Pentaquarks and possible anomalies at LHCb

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Conference on New Physics at the Large Hadron Collider
Nanyang Technological University, Singapore
29th Feb - 4th Mar 2016

Outline

- The LHCb experiment and the LHC Run 1 dataset
- Discovery of pentaquarks at LHCb

- $\Lambda_b^0 \rightarrow J/\psi K^- p$

- Evidence for anomalies in the flavour sector

- Lepton Universality

- Branching fraction ratio $\mathcal{B}(B^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau) / \mathcal{B}(B^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)$
 - Branching fraction ratio $\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-) / \mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)$

- FCNCs in $b \rightarrow s$ transitions

- Angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
 - Differential branching fraction $\mathcal{B}(B \rightarrow K^{(*)} \mu^+ \mu^-)$
 - Differential branching fraction $\mathcal{B}(B_s^0 \rightarrow \phi \mu^+ \mu^-)$
 - Differential branching fraction $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$

- FCNCs in $b \rightarrow d$ transitions

- Total branching fraction $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$

- The CKM sector

- Exclusive measurement of $|V_{ub}|$

- Conclusions and outlook

The LHCb detector and data set

Int. J. Mod. Phys. A30 (2015) 1530022

LHCb is a dedicated flavour physics experiment covering the forward rapidity regions at the LHC

LHC Run 1 (2010-2012) provided 3 fb^{-1} of integrated luminosity in pp collisions at $\sqrt{s} = 7$ and 8 TeV

- Precision **vertex reconstruction**: $\approx 13 \mu\text{m}$ resolution in x and y and $\approx 20 \mu\text{m}$ in IP
 - Secondary vertices from heavy flavour decays
- Proper **decay time resolution** $\approx 40 \text{ fs}$
 - Good separation of primary and secondary vertices
- Excellent momentum and **mass resolution**: typically 8 – 22 MeV/c^2
 - Relatively low combinatorial backgrounds

The LHCb detector and data set

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LHCb is a dedicated flavour physics experiment covering the forward rapidity regions at the LHC

LHC Run 1 (2010-2012) provided 3 fb^{-1} of integrated luminosity in pp collisions at $\sqrt{s} = 7$ and 8 TeV

- Excellent **charged particle identification** using RICH detectors
 - 95% efficiency for $K^\pm$ with 5% $\pi^\pm$ misID
 - Good rejection of peaking backgrounds
- Clean identification of **muons**
 - 97% efficiency with 1% - 3% hadron misID
- Flexible **low-pT trigger**: typically down to 300 MeV/c

LHC Run 2 (2015-2018) is now underway at $\sqrt{s} = 13$ TeV

Discovery of pentaquarks

PRL 115 (2015) 072001

Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \rightarrow J/\psi K^- p$ decays

Approx 25000 signal events

P_C^+ is charmonium pentaquark

Pentaquarks

PRL 115 (2015) 072001

- Component mass spectra from 25000 $\Lambda_b^0 \rightarrow J/\psi K^- p$ decays
- Clear indication of many Λ^* states in the $K^- p$ spectrum
- Peaking structure in the $J/\psi p$ mass spectrum

Pentaquarks

PRL 115 (2015) 072001

Log likelihood fit (red points) to an amplitude model of the 3-body final state incorporating the two interfering processes

$$\begin{aligned} \Lambda_b^0 &\rightarrow J/\psi \Lambda^* & \text{with} & \quad \Lambda^* \rightarrow K^- p \\ \Lambda_b^0 &\rightarrow P_c^+ K^- & \text{with} & \quad P_c^+ \rightarrow J/\psi p \\ & & \text{and} & \quad J/\psi \rightarrow \mu^+ \mu^- \end{aligned}$$

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	?	≈ 2585	200	0	6

- Unable to fit the $J/\psi p$ mass spectrum when including only $\Lambda_b^0 \rightarrow J/\psi \Lambda^*$

Pentaquarks

PRL 115 (2015) 072001

Very good fits to mass spectra and angular distributions when two pentaquark states are included in the fit

Phase variation of the pentaquark amplitudes in the fit shows expected resonance behaviour

