Flavour Physics

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Useful resources & acknowledgments

- Heavy Flavour Averaging Group (HFLAV)  https://hflav.web.cern.ch

- CKMfitter  ckmfitter.in2p3.fr  Utfit  www.utfit.org/UTfit/

- Particle Data Group reviews  pdg.lbl.gov

- Books:
  - CP violation, I.I. Bigi and A.I. Sanda (CUP, 2000)
  - CP violation, G.C. Branco, L. Lavoura & J.P.Silva (OUP, 1999)

- Reviews & lectures:
  - M. Blanke, arXiv:1704.03753

Thanks to flavour lecturers at this school in previous years, who provided inspiration for some of the material shown (esp. T. Gerson, J. Zupan & M-H. Schune).
What is flavour physics and why should we care?
What is flavour physics?

The concept of ‘flavour’ in particle physics relates to the existence of different families of quarks*, and how they couple to each other

i.e. 6 known flavours of quark, grouped into 3 generations

Open questions:
• why 3 generations ?
• why do the quarks exhibit this striking hierarchy in mass ?

These mysteries make the ‘flavour sector’ of the Standard Model of great interest.

* the concept of flavour extends to the lepton sector too

Not to linear scale !

mass in MeV/c²

Flavour physics
Guy Wilkinson

September 2019
In the Standard Model quarks can only change flavour through emission of a W boson (i.e. weak force). For example a t quark can decay into a b, s or d quark:

But these decays are not equally likely. At the amplitude level they are weighted by factors that are elements of the Cabibbo-Kobyashi-Maskawa (CKM) matrix, and these factors vary dramatically – here is another hierarchy we don’t understand!

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} =
\begin{pmatrix}
0.9705 - 0.9770 & 0.21 - 0.24 & 0 - 0.014 \\
0.21 - 0.24 & 0.971 - 0.973 & 0.036 - 0.070 \\
0 - 0.014 & 0.036 - 0.070 & 0.997 - 0.999
\end{pmatrix}
\]

These elements of the CKM matrix are also fundamental parameters of the Standard Model. Why they have these values is another great mystery.
Parameters of the Standard Model

• 3 gauge couplings
• 2 Higgs parameters
• strong CP parameter $\theta$
• 6 quark masses
• 3 quark mixing angles + 1 phase \([i.e. \text{CKM matrix}]\)
• 3 (+3) lepton masses
• (3 lepton mixing angles + 1 phase \([i.e. \text{PMNS matrix}]\))

() = with Dirac neutrino masses
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() = with Dirac neutrino masses

These are all flavour parameters!
Parameters of the Standard Model

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\[ () = \text{with Dirac neutrino masses} \]
CP violation

CP violation (CPV) → difference in behaviour between matter and anti-matter.

First discovered in the kaon system in 1964, opportunities of study were limited until colliders arrived that could make lots & lots of b-quark hadrons, e.g. the LHC

A recent example from LHCb - look at B meson decaying into a pion & two kaons…

…the decay probabilities are manifestly different for $B^-$ & $B^+$! In the Standard Model CPV is accommodated, *but not explained*, by an imaginary phase in the CKM matrix
Cosmological connections?

As first pointed out by Andrei Sakharov, CP-violation is one requirement for explaining baryogenesis – the process that took us from the equal amounts of matter and anti-matter produced in the Big Bang, to the matter dominated universe of today.

The problem is that the CP-violation that appears in the Standard Model, is woefully inadequate to explain the matter-antimatter asymmetry we have today.

This is a big problem with the Standard Model!

More & better measurements may point a way forward.
Problems with the Standard Model

The Standard Model (SM) cannot be a final theory

We have already encountered the following shortcomings:

- No explanation for baryogenesis
- No explanation for the quark or CKM hierarchy
- No real explanation for CP violation, and why it is only found in the weak interaction.

And there are plenty of others, for example:

- No explanation for dark matter or dark energy
- No explanation for neutrino masses
- Gravity not included
- No explanation for why the Higgs boson has the mass it does (left to itself the theory would make it much, much heavier)

More ambitious theories (e.g. supersymmetry or SUSY) can solve at least some of these problems. They generally predict new particles or effects outside the SM. Finding these effects is the goal of the LHC & many other present/planned facilities!
Breaching the walls of the Standard Model

The HEP community is searching for ‘New Physics’ - to find this we need to penetrate the walls of the Standard Model fortress. There are two strategies used in this search.

Direct

Use the high energy of, *e.g.* the LHC to produce the New Physics particles, which we then detect.

Indirect

Make precise measurements of processes in which New Physics particles enter through ‘virtual loops’.

Both methods are powerful. Flavour physics follows the ‘indirect’ approach.
Indirect measurements – an established tradition in science

Eratosthenes was able to determine the circumference of the earth using indirect means…
Indirect measurements – an established tradition in science

Eratosthenes was able to determine the circumference of the earth using indirect means…

…around 2.2 thousand years prior to the direct observation.
Indirect measurements – an established tradition in science

In flavour physics the guiding principle is to probe processes where loop diagrams are important, as here non-SM particles may contribute (but as we will see, tree-mediated decays also have their role to play)

Indirect search principle

Precise measurements of low energy phenomena tells us about unknown physics at energies far beyond direct searches (~$10^4$ TeV in some cases)
Indirect measurements – an established tradition in science

In flavour physics the guiding principle is to probe processes where loop diagrams are important, as here non-SM particles may contribute (but as we will see, tree-mediated decays also have their role to play).

Indirect search principle

Precise measurements of low energy phenomena tells us about unknown physics at energies far beyond direct searches (~10^4 TeV in some cases).
Indirect measurements –
an established tradition in science

Indirect search principle

→ Precise measurements of low energy phenomena tells us about unknown physics at energies far beyond direct searches (~10^4 TeV in some cases)

For this reason it's rather surprising that (spoiler alert!) most flavour measurements so far agree with the SM, as naturalness told us New Physics is expected at TeV scale → the New Physics Flavour Puzzle.

Either, there is something specific about the flavour-structure of the New Physics that is masking the effect…

…or we have put too much trust in naturalness.

Either way, flavour is central to the story!
Outline of the lecture contents and schedule
Flavour topics that we won’t be covering

Flavour encompasses a huge range of areas of study & corresponding experimental activity. The following are genuine topics of flavour, but ones we will not cover.

- Kaon physics  (OK, we will say a little, but not really do it justice)
- Suppressed top decays
- Flavour and CPV violation in the Higgs sector
- Charged lepton-flavour violation, e.g. $\mu \rightarrow e\gamma$
- (g-2) muon anomaly
- All neutrino physics

Instead we will focus on beauty physics, with some discussion on charm.
Lecture outline

• Introduction ✓
• Birth of flavour physics & the kaon sector
• The beautiful millennium
• Flavour structure of the SM
• The Unitarity Triangle and CPV measurements
• Spectroscopy (a brief digression)
• FCNCs or ‘rare decays’
• Charm physics
• Future of flavour

Note the approach will (necessarily) be from an experimentalist’s perspective.
The birth of experimental flavour physics and the (continuing) importance of kaon studies
Events of 1964

Cassius Clay becomes heavyweight champion of the world

Martin Luther King Jnr. wins Nobel Peace Prize

Nelson Mandela sentenced to life imprisonment

Change of face in the Kremlin
EVIDENCE FOR THE $2\pi$ DECAY OF THE $K^0_2$ MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the $2\pi$ decay of the $K^0_2$ meson. Several previous experiments have served to set an upper limit of $1/300$ for the fraction of $K^0_2$'s which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, $K^0_2$ mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a $1\frac{1}{2}$-in. $\times$ 1 $\frac{1}{2}$-in. × 48-in. collimator at an average distance of 14.5 ft. from the internal target. This collimator was followed by a sweeping and a 6-in. $\times$ 6-in. $\times$ 1 $\frac{1}{2}$-in. thick aluminum first collimator, and a 1 $\frac{1}{2}$-in. thick second collimator, and a 1 $\frac{1}{2}$-in. thick second collimator. The experimental layout is shown in relation to the beam in Fig. 1. The detector for the decay

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, $m^*$, assuming each charged particle had the mass of the charged pion. In this detector the $K_{e3}$ decay leads to a distribution in $m^*$ ranging from 280 MeV to $\sim$536 MeV; the $K_{\mu3}$, from 280 to $\sim$516; and the $K_{\pi3}$, from 280 to 363 MeV. We emphasize that $m^*$ equal to the $K^0$ mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, $\theta$, between it and the direction of the $K^0_2$ beam were determined. This angle should be zero for two-body decay and is, three-body

Discovery of CP violation (in kaon decays)
Nobel Prize for physics in 1980
Nobel Prize for physics in 1980

27/11/14
YSDA seminar
Discovery of CP violation

Observation of $45 \pm 10 \pi^+\pi^-$ decays in a $K^0_L$ beam \cite{Christenson:1964fg}.

Interpretation: $K^0_L$ not a pure CP-odd eigenstate. Level of CP-even ‘contamination’ given by $\varepsilon$, which is now measured to be $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$ \cite{PDG}.
The heroic quest for $\varepsilon'$

In the CKM paradigm $K^0_L \rightarrow \pi\pi$ is readily explained as *indirect* CPV. CKM also allows for the possibility of *direct* CPV, which can be revealed by measuring the relative rates of $K^0_S$ and $K^0_L$ into $\pi^+\pi^-$ and $\pi^0\pi^0$, which give the parameter $\text{Re}(\varepsilon'/\varepsilon)$.

A non-zero $\text{Re}(\varepsilon'/\varepsilon)$ implies direct CPV, & is consistent with CKM picture. Historically, other models (*e.g.* superweak [Wolfenstein, PRL 13 (1964) 562]) predicted zero direct CPV. Effect is very small, experiment is hard, and first measurements were ambiguous.
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Effect is very small, experiment is hard, and first measurements were ambiguous. A second round of experiments (NA48, KTeV) was required to show $\text{Re}(\varepsilon'/\varepsilon) \neq 0$.

Lattice QCD prediction not as precise as experiment, but progress being made. Heroic work! Kaon physics is very difficult - small effects & theoretically challenging.
In search of the ultra-rare

CP violation is not the whole story. Kaons system is also well suited for searches for forbidden or ultra-suppressed decays, the most topical of which is $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. In SM $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11}$ [Buras et al., JHEP 1511 (2015) 033], but New Physics enhancements possible with sensitivity to mass scales under 100 TeV.

BNL experiments E949 & E787 saw 3 events [PRD 77 (2008) 052003], consistent with SM. NA62, here at CERN, aims to observe $\sim 100$ and make precise measurement of BR.

Pilot measurement released [PLB 791 (2019) 156], based on a few weeks of data taking.
In search of the ultra-rare

CP violation is not the whole story. Kaons system is also well suited for searches for forbidden or ultra-suppressed decays, the most topical of which is $K^+ \rightarrow \pi^+ \nu \bar{\nu}$.

Kaon studies have played a critical role in the development of flavour physics. They will continue to do so in future.

However, in the past 2-3 decades the focus has been on beauty:

- A huge number of decays and processes to explore
- Sizable CPV effects expected (& observed)
- In many cases theoretically clean predictions are available

Pilot measurement released [PLB 791 (2019) 156], based on a few weeks of data taking.
We live in a golden age of flavour!

An introduction to the experiments of B physics
We can date the start of modern flavour physics to the 2001 measurements of the CP-violating asymmetry in $B^0 \to J/\psi K^0$ decays that give unitarity triangle angle $\beta$.

These studies, when improved with larger samples, confirmed the CKM paradigm as the dominant mechanism of CP violation in nature (→ 2008 Nobel Prize), and also opened up a rich and wide spectrum of complementary measurements.
2001 – opening of the age of flavour

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No other area of particle physics has delivered such a rich and extensive set of results during this period!
Why have we made progress?

Very important flavour-physics measurements were performed prior to 2001 (e.g. at ARGUS, CLEO, the SPS and LEP), but since then there has been an avalanche of results. What has enabled this explosion of progress?

- High-luminosity accelerators with large $b\bar{b}$ production cross-sections;
  - Number of $b$-hadrons produced at LEP $\sim 10^7$
  - Number of $b$-hadrons produced (so far) at LHCb $\sim 10^{12}$
- Improved and dedicated instrumentation, e.g. vertex detectors and RICHes;
- Improved triggering, essential for hadron collider experiments;
- And not forgetting progress in theory, in particular lattice QCD.

![Impact of silicon on $b$-lifetime measurement](chart)

![Cherenkov angle vs momentum in LHCb RICH](diagram)
Heroes of the age of flavour

b-factories

BaBar (SLAC) & Belle (KEK)
Operated in the 2000’s e⁺e⁻ machines with asymmetric beams for time-dep studies, mainly at Y(4S), hence B⁰ and B⁺ samples. Considered ‘clean’ environments.

