Selected Topics of Heavy Flavor Physics @ CEPC

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CEPC2014 @ SJTU, 2014/09/12

Outline

1. Why do we study HFP ?
2. Where do we study HFP ?
3. What can we do @ CEPC ?
4. Summary

1.Why do we study HFP ?

- 1963: concept of flavour mixing [Cabibbo].
- 1964: discovery of CP violation in $K_L \to \pi^+\pi^-$ [Christenson *et al.*].
- 1970: introduction of the charm quark to suppress the flavour-changing neutral currents (FCNCs) [Glashow, Iliopoulos & Maiani].
- 1973: quark-flavour mixing with 3 generations allows us to accommodate CP violation in the SM [Kobayashi & Maskawa].
- 1974: estimate of the charm-quark mass with the help of the K^0–$\bar{K}^0$ mixing frequency [Gaillard & Lee].
- 1980s: the large top-quark mass was first suggested by the large B^0–$\bar{B}^0$ mixing seen by ARGUS (DESY) and UA1 (CERN).

1.Why do we study HFP ?

After the discovery of the“ Higgs” boson, there remain lots of questions in flavor part in SM.

- Lack of a fundamental theory of flavor.

  Quark mixings, Yukawa couplings, The Hierarchy of the quark mess and CKM matrix elements,…

- Tensions in the SM fit.

  Vub, $\varepsilon_K \sim \sin 2\beta$, R_b,
  $B \to K^{(*)} l^+ l^-$,
  $B \to \pi^0\pi^0$, $A_{CP}(B \to K\pi)$

- Unexplored territory

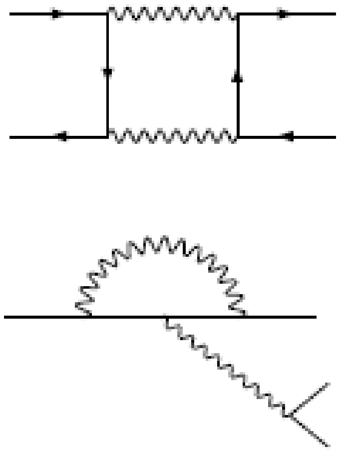
  B meson rare decays

- Matter-antimatter asymmetry in the universe

  $B \to J/\psi K$, $B_S \to J/\psi\phi$, ….

HFP offers us a good plat for searching for the possible New Physics

- New Physics (NP): → $\boxed{\text{typically new patterns in the flavour sector}}$
  - supersymmetric (SUSY) scenarios;
  - left–right-symmetric models;
  - models with extra Z' bosons;
  - scenarios with extra dimensions;
  - "little Higgs" scenarios ...



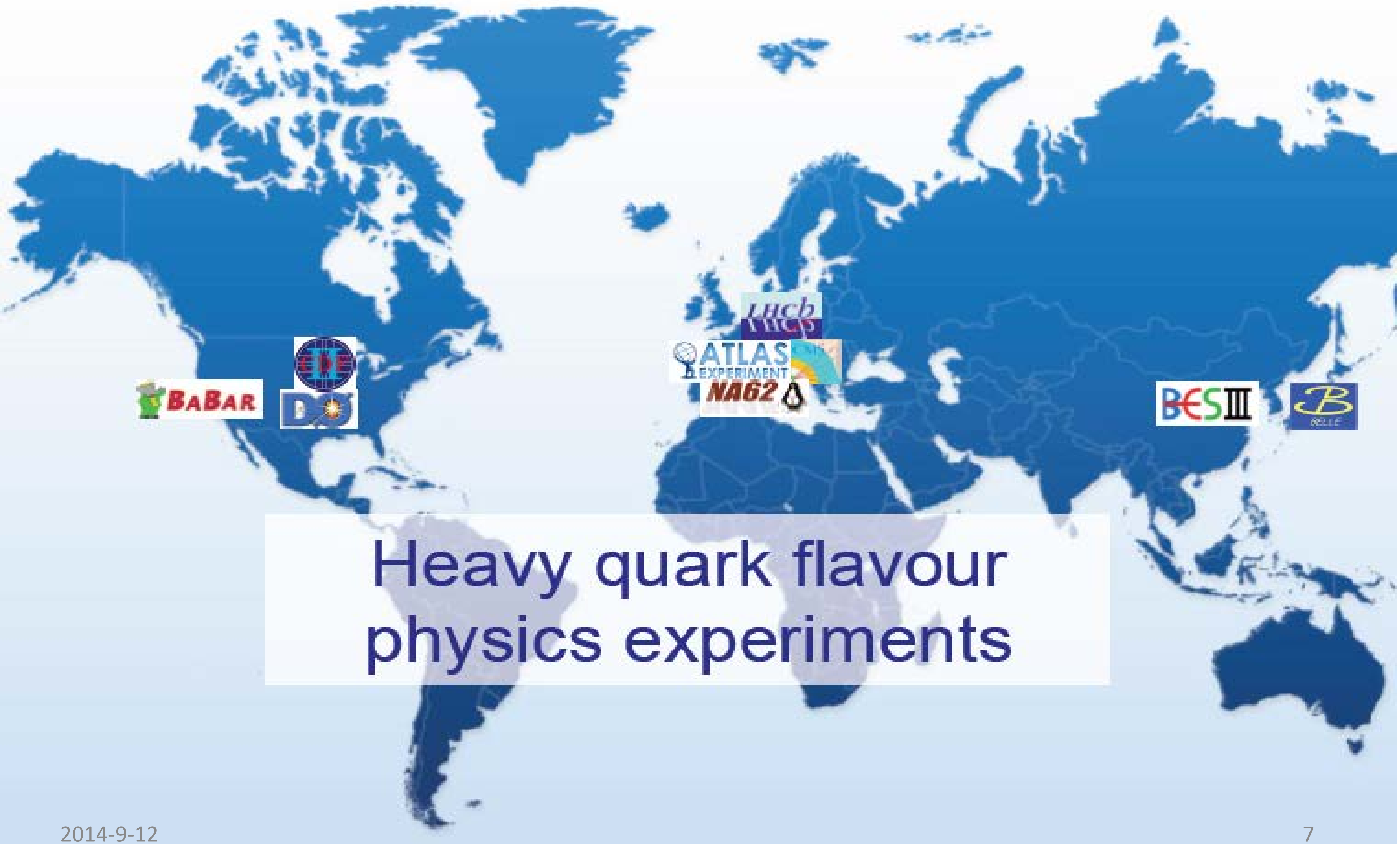
- Sensitivity to NP through virtual quantum effects:
- Interplay with direct NP searches at ATLAS & CMS:[1]
  - If NP particles are produced and detected through their decays at the LHC, flavour-physics information helps to determine/narrow the underlying NP model and to establish new sources of CP violation.
  - NP effects could in fact show up *first* in the flavour sector, also if NP particles are too heavy to be produced directly at the LHC.

