Overview of quark flavour results

The Zoologist’s Guide to the Galaxy

What Animals on Earth Reveal About Aliens — and Ourselves

Dr Arik Kershenbaum

Vladimir V. Gligorov, CNRS/LPNHE

With material from the LHCb, CMS, ATLAS, BES III, NA62, BaBar, Belle & Belle II experimental collaborations & the HFLAV, CKMFitter, and UTFit averaging groups

ICHEP 2022, Bologna, 12.07.2022
Object of study

Elementary Particles

Quarks

Leptons

Three Generations of Matter

Credit: ROOT team
Object of study

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
= 
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]
Object of study

Elementary Particles

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>$e$</td>
</tr>
<tr>
<td>$c$</td>
<td>$\mu$</td>
</tr>
<tr>
<td>$t$</td>
<td>$\tau$</td>
</tr>
<tr>
<td>$d$</td>
<td>$\nu_e$</td>
</tr>
<tr>
<td>$s$</td>
<td>$\nu_\mu$</td>
</tr>
<tr>
<td>$b$</td>
<td>$\nu_\tau$</td>
</tr>
</tbody>
</table>

Three Generations of Matter

Force Carriers

Credit: ROOT team

\[
\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}} \quad \alpha = \phi_2
\]

\[
\frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}} \quad \beta = \phi_3
\]

\[
(0,0) \quad \gamma = \phi_3
\]

\[
(1,0)
\]
Mapping the apex

Berwyn mountain,
Wales
Three decades of immense progress...
Three decades of immense progress...
Three decades of immense progress...
Three decades of immense progress...
We know that BSM physics with generic flavour couplings is ruled out to $10^5$ TeV!

...teaching us the scale of BSM physics...
The apex of the CKM triangle remains one of the safest long-term paths to constraining generic NP models!

...and giving motivation for the future!

Fig. 25: Present (lighter) and future Phase 2 (darker) constraints on the NP scale from the UTfit NP analysis. The right panel shows constraints assuming NP is weakly coupled, has MFV structure of couplings, and enters observables only at one loop, see text for details.
The tree-level path to the apex
The tree-level path to the apex

\[ \pm \]

\[ \rho \]

NEW @ ICHEP 2022

summer22
tree-only

\[ \gamma \]

\[ V_{ub} / V_{cb} \]

\[ r_D e^{-i\delta_D} \]

\[ D^0 K^+ \]

\[ B^+ \]

\[ K^- \pi^+ \]

\[ r_B e^{i(\delta_B + \gamma)} \]

\[ D^0 K^+ \]

~10^{-7} (!) theory uncertainty on the interpretation of experimental observables in terms of the CKM angle \( \gamma \)!

(Zupan & Brod 1308.5663)
We are approaching the 5% uncertainty level on $\gamma$ from direct measurements. It takes many ingredients to measure $\gamma$.

\[ \gamma = (65.4^{+3.8}_{-4.2})^\circ \]

Figure 5: Profile likelihood contours for the charm decay parameters, showing the breakdown of sensitivity amongst different sub-combinations of modes. The contours indicate the 68.3% and 95.4% confidence region.
The experimental road has been long
The compendium of legacy Run 1+2 LHCb measurements is nearing completion.

But the pieces are coming together now

Legacy LHCb Run 1+2 analysis of $B \to D(4H)K$ decays

$\mathcal{A}_{\text{CP}} \sim 85\%$

$\gamma = \left( 54.8 \pm 6.0 + 0.6 + 6.7 \right) ^\circ$

Tim Evans @ ICHEP 2022
Permille level $\gamma$ will require teamwork!

$B^{\pm}\rightarrow D(4h)K^{\pm}:$

4h modes could eventually rival $K_S HH$ (!!) if strong phases would be measured better, but will be limited very quickly if they cannot!
Permille level $\gamma$ will require teamwork!

\[ B^\pm \rightarrow D(4h)K^\pm: \]

4h modes could eventually rival $K_SHH$ (!!!) if strong phases would be measured better, but will be limited very quickly if they cannot!

\[ B^\pm \rightarrow D(K_{shh})K^\pm: \]

