Highlights of LHCb

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On behalf of the LHCb collaboration

- The LHCb Detector
- LHCb and Higgs?
- Selected (core) highlights
  - Rare decays
  - CKM parameters
  - Charm
- Conclusions
The LHCb Collaboration

Countries member of the LHCb Collaboration (March 2013)

Collaborating institutes:

- Center for High Energy Physics, Tsinghua University, Beijing, China
- And another 59 institutes
LHCb and Luminosity

- Peak luminosity: $3 - 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- Automatic luminosity leveling
- $\sim 94\%$ recorded/delivered.
- $\int L = 0.035 + 1.1 + 2. \text{ fb}^{-1}$ in 2010+2011+2012
- Published results mainly from 2011 data.
The LHCb Detector \( 2 < \eta < 5 \)

In LHCb acceptance, \( \sqrt{s} = 7 \) TeV:

- \( \sigma(pp) = 59 \) mb (J. Instrum. 7 (2012) P01010)
- \( \sigma(pp) \rightarrow c\bar{c}X = 1.4 \) mb (arXiv:1302.2864)
- \( \sigma(pp) \rightarrow b\bar{b}X = 0.075 \) mb (PLB 698 (2011))
VELO Performance (arXiv:1302.5259)

**VELO:**
- 84 Si-sensors (semi CD size)
- 8 (30) mm from beam in closed (open) position
- Radiation: $0.5 \times 10^{14} \text{ 1 MeV n-equivalent per fb}^{-1}$
- $\sigma(\text{IP}) = 20 \mu\text{m} (p_T \text{ few GeV/c tracks})$

\[ \Delta m_s \text{ with } B_s^0 \rightarrow D_s^- \pi^+ \]
- $\sim 34000$ events with $D_s^- \rightarrow \phi\pi^-, K^*K^-, K^+K^-\pi^-, K^-\pi^+\pi^-, \pi^+\pi^-\pi^-$
- $\Delta m_s = 17.768 \pm 0.023(\text{stat}) \pm 0.006(\text{syst}) \text{ ps}^{-1}$
- most precise measurement of $\Delta m_s$ to date.

Shanghai, June 3-5, 2013
Tracking

TT 4 Si-planes: $\sigma - \text{hit} \sim 50 \mu m$
- 4 Tm dipole field
IT $3 \times 4$ Si-planes: $\sigma - \text{hit} \sim 50 \mu m$
OT $3 \times 8$ straw-tube plane: $\sigma - \text{hit} \sim 200 \mu m$

- Excellent invariant mass resolution!

$\sigma \sim 22 \text{ MeV}/c^2$ for $B \rightarrow hh$;

$\sigma_{\mu \mu} = 43 \text{ GeV}/c^2$ for $\gamma(1S)$;
- 484 HPDs outside LHCb acceptance.
- 1024 pixels $2.5 \times 2.5$ mm/HPD
- $\epsilon(K^{\pm}) \sim 95\%$ for $\sim 5\% \pi \to K$ mis-id

Without PID $B^0 \to \pi^+\pi^-$ completely dominated by $B^0 \to K^+\pi^-$
Calorimetry

- Scintillating Pad Detector: 5984 cells
  Distinguish e/γ in Level-0 Trigger.
- Preshower: Pb/scintillator, 5984 cells, 2.5 $X_0$
- Electromagnetic-Cal.: Pb shashlik,
  5984 cells, 25 $X_0$, $\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 1\%$
- Hadron-Cal.: iron/scintillating tiles, 1468 cells, 5.6$\lambda_I$
  Level-0 hadron Trigger. $\frac{\sigma_E}{E} = \frac{80\%}{\sqrt{E}} \oplus 10\%$
- Cell-sizes: $4 \times 4 \rightarrow 26 \times 26$ cm$^2$

Shanghai, June 3-5, 2013
Muon System (arXiv:1211.1346)

