B factories

XXXIX IMFP
7th to 11th February 2011
LSN Canfranc Underground Laboratory

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Outline

- Flavor Physics in the quark sector
- B factories
- CP violation and CKM in B mesons
- Searches for New Physics
- Summary and perspectives

- Many more measurements and observations not discussed here:
  - Lepton flavor violation
  - Observation of many new states: \( \eta_b(1S) \); e.g. \( D_{s0}^*(2317) \); charmonium-like states (X, Y, Z families)
  - Tau and charm physics
  - ...

This talk sketches some topics of the work of many people, over more than one decade, from \(~800\) publications...
Flavor Physics in the Standard Model (SM) in the quark sector

In the SM, charged weak interactions among quarks are codified in a 3×3 unitarity matrix, the CKM Matrix.

\[ V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]

This matrix conveys the fact that the quarks participating in weak processes are a linear combination of mass eigenstates.

The fermion sector is poorly constrained by SM + Higgs Mechanism mass hierarchy and CKM parameters.
Flavor Physics in the quark sector of the Standard Model (SM)

Flavor Physics has played a key role in the history of Particle Physics

“Discoveries” and construction of the SM Lagrangian

- 1970 Charm quark from FCNC and GIM mechanism $K^0 \rightarrow \mu\mu$
- 1973 3rd generation from CP violation in kaon ($\varepsilon_K$) KM-mechanism
- 1974 Discovery of the $J/\psi$ meson, the first excited state of a $c\bar{c}$ bound state
- 1976 Discovery of the neutral D meson
- 1977 First speculations on charm mixing and CP violation in charm
- 1978 Discovery of the $\Upsilon(4S)$ meson, excited state of a $b\bar{b}$ bound state
- 1983 Discovery of the neutral and charged B mesons
- 1990 Heavy top from B oscillations $\Delta m_B$

- 2001 ...
Flavor Physics in the quark sector of the Standard Model (SM)

- Success of the description of FCNC and CPV in SM

Dominated by $\Delta m_d, V_{ub}, V_{cb}, \epsilon_K$, limit on $\Delta m_s$ and Lattice

- The first fundamental test of agreement between direct and indirect measurements of $\sin 2\beta$
- A single irreducible phase in the weak interaction (CKM) matrix accounts for most of the CP violation observed in kaons and B’s
Flavor Physics in the quark sector of the Standard Model (SM)

✓ … Success of the description of FCNC and CPV in SM

Dominated by $\Delta m_d$, $V_{ub}$, $V_{cb}$, $\epsilon_K$, limit on $\Delta m_s$ and Lattice

The first fundamental test of agreement between direct and indirect measurements of $\sin 2\beta$

A single irreducible phase in the weak interaction (CKM) matrix accounts for most of the CP violation observed in kaons and B’s

Critical role of the B factories in the verification of the KM hypothesis
B physics and CKM

- B physics probes the range and phases of 3rd generation CKM elements through both tree and one-loop processes
- Angles related to CP violation measurements
- Lengths of sides related to magnitudes of CKM elements (i.e. CP conserving measurements)

\[
V = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

- Redundant determinations of the 4 parameters using theoretically and experimentally independent methods
  - CP conserving: \(|V_{us}|, |V_{cb}|, |V_{td}|, |V_{ub}|\)
  - CP violating: \(\alpha, \beta, \gamma, \varepsilon_K, \beta_s\)
  - Tree level: \(\ldots, |V_{ub}|, \gamma\)
  - Loop level: \(\ldots, |V_{td}|, \beta, \alpha\)

- Validate methodology and interpret to search for new physics

\[B \rightarrow X_u l \nu\]
\[B \rightarrow \pi, \rho l \nu\]
\[B^+ \rightarrow l^+\nu\]
\[B \rightarrow X_{ds} \gamma\]
\[B \rightarrow \pi \pi, \rho \pi, \rho \rho \ldots\]
\[B \rightarrow DK\]
\[B \rightarrow J/\psi K^0\]

+other charmonium +from Penguins
Measuring the phases from CPV

- CKM phases measurable when there are two paths to reach the same final state, and strong phases do not vanish

\[ |A(B \to f)|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(\Delta\varphi_{\text{weak}} + \Delta\delta_{\text{strong}}) \]

\[ |A(\bar{B} \to \bar{f})|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(-\Delta\varphi_{\text{weak}} + \Delta\delta_{\text{strong}}) \]

- **Textbook example**: interference between \(B^0 \to J/\Psi K_S\) (\(b \to c \bar{c} s\)) and \(\bar{B}^0 \to J/\Psi K_S\) (\(\bar{b} \to c \bar{c} \bar{s}\)) decays allows determination of \(\beta\)

Next largest amplitude \((\lambda^2)\) has same weak phase
Other CKM corrections are Cabibbo suppressed \(O(\lambda^4)\)

**CP asymmetry**

\[ A_{CP,f}(\Delta t) \equiv \frac{\Gamma_{B^0 \to f}(\Delta t) - \Gamma_{\bar{B}^0 \to \bar{f}}(\Delta t)}{\Gamma_{B^0 \to f}(\Delta t) + \Gamma_{\bar{B}^0 \to \bar{f}}(\Delta t)} = -C_f \cos(\Delta m \Delta t) + S_f \sin(\Delta m \Delta t) \]

\[ S_f \text{ and } C_f \text{ depend on the CKM angles} \]

\[
\begin{align*}
1 - |\lambda_f|^2 &\approx 0 \\
-2 \text{ Im} \lambda_f &\approx -\eta_{fCP} \sin 2\beta \\
\lambda_f &= \frac{q \bar{A}_f}{p A_f} 
\end{align*}
\]
The asymmetric B factory concept

\[ \beta \gamma_{\Upsilon(4S)} = 0.425 \quad \text{and} \quad 0.56 \]