Will eventually be limited at 1 degree level by current BESIII measurements, therefore vital that BESIII goes ahead and collects 10x the current $\psi(3770)$ dataset!
Belle II is also showing its capabilities

\[ \gamma = (78.4 \pm 11.4 \text{ (stat.)} \pm 0.5 \text{ (syst.)} \pm 1.0 \text{ (ext.)})^\circ \]

Joint analysis of \( B \to D(K_sHH)K \) decays with Belle + Belle II data

Significantly improved mass resolution! Not competitive yet but promising for future.
The quest for $V_{ub}$ & $V_{cb}$

Inclusive-exclusive tensions remain in $V_{cb}$, are reduced in $V_{ub}$

Tension in $V_{ub}$ is around 2-3 sigma depending on inputs

$V_{cb}$ remains at 3 sigma, further experimental input must be matched by theory/lattice progress

Note: this inclusive-exclusive discrepancy is what we call a “puzzle”, not what we call an “anomaly”...
Belle II enters the quest for $V_{ub}$ & $V_{cb}$

Excellent showcase of Belle II capabilities, precisions approaching B-factories in some places
The up sector

Socotra island,
Yemen
CPV in charm observed by LHCb in the difference of CP asymmetries for the $\pi\pi$ and KK final states.

Now beginning to characterise the individual asymmetries with exquisite precision and systematics control!
Combination of the measurement of CP violation in the KK mode with the difference between KK and $\pi\pi$ leads to the first single-mode evidence (3.8$\sigma$) of CPV in $\pi\pi$

Systematics controlled at the $10^{-4}$ level — essential to scale to $10^{-5}$

$$a_{K-K^+}^d = (7.7 \pm 5.7) \times 10^{-4}$$

$$a_{\pi^-\pi^+}^d = (23.2 \pm 6.1) \times 10^{-4}$$

with $\rho(a_{KK}^d, a_{\pi\pi}^d) = 0.88$
Charm mixing well-established since more than a decade!
Charm mixing well-established since more than a decade! Experimental diversity & consistency key to long-term systematics control. Improved BESIII inputs again crucial to long-term sensitivity!
Flavour discoveries

rose-veiled fairy wrasse
New conventional mesons @ LHC
New conventional baryons @ LHC

Credit to Patrick Koppenburg https://www.nikhef.nl/~pkoppenb/particles.html
New exotics @ LHC

Observed by LHCb in 2020
and new for ICHEP 2022
confirmed by ATLAS/CMS!
The LHC is quite the hadron factory!

Featuring the new proposed naming scheme from LHCb
But what are these 4,5-quark states?

Molecule model - nuclear forces

F.-K. Guo et al., Rev. Mod. Phys. 90 (2018) 015004
But what are these 4,5-quark states?

Pentaquark (“exotic”) baryons

‣ Pentaquark baryons already present in original Gell-Mann, Zweig formulation of quark model (1964)

‣ Discovery of pentaquark candidates at LHCb in 2015 after 50 years of experimental searches. Renaissance of hadron spectroscopy

‣ Different models proposed for quark composition and binding mechanisms of pentaquark “exotic” states

‣ Precise measurements of mass, width, quantum numbers, and identification of isospin multiplets are needed to understand their nature

Molecule model - nuclear forces

Tightly bound quarks - color forces

F.-K. Guo et al., Rev. Mod. Phys. 90 (2018) 015004

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A. Esposito, A Pilloni, A. D. Polosa, Phys. Rept. 668 (2017) 1
J.-M. Richard, Few Body Syst. 57 (2016) 1185
But what are these 4,5-quark states?

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Molecule model - nuclear forces

Tightly bound quarks - color forces

Rescattering - kinematic effects

F.-K. Guo et al., Rev. Mod. Phys. 90 (2018) 015004
A. Esposito, A Pilloni, A. D. Polosa, Phys. Rept. 668 (2017) 1
J.-M. Richard, Few Body Syst. 57 (2016) 1185
5-quark states: a discovery and more hints

**PHYS. REV. LETT. 122 (2019) 222001**


**SCIENCE BULLETIN 66 (2021) 1278**
The latest member of the zoo: $P_{\psi_s}(4338)$

Clear observation of a five-quark state decaying into $J/\psi \Lambda$

Based on a 10x bigger dataset than previous CMS analysis of the same $B \rightarrow J/\psi \Lambda p$ final state

