First Results and Prospects from the LHCb Experiment

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Flavor Physics and CP Violation 2010
25 - 29 May 2010
FPCP, Torino, Italy
Outline

- LHCb Experiment
- Detector Performance
- Minimum Bias Events
- Charm Production
- Early B Physics Prospects
- Outlook and Conclusions

LHCb Experiment
Crucial for LHCb physics programme:

- optimised geometry and choice of luminosity
- **Trigger** efficient in hadronic & leptonic modes
- excellent tracking and **Vertexing** ($\sigma_m, \sigma_\tau$)
- excellent particle ID - RICH

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First LHCb Events at 7 TeV

30th March 2010

LHCb Event Display

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Luminosity

- **LHC is ramping up**
  - Expect $O(200 \text{ pb}^{-1})$ in 2010
  - 0.2 to 1 pb$^{-1}$ summer conferences

- **Sensitivity Studies (MC)**
  - At $E_{cm} = 14 \text{ TeV}$
  - Event yields 2 fb$^{-1}$ per annum
  - LHCb design luminosity of $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
  - Cross section $(b-b\bar{b}) = 500 \mu\text{b}$

- **Outlook/Comparison**
  - For 2011 expect design luminosity and $\sim 1 \text{ fb}^{-1}$ of data
  - Lower energy, smaller cross section, large uncertainty
  - Small reduction in statistical precision for 2011

Last LHCC meeting: “With current luminosity projections LHCb is the only detector capable to achieve almost completely its full physics potential during the 2010-2011 run.”
LHCb Trigger

- **Trigger Strategy**
  - Lower collision rate in 2010 allows to lower thresholds
  - Benefits charm physics

- **2010 Trigger Operations**
  - L0 - Min. Bias trigger
    - Low $E_T$ and $p_T$ cuts
    - All stored, rate < 2 kHz
  - L0 x HLT1 (current status)
    - Up to L0 rate of 25 kHz
    - Looser IP cuts
  - HLT2 will be phased in
    - 25 kHz < L0 rate < 300 kHz

- **Trigger Implementation**
  - L0 Hardware
    - $L0_{e,\gamma}$, $L0_{had}$, $L0_{\mu}$
  - HLT1
    - Confirm L0 $p_T$, IP
  - HLT2
    - Inclusive & Exclusive Channels

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![L0 x HLT efficiency for J/ψ](image)
VELO - VErtex LOcator

- VELO Performance
  - Closing VELO in 10 min to 10 um accuracy
  - Alignment with primary vertices
  - Hit residual as expected
  - Impact parameter resolution $\sim 1/p_T$
  - Performance close to expectations

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IP$_x$ Resolution Vs $1/p_T$

LHCb Velo Preliminary

2010 Data: $16.19(9) + 26.87(6)/p_T$\,\mu m

Simulation: $10.9(1) + 23.25(9)/p_T$\,\mu m
VELO and Tracking Stations

- Good agreement between data and MC
Ring Imaging Cherenkov Counters

RICH1
LHCb data (preliminary)
Kaon ring

RICH 1

Nov/Dec 2009
LHC beams $\sqrt{s} = 900$ GeV

RICH2
LHCb data (preliminary)
Kaon ring

Orange points $\rightarrow$ photon hits
Continuous lines $\rightarrow$ expected distribution for each particle hypothesis

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Particle Identification

$\phi \rightarrow KK$ at 900 GeV

- PID Performance
  - Alignment and Calibration underway
  - Angular resolutions close to expectations
  - Calibration of efficiencies and Mis-id rates with data ($K_S, \Lambda, \phi$ and $D^{**}$)

$\phi \rightarrow KK$ at 7 TeV

$\phi \rightarrow KK$ at 7 TeV

Events / (1 MeV/c^2)

