Recent results from LHCb

29\textsuperscript{th} of June 2015

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on behalf of the LHCb collaboration

The XXII International Workshop
High Energy Physics and Quantum Field Theory (QFTHEP-2015)
Samara, Russia / June 24 – July 1, 2015
Main goal of this talk: Show how precise LHCb measurements in b- and c-sectors make constraints on fundamental parameters of Standard Model (SM) and provide New Physics (NP) searches.

- Standard Model (SM) and its difficulties
  - Cabibbo-Kobayashi-Maskawa (CKM) matrix, CP violation (CPV)
  - Why and where to find New Physics (NP)? MFV or not?
  - Power of indirect measurements

- LHCb setup (apparatus, physical program etc.)

- Selected results
  - Rare decays
  - Results which demonstrate tensions with SM predictions
  - Studies of the CKM parameters
  - Physics with $b$- and $c$-tagger jets.

- Summary and Outlook (what can be achieved after upgrade?)
Also check LHCb talks at LHC Seminars

30 Jun 2015 Brian Hamilton, "Measurement of the semitauonic decay $B^0 \to D^*\tau\nu$ at LHCb"
soon at https://cds.cern.ch

26 May 2015 Victor Coco, "Observation of top-quark production in the forward region with LHCb"
https://cds.cern.ch/record/2018487?ln=en

24 Mar 2015 Patrick Owen, "First determination of $V_{ub}$ using the exclusive decay $\Lambda_b \to p\mu\nu$ with the LHCb detector"
https://cds.cern.ch/record/2004374?ln=en

10 Feb 2015 Marco Pappagallo, "Latest results on b-hadron spectroscopy at LHCb"
https://cds.cern.ch/record/1988103?ln=en

18 Nov 2014 Sevda Esen, "Measurement of the $B_s$ mixing phase at LHCb"
https://cds.cern.ch/record/1971320?ln=en

30 Sep 2014 Mika Anton Vesterinen, "Measurement of semileptonic asymmetries at LHCb"
https://cds.cern.ch/record/1951445?ln=en

12 Aug 2014 Manuel Tobias Schiller, "Gamma measurements in $B_s \to D_s K$ and other tree-level decays"
https://cds.cern.ch/record/1749146?ln=en

3 Jun 2014 Greig Cowan, "Confirmation of the $Z(4430)$-resonance and other exotic meson results from the LHCb experiment"
https://cds.cern.ch/record/1706201?ln=en

18 Mar 2014 Albert Puig Navarro, "Observation of photon polarization in the $b \to s\gamma$ transition at LHCb"
https://cds.cern.ch/record/1706201?ln=en
Introduction
No doubt that SM is great achievement!
(no large conflict with HEP, but some tension will be discussed in this talk)

**Reasons for New Physics (NP):**

1) Neutrino sector
   - mass
   - oscillations

2) Hierarchy of quark masses

3) Radiative correction to $m_H$
   - fine tuning
   - desert between $M_{EW}$ and $M_{GUT}$

4) Astrophysics
   - dark matter
   - baryon asymmetry of Universe

SUSY was considered as a good candidate to solve 2) & 3) (CPV is needed)

Great success of ATLAS and CMS in determination of Higgs boson parameters.
Indirect measurements at LHC

- How NP related to flavour physics?
- Is NP weakly coupled to flavour sector (MFV) or at very high scale?

**Important** to have a probes beyond LHC energies (direct observation)!

- Better to use processes which are either forbidden either highly suppressed in SM

**Flavour Changing Neutral Currents (FCNC)** can be such a probe

- Many historical successful HEP examples (Kaon CPV → KM predictions of $3^{\text{rd}}$ quark generation, neutral currents → Z-discovery, B-meson mixing → top quark mass scale)

- Direct searches are restricted by LHCb kinematics conditions, but they are possible! (this talk: search for massive long-lived particles)
Cabibbo-Kobayashi-Maskawa

- Flavour eigenstates do not coincide with weak eigenstates
- Mixing matrix $V_{\text{CKM}}$
- CP violating phase can appear if we have 3 generations of fermions
- Elements of the CKM matrix appear at the decay vertices

