physics program

(searching new physics hidden in beauty and charm)

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On behalf of the LHCb collaboration

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Flavor Physics: the Quest of New Physics

LHCb experiment
- B Physics at Hadron Collider
- LHCb spectrometer
- Tracking, PID, Flavor tagging, Trigger schemes and performances

Expected physics performance (examples)
- $\sin 2\beta$
- Measurements of $\gamma$
- $B_s$ mixing phase $2\beta_s$
- $b \to ssss$ penguins
- $B_s \to \mu^+\mu^-$
- $B_s \to K^* \ell\ell$
- Charm physics
Flavor Physics: The Quest of New Physics

The main purpose of B (D and K) physics is now to **search for new physics effects in flavor-mixing, CP violation and rare decays.**

- **Consistency check of UT (angles and sides):** need more statistics, esp. need improvement for γ (for “Reference UT” in Tree vs Loop) and Lattice QCD
- **Compare different measurements of the same quantities, one which is insensitive and another one which is sensitive to NP** (e.g., sin2β from B⁰ → J/ψ Kₛ and B⁰ → φKₛ)
- **Vₜₛ (loop-induced processes):**
  - |ΔF|=1 FCNC rare decays (e.g., b→sγ, b→sl⁺l⁻, Bₗ→μμ)
  - |ΔF|=2 FCNC mixing (e.g., Bₛ mixing phase 2βₛ with Bₛ → J/ψ φ)
- **Etc.**

⇒ the 2nd generation “b-physics” experiments: **pursuing the NP searches with precision measurements** (and if NP is discovered, put constraints on its flavor structure)

### Three major themes:

1. **Precision determination of CKM elements to seek deviations from SM**
2. **New physics via CP-violating phases**
3. **New physics via rare decays**

### Look for everywhere:

- Consistency check of UT (angles and sides): need more statistics, esp. need improvement for γ (for “Reference UT” in Tree vs Loop) and Lattice QCD
- Compare different measurements of the same quantities, one which is insensitive and another one which is sensitive to NP (e.g., sin2β from B⁰ → J/ψ Kₛ and B⁰ → φKₛ)
- Vₜₛ (loop-induced processes):
  - |ΔF|=1 FCNC rare decays (e.g., b→sγ, b→sl⁺l⁻, Bₗ→μμ)
  - |ΔF|=2 FCNC mixing (e.g., Bₛ mixing phase 2βₛ with Bₛ → J/ψ φ)
- Etc.
LHCb: > 600 scientists
47 universities and laboratories
15 countries

A Large Hadron Collider beauty experiment for precision measurements of CP violation and rare decays
LHC cooling status and startup

- Cooling down is performing well, aiming for machine cooled down in early July
- Beam injected end July - early August. First collisions 1-2 months later
- Luminosity $\sim 10^{31} \text{ cm}^{-2}\text{s}^{-1}$, $\sqrt{s} = 10 \text{ TeV}$
LHCb environment @LHC

large cross section:
- $500 \, \mu b$ (230 $\mu b$ in $4.9 > \eta > 1.9$ (forward region))

All species of B hadrons produced:
- $(B^\pm, B_d, B_s, B_c, b$-baryons) [40%, 40%, 10%, 0.1%, 10%]

$\sigma_{bb}/\sigma_{\text{inel}} = 0.6\%$ at LHC: trigger is a major issue

bb̄ production correlated and sharply peaked forward backward:
- single-arm spectrometer is OK
- since b quarks are correlated
  ➔ important for tagging

Luminosity $\mathcal{L}=2\times10^{32} \, \text{cm}^2\text{s}^{-1}$ (de-tuned beams):
- clean environment ($\langle n \rangle = 0.5$)
- less radiation damage
- 5 $10^{11}$ B hadrons (in acceptance) in $10^7$ sec (1 year, 2 fb$^{-1}$)
- 10 fb$^{-1}$ by 2013
LHCb: Forward Spectrometer

**VELO**: Vertex Locator (around interaction point)
**TT, T1, T2, T3**: Tracking stations
**RICH1-2**: Ring Imaging Cherenkov detectors

**ECAL, HCAL**: Calorimeters
**M1–M5**: Muon stations

Requirements for B physics:
- excellent tracking and vertexing ($\sigma_m, \sigma_\tau$)
- excellent particle ID
- flexible and efficient trigger
View of the LHCb cavern

Installation complete, commissioning well-underway
PID, tracking and tagging performances

Average b-decay track resolutions:

- impact parameter: ~30 μm
- momentum: ~0.36%

Typical B resolutions:

- proper time: ~40 fs (essential for $B_s$ physics)
- mass: 8 – 18 MeV/c²

PID average performance:

- kaon ID efficiency: 95%
- π mis-ID: 5%

Good K/π separation in the 2 – 100 GeV/c range

Expected tagging performance:

(on triggered and selected MC events)

\[ \varepsilon(1-2\omega)^2 = 7 – 9\% \text{ for } B_s \]

\[ \varepsilon(1-2\omega)^2 = 4 – 5\% \text{ for } B_d \]

<table>
<thead>
<tr>
<th>$B_s \rightarrow \mu\mu$</th>
<th>Mass resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \rightarrow D_s \pi$</td>
<td>14 MeV/c²</td>
</tr>
<tr>
<td>$B_s \rightarrow J_\psi \phi$</td>
<td>16 MeV/c²</td>
</tr>
<tr>
<td>$B_s \rightarrow J/\psi \phi$</td>
<td>8 MeV/c² (*)</td>
</tr>
</tbody>
</table>

(*) with $J/\psi$ mass constraint

![Invariant mass distribution](image)
Trigger Performance and Rates

Algorithms and performances:

- **Hardware level (L0)**, max. 1 MHz output rate:
  algorithms mature

- **Software level (HLT=High Level Trigger)**:
  prototype available within time budget for a limited set of channels

- **L0*HLT efficiencies**: typically 30%–80% for offline-selected signal events, depending on channel

### Output rate | Event type | Physics
--- | --- | ---
200 Hz | Exclusive B candidates | B (core program)
600 Hz | High mass di-muons | J/ψ, b→J/ψX (unbiased)
300 Hz | D* candidates | Charm
900 Hz | Inclusive b (e.g., b → μ) | B (data mining)

Johannes Albrecht's talk

**Event size**: ~ 50kB
LHCb: Physics Program
(examples)

Sin2\(\beta\) with \(B^0 \rightarrow J/\psi K_S\)

Expected to be one of the first CP measurement:

Demonstrate (already with \(\leq 0.5\) fb\(^{-1}\)) that we can keep under control the main ingredient of a CP analysis, in particular the tagging performance extraction from the control sample \(B^0 \rightarrow J/\psi K^0\).

"Yesterday’s sensation is Today’s calibration and Tomorrow’s background”
— hep physics’ adage

\[
A_{CP}(t) = \frac{N\left(\overline{B}^0 \rightarrow J/\psi K_S\right) - N\left(B^0 \rightarrow J/\psi K_S\right)}{N\left(\overline{B}^0 \rightarrow J/\psi K_S\right) + N\left(B^0 \rightarrow J/\psi K_S\right)}
\]

Sensitivity: 236k events/2 fb\(^{-1}\) with B/S= 0.6 (bb) and 7.7 (prompt J/\(\psi\))
\(\Rightarrow \sigma(\text{sin}2\beta) = 0.020\)
[B factories: 0.025 (850 fb\(^{-1}\))]
Measurements of the angle $\gamma$

**$B^+ \to D^{(*)0} K^{(*)+}$:**

Tree: $b \to c$, dominant

$B^- \begin{cases} \bar{u} \\ \bar{c} \end{cases} \to W^+ s \to \{ \bar{u} \bar{s}, s \bar{u} \} K^{(*)-}$

$B^- \begin{cases} \bar{u} \\ \bar{c} \end{cases} \to W^- u \to \bar{u} c \to \{ \bar{u} c, s \bar{u} \} D^{(*)0}$

Reconstruct $D$ in final states accessible to both $D^0$ and $\bar{D}^0$:

- **GLW**: $D$ decays to CP eigenstates
- **ADS**: $D$ decays to flavor states
- **GGSZ**: $D$ decays to $K_S\pi^+\pi^-$ (interference in Dalitz plot)

<table>
<thead>
<tr>
<th>B mode</th>
<th>D mode</th>
<th>Method</th>
<th>$\sigma_{\text{stat}}(\gamma)$ [2 fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to D^+K^-$</td>
<td>$K\pi, \ K K/\pi\pi$</td>
<td>counting,ADS+GLW</td>
<td>$11 - 14^\circ$</td>
</tr>
<tr>
<td>$B^+ \to D^+K^-$</td>
<td>$K_S\pi\pi$</td>
<td>Dalitz, GGSZ</td>
<td>$7 - 12^\circ$</td>
</tr>
<tr>
<td>$B^+ \to D^+K^-$</td>
<td>$KK\pi\pi$</td>
<td>$4$-body Dalitz</td>
<td>$18^\circ$</td>
</tr>
<tr>
<td>$B^0 \to D^0K^{*0}$</td>
<td>$K\pi, \ K K, \pi\pi$</td>
<td>counting,ADS+GLW</td>
<td>$9^\circ$</td>
</tr>
</tbody>
</table>