$\sigma_{\text{Gauss}} = 1.75 \pm 0.32 \text{ MeV}$

$m = 1019.61 \pm 0.22 \text{ MeV}$

$N_{\text{Signal}} = 574.4 \pm 35.5$

$65 \text{ mb}^{-1}$
Strange Hadrons at \( \sqrt{s} = 7 \) TeV

**K_S \rightarrow \pi \pi**

- LHCb Preliminary
- \( \sqrt{s} = 7 \) TeV Data
- \( m_\pi = 497.23 \pm 0.01 \) MeV
- \( \sigma_\pi = 6.51 \pm 0.14 \) MeV
- \( \sigma_\pi / \sigma_\pi = 0.447 \pm 0.004 \)
- \( N_{signal} = 99,595.7 \pm 349.2 \)
- 65 \( \mu b^{-1} \)

**\Lambda \rightarrow p \pi**

- LHCb Preliminary
- \( \sqrt{s} = 7 \) TeV Data
- \( m_\pi = 1.11574 \pm 0.01 \) MeV
- \( \sigma_\pi = 2.83 \pm 0.15 \) MeV
- \( \sigma_\pi / \sigma_\pi = 0.345 \pm 0.013 \)
- \( N_{signal} = 22,231.1 \pm 187.9 \)
- 65 \( \mu b^{-1} \)

**\Xi \rightarrow \Lambda \pi**

- LHCb Preliminary
- \( \sqrt{s} = 7 \) TeV
- 75M mbias events
- \( N(Signal) = 2933 \)
- \( \sigma = 2.45 \) MeV
- \( m(\text{PDG}) = 1321.7 \pm 0.07 \) MeV
- \( m = 1322.12 \pm 0.06 \) MeV

**\Omega \rightarrow \Lambda p \pi**

- LHCb Preliminary
- \( \sqrt{s} = 7 \) TeV
- 75M mbias events
- \( N(Signal) = 375 \)
- \( \sigma = 2.80 \) MeV
- \( m(\text{PDG}) = 1672.45 \pm 0.29 \) MeV
- \( m = 1672.30 \pm 0.24 \) MeV
2009 Data Sample
- \( \sqrt{s} = 900 \text{ GeV} \)
- 6.8±1.0 \( \mu b^{-1} \)

Measurement
- \( K_S \) reconstruction in \( \pi\pi \) mode
- Vertex detector (open) not used

Luminosity
- from beam-beam and beam-gas
- Achieved 15% precision

Results
- Transverse Momentum \( p_T \)
- in 3 bins of rapidity \( y \)
- Consistent with Pythia 6.4 and Perugia0 tuning

Outlook
- Final \( K_S, \Lambda, \Lambda\bar{b}ar \) and \( p, p\bar{b}ar \) at \( \sqrt{s} = 900 \text{ GeV} \) & 7 \text{ TeV} in preparation
$J/\psi \rightarrow \mu^+\mu^-$ at $\sqrt{s} = 7$ TeV

- Muon system
  - Fully operational
  - Pion and kaon misidentification rates close to MC expectations
- $J/\psi \rightarrow \mu^+\mu^-$
  - 128 candidates in $0.8$ nb$^{-1}$
    - Tight muon selection
    - To measure muon efficiency larger data set required
- Pseudo proper time

Candidates for inclusive $J/\psi$ from B decays
Are any of these from exclusive B decays?

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21 April 2010: LHCb observes first reconstructed Beauty Particle

B^+ \rightarrow J/\psi K^+

 Tracks from primary vertex

[mm]

XY Projection

B^+ \rightarrow J/\psi K^+

J/\psi \rightarrow \mu^+ \mu^-
Charm – the First-Year Beauty?

- **Mixing**
  - Well established
  - SM prediction limited precision

- **CP violation**
  - Weak limits
  - Negligible in SM
  - Large New Physics contribution possible
  - Needs sensitivity below <0.1%

- **Precision Charm Physics**
  - Crucial for future heavy flavour programme

- **LHCb**
  - Competitive with 100 pb⁻¹

- **LHCb charm programme**
  - Charm signals in first month of 7 TeV data
  - Yields benefit from lower trigger thresholds
  - Open charm production for summer conferences
  - $\gamma_{CP}$, $\Delta \Gamma$, ... with 100 pb⁻¹

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**$	extbf{D}^0$ Mesons at $\sqrt{s} = 7$ TeV**

- **$\textbf{D}^0 \to \textbf{K}^- \pi^+$**
  - 0.8 nb$^{-1}$
  - LHCb Preliminary
  - $\sqrt{s} = 7$ TeV Data
  - $N_{\text{sig}} = 1539 \pm 46$
  - $N_{\text{bkg}} = 1043 \pm 40$
  - Gauss $\mu = 1363.38 \pm 0.27$ MeV
  - Gauss $\sigma = 8.69 \pm 0.24$ MeV
  - Poly $p = 0.127 \pm 0.004$

- **$\textbf{D}^*+ \to \textbf{D}^0 \pi^+$, $\textbf{D}^0 \to \textbf{K}^- \pi^+$**
  - 0.8 nb$^{-1}$
  - LHCb Preliminary
  - $\sqrt{s} = 7$ TeV Data
  - $N_{\text{sig}} = 255 \pm 19$
  - $N_{\text{bkg}} = 284 \pm 20$
  - Gauss $\mu = 145.466 \pm 0.057$ MeV
  - Gauss $\sigma = 7.433 \pm 0.050$ MeV
  - BG Shape Par $= 3.088 \pm 0.79$

- **$\textbf{D}^0 \to \textbf{K}^- \pi^+$**
  - 0.8 nb$^{-1}$
  - LHCb Preliminary
  - $\sqrt{s} = 7$ TeV Data
  - $N_{\text{sig}} = 125 \pm 14$
  - $N_{\text{bkg}} = 170 \pm 15$
  - Gauss $\mu = 1863.56 \pm 0.84$ MeV
  - Gauss $\sigma = 7.04 \pm 0.78$ MeV
  - Poly $p = 0.005 \pm 0.13$

- **$\textbf{D}^*+ \to \textbf{D}^0 \pi^+$, $\textbf{D}^0 \to \textbf{K}^- \pi^+$**
  - 0.8 nb$^{-1}$
  - LHCb Preliminary
  - $\sqrt{s} = 7$ TeV Data
  - $N_{\text{sig}} = 29.7 \pm 4.6$
  - Mass $\mu = 1864.2 \pm 1.4$ MeV/c$^2$
  - Mass $\sigma = 6.3 \pm 1.0$ MeV/c$^2$

**Expect several million tagged $\textbf{D}^0 \to \textbf{K}\textbf{K}$ in 100 pb$^{-1}$**
Charm Hadrons at $\sqrt{s} = 7$ TeV

$D^+ \rightarrow K^- \pi^+ \pi^+$

$\Lambda_c^+ \rightarrow K^- p \pi^+$

RICH PID
- Essential for charmed hadrons $D^0, D^+, D_s^+$ and $\Lambda_c^+$
Ds mesons
- Important for Bs physics

Direct CP violation in charm decays
- $D^+ \rightarrow K^+K^-\pi^+$ is Cabibbo suppressed, can interfere with gluonic Penguin, sensitive to New Physics
- Control channels - Cabibbo favoured $D_s^+ \rightarrow K^+K^-\pi^+$ and $D^+ \rightarrow K^+\pi^-\pi^+$
- Expect several million events in 100 pb$^{-1}$
First $B_s$ Candidate with good S/B, consistent with expectations, Expect ~100k events in 100 pb⁻¹

- $B_s \rightarrow D_s^+ \mu^- \nu$
- $D_s^+ \rightarrow \phi(K^+K^-)\pi^+$

- b-bbar cross section
  - Semileptonic decays
  - Non-prompt $J/\psi$
  - Measurement planned for summer conferences
Is there NP in $B_s^0$-$\bar{B}_s^0$ mixing?
- $B_s \to J/\psi\phi$ is golden mode at hadron colliders
- Very precise SM prediction for small weak phase $\phi_s = -2\beta_s$
- $\phi_s(J/\psi\phi) = -0.0368 \pm 0.0017$

Current Results
- From CDF and D0
- Prefer non-zero $\phi_s$

Weak Limits on new physics
- Weak phase in $B_s$ mixing $\phi_s$ is not well measured yet
- New Physics could be around the corner!

$\text{Re}(\Delta_q) + i\text{Im}(\Delta_q) = \frac{\langle B^0|H_{\text{full}}|\bar{B}^0\rangle}{\langle B^0|H_{\text{SM}}|\bar{B}^0\rangle}$
Prospects with $B_s \rightarrow J/\psi \phi$

- **Probe New Physics**
  - In box diagrams

- **Expected Sensitivity**
  - yield: 117k in 2 fb$^{-1}$
  - $\sigma (\phi_s) \sim 0.07$ with 1 fb$^{-1}$

- **Exciting Prospects**
  - If $\phi_s$ at Tevatron central value
  - LHCb will make 5$\sigma$ discovery of new physics in this run

- **Additional measurements**
  - CP-eigenstate
    - $B_s \rightarrow J/\psi f_0(980)$
    - $f_0(980) \rightarrow \pi^+ \pi^-$

![Graph showing uncertainties and precision requirements](image)

**Precision required to establish $\phi_s = 0.7$ at 5$\sigma$**

- **Probe New Physics**
  - in penguin diagrams
  - Best mode $B_s \rightarrow \phi \phi$
**$A_{fs}$ - CP Violation in Mixing**

- **Flavour specific Asymmetry**
  - New D0 measurement
    \[ A_{fs}^b = (-0.957 \pm 0.251 \text{ (stat)} \pm 0.146 \text{ (syst)}) \% \]

- **$A_{fs}$ at LHCb**
  - MC sensitivity study for untagged $B_{s(d)} \rightarrow D_{s(d)} \mu \nu$ & $B_s \rightarrow D_s \pi$
    \[ A_{fs}^{\text{untag}} = \frac{\Gamma(B_s^0 \rightarrow D_s \mu \nu) - \Gamma(B_s^0 \rightarrow D_s \bar{\mu} \bar{\nu})}{\Gamma(B_s^0 \rightarrow D_s \mu \nu) + \Gamma(B_s^0 \rightarrow D_s \bar{\mu} \bar{\nu})} \]

- **Key Method:** $\Delta A_{fs} = A_{fs}^s - A_{fs}^d$
  - Expect $\sim 1M$ $B_{s(d)} \rightarrow D_{s(d)} \mu \nu$ events in 1 fb$^{-1}$ at 7 TeV
  - Statistical sensitivity for $\Delta A_{fs}$ at 0.1% level
  - Method is robust against production, detector asymmetries

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N. Brook et al., Public LHCb note 2007
Highly suppressed in SM
- Prediction
  $\text{BR}(B_s \rightarrow \mu^+\mu^-) = (3.86 \pm 0.15) \times 10^{-9}$
- could be strongly enhanced in SUSY

Constrained MSSM
- $\text{BR}(B_s \rightarrow \mu^+\mu^-) \sim \tan^6 \beta / M_{H^2}$
- Predicts much larger
  $\text{BR}(B_s \rightarrow \mu^+\mu^-) \sim \text{a few } 10^{-9} \text{ to } 10^{-7}$
- Dependent on gaugino mass $m_{1/2}$
Studies for $B_s \rightarrow \mu^+\mu^-$

- **Muon Identification**
  - Using $K_S$ and $\Lambda$ decays

- **Geometrical Likelihood**
  - Using $K_S$ decays

- **Trigger efficiency**
  - L0xHLT1
  - using $J/\psi \rightarrow \mu^+\mu^-$

Good agreement between data and MC

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**Expected Sensitivity**
- 200 pb\(^{-1}\) to improve upon expected Tevatron limit with 8fb\(^{-1}\)
- 3 fb\(^{-1}\) for 3σ evidence and 10 fb\(^{-1}\) for 5σ observation of SM value @ 14TeV
Prospects with $B \to K^{*}\mu\mu$

With 1 fb$^{-1}$ LHCb expects 1200 events with $q^2 < 6$ GeV$^2$

At Belle central value, SM could be excluded at 4$\sigma$
First fully reconstructed Hadronic B Candidate

\[ B^- \rightarrow D^0 \pi^- , \quad D^0 \rightarrow K^- \pi^+ \]
“ADS+GLW” Strategy

- Diagrams interfere, sensitive to CKM angle $\gamma$
- Measure the relative rates of $B^- \to D K^-$ and $B^+ \to D K^+$ decays with $D$'s in final states such as: $K^-\pi^+$ and $K^+\pi^-$, $K^-\pi^+\pi^-\pi^+$ and $K^+\pi^+\pi^-\pi^-$, $K^-K^-$
- Similar method for neutral $B^0 \to D K^0$ decays (GLW)
- Will also use Dalitz plot of $D^0$ decays into a 3-body CP eigenstate $D^0 \to K_S^0 \pi^+\pi^-$

Prospects for CKM angle $\gamma$

- With 100 pb-1 can improve upon B-factories
- Expect 70 doubly Cabibbo suppressed events in ADS
- Estimated precision $7^\circ$ in 1 fb$^{-1}$
No time to discuss here

- CP asymmetries in gluonic $b \rightarrow s$ penguin decays
  - $B_s \rightarrow \phi \phi, K^*K^*$
- Charmless Hadronic $B$ Decays
  - Time-dependent $B_d, B_s \rightarrow \text{hh}$ analysis, $B_s$ mixing - $B_s \rightarrow D_s \pi$
- Radiative penguin decays
  - $B_s \rightarrow \phi \gamma, B_s \rightarrow K^* \gamma$
- Radiative CKM angle $\gamma$
  - 3-body Dalitz decays, $B_s \rightarrow D_s K$
- CKM angle $\sin 2 \beta$
  - $B_d \rightarrow J/\psi K_S$
- CKM angle $\alpha$
  - $B \rightarrow \rho \pi$
- Spectroscopy
  - $X, Y, Z, ...$
- Unexpected
  - Long lived particles, e.g. hidden valleys
Outlook

- $<\approx 1 \text{ pb}^{-1}$  
  - Summer 2010
  - Charm and B cross sections at 7 TeV and high rapidity
  - with D and J/psi mesons and semileptonic B decays

- $\sim 200 \text{ pb}^{-1}$  
  - 2010
  - Compete with or improve upon Tevatron and B-factories
  - $\text{Bs} \rightarrow \text{J/}\psi \phi, \text{Bs} \rightarrow \mu\mu$, $\text{Bd} \rightarrow \text{K*}\mu\mu$, Bs mixing, CKM angle $\gamma$, 

- $\sim 1 \text{ fb}^{-1}$  
  - 2011
  - Start of full LHCb physics programme
  - Probe new physics in CP Violation and rare heavy flavour decays

- **LHC Physics in ~2015**
  - New Physics (NP) will hopefully be discovered by ATLAS/CMS and LHCb
  - New Physics will very likely show up in Flavour observables
  - Better Flavour Physics will be required to elucidate NP flavour structure or probe NP at higher mass scale

- **LHCb Upgrade**
  - LHC is a Super Flavour factory, $O(1\text{MHz})$ rate of b-quarks
  - Operate experiment at $\sim 10$ times design luminosity

See talk by Frederic Machefert

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Conclusions

- **LHCb experiment is fully commissioned**
  - All detectors are working close to expectations
- **Data taking with LHC beams at 7 TeV**
  - Detector performance close to expectations
  - Alignment and calibration well underway
  - Trigger, Vertex detector and Particle ID close to expectations
- **LHCb Detector Performance is excellent**
  - Many strange and charm hadrons already observed
  - First Beauty particles observed
  - Exciting prospects with 100 pb$^{-1}$ in 2010
- **Looking forward to analyse full 2010/11 LHC data set**
  - Could observe New Physics with this run
- **LHCb upgrade R&D has started**
B Production at $\sqrt{s} = 7$ TeV