Tevatron experiments

CDF & D0

LHC high-p_T experiments

ATLAS & CMS
Their excellent instrumentation gives them great capabilities in certain b-physics topics, especially those with dilepton final states.

Important contributions also from BESIII, an e⁺e⁻ experiment in Beijing. Operates below the Y(4S), but provides critical measurements of open charm & spectroscopy (at did CLEO-c).
Heroes of the age of flavour - LHCb

Designed to be a *dedicated* experiment for b- and c-physics at the LHC.
Heroes of the age of flavour - LHCb

Designed to be a dedicated experiment for b- and c-physics at the LHC.

Dedicated in the sense of the following attributes:

- **Acceptance**
  
  Spectrometer geometry is optimised to capture forward-peaked bbbar production.
Heroes of the age of flavour - LHCb

Designed to be a dedicated experiment for b- and c-physics at the LHC.

Dedicated in the sense of the following attributes:

- **Acceptance**
- **Instrumentation**

Vertex locator (VELO) and RICH system give unique capabilities for b-physics.

One-half of the VELO under construction

A b-hadron decay vertex

Array of RICH photodetectors

Momentum [GeV/c]
Heroes of the age of flavour - LHCb

Designed to be a dedicated experiment for b- and c-physics at the LHC.

Dedicated in the sense of the following attributes:

- Acceptance
- Instrumentation
- Trigger

Trigger fully optimised for b-physics. Allows lower \( p_T \) thresholds than at ATLAS and CMS and ability to select hadronic final states.
Heroes of the age of flavour - LHCb

Designed to be a dedicated experiment for b- and c-physics at the LHC.

Dedicated in the sense of the following attributes:

- Acceptance
- Instrumentation
- Trigger
- Operating luminosity

In run 1 & 2 luminosity deliberately set to be lower than at ATLAS & CMS, in order to provide best environment for b-physics measurements.

Total data sample from run 1 & run 2 around 9 fb\(^{-1}\).
Heroes of the age of flavour - LHCb

Designed to be a *dedicated* experiment for b- and c-physics at the LHC.

Dedicated in the sense of the following attributes:

- Acceptance
- Instrumentation
- Trigger
- Operating luminosity

(But these attributes allow for important & unique studies beyond flavour, *e.g.* spectroscopy, electroweak, fixed-target proton-gas collisions…).

LHCb data-taking is now complete, and an upgraded detector is being installed.
Flavour structure of the Standard Model
Neutral currents are flavour conserving at tree level

- Photon, gluon, Z have flavour (generation) – universal interactions
- Higgs has flavour-diagonal interactions proportional to quark mass

Whereas only the charged-current $W$ couplings are flavour changing, with a very non-trivial structure $\rightarrow V_{\text{CKM}}$
The CKM matrix appears in the SM Lagrangian as a consequence of diagonalising the mass matrices. Therefore connected to quark masses (& Higgs mechanism).

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

It must be unitarity, \( V_{\text{CKM}}^\dagger V_{\text{CKM}} = V_{\text{CKM}} V_{\text{CKM}}^\dagger = 1 \), and can be parameterised with three angles and one imaginary phase, which is the origin of SM CPV.

This tight system of four parameters means that CKM physics is highly predictive!

One representation [Chau & Keung, PRL 53 (1984) 1802]:

\[
V_{\text{CKM}} = \begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\]

Measurements indicate a striking hierarchy: \( s_{12}\sim 0.2, s_{23}\sim 0.04, s_{12}\sim 0.004 \).
A fit to data, imposing unitarity constraint [PDG review], and showing magnitudes:

\[
V_{\text{CKM}} = \begin{pmatrix}
0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\
0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\
0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032
\end{pmatrix}
\]

or represented graphically:

This is presumably telling us something, but what? (very different picture to one seen in neutrino sector)

Hierarchy motivates an alternative representation based on expansion in \( \lambda = \sin \theta_c \).
CKM matrix expressed in Wolfenstein parametrisation

In the Wolfenstein parameterisation the matrix is expanded in orders of $\lambda \sim 0.23$.

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

This is expanded to $\lambda^3$, which will be adequate for most of our subsequent discussion, but not all…

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

[Wolfenstein, PRL 51 (1983) 1945]
CKM matrix expressed in Wolfenstein parametrisation

In the Wolfenstein parameterisation the matrix is expanded in orders of $\lambda \sim 0.23$.

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

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$$V_{\text{CKM}} = \begin{pmatrix} 1 - \frac{1}{2} \lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2} \lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Note that at order $\lambda^3$ only two elements are complex: $V_{ub}$ and $V_{td}$. Thus transitions involving these vertices will be of great interest in CPV studies (but please don’t forget that it is only phase differences between transitions that are physical).
Back to FCNCs – although forbidden at tree level, they still occur, albeit suppressed

FCNCs do occur, but through higher-order diagrams

<table>
<thead>
<tr>
<th>Charged currents</th>
<th>Neutral currents</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}(K^+ \to \mu^+\nu) = 64%$</td>
<td>$\text{BR}(K_L \to \mu^+\mu^-) = 7 \times 10^{-9}$</td>
</tr>
<tr>
<td>$\text{BR}(D^+ \to K^0\mu^+\nu) = 9%$</td>
<td>$\text{BR}(D^0 \to \pi^0\mu^+\mu^-) &lt; 1.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\text{BR}(B^- \to D^0\bar{\nu}) = 2.3%$</td>
<td>$\text{BR}(B^- \to K^{*-}\ell^+\ell^-) = 5 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

The decay rates of FCNCs tend to be highly suppressed w.r.t. tree-level processes.
Suppression of FCNCs is explained by the GIM mechanism:

- Cancellation of diagrams relies on unitarity of $V_{\text{CKM}}$
- Suppression set by the mass-squared difference of the virtual quarks, & would be perfect in the degenerate limit
- GIM, and the smallness of $\text{BR}(K^0_L \rightarrow \mu^+\mu^-)$ led to the prediction of the charm quark

The Unitarity Triangle and CPV measurements
The CKM matrix must be unitarity: \[ V_{\text{CKM}}^\dagger V_{\text{CKM}} = V_{\text{CKM}} V_{\text{CKM}}^\dagger = 1 \]

This imposes various constraints, including \[ \sum_k V_{ik} V_{jk}^* = 0 \text{ where } i \neq j . \]

There are 6 such independent relations, which can be represented as unitarity triangles in the complex plane. Experimentally, the most interesting is:

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

As the sides are of similar length, & its parameters can be studied in $B^0$, $B^+$ decays. Another, relevant for $B^0_s$ physics is:

\[ V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0 \]

Note that the area of all triangles is the same = $\frac{1}{2} J$, the Jarlskog invariant.

\[ J = c_{12} c_{13}^2 c_{23} s_{12} s_{13} s_{23} \sin \delta \approx 3 \times 10^{-5} \]

[Jarlskog, PRL 55 (1985) 1039]
‘The’ Unitarity Triangle

Three complex vectors sum to zero

→ triangle in Argand plane

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

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

Expressions for angles:

\[ \alpha = \arg \left[ -\frac{V_{td}V_{tb}^*}{V_{ub}V_{cb}^*} \right] \]

\[ \beta = \arg \left[ -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right] \]

\[ \gamma = \arg \left[ -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right] \]

Upper vertex:

\[ \bar{\rho} + i\bar{\eta} = -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*) \]

\[ \bar{\rho} = \rho(1 - \lambda^2/2 + \cdots) \quad \bar{\eta} = \eta(1 - \lambda^2/2 + \cdots) \]

(\(\varphi_2, \varphi_1 \& \varphi_3\) alternative notation)
‘The’ Unitarity Triangle

Three complex vectors sum to zero

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

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

\[ (\rho, \eta) \]

Goal of Unitarity Triangle tests

Over-constrain triangle by making measurements of all parameters, in particular, comparing those made in tree-level processes (pure SM) and those made with loops (New Physics sensitive).

We hope to find inconsistencies!

Upper vertex:

\[ \bar{\rho} + i\bar{\eta} = -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*) \]

\[ \bar{\rho} = \rho(1 - \lambda^2/2 + \cdots) \quad \bar{\eta} = \eta(1 - \lambda^2/2 + \cdots) \]

(\(\varphi_2\), \(\varphi_1\) & \(\varphi_3\) alternative notation)
The $B^0_s$ Unitarity Triangle

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

The $B^0_s$ triangle is very squashed, & contains a small angle $\beta_s$ ($= -\phi_s/2$ – see later).
The Unitarity Triangle – how do we know what we know?
The Unitarity Triangle – how do we know what we know?

Length of side opposite $\gamma$ is given by ratio of $B^0$ & $B^0_s$ mixing freq.s & lattice QCD.
**Digression on neutral-meson mixing**

Mixing is critical for much of what follows, so warrants a recap of essentials. Phenomenon occurs for $K^0$, $D^0$, $B^0$ and $B^0_s$ systems. Physically caused by either

- Virtual, Short-range (box diagrams)
- and/or On-shell, long-range (common intermediate states)

Physical states are superposition of flavour eigenstates:

$$B^0_{S,L} = pB^0 \pm q\bar{B}^0$$

$p$ & $q$ are complex and $|p|^2 + |q|^2 = 1$

If CP is conserved the physical states = CP eigenstates, which means $\left|\frac{q}{p}\right| = 1$.

Known not to be the case in the $K^0$ system, where $\varepsilon = \frac{p-q}{q-p} \approx 2 \times 10^{-3}$, and the SM calculations indicate small, but finite, breaking in other systems too.

Mass and width splittings between physical states:

$$\Delta m = m_L - m_S \quad \text{set by short-range effects}$$

$$\Delta \Gamma = \Gamma_S - \Gamma_L \quad \text{set by long-range effects}$$
Digression on neutral-meson mixing

There is a wide range in the sizes of the mixing parameters across the four systems, which has significant practical consequences for measurements.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta m / \Gamma$</th>
<th>$\Delta \Gamma / 2\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0$</td>
<td>Large ~500</td>
<td>Maximal ~1</td>
</tr>
<tr>
<td>$D^0$</td>
<td>Small 0.39 ± 0.11 %</td>
<td>Small 0.65 ± 0.06%</td>
</tr>
<tr>
<td>$B^0$</td>
<td>Medium 0.769 ± 0.004</td>
<td>Small (20 ± 5) $\times 10^{-4}$</td>
</tr>
<tr>
<td>$B^0_s$</td>
<td>Large 26.81 ± 0.08</td>
<td>Medium 0.0675 ± 0.004</td>
</tr>
</tbody>
</table>

Aside: the New Physics flavour puzzle

Remark – mixing parameters are what they are because of SM (CKM, GIM & quark masses) and could easily be perturbed by New Physics, so bounds can be set.

Add to SM Lagrangian higher order terms that would contribute to neutral meson mixing and CPV

\[ \Delta L_{\text{NP}} = \sum_{i \neq j}^{c_{ij}^{\text{NP}}} \left( \frac{\Lambda_{\text{NP}}^2}{Q_L i \gamma^\mu Q_{Lj}} \right)^2, \]

where \( c_{ij}^{\text{NP}} \) is the coupling, and \( \Lambda_{\text{NP}} \) the mass scale of the New Physics.

If we assuming the coupling is \( \sim 1 \), (i.e. generic) obtain the following \( \rightarrow \) bounds on \( \Lambda_{\text{NP}} \) [Nir, arXiv:1605.00433].

<table>
<thead>
<tr>
<th>System</th>
<th>CP-conserving observables</th>
<th>CP-violating Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K^0 )</td>
<td>( 1 \times 10^3 ) TeV</td>
<td>( 2 \times 10^4 ) TeV</td>
</tr>
<tr>
<td>( D^0 )</td>
<td>( 1 \times 10^3 ) TeV</td>
<td>( 3 \times 10^3 ) TeV</td>
</tr>
<tr>
<td>( B^0 )</td>
<td>( 4 \times 10^2 ) TeV</td>
<td>( 8 \times 10^2 ) TeV</td>
</tr>
<tr>
<td>( B^0_s )</td>
<td>( 7 \times 10^1 ) TeV</td>
<td>( 2 \times 10^2 ) TeV</td>
</tr>
</tbody>
</table>

These are enormous! And naturalness told us to expect New Physics at the TeV scale. Something is wrong…

Get out clause: couplings are not \( \sim 1 \). One possibility, structure is more specific e.g. same as in the SM (‘minimal flavour violation’ [Ambrosio et al., NPB 645 (2002) 155] ).
Digression on neutral-meson mixing

Mixing leads to an oscillation of probability to observe meson in either flavour eigenstate with proper time, e.g. if at $t=0$ we have a $B^0$, then at later time $t$:

$$\text{Prob. to decay as } \frac{B^0}{\overline{B}^0} \propto e^{-\Gamma_d t} (1 \mp \cos \Delta m_d t)$$

Time-integrated $B$-oscillations were first observed by UA1 [PLB 186 (1987) 247] & ARGUS [PLB 192 (1987) 245]. $B^0$ ($B^0_s$) oscillations first resolved by ALEPH (CDF).
In $B^0_s$ systems, mixing driven by $\Delta m_{d(s)}$ and is calculable in SM.

