B_s^0 mixing in Herwig truth level samples of CEPC

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What Physics process we want to study

Neutral B meson mixing

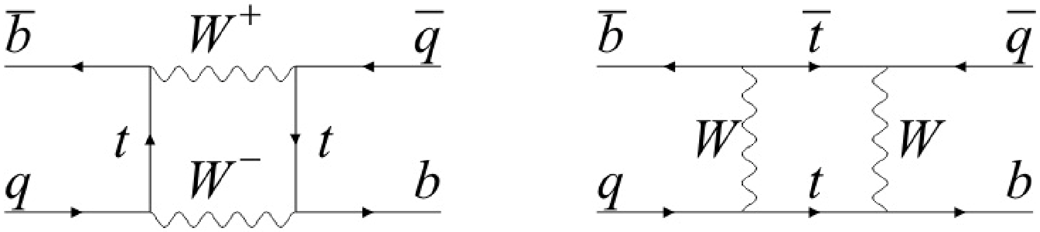


Figure 75.1: Dominant box diagrams for the $B_q^0 \to \overline{B_q}^0$ transitions ($q = d$ or s). Similar diagrams exist where one or both t quarks are replaced with c or u quarks.

Neutral mesons with strange, charm or beauty quantum numbers can mix with their antiparticles, as these quantum numbers are not conserved by the weak interaction. B_s^0 / $\overline{B_s^0}$ is one such example.

https://pdg.lbl.gov/2023/reviews/rpp2022-rev-b-bar-mixing.pdf

Herwig truth level samples

- The Herwig samples we analyzed are from: /cefs/higgs/yudongw/Generator2/Samples/Herwig/zpole_bb/slcio/
- There are 1000 files named as “zpole_bb_${job}.slcio”, where “${job}” represents the file number, e.g. zpole_bb_00001.slcio.
- Each file contains 10000 events. One can get that by `lcio_event_counter xxx.slcio`.
- Samples are said to be at the Truth Level.

B_s^0 mixing pattern in Herwig

- All B_s^0 / $\overline{B_s^0}$ mixing or decay in patterns like: `s1(t1) -> s2(t2) -> f(t3)`, where s1 and s2 represent the states(as shown right, event#1418 s1: $\overline{B_s^0}$ s2: B_s^0) at time t1 and t2 respectively and f is daughter particles decayed from s2(e.g. $B_s^0 \to D_s^- \pi^+$, f:$D_s^- \pi^+$).

```
event#1418  anti_Bs0——>Bs0——>
event#1422  Bs0——>Bs0——>
event#1430  Bs0——>anti_Bs0——>
event#1452  anti_Bs0——>Bs0——>
event#1457  anti_Bs0——>Bs0——>
event#1463  anti_Bs0——>anti_Bs0——>
event#1512  Bs0——>anti_Bs0——>
event#1526  Bs0——>Bs0——>
```

- Notice that s1 and s2 can be the same state in the mixing pattern in Herwig(e.g. event#1422), which means s1 and s2 can have the same PDG_ID. However, we checked that they are not in the same memory address and with different serial number.

question here:

The mixing or decay pattern is strange, just 2 steps: s1->s2->f ?

B_s^0 mixing pattern in Herwig

- t1, t2 and t3 are the production time of s1, s2 and f in the rest frame of B_s^0 / $\overline{B_s^0}$ respectively. We get them as following:

- First the function MCParticle::getTime() returns a time in the Lab frame. So one should do a boost transformation to the rest frame of B_s^0 / $\overline{B_s^0}$ in order to have a right decay time distribution. We do that according to formula: $t_{rest} = \frac{mass}{E_{lab}} * t_{lab}$, with functions MCParticle::getMass() and MCParticle::getEnergy().

- Check the description and unit for functions we used.

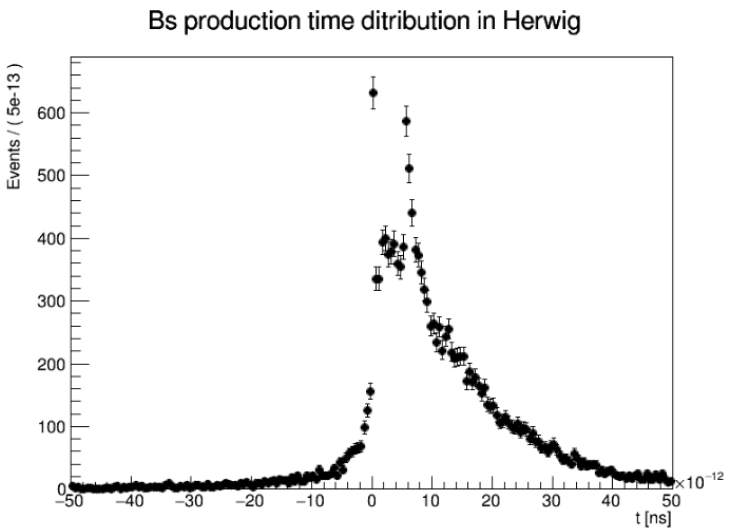
virtual float	**getTime** () const =0 The creation time of the particle in [ns] wrt.

