Quarks Flavour Physics

A word of introduction

Flavour physics:

- Quantum numbers of elementary particles: I, C, S, T, B'...
- Global symmetry of strong interactions; broken in electroweak

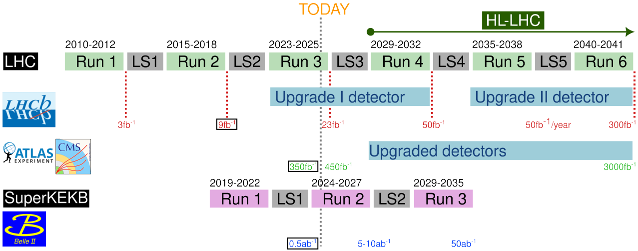
Open questions:

- Why are there 3 generations of quarks? Do they mirror leptons?
- Why do they have such specific masses and mixing angles?
- What explains the level of CP violation?

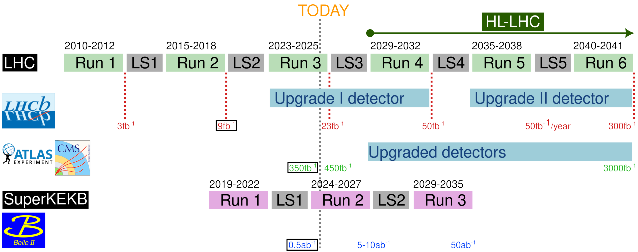
At the (HL-)LHC

- Focus on heavy flavour: big themes CP violation and rare decays
- Complements direct searches for New Physics at energy frontier
- Indirect searches at high precision probe higher energy scales

A flavour programme at the LHC



A flavour programme at the LHC



Major UK presence. Take LHCb:

- 11 institutes - 200 authors (15% of total)
  - 50 seniors, 70 PDRAs, 70 PhD, 30 eng. + tech.
- Presence in leadership roles from management to physics to operations to detector projects
- Backing of UKRI infrastructure fund: $\sim$ £50M for LHCb at HL-LHC

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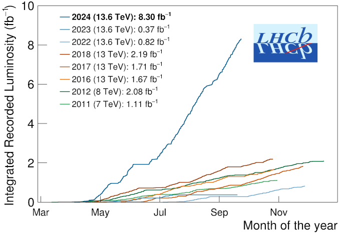
LHCb: From Upgrade 1 to Upgrade 2



- Run 3 harvest proceeding at pace. UT and third GPU included
- Designed to accumulate 50 fb^{-1}; will do by Run 4
- U2 targets 300 fb^{-1}- after 6 years, LHCb reaches LHC limits at P8

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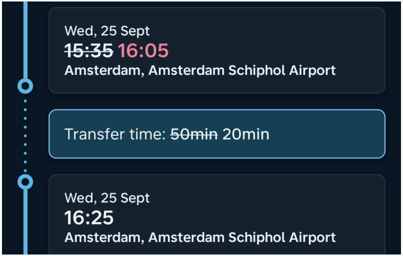
Physics opportunities for flavour at HL-LHC

A whistlestop tour of ~~Schipol~~ flavour physics



- Comprehensive review: ‘Physics Case for an LHCb Upgrade 2’

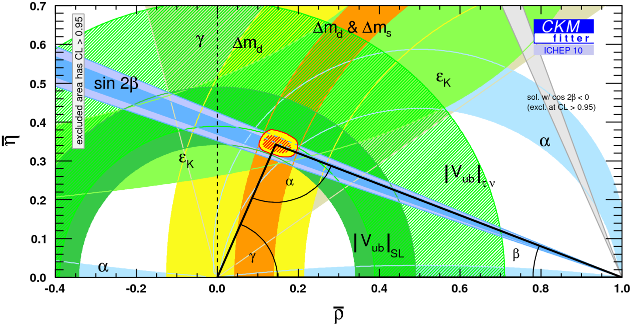
HL-LHC physics case is unique on many meaningful timescales:

- LHCb: wide range of results at better precision than any current or foreseen project
- ATLAS and CMS: competitive in a number of key areas