Depends on CKM elements in box & factors that can be calculated in lattice QCD.

For $B^0_s$ case $\rightarrow$

$$\Delta m_s = \frac{G_F^2}{6 \pi^2} m_{B_s} m_w^2 \eta_B S_0(x_t) f_{B_s}^2 B_s \left| V_{ts} V_{tb}^* \right|^2$$

Equivalent expression for $B^0$ mixing, involving $V_{td}$. Ratio of frequencies is then

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d}}{m_{B_s}} \frac{V_{td}^2}{V_{ts}^2} \xi_{\Delta m}^2$$

$\xi_{\Delta m}$, being a ratio of QCD factors of value close to 1 can be calculated to a few % in lattice QCD, hence giving access to $|V_{td}|/|V_{ts}|$. 

[EPJC 79 (2019) 706]
The Unitarity Triangle – how do we know what we know?

\[ \frac{|V_{ud}V_{ub}^*|}{|V_{cd}V_{cb}^*|} = \left(1 - \frac{\lambda^2}{2}\right) \frac{1}{\lambda} \left| \frac{V_{ub}}{V_{cb}} \right| \]

Length of side opposite $\beta$ is given by measuring $|V_{ub}|/|V_{cb}|$ from ratio $b \to u / b \to c$. 
Measuring $|V_{ub}| / |V_{cb}|$

We can measure the ratio of $b \to ul\nu$ to $b \to cl\nu$ processes at hadron level, but then must use theory or lattice QCD to correct back to quark level.

Two broad strategies followed:

- **Inclusive** $b \to X_u l\nu$, using e.g. endpoint of $p_l$ spectrum to isolate signal from $b \to X_c l\nu$
  \[ |V_{ub}| = (4.49 \pm 0.28) \times 10^{-3} \]  
  [2018 PDG review]

- **Exclusive**, e.g. $B \to \pi l\nu$. But then need calculation of hadronic form factor.
  \[ |V_{ub}| = (3.70 \pm 0.16) \times 10^{-3} \]  
  [2018 PDG review]

There is tension between these two numbers at the $\sim 2.5\sigma$ level, which means that a conservative approach is advisable when using the results to set UT constraints. Much activity underway to understand this issue, & we can be hopeful of progress!
The Unitarity Triangle – how do we know what we know?

This band comes from CPV measurements in kaon decays. Theory limited.

Information on $\alpha$ comes from time-dependent measurements on $B^0$ decays to charmless final states, e.g. $B \rightarrow \rho^+\rho^-$. It probes a combination of the processes that occur in the $\beta$ and $\gamma$ measurements, and IMO does not bring independent info, & we will not discuss it further. (But of course any measurement is valuable!)
The Unitarity Triangle – how do we know what we know?

Now we will discuss the CPV measurements that access the angles $\beta$ and $\gamma$. 
Decays into CP eigenstates: $B^0 \rightarrow J/\psi K_S$


Incidentally, someone who was amongst the first to realise the potential of $b$-hadrons in CPV studies, and one responsible for a seminal paper, has since followed a very different career…

Obama-era U.S. defense secretary toasts the latest CP-violation results from LHCb

>750 citations
Decays into CP eigenstates: $B^0 \rightarrow J/\psi K_S$


For meson that is $B^0$ or $B^0$ bar at $t=0$, which decays into CP-eigenstate $f_{CP}$ at time $t$:

\[
\Gamma (B^0_{phys} \rightarrow f_{CP}(t)) \propto e^{-\Gamma t} \left( 1 - (S \sin(\Delta m t) - C \cos(\Delta m t)) \right)
\]
\[
\Gamma (\bar{B}^0_{phys} \rightarrow f_{CP}(t)) \propto e^{-\Gamma t} \left( 1 + (S \sin(\Delta m t) - C \cos(\Delta m t)) \right)
\]

\[
S = \frac{2 \Im(\lambda_{CP})}{1 + |\lambda_{CP}^2|} \quad C = \frac{1 - |\lambda_{CP}^2|}{1 + |\lambda_{CP}^2|} \quad \lambda_{CP} = \frac{q}{p} \frac{\bar{A}}{A}
\]

Key point: to observe a complex phase we need to have two (or more) interfering amplitudes, as here

* These expressions assumes width-splitting $\Delta \Gamma = 0$, which is an excellent approximation in $B^0$ system.
Decays into CP eigenstates: $B^0 \to J/\psi K_S$


For meson that is $B^0$ or $B^0\bar{b}$ at $t=0$, which decays into CP-eigenstate $f_{CP}$ at time $t$:

$$\Gamma (B^0_{phys} \to f_{CP}(t)) \propto e^{-\Gamma t} \left( 1 - (S \sin(\Delta m t) - C \cos(\Delta m t)) \right)$$

There are three ways that CP violation can appear:

CPV in the decay (or ‘direct CPV’).

(This is also the only possibility that applies for charged hadron decays.)

\[
S = \frac{2 \Im(\lambda_{CP})}{1 + |\lambda_{CP}^2|} \quad C = \frac{1 - |\lambda_{CP}^2|}{1 + |\lambda_{CP}^2|} \quad \lambda_{CP} = \frac{q}{p} \frac{\bar{A}}{A}
\]

* These expressions assumes width-splitting $\Delta \Gamma = 0$, which is an excellent approximation in $B^0$ system.
Decays into CP eigenstates: $B^0 \rightarrow J/\psi K_S$


For meson that is $B^0$ or $B^{0\,\text{bar}}$ at $t=0$, which decays into CP-eigenstate $f_{CP}$ at time $t$:

$$\Gamma (B^0_{\text{phys}} \rightarrow f_{CP}(t)) \propto e^{-\Gamma t} \left| 1 - (S \sin(\Delta m t) - C \cos(\Delta m t)) \right|$$

$$\Gamma (\overline{B}^0_{\text{phys}} \rightarrow f_{CP}(t)) \propto e^{-\Gamma t} \left| 1 + (S \sin(\Delta m t) - C \cos(\Delta m t)) \right|$$

$$S = \frac{2 \Im(\lambda_{CP})}{1 + |\lambda_{CP}^2|} \quad C = \frac{1 - |\lambda_{CP}^2|}{1 + |\lambda_{CP}^2|} \quad \lambda_{CP} = \frac{q}{p} \frac{\bar{A}}{A}$$

There are three ways that CP violation can appear:

CPV in the mixing (one category of so-called ‘indirect CPV’).

Occurs if there are different ways to oscillate $B^0 \leftrightarrow B^{0\,\text{bar}}$. In SM very small.

* These expressions assumes width-splitting $\Delta \Gamma = 0$, which is an excellent approximation in $B^0$ system.
Decays into CP eigenstates: $B^0 \rightarrow J/\psi K_S$


For meson that is $B^0$ or $B^0$bar at $t=0$, which decays into CP-eigenstate $f_{CP}$ at time $t$:

$$
\Gamma (B^0_{phys} \rightarrow f_{CP}(t)) \propto e^{-\Gamma t} \left( 1 - (S \sin(\Delta m t) - C \cos(\Delta m t)) \right)
$$

$$
\Gamma (\bar{B}^0_{phys} \rightarrow f_{CP}(t)) \propto e^{-\Gamma t} \left( 1 + (S \sin(\Delta m t) - C \cos(\Delta m t)) \right)
$$

$$
S = \frac{2 \Im(\lambda_{CP})}{1 + |\lambda_{CP}^2|} \quad C = \frac{1 - |\lambda_{CP}^2|}{1 + |\lambda_{CP}^2|} \quad \lambda_{CP} = \frac{q}{p} \frac{A}{\bar{A}}
$$

There are three ways that CP violation can appear:

CPV in mixing-decay interference (also a category of ‘indirect CPV’, & the most relevant in the $B^0\bar{B}^0$bar and $B^0_s\bar{B}^0_s$bar systems).

$\text{Im}\lambda_{CP} \neq 0$

* These expressions assumes width-splitting $\Delta\Gamma=0$, which is an excellent approximation in $B^0$ system.
Decays into CP eigenstates: $B^0 \rightarrow J/\psi K_S$


For meson that is $B^0$ or $B^0$ bar at $t=0$, which decays into CP-eigenstate $f_{CP}$ at time $t$:

\[
\begin{align*}
\Gamma \left( B^0_{phys} \rightarrow f_{CP}(t) \right) &\propto e^{-\Gamma t} \left( 1 - (S \sin(\Delta m t) - C \cos(\Delta m t)) \right) \\
\Gamma \left( \bar{B}^0_{phys} \rightarrow f_{CP}(t) \right) &\propto e^{-\Gamma t} \left( 1 + (S \sin(\Delta m t) - C \cos(\Delta m t)) \right)
\end{align*}
\]

\[
S = \frac{2 \Im(\lambda_{CP})}{1 + |\lambda_{CP}^2|} \hspace{1cm} C = \frac{1 - |\lambda_{CP}^2|}{1 + |\lambda_{CP}^2|} \hspace{1cm} \lambda_{CP} = \frac{q}{p} \frac{\bar{A}}{A}
\]

Consider the classic case $B^0 \rightarrow J/\psi K_S$:

- Compared to the CPV signal we are expecting in B physics, we can treat $K_S$ as a CP eigenstate.
- And in this decay $C \approx 0$, with no significant direct CPV (all the CPV comes from mixing-decay interference).

NB both these assumptions can be checked / corrected for.

* These expressions assumes width-splitting $\Delta \Gamma = 0$, which is an excellent approximation in $B^0$ system.
Decays into CP eigenstates: $B^0 \rightarrow J/\psi K_S$


For meson that is $B^0$ or $B^0$ bar at $t=0$, which decays into CP-eigenstate $f_{CP}$ at time $t$:

\[
\Gamma (B^0_{phys} \rightarrow f_{CP}(t)) \propto e^{-\Gamma t} \left(1 - (S \sin(\Delta m t) - C \cos(\Delta m t))\right) \\
\Gamma (B^0_{phys} \rightarrow f_{\bar{CP}}(t)) \propto e^{-\Gamma t} \left(1 + (S \sin(\Delta m t) - C \cos(\Delta m t))\right) 
\]

\[
S = \frac{2 \Im(\lambda_{CP})}{1 + |\lambda_{CP}|^2} \quad C = \frac{1 - |\lambda_{CP}|^2}{1 + |\lambda_{CP}|^2} \quad \lambda_{CP} = \frac{q}{p} \frac{\bar{A}}{A}
\]

Consider the classic case $B^0 \rightarrow J/\psi K_S$:

\[
\lambda_{J/\psi K_S} = \frac{V^*_{tb}V_{td}V_{cb}V^*_{cs}}{V_{tb}V^*_{td}V^*_{cb}V_{cs}} = e^{i2\beta} \quad \text{Im} \, \lambda_{J/\psi K_S} = \sin 2\beta
\]

* These expressions assume width-splitting $\Delta \Gamma = 0$, which is an excellent approximation in $B^0$ system.
Decays into CP eigenstates: $B^0 \rightarrow J/\psi K_S$


For meson that is $B^0$ or $B^0$ bar at $t=0$, which decays into CP-eigenstate $f_{CP}$ at time $t$:

\[
\Gamma (B^0_{phys} \rightarrow f_{CP}(t)) \propto e^{-\Gamma t} \left[ 1 - (S \sin(\Delta m t) - C \cos(\Delta m t)) \right]
\]

\[
\Gamma (\bar{B}^0_{phys} \rightarrow \bar{f}_{CP}(t)) \propto e^{-\Gamma t} \left[ 1 + (S \sin(\Delta m t) - C \cos(\Delta m t)) \right]
\]

\[
S = \frac{2 \tilde{\lambda}(\lambda_{CP})}{1 + |\lambda_{CP}^2|}, \quad C = \frac{1 - |\lambda_{CP}^2|}{1 + |\lambda_{CP}^2|}, \quad \lambda_{CP} = \frac{q}{p} \frac{\bar{A}}{A}
\]

In practice we measure a $t$-dependent CP asymmetry:

\[
a_{CP}(t) \equiv \frac{\Gamma(\bar{B}^0_s(t) \rightarrow J/\psi K^0_S) - \Gamma(B^0_s(t) \rightarrow J/\psi K^0_S)}{\Gamma(\bar{B}^0_s(t) \rightarrow J/\psi K^0_S) + \Gamma(B^0_s(t) \rightarrow J/\psi K^0_S)}
\]

\[
= \sin 2\beta \sin(\Delta m t)
\]

* These expressions assumes width-splitting $\Delta \Gamma = 0$, which is an excellent approximation in $B^0$ system.

