Role of Flavor factories in the LHC Era

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5th Int’l WS on HEP in the LHC Era,
Valparaiso, Chile Dec. 16-20, 2013
Standard Model

5 Higgs Scalars (include charged $H^\pm$)

Supersymmetry

Higgs

Quarks & Leptons

Bosons

Graviton

Higgs

Higginos

Squarks

Sleptons

Gauginos

Gravitino

Dark Matter

Hierarchy problem

Many New Particles
Standard Model & Beyond

GUT theories/ Extra-dimensions/...

Higgs

Quarks & Leptons

Bosons

Graviton

Higgs

Higgs-doublet models

4th generation quarks

lepto-quarks

heavy Z & W±

Dark Matter
Hierarchy problem
Many “Beyond-the SM” Theories

Almost all predict new massive particles
What can flavor factories say about physics that is 2 orders-of-magnitude beyond their energy range?
Example 1: particle-antiparticle mixing

\[ \Delta m_s = 17.768 \pm 0.023 \text{ (stat)} \pm 0.006 \text{ (syst)} \text{ ps}^{-1} \]

\[ \Delta m_s^{SM} = 17.5 \pm 2.5 \text{ ps}^{-1} \]

See yesterday’s talk by G. Graziani
Ancient history: \( K^0 \leftrightarrow K^0 \) mixing

\[
\begin{pmatrix}
    d' \\
    s'
\end{pmatrix} = 
\begin{pmatrix}
    V_{ud} & V_{us} \\
    V_{cd} & V_{cs}
\end{pmatrix}
\begin{pmatrix}
    d \\
    s
\end{pmatrix} = 
\begin{pmatrix}
    \cos \theta_C & \sin \theta_C \\
    -\sin \theta_C & \cos \theta_C
\end{pmatrix}
\begin{pmatrix}
    d \\
    s
\end{pmatrix}
\]

\( \theta_C = \) Cabibbo angle

4-quark world:

\[
\Delta m_{SM} \propto G_F^2 \left( V_{us}^* V_{ud} f(m_u) + V_{cs}^* V_{cd} f(m_c) \right)
\]

\[
\Delta m_{SM} \propto G_F^2 \left( f(m_u) - f(m_c) \right) \cos \theta \sin \theta \approx G_F^2 m_c^2 \cos \theta \sin \theta
\]
$$|\Delta m_s| = |M_{K_S} - M_{K_L}|$$
constrained original prediction of c-quark mass

Original GIM paper:

Weak Interactions with Lepton-Hadron Symmetry

S. L. Glashow, J. Iliopoulos, and L. Maiani
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

... from the observed $K_1K_2$ mass difference we now conclude that $\Delta$ must be not larger than 3–4 GeV.
6-quark era: $B^0 \leftrightarrow B^0$ mixing

$\Delta B=2$ process:

$$\begin{align*}
\Delta m_{SM} &\propto G_F^2 (V_{ub}^* V_{ud} f(m_u) + V_{cb}^* V_{cd} f(m_c) + V_{tb}^* V_{td} f(m_t)) \\
\text{(Unitarity: } & V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0) \\
\Delta m_{SM} &\propto G_F^2 m_t^2 |V_{tb}^* V_{td}|^2
\end{align*}$$
$m_t$ prediction from $B_d \leftrightarrow B_d$ mixing

$B^0_d - \bar{B}^0_d$ mixing and the prediction of the top-quark mass in an independent particle potential model

N. Barik

*Physics Department, Utkal University, Bhubaneswar-751 004, India*

P. Das, A. R. Panda, and K. C. Roy

*Physics Department, Kendrapara College, Kendrapara-754 211, India*

(Received 22 December 1992; revised manuscript received 30 April 1993)

$m_t = 167^{+16}_{-17}$ GeV

*PDG 2012: $m_t = 173.5 \pm 0.6 \pm 0.6$ GeV*
particle ↔ particle mixing with SUSY

\[ \frac{\Delta m_{\text{SUSY}}}{\Delta m_{\text{SM}}} \approx 10^4 \left( \frac{100 \text{ GeV}}{m_\tilde{Q}} \right)^2 \left( \frac{\Delta m^2_{\tilde{Q}}}{m^2_{\tilde{Q}}} \right)^2 \text{Re} \left[ (K_L)_{13} (K_R)_{13} \right] < 1 \]

If \( m_\tilde{Q} \approx 1 \text{ TeV} \) \( \Rightarrow \left( \frac{\Delta m^2_{\tilde{Q}}}{m^2_{\tilde{Q}}} \right)^2 \text{Re} \left[ (K_L)_{13} (K_R)_{13} \right] < 0.01 \)

i.e., accessible at the LHC

S.I. vertices!!