Full amplitude analysis testing numerous alternative hypotheses

$J = 1/2$ assigned, $P=-1$ preferred

$$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4 \text{ MeV}$$

$$\Gamma_{P_{cs}} = 7.0 \pm 1.2 \pm 1.3 \text{ MeV}$$

NEW @ ICHEP 2022

Nicola Neri @ ICHEP 2022
4-quark states: a growing family
4-quark states: a growing family
4-quark states: a growing family

Bump on right-hand side of 6900 is prominent in CMS data and a hint exists in LHCb?
4-quark states: a growing family

Both ATLAS and CMS fit their data with various models also explored in the LHCb paper. The data is suggestive of interference effects, however further study and more data is needed!
4-quark states: a growing family

ATLAS also see an excess in $J/\psi + \psi(2S)$, precise nature and composition are for the moment unclear. Any structure in $J/\psi + \psi(2S)$ could appear in $J/\psi + J/\psi$ as a partially reconstructed decay.
Latest 4-quark states from LHCb

Observation of isospin triplet [csud] 4-quark states

$X(3960)$ and $X_{c0}(3930)$ are either not the same resonance, or they are the same non-conventional charmonium-like state

A lot of work remains to determine the properties of these particles

$M(D_s\pi)$ well described by adding a $J^P = 0^+ T_{cs0}^a (2900)$ in each channel
Anomalous couplings
$B^0, B_{s}^0 \rightarrow \mu\mu$: the king penguin

The ultimate experimental beauty hadron decay for probing BSM effects

1. Highly suppressed in the SM
2. Highly enhanceable elsewhere
3. Experimentally accessible
4. Theoretically pristine
2/3 pieces of the LHC Run 1+2 legacy now in place. Excellent agreement with SM but a great deal of work ahead to observe $B^0 \rightarrow \mu\mu$ and eventually also $b \rightarrow \mu\mu\gamma$?

**NEW @ ICHEP 2022**

**CMS-PAS-BPH-21-006**

**CMS Preliminary**

$\sqrt{s} = 13$ TeV, $L = 140$ fb$^{-1}$

- Data
- Full PDF
- Combinatorial bkg
- Peaking bkg

**SM Prediction**


**CMS**

JHEP 04 (2020) 188

0.65 $\pm$ 0.72

**CMS**

JHEP 04 (2020) 098

- ATLAS

JHEP 04 (2019) 098

- ATLAS+CMS+LHCb

BPH-20-003

- CMS

JHEP 04 (2020) 188

ALTERNATIVE USING $B_s \rightarrow J/\psi \phi$:
Beyond $\mu\mu$: other leptonic $b$ decays

Phenomenologically complementary but in many cases far more experimentally challenging.
LHC, ultimate charm factory: $D^0 \rightarrow \mu\mu$

Extremely challenging due to overwhelming backgrounds e.g. $D^0 \rightarrow \pi\pi$. Stringent validation of LHCb’s muon identification!

$\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) < 2.94 \times 10^{-9}$ @ 90 (95)% CL

Most stringent limit on charm FCNC transitions to date with full legacy LHCb Run 1+2 dataset!
Evidence of the decay and good agreement with the SM. A tremendous achievement for NA62!

A future observation of $K^0 \rightarrow \pi^0 \nu \nu$ opens a fifth way to constrain the apex of the CKM Unitarity Triangle.
Angular tests in $b\to s\mu\mu$ decays

Rich laboratory for SM tests: the angular structure of these decays leads to many phenomenologically complementary observables.

A clear pattern of deviations from the SM has been observed in the last years, however there is ongoing debate over its cause (e.g. charm loops).

Recent experimental progress

Impressive progress towards the legacy Run 1+2 results across LHC collaborations, and eagerly awaiting Belle 2!
Lepton universality tests in $b \rightarrow s l l$ decays

Theoretically pristine observables!

Even the percent level “theory” uncertainties we quote are driven by modelling of radiative effects in electron reconstruction rather than any QCD effects.

Experimentally challenging because of electron reconstruction and resolution.

