Future b and c experiment with hadron machine

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Representing LHCb collaboration
Two ways of advancing “energy frontier”

- Flavor physics offers many loop processes to study (FCNC, mixing, CPV):
  - Some spectacular successes in the past (existence of charm quark, 3\textsuperscript{rd} generation, top quark mass)
  - Very existence of flavor sector with puzzling hierarchy hints NP
- Advancing precision of flavor experiments (statistics & systematics) and advancing collision energy for direct NP searches are complementary:
  - Both must continue
Future (beyond first round of LHC experiments)

- Physics beyond Standard Model will have or will not have been observed in direct searches at LHC at a TeV energy scale
- In either case flavor physics experiments must carry on:
  - To reveal flavor structure of NP observed in direct searches
  - To probe for NP in multi-TeV range if no NP observed in direct searches
- Future b and c experiments:
  - At $e^+e^-$ collisions: Super-KEKB, Super-B (previous talks)
  - At hadronic collisions: LHCb upgrade (this talk)
Existing LHCb detector

- **Forward geometry:**
  - $10^{12}$ bb/2 fb$^{-1}$ produced
  - both B hadrons in acceptance for tagging
  - excellent proper time resolution (40 fs)
  - Space for RICH detectors (K/$\pi$ separation 2-100 GeV)

- **Adjustable luminosity:**
  - $(2-5) \times 10^{32}$ cm$^{-2}$s$^{-1}$ i.e. factor 50-20 below peak luminosity of LHC to limit:
    - number of interactions per bunch crossings
    - radiation dose
    - data rates in trigger

- **Hardware & software triggers:**
  - Hardware L0: high Pt $\mu$, charged hadron, and e/$\gamma$ triggers (10 MHz $\rightarrow$ 1 MHz)
  - Software High Level Triggers (large CPU farm):
    - HLT1: confirm L0 seeds with the tracking detectors, add Impact Parameter cuts
    - HLT2: full event reconstruction and off-line like selections to reduce rate to 2 kHz
Construction almost final.
Detector Commissioning ongoing.
LHCb physics program

- By 2013 LHCb expects to accumulate 10 fb$^{-1}$. Allows for wide range of analyses, with high sensitivity to new physics.

- Some highlights:
  - Observation of B$_s$→μμ at SM value
  - B$_s$ mixing phase measured with uncertainty of 0.01 rad (SM expectation: -0.036±0.003)
  - B→K*$μμ$ : ‘0-point’ of FB asymmetry measured to 7%
  - Precise determination of $γ$
    - tree-level value known to ~2°
    - NP-sensitive measurements with Penguin modes (eg. B→hh)
  - Search for NP CPV in gluonic penguins, e.g. B$_s$→φφ
  - D$^0$ mixing measurements & searches for charm CPV to 10$^{-3}$
Why LHCb upgrade?

- Many important measurements will be statistics limited in 10 fb\(^{-1}\)
  - Aim at \(~100\) fb\(^{-1}\) for a significant gain in sensitivity
- LHCb statistics is not limited by the LHC luminosity but by the detector itself:
  - Radiation damage (spec was <20 fb\(^{-1}\))
  - No gain from increased luminosity for channels relying on L0 hadron trigger
  - Significant problems with spill-over in straw tracking stations
Choice of luminosity

- Instantaneous luminosity to be increased by a factor of 10
  - Bunch crossing rate with at least 1 visible pp-interaction up by a factor of 3
  - Number of pp-interactions per non-empty bunch crossing up by a factor of 2 (4 including spillover)
- This luminosity upgrade does not require any changes to the LHC. It is also compatible with SLHC proposed for ATLAS & CMS.
Upgraded detector – radiation hardness

• Present vertex detector (VELO) has long R & φ strips and is not particularly radiation hard.
  – We are planning to replace it after ~6 fb⁻¹ even without an upgrade.
• Short strips (strixels) or pixels are needed.
  – This will also help pattern recognition and enable stand-alone momentum measurement if magnetic field is generated in the vertex detector area (presently no field, would help moving IP requirements to the lowest trigger level)
  – Number of different technologies are being considered. The R&D program has started.
  – Other possible improvements: removing RF foil (50% of present X₀ budget), moving VELO closer to the beam (presently at 8mm which is conservative)
• Possibly replace inner region of EM calorimeter:
  – With the same technology (shashlik) but smaller segmentation
  – With rad hard crystals (would improve energy resolution)
• Possibly may also have to replace MWPC in the inner region of the first muon superlayer
  – by triple GEM-detectors (already in use in parts of the detector)
Upgraded detector – trigger & FE

• Present Front End & trigger electronics:
  – limit readout from detectors not included in L0 trigger (all tracking detectors, RICHes) to 1MHz
  – limit L0 decision time to a few µs

