Heavy flavor physics after the Higgs discovery
Yuehong Xie, Central China Normal University

Mass generation

Implication

Understanding

Physics of flavor

National HEP Conference
Wuhan, China, 18-23 April 2014
The big picture
Understanding the Higgs

- W/Z: seem to understand the mass generation
- Fermions: picture unclear

- mass generation? \( y_e \bar{L} H e_R + h.c. \rightarrow y_e \frac{\sqrt{2}}{2} (\bar{e}_L e_R + \bar{e}_R e_L) \)

- flavor mixing? \( J^{\mu+} = \frac{1}{\sqrt{2}} \bar{u}_L^i \gamma^\mu d_L^i \rightarrow \frac{1}{\sqrt{2}} \bar{u}_L^i \gamma^\mu (U_u^L)^{ij} \bar{u}_R^j d_L^i \)
Quark mixing in the SM

\[ \mathcal{L}_{\text{SM}} = \overbrace{\mathcal{L}_G(\psi, W, \phi)} + \overbrace{\mathcal{L}_H(\phi)} + \overbrace{\mathcal{L}_Y(\psi, \phi)} \]

- kinetic energy + gauge IA
- Higgs potential \rightarrow spontaneous symmetry breaking
- Yukawa IA \rightarrow fermion masses

EWSB & diagonalisation of Yukawa mass matrix \Rightarrow CKM quark mixing matrix

\[ V_{\text{CKM}} = \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} \]

L. Wolfenstein PRL 51 (1983) 1945

CP violation accommodated by a single complex phase
Triumph of CKM

Overall very successful to describe collider data

Though no explanation of the matter dominance in the Universe …
Flavor is still a mystery

- What is the dynamic origin of the patterns of fermion masses and flavor mixing?
- What are sources of flavor symmetry breaking & CP violation (beyond Yukawa couplings)?

New physics (NP) beyond the SM is expected
Is there a NP flavor problem?

\[ \mathcal{L}_{EFT} = \Lambda_{UV}^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2 + \mathcal{L}^{\text{gauge}}_{\text{SM}} + \mathcal{L}^{\text{Yukawa}}_{\text{SM}} + \frac{\mathcal{L}^{(5)}}{\Lambda_{UV}} + \frac{\mathcal{L}^{(6)}}{\Lambda_{UV}^2} + \ldots \]

Electroweak symmetry breaking → Higgs mass

\[ h \quad h \sim \frac{g_T^2}{16\pi^2} \Lambda_{UV}^2 \]

No fine-tuning → bounds on flavor mixing → assuming generic flavor structure

\[ \Lambda_{\text{Higgs}} < \sim 1 \text{ TeV} \quad \text{(unless nature is fine tuned)} \]

\[ \Lambda_{\text{flavor}} \gg 1 \text{ TeV} \quad \text{(unless NP is special)} \]

NP FCNC must be suppressed to be consistent with data.
Bounds from FCNC data

\[ \mathcal{L}_{SM} + \frac{g_X^2}{\Lambda_{UV}^2} (\bar{Q}_i Q_j)(\bar{Q}_i Q_j) \]

Heavy flavor

Generic bounds on New Physics scale (for $g_X \sim 1$)
Possible scenarios

NP below 1 TeV excluded with 8 TeV LHC data

I. Weakly interacting NP at few TeV with mild flavor symmetry breaking

II. NP above few TeV, Higgs fine-tuned, new particles too heavy for LHC

Either way, there will be small but detectable deviations from SM in some observables.

Major goal of flavor physics in coming years: search for NP at high precision and in wide scope!
Rare decays
\[ B_s \rightarrow \mu^+\mu^- \] discovery

- Sensitive to NP scalar couplings
- SM: FCNC and helicity suppression

\[ B(B_s^0 \rightarrow \mu^+\mu^-) = (3.56 \pm 0.30) \times 10^{-9} \]

EPJC 72(2012)2172

- CMS+LHCb measurement

\[ B(B_s^0 \rightarrow \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9} \]

CMS-PAS-BPH-13-007
LHCb-CONF-2013-012
Next goals

- Precision measurement of $\text{Br}(B_s \rightarrow \mu^+\mu^-)$
- Discover $B_d \rightarrow \mu^+\mu^-$ (large NP effect still possible)
- Monitor $\text{Br}(B_s \rightarrow \mu^+\mu^-) /\text{Br}(B_d \rightarrow \mu^+\mu^-)$ (power test of MFV)
$B^0 \rightarrow K^{*\mu^+\mu^-}$

Sensitive to NP in EW loop

Angular observables $A_{FB}, P_{4-8}$, insensitive to form factors

NP? SM not understood? Poor precision?