Wolfenstein parametrization to demonstrate CKM elements hierarchy

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(q - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - q - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4).$$

$$A(d \to u) \propto i \frac{g_2}{2\sqrt{2}} \bar{u}V_{ud}\gamma_\mu(1 + \gamma_5)d$$

$$A(u \to d) \propto i \frac{g_2}{2\sqrt{2}} \bar{d}V_{ud}^*\gamma_\mu(1 + \gamma_5)u$$
Unitarity triangles

\begin{align*}
V_{ud}V_{cd}^{*} + V_{us}V_{cs}^{*} + V_{ub}V_{cb}^{*} &= 0, \\
V_{ud}V_{td}^{*} + V_{us}V_{ts}^{*} + V_{ub}V_{tb}^{*} &= 0, \\
V_{cd}V_{td}^{*} + V_{cs}V_{ts}^{*} + V_{cb}V_{tb}^{*} &= 0, \\
V_{ud}V_{us}^{*} + V_{cd}V_{cs}^{*} + V_{td}V_{ts}^{*} &= 0, \\
V_{ub}V_{us}^{*} + V_{cb}V_{cs}^{*} + V_{tb}V_{ts}^{*} &= 0, \\
V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} &= 0.
\end{align*}

- 2 of 6 relations have all three contributions of the same size.
- Parameters of the triangle can be measured at the decay.
- Contain experimentally known CPV source in SM.
- Can be drawn as a triangle in the complex plane.
- Many different experimental constraints.
- In this talk, we will show LHCb results on \(|V_{ub}|, \sin(2\beta), \gamma\).
- Other triangles are also very important.
- Unitarity of CKM \Rightarrow |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.

\begin{align*}
O(\lambda) + O(\lambda) + O(\lambda^2) &= 0, \\
O(\lambda^2) + O(\lambda^2) + O(\lambda^4) &= 0. \\
O(\lambda^3) + O(\lambda^3) + O(\lambda^3) &= 0, \\
A\lambda^3(1 - \rho - i\eta) + (-A\lambda^3) + A\lambda^3(\rho - i\eta) &= 0.
\end{align*}
LHCb features
Beauty and charm production

- **LHCb: forward spectrometer** $2 < \eta < 5$

  (ATLAS & CMS: $|\eta|<2.5$)

- In LHCb acceptance ($pp$-collisions $\sqrt{s} = 7\text{TeV}$)

  \[ \sigma(b\bar{b}) = 75.3 \pm 5.4 \pm 13.0 \ \mu b \]

  \[ \sigma(c\bar{c}) = 1419 \pm 12 \pm 116 \ \mu b \sim 20 \times \sigma(b\bar{b}) \]

  Largest charm samples in the world

  Nucl.Phys.B871 (2013) 1
Operation in 2010/12

**pp-collisions at $\sqrt{s} = 7 & 8$ TeV (2011-12)**

- High recording efficiency
- 50 ns between bunch crossings
  (will try 25 ns this year)
- Constant luminosity of $\sim 4 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$
  (twice higher than design luminosity)
- 1.7 visible interaction per bunch crossing

**pPb-collisions at $\sqrt{s_{NN}} = 5$ TeV in 2013**

LHCb also has set of **pp** data at $\sqrt{s} = 2.76$ TeV (collected in 2011)
Experimental setup

\[ \epsilon_{PID}(\mu) \approx 97\% \]
\[ \text{MisID} (\pi \rightarrow \mu) \approx 3\% \]

\[ \epsilon_{PID}(K) \approx 95\% \]
\[ \text{MisID} (K \rightarrow \pi) \approx 5\% \]


\[ \sigma_{(IP)} \approx 20 \mu m \]
\[ \delta_{p/p} = 0.4 - 0.6\% \]
\[ \epsilon_{track} > 96\% \]

LHCb performance during Run I:

LHCb data analysis

Efficient trigger (L0/HLT1/HLT2):

40MHz → 5kHz

Tagging if needed

Event selection

Kinematical and topological info
(p_T, p, IP, vertex and track quality)

PID information

Cut based or multivariate selection
BDT, Neurobayes, etc.

Optimization of selection
Using MC
Using small sample of real data

Angular analysis++

Check for systematics

And a lot of other checks!

