

Heavy Flavour Physics

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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:

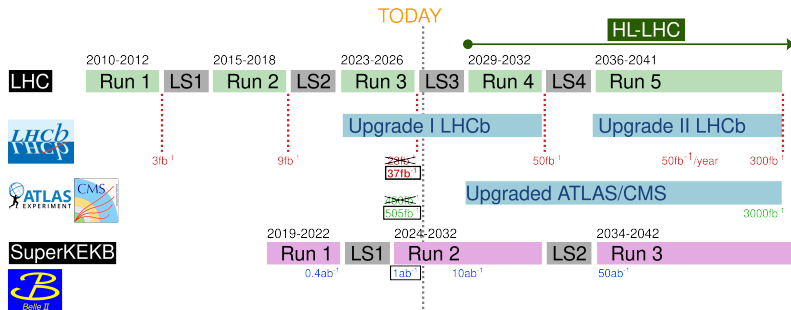
- Why are there 3 generations of quarks? Do they mirror leptons?
- Why do they have such specific masses and mixing angles?

At the (HL-)LHC

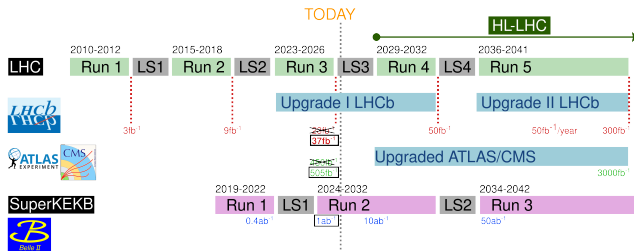
- Most NP enhances CPV; dedicated measurements essential
- Rare decays: NP effects can rival SM amplitudes
- Complements direct searches for New Physics at energy frontier
- Indirect searches at high precision probe higher energy scales



A flavour programme at the LHC and SuperKEKB



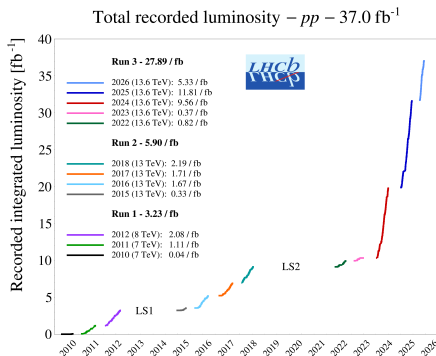
A flavour programme at the LHC and SuperKEKB



Major UK presence. Take LHCb:

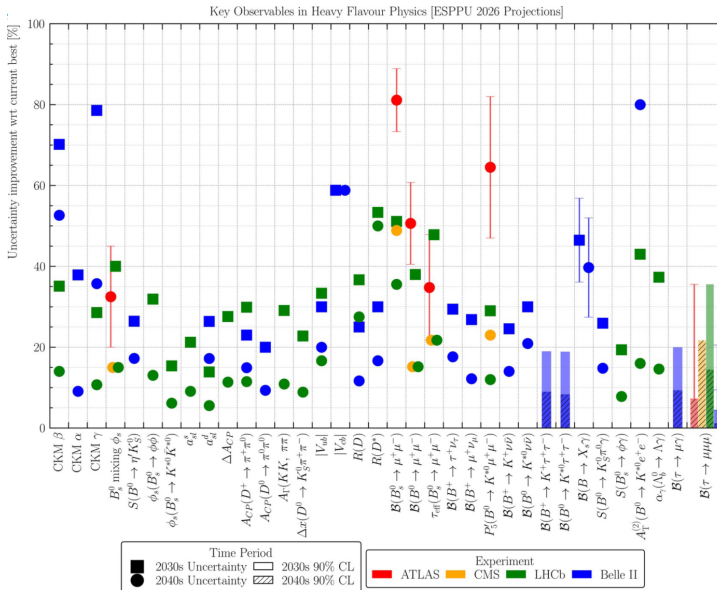
- 11 institutes - 206 authors (18% of total)
 - 50 seniors, 70 PDRAs, 70 PhD, 30 eng. + tech.
- Spokesperson, Operations Coordinator, deputy Physics Coordinator all UK (and many WG conveners/project leaders)
- 1 in 3 LHCb papers submitted 24-26 have a UK proponent