Coherent B meson production (L=1)

\[ e^-(9.0 \text{ GeV}) \quad \Upsilon(4S) \quad e^+(3.1 \text{ GeV}) \]

\[ B_{\text{tag}} \]

\[ B_{\text{rec}} \]

\[ \Delta z \approx 250 \mu m \]

\[ \Delta t \approx \frac{\Delta z}{\langle \beta \gamma \rangle} \frac{1}{c} \]

\[ \Delta t \text{ is a signed quantity} \]

\[ \sigma_{\Delta t} \sim 1 \text{ ps} \Leftrightarrow 170 \mu m \]

Tagging performance:

\[ Q = \epsilon (1 - 2w)^2 \sim 30\% \]

Tag vertex reconstruction

Exclusive B Meson and vertex reconstruction

High-statistics self-tagging

“B-flavor” sample to

✓ calibrate tagging
✓ measure \( \Delta z \) resolution

B-Flavor Tagging

Start the Clock

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Additional experimental techniques

- Veto significant/potentially dangerous B decay backgrounds
- Resonance masses, decay angles, helicity in $P \rightarrow PV$, $V \rightarrow PP$ decays
- Suppress continuum $e^+e^- \rightarrow q\bar{q}$ ($q=u,d,s,c$) background using event topology (multivariate methods)

- Characterize B candidates using
  - Beam-energy substituted mass
  - Energy difference
- Maximum likelihood fits to $m_{ES}$, $\Delta E$, Fisher, PID, $\Delta t$, tagging, etc
- Use sidebands and control samples to check backgrounds

In general, search for a needle in a haystack
BaBar detector

**DIRC (PID)**
- 144 quartz bars
- 11000 PMs

**1.5T solenoid**

**EMC**
- 6580 CsI(Tl) crystals

**Drift Chamber**
- 40 stereo layers

**Silicon Vertex Tracker**
- 5 layers, double sided strips

**Instrumented Flux Return**
- iron / RPCs / LSTs (muon / neutral hadrons)

**e^+ (3.1 GeV)**

**e^- (8-9 GeV)**

very stable detector, good particle identification, (kaon, pion, electron, muon),
e^+ e^- is a clean environment: excellent tracking, triggering, tagging...

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The Belle detector is a very stable detector, good for particle identification (kaon, pion, electron, muon), with $e^+e^-$ as a clean environment for excellent tracking, triggering, and tagging.

**KLM ($K_1\mu$) Detector:** Sandwich of 14 RPCs and 15 iron plates

**Solenoid:** 1.5 T

**Silicon Vertex Detector:**
- 3/4 detection layers
- Vertex resolution $\sim 100\mu m$

**Central Drift Chamber**
- 8,400 sense wires
- PID with $dE/dx$

**Electromagnetic Cal:**
- CsI(Tl) crystal
- $\sigma_{e}/E \sim 1.6\%$ @ 1 GeV

**Time-of-Flight Counter:**
- $K/\pi$-ID of high $p$

**Aerogel Cerenkov Counter:**
- Refractive index $n=1.01 - 1.03$
- $K/\pi$ of middle $p$
B factories, luminosity frontier...

1.2 \times 10^7, 1.7 \times 10^8 \ Y(3S), \ Y(2S)

\approx 10^9 \ B \overline{B}, \ D \overline{D}, \ \tau^+\tau^- \ pairs

\approx 5 \times 10^8 \ B \overline{B}, \ D \overline{D}, \ \tau^+\tau^- \ pairs

\approx 1.2 \times 10^8, 1.0 \times 10^8 \ Y(3S), \ Y(2S)

\approx \ 5 \times 10^8 \ B \overline{B}, \ D \overline{D}, \ \tau^+\tau^- \ pairs

\approx 1.2 \times 10^7, 1.7 \times 10^8 \ Y(3S), \ Y(2S)

> 1 \text{ ab}^{-1}

On resonance:

\(Y(5S): 121 \text{ fb}^{-1}\)

\(Y(4S): 711 \text{ fb}^{-1}\)

\(Y(3S): 3 \text{ fb}^{-1}\)

\(Y(2S): 24 \text{ fb}^{-1}\)

\(Y(1S): 6 \text{ fb}^{-1}\)

Off reson./scan:

\approx 100 \text{ fb}^{-1}

\approx 550 \text{ fb}^{-1}

On resonance:

\(Y(4S): 433 \text{ fb}^{-1}\)

\(Y(3S): 30 \text{ fb}^{-1}\)

\(Y(2S): 14 \text{ fb}^{-1}\)

Off resonance:

\approx 54 \text{ fb}^{-1}
What happened since (selection)