squarks are highly degenerate and/or mixing angles very small
\[ \frac{\Delta m^2_{Q}}{\langle m^2_{Q} \rangle} \ll 1 \] ??

not for quark masses:

\[ \frac{\Delta m^2_{q}}{\langle m^2_{q} \rangle} \approx \left( \frac{m_t^2}{m_t m_c} \right) \approx 100 \]

nor for lepton masses.
Invoke a horizontal symmetry that results in small values for the *down-type* squark mixing. This fixes *up-type* squark mixing elements $\approx \sin \theta_c \ (\sim 0.2)$. Expect large effects in $D^0$-$\bar{D}^0$ mixing. e.g. $\Delta m \sim 6 \times 10^{-11}$ MeV.
$D^0 \leftrightarrow \bar{D}^0$ mixing 2013

$\Delta C=2$ process:

$D^0 \rightarrow W^\pm d, s, b \rightarrow W^\pm \bar{c}\bar{u}\bar{u}$

$\Delta m = \frac{\Delta m}{\Gamma}$ (%)

$x \leq 0.81\%$

$x = \frac{\Delta m}{\Gamma}$ (%)

$1/10 \times$ expectations based on alignment

$x = \frac{\Delta m}{\Gamma} < 0.0081 \Rightarrow \Delta m < 0.7 \times 10^{-11}$ MeV
$\Delta F=2$ mixing constraints on SUSY

Validity of SM particle-particle mixing calculations require:

$\rightarrow$ SUSY flavor-mixing matrices are very nearly diagonal

and/or

$\rightarrow$ SUSY squark masses are nearly degenerate

and/or

$\rightarrow$ Squark masses $>>1$ TeV

- for some unknown reason & unlike CKM or $\nu$ mixing ("Flavor Problem")
- very unlike quark masses
- well beyond the reach of the LHC
Limits on Generic $\Delta F=2$ BSM Mass Scale

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda_i} O_i (\Delta F=2) \]

Limits on $\Lambda_i$ for $c_i=1$

Example 2: Charged Higgs?
$B \rightarrow \tau \ldots$ decays

$B^+ \rightarrow \tau^+ \nu$

$B^+ \rightarrow \tau^+ \nu$

$B \rightarrow D^{(*)} \tau^+ \nu$

$B \rightarrow D^{(*)} \tau^+ \nu$

$R = \frac{Bf(B \rightarrow D^{(*)} \tau^+ \nu)}{Bf(B \rightarrow D^{(*)} \mu^+ \nu)} = 1 - \frac{3m_b m_\tau}{2m_H^2} \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta} + ...$

$Bf(B^+ \rightarrow \tau^+ \nu) = Bf_{SM} r_H = Bf_{SM} \left(1 - \frac{m_B^2}{m_H^2} \tan^2 \beta\right)$
B → τν candidate event in Belle

$e^+e^- \rightarrow Y(4S) \rightarrow B^+B^-$

Missing momentum
$B \rightarrow \tau \nu$ & $B \rightarrow D^{(*)} \tau \nu$ results

$B \rightarrow \tau \nu$

$B \rightarrow D^{(*)} \tau \nu$

$BF(B \rightarrow \tau \nu) (10^{-4})$

$BF(%)$
Compare Type-II 2HDM with SM

all results are consistent (within 2 $\sigma$) with SM expectations

preferred values of $\tan\beta/M_{H^\pm}$ are different for $\tau^+\nu$, $D\tau^+\nu$ and $D^*\tau^+\nu$ modes
Current B-factory limits on charged Higgs

“Type-II” Higgs Doublet Model

$M_{H^+}$

ATLAS with 30 fb$^{-1}$

Belle+BaBar

$\tan\beta$
Expected BelleII reach

\[ \begin{align*}
M_{H^+} & \leq 2.5 \text{ TeV} \\
M_{H^+} & \leq 1.5 \text{ TeV} \\
M_{H^+} & \leq 1 \text{ TeV}
\end{align*} \]

BelleII (projected with 50 ab\(^{-1}\))

Belle/BaBar (1.5 ab\(^{-1}\))

\[ \tan \beta \]
B$\rightarrow\tau^+$... decays and charged Higgses

- Best charged Higgs model limits with $\tan\beta > 1$ are from B decays
- Super-B factory Mass reach similar to that of the LHC
- If an $H^+$ is found, B decay measurements will critical for assaying is “DNA.”
Example 3: BSM CP Violation searches

Well motivated:

Baryon asymmetry of the Universe:

$$\frac{n_B}{n_\gamma} \bigg|_{\text{WMAP}} = (5.1^{+0.3}_{-0.2}) \times 10^{-10}$$

SM expectation (KM CPV phase):

$$\frac{n_B}{n_\gamma} \bigg|_{\text{SM}} \approx 10^{-20}$$

too small by 10 orders-of-mag.