B $\rightarrow$ D$^+$ $\mu^-$ $\nu$,
D$^+ \rightarrow \phi(K^+K^-)\pi^+$
LHCb Upgrade Plans

- **Status of LHC Physics in ~2015**
  - New Physics may or may not be discovered by ATLAS/CMS and LHCb
  - New Physics will very likely show up in Flavour observables

- **Flavour physics beyond the first phase of LHC**
  - Better Flavour Physics will be required
to elucidate the NP flavour structure or probe NP at higher mass scale
  - LHC is a Super Flavour factory
  - $10^6$ Hz of b-quarks produced → LHCb Upgrade

- **LHCb Upgrade Strategy**
  - running at 10 times design luminosity, i.e. at ~ $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$
  - read out full experiment at 40 MHz, currently at 1 MHz
  - → vertex and photon detector needs to be replaced
  - Upgrade expected at ~ 2016, R&D has started

See talk by Frederic Machefert
Outlook

- \( \approx 1 \text{ pb}^{-1} \) summer
  - Charm and B cross sections at 7 TeV and high rapidity using D, J/ψ and semileptonic decays
- \( \approx 200 \text{ pb}^{-1} \) 2010
  - Compete with or improve on Tevatron and B-factories
  - \( B_s \to J/\psi \phi , B_s \to \mu \mu \), \( B_d \to K^* \mu \mu , B_s \) mixing, CKM angle \( \gamma \),
- \( \approx 1 \text{ fb}^{-1} \) 2011
  - LHCb physics programme
  - Probe new physics in CP Violation and rare heavy flavour decays
- No time to discuss
  - CP asymmetries in gluonic \( b \to s \) penguin decays,
    - \( B_s \to \phi \phi , K^* K^* \)
  - Charmless Hadronic B Decays, time-dependent
    - \( B_d , B_s \to \mu \mu \) analysis
  - CKM angle \( \gamma \)
    - 3-body Dalitz decays
  - Radiative penguin decays
    - \( B_s \to \phi \gamma , B_s \to K^* \gamma \)
  - CKM angle \( \sin 2\beta \)
    - \( B_d \to J/\psi K_S \)
  - CKM angle \( \alpha \)
    - \( B \to \rho \pi \)
  - Spectroscopy \( X, Y, Z \),
- LHCb upgrade
  - After \( \approx 2015 \)

See talk by Frederic Machefert
Courtesy, Nuno Leandro

Minimum Bias

\[ \frac{\sigma \cdot \varepsilon}{\sigma_{mb}} \]

- \( \pi^{\pm} \) production
- \( \pi^{0} \) production
- \( K^{0} \) production
- \( \Lambda \) production
- \( \Lambda \) production
- \( \phi \) production
- D-meson production
- \( J/\Psi \) production
- \( J/\Psi \) from \( bb \)
- \( B_d \rightarrow J/\Psi K_s \) production

10^8 minimum bias @ 2kHz

LHCb at \( \sim 3 \times 10^8 \) events

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Example of performance: p-π discrimination

- Alignment and calibration still in early stages
- Thus, impressive to have such reasonable agreement between MC and data so soon!

Expect marked improvements in the coming weeks
$D_s \rightarrow \phi\pi, \sqrt{s} = 7 \text{ TeV data}$

\[ D_{(s)}^+ \rightarrow \phi\pi^+, \phi \rightarrow KK \]

- **RICH PID**
  - Crucial for $D_s$
  - Facilitated finding first $B$ candidate $B^+ \rightarrow J/\psi K^+$
  - Particle zoo is increasing each day: $\Lambda_c, \Omega^-$, ...
  - PID performance results will appear soon

- **Exciting Outlook**
  - After a few weeks of data taking, RICH is running very well and used to produce first results
  - Looking forward to increasing data sets for physics analysis

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The End