- MWPC, projective in Y for L0-trigger.
- GEM in inner part M1
- 120k pads and strips.
- Eff > 99% by OR. 2 layers per station.
- Covers 435 m²
- Pads: 1×2.5 cm² (M1-inner) to 16×20 cm² (M5-outer)
- Combine strips → 26k pads for the trigger
- First Level trigger efficient down to low $p_T$

![Diagram of the Muon System](image)

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**L0Muon Efficiency**

![Graph showing L0Muon Efficiency](image)

**J. Instrum. 8 (2013) P04022**

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Shanghai, June 3-5, 2013
Trigger Overview

Level-0 (hardware):
- Largest $E_T$ hadron, $e(\gamma)$ and $\mu$.
  Typical thresholds: 3.5, 2.5, 1.5 GeV.
- Max accept rate 1 MHz.

High Level Trigger (software):
- Access to all info in 29000 HLT jobs.
- First partial (large IP, muons) event reco.
- Then full reco, and mass cuts $\rightarrow$ 4.5 kHz.
$\epsilon \sim 90(30)\%$ for $B-$decays to $\mu\mu X$(hadrons)
LHCb and Higgs (like)?

- LHCb covers forward region, complementary to GPDs.
- Acceptance $\sim 5(11)\%$ at $\sqrt{s} = 7(14)$ TeV.
- Most promising channel: $H \rightarrow \tau^+\tau^-$

- Complementary at work:
  
  \[ A_W = \frac{\sigma_{W^+} - \sigma_{W^-}}{\sigma_{W^+} + \sigma_{W^-}} \]
“Calibrating” $\tau$-reconstruction using $Z$ decays.

- $\sigma(Z)$ using both $\mu^+\mu^-$ and $\tau^+\tau^-$ decays.
- Consider following $\tau$-decays:
  $\tau\mu\tau\mu$, $\tau\mu\tau e$, $\tau\mu\tau h$, $\tau e\tau h$
- Most shapes and yields taken from data: side-bands, same-sign
- Find: $\frac{\sigma_{pp \to Z \to \tau\tau}}{\sigma_{pp \to Z \to \mu\mu}} = 0.93 \pm 0.09$
- Excellent agreement!
\[ H \rightarrow \tau^+ \tau^- \]

- Assume theoretical \( \sigma(Z \rightarrow \tau^+ \tau^-) \)
- \( \sigma(\text{SM} - \text{Higgs}) \lesssim 3 \text{ pb} \) for \( 2 < \eta < 4.5 \)
- MSSM (M\(_{\text{max}}\) scenario):
  \[ \tan \beta > 32(70) \text{ for } M_{A^0} = 90(150) \text{ GeV/c}^2 \]

Outlook:
- \( \sqrt{s} = 7 \rightarrow 14 \text{ TeV}: \text{Acc} \times 2, \sigma \times 2 \)
- Increase \( \int L \)
- Upgrade: see later
Highlights in Rare Decays

- Rarest B-decay observed:
  - $B^+ \rightarrow \pi^+ \mu^+ \mu^-$: 5.2 $\sigma$ significance
  - $\mathcal{B} = (2.3 \pm 0.6 \text{ (stat.)} \pm 0.1 \text{ (syst.)}) \times 10^{-8}$

For NP discovery look for:
  a) Decays with $\mathcal{B}(\text{NP} \sim \text{SM}) \rightarrow \text{FCNC}$ decays.
  b) SM predictions “precise”.