- Improvement of the $\beta$ angle measurement 4%
- Measurement of $\beta$ from penguin dominated processes
- Surprise…B factories also measured quite precisely the other angles
  \[ \alpha \sim 7^\circ \quad \gamma \sim 15^\circ \]
- Measurement of the direct CP violation in charmless decays
- Improved measurement of $|V_{ub}|$, $|V_{cb}|$ (6-7%), 1.5%
  (improved theory, moment analyses,…)
- First measurement of the leptonic decay $B \rightarrow \tau \nu$
- Measurement of $B_S$ oscillations $\Delta m_S$ (Tevatron)
- First measurement of the CP violation in the $B_S$ sector (Tevatron)
- Measurement of $Br$ and CP asymmetries in radiative and dilepton decays
- Surprise…Strong evidence for $D^0-\bar{D}^0$ oscillations. CP violation in charm?
- Observation of many new and unexpected states: $\eta_b(1S)$, $D_{s0}^*(2317)$, charmonium-like states ($X$, $Y$, $Z$ families)
- Largely improved limits on lepton flavor violation
- Direct searches for light new physics
- …
\( \sin 2\beta \text{ in } b \rightarrow c\bar{c}s \text{ decays} \)

\[ B^0 \rightarrow J/\psi K_S^0, J/\psi K^{*0}, \psi(2S)K_S^0, J/\psi K_L^0, \eta_c K_S^0, \chi_c K_S^0 \]

\[ \sin(2\beta) \equiv \sin(2\phi_1) \]

\[ \beta = (21.1 \pm 0.9)^\circ \]
The UT angle $\alpha$

- Access to $\alpha$ from the interference of $b\to u$ Tree decay ($\gamma$) with $B^0-\overline{B}^0$ mixing ($2\beta$) complicated by Penguin contribution

\[ \alpha = \pi - (\beta + \gamma) \]

- $B^0-\overline{B}^0$ mixing
  - $B^0 \to \gamma \to \bar{b} V_{tb}^* V_{td} / V_{tb} V_{td} \to \bar{d}$
  - $\beta$

- Tree decay
  - $A \propto V_{ud}^* V_{ub}$

- Penguin decay
  - $A \approx V_{td}^* V_{tb}$

\[
\lambda_{f_{cp}} = \frac{q}{p} \frac{A}{A} = \eta_{f_{cp}} e^{-i2\beta} e^{-i2\gamma} = \eta_{f_{cp}} e^{i2\alpha}
\]
\[
S_{f_{cp}} = -\eta_{f_{cp}} \sin 2\alpha
\]
\[
C_{f_{cp}} = 0
\]

$T(P) = \text{tree (penguin) amplitude}$

\[
\delta = \delta_p - \delta_T, \text{ strong phase difference}
\]

- To extract $\alpha$ from $\alpha_{eff}$ requires SU(2) isospin symmetry between $u$ and $d$ quarks ($m_u \sim m_d$), which allows to relate $A(B^0 \to h^+ h^+$), $A(B^0 \to h^0 h^0$) and $A(B^+ \to h^+ h^0$), + CP conj.

**How can we obtain $\alpha$ from $\alpha_{eff}$?**

Gronau/London analysis

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B factories
Measure 6 observables (for 6 parameters to be determined) from the 6 samples, \( B^0 \to \pi^+\pi^- \), \( B^0 \to \pi^0\pi^0 \) and \( B^+ \to \pi^+\pi^0 \), + their CP conjugates

\[
S_{\pi^+\pi^-}, C_{\pi^+\pi^-}, C_{\pi^0\pi^0}, BF_{\pi^+\pi^-}, BF_{\pi^0\pi^0}, BF_{\pi^0\pi^0}
\]

Still, 1.9\( \sigma \) difference
Measure 7 observables (for 6 parameters to be determined) from the 6 samples, $B^0 \rightarrow \pi^+\pi^-$, $B^0 \rightarrow \pi^0\pi^0$ and $B^+ \rightarrow \pi^+\pi^0$, + their CP conjugates

$$S_{\rho^+\rho^-}, C_{\rho^+\rho^-}, S_{\rho^0\rho^0}, C_{\rho^0\rho^0}, BF_{\rho^+\rho^-}, BF_{\rho^+\rho^0}, BF_{\rho^0\rho^0}, f_L$$

- $B \rightarrow \rho\rho$ experimentally challenging
  - Up to $2\pi^0$ in final state
  - $\rho$ is broad
  - VV final state
- But more efficient than $\pi\pi$
  - BF’s $\sim5\times$ times larger
  - Penguin pollution smaller than in $\pi\pi$
  - $\sim100\%$ longitudinally polarized $\Rightarrow$ almost pure CP even state
  - All isospin modes have time dependent information

Contour lines give $-2\ln(L) = \Delta \chi^2 = 1$, corresponding to 68.7% CL for 2 dof
\( \alpha \) determination

Mainly determined by \( B \to \rho \pi \) isospin analysis

\[ \alpha = \left( 89.0^{+4.4}_{-4.2} \right) \]^\circ

\[ \alpha = (91.4 \pm 6.1)^\circ \]
The UT angle $\gamma$ from $B \to DK$

- Measure interference between tree amplitudes $b \to u$ and $b \to c$

- Use final state accessible from both $D^0$ and $\bar{D}^0$

- Largely unaffected by New Physics

- Clear theoretical interpretation of observables in terms of $\gamma$

- Difficult because BF are small due to CKM suppression $(10^{-5}-10^{-7})$, so not many events and $r_B = |A_{ub}|/|A_{cb}|$ is small due to further CKM and color suppressions (small interference)
\( \gamma \) from B\( \to \)DK

Complementary methods applied on same B decay modes share the same hadronic parameters \((r_B, \delta_B)\) and \(\gamma\)

Strategy: many decay chains are analyzed and then combined to improve the overall sensitivity to \(\gamma\)
$\gamma$ from $B \to DK$  

"Golden" Dalitz plot method

$$x_{\pm} \equiv \text{Re} \left\{ \frac{A_{ub}^{B^\pm}}{A_{cb}^{B^\pm}} \right\} = r_{B^\pm} \cos(\delta \mp \gamma)$$

$$y_{\pm} \equiv \text{Im} \left\{ \frac{A_{ub}^{B^\pm}}{A_{cb}^{B^\pm}} \right\} = r_{B^\pm} \sin(\delta \mp \gamma)$$

