** Future Prospects In Flavour Physics**

Marco Ciuchini

** timeline of flavour physics experiments**

** going BSM with flavour physics: why and why now**

** the twofold role of flavour physics in next years**
Timeline of flavor experiments

Experimental Flavour Landscape: 2011 - 2030

- Proposed LHCb Upgrade (2018)
- SuperB
- Belle II (2014)
- NA62 (2012)
- KLOE2 (2011)
- BES III (2011)
- LHCb (2010, 2015, 2020)

Near (BESIII, KLOE2, LHCb, MEG, KOTO)
Far (Belle-II, SuperB, Mu2e)
Farther (LHCb upgrade)

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

Relevant dates are when full samples are collected

arXiv:1109.5028
Indirect searches look for new physics through virtual effects of new particles in loop corrections

* SM FCNCs and CP-violating processes occur at the loop level

* SM FV and CPV are governed by the weak interactions and suppressed by mixing angles

* SM quark CPV comes from a single source (neglecting $\theta_{QCD}$)

New Physics does not necessarily share the SM pattern of FV and CPV: very large NP effects are possible

Past (SM) successes in anticipating heavy flavours:

1970: charm from $K^0 \rightarrow \mu^+\mu^-$ (GIM)

1973: 3rd generation from $\epsilon_K$ (Kobayashi & Maskawa)

mid 80s+: heavy top from semileptonic decays & $\Delta m_B$
Going BSM with flavour physics: why now?

* current and next-generation flavour experiments will be able to improve the experimental precision/sensitivity by one order of magnitude
* enough NP-insensitive observables to pin down the SM contribution with the required accuracy
* several NP-sensitive observables not limited by systematics or theoretical uncertainties

Overall, the NP sensitivity extends to (i) the TeV region for SM-like flavour violation and to (ii) tens of TeV or more in less constrained cases
Precision flavour physics & theory uncertainties

<table>
<thead>
<tr>
<th>no theory improvements needed</th>
<th>( \beta(J/\psi K), \gamma(DK), \alpha(\pi\pi)^*, ) lepton FV and UV, CPV in ( B \to X_{s+d}\gamma ), D and ( \tau ) decays zero of FB asymmetry ( B \to X_s l^+l^- )</th>
<th>NP insensitive or null tests of the SM or SM already known with the required accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>improved lattice QCD</td>
<td>meson mixing, ( B \to D(<em>)l\nu ), ( B \to \pi(\rho)l\nu ) ( B \to K^</em>\gamma, B \to \rho\gamma, B \to l\nu, B_s \to \mu\mu )</td>
<td>target error: (~1-2%) Feasible (see below)</td>
</tr>
<tr>
<td>improved OPE+HQE</td>
<td>( B \to X_{u,c}l\nu, (B \to X_s\gamma) )</td>
<td>target error: (~1-2%) Possibly feasible with large samples. Detailed studies required</td>
</tr>
<tr>
<td>improved QCDF/SCET or flavour symmetries</td>
<td>( S ) from TD ( A_{CP} ) in ( b \to s ) transitions</td>
<td>target error: (~2-3%) large and hard to improve uncertainties on small corrections. FS+data can bound the th. error</td>
</tr>
</tbody>
</table>
**Lattice QCD**