• As the luminosity is increased by a factor of 10, the trigger must become more selective
  – visible bb cross-section alone will reach ~0.4 MHz (total ~30 Mhz)
  – the present L0 trigger scheme breaks down.
    • The efficiency (especially for modes with no muons) decreases wiping out the luminosity gain.
  – more selective trigger requires use of tracking information early on and longer decision time (latency):
    • On top of sustaining higher luminosities can improve trigger efficiency for hadronic modes by a factor of 2

• Solution is to readout all detectors synchronously at 40 MHz (bunch crossing frequency) and make all trigger decisions in the CPU farm:
  – All FE electronics must be replaced!
  – Requires new photo-detectors in RICH detectors, since present HPDs cannot be readout at this rate
Upgraded detector – Outer Tracker

- Tracking stations behind the magnet consists of straw tubes (OT) and silicon strips in the inner part (IT).
- Spill over increases occupancy in OT by a factor of 4 with significant degradation on tracking performance (lower efficiency, higher ghost rate).
- **Possible solutions:**
  - Faster gas to reduce spill over
  - Increase IT area, decrease OT area
  - Replace straws by new technology (Scintillating Fiber tracker?)
• Since RICH photo-detectors must be replaced, contemplate (optional) more drastic redesign of hadron ID system:
  – Remove RICH1 significantly reducing dead material in the tracking system (improves momentum resolution, e/γ detection)
  – RICH2 then must also be replaced to cover lower particle momenta:
    • Its aperture must be increased by enlarging & moving closer to the interaction point
    • Requires integration with the tracking devices
Physics with the upgraded LHCb detector

Mixing phases

• No dedicated physics studies yet; all numbers come from results of LHCb 10 fb\(^{-1}\) simulations scaled by factor of 20 for hadronic channels, and 10 for channels with muons.

• CPV phase in \(B_s \rightarrow J/\psi\phi\):
  – Mixing and decay phases are both small in SM.
  – Good place to look for NP in mixing diagram.
  – Large value would exclude MFV hypothesis.
  – LHCb will hopefully see beyond-SM phase.
  – Upgraded LHCb will make precise measurement.

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<thead>
<tr>
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<th>LHCb</th>
<th>Upgraded LHCb</th>
<th>(\phi_s) - SM expectation</th>
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<tbody>
<tr>
<td>Luminosity</td>
<td>2 fb(^{-1})</td>
<td>10 fb(^{-1})</td>
<td>100 fb(^{-1})</td>
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<tr>
<td>(S(B_s \rightarrow J/\psi\phi))</td>
<td>±0.02</td>
<td>±0.01</td>
<td>±0.003</td>
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<td>-0.036±0.003</td>
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• Similar precision in CPV phase in \(B_d \rightarrow J/\psi K_s (\sin 2\beta)\).
  – Vast statistics will permit understanding of systematics (e.g. from tagging).
  – Mixing phase is large in SM.
  – Not likely to reveal NP by itself.
  – Providing constraints for interpretation of other measurement.
CPV phases and gluonic penguins

- Decay channels mediated by penguin diagrams can peak up additional phases from NP in the loops
- Hint of disagreement between mixing phase measured in trees and loops with the present data (Belle & BaBar):
  - $S(B_d \to \phi K_s) - S(B_d \to J/\psi K_s) = 0.29 \pm 0.17$ (expect $\approx 0$ in SM, since each $\approx \sin^2 \beta$)
  - Sensitivity of (LHCb) upgraded LHCb with $10fb^{-1}$ $100 fb^{-1}$:
    $S(B_d \to \phi K_s)$ to $(\pm 0.1) \pm 0.025$
- Even better to look for extra phases of penguin diagrams in $B_s$ sector, since the mixing phase is small:
  - Golden mode: $B_s \to \phi \phi$:
    - In SM mixing and decay phase (both small) approximately cancel each other, thus expect $S(B_s \to \phi \phi) \approx 0$.
    - (LHCb) upgraded LHCb with $10fb^{-1}$ $100 fb^{-1}$ can measure: $S(B_s \to \phi \phi)$ to $(\pm 0.05) \pm 0.01$
CPV phases and radiative penguin

\[ B_s^0 \rightarrow \phi \gamma \] is particularly sensitive to right-handed currents:

- (LHCb) upgraded LHCb sensitivity:
  \[ S(B_s \rightarrow \phi \gamma) \text{ to } (\pm 0.05) \pm 0.02 \]
- Additional sensitivity via hyperbolic-sine term in decay width:
  \[ A_{\Delta\Gamma} \sinh(\Delta\Gamma t / 2) \] :
  - \( \Delta\Gamma \) Negligible in \( B_d \) decays
  - (LHCb) upgraded LHCb sensitivity: \( A_{\Delta\Gamma} \) to \((\pm 0.1) \pm 0.03\)
  - Reach the level of theoretical uncertainties with the upgraded detector
Measurements of $\gamma$