Challenging the Standard Model through Flavor Studies

Before searching for NP, we have to understand the SM picture!

- The key problem:
  - ◇ *impact of strong interactions* → "hadronic" uncertainties
- The B-meson system is a *particularly promising* flavour probe:
  - Offers various strategies to eliminate the hadronic uncertainties and to determine the hadronic parameters from the data.
  - Simplifications through the large b-quark mass.
  - Tests of clean SM relations that could be spoiled by NP ...
- This feature led to the "rise of the B mesons":
  - K decays dominated for more than 30 years: *discovery* of (indirect) CP violation [$\to \varepsilon_K$] and direct CP violaton [$\to$ Re$(\varepsilon'/\varepsilon)$].
  - Since this decade the stage is governed by B mesons → our focus

2.Where do we study HFP ?



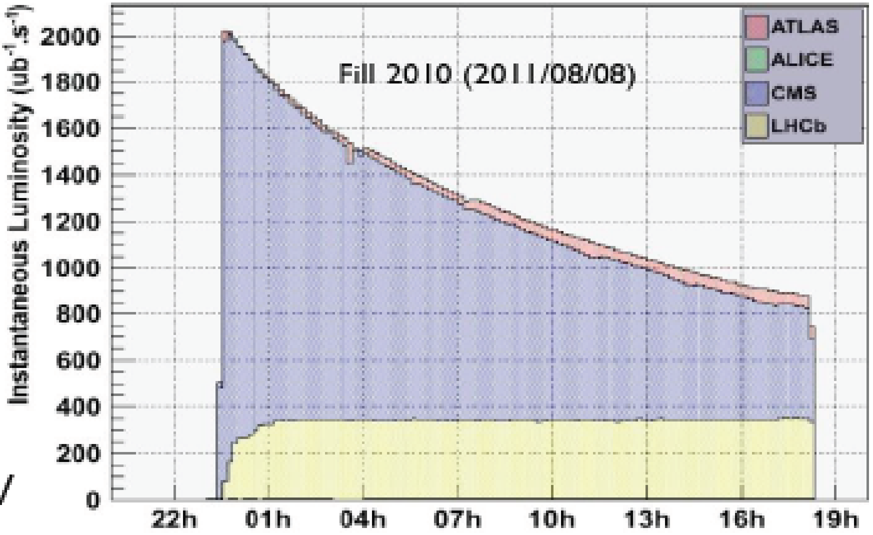
Heavy quark flavour physics experiments

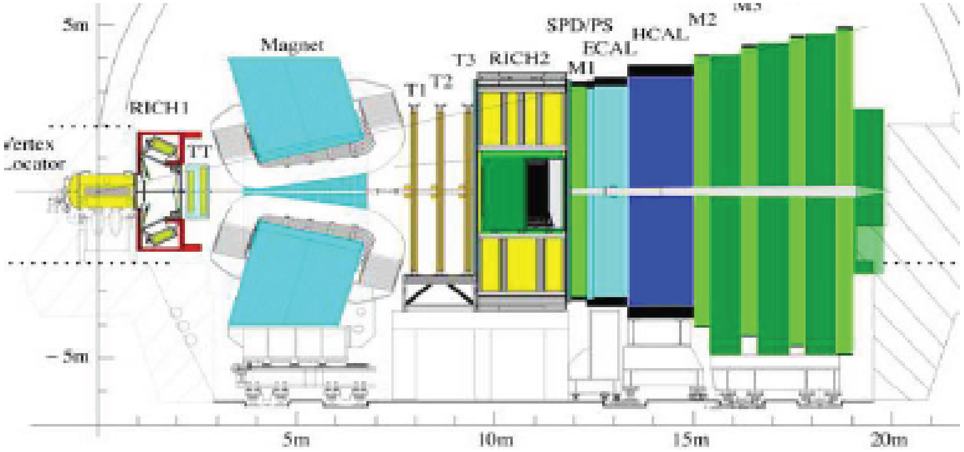
Quark Flavor @ LHC

- The LHC is a flavour factory
  - Large $b\bar{b}$ production rate: $\sigma_{bb} \sim 75\mu b$ for both ATLAS/CMS and LHCb

- ATLAS and CMS collect large samples of beauty events
  - Good trigger & PID for hard muons
  - No hadron PID
  - Total dataset: $5fb^{-1}$ @7TeV and $25fb^{-1}$@8TeV