LHCb: From Upgrade 1 to Upgrade 2

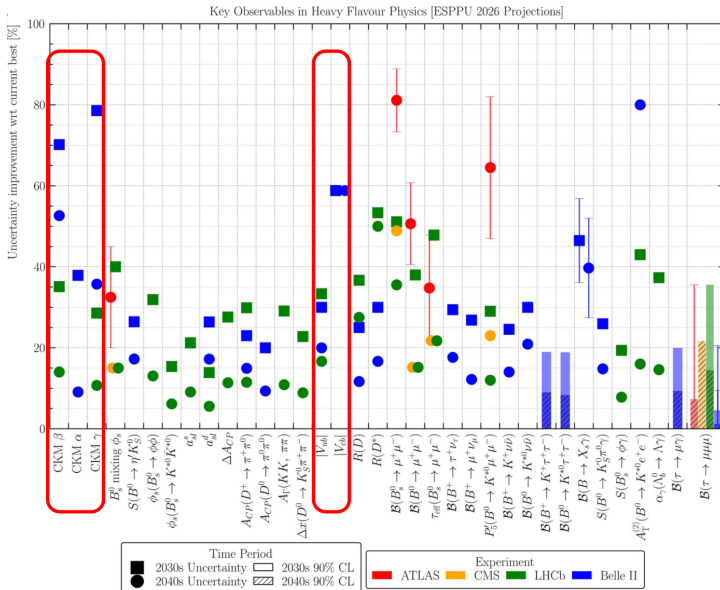


- LHCb Upgrade 1 (Run 3+4) designed to accumulate 50 fb^{-1} .
- 56% already at end of Run 3. Run 4 will deliver.
- U2 - 300 fb^{-1} . Only after 6 years LHCb does reach P8 limits.

Heavy Flavour: at end of LHC and SuperKEKB



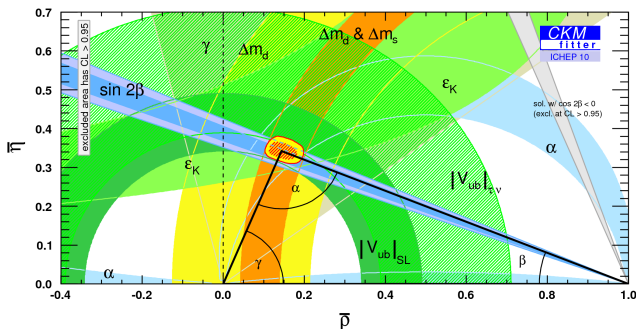
Unitarity triangle sides/angles



Unitarity Triangles

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

A loosely over-constrained picture **before the LHC**:

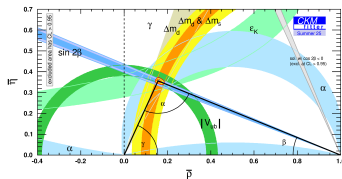
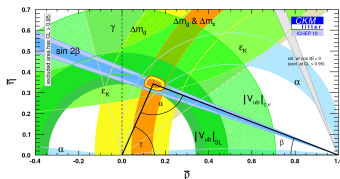


Changes driven by

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

Unitarity Triangles

Express unitarity of CKM matrix; New Physics can break them open
Dramatic increase in precision up to latest CKMfitter averages:

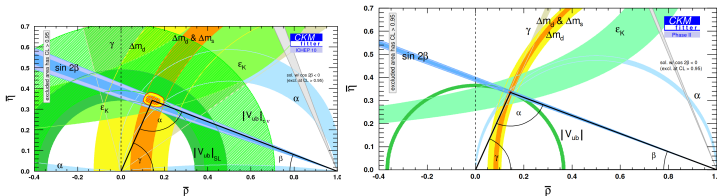


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- Tree-level constraints (γ , $|V_{ub}|$)
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Unitarity Triangles

Express unitarity of CKM matrix; New Physics can break them open
Room for non-unitarity will shrink radically by Run 5:

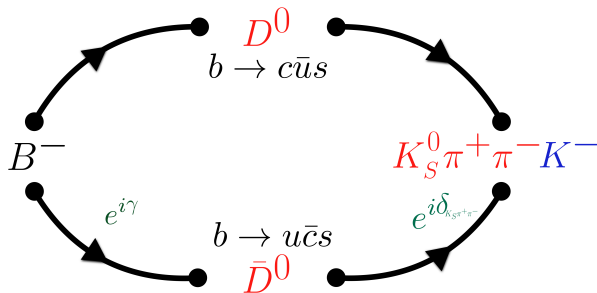


Changes driven by

- Tree-level constraints (γ , $|V_{ub}|$)
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Unitarity triangle: angle γ

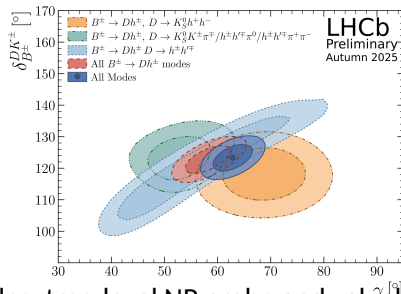
- Time-integrated measurement of $B^- \rightarrow DK^-$ decays; direct CPV
- Theoretically clean tree-level process; QCD controlled by data



- Relies on external inputs to control QCD in charm (crucial UK role in CLEO and BES-III)

Unitarity triangle: angle γ

- Standard candle in UT measurements
- One decay dominates at Belle II; multiplicity of modes at LHCb

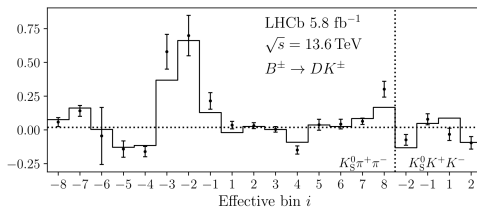
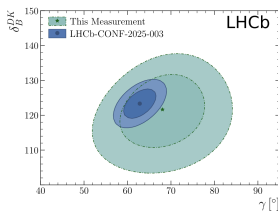


- Compare modes: tree-level NP probe and valuable cross-check
- Continues to be statistically limited

- Today: 2.6° precision (improved by 0.9° since 2022!) [LHCb-CONF-2025-003](#)
- Ensemble reaches 1° at end of U1
- Individual modes reach 1° at end of U2

Unitarity triangle: angle γ

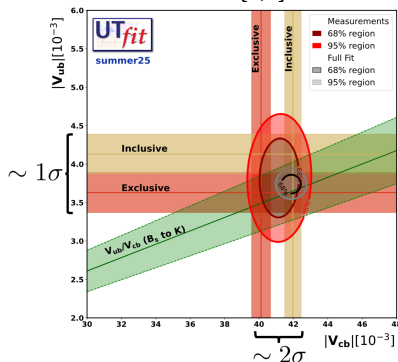
- Run 3 data and new approaches having an impact



- First γ measurement with Run 3: 4.7° precision ($\approx 40^\circ$ in Run 1!) 2605.03501

Unitarity triangle: sides

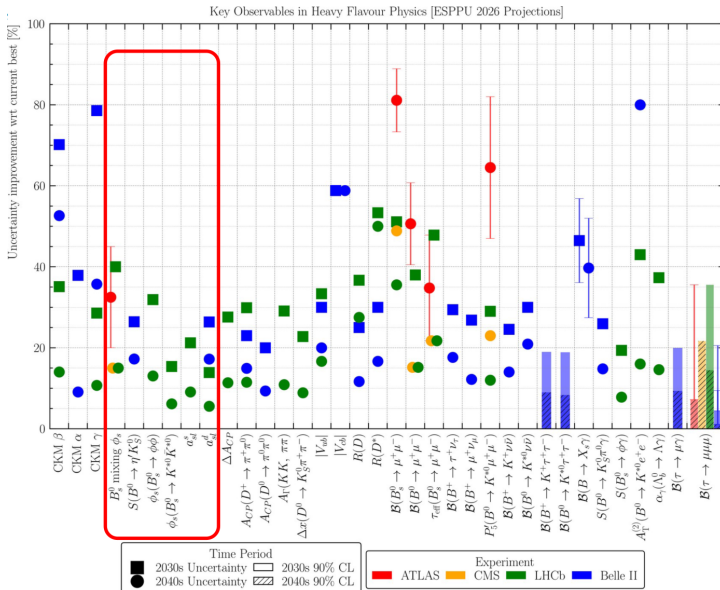
- Historical tension incl. vs excl. $V_{\{u,c\}b}$ **diminished**



