Looking beyond the Standard Model with the LHCb detector
What is LHCb?
A forward spectrometer for the LHC
with excellent tracking resolution

![Graph showing X and Y resolution - offline, exactly 1 PV](image)

- $\chi^2/\text{ndf} = 59.8/33$
- Prob = 0.002913
- X - Const 0.1061 ± 0.009001
- Power 0.6656 ± 0.0661
- Epsilon 0.0004835 ± 0.001658

![Graph showing Events/0.05 ps](image)

- $\sigma_{eff} = 45 \text{ fs}$

![Diagram of LHCb VELO Preliminary](image)
with excellent tracking resolution

LHCb’s is uniquely able to make high precision time-dependent $B_s$ sector measurements
and charged hadron separation
The LHC environment

- **40 MHz bunch crossing rate**
- **L0 Hardware Trigger**: 1 MHz readout, high $E_T/P_T$ signatures
  - 450 kHz $h^\pm$
  - 400 kHz $\mu/\mu\mu$
  - 150 kHz $e/\gamma$
- **Software High Level Trigger**: 29000 Logical CPU cores
  - Offline reconstruction tuned to trigger time constraints
  - Mixture of exclusive and inclusive selection algorithms
- **5 kHz Rate to storage**
- **Defer 20% to disk**
More than a B-factory

1. All $b\bar{b}$ events
More than a B-factory

1. All bbar events
2. All dimuon events
More than a B-factory

1. All bbar events
2. All dimuon events
3. As much charm signal as I can fit into a few kHz
More than a B-factory

1. All bbar events
2. All dimuon events
3. As much charm signal as I can fit into a few kHz
4. W/Z/Jets
More than a B–factory

1. All bbar events
2. All dimuon events
3. As much charm signal as I can fit into a few kHz
4. W/Z/Jets
5. Heavy things far from the pp vertex
Trigger signatures

B meson signatures:
- Large child transverse momentum
- Large child impact parameter or vertex displacement
- DiMuon candidate

“A B is the elephant of the particle zoo: it is very heavy and lives a long time” -- T. Schietinger
Real time event selection

1. Information gathering ("reconstruction") stage
Real time event selection

1. Information gathering ("reconstruction") stage
Real time event selection

1. Information gathering ("reconstruction") stage

2. Event selection stage
Real time event selection

1. Information gathering ("reconstruction") stage

2. Event selection stage

⇒

Selected
Rejected
Real time event selection

1. Information gathering ("reconstruction") stage

2. Event selection stage

3. Next reconstruction stage
Displaced track trigger

1. Full reconstruction of tracks in vertex locator
   Select displaced tracks

2. Reconstruction of displaced tracks in regions of interest

Region of interest defined by assumed track P&P
This satisfies almost all the wishlist

1. All bbar events
2. All dimuon events
3. As much charm signal as I can fit into a few kHz
4. W/Z/Jets
5. Heavy things far from the pp vertex

For dimuons and high $p_T$ muons we can be even more inclusive and not require displacement from the primary pp vertex, since they are rare enough.
A topological decision tree trigger

![Diagram showing decision tree](image-url)

### Figure 7: Lifetime acceptance function for an event of a two-body hadronic decay.

The shaded, light blue regions show the bands for accepting a track. After IP2 is too low in (a), it reaches the accepted range in (b). The actual measured lifetime lies in the accepted region (c), which continues to larger lifetimes (d).

### Figure 1:

B-candidate masses from $B \rightarrow K\pi\pi$ decays: (left) HLT2 2-body topological trigger candidates; (right) HLT2 3-body topological trigger candidates. In each plot, both the measured mass of the $n=2,3$ particle used in the trigger candidate (shaded) and the corrected mass obtained using Eq. 1 (unshaded) are shown. See Section 2 for discussion.

B mesons are long-lived particles; their mean flight distance in the LHC detector is $O(1 \text{ cm})$. The HLT2 topological lines exploit this fact by requiring that the trigger candidate's flight-distance $\chi^2$ value be greater than 64. The direction of flight is also required to be downstream, i.e., the secondary vertex must be downstream of the primary vertex. A large flight distance combined with a high parent mass results (on average) in daughters with large impact parameters. The HLT2 topological lines require that the sum of the daughter IP $\chi^2$ values be greater than 100, 150 and 200 for the 2-body, 3-body and 4-body lines, respectively.

One of the larger background contributions to the HLT2 topological lines comes from prompt $D$ mesons. To reduce this background, the HLT2 topological lines require that all $(n-1)$-body objects used by an $n$-body line either have a mass greater than 2.5 GeV (the object is too heavy to be a $D$) or that they have an IP $\chi^2 > 16$ (the object does not point at the primary vertex). An exhaustive list of the cuts used in all three of the HLT2 topological lines is given in Table 1.

### Table 2

The efficiency of the HLT2 topological lines on events that pass the L0 and HLT1 one-track triggers for various offline-selected $B$-decay Monte Carlo samples.
A topological decision tree trigger

\[ m_{\text{corrected}} = \sqrt{m^2 + |p'_{T\text{missing}}|^2 + |p'_{T\text{missing}}|^2} \]

The diagram illustrates the process of correcting a mass where:
- \( m \) is the mass of the trigger candidate,
- \( p'_{T\text{missing}} \) is the transverse momentum of the missing particle.

The corrected mass is obtained using the equation above, and the diagram shows the distribution of the corrected and measured masses for 2-body candidates.
The corrected mass goes into a multivariate algorithm to ensure both maximum background suppression and maximum inclusiveness.

For example, events with high enough $p_T$ are always accepted.

Measured output is almost 100% consistent with $b\bar{b}$ events.

We also have dedicated charm triggers, ask me if you want to know more about these!

See also LHCb public notes and trigger publications
LHCb-PUB-2011-002,003,016
http://arxiv.org/abs/1211.3055
The CKM matrix
aka finding Waldo
The CKM matrix

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

\[
V_{\text{CKM}} = \begin{pmatrix}
  1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
  -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
  A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
+ \sum_{n=4}^{N} O(\lambda^n)
\]
As a triangle
Experimental status through the years
Experimental status through the years
Experimental status through the years
Experimental status through the years

Further “experimental” evidence for interest in CKM matrix: Nobel prize...
The CKM triangle “state of the art”…
Zooming in on the apex

- $\sin 2\beta$
- $|V_{ub}|_{\tau\nu}$
- $|V_{ub}|_{SL}$
- $\Delta m_d$ & $\Delta m_s$
- $\Delta m_d$
- $\varepsilon_K$
- $\varepsilon_K$
- $\alpha$
- $\gamma$
- $\beta$
- $\rho$

excluded area has CL $> 0.95$

sol. w/ $\cos 2\beta < 0$
(excl. at CL $> 0.95$)
Why does the apex matter?

1. We know that Standard Model CP violation (through CKM matrix) cannot explain baryogenesis: we need new sources of CP violation.

2. These new sources should (generally) affect different observables in different ways.

3. Overconstraining the apex therefore tests the consistency of the Standard Model picture of CP violation: we want to know at what level it breaks down.
Ultimate theory error on $\gamma$

\[
\begin{align*}
\begin{array}{c}
\text{b} \\
\hline
\text{u} \\
\hline
\end{array}
\quad & 
\begin{array}{c}
\text{c} \\
\hline
\text{s} \\
\hline
\end{array}
\quad & 
\begin{array}{c}
\text{b} \\
\hline
\text{c} \\
\hline
\end{array}
\quad & 
\begin{array}{c}
\text{u} \\
\hline
\text{s} \\
\hline
\end{array}
\end{align*}
\]

\[
\begin{align*}
\begin{array}{c}
\text{b} \\
\hline
\text{u} \\
\hline
\end{array}
\quad & 
\begin{array}{c}
\text{c} \\
\hline
\text{s} \\
\hline
\end{array}
\quad & 
\begin{array}{c}
\text{b} \\
\hline
\text{b}, \text{s}, \text{d} \\
\hline
\end{array}
\quad & 
\begin{array}{c}
\text{c} \\
\hline
\text{s} \\
\hline
\end{array}
\end{align*}
\]

\[
\begin{align*}
\begin{array}{c}
\text{b} \\
\hline
\text{u} \\
\hline
\end{array}
\quad & 
\begin{array}{c}
\text{b}, \text{c}, \text{u} \\
\hline
\text{s} \\
\hline
\end{array}
\quad & 
\begin{array}{c}
\text{b} \\
\hline
\text{W, Z} \\
\hline
\end{array}
\quad & 
\begin{array}{c}
\text{c} \\
\hline
\text{W} \\
\hline
\end{array}
\end{align*}
\]

\[
\begin{align*}
\begin{array}{c}
\text{b} \\
\hline
\text{u} \\
\hline
\end{array}
\quad & 
\begin{array}{c}
\text{b}, \text{s}, \text{d} \\
\hline
\text{c} \\
\hline
\end{array}
\quad & 
\begin{array}{c}
\text{b} \\
\hline
\text{W} \\
\hline
\end{array}
\quad & 
\begin{array}{c}
\text{c} \\
\hline
\text{s} \\
\hline
\end{array}
\end{align*}
\]
What scales does $\gamma$ probe?