This is theoretically clean! (no QCD murkiness)
Decays into CP eigenstates: $B^0 \rightarrow J/\psi K_S$


To reiterate, measurement probes interference between box and tree diagrams:

Sensitive to any CP violating phases in either, but these are only expected in the box. In the SM come from phase-difference associated with $V_{td}$ coupling, but could arise from other sources in New Physics. So possible $\sin 2\beta_{\text{meas}} \neq \sin 2\beta_{\text{SM}}$!

* These expressions assumes width-splitting $\Delta \Gamma=0$, which is an excellent approximation in $B^0$ system.
Flavour tagging & other practical considerations

Measurement demands we know whether decaying meson was $B^0$ or $B^{0}\bar{b}$ at birth. This requires *flavour tagging*. Look at either decay products of the other $b$-hadron (‘opposite sign’) or for fragmentation products associated with signal $B$ (‘same sign’).

Flavour tag decision can be wrong, either through misidentification of mixing of OS $b$-hadron. This leads to *dilution* of asymmetry, and reduces effective signal statistics by a large factor (up to $x \sim 1/30$) at hadron collider experiments.

For $t$ variable in asymmetry, we need to know proper time between birth & death of signal $B$, which at LHC is related to distance between primary and decay vertices.

* NB in high-$p_T$ physics the term ‘flavour tagging’ means something different, typically ‘is this jet b-like or c-like ?’. 
Flavour tagging & other practical considerations

Life is easier for BaBar/Belle and Belle-II. Life at the $\Upsilon(4S)$ means no fragmentation particles and production of coherent $B^0$-$\bar{B}^0$ system → (i) No same sign tag (bad), (ii) many fewer mistags (very good), (iii) no mixing until one $B$ decays (very good).

The dilution is less than at LHC, and reduces effective signal statistics by only $\sim 1/3$.

Why do $B$-factories have asymmetric beam energies? For coherent system what matters is the time-difference $\Delta t$ between the two $B$ decays. At the $\Upsilon(4S)$ the mesons are produced at rest, & so it is necessary to boost system to measure $\Delta t$. 
We can date the start of modern flavour physics to the 2001 measurements of the CP-violating asymmetry in $B^0 \to J/\psi K^0$ decays that give unitarity triangle angle $\beta$. These studies, when improved with larger samples, confirmed the CKM paradigm as the dominant mechanism of CP violation in nature (→ 2008 Nobel Prize), and also opened up a rich and wide spectrum of complementary measurements.
sin2\(\beta\): current status and impact of the LHC

Global state of play:

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

sin2\(\beta\) now known to 3%, with significant improvements expected in coming decade.

LHCb run 1 J/\(\psi\)K\(_S\) result has similar precision to B factories

Both solutions for \(\beta\) shown in UT plane.
The long march: towards a precise determination of the UT angle $\gamma$

A particular responsibility for flavour physics at the LHC (& Belle II) is to improve our knowledge of the angle $\gamma$.

The predicted value of $\gamma$ in context of SM is known very well from other triangle parameters (& will be known even better as experiment & lattice QCD improve).

A key task of flavour physics is to match this precision in a direct measurement!
The long march: towards a precise determination of the UT angle $\gamma$

This angle is special – it can be measured at tree-level through $B\to DK$ decays.

If we reconstruct $D^0$ and $\bar{D}^0$ in a state accessible to both, interference occurs & decay rates become sensitive to relative phase between $V_{cb}$ and $V_{ub}$, which is $\gamma$.

There are QCD nuisance parameters involved, but sufficient observables can be measured to determine these without any assumption. Theoretically ultra clean!

Tree level means New Physics unlikely to perturb measured value from the $\gamma$ of the SM (c.f. $\beta$), hence measurement provides ‘SM benchmark’ for other tests!
The Unitarity Triangle: measuring $\gamma$

To access these interference effects means looking for rather suppressed decays, e.g. this $B^- \to DK^-$ decay, with $D \to K^+\pi^-$ (and $B^+$ conjugate case): visible BR $\sim 10^{-8}$. Hence out of reach to previous generation of flavour physics experiments.

Very significant CP violation observed, that can be cleanly related to the phase $\gamma$. 
A powerful sub-set of $B \to DK$ analyses is when the $D$ decays into a multibody final state, of which $K_S \pi \pi$ is the most prominent example. Variation of $D$ strong phase over Dalitz space leads to corresponding variation in interference and CP violation.

Analysis of ~3000 decays from 2 fb$^{-1}$ of early Run 2 data.

A Dalitz plot is a 2D display of phase space for a three-body decay, where bands manifest intermediate resonances, and their spin structure e.g. $D \to K^*(892)\pi$.

These are the Dalitz plots of the $D \to K_S \pi \pi$ decays arising from the $B \to DK$ decays.
A powerful sub-set of $B \to DK$ analyses is when the $D$ decays into a multibody final state, of which $K_S\pi\pi$ is the most prominent example. Variation of $D$ strong phase over Dalitz space leads to corresponding variation in interference and CP violation.

Analysis of $\sim$3000 decays from 2 fb$^{-1}$ of early Run 2 data. Study yields in bins of Dalitz space, chosen for optimal sensitivity.

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γ measurement at LHCb with $B \to DK$ decays: $D \to K_S \pi \pi$ (and $K_S KK$) with Run 2 data

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Analysis of $\sim 3000$ decays from 2 fb$^{-1}$ of early Run 2 data.

Study yields in bins of Dalitz space, chosen for optimal sensitivity.

CP asymmetries visible by eye, but quantitative analysis requires external input...
Measuring $\gamma$ – a synergy of experiments

In order to make sense of these CP asymmetries, we need to know how the CP-conserving strong phase between $D$ & $D_{\text{bar}}$ varies over the Dalitz plot. This information can be measured in bins on the Dalitz plot from quantum-correlated $\psi(3770)\rightarrow D\bar{D}$ events, available at CLEO-c [PRD 82 (2010) 112006].

CLEO-c data adequate for current LHCb sample sizes. LHCb Upgrade data & Belle II will require improved measurements from BES III!
Measuring $\gamma$ – a synergy of experiments

In order to make sense of these CP asymmetries, we need to know how the CP-conserving strong phase between D & Dbar varies over the Dalitz plot. This information can be measured in bins on the Dalitz plot from quantum-correlated $\psi(3770) \rightarrow DD\overline{D}$ events, available at CLEO-c [PRD 82 (2010) 112006].

These strong-phase measurements are an excellent example of synergy between HEP facilities!
γ measurement at LHCb with $B \rightarrow DK$ decays: $D \rightarrow K_S \pi \pi$ (and $K_S KK$) with Run 2 data

A powerful sub-set of $B \rightarrow DK$ analyses is when the $D$ decays into a multibody final state, of which $K_S \pi \pi$ is the most prominent example. Variation of $D$ strong phase over Dalitz space leads to corresponding variation in interference and CP violation.

Compatible with Run 1 analysis of same channel

Together gives: $\gamma = 80^\circ \pm 10^\circ$
LHCb: combining $B \to DK$ modes for $\gamma$

The $B \to D(K_{S,\pi\pi}, K_{S,KK})K$ result may be combined together with those of other $B \to DK$ analyses. They depend on common nuisance parameters, but have different degeneracies $\to$ whole is greater than the sum of the parts!

Nicely compatible and pick out a unique solution.

$LHCb$ - CONF - 2018-002
LHCb: current precision on $\gamma$

Global LHCb average, now including information from time-dependent analyses of Run 1 data with $B_s$ [JHEP 03 (2018) 059] and $B^0$ decays [JHEP 06 (2018) 084].

$$\gamma = (74.0^{+5.0}_{-5.8})^\circ$$

Result is to be compared with indirect prediction of $(65.6^{+1.0}_{-3.4})^\circ$ [CKMfitter, 2018].

Compatible, albeit with a little tension ($\sim 2\sigma$).

Big improvements expected in near future, as still little Run 2 data in average.
Unitarity Triangle: ~25 years of progress
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Enormous improvements in precision, thanks to both experiment and theory (esp. lattice)!
There is broad consistency between all current measurements of the UT. (But, a closer look can reveal intriguing tensions, e.g. [Blanke & Buras, *EPJC* 79 (2019) 159].)

The CKM paradigm is the dominant mechanism of CPV in nature, but it is certainly possible for New Physics to give \( \sim 10\% \) level effects. More measurements needed!
Unitarity Triangle: tree-level observables

Unitarity Triangle formed from only tree-level quantities → assumed pure SM.

Tree observables are $\gamma$ & the $|V_{ub}|/|V_{cb}|$ side, here showing exclusive measurement.
Unitarity Triangle formed from only loop-level quantities → possibility of NP effects.

There is good consistency between the tree and loop measurements. There’s a need to improve the precision of former to allow for a more sensitive comparison.
Indirect CPV in $B_s$ system: $\varphi_s$

Measuring the CPV phase, $\varphi_s$, in $B_s$ mixing-decay interference, e.g. with $B_s \to J/\Psi \Phi$, is the $B_s$ analogue of the sin2\(\beta\) measurement. In the SM this phase is very small & precisely predicted. Box diagram offers tempting entry point for NP!

Once more interference between mixing...

Now we probe CKM elements that are complex only at higher order

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

\[
\begin{pmatrix}
-\frac{1}{8}\lambda^4 + \mathcal{O}(\lambda^6) & \mathcal{O}(\lambda^7) & 0 \\
\frac{1}{2}A^2\lambda^5[1 - 2(\rho + i\eta)] + \mathcal{O}(\lambda^7) & -\frac{1}{8}\lambda^4(1 + 4A^2) + \mathcal{O}(\lambda^6) & \mathcal{O}(\lambda^8) \\
\frac{1}{2}A\lambda^5(\rho + i\eta) + \mathcal{O}(\lambda^7) & \frac{1}{2}A\lambda^4(1 - 2(\rho + i\eta)) + \mathcal{O}(\lambda^6) & -\frac{1}{2}A^2\lambda^4 + \mathcal{O}(\lambda^6)
\end{pmatrix}
\]

\[\phi_s^{\text{SM}} \equiv -2\text{arg}\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -36.3^{+1.6}_{-1.5} \text{ mrad}\]
Indirect CPV in $B_s$ system: $\varphi_s$

Measuring the CPV phase, $\varphi_s$, in $B_s$ mixing-decay interference, e.g. with $B_s \rightarrow J/\Psi \Phi$, is the $B_s$ analogue of the sin2$\beta$ measurement. In the SM this phase is very small & precisely predicted. Box diagram offers tempting entry point for NP!

Once more interference between mixing...

Now we probe CKM elements that are complex only at higher order...

Recall the squashed $B^0_s$ triangle:

\[ \begin{align*} 
0 & \quad \frac{1}{2} A \lambda^5 \left[ 1 - 2(\rho + i\eta) \right] + \mathcal{O}(\lambda^7) \\
\frac{1}{2} A \lambda^5 (\rho + i\eta) + \mathcal{O}(\lambda^7) & \quad -\frac{1}{2} A \lambda^4 (1 + 4 A^2) + \mathcal{O}(\lambda^6) \\
\frac{1}{2} A \lambda^4 (1 - 2(\rho + i\eta)) + \mathcal{O}(\lambda^6) & \quad -\frac{1}{2} A^2 \lambda^4 + \mathcal{O}(\lambda^6) \\
\end{align*} \]

\[ \phi_{s}^{\text{SM}} \equiv -2 \arg \left( -\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right) = -36.3^{+1.6}_{-1.5} \text{ mrad} \]
**Indirect CPV in $B_s$ system: $\varphi_s$**

Measuring the CPV phase, $\varphi_s$, in $B_s$ mixing-decay interference, e.g. with $B_s \rightarrow J/\Psi \Phi$, is the $B_s$ analogue of the $\sin 2\beta$ measurement. In the SM this phase is very small & precisely predicted. Box diagram offers tempting entry point for NP!

However the measurement is considerably trickier than is the case for $\sin 2\beta$:

- $J/\Psi \phi$ is a vector-vector final state, so requires angular analysis to separate out CP+ & CP-
- Very fast oscillations ($\Delta m_s >> \Delta m_d$)
- Possibility of $KK$ S-wave under $\phi$

Heroic early analyses performed by Tevatron. Consistent results and mild ($\sim 1\sigma$) tension with SM.
Indirect CPV in $B_s$ system: $\varphi_s$

Measuring the CPV phase, $\varphi_s$, in $B_s$ mixing-decay interference, e.g. with $B_s \to J/\Psi \Phi$, is the $B_s$ analogue of the $\sin 2\beta$ measurement. In the SM this phase is very small & precisely predicted. Box diagram offers tempting entry point for NP!

However the measurement is considerably trickier than is the case for $\sin 2\beta$:

- One other detail: in contrast to the $B^0$ case, the width-splitting $\Delta \Gamma_s$ between the mass eigenstates $I_s$ is here non-negligible (~0.1). When included in the formalism this brings additional handles to the analysis, & also provides an additional observable to be measured.

