B_s^0 oscillations as a probe of decays with invisible particles

Adam Morris[1,2], Anton Poluektov[1]

[1] Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
[2] Universität Bonn - Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany

30 July 2020

ICHEP 2020

Based on publication [arXiv:1911.12729, JHEP 02 (2020) 163]

B decays with invisible particles

- Many important analyses of B decays involve final states with invisible or poorly reconstructed particles.
  - Final states with neutrinos
  - Hadronic decays with neutrons, K^0_{L}.
  - NP candidates: heavy neutrinos, ALPs, other dark matter candidates.

e^+e^- B-factories

- $B\overline{B}$ produced w/o additional particles
- Fully reconstruct the other *(tag)* B meson $\Rightarrow$ constrain 4-momentum of the *probe* B

Hadron machines (LHCb, ...)

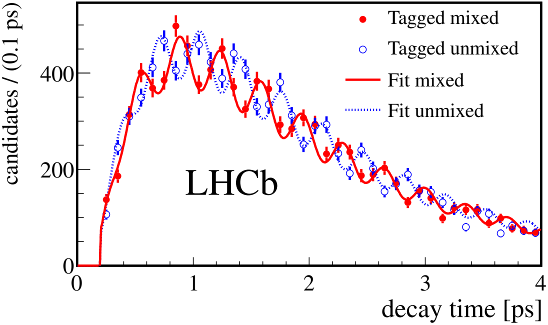
- No kinematic constraints
- Use topology of the B decay to constrain direction of flight, but no constraint on $|p_B|$.
- Not sufficient if *e.g.* mass of heavy invisible particle is unknown, or > 1 neutrino, ...
- In general, large background from B hadron decays.

B decays with invisible particles

- Propose a technique where background rejection and kinematic constraints are obtained from the B_s^0 oscillation pattern.

  [arXiv:1911.12729, JHEP 02 (2020) 163]
- Tested with simulation for a simple case: $B_s^0 \to AX$, where A is reconstructed, and X is invisible (possibly with unknown mass).
  - NP example: [G. Elor, M. Escudero, A. Nelson, "Baryogenesis and Dark Matter from B mesons"]: model where both baryon asymmetry and DM are explained by B meson oscillations with subsequent decays to DM particles.
  - Possible SM benchmark analysis: $B_s^0 \to D_s^- p\bar{n}$ (expect sufficiently large Br)
- Could be applied to other final states with unreconstructed particles, *e.g.* semileptonic.

B_s^0 oscillations



Oscillations in $B_s^0 \to D_s^- \pi^+$ [LHCb-PAPER-2013-006]

$$f(t) \propto e^{-\Gamma_s t} \left[\cosh \left(\frac{\Delta\Gamma_s\, t}{2} \right) \pm \cos(\Delta m_s\, t) \right],$$

Calculation of decay time needs vertex displacement x and B momentum p_B:

$$t = x \frac{M_B}{p_B}$$

A very specific pattern that can be used to

- remove non-B_s^0 backgrounds
- constrain p_B

Reconstruction of B_s^0 momentum

Consider the decay $B_s^0 \to AX$, where

- A is reconstructed and X is invisible.
- B_s^0 decay vertex is measured (*e.g.* A is decaying strongly)
- B_s^0 flavour is tagged

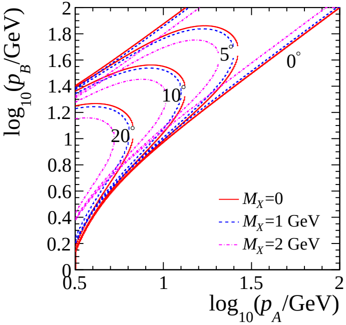
Two solutions for p_B:

$$p_B = \frac{\left(M_B^2 + \Delta\right) p_A \cos\theta \pm E_A \sqrt{\Delta^2 + M_B^2(M_B^2 + \Delta - 4M_A^2 - 4p_A^2 \sin^2\theta)}}{2(M_A^2 + p_A^2 \sin^2\theta)},$$

where $\Delta \equiv M_A^2 - M_X^2$,

$E_A \equiv \sqrt{M_A^2 + p_A^2}$.