Unitarity Triangles

Express unitarity of CKM matrix; New Physics can break them open

A loosely over-constrained picture before the LHC:



Changes driven by

- Tree-level constraints (γ, $|V_{ub}|$)
- Loop-level constraints ($sin(2\beta)$, Δm_d, Δm_s)

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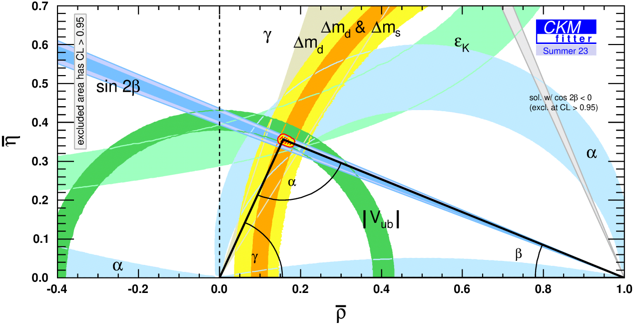
Unitarity Triangles

Express unitarity of CKM matrix; New Physics can break them open

Dramatic increase in precision up to latest CKMfitter averages:



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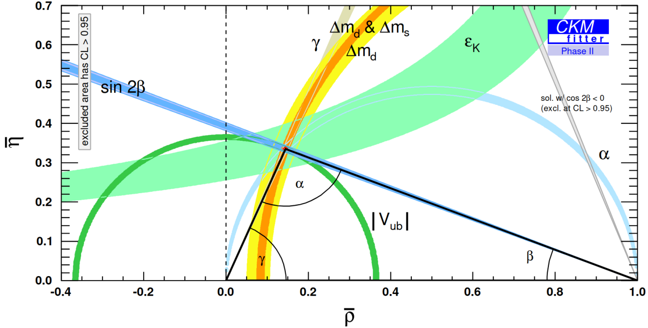
Unitarity Triangles

Express unitarity of CKM matrix; New Physics can break them open

Room for non-unitarity will shrink radically by Run 6:

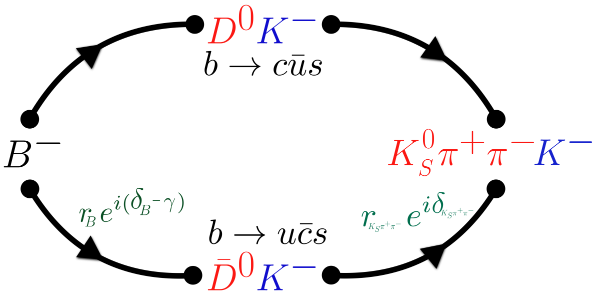


Changes driven by

- Tree-level constraints (γ, $|V_{ub}|$)
- Loop-level constraints ($sin(2\beta)$, Δm_d, Δm_s)

Unitarity triangle: angle γ

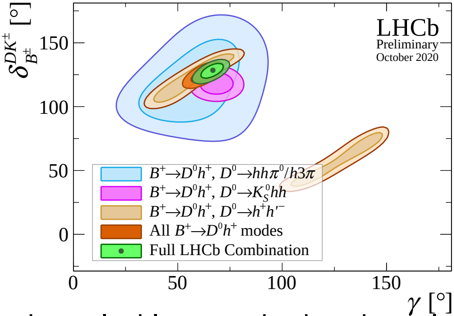
- Time-integrated measurement of $B^- \longrightarrow DK^-$ decays; direct CPV
- Tree-level process; QCD controlled by data



- Relies on external inputs to control QCD in charm

Unitarity triangle: angle γ

- One decay dominates at Belle II; multiplicity of modes at LHCb



- Compare modes: valuable cross-check and tree-level NP probe
- Systematic uncertainties comparable to statistical

- Today: 2.8° precision (0.7° since 2022!)
- Ensemble reaches 1° at end of U1
- Individual modes reach 1° at end of U2