Additional source of CPV is required:

lepton-sector (ν’s)?
4th generation quarks)?
(SUSY has ~40 CPV phases)

New Physics CPV searches are ~QCD-uncertainty-free!
Probing CPV with Penguins
NP in Penguin loops

\[
b \rightarrow s \quad \text{FCNC decay}
\]

\[\begin{align*}
\text{SM} & \quad \text{NP} \\
\begin{array}{c}
\begin{array}{c}
B \quad B
\end{array}
\end{array} & \quad \begin{array}{c}
\begin{array}{c}
\tilde{u}, \tilde{d}
\end{array}
\end{array}
\]

\(t\)-quark is the dominant contributor
CPV in $B \leftrightarrow B$ mixing

$B_0$ mixing

$V_{cb}$

no CP phase

$V_{tb}$

$V^*_{td}$

$|\propto V^*_{td}^2|$ $|\propto \sin 2\phi_1|$
final results from Belle & BaBar

Belle PRL 198, 171802

BaBar PRD 79, 0720090

Tree-avg: \( \sin^2 \phi_1 = 0.679 \pm 0.020 \)

stat error only: \( \pm 0.018 \)
Penguin - avg: $\sin 2\phi_1^{\text{eff}} = 0.64 \pm 0.03$

Belle PRD 82, 073001

BaBar PRD 79, 052003


### CPV results with Penguins

\[
\sin(2\beta^{\text{eff}}) = \sin(2\phi_1^{\text{eff}})
\]

**Penguin - avg:**  
\[
\sin^2\phi_1^{\text{eff}} = 0.64 \pm 0.03
\]

**Tree - avg:**  
\[
\sin 2\phi_1 = 0.679 \pm 0.020
\]

Uncertainties in individual channels >10\text{--}20\% (all are statistics limited)

NP masses below \text{1}\text{~TeV} are ruled out
Future with 50 ab-1

New Physics
(SUSY GUT, Warped Extra Dimension, String-inspired MSSM, ...)

Belle (July 2006, 492 fb⁻¹)
SuperKEKB (50 ab)

Now

probing mass scales of ~10 TeV
Example 4: Hadron Physics

Strongly Interacting particles:

Standard Model

Theory

colored quarks & gluons

long-distance QCD

Nature

Experiment

B&W mesons & baryons
Quarkonium spectra

charmonium (cc) mesons

- $\eta_c(1^1S_0)$
- $\psi(1^3S_1)$
- $\eta_c(2^1P_1)$
- $\psi'(2^3S_1)$
- $J/\psi(1^3S_1)$

- $\eta_c(3^1S_1)$
- $\eta_c(3^1S_0)$
- $h_c(2^1P_1)$
- $\psi''(1^3D_1)$

bottomonium (bb) mesons

- $\eta_b(2^1S_0)$
- $h_b(1^1P_1)$
- $\eta_b(3^1S_0)$

- $X_{bc}(2^3P_1)$
- $X_{bc}(3^3P_0)$
- $X_{bc}(1^3P_1)$
- $X_{bc}(2^3P_2)$
- $X_{bc}(3^3P_2)$

established cc states
predicted, undiscovered

established bb states
states found recently
the Y(4260)

found by BaBar in $e^+e^- \rightarrow \gamma_{ISR} \pi^+\pi^- J/\psi$

must be $J^{PC}=1^{--}$

classification
classification
classification
classification

confirmed by CLEO & Belle: CLEO PRD 74, 091104 Belle PRL 99, 182004
Y(4260) = non-standard?