Trigger

Selection using SV/PV separation:
PV = Primary Vertex
DV = Daughter Vertex
(secondary vertex SV)

Typical flight distance of B meson ~ 1 cm
Physics program of LHCb

**GOAL:** Search for evidence of NP in CP violation and rare decays of beauty and charm hadrons. (Probing large mass scales via study of virtual quantum loops of new particles)

LHCb results are available in more than 260 papers submitted to journals and 120 conference contributions

Main direction of searches:

1) **Rare decays**
   - RD with di-muons
2) **Properties of the B systems**
   - CPV, $\Delta m_s, \Gamma_s, \Delta \Gamma, \phi_s$; CKM $\beta, \gamma, |V_{ub}|$ determination
3) **Mixing and CPV in the D mesons**
   - Mixing observ., $\Delta A(CP)$
4) **Spectroscopy and production of heavy quarks + Exotics**
5) **Electroweak physics** (top quark in fd.region, $W+c-/b$-jet)
6) **Soft QCD physics, pA and Ap results**
Rare decays and test of lepton universality

1) $B_{s,d}^0 \to \mu^+\mu^-$

2) $B^0 \to K^*\mu^+\mu^-$

3) $B^+ \to K^+\mu^+\mu^- / B^+ \to K^+e^+e^-$

4) $B_s^0 \to \phi\mu^+\mu^-$

5) $\bar{B}^0 \to D^*\tau\bar{\nu}$
NP and flavour symmetry; Wilson's coefficients

- Progress of theory calculations allows to take into account QCD corrections needed for SM FCNC implementation to decays. (Calculation of $C_i$ in SM as well as quite precise predictions for certain processes)

- $H_{\text{eff}}$ is an effective way to test different classes of possible NPs, because $C_i$ depend on their flavour structures.

- **Minimal Flavour Violation (MFV) paradigm**: NP has same source of FV as SM $\Rightarrow$ real numbers, same CPV effects, relations like:

$$
\text{BR}(B_s \to \mu^+\mu^-) = \frac{\tau_{B_s} f_{B_s}^2 m_{B_s} |V_{ts}|^2}{\tau_{B_d} f_{B_d}^2 m_{B_d} |V_{td}|^2}
$$

$$
\Delta F = 1 \text{ operators in the SM and in MFV}
$$

$$
H_{\text{eff}} = -\frac{4 G_F}{\sqrt{2}} \frac{e^2}{16\pi^2} V_{tb} V_{ts}^* \sum_i C_i O_i + \text{h.c.}
$$

**Example**

$$
O_9 = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)
$$

$$
O_{10} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)
$$

- If NP contains additional FV sources of $C_i$ become complex as well as new CPV effects might appear!
Rare decays $B^{(s)}_0 \rightarrow \mu^+\mu^-$

- Helicity suppressed in SM
- $\Delta\Gamma_s$ correction [PRD 86, 014027]

$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-)_{SM} = (3.66 \pm 0.23) \times 10^{-9}$

$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)_{SM} = (1.06 \pm 0.09) \times 10^{-10}$


5% precision SM calculations!

Ratio is power discriminator as well

$$\mathcal{R} \equiv \frac{\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)_{SM}}{\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-)_{SM}} = 0.0295^{+0.0028}_{-0.0025}$$

Sensitive to new scalar, pseudoscalar, axial-vector particles in loops

In MSSM:

$$c_{S,P}^{\text{MSSM}} \propto \frac{m_b^2 m_\mu^2 \tan^6 \beta}{M_A^4}$$
Observation of the rare $B_s^0 \to \mu^+ \mu^-$ decay from the combined analysis of CMS and LHCb data

The CMS and LHCb collaborations*

respectively. An example of the charged current is the decay of the $\pi^+$ meson, which consists of an up ($u$) quark of electrical charge $+2/3$ of the charge of the proton and a down ($d$) antiquark of charge $+1/3$. A pictorial representation of this process, known as a Feynman diagram, is shown in Fig. 1a. The $u$ and $d$ quarks are ‘first generation’ or lowest mass quarks. Whenever a decay mode is specified in this Letter, the charge conjugate mode is implied.

at CERN started operating, no evidence for either decay mode had been found. Upper limits on the branching fractions were an order of magnitude above the standard model predictions. The CMS (Compact Muon Solenoid) and LHCb (Large Hadron Collider beauty) collaborations have performed a joint analysis of the data from

Analysis of $B^0 \to K^*\mu^+\mu^-$

Fit result for $1 < q^2 < 6 \text{ GeV}^2/c^4$

- Loose preselection cuts
- Using BDT trained on proxy $B \to K^*J/\psi$
- Background from upper B sideband
- Choice of variables to avoid biases on angles and $q^2=m^2(\mu\mu)$
- Final selection from BDT decay time, flight direction, trk/vtx quality, $p_T$, PID