Lattice QCD can reach the $O(1\%)$ precision goal on time

V. Lubicz, SuperB CDR, arXiv:0709.0451
updated in arXiv:1008.1541

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Hadronic Parameter</th>
<th>Status End 2006</th>
<th>6 TFlops (Year 2009)</th>
<th>Status End 2009</th>
<th>60 TFlops (Year 2011)</th>
<th>1-10 PFlops (Year 2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K \rightarrow \pi l \nu$</td>
<td>$f_+^{K\pi}(0)$</td>
<td>0.9 %</td>
<td>0.7 %</td>
<td>0.5 %</td>
<td>0.4 %</td>
<td>&lt; 0.1 %</td>
</tr>
<tr>
<td>$\varepsilon_K$</td>
<td>$\hat{B}_K$</td>
<td>11 %</td>
<td>5 %</td>
<td>5 %</td>
<td>3 %</td>
<td>1 %</td>
</tr>
<tr>
<td>$B \rightarrow l \nu$</td>
<td>$f_B$</td>
<td>14 %</td>
<td>3.5-4.5 %</td>
<td>5 %</td>
<td>2.5-4.0 %</td>
<td>1.0-1.5 %</td>
</tr>
<tr>
<td>$\Delta m_d$</td>
<td>$f_{B_s}\sqrt{B_{B_s}}$</td>
<td>13 %</td>
<td>4-5 %</td>
<td>5 %</td>
<td>3-4 %</td>
<td>1-1.5 %</td>
</tr>
<tr>
<td>$\Delta m_d/\Delta m_s$</td>
<td>$\xi$</td>
<td>5 %</td>
<td>3 %</td>
<td>2 %</td>
<td>1.5-2 %</td>
<td>0.5-0.8 %</td>
</tr>
<tr>
<td>$B \rightarrow D/D^* l \nu$</td>
<td>$\mathcal{F}_{B \rightarrow D/D^*}$</td>
<td>4 %</td>
<td>2 %</td>
<td>2 %</td>
<td>1.2 %</td>
<td>0.5 %</td>
</tr>
<tr>
<td>$B \rightarrow \pi/\rho l \nu$</td>
<td>$f_+^{B\pi}, \ldots$</td>
<td>11 %</td>
<td>5.5-6.5 %</td>
<td>11 %</td>
<td>4-5 %</td>
<td>2-3 %</td>
</tr>
<tr>
<td>$B \rightarrow K^*/\rho (\gamma,l^+l^-)$</td>
<td>$T_1^{B \rightarrow K^*/\rho}$</td>
<td>13 %</td>
<td>——</td>
<td>13 %</td>
<td>——</td>
<td>3-4 %</td>
</tr>
</tbody>
</table>
**Comparison of present and future flavour experiments on “golden modes” (an incomplete list)**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>~ 1 ab⁻¹</td>
<td>5 fb⁻¹</td>
<td>75 ab⁻¹</td>
<td>50 fb⁻¹</td>
<td></td>
</tr>
</tbody>
</table>

- **τ Decay**
  - τ → μγ
  - τ → eγ

- **B_{u,d} Decays**
  - B → τν, μν
  - B → K⁺νν
  - S in B → K⁺π⁻γ
  - S (other penguin modes)
  - A_{CP} (B → X_s γ)
  - BR(B → X_s γ)
  - BR(B → X_s l⁺l⁻)
  - BR(B → K⁺l⁺l⁻)

- **B_s Decays**
  - B_s → μμ
  - β_s from B_s → J/ψφ
  - B_s → γγ
  - a_{sl}

- **D Decays**
  - Mixing parameters
  - CP Violation

- **Precision Electroweak**
  - sin²θ_W at ϒ(4S)
  - sin²θ_W at Z-Pole

**Note:**

- Benefit from polarised e⁻ beam
- Very precise with improved detector
- Statistical limited: ang. analysis with >75 ab⁻¹
- Right handed currents
- SuperB measures many more modes
- Systematic error is main challenge
- Control systematic error with data
- SuperB measures e mode well, LHCb does μ
- Clean NP search
- b fragmentation limits interpretation at Z polebas

---

**Based on arXiv:1109.5028**

---

Marco Ciuchini  
IFAE 2012 – Ferrara, April 12
The twofold role of flavour physics

Depending on the scenario, flavour physics can be used in two “modes” with different aimings

1. “NP-Lagrangian reconstruction” mode
   - external information on NP required
   - main tool: correlations among observables
   - need theoretical control on uncertainties of both SM and NP contributions

2. “Discovery” mode
   - look for deviation from the SM whatever the origin
   - need theoretical control of the SM contribution only
   - in general, cannot provide precise information on NP scale, but a positive result would be a strong evidence that NP is not too far (i.e. in the multi-TeV region)
MSSM: flavour violation in the squark sector

\[ M^2_{\tilde{d}} \approx \begin{pmatrix} m^2_{\tilde{d}_L} & m_{\tilde{d}}(A_d - \mu \tan \beta) & (\Delta^d_{12})_{LL} & (\Delta^d_{12})_{LR} \\ (\Delta^d_{12})_{RL} & m^2_{\tilde{d}_R} & (\Delta^d_{12})_{RR} \\ m^2_{\tilde{\chi}_L} & m_{\tilde{\chi}}(A_s - \mu \tan \beta) & m^2_{\tilde{\chi}_R} \\ (\Delta^d_{23})_{LL} & (\Delta^d_{23})_{LR} & (\Delta^d_{23})_{RR} \end{pmatrix} \]