- Determined via tree-level processes ($B^\pm \rightarrow D^0 K^\pm$, $B_s \rightarrow D_s^{\mp} K^\pm$), thus serves as another “standard candle” for constraints on unitarity triangle parameters.
- LHCb with 10 fb$^{-1}$ will measure $\gamma$ to $\pm 2.5^\circ$.
- Very large statistics with upgraded LHCb (examples):
  - 620,000 $B_s \rightarrow D_s^{\mp} K^\pm$ (interference via $B_s$ mixing, very clean way to measure $\gamma + \phi_s$)
  - 500,000 $B^\pm \rightarrow D^0 (K_s \pi \pi) K^\pm$
  - 5,600,000 $B^\pm \rightarrow D^0 (K \pi) K^\pm$
- Statistical uncertainty in several modes below $1^\circ$
- Systematic uncertainties largely uncorrelated, and often can be measured in control samples
- Upgraded LHCb will allow $\gamma$ determination to $< \pm 1^\circ$
Loop decays very sensitive to many extensions of SM.
LHCb will hopefully detect beyond-SM signal in $B_s \rightarrow \mu\mu$
To lower experimental error below the theoretical uncertainty on SM prediction (10%), upgraded LHCb will be needed
With upgraded LHCb it should also be possible to observe $B_d \rightarrow \mu\mu$ at SM level ($\sim 1 \times 10^{-10}$)
$B_d \rightarrow K^{*0}\mu\mu$

- Sensitive to NP in small $\tan\beta$ range.
- Zero point of forward-backward asymmetry in $M_{\mu\mu}^2$ will be measured to $(\pm 0.3) \pm 0.07$ GeV$^2$ with (LHCb-10 fb$^{-1}$) upgraded LHCb-100 fb$^{-1}$.
- The latter exceeds present theoretical uncertainty on SM predictions.
- Additional sensitivity via transversity amplitudes (analysis of full angular correlation)
- Measurement of $(|A_\perp| - |A_\parallel|) / (|A_\perp| + |A_\parallel|)$ for theoretically preferred region ($M_{\mu\mu}^2<6$ GeV$^2$) to $(\pm 0.2) \pm 0.06$ for (LHCb) upgraded LHCb vs theoretical error of $\pm 0.003$
- We will also study $B_d \rightarrow \rho(\omega)\mu\mu$ and $B_s \rightarrow \phi\mu\mu$, $B_s \rightarrow K^{*0}\mu\mu$

(see G. Eigen’s talk)
D⁰ mixing and CPV

B → D*⁺X
D⁰ → Kπ

Partially reconstruct B decay vertex to find birth position of D⁰ - gives good proper time resolution

- From wrong sign Kπ measure:
  - \(x''^2\) to \(±2\times10^{-5}\)
  - \(y'\) to \(±3\times10^{-4}\)

- From KK measure:
  - \(y_{CP}\) to \(±1.5\times10^{-4}\)
Other selected topics

• Lepton flavor violating decay $\tau \rightarrow \mu \mu \mu$.
  – BR($\tau \rightarrow \mu \mu \mu$) sensitivity $2 \times 10^{-9}$ (preliminary estimate)

• Sensitivity to long-lived (vertex detector is 1 m long) NP particles decaying to $b\bar{b}$.
  – For example, “hidden valley” model
    $\text{Higgs} \rightarrow \pi_{\nu}^0 (b\bar{b}) \pi_{\nu}^0 (b\bar{b})$
    where $\pi_{\nu}^0$ are new $\nu$-flavored particles

Strassler & Zurek
Conclusions

• LHCb about to take over the baton of flavor physics.
  – 10 fb\(^{-1}\) expected by ~2013: wealth of exciting discoveries and measurements in store.

• Require upgraded flavor experiment to capitalize on what is learnt at early LHC, and to exploit fully enormous b production cross-section and access to \(B_s\) sector:
  – Updated readout, trigger and vertex detector will be critical in upgrade.
  – Significant changes needed elsewhere (e.g. RICH photodetectors)
  – Experiment compatible with, but not reliant on, machine upgrade.
  – General physics capabilities clear; details under study.

• EOI recently approved by the collaboration and submitted to LHCC (CERN/LHCC/2008-007, April 22, 2008)
  – Aim at upgraded LHCb detector to start taking data in 2015
  – 100 fb\(^{-1}\) collected by 2020
  – Starting detector R&D