[LHCb-CONF-2015-002]
Analysis of $B^0 \rightarrow K^*\mu^+\mu^-$

- three angles + $q^2$ to describe data
- $F_L$, $A_{FB}$ & $S_i$ bilinear combinations of amplitudes (short-distance interaction + hadronic form factors)
- Precise theoretical calculations

Altmannofer, Bharucha, Straub, Zwicki [1503.05534][1411.3161]
Analysis of $B^0 \to K^* \mu^+ \mu^-$

- $P'_{4,5} = S_{4,5} \cdot [F_L \cdot (1-F_L)]^{-1/2}$
- Less dependent on form factor
- Consistent with previous result \textbf{PRL 111, 191802}
- 2.9σ deviation for [4,6] and [6,8] GeV$^2$/c$^4$ bin
- Naive combinations 3.7σ local significance

What theory can say about $B^0 \to K^* \mu^+ \mu^-$?

- Global fit of the available $b \to s\gamma \& b \to sll$
- $C_9^{NP} = -1.5$, 4.5σ deviation from SM
- Matias, Descotes-Genon, Vitro: \textbf{PRD 88, 074002}

- Straub, Altmannshofer: \textbf{EPJC 73, 2646},
- \textbf{arXiv:1503.06199} (3fb$^{-1}$ result is discussed)
- 3σ discrepancy, modification of $C_9$ needed
- Possible solution – flavour changing $Z'$
Test of lepton flavour universality

- In Standard Model
  \[ R_K = \frac{\int_{q^2=1 \text{ GeV}^2/c^4}^{q^2=6 \text{ GeV}^2/c^4} (d\mathcal{B}[B^+ \rightarrow K^+ \mu^+ \mu^-]/dq^2) dq^2}{\int_{q^2=1 \text{ GeV}^2/c^4}^{q^2=6 \text{ GeV}^2/c^4} (d\mathcal{B}[B^+ \rightarrow K^+ e^+ e^-]/dq^2) dq^2} = 1 \pm O(10^{-3}) \]

- Event migration (MC)
- Bremsstrahlung
- Double ratio with $B^+ \rightarrow J/\psi K^+$ to cancel systematics
- $3/fb$ dataset

\[ R_K = 0.745^{+0.090}_{-0.074} \text{(stat.)} +0.036 \text{(syst.)} \]

- Deviation from SM expectation at $2.9\sigma$ level

- QCD can't explain NON-LFU
- Non universal Z' can produce such effect
- Ghosh et al. arXiv:1408.4097
- Such explanation in agreement with $P_5$' anomaly
Analysis of $B_s^0 \rightarrow \phi \mu^+ \mu^-$

- Analysis similar to $B^0 \rightarrow K^* \mu \mu$
- No sensitivity to $P'_5$
- Measurement of branching fraction and angular analysis
- Theory: arXiv:1411.3161, 1503.05534
- New analysis confirms tension in 1fb$^{-1}$ dataset analysis JHEP 07 (2013) 084
- Extrapolation to full $q^2$ range
  (using PRD 66, 034002 & PRD 71, 014029)

\[
\frac{\mathcal{B}(B^0_s \rightarrow \phi \mu \mu)}{\mathcal{B}(B^0_s \rightarrow \phi J/\psi)} = (7.40^{+0.42}_{-0.40} \pm 0.20 \pm 0.21) \times 10^{-4}
\]
\[
\mathcal{B}(B^0_s \rightarrow \phi \mu \mu) = (7.97^{+0.45}_{-0.43} \pm 0.22 \pm 0.23 \pm 0.60) \times 10^{-7}
\]
Analysis of $\bar{B}^0 \rightarrow D^*\tau\bar{\nu}$

- Measurement of the ratio:

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B \rightarrow D^*\tau\bar{\nu})}{\mathcal{B}(B \rightarrow D^*\mu\bar{\nu})}$$

- Theoretically clean

- Sensitive to charged Higgs or non-MFV couplings favoring $\tau$.

- No narrow signal structures for signal, many bkg.

- Isolation technique against partially reco. bkg.