1 fb$^{-1}$ results, PRL 111 (2013) 191801

See 3.7$\sigma$ local tension in $P_5^- \rightarrow 0.5\%$ global p-value
# Lepton flavor violation

## LHCb results

<table>
<thead>
<tr>
<th>BR</th>
<th>@ 90(95)% CL</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow e^+ \mu^-$</td>
<td>$1.1 (1.4) \times 10^{-8}$</td>
<td>PRL 111 (2013) 141801, LHCb, World’s best</td>
</tr>
<tr>
<td>$B^0 \rightarrow e^+ \mu^-$</td>
<td>$2.8 (3.7) \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^- \mu^+ \mu^-$</td>
<td>$8.3(10.2) \times 10^{-8}$</td>
<td>Competitive with Belle</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \bar{\nu}_\mu \mu^-$</td>
<td>$4.6(5.9) \times 10^{-7}$</td>
<td>World’s first</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \nu \mu^- \mu^-$</td>
<td>$5.4(6.9) \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^- \mu^+ \mu^-$</td>
<td>Best limit from BELLE $2.1 \times 10^{-8}$</td>
<td>PLB 687 (2010) 139, Belle</td>
</tr>
</tbody>
</table>

Fatima Soomro (INFN)
New results at a glance

**Very rare decays**
- $B_{(s)}\rightarrow\mu\mu$ [3fb$^{-1}$/arXiv:1307.5024]
- $D\rightarrow\mu\mu$ [0.9fb$^{-1}$/arXiv:1305.5050]
- $K_{s}\rightarrow\mu\mu$ [1fb$^{-1}$/arXiv:1209.4029]
- $B\rightarrow4\mu$ [1fb$^{-1}$/arXiv:1303.1092]
- $B^{+}\rightarrow\pi^{+}\mu\mu$ [1fb$^{-1}$/arXiv:1210.2645]

**Angular an isospin analysis**
- $B\rightarrow K^{*}\mu\mu$ [1fb$^{-1}$/arXiv:1308.1707] [1fb$^{-1}$/arXiv:1304.6325]
- $\Lambda_{b}\rightarrow\Lambda\mu\mu$ [1fb$^{-1}$/arXiv:1306.2577]
- $B_{s}\rightarrow\phi\mu\mu$ [1fb$^{-1}$/arXiv:1305.2168]
- $B\rightarrow K^{(*)}\mu\mu$ [1fb$^{-1}$/arXiv:1205.3422]
- $\psi(4160)$ [3fb$^{-1}$/arXiv:1307.7595]

**CP Asymmetries**
- $B\rightarrow K^{*}\mu\mu$ [1fb$^{-1}$/arXiv:1210.4492]
- $B^{+}\rightarrow K^{+}\mu\mu$ [1fb$^{-1}$/arXiv:1308.1340]

**No SM processes**
- $B^{+}\rightarrow X\mu^{-}\mu^{-}$ [0.41fb$^{-1}$/arXiv:1201.5660]
- $B_{(s)}\rightarrow X\mu\mu$ [1fb$^{-1}$/arXiv:1307.4889]
- $\tau\rightarrow 3\mu, \tau\rightarrow p\mu\mu$ [1fb$^{-1}$/arXiv:1304.4518]

**Radiative decays**
- $B\rightarrow K^{*}\gamma, B_{s}\rightarrow \phi\gamma$ [1fb$^{-1}$/arXiv:1202.6267]
- $B^{+}\rightarrow K^{+}\pi^{-}\pi^{+}\gamma$ [3fb$^{-1}$/arXiv:1402.6852]
B mixing and CPV
Probes of NP in $B_s$ mixing

