A first discussion of 13 TeV results

Precision measurements

Tim Gershon
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LHCski 2016

14th April 2016
Opening comment

- Following the Higgs boson discovery, most experimental particle physics could be said to be precision measurements
  - studies of known SM particles
    - H, t, W, Z, B, D, K, ν, ...
  - searches for deviations from precise SM predictions
    - EWPO, H couplings, CKM unitarity triangle fits, (g-2)$_\mu$, ...
  - searches for very rare phenomena
    - H→τν, B→μμ, K→πνν, μ→eγ, 0ν2β, proton decay, EDMs, DM searches, ...
- I will cover only aspects related to heavy flavour physics
  - CP violation and rare decays
  - no claim these are the most precise measurements being performed!
Precision measurements in heavy flavour physics

with a bias towards results from the LHC

but with rather few 13 TeV results

after all, precision measurements take time …

but see the talk by Barbara Storaci this afternoon
Quark flavour mixing
a.k.a. CKM phenomenology

- CKM theory is highly predictive
  - huge range of phenomena over a massive energy scale predicted by only 4 independent parameters (+ $G_F + m_q + \text{QCD}$)

- CKM matrix is hierarchical
  - distinctive flavour sector of Standard Model not necessarily replicated in extended theories $\rightarrow$ strong constraints on NP models

- CKM mechanism introduces CP violation
  - only source of CP violation in the Standard Model ($m_\nu = \theta_{\text{QCD}} = 0$)
Two routes to heaven
for quark flavour physics

CP violation
(extra sources must exist)

But
- No guarantee of the scale
- No guarantee of effects in the quark sector
- Realistic prospects for CPV measurement in $\nu_s$ due to large $\theta_{13}$

SM

Rare decays
(strong theoretical arguments)

But
- How high is the NP scale?
- Why have FCNC effects not been seen?

NP

Absence of clear NP signals at ATLAS/CMS $\rightarrow$ argument for searches via rare decays stronger

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Precision measurements
Loop diagrams for discovery

- Contributions from virtual particles in loops allow to probe far beyond the energy frontier
- History shows this approach to be a powerful discovery tool
- Interplay with high-\( p_T \) experiments:
  - NP discovered: probe the couplings
  - NP not discovered: explore high energy parameter space
- NP contributions to tree-level processes also possible in some models

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CP violation & the Unitarity Triangle
The Unitarity Triangle

- The CKM matrix must be unitary
  \[ V_{CKM}^+ V_{CKM} = V_{CKM} V_{CKM}^+ = 1 \]
- Provides numerous tests of constraints between independent observables, such as
  \[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \]
  \[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \]

Consistency of measurements tests the Standard Model and provides model-independent constraints on New Physics.
\[ |V_{ub}/V_{cb}| \text{ from } \Lambda_{b} \rightarrow p\mu\nu/\Lambda_{b} \rightarrow \Lambda_{c} \mu\nu \]

- Long standing discrepancy between exclusive and inclusive determinations of both \( V_{ub} \) and \( V_{cb} \)

\[ |V_{cb}| = (42.4 \pm 0.9) \times 10^{-3} \text{ (inclusive)} \quad |V_{ub}| = (4.41 \pm 0.15 \pm 0.15) \times 10^{-3} \text{ (inclusive),} \]
\[ |V_{cb}| = (39.5 \pm 0.8) \times 10^{-3} \text{ (exclusive)} \quad |V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \text{ (exclusive).} \]

- Use of \( b \) baryon decays provides complementary alternative to \( B \) mesons

- At LHCb, exploit displaced vertex to reconstruct corrected mass

\[ M_{corr} = \sqrt{p_{\perp}^2 + M_{p\mu}^2} + p_{\perp} \]


PDG 2014

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\[ |V_{ub}|/|V_{cb}| \text{ from } \Lambda_b \to p\mu\nu/\Lambda_c \to \Lambda\mu\nu \]

- Can then reconstruct \( q^2 = m(\mu\nu)^2 \)
  - Select events with \( q^2 > 15 \text{ GeV}^2 \)
  - Highest rate, best resolution & most reliable theory (lattice) predictions
- Use isolation MVA to suppress background
- Fit \( M_{\text{corr}} \) to obtain signal yields