Significance for direct CP violation is $3.5\sigma$ for each experiment

$\Rightarrow$ First strong evidence for direct CPV in charged $B$ decays

$\gamma = (68.4^{+15}_{-14} \pm 4 \pm 3)^{\circ}$

$\gamma = (78^{+11}_{-12} \pm 4 \pm 9)^{\circ}$
Mainly determined by Dalitz plot analysis
Semileptonic B decays give direct access to magnitudes of the CKM matrix elements

\[ M(M_{q\bar{q}} \rightarrow X_{q'\bar{q}} \ell\bar{\nu}) = -i \frac{G_F}{\sqrt{2}} V_{q'Q} L^\mu H_\mu \]

\[ L^\mu = \overline{u}_i \gamma^\mu (1 - \gamma_5) v_j \]

\[ H_\mu = \langle X|\overline{q}'\gamma_\mu (1 - \gamma_5)Q|X \rangle \]

Challenge is to understand hadronic current

✓ Inclusive: \( b \rightarrow q l \nu + \text{QCD corrections} + \text{OPE}(\alpha_s, \Lambda/m_b) \), also relevant for \( b \rightarrow s \gamma \)

✓ Exclusive: form factor(s) describing \( B \rightarrow l\nu \) hadron -- LQCD

Alternative: purely leptonic B decays (e.g. \( B \rightarrow \tau \nu \))

\[ \mathcal{B}(B^- \rightarrow \tau^-\bar{\nu}_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi} \left( 1 - \frac{m_\tau^2}{m_H^2} \right)^2 f_B^2 |V_{ub}|^2 \tau_B, \]

✓ Theory more straightforward, still LQCD for \( f_B \)

✓ Underconstrained events ⇒ tagged (recoil) samples
Methodology: the recoil method

- Knowledge of signal kinematics, missing energy and suppression of combinatorial background
- But low reconstruction efficiency
- Used for inclusive measurements or for decays with multiple neutrinos
  - Hadronic tags (e.g. \( B \to D \pi \)), efficiency ~0.3%
  - Semileptonic tags (e.g. \( B \to Dl\nu \)), efficiency ~0.6%

\[ m_{ES} = \sqrt{E_{beam}^* - p_B^*} \]
\[ \Delta E^* = E_B^* - E_{beam}^* \]
Inclusive $|V_{ub}|$

$$\Gamma(\bar{B} \to X_u \ell \bar{\nu}) = \frac{G_F^2 |V_{ub}|^2 m_b^5}{192 \pi^3} [1 + \mathcal{O}(\alpha_s) + \mathcal{O}(1/m_b^2) + h.c.]$$

- Challenge for $B \to X_u \ell \nu$ determination due to background from CKM-favored $B \to X_c \ell \nu$ decays

$$\frac{\Gamma(b \to u \ell \nu)}{\Gamma(b \to c \ell \nu)} \approx \frac{|V_{ub}|}{|V_{cb}|} \approx \frac{1}{50}$$

- Kinematic selection required to suppress backgrounds, but cuts restrict phase space, hence OPE unapplicable unless one uses a shape function

- Introduces dependencies on non-perturbative shape functions to account for efficiency loss in inaccessible regions of phase space
- Trade-off between extending measurements into higher background regions and increased theory uncertainties on $|V_{ub}|$ extraction
Inclusive $|V_{ub}|$

- Experiments use hadronic tag and select high momentum leptons ($p_{l}^* > 1$ GeV/c)
- Further background suppressions using multivariate techniques
- Fit to other variables ($M_{X}$, $q^{2}$)

\[ \Delta B(B \rightarrow X_{u} \ell \nu; p_{l}^* > 1.0 \text{ GeV/c}) = \\
(1.80 \pm 0.13 \pm 0.15) \times 10^{-3} \\
(1.96 \pm 0.17 \pm 0.16) \times 10^{-3} \]

- BaBar also performs partial branching fraction measurement in six regions of phase space which have limited charm background
- Partial branching fraction measurements translated into values of $|V_{ub}|$ using theoretical models (BLNP, GGOU, DGE, ADFR)
$|V_{ub}|$ from $B \to (\pi, \rho) l \nu$

- $|V_{ub}|$ can be extracted from measurements of exclusive $B \to \pi l \nu$ and $B \to \rho l \nu$ differential branching ratios
  \[
  \frac{d\Gamma(B \to \pi l \nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |p_\pi|^3 |f_+(q^2)|^2
  \]

- Theory input needed for form factor $f_+(q^2)$ determination
- Branching fractions extracted from simultaneous fits to $m_{ES}$, $\Delta E$ and $q^2$
- Extract shape of the $B \to \pi l \nu$ form factor from differential branching fraction spectrum

Alternatively, $|V_{ub}|$ can be extracted from a simultaneous fit data and lattice (FNAL/MILC)
$|V_{ub}|$ semileptonic summary

- $|V_{ub}| = (4.46 \pm 0.27 \pm 0.24) \times 10^{-3}$
  - Inclusive $B \rightarrow X_u l^+ \nu (p_{T}^* > 1.0 \text{ GeV/c}, M_X, q^2 \text{ fit})$

- $|V_{ub}| = (4.32 \pm 0.16 \pm 0.23) \times 10^{-3}$
  - Inclusive $B \rightarrow X_u l^+ \nu$ HFAG average

- $|V_{ub}| = (4.27 \pm 0.23 \pm 0.26) \times 10^{-3}$  
  - New
  - Inclusive $B \rightarrow X_u l^+ \nu (p_{T}^* > 1.0 \text{ GeV/c}, M_X, q^2 \text{ fit})$