- Shapes are taken from simulation, validated against data

$$\mathcal{R}(D^*) = 0.336 \pm 0.027 \pm 0.030$$

- Agreement with SM at 2.1σ

- Main systematic comes from the size of simulated sample
CKM studies

1) $|V_{ub}|$ determination

2) Measurement of $\sin(2\beta)$

+ reminder about LHCb -measurement of $\gamma$
$|V_{ub}|$ measurement

- $|V_{ub}|$ has largest fractional uncertainty among all other CKM elements
- Discrepancy between exclusive ($B \to \pi l \nu$) and inclusive (any $b \to u l \nu$) determination of $|V_{ub}|$

\[ d\Gamma/dq^2 = \frac{G_F^2 |V_{ub}|^2 p_\pi^3}{24\pi^3} |f+(q^2)|^2 \]

$|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$

A negative right-handed $V+A$ current was considered as a possible puzzle solution.
\[ |V_{ub}| \] measurement

- LHCb measures ratio:
  \[ \frac{\mathcal{B}(\Lambda_b^0 \to p\mu\nu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \to pK\pi\mu\nu)} \]

- Sensitive to \( |V_{ub}| / |V_{cb}| \)

- Direct Lattice QCD calculation gives sufficient precision for high \( q^2 \) [arXiv:1503.01421]

- Corrected mass is good discriminating variable
  \[ M_{\text{corr}} = \sqrt{p^2 + M_{p\mu}^2} + p_\perp \]

- Two solutions for \( q^2 \), bin migration problem
  both required to be > 15 GeV\(^2\)/c\(^4\)

- Isolation technique sensitive to the extra tracks close to SV for background reduction

- Main systematics from: \( \Lambda_c \to pK\pi \) BF and decay model, trigger and tracking efficiency
\[ |V_{ub}| \text{ measurement} \]

- Measured ratio is:
\[ \frac{B(\Lambda_b^0 \to \rho \nu)}{B(\Lambda_b^0 \to \Lambda_c \mu \nu)}_{q^2 > 15 \text{ GeV}^2} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2} \]

- Using exclusive measurement of the \( |V_{cb}| \):
\[ |V_{ub}| = (3.27 \pm 0.15(\text{exp}) \pm 0.17(\text{theory}) \pm 0.06(|V_{cb}|)) \times 10^{-3} \]

- 3.5\sigma tension to the inclusive measurements

- Right-handed current hypothesis is in trouble
\[ \chi^2/\text{ndf} = 2.8 / 1, \text{ p-value}=9\% \to 16.0/2, 0.03\% \]

- Other CKM parameters:
LHCb measurements of $\sin(2\beta)$

- $B^0 \to J/\psi K^0_s$ is tree-level dominated decay, negligible contribution from penguins

- Time dependent CP asymmetry to measure:

$$A(t) = \frac{\Gamma(\overline{B}^0(t) \to J/\psi K_s^0) - \Gamma(B^0(t) \to J/\psi K_s^0)}{\Gamma(\overline{B}^0(t) \to J/\psi K_s^0) + \Gamma(B^0(t) \to J/\psi K_s^0)} = \frac{S \sin(\Delta m t) - C \cos(\Delta m t)}{\cosh(\frac{\Delta \Gamma t}{2}) + A \Delta \Gamma \sinh(\frac{\Delta \Gamma t}{2})}$$

- For $B^0$ mesons $\Delta \Gamma \approx 0$ => two CP observables: $A(t) = S \sin(\Delta m t) - C \cos(\Delta m t)$

- $S \approx \sin(2\beta)$
- Good tagging is required
- 41 560 ± 270 signal events

arXiv:1503.07089
LHCb measurements of $\sin(2\beta)$

- **arXiv:1503.07089** $B^0 \rightarrow J/\psi K^0_s$

- Multidimensional PDF includes reconstructed mass, decay time, **flavour tagging**

  $\varepsilon_{\text{tag}} = 36.5\%, \omega_{\text{miss}} = 35.6\%$

- Consistent with Belle and BaBar results

- Most precise time-dependent CPV

  measurement at hadron machine!