$$|\delta \gamma| \lesssim \mathcal{O}(10^{-7})$$

<table>
<thead>
<tr>
<th>Probe</th>
<th>$\Lambda_{NP}$ for (N)MFV NP</th>
<th>$\Lambda_{NP}$ for gen. FV NP</th>
<th>$B\bar{B}$ pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ from $B \to DK^{1)}$</td>
<td>$\Lambda \sim \mathcal{O}(10^2$ TeV)</td>
<td>$\Lambda \sim \mathcal{O}(10^3$ TeV)</td>
<td>$\sim 10^{18}$</td>
</tr>
<tr>
<td>$B \to \tau \nu^{2)}$</td>
<td>$\Lambda \sim \mathcal{O}($ TeV)</td>
<td>$\Lambda \sim \mathcal{O}(30$ TeV)</td>
<td>$\sim 10^{13}$</td>
</tr>
<tr>
<td>$b \to s s d^{3)}$</td>
<td>$\Lambda \sim \mathcal{O}($ TeV)</td>
<td>$\Lambda \sim \mathcal{O}(10^3$ TeV)</td>
<td>$\sim 10^{13}$</td>
</tr>
<tr>
<td>$\beta$ from $B \to J/\psi K_S^{4)}$</td>
<td>$\Lambda \sim \mathcal{O}(50$ TeV)</td>
<td>$\Lambda \sim \mathcal{O}(200$ TeV)</td>
<td>$\sim 10^{12}$</td>
</tr>
<tr>
<td>$K - \bar{K}$ mixing$^{5)}$</td>
<td>$\Lambda &gt; 0.4$ TeV (6 TeV)</td>
<td>$\Lambda &gt; 10^{3(4)}$ TeV</td>
<td>now</td>
</tr>
</tbody>
</table>

Acknowledgements:
We would like to thank Dan Pirjol for collaboration at earlier stages of this work and many discussions and helpful comments on the manuscript. J.B. and J.Z. were supported in part by the U.S. National Science Foundation under CAREER Grant PHY-1151392. J.B. would like to thank the Kavli Institute for Theoretical Physics for hospitality.

1. Gamma from $B \rightarrow DK$ measures the tree-level apex.

2. Other measurements (including measurements of gamma, e.g. from $B \rightarrow hh$) are sensitive to loop diagrams.

$\Rightarrow$ Any discrepancy allows us to learn about the scale (and maybe the nature) of physics Beyond the Standard Model.
The many faces of $\gamma$

The number of ways in which it is being measured is growing...
But the same basic idea

But they all involve interfering $V_{ub}$ and $V_{cb}$ decays to the same final state.
How clean are our signals?

The “ADS” $B \to DK$ decay mode, total branching fraction $O(10^{-7})$
Combining the individual measurements

- ADS/GLW 1 fb$^{-1}$ analysis
- GGSZ 3 fb$^{-1}$ analysis
Combining the individual measurements

\( \gamma = (67 \pm 12)° \)
What about the 2D likelihoods?
Compared to the B–factories
The Dimuon Trinity

\( B_s \to J/\psi h h \)

\( B \to X_s \mu \mu \)

\( B \to \mu \mu \)
We love dimuons

\[ B^0_s \rightarrow \mu^+ \mu^- ? \]
And we love loop diagrams
B→μμ, the father of all dimuons

Precise SM predictions due to decay diagrams

- $\text{Br}(B_d^{−} \to \mu \mu) = (1.1 \pm 0.2) \times 10^{-10}$
- $\text{Br}(B_s^{−} \to \mu \mu) = (3.5 \pm 0.2) \times 10^{-9}$

Buras et al, EPJ C72 (2012) 2172; see also PRL109 (2012) 041801

A quest of decades...

Signature:

[Diagram showing a mu+ and a mu- with a 1 cm distance between them]
LHCb and CMS, united we stand


![Graph showing candidates with BDT>0.7 and 3 fb⁻¹ data](image)

\[ B(B_s^0 \rightarrow \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}, \]

\[ B(B^0 \rightarrow \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}) \times 10^{-10} \]

\[ \rightarrow 4.0\sigma \]


![Graph showing weighted events with CMS data](image)

\[ B(B_s^0 \rightarrow \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}, \]

\[ B(B^0 \rightarrow \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10} \]

\[ \rightarrow 4.3\sigma \]
$B^0/B^0_s \rightarrow \mu \mu$, the golden ratio
\[ \frac{1}{d^4 \Gamma/d\Gamma dq^2} \frac{d^4 \Gamma}{d\theta d\theta K d\phi dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_l ight. \\
- F_L \cos \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi \\
+ \left. S_6^s \sin^2 \theta_K \cos \phi + S_7 \sin 2\theta_K \sin \theta_l \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right] \]

\[ q^2 = \text{dimuon invariant mass}^2 \]

Example observables: forward-backward asymmetry (sensitive to \( S_6 \)), \( K^*^0 \) longitudinal polarization...
B^0 \rightarrow K^* \mu\mu angular analysis

B candidate mass in bins of q^2
(in total: 883\pm34 candidates in 1/fb)
at low $q^2$, ratios $P'_{i=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$ largely free of FF uncertainties, while sensitivity to NP remains (Descotes-Genon, Hurth, Matias, Virto, arXiv:1303.5794)
We also love tensions

At low $q^2$, ratios $P'_{i=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_{1L}(1-F_{1L})}}$ largely free of FF uncertainties, while sensitivity to NP remains (Descotes-Genon, Hurth, Matias, Virto, arXiv:1303.5794)

2.8σ global significance : 3 fb⁻¹ result coming soon!
The isospin puzzle

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

**SM prediction**: basically 0

$$B^0 \rightarrow K^0\mu^+\mu^- \rightarrow K_s\mu^+\mu^-$$

$$B^+ \rightarrow K^+\mu^+\mu^-$$

$$B^0 \rightarrow K^{*0}\mu^+\mu^- \rightarrow K^+\pi^-\mu^+\mu^-$$

$$B^+ \rightarrow K^{*+}\mu^+\mu^- \rightarrow K_s^0\pi^+\mu^+\mu^-$$
The isospin puzzle

4.4σ says "not 0". What gives? Again, 3fb⁻¹ result coming soon!
The angular observables dominate the systematic uncertainty of 10% due to the branching fraction of the normalisation channel. This is small compared to the exponential shape. Peaking backgrounds cause a systematic uncertainty of 1–2% on the linear function to describe the mass distribution of the background instead of the nominal 0. The magnitude of the signal decay in the B to Xs mu mu sector is typically of the order of 1–2%. The correction procedure for the impact parameter leads to a systematic uncertainty of 1–2%. Other systematic uncertainties of the same resolution have an effect of up to 5%, which is evaluated by using a correction procedure for the impact parameter (up to 5%) in each bin. Simulated events are corrected for known and theoretical uncertainties. The background shape has an effect of up to 5%. Averaging the relative uncertainty on the branching fraction of the normalisation channel.

The systematic uncertainties will be discussed in detail in section 4.1. The differential branching fraction arises from the uncertainty on the branching fraction of the normalisation channel. The size of the systematics uncertainties on the differential branching fraction is measured to be 0.05 ± 0.07. No error band is given for the theory prediction. The dashed curve denotes the leading order prediction scaled to a total branching fraction of 0.05. The background shape has an effect of up to 5%, which is evaluated by using a correction procedure for the impact parameter. Averaging the relative uncertainty on the branching fraction of the normalisation channel. The total branching fraction is 0.1 ± 0.06. Error bars include both statistical uncertainties.

Many of the systematic uncertainties are determined using unbinned maximum likelihood fits to the data.

Figure 2: Invariant mass of K^+ K^- mu + mu - candidates in six bins of invariant dimuon mass squared.
B→X_sμμ, the B_s sector
\(B_s \to J/\psi \pi \pi \) and \(B_s \to J/\psi KK\)
Simultaneous lifetime/angular fit

- **CP-even**
- **CP-odd**
- **S-wave**
\[ \mathcal{B}_s \to \varphi \varphi \text{ (ok, not a dimuon, but ...)} \]
What of the future?
Building an experiment 101

LHCb Management

Funding agencies
Let’s be optimists
What is our upgrade all about?
What is our upgrade all about?

Only being able to read out the full detector at 1 MHz severely limits the event yields for hadronic modes.

To run at higher luminosity we must remove this bottleneck.

=> Full 40 MHz detector readout

=> All software trigger

=> Keep a hardware LLT (low-level trigger) as a backup for early running before the full farm is purchased

=> Run at $2 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
Also improve some subdetectors

- UT
- SciFi
- MUONS
- VeloPix
- RICH
- CALO

UPGRADED
RETAINED
PID performance in the upgrade

Figure 2.31: The PID performance of the upgraded geometrical layout for Lumi4, 10 and 20.

(i) Completion of R&D

Several of the tasks included in the schedule will involve further R&D prior to production.