- Crucial inputs from lattice; LHCb and Belle II lead
- LHCb uses $\Lambda_b \rightarrow p \mu^- \bar{\nu}_\mu$ and $B_s^0 \rightarrow K^- \mu^+ \nu_\mu$
 - Only** the HL-LHC will provide such large samples of Λ_b and B_s^0

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

CPV in mixing



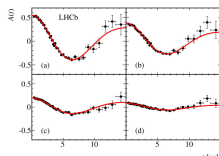
CPV in B mixing

- NP can enhance CPV in B mixing; very small in SM
- Theoretically clean null test; $\Lambda_{NP} > 100+ \text{ TeV}$
- Measure in abundant semileptonic decays (no CPV in decay)

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

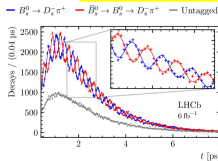
- Can control effects of (very different) B^0 and B_s^0 mixing

Eur. Phys. J. C76 (2016) 412

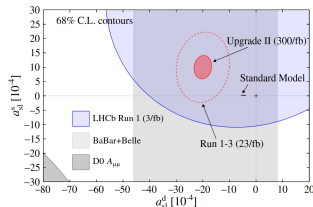


$$\Delta m_d = 0.5050 \pm 0.0021 \pm 0.0010 \text{ ps}^{-1}$$

Nature Phys. 18 (2022) 1



$$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032 \text{ ps}^{-1}$$



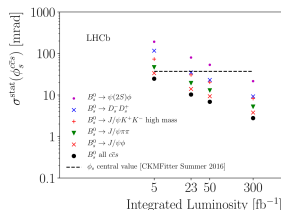
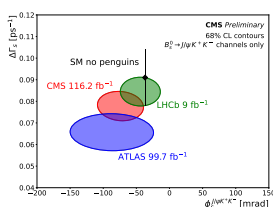
- $a_{\text{SL}}^d (a_{\text{SL}}^s)$ precision from 0.2 (0.3) % now to 0.02 (0.03) % at HL-LHC 1808.08865

CPV in interference of B mixing and decay

- Flagship $B_s^0 \rightarrow J/\psi \phi$: expect SM phase very small (~ -40 mrad)

$$\phi_{s,i} = \underbrace{-2\beta_s}_{\text{Different polarization states}} + \underbrace{\phi_s^{\text{BSM}}}_{\text{Std from tree contribution}} + \underbrace{\Delta\phi_{s,i}^{J/\psi\phi}(a'_i, \theta'_i)}_{\text{possible BSM phase}}$$

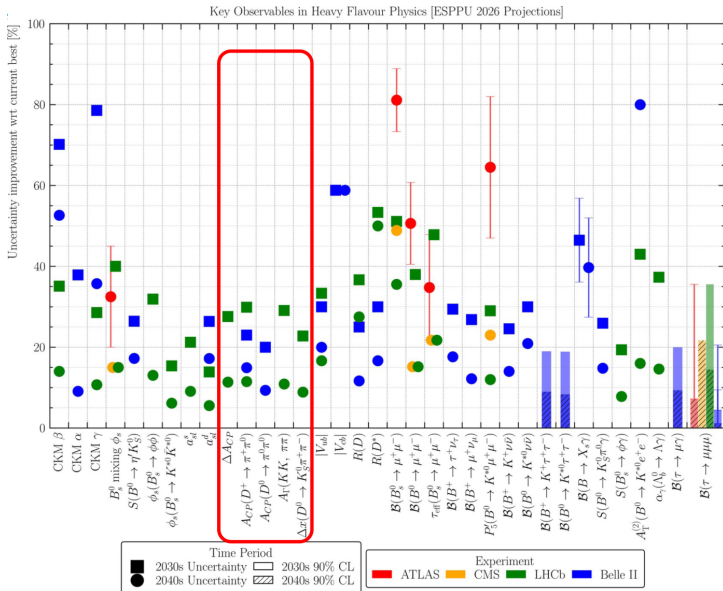
shift introduced by the presence of penguin pollution