- $|V_{ub}| = (2.95 \pm 0.31) \times 10^{-3}$
  - Exclusive $B \rightarrow \pi l^+ \nu$ (fit with lattice)

- $|V_{ub}| = (3.40 \pm 0.20) \times 10^{-3}$
  - Exclusive $B \rightarrow \pi l^+ \nu$ HFAG average (HPQCD)

- $|V_{ub}| = (3.43 \pm 0.33) \times 10^{-3}$
  - New
  - Exclusive $B \rightarrow \pi l^+ \nu$ (fit with lattice)

- Significant improvements in techniques for $|V_{ub}|$ extraction in recent years, but longstanding discrepancy between inclusive and exclusive determinations persists (~2.5$\sigma$)
\[ |V_{ub}| \text{ and } B^+ \rightarrow \tau^+ \nu \]

- Theoretically clean determination of $|V_{ub}|$ from helicity suppressed leptonic modes

\[
\mathcal{B}(B^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 |V_{ub}|^2 f_{B^+} f_{\ell \nu}^B}{8\pi^2} n_\ell^2 n_B^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2
\]

- Experimentally challenging due to small branching fractions and limited kinematic information
  - Only accessible to B factories
  - Possible to use both hadronic and semileptonic reconstruction of tag B

- Essentially no additional loss of kinematic information from use of $B \rightarrow D^{(*)}\ell \nu$ tags

\[ m_{ES} \equiv \sqrt{E_{\text{beam}}^2 - p_B^2} \]
\[ \Delta E^* \equiv E_{B}^* - E_{\text{beam}}^* \]

\[ \cos \theta_{B,D^{(*)}\ell} = \frac{2E_{\text{beam}}^* f_{B^{(*)}\ell} - m_B^2 - M_{D^{(*)}\ell}^2}{2P_B^{\text{ cms}} \cdot P_{D^{(*)}\ell}^{\text{ cms}}} \]
$|V_{ub}|$ and $B^+ \rightarrow \tau^+ \nu$

- Topological selection of $\tau$ decay candidates in $e$, $\mu$, $\pi$ and $\rho$ modes from particles not associated with the tag B candidate

- Signal $B^+ \rightarrow \tau^+ \nu$ events expected to have little or no other activity in the detector, while backgrounds have higher multiplicity

- Characterize additional activity by $E_{\text{extra}}$, summed energy of all remaining calorimeter activity

- Validate $E_{\text{extra}}$ shape using samples in which the 2$^\text{nd}$ B is exclusively reconstructed
$|V_{ub}|$ and $B^+ \rightarrow \tau^+ \nu$

### Hadronic tag

$3.3\sigma$

### Semileptonic tag

$3.6\sigma$

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**Decay Mode** $\epsilon \times 10^{-4}$ **Branching Fraction** $(\times 10^{-4})$

- $\tau^+ \rightarrow e^+ \nu \bar{\nu}$: $2.73 \pm 0.20\%$ $0.39\pm0.09\%$
- $\tau^+ \rightarrow \mu^+ \nu \bar{\nu}$: $2.92\pm0.16\%$ $1.23\pm0.09\%$
- $\tau^+ \rightarrow \pi^+ \nu$: $1.55\pm0.14\%$ $4.0\pm1.2\%$
- $\tau^+ \rightarrow \rho^+ \nu$: $0.85\pm0.13\%$ $4.3\pm1.9\%$
- **combined**: $8.05\pm0.57\%$

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**Decay Mode** **Signal Yield** $\epsilon$, $10^{-4}$ **Branching Fraction** $B$, $10^{-4}$

- $\tau^+ \rightarrow e^- \nu \bar{\nu}$: $73^{+23}_{-18}$ $5.9$ $1.90^{+0.59}_{-0.37}\%$
- $\tau^- \rightarrow \mu^- \nu \bar{\nu}$: $12^{+18}_{-17}$ $3.7$ $0.57\pm0.18\%$
- $\tau^- \rightarrow \pi^- \nu \bar{\nu}$: $55^{+21}_{-20}$ $4.7$ $1.50^{+0.59}_{-0.37}\%$
- **Combined**: $143^{+36}_{-35}$ $14.3$ $1.54^{+0.38}_{-0.37}\%$

Larger than favored by semileptonic $|V_{ub}|$...
**|V_{ub}| and B^+\rightarrow\tau^+\nu**

- Comparison with B mixing measurements permits cancelation of parametric uncertainty from $f_B$

\[ \Delta m_d = \frac{G_F^2}{6\pi^2} \eta_B m_B f_B^2 B_d m_W^2 S(x_t) |V_{td} V_{tb}^*|^2 \]

\[ \eta_B = 0.551 \pm 0.007 \quad S(x_t) \approx 0.784 x_t^{0.75} \quad x_t = \frac{m_t^2}{m_W^2} \]

\[ \frac{Br(B^- \rightarrow \tau^- \nu)}{\Delta m_d} = \frac{3\pi}{4} \frac{m_\tau^2}{m_W^2 S(x_t)} \left( 1 - \frac{m_\tau^2}{m_B^2} \right)^2 \frac{\tau_{B_d}}{B_{B_d}} \frac{1}{|V_{ud}|^2} \left( \sin \beta \right)^2 \]

- ...but odd correlation between B→τν and sin2β

- Tension with respect to indirect determination from sin2β at the level of 3σ
  - Not driven by the semileptonic value of |V_{ub}| nor $f_B$

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Global SM fit

...today clear impact on B-factories (angles and sides) ... 2000

Coherent picture of FCNC and CPV processes in SM

CKM matrix is the dominant source of flavour mixing and CP violation!