Pentaquarks

PRL 115 (2015) 072001

- Masses and widths of the pentaquark Breit-Wigner peaks

- $M(P_c(4380)^+) = 4380 \pm 8 \pm 29 \text{ MeV}$
- $\Gamma(P_c(4380)^+) = 205 \pm 18 \pm 86 \text{ MeV}$
- $M(P_c(4450)^+) = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$
- $\Gamma(P_c(4450)^+) = 39 \pm 5 \pm 19 \text{ MeV}$

- Preferred spins are $3/2$ and $5/2$, and parities are opposite
- The structures cannot be accounted for by any known sources

Lepton Universality: $B^0 \rightarrow D^* \tau \nu$

PRL 115 (2015) 112001

- LHCb has measured the ratio of branching fractions
 - $R(D^*) = \text{BF}(B \rightarrow D^* \tau \nu) / \text{BF}(B \rightarrow D^* \mu \nu)$
- Tree-level process sensitive to new physics contributions e.g. charged Higgs bosons
- Theory predicts $R(D^*) = 0.252 \pm 0.003$ (HPQCD, Phys. Rev. D92, 054510 (2015))
 - ... and $R(D) = 0.300 \pm 0.008$ (S. Fajfer et al., Phys. Rev. D85, 094025 (2012))
- D^* candidates selected with $D^{*+} \rightarrow D^0(\rightarrow K^- \pi^+) \pi^+$
 - Use $\Delta m = m(K^- \pi^+ \pi^+) - m(K^- \pi^+)$ to obtain clean signal
- $R(D) = \text{BF}(B \rightarrow D \tau \nu) / \text{BF}(B \rightarrow D \mu \nu)$ is more difficult to measure at LHCb, because of more feed-down from higher charm resonances (no use of Δm to select signal) and more background

Lepton Universality: $B \rightarrow D^* \tau \nu$

PRL 115 (2015) 112001

- Signal channel $B \rightarrow D^* \tau \nu$ uses $\tau \rightarrow \mu \nu \nu$
- Same topology as the control channel
 $B \rightarrow D^* \mu \nu$
- Approximate B rest frame constructed using
 - Momentum of reconstructed final-state particles
 - Direction from primary vertex to B decay vertex
- Signal, normalisation and backgrounds distinguished by missing-mass-squared, m_{miss}^2 and muon energy, E_μ^* , in B frame
- Fits, using templates, give yields in bins of q^2 , the squared 4-momentum transfer to the lepton system

Lepton Universality: $B \rightarrow D^* \tau \nu$

PRL 115 (2015) 112001

- HFAG compilation of BaBar, Belle and LHCb measurements, including BaBar and Belle measurements of $R(D^*)$ and $R(D)$

- Combination of measurements is **3.9 σ from the SM prediction**
- This is now the largest experimental discrepancy with the SM

$$R_D = \frac{\mathcal{B}(B^0 \rightarrow D^- \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^- \ell^+ \nu_\ell)}$$

Lepton universality: $R_K = \text{BF}(B^+ \rightarrow K^+ \mu^+ \mu^-) / \text{BF}(B^+ \rightarrow K^+ e^+ e^-)$

PRL 113 (2014) 151601

- LHCb has measured the ratio of branching fractions
 - $R_K = \text{BF}(B^+ \rightarrow K^+ \mu^+ \mu^-) / \text{BF}(B^+ \rightarrow K^+ e^+ e^-)$
- **Loop-level process** highly sensitive to new physics contributions in the loops, e.g.
 - New scalar or pseudoscalar interactions
 - Z' bosons that couple differently to muons and electrons
- Large theoretical uncertainties in absolute BF's largely cancel in the ratio
- SM prediction $R_K = 1.0003 \pm 0.0001$ (Bobeth et. al., JHEP 0712, 040 (2007))
- LHCb measures R_K in the range $1 < q^2 < 6 \text{ GeV}^2/c^4$, so excluding the charmonium resonance region

Lepton universality: $R_K = \text{BF}(B^+ \rightarrow K^+ \mu^+ \mu^-) / \text{BF}(B^+ \rightarrow K^+ e^+ e^-)$

PRL 113 (2014) 151601

Fitted mass distribution for case where the event is triggered by one of the electrons