$M_{12}$ causing $B_s$ mixing, sensitive to NP

- CPV in mixing: $a^{s}_{fs} \approx |\Gamma_{12}/M_{12}|\sin\phi_{12}$ where $\phi_{12} = \text{arg}(-M_{12}/\Gamma_{12})$

- Mass difference: $\Delta m_s = m_H - m_L \approx 2|M_{12}| \propto (V_{ts}^*V_{tb})^2$

- Width difference: $\Delta \Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi_{12}$

- Phase difference $\phi_s$ between $B_s \rightarrow f_{CP}$ and $B_s \rightarrow B_s \rightarrow f_{CP}$
$\phi_s$ and $\Delta \Gamma_s$ from $B_s \rightarrow J/\Psi h^+ h^-$

Agrees with SM expectation

LHCb dominating

PRD 87 (2013) 112010, LHCb, 1fb$^{-1}$
LHCb: $\phi_s = 0.01 \pm 0.07 \pm 0.01$ rad
$\Delta \Gamma_s = 0.100 \pm 0.016 \pm 0.003$ ps$^{-1}$

SM: $\phi_s = -0.036 \pm 0.002$ rad,
$\Delta \Gamma_s = 0.087 \pm 0.021$ ps$^{-1}$

PRD 84 (2011) 033005, Charles et al.
CPV in $B_s$ mixing: $a_{fs}^s$

\[ A_{meas}^s = \frac{N_D^s \mu^+ \varepsilon \mu^+ - N_D^s \mu^- \varepsilon \mu^-}{N_D^s \mu^+ \varepsilon \mu^+ + N_D^s \mu^- \varepsilon \mu^-} \]

Most precise measurement
\[ a_{fs}^s = 2A_{meas}^s = -0.06 \pm 0.50 \pm 0.36 \%
\]

Consistent with SM
World’s most precise $\Delta m_s$ measurement (from $B_s \rightarrow D_s^+\pi^-$)

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006$ ps$^{-1}$

NJP 15 (2013) 053021, LHCb

SM prediction: $\Delta m_s = 17.3 \pm 2.6$ ps$^{-1}$

arXiv: 1102.4274, Lenz & Nierste

$\Delta m_s \propto f_{B_s}^2 B_{B_s}$

Uncertainty of SM prediction dominated by uncertainty of hadronic parameters from lattice QCD
**$B_s$ mixing: implication**

- Model independent analysis of NP in $B_s$ mixing
  
  \[ M_{12}^s = M_{12}^{SM,s} \Delta_s \]

  Major constraints on NP in $M_{12}$ come from $\Delta m_s$ and $\phi_s$

- $B_s$ mixing is SM-like
  - Room for $O(10\%)$ NP contribution in $B_s$ mixing

- Similar situation for $B_d$ mixing

Lenz et al., arXiv:1203.0238
CPV in $B_s \to K^+K^-$

JHEP 10(2013)183, LHCb

$$A(t) = \frac{-C_f \cos(\Delta m_s t) + S_f \cos(\Delta m_s t)}{\cosh \left(\frac{\Delta \Gamma_s}{2} t\right)} - A^\Delta \Gamma \sinh \left(\frac{\Delta \Gamma_s}{2} t\right)$$

$$C_{KK} = 0.14 \pm 0.11 \text{ (stat)} \pm 0.03 \text{ (syst)},$$

$$S_{KK} = 0.30 \pm 0.12 \text{ (stat)} \pm 0.04 \text{ (syst)},$$

Next step: use SU(3) symmetry for combination with $B^0 \to \pi^+\pi^-$ to determine $\phi_s$ and $\gamma$
CPV in $B^+ \rightarrow h_1^+ h_1^- h_2^+$

- Significant CPV observed, which depends on Dalitz space, e.g. PRL 112 (2014) 011801, LHCb

