CKM Fits: What the Data Say (Focused on B Physics)
S. T’Jampens

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CKM Fits: What the Data Say
(focused on B-Physics)

Stéphane T’JAMPENS
LAPP (CNRS/IN2P3 & Université de Savoie)
Outlines:

- CKM phase invariance and unitarity
- Statistical issues
- CKM metrology
  - Inputs
    - Tree decays: $|V_{ub}|, |V_{cb}|$
    - Loop decays: $\Delta m_d, \Delta m_s, \epsilon_K$
    - UT angles: $\alpha, \beta, \gamma$
  - The global CKM fit
- What about New Physics?
- Conclusion

Charm is interesting in several special areas, but I will concentrate on b’s
The Unitary Wolfenstein Parameterization

The standard parameterization uses Euler angles and one CPV phase $\rightarrow$ unitary!

$$ V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_3 e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} $$

Now, define $s_{12} \equiv \lambda$ $s_{23} \equiv A\lambda^2$ $s_{13}e^{-i\delta} \equiv A\lambda^3(\rho - i\eta)$

And insert into $V \rightarrow V$ is still unitary! With this one finds (to all orders in $\lambda$):

$$ \bar{\rho} + i\bar{\eta} = \frac{\sqrt{1 - A^2\lambda^4(\bar{\rho} + i\bar{\eta})}}{\sqrt{1 - \lambda^2[1 - A^2\lambda^4(\bar{\rho} + i\bar{\eta})]}} $$

where:

$$ \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} $$

$$ \lambda^2 \equiv \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \quad A^2\lambda^4 \equiv \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2} $$

Physically meaningful quantities are phase-convention invariant

Four unknowns [unitary-exact and phase-convention invariant]: $A, \lambda, \bar{\rho}, \bar{\eta}$
The CKM Matrix: Four Unknowns

Measurement of Wolfenstein parameters:

- $\lambda$ from $|V_{ud}|$ (nuclear transitions) and $|V_{us}|$ (semileptonic $K$ decays)
  - combined precision: 0.5%

- $A$ from $|V_{cb}|$ (inclusive and exclusive semileptonic $B$ decays)
  - combined precision: 2%

- $\bar{\rho}, \bar{\eta}$ from (mainly) CKM angle measurements:
  - combined precision: 20\% ($\rho$), 7\% ($\eta$)
Predictive Nature of KM Mechanism

All measurements must agree

Pre B-Factory:

Can the KM mechanism describe flavor dynamics of many constraints from vastly different scales?

This is what matters and not the measurement of the CKM phase’s value \textit{per se}
The (rescaled) Unitarity Triangle: The $B_d$ System

Convenient method to illustrate (dis-)agreement of observables with CKM predictions

\[ \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0 \]

phase invariant: $\bar{\rho} + i\bar{\eta}$

"There is no such thing as $\alpha/\phi_2$"

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

$B \rightarrow D^{(*)}K^{(*)}$

$B \rightarrow D_{K_S^0\pi^+\pi^-}K^{(*)}$

$B^0 \rightarrow DK^0_S$, ...

$B^0 \rightarrow D^+\pi(\rho)$

$B^0 \leftrightarrow \bar{B}^0 : \Delta m_d$

$B \rightarrow \rho(\omega)\gamma / B \rightarrow K^{(*)}\gamma$

$B^0 \rightarrow J/\psi K^0_S$, ...

$B^0 \rightarrow \phi K^0_S$, ...

$B \rightarrow u\ell\nu$

$B \rightarrow c\ell\nu$

$b \rightarrow c\bar{c}s$

$b \rightarrow s\bar{s}s$
The Unitarity Triangle: The $B_s$ System (hadron machines)

(sb) triangle ("$B_s$ triangle"): 

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

$O(\lambda^4) + O(\lambda^2) + O(\lambda^2) = 0$

⇒ squashed triangle

$$\chi = \beta_s = \arg \left[ -\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*} \right]$$

Attention: sign

(ut) triangle:

$$V_{td}V_{ud}^* + V_{ts}V_{us}^* + V_{tb}V_{ub}^* = 0$$

$O(\lambda^3) + O(\lambda^3) + O(\lambda^3) = 0$

⇒ non-squashed triangle

$B_s^0 \leftrightarrow \bar{B}_s^0 : \Delta m_s / \Delta m_d$

$B_s^0 \rightarrow \mu^+ \mu^-$ (BR for $B_s^0 \sim 1 \times 10^{-10}$)

$B_s^0 \rightarrow D_s K$

$B_s^0 \rightarrow K^+ K^-$

$B_s^0 \rightarrow J / \psi K_s^0$

$B_s^0 \rightarrow D_s^+ D_s^-$, ...

$B_s^0 \rightarrow \bar{B}_s^0$

$B_s^0 \rightarrow J / \psi \phi, ...$

$b \rightarrow c\bar{c}s$

$b \rightarrow s\bar{s}s$
Probing short distance (quarks) but confined in hadrons (what we observe)

➔ QCD effects must be under control (various tools: HQET, SCET, QCDF, LQCD,…)
➔ “Theoretical uncertainties” have to be controlled quantitatively in order to test the Standard Model. There is however no systematic method to do that.
Digression: Statistics
Frequentist: probability about the data (randomness of measurements), given the model

\[ P(\text{data}|\text{model}) \]

Hypothesis testing: given a model, assess the consistency of the data with a particular parameter value \( \Rightarrow \) 1-CL curve (by varying the parameter value)

Bayesian: probability about the model (degree of belief), given the data

\[ P(\text{model}|\text{data}) \times \text{Likelihood(}\text{data, model}\text{)} \]

Although the graphical displays appear similar: the meaning of the “Confidence level” is not the same. It is especially important to understand the difference in a time where one seeks deviation of the SM.
The Bayesian approach in physical science fails in the sense that nothing guarantees that my uncertainty assessment is any good for you - I'm just expressing an opinion (degree of belief). To convince you that it's a good uncertainty assessment, I need to show that the statistical model I created makes good predictions in situations where we know what the truth is, and the process of calibrating predictions against reality is inherently frequentist."


How to read a Posterior PDF?
→ updated belief (after seeing the data) of the plausible values of the parameter
♭ it's a bet on a proposition to which there is no scientific answer

My talk is about “What the Data say”, thus I will stick to the frequentist approach
Metrology: Inputs to the Global CKM Fit

I) Direct Measurement: magnitude
   $|V_{ud}|$ and $|V_{us}|$ [not discussed here]
   $|V_{ub}|$ and $|V_{cb}|$
   $B^+ \rightarrow \tau^+\nu$

   CPV in $K^0$ mixing [not discussed here]
   $B_d$ and $B_s$ mixing

II) Angle Measurements:
   $\sin 2\beta$
   $\alpha: (B \rightarrow \pi\pi, \rho\rho, \rho\pi)$
   $\gamma: \text{ADS, GLW, Dalitz (GGSZ)}$
$|V_{cb}|$ and $|V_{ub}|$
$|V_{cb}|$ (→ $A$) and $|V_{ub}|$

For $|V_{cb}|$ and $|V_{ub}|$ exist exclusive and inclusive semileptonic approaches (complementary)

<table>
<thead>
<tr>
<th>exclusive</th>
<th>inclusive</th>
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<tbody>
<tr>
<td>$b \rightarrow u$</td>
<td>$b \rightarrow c$</td>
</tr>
<tr>
<td>$B \rightarrow \pi \ell \nu$</td>
<td>$B \rightarrow X_u \ell \nu$</td>
</tr>
<tr>
<td>$B \rightarrow D^* \ell \nu$</td>
<td>$B \rightarrow X_c \ell \nu$</td>
</tr>
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</table>

Complication for charmless decays:

$$\frac{\Gamma(b \rightarrow ul\nu)}{\Gamma(b \rightarrow cl\nu)} \approx \left| \frac{|V_{ub}|^2}{|V_{cb}|^2} \right| \approx \frac{1}{50}$$

- need to apply kinematic cuts to suppress $b \rightarrow c\ell\nu$ background
- measurements of partial branching fractions in restricted phase space regions
- theoretical uncertainties more difficult to evaluate

OPE parameters measured from data (spectra and moments of $b \rightarrow s\gamma$ and $b \rightarrow c\ell\nu$ distributions)

$|V_{ub}|$ (→ $\rho^2 + \eta^2$) is crucial for the SM prediction of $\sin(2\beta)$

