Why ?

Interactions of the different flavours of the quark and lepton sector

Any physics model (SM or NP) has to deal with this

In SM this is through the Yukawa couplings to the Higgs field and the weak force

Misalignment of these gives structure of CKM matrix

\[ m_u = O(10^{-5}) \ m_t, \ |V_{ub}| = O(10^{-3}) \ |V_{tb}| \]

Any NP model with new flavoured particles or flavour breaking interactions must “hide” behind SM interactions

NP mass scale very large (>~100 TeV)

or

NP mimics Yukawa couplings (minimal flavour violation)

In all cases flavour physics will enlighten or constrain us
What?

Poke holes in the Standard Model
  Find inconsistencies that are not (yet) explainable within the SM

Understand the origin of mass
  Provide evidence for an extended Higgs sector

Provide a dark matter candidate
  A SUSY neutralino discovered through loop diagrams of $B$ decays
  A massive Majorana neutrino

Enlighten us on $CP$ violation in Universe
  Reveal that the $CP$ violation from the Yukawa coupling cannot explain observations
What?

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  - Find inconsistencies that are not (yet) explainable within SM
- Understand the origin of mass
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- Enlighten us on $CP$ violation in Universe
  - Reveal that the $CP$ violation from the Yukawa coupling cannot explain observations
How?

Think of properties of quarks that we are interested in

**Lifetime**

Both b- and c-hadrons have lifetime in ps region. With momentum in 100 GeV region this gives decay distance around 10 mm.

**Mass of bottom and top**

Mass of decaying quark sets transverse momentum scale

\[ p_T/p \] sets geometry of detector

Forward detector for c- and b-hadrons

4π for t decay
How?

QCD background

To see the effects of New Physics in heavy flavour decays we need to be able to calculate how the SM looks like

Uncertainties coming from QCD is the main problem here

Two ways out of this

Look for decays with leptons in
Look for CP violation

Trigger

Decays of interest range from

Precision CP violation in Charm $\rightarrow$ kHz signal
B decays with $10^{-10}$ branching fraction $\rightarrow$ 10 nHz signal
Where?

LHCb, ATLAS and CMS all have a heavy flavour programme

LHCb designed for bottom and charm physics

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<th>LHCb</th>
<th>ATLAS</th>
<th>CMS</th>
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Production

Production of $t$ and $\bar{t}$ can have different kinematic distributions

- $gg \rightarrow t\bar{t}$ symmetric but $q\bar{q} \rightarrow t\bar{t}(g)$, $qg \rightarrow t\bar{t}$ asymmetric from interference and underlying different structure functions of $q$ and $\bar{q}$

- In SM $t$ produced slightly closer to beam-axis than $\bar{t}$

Highly interesting to study due to unexpected results from $t\bar{t}$ forward-backward asymmetry at Tevatron

\[ \Delta |y| = |y(t)| - |y(\bar{t})| \]

\[ A_c = \frac{\#(\Delta |y| > 0) - \#(\Delta |y| < 0)}{\#(\Delta |y| > 0) + \#(\Delta |y| < 0)} \stackrel{\text{SM}}{=} (11.5 \pm 6) \times 10^{-3} \]
Production

CMS look in 5 fb$^{-1}$ for $t\bar{t} \rightarrow W^{+} b W^{-} \bar{b}$ with $b \rightarrow \text{hadrons}$, $W \rightarrow l^{\pm} \nu$

Selection very clean, total of 45k $t\bar{t}$ pairs
Production

Resulting asymmetry

\[ A_C = (4 \pm 10 \pm 11) \times 10^{-3} \text{ (CMS) } 5 \text{ fb}^{-1} \]
\[ A_C = (18 \pm 28 \pm 23) \times 10^{-3} \text{ (ATLAS) } 1 \text{ fb}^{-1} \]

Tests against NP models shows that models satisfying Tevatron result are not excluded by LHC results
Production

LHCb is not sensitive to the top asymmetry but can measure the same quantity for b hadrons

Double triggered b-hadron events used for 2 b-jets

Flavour tagged from semi-leptonic decays

\[ A_c = (5 \pm 5 \pm 5) \times 10^{-3} \]
\[ A_c = (43 \pm 17 \pm 24) \times 10^{-3} \]

\( m_{b\bar{b}} > 100 \text{GeV} \)