No unassigned $J^{PC} = 1^{--}$ cc levels

No sign of $Y(4260) \rightarrow D(\ast)D(\ast)\ldots$ decays

$\Gamma(Y(4260) \rightarrow \pi^{+}\pi^{-}J/\psi) > 1$ MeV

huge by charmonium standards
Is there a b-quark version of Y(4260)?
Is there any anomaly in $\Upsilon(4S,5S) \rightarrow \pi^+\pi^- \Upsilon(1S)$?
\[ \Gamma \gamma(4S) \rightarrow \pi^+ \pi^- \gamma(1S) \]

Belle: PRD 75 071103

\[ 477 \text{ fb}^{-1} \]

Belle: PRL 100 112001

\[ 23.6 \text{ fb}^{-1} \]

Lum \( \sim 1/20^{th} \)

\( \sigma \sim 1/5^{th} \)

Signal \( \sim \times 6 \)

<table>
<thead>
<tr>
<th>parent</th>
<th>( N(\pi^+ \pi^- \gamma(1S)) )</th>
<th>( \Gamma(\gamma_{nS} \rightarrow \pi^+ \pi^- \gamma_{1S}) )</th>
<th>( \Gamma_{\text{theory}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma(4S) )</td>
<td>52\pm10</td>
<td>1.75 \pm 0.35 \text{ keV}</td>
<td>1.47 \pm 0.03 \text{ keV}</td>
</tr>
</tbody>
</table>

\( \sim 400 \text{ times theory expectation!!} \)
“\( \Upsilon(5S) \) \( \rightarrow \pi^+\pi^- \Upsilon(1S) \)?

[Graph showing the mass spectrum with various states and their assignments.]
"\( \Upsilon(5S) \) → \( \pi^- Z_{b1,2}^{+} \) → \( \pi^+ \Upsilon(1,2,3S) \)

**Belle PRL 108, 122001 (2012)**

121.4 fb⁻¹

<table>
<thead>
<tr>
<th>Mass [GeV/c²]</th>
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<tbody>
<tr>
<td>10.610 MeV</td>
</tr>
<tr>
<td>10.660 MeV</td>
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**Diagram:**
- \( \pi^- \) and \( \pi^+ \) transitions
- \( \Upsilon(5S) \) and \( \Upsilon(1,2,3S) \) states
- \( \eta_b(1S_0) \), \( \eta_b(2S_0) \), \( \eta_b(3S_0) \)
- \( \chi_{b1}(2D) \), \( \chi_{b1}(3P) \)
- \( \chi_{b2}(2P) \), \( \chi_{b2}(3P) \)
- \( \chi_{b3}(1P) \), \( \chi_{b3}(2P) \)
- \( \chi_{b4}(1P) \), \( \chi_{b4}(2P) \)

**Legend:**
- Established \( \bar{b}b \) states
- Recently found \( \bar{b}b \) states
- Charged \( \bar{b}b \) states

**Graph:**
- Mass vs. \( J^{PC} \)
- \( \Upsilon(nS) \) and \( \pi^+ \) mass spectrum
- \( \pi^- \) and \( \pi^+ \) branching ratios

**References:**
- \( \Upsilon(10860) \), \( \Upsilon(4S_1) \), \( \Upsilon(1S_1) \), \( \Upsilon(3S_1) \), \( \Upsilon(5S_1) \)

**Equations:**
- \( \Upsilon \rightarrow \pi^- Z_{b1,2}^{+} \)
- \( \pi^+ \Upsilon(1,2,3S) \) transitions
Summary of parameter measurements

- $Z_b(10610)$: $M=10608 \pm 2$ MeV, $\Gamma=18.4 \pm 2.4$ MeV
- $Z_b(10650)$: $M=10653 \pm 2$ MeV, $\Gamma=11.5 \pm 2.2$ MeV

Belle PRL 108, 122001

March 2012
$Z_b(106010)^\pm$

$Z_b(106050)^\pm$

B-$\bar{B}^*$ **molecule**

$B^*-$-$\bar{B}$ **molecule**

$M_{Z_b(106010)} - (M_B + M_{B^*}) = + 3.6 \pm 1.8$ MeV

$M_{Z_b(106010)} - 2M_{B^*} = + 3.1 \pm 1.8$ MeV

Slightly unbound threshold resonances??

**Belle:**

\[ M = 10608.1 \pm 1.7 \text{ MeV} \]
\[ \Gamma = 15.5 \pm 2.4 \text{ MeV} \]

**PDG:**

\[ M_B + M_{B^*} = 10604.5 \pm 0.6 \text{ MeV} \]

**Belle:**

\[ M = 10653.3 \pm 1.5 \text{ MeV} \]
\[ \Gamma = 14.0 \pm 2.8 \text{ MeV} \]

**PDG:**

\[ M_{B^*} + M_{B^*} = 10650.2 \pm 1.0 \text{ MeV} \]
Are there c-quark versions of $Z_b$’s?

Y(4260) discovered

Is there a b-quark equivalent?