Selected decays:
  - $B_s \rightarrow \mu^+ \mu^-$
  - $B^0 \rightarrow K^* \mu^+ \mu^-$

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$B_{(s)}^0 \rightarrow \mu^+ \mu^-$

**SM:**
- No tree level decay
- Helicity suppressed
- Expected time integrated
  $B(B_s \rightarrow \mu^+ \mu^-) = (3.54 \pm 0.30) \times 10^{-9}$

**NP:**
- MSSM: $\mathcal{B} \propto \tan^6 \beta / M_{A^0}^4$
- Pre-LHC parameter space example:
\[ B^{0}_{(s)} \rightarrow \mu^+ \mu^- \]

Experimentally

Trigger eff: \( \sim 90\% \)

Train BDT to distinguish background:

- both \( B \rightarrow \mu X, B \rightarrow \pi(K)\mu\nu, \Lambda_b \rightarrow p\mu\nu, B_c \rightarrow J/\psi\mu\nu, B_s \rightarrow D_s(\mu\nu)\mu\nu, B \rightarrow \pi\mu\mu \)
- MC to train, data (side bands) to calibrate.
- Variables: IP(\( \mu, B \)), \( p_T \), \( \tau \), \( B \)-vertex, helicity angle and \( \mu \)-isolation

from signal:

- Excellent signal proxy: \( B \rightarrow h^+ h'^- \)
  triggered on other B.
- Blind analysis
- \( B \) normalisation:
  - \( B^+ \rightarrow J/\psi K^+, B^0 \rightarrow K^- \pi^+ \)
  - \( f_s/f_d = 0.256 \pm 0.020 \) (hep-ph:1301.5286)
\[ B^{0}_{(s)} \rightarrow \mu^{+}\mu^{-} \]
$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-)$

Upper limit:
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 9.4 \times 10^{-10}$

at 95% CL

Evidence:
$\mathcal{B}(B_s \rightarrow \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$

with 3.5 $\sigma$

SM-reminder $(3.54 \pm 0.30) \times 10^{-9}$
$B_d^0 \rightarrow K^* \mu^+ \mu^-$

**SM:**
- $B \rightarrow sll$ FCNC decay.
- Rates, asymmetries and angular distributions have clean SM predictions.
- Experimentally clean

**NP:**
- Contributions also at low $\tan\beta$, i.e. complementary to $B \rightarrow \mu\mu$
- Many variables to test NP models.
$B_d^0 \rightarrow K^* \mu^+ \mu^-$ Experimentally

- Select $K^*$ decay
- Bin in $q^2 = M_{\mu^+\mu^-}$ (exclude $J/\psi$, $\psi(2S)$)
- Fit yield/bin

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Angular Analysis

- Decay angular distribution: $\text{func}(\theta_K, \theta_l, \phi)$
- Fit for amplitudes $A_{FB}$, $F_L$, $S_3$ and $A_9$
- SM: $A_{FB} = 0$ at $q^2 = 4.36^{+0.33}_{-0.31}$ GeV$^2$/c$^4$ (JHEP 01 (2012) 107)
- LHCb: $A_{FB} = 0$ at $q^2 = 4.9 \pm 0.9$ GeV$^2$/c$^4$
NP constraints from FCNC
Altmannshofer and Straub,
JHEP 08(2012)121

- NP in FCNC transition probed by modification to 9 Wilson operators in the Hamiltonian.
- Include data from CDF, D0, Belle, Babar, Atlas, CMS and LHCb.
- Angular analysis of $K^*\mu\mu$ imposes strongest constraints.
- $B_s \to \mu\mu$ (2011 data!) becomes competitive (for $C_{10}$)

Conclusion: no deviations from SM (yet, check with more data...).
Selected CKM parameters

CKM-angle $\gamma^a$

- Least well know:
  - direct measurement $\gamma = (66 \pm 12)^\circ$
- Prediction from global CKM fit without direct measurements: $\gamma^{(\text{fit})} = (67.2^{+4.4}_{-4.6})^\circ$
- Hence: consistent, but very large error.
- Measure in tree decays: $B^{\pm} \to (D^0)^K(\pi)^\pm$

$B_s$ weak mixing phase $\phi_s$

- Analogue of $2\beta$ of $B^0$-mixing.
- precisely predicted:
  $\phi_s = -0.036 \pm 0.002$ PRD84(2011)033005
- Measure in $B_s \to J/\psi K^+ K^- (J/\phi \pi^+ \pi^-)$

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$^a$plot/numbers from CKMfitter

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\( \gamma \) Measurements

- phase between amplitudes \( \propto \gamma \)
- relative magnitude \( r_B \)

- Example: “GGSZ” mode: \( D \to K_S h^+ h^- \)
- Construct Dalitz distributions.

