Detector and Physics Performance of the LHCb Experiment

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Representing the LHCb Collaboration

- Introduction
- Physics motivations
- Detector performance
- Topics on physics potentials
- Conclusions

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LHCb is a *dedicated* B physics experiment at the LHC
Forward spectrometer (running in pp collider mode)

\[ \sigma_{b\bar{b}}(14\text{TeV}) \sim 500 \mu b \]

\[ \sim 10^{12} \text{ b} \bar{b} / \text{year} \quad @ \, L = 2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1} \]

Great potential for B physics!
The Standard model CP violation is described by the single complex phase in the CKM matrix, two unitarity triangles relevant to B physics at LHCb stat.

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$V_{ub}V_{ub}^* + V_{ts}V_{us}^* + V_{td}V_{ud}^* = 0$$

To test SM and explore possible new physics, next generation B experiments needs to over constraint the unitarity triangles...

Measurement of the angle $\gamma$ will be crucial when LHCb starts to take data
• Many final states need to be reconstructed …

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**HIGH STATISTICS**

- **B** serves as essential samples.
- Robust and efficient trigger, even for non-leptonic decays.
- Good decay vertex resolution; good tracking; good particle identification.

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**EFFICIENT TRIGGER FOR NON-LEPTONS**

- \( B \to D^* \pi, D^*3\pi \)
- \( B \to \rho \pi \)
- \( B_s \to D_s \pi \)
- \( B_{d,s} \to D_{d,s}^+ D_{d,s}^- \)
- \( B \to \rho^+ \rho^- \)
- \( B \to K^{*0} \bar{K}^{*0} \)
- \( B \to D^* K^* \)
- \( B \to K^* \gamma \)
- \( B_s \to K^{*+} K^{*-} \)
- \( B_s \to J/\psi \phi \)
- \( B_s \to J/\psi K_s \)
- \( B_{d,s} \to J/\psi K_s \)
- \( B_{d} \to J/\psi K_s \)
- \( B_{d} \to J/\psi \rho^0 \)
- \( B_{s,d} \to \mu^+ \mu^- \quad (O(10^{-9})!) \)
Detector performance
1. Geometry

Inner acceptance 10 mrad from conical beryllium beam pipe
**Detector performance**

2. Vertex and Tracking

Vertex locator around the interaction region
Silicon strip detector with ~30 µm impact-parameter resolution
Vertex Locator

beams axis

collision point

\(~ 1 \text{m}\)

200\(\mu\text{m}\) n-on-n Si short strips
double metal layer for readout
with Beetle chip (1/4 \(\mu\text{m}\) CMOS)

They have to be placed in secondary vacuum \(\rightarrow\) complex mechanics

total 172 k channels
occupancy < 1\%
Tracking system and dipole magnet to measure angles and momenta
\[ \frac{\Delta p}{p} \sim 0.4 \%, \text{ mass resolution} \sim 14 \text{ MeV (for } B_s \rightarrow D_s K) \]
Magnetic field regularly reversed to reduce experimental systematics
Silicon Tracker

Trigger Tracker and Inner Tracker

- Magnet
- RICH1
- TT
- T1 T2 T3
- Insulation plate
- Cooling plate
- Hybrid ladder support
- Si sensor
- (x-u-v-x) planes

~1.4×1.2 m²
Magnet support at UX8

Fe plate for the yoke

All the coils
• **B_s oscillation frequency as an example**

Fully reconstructed decay
→ excellent momentum resolution
Decay length resolution \( \sim 200 \, \mu m \)
→ Proper time resolution \( \sim 40 \, fs \)

5\(\sigma\) measurement in one year for \(\Delta m_s\) up to 68 ps\(^{-1}\)

Once a \(B_s - B_s\) oscillation signal is seen, the frequency is precisely determined:
\[ \sigma (\Delta m_s) \sim 0.01 \, \text{ps}^{-1} \]
Two **RICH** detectors for charged hadron identification
Provide $> 3\sigma$ $\pi$–$K$ separation for $3 < p < 80$ GeV
Typical event in the RICH1 photon detectors

Performance of particle ID

No RICH

With RICH
**Detector performance**

4. Calorimeters

*Calorimeter system* to identify electrons, hadrons and neutrals. Important for the first level of the trigger

\[
\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} + 1.5\% \quad \text{(ECAL)}
\]

\[
= \frac{75\%}{\sqrt{E}} + 10\% \quad \text{(HCAL)}
\]
Muon system to identify muons, also used in first level of trigger
Efficiency ~ 94% for pion misidentification rate ~ 3%
• The background condition is challenging:

\[ \sigma_{\text{bb}} \sim 500 \mu \text{b} \quad \rightarrow S / B \sim 10^{-3} \]

\[ \sigma_{\text{inelastic}} \sim 80 \text{mb} \]

• LHCb plans to run at luminosity \(2 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}\)

( c.f. LHC designed luminosity \(10^{34} \text{cm}^{-2} \text{s}^{-1}\), beam will be defocused without affecting other interaction points)

— single interactions per bunch crossing

— less radiation damage

Detector performance

6. Trigger system
**pp collisions**

- **L0**: high $p_T$ + not too busy
  - Fully synchr. (40 MHz), 4μs latency
  - On custom boards

- **L1**: IP + high $p_T$
  - Ave. latency: 1 ms (max 50 ms)

- **HLT + reconstruction**
  - Full detector: $\sim$ 40 kb / evt

- Single PC farm $\sim$ 1800 CPUs

- **b-particles**: higher mass $\rightarrow$ high $E_T$
  - longer lifetime $\rightarrow$ 2nd Vertex
  - leptons in final states

1. high $E_T$ (a few GeV/c)
   - electrons, muons or hadrons
2. pile-up veto
3. vertex structure and $p_T$ of tracks
4. full reconstruction

~ 40 MHz
~ 1 MHz
~ 40 kHz
~ 200 Hz
Selected topics on physics potentials

1. Measurement of the angle $\gamma$ from $B_s \rightarrow D_s^{\pm} K^\mp$

- CP asymmetry arises from interference between two tree diagrams via $B_s$ mixing: $B_s \rightarrow D_s^+ K^-$ and $B_s \rightarrow D_s^- K^+$

- Measures $\gamma - 2\chi \rightarrow$ extract $\gamma$

  ($\chi$ is determined using $B_s \rightarrow J/\psi \phi$ decay, $\sigma(\sin 2\chi) \sim 0.06$ for one year)
• The strong phase difference of the two diagrams can be resolved by fit two time-dependent asymmetries:

\[ \text{Phase of } D_s^+K^- \text{ asymmetry is } \Delta - (\gamma - 2\chi) \]
\[ \text{Phase of } D_s^-K^+ \text{ asymmetry is } \Delta + (\gamma - 2\chi) \]

→ can extract both \( \Delta \) and \( \gamma - 2\chi \)

• Background from Bs → Ds π is suppressed using PID information from RICH1 & RICH2
→ remaining contamination ~ 10%

• Reconstruct using Ds^- → K^-K^+π^- 5400 signal events/year

\[ \sigma(\gamma) \sim 14^\circ \text{ in one year} \]

Asymmetries for 5 years of simulated data

Theoretically clean; insensitive to new physics
Selected topics on physics potentials

2. Measurement of the angle $\gamma$ from $B^0 \rightarrow \pi^+\pi^-$, $B_s \rightarrow K^+K^-$

• $b \rightarrow u$ processes with possible large $b \rightarrow d(s)$ penguin contributions

Tree diagram

Penguin diagram (example)

• Measure time-dependent CP asymmetries for $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$

$$A_{CP}(t) = A_{dir} \cos(\Delta m t) + A_{mix} \sin(\Delta m t)$$

→ extract four asymmetries

$$A_{dir}(B^0 \rightarrow \pi^+\pi^-) = f_1(d, \theta, \gamma) \quad\quad d e^{i\theta} = \text{ratio of penguin and tree amplitudes in } B^0 \rightarrow \pi^+\pi^-$$

$$A_{mix}(B^0 \rightarrow \pi^+\pi^-) = f_2(d, \theta, \gamma, \beta) \quad\quad d' e^{i\theta'} = \text{ratio of penguin and tree amplitudes in } B_s \rightarrow K^+K^-$$

$$A_{dir}(B_s \rightarrow K^+K^-) = f_3(d', \theta', \gamma)$$

$$A_{mix}(B_s \rightarrow K^+K^-) = f_4(d', \theta', \gamma, \chi)$$
• Assume U-spin flavour symmetry (under interchange of d and s quarks)
  \[ d = d' \text{ and } \theta = \theta' \] [R. Fleischer, PLB 459 (1999) 306]

• Taking \( \beta \) and \( \chi \) from other channels → can solve for \( \gamma \)

  blue bands from \( B_s \rightarrow K^+K^- \) (95% CL)
  red bands from \( B^0 \rightarrow \pi^+\pi^- \) (95% CL)
  ellipses are 68% and 95% CL regions (\( \gamma_{\text{input}} = 65^\circ \))

  \( \sigma(\gamma) \sim 5^\circ \) in one year

Theoretical uncertainty from U-spin assumption (can be tested);
Sensitive to new physics in the penguin loops

“fake” solution
Selected topics on physics potentials

3. Measurement of the angle $\gamma$ from $B^0 \to D^0 K^{*0}, \bar{D}^0 K^{*0}$

- CP asymmetry arises from interference between two tree diagrams via $D^0$-mixing
• Measure six rates (following 3 + CP-conjugates)

γ can be extracted from triangles [Gronau and Wyler, PLB 265 (1991) 172, Dunietz, PLB 270(1991) 75]

1. $B^0 \rightarrow \bar{D}^0 (\rightarrow K^+\pi^-) + K^{*0}$
2. $B^0 \rightarrow D^0 (\rightarrow K^-\pi^+) + K^{*0}$
3. $B^0 \rightarrow D_{CP} (\rightarrow K^+K^-) + K^{*0}$

$$D_{CP} = (D^0 + \bar{D}^0)/\sqrt{2} : CP-even eigenstate of D^0 - \bar{D}^0 system$$

• 3.4K, 0.5K and 0.6K events respectively for one year data taking

\[\sigma(\gamma) \sim 7-8^\circ \text{ in one year}\]

No theoretical uncertainties; sensitive to new physics in $D_{CP}$
Selected topics on physics potential

Outlook

• A possible scenario after the LHCb measurement of $\gamma$: new physics?

• Many other interesting topics not covered by this talk

→ TDR, LHCb notes, …
**Conclusions**

- LHCb is dedicated to the study of B physics, with a devoted trigger, excellent vertex and momentum resolution, and particle identification
- Construction of the experiment is progressing well
  It will be ready for first LHC collisions in 2007
- LHCb will give unprecedented statistics for B decays,
  including access to the B_s meson, unavailable to the B factories
- \( \text{B}_s - \text{B}_{\overline{s}} \) oscillations will be measured precisely
  \[ > 5\sigma \text{ for } \Delta m_s \text{ up to } 68 \text{ ps}^{-1} \]
  \[ \sigma (\Delta m_s) \sim 0.01 \text{ ps}^{-1} \]
- Many measurements of rare decays and CP asymmetries will be performed
  \[ \sigma (\sin 2\beta) \sim 0.02 \]
  \[ \sigma (\sin 2\chi) \sim 0.06 \]
  \[ \sigma (\gamma) \leq 10^\circ \]
- CP angles determined via channels with different sensitivity to new physics
  \( \rightarrow \) detailed test of the CKM description of the quark sector