- Charmonium (e.g. $J/\psi \rightarrow \mu \mu$) region corresponds to tree-level processes, excluded in this and other FCNC analyses by selecting $1 < q^2 < 6 \text{ (GeV}^2/\text{c}^4)^2$
- Electron channel poses particular experimental problems owing to bremsstrahlung
- Unbinned extended maximum-likelihood fits to get the event yields
- Separate fits for three independent configurations of the trigger

$$R_K(\text{LHCb}, 1 < q^2 < 6 \text{ GeV}^2/\text{c}^4) = 0.745^{+0.090}_{-0.074} \pm 0.036$$

- The LHCb measurements is **2.6 σ from the SM prediction**

Angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays

JHEP 02 (2016) 104

- Another flavour-changing neutral current process, sensitive to new physics in loops
- Decay angular distribution
 - described by angles θ_l , θ_K , ϕ

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\ + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_l \\ - F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\ + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi \\ + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi \\ \left. + S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]$$

- Depends on QCD effects in $B \rightarrow K^*$ transition
 - Wilson coefficients (short distance)
 - Form factors (long distance)
- Studied in terms of optimal observables P_i'
- Optimal observables P_4' , P_5' , P_6' , P_8' are free of form factor uncertainties $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$

ϕ is the angle between decay planes in the B^0 rest frame

Angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays

JHEP 02 (2016) 104

- LHCb report a complete set of observables for the first time, based on the full angular distribution
- Maximum-likelihood fit over the range $1 < q^2 < 6 \text{ GeV}^2/c^4$

Angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays

JHEP 02 (2016) 104

- Distributions of the observables are largely compatible with the SM predictions, apart from P_5'
- Local deviations of 2.8σ and 3.0σ
- Can be accommodated by modifying the real part of the vector coupling strength of the decays, $\Re(C_9)$
 - Requires a shift from SM value corresponding to 3.4σ
 - A lot of theory work ongoing to better understand this effect
 - Is it new physics (e.g. a new vector particle) or an unexpectedly large hadronic effect?

“DHMV” SM predictions from
S. Descotes-Genon et al., JHEP 12, 125 (2014)

Differential branching fractions for FCNC processes

- $B \rightarrow K^{(*)} \mu^+ \mu^-$ *JHEP 06 (2014) 133*
- $B_s^0 \rightarrow \phi \mu^+ \mu^-$ *JHEP 09 (2015) 1179*
- $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ *JHEP 06 (2015) 115*
- FCNC $b \rightarrow s$ transitions that are highly sensitive to new physics contributions such as new heavy vector or axial-vector particles predicted in SM extensions
- Yields obtained in bins of q^2 (excluding charmonium regions) using maximum-likelihood fits

$$B \rightarrow K^{(*)} \mu^+ \mu^-$$

Theory predictions from C. Bobeth et al., JHEP 07, 067 (2015) and arXiv:1111.2448

Differential branching fractions for FCNC processes

- $B \rightarrow K^{(*)} \mu^+ \mu^-$ *JHEP 06 (2014) 133*
 - $B_s^0 \rightarrow \phi \mu^+ \mu^-$ *JHEP 09 (2015) 1179*
 - $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ *JHEP 06 (2015) 115*
- For $B_s^0 \rightarrow \phi \mu^+ \mu^-$ at $1.0 < q^2 < 6 \text{ GeV}^2$ the measured differential branching fraction is 3.3σ below the SM theory prediction
- For $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ theory modelling simplified since only a single, long-lived baryon in the final state
 - Baryonic system gives sensitivity to additional observables
 - Statistics currently too low for full angular analysis or conclusion on BF

Theory predictions from W. Altmannshofer and D. M. Straub, Eur. Phys. J. C75, 382 (2015); and A. Bharucha, D. M. Straub and R. Zwicky, arXiv: 1503.05534

Theory predictions from W. Detmold and S. Meinel, arXiv:1602.01399

The rare decays $B_s^0 \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$

CMS and LHCb collaborations, Nature 68 (2015) 522

- A well-known story by now, but, just to complete the picture ...
- Two other FCNC processes, $B^0 \rightarrow \mu^+ \mu^-$ and $B_s^0 \rightarrow \mu^+ \mu^-$

