Flavour physics, status and prospects

Vladimir V. Gligorov
CERN-EP Seminar, June 17th 2014
Quark mixing in the Standard Model

Imaginary component gives rise to matter-antimatter asymmetry (CP violation)
Equal amount of matter and antimatter created.

Today: almost no antimatter in the universe.

So where did all the antimatter go?
Other reasons exist

Hierachy, naturaleness, etc.

Inconsistency between SM picture of CPV and Big Bang comes directly from the quark masses and cannot be explained away though.

Assume Big Bang picture is correct, there must be sources of CPV outside the SM!
Potential NP is constrained by flavour

Hierachy, naturaleness, etc.

Inconsistency between SM picture of CPV and Big Bang comes directly from the quark masses and cannot be explained away though.

Assume Big Bang picture is correct, there must be sources of CPV outside the SM!

For the purposes of this talk, “flavour physics” really means “quark flavour physics”, with apologies to neutrinos, lepton flavour violation, etc.

Specifically measurements which tell us about the matter-antimatter discrepancy.

Existing flavour measurements constrain generic New Physics at the TeV scale, competitive with direct searches.

Tools of our trade
B-factories: hermetic detectors, low background, mainly access $B^0,^+ \text{ and charm}$

Belle is being upgraded, Belle II aims to collect 50x the Belle dataset.
CDF/D0/ATLAS/CMS: hermetic detectors but hadronic environment, much higher backgrounds.
LHCb : forward spectrometer for flavour physics at LHC
Physics Objectives and Detector Overview

The apparatus of KOTO experiment is characterized by two photons in the calorimeter with the assumption that those are undoped CsI crystals used at the Fermilab neutrino experiments. The remaining events after various kinematical cuts. For the Pt target the invariant mass distribution and momentum spectra indicate the number of events which passed the cut given in the row.

**Table 7**

<table>
<thead>
<tr>
<th>Two photon distance</th>
<th>Target Flux (normalized to $2 \times 10^{13}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_L$</td>
<td>$D_p$</td>
</tr>
<tr>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td>500</td>
<td>550</td>
</tr>
<tr>
<td>600</td>
<td>650</td>
</tr>
</tbody>
</table>

**Table 6**

<table>
<thead>
<tr>
<th>Vertex position</th>
<th>Two photon distance</th>
<th>$M$ (MeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>400</td>
<td>243</td>
</tr>
<tr>
<td>3</td>
<td>500</td>
<td>364</td>
</tr>
<tr>
<td>4</td>
<td>600</td>
<td>381</td>
</tr>
</tbody>
</table>

**Figure 4.2.**

NA62

- Hadron Beam 750 MHz
- Kaon identification CEDAR
- GTK
- CHANTI
- Fiducial Region 65m
- Total Length 270m

KOTO

- $K_L$ decay
- CHOD
- RICH
- STRAW Tracker
- Photons and Muons
- Veto

NA62/KOTO: forward spectrometers for rare kaon decays
1. Flavour physics today
2. Flavour physics in 2030
3. How do we get there?
Here & Now
The unitarity triangle

Unitary matrix $\Rightarrow$ 6 triangles in imaginary plane, one experimentally convenient
The apex of the triangle

Overconstraining the apex tests the consistency of the SM picture of CP Violation

Similar plots with Bayesian treatment available at www.utfit.org
How do we measure $\gamma$?

Interfering $V_{ub}$ and $V_{cb}$ decays to the same final state.
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>$BB$ pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ from $B \to DK$</td>
<td>$\Lambda \sim \mathcal{O}(10^2 \text{ TeV})$</td>
<td>$\Lambda \sim \mathcal{O}(10^3 \text{ TeV})$</td>
<td>$\sim 10^{18}$</td>
</tr>
<tr>
<td>$B \to \tau\nu$</td>
<td>$\Lambda \sim \mathcal{O}(\text{ TeV})$</td>
<td>$\Lambda \sim \mathcal{O}(30 \text{ TeV})$</td>
<td>$\sim 10^{13}$</td>
</tr>
<tr>
<td>$b \to ssd$</td>
<td>$\Lambda \sim \mathcal{O}(\text{ TeV})$</td>
<td>$\Lambda \sim \mathcal{O}(10^3 \text{ TeV})$</td>
<td>$\sim 10^{13}$</td>
</tr>
<tr>
<td>$\beta$ from $B \to J/\psi K_S$</td>
<td>$\Lambda \sim \mathcal{O}(50 \text{ TeV})$</td>
<td>$\Lambda \sim \mathcal{O}(200 \text{ TeV})$</td>
<td>$\sim 10^{12}$</td>
</tr>
<tr>
<td>$K - \bar{K}$ mixing</td>
<td>$\Lambda &gt; 0.4 \text{ TeV} (6 \text{ TeV})$</td>
<td>$\Lambda &gt; 10^{3(4)} \text{ TeV}$</td>
<td>now</td>
</tr>
</tbody>
</table>

A decade of overachievement...

References, left to right:
... and $\gamma$ in the LHC era

The “ADS” $B \to DK$ decay mode, total branching fraction $O(10^{-7})$
LHCb and the B-factories combined
\[ \sin(2\beta), \alpha \]

**BELLE \( \sin(2\beta) \)**

![BELLE sin(2β)](image1)

**BABAR \( \sin(2\beta) \)**

![BABAR sin(2β) and BABAR α](image2)

\[ \sin(2\beta) = 0.682 \pm 0.019 \text{ (PDG)} \]

Unlike measurements of \( \gamma \), all measurements of \( \beta \) or \( \alpha \) have some "penguin pollution". At present compatible with \( \alpha + \beta + \gamma = \pi \) ⇒ "consistency check" key for the HL era!
$V_{ub}$: inclusive, exclusive

<table>
<thead>
<tr>
<th></th>
<th>BABAR Exclusive</th>
<th>BELLE Inclusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) $0 &lt; q^2 &lt; 16$ GeV$^2$</td>
<td>b) $16 &lt; q^2 &lt; 26.4$ GeV$^2$</td>
<td></td>
</tr>
</tbody>
</table>

![Graphs showing $B^0 \rightarrow \ell \nu$ and $B^+ \rightarrow \ell \nu$ decay channels](https://example.com/graphs)

<table>
<thead>
<tr>
<th></th>
<th>Events</th>
<th></th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>M$_X$ (GeV/c$^2$)</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$q^2$ (GeV$^2$/c$^2$)</td>
<td>0</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>

$|V_{ub}| = (4.41 \pm 0.15 \pm 0.15) \times 10^{-3}$ \hspace{1cm} (inclusive),

$|V_{ub}| = (3.23 \pm 0.31) \times 10^{-3}$ \hspace{1cm} (exclusive).

Exclusive: needs lattice input for form factors
Inclusive: large backgrounds, HQE uncertainties
$V_{ub}$ : $B \rightarrow \tau \nu$

One of the more famous historical tensions, but now in pretty good agreement. Belle II upgrade will improve precision by an order of magnitude however!

References, left to right:
Back to the apex

Continue to improve precision on all measurements to overconstrain the apex. Progress in theory/lattice calculations critical to exploit experimental data.
The Dimuon Trinity

$B_s \rightarrow J/\psi h h$

$B \rightarrow X_s \mu \mu$

$B \rightarrow \mu \mu$

The Dimuon Trinity
We all love dimuons

References, left to right:
LHCb-CONF-2012-025
http://cms.web.cern.ch
http://www.atlas.ch
And we all love loop diagrams
**B→μμ, the ne plus ultra of dimuons**

Precise SM predictions due to decay diagrams

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

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

![Graph](Image)

Signature:

- $1 \text{ cm}$
- $\mu^+$
- $\mu^-$

![Graph](Image)
The LHCb and CMS signals


![LHCb Invariant Mass Distribution](image1.png)

\[ B(B_s^0 \rightarrow \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}, \]
\[ B(B^0 \rightarrow \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}) \times 10^{-10} \]

--- \( \rightarrow 4.0 \sigma \)


![CMS Invariant Mass Distribution](image2.png)

\[ B(B_s^0 \rightarrow \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}, \]
\[ B(B^0 \rightarrow \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10} \]

--- \( \rightarrow 4.3 \sigma \)
$\mathcal{B}^0 / \mathcal{B}^{0_s} \rightarrow \mu \mu$, the golden ratio

\[ \mathcal{B}(\mathcal{B}^0 \rightarrow \mu^+ \mu^-) \times 10^{-9} \]

\[ \mathcal{B}(\mathcal{B}_s^0 \rightarrow \mu^+ \mu^-) \times 10^{-9} \]

Modified from [Straub, 2012]

(arXiv:1012.3893)
B→X_s μμ, the gift that keeps on giving

\[
\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\theta/d\theta_K d\varphi dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_L \right. \\
- F_L \cos^2 \theta_K \cos 2\theta_L + S_3 \sin^2 \theta_K \sin^2 \theta_L \cos 2\varphi \\
+ S_4 \sin 2\theta_K \sin 2\theta_L \cos \varphi + S_5 \sin 2\theta_K \sin \theta_L \cos \varphi \\
+ \left. S_6^s \sin^2 \theta_K \cos \theta_L + S_7 \sin 2\theta_K \sin \theta_L \sin \varphi \right. \\
+ S_8 \sin 2\theta_K \sin 2\theta_L \sin \varphi + S_9 \sin^2 \theta_K \sin^2 \theta_L \sin 2\varphi \]
\]

q^2 = dimuon invariant mass^2

Example observables: forward backward asymmetry (sensitive to S_6), K^0 longitudinal polarization...
So many observables, so little time

LHCb : JHEP 08 (2013) 131
CMS : 1308.3409v2
ATLAS : ATLAS-CONF-2013-038
BELLE : 1402.7134v1
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 $P'_{i=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$ 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!
But the tension has to be consistent

Fit the $K^+\mu\mu$ “anomaly” together with

$B\to\mu\mu$
$B\to X_s\gamma$, $K^+\gamma$
$B\to X_s\mu\mu$ inclusive

and interpret in terms of NP contributions to the Wilson coefficients

Whatever you think of this specific fit, the approach is clearly correct => we are looking for a consistent pattern of deviations!
\( B_s \to J/\psi \pi\pi \) and \( B_s \to J/\psi KK \)

**CPV in interference of decay and mixing**
Everyone gets in on the act…
3 fb$^{-1}$ $B_s \rightarrow J/\psi \pi \pi$, hot off the press

$\phi_s = 70 \pm 68 \pm 8$ mrad, $|\lambda| = 0.89 \pm 0.05 \pm 0.01$. 

Interference of decay and mixing means predicted CPV in SM is ~0
Hence an excellent null test
Also experimentally "golden", as it is almost background free => like an honorary dimuon!

\[
\phi_s = -0.17 \pm 0.15 \text{ (stat)} \pm 0.03 \text{ (syst)},
\]
\[
\lambda = 1.04 \pm 0.07 \text{ (stat)} \pm 0.03 \text{ (syst)}.
\]
Summary of $\phi_s$ status

\begin{itemize}
  \item CP-even
  \item CP-odd
  \item S-wave
\end{itemize}

All measurements happily agree with the SM

$\Delta M_k = 17.77 \pm 0.12 \text{ ps}^{-1}$

$SM \ p\text{-value} = 29.8\%$

$L = 4.9 \text{ fb}^{-1}$

$L = 9.6 \text{ fb}^{-1}$
Another way of looking at mixing

$B_s^0$ $u, c, t$ $W^+$ $\bar{s}$ $\bar{b}$
$s$ $W^-$

$\overline{B}_s^0$ $\bar{u}, \bar{c}, \bar{t}$
$\bar{b}$ $\bar{d}$

$B^0$ $u, c, t$ $W^+$
$b$ $W^-$

$\overline{B}^0$ $\bar{u}, \bar{c}, \bar{t}$
$b$ $d$

CPV in mixing essentially 0 in SM
$\Rightarrow$ Measure using $B \to D\mu X$ decays
$\Rightarrow$ Another excellent null test
The $A_{SL}$ anomaly...
...or the Standard Model?

...but global agreement with Standard Model at 1.5σ
Taus are leptons too

\[
\overline{B}\{\begin{array}{c}
\bar{q} \\
\end{array}\} \rightarrow b \rightarrow \begin{array}{c}
W^-/H^- \\
\tau^- \\
\bar{\nu}_\tau \\
\end{array} \rightarrow c \rightarrow \begin{array}{c}
\bar{q} \\
\bar{q} \\
\bar{q} \\
\end{array} \}
\]

\[D^{(*)}\]

Charged Higgs contributions affect DTV and D*TV differently
Taus are leptons too

\[ \overline{B}\{ b \rightarrow \tau^{-} \overline{q} \overline{q} \rightarrow c \overline{q} \} D^{(*)} \]

Challenging analysis, significant backgrounds even at B-factories
Taus are leptons too

\[ \overline{B} \{ b \to q, c \to q \} D(*) \]

\[ W^-/H^- \to \tau^- \]

\[ \overline{\nu}_\tau \]

\[ \tan \beta/m_{H^+} \ (\text{GeV}^{-1}) \]

\[ \mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042, \]
\[ \mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018, \]

Results 3.4σ away from SM but also exclude type II 2HDM
The up sector
Setting the scene

$$V_{\text{CKM}} = \left( \begin{array}{ccc} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{array} \right) + \sum_{n=4}^{N} O(\lambda^n)$$

First two gen. matrix real, so charm CPV highly suppressed in SM
Top mass $>>$ mass of other quarks, NP preferentially couples to top
Overall picture of charm mixing/CPV

Constrains generic NP at $\sim 10^3 - 10^4$ TeV
Both CDF and D0 measure FB-asymmetries above SM, D0 does not see enhancement at high \( m_t \). Cannot measure same quantity at LHC but related measurements compatible with SM.
D0, 9.7 fb⁻¹

Data

MC@NLO

--- Fit to data

D0, 9.7 fb⁻¹

Data

MC@NLO

--- Fit to data

CDF Data, 9.4 fb⁻¹

Cf$_{w}= (15.5 \pm 4.8) \times 10^{-4} \, (GeV/c)^{2}$

tf Prediction

Cf$_{w}= (3.4 \pm 1.2) \times 10^{-4} \, (GeV/c)^{2}$

CDF Data, 9.4 fb⁻¹

Cf$_{w}= (25.3 \pm 6.2) \times 10^{-2}$

tf Prediction

Cf$_{w}= (9.7 \pm 1.5) \times 10^{-2}$

Parton-Level $M_{t}$ (GeV/c²)

Parton-Level $|\Delta y|$
In broad agreement with SM, need NNLO QCD predictions to help resolve differences.
The strange sector
The physics of NA62

Rare decay, $(8.5 \pm 0.7) \times 10^{-11}$ in SM

Aim to measure with 10% experimental precision by collecting ~100 signal events
The physics of NA62

Require $0(0.01\%)$ pion-muon discrimination, $0(100\text{ps})$ time-stamping in the trackers, excellent vetoes for neutral particles.
Fantasizing about the future

Basically gives an independent measure of $\sin(2\beta)$!
The Future Is Now!
Latest crystal ball projections

<table>
<thead>
<tr>
<th></th>
<th>LHC era</th>
<th>HL-LHC era</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS &amp; CMS</td>
<td>25 fb⁻¹</td>
<td>100 fb⁻¹</td>
</tr>
<tr>
<td>LHCb</td>
<td>3 fb⁻¹</td>
<td>8 fb⁻¹</td>
</tr>
<tr>
<td>Belle II</td>
<td>—</td>
<td>0.5 ab⁻¹</td>
</tr>
</tbody>
</table>

+NA62, 10% on BR(K⁺→π⁺VV) roughly by end of Run II
+TLEP collecting 2*10¹¹ Z→bbar by 20XX?
+KOTO observes K⁰→π⁰VV by the end of Run II?

https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour
Some example signal rates

- ATLAS/CMS HL-LHC (?)
- LHCb upgrade 100 fb⁻¹ (Multiply by 20 for ccbar)
- LHCb 8 fb⁻¹
- Belle II 50 ab⁻¹
- B-factories

B-factories/Belle II should be scaled by ~10 compared to LHCb to account for efficiencies, hermetic detectors, and a cleaner environment.

Effective size of ATLAS/CMS sample depends on their trigger evolution.
A few key observables

- $B \to \mu\mu$
- $b \to s$ penguins
- $K^* \mu\mu$
- Gamma from Trees

https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour
## Personal aside on complementarity

<table>
<thead>
<tr>
<th></th>
<th>LHCb upgrade</th>
<th>Belle II</th>
<th>ATLAS/CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rare B decays</td>
<td>******</td>
<td>***</td>
<td>****</td>
</tr>
<tr>
<td>$B_s$ mixing</td>
<td>******</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>$B_d$ mixing</td>
<td>**</td>
<td>******</td>
<td></td>
</tr>
<tr>
<td>Incl. processes ($X_s\gamma$, $X_s\ell\ell$, etc.)</td>
<td></td>
<td>******</td>
<td></td>
</tr>
<tr>
<td>b-baryon and $B_c$ physics</td>
<td>******</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>Charm, charged final states</td>
<td>******</td>
<td>**</td>
<td>?</td>
</tr>
<tr>
<td>Charm, neutral final states</td>
<td>**</td>
<td>******</td>
<td></td>
</tr>
<tr>
<td>LFV ($\tau\rightarrow\mu\gamma,\mu\mu\mu$)</td>
<td>**</td>
<td>******</td>
<td>?</td>
</tr>
</tbody>
</table>

Publicity plots are made with observables which are by definition common to all experiments, therefore they hide the complementarity of the programme.
If the CMS tracker performs like this in the HL-LHC era, and you read 1 MHz into your HLT, CMS will be a heck of a flavour factory not only for $B_s \rightarrow \mu \mu$.

Even imagining that the B-physics hardware trigger was a pure prescale, which it won’t be, CMS would have the same effective luminosity as LHCb.

Are there plans for charm physics with the CMS upgrade? If not, why not?
The impact on the UT, 2020

https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

The impact on the UT, 2030

http://arxiv.org/abs/1309.2293
Let’s add a bit of wishful thinking

Let's add a bit of wishful thinking

https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

Let's talk about practicalities
Charm, a window into the future...

![LHCb Fit and Pull](http://arxiv-web3.library.cornell.edu/abs/1310.7201)
LHCb

$\bullet$ Data

Fit

Signal

Rnd. $\pi_s$

$D^0 \rightarrow K\pi\pi^0$

$D_s^+ \rightarrow K^+K\pi^+$

Comb. bkg

Entries / (0.02 MeV/c²)

10^4

10^3

10^2

10

Pull

5

0

-5

140

145

150

$\Delta m$ [MeV/c²]

...of computing

$>10^9$ signal events

Imagine performing toy studies to evaluate fit biases!

Must take advantage of future computing architecture

Code parallelization key

Also critical to enable progress in lattice QCD

Where charm goes, there beauty will follow soon enough.
I want to talk about something else though:

Real-time data analysis
Why do we need triggers at the LHC?

Input data rate of the LHCb experiment = 1.5 TB/second

NB: ATLAS/CMS about a bit more than one order of magnitude above LHCb
Why do we need triggers at the LHC?

Input data rate of the LHCb experiment = 1.5 TB/second

This means about 15000 PB of data every year

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Input data rate of the LHCb experiment = 1.5 TB/second

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Twitter

NB: ATLAS/CMS about a bit more than one order of magnitude above LHCb
Why do we need triggers at the LHC?

- Input data rate of the LHCb experiment = 1.5 TB/second
- This means about 15000 PB of data every year

- Facebook: 3 PB
- Twitter: 180 PB
- BBC iPlayer: 2500 PB
- Facebook: 11000 PB

NB: ATLAS/CMS about a bit more than one order of magnitude above LHCb
Why do we need triggers at the LHC?

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<table>
<thead>
<tr>
<th>Service</th>
<th>Data (PB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBC iPlayer</td>
<td>3</td>
</tr>
<tr>
<td>Facebook</td>
<td>180</td>
</tr>
<tr>
<td>Twitter</td>
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<td>ATLAS/CMS</td>
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AT&T networks

BBC iPlayer

Facebook

Twitter

NB: ATLAS/CMS about a bit more than one order of magnitude above LHCb
Why do we need triggers at the LHC?

Input data rate of the LHCb experiment = 1.5 TB/second

This means about 15000 PB of data every year

Google was at ~7000 PB/year in 2008, so goodness knows where it is today...

AT&T networks

BBC iPlayer

Facebook

Twitter

NB: ATLAS/CMS about a bit more than one order of magnitude above LHCb
It is mostly about the money

Facebook ~= 180 PB/year

Facebook spending on data
~= 600 M$/year (circa 2011)
It is mostly about the money

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Facebook spending on data
~= 600 M$/year (circa 2011)

Scaled cost of triggerless storage of LHCb ~= 50 B$/year

Total LHC budget ~= 10 B$
It is mostly about the money

- Facebook ~= 180 PB/year
- Facebook spending on data ~= 600 M$/year (circa 2011)

**Nota bene**: Even assuming infinite resources, transferring 1.5 TB/second from the detectors to storage is not easy... although we are getting to the point where it is possible (more on this later)

**Nota bene 2**: Processing data is way cheaper than storing it

Real time event selection == Money

Scaled cost of triggerless storage of LHCb ~= 50 B$/year

Total LHC budget ~= 10 B$
Collisions at the LHC: summary

- **Proton - Proton**: 2804 bunch/beam
- **Protons/bunch**: \(10^{11}\)
- **Beam energy**: 7 TeV \((7 \times 10^{12} \text{ eV})\)
- **Luminosity**: \(10^{34} \text{ cm}^{-2} \text{s}^{-1}\)
- **Crossing rate**: 40 MHz
- **Collision rate**: \(10^7 - 10^9\)

**New physics rate**: \(\approx 0.00001 \text{ Hz}\)

Event selection: 1 in \(10,000,000,000,000\)

The traditional view of triggers...
Found It!!

Congratulations, it only took you 65298 seconds

Triggers today
Enter the MHz signal era

In the HL-LHC era triggers will discriminate between different signal classes!

In the HL-LHC era triggers will discriminate between different signal classes!
Triggers today

Triggers in the future
More precision ⇒ real time analysis

Figure 2: Online control flow of the split HLT.

- Resource sharing between HLT1 and HLT2 tasks during data taking. How do we prioritize them? How flexible do we want to be?
- Events entering the HLT must be fully processed by HLT1 and then deferred until the relevant alignment/calibration is available for HLT2 to use. See Fig. 2 for a proposed structure.
- Do we want to allow a looser (in terms of tracking cuts) HLT1 to run when HLT2 is not running because the events on the buffer disks are not ready to be processed yet?
- Through an as-yet to be specified channel, a failure to provide constants will be communicated to the Hlt2 processes. This information can be used to (un)gate (as we do with the ODIN event type and the Velo closing) alternative lines. Finally, this bit of information will be stored in the HltDecReports as a 'process mode' value. So the 'backup' configuration is always 'contained within the 'nominal' configuration, and there is no need for an 'alternate' TCK. It also 'cleanly' indicates to the users when this situation occurred. This feature may also be used to allow dynamic prescales.
- How do we flag HLT1 deferred events as ready for HLT2 processing?
And so on into the upgrade era
Charm signal purity from LHCb trigger

**Graphs:**
- **Left:** LHCb Trigger $\sqrt{s} = 8$ TeV Data.
  - HLT2 $D^0 \rightarrow K^- \pi^+$
- **Right:** LHCb Simulation Upgrade.
  - $m_{K\pi}$ [MeV/c²]

Remember we said charm today == beauty tomorrow. I hope you are getting scared about systematics.
Real time MVA is challenging

In the future the trigger/DAQ systems will perform almost all the event reconstruction, detector calibration, and signal selection.

We need multivariate trigger algorithms which are safe for real-time use and robust against detector inefficiencies.

Have made a start on this at LHCb, but a lot of R&D still needed!

See also LHCb–PUB–2011–002, 003, 016
http://arxiv.org/abs/1211.3055

Gligorov&Williams http://arxiv.org/abs/1210.6861
The rewards are great, however

Probes $\sim 10^3$ TeV for non-hierarchical NP

Probes $\sim 10-20$ TeV for hierarchical tree-level NP

Probes $\sim 1-2$ TeV for hierarchical loop-level NP

Competitive/complementary with direct searches!

$\text{https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour}$

J. Charles et al. $\text{http://arxiv.org/abs/1309.2293}$
Ceterum censeo, flavour importante est

GPDs directly observe new physics?

YES

Need to measure flavour structure to differentiate NP models

NO

Flavour sets scale of NP and guides design of future direct searches

FLAVOUR STUDIES REQUIRED
Backups
LHCb and the B-factories combined
The leading e + e −→ γ process is split into two subprocesses: the box diagram, and from vertex corrections, shown in Fig. 2, and from double penguin diagrams. In addition there are also self-energy diagrams for the propagators of external legs, which however have exactly the same structure as the box diagrams. Ultimately the CKM structure of the box diagram is di

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Combining the individual measurements

- ADS/GLW 1 fb\(^{-1}\) analysis
- GGSZ 3 fb\(^{-1}\) analysis

LHCb Preliminary
D⁰ mixing and CPV

Figure 1: Distribution of $M(D⁰\pi⁺)$ for selected (a) right-sign $D⁰ \rightarrow K \pi⁺$ and (b) wrong-sign $D⁰ \rightarrow K⁺\pi$ candidates.

Figure 2: Efficiency-corrected ratios of WS-to-RS yields for (a) $D\pi⁺$ decays, (b) $D\pi⁻$ decays, and (c) their differences as functions of decay time in units of $D⁰$ lifetime. Projections of fits allowing for (dashed line) no CP violation, (dotted line) no direct CP violation, and (solid line) full CP violation are overlaid. The abscissa of the data points corresponds to the average decay time over the bin; the error bars indicate the statistical uncertainties.
$D^0$ mixing and CPV
D⁰ mixing and CPV

Figure 1: Efficiency-corrected ratios of WS-to-RS yields for (a) right-sign and (b) wrong-sign D⁰ candidates. The data are shown with points, and the fits are shown as solid or dashed lines. The shaded regions correspond to the 68.3% CL confidence intervals.

Figure 2: Two-dimensional confidence regions in the (x', y') plane. For each fit, 10⁴ WS-to-RS ratio data points are used, corresponding to 10⁴ bins of decay time, distinguishing 13 ranges of decay time, distinguishing between the fit without and with CPV allowed.

The projections of fits (a) right-sign, (b) wrong-sign, and (c) no CPV are overlaid. The abscissa of the data points corresponds to the average decay lifetime. The dashed (solid) curves in (a) and (b) indicate the contours of the mixing parameters 

![Graphs](image)

Indirect CPV, $A_\Gamma$

$$A_\Gamma \equiv \frac{\hat{\Gamma} - \hat{\Gamma}}{\hat{\Gamma} + \hat{\Gamma}} \approx \eta_{CP} \left( \frac{A_m + A_d}{2} y \cos \phi - x \sin \phi \right)$$

![Graphs showing the evolution of fit projections in LHCb](http://arxiv-web3.library.cornell.edu/abs/1310.7201)
Indirect CPV, $A_\Gamma$

$$A_\Gamma \equiv \frac{\hat{\Gamma} - \hat{\Gamma}}{\hat{\Gamma} + \hat{\Gamma}} \approx \frac{A_m + A_d}{2} \frac{y \cos \phi - x \sin \phi}{\pi}$$

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

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

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

http://arxiv-web3.library.cornell.edu/abs/1310.7201
Inclusive B trigger performance

Figure 4.10: Efficiency on offline-filtered signal events vs TOPO output rate for a subset of the decays studied. The red dotted line shows the Run 1 trigger efficiency, while the dot-dashed green line shows twice the Run 1 efficiency for hadronic final states. The vertical dotted lines show the three output-rate scenarios considered in this study.

The availability of all high-PT tracks, irrespective of their displacement from PVs, at the first trigger stage makes it possible to select hadronic decay modes in a lifetime unbiased manner. This will be the first time that such triggers can be deployed at full input rate at a hadron collider. In this context, lifetime unbiased means that there are no selection criteria on quantities which are correlated with the signal particle's decay-time, apart from an explicit lower cut on the decay-time itself. Thus, what is unbiased is the shape of the decay-time distribution. A downscaled sample of events at small decay-times will be kept in order to study decay-time resolution in a data-driven manner. The benefits of this approach are that one removes any need to control decay-time resolution or acceptance functions which reduces the systematic uncertainties of a lifetime-based measurement.

Implementation

A complete description of the implementation is given in Ref. [38]. The challenges of this approach are to control the time taken to form all possible track combinations and the output rate. Of these the timing is the more critical issue, since it affects the general feasibility of the method, while the output rate needs to be tuned for each decay mode.
Including direct CPV into the picture
The CKM matrix

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

\[
V_{CKM} =
\begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
+ \sum_{n=4}^{N} O(\lambda^n)
\]
As a triangle
Experimental status through the years
Experimental status through the years
Experimental status through the years
Experimental status through the years
The CKM triangle “state of the art”...
B → X_s μμ, the B_s sector
B→X_s μμ, the B_s sector

![Graph showing the angular observables and branching fraction for B→X_s μμ.](image)
The many faces of $\gamma$

The number of ways in which it is being measured is growing...
Combining the individual measurements

LHCb Preliminary

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

\[ \gamma = (67 \pm 12)° \]
What about the 2D likelihoods?
The observables presented in Table 2 are a small subset of the many interesting channels in flavour physics. For most other channels, the expected reduction in uncertainty is comparable, as discussed in more detail in Ref. [3, 9] for LHCb and in Ref. [4] for Belle II. Advances in theoretical understanding, including improved lattice QCD calculations, are also anticipated. These combine to an exciting future for heavy flavour physics throughout the HL-LHC era.

<table>
<thead>
<tr>
<th>Observable</th>
<th>CMS</th>
<th>LHCb</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Run 5+</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(B^0 \rightarrow \mu^+ \mu^-)$</td>
<td>&gt; 100%</td>
<td>220%</td>
<td>71%</td>
<td>110%</td>
<td>47%</td>
<td>60%</td>
<td>40%</td>
</tr>
<tr>
<td>$B(B_s^0 \rightarrow \mu^+ \mu^-)$</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>$\phi_s(B^0_s \rightarrow J/\psi \phi)$</td>
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<td></td>
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<tr>
<td>$\phi_s(B^0_s \rightarrow \phi \phi)$</td>
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<tr>
<td>$\gamma$</td>
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<tr>
<td>$A_\Gamma(D^0 \rightarrow K^+ K^-)$</td>
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<td></td>
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<tr>
<td>$q_0^2 A_{FB}(K^{*0} \mu^+ \mu^-)$</td>
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<tr>
<td>$t \rightarrow qZ$</td>
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<tr>
<td>$t \rightarrow q\gamma$</td>
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</tbody>
</table>
Table 3: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb$^{-1}$ recorded during Run 2) and for the LHCb Upgrade (50 fb$^{-1}$). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHC Run 1</th>
<th>LHCb 2018</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$\phi_s(B_s^0 \rightarrow J/\psi \phi)$ (rad)</td>
<td>0.05</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim 0.003$</td>
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<tr>
<td></td>
<td>$\phi_s(B_s^0 \rightarrow J/\psi f_0(980))$ (rad)</td>
<td>0.09</td>
<td>0.05</td>
<td>0.016</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$A_{\text{eff}}(B_s^0)$ (10$^{-3}$)</td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>0.03</td>
</tr>
<tr>
<td>Gluonic</td>
<td>$\phi_{\text{eff}}(B_s^0 \rightarrow \phi \phi)$ (rad)</td>
<td>0.18</td>
<td>0.12</td>
<td>0.026</td>
<td>0.02</td>
</tr>
<tr>
<td>Penguin</td>
<td>$\phi_{\text{eff}}(B_s^0 \rightarrow K^{*0} K^{*0})$ (rad)</td>
<td>0.19</td>
<td>0.13</td>
<td>0.029</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_{\text{eff}}(B_s^0 \rightarrow \phi K_S^0)$ (rad)</td>
<td>0.30</td>
<td>0.20</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed</td>
<td>$\phi_{\text{eff}}(B_s^0 \rightarrow \phi \gamma)$</td>
<td>0.20</td>
<td>0.13</td>
<td>0.030</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>Currents</td>
<td>$\tau_{\text{eff}}(B_s^0 \rightarrow \phi \gamma)/\tau_{B_s^0}$</td>
<td>5%</td>
<td>3.2%</td>
<td>0.8%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak</td>
<td>$S_3(B^0 \rightarrow K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
</tr>
<tr>
<td>Penguin</td>
<td>$q_0^2 A_{FB}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)$</td>
<td>10%</td>
<td>5%</td>
<td>1.9%</td>
<td>$\sim 7%$</td>
</tr>
<tr>
<td></td>
<td>$A_1(K \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.14</td>
<td>0.07</td>
<td>0.024</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \rightarrow \pi^+ \mu^+ \mu^-)/B(B^+ \rightarrow K^+ \mu^+ \mu^-)$</td>
<td>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs</td>
<td>$B(B_s^0 \rightarrow \mu^+ \mu^-)$ (10$^{-9}$)</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td>Penguin</td>
<td>$B(B^0 \rightarrow \mu^+ \mu^-)/B(B_s^0 \rightarrow \mu^+ \mu^-)$</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity</td>
<td>$\gamma(B \rightarrow D^{(<em>)} K^{(</em>)})$</td>
<td>7°</td>
<td>4°</td>
<td>1.1°</td>
<td>negligible</td>
</tr>
<tr>
<td>Triangle</td>
<td>$\gamma(B_s^0 \rightarrow D^{\pm} K^{\mp})$</td>
<td>17°</td>
<td>11°</td>
<td>2.4°</td>
<td>negligible</td>
</tr>
<tr>
<td>Angles</td>
<td>$\beta(B^0 \rightarrow J/\psi K_S^0)$</td>
<td>1.7°</td>
<td>0.8°</td>
<td>0.31°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_{\Gamma}(D^0 \rightarrow K^+ K^-)$ (10$^{-9}$)</td>
<td>3.4</td>
<td>2.2</td>
<td>0.5</td>
<td>–</td>
</tr>
<tr>
<td>CP violation</td>
<td>$\Delta A_{CP}$ (10$^{-3}$)</td>
<td>0.8</td>
<td>0.5</td>
<td>0.12</td>
<td>–</td>
</tr>
</tbody>
</table>

The future, LHCb
The future, Belle II

<table>
<thead>
<tr>
<th>Observable</th>
<th>Belle 2006 (~0.5 ab⁻¹)</th>
<th>SuperKEKB (5 ab⁻¹)</th>
<th>SuperKEKB (50 ab⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic $b \to s$ transitions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta S_{\phi K^0}$</td>
<td>0.22</td>
<td>0.073</td>
<td>0.029</td>
</tr>
<tr>
<td>$\Delta S_{\phi' K^0}$</td>
<td>0.11</td>
<td>0.038</td>
<td>0.020</td>
</tr>
<tr>
<td>$\Delta S_{K_0^0 K_0^0 K_0^0}$</td>
<td>0.33</td>
<td>0.105</td>
<td>0.037</td>
</tr>
<tr>
<td>$\Delta A_{\pi^0 K_0^0}$</td>
<td>0.15</td>
<td>0.072</td>
<td>0.042</td>
</tr>
<tr>
<td>$A_{\phi\phi K^+}$</td>
<td>0.17</td>
<td>0.05</td>
<td>0.014</td>
</tr>
<tr>
<td>$\phi_{13}^{eff}(\phi K_S)$ Dalitz</td>
<td>3.3°</td>
<td>1.5°</td>
<td></td>
</tr>
<tr>
<td>Radiative/electroweak $b \to s$ transitions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{K^0 s^{\pi\gamma}}$</td>
<td>0.32</td>
<td>0.10</td>
<td>0.03</td>
</tr>
<tr>
<td>$B(B \to X_s\gamma)$</td>
<td>13%</td>
<td>7%</td>
<td>6%</td>
</tr>
<tr>
<td>$A_{\text{CP}}(B \to X_s\gamma)$</td>
<td>0.058</td>
<td>0.01</td>
<td>0.005</td>
</tr>
<tr>
<td>$C_9$ from $\overline{A}_{FB}(B \to K^*\ell^+\ell^-)$</td>
<td>-</td>
<td>11%</td>
<td>4%</td>
</tr>
<tr>
<td>$C_{10}$ from $\overline{A}_{FB}(B \to K^*\ell^+\ell^-)$</td>
<td>-</td>
<td>13%</td>
<td>4%</td>
</tr>
<tr>
<td>$C_7/C_9$ from $\overline{A}_{FB}(B \to K^*\ell^+\ell^-)$</td>
<td>-</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>$R_K$</td>
<td></td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>$B(B^+ \to K^+\nu\nu)$</td>
<td>$\dagger\dagger &lt; 3 \mathcal{B}_\text{SM}$</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>$B(B^0 \to K^{*0}\nu\bar{\nu})$</td>
<td>$\dagger\dagger &lt; 40 \mathcal{B}_\text{SM}$</td>
<td>35%</td>
<td></td>
</tr>
<tr>
<td>Leptonic/semileptonic $B$ decays</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B^+ \to \tau^+\nu)$</td>
<td>$3.5\sigma$</td>
<td>10%</td>
<td>3%</td>
</tr>
<tr>
<td>$B(B^+ \to \mu^+\nu)$</td>
<td>$\dagger\dagger &lt; 2.4\mathcal{B}_\text{SM}$</td>
<td>4.3 ab⁻¹ for 5σ discovery</td>
<td></td>
</tr>
<tr>
<td>$B(B^+ \to D\tau\nu)$</td>
<td>$-\phantom{0.05}$</td>
<td>8%</td>
<td>3%</td>
</tr>
<tr>
<td>$B(B^0 \to D\tau\nu)$</td>
<td>$-\phantom{0.05}$</td>
<td>30%</td>
<td>10%</td>
</tr>
<tr>
<td>LFV in $\tau$ decays (U.L. at 90% C.L.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(\tau \to \mu\gamma)$ [10⁻⁹]</td>
<td>45</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>$B(\tau \to \mu\eta)$ [10⁻⁹]</td>
<td>65</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>$B(\tau \to \mu\mu\mu)$ [10⁻⁹]</td>
<td>21</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Unitarity triangle parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sin 2\phi_1$</td>
<td>0.026</td>
<td>0.016</td>
<td>0.012</td>
</tr>
<tr>
<td>$\phi_2 (\pi\pi)$</td>
<td>$11^\circ$</td>
<td>$10^\circ$</td>
<td>$3^\circ$</td>
</tr>
<tr>
<td>$\phi_2 (\rho\rho)$</td>
<td>$68^\circ &lt; \phi_2 &lt; 95^\circ$</td>
<td>$3^\circ$</td>
<td>$1.5^\circ$</td>
</tr>
<tr>
<td>$\phi_2 (\text{combined})$</td>
<td>$62^\circ &lt; \phi_2 &lt; 107^\circ$</td>
<td>$3^\circ$</td>
<td>$1.5^\circ$</td>
</tr>
<tr>
<td>$\phi_3 (D^{(<em>)}K^{(</em>)})$ (Dalitz mod. ind.)</td>
<td>$20^\circ$</td>
<td>$7^\circ$</td>
<td>$2^\circ$</td>
</tr>
<tr>
<td>$\phi_3 (D^{(*)}\pi)$</td>
<td>$-\phantom{0.05}$</td>
<td>16°</td>
<td>5°</td>
</tr>
<tr>
<td>$\phi_3$ (Dalitz-modulated)</td>
<td>$-\phantom{0.05}$</td>
<td>18°</td>
<td>6°</td>
</tr>
<tr>
<td>$\phi_3$ (Dalitz-modulated)</td>
<td>$-\phantom{0.05}$</td>
<td>6°</td>
<td>$1.5^\circ$</td>
</tr>
<tr>
<td>$\phi_3$ (Dalitz-modulated)</td>
<td>$-\phantom{0.05}$</td>
<td>6°</td>
<td>$1.5^\circ$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>(\text{inclusive})$</td>
<td>$6%$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>(\text{exclusive})$</td>
<td>$15%$</td>
</tr>
<tr>
<td>$\chi^2/\nu$</td>
<td>$90.0%$</td>
<td>$&lt;1.0%$</td>
<td>$&lt;0.0%$</td>
</tr>
</tbody>
</table>

S. Monteil

Flavours

11
A forward spectrometer for the LHC
with excellent tracking resolution

\[ \sigma_{\text{eff}} = 45 \text{ fs} \]
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 $\mu^2$ $\mu/\mu$ $\mu$
- 400 kHz $150$ kHz $\text{e}/\gamma$

Offline reconstruction tuned to trigger time constraints

5 kHz Rate to storage

Defer 20% to disk

Software High Level Trigger

- 29000 Logical CPU cores
- Mixture of exclusive and inclusive selection algorithms
Trigger signatures

"A B is the elephant of the particle zoo: it is very heavy and lives a long time" -- T. Schietinger

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

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 $IP$. After $IP_2$ 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).
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
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
A topological decision tree trigger

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 $B \to K \pi \pi$ decays: (left) HLT2 2-body topological trigger candidates; (right) HLT2 3-body topological trigger candidates. In each plot, both the measured mass of the 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.

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.
A topological decision tree trigger

\[ m_{corrected} = \sqrt{m^2 + |p_{Tmissing}'|^2 + |p_{Tmissing}'|} \]
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** $B_{S}\rightarrow D_{S}K$
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 $B_{S} \to D_{S}K$
Aside on the CKM matrix structure

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

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

colour favoured

doubly Cabibbo suppressed

colour suppressed

Cabibbo favoured
Observables ↔ physics parameters

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

A_{\pi}^{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

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

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

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

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

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

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

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

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

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

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

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

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

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

![Graph showing the Cabbibo-favoured signals](image)
The singly Cabbibo–Suppressed signals

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

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

Branching fraction ratios consistent with CF D⁰ decay mode

\[ R_{CP} = \langle P_{KK/\pi}^{K^0}, P_{KK/\pi}^{\pi^0} \rangle = 1.007 \pm 0.038 \pm 0.012 \]
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 $D \rightarrow hhhh$

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 $B_{S} \rightarrow D_{S}K$
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 $\gamma$ when treated in this integrated manner than the two-body modes. However, they can still provide a good constraint on $r_B$. 

\[
\Gamma(B^\pm \to D(K^{\mp}\pi^+\pi^+\pi^-)K^\pm) \propto 1 + (r_B r_D^{K3\pi})^2 + 2 R_{K3\pi} r_B r_D^{K3\pi} \cos(\delta_B - \delta_D^{K3\pi} \pm \gamma),
\]

\[
\Gamma(B^\pm \to D(K^{\mp}\pi^0\pi^+\pi^-)K^\pm) \propto r_B^2 + (r_D^{K3\pi})^2 + 2 R_{K3\pi} r_B r_D^{K3\pi} \cos(\delta_B + \delta_D^{K3\pi} \pm \gamma),
\]
The Cabbibo-favoured signals

![Graph showing distributions of $B^{-}\rightarrow [K^{-}\pi^{+}\pi^{+}\pi^{+}]_D K^{-}$ and $B^{+}\rightarrow [K^{+}\pi^{-}\pi^{+}\pi^{+}]_D K^{+}$, and $B^{-}\rightarrow [K^{-}\pi^{+}\pi^{+}\pi^{+}]_D \pi^{-}$ and $B^{+}\rightarrow [K^{+}\pi^{-}\pi^{+}\pi^{+}]_D \pi^{+}$]
The ADS signals

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

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

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

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

\[
A_{\text{ADS}(K)}^{K^3\pi} = \frac{R_{K}^{K^3\pi,-} - R_{K}^{K^3\pi,+}}{R_{K}^{K^3\pi,-} + R_{K}^{K^3\pi,+}} = -0.42 \pm 0.22
\]

\[
A_{\text{ADS}(\pi)}^{K^3\pi} = \frac{R_{\pi}^{K^3\pi,-} - R_{\pi}^{K^3\pi,+}}{R_{\pi}^{K^3\pi,-} + R_{\pi}^{K^3\pi,+}} = +0.13 \pm 0.10
\]

ADS modes established at $>5\sigma$ significance!
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 \( B \to Dhh \)

Frequentist \( \gamma \) combination

Time dependent CPV in \( B_{S} \to D_{S}K \)
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.
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.

\[
N_{+i}^+ = n_{B^+}[K_{-i} + (x_i^2 + y_i^2)K_{+i} + 2\sqrt{K_{+i}K_{-i}}(x_i c_{+i} - y_i s_{+i})]
\]

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

\(c_i, s_i\) are the CLEO inputs

\(K_i\) are the yields of tagged \(D^0\) decays in each bin
$K_S\pi\pi$ and $K_SKK$ signals for $1 \text{ fb}^{-1}$

**Figure 1:**

- **Panel (a):** $B^z \rightarrow (K^0_S \pi^+ \pi^-)_D \pi^z$
  - LHCb
  - All $K^0_S$
  - Blue line: Sum, incl. combinatorics
  - Red line: Signal
  - Grey line: Partially reconstructed

- **Panel (b):** $B^z \rightarrow (K^0_S K^+ K^-)_D \pi^z$
  - LHCb
  - All $K^0_S$
  - Blue line: Sum, incl. combinatorics
  - Red line: Signal
  - Grey line: Partially reconstructed

**Figure 2:**

- **Panel (a):** $B^z \rightarrow (K^0_S \pi^+ \pi^-)_D K^z$
  - LHCb
  - All $K^0_S$
  - Blue line: Sum, incl. combinatorics
  - Red line: Signal
  - Grey line: Mis-ID
  - Grey line: Partially reconstructed

- **Panel (b):** $B^z \rightarrow (K^0_S K^+ K^-)_D K^z$
  - LHCb
  - All $K^0_S$
  - Blue line: Sum, incl. combinatorics
  - Red line: Signal
  - Grey line: Mis-ID
  - Grey line: Partially reconstructed
Dalitz distributions for 1 fb$^{-1}$
\( x^\pm, y^\pm \) for 1 fb\(^{-1}\)

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

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\(^{-1}\)
$x^\pm, y^\pm$ for 2 fb$^{-1}$

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

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

Dh GLW/ADS(h, K3|τ) + GGSZ

LHCb Preliminary

Dh GLW/ADS(h, K3|τ) + GGSZ

LHCb Preliminary
GLW/ADS 2D plots

Dh GLW/ADS(hh, K3π) + GGSZ

LHCb
Preliminary

Dh GLW/ADS(hh, K3π) + GGSZ
D_sK charm signals

**LHCb Preliminary**

- $L_{int}=1.0 \text{ fb}^{-1}$
  - $D_s \rightarrow K K \pi$
- $L_{int}=1.0 \text{ fb}^{-1}$
  - $D_s \rightarrow K \pi \pi$
- $L_{int}=1.0 \text{ fb}^{-1}$
  - $D_s \rightarrow \pi \pi \pi$

Candidates (4 MeV/c^2)

- $m(K K \pi)$ [MeV/c^2]
- $m(K K \pi)$ [MeV/c^2]
- $m(\pi \pi \pi)$ [MeV/c^2]
GGSZ asymmetries per bin 1fb$^{-1}$
GGSZ only extractions $1\text{fb}^{-1}$
\[ R_{K/\pi}^{K\pi} = 0.0774 \pm 0.0012 \pm 0.0018 \]
\[ R_{K/\pi}^{KK} = 0.0773 \pm 0.0030 \pm 0.0018 \]
\[ R_{K/\pi}^{\pi\pi} = 0.0803 \pm 0.0056 \pm 0.0017 \]
\[ A_{\pi}^{K\pi} = -0.0001 \pm 0.0036 \pm 0.0095 \]
\[ A_{K}^{K\pi} = 0.0044 \pm 0.0144 \pm 0.0174 \]
\[ A_{KK}^{KK} = 0.148 \pm 0.037 \pm 0.010 \]
\[ A_{\pi\pi}^{\pi\pi} = 0.135 \pm 0.066 \pm 0.010 \]
\[ A_{KK}^{KK} = -0.020 \pm 0.009 \pm 0.012 \]
\[ A_{\pi\pi}^{\pi\pi} = -0.001 \pm 0.017 \pm 0.010 \]
\[ R_{K}^{-} = 0.0073 \pm 0.0023 \pm 0.0004 \]
\[ R_{K}^{+} = 0.0232 \pm 0.0034 \pm 0.0007 \]
\[ R_{\pi}^{-} = 0.00469 \pm 0.00038 \pm 0.00008 \]
\[ R_{\pi}^{+} = 0.00352 \pm 0.00033 \pm 0.00007 \]

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} background. \text{A}_{\text{instr.}} quantifies the uncertainty on the production, interaction and detection asymmetries.

\begin{array}{|c|c|c|c|c|c|}
\hline
\times 10^{-3} & \text{PID} & \text{PDFs} & \text{Sim} & \text{A}_{\text{instr.}} & \text{Total} \\
\hline
R_{K/\pi}^{K\pi} & 1.4 & 0.9 & 0.8 & 0 & 1.8 \\
R_{K/\pi}^{KK} & 1.3 & 0.8 & 0.9 & 0 & 1.8 \\
R_{K/\pi}^{\pi\pi} & 1.3 & 0.6 & 0.8 & 0 & 1.7 \\
A_{K}^{K\pi} & 0 & 1.0 & 0 & 9.4 & 9.5 \\
A_{K}^{KK} & 0.2 & 4.1 & 0 & 16.9 & 17.4 \\
A_{K}^{\pi\pi} & 1.6 & 1.3 & 0.5 & 9.5 & 9.7 \\
A_{\pi}^{K\pi} & 1.9 & 2.3 & 0 & 9.0 & 9.5 \\
A_{\pi}^{KK} & 0.1 & 6.6 & 0 & 9.5 & 11.6 \\
A_{\pi}^{\pi\pi} & 0.1 & 0.4 & 0 & 9.9 & 9.9 \\
R_{K}^{-} & 0.2 & 0.4 & 0 & 0.1 & 0.4 \\
R_{K}^{+} & 0.4 & 0.5 & 0 & 0.1 & 0.7 \\
R_{\pi}^{-} & 0.01 & 0.03 & 0 & 0.07 & 0.08 \\
R_{\pi}^{+} & 0.01 & 0.03 & 0 & 0.07 & 0.07 \\
\hline
\end{array}
Table 2: Systematic uncertainties on the observables. PID refers to the fixed efficiency for the bachelor DLL$_{K\pi}$ requirement which is determined using the $D^{*\pm}$ 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. $A_{\text{instr.}}$ 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>$R_{K^{3\pi}}$</td>
<td>1.7</td>
<td>1.2</td>
<td>1.5</td>
<td>0.0</td>
<td>2.6</td>
</tr>
<tr>
<td>$A_{K^{3\pi}}$</td>
<td>0.2</td>
<td>1.3</td>
<td>0.1</td>
<td>9.9</td>
<td>10.0</td>
</tr>
<tr>
<td>$A_{K^{3\pi}}$</td>
<td>0.6</td>
<td>4.4</td>
<td>0.3</td>
<td>17.1</td>
<td>17.7</td>
</tr>
<tr>
<td>$R_{K^{3\pi},-}$</td>
<td>0.4</td>
<td>0.7</td>
<td>0.1</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>$R_{K^{3\pi},+}$</td>
<td>0.4</td>
<td>0.9</td>
<td>0.2</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>$R_{K^{3\pi},-}$</td>
<td>0.02</td>
<td>0.09</td>
<td>0.01</td>
<td>0.06</td>
<td>0.11</td>
</tr>
<tr>
<td>$R_{K^{3\pi},+}$</td>
<td>0.04</td>
<td>0.08</td>
<td>0.02</td>
<td>0.06</td>
<td>0.11</td>
</tr>
</tbody>
</table>

$R_{K^{3\pi}} = 0.0771 \pm 0.0017 \pm 0.0026$

$A_{K^{3\pi}} = -0.029 \pm 0.020 \pm 0.018$

$A_{K^{3\pi}} = -0.006 \pm 0.005 \pm 0.010$

$R_{K^{3\pi},-} = 0.0072 \pm 0.0003 \pm 0.0008$

$R_{K^{3\pi},+} = 0.0175 \pm 0.0003 \pm 0.0010$

$R_{K^{3\pi},-} = 0.00417 \pm 0.00054 \pm 0.00011$

$R_{K^{3\pi},+} = 0.00321 \pm 0.00048 \pm 0.00011$
GGSZ full results 1fb$^{-1}$

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 $D \to K_s^0K^+K^-$ 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>$x_-$ [×10$^{-2}$]</td>
<td>0.0 ± 4.3 ± 1.5 ± 0.6</td>
<td>1.6 ± 4.8 ± 1.4 ± 0.8</td>
</tr>
<tr>
<td>$y_-$ [×10$^{-2}$]</td>
<td>2.7 ± 5.2 ± 0.8 ± 2.3</td>
<td>1.4 ± 5.4 ± 0.8 ± 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>$x_+$ [×10$^{-2}$]</td>
<td>-10.3 ± 4.5 ± 1.8 ± 1.4</td>
<td>-8.6 ± 5.4 ± 1.7 ± 1.6</td>
</tr>
<tr>
<td>$y_+$ [×10$^{-2}$]</td>
<td>-0.9 ± 3.7 ± 0.8 ± 3.0</td>
<td>-0.3 ± 3.7 ± 0.9 ± 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>