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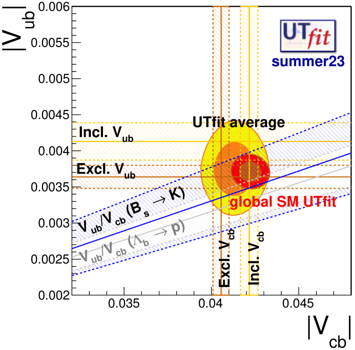
Unitarity triangle: sides

- Historical tension incl. vs excl. $V_{\{u,c\}b}$ diminished



- Crucial inputs from lattice QCD; complementary role for Belle II
- LHCb uses $\Lambda_b \to p\mu^- \overline{\nu_\mu}$ and $B^0_s \to K^- \mu \nu_\mu$
  - Unparalleled samples of Λ_b and B^0_s will be available at the HL-LHC

- $|V_{ub}|/|V_{cb}|$ reaches 1% precision at HL-LHC

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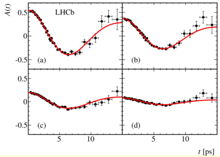
Indirect CPV: in B mixing

- NP can enhance CPV in B mixing; very small in SM
- Theoretically clean null test
- Measure in abundant semileptonic decays (no CPV in decay)

$$A_{\rm sl}^q(t) \equiv \frac{N-\bar{N}}{N+\bar{N}} = \frac{a_{\rm sl}^q}{2} - \left[a_p + \frac{a_{\rm sl}^q}{2}\right]\cdot\left[\frac{\cos\Delta M_q t}{\cosh\Delta\Gamma_q t/2}\right]$$

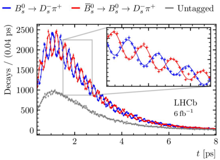
- Can control effects of (very different) B^0 and B^0_s mixing

Eur. Phys. J. C76 (2016) 412

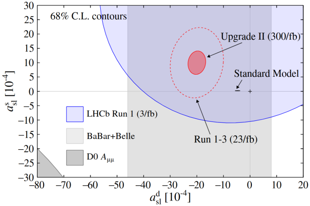


Δm_d = 0.5050 ± 0.0021 ± 0.0010 ps^{-1}

Nature Phys. 18 (2022) 1



Δm_s = 17.7683 ± 0.0051 ± 0.0032 ps^{-1}



- a^d_{SL} (a^s_{SL}) precision from 0.2 (0.3) % now to 0.02 (0.03) % at HL-LHC

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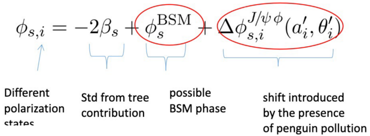
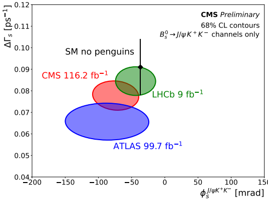
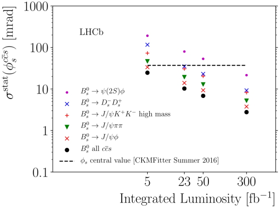
Indirect CPV: interference of B mixing and decay

- Flagship $B_s^0 \to J/\psi\,\phi$: expect SM phase very small ($\sim -40\,\mathrm{mrad}$)







- Powerful probe $B_s^0 \to \phi\phi$: sensitivity now nearing $100\,\mathrm{mrad}$
- U-spin relates $B_s^0 \to D_s^+ D_s^-$ & $B^0 \to D^+ D^-$: extra tests

- $\sigma(\phi_s)$ from $B_s^0 \to J/\psi\,\phi$ at $23\,\mathrm{mrad}$ (LHCb), $24\,\mathrm{mrad}$ (CMS), $42\,\mathrm{mrad}$ (ATLAS)
- Reach $3\,\mathrm{mrad}$ sensitivity at HL-LHC

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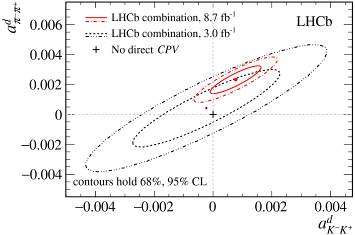
Direct CP violation in charm

- Complementary physics to phenomena of down-type quarks
- Dir. CPV in decay observed in 2019; analysis of 70M $D^0 \to K^+K^-, \pi^+\pi^-$ decays
  - $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$
- Is $\Delta A_{CP} = -15 \pm 3 \times 10^{-4}$ compatible with SM?