$b \rightarrow s \tau \tau$ even more so due to missing energy

Effective LHCb legacy Run 1+2 statistical sensitivity to e-$\mu$ lepton universality in branching ratios is $\sim$2-3%
LHCb is focused on completing a combined analysis of $R_K$ & $R_{K^*}$ with the Run 1+2 legacy dataset. This work has led to a deeper understanding of systematics which will be reflected in the final result. While $R_K+R_{K^*}$ gives bulk of sensitivity, tests in $B^0\to \phi\pi\pi$, $K\pi\pi\pi$, and $K\pi\pi$ at high $K\pi$ mass also progressing. 

Exp status of $b\to s\mu\mu$ LU tests

|----------|-----------------|----------|-----------------|

Precision dominated by LHCb, Belle 2 will be able to independently verify with ~10ab$^{-1}$. Will be interesting to see the eventual impact of the parked CMS dataset.

Credit for script: Sebastian Schmitt
Signal from maximum likelihood fit in bins of $p_T(\gamma_{1D43E} + \gamma_{uni0305})$ and BDT output

Branching fraction $BF(\gamma_{uni2192} \to \gamma_{uniD3D}/uniD713 \gamma_{uni2192})$

$- \text{Corresponding upper limit @ 90\% CL } BF(\gamma_{uni2192} \to \gamma_{uniD3D}/uniD713 \gamma_{uni2192})$

Inclusive method offers 20\%—350\% sensitivity improvement over previous approaches ($1.9^{+1.6}_{-1.5} \times 10^{-5} < 4.1 \times 10^{-5}$)

Search for $(\gamma_{uni2192})B(\gamma_{uniK} \to \gamma_{uniK} \bar{\gamma}_{uni03BD} \bar{\gamma}_{uni03BD})$

Complementary progress from Belle II

Belle II measurement of $(\gamma_{uni2192})B_{\gamma_{uniJ}/uni03C8}$(/uni2192/e+/e−, /uniD707+/uniD707−)$\times 189 \text{ fb}^{-1}$

Not an EW penguin process but a control channel for $(\gamma_{uni2192})B_{\gamma_{uniJ}/uni03C8}$(/uni2192/e+/e−, /uniD707+/uniD707−),

$\Rightarrow$ Validate $(\gamma_{uni2192})B_{\gamma_{uniJ}/uni03C8}$(/uni2192/e+/e−, /uniD707+/uniD707−) measurement, lepton identification

Reconstruct $(\gamma_{uni2192})B_{\gamma_{uniJ}/uni03D3D}/uniD713 \gamma_{uni2192}$ and $(\gamma_{uni2192})B_{\gamma_{uniJ}/uni03D3D}/uniD713 \gamma_{uni2192}$

Signal yield extracted from the fit of $M_{bc}$ and $M_{bc}E^8$

Lepton identification systematic uncertainty improved wrt Belle

$R_{\gamma_{uniK}^+}(J/\psi) = 1.009 \pm 0.022 \pm 0.008$  
$R_{\gamma_{uniK}^0}(J/\psi) = 1.042 \pm 0.042 \pm 0.008$

NEW! Lepton identification systematic uncertainty improved wrt Belle

$R_{\gamma_{uniK}^+}(J/\psi) = 0.994 \pm 0.011 \pm 0.010$  
$R_{\gamma_{uniK}^0}(J/\psi) = 0.993 \pm 0.015 \pm 0.010$

Belle II (Preliminary)

$\int L dt = 189 \text{ fb}^{-1}$

$B^0 \to K^0_{\gamma_{uniD3D}} J/\psi(e^+ e^-)$

Data

Signal

Background

Fit

PRL 127, 181802

Eldar Ganiev @ ICHEP 2022

NEW @ ICHEP 2022
Tests with radiative decays

Phenomenologically complementary tests with $b \to s$ penguins which probe a different set of operators to the leptonic modes.

Rich complementarity between LHCb’s statistical power & unique reach for baryon decays and Belle II’s clean environment & unique reach for inclusive decays.
LU tests in $b \rightarrow c \tau \nu / b \rightarrow c(\mu, e)\nu$ decays

Sadly no “headline” new results in this 2D plane for ICHEP 2022…

See Robin’s and Admir’s talks for connections of anomaly models to high-PT searches!
Almost fully inclusive test of electron-muon lepton universality in $b \rightarrow c \ell \nu$ transitions

Paves the way for the first such inclusive test of tau-muon and tau-electron universality

Powerful demonstration of complementary capabilities of Belle II in semileptonic decays

\[
R(X_e/\mu)_{p_T > 1.3\text{GeV}} = 1.033 \pm 0.010^{\text{stat}} \pm 0.020^{\text{syst}}
\]
Direct LFV/LNV/BNV searches

LFV/LNV go naturally together with LUV — most models which explain the LUV anomalies predict LFV/LNV effects, often near current reach!