- Bin Dalitz (appropriately..)
- Fit for \( \gamma, r_B \), etc..
\( \gamma \) Measurement

- GGSZ\(^a\) mode \((B^\mp \rightarrow DK^\pm, D \rightarrow K_S^0\pi^\pm\pi^\mp\) and \(D \rightarrow K_S^0K^\pm K^\mp\)\) resolves \(\gamma\) ambiguity (only \(|180^\circ|\) remains)
- GLW\(^b\) mode: \(D \rightarrow K^\pm K^\mp\) and \(D \rightarrow \pi^\pm\pi^\mp\)
- ADS\(^c\) mode: \(Dh^\mp\), \(D \rightarrow \pi^\pm K^\mp\) and \(D \rightarrow \pi^\mp K^\pm\)

- Already compatible with beauty factories \((\sigma_\gamma = 12^\circ)\) with 2011 \((1.0 \text{ fb}^{-1})\) data.

\(^c\)Atwood, Dunietz, Soni: PR D63(2001)036005
γ Measurements

- What about $\rightarrow D\pi^{\pm}$ modes?
- Combine $\rightarrow D\pi^{\pm}$ and $\rightarrow DK^{\pm}$ for 2011 (1.0 fb$^{-1}$) data.
- $\gamma \in [54.9, 85.4]^\circ$ at 68% CL
- $\gamma \in [41.8, 98.1]^\circ$ at 95% CL

Improve accuracy with 3× statistics already on tape.
$B_s$ weak mixing phase $\phi_s$

$B_s \to J/\psi X$ to CP-eigenstates, interference of mixing-direct decay gives rise to CP-violating phase $\phi_s$.

Global (indirect) fits to data gives in SM (ignoring sub-leading penguins) $\phi_s = -0.0364 \pm 0.0016 \, \text{rad}^a$

- 2011: $\sim 28k \, B_s \to J/\psi(\mu\mu)K^+K^-$ events
- $J/\psi\phi$ is a VV state, disentangle CP-even/odd with angular and time-dependent analysis.

- 2011: $\sim 7k \, B_s \to J/\psi(\mu\mu)f^0(\pi^+\pi^-)$ events
- Simpler analysis: $f^0$ single CP-state
- Combinatorial background:

  $B^- \to J/\psi K(\pi)^-, \bar{B}^0 \to J/\psi\pi\pi, \ B_s \to J/\psi\eta', \ B_s \to J/\psi\phi(\pi^+\pi^-\pi^0)$ and $\bar{B}^0 \to J/\psi K^-\pi^+$

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\(^a\)PR D84 (2011) 033005, CKMFitter

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$B_s$ weak mixing phase $\phi_s$

- Tag the flavour of $B$ at origin with:
  - associated $s$ with $B_s$ (SST)
  - decay product other $B$ (OST)
- Calibrate OST(SST) in data with:
  $B^+ \rightarrow J/\psi K^+ \ (B_s \rightarrow D_s^- \pi^+)$
- Effective tagging efficiency:
  $(3.13 \pm 0.12 \pm 0.20)\%$

- Combined result:
  $\phi_s = 0.01 \pm 0.07\text{(stat)} \pm 0.01\text{(syst)} \text{ rad}$
- Decay width difference: $\Delta \Gamma_s = 0.661 \pm 0.004\text{(stat)} \pm 0.006\text{(syst)} \text{ ps}^{-1}$
Charm

- $\sigma(c\bar{c}) = 1419 \pm 12\text{(stat)} \pm 116\text{(syst)} \pm 65\text{(frag)} \mu$b at $\sqrt{s} = 7$ TeV in LHCb acceptance.
- Visible $\sigma(pp) \sim 59 \pm 2$ mb at $\sqrt{s} = 7$ TeV (J. Instrum. 7 (2012) P01010)
- Plot: $\sim$min when running at full LHCb luminosity.