θ: angle between B_s^0 and A

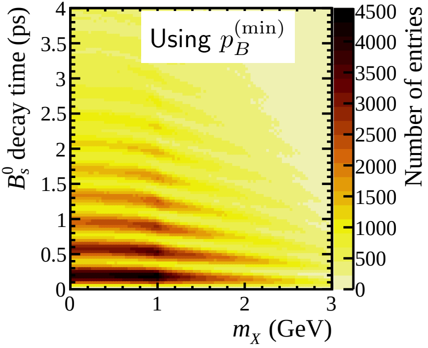


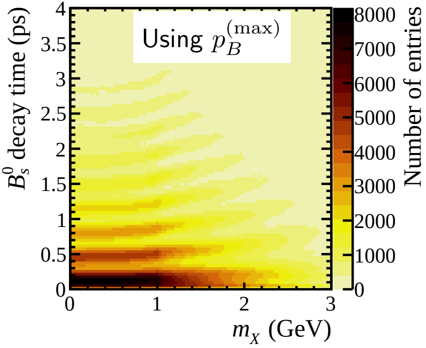
Example: $M_A = 2\,\mathrm{GeV}$

Toy MC with perfect tagging and vertex resolution

$B_s^0 \to AX$, $M_A = 2\,\mathrm{GeV}$, $M_X = 1\,\mathrm{GeV}$.

Decay time distribution as a function of probe mass m_X.





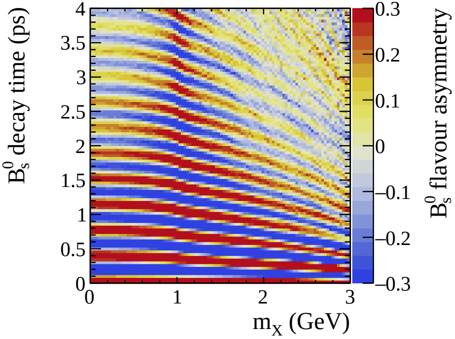
Correct frequency $\omega = \Delta m_s$ for $m_X = M_X$

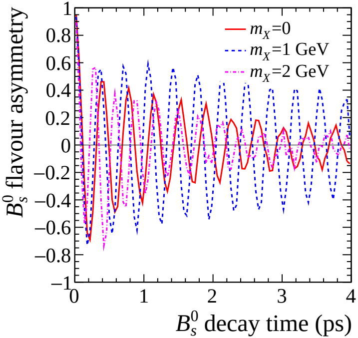
$p_B^{(\mathrm{min})}$ provides better oscillating pattern (more often the right solution)

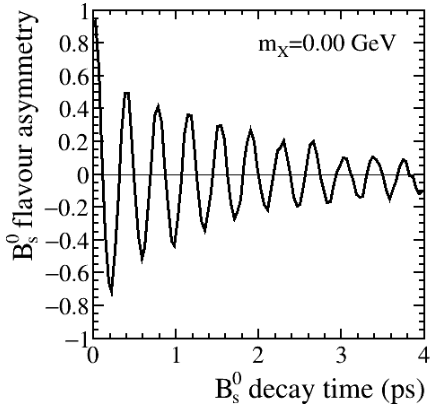
Instead of absolute rates of the B_s^0 and $\overline{B}_s^0$ mesons, it is convenient to deal with flavour asymmetry

$$a_{B_s^0}(t) = \frac{N_{\mathrm{unmix}}(t) - N_{\mathrm{mix}}(t)}{N_{\mathrm{unmix}}(t) + N_{\mathrm{mix}}(t)},$$

Use only $p_B^{(\mathrm{min})}$ solution.







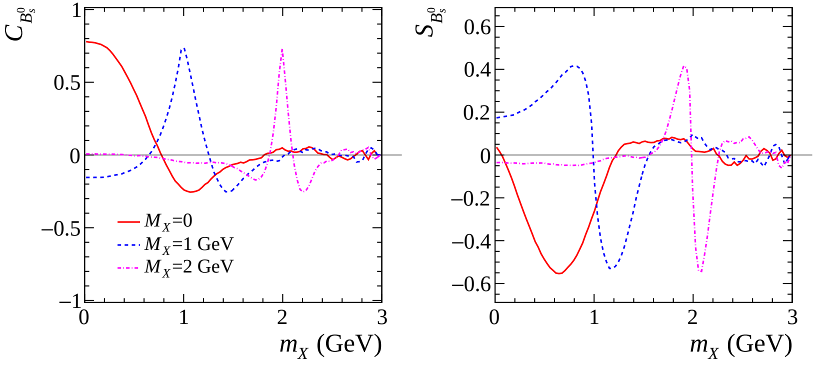
"Resonance" at the true mass M_X

B_s^0 oscillation harmonic in flavour asymmetry

To avoid having to deal with low-frequency components, consider only the harmonic of B_s^0 oscillation frequency in the flavour asymmetry:

$$A_{B_s^0} \equiv C_{B_s^0} + iS_{B_s^0} = \int a_{B_s^0}(t) e^{i\Delta m_s t}\, dt,$$