virtual double	**getMass** () const =0 Returns the mass of the particle in [GeV] - only float used in files.

virtual double	**getEnergy** () const =0 Returns the energy of the particle (at the vertex) in [GeV] computed from the particle's momentum and mass - only float used in files.

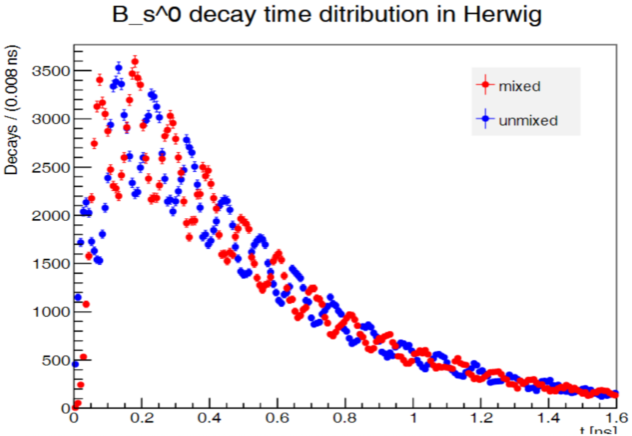
The production time `t1` of B_s^0

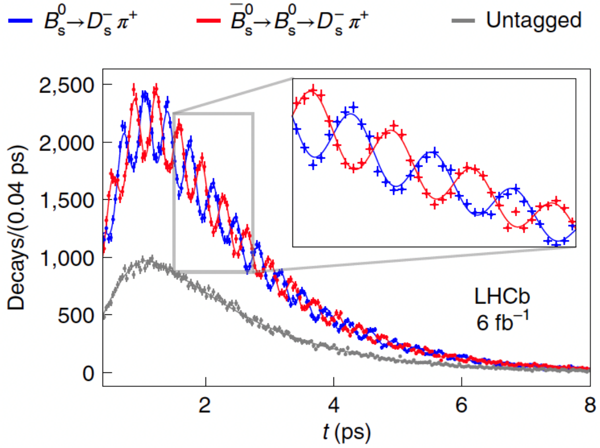
- The production time of B_s^0 in the truth level is a distribution with mean value at about 10^{-21} s, but some production time is negative?!
- We accepted that as the time returned in the samples is with a resolution. But resolution appears in truth level samples?



The decay time `t3 − t1` distribution of B_s^0

- We call `s1==s2` unmixed, and `s1!=s2` mixed.
- We consider the decay time is `t3-t1`.
- All decay modes are counted.
- The decay time distribution we obtained without fitting is as shown in the top right.
- Comparing with LHCb result from data[Nat. Phys. 18, 1–5 (2022)] in the bottom right, there are two noticeable problems:
  1. Incorrect time scale(About two orders of magnitude larger).
  2. Not like a ‘truth level’ decay time distribution.
- ..