Figure 2.32: The kaon identification efficiency (magenta and red) and pion misidentification probability (grey and blue) as a function of track momentum for the upgraded geometry at Lumi20 (with DLL cuts of 0 and 5, respectively).
VELOPIX performance in the upgrade

<table>
<thead>
<tr>
<th></th>
<th>Existing VELO [%]</th>
<th>Upgraded VELO [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\nu = 2$</td>
<td>$\nu = 7.6$</td>
</tr>
<tr>
<td>Ghost rate</td>
<td>6.2</td>
<td>25.0</td>
</tr>
<tr>
<td>Clone rate</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VELO, $p &gt; 5 \text{ GeV/c}$</td>
<td>95.0</td>
<td>92.7</td>
</tr>
<tr>
<td>long</td>
<td>97.9</td>
<td>93.7</td>
</tr>
<tr>
<td>long, $p &gt; 5 \text{ GeV/c}$</td>
<td>98.6</td>
<td>95.7</td>
</tr>
<tr>
<td>$b$-hadron daughters</td>
<td>99.0</td>
<td>95.4</td>
</tr>
<tr>
<td>$b$-hadron daughters, $p &gt; 5 \text{ GeV/c}$</td>
<td>99.1</td>
<td>96.6</td>
</tr>
</tbody>
</table>

Figure 23: Pattern recognition performance of the upgrade VELO as function of the number of primary vertices, measured using simulated events containing the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$. (left: reconstruction efficiency for particles reconstructible as long tracks, right: ghost rate).
The all-software trigger

LHCb Upgrade Trigger Diagram

40 MHz bunch crossing rate

LLT : 10-30 MHz readout, high $P_T$ signatures ($h^\pm/\mu/\mu/e/\gamma$)

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

20 kHz Rate to storage
The all-software trigger

LHCb Upgrade Trigger Diagram

**40 MHz bunch crossing rate**

**LLT : 10-30 MHz readout, high Pr signatures (h±/µ/µµ/e/γ)**

**Software High Level Trigger**

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers

**20 kHz Rate to storage**

### LHCb Upgrade Trigger Diagram

<table>
<thead>
<tr>
<th></th>
<th>Run 3</th>
<th>Run 4</th>
<th>Run 5+</th>
</tr>
</thead>
</table>
|                      | 2019–21| 2024–26| 2028–30+
| LLT rate (MHz)       | 10     | 15     | 15     |
| $E_T$ cut (GeV)      | 3.2    | 2.4    | 2.4    |
| $\phi_s(B^0_s \rightarrow \phi\phi)$ | 1.35   | 1.6    | 1.6    |
| $\gamma(B^+ \rightarrow DK^+)$ | 1.35   | 1.6    | 1.6    |
| $A_T(D^0 \rightarrow K^+K^-)$ | 1.4    | 2.1    | 2.1    |

Gain 50–100% efficiency for hadronic final states

Aim to eventually run “quasi-triggerless” : implement offline reconstruction and selections in the trigger for any final state which can be reconstructed by the detector.
Stat uncertainty projections

B→μμ

b→s penguins

K*μμ

Gamma from Trees
Tremendous reach whatever happens

GPDs directly observe new physics? yes → Need to measure flavour parameters beyond the LHC

no → Need to search for new physics beyond LHC scales → FLAVOUR STUDIES REQUIRED
Backups
More $B^0\rightarrow K^*\mu\mu$ angular analysis

In order to estimate the size of the bias, it is assumed that the transverse asymmetries are small in the SM. Previous analyses by LHCb, BaBar, Belle and CDF have not considered the dependence of the angular observables. Neglecting these terms leads to a bias in the measurement of the muon mass was small compared to that of the dimuon system. Whilst this assumption is expected to be suppressed by the size of the strong phases and be close to zero in every bin. In the previous section, when fitting the angular distribution, it was assumed that the angular terms receive an additional correction. This functional form displays the correct behaviour since it tends to zero as $q^2$ rises linearly (with the constraint that $q^2 < 0$). Even though $\frac{1}{(1 - \frac{m_\mu^2}{q^2} - \frac{m_\mu^2}{q^2})}$ is generally unknown, it can be estimated by summing over the observed candidates. A concrete example of how this is done is given in appendix IQQFCITGGOGPVYKVJRTGFKEVKQPU. The experimental data points overlay the SM prediction across each bin and comparing this to the value that is obtained from the fit to the 0 $q^2$ bin, reflecting the dominance of the photon contribution in this region. The lowest $q^2$ bin has been corrected for the transverse asymmetry dependence, proportional to $q^2$. The lowest $q^2$ bin is indicated by $q^2 = q^2_{\text{min}}$. The lowest $q^2$ bin has been corrected for the transverse asymmetry dependence, proportional to $q^2$. The lowest $q^2$ bin is indicated by $q^2 = q^2_{\text{min}}$.

The coe cient $\frac{1}{(1 - \frac{m_\mu^2}{q^2} - \frac{m_\mu^2}{q^2})}$ is used. This functional form displays the correct behaviour since it tends to zero as $q^2$ rises linearly (with the constraint that $q^2 < 0$). Even though $\frac{1}{(1 - \frac{m_\mu^2}{q^2} - \frac{m_\mu^2}{q^2})}$ is generally unknown, it can be estimated by summing over the observed candidates. A concrete example of how this is done is given in appendix IQQFCITGGOGPVYKVJRTGFKEVKQPU. The experimental data points overlay the SM prediction across each bin and comparing this to the value that is obtained from the fit to the 0 $q^2$ bin, reflecting the dominance of the photon contribution in this region. The lowest $q^2$ bin has been corrected for the transverse asymmetry dependence, proportional to $q^2$. The lowest $q^2$ bin is indicated by $q^2 = q^2_{\text{min}}$. The lowest $q^2$ bin has been corrected for the transverse asymmetry dependence, proportional to $q^2$. The lowest $q^2$ bin is indicated by $q^2 = q^2_{\text{min}}$.
$K_s \rightarrow \mu \mu$

Figure 3. Background model fitted to the data separated along (left) TIS and (right) TOS trigger categories. The vertical lines delimit the search window.

$$\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-) < 11(9) \times 10^{-9}$$
D⁰ mixing

Events are triggered by signatures consistent with a particle originating from the PV. Selected candidates with fit projections overlaid. The bottom plots show the normalized residuals between the data points and the fits.
D⁰ mixing

![Graph showing decay time evolution](image)

<table>
<thead>
<tr>
<th>Fit type</th>
<th>Parameter</th>
<th>Fit result (10⁻³)</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing (9.5/10)</td>
<td>( R_D )</td>
<td>3.52 ± 0.15</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>( y' )</td>
<td>7.2 ± 2.4</td>
<td>-0.954</td>
</tr>
<tr>
<td></td>
<td>( x^2 )</td>
<td>-0.09 ± 0.13</td>
<td>1</td>
</tr>
<tr>
<td>No mixing (98.1/12)</td>
<td>( R_D )</td>
<td>4.25 ± 0.04</td>
<td>1</td>
</tr>
</tbody>
</table>
\[ A_{\Gamma} \equiv \frac{\hat{\Gamma} - \tilde{\Gamma}}{\hat{\Gamma} + \tilde{\Gamma}} \approx \eta_{CP} \left( \frac{A_m + A_d}{2} y \cos \phi - x \sin \phi \right) \]
\[ A_{\Gamma} \equiv \frac{\hat{\Gamma} - \hat{\Gamma}}{\hat{\Gamma} + \hat{\Gamma}} \approx \eta_{CP} \left( \frac{A_m + A_d}{2} y \cos \phi - x \sin \phi \right) \]

\[ A_{\Gamma} (KK) = (-0.35 \pm 0.62 \pm 0.12) \cdot 10^{-3} \]

\[ A_{\Gamma} (\pi\pi) = (0.33 \pm 1.06 \pm 0.14) \cdot 10^{-3} \]

<table>
<thead>
<tr>
<th>Source</th>
<th>( A_{\Gamma}^{\text{unb}} (KK) )</th>
<th>( A_{\Gamma}^{\text{unb}} (KK) )</th>
<th>( A_{\Gamma}^{\text{unb}} (\pi\pi) )</th>
<th>( A_{\Gamma}^{\text{unb}} (\pi\pi) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partially reconstructed backgrounds</td>
<td>( \pm 0.02 )</td>
<td>( \pm 0.09 )</td>
<td>( \pm 0.00 )</td>
<td>( \pm 0.00 )</td>
</tr>
<tr>
<td>Charm from ( b ) decays</td>
<td>( \pm 0.07 )</td>
<td>( \pm 0.55 )</td>
<td>( \pm 0.07 )</td>
<td>( \pm 0.53 )</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>( \pm 0.02 )</td>
<td>( \pm 0.40 )</td>
<td>( \pm 0.04 )</td>
<td>( \pm 0.57 )</td>
</tr>
<tr>
<td>Acceptance function</td>
<td>( \pm 0.09 )</td>
<td>( - )</td>
<td>( \pm 0.11 )</td>
<td>( - )</td>
</tr>
<tr>
<td>Magnet polarity</td>
<td>( - )</td>
<td>( \pm 0.58 )</td>
<td>( - )</td>
<td>( \pm 0.82 )</td>
</tr>
<tr>
<td>Total syst. uncertainty</td>
<td>( \pm 0.12 )</td>
<td>( \pm 0.89 )</td>
<td>( \pm 0.14 )</td>
<td>( \pm 1.13 )</td>
</tr>
</tbody>
</table>

**Acknowledgements**

Collaboration, B. Aubert at the LHCb institutes. We acknowledge support from BMBF (Germany), INFN (Italy), NWO and SURF (The Netherlands), PIC (Spain); SNSF and SER (Switzerland); NAS Ukraine. The theoretical calculation of \( \tau \) is presented by CERN and from the national agencies.
HFAG charm latest

The diagrams show the latest results from the HFAG charm collaboration, focusing on CPV (Charge Parity Violation) in the CHARM 2013 analysis. The plots display the distribution of $x$ and $y$ parameters, with contour lines indicating the significance levels (1σ, 2σ, 3σ, 4σ, 5σ) for the data points.
HFAG charm latest
K^0_{ee} in the low q^2 region

Figure 1. Dominant Standard Model diagrams contributing to the decay $B^0 \to K^{*0} e^+ e^-$. Furthermore, the formalism is greatly simplified due to the negligible lepton mass. It is therefore interesting to carry out an angular analysis of the decay $B^0 \to K^{*0} e^+ e^-$ in the region where the dilepton mass is less than 1000 MeV/c^2. The lower limit is set to 30 MeV/c^2 since below this value the sensitivity for the angular analysis decreases because of a degradation in the precision of the orientation of the $e^+ e^-$ decay plane due to multiple scattering. Furthermore, the contamination from the $B^0 \to K^{*0} e^+ e^-$ decay, with the photon converting into an $e^+ e^-$ pair in the detector material, increases significantly as $q^2 \to 0$. The first step towards performing the angular analysis is to measure the branching fraction in this very low dilepton invariant mass region. Indeed, even if there is no doubt about the existence of this decay, no clear signal has been observed in this region and therefore the partial branching fraction is unknown. The only experiments to have observed $B^0 \to K^{*0} e^+ e^-$ to date are BaBar and Belle, which have collected about $30 B^0 \to K^{*0} e^+ e^-$ events each in the region $q^2 < 2 GeV/c^4$, summing over electron and muon final states.