- Triggered theoretical interests
  - Light resonance, PRD 87 (2013) 076007, Zhang, Guo, Yang
  - SU(3) flavor symmetry breaking, arXiv:1307.7186, Xu, Li, He
  - $B_s$ three body decays, arXiv:1401.5514, Cheng & Chua
Loop vs tree determination

Loop processes
Sensitive to NP

Consistent picture, room for $O(10\%)$ NP contribution
- Need higher precision, particularly for $\gamma$ and $V_{ub}$
- Need to reduce theoretical uncertainty, particularly penguin pollutions in $B_d \rightarrow J/\Psi K_s$ for $\sin 2\beta$

tree processes
“standard candle”
\( \gamma \) measurements

- Tree processes \( B \rightarrow Dh \)

  - LHCb \( 1\,fb^{-1} \): \( \gamma = (67 \pm 12)^\circ \)
  - Belle: \( \gamma = (68 \pm 15)^\circ \)
  - Babar: \( \gamma = (69 \pm 17)^\circ \)

  Combination \( \gamma = 68.0^{+8.0}_{-8.5}^\circ \) \((CKMFitter, FPCP 2013)\)

- Indirect determination \((CKMFitter)\)

  \( \gamma = (66.6 \pm 6.4)^\circ \)
$V_{ub}$ problem

Inclusive $B \rightarrow X_u \ell \nu$

$|V_{ub}| = (4.41 \pm 0.15_{exp}^{+0.15}_{-0.17_{th}}) \cdot 10^{-3}$

Kinematic constraints due to charm background.
HQE + resummation.

Exclusive $B \rightarrow \pi \ell \nu$

$|V_{ub}| = (3.23 \pm 0.31) \cdot 10^{-3}$

Lattice QCD form factor
QCD sum rules
analyticity

- $V_{ub} - \sin 2\beta - \epsilon_K$ connection
- Bet on exclusive ...
What is the effect of the penguin on CPV?

pQCD calculation: very small \( \sim 10^{-3} \)

PLB 672 (2009) 349, Gronau & Rosner

SU(3) flavor symmetry constraint: up to 0.1

PRD 79 (2009) 014005, Faller, Fleischer & Mannel

cf. experimental error <0.01 after LHCb upgrade
Charm mixing and CPV
**D^0 mixing discovery**

- First single-experiment measurement >5σ significance
- Rotation of mixing parameters by strong phase difference

No-mixing (x’=0, y’=0) excluded

\[ R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R_D} y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left( \frac{t}{\tau} \right)^2 \]
**Charm CPV**


\[
A_{CP} = \frac{\Gamma(D^0 \rightarrow hh^-) - \Gamma(\bar{D}^0 \rightarrow hh^-)}{\Gamma(D^0 \rightarrow hh^-) + \Gamma(\bar{D}^0 \rightarrow hh^-)}
\]

\[
\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi)
\]

- \(D^*\) tagged sample (preliminary) \(\Delta A_{CP} = (-0.34 \pm 0.15 \text{ (stat)} \pm 0.10 \text{ (sys)})\) \%
- \(\mu\) tagged sample \(\Delta A_{CP} = (+0.49 \pm 0.30 \text{ (stat)} \pm 0.14 \text{ (sys)})\) \%

Consistent with no CP violation hypothesis

No indication of CPV in any \(D\) decays or in \(D^0\) mixing. Controversial question: how big can \(D\) CPV be in SM?
Charm phenomenology

Charm quarks are too light for HQE and too heavy for ChPT?

\[ \frac{\Lambda_{QCD}}{m_c} \sim 0.3 \quad \text{vs} \quad \frac{\Lambda_{QCD}}{m_b} \sim 0.1 \]

Good realm to test various approaches

- HQE might still work
  e.g. Lenz, Rauh, Phys.Rev. D88 (2013) 034004

- Lattice QCD may one day be able to provide input on hadron matrix elements of open charm decays.
  e.g. Carrasco et al., PoS LATTICE2012 (2012) 105
Exotics
### $B \rightarrow D(*)\tau^+\nu$ puzzle