- See also **arXiv:1503.07055** $B^0_s \rightarrow J/\psi K^0_s$

- Is used to constrain penguin contributions, which are enhanced for this decay since it is CKM suppressed

\[ S = 0.731 \pm 0.035 \text{ (stat)} \pm 0.020 \text{ (syst)}, \]
\[ C = -0.038 \pm 0.032 \text{ (stat)} \pm 0.005 \text{ (syst)}, \]
Don't forget about LHCb measurements of $\gamma$

- LHCb-CONF-2014-004
- $\gamma$ is the only UT angle that can be directly measured at tree-level
- Many channels to study
  - Interference between $D$ and $D$-bar
  - A lot of $D$ final states
- Combined results from several analyses sensitive to $\gamma$

Don't forget about LHCb measurements of $\gamma$

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DK only (68% CL)

$\gamma = (73^{+9}_{-10})^\circ$

$r_B = 0.091^{+0.008}_{-0.009}$

$\delta_B = (127^{+10}_{-12})^\circ$

- Consistent with Belle and BaBar results
- More precise than B factories!
- Negligible theoretical uncertainty ($\sim 10^{-6}$)

- NEW: LHCb-PAPER-2015-014 for $B^\pm \rightarrow [h h' h^0]_D h^\pm$

  - First evidence of $B^+ \rightarrow [K^+ K^- \pi^0]_D K^+$
  - First observation of $B^+ \rightarrow [K^- K^+ \pi^-]_D \pi^+$

- NEW: LHCb-PAPER-2015-014 for $B^\pm \rightarrow [h h' h^0]_D h^\pm$
Physics with $b$-tagged jets

1) Top quark production in forward region

2) Direct search for massive long-lived particles
A bit about $c$- and $b$-jets tagging.

**Jet ID:** anti-$k_T$ algo with a distance parameter 0.5.

**Particle flow approach** → charged & neutral particle inputs.

**SV-tagger algorithm:**

- Displaced: $\chi^2_{IP} > 16$; High $p_T > 0.5$ GeV/c
- Inclusive 2-body vertexing:
  - DOCA < 0.2 mm, $\chi^2_{vertex} < 10$
  - $0.4 < m_{vertex} < m_{b0}$ (all particles assigned to $\pi$)
  - $\Delta R(PV-SV, jet) < 0.5$
- Merge into n-body
  - Not more than 1 track with $\Delta R(trk, jet) < 0.5$
  - $p_T > 2$ GeV/c, Flight-Distance-$\chi^2 > 5\sigma$
  - $(PV-SV)/p < 1.5$ mm/GeV
- BDT(bc|udsg), BDT(b|c) $M, M_{cor}, FD_T^{SV}, \Delta R(SV, jet), N_{trk}^{SV}$,
  - $N_{trk}^{SV}(\Delta R<0.5)$, $Q_{SV}, FD^{SV} \chi^2, \Sigma \chi^2_{IP}$

**Data samples (tagging):**

- Fully reconstructed $b$-hadron + jet
- Fully reconstructed $c$-hadron + jet
- $\mu(b,c) +$ jet
- Prompt isolated high-$p_T$ muon + jet
$W \rightarrow \mu \nu$ final state.

Jets tagged with the SV-tagger.

$p_T(\mu) > 20$ GeV, $2.0 < \eta_\mu < 4.5$

$p_T(j) > 20$ GeV, $2.2 < \eta_j < 4.2$

$\Delta R(\mu, j) > 0.5$

$p_T(\mu + j) > 20$ GeV

\textbf{arXiv:1505.04051}
Top quark observation

\( W + c\text{-jet:} \)

- Free of top contribution (method validation)
- NLO SM prediction folded to LHCb-detector response
- Yields are in a good agreement with SM predictions
- Charge asymmetry: 2\( \sigma \) difference with SM prediction

\[
\mathcal{A}(Wq) = \frac{\sigma(W^+q) - \sigma(W^-q)}{\sigma(W^+q) + \sigma(W^-q)}
\]

\( W + b\text{-jet:} \)

- Discrepancy between data and \( Wb \) predictions
- Good agreement with \( Wb + \text{top} \) predictions
- Profile likelihood to compare \( Wb + \text{top} \) and \( Wb \)
- \( N(Wb) \) and \( A(Wb) \)-shapes fixed, yields variation
- 5.4\( \sigma \) observation of top production in forward region

arXiv:1506.00903
Top quark & W + c- / b-jet results

- Study of W boson production in association with beauty and charm
  arXiv:1505.04051
- Identification of beauty and charm quark jets at LHCb
  arXiv:1504.07670
- First observation of top-quark production in the forward region
  arXiv:1506.00903
Direct search for long-lived particles

– Generic search for heavy $25 < m < 50 \text{GeV/c}^2$ long-lived $1 < t < 200 \text{ps}$ particles using displaced two-jet vertices