The LHCb detector, dataset and analysis strategy

The study reported here is based on pp collision data, corresponding to an integrated luminosity of $1.0 fb^{-1}$, collected at the Large Hadron Collider (LHC) with the LHCb detector at a centre-of-mass energy of 7 TeV during 2011. The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. It includes a high precision tracking system consisting of a silicon-strip vertex detector (VELO) surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power
Figure 3. Invariant mass distributions for the $B^0\rightarrow J/\psi(K\pi)\pi^0$ decay mode for the (left) HWElectron and (right) HWTIS trigger categories. The dashed line is the signal PDF, the light grey area corresponds to the combinatorial background, the medium grey area is the partially reconstructed hadronic background and the dark grey area is the partially reconstructed $J/\psi$ background component.
$K^*_{0}ee$ in the low $q^2$ region

\[ \mathcal{B}(B^0 \rightarrow K^*_{0} e^+ e^-)_{30-1000 \text{ MeV}/c^2} = (3.1^{+0.9}_{-0.8} +0.2_{-0.3} \pm 0.2) \times 10^{-7}. \]
LFV searches

- Left diagram: \( W \to \nu_j \mu^- \bar{\nu}_j \)
- Right diagram: \( \tau^- \to \mu^- \mu^+ \)

(a) and (b) illustrate the candidates distribution in the mass of \( \phi(\mu^+\mu^-) \pi^- \) for LHCb.
LFV searches

![Graphs showing candidates in different mass ranges.](image)

- **Graph (a):** $M_{\text{sub}} \in [0.65, 1.0]$, $M_{\text{PID}} \in [0.725, 1.0]$
- **Graph (b):** $M_{\text{sub}} \in [0.40, 1.0]$
- **Graph (c):** $M_{\text{sub}} \in [0.40, 1.0]$

The likelihood values for (most signal-like) to (most background-like) are indicated in the graphs.

**Table 2**

<table>
<thead>
<tr>
<th>Mass Range</th>
<th>Candidates / (10 MeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
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</tbody>
</table>

**Table 3**

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We express our gratitude to our colleagues in the CERN accelerator complexes, the CERN support service, the CERN experimental collaborations and, of course, to our funding agencies. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); NSFC (China); ANCS/IFA (Romania); Ministry of Education and Science of the Russian Federation, together with the Russian Foundation for Basic Research, theDynarex Foundation and the Joint Institute for Nuclear Research; Ministry of Education, Youth and Sports (Czech Republic); Academy of Finland, Quadrature Program of the Academy of Finland, mineralogy project and Geological Survey of Finland (Finland); American Physical Society, the NSF, the Pappalardo Fellowship Fund, the University of Chicago, Institute of Physics and the University of Illinois at Urbana-Champaign (USA); BMBF, DFG, HGF, MPG, AvH Foundation, and the Leibniz Association (Germany); INFN (Italy); Ministry of Education and Research (Israel); Natural Science Foundation of China, 100 Talents Program of China, Huairou Young Scholar Program, and the Chinese Academy of Sciences (China); the Council of Scientific and Industrial Research, the Department of Atomic Energy, the Department of Electronics, and the Department of Space (India); and the Government of Canada through NSERC, CFI, and PPARC (Canada); INFN (Italy); Ministry of Education and Research (Israel); Natural Science Foundation of China, 100 Talents Program of China, Huairou Young Scholar Program, and the Chinese Academy of Sciences (China); the Council of Scientific and Industrial Research, the Department of Atomic Energy, the Department of Electronics, and the Department of Space (India); and the Government of Canada through NSERC, CFI, and PPARC (Canada); INFN (Italy); Ministry of Education and Research (Israel); Natural Science Foundation of China, 100 Talents Program of China, Huairou Young Scholar Program, and the Chinese Academy of Sciences (China); the Council of Scientific and Industrial Research, the Department of Atomic Energy, the Department of Electronics, and the Department of Space (India); and the Government of Canada through NSERC, CFI, and PPARC (Canada); INFN (Italy); Ministry of Education and Research (Israel); Natural Science Foundation of China, 100 Talents Program of China, Huairou Young Scholar Program, and the Chinese Academy of Sciences (China); the Council of Scientific and Industrial Research, the Department of Atomic Energy, the Department of Electronics, and the Department of Space (India); and the Government of Canada through NSERC, CFI, and PPARC (Canada).
LFV searches

![Figure 4](image_url)

(a) Distribution of $\text{CL}_1$ for the expected limits of $\tau \rightarrow \mu^+ \mu^- \mu^-$ as functions of the assumed branching fractions, under the hypothesis to observe background events only.

(b) Distribution of $\text{CL}_1$ for the expected limits of $\tau \rightarrow \mu^- \mu^+ \mu^-$ as functions of the assumed branching fractions, under the hypothesis to observe background events only.

(c) Distribution of $\text{CL}_1$ for the expected limits of $\tau \rightarrow \mu^- \mu^+ \mu^-$ as functions of the assumed branching fractions, under the hypothesis to observe background events only.
Prophecy for 2010 -- clearly a bit optimistic!
A decade of overachievement...

Belle ADS

BABAR ADS

CDF ADS

FIG. 2: $\Delta E$ distributions ($N\beta > 0.9$) for $|K^+\pi^-|p\bar{K}^-$ (left upper), $|K^-\pi^+|p\bar{K}^+$ (right upper), $|K^+\pi^-|p\bar{\pi}^-$ (left lower), and $|K^-\pi^+|p\pi^-$ (right lower). The curves show the same components as in Fig. 1.

FIG. 8: (color online). Projections on mass (a, b, c) and $NN$ (d, e, f) of the fit results for $DK^+$ (a, d), $DK^+\bar{K}^-$ (b, e) and $DK^+\bar{K}^-\bar{K}^+$ (c, f) WS decays, for samples enriched in signal with the requirements $NN > 0.94$ (mass projections) or $3.275 < m < 3.285$ GeV$^2$ ($NN$ projections). The points with error bars are data. The curves represent the fit projections for signal plus background (solid), the sum of all background components (dashed), and $\bar{q}$ background only (dotted).

FIG. 1: Invariant mass distributions of $B^+ \to D^+\bar{K}^-$ for the suppressed mode (bottom row on the left) and intermediate modes on the right). The peak mass is assigned to the charged track from the $B$ candidate decay vertex. The projections of the common likelihood fit (see text) are overlaid.

Left to right:

arXiv:1103.5951v2

PRD 82 072006 (2010)

arXiv:1108.5765v2
What has this enabled LHCb to produce?

- GLW/ADS in $B \to DK, D\pi$ with $D \to hh$
- ADS in $B \to DK, D\pi$ with $D \to hhhh$
- GGSZ in $B \to DK$ with $D \to K_S hh$
- GLW in $B \to DK^0$
- GLW in $B \to Dhhh$

Frequentist $\gamma$ combination

Time dependent CPV in $B_S \to D_S K$
What has this enabled LHCb to produce?

**GLW/ADS in** $B \to D K, D \pi$ with $D \to h h$

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**GGSZ in** $B \to D K$ with $D \to K S h h$

**GLW in** $B \to D K^0$

**GLW in** $B \to D h h h$

**Frequentist $\gamma$ combination**

**Time dependent CPV in** $B_s \to D_s K$
Aside on the CKM matrix structure

\[
\begin{bmatrix}
  d & s & b \\
  u & c & t \\
  t & b & u
\end{bmatrix}
\]

Bigger box == stronger coupling
(not to scale)
Observables $\Leftrightarrow$ physics parameters

double Cabibbo suppressed

colour suppressed

colour favoured

$B^+ \bar{b} \rightarrow u \bar{s} K^+$

$D^0 \bar{c} \rightarrow u \bar{d} \pi^+$

$D^0 \bar{c} \rightarrow c \bar{u} K^-$

$B^+ \rightarrow u \bar{s} K^+$

$D^0 \rightarrow c \bar{u} \pi^+$

$D^0 \rightarrow c \bar{u} K^-$
Observables $\leftrightarrow$ physics parameters

\[
\begin{align*}
R_{K/\pi}^{K\pi} &= \frac{1 + (r_{BRD})^2 + 2r_{BRD} \cos(\delta_B - \delta_D) \cos \gamma}{1 + (r_{BRD})^2 + 2r_{BRD} \cos(\delta_B - \delta_D) \cos \gamma}
\end{align*}
\]

\[
R_{K/\pi}^{KK} = \frac{1 + r_B^2 + 2r_B \cos \delta_B \cos \gamma}{1 + r_B^2 + 2r_B \cos \delta_B \cos \gamma}
\]

\[
A_{\pi}^{F_{uv}} = 2r_{BRD} \sin(\delta_B - \delta_D) \sin \gamma
\]

\[
A_{\pi}^{F_{uv}} = 2r_B^2 \sin(\delta_B - \delta_D) \sin \gamma
\]

\[
A_{\pi}^{KK} = 2r_B \sin \delta_B \sin \gamma
\]

\[
A_{\pi}^{\pi} = 1 + r_B^2 + r_B \cos \delta_B \cos \gamma
\]

\[
A_{K/\pi}^{KK} = 2r_B \sin \delta_B \sin \gamma
\]

\[
A_{K/\pi}^{\pi} = 1 + r_B^2 + r_B \cos \delta_B \cos \gamma
\]

\[
A_{\pi}^{ADS} = \frac{\frac{r_B^2 + r_D^2 + 2r_{BRD} \cos(\delta_B + \delta_D) \cos \gamma}{1 + (r_{BRD})^2 + 2r_{BRD} \cos(\delta_B - \delta_D) \cos \gamma}}
\]

\[
A_{\pi}^{ADS} = \frac{2r_{BRD} \sin(\delta_B + \delta_D) \sin \gamma}{r_B^2 + r_D^2 + 2r_{BRD} \cos(\delta_B + \delta_D) \cos \gamma}
\]

\[
R_{\pi}^{ADS} = \frac{r_B^2 + r_D^2 + 2r_{BRD} \cos(\delta_B + \delta_D) \cos \gamma}{1 + (r_{BRD})^2 + 2r_{BRD} \cos(\delta_B - \delta_D) \cos \gamma}
\]

\[
A_{\pi}^{ADS} = \frac{2r_{BRD} \sin(\delta_B + \delta_D) \sin \gamma}{r_B^2 + r_D^2 + 2r_{BRD} \cos(\delta_B + \delta_D) \cos \gamma}
\]
Observables $\leftrightarrow$ physics parameters

$r_B, \delta_B$ are the amplitude ratio and relative strong phase of the interfering $B$ decays

\[
R_{K/\pi}^{K\pi} = R \frac{1 + (r_B r_D)^2 + 2 r_B r_D \cos(\delta_B - \delta_D) \cos \gamma}{1 + (r_B^2 r_D)^2 + 2 r_B^2 r_D \cos(\delta_B^2 - \delta_D) \cos \gamma}
\]

\[
R_{K/\pi}^{KK} = R \frac{1 + r_B^2 + 2 r_B \cos \delta_B \cos \gamma}{1 + r_B^2 + 2 r_B^2 \cos \delta_B \cos \gamma}
\]

\[
A_{\pi}^{F_{uv}} = \frac{2 r_B r_D \sin(\delta_B - \delta_D) \sin \gamma}{1 + (r_B r_D)^2 + 2 r_B r_D \cos(\delta_B - \delta_D) \cos \gamma}
\]

\[
A_{\pi}^{F_{uv}} = \frac{2 r_B^2 r_D \sin(\delta_B^2 - \delta_D) \sin \gamma}{1 + (r_B^2 r_D)^2 + 2 r_B^2 r_D \cos(\delta_B^2 - \delta_D) \cos \gamma}
\]

\[
A_{KK}^{K} = A_{\pi}^{\pi} = \frac{2 r_B \sin \delta_B \sin \gamma}{1 + r_B^2 + r_B \cos \delta_B \cos \gamma}
\]

\[
A_{KK}^{K} = A_{\pi}^{\pi} = \frac{2 r_B \sin \delta_B \sin \gamma}{1 + r_B^2 + r_B^2 \cos \delta_B \cos \gamma}
\]

\[
R^{ADS}_{K} = \frac{r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos \gamma}{1 + (r_B r_D)^2 + 2 r_B r_D \cos(\delta_B - \delta_D) \cos \gamma}
\]

\[
A^{ADS}_{\pi} = \frac{2 r_B r_D \sin(\delta_B + \delta_D) \sin \gamma}{r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos \gamma}
\]

\[
R_{\pi}^{ADS} = \frac{r_B^2 + r_D^2 + 2 r_B^2 r_D \cos(\delta_B^2 + \delta_D) \cos \gamma}{1 + (r_B^2 r_D)^2 + 2 r_B^2 r_D \cos(\delta_B^2 - \delta_D) \cos \gamma}
\]

\[
A_{\pi}^{ADS} = \frac{2 r_B^2 r_D \sin(\delta_B^2 + \delta_D) \sin \gamma}{r_B^2 + r_D^2 + 2 r_B^2 r_D \cos(\delta_B^2 + \delta_D) \cos \gamma}
\]
\( r_B, \delta_B \) are the amplitude ratio and relative strong phase of the interfering B decays

\( r_D, \delta_D \) are hadronic parameters describing the \( D^0 \to K\pi(\pi K) \) decays

\( r_D \) is the amplitude ratio of the CF to DCS \( D^0 \) decays

\( \delta_D \) is the relative strong phase between the CF and DCS decays

Both are taken from CLEO measurements.
Observables ↔ physics parameters

\( r_B, \delta_B \) are the amplitude ratio and relative strong phase of the interfering \( B \) decays

\( r_D, \delta_D \) are hadronic parameters describing the \( D^0 \to K\pi(\pi K) \) decays

\( r_D \) is the amplitude ratio of the CF to DCS \( D^0 \) decays

\( \delta_D \) is the relative strong phase between the CF and DCS decays

Both are taken from CLEO measurements

Notice that ADS asymmetries are enhanced by the absence of a “1 +” term in the denominator compared to the GLW ones

\[
R_{K/\pi}^{K\pi} = R \frac{1 + (r_B r_D)^2 + 2r_B r_D \cos(\delta_B - \delta_D) \cos \gamma}{1 + (r_B^2 r_D)^2 + 2r_B^2 r_D \cos(\delta_B^2 - \delta_D^2) \cos \gamma}
\]

\[
A_{\pi}^{K} = A_{\pi}^{\pi} = 2r_B \sin \delta_B \sin \gamma \frac{2r_B \sin \delta_B \sin \gamma}{1 + r_B^2 + r_B \cos \delta_B \cos \gamma}
\]

\[
A_{\pi}^{KK} = A_{\pi}^{\pi} = 2r_B \sin \delta_B \sin \gamma \frac{2r_B \sin \delta_B \sin \gamma}{1 + r_B^2 + r_B \cos \delta_B \cos \gamma}
\]

\[
R^{ADS} = \frac{r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos \gamma}{1 + (r_B^2 r_D)^2 + 2r_B^2 r_D \cos(\delta_B^2 + \delta_D^2) \cos \gamma}
\]

\[
A^{ADS} = \frac{2r_B r_D \sin(\delta_B + \delta_D) \sin \gamma}{r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos \gamma}
\]
The Cabbibo-favoured signals

\[ B^- \rightarrow [K^- \pi^+]_D K^- \]

\[ B^+ \rightarrow [K^+ \pi^-]_D K^+ \]

\[ B^- \rightarrow [K^- \pi^+]_D \pi^- \]

\[ B^+ \rightarrow [K^+ \pi^-]_D \pi^+ \]
The singly Cabbibo-Suppressed signals

KK and ππ show similar-sized CP asymmetries, in the same direction

\[ A_{CP+} = \langle A_{K}^{KK}, A_{K}^{\pi\pi} \rangle = 0.145 \pm 0.032 \pm 0.010 \]

Branching fraction ratios consistent with CF D⁰ decay mode

\[ R_{CP+} = \frac{\langle R_{K}^{KK}, R_{K}^{\pi\pi} \rangle}{R_{K\pi}} = 1.007 \pm 0.038 \pm 0.012 \]
The ADS signals

The Kaon mode shows a large CP asymmetry

\[ A_{ADS(K)} = \frac{R^{-}_K - R^{+}_K}{R^{-}_K + R^{+}_K} = -0.520 \pm 0.150 \pm 0.021 \]

And there is also a hint of something in the pion mode!

\[ A_{ADS(\pi)} = \frac{R^{-}_\pi - R^{+}_\pi}{R^{-}_\pi + R^{+}_\pi} = 0.1426 \pm 0.0621 \pm 0.0110 \]

ADS modes established at >5\( \sigma \) significance

Combining all two body modes, direct CPV is observed at 5.8\( \sigma \) significance
What has this enabled us to produce?

GLW/ADS in $B \rightarrow DK, D\pi$ with $D \rightarrow hh$

**ADS in $B \rightarrow DK, D\pi$ with $D \rightarrow hhhhh**

GGSZ in $B \rightarrow DK$ with $D \rightarrow K_{s}hh$

GLW in $B \rightarrow DK^{0*}$

GLW in $B \rightarrow Dhhh$

Frequentist $\gamma$ combination

Time dependent CPV in $B_{s} \rightarrow D_{s}K$
\[ \Gamma(B^\pm \to D(K^\mp \pi^\mp \pi^+ \pi^-)K^\pm) \propto 1 + (r_B r_D K_3^\pi)^2 + 2 R_{K3\pi} r_B r_D K_3^\pi \cos(\delta_B - \delta_D K_3^\pi \pm \gamma), \]
\[ \Gamma(B^\pm \to D(K^\mp \pi^\mp \pi^+ \pi^-)K^\pm) \propto r_B^2 + (r_D K_3^\pi)^2 + 2 R_{K3\pi} r_B r_D K_3^\pi \cos(\delta_B + \delta_D K_3^\pi \pm \gamma), \]

Same formalism as for the two-body case, except for the coherence factor \( R_{K3\pi} \). This is necessary because the \( D^0 \) decay is a sum of amplitudes varying across the Dalitz plot; when we perform an analysis integrating over these amplitudes, we lose sensitivity from the way in which they interfere.

\( R_{K3\pi} \) has been measured at CLEO and is small (∼0.33) which indicates that these modes have a smaller sensitivity to γ when treated in this integrated manner than the two-body modes. However, they can still provide a good constraint on \( r_B \).
The Cabbibo-favoured signals

\[ B^- \rightarrow [K^- \pi^+ \pi^+ \pi^-]_D K^- \]

\[ B^+ \rightarrow [K^+ \pi^- \pi^- \pi^-]_D K^+ \]

\[ B^- \rightarrow [K^- \pi^+ \pi^+ \pi^-]_D \pi^- \]

\[ B^+ \rightarrow [K^+ \pi^- \pi^- \pi^-]_D \pi^+ \]
The ADS signals

- $B^\to[\pi K^+\pi^+\pi^-]_{D} K^-$
- $B^\to[\pi^+K^-\pi^+\pi^-]_{D} K^+$
- $B^\to[\pi K^+\pi^+\pi^-]_{D} \pi$
- $B^\to[\pi^+K^-\pi^+\pi^-]_{D} \pi^+$

$\text{Events (}\times 10 \text{ MeV}/c^2\)$

$m(Dh^2) \ [\text{MeV}/c^2]$
Once again, indications of CP asymmetries in both the Kaon and the Pion modes

And again, going in the same direction as for the two-body modes.

\[
A_{\text{ADS}(K)}^{K3\pi} = \frac{(R_{K}^{K3\pi, -} - R_{K}^{K3\pi, +})}{(R_{K}^{K3\pi, -} + R_{K}^{K3\pi, +})} = -0.42 \pm 0.22
\]

\[
A_{\text{ADS}(\pi)}^{K3\pi} = \frac{(R_{\pi}^{K3\pi, -} - R_{\pi}^{K3\pi, +})}{(R_{\pi}^{K3\pi, -} + R_{\pi}^{K3\pi, +})} = +0.13 \pm 0.10
\]

ADS modes established at >5\sigma significance!
What has this enabled LHCb to produce?

GLW/ADS in $B \rightarrow DK, D\pi$ with $D \rightarrow hh$

ADS in $B \rightarrow DK, D\pi$ with $D \rightarrow hhhh$

**GGSZ** in $B \rightarrow DK$ with $D \rightarrow K_S hh$

GLW in $B \rightarrow DK^{0*}$

GLW in $B \rightarrow Dhhh$

Frequentist $\gamma$ combination

Time dependent CPV in $B_s \rightarrow D_s K$
Here the decay chain is $B \to D^0 K$, with $D^0 \to K_S \pi\pi/K\bar{K}K$

The $D^0$ decays proceed through many interfering amplitudes, some of which are Cabbibo-favoured, some singly Cabbibo-suppressed, and some doubly Cabbibo-suppressed

You are effectively doing a simultaneous ADS/GLW analysis, as long as you understand how the amplitudes and their phases vary across the Dalitz plot.
Here the decay chain is $B \rightarrow D^0 K$, with $D^0 \rightarrow K_S \pi \pi / K_S K K$

The $D^0$ decays proceed through many interfering amplitudes, some of which are Cabbibo-favoured, some singly Cabbibo-suppressed, and some doubly Cabbibo-suppressed.

You are effectively doing a simultaneous ADS/GLW analysis, as long as you understand how the amplitudes and their phases vary across the Dalitz plot.

"Model-independent" : Bin the Dalitz plot and fit for yield of $B^+$ and $B^-$ in each bin of the Dalitz plot, plugging in the strong phase in each bin from a CLEO measurement.

$$N^+_{+i} = n_{B^+}[K_{-i} + (x^2 + y^2)K_{+i} + 2\sqrt{K_{+i}K_{-i}}(x_c s_i - y_c s_i)]$$

$$x_z = r_B \cos(\delta_B \pm \gamma), \ y_z = r_B \sin(\delta_B \pm \gamma)$$

c_i, s_i are the CLEO inputs

$K_i$ are the yields of tagged $D^0$ decays in each bin
$K_S \pi \pi$ and $K_S K K$ signals for 1 fb$^{-1}$
Dalitz distributions for 1 fb$^{-1}$
$x^\pm, y^\pm$ for 1 fb$^{-1}$

\[ x_i = r_B \cos(\delta_B \pm \gamma), \quad y_i = r_B \sin(\delta_B \pm \gamma) \]

Largest systematic arises from the assumption of no CPV in the control mode $D\pi$

Little stand-alone sensitivity due to “unlucky” fluctuation of $r_B$
Dalitz distributions for 2 fb$^{-1}$

\[ m_{2}^{2} \text{ [GeV}^{2}/c^{4}] \]

LHCb preliminary
\[ \int L \, dt = 2.0 \text{ fb}^{-1} \]

\[ B^{+} \]

\[ K_{S}\pi\pi \]

\[ m_{2}^{2} \text{ [GeV}^{2}/c^{4}] \]

LHCb preliminary
\[ \int L \, dt = 2.0 \text{ fb}^{-1} \]

\[ B^{-} \]

\[ K_{S}\pi\pi \]

\[ m_{2}^{2} \text{ [GeV}^{2}/c^{4}] \]

LHCb preliminary
\[ \int L \, dt = 2.0 \text{ fb}^{-1} \]

\[ B^{+} \]

\[ K_{S}K\pi \]

\[ m_{2}^{2} \text{ [GeV}^{2}/c^{4}] \]

LHCb preliminary
\[ \int L \, dt = 2.0 \text{ fb}^{-1} \]

\[ B^{-} \]

\[ K_{S}K\pi \]
$x^\pm, y^\pm$ for 2 fb$^{-1}$

$$x_\pm = r_B \cos(\delta_B \pm \gamma), \quad y_\pm = r_B \sin(\delta_B \pm \gamma)$$

![Graphs showing $x$ and $y$ distributions for $B^+$ and $B^-$ mesons with LHCb Preliminary significance.](image)

$\gamma = (57 \pm 16)^{\circ}$
CLEO inputs
GLW/ADS 2D plots
GLW/ADS 2D plots

Dh GLW/ADS(hh, K3π) + GGSZ

LHCb Preliminary

Dh GLW/ADS(hh, K3π) + GGSZ

LHCb Preliminary
D$_s$K charm signals

- $L_{cm}=1.0$ fb$^{-1}$
  - $D_{s} \rightarrow KK\pi$

- $L_{cm}=1.0$ fb$^{-1}$
  - $D_{s} \rightarrow K\pi\pi$

- $L_{cm}=1.0$ fb$^{-1}$
  - $D_{s} \rightarrow \pi\pi\pi$
GGSZ asymmetries per bin 1fb$^{-1}$

Effective bin number
GGSZ only extractions $1\text{fb}^{-1}$

- $\gamma$ (degrees)
- $\delta_B$ (degrees)
- $\gamma$ (degrees)
GLW/ADS full results

\[
\begin{align*}
R_{K/\pi}^K &= 0.0774 \pm 0.0012 \pm 0.0018 \\
R_{K/\pi}^{K/K} &= 0.0773 \pm 0.0030 \pm 0.0018 \\
R_{K/\pi}^{\pi/\pi} &= 0.0803 \pm 0.0056 \pm 0.0017 \\
A_{K/\pi}^{K} &= -0.0001 \pm 0.0036 \pm 0.0095 \\
A_{K/\pi}^{K/K} &= 0.0044 \pm 0.0144 \pm 0.0174 \\
A_{K/\pi}^{K\pi} &= 0.148 \pm 0.037 \pm 0.010 \\
A_{K/\pi}^\pi &= 0.135 \pm 0.066 \pm 0.010 \\
A_{K/\pi}^{K\pi} &= -0.020 \pm 0.009 \pm 0.012 \\
A_{K/\pi}^{\pi\pi} &= -0.001 \pm 0.017 \pm 0.010 \\
R_{K}^{-} &= 0.0073 \pm 0.0023 \pm 0.0004 \\
R_{K}^{+} &= 0.0232 \pm 0.0034 \pm 0.0007 \\
R_{\pi}^{-} &= 0.00469 \pm 0.00038 \pm 0.00008 \\
R_{\pi}^{+} &= 0.00352 \pm 0.00033 \pm 0.00007.
\end{align*}
\]

Table 2: Systematic uncertainties on the observables. PID refers to the fixed efficiency of the DLL_{K/\pi} cut on the bachelor track. PDFs refers to the variations of the fixed shapes in the fit. “Sim” refers to the use of simulation to estimate relative efficiencies of the signal modes which includes the branching fraction estimates of the \Lambda_b^0 background. \(A_{\text{instr.}}\) quantifies the uncertainty on the production, interaction and detection asymmetries.

<table>
<thead>
<tr>
<th>\times 10^{-3}</th>
<th>PID</th>
<th>PDFs</th>
<th>Sim</th>
<th>(A_{\text{instr.}})</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_{K/\pi}^K)</td>
<td>1.4</td>
<td>0.9</td>
<td>0.8</td>
<td>0</td>
<td>1.8</td>
</tr>
<tr>
<td>(R_{K/\pi}^{K/K})</td>
<td>1.3</td>
<td>0.8</td>
<td>0.9</td>
<td>0</td>
<td>1.8</td>
</tr>
<tr>
<td>(R_{K/\pi}^{\pi/\pi})</td>
<td>1.3</td>
<td>0.6</td>
<td>0.8</td>
<td>0</td>
<td>1.7</td>
</tr>
<tr>
<td>(A_{K/\pi}^{K})</td>
<td>0</td>
<td>1.0</td>
<td>0</td>
<td>9.4</td>
<td>9.5</td>
</tr>
<tr>
<td>(A_{K/\pi}^{K/K})</td>
<td>0.2</td>
<td>4.1</td>
<td>0</td>
<td>16.9</td>
<td>17.4</td>
</tr>
<tr>
<td>(A_{K/\pi}^{K\pi})</td>
<td>1.6</td>
<td>1.3</td>
<td>0.5</td>
<td>9.5</td>
<td>9.7</td>
</tr>
<tr>
<td>(A_{K/\pi}^\pi)</td>
<td>1.9</td>
<td>2.3</td>
<td>0</td>
<td>9.0</td>
<td>9.5</td>
</tr>
<tr>
<td>(A_{K/\pi}^{K\pi})</td>
<td>0.1</td>
<td>6.6</td>
<td>0</td>
<td>9.5</td>
<td>11.6</td>
</tr>
<tr>
<td>(A_{K/\pi}^{\pi\pi})</td>
<td>0.1</td>
<td>0.4</td>
<td>0</td>
<td>9.9</td>
<td>9.9</td>
</tr>
<tr>
<td>(R_{\pi}^{-})</td>
<td>0.2</td>
<td>0.4</td>
<td>0</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>(R_{\pi}^{+})</td>
<td>0.4</td>
<td>0.5</td>
<td>0</td>
<td>0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>(R_{\pi}^{-})</td>
<td>0.01</td>
<td>0.03</td>
<td>0</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>(R_{\pi}^{+})</td>
<td>0.01</td>
<td>0.03</td>
<td>0</td>
<td>0.07</td>
<td>0.07</td>
</tr>
</tbody>
</table>
Table 2: Systematic uncertainties on the observables. PID refers to the fixed efficiency for the bachelor DLL\textsubscript{K\pi} requirement which is determined using the D*± calibration sample. PDFs refers to the variations of the fixed shapes in the fit. Sim refers to the use of simulation to estimate relative efficiencies of the signal modes. A\textsubscript{instr.} quantifies the uncertainty on the production, interaction and detection asymmetries.