- Beginning to separate KK and $\pi\pi$ contributions: few $\times 10^{-4}$

- At end of Run 4 asymmetries reach 10^{-4}
- Only LHCb @ 300 fb^{-1} will reach 10^{-5} precision to understand if NP is at play here

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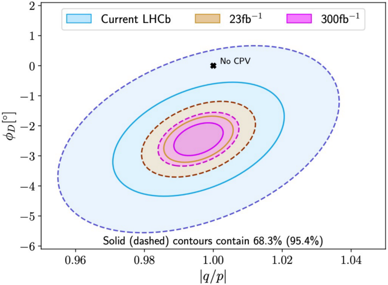
Indirect CP violation in charm

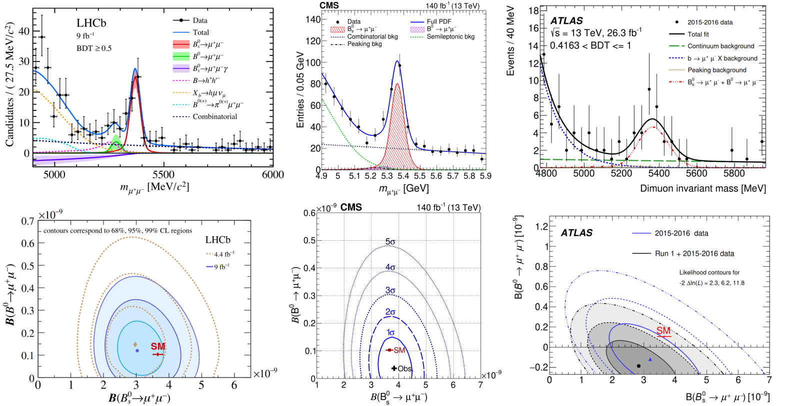
- HL-LHC the only chance to probe at SM level ($10^{-4} - 10^{-3}$)
- Diverse probes. External inputs from BES-III important
  - DCS $D^0 \to K^+\pi^-$ and $D^0 \to K^+\pi^-\pi^+\pi^-$ decays
  - $D^0 \to K^0_S\pi^+\pi^-$ decays via 'bin-flip' analysis: TD Dalitz
  - CS $D^0 \to K^+K^-, \pi^+\pi^-$ decays: billions at U2
- Evolution in the $D \to K\pi$ system:



- U2 precision across modes reaches down to $\sigma(|q/p|) \sim 0.002$ and $\sigma(\phi_D) \sim 0.1°$

Rare beauty

- $B^0_s \to \mu^+\mu^-$ loop- & helicity-suppressed. B^0 smaller by $\frac{|V_{td}|^2}{|V_{ts}|^2}$
- Observed by ATLAS, CMS, and LHCb. Powerful test of MFV



- At HL-LHC all experiments expect B^0_s BF at 2-5% level
- Expect SM prediction to improve with further lattice QCD advances

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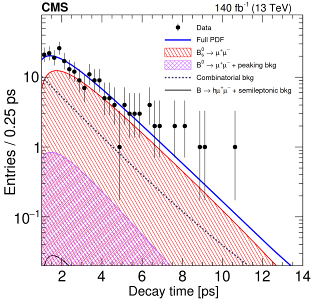
Rare beauty

- ATLAS, CMS, and LHCb all measure effective lifetime
  - complementary constraint: roles played by new scalars/pseudoscalars
- SM: heavy eigenstate $\rightarrow \mu^+\mu^-$; NP perturbs relationship to $\tau_{B_s^0}$