PR D92 (2015) 034503

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\[ \frac{|V_{ub}|}{|V_{cb}|} \text{ from } \Lambda_b \rightarrow p\mu\nu/\Lambda_b \rightarrow \Lambda_c \mu\nu \]

- Rules out models with RH currents
- Compatible with UT fit (\(\beta,\gamma\))

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Precision measurements
\[
\frac{|V_{td}|}{|V_{ts}|} \text{ from } \Delta m_d / \Delta m_s
\]

LHCb-PAPER-2015-031

- \( \Delta m_s \) now precisely known
- limitation on knowledge of UT side from lattice (improving fast) and \( \Delta m_d \)
- new measurement uses \( B^0 \rightarrow D^{(*)-}\mu\nu \) decays

\[
\Delta m_d = (505.0 \pm 2.1 \text{ (stat)} \pm 1.0 \text{ (syst)}) \text{ ns}^{-1}
\]

single most precise determination

precision of previous world average

\[
\Delta m_s = 17.768 \pm 0.023 \pm 0.006 \text{ ps}^{-1}
\]

(LHCb NJP 15 (2013) 053021)


\[
\Delta m_s = 17.768 \pm 0.023 \pm 0.006 \text{ ps}^{-1}
\]

(LHCb NJP 15 (2013) 053021)

only 2012 \( B^0 \rightarrow D^-\mu\nu \) data shown
\[ |V_{td}/V_{ts}| \text{ from } \Delta m_d/\Delta m_s \]