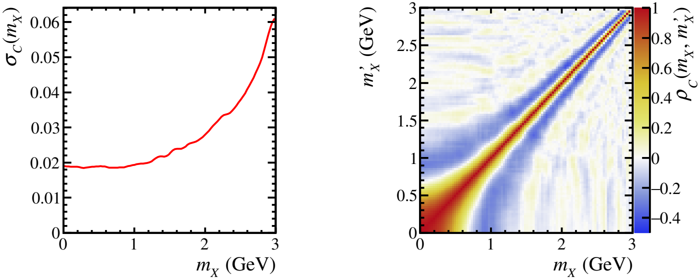
Use only $t > 0.8\,\mathrm{ps}$ to calculate the integral (B_s^0 selection)



$C_{B_s^0}$ reaches maximum at $m_X = M_X$, and $S_{B_s^0}$ crosses zero.

Technical details

- **Statistical uncertainties** in the Fourier spectrum are correlated (same events are used for different m_X). Deal with it using bootstrapping.

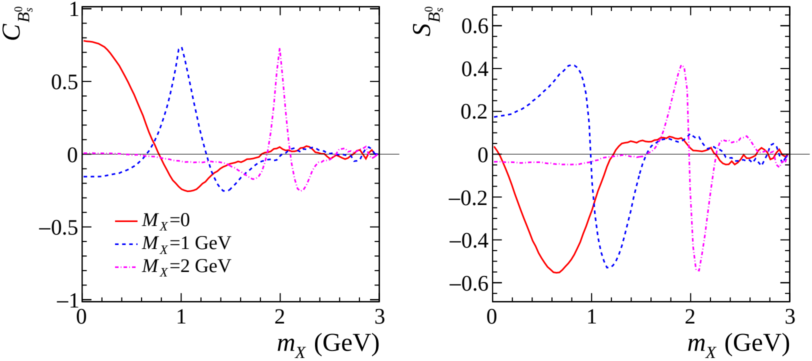


- **Vertex resolution** affects the performance of the method (uncertainty in measurement of $\theta \Rightarrow$ decoherence at highter decay times).
- **Flavour tagging** affects stat. uncertainty. Typical value for LHCb: 6% in for hadronic final states. [JHEP 03 (2018) 059]

Effect of finite vertex resolution

Finite transverse resolution of B_s^0 vertex σ_x affects p_B reconstruction (via θ). Typical vertex resolution is a few tens of μm (depends on kinematics and multiplicity)

Apply vertex smearing in MC.

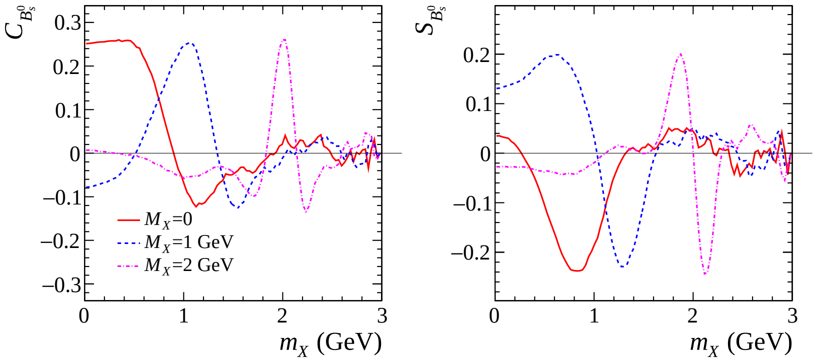


Ideal vertex resolution, 10^5 events of each B_s^0 flavour

Effect of finite vertex resolution

Finite transverse resolution of B_s^0 vertex σ_x affects p_B reconstruction (via θ). Typical vertex resolution is a few tens of $\mu\mathrm{m}$ (depends on kinematics and multiplicity)

Apply vertex smearing in MC.