- For LHCb, HL-LHC reduces uncertainty on lifetime from 10% (now) to 2%
- 100 tagged $B_s^0 \rightarrow \mu^+\mu^-$ decays $\Rightarrow$ CP asymmetry measurement

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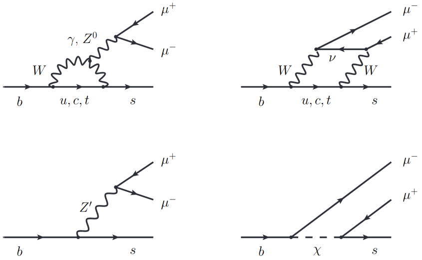
$b \to s\ell^+\ell^-$

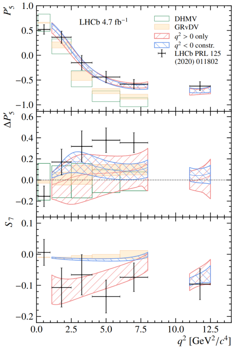
- FCNC suppressed in the SM. but wealth of NP openings
- Charm CPV reminds us: progress to discovery can follow a winding path

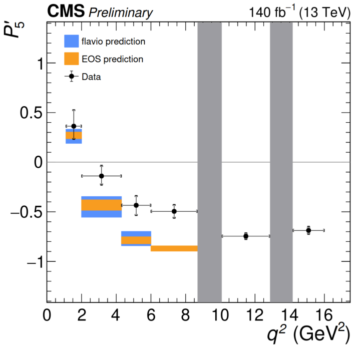


- Allowed NP contributions at $\mathcal{O}(1)$ in coupling to (axial)vector decay motivates greater precision

$b \to s\ell^+\ell^-$

- Tensions in observables dependent upon Wilson Coefficients of NP had neared 3σ in $B^0 \to K^*\mu^+\mu^-$
- Amplitude analysis of decay angles & $m(K^-\pi^+)^2$, $m(\mu^+\mu^-)^2$ disentangles long-distance effects: tensions reduced





- A consistent picture at CMS and LHCb

Dan Johnson

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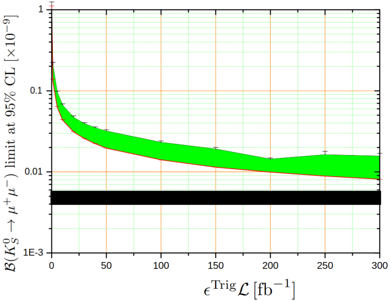
Rare strange

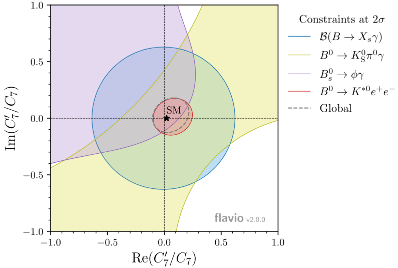
- Strongly suppressed $s \longrightarrow d$ FCNC transitions
- $K^0_S \longrightarrow \mu^+\mu^-$ long-range dominate. SM prediction $\sim 10^{-11}$
- Best limit comes from LHCb Run 1: $\mathscr{B} < 8 \times 10^{-10}$ at 90% CL



- U2 allows to reach close to the SM prediction; pick up the baton after HIKE cancellation
- Studies of rare hyperons also open up, benefitting from low-momentum proton ID proposed for LHCb U2

Radiative processes

- Photons emitted in $b \to s\gamma$ transitions are, in SM, LH, but many NP models introduce a significant RH component
- γ polarisation constrains RH currents
- Angle between e^+e^- and $K\pi$ decay planes in $B^0 \to K^{*0}e^+e^-$ at low-q^2 very sensitive to $b \to s\gamma$ photon helicity



- Uncertainties on the observables (transverse asymmetries) from 10% (now) to 2% in U2
- Unique sensitivity at LHCb to search for RH currents