See Toshinori’s talk for an overview of charged LFV experiments!
Many new or improved limits are being set in last years: probing $10^{-5}$ to $10^{-9}$ in beauty decays (worse limits when $\tau$ leptons are involved in the decay), $10^{-6}$ to $10^{-8}$ in charm decays, $10^{-10}$ to $10^{-11}$ in strange decays.
The Future Is Now!

Towards the 2030s
Exploring the next decades of flavour

Large Hadron Collider (LHC)
- Run 1: 7 TeV -- 8 TeV
- Run 2: 13 TeV
- Run 3: 13.6 TeV
- LS1: 9 fb⁻¹
- LS2: 190 fb⁻¹
- LS3: 35 fb⁻¹
- LS4: 450 fb⁻¹
- LS5: 300 fb⁻¹
- LS6: 3000 fb⁻¹

High Luminosity LHC (HL-LHC)
- Run 1: 14 TeV
- Run 2: 300 fb⁻¹
- Run 3: 3000 fb⁻¹

SuperKEKB
- Belle II: 400 fb⁻¹
- LS1: 7 ab⁻¹
- LS2: 50 ab⁻¹

BESIII
- 3 fb⁻¹ @ √s = 3.773 GeV
- 3 fb⁻¹ @ √s = 4.178 GeV
- 3 fb⁻¹ @ √s = 4.64 GeV

STCF
- 1 ab⁻¹ @ √s = 3.773 GeV

FCC-ee
- Upgrade I
- Upgrade II
- GPD

Numbers are indicative, for official projections from collaborations see next slides.

Taken from Archilli & Altmannshofer (2206.11331)
Latest Belle II and LHCb plans

Belle II reaches 50 ab\(^{-1}\) at around the same time as LHCb’s second upgrade is scheduled to start datataking.
Key LHCb/Belle II sensitivity projections

### Belle II (Upgrade snowmass whitepaper)

<table>
<thead>
<tr>
<th>Observable</th>
<th>2022</th>
<th>Belle-II, BaBar</th>
<th>Belle-II, 5 ab(^{-1})</th>
<th>Belle-II, 50 ab(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sin 2\beta/\phi_1)</td>
<td>0.03</td>
<td>0.012</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>(\gamma/\phi_3) (Belle+BelleII)</td>
<td>11°</td>
<td>4.7°</td>
<td>1.5°</td>
<td></td>
</tr>
<tr>
<td>(\alpha/\phi_2) (WA)</td>
<td>4°</td>
<td>2°</td>
<td>0.6°</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>) (Exclusive)</td>
<td>4.5%</td>
<td>2%</td>
</tr>
<tr>
<td>(S_{CP}(B \to \eta K^0_S))</td>
<td>0.08</td>
<td>0.03</td>
<td>0.015</td>
<td></td>
</tr>
<tr>
<td>(A_{CP}(B \to \pi^0 K^0_S))</td>
<td>0.15</td>
<td>0.07</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>(S_{CP}(B \to K^{*0}\gamma))</td>
<td>0.32</td>
<td>0.11</td>
<td>0.085</td>
<td></td>
</tr>
<tr>
<td>(R(B \to K^\pm\ell^\pm\ell^-))</td>
<td>0.26</td>
<td>0.09</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>(R(B \to D^\pm\tau\nu))</td>
<td>0.018</td>
<td>0.009</td>
<td>0.0045</td>
<td></td>
</tr>
<tr>
<td>(R(B \to D\tau\nu))</td>
<td>0.034</td>
<td>0.016</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>(B(B \to \tau\nu))</td>
<td>24%</td>
<td>9%</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>(B(B \to K^{*}\nu\bar{\nu}))</td>
<td>—</td>
<td>25%</td>
<td>9%</td>
<td></td>
</tr>
</tbody>
</table>

| \(\mathcal{B}(\tau \to \mu\gamma)\) UL | \(42 \times 10^{-9}\) | \(22 \times 10^{-9}\) | \(6.9 \times 10^{-9}\) |
| \(\mathcal{B}(\tau \to \mu\mu\tau)\) UL | \(21 \times 10^{-9}\) | \(3.6 \times 10^{-9}\) | \(0.36 \times 10^{-9}\) |

### LHCb and upgrades (Framework TDR)

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current LHCb (up to 9 fb(^{-1}))</th>
<th>Upgrade I (23 fb(^{-1}))</th>
<th>Upgrade II (50 fb(^{-1}))</th>
<th>Upgrade III (300 fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CKM tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\gamma (B \to DK, etc.))</td>
<td>4°</td>
<td>1.5°</td>
<td>1°</td>
<td>0.35°</td>
</tr>
<tr>
<td>(\phi_1 (B^0 \to J/\psi\phi))</td>
<td>32 mrad</td>
<td>14 mrad</td>
<td>10 mrad</td>
<td>4 mrad</td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
<td>(A^0_s \to p\mu^-\bar{\nu}_\mu, etc.))</td>
</tr>
<tr>
<td>(a^0_s (B^0 \to D^{\pm}\mu^\pm\nu_\mu))</td>
<td>(36 \times 10^{-4})</td>
<td>(8 \times 10^{-4})</td>
<td>(5 \times 10^{-4})</td>
<td>(2 \times 10^{-4})</td>
</tr>
<tr>
<td>(a^+<em>{1s} (B^0 \to D_s^{\pm}\mu^\pm\nu</em>\mu))</td>
<td>(33 \times 10^{-4})</td>
<td>(10 \times 10^{-4})</td>
<td>(7 \times 10^{-4})</td>
<td>(3 \times 10^{-4})</td>
</tr>
</tbody>
</table>

**Charm**

- \(\Delta A_{CP} (D^0 \to K^+K^-, \pi^+\pi^-)\) | \(29 \times 10^{-5}\) | \(13 \times 10^{-5}\) | \(8 \times 10^{-5}\) | \(3.3 \times 10^{-5}\) |
- \(A_T (D^0 \to K^+K^-, \pi^+\pi^-)\) | \(11 \times 10^{-5}\) | \(5 \times 10^{-5}\) | \(3.2 \times 10^{-5}\) | \(1.2 \times 10^{-5}\) |
- \(\Delta x (D^0 \to K^0_{\pi^+}\pi^-)\) | \(18 \times 10^{-5}\) | \(6.3 \times 10^{-5}\) | \(4.1 \times 10^{-5}\) | \(1.6 \times 10^{-5}\) |

**Rare Decays**

- \(\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)\) | 69% | 41% | 27% | 11% |
- \(\mathcal{S}_{\mu\mu} (B^0_s \to \mu^+\mu^-)\) | — | — | — | 0.2 |
- \(A_T^{(2)} (B^0 \to K^{0}\mu^+\mu^-)\) | 0.10 | 0.060 | 0.043 | 0.016 |
- \(A_T^{(3)} (B^0 \to K^{0}\mu^+\mu^-)\) | 0.10 | 0.060 | 0.043 | 0.016 |
- \(A_{T\gamma} (B^0 \to K^{+}\mu^-\gamma)\) | \(+0.41\) | \(+0.35\) | \(+0.48\) | \(+0.35\) |
- \(S_{\gamma\gamma} (B^0 \to K^{+}\mu^-\gamma)\) | \(+0.71\) | \(+0.66\) | \(+0.76\) | \(+0.76\) |
- \(\alpha_{\gamma} (A^0_s \to \tau\gamma)\) | \(-0.29\) | \(-0.24\) | \(-0.28\) | \(-0.28\) |

**Lepton Universality Tests**

- \(R_K (B^+ \to K^+\mu^+\ell^-)\) | 0.044 | 0.025 | 0.017 | 0.007 |
- \(R_{K^+} (B^0 \to K^+\ell^+\ell^-)\) | 0.12 | 0.034 | 0.022 | 0.009 |
- \(R(D^+) (B^0 \to D^{*-}\ell^+\nu_\ell)\) | 0.026 | 0.007 | 0.005 | 0.002 |

Vital to underline that LHCb and Belle II primarily complement each other! They will also check each other across key observables — rare processes, spectroscopy & CKM metrology. LHCb’s unique reach in charm reminds that LHC is the biggest ever charm factory — essential to exploit it.
CKM metrology: today

Fig. 21: Constraints on the unitarity triangle from the CKMfitter global analysis: global fit (top), tree only (center), loop only (bottom), for Phase 1 (left) and Phase 2 (right).

Fig. 22: Constraints on the unitarity triangle for the $B_s$ meson from the CKMfitter global analysis for Phase 1 (left) and Phase 2 (right).
A permille understanding of the Unitarity triangle apex is fundamental and worth the next decades of our lives to achieve!
Complementarity with HL-LHC GPDs

HL-LHC Yellow Report

Can independently measure multiple key observables — vital that HL-LHC GPD triggers give full impact
Diversity is the strength of flavour

Flavour physics has a vibrant present and a future worth our efforts! Underpinned by a rich phenomenology and the complementarity of flavour experiments and facilities.

In addition to the flavour factories (LHCb and Belle II) and the LHC’s general purpose detectors, dedicated experiments and facilities like BESIII, NA62, KOTO, will be crucial in mapping the fundamental properties of how quarks mix and combine for the next generations!

See Admir’s talk for the crucial role theory will play in this effort.

FCC-ee may carry the torch into the second half of this century, with complementary insights into the flavourful nature of fundamental particles from the Z pole. I hope to see many of you along this road!
Backup
Time-dependent analyses of $B_s$ decays

$b\rightarrow cc$ and $b\rightarrow ss$ processes provide many complementary null tests of the Standard Model!

LHCb, ATLAS, CMS can all make these measurements — critical for long-term confidence in results.

LHCb combined

$17.7683 \pm 0.0051\text{ (stat)} \pm 0.0032\text{ (syst)} \text{ ps}^{-1}$
Exploiting synergies of beauty & charm

Full power comes from global fits to all sectors & experiments — an organisational and scientific challenge!
The quest for $V_{ub}$ & $V_{cb}$

Measurements by Belle shed light on $V_{ub}$ & $V_{cb}$

Inclusive-exclusive tensions remain in $V_{cb}$, are reduced in $V_{ub}$

Tension in $V_{ub}$ from 2-3 sigma depending on inputs

$V_{cb}$ remains at 3 sigma, further experimental input must be matched by progress in theory/lattice calculations

Discrepancy in $V_{ub}/V_{cb}$ from $B \to K\mu\nu$ at low/high $q^2$ needs to be understood better, implication for calculation of form-factors
BESIII results impact on $V_{cs}$

Comparison of $|V_{cs}|^2$

From LQCD calculations (FLAVG19)

$$f_{Ds}^2 = 249.9 \pm 0.5$$

Combined $\rightarrow 0.979 \pm 0.007 \pm 0.008$

1% precision!
One slide show of di-J/$\psi$ 4-quark states

Credit: Giacomo Graziani
Time-dependent analyses of $B_s$ decays

Important to resolve the ongoing tension in measurements of the $B_s$ lifetime and width difference of the light and heavy eigenstates!
Must improve all measurements: not only $\phi_s$ but also individual lifetimes.
Cross-experiment work on common experimental assumptions seems vital.
Latest 4-quark states from BESIII

Too many results to truly do them justice — a cornerstone of the BESIII programme

Pick here the characterisation of $Y(4230)$ and $Y(4320)$ states in $J/\psi\pi\pi$ decays

\[
\begin{align*}
M_{Y(4230)} &= 4221.4 \pm 1.5 \pm 2.0 \text{ MeV}/c^2 \\
\Gamma_{Y(4230)} &= 41.8 \pm 2.9 \pm 2.7 \text{MeV}
\end{align*}
\]

\[
\begin{align*}
M_{Y(4320)} &= 4298 \pm 12 \pm 26 \text{ MeV}/c^2 \\
\Gamma_{Y(4320)} &= 127 \pm 17 \pm 10 \text{ MeV}
\end{align*}
\]

$Y(4230)$

$Y(4320)$

$\psi(4415)$?

$Y(4500)$?
LU tests in LHCb, challenges