Yes, & it decays to $Z_b$ states

Are there c-quark versions of $Z_b$’s?
run BEPCII/BESIII as a Y(4260) factory

$$e^+e^- \rightarrow \pi^+\pi^- J/\psi$$
@ $E_{cm}=4260$ MeV

BESIII PRL 110. 252001

$\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi) = (62.9\pm1.9\pm3.7)$ pb
Y(4260) → π⁻Z_c(3900)⁺

\[ \pi^+ J/\psi \]

- Mass = (3899.0 ± 3.6 ± 4.9) MeV
- Width = (46 ± 10 ± 20) MeV
- Fraction = (21.5 ± 3.3 ± 7.5)%

Significance >8σ

confirmed by Belle PRL 110. 252002
Mass = (3883.9 ± 1.5 ± 4.2) MeV
Width = (24.8 ± 3.3 ± 11.0) MeV
DD*/π⁺π⁻ J/ψ = 6.2 ± 1.1 ± 2.7
Z_b \& Z_c \text{ mesons} \\
--"smoking guns" for non-qq mesons--

- decay to $\gamma$ (nS) ($J/\psi$) $\Rightarrow$ must contain b$\bar{b}$ (c$\bar{c}$) pair
- electrically charged $\Rightarrow$ must contain u$\bar{d}$ pair

$B^0$-$B^{*+}$ "molecule"?  Diquark-diantiquark?  Mixture?
Summary

- Flavor factories will play a crucial complementary role to energy frontier physics
  
  >> flavor physics results tightly constrain potential New Physics theories
  >> mass scales of ~10 TeV can be accessed for many New Physics scenarios
  >> essential for establishing the “DNA” of any new energy frontier discovery

- Existing flavor factories have uncovered a new spectroscopy of hadrons
  
  >> more and better data are needed to help develop a theory for these states
  >> flavor factories and energy-frontier experiments are active in this area.
Backup
\[ B^\pm \rightarrow \tau^\pm \nu \]

Decays w/ “Missing E(>1\nu)”

**SM:**

\[ \beta(B \rightarrow \tau\nu) = \frac{G_F^2 m_B}{8\pi} m^2_\tau (1 - \frac{m^2_\tau}{m^2_B})^2 \frac{f_B^2}{|V_{ub}|^2} \tau_B \]

B decay constant ↔ Lattice QCD

**BSM:** sensitive to New Physics from H^±
Validate the $E_{ECL}$ simulation using double-tagged events (with $B \rightarrow D^* \ell \nu$ on the signal side)

Extra Calorimeter Energy

Signal reconstruction (purity ~ 90%)

$B^- \rightarrow D^{*0} \ell^- \nu$

$D^0 \pi^0$

$K^- \pi^+$

$K^- \pi^+ \pi^- \pi^+$

MC:

$B^+ B^-:$ $494 \pm 18$

$B^0 \bar{B}^0:$ $8 \pm 2$

Combined: $502 \pm 18$

Data: $458$
What do we measure?

Flavor-tag decay
($B^0$ or $\bar{B}^0$ ?)

Asymmetric energies

$e^-$

$e^+$

$t=0$

$\Delta z$

$\sin 2\phi_1$

$B - \bar{B}$

$B + \bar{B}$

(tags)

more $B$ tags

more $\bar{B}$ tags

This is for $CP=-1$; for $CP=+1$, the asymmetry is opposite
“ϒ(5S)” $\rightarrow \pi^+\pi^- \, \Upsilon \, (1S)$?
$Z_{b1}$ & $Z_{b2}$, “smoking guns” for non-q\bar{q} mesons

- decays to $\gamma$ (nS) & $h_b$(nP) \iff must contain b\bar{b} pair
- electrically charged \iff must contain u\bar{d} pair

$B^0 - B^{*+}$ “molecule”? Diquark–diantiquark? Mixture?
Dalitz plots & 1D projections

\[
M^2(\pi^+ J/\psi) \text{ (GeV/c}^2)\]

\[
M^2(\pi J/\psi) \text{ (GeV/c}^2)^2\]

Events / 0.02 GeV/c^2

M(\pi^+ J/\psi) \text{ (GeV/c}^2)
$Z_c(3900)$ confirmed by Belle

- Couples to $\bar{c}c$
- Has electric charge
- At least 4-quarks
- What is its nature?

Belle arXiv: 1304.0121 to appear in PRL

- Mass $= (3894.5 \pm 6.6 \pm 4.5)$ MeV
- Width $= (63 \pm 24 \pm 26)$ MeV
- Fraction $= (29.0 \pm 8.9)\%$ (stat. error only)