- Possibility of KK S-wave under $\varphi$

Heroic early analyses performed by Tevatron. Consistent results and mild (~1$\sigma$) tension with SM.
**φ_s — impact of LHCb**

LHC has been able to go far beyond the Tevatron measurements, thanks to much larger yields, and (in case of LHCb) excellent proper time resolution, & access to complementary modes beyond J/ψφ (e.g. B_s → J/ψππ pursued in [PLB 713 (2012) 378].)

B_s → J/ψφ signal peak in early Run 2 analysis (117k decays, in 1.9 fb⁻¹ c.f. 6.5k at CDF).

Results for early Run 2 J/ψφ study, together with Run 1 measurements.

\[ \phi_s = -0.041 \pm 0.025 \text{ rad} \quad \Delta \Gamma_s = 0.0816 \pm 0.0048 \text{ ps}^{-1} \]
Measurement of $\varphi_s$ at ATLAS and CMS

Measurement of $\varphi_s$ is an key goal of the ATLAS and CMS flavour physics programme, enabled by excellent detector performance and $J/\Psi \rightarrow \mu \mu$ trigger.

e.g. ATLAS $B_s \rightarrow J/\Psi \phi$ preliminary Run 2 analysis with 80 fb$^{-1}$ [ATL-CONF-2019-009]:

Proper decay time

Transversity angle $\varphi_T$

Results, including those of Run 1 [JHEP 08 (2016) 147]

Combining with Run 1 results [JHEP 08 (2016) 147]

$$\phi_s = -0.076 \pm 0.034 \text{ (stat.)} \pm 0.019 \text{ (syst.) rad}$$

$$\Delta \Gamma_s = 0.068 \pm 0.004 \text{ (stat.)} \pm 0.003 \text{ (syst.) ps}^{-1}$$
Measurement of $\varphi_s$ is an key goal of the ATLAS and CMS flavour physics programme, enabled by excellent detector performance and $J/\Psi \rightarrow \mu\mu$ trigger.

e.g. CMS $B_s \rightarrow J/\Psi \varphi$ 8 TeV analysis [PLB 757 (2016) 97]

\[ \varphi_s = -0.075 \pm 0.097 \text{ (stat)} \pm 0.031 \text{ (syst)} \text{ rad}, \]
\[ \Delta \Gamma_s = 0.095 \pm 0.013 \text{ (stat)} \pm 0.007 \text{ (syst)} \text{ ps}^{-1}. \]
$\varphi_s$ : the impact of the LHC

$\Phi_s$ post Tevatron and early LHC data

$\varphi_s^{c\bar{c}s}$ [rad]

$\Delta \Gamma_s$ [$\text{ps}^{-1}$]

LHCb $0.4 \text{ fb}^{-1}$ + CDF $5.2 \text{ fb}^{-1}$ + DØ $8 \text{ fb}^{-1}$

68% CL contours ($\Delta \log \mathcal{L} = 1.15$)
$\phi_s$: the impact of the LHC

$\phi_s$ post Run 1 LHC and including some Run 2 ATLAS & LHCb data

$\phi_s$ post Tevatron and early LHC data
$\phi_s$: the current state of play

$\phi_s = -55 \pm 21 \text{ mrad}$

$\phi_s$ now measured with $\sim 20 \text{ mrad}$ precision and so far compatible with SM. Hint of non-zero value emerging – will be interesting with full Run 2 dataset!
Spectroscopy (a digression)

Hadron spectroscopy is not flavour physics. However flavour-physics experiments are ideally suited for discovering and studying new states, and many high impact results have emerged of this nature.
Spectroscopy - the conventional

Many new states found at the LHC, most of which fit within the ‘vanilla’ quark model

CMS discovery of excited $B_c$ states [PRL 122 (2019) 132001]

LHCb discovery of the $\Xi^{++}_{cc}$ [PRL 119 (2017) 112001]

“Barons can now be constructed from quarks by using the combinations $qqq$, $qqqqq$, etc, while mesons are made out of $qq$, $q\bar{q}q\bar{q}$, etc.”

Murray Gell-Mann
Spectroscopy - the exotic

Other states, many discovered in $e^+e^-$, are good candidates to be ‘exotic’:

- Observation of the $X(3872)$ at Belle [PRL 91 (2003) 262001]
- Observation of the $Z(4430)^+$ at Belle [PRL 100 (2008) 142001]

"Baryons can now be constructed from quarks by using the combinations $qqqqq$, etc, while mesons are made out of $qq$, $qqqqq$, etc."

Murray Gell-Mann
Spectroscopy results – provoke great interest among physicists

Top cited Belle physics papers

1. Observation of a narrow charmonium - like state in exclusive B+ → K− π+ π− J / ψ decays
   Published in Phys.Rev.Lett. 91 (2003) 282001
   DOI: 10.1103/PhysRevLett.91.282001
   e-Print: hep-ex/0309032 | PDF
   References | BibTeX | LaTeX(US) | LaTeX(EU) | HarvMac | EndNote
   ADS Abstract Service | ADS Abstract Service | Link to PRESS RELEASE
   Detailed record - Cited by 1656 records

2. Observation of large CP violation in the neutral B meson system
   Published in Phys.Rev.Lett. 87 (2001) 091802
   KEK-PREPRINT-2001-50, BELLE-PREPRINT-2001-10
   DOI: 10.1103/PhysRevLett.87.091802
   e-Print: hep-ex/0107061 | PDF
   References | BibTeX | LaTeX(US) | LaTeX(EU) | HarvMac | EndNote
   ADS Abstract Service | OSTI.gov Server
   Detailed record - Cited by 951 records

Top cited LHCb physics papers

1. Test of lepton universality using B+ → K+ ℓ+ ℓ− decays
   Published in Phys.Rev.Lett. 113 (2014) 151601
   DOI: 10.1103/PhysRevLett.113.151601
   References | BibTeX | LaTeX(US) | LaTeX(EU) | HarvMac | EndNote
   CERN Document Server | ADS Abstract Service
   Detailed record - Cited by 853 records

2. Observation of J/ψp Resonances Consistent with Pentaquark States in Λ_b0 → J/ψK− p Decays
   DOI: 10.1103/PhysRevLett.115.072001
   References | BibTeX | LaTeX(US) | LaTeX(EU) | HarvMac | EndNote
   CERN Document Server | ADS Abstract Service | Interactions.org article | Link to BBC News article | Link to Symmetry Magazine
   News article | Link to PBS website | Link to Scientific American article
   Detailed record - Cited by 792 records
Spectroscopy results – provoke great interest among public too

e.g. reactions to LHCb study of resonant nature of Z(4430)\(^{-}\) [PRL 112 (2013) 222002]
Spectroscopy results – provoke great interest among public too

e.g. reactions to LHCb study of resonant nature of $Z(4430)^-$ [PRL 112 (2013) 222002]
The hunt for pentaquarks – a long journey with several cul-de-sacs

Pentaquark signals have been claimed before, for example the $\Theta^+$ (sbar uudd) ‘seen’ by several experiments in the early 2000s.

After an initial rush of confirmations, null results from more sensitive experiments appeared, & eventually it was accepted to be non-existent.

“The whole story – the discoveries themselves, the tidal wave of papers by theorists and phenomenologists that followed, and the eventual ‘undiscovery’ - is a curious episode in the history of science.” PDG 2008

[for more information, see Hicks, Eur. Phys. J. H 37 (2012) 1]
J/Ψp resonances consistent with pentaquark states

Large & pure sample of $\Lambda_b \rightarrow J/\Psi pK$ decays

Distinctive structure in $J/\Psi p$ spectrum

Amplitude model of conventional states can reproduce $Kp$ spectrum well enough…

…but cannot describe the $J/\Psi$ projection at all.

Naïve first impression: this is exotic! (uudccbar).

~26k events
~95% purity
J/Ψp resonances consistent with pentaquark states

Can only describe data satisfactorily by adding two exotic pentaquark states with content uudccbar. Best fit has J=3/2 and 5/2 with opposite parities.

\[ P_c(4380): \]
\[ M = 4380 \pm 8 \pm 29 \text{ MeV}, \]
\[ \Gamma = 205 \pm 18 \pm 86 \text{ MeV} \]

\[ P_c(4450): \]
\[ M = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}, \]
\[ \Gamma = 39 \pm 5 \pm 19 \text{ MeV} \]
Pentaquarks – why more data matters

Run 2 data and improved selection provide x9 increase in signal

Run 1

Run 1 + Run 2

More going on here than first thought…

Hello !

[PRL 115 (2015) 072001]

[PRL 122 (2019) 222001]
A new narrow state is observed at 4312 MeV, and the previous narrowish state is resolved into two close-lying narrower states. An amplitude analysis is required to determine $J^P$ and decide on whether broad $P_c(4380)$ still required.
Intriguingly, two of the states lie just below the $\Sigma_c D^{(*)0}$ thresholds, which supports a molecular meson-baryon bound state picture of the pentaquarks. See e.g. [Wang et al., PRC 84 (2011) 015203], [Zhang et al., CPC 36 (2012) 6], [Wu et al., PRC 85 (2012) 044002].
We have been talking a lot about FCNCs already in the context of mixing, but now we switch the focus to very rare FCNC decay modes.
Flavour-changing Neutral Currents (FCNCs) or ‘rare decays’ as a probe of New Physics

FCNC decays proceed through higher order diagrams $\rightarrow$ suppressed in SM and susceptible to New Physics contributions.

e.g. Penguin diagram (nomenclature introduced by John Ellis in 1977 after lost bet [Ellis et al., NPB 131 (1977) 285].)

Most interesting measurements involve EM & weak penguins, with photon or dileptons – precise predictions.

(EM) Radiative penguin

EM penguin first discovered by CLEO in $B\rightarrow K^*(892)\gamma$ (BR$\sim 10^{-5}$) [CLEO, PRL 71 (1993) 674].

Studies of radiative penguins still very important, but we will not discuss them further.
The golden modes: $B_s \rightarrow \mu^+\mu^-$, $B^0 \rightarrow \mu^+\mu^-$

These decay modes can only proceed through suppressed loop diagrams.

In SM they happen extremely rarely ($B_s \rightarrow \mu\mu \sim 4 \times 10^{-9}$, $B^0 \rightarrow \mu\mu$ 30x lower), but the rate is very well predicted (e.g. <5% for $B_s \rightarrow \mu\mu$).

Many models of New Physics (e.g. SUSY) can modify rate significantly!

A ‘needle-in-the haystack’ search, which has been pursued for over 25 years.

Before the LHC, Fermilab experiments were pushing the limits down towards $10^{-8}$. 
Historical plot from around the turn-on of the LHC, showing how a measurement of the BR of both modes provides powerful discrimination between New Physics models.

\[B_s \rightarrow \mu^+\mu^-, \quad B^0 \rightarrow \mu^+\mu^-:\text{ the model killer}\]
Finding the needle in the haystack

There are lots of B-decays that look rather similar to $B_s \rightarrow \mu \mu$. And ‘rather similar’ is very dangerous when you are searching for such a rare decay.

Most sensitive analyses (LHCb, CMS) do not rely on traditional ‘cut-based’ approach. Rather, they employ a sequence of two boosted decision trees (BDTs).

BDTs must not just search for a B-decay, as in trigger, but must look for one which is $B_s \rightarrow \mu \mu$.

e.g. compare momentum vector of decay with vertex separation vector

Above, just one of many signatures that are used. Where possible calibrate BDTs on data (e.g. same topology $B^0 \rightarrow K\pi$ decays). Normalise signal yield to $B_s \rightarrow J/\psi K$ or $B^0 \rightarrow K\pi$ to determine BR.
The search is over: $B_s \rightarrow \mu^+\mu^-$ observed!

The signal finally showed up during Run 1, where LHCb found first evidence [PRL 110 (2013) 021801], & then a combined LHCb-CMS analysis yielded a 5$\sigma$ observation [Nature 522 (2015) 68]. The BR, measured to 25%, agrees with the SM...

\[
B(B^0_s \rightarrow \mu^+\mu^-) = \left(2.8^{+0.7}_{-0.6}\right) \times 10^{-9} \quad (6.2\sigma)
\]

\[
B(B^0 \rightarrow \mu^+\mu^-) = \left(3.9^{+1.6}_{-1.4}\right) \times 10^{-10} \quad (3.0\sigma)
\]

…however the analysis also searched for the even rarer $B^0 \rightarrow \mu\mu$. Here there is also a hint of a signal. Picture is intriguing & provided encouragement for Run 2!
LHCb $B^0_{(s)} \rightarrow \mu^+\mu^-$ run 2 update

Early in Run 2 LHCb returned to this critical observable with an improved analysis (~50% combinatoric background than previously). Run 1 + 1.4 fb$^{-1}$ of Run 2 data.