<table>
<thead>
<tr>
<th></th>
<th>Babar</th>
<th>SM: HQET</th>
<th>SM: pQCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(D)$</td>
<td>0.440±0.058±0.042</td>
<td>0.297±0.017</td>
<td>0.430$^{+0.021}_{-0.026}$</td>
</tr>
<tr>
<td>$R(D^*)$</td>
<td>0.332±0.024 ±0.018</td>
<td>0.252±0.003</td>
<td>0.301±0.013</td>
</tr>
</tbody>
</table>

$$R(D) = \frac{\Gamma(B \rightarrow D\tau\nu)}{\Gamma(B \rightarrow D\ell\nu)} \quad R(D^*) = \frac{\Gamma(B \rightarrow D^*\tau\nu)}{\Gamma(B \rightarrow D^*\ell\nu)}$$

Charged Higgs? Not from 2HDM

SM prediction reliability?

Measurement biases?
Charged “charmonium” particles

arXiv: 1404.1903, LHCb

LHCb

$Z_c(4430)^- \quad 1^+$

PRL 110 (2013) 252001, BES III

$Z_c(3900)^-$

PRL 111 (2013) 242001, BES III

$Z_c(4020)^- \quad 1^+?$

arXiv: 1308.2760, BES III

$Z_c(4025)^- \quad 1^+?$
Understanding QCD
B_c physics

B_c^+ \rightarrow J/\psi \pi^+

PRL 109 (2012) 232001, LHCb

Relative production cross section
Consistent with theory calculations
EPJC 38 (2004) 267, Chang & Wu
PRD 89 (2014) 034008, Qiao et al.

B_c^+ \rightarrow J/\psi \mu^+ \nu X

arXiv: 1401.6932, LHCb

Most precise B_c lifetime measurement

τ=509 ± 8 ± 12 fs
J/Ψ production

Cross section

EPJC 71 (2011) 1645, LHCb

PRL 106 (2011) 042002, Ma, Wang & Chao

polarisation

EPJC 73 (2013) 2631, LHCb

J/ψ production in p-Pb collisions

JHEP 1306 (2013) 064, LHCb

Nuclear modification factor:

\[ R_{pA}(y) = \frac{1}{A} \cdot \frac{d\sigma_{pA}}{dy}(y) / \frac{d\sigma_{pp}}{dy}(y) \]

Clear cold nuclear matter effect identified in p-Pb collisions: benchmark for search of QGP signals in Pb-Pb data.
On Lattice QCD side

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$B_k$</td>
<td>0.86 (17%)</td>
<td>0.766 (1.3%)</td>
</tr>
<tr>
<td>$f_{Bs}$</td>
<td>0.238 MeV (13%)</td>
<td>0.227 (2%)</td>
</tr>
<tr>
<td>$f_{Bs}/f_B$</td>
<td>1.24 (6%)</td>
<td>1.20 (1.8%)</td>
</tr>
<tr>
<td>$B_{Bs}$</td>
<td>1.34 (9%)</td>
<td>1.33 (4.5%)</td>
</tr>
<tr>
<td>$B_{Bs}/B_B$</td>
<td>1.00 (3%)</td>
<td>1.06 (10%)</td>
</tr>
</tbody>
</table>

Important progresses made in methods, computation power and algorithms

Further improvement desirable
Hadronic matrix elements

HQE/OPE, lattice, (QCD sum rules)  
QCD factorization, (flavour symmetries)

\[ \langle 0 \mid O \mid B \rangle \quad \langle B \mid O \mid B \rangle \quad \langle M \mid O \mid B \rangle \quad \langle M_1 M_2 \mid O \mid B \rangle \]

Increasingly difficult

\( \gamma \) from \( B \to DK \)  
\[ B \to \tau \nu_\tau \quad B \to D \tau \nu_\tau \quad B \to \rho \gamma \quad B \to K^{(*)} \ell \ell \]

Direct CP asym

\[ B_s \to \mu^+ \mu^- \quad |V_{ub}| \quad B \to K \nu \bar{\nu} \quad B \to \pi K, KK, \ldots \]

\[ B_s \to \pi \pi \quad B \to \pi \pi \quad B_s \to \phi \phi, K^*0 \bar{K}^*0 \]