- Powerful probe $B_s^0 \rightarrow \phi\phi, K^{*0}\bar{K}^{*0}$: sens. nearing 100 mrad
- $b \rightarrow ds\bar{s}$ & $b \rightarrow sd\bar{d}$: gluonic penguins. SM tension $> 4\sigma$ 2512.05102

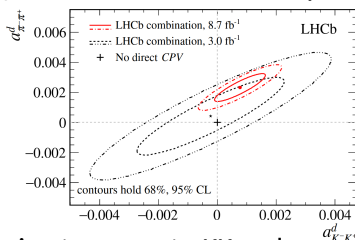
- $\sigma(\phi_s)$ from $B_s^0 \rightarrow J/\psi \phi$ at 23 mrad (LHCb), 24 mrad (CMS), 42 mrad (ATLAS)
- Reach 3 mrad sensitivity at HL-LHC 1808.08865

CPV in Charm



Direct CP violation in charm

- Complementary flavour probe to B physics; NP couplings in up-sector?
- Dir. CPV in decay observed in 2019; analysis of 70M $D^0 \rightarrow K^+ K^-, \pi^+ \pi^-$ decays: $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$
- Is $\Delta A_{CP} = -15 \pm 3 \times 10^{-4}$ compatible with SM?

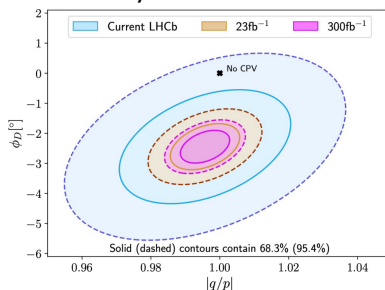


- Beginning to separate KK and $\pi\pi$ contributions: few $\times 10^{-4}$

- At end of Run 4 asymmetries reach 10^{-4} 1808.08865
- Only LHCb @ 300 fb⁻¹ will reach 10^{-5} precision to understand if NP is at play here

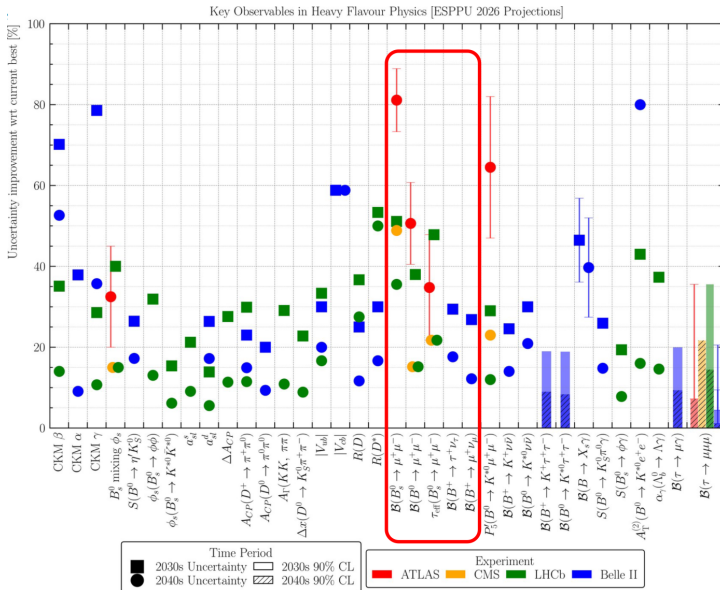
Indirect CP violation in charm

- HL-LHC: only chance to probe SM level ($10^{-4} - 10^{-3}$) 1808.08865
- Diverse probes. External inputs from BES-III important
 - DCS $D^0 \rightarrow K^+ \pi^-$ and $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$ decays
 - $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays via 'bin-flip' analysis: TD Dalitz
 - CS $D^0 \rightarrow K^+ K^-$, $\pi^+ \pi^-$ decays: billions at U2
- Evolution in the $D \rightarrow K\pi$ system:



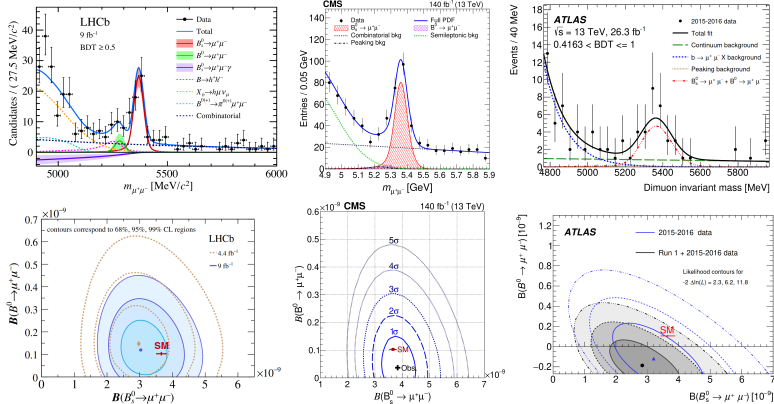
- U2 precision across modes reaches down to $\sigma(|q/p|) \sim 0.002$ and $\sigma(\phi_D) \sim 0.1^\circ$

Rare beauty



Rare beauty

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

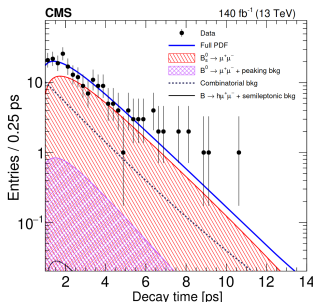


- At HL-LHC all experiments expect B_s^0 BF at 2-5% level
- Expect SM prediction to improve with further lattice QCD advances

Rare beauty

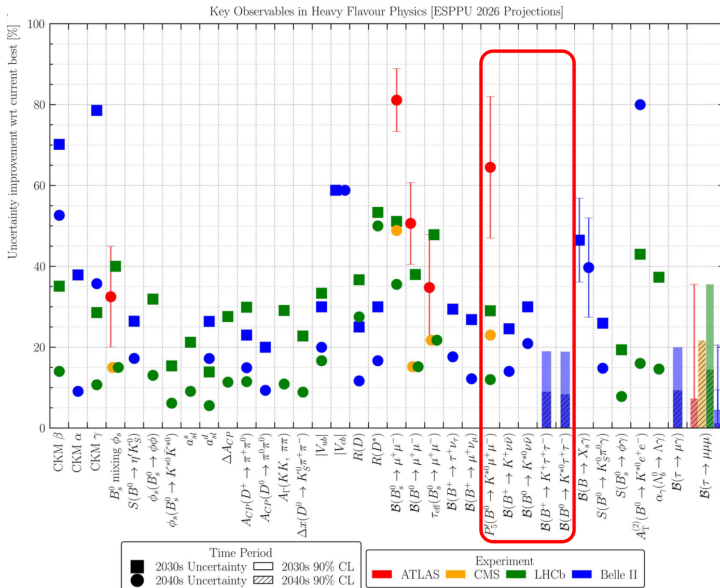
2108.09284 2212.10311 1910.12127

- 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 $\tau_{B_s^0}$



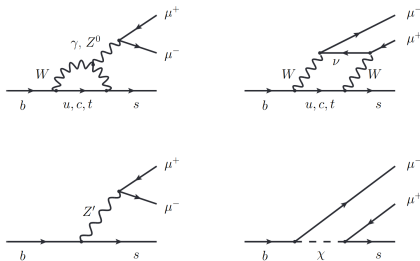
- For LHCb, Run 5 reduces uncertainty on lifetime from 10% (now) to 2%
- 100 tagged $B_s^0 \rightarrow \mu^+ \mu^-$ decays $\Rightarrow$ CP asymmetry measurement

$$b \rightarrow sl^+ l^-$$



$$b \rightarrow sl^+l^-$$

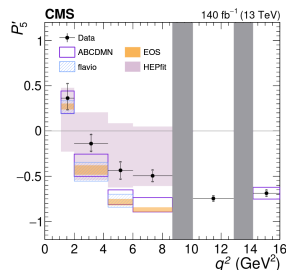
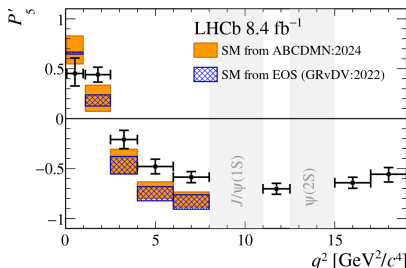
- FCNC suppressed in the SM. but wealth of NP openings