<table>
<thead>
<tr>
<th>×10\textsuperscript{-3}</th>
<th>PID</th>
<th>PDFs</th>
<th>Sim</th>
<th>A\textsubscript{instr.}</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>R\textsubscript{K3}\textsubscript{K/π}</td>
<td>1.7</td>
<td>1.2</td>
<td>1.5</td>
<td>0.0</td>
<td>2.6</td>
</tr>
<tr>
<td>A\textsubscript{K3}\textsubscript{K/π}</td>
<td>0.2</td>
<td>1.3</td>
<td>0.1</td>
<td>9.9</td>
<td>10.0</td>
</tr>
<tr>
<td>A\textsubscript{K3}\textsubscript{π}</td>
<td>0.6</td>
<td>4.4</td>
<td>0.3</td>
<td>17.1</td>
<td>17.7</td>
</tr>
<tr>
<td>R\textsubscript{K3}κ,−</td>
<td>0.4</td>
<td>0.7</td>
<td>0.1</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>R\textsubscript{K3}κ,\textsubscript{π,}+</td>
<td>0.4</td>
<td>0.9</td>
<td>0.2</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>R\textsubscript{π3}κ,−</td>
<td>0.02</td>
<td>0.09</td>
<td>0.01</td>
<td>0.06</td>
<td>0.11</td>
</tr>
<tr>
<td>R\textsubscript{π3}κ,\textsubscript{π,}+</td>
<td>0.04</td>
<td>0.08</td>
<td>0.02</td>
<td>0.06</td>
<td>0.11</td>
</tr>
</tbody>
</table>

\[
P_{K3}^{K/π} = 0.0771 \pm 0.0017 \pm 0.0026
\]
\[
A_{K3}^{K/π} = -0.029 \pm 0.020 \pm 0.018
\]
\[
A_{K3}^{π} = -0.006 \pm 0.005 \pm 0.010
\]
\[
P_{K3}^{κ,−} = 0.0072 \pm 0.0005 \pm 0.0008
\]
\[
P_{K3}^{κ,\textsubscript{π,}+} = 0.0175 \pm 0.0004 \pm 0.0010
\]
\[
P_{π3}^{κ,−} = 0.00417 \pm 0.00054 \pm 0.00011
\]
\[
P_{π3}^{κ,\textsubscript{π,}+} = 0.00321 \pm 0.00048 \pm 0.00011
\]
Table 3: Results for $x_\pm$ and $y_\pm$ from the fits to the data in the case when both $D \to K_S^0 \pi^+ \pi^-$ and $D \to K_S^0 K^+ K^-$ are considered and when only the $D \to K_S^0 \pi^+ \pi^-$ final state is included. The first, second, and third uncertainties are the statistical, the experimental systematic, and the error associated with the precision of the strong-phase parameters, respectively. The correlation coefficients are calculated including all sources of uncertainty (the values in parentheses correspond to the case where only the statistical uncertainties are considered).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>All data</th>
<th>$D \to K_S^0 \pi^+ \pi^-$ alone</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_-$ [$\times 10^{-2}$]</td>
<td>$0.0 \pm 4.3 \pm 1.5 \pm 0.6$</td>
<td>$1.6 \pm 4.8 \pm 1.4 \pm 0.8$</td>
</tr>
<tr>
<td>$y_-$ [$\times 10^{-2}$]</td>
<td>$2.7 \pm 5.2 \pm 0.8 \pm 2.3$</td>
<td>$1.4 \pm 5.4 \pm 0.8 \pm 2.4$</td>
</tr>
<tr>
<td>corr($x_-, y_-$)</td>
<td>$-0.10 (-0.11)$</td>
<td>$-0.12 (-0.12)$</td>
</tr>
<tr>
<td>$x_+$ [$\times 10^{-2}$]</td>
<td>$-10.3 \pm 4.5 \pm 1.8 \pm 1.4$</td>
<td>$-8.6 \pm 5.4 \pm 1.7 \pm 1.6$</td>
</tr>
<tr>
<td>$y_+$ [$\times 10^{-2}$]</td>
<td>$-0.9 \pm 3.7 \pm 0.8 \pm 3.0$</td>
<td>$-0.3 \pm 3.7 \pm 0.9 \pm 2.7$</td>
</tr>
<tr>
<td>corr($x_+, y_+$)</td>
<td>$0.22 (0.17)$</td>
<td>$0.20 (0.17)$</td>
</tr>
</tbody>
</table>
What has this enabled us to produce?

GLW/ADS in $B \rightarrow DK, D\pi$ with $D \rightarrow hh$

ADS in $B \rightarrow DK, D\pi$ with $D \rightarrow hhhh$

GGSZ in $B \rightarrow DK$ with $D \rightarrow K_S hh$

GLW in $B \rightarrow D K^0^*$

GLW in $B \rightarrow D hhh$

Frequentist $\gamma$ combination

Time dependent CPV in $B_S \rightarrow D_S K$
Observables ↔ physics parameters

Sensitivity to $\gamma$ comes from the time-dependent interference of the $V_{ub}$ and $V_{cb}$ decay rates.

Can perform both flavour tagged and flavour untagged measurements.

The sizes of the interfering diagrams are expected to be similar, leading to large interference and good per-event sensitivity to $\gamma$. 
Observables $\leftrightarrow$ physics parameters

\[
A(B^0_q \to D_q \bar{u}_q) = \frac{C \cos(\Delta m\tau) + S \sin(\Delta m\tau)}{\cosh(\Delta \Gamma t/2) - A_{\Delta\Gamma} \sinh(\Delta \Gamma t/2)}
\]

\[
C = -\frac{1-x_q^2}{1+x_q^2}
\]

\[
S = \frac{2x_q \sin(\gamma + \delta_q + \phi_q)}{(x_q^2 + 1)}
\]

\[
A_{\Delta\Gamma} = \frac{2x_q \cos(\gamma + \delta_q + \phi_q)}{(x_q^2 + 1)}
\]

Ratio of CKM-suppressed to CKM-favoured amplitudes, $\sim 0.4$ in $B_s \to D_s K$
Observables $\leftrightarrow$ physics parameters

TOY SIMULATION
Observables ⇔ physics parameters

TOY SIMULATION
Observables ↔ physics parameters

TOY SIMULATION
In the limit of large statistics, the different observables combine in such a way as to give only a twofold ambiguity on the angle $\gamma$

This relies on having both the “tagged” and “untagged” observables

Luckily nature has been kind with a large value of $\Delta \Gamma_s/\Gamma_s \sim 15.9\%$!
Signals in the data

Clean high yield control mode $B_s \rightarrow D_s \pi$

1) Allows to constrain backgrounds in $D_s K$

2) Allows flavour tagging calibration
Backgrounds in $D_sK$

LHCb Preliminary $L_{\text{int}} = 1.0$ fb$^{-1}$

- Data
- Signal $B \rightarrow D_sK$
- $B_{(d,s)} \rightarrow D_s^{(*)}K^{(*)}$
- $B_s \rightarrow D_s^{(*)}(\pi\rho)$
- $\Lambda_b \rightarrow D_s^+\rho$
- $\Lambda_b \rightarrow \Lambda_c K$
- $B_d \rightarrow DK$
- Combinatorial
Propertime resolution/acceptance

Propertime resolution taken from simulation scaled by the difference between simulation and data resolutions measured on a control channel (15%)

Effective propertime resolution is \(~50\) fs

Acceptance taken from a fit to the $B_S \rightarrow D_S \pi$ data fixing the lifetime and oscillation frequency to the WA values

Corrected by the ratio of acceptances observed in the simulation
Tagging based on the “opposite-side” B decay

Mixture of

Single particle tag : e, μ, K
Vertex charge tag

Combined using a Neural Network trained on simulated events

Tagging performance is calibrated on self tagging control channels in the data

Analysis uses the predicted per-event mistag to maximize sensitivity
The time uses a statistical background subtraction technique (the “sPlot” method) in order to avoid modelling the time dependence of the backgrounds.

Fit performance verified in through studies of 2000 pseudoexperiment ensembles.

Systematic uncertainties calculated from similar pseudoexperiment ensembles, varying fixed parameters and computing toy-by-toy differences between the nominal and modified fit.

See Arxiv physics.data_an 0402083, 0905.0724
Table 4: Fitted values of the $B^0_s \rightarrow D_s^{\mp} K^\pm$ CP-asymmetry observables with statistical and systematic uncertainties. All systematics are given as fractions of the statistical uncertainty. Systematics are added in quadrature under the assumption that they are uncorrelated.