- $\Delta m_s$ now precisely known
- limitation on knowledge of UT side from lattice (improving fast) and $\Delta m_d$
- new measurement uses $B^0 \to D^{(*)-}\mu\nu$ decays

```plaintext
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only 2012 $B^0 \to D^-\mu\nu$ data shown
Importance of $\gamma$ from $B \rightarrow DK$

- $\gamma$ plays a unique role in flavour physics
  - the only CP violating parameter that can be measured through tree decays (*)
  
- A benchmark Standard Model reference point
  - doubly important after New Physics is observed

\[ \propto V_{cb} V_{us}^* \]

\[ \propto V_{ub} V_{cs}^* \]

Variants use different B or D decays require a final state common to both $D^0$ and $\bar{D}^0$
$\gamma$ from $B^+ \to DK^+$, $D \to KK, \pi\pi, K\pi$

LHCb-PAPER-2016-003

D → Kπ (favoured)

D → πK ("ADS" suppressed)

small asymmetries due to production and detection effects

B → Dπ control mode helps to separate effects

large CP violating asymmetries – first 5σ observation in a single B → DK channel

effects also possible in B → Dπ

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$\gamma$ from $B^+ \rightarrow DK^+$, $D \rightarrow KK, \pi \pi, K\pi$

LHCb-PAPER-2016-003

D $\rightarrow \pi \pi$ ("GLW" CP+ state)

D $\rightarrow KK$ ("GLW" CP+ state)

CP violating asymmetries visible but not 5σ significant
\[ \gamma \text{ from } B^+ \rightarrow DK^+, \; D \rightarrow KK, \pi\pi, \; K\pi \]

**Measurements reaching percent level precision**

Some tension in the \( A_{CP^+} \) average (\( \chi^2 = 16/4 \) dof) but no other sign of experimental disagreements

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Precision measurements
\[ \gamma \text{ from } B^0 \rightarrow D K^{*0}, \ D \rightarrow K_S \pi \pi, \ K_S KK \]

**LHCb-PAPER-2016-006,7**

- \( B^0 \rightarrow D K^{*0} \) rarer, but with larger interference effects, than \( B^+ \rightarrow D K^+ \)
- \( D \rightarrow K K, \pi \pi, \ K \pi \) previously studied in PR D90 (2014) 112002

Now consider “GGSZ” modes with both model-independent (LHCb-PAPER-2016-006) and -dependent (LHCb-PAPER-2016-007) analyses

- \( D \rightarrow K_S \pi \pi \) (both MI & MD)
- \( D \rightarrow K_S KK \) (MI only)

\( B_s^0 \) decays to same final states provide control channels
$\gamma$ from $B^0 \rightarrow DK^{*0}$

For $B^0 \rightarrow DK^{*0}$, width of the $K^{*0}$ resonance introduces a dilution factor that depends on the $B^0 \rightarrow DK^+\pi^-\pi^-$ Dalitz plot.

This has been studied with $D \rightarrow K\pi$ (LHCb-PAPER-2015-017), $KK$ and $\pi\pi$ (LHCb-PAPER-2015-059) decays.

Interference effects in the $D^{*+} - K^*$ overlap region enhance sensitivity to $\gamma$. 
γ combination

Many observables with sensitivity to γ

- $B^+ \rightarrow D K^+$, $D \rightarrow h^+ h^-$, GLW/ADS, 3 fb$^{-1}$
- $B^+ \rightarrow D K^+$, $D \rightarrow h^+ \pi^0$, quasi-GLW/ADS, 3 fb$^{-1}$
- $B^+ \rightarrow D K^+$, $D \rightarrow h^+ \pi^0$, quasi-GLW/ADS, 3 fb$^{-1}$
- $B^+ \rightarrow D K^+$, $D \rightarrow K_0^0 h^+$, model-independent GGSZ, 3 fb$^{-1}$
- $B^+ \rightarrow D K^+$, $D \rightarrow K_0^0 K^+ \pi^-$, GLS, 3 fb$^{-1}$
- $B^0 \rightarrow D K^+ \pi^-$, $D \rightarrow h^+ h^-$, GLW-Dalitz, 3 fb$^{-1}$
- $B^0 \rightarrow D K^+ \pi^-$, $D \rightarrow K^0$ ADS, 3 fb$^{-1}$
- $B^0 \rightarrow D K^+ \pi^-$, model-dependent GGSZ, 3 fb$^{-1}$
- $B^0 \rightarrow D K^+$, $D \rightarrow h^+ h^-$, GLW/ADS, 3 fb$^{-1}$
- $B^0 \rightarrow D K^+$, $D \rightarrow h^+ h^-$, GLW/ADS, 3 fb$^{-1}$
- $B^0 \rightarrow D K^+$, $D \rightarrow K_0^0 K^+ \pi^-$, model-independent GGSZ, 3 fb$^{-1}$
- $B^0 \rightarrow D K^+$, $D \rightarrow D_{s0}^+ K^\pm$, time-dependent, 1 fb$^{-1}$

New results discussed on previous slides

[4] LHCb collaboration, R. Aaij et al., Measurement of CP observables in $B^\pm \rightarrow D K^\pm$ and $B^\mp \rightarrow D_{s0}^\pm \pi^\mp$ with two- and four-body $D$ meson decays, LHCb-PAPER-2016-003, in preparation.

