.0	$15.021 \pm 0.049 \pm 0.002$	$5\sigma_{\text{stat}}$ limit
	22.5	$22.396 \pm 0.072 \pm 0.005$	
20	15.0	$14.949 \pm 0.033 \pm 0.002$	$5\sigma_{\text{stat}}$ limit
	20.0	$20.041 \pm 0.068 \pm 0.005$	
	27.0	$26.948 \pm 0.070 \pm 0.003$	
30	15.0	$14.942 \pm 0.028 \pm 0.004$	$5\sigma_{\text{stat}}$ limit
	20.0	$20.010 \pm 0.043 \pm 0.002$	
	29.5	$29.708 \pm 0.083 \pm 0.007$	

The Δm_s measurement, if within the reach of ATLAS, will be dominated by statistical errors.

Conclusions

For an integrated luminosity of 10 fb^{-1} (statistical errors only),

- 5σ measurement of Δm_s possible up to 22.5 ps^{-1}
- experiment will be 95% CL sensitive up to 36.0 ps^{-1}
- accuracy of $\sim 0.07 \text{ ps}^{-1}$ expected at $\Delta m_s = 22.5 \text{ ps}^{-1}$

The effect of the **systematic uncertainties** will be rather limited, provided that precision of $f_{B_s^0}$ fraction and proper-time parameterisation are improved.

“The values obtained in this note for the measurement limits and accuracies should be re-evaluated at a later time, taking into account the changes in the detector geometry [...]”