- 7.8 $\sigma$ signal & first single-experiment observation!
- Precise measurement of branching fraction
  
  $$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$
- No evidence yet of the corresponding $B^0$ decay.

Uses only 1/4 of Run 2 data, so ‘legacy’ Run 1+2 result will be much more precise.
CMS $B^0_{(s)} \rightarrow \mu^+ \mu^-$ run 2 update

Last month: a CMS preliminary update based on Run 1 (25 fb$^{-1}$) & 2016 Run 2 (36 fb$^{-1}$).

\[ B(B_s^0 \rightarrow \mu^+ \mu^-) = [2.9^{+0.7}_{-0.6} \text{(exp)} \pm 0.2 \text{(frag)}] \times 10^{-9} \]

The ‘frag’ systematic concerns knowledge of ratio of production of $B_s$ to $B^+$ mesons (i.e. fragmentation). This enters because of $B^+ \rightarrow J/\psi K^+$ normalisation mode.

Measured by LHCb and extrapolated into kinematic acceptance of CMS.

Also this year, ATLAS published a 2015-16 run 2 update [JHEP 04 (2019) 098] to augment their Run 1 result [EPJC 76 (2016) 513]. We await full Run 2 results from all experiments!
The state of play

**LHCb**

- $\text{BR}(B_s \rightarrow \mu\mu) = 3.0^{+0.7}_{-0.6} \times 10^{-9}$
- $\text{BR}(B^0 \rightarrow \mu\mu) < 3.4 \times 10^{-10}$

**CMS (prelim)**

- $\text{BR}(B_s \rightarrow \mu\mu) = 2.9^{+0.7}_{-0.6} \times 10^{-9}$
- $\text{BR}(B^0 \rightarrow \mu\mu) < 3.6 \times 10^{-10}$

**ATLAS**

- $\text{BR}(B_s \rightarrow \mu\mu) = 2.8^{+0.8}_{-0.7} \times 10^{-9}$
- $\text{BR}(B^0 \rightarrow \mu\mu) < 2.1 \times 10^{-10}$

- Each result is compatible with the SM;
- $B_s \rightarrow \mu\mu$ measurements are clustering at a slightly lower value than SM (at level of $\sim 2\sigma$);
- $B^0 \rightarrow \mu\mu$ is proving elusive;
- Full Run 2 results will be interesting;
Lessons from, & future of, $B^0(s)\rightarrow\mu\mu$ measurements

• Prior to LHC turn on, an enhanced $\text{BR}(B_s\rightarrow\mu\mu)$ was one of the great hopes for a rapid discovery of New Physics. This hope has not been realised.

• Nonetheless, the absence of an enhancement is a very powerful input in excluding certain classes of New Physics model. e.g. 95% CL excluded region in $M_H$ vs. $\tan\beta$ space for two-Higgs doublet model [Gfitter group, Hallet et al., EPJC 78 (2018) 675].

• Better measurements are essential, as we are still far from theory limit (which will improve). Even truer for ratio $\text{BR}(B_s\rightarrow\mu\mu)/\text{BR}(B^0\rightarrow\mu\mu)$. These decays still have much to tell us!

• Next step in the journey will be observation of $B^0\rightarrow\mu\mu$. 

- 68% C.L. (as in 2017)
Unlocking new observables with $B_s \rightarrow \mu^+ \mu^-$

Remarkably, the sample of $B_s \rightarrow \mu \mu$ decays now available is sufficient to begin probing new observables. E.g., since the sample is in fact constituted of both $B_s$ & $B_s$ bar mesons, a lifetime measurement brings very valuable new information.

The effective lifetime [K. De Bruyn et al., PRL 109 (2012) 041801] :

$$\tau_{\mu^+ \mu^-} = \frac{\tau_{B_s^0}}{1 - y_s^2} \left( \frac{1 + 2A_{\Delta \Gamma}^{\mu^+ \mu^-} y_s + y_s^2}{1 + A_{\Delta \Gamma}^{\mu^+ \mu^-} y_s} \right)$$

where

- $y_s \equiv \tau_{B_s^0} \Delta \Gamma / 2 \approx 0.06$, $\Delta \Gamma$ being the lifetime splitting between the mass eigenstates;

- $A_{\Delta \Gamma}^{\mu \mu}$ is a term that is 1 in SM, but can take any value between -1 & 1 for New Physics.

Accessing $A_{\Delta \Gamma}^{\mu \mu}$ through $\tau_{\mu \mu}$ tells us things that the BR alone does not.
Unlocking new observables with $B_s \rightarrow \mu^+ \mu^-$

Remarkably, the sample of $B_s \rightarrow \mu \mu$ decays now available is sufficient to begin probing new observables. *E.g.*, since the sample is in fact constituted of both $B_s$ & $B_s\bar{b}$ mesons, a lifetime measurement brings very valuable new information.

Proof-of-principle measurements conducted by LHCb and CMS:

During HL-LHC era these will reach very interesting levels of precision.

One may also dream of performing flavour-tagged CP asymmetry measurements!
$B^0 \rightarrow K^* l^+ l^-$ and friends – the gift that keeps on giving

FCNC processes involving the transition $b \rightarrow s l^+ l^-$ (and indeed $b \rightarrow d l^+ l^-$) are not ultra rare, but provide an exceedingly rich set of observables to probe for NP effects, that are sensitive to non-SM helicity structures (and more).

Many realisations, but the poster-child decay is $B^0 \rightarrow K^{*0} l^+ l^-$, with $K^{*0} \rightarrow K^+ \pi^-$. 

$\phi$ is angle between $K\pi$ and $\mu\mu$ decay frame

Four-body final state can be characterised in terms of three angles, $\Theta_\ell$, $\theta_K$ and $\phi$, & $q^2$, & the invariant-mass of the dilepton pair (see e.g. [LHCb, PRL 111 (2013) 191801]).
B⁰ → K*¹l⁺l⁻ and friends – the gift that keeps on giving

Differential cross-section w.r.t. solid angle and q² can be expressed in terms of eight coefficients: F_L, A_FB and S_i (other choices are available):

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

Note, this is the CP-averaged expression (i.e. assuming no CPV).

F_L – fraction of longitudinal polarisation of K*

A_FB – forward-backward asymmetry of dilepton pair in B-meson frame
B⁰ → K*¹l⁺l⁻ and friends – the gift that keeps on giving

Three practical considerations:

1. Analysis must allow for an S-wave contribution in Kπ system, in addition to P wave that comes from K*(892) – important, but we won’t discuss it here.

2. In pp environment, it is easier to reconstruct muons than electrons, so unless stated, measurements are made with di-muon final state.

3. Form-factor (i.e. QCD) uncertainties in predictions of coefficients can be reduced by changing to a set of optimised uncertainties [Descotes-Genon et al., JHEP 01 (2013) 048], in which first order uncertainties cancel, i.e. more robust:

\[
P_1 = \frac{2S_3}{(1 - F_L)} = A_{T}^{(2)}, \quad P_3 = \frac{-S_9}{(1 - F_L)}, \quad P_6' = \frac{S_7}{\sqrt{F_L(1 - F_L)}}.
\]

Hard to visualise what these mean, but they can be predicted in SM, & in terms of general NP predictions, rather well. Also very robust against detector bias!
The B factories studied $B^0 \to K^* l^+ l^-$ with enthusiasm. Initial results, e.g. for forward-backward asymmetry, were intriguing. But sample sizes inadequate for firm conclusions. Situation changed with the turn-on of the LHC.

(NB: the J/ψ and ψ’ regions are excluded, as these ccbar resonances occur through tree-level processes and do not probe physics we are interested in.)
B⁰→K*⁺l⁺l⁻ - impact of the LHC

The B factories studied B⁰→K*⁺l⁺l⁻ with enthusiasm. Initial results, e.g. for forward-backward asymmetry, were intriguing. But sample sizes inadequate for firm conclusions. Situation changed with the turn-on of the LHC.

(NB: the J/ψ and ψ’ regions are excluded, as these ccbar resonances occur through tree-level processes and do not probe physics we are interested in.)

Hints of non-SM behaviour in early analyses not confirmed by high-statistics measurement (although mild tension at low q²). What about ‘optimal observables’?
The ‘optimum observable’ that has attracted most attention is $P_5^\prime$. A deviation at low $q^2$, first seen in an early LHCb analysis \cite{PRL 108 (2012) 181806}, persisted with the full Run 1 data set \cite{JHEP 02 (2016) 104}, & is not contradicted by other experiments.

A word of caution. The SM uncertainties shown here are from one group. There are other values on the market, and some are more conservative. Meanwhile, work is ongoing to constrain QCD uncertainties from data, \textit{e.g.} \cite{LHCb, EPJ C77 (2017) 161}.
The ‘optimum observable’ that has attracted most attention is $P_{S}^{'}$. A deviation at low $q^{2}$, first seen in an early LHCb analysis [PRL 108 (2012) 181806], persisted with the full Run 1 data set [JHEP 02 (2016) 104], & is not contradicted by other experiments. None of these measurements are individually precise, but the overall picture is very similar to LHCb. Does not smell like a statistical fluctuation…
B^0 → K^{*0} l^+ l^- and friends: the P_5' puzzle

There is another interesting observation. All the LHC measurements are made with dimuons, whereas the Belle result comes from dimuons and dielectrons. Individual results are also available for each lepton final state.

In the bin of interest it is the dimuon result that is most discrepant, although with the small sample size there is consistency between both final states.
**B^0 → K^* l^+ l^- and friends: differential x-secs**

P_{5}' is not the only funny thing going on in b→(s,d)l^+ l^- decays.

All measurements undershoot prediction at low q^2. (BTW, all made with *dimuons*)… Intriguing – but maybe the uncertainties in theory are larger than claimed? Can we identify an observable where the theory uncertainties are negligible?
The cleanest way to probe these decays are with lepton universality (LU) tests, i.e. comparing decays with di-electrons and di-muons. Negligible theory uncertainty.

Ratios of decay rates have been measured for $b \rightarrow s \mu^+ \mu^- / b \rightarrow s e^+ e^-$ for $\sim 1 < q^2 < 6 \text{ GeV}^2$ for both $B \rightarrow K l^+ l^-$ ($R_K$) and $B^0 \rightarrow K^* l^+ l^-$ ($R_{K^*}$). In SM we expect $\approx 1$ for both.
The cleanest way to probe these decays are with lepton universality (LU) tests, *i.e.* comparing decays with di-electrons and di-muons. *Negligible* theory uncertainty.

Ratios of decay rates have been measured for $b \to s \mu^+\mu^-/b \to s e^+e^-$ for $\sim 1 < q^2 < 6$ GeV$^2$ for both $B \to K l^+l^-$ ($R_K$) and $B^0 \to K^* l^+l^-$ ($R_{K^*}$). In SM we expect $\approx 1$ for both.

In both cases measurements are $\sim 2.5 \sigma$ below SM!
b→sℓ⁺ℓ⁻ lepton universality tests – more about the measurements (with focus on \( R_{K^*} \)) [JHEP 08 (2017) 055]

Precision is limited by size of electron sample, which is \(~100\) decays in bin of measurement (muon sample is around 3-4 x larger).
Isn’t measurement vulnerable to knowledge of lepton id efficiency? No, because $R_{K^*}$ is normalised to $B^0 \rightarrow K^* J/\psi$ (and its known $J/\psi \rightarrow l^+ l^-$ obeys lepton universality) which makes all such dependencies second order.

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-))} \bigg/ \frac{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-))}$$

Nonetheless, checks are made by measuring whether the relevant ratios for $B^0 \rightarrow K^* J/\psi$ and indeed $B^0 \rightarrow K^* \psi(2S)$ are compatible with unity – they are.
b→sl⁺l⁻ lepton universality tests – more about the measurements (with focus on $R_{K^*}$) [JHEP 08 (2017) 055]

Measurements are made below $J/\psi$ – it is the low $q^2$ region where odd behaviour has been seen in other studies. High $q^2$ measurements will come in future.

However a second $R_{K^*}$ measurement exists at very low $q^2$. This also is >2σ low w.r.t. SM. Interesting! However, any deviation in this region is harder to explain by New Physics (see later), as ‘photon pole’ dominates decay process.
b→sl⁺l⁻ lepton universality tests – Belle results

Belle has recently released $R_K$ and $R_{K^*}$ measurements (both exploiting $B^0$ and $B^+$ modes, assuming isospin conservation) in a variety of binning schemes.

All results compatible with LHCb & SM (but significantly less precise than LHCb).
Analysing FCNC data in context of effective field theory

The $b \to s l^+ l^-$ results can be qualitatively ‘explained’ by hypothesising that $b \to s e^+ e^-$ largely obeys the SM, but New Physics intervenes for $b \to s \mu^+ \mu^-$ at low $q^2$.