Many efforts made in pQCD (e.g. NNLO for radiative decays, NLO (EW) and NNLO (QCD) for \( B_s \to \mu^+ \mu^- \))

No suitable method to reliably account for long distance contributions (e.g. penguin pollution in \( b \to c \bar{c} \bar{b} \bar{b} \) decays, charm sector)
Wish list to theoreticians

• Significant improvement in precision of hadronic parameters from Lattice QCD
  Form factors, bag parameters, decay constants, ME, …

• Reliable QCD calculation methods
  SM predictions of CPV in B & charm sector
  penguin pollution in \( b \rightarrow c \ c \bar{c} \ \ s \) decays
  SM prediction of \( R(D) \) and \( R(D^*) \)
  …

• Identification of many new observables
  Clean, sensitive to NP and measurable
Future prospects
Flavor landscape till 2030

- **Proposed LHCb Upgrade** (2018)
- **SuperB**
- **Belle II**
- **KLOE2**
- **BES III**
- **NA62**

**LHC shutdowns:**
- 2013 (~19 months)
- 2017 (~12 months)
- 2021 (~24 months)

**LHCb**
- 3 fb⁻¹ @ 7-8 TeV
- 5 fb⁻¹ @ 13 TeV

**50 fb⁻¹ @ 14 TeV**

- On the time-scale that SuperB will accumulate 75 ab⁻¹, it is expected that Belle II will be able to integrate 50 ab⁻¹ at the (4S). One would then expect that SuperB will outperform Belle II in terms of precision by about 20% in general for measurements that are not limited by systematic uncertainties. Where measurements will be limited by systematic uncertainties, the expectation of the ultimate precision reached depends on assumptions that have entered into extrapolations, and differences between experiments should be interpreted as a possible range of the ultimate precision attainable.

- SuperB can run at energies below the (2S), and will run at both the (1S) and (3770). This provides SuperB with a significantly broader physics programme through the direct searches for light scalar mesons (Higgs and Dark Matter), tests of lepton universality, searches for Dark Forces, and so on. Measurements at charm threshold will feed back into the B physics programme of all flavour experiments: for example reducing model uncertainties in the measurement of the Unitarity triangle angle, and improving the precision of charm mixing measurements. Other charm threshold measurements will also enable lattice QCD to be tested more precisely in a regime where calculations are better understood. This will impact upon the corresponding work in B decays.

- The electron beam at SuperB will be polarised to at least 80% for running at the (4S). The polarized electron beam provides SuperB with the ability to perform precision electroweak studies in an energy regime free from hadronic uncertainties related to b fragmentation that otherwise limit the interpretation of SLC/LEP measurements, and also provides an additional kinematic variable to support background fighting techniques in rare and Lepton Flavour Violating (LFV) τ⁻ decay studies. The benefits of polarisation for τ⁻ LFV are model dependent.

More details on the Belle II experiment and physics programme can be found in Ref. [13].
## LHCb upgrade physics sensitivity