\bar{\rho} = 0.144 \pm 0.025 (~15\%)

\bar{\eta} = 0.342 \pm 0.016 (~4\%)
Discrepancies persist between inclusive and exclusive $|V_{ub}|$ determinations

- Precision on $\gamma$ should be improved at least $\times4$ to have stringent test of SM

$|V_{ub}|$ and $\gamma$ select $\rho$-$\eta$ value independently of most types of NP $\rightarrow$ SM candle type of measurement

- Recent (and internally consistent) $B^+ \rightarrow \tau^+ \nu$ measurements favors larger $|V_{ub}|$

- Tension between direct and indirect determinations of $\sin2\beta$ and $Br(B^+ \rightarrow \tau^+ \nu)$ ($\sim2.2\sigma$ and $\sim2.8\sigma$)
  - Not driven by the semileptonic value of $|V_{ub}|$ nor $f_B$
  - Another way: to accommodate $B \rightarrow \tau\nu$ we need larger $|V_{ub}|$, but to accommodate $\sin2\beta$ we need lower $|V_{ub}|$

- Discrepancies in the CP asymmetry in $B_S$ sector ($\sim3\sigma$) should also be considered!

- Improvement in predictions and measurements are of the outmost importance
Searching for New Physics

- New Physics at 10 GeV?

- Virtual, BSM contributions...especially in loops!
  - In general induces (additional) FCNC

- Decay rates, CP asymmetries, angular distributions all can be affected by NP effects

- The particle in the loop can be very heavy...sensitive measurements can probe NP at the multi-TEV scale

- ...and also searches for directly produced low mass states

- Huge datasets collected by B-factories at all γ(nS) resonances allow to explore NP...Luminosity frontier

- Complementary to direct searches at energy frontier (Tevatron, LHC)
\[ B^+ \rightarrow \tau^+ \nu \]

With charged Higgs
\[ \mathcal{B} = \mathcal{B}_{SM} \times \left( 1 - \frac{m_B^2}{m_H^2} \tan^2 \beta \right)^2 \]

Discrepancy between SM fit and WA BR
\[
\begin{align*}
B_{WA}(B^+ \rightarrow \tau^+ \nu) &= (1.68 \pm 0.31) \times 10^{-4} \\
B_{CKM}(B^+ \rightarrow \tau^+ \nu) &= (0.76^{+0.114}_{-0.061}) \times 10^{-4}
\end{align*}
\]

Conversely, we can set exclusion regions in \( m(H^+) \) vs \( \tan \beta \)
\[ B_{SM}(B^+ \rightarrow \tau^+ \nu) = (1.20 \pm 0.25) \times 10^{-4} \]

Using \( f_B \) (HPQCD) and \(|V_{ub}|\) (HFAG)

- Helicity Suppression (disfavours \( l=e \), favours \( l=\tau \))
If single phase dominates, SM predicts $S = \sin 2\beta$, $C = 0$

- Dominant CKM factors as in $J/\psi K_S$

- Sensitivity in the loop to New Physics effects

- After a long story of disagreement... Today there is a rather good agreement between
  - $b \rightarrow q\bar{q}s$: $\sin 2\beta_{\text{eff}} = 0.64 \pm 0.04$ (Naïve average)
  - $b \rightarrow c\bar{c}s$: $\sin 2\beta = 0.672 \pm 0.023$ (0.028 with theo. error)

...but low side bias?
Radiative penguin decays $b \to s\gamma$

- For $E_\gamma > 1.6$ GeV, SM prediction to $O(\alpha_s^2)$ is $B_{SM} (B \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$

- $B \to X_s\gamma$ from **sum of exclusive states**
  - Reconstruct $X_{s/d}$ as $K/\pi$ + up to 4 pions
  - Must correct the observed rate by the fraction of decays not reconstructed…
    ...depends on fragmentation model

  $$B(B \to X_s\gamma) = (2.3 \pm 0.1 \pm 0.3) \times 10^{-4}$$

  $$B(B \to X_d\gamma) = (9.2 \pm 2.0 \pm 2.3) \times 10^{-6}$$
  for $M_X < 2.0$ GeV

- Can be used for independent determination of $|V_{td}|/|V_{ts}|$

  $$\frac{\Gamma(b \to d\gamma)}{\Gamma(b \to s\gamma)} = \zeta^2 \left| \frac{V_{td}}{V_{ts}} \right|^2 (1 + \Delta R)$$

  Requires extrapolate up to full mass range…another (small) theory error. $\zeta$ And DR from UT fit…
Inclusive $B \rightarrow X_s \gamma$

- Error on **inclusive measurement** blows up at lower photon energy
  - Balance between statistical errors and the error from extrapolating down to 1.6 GeV (shape function, as in inclusive $|V_{ub}|$)

- Use recoil method or high p lepton to tag events…
  - $B \rightarrow d \gamma$ background is subtracted out

\[ B_{HFAG} (B \rightarrow X_s \gamma) = (3.55 \pm 0.26) \times 10^{-4} \]
Dilepton penguin decays $b \rightarrow s l^+ l^-$

- Decay rate $\times 10^{-2}$ smaller than $b \rightarrow s \gamma$
- BUT, more observables sensitive to NP
- For example, exclusive $B \rightarrow K^* l^+ l^-$
  - $K^*$ longitudinal polarization
  - Lepton FB asymmetry
  - BR's, lepton flavor, isospin asymmetry,…
- Amplitudes and their NP effects can be expressed in terms of effective Wilson coefficients
  - $C_7^{\text{eff}}$, from the EW penguin
  - $C_9 (V)$ and $C_{10} (A)$, from the interference of the Z penguin and $W^+ W^-$ box diagrams