LHC, ILC - HE frontier

LHCb, SuperB

and similarly for \( M^2_{\tilde{u}} \)

NP scale: \( m_{\tilde{q}} \)

FV & CPV couplings: \( (\delta^d_{ij})_{AB} = (\Delta^d_{ij})_{AB}/m_{\tilde{q}}^2 \)
Determination of $(\delta_{23}^d)_{LR}$ using SuperB data

**BR($B \rightarrow X_s \gamma$)**

**BR($B \rightarrow X_s \Pi$)**

$A_{CP}(B \rightarrow X_s \gamma)$

all together

reconstructed

$|\delta_{23}|_{LR} = 0.026 \pm 0.005$

$\arg(\delta_{23})_{LR} = (44.5 \pm 2.6)^\circ$

**Im$(\delta_{23}^d)_{LR}$ vs Re$(\delta_{23}^d)_{LR}$**

reconstruction of

$(\delta_{23}^d)_{LR} = 0.028 \ e^{i \pi/4}$ for

$\Lambda = m_{\tilde{g}} = m_{\tilde{q}} = 1$ TeV

**“3$\sigma$” sensitivity plot**

i) sensitive to $m_{\tilde{q}} < 20$ TeV

ii) sensitive to $|{(\delta_{23}^d)_{LR}}| > 10^{-2}$ for $m_{\tilde{q}} < 1$ TeV

i) sensitive to $m_{\tilde{q}} < 20$ TeV

ii) sensitive to $|{(\delta_{23}^d)_{LR}}| > 10^{-2}$ for $m_{\tilde{q}} < 1$ TeV

Marco Ciuchini

IFAE 2012 – Ferrara, April 12
OVERALL SUSY ASSESSMENT

studying correlations in flavour observables, together with high-p_\perp info, we can learn about:

* the SUSY-breaking mechanism
* the flavour breaking mechanism
* the underlying presence of a GUT structure
* the origin of lepton flavour violation

**Conclusions**

* intense experimental activity programmed for the next 20 years in all flavour sectors: entering the era of precision flavour physics

* a serious challenge for theory to keep up with the expected experimental precision. Yet perspectives are encouraging

* twofold goal:
  - study the flavour structure of new particles at the TeV scale
  - getting hint/evidence for the presence of NP in the multi-TeV region
Spare Slides
<table>
<thead>
<tr>
<th>Observable</th>
<th>Current value</th>
<th>Experiment</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}(B_s \rightarrow \mu\mu)$ $(\times 10^{-9})$</td>
<td>$&lt; N^a$</td>
<td>LHCb</td>
<td>±1</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>LHCb upgrade</td>
<td>±0.3</td>
</tr>
<tr>
<td>$2\beta_s$ from $B_s^0 \rightarrow J/\psi\phi$ (rad)</td>
<td>$0.003 \pm 0.009^b$</td>
<td>LHCb</td>
<td>0.019</td>
</tr>
<tr>
<td></td>
<td>0.002 0.038</td>
<td>LHCb upgrade</td>
<td>0.006</td>
</tr>
<tr>
<td>$S$ in $B_s \rightarrow \phi\gamma$ *</td>
<td></td>
<td>LHCb</td>
<td>0.07</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\nu\bar{\nu}$ (% BR measurement)</td>
<td>7 events</td>
<td>NA62</td>
<td>100 events (10%)</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \pi^0\nu\bar{\nu}$</td>
<td></td>
<td>KOTO</td>
<td>3 events (observe)</td>
</tr>
<tr>
<td>$BR(\mu \rightarrow e\gamma)$ $(\times 10^{-13})$</td>
<td>$&lt; 2.024$</td>
<td>MEG</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>$R_{\mu\mu}$</td>
<td>$&lt; 7 \times 10^{-12}$</td>
<td>COMET/Mu2E</td>
<td>$&lt; 6 \times 10^{-17}$</td>
</tr>
<tr>
<td>Observable/mode</td>
<td>Current now</td>
<td>LHCb (2017) $5,\text{fb}^{-1}$</td>
<td>Super $B$ (2021) $75,\text{ab}^{-1}$</td>
</tr>
<tr>
<td>----------------</td>
<td>-------------</td>
<td>-------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\gamma\ (\times 10^{-9})$</td>
<td>&lt; 44</td>
<td>&lt; 2.4</td>
<td>&lt; 5.0</td>
</tr>
</tbody>
</table>