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb 2018</th>
<th>Upgrade (50 fb⁻¹)</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bˢ₀ mixing</strong></td>
<td>$2\beta_s (Bˢ₀ → J/ψ \phi)$</td>
<td>0.10 [137]</td>
<td>0.025</td>
<td>0.008</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s (Bˢ₀ → J/ψ f₀(980))$</td>
<td>0.17 [213]</td>
<td>0.045</td>
<td>0.014</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\alpha_{sl}^s$</td>
<td>$6.4 \times 10^{-3}$ [43]</td>
<td>$0.6 \times 10^{-3}$</td>
<td>$0.2 \times 10^{-3}$</td>
<td>$0.03 \times 10^{-3}$</td>
</tr>
<tr>
<td><strong>Gluonic penguins</strong></td>
<td>$2\beta_{s\text{eff}} (B,s → \phi\phi)$</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_{s\text{eff}} (B,s → K⁺K⁻)$</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_{s\text{eff}} (B,s → K⁺K₀⁻)$</td>
<td>0.17 [43]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Right-handed currents</strong></td>
<td>$2\beta_{s\text{eff}} (B,s → \phi\gamma)$</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{\text{eff}} (B,s → \phi\gamma)/\tau_{B₀}$</td>
<td>–</td>
<td>5%</td>
<td>1%</td>
<td>0.2%</td>
</tr>
<tr>
<td><strong>Electroweak penguins</strong></td>
<td>$S_3 (B⁰ → K⁺⁺μ⁺\mu⁻; 1 &lt; q^2 &lt; 6 \text{ GeV}²/c⁴)$</td>
<td>0.08 [67]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$s_0 A_{FB} (B⁰ → K⁺⁺μ⁺\mu⁻)$</td>
<td>25% [67]</td>
<td>6%</td>
<td>2%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>$A_1 (Kμ⁺\mu⁻; 1 &lt; q^2 &lt; 6 \text{ GeV}²/c⁴)$</td>
<td>0.25 [76]</td>
<td>0.08</td>
<td>0.025</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B(B⁺ → \pi⁺μ⁺\mu⁻)/B(B⁺ → K⁺μ⁺μ⁻)$</td>
<td>25% [85]</td>
<td>8%</td>
<td>2.5%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td><strong>Higgs penguins</strong></td>
<td>$\mathcal{B}(B⁰ → \mu⁺\mu⁻)$</td>
<td>$1.5 \times 10^{-9}$ [13]</td>
<td>$0.5 \times 10^{-9}$</td>
<td>$0.15 \times 10^{-9}$</td>
<td>$0.3 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>$\mathcal{B}(B⁰ → \mu⁺\mu⁻)/\mathcal{B}(B⁰ → \mu⁺\mu⁻)$</td>
<td>–</td>
<td>$\sim 100%$</td>
<td>$\sim 35%$</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td><strong>Unitarity angles</strong></td>
<td>$\gamma (B → D^{(<em>)}K^{(</em>)})$</td>
<td>$\sim 10–12°$ [243, 257]</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma (B⁺₀ → D⁺K⁺)$</td>
<td>–</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta (B⁺ → J/ψ K⁺₀)$</td>
<td>0.8° [43]</td>
<td>0.6°</td>
<td>0.2°</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>Charm CP violation</strong></td>
<td>$A_Γ$</td>
<td>$2.3 \times 10^{-3}$ [43]</td>
<td>$0.40 \times 10^{-3}$</td>
<td>$0.07 \times 10^{-3}$</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>$ΔA_{CP}$</td>
<td>$2.1 \times 10^{-3}$ [18]</td>
<td>$0.65 \times 10^{-3}$</td>
<td>$0.12 \times 10^{-3}$</td>
<td>–</td>
</tr>
</tbody>
</table>

10 times better precision in major heavy flavor measurements (B mixing and CPV, charm mixing and CPV and rare decays)
Promising modes for upgrade

- CPV in $B_s \rightarrow \phi\phi$: probing NP in $b \rightarrow s$ penguin

- $B_s \rightarrow \phi\gamma$: probing right handed NP

Measure effective lifetime to determine photon polarization

PLB 664 (2008) 174, Muheim, Xie, Zwicky
Belle II physics program

Strengths: radiative B decays
decays into $\nu$
$V_{ub}$, $V_{cb}$

B Physics @ Y(4S)

<table>
<thead>
<tr>
<th>Observable</th>
<th>$B$ Factories (2 ab$^{-1}$)</th>
<th>SuperB (75 ab$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin(2\beta) {J/\psi K^0}$</td>
<td>0.018</td>
<td>0.005 ($\dagger$)</td>
</tr>
<tr>
<td>$\cos(2\beta) {J/\psi K^{*0}}$</td>
<td>0.30</td>
<td>0.05</td>
</tr>
<tr>
<td>$\sin(2\beta) {D^*+D^-}$</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>$\cos(2\beta) {D^0}$</td>
<td>0.20</td>
<td>0.04</td>
</tr>
<tr>
<td>$S(J/\psi \pi^\tau)$</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>$S(\phi K^0)$</td>
<td>0.20</td>
<td>0.03</td>
</tr>
<tr>
<td>$S(\psi K^0)$</td>
<td>0.13</td>
<td>0.02 ($\dagger$)</td>
</tr>
<tr>
<td>$S(K^0_{2S} K^0_{2S})$</td>
<td>0.02 ($\dagger$)</td>
<td></td>
</tr>
<tr>
<td>$S(K^0_{2S} K^{*0})$</td>
<td>0.15</td>
<td>0.02 ($\dagger$)</td>
</tr>
<tr>
<td>$S(K^{*0})$</td>
<td>0.15</td>
<td>0.02 ($\dagger$)</td>
</tr>
<tr>
<td>$S(\phi K^0)$</td>
<td>0.17</td>
<td>0.02 ($\dagger$)</td>
</tr>
<tr>
<td>$S(K^0_{2S} K^{*0})$</td>
<td>0.12</td>
<td>0.02 ($\dagger$)</td>
</tr>
</tbody>
</table>