A more quantitative analysis can be made in context of effective field theory.

Real theory

Effective theory

$$A(i \to f) = \langle f | H_{\text{eff}} | i \rangle$$

See, e.g. [Buchalla et al., Rev. Mod. Phys. 68 (1996) 1125].
Analysing FCNC data in context of effective field theory

Operator product expansion:

\[ H_{\text{eff}} \propto V_{tb} V_{ts}^* \sum_i \left( C_i O_i + C'_i O'_i \right) \]

Model independent ! Expansion performed in a complete basis of four-body operators that contribute differently to each FCNC process.

\[ O^{(i)}_7 \propto (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \]
\[ O^{(i)}_9 \propto (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\ell} \gamma_\mu l) \]
\[ O^{(i)}_{10} \propto (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\ell} \gamma_\mu \gamma_5 l) \]
\[ O^{(i)}_S \propto (\bar{s} P_{L(R)} b) (\bar{\ell} \ell) \]
\[ O^{(i)}_P \propto (\bar{s} P_{L(R)} b) (\bar{\ell} \gamma_5 l) \]

<table>
<thead>
<tr>
<th>Transition</th>
<th>( C_7^{(i)} )</th>
<th>( C_9^{(i)} )</th>
<th>( C_{10}^{(i)} )</th>
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<tr>
<td>( b \rightarrow s\gamma )</td>
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<td>( b \rightarrow \ell^+\ell^- )</td>
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<td>( b \rightarrow s\ell^+\ell^- )</td>
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\( C_i \) are the **Wilson coefficients**. Calculable in SM, but can be affected by New Physics.
Current status of fits to FCNC data

- Ensemble of all FCNC data gives a consistent picture
- Best fit is inconsistent with SM by more than 5σ!
- *BUT*, this assumes taking uncertainties on SM predictions for, e.g., $P_5'$ at face value.
- One excellent fit allows for NP shift for muons alone of opposite sign in $C_9$ & $C_{10}$, & a modest lepton-universal shift in $C_9$.

[Diagram showing FCNC data analysis with SM, LU-violating, and LU-conserving observables.]

(ignore dotted lines, which refer to fits with earlier results)
Current status of fits to FCNC data

- Ensemble of FCNC data gives a consistent picture.
- Best fit is inconsistent with SM by more than 5σ!
- BUT, this assumes taking uncertainties on SM predictions for, e.g., $P_5'$ at face value.
- One excellent fit allows for NP shift for muons alone of opposite sign in $C_9$ & $C_{10}$, & a modest lepton-universal shift in $C_9$.

Popular explanations of these effects include:

- **Flavour-changing Z’**
  
  *e.g.* [Altmannshofer & Straub, EPJC 73 (2013) 2646],
  [Gauld, Goertz & Haisch, PRD 89 (2014) 015005],
  [Altmannshofer & Straub, EPJC 75 (2015) 382],
  [Crivellin *et al.*, PRD 92 (2015) 054013].

- **Leptoquarks**
  
  *e.g.* [Hiller & Schmaltz, PRD 90 (2014) 054014],
  [Alonso *et al.*, arXiv:1505.05164],
  [Fajfer & Ksnik, PLB 755 (2016) 270].

These may be within reach of direct detection at ATLAS & CMS.
b→(s,d)l+ℓ−: near-term experimental prospects

New experimental input is mandatory to conclude on the b→sℓ+ℓ− anomalies.

- LHCb Run 2 dimuon results on P_5' and other optimal observables, and equivalent studies with dielectrons.

- LHCb full Run 2 results on R_K (so far only 2015-16 analysed) and on R_{K^*} (so far only Run 1 analysed), and analogous modes, e.g. Λ_b→pK_1+ℓ−, B_s→φℓ+ℓ−.

- R_K and R_{K^*} results from other LHC experiments.

- Results from Belle II.

Most valuable will be theoretically clean observables that test lepton universality.

Personal opinion: even if current anomaly dissipates, the story has been very useful for focusing attention on one of the less well understood features of the SM (lepton universality), & also illustrating the power of a complementary ensemble of measurements. Whatever, b→(s,d)l+ℓ− studies are sure to remain of great interest!
There is another class of decays, $b \to c \ell \nu$, (tree level – not a FCNC!) where there is a stubborn longstanding tension between data and the SM expectation.

$$R(D^*) \equiv \frac{\text{BR}(B \to D^{(*)} \tau \nu)}{\text{BR}(B \to D^{(*)} \mu \nu)}$$

Studies originally motivated by sensitivity to charged Higgs, but results do not favour this explanation and fit better with leptoquark explanation, but requires some ingenuity to simultaneously explain this and $b \to s l^+ l^-$ anomaly.

Missing energy means that measurements are ideal for B-factories, but competitive studies have come from LHCb. More experimental input essential!
Mixing and CPV in charm

~15 years ago, a flavour-physics lecturer would have been strongly tempted to skip over charm. A subject with a glorious past (e.g. GIM, J/ψ), but little future.

Why so? Firstly, mixing known to be small (GIM cancellations almost exact, due to absence of super-heavy quarks in loops), maybe very small.

Charm mixing parameters

Off-shell intermediate (short-range) states sensitive to New Physics

\[ x_D = \frac{\Delta m}{\Gamma} \]

On-shell intermediate (long-range) states

\[ y_D = \frac{\Delta \Gamma}{2\Gamma} \]

How small is small? ~ 0.01? << 0.01?? This is the other problem. Charm is neither ‘heavy’ or ‘light’ & so hadronic calculations are tough.

Infamous plot, first made by Nelson, & here updated by Petrov, showing (very) wide range in predicted values of \( x_D \) & \( y_D \).
Mixing and CPV in charm

~15 years ago, a flavour-physics lecturer would have been strongly tempted to skip over charm. A subject with a glorious past (e.g. GIM, J/ψ), but little future. Similarly, CPV, both indirect (i.e. in mixing-related phenomena) and direct, is also expected to be very small, once more because of absence of third-generation participating in virtual loops (a 2x2 CKM matrix is almost real…).

Reminder:

- CPV in mixing →
  \[ \left| \frac{q}{p} \right| \neq 1 \]

- CPV in decay-mixing interference →
  \[ \phi = \arg\left(\frac{qA\bar{a}r}{pA}\right) \neq 0 \]

10+ years ago, the constraints on indirect CPV in charm were very weak (unsurprising, as one first needs sensitivity to mixing).

But charm is a priori a good place to look for New Physics (NP) effects!

(i) Only system in which virtual loops involving up-type quarks can be probed;
(ii) NP effects will be easier to see when the SM ‘background’ is so small.
Mixing studies with ‘wrong-sign’ $D^0 \to K^+ \pi^-$

Several ways to access mixing. One sensitive way is to search for interference effects involving Doubly Cabibbo-Suppressed decays, e.g. $D^0 \to K^+ \pi^-$. 

Decay-time dependent rate

Normalise by right-sign decay rate:

$$R(t) \approx R_D + \sqrt{R_D} \ y'^2 \ \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left( \frac{t}{\tau} \right)^2$$

$[\frac{DCS \ amp}{CF \ amp}]^2 \sim |0.06|^2$

(expansion in $x'$ & $y'$, which are small)

Where $\delta \sim 10^\circ$ is strong-phase difference between CF & DCS amplitudes

Where $\delta \sim 10^\circ$ is strong-phase difference between CF & DCS amplitudes
First evidence from the B-factories!

As data accumulated at the B-factories, a non-zero mixing signal began to emerge.

BaBar: 4k WS $K\pi$ signal decays with 384 fb$^{-1}$.

Proper-time distribution.

Residuals between data and no-mixing fit.

[BaBar, PRL 98 (2007) 211802]
Rise of the hadron machines

First observation of signal in single measurement required statistical muscle of hadron machines. In 2013 LHCb & CDF published first \( (>5\sigma) \) measurements.

This is the WS/RS ratio vs. proper time.

Linear slope comes from mixing-decay interference.

LHCb sample is a just small fraction of Run 1, but is order of magnitude larger than that of BaBar. These measurements also benefit from better time resolution.
Where are we now with charm mixing?

$y_D$ is now reasonably well known, but $x_D$ less so. In fact there is still only $\sim 3 \sigma$ evidence that $x_D$ is non-zero. Important to improve our knowledge of $x_D$, as size of mixing parameters modulated size of any indirect CPV observable.

![Graph showing $y$ vs. $x$ with contours representing 68% and 95% CL, with a legend indicating current world average and recent Run 1 $D \rightarrow K_S \pi \pi$ result from LHCb [PRL 122 (2019) 231802].]
Search for indirect CPV in charm with Run 2 data

LHCb samples have grown rapidly, and now allow for high sensitivity searches for mixing-induced CPV, e.g. take WS $K\pi$ analysis used for mixing discovery, now updated with full Run 1 data & $2 \text{ fb}^{-1}$ from Run 2, and study $D^0$ & $D^0\bar{\text{b}}$ separately.

Study ratio of WS (i.e. $D^0 \to K^+\pi^-$)...

…to RS (i.e. $D^0 \to K^-\pi^+$), vs. proper decay time

For $D^0$...

…and $D^0\bar{\text{b}}$...

…and difference of both.

Difference flat $\to$ no sign of indirect CPV (yet).

[PRD 97 (2018) 031101]
Search for indirect CPV in charm with Run 2 data

LHCb samples have grown rapidly, and now allow for high sensitivity searches for mixing-induced CPV, e.g. take WS K$^\pi$ analysis used for mixing discovery, now updated with full Run 1 data & 2 fb$^{-1}$ from Run 2, and study D$^0$ & D$^{0\bar{} }$ separately.

Significant increase in sensitivity since pre-LHC era…

…now starting to approach the region where indirect CPV could lurk!

[PRD 97 (2018) 031101]
Searches for direct CPV in charm

And what of direct CPV? Recall we need (at least) two interfering diagrams, so we should pick a decays where leading tree diagram is not overwhelmingly dominant → singly Cabibbo-suppressed (SCS) decays, e.g. $D^0 \rightarrow K^+ K^-$, $D^0 \rightarrow \pi^+ \pi^-$. 

We measure an asymmetry

$$\mathcal{A}_{CP} = \frac{D^0 \rightarrow K^+ K^- - \overline{D}^0 \rightarrow K^+ K^-}{D^0 \rightarrow K^+ K^- - \overline{D}^0 \rightarrow K^+ K^-}$$

The meson is neutral, but we are interested in direct CPV, so measure the time-integrated asymmetry (still, possible residual indirect CPV effects must be accounted for in interpretation - a charged decay, e.g. $D^+ \rightarrow \pi^+ \pi^- \pi^+$, does not have this issue).
Direct CPV measurements – practical considerations

At the LHC can exploit two production modes, prompt (i.e. from primary interaction / vertex (PV)), or secondary (from B decay). Prompt is more abundant.

Furthermore, in prompt case, choose to reconstruct $D^{*+} \rightarrow D^0 \pi^+_S$ decays, as the charge of the ‘slow pion’ tags flavour ($D^0$ or $D^0$ bar) - needed to construct $A_{CP}$. In secondary case the tag comes from charge of muon in a semileptonic B decay.
Direct CPV measurements – practical considerations

When probing a sub-% $A_{CP}$, one must worry about sources of fake asymmetry that will contribute to raw value. So for $D^*$ tagged events* & final state $f$:

$$A_{raw}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_S) + A_P(D^{*+})$$

- what we are after
- detection asymmetry for final state
- detection asymmetry for slow pion
- production asymmetry: there can be different numbers of $D^{*+}$ and $D^{-}$ produced in acceptance

* Analogous expression for semileptonic tags
Direct CPV measurements – practical considerations

When probing a sub-% $A_{\text{CP}}$, one must worry about sources of fake asymmetry that will contribute to raw value. So for $D^*$ tagged events* & final state $f$:

$$A_{\text{raw}}(f) = A_{\text{CP}}(f) + A_{\text{d}}(f) + A_{D}(\pi_S) + A_{P}(D^{*+})$$

what we are after

detection asymmetry for slow pion

production asymmetry: there can be different numbers of $D^{*+}$ and $D^{*-}$ produced in acceptance

Consider $A_{\text{raw}}$ for two final states: $K^+K^-$ and $\pi^+\pi^-$:

- $A_{\text{CP}}$ is not expected to be the same, as direct CP violation is final-state specific (indeed the naïve expectation if hadronic physics works just the same for both is that $A_{\text{CP}}(KK) = - A_{\text{CP}}(\pi\pi)$);

- But $A_{D}(\pi_S)$ & $A_{P}(D^{*+})$ is independent of final state, in given phase space region.