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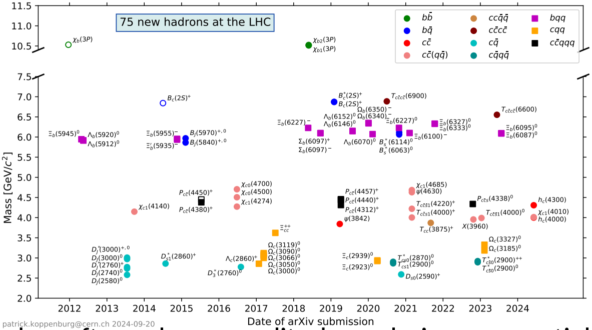
Beyond flavour: spectroscopy

- Discovery has been unrelentingly linear since Run 1



- Searches often rely on amplitude analysis; exponentially harder as statistics increase → involve theorists earlier
- Unknown unknowns. But clear targets with U2 statistics:
  - Properties of tetraquarks and pentaquarks
  - Searches for new pentaquarks (e.g. with strangeness in $\Lambda_b \rightarrow J/\psi \Lambda \phi$)
  - Doubly heavy baryons and precision charmonium

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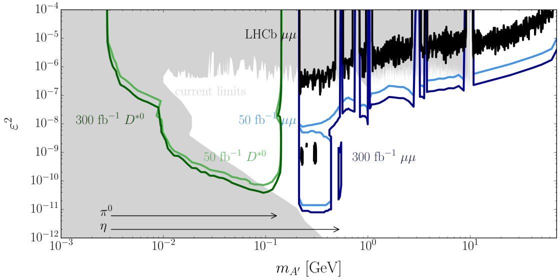
Beyond flavour: LLP searches

- LHCb made its mark through stringent $A' \rightarrow \mu^+\mu^-$ limits



- U2 will saturate geometrical limitations, fully exploring theoretically preferred parameter space
- Complementarity of proposed transverse LLP detectors (CODEX-b, MATHUSLA, ANUBIS)

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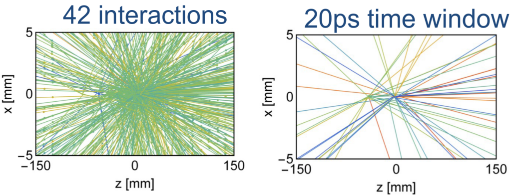
LHCb Upgrade 2: the challenge of pileup

A few highlights from the LHCb U2 FTDR Retaining U1 performance in U2 collisions from 2×10^{33} to 1×10^{34} requires a revolution: 3D → 4D: vertexing

- 50 ps per hit
- Pixel pitch $55\mu m$
- Extreme fluence $6 \times 10^{16} n_{eq}/cm^2$



UK groups leading sensor R&D, prototype 4D demonstrator, high-rate read-out technologies

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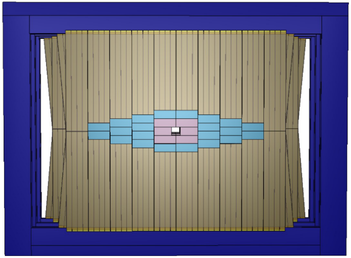
Detector innovation for flavour at HL-LHC

Innermost fibres of downstream SciFi reach EoL at Run 5.

Occupancies at HL-LHC exceed 10%

Replace with large-area silicon detector (MAPS): ‘Mighty Tracker’



- UK leadership from chip design & integration to simulation
- Activity of more than half UK LHCb groups

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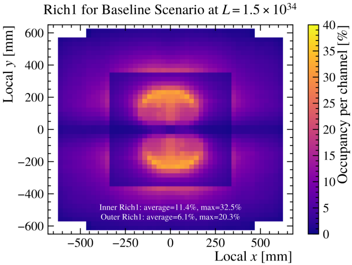
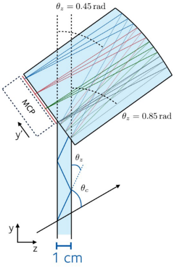
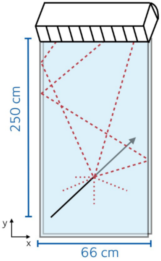
Detector innovation for flavour at HL-LHC