$|V_{cb}|$ (→ $A$) is important in the kaon system ($\epsilon_K$, $BR(K\rightarrow\pi\nu\nu)$, …)
|V_{cb}| and |V_{ub}|

|V_{cb}|:  Precision measurement: 1.7% !

|V_{cb}\text{incl.}[10^{-3}] = 41.70 \pm 0.70 |V_{ub}|\text{incl.}[10^{-3}] = 39.7 \pm 2.0

w/ FF=0.91\pm0.04  

|V_{cb}|\text{excl.}[10^{-3}] = 39.7 \pm 2.0  

|V_{ub}|:  

SF params. from b\to c/\nu, OPE from BLNP
BR precision \sim 8\%, |V_{ub}| excl. \sim 16\%: theory dominated
HFAG with our error budget

our average

|V_{ub}| [10^{-3}] = 4.10 \pm 0.09_{\text{exp}} \pm 0.39_{\text{theo}}
$B^+ \rightarrow \tau^+ \nu_\tau$

- Helicity-suppressed annihilation decay sensitive to $f_B \times |V_{ub}|$
- Powerful together with $\Delta m_d$: removes $f_B$ (Lattice QCD) dependence
- Sensitive to charged Higgs replacing the $W$ propagator

$$\text{BR}(B^+ \rightarrow \tau^+ \nu_\tau) = \frac{G_F^2 m_{B^+} m_{\tau^+}}{8\pi} m_{\tau}^2 \left(1 - \frac{m_{\tau}^2}{m_{B^+}^2}\right)^2 f_B^2 |V_{ub}|^2$$

**ICHEP06**

$\text{BR}[10^{-4}]=0.88^{+0.68}_{-0.67} \text{ (stat)} \pm 0.11 \text{ (syst)}$

(320m)

$\text{BR}[10^{-4}]=1.79^{+0.56}_{-0.49} \text{ (stat)}^{+0.39}_{-0.46} \text{ (syst)}$

(447m)

- Prediction from global CKM fit:

$$\text{BF}(B^+ \rightarrow \tau^+ \nu_\tau) = (0.87^{+0.13}_{-0.20}) \times 10^{-4}$$
$\Delta m_d$ and $\Delta m_s$
**Δm_d and Δm_s: constraints in the (ρ-η) plane**

\[
\Delta m_s = \frac{G_F^2}{6\pi^2} m_{B_d} m_W^2 \eta_B S_0(x_t) f_{B_d}^2 B_d |V_{ts} V_{tb}^*|^2
\]

Very weak dependence on $\bar{\rho}$ and $\bar{\eta}$

The point is:

\[
f_{B_s}^2 B_s = \frac{f_{B_d}^2 B_d}{f_{B_s}^2 B_d} f_{B_d}^2 B_d = \xi^2 f_{B_d}^2 B_d
\]

ξ: SU(3)-breaking corrections

Measurement of $\Delta m_s$ reduces the uncertainties on $f_{B_d}^2 B_d$ since $\xi$ is better known from Lattice QCD

$\sigma_{rel}(\frac{f_{B_d}^2}{f_{B_s}^2} B_d) = 36\% \quad \rightarrow \quad \sigma_{rel}(\frac{\xi^2}{f_{B_s}^2 B_s / f_{B_d}^2 B_d}) = 10\%$

→ Leads to improvement of the constraint from $\Delta m_d$ measurement on $|V_{td} V_{tb}^*|^2$

\[
\Delta m_d = \frac{G_F^2}{6\pi^2} m_{B_d} m_W^2 \eta_B S_0(x_t) f_{B_d}^2 B_d |V_{td} V_{tb}^*|^2 \propto A^2 \lambda^6 \left[ (1 - \bar{\rho})^2 + \bar{\eta}^2 \right]
\]
\[ \Delta m_s : 17.77 \pm 0.10 \text{(stat.)} \pm 0.07 \text{ (syst.) ps}^{-1} \]

The signal has a significance of 5.4\( \sigma \).
First strong indication that $B_s$-$B_s$ mixing is probably SM-like.
angle $\beta$
**sin2β**

- “The” *raison d’être* of the B factories:
  \[ \sin(2β) \equiv \sin(2φ_1) \]

- Conflict with \( \sin^2β_{\text{eff}} \) from s-penguin modes? (New Physics (NP)?)

NP can contribute differently among the various s-penguin modes (Naïve average: 0.52 ± 0.05).

NB: a disagreement would falsify the SM. The interference NP/SM amplitudes introduces hadronic uncertainties

⇒ Cannot determine the NP parameters cleanly
angle $\alpha$
angle $\alpha$

**Tree:** dominant

$B^0 \left\{ \begin{array}{c} b \\ \bar{d} \end{array} \right\} \pi^- \left\{ \begin{array}{c} \bar{u} \\ d \end{array} \right\}$

$\propto V_{ub} V_{ud}^*$

$\propto \lambda^3$

**Penguin:** competitive?

$B^0 \left\{ \begin{array}{c} b \\ \bar{d} \end{array} \right\} \pi^- \left\{ \begin{array}{c} \bar{u} \\ d \end{array} \right\}$

$\propto V_{tb} V_{td}^*$

$\propto \lambda^3$

**Time-dependent CP observable:**

$$A_{h^+h^-}(t) = S_{h^+h^-} \cdot \sin(\Delta m_d t) - C_{h^+h^-} \cdot \cos(\Delta m_d t)$$

$$= \sqrt{1 - C_{h^+h^-}^2} \cdot \sin(2\alpha_{\text{eff}}) \cdot \sin(\Delta m_d t) - C_{h^+h^-} \cdot \cos(\Delta m_d t)$$

**Time-dependent CP analysis of $B^0 \rightarrow \pi^+\pi^-$ alone determines $\alpha_{\text{eff}}$: but, we need $\alpha$!**

**Isospin analysis**

($\alpha$ can be resolved up to an 8-fold ambiguity within $[0,\pi]$)
# Isospin Analysis: $B \rightarrow \pi \pi$

<table>
<thead>
<tr>
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<th>BABAR (347m)</th>
<th>Belle (532m)</th>
<th>Average</th>
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</thead>
<tbody>
<tr>
<td>$S_{\pi\pi}$</td>
<td>$-0.53 \pm 0.14 \pm 0.02$</td>
<td>$-0.61 \pm 0.10 \pm 0.04$</td>
<td>$-0.58 \pm 0.09$</td>
</tr>
<tr>
<td>$C_{\pi\pi}$</td>
<td>$-0.16 \pm 0.11 \pm 0.03$</td>
<td>$-0.55 \pm 0.08 \pm 0.05$</td>
<td>$-0.39 \pm 0.07$</td>
</tr>
</tbody>
</table>

"agreement": $2.6\sigma$

BABAR & Belle

**Graph:**
- $\pi^+ \pi^- S_{CP}$ vs $C_{CP}$
- 1-CL vs $\alpha$ (deg)
- Contours give $-\Delta\chi^2 = 1$, corresponding to 68.3% CL for 2 dof
Isospin Analysis: $B \rightarrow \rho \rho$

<table>
<thead>
<tr>
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<th>BABAR (347m)</th>
<th>Belle (275m)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{\rho\rho}$</td>
<td>$-0.19 \pm 0.21^{+0.05}_{-0.07}$</td>
<td>$0.08 \pm 0.41 \pm 0.09$</td>
<td>$-0.13 \pm 0.19$</td>
</tr>
<tr>
<td>$C_{\rho\rho}$</td>
<td>$-0.07 \pm 0.15 \pm 0.06$</td>
<td>$0.0 \pm 0.3 \pm 0.09$</td>
<td>$-0.06 \pm 0.14$</td>
</tr>
</tbody>
</table>

**BABAR & Belle**

**Isospin analysis:**

$\alpha = [94 \pm 21]^\circ$
Isospin Analysis: angle $\alpha_{\text{eff}} [B \to \pi\pi/\rho\rho]$

- Isospin analysis $B \to \pi\pi$:
  
  $|\alpha - \alpha_{\text{eff}}| < 32.1^\circ$ (95% CL)

- Isospin analysis $B \to \rho\rho$:
  
  $|\alpha - \alpha_{\text{eff}}| < 22.4^\circ$ (95% CL)
The $B \to \rho \pi$ System

Dominant mode $\rho^+ \pi^-$ is not a $CP$ eigenstate

Amplitude interference in Dalitz plot

Aleksan et al, NP B361, 141 (1991)

Snyder-Quinn, PRD 48, 2139 (1993)

simultaneous fit of $\alpha$ and strong phases

Measure 26 (27) bilinear Form Factor coefficients

correlated $\chi^2$ fit to determine physics quantities

Lipkin et al., PRD 44, 1454 (1991)
Isospin Analysis: angle $\alpha [B \rightarrow \pi\pi / \rho\pi / \rho\rho]$

$\alpha_{B\text{-Factories}} = [93^{+11}_{-9}]^\circ$

$\alpha_{\text{Global Fit}} = [100^{+5}_{-7}]^\circ$

$B \rightarrow \rho\rho$: at very large statistics, systematics and model-dependence will become an issue

$B \rightarrow \rho\pi$ Dalitz analysis: model-dependence is an issue!
angle $\gamma$
angle $\gamma$ [next UT input that is not theory limited]

$b \to c\bar{u}s, u\bar{c}s$

Tree: dominant
\[ \propto V_{cb}V_{us}^* \propto \lambda^3 \]

Tree: color-suppressed
\[ \propto V_{ub}V_{cs}^* \propto \lambda^3 \sqrt{\rho^2 + \eta^2} \]

Relative CKM phase: $\gamma$

Several variants:

- **GLW**: $D^0$ decays into $CP$ eigenstate
- **ADS**: $D^0$ decays to $K^-\pi^+$ (favored) and $K^+\pi^-$ (suppressed)
- **GGSZ**: $D^0$ decays to $K_S\pi^+\pi^-$ (interference in Dalitz plot)

All methods fit simultaneously: $\gamma$, $r_B$ and $\delta$ (different $r_B$ and $\delta$)

\[ \{r_B, r_B^*\} \; \text{how small?} \]

$\sigma_\gamma$ depends significantly on the value of $r_B$
Constraint on $\gamma$

$$r_B(DK) = 0.10^{+0.03}_{-0.04}$$
$$r_B(D^*K) = 0.10^{+0.04}_{-0.06}$$
$$r_B(DK^*) = 0.11^{+0.09}_{-0.11}$$

$$\gamma_{B-\text{Factories}} = [60^{+38}_{-24}]^\circ$$
$$\gamma_{\text{Global Fit}} = [59^{+9}_{-4}]^\circ$$
Putting it all together: the global CKM fit

Inputs:

- $|V_{ub}/V_{cb}|$
- $\Delta m_d$
- $\Delta m_s$
- $B \to \tau\nu$
- $|\varepsilon_K|$
- $\sin 2\beta$
- $\alpha$
- $\gamma$
The global CKM fit: Testing the CKM Paradigm

CP Conserving

CP-violating observables imply CP violation!

Angles (no theory)

No angles (with theory)
The global CKM fit: Testing the CKM Paradigm (cont.)

Tree (NP-Free)  “Reference UT”

[No NP in \( \Delta l=3/2 \) b\( \rightarrow \)d EW penguin amplitude
Use \( \alpha \) with \( \beta \) (charmonium) to cancel NP amplitude]

Conceptual figure showing the CKM mechanism as the dominant source of CP violation.

The global fit is not the whole story: several \( \Delta F=1 \) rare decays are not yet measured ➔ Sensitive to NP
The global CKM fit: selected predictions

**Wolfenstein parameters:**

\[
A = 0.806^{+0.014}_{-0.014} \quad \lambda = 0.2272^{+0.0010}_{-0.0010} \quad \bar{\rho} = 0.195^{+0.022}_{-0.055} \quad \bar{\eta} = 0.326^{+0.027}_{-0.015}
\]

**Jarlskog invariant:**

\[J = (2.91^{+0.25}_{-0.14}) \times 10^{-5}\]

**UT Angles:**

\[
\alpha = (99.0^{+4.0}_{-9.4})^\circ \quad \beta = (22.03^{+0.72}_{-0.62})^\circ \quad \gamma = (59.0^{+9.2}_{-3.7})^\circ \quad \Sigma_{\text{meas.}} = (175^{+40}_{-27})^\circ
\]

**UT sides:**

\[R_u = 0.380^{+0.011}_{-0.009} \quad R_t = 0.868^{+0.060}_{-0.025}\]

**B-B mixing:**

\[\Delta m_s = (18.9^{+5.7}_{-2.8}) \text{ ps}^{-1} \quad \text{(CKM Fit)} \quad \Delta m_s : 17.77 \pm 0.1 \text{(stat.)} \pm 0.07 \text{ (syst.) ps}^{-1} \quad \text{(direct,CDF)}\]

**B\rightarrow\tau\nu**

\[\text{BF}(B^+ \rightarrow \tau^+ \nu_{\tau}) = (0.87^{+0.13}_{-0.20}) \times 10^{-4} \quad \text{(CKM Fit)} \quad (1.45^{+0.46}_{-0.43}) \times 10^{-4} \quad \text{(direct,WA)}^{36}\]
New Physics?
New Physics in $B_d$-$\bar{B}_d$ Mixing?

$$r_d^2 \exp(2i\theta_d) = \frac{\langle B^0|H_{\text{full}}^{\text{eff}}|\bar{B}^0 \rangle}{\langle B^0|H_{\text{SM}}^{\text{eff}}|\bar{B}^0 \rangle}$$

No significant modification of the $B$-$\bar{B}$ mixing amplitude.
Hypothesis: NP in loop processes only (negligible for tree processes)

Mass difference: $\Delta m_s = (\Delta m_s)^{SM} r_s^2$

Width difference: $\Delta \Gamma_s^{CP} = (\Delta \Gamma_s)^{SM} \cos^2(2\chi - 2\theta_s)$

Semileptonic asymmetry:
$A_{SL}^s = -\text{Re}(\Gamma_{12}/M_{12})^{SM} \sin(2\theta_s)/r_s^2$

$S\psi \phi = \sin(2\chi - 2\theta_s)$

UT of $B_d$ system: non-degenerated
$\Rightarrow (h_d, \sigma_d)$ strongly correlated to the determination of $(\rho, \eta)$

UT of $B_s$ system: highly degenerated
$\Rightarrow (h_s, \sigma_s)$ almost independent of $(\rho, \eta)$

$B_s$ mixing phase very small in SM: $\chi = -1.02 \pm 0.06$ (deg)
$\Rightarrow$ Bs mixing: very sensitive probe to NP

NP wrt to SM:
- reduces $\Delta \Gamma_s$
- enhances $\Delta m_s$
NP in $B_s$ System

$\Delta m_s, \Delta \Gamma_s$ and $A_{s,SL}$

$\sigma(\Delta m_s) = 0.035$, $\sigma(\sin(2\chi)) = 0.1$

First constraint for NP in the $B_s$ sector
Still plenty of room for NP
Large theoretical uncertainties: LQCD

$h_s \sim\leq 3$ ($h_d \sim\leq 0.3$, $h_K \sim\leq 0.6$)
\( \beta_s = (-0.56^{+0.44}_{-0.41}) \) (stat+syst) [rad]

Time-dependent angular distribution of untagged decays \( B_s \to J/\psi\phi \) + charge asymmetry

- Prediction from global CKM fit:
  \( \beta_s = (-0.0175^{+0.0015}_{-0.0008}) \) [rad]

- Precision prediction
- Sensitive test to NP
NP in $b \rightarrow s$ transitions?
NP related solely to the third generations?
Conclusion

• CKM mechanism: success in describing flavor dynamics of many constraints from vastly different scales.

• Improvement of Lattice QCD is very desirable [Charm/tau factory will help]

• $B_s$: an independent chapter in Nature’s book on fundamental dynamics
  • there is no reason why NP should have the same flavor structure as in the SM
  • $B_s$ transitions can be harnessed as powerful probes for NP ($\chi$: “NP model killer”)

• With the increase of statistics, lots of assumptions will be needed to be reconsidered [e.g., extraction of $\alpha$ from $B \rightarrow 3\pi, 4\pi$, etc., $P_{EW}$, …]

• Before claiming NP discovery, be sure that everything is “under control” (assumptions, theoretical uncertainties, etc.)
  ➔ null tests of the SM

• There are still plenty of measurements yet to be done
BACKUP SLIDES
Radiative Penguin Decays: $\text{BR}(B \rightarrow \rho \gamma)/\text{BR}(B \rightarrow K^* \gamma)$

$B \rightarrow \rho \gamma \ (\propto |V_{td}|^2)$ & $B \rightarrow K^* \gamma \ (\propto |V_{ts}|^2)$ sensitive to New Physics

![Diagram of loop and annihilation diagrams]

Additional amplitude contribution to charged modes => less reliable

$$\frac{BF(B^0 \rightarrow \rho^0 \gamma)}{BF(B^0 \rightarrow K^{*0} \gamma)} = 1.023 \frac{1}{2} \left| \frac{V_{td}}{V_{ts}} \right|^2 \xi^{-2} (1 + \Delta)$$

<table>
<thead>
<tr>
<th>BABAR (347m)</th>
<th>Belle (386m)</th>
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<tbody>
<tr>
<td>$\rho^0 \gamma$</td>
<td>$0.77^{+0.21}_{-0.19} \pm 0.07$</td>
</tr>
<tr>
<td>$\rho^+ \gamma$</td>
<td>$1.06^{+0.35}_{-0.31} \pm 0.09$</td>
</tr>
</tbody>
</table>
### FLAVOR STRUCTURE

<table>
<thead>
<tr>
<th></th>
<th>$b \to s$</th>
<th>$b \to d$</th>
<th>$s \to d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta F=2$ box</td>
<td>$\Delta M_{B_s}$, $A_{CP}(B_s \to \psi(\phi))$</td>
<td>$\Delta M_{B_d}$, $A_{CP}(B_d \to \psi K)$</td>
<td>$\Delta M_K$, $\epsilon_K$</td>
</tr>
</tbody>
</table>
| $\Delta F=1$  
4–quark box | $B_d \to \phi K$, $B_d \to K \pi$, ... | $B_d \to \pi \pi$, $B_d \to \rho \pi$, ... | $\epsilon'/\epsilon$, $K \to 3\pi$, ... |
| gluon penguin | $B_d \to X_s \gamma$, $B_d \to \phi K$, $B_d \to K \pi$, ... | $B_d \to X_d \gamma$, $B_d \to \pi \pi$, ... | $\epsilon'/\epsilon$, $K_L \to \pi^0 \ell \ell$, ... |
| $\gamma$ penguin | $B_d \to X_s \ell \ell$, $B_d \to X_s \gamma$ | $B_d \to X_d \ell \ell$, $B_d \to X_d \gamma$ | $\epsilon'/\epsilon$, $K_L \to \pi^0 \ell \ell$, ... |
| $Z^0$ penguin | $B_d \to X_s \ell \ell$, $B_s \to \mu \mu$ | $B_d \to X_d \ell \ell$, $B_d \to \mu \mu$ | $\epsilon'/\epsilon$, $K_L \to \pi^0 \ell \ell$, $K \to \pi \nu \nu$, $K \to \mu \mu$, ... |
| $H^0$ penguin | $B_s \to \mu \mu$ | $B_d \to \mu \mu$ | $K_{L,S} \to \mu \mu$ |

G. Isidori – Beauty ‘03
Bayes at work

Zero events seen

\[ P(n; \lambda) = e^{-\lambda} \frac{\lambda^n}{n!} \]

Posterior \( P(\lambda) \)

Prior: uniform

\[ \int_{0}^{3} P(\lambda) \, d\lambda = 0.95 \]

Same as Frequentist limit - Happy coincidence
Bayes at work again

Is that uniform prior really credible?

Posterior $P(\lambda)$

$P(0 \text{ events}|\lambda)$

Prior: uniform in $\ln \lambda$

Upper limit totally different!

$\int_{0}^{3} P(\lambda) \, d\lambda \gg 0.95$
Bayes: the bad news

• The prior affects the posterior. It is your choice. That makes the measurement subjective. This is BAD. (We’re physicists, dammit!)

• A Uniform Prior does not get you out of this.

• Beware snake-oil merchants in the physics community who will sell you Bayesian statistics (new – cool – easy – intuitive) and don’t bother about robustness.
Hypersphere:

One knows nothing about the individual Cartesian coordinates $x, y, z$…

What do we known about the **radius** $r = \sqrt{x^2 + y^2 + \ldots}$?

One has achieved the remarkable feat of learning something about the radius of the hypersphere, whereas one knew nothing about the Cartesian coordinates and without making any experiment.

6D space