Charm mixing and CPV

<table>
<thead>
<tr>
<th>Mode</th>
<th>Observable</th>
<th>$T(4S)$ (75 ab$^{-1}$)</th>
<th>$\psi(3770)$ (300 fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K^+\pi^-$</td>
<td>$x^2$</td>
<td>$3 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$y^2$</td>
<td>$7 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$D^0 \rightarrow K^+K^-$</td>
<td>$y_{CP}$</td>
<td>$5 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$D^0 \rightarrow D^0 K^0 K^0$</td>
<td>$x$</td>
<td>$4.9 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$y$</td>
<td>$3.5 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>\eta/\rho</td>
<td>$</td>
</tr>
<tr>
<td>$\psi(3770) \rightarrow D^0\overline{D}^0$</td>
<td>$\phi$</td>
<td>$2^\circ$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\cos \delta$</td>
<td>$(0.01 - 0.02)$</td>
<td></td>
</tr>
</tbody>
</table>

$\beta_s$ Physics @ Y(5S)

<table>
<thead>
<tr>
<th>Observable</th>
<th>Error with 1 ab$^{-1}$</th>
<th>Error with 30 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \Gamma$</td>
<td>$0.16$ ps$^{-1}$</td>
<td>$0.03$ ps$^{-1}$</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>$0.07$ ps$^{-1}$</td>
<td>$0.01$ ps$^{-1}$</td>
</tr>
<tr>
<td>$\beta_s$ from angular analysis</td>
<td>$20^\circ$</td>
<td>$8^\circ$</td>
</tr>
<tr>
<td>$A_{SL}$</td>
<td>$0.006$</td>
<td>$0.004$</td>
</tr>
<tr>
<td>$A_{CH}$</td>
<td>$0.004$</td>
<td>$0.004$</td>
</tr>
<tr>
<td>$B(B_s \rightarrow \mu^+\mu^-)$</td>
<td>$- &lt; 8 \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>V_{td}/V_{ts}</td>
<td>$</td>
</tr>
<tr>
<td>$B(B_s \rightarrow \gamma\gamma)$</td>
<td>$38%$</td>
<td>$7%$</td>
</tr>
<tr>
<td>$\beta_s$ from $J/\psi \phi$</td>
<td>$10^\circ$</td>
<td>$3^\circ$</td>
</tr>
<tr>
<td>$\beta_s$ from $B_s \rightarrow K^0\overline{K}^0$</td>
<td>$24^\circ$</td>
<td>$11^\circ$</td>
</tr>
</tbody>
</table>
What will we learn in 2030?

• Reduce errors of key flavor measurements by a factor of 10
  – Probe few % NP contribution in FCNC processes

• Obtain the pattern of many flavor observables in B and D decays
  – May tell us a lot about the allowed form of NP and severely limit NP parameter space

• Measure CP violation in B and D systems very precisely
  – Hopefully tell us whether there is new source of CP violation
Conclusions

• Heavy flavor physics offers an opportunity to probe NP far above 1 TeV. It is also a necessary ingredient to fully understand the Higgs sector and mass generation mechanism.

• Regardless of whether LHC will discover NP or not, flavor physics will tell us a lot.

• Go for higher precision, wider scope & better understanding of SM!