**$B_{u,d}$ Decays**

- $\text{BR}(B \rightarrow \tau\nu\ (\times 10^{-4}))$ : $1.64 \pm 0.34$
- $\text{BR}(B \rightarrow \mu\nu\ (\times 10^{-6}))$ : < 1.0
- $\text{BR}(B \rightarrow \mu^+\mu^-\ (\times 10^{-6}))$ : < 1.1

**$A_{CP}$**

- $\text{BR}(B \rightarrow X_{s+d}\gamma\ (\times 10^{-4}))$ : 0.060 ± 0.060
- $\text{BR}(B \rightarrow K\mu^+\mu^-\ (\times 10^{-6}))$ : 250°
- $\text{BR}(B \rightarrow K\kappa^\pm\kappa^-\ (\times 10^{-6}))$ : 1.15 ± 0.16

**$S$ in $B \rightarrow K_0^\pm\pi^\pm$**

- $S$ in $B \rightarrow K_0^\pm\pi^\pm\gamma$ : −0.15 ± 0.20
- $S$ in $B \rightarrow \eta'K^0$ : 0.59 ± 0.07
- $S$ in $B \rightarrow \phi K^0$ : 0.56 ± 0.17

**$B^0$ Decays**

- $\text{BR}(B^0 \rightarrow \gamma\gamma\ (\times 10^{-6}))$ : < 8.7
- $A_{SL}^\prime\ (\times 10^{-3})$ : −7.87 ± 1.96

**$D$ Decays**

- $x$ : (0.63 ± 0.20)%
- $y$ : (0.75 ± 0.12)%
- $u_{CP}$ : (1.11 ± 0.22)%
- $|q/p| : (0.91 ± 0.17)%
- $\text{arg}\{q/p\} (°)$ : −10.2 ± 9.2

**Other processes Decays**

- $\sin^2 \theta_W$ at $\sqrt{s} = 10.58\,\text{GeV/c}^2$ : 0.0002

---

Marco Ciuchini

IFAE 2012 – Ferrara, April 12
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ from $u \bar{u} d$</td>
<td>6.1°</td>
<td>$5^\circ_a$</td>
<td>1°</td>
<td>1°</td>
<td>$^b$</td>
<td>1 – 2° clean</td>
</tr>
<tr>
<td>$\beta$ from $c \bar{c} s$ (S)</td>
<td>0.9° (0.024)</td>
<td>0.5° (0.008)</td>
<td>0.1° (0.002)</td>
<td>0.3° (0.007)</td>
<td>0.2° (0.003)</td>
<td>clean</td>
</tr>
<tr>
<td>$S$ from $B_d \rightarrow J/\psi \pi^0$</td>
<td>0.21</td>
<td>?</td>
<td>0.014</td>
<td>0.021 (est.)</td>
<td>?</td>
<td>clean</td>
</tr>
<tr>
<td>$S$ from $B_s \rightarrow J/\psi K_s^0$</td>
<td>0.11°</td>
<td>$\sim 4^\circ$</td>
<td>1°</td>
<td>1.5°</td>
<td>0.9°</td>
<td>clean</td>
</tr>
<tr>
<td>$\gamma$ from $B \rightarrow DK$</td>
<td>1.7</td>
<td>0.5%</td>
<td>0.6 (est.)</td>
<td>dominant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ (inclusive) %</td>
<td>2.2</td>
<td>1.0%</td>
<td>1.2 (est.)</td>
<td>dominant</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ (exclusive) %</td>
<td>4.4</td>
<td>2.0%</td>
<td>3.0</td>
<td>dominant</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$ (inclusive) %</td>
<td>7.0</td>
<td>3.0%</td>
<td>5.0</td>
<td>dominant</td>
</tr>
</tbody>
</table>