[5] LHCb collaboration, R. Aaij et al., A study of CP violation in $B^\pm \rightarrow D_h^\pm (h = K, \pi)$ with the modes $D \rightarrow K^+ \pi^- \pi^0$, $D \rightarrow \pi^+ \pi^- \pi^0$ and $D \rightarrow K^+ K^- \pi^0$, Phys. Rev. D91 (2015) 112014, arXiv:1504.05442

[6] LHCb collaboration, R. Aaij et al., Measurement of the CKM angle $\gamma$ using $B^0 \rightarrow D K^\pm$ with $D \rightarrow K_0^0 \pi^+ \pi^-$, $K_0^0 K^+ K^-$ decays, JHEP 10 (2014) 097, arXiv:1408.2748

[7] LHCb collaboration, R. Aaij et al., A study of CP violation in $B^\pm \rightarrow D K^\pm$ and $B^* \rightarrow D \pi^\pm$ decays with $D \rightarrow K_0^0 K^0 \pi^\mp$ final states, Phys. Lett. B733 (2014) 30, arXiv:1402.2982


[10] LHCb collaboration, R. Aaij et al., Measurement of the CKM angle $\gamma$ using $B^0 \rightarrow D K^0$ with $D \rightarrow K_0^0 \pi^+ \pi^-$ decays, LHCb-PAPER-2016-007, in preparation.


γ combination

Many observables with sensitivity to γ

γ = (70.9 \pm 7.1 \pm 8.5)°

World average including BaBar, Belle, CDF results will give marginally better precision

Not yet at desired precision, but great progress
Charm mixing with $D \rightarrow K\pi\pi\pi$

LHCb-PAPER-2015-057

Multibody charm decays also of interest to study charm oscillations (also to constrain hadronic parameters needed in the $\gamma$ fit)

Charm mixing parameters <1%

Still not established whether $x \equiv \Delta m_D / \Gamma_D \neq 0$
No evidence for CP violation in the charm system, whether in mixing, decay or mixing-decay interference

Latest: $\Delta A_{CP} \equiv A_{CP}(D \rightarrow KK) - A_{CP}(D \rightarrow \pi\pi) = (-0.10 \pm 0.08 \pm 0.03)\%$

Much stronger constraints obtained with minimal assumption on CPV in decays
Charm CP violation

No evidence for CP violation in the charm system, whether in mixing, decay or mixing-decay interference

Latest: $\Delta A_{CP} \equiv A_{CP}(D \to KK) - A_{CP}(D \to \pi\pi) = (-0.10 \pm 0.08 \pm 0.03) \%$

Much stronger constraints obtained with minimal assumption on CPV in decays
$B^0$ and $B_s^0$ mixing phases: $\sin(2\beta)$ & $\varphi_s$

Possible penguin pollution controlled by SU(3) partners

LHCb: PRL 114 (2015) 041801;
PL B736 (2014) 186;
ATLAS: arXiv:1601.03297;
CMS: PL B757 (2016) 97

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Precision measurements

CP violation in $B^0_{(s)}$ mixing

- Evidence of non-SM CP violation in inclusive dimuon asymmetry from the D0 collaboration
  - PRD 89 (2014) 012002

- Semileptonic asymmetries $A_{SL}(B^0)$ and $A_{SL}(B^0_s)$ however consistent with SM $\sim (0,0)$
  - $A_{SL}(B^0)$ by BaBar, Belle, LHCb, D0
  - $A_{SL}(B^0_s)$ by LHCb (1/fb), D0
    - final LHCb Run I analysis in progress

- Possibility of additional contributions to inclusive dimuon asymmetry under investigation
  - PR D87 (2013) 074020
Limits on BSM contributions to $\Delta B=2$

Define $M_{12}^q = M_{12}^{SM,q} \Delta_q$ and obtain constraints on $(\text{Re } \Delta_q, \text{Im } \Delta_q)$
(here not including anomalous D0 dimuon asymmetry result)

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Precision measurements
Rare (and some not so rare) decays
Kaon physics

- SM amplitudes most suppressed in kaons
  - Best NP sensitivity
  - Plots for $\Delta F=2$, but also true for rare decays
    - Kaon $\Delta F=2$ sensitivity limitation from lattice – great recent progress (e.g. PRL 115 (2015) 212001)

- Particularly interesting in MFV models
  - Same flavour suppression as SM
The holy grail of kaon physics: $K \to \pi \nu \bar{\nu}$

- **FCNC loop processes:** $s \to d$ coupling and highest CKM suppression

- **Very clean theoretically:** Short distance contribution. No hadronic uncertainties.


\[
\text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \left( \frac{|V_{cb}|}{0.0407} \right)^{2.8} \left( \frac{\gamma}{73.2^\circ} \right)^{0.74} = (8.4 \pm 1.0) \cdot 10^{-11}
\]

\[