- UK leadership ab initio, dominating Ring Imaging Cherenkov detectors; continues into U2
- RICH: photon detectors with fast timing → 4D photons assigned to individual vertices
- TORCH: managing mis-ID backgrounds, including high-multiplicity, low-p final states requires new PID detectors







UK-initiated; UK-led

Conclusion

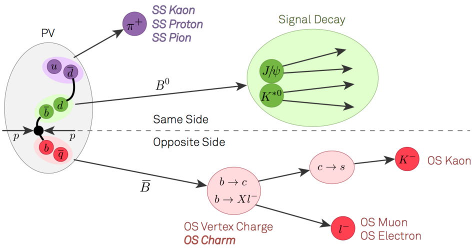
“Exploit the full physics potential of the LHC, including flavour”

- **The LHCb upgrade II is essential to fulfil that mandate**
- Wealth of physics possible sensitive to New Physics at energy scales far exceeding direct searches
- Many of the flagship analyses will remain statistically dominated
- ATLAS and CMS will play important roles; LHCb will dominate
- No competition is likely on the HL-LHC timescale

Backup content

Unitarity triangle: γ - other decays

- Many other decays provide γ sensitivity
  - Varying dependence upon other UT angles, e.g. tree-level $B_s^0 \to D_s^{\mp} K^{\pm}$: $2\beta_S - \gamma$
  - Introduction of U-spin assumptions & loop-exposure, e.g. $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$
- TD CPV measurement in $B_s^0 \to D_s^{\mp} K^{\pm}$ as an example:
  - Reaches 1° precision for γ at end of U2
  - Main systematics (B backgrounds, Δm_S input) scale with statistics into U2
  - Must maintain LHCb performance $U1 \to U2$ in vertex-association for flavour-tagging & decay-time determination



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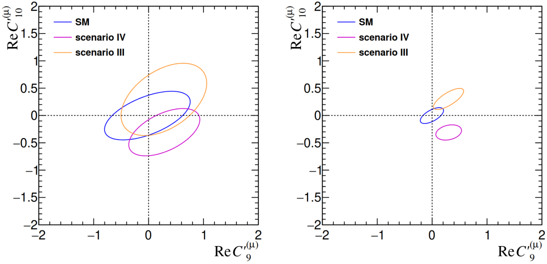
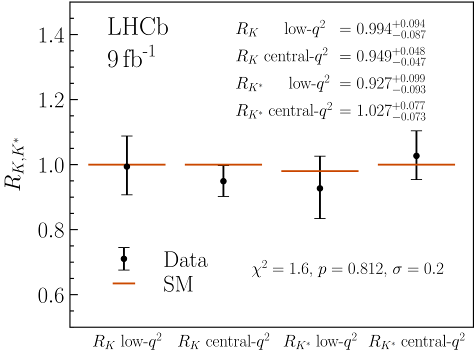
$b \to s\ell^+\ell^-$

- LHCb U2 physics case defined 4 scenarios depending on confirmation or reduction in tensions apparent in 2018.
- III and IV more compatible with recent results; U2 statistics and complementarity of decay modes will distinguish them:



Lepton universality in $b \to q\ell^+\ell^-$ decays

- Anomaly has receded... for now



- In U2 expect 46,000 $B^+ \to K^{*+}e^+e^-$ and 20,000 $B^0 \to Ke^+e^-$ decays; precision on R_{K,K^*} better than 1%
- U2 statistics open up complementary modes: $B^+ \to \pi^+\ell^+\ell^- \Rightarrow \sigma(R_\pi) \sim$ few %

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Rare charm

- Anomalies in b-hadrons underlines need for studies of FCNC in up-type quarks: key example $D^0 \to \mu^+\mu^-$
- In charm sector GIM suppression more effective than down-type (no decoupled heavy d-type quark)
- Short distance contributions 10^{-18}; long distance ($D^0 \to \gamma\gamma$ recomb.) 10^{-11}
- Currently $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ at 90% CL
- Will reach 2×10^{-10} at U2
- Up-type parallels to $b \to s\ell^+\ell^-$ approach SM precision at U2: