LHCb Physics Program
On behalf of the LHCb collaboration
A spokesperson of any LHC collaboration has to believe that there will be discovery of New Physics at LHC.

General Purpose Detectors are designed for direct observation of New Particles.

LHCb has a different strategy.

Experimental observables sensitive to New Particles through the interference effects with well studied objects, $b$-quarks.

Various Scenarios

No space left for the 4th possibility

<table>
<thead>
<tr>
<th>ATLAS CMS high $p_T$ physics</th>
<th>BSM</th>
<th>Only SM</th>
<th>BSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb flavour physics</td>
<td>Only SM</td>
<td>BSM</td>
<td>BSM</td>
</tr>
<tr>
<td>Particle Physics</td>
<td>😊</td>
<td>😊</td>
<td>😊²</td>
</tr>
</tbody>
</table>
Examples of processes mediated by loop diagrams in b-physics

- \( B_{d,s} \) oscillations: box diagram

- Penguin diagrams:
  - Radiative penguin: \( B_s \rightarrow \phi \gamma \)
  - Electroweak penguin: \( B \rightarrow K^* \mu \mu \)
  - Strong penguin: \( B \rightarrow \pi \pi, B_s \rightarrow \phi \phi \)

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**Oscillation box**

\[
\begin{align*}
\overline{b} &\quad W^+ & u, c, t &\quad W^- &\quad \overline{q} \\
B_q &\quad q & u, c, t &\quad B_q \\
V_{iq} &\quad V^*_{ib} & & &
\end{align*}
\]
Search for NP in CPV by comparing observables measured in tree and loop topologies

\[ \beta(\text{tree+box}) \text{ in } B \rightarrow J/\psi K_s \]

\[ \gamma(\text{tree}) \text{ in many channels} \]

\[ \beta_s(\text{tree+box}) \text{ in } B_s \rightarrow J/\psi \phi \]

\[ \beta(\text{peng+box}) \text{ in } B \rightarrow \phi K_s \]

\[ \gamma(\text{peng+tree}) \text{ in } B \rightarrow \rho \rho, \rho \pi, \pi \pi \text{ or } B_s \rightarrow K K \]

\[ \beta_s(\text{peng+box}) \text{ in } B_s \rightarrow \phi \phi \]

New heavy particles, which may contribute to d- and s- penguins, could lead to some phase shifts in all three angles:

\[ \delta \gamma(\text{NP}) = \gamma(\text{peng+tree}) - \gamma(\text{tree}) \]

\[ \delta \beta(\text{NP}) = \beta(\text{B} \rightarrow \phi K_s) - \beta(\text{B} \rightarrow J/\psi K_s) \neq 0 \]

\[ \delta \beta_s(\text{NP}) = \beta_s(\text{B}_s \rightarrow \phi \phi) - \beta_s(\text{B}_s \rightarrow J/\psi \phi) \]
Current sensitivity to New Physics in CPV measurements

- **In box diagrams**

  $\beta$ vs $|V_{ub}/V_{cb}|$ is limited by theory ($\sim 10\%$ precision in $|V_{ub}|$) (d-box)

  $\beta_s$ not measured accurately (indication of large value from CDF/D0) (s-box)

- **In penguin diagrams:**

  $\sigma(\delta \gamma (NP)) \sim 30^\circ$ (d-penguin)

  $\sigma(\delta \beta (NP)) \sim 10^\circ$ (s-penguin)

  $\sigma(\delta \beta_s (NP))$ not measured (s-penguin)

  $PS \, \delta \beta (NP) \approx \delta \beta_s (NP)$
Current sensitivity to New Physics in Rare Decays (combination of various box and penguin diagrams)

Experiments are just reaching an interesting level of sensitivity in exclusive decays:

- $A_{FB}$ in $B \to K^*\mu\mu$ (BELLE/BaBar)
- Photon polarization in $B \to K^*\gamma$ (BELLE/BaBar)
- $BR (B_s \to \mu\mu)$ (CDF /D0)
- $BR (D^0 \to \mu\mu)$ (CDF)
- Lepton FlavorViolation in $\tau$ decays (BELLE/BaBar)

Contribution from LHCb is extremely important !!!

Background suppression is a challenge
LHCb Running Conditions

- Bunch crossing frequency: ~ 40 MHz

- For LHCb \( L \sim 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \)
  (less focusing of the beam locally)
  \( \rightarrow \) multiple interactions are subdominant

- Prospects for data samples:
  - 2 fb\(^{-1}\) in 1 nominal LHC year
  - \(~10 \text{ fb}^{-1}\) in a few years
  - \(~100 \text{ fb}^{-1}\) after possible upgrade to run at
  \( L \sim 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \)
LHCb key measurements are potentially sensitive to discovery of New Physics

- In CP–violation
  - $\phi_s$
  - $\gamma$ in trees
  - $\gamma$ in loop

- In Rare Decays
  - $A_{FB}$ in $B \rightarrow K^*\mu\mu$
  - BR ($B_s \rightarrow \mu\mu$)
  - Polarization of photon in radiative penguin decays

- Mixing and CP–violation in Charm sector

- Search for Lepton Flavor Violation in $\tau \rightarrow \mu\mu\mu$
LHCb sensitivities for the key measurements

Int. Lumi

- For nominal LHC year  
  (2 fb⁻¹)

- For a few years of running at 2-5 × 10³²  
  (10 fb⁻¹)

  Accuracy is limited by statistics

- Do we need larger data samples?  
  (≈ 100 fb⁻¹)

  - Theoretical uncertainties
  - Study of systematic accuracy is ongoing
LHCb prospects for $\beta_s$

- $\phi_s = -2\beta_s$ is the counterpart of $\phi_d = 2\beta$

- $\phi_s (J/\psi\phi)[SM] = 0.0368\pm0.0017$ (CKMfitter)

Most accurate SM prediction $\Rightarrow$ increased sensitivity to New Physics effects in the $B_s$-$B_s$ system: if NP in the box loop

$$\phi_s = \phi_s(SM) + \phi_s(NP)$$

- High BR($B_s \rightarrow J/\psi\phi$) and trigger eff.
  LHCb yield in 2 fb$^{-1}$ 115 k

- $J/\psi\phi$ is not a pure CP-eigenstate;
  angular analysis is needed to separate odd and even states

See talk of A. Sarti

<table>
<thead>
<tr>
<th>Decay</th>
<th>Yield (2 fb$^{-1}$)</th>
<th>$\sigma (\phi_s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \eta_{\gamma\gamma}$</td>
<td>8.5 k</td>
<td>0.109</td>
</tr>
<tr>
<td>$J/\psi \eta_{\pi\pi\pi}$</td>
<td>3 k</td>
<td>0.142</td>
</tr>
<tr>
<td>$J/\psi \eta'_{\pi\pi\eta}$</td>
<td>2.2 k</td>
<td>0.154</td>
</tr>
<tr>
<td>$J/\psi \eta'_{\rho\gamma}$</td>
<td>4.2 k</td>
<td>0.08</td>
</tr>
<tr>
<td>$\eta_c \phi$</td>
<td>3 k</td>
<td>0.108</td>
</tr>
<tr>
<td>$D_s^+ D_s^-$</td>
<td>4k</td>
<td>0.133</td>
</tr>
<tr>
<td>All CP eig</td>
<td>-</td>
<td>0.046</td>
</tr>
<tr>
<td>$J/\psi \phi$</td>
<td>115 k</td>
<td>0.03</td>
</tr>
<tr>
<td>All</td>
<td>-</td>
<td>0.021</td>
</tr>
</tbody>
</table>
**LHCb prospects for $\gamma$**

- **In trees:**
  - **Interference between tree-level decays**
    - Favored: $V_{cb} \, V_{us}^*$
    - Common final state: $K^{(*)-}$
    - Parameters: $\gamma$, $(r_B, \delta_B)$ per mode

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$B^- \rightarrow D^0 K^-$</td>
<td>$A(B^- \rightarrow D^0 K^-) = r_B e^{i\delta_B} e^{-i\gamma}$</td>
</tr>
<tr>
<td>$B^- \rightarrow D^0 K^-$</td>
<td>$A(B^- \rightarrow D^0 K^-) = r_B e^{i\delta_B} e^{-i\gamma}$</td>
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Three methods for exploiting interference (choice of $D^0$ decay modes):
- **(GLW):** Use CP eigenstates of $D^{(*)0}$ decay, e.g. $D^0 \rightarrow K^+ K^- / \pi^+ \pi^- , K_s \pi^0$
- **(ADS):** Use doubly Cabibbo-suppressed decays, e.g. $D^0 \rightarrow K^+ \pi^-$
- **(Dalitz):** Use Dalitz plot analysis of 3-body $D^0$ decays, e.g. $K_s \pi^+ \pi^-$

- **Mixing induced CPV measurement in $B_s \rightarrow D_s K$ decays**
  - (Specific for LHCb)

- **Interference of trees and penguins**
  - CP asymmetries of $B^0 \rightarrow \pi \pi$ and $B_s \rightarrow KK$ events assuming U-spin symmetry
γ with trees

- Perform global fit to $B \rightarrow DK$ with common parameters
  - Include results from $B^0$ and $B_s$ time dependent analyses.

<table>
<thead>
<tr>
<th>$\delta_{B^0}$ (°)</th>
<th>0</th>
<th>45</th>
<th>90</th>
<th>135</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_\gamma$ for 0.5 fb$^{-1}$ (°)</td>
<td>8.1</td>
<td>10.1</td>
<td>9.3</td>
<td>9.5</td>
<td>7.8</td>
</tr>
<tr>
<td>$\sigma_\gamma$ for 2 fb$^{-1}$ (°)</td>
<td>4.1</td>
<td>5.1</td>
<td>4.8</td>
<td>5.1</td>
<td>3.9</td>
</tr>
<tr>
<td>$\sigma_\gamma$ for 10 fb$^{-1}$ (°)</td>
<td>2.0</td>
<td>2.7</td>
<td>2.4</td>
<td>2.6</td>
<td>1.9</td>
</tr>
</tbody>
</table>

γ in penguin loops: $B^0 \rightarrow \pi\pi$ and $B_s \rightarrow KK$

- Fit CP asymmetries of $B^0 \rightarrow \pi\pi$ and $B_s \rightarrow \pi\pi$ event
  - 4 observables: $A^\text{dir}_{\pi\pi}, A^\text{mix}_{\pi\pi}, A^\text{dir}_{KK}, A^\text{mix}_{KK}$

- Parameters: $\gamma$, penguin to tree amplitude ratio $d_{\pi\pi} e^{i\Theta_{\pi\pi}}, d_{KK} e^{i\Theta_{KK}}$

- Weak U-spin constraint
  - $d_{\pi\pi} = d_{KK} \pm 20\%$, $\Theta_{\pi\pi}, \Theta_{KK}$ independent
  - Measures $\gamma$ under certain assumptions on U-spin symmetry

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>2 fb$^{-1}$</th>
<th>10 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_\gamma$ (°)</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>$\sigma_{d_{\pi\pi}}$</td>
<td>0.18</td>
<td>0.09</td>
</tr>
<tr>
<td>$\sigma_{\Theta_{\pi\pi}}$ (°)</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>$\sigma_{\Delta\Theta}$ (°)</td>
<td>17</td>
<td>12</td>
</tr>
</tbody>
</table>

See talk of V. Gibson
Measurement of the photon polarization in $B_s \rightarrow \phi \gamma$ decay

See poster of L. Shchutska

$b \rightarrow \gamma (L) + (m_s/m_b) \times \gamma (R)$

$\phi \gamma$ produced in $B_s$ and $\bar{B}_s$ decays do not interfere in SM $\rightarrow$ corresponding $A_{CP} = 0$

$\Gamma (B_q (\bar{B}_q) \rightarrow f^{CP} \gamma) \propto e^{-\Gamma_q t} \left( \cosh \frac{\Delta \Gamma_q t}{2} - A^\Delta \sinh \frac{\Delta \Gamma_q t}{2} \pm \right.$

$\left. \pm C \cos \Delta m_q t \mp S \sin \Delta m_q t \right)$

SM:

- $C = 0$ direct CP-violation
- $S = \sin 2\psi \sin \phi$
- $A^D = \sin 2\psi \cos \phi$

- Expected signal yield is 11k per nominal LHCb year

- Sensitivity: $\sigma (A^D)=0.22$, $\sigma (S)=\sigma (C)=0.11$ for 2fb$^{-1}$
  
  $\sigma (A^D)=0.09$ for 10fb$^{-1}$

To be compared with current accuracy from B-factories: $\sigma (\sin 2\psi) \sim 0.4$
**B → K^*\mu\mu**

See talk of W. Reece

In SM this b → s penguin decay contains right-handed calculable contribution but this could be added to by NP resulting in modified angular distributions

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4} F_0 \sin^2\theta_\ell + \frac{3}{8} F_T (1 + \cos^2\theta_\ell) + A_{FB} \cos\theta_\ell
\]

- Described by three angles ($\theta_\ell$, $\phi$, $\theta_K$) and di-$\mu$ invariant mass $q^2$

- Forward-backward asymmetry $A_{FB}$ of $\theta_\ell$ distribution of particular interest:
  - Varies between different NP models →
  - At zero-point, dominant theor. uncert. from $B_d \to K^*$ form-factors cancels at LO
B → K*μμ

- Forward-backward asymmetry $A_{FB} (s)$ in $μμ$-rest frame is a sensitive NP probe
- Predicted zero of $A_{FB} (s)$ depends on Wilson coefficients $C_7^{\text{eff}} / C_9^{\text{eff}}$

- LHCb, 10 fb$^{-1}$

- ~7k events / 2fb$^{-1}$ with B/S ~ 0.2
- After 10 fb$^{-1}$ zero of $A_{FB}$ located to ±0.28 GeV$^2$ (0.5 GeV$^2$ after 2 fb$^{-1}$)
- Providing 7% stat. error on $C_7^{\text{eff}} / C_9^{\text{eff}}$
- Full angular analysis gives better discrimination between models. Looks promising
$B_s \to \mu\mu$

- Super rare decay in SM with well predicted $BR(B_s \to \mu\mu) = (3.55\pm0.33) \times 10^{-9}$

- Potentially sensitive to NP
  
  In MSSM $BR \propto \tan^6\beta / M_A^4$

- Best present limit is from CDF:
  
  $BR(B_s \to \mu\mu) < 4.7 \times 10^{-8}$ @ 90% CL

- LHCb selects a signal using 3D likelihood of invariant mass, geometrical variables and PID:
  
  - Uncorrelated variables with different control samples
  
  - Invariant mass resolution is $\sim 20$ MeV/c$^2$
$B_s \rightarrow \mu\mu$

- For the SM prediction, LHCb expects 8 signal and 12 background events in the most sensitive bin in 2 fb$^{-1}$. Background is dominated by semileptonic decays of different $b$.

- 3$\sigma$ evidence with 2 fb$^{-1}$, 5$\sigma$ observation with 6 fb$^{-1}$

For more precision measurement, one needs the absolute normalization. Measurements of $B_s$ BR at $Y(5S)$ by BELLE would be welcome.
Charm Physics

Charm has unique sensitivity to NP since loop diagrams involve down-type quarks

- **Precision measurements of** $x$ & $y$, mixing parameters in the charm system (factor of 5 improvement wrt current accuracy)

  - **Wrong Sign ($D^0 \rightarrow \pi^- K^+$) mixing analysis**
    
    $x' = x \cos\delta + y \sin\delta \quad y' = y \cos\delta - x \sin\delta$

    with 10 fb$^{-1}$  $N(\text{ws}) = 232500$
    
    $x'^2 \pm 0.064 \text{ (stat.)} \times 10^{-3}$ & $y' \pm 0.87 \text{ (stat.)} \times 10^{-3}$

  - **Singly Cabibbo Suppressed 2-body lifetime ratio measurement of** $y_{CP}$: $D^0 \rightarrow K^- K^+, \pi^- \pi^+$

    $y_{CP} \equiv \frac{\tau(D^0 \rightarrow K^- \pi^+)}{\tau(D^0 \rightarrow (K^+ K^-, \pi^+ \pi^-))} - 1 = y \cos\phi - x \sin\phi \left[ \frac{R_m^2 - 1}{2} \right]$

    with 10 fb$^{-1}$  $N(D^0 \rightarrow K^- K^+ \text{ from secondary } D^{(*+)}) \sim 8 \times 10^6$
    