\text{BR}(K_L \to \pi^0 \nu \bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \left( \frac{|V_{ub}|}{0.00388} \right)^2 \left( \frac{|V_{cb}|}{0.0407} \right)^2 \left( \frac{\sin \gamma}{\sin 73.2^\circ} \right)^2 = (3.4 \pm 0.6) \cdot 10^{-11}
\]

- **Experiments:**

\[
\text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = \left( 17.3^{+11.5}_{-10.5} \right) \times 10^{-11} \quad \text{Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)}
\]

\[
\text{BR}(K_L \to \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8} \quad \text{(90\% C.L.)} \quad \text{Phys. Rev. D 81, 072004 (2010)}
\]
The holy grail of kaon physics: $K \to \pi \nu \bar{\nu}$

- **FCNC loop processes**: $s \to d$ coupling and highest CKM suppression

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  \]

- **Future experiments**
  - **NA62 @ CERN**: aim for $\sim$10% BF measurement
  - **K0T0 @ J-PARC**: aim for observation at SM BF
NA62 Apparatus

**Detectors for Secondary Beam**
- Kaon ID (KTAG)
- Beam Tracker
- Beam guard ring (CHANTI)

**SPS proton**
- 400 GeV
- $10^{12}$ p/s
- 3.5 s spill

**Secondary Beam**
- 75 GeV/c, $\Delta p/p \sim 1\%$
- $X,Y$ Divergence $< 100 \mu$rad
- $K(6\%), \pi(70\%), p(23\%)$
- Total rate: 750 MHz
- Beam size: $6.0 \times 2.7$ cm$^2$

**Kaon Decay**
- $\sim 5$ MHz
- $4.5 \times 10^{12}$/year
- 60 m length
- $10^{-6}$ mbar vacuum

**Detectors for decay products**
- Charged particle tracking
- Charged particle time stamping
- Photon detection
- Particle ID

Slide by G. Ruggiero, Moriond EW 2016
Resolution close to design
Further background suppression from downstream particle identification and photon vetoes
Data-taking continues in 2016
• 1 event found in signal box (2013 data)
  • $0.36 \pm 0.16$ expected
• Main background from hadronic interactions
  • Significant improvements in background rejection obtained
• Much increased (>5x) data sample in 2015; more in 2016/7
  • Reach Grossman-Nir bound by 2017

Details in talk by H. Nanjo, KEKFF 2015
\[ B_{s} \rightarrow \mu^{+}\mu^{-} \]

**Killer app. for new physics discovery**

Very rare in Standard Model due to

- absence of tree-level FCNC
- helicity suppression
- CKM suppression

... all features which are not necessarily reproduced in extended models

\[
B(B_{s} \rightarrow \mu^{+}\mu^{-})^{SM} = (3.66 \pm 0.23) \times 10^{-9}
\]

\[
B(B_{s} \rightarrow \mu^{+}\mu^{-})^{MSSM} \sim \tan^{6}\beta/M^{4}_{A0}
\]

Intensively searched for over 30 years!
Combination of CMS and LHCb data results in first observation of $B_s \rightarrow \mu^+\mu^-$ and first evidence for $B^0 \rightarrow \mu^+\mu^-$

Results consistent with SM at 2σ level
$B_s \rightarrow \mu^+ \mu^-$

Cleanest of 3 BDT bins

Able to distinguish $B^0$ and $B_s^0$ peaks

Sensitivity comparable to CMS and LHCb

One to watch in Run 2

Compatibility of the simultaneous fit with the SM:

$p$-value = 0.048 (2.0σ)

$B(B^0 \rightarrow \mu^+ \mu^-) < 4.2 \times 10^{-10}$ at 95% CL

$B(B_s^0 \rightarrow \mu^+ \mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9}$
Full angular analysis of $B^0 \to K^{*0} \mu^+ \mu^-$

- $B^0 \to K^{*0} \mu^+ \mu^-$ provides superb laboratory to search for new physics in $b \to s l^+ l^-$ FCNC processes
  - rates, angular distributions and asymmetries sensitive to NP
  - experimentally clean signature
  - many kinematic variables … with clean theoretical predictions
- Full set of observables measured – only a subset shown

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Precision measurements
Full angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Comparison to other experiments
(up until now, only LHCb does a full angular analysis)

CMS (PLB 753 (2016) 424) quite competitive, especially at high $q^2$
Tension with SM in the $P_{5}'$ observable

- Dimuon pair is predominantly spin-1
  - either vector (V) or axial-vector (A)
- There are 6 non-negligible amplitudes
  - 3 for VV and 3 for VA ($K^{*0}\mu^+\mu^-$)
  - expressed as $A_{L,R,0,\perp,\parallel}$ (transversity basis)