Hints of anomalously large positive $A_{FB}$ at low and high $q^2$

similar situation in CDF/BaBar's case
(Semi)Inclusive $B \to X_s l^+ l^-$

- From **sum of exclusive states**
  - Reconstruct $X_s$ as $K^\pm/K_s$ + up to 4 pions
  - $B_{HFAG}(B \to X_s l^+ l^-) = (3.66 \pm 0.77) \times 10^{-6}$
  
  for $q^2 > 0.2 \text{ GeV/c}^2$

- SM (Ali et al): $B_{GM} = (4.2 \pm 0.7) \times 10^{-6}$
- SM (Gambino et al): $B_{SM} = (4.4 \pm 0.7) \times 10^{-6}$

MC/Data differences $\Rightarrow$ fragmentation models

MC/Data differences $\Rightarrow$ NP?
Many radiative and dilepton measurements!

- **BR’s**
  - Also CP asymmetries
    - Expected to be almost zero in the SM
    - Null test for new physics search
    - All compatible with zero
  - Crucial to improve the precision

IMFP 2011, LSC

B factories
New physics with charm

- Charm is an up-type quark!
  - NP inducing FCNC process could reveal couplings substantially stronger for up-type than for down-type quarks
  - But “SM” background much smaller for FCNC of up-type quarks (smaller signals)
- \textbf{CP violation} (and mixing?) is the way to explore new physics with charm
- Short-distance contributions from mixing box diagrams in the SM expected to be small
  - b quark is CKM-suppressed
  - s and d quarks are GIM suppressed
  - Contributes mainly to $x=\Delta m/\Gamma$
  - NP would show up here, $y=(\Gamma_1-\Gamma_2)/2\Gamma$
    - mostly unaffected
- Long-distance contributions expected to dominate, still small effect, but hard to estimate precisely
- SM CP violation at $10^{-3}$ level
  - NP could increase up to few % level

Most SM predictions: $x,y \sim 0.001-0.01$ and $|x|<|y|$ or $|x|>>|y|$ could be hint of NP
Evidence for charm mixing

- In 2007, 30 years after A. Pais and S.B. Treiman first speculated about it, B factories reported the first evidence for D^0-D^0 mixing (quickly confirmed by CDF).

- **Text book example**: Wrong sign (WS) K+p- final states from D0 decays from 2 sources: via double-Cabibbo-suppressed (DCS) decays or via mixing followed by Cabibbo-favored (CF) decays.

\[
\frac{dN_{WS}}{dt} \propto e^{-\Gamma t} \left( R_D + y' \sqrt{R_D} (\Gamma t) + \frac{x'^2 + y'^2}{4} (\Gamma t)^2 \right)
\]

- Time evolution (|x| \ll 1, |y| \ll 1):

- **DCS Interference Mixing**

- \[ R_D = \frac{B(D^0 \rightarrow K^+\pi^-)}{B(D^0 \rightarrow K^-\pi^+)} \approx 3 \cdot 10^{-3} \]

- Phase between DCS and CF decays not directly measurable at B Factories

\[ x' = x \cos \delta_{K\pi} + y \sin \delta_{K\pi} \]

\[ y' = -x \sin \delta_{K\pi} + y \cos \delta_{K\pi} \]

Analysis of the proper time distribution of WS events permits extraction of D^0 mixing parameters y', x'.

---

IMFP 2011, LSC  B factories
Evidence for charm mixing

- Wrong sign $D^0$ decay time distribution using right sign (RS) decay time and resolution function

- Mixing parameters

\[
R_D = (0.303 \pm 0.016 \pm 0.01)\% \\
y' = (0.97 \pm 0.44 \pm 0.31)\% \\
\chi^2 = (-0.022 \pm 0.03 \pm 0.021)\%
\]

- Ratio of WS/RS events varies as a function of time due to mixing
Charm mixing and CPV

- Averages with CP violation allowed with all available measurements: mostly from B factories, but also CDF and CLEO-c (from about 30 “mixing” observables)

\[
x = (0.63^{+0.19}_{-0.20})\% \\
y = (0.75 \pm 0.12)\%
\]

- Evidence of D^0 mixing exceeds 10\(\sigma\) combining all experimental results, but no single measurement exceeds yet 5\(\sigma\)
- No evidence for CP violation (either in mixing, decay or interference)
Charm mixing and CPV

EPS 2009, before the new $D^0 \to K_S\pi^+\pi^- + K_SK^+K^-$ results from BaBar, so far the most precise single and direct measurement of $x$ and $y$

$$x = (0.98 \pm 0.25)\%$$
$$y = (0.83 \pm 0.16)\%$$

✓ Evidence of $D^0$ mixing exceeds $10\sigma$ combining all experimental results, but no single measurement exceeds yet $5\sigma$

✓ No evidence for CP violation (either in mixing, decay or interference)
A number of BSM models predict light weakly-interacting degrees of freedom

E.g. NMSSM models with light CP-odd Higgs

- CP-odd Higgs, $A^0$, below $2m_b$, is not constrained by LEP
- Large BR($\gamma \rightarrow \gamma A^0$) possible
- Search in the unprecedented $\gamma(nS)$ samples@B factories

Also models with low-mass dark matter and/or gauge bosons motivated by $\gamma$-ray and positron emission from galactic center (INTEGRAL, PAMELA, ATIC, etc.)