- Measurements now probe NP contributions at scale of 10s of TeV
- Current constraints still allow $\mathcal{O}(1)$ NP contributions to (axial)vector operators, motivating greater precision

$$b \rightarrow sl^+l^-$$

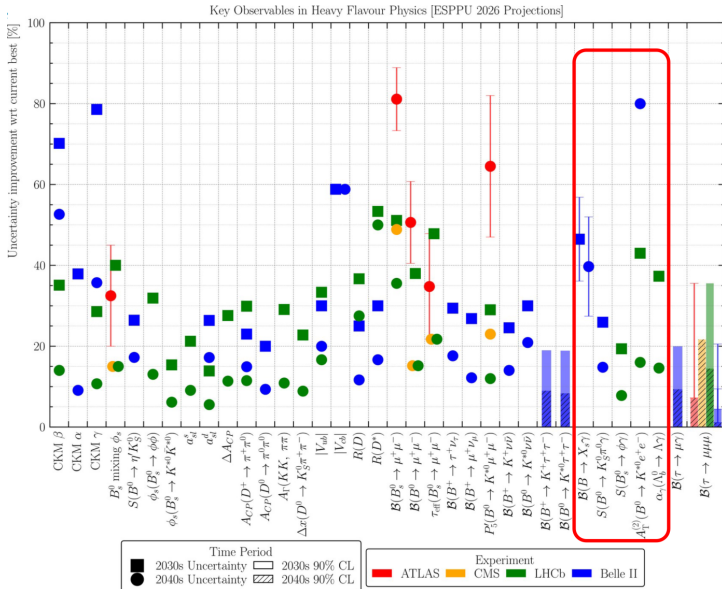
- Tensions in observables dependent upon NP Wilson Coefficients
- **Angular analysis** of decay disentangles long-distance effects



- And new modes: $B^0 \rightarrow K^{*0} \tau^+ \tau^-$ [2510.13716](#)
- A consistent picture at **CMS** and **LHCb**
- Both in tension with SM at $\approx 4\sigma$

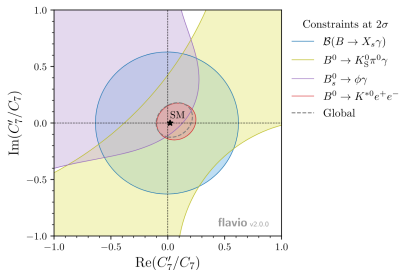


$$b \rightarrow s\gamma$$



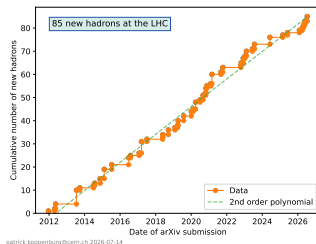
Radiative processes 2010.06011 2411.10127

- Photons emitted in $b \rightarrow s\gamma$ 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 $B^0 \rightarrow K^{*0}e^+e^-$ at low- q^2 very sensitive to $b \rightarrow s\gamma$ photon helicity



- Uncertainties on the observables (transverse asymmetries) from 10% (now) to 2% in U2
- Powerful probes for RH currents with LHCb and Belle-II

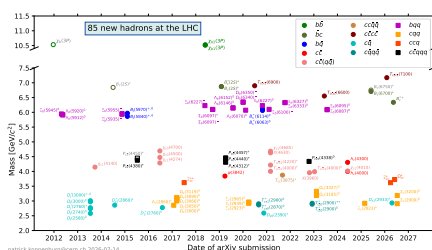
-
- Figure 1 is a scatter plot showing the mass of various hadrons (in MeV/c^2) versus the date of arXiv submission (from 2012 to 2027). The y-axis ranges from 2.5 to 11.5 MeV/c^2 , and the x-axis ranges from 2012 to 2027. The plot displays a large number of data points, each representing a specific hadron. A box labeled "85 new hadrons at the LHC" is placed around the year 2015. The legend indicates the following color coding for the hadrons:
- $b\bar{b}$ (green)
 - $c\bar{c}$ (orange)
 - $s\bar{s}$ (purple)
 - $u\bar{u}$ (pink)
 - $d\bar{d}$ (light blue)
 - $u\bar{c}$ (dark blue)
 - $c\bar{s}$ (dark purple)
 - $u\bar{s}$ (light purple)
 - $d\bar{s}$ (light blue)
 - $u\bar{b}$ (dark blue)
 - $c\bar{b}$ (dark purple)
 - $s\bar{b}$ (light purple)
 - $u\bar{d}$ (light blue)
 - $c\bar{d}$ (dark blue)
 - $s\bar{d}$ (light purple)
 - $u\bar{u}$ (pink)
 - $d\bar{d}$ (light blue)
 - $s\bar{s}$ (purple)
 - $c\bar{c}$ (orange)
 - $b\bar{b}$ (green)
- The plot shows a general trend of increasing mass over time, with many points clustered between 3.5 and 7.5 MeV/c^2 .