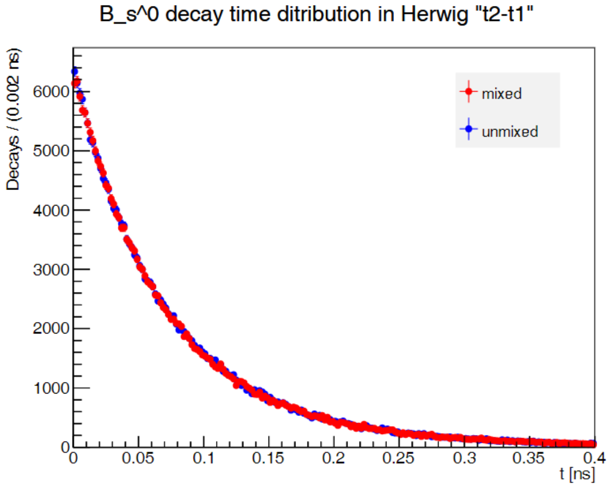


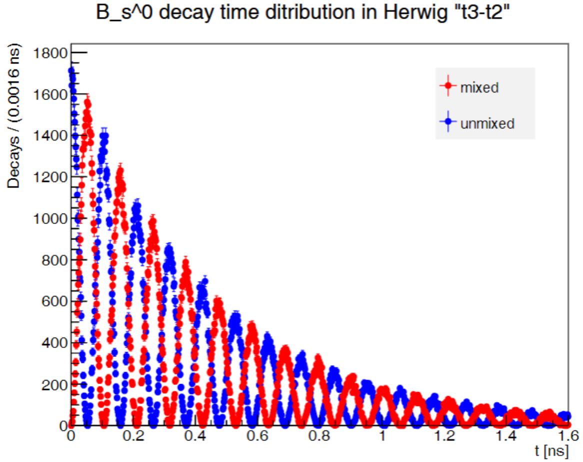


`t2-t1` and `t3-t2` distributions

- We then checked the distributions of `t2-t1` and `t3-t2` as shown in the figure on the right.

- These two distributions make us confused:
  1. What do they mean in physics?
  2. Why times of `s1->s2`(t2-t1) is like an exponential distribution?
  3. Why times of `s2->f`(t3-t2) is like the standard oscillatory distribution?(see next slides)
  4. Is the state `s2` the decay state or intermediate state? If s2 is the decay state of Bs, but why `t3-t2` is not 0?





`t3-t2` distribution fitting

- We can fit `t3-t2` distribution with the standard oscillatory distribution formula:

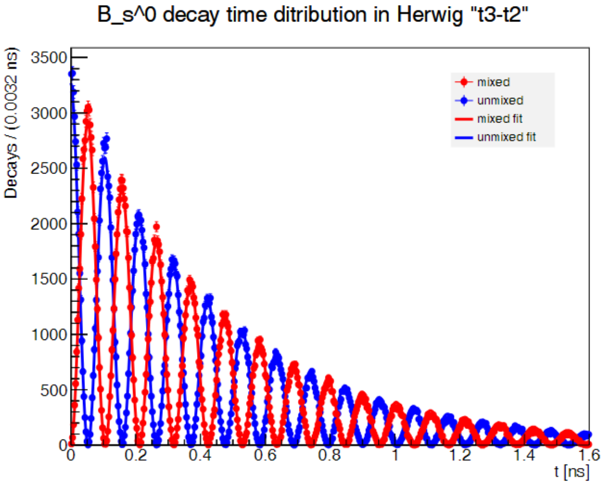
$$P(t) \sim e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + C \cdot \cos(\Delta m_s t)\right]$$

which from LHCb result[Nat. Phys. 18, 1–5 (2022)], $B_s^0 \rightarrow D_s^- \pi^+$ decay time distribution in the absence of detector effects.

- The parameters fitted are not same as the LHCb result value.

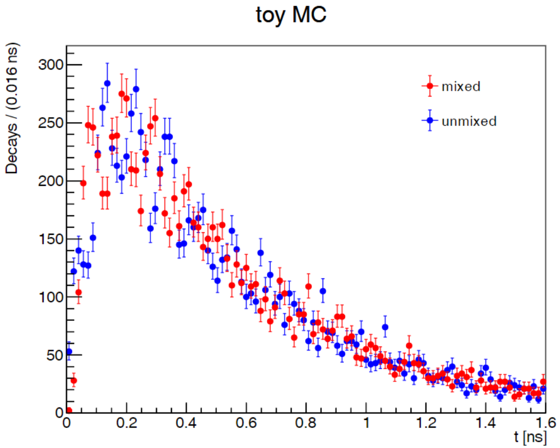
```
 EXT PARAMETER                                     STEP         FIRST
 NO.   NAME      VALUE            ERROR          SIZE       DERIVATIVE
  1  Delta_Gamma_s    1.16342e+00   1.13884e-02   4.88288e-04   4.93584e-01
  2  Delta_mass_s    5.93671e+01   3.69600e-03   1.95183e-05  -1.58417e+00
  3  Gamma_s      2.20343e+00   5.29071e-03   1.79273e-04   4.09741e-01
                               ERR DEF= 0.5
EXTERNAL ERROR MATRIX.    NDIM=  25    NPAR=  3    ERR DEF=0.5
 1.297e-04 -1.243e-05  4.081e-05
-1.243e-05  1.366e-05 -3.912e-06
 4.081e-05 -3.912e-06  2.799e-05
PARAMETER  CORRELATION COEFFICIENTS
      NO.  GLOBAL      1      2      3
       1  0.69671   1.000 -0.295  0.677
       2  0.29534  -0.295  1.000 -0.200
       3  0.67734   0.677 -0.200  1.000
```