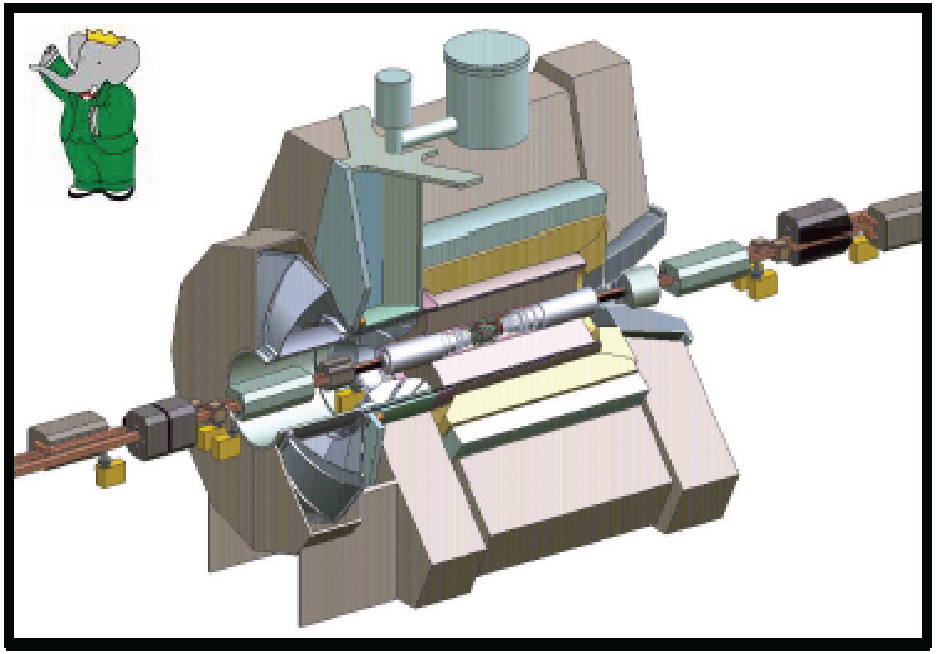
LHC luminosity profile

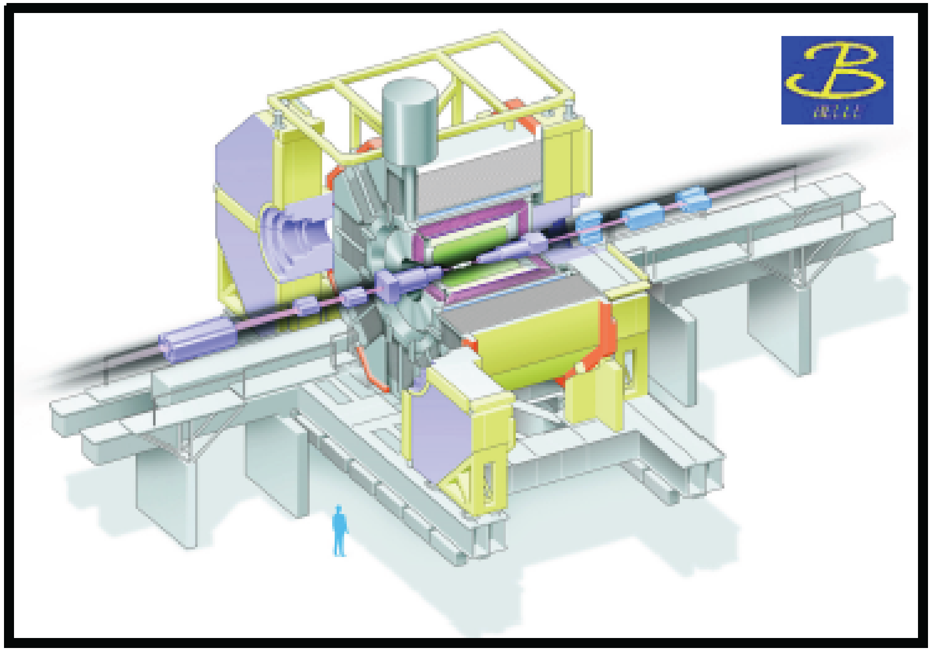




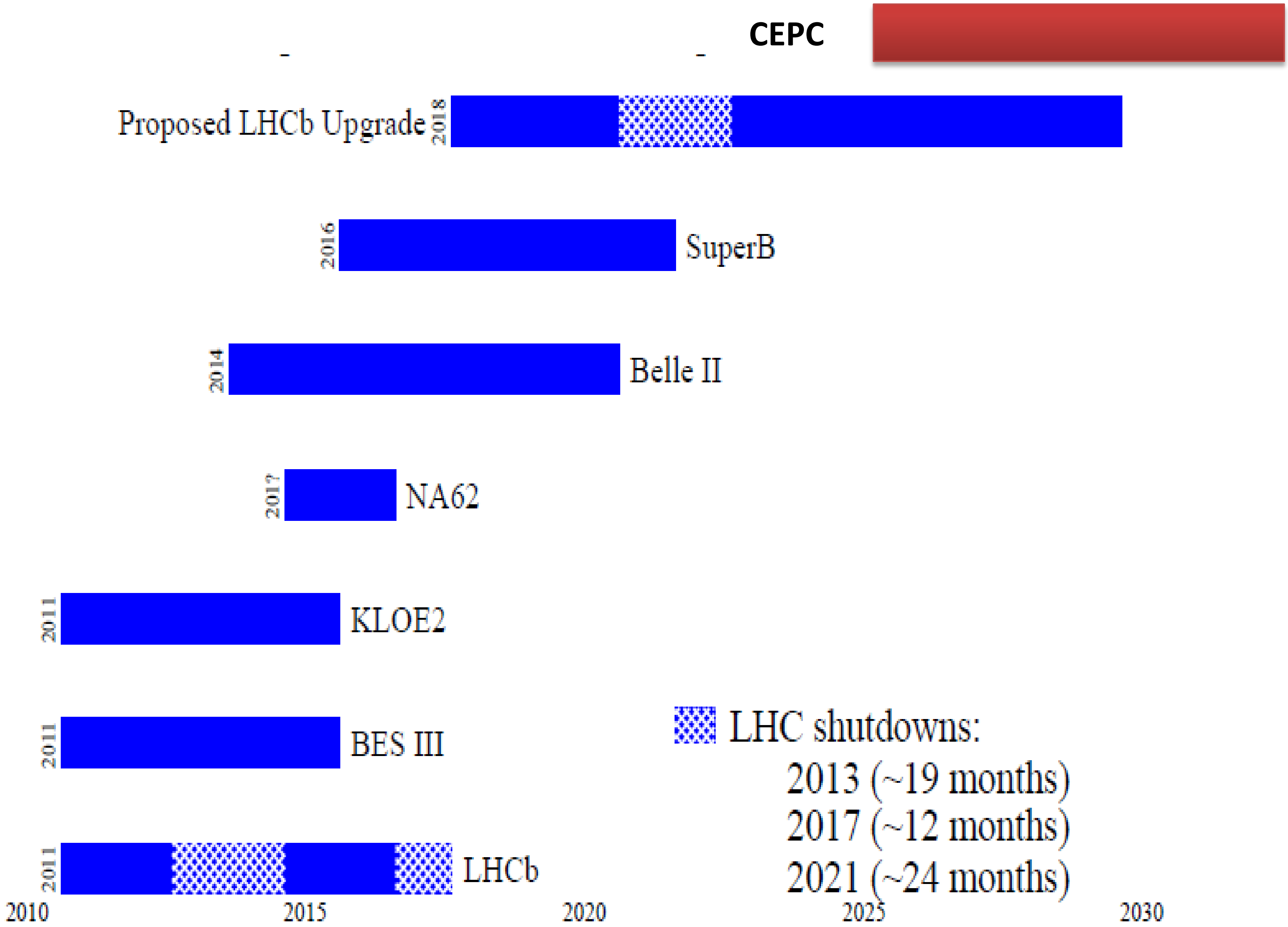
- LHCb: the LHC flavour experiment
  - Very efficient and flexible trigger
  - Good muon & hadron PID
  - Luminosity leveling at 4×10^{32} → Constant luminosity for entire fill
  - Total dataset: $1fb^{-1}$ @ 7TeV and $2.1fb^{-1}$ @ 8TeV