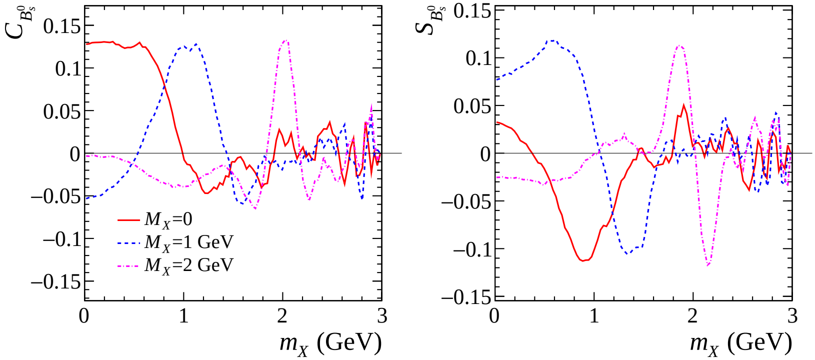


Vertex resolution $\sigma_x = 20\,\mu\mathrm{m}$, 10^5 events of each B_s^0 flavour

Effect of finite vertex resolution

Finite transverse resolution of B_s^0 vertex σ_x affects p_B reconstruction (via θ).
Typical vertex resolution is a few tens of μm (depends on kinematics and multiplicity)

Apply vertex smearing in MC.

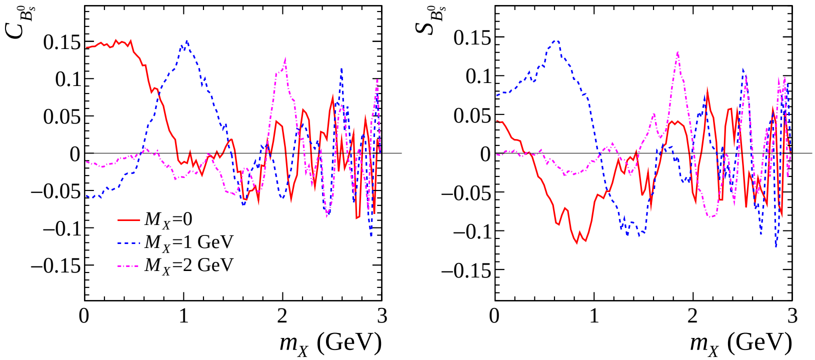


Vertex resolution $\sigma_x = 40\,\mu\text{m}$, 10^5 events of each B_s^0 flavour

Effect of finite vertex resolution

Finite transverse resolution of B_s^0 vertex σ_x affects p_B reconstruction (via θ).
Typical vertex resolution is a few tens of μm (depends on kinematics and multiplicity)

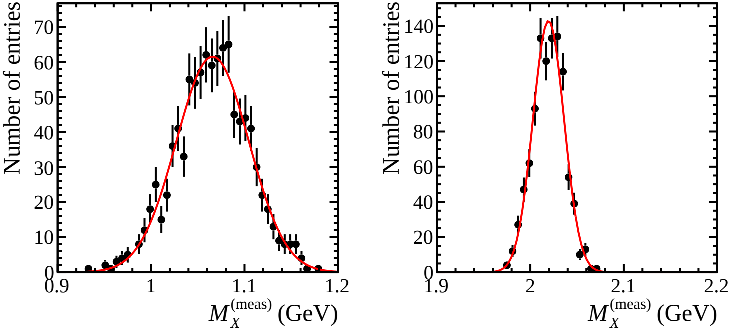
Apply vertex smearing in MC.



Vertex resolution $\sigma_x = 40\,\mu\mathrm{m}$, 10^4 events of each B_s^0 flavour

Mass resolution and signal significance

Realistic scenario for LHCb:
vertex resolution $\sigma_x = 40\,\mu\text{m}$, $\sigma_z = 300\,\mu\text{m}$, 10^4 events of each B_s^0 flavour



1000 toys, M_X measured as zero-crossing point of $S_{B_s^0}$.

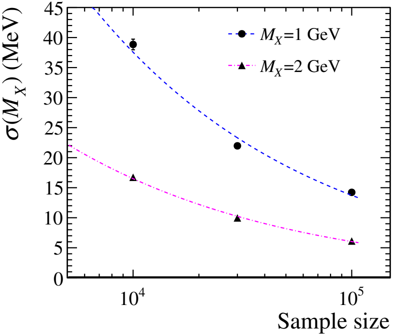
Better resolution for higher-mass X

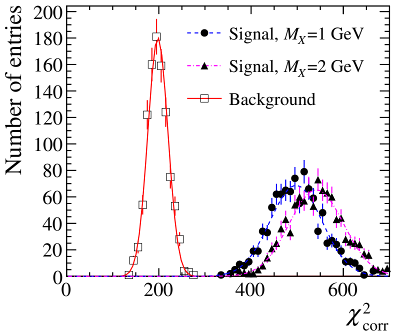
Some bias towards larger mass due to not exactly sinusoidal flavour asymmetry (decoherence at larger t), can be corrected with MC.

