Quark Flavour Physics

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Looking for NP with B decays

CDF

Measurement of $B_0 \rightarrow \mu^+ \mu^-$ with CMS

Urs Langenegger
(PSI)

for the CMS collaboration

EPS HEP Stockholm

2013/07/19

- Introduction
- motivation and methodology
- detector

- Analysis
- selection
- validation

- Results
- $B_0 \rightarrow \mu^+ \mu^-$ and $B_0 \rightarrow \mu^+ \mu^-$

arxiv:1307.5025, subm. to PRL
The relevance of flavour

The **flavour sector of the SM** is strictly predictive
- Single source of CP violation in charged weak currents
- Suppressions due to hierarchy of CKM elements
- Suppression of flavor-changing neutral currents (FCNC, loop only)
- Suppression of chirality flips due to small quark masses

CKM unitarity triangle tested at the few percent level!
The relevance of flavour

New physics might not respect the many suppressions of the SM:

• Search for physics beyond SM in the “quantum” way: increase luminosity and look for indirect effects due to virtual particles

• Complementary to the “relativistic” way: increase energy and look for direct production of new particles

• Experimental reach (with significant simplifying assumptions)

(proton decay)

(neutrino properties)

(mu to e)

(Flavor (quarks))

(dark matter)

LHC

Tevatron

Indirect searches probe higher mass scales! (from Z. Ligeti)
Outline

• The experimental facilities
• CKM physics and CP violation
• Rare K & B decays
• Tree decays with $\tau$ leptons
• Conclusion
Experiments and data samples

LHCb
Forward spectrometer optimised for heavy flavour physics at the LHC

Large acceptance, $<2^\circ <5^\circ$
Low trigger thresholds
Precise vertexing
Efficient particle identification
Large boost ($B$ mesons flight $\sim1cm$)

Rare decays @ LHCb

Justine Serrano

Recorded integrated luminosity:
- $1 \text{ fb}^{-1}$ @ 7TeV (2011)
- $2 \text{ fb}^{-1}$ @ 8TeV (2012)

LHCb Integrated Luminosity pp collisions 2010-2012

~$1.5 \times 10^9$ BB pairs

> $1 \text{ ab}^{-1}$
On resonance:
- $\Upsilon(5S)$: 121 fb$^{-1}$
- $\Upsilon(4S)$: 711 fb$^{-1}$
- $\Upsilon(3S)$: 3 fb$^{-1}$
- $\Upsilon(2S)$: 25 fb$^{-1}$
- $\Upsilon(1S)$: 6 fb$^{-1}$
Off res./scan:
- $\sim 100 \text{ fb}^{-1}$

~$550 \text{ fb}^{-1}$
On resonance:
- $\Upsilon(4S)$: 433 fb$^{-1}$
- $\Upsilon(3S)$: 30 fb$^{-1}$
- $\Upsilon(2S)$: 14 fb$^{-1}$
Off res./scan:
- $\sim 54 \text{ fb}^{-1}$

July 7th, 2016
C. Bozzi - SÜSY2016 - Melbourne
They play a role as well!

\[
\sqrt{s_{\text{TeVatron}}} = 2 \text{ TeV} \\
L_{\text{TeVatron}} \sim 10 / \text{fb / exp}
\]

\[
\sqrt{s_{\text{LHC}}} = 7 - 8 \text{ TeV} \\
L_{\text{LHC}} \sim 25 / \text{fb / exp}
\]
We have been directly measuring these angles since 1998. OPAL, CDF, ALEPH, BaBar, Belle and LHCb have contributed to these measurements.

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

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

CKM unitarity triangle tested at the few percent level!
CKM matrix and unitarity triangle

We have been directly measuring these angles since 1998. OPAL, CDF, ALEPH, BaBar, Belle and LHCb have contributed to these measurements.

Beauty: \( \alpha, \beta(s), \gamma \)

\( B \rightarrow \pi \pi, \pi \pi, \pi \pi, a_1 \pi \)

\( B \rightarrow D \left( \pi \pi \right), K \left( \pi \pi \right) \)

\[ W^+ \]

\[ V_{ij} \]

\[ q_i = u, c, t \]

\[ q_j = \bar{d}, \bar{s}, \bar{b} \]

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

\( V_{\text{CKM}} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \)

CKM unitarity triangle tested at the few percent level!

\[ (0,0) \]

\[ (1,0) \]

\[ \phi_1 = \beta \]

\[ \phi_2 = \alpha \]

\[ \phi_3 = \gamma \]
Progress in $\gamma$ measurements

- Measure interference between CKM-favored and CKM-suppressed amplitudes in $B \rightarrow D(*)K(*)$ tree-level decays
- Exploit D meson decays in CP eigenstates (GLW, GGSZ) or Cabibbo-favoured / -suppressed final states (ADS)
- The ultimate precision on $\gamma$ determined from tree decays will be reached through many individual measurements, with very different sensitivities (due to different $b \rightarrow u$ and $b \rightarrow c$ amplitude ratios)
Several measurements considered

(all but the last one on the full Run1 data sample)

- $B^+ \rightarrow DK^+, D \rightarrow h^+h^-$, GLW/ADS
- $B^+ \rightarrow DK^+, D \rightarrow h^+\pi^-\pi^+\pi^-$, quasi-GLW/ADS
- $B^+ \rightarrow DK^+, D \rightarrow h^+h^0, \text{quasi-GLW/ADS}
- B^+ \rightarrow DK^+, D \rightarrow K_S^0h^+h^-$, model-ind. GGSZ
- $B^+ \rightarrow DK^+, D \rightarrow K_S^0K^+\pi^-, \text{GLS}$
- $B^0 \rightarrow DK^+\pi^-, D \rightarrow h^+h^-$, GLW-Dalitz
- $B^0 \rightarrow DK^{*0}, D \rightarrow K^+\pi^-, \text{ADS}$
- $B^0 \rightarrow DK^{*0}, D \rightarrow K_S^0\pi^+\pi^-, \text{model-dep. GGSZ}$
- $B^+ \rightarrow DK^{*+}\pi^-, D \rightarrow h^+h^-, \text{GLW/ADS}$
- $B^0 \rightarrow D_s^{\mp}\pi^+, \text{time-dep., 1 fb}^{-1}$

\[ \gamma = (70.9 \pm 7.1 \pm 8.5)^\circ \]

Significant progress!
The problem

This has been a problem for a while

|\( |V_{ub}| : \text{tension}^{\text{TM}} |\)

PDG version

- 2004
- 2006
- 2008
- 2010
- 2012
- 2014

Exclusive

Inclusive

|\( |V_{ub}| \) |
Measuring $|V_{ub}|/|V_{cb}|$ at LHC

- Baryonic decays $\Lambda_b \rightarrow p\mu\nu$ / $\Lambda_b \rightarrow \Lambda_c\mu\nu$ give clean samples
  - Protons are rarer than pions/kaons
- Suppress backgrounds by using isolation criteria
- No constraint from beam energy at a hadron machine
- Use constraint given by measurable flight direction to close kinematics

$$m_{\text{corr}} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp$$
Measuring $|V_{ub}|/|V_{cb}|$ at LHC

Using PDG exclusive average of $|V_{cb}|$:

$|V_{ub}| = (3.27 \pm 0.15_{\text{exp}} \pm 0.17_{\text{theory}} \pm 0.06_{|V_{cb}|}) \times 10^{-3}$

Models with RH currents ruled out
Result compatible with UT fits

$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)} q^2 > 15 \text{ GeV}^2/c^4$

$= (1.00 \pm 0.04(\text{stat}) \pm 0.08(\text{syst})) \times 10^{-2}$

Theory most predictive in given $q^2 = m^2(\mu\nu)$ ranges!

A precise measurement of $\Delta m_d$

Both $B^0 \rightarrow D^* \mu^+ \nu X$ and $B^0 \rightarrow D^* \mu^+ \nu X$ used. $B^0 \rightarrow D^* \mu^+ \nu X$ 2012 data shown as an example

$\Delta m_d = (505.0 \pm 2.1 \text{ (stat)} \pm 1.0 \text{ (syst)}) \text{ ns}^{-1}$

- Constraint on $|V_{td}|/|V_{ts}|$ when combined with precise $\Delta m_s$ measurement
- Recent results from Lattice QCD pave the way for tightening the mixing constraints on the unitarity triangle

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006 \text{ ps}^{-1}$
CP violation in B mixing

- LHCb measurements of semileptonic asymmetries $a_{sI}^s$, $a_{sI}^d$ consistent with Standard Model and with other measurements by Babar, Belle, D0
- Evidence for non-SM effects in inclusive di-muon asymmetry from D0 is not confirmed
- Still an order of magnitude to go to match theoretical precision

$$a_{sI}^d \left[ \text{SM} \right] = \left( -4.7 \pm 0.6 \right) \times 10^{-4}$$

$$a_{sI}^s \left[ \text{SM} \right] = \left( 2.22 \pm 0.27 \right) \times 10^{-5}$$

$\mathcal{A}_{sI}^s = \left( 0.39 \pm 0.26 \pm 0.20 \right)\%$

Artuso, Borissov, Lenz [arxiv:1511.09466]
There is another unitarity triangle

\[
V_{CKM} = \begin{pmatrix}
1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8} & \frac{\lambda}{A\lambda^3[1 - \bar{\rho} - i\bar{\eta}]/2} & \frac{A\lambda^3(\bar{\rho} - i\bar{\eta})(1 + \frac{\lambda^2}{2})}{1 - A^2\lambda^4/2} \\
-\lambda + A^2\lambda^5[1 - 2(\bar{\rho} + i\bar{\eta})]/2 & 1 - \frac{\lambda^2}{2} - \frac{\lambda^4(1 + 4A^2)/8}{A\lambda^3[1 - \rho - i\eta]} & -A\lambda^2 + A\lambda^4[1 - 2(\bar{\rho} + i\bar{\eta})]/2 \\
A\lambda^2 & -A\lambda^2 + A\lambda^4[1 - 2(\rho + i\eta)]/2 & 1 - A^2\lambda^4/2
\end{pmatrix} + \mathcal{O}(\lambda^6)
\]

Measure \( \beta_s = \arg[V_{ts}V_{tb}^*/V_{cs}V_{cb}^*] \) from interference between decays with and without mixing in tree-level \( b \to ccs \) decays

\( B_s \to J/\psi \phi, B_s \to J/\psi K^+K^-, B_s \to J/\psi \pi^+\pi^-, B_s \to D_s^+D_s^- \)

\[
\phi_s^{c\bar{c}s} = -2 \arg \left( -\frac{V_{cb}V_{cs}^*}{V_{tb}^*V_{ts}} \right) = -2\beta_s
\]

Penguin contributions neglected

LHCb measurements support this assumption


July 7th, 2016
Recent ATLAS result on $B_s \rightarrow J/\psi \, \phi$

**time-dependent, flavour-tagged angular analyses**

$$\frac{d^4 \Gamma(B_s^0 \rightarrow J/\psi K^+ K^-)}{dtd\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega).$$

$$h_k(t) = N_k e^{-\Gamma_s t} \left[ a_k \cosh\left(\frac{1}{2} \Delta \Gamma_s t\right) + b_k \sinh\left(\frac{1}{2} \Delta \Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t) \right]$$

arXiv:1601.03297
CP violation in $B_s$ mixing and decay

Statistical precision driven by tagging power:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Tagging power $\epsilon_{tag}(1 - 2\omega_{tag})^2$</th>
<th>CMS</th>
<th>ATLAS</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$(1.307 \pm 0.032)%$</td>
<td>$(1.49 \pm 0.02)%$</td>
<td>$(3.73 \pm 0.15)%$</td>
</tr>
</tbody>
</table>
New physics in $B_d$ and $B_s$ mixing

\[ C_{B_q} e^{2i\phi_{B_q}} = \frac{\langle B_q^0 | H_{\text{full}}^\text{eff} | \bar{B}_q^0 \rangle}{\langle B_q^0 | H_{\text{SM}}^\text{eff} | \bar{B}_q^0 \rangle}, \quad (q = d, s), \]

Sources of error: CKM ~ M.E. ~ 10%

$C_{B_d} = 1.08 \pm 0.15$ ([0.79, 1.40] @ 95%)
\[ \phi_{B_d} = (-2.8 \pm 2.8)^\circ \ ([{-8.5, 2.7}]^\circ @ 95\%) \]
Sources of error: CKM ~ M.E. ~ 5%

$C_{B_s} = 1.141 \pm 0.087$ ([0.97, 1.32] @ 95%)
\[ \phi_{B_s} = (0 \pm 1)^\circ \ ([{-2, 2}]^\circ @ 95\%) \]
sources of error: CKM ~ M.E. ~ 5%

Courtesy of Luca Silvestrini
New physics in $B_d$ and $B_s$ mixing

\[ C_{B_q} e^{2i\phi_{B_q}} = \frac{\langle B_q^0 | H_{\text{full}} | \bar{B}_q^0 \rangle}{\langle B_q^0 | H_{\text{eff}}^{\text{SM}} | B_q^0 \rangle}, \quad (q = d, s), \]

- $C_{B_d} = 1.08 \pm 0.15$ ([0.79,1.40] @ 95%)
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- $\phi_{B_s} = (0 \pm 1)^\circ$ ([−2,2]° @ 95%)
- Sources of error: CKM ~ M.E. ~ 5%

30-40% effects due to NP still allowed!
Rare kaon decays: $K \rightarrow \pi \nu \bar{\nu}$

Precise BR measurements of $K \rightarrow \pi \nu \bar{\nu}$ offer:
- unique constraints on CKM unitarity
- potential evidence for new physics

Within the next 2-3 years:
- **NA62** (CERN) will measure $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ to 10%
- **KOTO** (JPARC) will observe a few $K_L \rightarrow \pi^0 \nu \bar{\nu}$ events

Longer term: KOTO Step 2 with $\sim 100$ $K_L \rightarrow \pi^0 \nu \bar{\nu}$ event sensitivity?
Rare B decays: $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- $B \rightarrow K^* \mu\mu$ is described by 3 angles and di-muon invariant mass squared $q^2$

$$
\frac{1}{d(\Gamma + \Gamma)/dq^2} \frac{d^4(\Gamma + \Gamma)}{dq^2 d\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \\
+ \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_l \\
- F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi \\
+ \frac{3}{2} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi \\
- S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]
$$

Observables in green are functions of Wilson coefficients and form factors. They depend on $q^2$

$A_{FB}$ zero crossing point precisely predicted in SM: $q_0^2 = \left(4.36^{+0.33}_{-0.31}\right) GeV^2 / c^4$
Full angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- Angular analysis provides many observables that are sensitive to NP. Full set measured – only a subset is shown here.

- Exploit optimized observables to reduce FF uncertainties, e.g.

$$P_5' = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$$

- All results compatible with SM except $P_5'$, which shows local discrepancy at the 3σ level
B\rightarrow K^*\mu\mu: other recent results

- **LHCb**: 
  - S-wave fraction \textsuperscript{NEW!} 
  - B^0\rightarrow K\pi\mu\mu in the K*(1430) region \textsuperscript{LHC-B-PUB-2015-025}

- **Belle**: lower statistics but
  - Also B\rightarrow K^*ee
  - B^+ modes

- **CMS**: lower signal yields
  \rightarrow simpler analysis, but still interesting measurements of F_L and A_{FB}

\textsc{E. Bowen} \quad \textsc{M. Rozanska} \quad \textsc{T. Browder} \quad \textsc{G. W.S. Hou}
Interpretation(s)

LHCb and Belle have reported results using the form factor independent formalism. LHCb claim a discrepancy at the level of $3.4\sigma$ from the SM predictions referenced. Several groups are computing these errors; most stop at $6\text{ GeV}^2$. Several groups are using these results to perform global fits (see Thomas Mannel’s talk for more detail) to look for patterns in the anomalies.

Theory SM predictions

Ciuchini et al: effects due to long-distance charm loops could sizably affect the SM predictions

No definitive conclusion. More data and theoretical studies needed.
First observation of $B_s \to \mu \mu$ and first evidence for $B^0 \to \mu \mu$
Consistent with SM at $2\sigma$

**Motivations**

- Rare in SM: FCNC, hel.-suppressed
- Sensitive to scalar and pseudoscalar NP contributions
- Precise SM prediction [Buras et al., 2012, Bruyn et al., 2012]

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

\[
B(B^0 \to \mu^+ \mu^-) \overset{\text{SM}}{=} (1.07 \pm 0.10) \times 10^{-10}
\]

**ATLAS entering into the game!**

**ATLAS**

- $\sqrt{s} = 7$ TeV, 4.9 fb$^{-1}$
- $\sqrt{s} = 8$ TeV, 20 fb$^{-1}$

**Contours for $-2 \Delta \ln(L) = 2.3$, 6.2, 11.8 from maximum of $L$**

**arXiv:1604.04263**

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**Results consistent with**

- Combination of CMS & LHCb: Nature 522 (2015) 68

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**Mathieu Perrin Terrin CPPM**

**July 7th, 2016**

C. Bozzi - SUSY21
Lepton universality: $R_K$

Deficit of $K\mu\mu$ w.r.t. $Kee$, ratio $R_K$ below the SM at 2.6$\sigma$ level

$R_K = 0.64^{+0.39}_{-0.30} \pm 0.06$ \text{BABAR preliminary}

$R_K = 0.74^{+0.40}_{-0.31} \pm 0.06$ [BaBar PRD 86, 032012 (2012)]

$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$ [LHCb PRL 113, 151601 (2014)]

$(1 < q^2 < 6 \text{ GeV}^2)$
Lepton universality: semi-tauonic decays

- $B \rightarrow D(*)\tau\nu$ are tree level decays mediated by a $W$ in SM
- Lepton universality in SM, might be broken by mass-dependent couplings
- Probe SM extensions to models with enlarged Higgs sector, e.g. 2-Higgs Doublet Model (2HDM) of MSSM

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

- Renewed interest in this area, due to anomalous result of Babar

$R(D) = \frac{Br(B \rightarrow D\tau\nu)}{Br(B \rightarrow D\ell\nu)} = \begin{cases} 0.440 \pm 0.072 & \text{BaBar} \\ 0.297 \pm 0.017 & \text{SM} \end{cases}$

$R(D^*) = \frac{Br(B \rightarrow D^*\tau\nu)}{Br(B \rightarrow D^*\ell\nu)} = \begin{cases} 0.332 \pm 0.030 & \text{BaBar} \\ 0.252 \pm 0.003 & \text{SM} \end{cases}$


Test SM by measuring ratios (theoretically and experimentally cleaner)

→ Probe SM by measuring ratios (theoretically and experimentally cleaner)
Experimental considerations

- Due to the presence of at least two neutrinos in the final state, B Factories offer the most favorable experimental environment.

- BB events are fully reconstructed
  - One B decay is fully reconstructed (hadronic or semileptonic tag)
  - Look for signal decay of 2\textsuperscript{nd} B meson

- However, due to the high boost of b hadrons at LHCb, it is possible to perform kinematical reconstruction with sufficient resolution.

\[
(\gamma \beta_z)_B = (\gamma \beta_z)_{D^*\mu} \quad \Rightarrow \quad (p_z)_B = \frac{m_B}{m(D^*\mu)} (p_z)_{D^*\mu}
\]
B → D*τν at LHCb

- Using muonic τ decay
- Main backgrounds (other than normalization): partially reconstructed B decays
  - D*(*)μν, D*3πX, D*D(s)(*)X...
  - use isolation criteria (MVA) and/or τ flight length
- Study their shapes with data control samples
- 3D fit to \(m^2_{\text{miss}}, E_\mu\), in 4 bins of \(q^2\).
- Simultaneously fit 3 control regions defined by isolation criteria

**R(D*) = 0.336 ± 0.027 ± 0.030**

- In agreement with Babar and Belle
- 2.1σ higher than the SM

PRL115, 111803 (2015)
B → D*τν at Belle (SL tags)

- Two-dimensional fit to neural network classifier output NN, and $E_{ECL}$, residual energy in the electromagnetic calorimeter; $E_{ECL} \approx$ for signal, tends to be higher for background.
- Signal, $B \rightarrow D^*\tau\nu$ (normalization) and $B \rightarrow D^{**}\tau\nu$ yields are floated in the fit, other components are fixed to MC expectation.

$$R(D^*) = 0.302 \pm 0.030^{\text{stat}} \pm 0.011^{\text{syst}}$$

1.6σ larger than the SM prediction

arXiv:1603.06711
Tension with SM at 4σ

Exciting prospects!

More channels:
- $B_s \rightarrow D_s \tau \nu_\tau$
- $\Lambda_b \rightarrow \Lambda_c \tau \nu_\tau$
- “Vub”: $\Lambda_b \rightarrow p \tau \nu_\tau$?

More $\tau$ decay modes:
- $\tau \rightarrow \pi \pi \pi \nu_\tau$
- $\tau \rightarrow \pi \pi \pi^0 \nu_\tau$
- $\tau \rightarrow \pi \nu_\tau$
Conclusion

• Studies in the quark flavour sector constitute great probes to search for new physics effects induced by virtual particles in tree and loop diagrams

• New physics has not been discovered, however there are intriguing “tensions”
  – Angular analysis of $K^*\mu\mu$
  – Measurement of $R_K$
  – $B \rightarrow D^{(*)}\tau\nu$

• These should be followed up by collecting more data, analyzing other decay modes and performing more accurate theoretical studies

• B Factories and hadron colliders nicely complement each other
  – Experiments at the B Factories are still performing measurements on their final samples several years after the end of their data taking
  – LHCb is now the major driver in many channels – the Run3 upgrade, well under way, will extend the reach and improve the precision in key modes
  – ATLAS and CMS can give substantial contributions in very rare decays with muons
  – Belle-II will be entering into the game soon
  – NA62 and KOTO will shed light on rare kaon decays
Current anomalies

- Some would be unambiguous NP signals
- Except for theoretically cleanest modes, cross-checks needed to build robust case
  - Measurements of related observables
  - Independent theory / lattice calc.

- Each could be a whole talk — I can only make a few comments

Cleanliness of theo. prediction (arb. units)

Discrepancy between exp. and SM prediction ($\sigma$)

Ligeti
Current anomalies

- Some would be unambiguous NP signals
- Except for theoretically cleanest modes, cross-checks needed to build robust case
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**THE ARROW OF HOPE**

- Discrepancy between exp. and SM prediction ($\sigma$)
- Cleanliness of theo. prediction (arb. units)

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July 7th, 2016

C. Bozzi - SUSY2016 - Melbourne
Backup
Very different energies and rates

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beams</th>
<th>cm Energy</th>
<th>Int. Lum</th>
<th># Events</th>
<th># Events</th>
<th>S/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>BABAR/Belle</td>
<td>e+e-</td>
<td>10.58</td>
<td>424+711</td>
<td>1.2 $10^9$</td>
<td>$\sim10^9$</td>
<td>0.25</td>
</tr>
<tr>
<td>LHCb</td>
<td>pp</td>
<td>7000 (8000)</td>
<td>1.0 (2.0)</td>
<td>$2\times10^{12}$</td>
<td>$\sim10^{11}$</td>
<td>$\sim0.005$</td>
</tr>
</tbody>
</table>

**e^+e^-:**
- initial state with well defined energy-momentum and quantum numbers
- simple events: exclusive 2-body or low multiplicity production
- full event reconstruction: B_tag and B_signal: full PID, $\pi^0 \rightarrow \gamma\gamma$ detection
- missing mass $\rightarrow$ neutrino reconstruction!

**pp:**
- very high rates, all flavor mesons and baryons produced,
- high BG requires selective trigger, restricted acceptance
- long decay paths, precision charged particle tracking, PID
- complex events, normalization, relative rates! Many innovative techniques!
Penguin processes

Radiative

Electroweak

“Higgs”

\[ H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left[ C_i(\mu)O_i(\mu) + C_i'(\mu)O_i'(\mu) \right] \]

Left-handed part
Right-handed part
Suppressed in SM

\[ O_7 \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^\mu_{\nu} \]

\[ O_9 \sim \bar{s}_L \gamma_{\mu} b_L \bar{\ell} \gamma^\mu \ell \]

\[ O_{10} \sim \bar{s}_L \gamma_{\mu} b_L \bar{\ell} \gamma^\mu \gamma_5 \ell \]

\[ O_S \sim \bar{s}_L b_R \bar{\ell} \ell \]

\[ O_P \sim \bar{s}_L b_R \bar{\ell} \gamma_5 \ell \]

Typical BR (SM)

10^{-5} – 10^{-4}

Br, \gamma polarization

Angular distributions

Branching ratios

i=1,2 Tree
i=3-6,8 Gluon penguin
i=7 Photon penguin
i=9,10 EW penguin
i=S (P) (Pseudo)scalar penguin

July 7th, 2016
C. Bozzi - SUSY2016 - Melbourne
LHCb

Forward spectrometer optimised for heavy flavour physics at the LHC
• Large acceptance 2<η<5
• Low trigger thresholds
• Precise vertexing
• Efficient particle identification
• Running at a constant luminosity of 4x10^{32} cm^{-2}s^{-1}, <\mu>\sim1.7, 4x design

Recorded integrated luminosity:
1 fb\(^{-1}\) @ 7TeV (2011)
2 fb\(^{-1}\) @ 8TeV (2012)

- Large boost (B mesons flight ~1cm)
- Huge production cross section (~300\(\mu\)b)
- Small S/B ratio