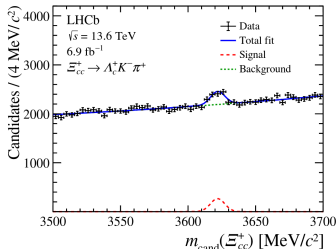
- 75 from LHCb; important contributions from ATLAS/CMS

Beyond flavour: spectroscopy

- Discovery has been unrelentingly linear since Run 1

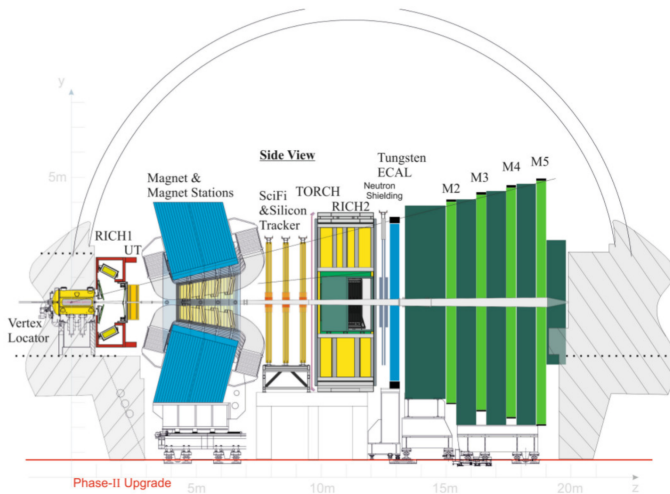


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- 75 from LHCb; important contributions from ATLAS/CMS
- Including this doubly-charming example using Run 3 data [2603.28456](#)

A detector to face the HL-LHC

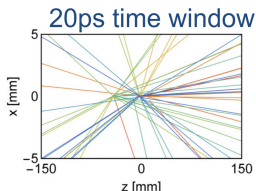
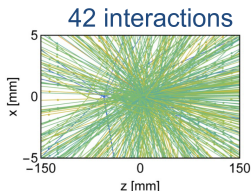


LHCb Upgrade 2: the challenge of pileup

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 $\rightarrow$ 4D: vertexing in VELO**

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



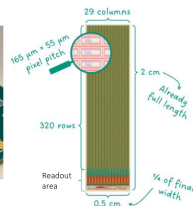
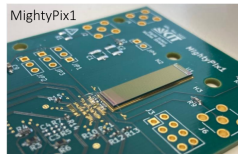
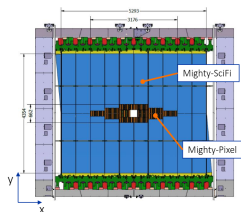
UK groups leading sensor R&D, prototype 4D demonstrator,
high-rate read-out technologies

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'

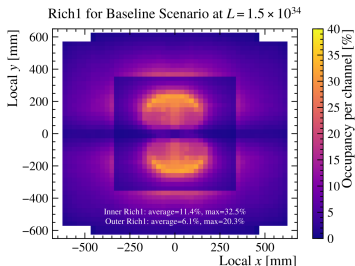


More in D. Wiedner's **ICHEP** talk

- UK leadership from chip design & integration to simulation
- More than half of UK groups involved

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



UK-initiated; project leader in UK; more than half UK groups
UK deliverables from mirrors to photon detectors and read-out, cryogenics to mechanics



Conclusion

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

- **The LHCb upgrade II is essential to fulfil that mandate**
- Upgrade II approved by LHCC/CERN; TDRs in preparation
- 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, CMS, and Belle II will play important roles; LHCb will dominate
- This physics output - and the technological innovations that will underpin it - hang in the UKRI balance