- E.g. “Dark Sector”
- DM particles in $\sim$TeV range, but new gauge bosons in $\sim$GeV range
- New gauge bosons decay to lepton pairs, antiproton production forbidden by kinematics or suppressed (explains PAMELA/ATIC features)
- Search for low-mass states in $e^+e^-$ annihilation@B factories
\[ \Upsilon(nS) \rightarrow \gamma + \text{Exotic} \]

- Searches performed in:
  - \( \Upsilon(2S,3S) \rightarrow \gamma \mu^+\mu^- \), \( \Upsilon(3S) \rightarrow \gamma \tau^+\tau^- \)
    - Look for a peak in the \( m(l^+l^-) \) spectrum
  - \( \Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S) \), \( \Upsilon(1S) \rightarrow \gamma + \text{invisible} \)
    - Missing mass + dipion recoil mass
    - Invisible is either a particle (e.g. \( A^0 \)), or a pair of DM particles, \( \chi \chi \)

- Well understood initial state
  - Narrow \( \Upsilon(2S) \) or \( \Upsilon(3S) \)
  - Fully or partially reconstructed final state, depending on the decay pattern of \( A^0 \)

- Look for \( e^+e^- \rightarrow l^+l^-l^+l^- \) final state (4e, 2e+2\( \mu \), 4\( \mu \)) as a function of two lepton mass

Key experimental signature: monochromatic photon in the Center-of-Mass (CM) frame
Light Higgs & DM limits

- $\Upsilon(1S)\rightarrow\gamma+\text{invisible}$
  - $\text{BR}(\Upsilon(1S)\rightarrow\text{invisible}) = [-1.6 \pm 1.4 \text{ (stat.)} \pm 1.6 \text{ (syst.)}] \times 10^{-4}$
  - $\text{BR}(\Upsilon(1S)\rightarrow\text{invisible}) < 3.0 \times 10^{-4} @ 90\% \text{ C.L.}$

- Resonant $\Upsilon(1S)\rightarrow\gamma A^0$ search

- $e^+e^-\rightarrow W'W'\rightarrow ll' l' l'$

  $$\sigma(e^+e^-\rightarrow W'W'\rightarrow ll' l' l') < (25 - 60) \text{ ab}$$
Conclusions and perspectives

- Great success of the B factories in the last decade
  - Many measurements in B, D, tau, quarkonium, etc. with quite a few unexpected results

- CKM mechanism confirmed
  - All measurements of quark mixing & CP violation consistent with CKM

- Several possible hints (“tensions”) for effects of physics BSM (\(\sin 2\beta\), \(B \rightarrow \tau \nu\), \(K^{*\ell^+\ell^-}\); \(A_{SL}\), \(\beta_S\) from Tevatron)
  - The contrary would be suspicious…
  - …3σ effects are 99.7% of the time wrong…but make life more interesting
  - Large contributions (~10%) from NP not excluded with current data sets

- Despite the huge progress made by B factories, much remains to be done
  - New and more precise measurements, better predictions

- Enormous discovery potential for next generation experiments…
Next generation B factories

- LHCb has great potential in many –but not all- sectors (Lluis Garrido’s talk yesterday)

- Important examples only accessible in e^+e^- collisions
  - \( B \rightarrow l\nu \), \( B \rightarrow K\nu\nu \), and rare \( \tau \) decays

- Two next generation e^+e^- experiments proposed and approved, target is >75fb^-1

- BelleII – upgrade of Belle, approved in Japan, commissioning starts ~2014

- SuperB – new approved in Italy, reusing BaBar/PEP-II hardware, commissioning starting ~2016

- The two designs share much in common. Main differences:
  - Potential for beam polarization at SuperB (\( \tau \) physics, LFV, etc.)
  - Running at \( \overline{D}D \) threshold in SuperB
<table>
<thead>
<tr>
<th>Observable</th>
<th>Babar/ Belle</th>
<th>LHCb (10fb⁻¹)</th>
<th>SLHCb (100fb⁻¹)</th>
<th>SuperB (75ab⁻¹)</th>
<th>Some Comment</th>
<th>Theo</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma )</td>
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<td>( V_{ub}/V_{cb} )</td>
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<td>( S(J/\psi\phi) )</td>
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<td>At 1° theo error controlled with data ?</td>
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<tr>
<td>( B \to \tau \nu, \mu \nu )</td>
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<td>Very precise if detector is improved</td>
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<td>S-Penguins</td>
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<td>SLHCb (very) precise for ( B \to \phi K ), ( Bs \to \phi \phi ) Not possible for ( Ks\pi^0, kskks, \eta ks, \omega k )</td>
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<td>( A_{CP}(B \to X_s \gamma) )</td>
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<td>Control syst. Is an issue</td>
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<td>( Br (B \to X_s \gamma) )</td>
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<td>Syst. Controlled with data ?</td>
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<td>( Br(B \to X_s l l) ) Angular var.</td>
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<td>( Br(B \to K^{*} l l) ) Angular var.</td>
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<td>( Br (B \to K(\phi) l \nu) )</td>
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<td>Could theory control @20%? Angular analysis are clean ?</td>
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<td>( Br (B \to K_2 \pi^0 \gamma) )</td>
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<td>Stat. limited. With more stat. angular analyses also possible</td>
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<td>( Br(B_3 \to \phi \gamma) )</td>
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<td>As precise as ( Br \to K_2 \pi^0 \gamma ) ?</td>
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<td>( Br (B_3 \to \mu \mu) )</td>
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<td>( \tau \to \mu \gamma )</td>
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<td>profit of polarized beams</td>
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<td>CPV charm</td>
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<td>CPV in SM negligible. So clean NP probe</td>
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</tbody>
</table>

**THEORY**

- Moderately Clean
- Clean Need Lattice
- Clean

From A. Stocchi

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