    $y_{CP} \pm 0.05 \text{ (stat.)}$
CP Violation in the charm sector is extremely small in SM
CP asymmetries possible in mixing ($A^M$) or in between mixing and decay ($A^I$)

\[ A^M \propto -y/2(|q/p| - |p/q|) \times \cos(\phi) \quad \& \quad A^I \propto x/2(|q/p| + |p/q|) \times \sin(\phi) \]

- Both $\phi$ and $(|q/p| - 1)$ are negligibly small in SM
  Existing limits:
  \[ |q/p| = 0.87 \pm 0.18 \quad \& \quad \phi = -9.1 \pm 8.1 \text{ degree} \]

- Higher sensitivity will come as mixing analyses improve precision
  → Sensitivity to many NP models

Example: CPV in Singly Cabibbo Suppressed decays (NP in penguins)
\[ D^0 \to KK, \pi\pi \]
\[ A_{CP} = \frac{\Gamma(D^0 \to KK(\pi\pi)) - \Gamma(D^0 \to KK(\pi\pi))}{\Gamma(D^0 \to KK(\pi\pi)) + \Gamma(D^0 \to KK(\pi\pi))} \]

With 10 fb\(^{-1}\) statistical sensitivity on $A_{CP}$ will reach $10^{-3}$ level

*May be observable!*
**CPV measurements**

NP in boxes:

- $\phi_s$ is the most sensitive measurement
  
  $\sigma(\phi_s) \sim 0.01$  Yes (theor. uncert. 0.002)

NP in penguins:

- Very difficult to measure

- $\gamma_{\text{tree}}$ vs $\gamma_{\text{loop}}$ requires assumption on the U-spin symmetry
  
  $\sigma(\delta\gamma) \sim \sigma(\gamma_{\text{loop}}) \sim 5^\circ$  Yes (?)

- $\gamma_{\text{tree}}$ vs $\alpha_{\text{loop}}$
  
  $\alpha$ is sensitive to NP contribution in penguins only if SU(2) breaks or large electro-weak penguins
  
  $\sigma(\delta\gamma) \sim \sigma(\alpha) \sim 4^\circ$  Yes (?)

- Probably the best sensitivity:
  
  $\beta_s$ in $B_s \to J/\psi\phi$
  
  $\sigma(\delta\beta_s) \sim \sigma(\beta_s) \sim 0.05$
  
  or $\beta$ in $B \to J/\psi K_s$
  
  $\sigma(\delta\beta) \sim \sigma(\beta) \sim 0.1$  Yes
**Rare B Decays**

**NP in penguins:**

- Photon polarization in $B_s \to \phi\gamma$ decay:
  \[ \sigma(A^4) = 0.09 \]  
  Yes (theor. uncert. ~0.01)

**NP in a mixture of loop diagrams:**

- $B \to K^*\mu\mu$
  \[ \sigma(s0) \sim 0.3 \text{ GeV}^2 \]  
  Yes (assuming theor. progress)

- $B_s \to \mu\mu$
  >5σ observation if SM  
  Yes (abs. norm. is required)

**Charm Physics**

Measured CP asymmetries approach SM prediction

**LVF in τ decays**

\[ \text{BR}(\tau \to 3\mu) < 10^{-8} \]  
using $\tau$ from $D_s \to \tau\nu$
The LHCb Upgrade

- **L0 hadron trigger**
  - Is bandwidth limited
  - Rate of HCAL triggers with $E_T > 2$ GeV increases from 4 to 25 MHz when lumi from 2 to $20 \times 10^{32}$

- **L0 muon trigger**
  - ~90% efficiency, scales with luminosity

- **L0 hadron trigger**
  - Only ~50% efficient
  - does not scale with luminosity
The LHCb Upgrade

- Must change all front end electronics (except muon system) to 40 MHz
  - all Si based devices are replaced
  - changing RICH photon detectors
  - Keep same Vertex Locator geometry for a few years, change to pixels or 3D devices later
  - Outer Tracker geometry to be slightly modified to keep occupancies acceptable

- Work on 40 MHz readout chip is starting
Summary

- Clean experimental signature of NP is unlikely at currently operating experiments

- **LHCb has a lot of opportunities to discover NP in a few years of data taking (with 10 fb⁻¹ data sample)**
  - Physics program is complementary to that of ATLAS & CMS

- Study of NP properties needs much improved precision in b-physics
  - **LHCb upgrade to collect 100fb⁻¹ is very important**