The rare decays $B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$

CMS and LHCb collaborations, *Nature* 68 (2015) 522

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = 2.8_{-0.6}^{+0.7} \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = 3.9_{-1.4}^{+1.6} \times 10^{-10} \text{ (3.2}\sigma \text{ evidence for } B^0 \rightarrow \mu^+\mu^-)$$

$$\frac{\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)}{\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)} = 0.14_{-0.06}^{+0.08}$$

2.3 σ above SM value

The CKM matrix element $|V_{ub}|$

Nature Physics 11 (2015) 743

- PDG 2014 reports a 3σ discrepancy between inclusive and exclusive measurements of $|V_{ub}|$

inclusive $b \rightarrow u \ell \nu$, $|V_{ub}| = (4.41 \pm 0.15^{+0.15}_{-0.17}) \times 10^{-3}$
 exclusive $B \rightarrow \pi \ell \nu$, $|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$

- LHCb uses the **exclusive channel** $\Lambda_b \rightarrow p \mu^- \bar{\nu}_\mu$
- First observation of this decay
- Measurement based on ratio

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow p \mu^- \bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu)} R_{\text{FF}}$$

R_{FF} is a ratio of form factors which has been evaluated using Lattice QCD (arXiv:1503.01421)

The CKM matrix element $|V_{ub}|$

Nature Physics 11 (2015) 743

- Normalisation channel identified via $\Lambda_c^+ \rightarrow p K^- \pi^+$
- Λ_b mass reconstructed as *corrected mass* using approximation to the Λ_b rest frame
- Fits to *corrected mass* distributions to determine yields

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow p \mu^- \bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu)} R_{\text{FF}}$$

The CKM matrix element $|V_{ub}|$

Nature Physics 11 (2015) 743

- Result $|V_{ub}| = (3.27 \pm 0.15 \text{ (stat)} \pm 0.16 \text{ (LQCD)} \pm 0.06 (V_{cb})) \times 10^{-3}$
- Confirms the discrepancy between inclusive and exclusive measurements, now at about 3.5σ
- Disfavours new physics models with a significant right-handed current

Summary of LHCb's most significant discrepancies with the SM

Observable	Discrepancy with SM
$R(D^{(*)})$ (incl. BaBar+Belle)	3.9σ
R_K	2.6σ
P_5' in $B^0 \rightarrow K^{*0} \mu \mu$	3.4σ
BF ($B \rightarrow K^{(*)} \mu \mu$)	Not quantified
BF ($B_s^0 \rightarrow \phi \mu \mu$)	3.0σ
BF ($B^0 \rightarrow \mu \mu$)	2.3σ
$ V_{ub} $ exclusive / inclusive	3.5σ

Possible anomalies ... a cautionary tale ...

arXiv: 1602.03160, submitted to Phys. Rev. Lett.

- LHCb has published **over 300 papers**, some with multiple results
 - **Some possible anomalies at $>2\sigma$ should be expected**
- CP-violation in charm: Measurement of the difference of time-integrated asymmetries in $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays

$$A_{\text{CP}}(D^0 \rightarrow f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)} \text{ with } f = K^+K^- \text{ and } \pi^+\pi^-$$

- A 3.5σ deviation from zero CP-violation in charm was reported from an LHCb study using 0.6 fb^{-1} of data (Phys. Rev. Lett. 108, 129903 (2012))
 - $\Delta A_{\text{CP}} = (-0.82 \pm 0.21 \pm 0.11) \%$
- The new result, using the full Run 1 dataset, is consistent with no CPV in charm
 - $\Delta A_{\text{CP}} = (-0.10 \pm 0.08 \pm 0.03) \%$
- This was a possible anomaly that turned out not to be an anomaly

Pentaquarks and possible anomalies at LHCb

Conclusions and Outlook

- With the LHC Run 1 data, LHCb has
 - Discovered pentaquarks
 - Identified a number of possible anomalies in the flavour sector
 - Violation of lepton universality
 - New physics in flavour-changing neutral currents
- But with over 300 papers, some apparent anomalies are expected
- The LHC Run 2 has now started
 - Expect 5 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$ by 2018
 - Increase LHCb statistics by typically x4 relative to Run 1
- How many of the “anomalies” will stand up?