<table>
<thead>
<tr>
<th>Systematic uncertainties ($\sigma_{\text{stat}}$)</th>
<th>$C$</th>
<th>$S_f$</th>
<th>$D_f$</th>
<th>$D_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toy corrected central value</td>
<td>1.01</td>
<td>-1.25</td>
<td>0.08</td>
<td>-1.33</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>0.50</td>
<td>0.56</td>
<td>0.68</td>
<td>0.60</td>
</tr>
<tr>
<td>Decay-time bias</td>
<td>0.03</td>
<td>0.05</td>
<td>0.05</td>
<td>0.00</td>
</tr>
<tr>
<td>Decay-time resolution</td>
<td>0.11</td>
<td>0.08</td>
<td>0.09</td>
<td>0.00</td>
</tr>
<tr>
<td>Tagging calibration</td>
<td>0.23</td>
<td>0.17</td>
<td>0.16</td>
<td>0.00</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.15</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Fixed parameters</td>
<td>0.15</td>
<td>0.22</td>
<td>0.20</td>
<td>0.40</td>
</tr>
<tr>
<td>Asymmetries</td>
<td>0.12</td>
<td>0.01</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>Momentum/length scale</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>k-factors</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
<td>0.08</td>
</tr>
<tr>
<td>Bias correction</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Total systematic ($\sigma_{\text{stat}}$)</td>
<td>0.46</td>
<td>0.50</td>
<td>0.35</td>
<td>0.43</td>
</tr>
</tbody>
</table>

No extraction of $\gamma$ for now because we did not have the time to evaluate the correlations between systematic uncertainties and we saw a non-negligible effect of including these on $\gamma$.

Will be done for the eventual paper.
What has this enabled us to produce?

GLW/ADS in $B \to DK, D\pi$ with $D \to hh$

ADS in $B \to DK, D\pi$ with $D \to hhhh$

GGSZ in $B \to DK$ with $D \to K_{S\eta}h$

GLW in $B \to DK^0\pi$

GLW in $B \to Dhh$

Frequentist $\gamma$ combination

Time dependent CPV in $B_s \to D_s K$
Quasi two-body approach: fewer events than DK, but bigger interference.
Cabibbo favoured normalization mode

Kaon from $K^*$ and from $D^0$ have the same sign, so no $B_d$ contribution
Cabibbo suppressed mode

\[ \mathcal{A}_d^{KK} = -0.45 \pm 0.23 \text{ (stat)} \pm 0.02 \text{ (syst)}, \]
\[ \mathcal{A}_d^{\text{fav}} = -0.08 \pm 0.08 \text{ (stat)} \pm 0.01 \text{ (syst)}, \]
\[ \mathcal{A}_s^{KK} = 0.04 \pm 0.16 \text{ (stat)} \pm 0.01 \text{ (syst)}, \]
\[ \mathcal{R}_d^{KK} = 1.36^{+0.37}_{-0.32} \text{ (stat)} \pm 0.07 \text{ (syst)}. \]
What has this enabled us to produce?

- GLW/ADS in $B \to DK, D\pi$ with $D \to hh$
- ADS in $B \to DK, D\pi$ with $D \to hhhh$
- GGSZ in $B \to DK$ with $D \to K_{s}hh$
- GLW in $B \to DK^{0*}$
- **GLW in $B \to Dhhh$**
- Frequentist $\gamma$ combination
- Time dependent CPV in $B_{s} \to D_{s}K$
Same formalism as for the two-body case, except for the coherence factor $\kappa$.

This is necessary because the B decay is a sum of amplitudes varying across the Dalitz plot; when we perform an analysis integrating over these amplitudes, we lose sensitivity from the way in which they interfere.

$\kappa=1$ means full sensitivity, $\kappa=0$ means no sensitivity.
Signals, favoured $B, D \rightarrow K\pi$

$LHCb$ Data
- **Signal**
- $D^{*\pm} \rightarrow D^{0}\pi^{\pm}$
- $D^{*} \rightarrow D^{0}\pi^{0}$
- $D^{*0} \rightarrow D^{0}\gamma$
- $D^{0}K\pi\pi$ refl
- Comb Bkg

$LHCb$ Preliminary

$LHCb$ Data
- **Signal**
- $D^{*\pm} \rightarrow D^{0}\pi^{\pm}$
- $D^{*} \rightarrow D^{0}\pi^{0}$
- $D^{*0} \rightarrow D^{0}\gamma$
- $D^{0}K\pi\pi$ refl
- Comb Bkg
Signals, favoured B, D → KK

$B^+ \rightarrow D^0 \pi \pi$, $D^0 \rightarrow KK$

$B^- \rightarrow D^0 \pi \pi$, $D^0 \rightarrow KK$

LHCb Preliminary

Candidates / (10 MeV/c²)

Mass (MeV/c²)

LHCb Data
- Signal
- $D^{*\pm} \rightarrow D^0 \pi^\pm$
- $D^* \rightarrow D^0 \pi^0$
- $D^{*0} \rightarrow D^0 \gamma$
- $\Lambda_b$ refl
- $D^0 K \pi \pi$ refl
- Comb Bkg

LHCb Preliminary

Candidates / (10 MeV/c²)

Mass (MeV/c²)

LHCb Data
- Signal
- $D^{*\pm} \rightarrow D^0 \pi^\pm$
- $D^* \rightarrow D^0 \pi^0$
- $D^{*0} \rightarrow D^0 \gamma$
- $\Lambda_b$ refl
- $D^0 K \pi \pi$ refl
- Comb Bkg
Signals, favoured $B, D \to \pi \pi$

$LHCb$ Data
- Signal
- $D^{*\pm} \to D^0 \pi^\pm$
- $D^* \to D^0 \pi^0$
- $D^{*0} \to D^0 \gamma$
- $D^0 K \pi \pi$ refl
- Comb Bkg

Mass (MeV/c$^2$)
Signals, suppressed $B, D \rightarrow K\pi$

**$B^+ \rightarrow D^0 K\pi\pi, D^0 \rightarrow K\pi$**

<table>
<thead>
<tr>
<th>Mass (MeV/c$^2$)</th>
<th>Candidates / (10 MeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5100</td>
<td>0</td>
</tr>
<tr>
<td>5200</td>
<td>0</td>
</tr>
<tr>
<td>5300</td>
<td>0</td>
</tr>
<tr>
<td>5400</td>
<td>0</td>
</tr>
<tr>
<td>5500</td>
<td>0</td>
</tr>
</tbody>
</table>

**$B^- \rightarrow D^0 K\pi\pi, D^0 \rightarrow K\pi$**

<table>
<thead>
<tr>
<th>Mass (MeV/c$^2$)</th>
<th>Candidates / (10 MeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5100</td>
<td>0</td>
</tr>
<tr>
<td>5200</td>
<td>0</td>
</tr>
<tr>
<td>5300</td>
<td>0</td>
</tr>
<tr>
<td>5400</td>
<td>0</td>
</tr>
<tr>
<td>5500</td>
<td>0</td>
</tr>
</tbody>
</table>
Signals, suppressed B, D→KK

\( B^+ \rightarrow D^0 K \pi \pi, \ D^0 \rightarrow KK \)

\( B^- \rightarrow D^0 K \pi \pi, \ D^0 \rightarrow KK \)

LHCb Preliminary

Candidates / (10 MeV/c^2)

LHCb Data

Signal

\( D^{*+} \rightarrow D^0 \pi^+ \)

\( D^+ \rightarrow D^0 \pi^+ \)

\( D^0 \rightarrow D^0 \gamma \)

\( \Lambda_b \) refl

\( D^{*+} \pi^+ \pi^- \) refl

\( D^0 D_s, D^0 K^*K \) refl

\( D^0 \pi^+ \pi^- \) refl

Comb Bkg

Mass (MeV/c^2)

LHCb Preliminary

Candidates / (10 MeV/c^2)

LHCb Data

Signal

\( D^{*+} \rightarrow D^0 \pi^+ \)

\( D^+ \rightarrow D^0 \pi^+ \)

\( D^0 \rightarrow D^0 \gamma \)

\( \Lambda_b \) refl

\( D^{*+} \pi^+ \pi^- \) refl

\( D^0 D_s, D^0 K^*K \) refl

\( D^0 \pi^+ \pi^- \) refl

Comb Bkg

Mass (MeV/c^2)
Signals, suppressed $B, D \to \pi \pi$

$B^+ \to D^0 K \pi \pi, D^0 \to \pi \pi$

$B^- \to D^0 K \pi \pi, D^0 \to \pi \pi$

LHCb Preliminary

- LHCb Data
- Signal
- $D^{*+} \to D^0 \pi^+$
- $D^* \to D^{0} \pi^0$
- $D^0 \to D^{0} \gamma$
- $D^* \to D^{0} \pi^\pi$ refl
- $D^0 D, D^0 K^* K$ refl
- $D^0 \pi \pi \pi$ refl
- Comb Bkg

Mass (MeV/c$^2$)

Candidates / (10 MeV/c$^2$)
Results

The final results for the relative rate $R_{CP+}$ and the asymmetries are

$$R_{CP+} = 0.95 \pm 0.11 \text{ (stat)} \pm 0.02 \text{ (syst)}$$
$$A_{s}^{CP+} = -0.14 \pm 0.10 \text{ (stat)} \pm 0.01 \text{ (syst)}$$
$$A_{s}^{K-\pi+} = -0.009 \pm 0.028 \text{(stat)} \pm 0.013 \text{(syst)} \quad (14)$$

We also measure asymmetries in the corresponding Cabibbo-favored decays, and find:

$$A_{d}^{CP+} = -0.018 \pm 0.018 \text{(stat)} \pm 0.007 \text{(syst)}$$
$$A_{d}^{K-\pi+} = -0.006 \pm 0.006 \text{(stat)} \pm 0.010 \text{(syst)} \quad (15)$$