Hence: collect “huge” statistics:
- Charm mixing
- Charm CPV
Charm Mixing

Right Sign (RS): $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$
- Cabibbo favoured
- $8.4 \times 10^6$ events

Wrong Sign (WS): $D^{*+} \rightarrow D^0(K^+\pi^-)\pi^+$
- Double Cabibbo suppressed and mixing
- $3.6 \times 10^4$ events

Ratio WS/RS: no mixing excluded at 9.1 $\sigma$. 
CPV well established in K, B-systems

CPV in charm (u-quark):
- Effectively 2-generation system
- 3rd enters through loops, hence
- expected to be very small: < 0.1%
- Exp:
  \[ \Delta A_{CP} = A_{CP}(D \to KK) - A_{CP}(D \to \pi\pi) \]
- HFAG (ICHEP 2012):
  \[ \Delta a_{CP}^{dir} = (-0.678 \pm 0.147)\% \]
Charm CPV: Experimentally

\[ A_{\text{RAW}} = \frac{N(D^0 \rightarrow f) - N(\bar{D}^0 \rightarrow f)}{N(D^0 \rightarrow f) + N(\bar{D}^0 \rightarrow f)} \approx A_{\text{CP}} + A_{\text{Detection}} + A_{\text{Production}} \]

\[ \Delta A_{\text{CP}} = A_{\text{CP}}(K^+ K^-) - A_{\text{CP}}(\pi^+ \pi^-) \approx A_{\text{Raw}}(K^+ K^-) - A_{\text{Raw}}(\pi^+ \pi^-) \]

\[ D^{*+} \rightarrow D(hh') \pi^+_{\text{tag}}: \]
- Update 0.6 → 1.0 fb^{-1}
- LHCb-CONF-2013-003
- Tag: (slow) \( \pi \) from \( D^* \)
- Use \( \delta m = M(D^*) - M(D) - M(\pi) \)

\[ B \rightarrow D(hh') \mu^+_{\text{tag}} X: \]
- 1.0 fb^{-1}
- New (complementary) measurement
- PLB 723 (2013)
- Tag (and trigger) with \( \mu \)
**Charm CPV**

### π-tagged
- Very clean signals!
- \( D \to \pi\pi \): 0.69 M events.
- \( D \to KK \): 2.24 M events.
- \( \Delta A_{CP} = (-0.34 \pm 0.15\text{(stat)} \pm 0.10\text{(syst)})\% \) [LHCb-CONF-2013-003]
- Supersedes: [PRL108.111602] \((-0.82 \pm 0.21 \pm 0.11)\%\)

### μ-tagged
- Clean signals
- \( D \to \pi\pi \): 0.22 M events.
- \( D \to KK \): 0.56 M events.
- \( \Delta A_{CP} = (+0.49 \pm 0.30\text{(stat)} \pm 0.14\text{(syst)})\% \) [arXiv:1303.2614]

- \( \pi - \mu \)-tag samples independent, differ 2.2σ
- Many cross-checks: B-field, time, etc...

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Charm CPV: Spring 2013

- Naïve average: \( \Delta A_{CP} = (-0.33 \pm 0.12)\% \)

- No “evidence” for CPV in charm anymore.
- 3 \times \) more statistics on tape!
Conclusion and Outlook

- LHCb dominates many key measurements in heavy flavour physics with 2011 data alone.
- Adding 2012 data will triple statistics.
- SM does very well!
- Searches however (in many channels) still far from theoretical precision: much room for improvement.

- $\sigma(b\bar{b})$ will double after LS1
- LHCb upgrade planned for 2018. (CERN-LHCC-2012-007)
- Allows $5\times$ increase in luminosity.
- Full software trigger: will more than double (hadronic) efficiency.

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