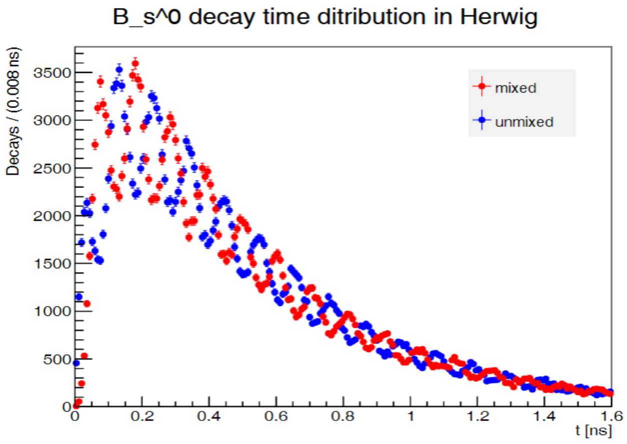
```
y = Delta_Gamma_s/(2*Gamma_s) =   0.264002468798
x = Delta_mass_s/Gamma_s      =   26.9430322981
```



`t3-t1` toy Monte Carlo

- Let X=t2-t1, Y=t3-t2 and Z=t3-t1=X+Y.
- We assume that X and Y are independent and X follows an exponential distribution, and Y follows the standard oscillatory distribution.
- So we can get the distribution of Z from Monte Carlo, which meets the decay time distribution of B_s^0 in Herwig.



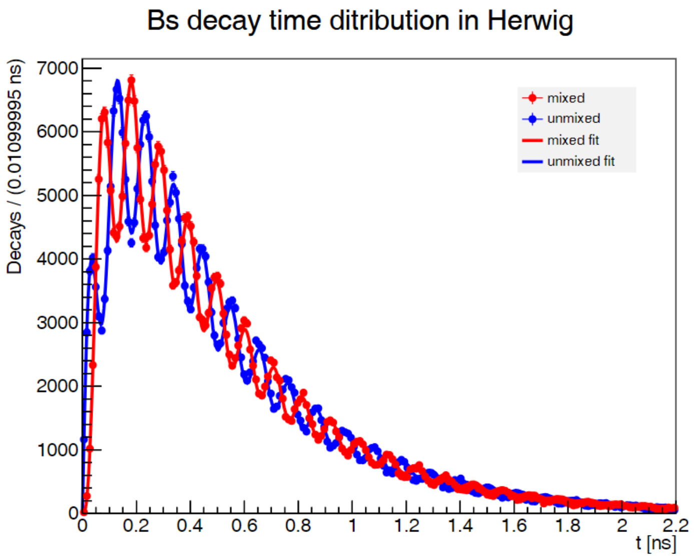


Fit the decay time distribution of B_s^0

- The test of toy Monte Carlo shows that the convolution of an exponential distribution and the standard oscillatory distribution can be used to fit the decay time distribution of B_s^0 in Herwig.

$$P(t) \sim e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + C\cdot\cos(\Delta m_s t)\right]$$

$$f(t) \propto \exp(-at) \otimes P(t)$$



EXT NO.	PARAMETER NAME	VALUE	CURRENT GUESS ERROR	STEP SIZE	FIRST DERIVATIVE
1	Delta_Gamma_s	6.22738e+00	2.58100e-02	0.00000e+00	-9.93840e+04
2	Delta_mass_s	5.95874e+01	1.75146e-02	0.00000e+00	-3.77546e+02
3	Gamma_s	5.55466e+00	1.15167e-02	0.00000e+00	1.97143e+05
4	a	8.00004e+00	7.33526e-02	-1.43284e+00	7.37003e+01

Summary and Questions

Even though we can fit the distribution well, we don’t understand it:

1. The mixing or decay pattern is strange, just 2 steps: s1->s2->f ?
2. If s2 is the decay state of Bs, but why `t3-t2` is not 0?
3. The creation time have chance to be negative, resolution appears in truth level samples?
4. Why t2->t1 distribution is like an exponential decay rather than oscillation?
5. Why the time scale is two orders of magnitude larger than the experimental result?

Thanks!