Other modes under study: $B^+ \to D^*(D \to K\pi, KK, \pi\pi)K^+$, $B^+ \to D(D \to K\pi\pi)K^+$, ...
Two tree decays (b→c and b→u), which interfere via Bs mixing:

- can determine $2\beta_s + \gamma$ hence $\gamma$ in a clean way
  - similar to $2\beta + \gamma$ extraction with $B^0 \rightarrow D^\star \pi$, but with
    - the advantage that the two decay amplitudes are
      - similar ($\sim \lambda^3$) and therefore their ratio can be extracted from data

LHCb expects 6.2k events/2 fb$^{-1}$

$B_{bb}/S < 0.18$ (@90 CL)

$B_s \rightarrow D_s \pi$ background 15±5% after PID cuts

- extract $2\beta_s + \gamma$, strong phase difference and amplitude ratio
  - $(B_s \rightarrow D_s \pi$ (140k/2 fb$^{-1}$) also used in the fit to constrain other
    parameters (mistag rates, $\Delta m_s$, $\Delta \Gamma_s$, ...))

$\Rightarrow \sigma(2\beta_s + \gamma) = 9 - 12^\circ$ with 2 fb$^{-1}$
$2\beta_s$ : $B_s$ mixing phase with $b \to c\bar{c}s$

$2\beta_s$ is the strange counterpart of $2\beta$:

- $\beta_s$ very small in SM and well-predicted: $(1.054^{+0.051}_{-0.049})^\circ$.
- Could be much larger in presence of New Physics

Golden $b \to ccs$ mode is $B_s \to J/\psi \phi$:

- but ... angular analysis needed to disentangle CP-even and CP-odd contributions

Current experimental situation:

- CDF: 2k, 1.35 fb$^{-1}$ – $+2\beta_s \in [0.32, 2.82]$ @68% CL
- D0: 2k, 2.8 fb$^{-1}$ – $+2\beta_s = 0.57^{+0.24}_{-0.30} +0.07_{-0.02}$ [PRL 100, 161802 (2008)]
- LHCb sensitivity with 2 fb$^{-1}$:
  - 131k $B_s \to J/\psi(\mu\mu)\phi$ events (before tagging), $B_{bb}/S = 0.12$, $\sigma_t = 36$ fs
  - $\sigma_{stat}(2\beta_s) = 0.023$
  - $\sigma_{stat}(\Delta \Gamma_s/\Gamma_s) = 0.0092$

Add also pure CP modes ($J/\psi\eta^{(')}$, $\eta_c\phi$, $D_s D_s$)

- low yields, high background
  - $\sim 25k$, $\sigma_{stat}(2\beta_s) = 0.046$
- With 10 fb$^{-1}$, obtain $>3\sigma$ evidence of CP violation ($2\beta_s \neq 0$), even if only SM
Constraints on NP from $2\beta_s$ measurement

NP in $B_s$ mixing:

- amplitude $M_{12}$ parametrized with $h_s$ and $\sigma_s$:

\[ M_{12} = \left( 1 + h_s e^{2i\sigma_s} \right) M_{12}^{SM} \]

LHCb can exclude already a significant region of allowed phase space with the very first data or ...
Time dependent CP analysis of pure penguin decays into CP eigenstates

\( B_s \rightarrow \phi \phi \): CP violation < 1% in SM, angular analysis required

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield (2 fb(^{-1}))</th>
<th>B/S</th>
<th>Weak phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B \rightarrow \phi K_s )</td>
<td>920</td>
<td>&lt; 1.1</td>
<td>( \sigma(\sin(2\beta_{s,\text{eff}})) = 0.23 )</td>
</tr>
<tr>
<td>( B_s \rightarrow \phi \phi )</td>
<td>3100</td>
<td>&lt; 0.8</td>
<td>( \sigma(2\beta_{s,\text{eff}}) = 0.11 )</td>
</tr>
</tbody>
</table>
Electroweak penguins. Many observables:

- **Forward-Backward asymmetry:**
  
  \[ A_{FB}(s=m_{ll}^2) = \frac{(N_F - N_B)}{(N_F + N_B)} \]

- **Zero of** \( A_{FB}(s) \) [\( s_0^{SM} = 4.31^{+0.31}_{-0.30} \) GeV\(^2/c^4\)]

- **\( F_L \) and \( A_T^{(2)} \) (long. pol. and trans. asym.)

- **Ratio of** ee and \( \mu\mu \) modes

**Current experimental situation:**

\[ \text{BR}(B_0^d \to K^0 \mu^+\mu^-) [10^{-6}] = 0.98^{+0.22}_{-0.021} \]

**Sensitivity (2 fb\(^{-1}\)):**

- 7200 evts, B/S\( \sim 0.5 \)
  
  \[ \sigma(s_0) = 0.5 \text{ GeV}^2/c^4 \]
B → K*ℓ⁺ℓ⁻

other observables based on tranversity amplitudes ($A_0, A_\perp, A_\parallel$)

- Fitting projections of $\phi, \theta_\ell, \theta_{K^*}$ angular distributions can give access to the fraction of longitudinal polarization $F_L$ and the transverse asymmetry $A_T^{(2)}$

$$A_T^{(2)}(s) = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}$$

$$F_L(s) = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

Points LHCb 2 fb⁻¹

Stat. precisions in the region $s = m_{\mu\mu}^2 \in [1, 6] \text{ (GeV/c}^2)^2$

where theory calculations are most reliable

<table>
<thead>
<tr>
<th></th>
<th>2 fb⁻¹</th>
<th>10 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_T^{(2)}$</td>
<td>±0.42</td>
<td>±0.16</td>
</tr>
<tr>
<td>$F_L$</td>
<td>±0.016</td>
<td>±0.007</td>
</tr>
<tr>
<td>$A_{FB}$</td>
<td>±0.020</td>
<td>±0.008</td>
</tr>
</tbody>
</table>
$B^0_s \rightarrow \mu^+\mu^-$

$B_s \rightarrow \mu\mu$ helicity suppressed:

sensitive to NP with S or P couplings

Well predicted in SM:

$$\text{BR}(B_s \rightarrow \mu\mu) \times 10^{-9} = 3.14^{+0.15}_{-0.25}$$

CKMfitter Summer 2007

Event selection:

- main issue: background rejection, dominated by combinatorial $bb \rightarrow \mu\mu X$ (suppressed by mass and vertex resolutions)
- SM Yield (2 fb$^{-1}$): Signal: 30 – Bkg: 83

Current limits from Tevatron:

CDF: BR < $5.8 \times 10^{-8}$ @95% CL

D0: BR < $9.3 \times 10^{-8}$ @95% CL

0.05 fb$^{-1}$ ⇒ overtake CDF+D0
0.5 fb$^{-1}$ ⇒ exclude BR values down to SM
2 fb$^{-1}$ ⇒ 3σ evidence of SM signal
6 fb$^{-1}$ ⇒ 5σ observation of SM signal
Charm Physics

LHCb will collect a large tagged $D^*\rightarrow D^0 \pi$ sample: 

- a dedicated $D^*$ trigger is foreseen for this purpose 
tag $D^0$ and anti-$D^0$ flavor with $\pi$ from $D^{*\pm}\rightarrow D^0 \pi^\pm$

(also used for PID calibration)

**D*-tagged signal yields in 2 fb$^{-1}$**
- $D^0\rightarrow K^+\pi^-$ right sign: 12.4 M
- $D^0\rightarrow K^+\pi^-$ wrong sign: 46.5 k
- $D^0\rightarrow K^+K^-$: 1.6 M

Interesting (sensitive to NP) and promising searches/measurements:

- **Time-dependent $D^0$ mixing with wrong-sign $D^0\rightarrow K^+\pi^-$**
  $\sigma_{\text{stat}}(x'^2) \sim 0.14\times10^{-3}$, $\sigma_{\text{stat}}(y') \sim 2\times10^{-3}$ with 2 fb$^{-1}$

- **Direct CP violation with $D^0\rightarrow K^+K^-$**
  $A_{CP} \leq 10^{-3}$ in SM, up to 1% (~current limit) with New Physics
  Expect $\sigma_{\text{stat}}(A_{CP}) \sim O(10^{-3})$ with 2 fb$^{-1}$

- **$D^0\rightarrow \mu^+\mu^-$**
  BR $\leq 10^{-12}$ in SM, up to $10^{-6}$ (~current limit) with New Physics
  Expect to reach down to $\sim 5\times10^{-8}$ with 2 fb$^{-1}$
Conclusion

Very interesting results will come already with first 0.5 fb\(^{-1}\) (~end of 2009) of data:

- \(B_s \rightarrow J/\psi\phi\): 2\(\beta_s\) measurement with \(~0.05\) precision
- \(B_s \rightarrow \mu\mu\): BR limit down to SM value
- \(B_d \rightarrow K^0\mu\mu\): \(~1800\) events, overtaking B-Factories statistics

This was only MC! The startup of LHC is coming:

- looking forward to starting working with real data and successful machine startup

"A new era in human knowledge has just started...
...a lot has already been found, but what is still to be discovered is more!"

[Galileo speaking with Sagredo in "Galileo’s life", by B. Brecht]