Potential to much improve this measurement
Rare decays

Look at decays which in the SM model can't happen at tree level

- Flavour changing neutral current decays the largest group
- Decays with dimuons are good candidates for rare searches

Rely on excellent muon identification
Rare decays

For B mesons the rare decay search started in 1984 at CLEO

Two-body decays of $B$ mesons

Various exclusive and inclusive decays of $B$ mesons have been studied using data taken with the CLEO detector at the Cornell Electron Storage Ring. The exclusive modes examined are mostly decays into two hadrons. The branching ratio for a $B$ meson to decay into a charmed meson and a charged pion is found to be about 2%. Upper limits are quoted for other final states $\psi K^-, \pi^+\pi^-$, $\rho^0\pi^-$, $\mu^+\mu^-$, $e^+e^-$, and $\mu^{\pm}\mu^{\mp}$. We also give an upper limit on inclusive $\psi$ production and improved charged multiplicity measurements.
Rare decays

For B mesons the rare decay search started in 1984 at CLEO

B. Search for exclusive $\bar{B}^0$ decays into two charged leptons

Our search for the $\pi^+\pi^-$ final state is not sensitive to the mass of the final-state particles, provided that they are light, since the mass enters only in the energy constraint. Therefore, the upper limit of 0.05% applies for any final-state particles with a pion mass or less. When the final-state particles are leptons the limits are improved by using the lepton identification capabilities of the CLEO detector. For the decay $\bar{B}^0 \rightarrow \mu^+\mu^-$, we improve our limit by requiring that both muons penetrate the iron and produce signals in drift chambers. We find no such events. After correcting for detection efficiency (33%), we set an upper limit of 0.02% at 90% confidence for this decay. We im-
The two very rare decays $B_s^0 → \mu^+ \mu^-$ and $B^0 → \mu^+ \mu^-$ have attracted much interest.

Easy to predict SM branching fraction with great precision:

$$BF(B_s^0 → \mu^+ \mu^-)_{SM} = 3.56 \pm 0.18 \times 10^{-9} \quad \text{(time averaged)}$$

$$BF(B^0 → \mu^+ \mu^-)_{SM} = 0.10 \pm 0.01 \times 10^{-9}$$

Sensitive to the scalar sector of flavour couplings.
$B \rightarrow \mu^+\mu^-$

Topology of decay simple

Challenge is to keep trigger and selection efficiency high, while rejecting combinatorial background
**B → µ⁺µ⁻**

Topology of decay simple

Challenge is to keep trigger and selection efficiency high, while rejecting combinatorial background
**B → µ^+µ^−**

Topology of decay simple

- Challenge is to keep trigger and selection efficiency high, while rejecting combinatorial background

Isolation of the dimuon vertex is very important

- For ATLAS and CMS the higher integrated luminosity compensates for lower trigger efficiency

LHCb has seen first evidence of B^0_s → µ^+µ^−

- BF = $3.2^{+1.5}_{-1.2} \times 10^{-9}$
- 3.5σ significant
**B → µ⁺µ⁻**

Challenge now is to look for $B^0 \rightarrow \mu^+ \mu^-$

In the SM suppressed by $|V_{ts}|^2 / |V_{td}|^2 \sim 25$

New physics not following this pattern may manifest itself as a higher $B^0 \rightarrow \mu^+ \mu^-$ rate

However lower rate and peaking backgrounds now a real issue

CMS have peaking background and signal at the same level

CMS : <1.8 $10^{-9}$ @95% CL
LHCb: <0.9 $10^{-9}$ @ 95%CL

**CMS B⁰ search window in red**
The penguin laboratory

The decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$, $K^{*0} \rightarrow K^\mp\pi^+$ is in the SM only possible at loop level

This means that SM and NP processes are put on equal footing.

Angular analysis of 4-body $K^-\pi^+\mu^+\mu^-$ final state brings large number of observables

Interference between these

$\mathcal{O}_{7\gamma}$  $\mathcal{O}_{9,10}$

... and their right-handed counterpart
**B^0 \rightarrow K^{*0}\mu^+\mu^-** angular analysis

LHCb, ATLAS and CMS all have access to the final state.

Only LHCb cover full dimuon mass range
**Constraints on new physics**

Measurements of $B \rightarrow \mu\mu$, $B \rightarrow K^*\mu\mu$, $B \rightarrow X_s \ell\ell$, $b \rightarrow s\gamma$ sets limits on the mass scale of non-SM contributions

Altmannshofer, Paradisi, Straub: JHEP 04 (2012) 008 + updates

\[ \mathcal{L} = \mathcal{L}_{SM} - \sum_{j=7,9,10} \frac{V_{tb} V_{ts}^*}{16\pi^2} \frac{e^{i\phi_j}}{\Lambda_j^2} \mathcal{O}_j \]

\sim \text{loop level CKM-like flavour violation}

Nothing with SM type flavour couplings below $O(400 \text{ GeV})$
Constraints on new physics

If on the other hand considering tree level processes with $O(1)$ couplings

Limits on this are in excess of 15 TeV

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{j=7,9,10} \frac{e^{i\phi_j}}{\Lambda_{j}^2} \theta_j$$

~tree level generic flavour violation
$B \rightarrow K^{(*)} \mu^+ \mu^-$ isospin analysis

Can look at the isospin asymmetry in rare decays

$$A_I = \frac{\Gamma(B^0 \rightarrow K^{(*)0} \mu^+ \mu^-) - \Gamma(B^+ \rightarrow K^{(*)+} \mu^+ \mu^-)}{\Gamma(B^0 \rightarrow K^{(*)0} \mu^+ \mu^-) + \Gamma(B^+ \rightarrow K^{(*)+} \mu^+ \mu^-)}$$

In full 2011 data, measure individual differential branching fractions
$B \to K^{(*)} \mu^+ \mu^-$ isospin analysis

Then form ratios

Result for $B \to K^* \mu^+ \mu^-$ in agreement with SM theory
But $B \to K \mu^+ \mu^-$ differs from zero expectation of above 4σ
No theory explanation of this yet, neither in or outside SM
CP violation

Challenges

Production asymmetries
  Asymmetric pp system

Detector asymmetries
  LHCb can flip magnetic field but not matter to antimatter!

Sub-dominant penguin diagrams
  Need interference to measure CP violation but not of too many diagrams ...

Trigger
  Many hadronic final states that very hard to trigger on

Calibration of particle identification
  Required to understand peaking backgrounds and performance of flavour tagging
The $B_s^0$ system

The $B_s^0$ can oscillate into its antiparticle

The weak eigenstates are no longer $B_s^0$ and $\bar{B}_s^0$

Two eigenstates with different mass and width

\[ B_s^0 \rightarrow D_s^- \pi^+ \]
The $B^0_s$ system

A demonstration of QM amplitude interference

Double slit experiment
- Different path length
- Same energy
- Gives direct measurement of electron wavelength

$B^0_s$ oscillation
- Different energies (mass)
- Same path length
- Gives measurement of mass difference

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006 \text{ ps}^{-1}$
The $B_s^0$ system

The $\varphi_s$ fit

Look for shared final state between $B_s^0$ and $\bar{B}_s^0$

$B_s^0 \rightarrow J/\psi \varphi$, $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

Weak phase in box diagram will show up as CP violation

In SM the expected CP violation asymmetry has magnitude

$$\varphi_s^{SM} = 2 \arg(-V_{ts} V_{tb}^*/V_{cs} V_{cb}^*) = 0.036 \pm 0.02$$

Plenty of space for NP to manifest itself
The $B^0_s$ system

Perform a simultaneous fit to lifetime, production flavour and three decay angles

**Lifetime projection**
CP-even and CP-odd components visible
The $B^0_s$ system

Perform a simultaneous fit to lifetime, production flavour and three decay angles

CP violation

Separated in one of the angular components
The $B^0_s$ system

Combined result with $B^0_s \to J/\psi \phi$, $B^0_s \to J/\psi \pi^+ \pi^-$

$$\phi_s = 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst)} \text{ rad},$$

$$\Gamma_s = 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst)} \text{ ps}^{-1},$$

$$\Delta \Gamma_s = 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst)} \text{ ps}^{-1}.$$
The $B^0_s$ system

Until recently there was a two-fold ambiguity in the measurement of the CP-violating phase.

How did the other (non-SM) option go away?