- $P_{5}'$ related to difference between relative phase of longitudinal (0) and perpendicularly (⊥) polarised amplitudes for VV and VA
  - constructed so as to minimise form-factor uncertainties

$$P_{5}' = \sqrt{2} \frac{\text{Re} \left( A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*} \right)}{\sqrt{(|A_0^L|^2 + |A_0^R|^2) \left(|A_\parallel^L|^2 + |A_\parallel^R|^2 + |A_\perp^L|^2 + |A_\perp^R|^2\right)}}$$

Sensitive to NP in V or A couplings (Wilson coefficients $C_9^{(i)}$ & $C_{10}^{(i)}$)
\[ B_s \rightarrow \phi \mu^+ \mu^- \]

- Full angular analysis performed
- Not self-tagging → complementarity to \( K^{*0} \mu^+ \mu^- \)
  - only a subset of many observables shown

Tension in branching fraction, but angular observables consistent with SM

Consistent picture in \( b \rightarrow s \ell^+ \ell^- \) branching fractions
Lepton universality – $R_K$

Deficit of $B \to K\mu^+\mu^-$ compared to expectation
also seen in $K\mu^+\mu^-/Ke^+e^-$ ratio ($R_K$)

Example mass fit for $Ke^+e^-$
Note huge tail due to energy loss

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

Only 2.6σ from SM but suggestive
\[ B \rightarrow D^{(*)}\tau\nu \]

- Powerful channel to test lepton universality
  - ratios \( R(D^{(*)}) = \frac{B(B \rightarrow D^{(*)}\tau\nu)}{B(B \rightarrow D^{(*)}\mu\nu)} \) could deviate from SM values, e.g. in models with charged Higgs

- Heightened interest in this area
  - anomalous results from BaBar
  - other hints of lepton universality violation, e.g. \( R_K, H \rightarrow \tau\mu \)


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Precision measurements
B → D*τν at LHCb

- Identify B → D*τν, D* → Dπ, D → Kπ, τ → μνν̅
  - Similar kinematic reconstruction to Λb → pμν
  - Assume p_{B,z} = (p_{D*} + p_μ)_z to calculate M_{miss}^2 = (p_{B} - p_{D*} - p_μ)^2
  - Require significant B, D, τ flight distances & use isolation MVA
- Separate signal from background by fitting in M_{miss}^2, q^2 and E_μ
  - Shown below high q^2 region only (best signal sensitivity)

R(D*) = 0.336 ± 0.027 ± 0.030
**B → D(∗)τν at Belle**

- Reconstruct one B in Y(4S) → BB event
  - Either hadronic (PR D92 (2015) 072014) or semileptonic (arXiv:1603.06711) decay mode
  - First application of semileptonic tagging for B → D(∗)τν
  - Look for signal in the recoil

**Precision measurements**

$$R(D^*) = 0.302 \pm 0.030 \pm 0.011$$
B → D^{(*)}\tau\nu

Tension with SM at 4.0\sigma

R(D^*) = 0.316 \pm 0.016 \pm 0.010
R(D) = 0.397 \pm 0.040 \pm 0.028

Careful averaging needed to account for statistical and systematic correlations

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Precision measurements
Summary

- Huge range of results in quark flavour physics
  - Impossible to cover everything – sorry for omissions
- Several interesting “tensions” to keep an eye on
  - Inclusive vs. exclusive $|V_{ub}|$ & CKM fit
  - Hints of lepton non-universality in $R_K$, $R(D)$ & $R(D^*)$
  - Rates in $b \to s l^+l^-$ & $P_5'$
- Much to look forward to
  - NA62 & KOTO
  - More results from LHC Run I & II (LHCb & ATLAS & CMS)
  - LHCb upgrade & Belle II
Beyond Run II – the LHCb Upgrade

- Beyond LHC Run II, the data-doubling time for LHCb becomes too long
  - Due to 1 MHz readout limitation and associated hardware (L0) trigger
- However, there is an excellent physics case to push for improved precision and an ever-broader range of observables
- Will upgrade the LHCb detector in the LHC LS2 (2018-20)
  - Upgrade subdetector electronics to 40 MHz readout
  - Make all trigger decisions in software
  - Operation at much higher luminosity with improved efficiency
    - order of magnitude improvement in precision (compared to today)
- Upgrade will be performed during LSII (now expected to be 2019-20)
  - Restart data taking in 2021 at instantaneous luminosity up to 2 $10^{33}$/cm$^2$/s
  - Upgrade detector qualified to accumulate 50/fb
LHC upgrade and the all important trigger

50 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures

- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu\mu$
- 150 kHz $e/\gamma$

Software High Level Trigger
- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

- 2 kHz Inclusive Topological
- 2 kHz Inclusive/Exclusive Charm
- 1 kHz Muon and DiMuon

Higher luminosity
→ need to cut harder at L0 to keep rate at 1 MHz
→ lower efficiency

- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at $L_{\text{inst}}$ up to $2 \times 10^{33}/\text{cm}^2/\text{s}$

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Precision measurements
LHC upgrade and the all important trigger

- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at $L_{\text{inst}}$ up to $2 \times 10^{33}/\text{cm}^2/\text{s}$

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LHCb detector upgrade

- RICH 1 redesigned; new photodetectors for RICH 1 and RICH 2
- Replacement of full tracking system
- Calorimetry and muons:
  - Redundant components of system removed; new electronics added; more shielding included

+ novel trigger and offline data management strategies
Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb$^{-1}$ recorded during Run 2) and for the LHCb Upgrade (50 fb$^{-1}$). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHC Run 1</th>
<th>LHCb 2018</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
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<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$\phi_s(B_s^0 \to J/\psi \phi)$ (rad)</td>
<td>0.050</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim$ 0.003</td>
</tr>
<tr>
<td></td>
<td>$\phi_s(B_s^0 \to J/\psi f_0(980))$ (rad)</td>
<td>0.068</td>
<td>0.035</td>
<td>0.012</td>
<td>$\sim$ 0.01</td>
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<tr>
<td></td>
<td>$A_{s\phi}(B_s^0)$ (10$^{-3}$)</td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>0.03</td>
</tr>
<tr>
<td>Gluonic</td>
<td>$\phi_{\text{eff}}(B_s^0 \to \phi\phi)$ (rad)</td>
<td>0.15</td>
<td>0.10</td>
<td>0.023</td>
<td>0.02</td>
</tr>
<tr>
<td>Penguin</td>
<td>$\phi_{\text{eff}}(B_s^0 \to K^{*0}K^{*0})$ (rad)</td>
<td>0.19</td>
<td>0.13</td>
<td>0.029</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_{\text{eff}}(B_s^0 \to \phi K_0^0)$ (rad)</td>
<td>0.30</td>
<td>0.20</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$\phi_{\text{eff}}(B_s^0 \to \phi\gamma)$</td>
<td>0.20</td>
<td>0.13</td>
<td>0.030</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_B$</td>
<td>5%</td>
<td>3.2%</td>
<td>0.8%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak Penguin</td>
<td>$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$q_0^2 A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$</td>
<td>10%</td>
<td>5%</td>
<td>1.9%</td>
<td>$\sim$ 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>0.09</td>
<td>0.05</td>
<td>0.017</td>
<td>$\sim$ 0.02</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \to \pi^+\mu^+\mu^-)/B(B^+ \to K^+\mu^+\mu^-)$</td>
<td>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>$\sim$ 10%</td>
</tr>
<tr>
<td>Higgs</td>
<td>$B(B_s^0 \to \mu^+\mu^-)$ (10$^{-9}$)</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td>Penguin</td>
<td>$B(B_s^0 \to \mu^+\mu^-)/B(B_s^0 \to \mu^+\mu^-)$</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>$\sim$ 5%</td>
</tr>
<tr>
<td>Unitarity</td>
<td>$\gamma(B \to D^{(<em>)}K^{(</em>)})$</td>
<td>7°</td>
<td>4°</td>
<td>1.1°</td>
<td>negligible</td>
</tr>
<tr>
<td>Triangle</td>
<td>$\gamma(B_s^0 \to D^{\pm}K^{\mp})$</td>
<td>17°</td>
<td>11°</td>
<td>2.4°</td>
<td>negligible</td>
</tr>
<tr>
<td>Angles</td>
<td>$\beta(B^0 \to J/\psi K_0^0)$</td>
<td>1.7°</td>
<td>0.8°</td>
<td>0.31°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_T(D^0 \to K^+K^-)$ (10$^{-4}$)</td>
<td>3.4</td>
<td>2.2</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>CP violation</td>
<td>$\Delta A_{CP}$ (10$^{-3}$)</td>
<td>0.8</td>
<td>0.5</td>
<td>0.12</td>
<td>0.12</td>
</tr>
</tbody>
</table>