B Factories: Belle and BaBar





- BaBar/Belle: record asymmetric e^+e^- collisions at Υ(4S) resonance
  - Very clean sample of entangled BB pairs (dominantly B^0 and $B^\pm$)
  - Boost of B^0 allows time dependent measurements
  - Experimentally clean environment
- Data taking 1999- 2008 / 2010 (BaBar / Belle)
  - Total dataset at Υ(4S): 530fb^{-1} / 1000fb^{-1}


CEPC
Proposed LHCb Upgrade
2018
2016
SuperB
2014
Belle II
2017
NA62
2011
KLOE2
2011
BES III
2011
LHCb
▨ LHC shutdowns:
2013 (~19 months)
2017 (~12 months)
2021 (~24 months)
2010
2015
2020
2025
2030

3.What can we do on HF @ CEPC ?

Honestly speaking, there is little space left after LHC-b (Large Background) and Super-b ("Low" Energy) for studying Beauty-Physics and Charm Physics.

However, there are some advantages over LHC-b and Super-b.

$$e^+ + e^- \rightarrow f + \bar{f}$$

- At CEPC, the produced b quark and anti-b quark are flying in the center of the mass. So, it is convenient to measure some time-dependent observables, for example, the time-dependence CP violation of the hadronic B meson decays.

$$\boldsymbol{L = 2.6 \times 10^{34}\ cm^{-2}\ s^{-1}}$$

Cross Section	$\sqrt{s} = m_Z$		$\sqrt{s} = 240\text{GeV}$	
Tau	1474 pb	1.2×10^{9}	4.3pb	3.5×10^{7}
Charm Pair	5237 pb	4.3×10^{9}	10.7pb	9.5×10^{7}
Beauty Pair	6549 pb	5.4×10^{9}	10.8pb	9.6×10^{7}

LHC-b(b-pair+X)	89.6×10^{6} Pb	5.8×10^{11}	$4.0 \times 10^{32}\ cm^{-2}\ s^{-1}$
Super-b (b-pair)	1100pb	1.4×10^{10}	$8.0 \times 10^{35}\ cm^{-2}\ s^{-1}$

there is few space left after LHC-b and Super-b for studying B physics and Charm Physics.

B Physics

- Since large cross section @ LHC-b (II) and high luminosity @ Super-b, the parameters of B-mixing and most rare decays could be measured precisely. The results from CEPC could crosscheck that from above two experiments.
  - $\boldsymbol{B \to X_S \gamma, B \to K^{(*)} l^+ l^-}, \boldsymbol{B \to D l \nu}$
  - $\boldsymbol{B} \to \mu^+\mu^-, \boldsymbol{B} \to \tau\nu$
  - $\boldsymbol{B} \to K\pi, \boldsymbol{B} \to \pi\pi, J/\psi\, K$
  - $\boldsymbol{B} \to K\phi, \boldsymbol{B} \to K\eta, KKK, \ldots$
- The time-dependent observables, for example, the time-dependence CP violation of the hadronic B meson decays, together with above measurements, help us test the SM , understand the QCD, and search for the possible effect of NP.

Bs Physics

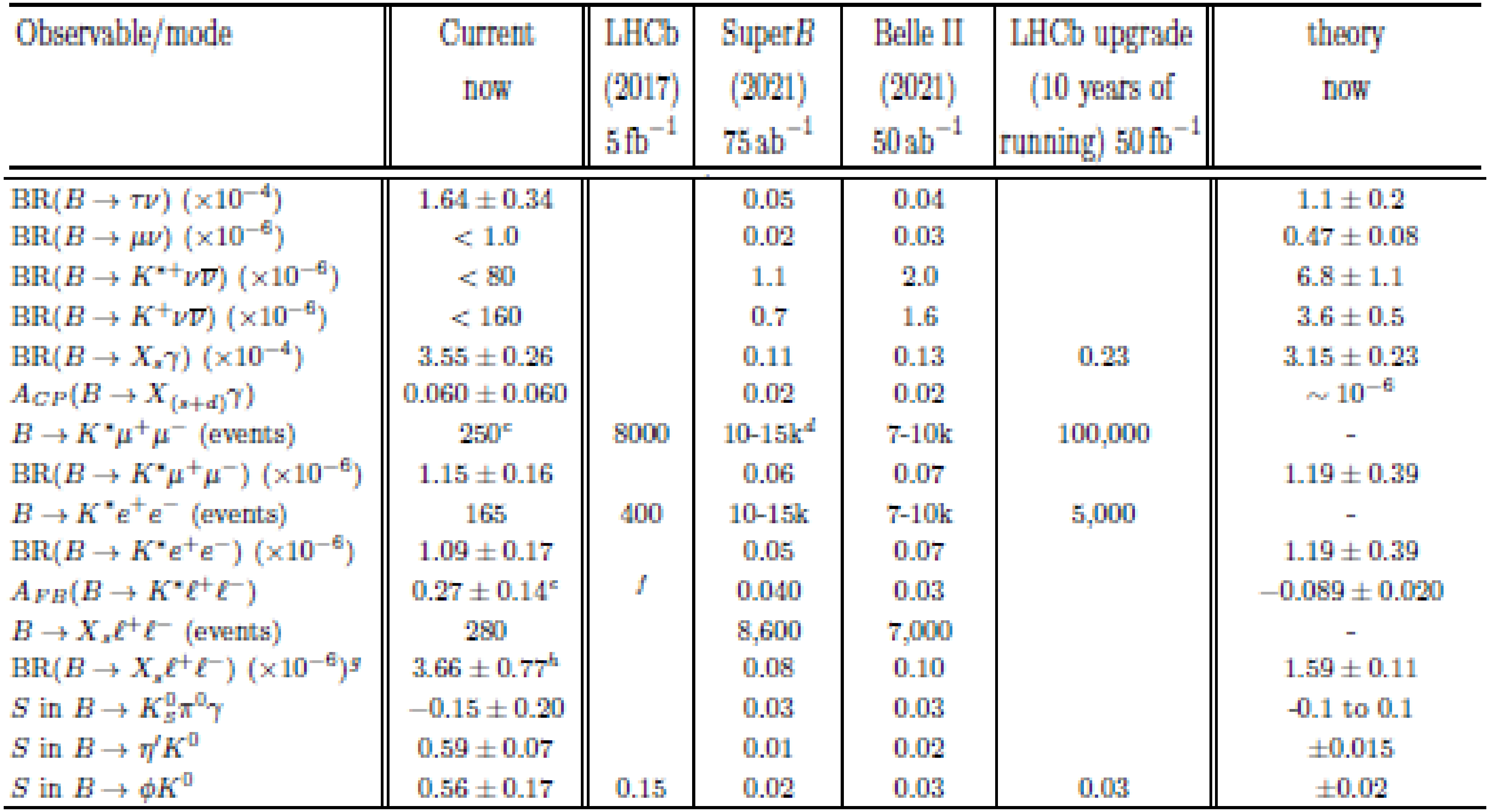
Bs meson, the strange "partners" of topical *Bd* decays are also important in HFP.

--$\boldsymbol{B_S} \rightarrow \mu^+\mu^-, \gamma\gamma, \pi\pi, K\pi, \phi\phi$

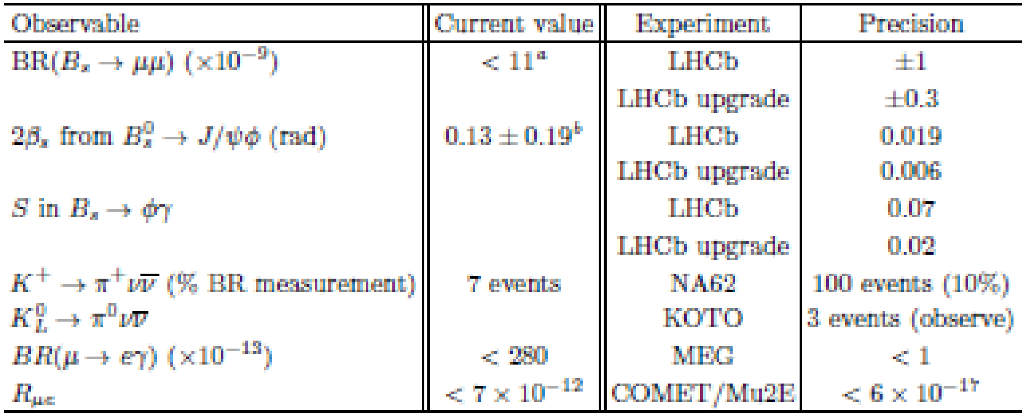
--$\boldsymbol{B_S}$ mixing and $\boldsymbol{B_S} \rightarrow J/\psi\,\phi, f_0(980)$

--$\boldsymbol{B_S} \rightarrow DsK$

- At two B-factories, Bs pairs are kinematically forbidden when running at the Υ(4*S*) resonance.
- The existing data about Bs are from hadronic experiments, CDF, D0 and LHCb with large background.
- Super-b running at the energy of the Υ(10860) resonance could produce Bs pairs, and the number of *Bs* mesons is estimated to be 5.9 × 10^8



Observable/mode	Current now	LHCb (2017) 5 fb^{-1}	Super$B$ (2021) 75 ab^{-1}	Belle II (2021) 50 ab^{-1}	LHCb upgrade (10 years of running) 50 fb^{-1}	theory now
$\mathrm{BR}(B \to \tau\nu)$ $(\times 10^{-4})$	1.64 ± 0.34		0.05	0.04		1.1 ± 0.2
$\mathrm{BR}(B \to \mu\nu)$ $(\times 10^{-6})$	< 1.0		0.02	0.03		0.47 ± 0.08
$\mathrm{BR}(B \to K^{*+}\nu\bar{\nu})$ $(\times 10^{-6})$	< 80		1.1	2.0		6.8 ± 1.1
$\mathrm{BR}(B \to K^{+}\nu\bar{\nu})$ $(\times 10^{-6})$	< 160		0.7	1.6		3.6 ± 0.5
$\mathrm{BR}(B \to X_s\gamma)$ $(\times 10^{-4})$	3.55 ± 0.26		0.11	0.13	0.23	3.15 ± 0.23
$A_{CP}(B \to X_{(s+d)}\gamma)$	0.060 ± 0.060		0.02	0.02		$\sim 10^{-6}$
$B \to K^*\mu^+\mu^-$ (events)	250^c	8000	10-15k^d	7-10k	100,000	-
$\mathrm{BR}(B \to K^*\mu^+\mu^-)$ $(\times 10^{-6})$	1.15 ± 0.16		0.06	0.07		1.19 ± 0.39
$B \to K^*e^+e^-$ (events)	165	400	10-15k	7-10k	5,000	-
$\mathrm{BR}(B \to K^*e^+e^-)$ $(\times 10^{-6})$	1.09 ± 0.17		0.05	0.07		1.19 ± 0.39
$A_{FB}(B \to K^*\ell^+\ell^-)$	0.27 ± 0.14^e	f	0.040	0.03		-0.089 ± 0.020
$B \to X_s\ell^+\ell^-$ (events)	280		8,600	7,000		-
$\mathrm{BR}(B \to X_s\ell^+\ell^-)$ $(\times 10^{-6})^g$	3.66 ± 0.77^h		0.08	0.10		1.59 ± 0.11
S in $B \to K_S^0\pi^0\gamma$	-0.15 ± 0.20		0.03	0.03		-0.1 to 0.1
S in $B \to \eta' K^0$	0.59 ± 0.07		0.01	0.02		± 0.015
S in $B \to \phi K^0$	0.56 ± 0.17	0.15	0.02	0.03	0.03	± 0.02



Observable	Current value	Experiment	Precision
$\mathrm{BR}(B_s \to \mu\mu)$ $(\times 10^{-9})$	$< 11^a$	LHCb	± 1
		LHCb upgrade	± 0.3
$2\beta_s$ from $B_s^0 \to J/\psi\phi$ (rad)	0.13 ± 0.19^b	LHCb	0.019
		LHCb upgrade	0.006
S in $B_s \to \phi\gamma$		LHCb	0.07
		LHCb upgrade	0.02
$K^+ \to \pi^+\nu\bar{\nu}$ (% BR measurement)	7 events	NA62	100 events (10%)
$K_L^0 \to \pi^0\nu\bar{\nu}$		KOTO	3 events (observe)
$BR(\mu \to e\gamma)$ $(\times 10^{-13})$	< 280	MEG	< 1
$R_{\mu e}$	$< 7 \times 10^{-12}$	COMET/Mu2E	$< 6 \times 10^{-17}$

CEPC

To be added

Bc Physics

- For Bc meson, although CDF、D0 and LHCb had collected some data, many results have large uncertainties because of the large background.
- At CEPC, about 10^4 Bc pairs can be produced.
  - The spectrums of Bc mesons
  - The life time and decay width
  - The weak decays of Bc meson with Charm
  - The weak decays of Bc meson without Charm
  - The Production of Bc meson in future colliders

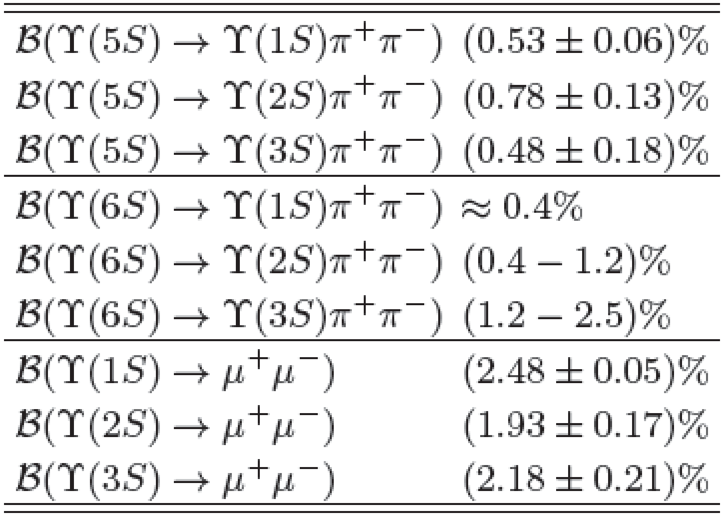
Mode	BR, %	Mode	BR, %	Mode	BR, %
$B_c^+ \to \eta_c e^+ \nu$	0.75	$B_c^+ \to J/\psi K^+$	0.011	$B_c^+ \to B_s^0 K^+$	1.06
$B_c^+ \to \eta_c \tau^+ \nu$	0.23	$B_c \to J/\psi K^{*+}$	0.022	$B_c^+ \to B_s^{*0} K^+$	0.37
$B_c^+ \to \eta'_c e^+ \nu$	0.041	$B_c^+ \to D^+ \overline{D}^0$	0.0053	$B_c^+ \to B_s^0 K^{*+}$	–
$B_c^+ \to \eta'_c \tau^+ \nu$	0.0034	$B_c^+ \to D^+ \overline{D}^{*0}$	0.0075	$B_c^+ \to B_s^{*0} K^{*+}$	–
$B_c^+ \to J/\psi e^+ \nu$	1.9	$B_c^+ \to D^{*+} \overline{D}^0$	0.0049	$B_c^+ \to B^0 \pi^+$	1.06
$B_c^+ \to J/\psi \tau^+ \nu$	0.48	$B_c^+ \to D^{*+} \overline{D}^{*0}$	0.033	$B_c^+ \to B^0 \rho^+$	0.96
$B_c^+ \to \psi' e^+ \nu$	0.132	$B_c^+ \to D_s^+ \overline{D}^0$	0.00048	$B_c^+ \to B^{*0} \pi^+$	0.95
$B_c^+ \to \psi' \tau^+ \nu$	0.011	$B_c^+ \to D_s^+ \overline{D}^{*0}$	0.00071	$B_c^+ \to B^{*0} \rho^+$	2.57
$B_c^+ \to D^0 e^+ \nu$	0.004	$B_c^+ \to D_s^{*+} \overline{D}^0$	0.00045	$B_c^+ \to B^0 K^+$	0.07
$B_c^+ \to D^0 \tau^+ \nu$	0.002	$B_c^+ \to D_s^{*+} \overline{D}^{*0}$	0.0026	$B_c^+ \to B^0 K^{*+}$	0.015
$B_c^+ \to D^{*0} e^+ \nu$	0.018	$B_c^+ \to \eta_c D_s^+$	0.86	$B_c^+ \to B^{*0} K^+$	0.055
$B_c^+ \to D^{*0} \tau^+ \nu$	0.008	$B_c^+ \to \eta_c D_s^{*+}$	0.26	$B_c^+ \to B^{*0} K^{*+}$	0.058
$B_c^+ \to B_s^0 e^+ \nu$	4.03	$B_c^+ \to J/\psi D_s^+$	0.17	$B_c^+ \to B^+ \overline{K^0}$	1.98
$B_c^+ \to B_s^{*0} e^+ \nu$	5.06	$B_c^+ \to J/\psi D_s^{*+}$	1.97	$B_c^+ \to B^+ \overline{K^{*0}}$	0.43
$B_c^+ \to B^0 e^+ \nu$	0.34	$B_c^+ \to \eta_c D^+$	0.032	$B_c^+ \to B^{*+} \overline{K^0}$	1.60
$B_c^+ \to B^{*0} e^+ \nu$	0.58	$B_c^+ \to \eta_c D^{*+}$	0.010	$B_c^+ \to B^{*+} \overline{K^{*0}}$	1.67
$B_c^+ \to \eta_c \pi^+$	0.20	$B_c^+ \to J/\psi D^+$	0.009	$B_c^+ \to B^+ \pi^0$	0.037
$B_c^+ \to \eta_c \rho^+$	0.42	$B_c^+ \to J/\psi D^{*+}$	0.074	$B_c^+ \to B^+ \rho^0$	0.034
$B_c^+ \to J/\psi \pi^+$	0.13	$B_c^+ \to B_s^0 \pi^+$	16.4	$B_c^+ \to B^{*+} \pi^0$	0.033
$B_c^+ \to J/\psi \rho^+$	0.40	$B_c^+ \to B_s^0 \rho^+$	7.2	$B_c^+ \to B^{*+} \rho^0$	0.09
$B_c^+ \to \eta_c K^+$	0.013	$B_c^+ \to B_s^{*0} \pi^+$	6.5	$B_c^+ \to \tau^+ \nu_\tau$	1.6
$B_c^+ \to \eta_c K^{*+}$	0.020	$B_c^+ \to B_s^{*0} \rho^+$	20.2	$B_c^+ \to c\bar{s}$	4.9

Decay Modes $(\Delta S = 0)$	$BR's(10^{-8})$	Decay Modes $(\Delta S = 1)$	$BR's(10^{-8})$
$\mathrm{B_c} \to \pi^+\pi^0$	0	$\mathrm{B_c} \to \pi^+\mathrm{K}^0$	$4.0^{+1.0}_{-0.6}(m_c)^{+2.3}_{-1.6}(a_i)^{+0.5}_{-0.3}(m_0)$
$\mathrm{B_c} \to \pi^+\eta$	$22.8^{+6.9}_{-4.6}(m_c)^{+7.2}_{-4.5}(a_i)^{+3.4}_{-4.2}(m_0)$	$\mathrm{B_c} \to \mathrm{K}^+\eta$	$0.6^{+0.0}_{-0.0}(m_c)^{+0.6}_{-0.5}(a_i)^{+0.2}_{-0.1}(m_0)$
$\mathrm{B_c} \to \pi^+\eta'$	$15.3^{+4.6}_{-3.1}(m_c)^{+4.8}_{-3.0}(a_i)^{+2.2}_{-2.8}(m_0)$	$\mathrm{B_c} \to \mathrm{K}^+\eta'$	$5.7^{+0.9}_{-0.9}(m_c)^{+1.0}_{-1.6}(a_i)^{+0.0}_{-0.3}(m_0)$
$\mathrm{B_c} \to \mathrm{K}^+\overline{\mathrm{K}}^0$	$24.0^{+2.4}_{-0.0}(m_c)^{+7.3}_{-6.0}(a_i)^{+6.8}_{-5.8}(m_0)$	$\mathrm{B_c} \to \mathrm{K}^+\pi^0$	$2.0^{+0.5}_{-0.3}(m_c)^{+1.2}_{-0.8}(a_i)^{+0.3}_{-0.1}(m_0)$