Actually what was a pain turns into a blessing.
The $B^0_s$ system

The final state $B^0_s \rightarrow J/\psi K^+K^-$ is not all through the narrow $\phi \rightarrow K^+K^-$ P-wave

Some broad S-wave at the 5% level

As moving across $\phi$ mass we see phase shift of Breit-Wigner

Get the sign of phase shift wrong if picking wrong ($\phi, \Delta \Gamma$) solution
The $B^0_s$ system

The unique solution can now be identified

Previous LHCb result
**CP angle $\gamma$**

The global fits to CKM parameters give a very precise prediction of CP angle $\gamma$ within SM

Precision in making the matching direct measurements only now emerging
**CP angle $\gamma$**

The global fits to CKM parameters give a very precise prediction of CP angle $\gamma$ within SM

Only now are precise direct measurement possible

- $B^-$ can decay into both $D^0$ and $\overline{D^0}$, diagrams very different amplitudes
  
  \[
  \begin{align*}
  B^- & \to s \bar{u} c \bar{u} & \to u \bar{s} c \bar{u} & K^- & \text{colour favoured} \\
  B^- & \to b \bar{u} d \bar{u} & \to b \bar{u} c \bar{u} & \overline{D^0} & \text{colour suppressed}
  \end{align*}
  \]

- Decays of $D^0$, $\overline{D^0}$ to same final state gives access to interference
  
  \[
  \begin{align*}
  D^0 & \to s \bar{u} c \bar{u} & \to u \bar{s} d \bar{u} & K^+ & \text{(doubly) cabibbo suppressed} \\
  \overline{D^0} & \to \bar{c} \bar{u} u \bar{u} & \to d \bar{u} u \bar{u} & \pi^- & \text{cabibbo favoured}
  \end{align*}
  \]
CP angle $\gamma$

The trigger of these decays is a challenge

Partial reconstruction of secondary B vertex is the only thing that works

A multivariate selection based on a BDT developed

Resolution pruned to avoid threshold effects

Selects the events that can subsequently be used offline

![Graph showing cumulative fraction vs. BBDT Response with data, minbias MC, charm MC, and bottom MC categories]
CP angle $\gamma$

Illustrate method with $B^\pm \rightarrow D K^\pm$, $D \rightarrow K_s^0 \pi^+ \pi^-$ decays

Dividing Dalitz plot in symmetric regions and comparing 4 rates for those gives strong phase and $\gamma$
CP angle $\gamma$

Illustrate method with $B^{\pm} \rightarrow DK^{\pm}$, $D \rightarrow K_{s}^{0} \pi^{+} \pi^{-}$ decays

Dividing Dalitz plot in symmetric regions and comparing 4 rates for those gives strong phase and $\gamma$
CP angle $\gamma$

Combined result from all different $B \to DK$ and $B \to D\pi$ modes
Search for FCNC in top quark decays

With massless quarks, FCNC decays are forbidden in the SM (GIM mechanism)

Comparing to the top mass, all other quarks are massless
Hence FCNC for top ($t \rightarrow c \, X$, $t \rightarrow u \, X$) are suppressed by factor $10^{-14}$ in SM

Search for $t \bar{t} \rightarrow (Z^0 \, u/c) (W^- \, b)$, $Z^0 \rightarrow l^+ l^-$, $W^- \rightarrow l^- \nu$

Three leptons in final state results in almost 100% trigger efficiency
Search for FCNC in top quark decays

Result is

\[ \text{BF}(t \to Z^0 u/c) < 0.73\% \text{ @ 95\% CL [ATLAS 2.1 fb}^{-1}] \]
\[ \text{BF}(t \to Z^0 u/c) < 0.07\% \text{ @ 95\% CL [CMS 19.5 fb}^{-1}] \text{ (prelim)} \]
Where to go now for LHCb?

Aim of upgrade during LS2 of LHC

- Improve annual yields by factor 10 (leptonic) to 20 (hadronic)

As elsewhere at LHC, the real limitation for progress is in the trigger

- The hardware trigger of LHCb at 1.1 MHz starves hadronic final states at luminosities above $\sim 3 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- Solution is to get rid of it and run a High Level Trigger at 40 MHz

Hardware upgrades

- Move pixel detector closer to beam to improve light quark rejection
- Keep occupancy low in RICH system and tracking
Conclusion

Flavour physics has sensitivity to mass scales that are well above the direct production scale accessible

- Many areas where measurements are far away from systematics limits imposed by experiments or theory
- Challenge is in many cases to obtain even larger event samples

Overall the SM comes out as matching the data very well

- Isospin result in $B \rightarrow K \mu \mu$ the most challenging thing to explain at the moment (in or outside SM)

Very fruitful relationship between phenomenologists and experimentalists to improve measurements and develop new channels