– Hidden valley $H \rightarrow \pi^o \pi^o$ as benchmark model

– $\sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 0.62/\text{fb}$

– Reconstruct $\pi^o$ with two (b-tagged) jets

– Fit mass in 5 bins $R_{xy}$

– No signal is observed

– Upper limits are better for decays into light quarks due to large multiplicity and smaller jet mass

$R_{xy}$ – distance to interaction region in transverse plane

EPJ C 75 (2015) 152
Direct search for long-lived particles

Complementary to ATLAS & CMS

More restrictive than Tevatron

EPJ C 75 (2015) 152
Summary

**LHCb, the forward spectrometer for precision studies in flavour physics domain**

Excellent performance of the LHC and LHCb has led to a lot of physics results

- Test of SM
- Search for NP
- Make CP violation measurements in b- and c-sectors
- Direct measurements as well

**World best quality of the results in charm and beauty physics!**

Most measurements agree with SM predictions, but some exciting tensions exist

=> Further studies certainly needed!

Presented here measurements use mainly the 3 fb$^{-1}$ dataset

(Several analyses still going)

**OUTLOOK:**

1) Plan to have more than ~ 5 fb$^{-1}$ at $\sqrt{s} = 13$-14 TeV during next LHC run (2015-18)

2) **Upgrade** (next slide)
# Outlook. **Theory vs. 50 fb$^{-1}$**

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHCb 2018</th>
<th>Upgrade (50 fb$^{-1}$)</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$2\beta_s (B_s^0 \rightarrow J/\psi \phi)$</td>
<td>0.025</td>
<td>0.008</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s (B_s^0 \rightarrow J/\psi f_0(980))$</td>
<td>0.045</td>
<td>0.014</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$a_{sl}^s$</td>
<td>$0.6 \times 10^{-3}$</td>
<td>$0.2 \times 10^{-3}$</td>
<td>$0.03 \times 10^{-3}$</td>
</tr>
<tr>
<td>Gluonic penguins</td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi \phi)$</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow K^{*0} \overline{K}^{*0})$</td>
<td>0.13</td>
<td>0.02</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta^{\text{eff}} (B^0 \rightarrow \phi K_S^0)$</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi \gamma)$</td>
<td>0.09</td>
<td>0.02</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau^{\text{eff}} (B_s^0 \rightarrow \phi \gamma)/\tau_{B_s^0}$</td>
<td>5 %</td>
<td>1 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Electroweak penguins</td>
<td>$S(3) (B^0 \rightarrow K^{*0} \mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$s_0 A_{\text{FR}} (B^0 \rightarrow K^{*0} \mu^+\mu^-)$</td>
<td>6 %</td>
<td>2 %</td>
<td>7 %</td>
</tr>
<tr>
<td></td>
<td>$A_1 (K \mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.08</td>
<td>0.025</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \rightarrow \pi^+ \mu^+\mu^-)/B(B^+ \rightarrow K^+ \mu^+\mu^-)$</td>
<td>8 %</td>
<td>2.5 %</td>
<td>$\sim 10 %$</td>
</tr>
<tr>
<td>Higgs penguins</td>
<td>$B(B_s^0 \rightarrow \mu^+\mu^-)$</td>
<td>$0.5 \times 10^{-9}$</td>
<td>$0.15 \times 10^{-9}$</td>
<td>$0.3 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>$B(B^0 \rightarrow \mu^+\mu^-)/B(B_s^0 \rightarrow \mu^+\mu^-)$</td>
<td>$\sim 100 %$</td>
<td>$\sim 35 %$</td>
<td>$\sim 5 %$</td>
</tr>
<tr>
<td>Unitarity triangle angles</td>
<td>$\gamma (B \rightarrow D^{(<em>)} K^{(</em>)})$</td>
<td>$4^\circ$</td>
<td>$0.9^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma (B_s^0 \rightarrow D_s K)$</td>
<td>$11^\circ$</td>
<td>$2.0^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta (B^0 \rightarrow J/\psi K_S^0)$</td>
<td>$0.6^\circ$</td>
<td>$0.2^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm CP violation</td>
<td>$A_\Gamma$</td>
<td>$0.40 \times 10^{-3}$</td>
<td>$0.07 \times 10^{-3}$</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>$\Delta A_{CP}$</td>
<td>$0.65 \times 10^{-3}$</td>
<td>$0.12 \times 10^{-3}$</td>
<td>–</td>
</tr>
</tbody>
</table>