Decay Modes $(\Delta S = 0)$	$BR's(10^{-7})$	Decay Modes $(\Delta S = 1)$	$BR's(10^{-8})$
$\mathrm{B_c} \to \pi^+\rho^0$	$1.7^{+0.1}_{-0.0}(m_c)^{+0.1}_{-0.2}(a_i)^{+0.6}_{-0.3}(m_0)$	$\mathrm{B_c} \to \mathrm{K}^+\rho^0$	$3.1^{+0.6}_{-0.8}(m_c)^{+1.2}_{-1.5}(a_i)^{+0.1}_{-0.2}(m_0)$
$\mathrm{B_c} \to \overline{\mathrm{K}}^0\mathrm{K}^{*+}$	$1.8^{+0.7}_{-0.1}(m_c)^{+4.1}_{-2.1}(a_i)^{+0.1}_{-0.0}(m_0)$	$\mathrm{B_c} \to \mathrm{K}^0\rho^+$	$6.1^{+1.3}_{-1.5}(m_c)^{+2.5}_{-2.9}(a_i)^{+0.2}_{-0.3}(m_0)$
$\mathrm{B_c} \to \pi^+\omega$	$5.8^{+1.4}_{-2.2}(m_c)^{+1.1}_{-1.3}(a_i)^{+0.4}_{-1.2}(m_0)$	$\mathrm{B_c} \to \mathrm{K}^+\omega$	$2.3^{+1.1}_{-0.3}(m_c)^{+1.8}_{-1.2}(a_i) \pm 0.1(m_0)$
$\mathrm{B_c} \to \rho^+\pi^0$	$0.5^{+0.1}_{-0.1}(m_c)^{+0.3}_{-0.2}(a_i)^{+0.2}_{-0.3}(m_0)$	$\mathrm{B_c} \to \mathrm{K}^{*0}\pi^+$	$3.3^{+0.7}_{-0.2}(m_c)^{+0.4}_{-0.4}(a_i)^{+0.2}_{-0.1}(m_0)$
$\mathrm{B_c} \to \rho^+\eta$	$5.4^{+2.1}_{-1.2}(m_c)^{+0.9}_{-1.4}(a_i) \pm 0.0(m_0)$	$\mathrm{B_c} \to \mathrm{K}^{*+}\pi^0$	$1.6^{+0.4}_{-0.1}(m_c)^{+0.3}_{-0.1}(a_i)^{+0.1}_{-0.0}(m_0)$
$\mathrm{B_c} \to \rho^+\eta'$	$3.6^{+1.4}_{-0.8}(m_c)^{+0.6}_{-0.9}(a_i) \pm 0.0(m_0)$	$\mathrm{B_c} \to \mathrm{K}^{*+}\eta$	$0.9^{+0.1}_{-0.0}(m_c)^{+0.6}_{-0.2}(a_i) \pm 0.0(m_0)$
$\mathrm{B_c} \to \overline{\mathrm{K}}^{*0}\mathrm{K}^+$	$10.0^{+0.5}_{-0.6}(m_c)^{+1.7}_{-3.3}(a_i)^{+0.0}_{-0.2}(m_0)$	$\mathrm{B_c} \to \mathrm{K}^{*+}\eta'$	$3.8 \pm 1.1(m_c)^{+1.0}_{-0.6}(a_i) \pm 0.0(m_0)$
		$\mathrm{B_c} \to \phi\mathrm{K}^+$	$5.6^{+1.1}_{-0.0}(m_c)^{+1.2}_{-0.9}(a_i)^{+0.3}_{-0.0}(m_0)$

The Exotic States of Bottom-like States.

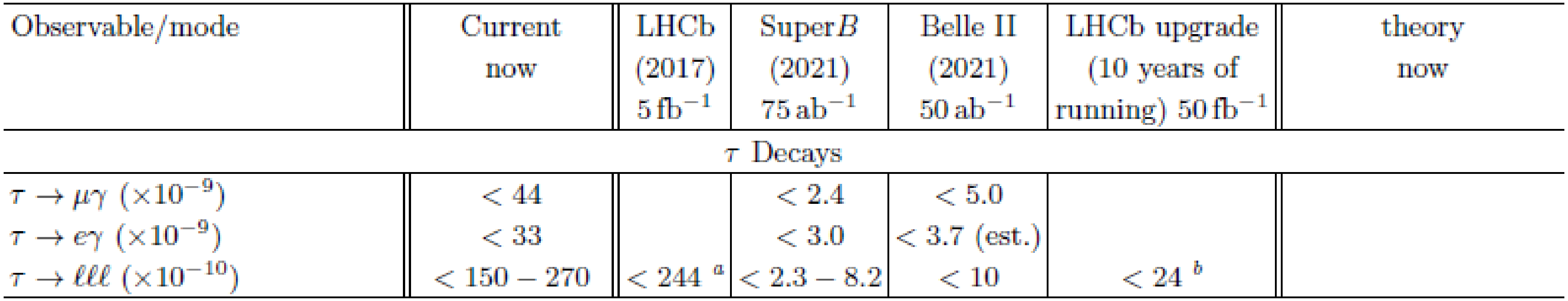
- For LHC-b, although it has large cross section, the uncertainties are large due to large background.
- In the Super-b, the energy is not enough to produce the exotic states of bottom-like states, for example Zb(10610), Zb(10650), and Y(n*S*) .



$\mathcal{B}(\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-)$	$(0.53 \pm 0.06)\%$
$\mathcal{B}(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)$	$(0.78 \pm 0.13)\%$
$\mathcal{B}(\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-)$	$(0.48 \pm 0.18)\%$
$\mathcal{B}(\Upsilon(6S) \to \Upsilon(1S)\pi^+\pi^-)$	$\approx 0.4\%$
$\mathcal{B}(\Upsilon(6S) \to \Upsilon(2S)\pi^+\pi^-)$	$(0.4 - 1.2)\%$
$\mathcal{B}(\Upsilon(6S) \to \Upsilon(3S)\pi^+\pi^-)$	$(1.2 - 2.5)\%$
$\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$	$(2.48 \pm 0.05)\%$
$\mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-)$	$(1.93 \pm 0.17)\%$
$\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-)$	$(2.18 \pm 0.21)\%$

Tau Physics

LFV in τ decays is one of the most important physics target in the HEP.



Observable/mode	Current now	LHCb (2017) $5\,\mathrm{fb}^{-1}$	Super$B$ (2021) $75\,\mathrm{ab}^{-1}$	Belle II (2021) $50\,\mathrm{ab}^{-1}$	LHCb upgrade (10 years of running) $50\,\mathrm{fb}^{-1}$	theory now
τ Decays						
$\tau \to \mu\gamma$ $(\times 10^{-9})$	< 44		< 2.4	< 5.0		
$\tau \to e\gamma$ $(\times 10^{-9})$	< 33		< 3.0	< 3.7 (est.)		
$\tau \to \ell\ell\ell$ $(\times 10^{-10})$	$< 150 - 270$	< 244 [a]	$< 2.3 - 8.2$	< 10	< 24 [b]	

So, CEPC has no advantage over Super B on tau physics.

But we expect some of decay modes could be measured at SppC, as more data about tau could be produced.

Contents

Summary

- The fermion pairs could be produced with large cross sections at Z-pole ($\sqrt{s} = m_Z$).
- For B, Bs, and Tau lepton, CEPC offer us a good place for crosschecking the results of LHCb and Super-b.
- For Bc and Y(ns), the measurement results are expected to be precise due to the low background.
- If some new particles are detected , flavor physics @CEPC could help us to identify the characters of them

THANK YOU