So measure $\Delta A_{\text{CP}}$, the difference between the two raw asymmetries:

$$\Delta A_{\text{CP}} \equiv A_{\text{raw}}(KK) - A_{\text{raw}}(\pi\pi) = A_{\text{CP}}(KK) - A_{\text{CP}}(\pi\pi)$$

taking care to weight samples so both have same distribution in phase space.
Dawn of a new era: observation of (direct) CPV in charm

$\Delta A_{CP}$ measurement, published earlier this year by LHCb, harnesses full statistical might of experiment, being first to use full Run 2 data set.

Method is intrinsically robust: e.g. syst. uncertainty on prompt analysis is $< 10^{-4}$.

Dull plots, because effect is tiny, and almost impossible to visualise.

Run 1 + Run 2

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

5.3$\sigma$ from 0!
Dawn of a new era: observation of (direct) CPV in charm

$\Delta A_{CP}$ measurement, published earlier this year by LHCb, harnesses full statistical might of experiment, being first to use full Run 2 data set.

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Dull plots, because effect is tiny, and almost impossible to visualise

Using indirect CPV constraints in these channels can deduce

\[ \Delta a_{CP}^{\text{dir}} = (-15.7 \pm 2.9) \times 10^{-4} \]

\[ i.e. \text{ direct CPV saturates result} \]
Dawn of a new era: observation of (direct) CPV in charm

ΔA_{CP} measurement, published earlier this year by LHCb, harnesses full statistical might of experiment, being first to use full Run 2 data set.

- Is the size of the effect compatible with SM expectations, or is it too high, indicating possible NP contributions? The theoretical community is (inevitably) divided.
  (e.g. compare [Chala, Lenz, Rusov & Scholz arXiv:1903.10490] with [Grossman and Schacht arXiv:1903.10952].)

- Next tasks for experiment: measure individual asymmetries & intensify searches in other modes. A very exciting programme lies ahead!

- Charm is certainly no longer the ‘poor relation’ of flavour physics!

Using indirect CPV constraints in these channels can deduce

$$\Delta a_{CP}^{\text{dir}} = (-15.7 \pm 2.9) \times 10^{-4}$$

i.e. direct CPV saturates result

Method is intrinsically robust: e.g. syst. uncertainty on prompt analysis is < 10^{-4}.
Future of flavour
Why persevere with flavour studies?

Devil’s advocate: given that CKM mechanism does a good job, and given that we have observed $B^0_s \rightarrow \mu\mu$ at (roughly) the right BR, why continue?

The big picture answer:

- The SM is incomplete;
- Many of the mysteries in the SM (& the cosmos) are related to flavour;
- Flavour observables can probe much higher mass scales than direct searches.

And some specific considerations:

- We know there are important phenomena still to be observed (e.g. mixing-induced CPV in $B^0_s$ system, mixing related CPV in charm, $B^0 \rightarrow \mu\mu$ etc.);
- Similarly, there are many important measurements that can be made, which are unfeasible with current sample sizes (e.g. electroweak Penguin studies with $b \rightarrow d l^+ l^-$ decays, or precise study of $P_5$ with $B^0 \rightarrow K^* e^+ e^-$);
- A very large number of current observables are theoretically clean &/or statistics limited, so higher precision is strongly motivated (e.g. sin2$\beta$, $\gamma$, $\varphi_s$, $R_K$, $R_{K^*}$, $BR(B^0_s \rightarrow \mu\mu)/BR(B^0 \rightarrow \mu\mu)$ etc);
- A rich field where surprises are guaranteed (e.g. no one was expecting charm mixing, direct charm CPV, the X(3872), pentaquarks…).
Unwise to assume $\sim 10\%$ (or even $0.1\%$) is 'good enough'

"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \rightarrow \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

- Lev Okun, "The Vacuum as Seen from Moscow"

\[ \text{BR} (K^0_L \rightarrow \pi\pi) \sim 2 \times 10^{-3} \quad \text{Cronin, Fitch et al., 1964} \]
The LHC schedule – current planning

2019 2021 2024 2027 2030
LS2 Run 3 LS3 Run 4 LS4 Run 5

Install LHCb Upgrade I
Install HL-LHC and ATLAS & CMS phase-II Upgrades
Install LHCb Upgrade II

Belle II Belle III ?
The LHC schedule – current planning

2019
LS2
Install LHCb Upgrade I

2021
Run 3

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Run 4

2030
LS4
Run 5
Install LHCb Upgrade II

Belle II

Belle III ?
Why Belle II?

B production at the Υ(4S) presents several advantages over hadron environment

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).

*e.g.* $B \rightarrow \tau \nu$

[Diagram of B meson decay to tau and neutrino]
**Why Belle II?**

B production at the \( \Upsilon(4S) \) presents several advantages over hadron environment

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).

- Low multiplicity environment permits excellent performance for final states with \( \pi^0 \)'s, \( \eta \)'s, photons. Also, good efficiency for long-lived particles \( K_S \) and \( K_L \).

  e.g. most modes suitable for sin2\( \beta \) measurements involving Penguin loops (\( b\to c\bar{c}c \bar{b} \)) are rather tough at LHCb…

  …and other important decays e.g. \( D^0\to \gamma\gamma \), \( B^0\to \pi^0\pi^0 \)… are essentially inaccessible.
**Why Belle II?**

B production at the $\Upsilon(4S)$ presents several advantages over hadron environment

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).
- Low multiplicity environment permits excellent performance for final states with $\pi^0$s, $\eta$'s, photons. Also, good efficiency for long-lived particles $K_S$ and $K_L$.
- Coherent $B^0\bar{B}^0$bar production at $\Upsilon(4S)$ makes flavour tagging easier and compensates for lower sample sizes in time-dependent CP measurements

*e.g.* in $\sin2\beta$ measurement with $B^0 \rightarrow J/\psi K_S$

- $\varepsilon$ (tag effective) BaBar $\sim 31\%$
  - [PRD 79 (2009) 072009]
- $\varepsilon$ (tag effective) LHCb $\sim 3\%$
  - [PRL 115 (2015) 031601]
SuperKEKB goals: luminosity of $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$ and 50 ab$^{-1}$ by 2027

An ambitious 40-fold increase in luminosity on KEKB, to be achieved by squeezing the beams by $\sim 1/20$ and doubling the currents.
SuperKEKB and Belle II roadmap

- 6 mo shutdown for RF upgrade
- 4 years for the design lumi.
- 8 mo shutdown assuming we replace PXD and TOP PMT
- Conservative bottom-up estimate
All sub-detectors upgraded from Belle, except for ECL crystals and part of the barrel KLM
The LHC schedule – current planning

- 2019: LS2
- 2021: Run 3
- 2024: LS3
- 2027: Run 4
- 2030: LS4

Install LHCb Upgrade I
Install HL-LHC and ATLAS & CMS phase-II Upgrades
Install LHCb Upgrade II

Belle II
Belle III ?
Indirect search strategies for New Physics, e.g. precise measurements & the study of suppressed processes in the flavour sector become ever-more attractive following the experience of Runs 1 & 2 that direct signals are elusive. Our knowledge of flavour physics has advanced spectacularly thanks to LHCb. Maintaining this rate of progress beyond Run 2 requires significant changes.

The LHCb Upgrade

1) Full software trigger
   - Allows effective operation at higher luminosity
   - Improved efficiency in hadronic modes

2) Raise operational luminosity to $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$

Necessitates redesign of several sub-detectors & overhaul of readout

*Huge increase in precision:* Upgrade + Run 2 yield in hadronic modes ~ 60x that of Run 1; also perform studies beyond the reach of the current detector.

Flexible trigger and unique acceptance also opens up opportunities in other topics apart from flavour (‘a general purpose detector in the forward region’).
Run 1 & 2 detector
Required modifications

VELO: replace with new Si-pixel detector

TT: replace with new Si-strip detector

RICH: new photodetectors and FE electronics, and modify RICH 1 optics + mechanics

OT & IT: replace with scintillating fibre (SciFi) tracker

Calo system: replace FE electronics and remove PS/SPD

Muon system: replace FE electronics and remove M1

Full s/w trigger → Replace read-out boards and DAQ
Upgrade I detector

Installation is occurring in LS2, i.e. right now! For monthly progress videos look here.
The LHC schedule – current planning

Install LHCb Upgrade I

Install HL-LHC and ATLAS & CMS phase-II Upgrades

Install LHCb Upgrade II

Belle II

Belle III?
LHCb Upgrade II – the ultimate LHC flavour experiment

Begin after LS4 (2030). Operate at up to $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ & collect (at least) 300 fb$^{-1}$.

Expression of interest

Full physics case

In parallel, many studies from the machine side, summarised in a report which identifies

“a range of potential solutions for operating LHCb Upgrade II at a luminosity of up to $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and permitting the collection of 300 fb$^{-1}$ or more at IP8 during the envisaged lifetime of the LHC”

[CERN-LHCC-2017-003]

[CERN-LHCC-2018-027, also arXiv:1808.08865]

[CERN-ACC-NOTE-2018-038]

Flavour physics
Guy Wilkinson

September 2019
LHCb Upgrade II – the ultimate LHC flavour experiment

Begin after LS4 (2030). Operate at up to $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ & collect (at least) $300 \text{ fb}^{-1}$.

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Approved by LHCC and Research Board to proceed to TDRs

Expression of interest

Full physics case

LHCb Upgrade II – the ultimate LHC flavour experiment
Upgrade-II physics highlights

Too much to cover – here are a few examples:

γ determination:
sub-degree precision

CPV in charm
down to $10^{-5}$

Resolving New Physics
models with $R_K$ and friends

Two key points:

• Many key theoretically clean observables will remain statistics limited even after Upgrade I (e.g. $\gamma$, $\phi_s$, $\sin 2\beta$, $R_K$ and friends, $B(B^0 \rightarrow \mu\mu)/B(B_s \rightarrow \mu\mu)$…

• Also, will be able to access new observables e.g. angular studies of $b \rightarrow d e^+e^-$. This will enable great advances in CPV tests, and will give an almost doubling of the New Physics mass scale (w.r.t. start of HL-LHC era) to which we are sensitive.
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): current status
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): start of HL-LHC

Flavour physics
Guy Wilkinson

September 2019
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): after Upgrade II
Opportunities at the Z pole: FCC-ee

FCC-ee is a proposed $e^+e^-$ collider for 2039→ that would run at the Z pole (91 GeV), WW threshold (161 GeV), HZ energies (240 GeV), ttbar energies (350 & 365 GeV). (CEPC is a parallel Chinese project, with shorter timescale & ~lower design lumi.).
Opportunities at the Z pole: FCC-ee

FCC-ee was initially conceived as a facility for precision-Higgs physics, but it could also operate at $Z^0$ with ultra-high luminosity ($10^5 \text{[!] above LEP}$). Extremely interesting possibilities for electroweak physics, and also $b$-physics.

![Graph showing luminosity vs. $\sqrt{s}$]

- **Z (91.2 GeV)**: $4.6 \times 10^{36} \text{ cm}^2\text{s}^{-1}$
- **W$^+W^-$ (161 GeV)**: $5.6 \times 10^{36} \text{ cm}^2\text{s}^{-1}$
- **$t\bar{t}$ (350 GeV)**: $3.8 \times 10^{34} \text{ cm}^2\text{s}^{-1}$
- **$t\bar{t}$ (365 GeV)**: $3.1 \times 10^{34} \text{ cm}^2\text{s}^{-1}$
- **HZ (240 GeV)**: $1.7 \times 10^{35} \text{ cm}^2\text{s}^{-1}$
- **HZ (250 GeV)**: $1.35 \times 10^{34} \text{ cm}^2\text{s}^{-1}$
- **HZ (260 GeV)**: $0.82 \times 10^{34} \text{ cm}^2\text{s}^{-1}$

[arXiv:1906.02693]
Opportunities at the Z pole: FCC-ee

100 ab\(^{-1}\) at Z pole $\rightarrow >10^{12}$ bbar pairs. Exciting b-physics programme, particularly promising for channels including neutrals & missing energy, e.g. $B_s \rightarrow \tau^+\tau^-, B^0 \rightarrow K^*\tau^+\tau^-$. 

Background involving $B \rightarrow D_s(\tau\nu)X$ decays

~1000 reconstructed events, which can be subjected to angular analysis in same way as current LHCb $K^*\mu\mu$ sample
The last ~20 years has delivered a rich and extensive set of results in the field of quark-flavour physics.

The measurements are important because they both address many of the open questions of the Standard Model, and they are intrinsically sensitive to very high mass scales.

The programme is ongoing. Belle II and the LHCb Upgrades will bring great leap forwards in precision, and will make new observables accessible. New experiments in very different facilities will bring complementary information.

We are truly living through a golden age of flavour!
Backups
Improving sensitivity to the Wilson coefficient $C_9$ and the corresponding limits on New Physics mass scales, under different assumptions, from $R_K$ and $R_{K^*}$.

New Physics sensitivity through FCNCs

Start of HL-LHC

After Upgrade II

Now

Flavour physics
Guy Wilkinson