Mass resolution and signal significance

Realistic scenario for LHCb:

vertex resolution $\sigma_x = 40\,\mu\text{m}$, $\sigma_z = 300\,\mu\text{m}$, 10^4 events of each B_s^0 flavour



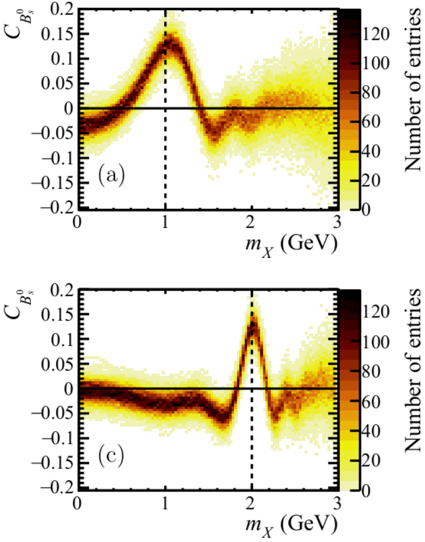


Mass resolution as a function of sample size, and signal significance test statistic taking into account correlation between different m_X.

Conclusion

- B_s^0 oscillations can help with partially reconstructed decays at hadronic machines
  - Remove any non-B_s^0 backgrounds
  - Provide additional kinematic constraint: p_B from the oscillation frequency
- Feasibility depends on flavour tagging performance and vertex resolution
  - Resolution is critical for topological reconstruction of B_s^0 momentum.
  - Can be tested with some high-stats modes already with current data sample
- Toy MC done for a case with $B_s^0 \to AX$ where X is massive and not reconstructed. B_s^0 oscillations provide sensitivity to X mass spectrum (which would be impossible with other techniques).
  - Possible applications: searches for NP in decays with invisible particles (e.g. ALPs, heavy neutrinos, other DM candidates), decays with neutrons, K_L^0 etc.
  - Similar technique can be used for SL decays with neutrinos to better constrain kinematic parameters. $E.g.$ instead of constraining X mass, could better constrain q^2 or angular parameters.

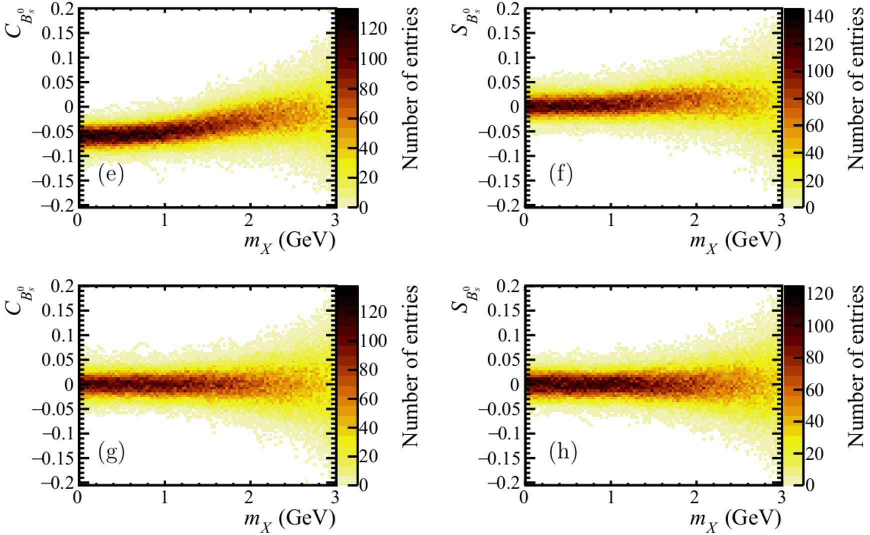
Non-B_s^0 background rejection



$B_s^0 \to AX$ m_X spectra for $M_X = 1\,\mathrm{GeV}$ (top) and $2\,\mathrm{GeV}$ (bottom)

1000 pseudoexperiments

Non-B_s^0 background rejection



$B^0 \to AX$ (top) and random flavour tag (bottom) m_X spectra

1000 pseudoexperiments