Heavy Flavour Physics: Current Status

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Introduction

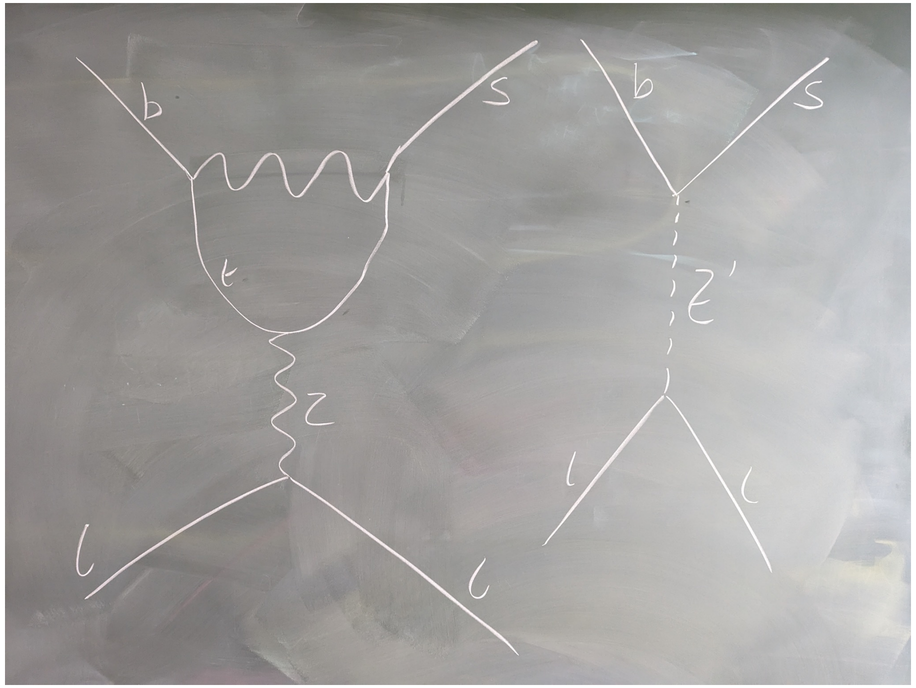
Key questions:

- Why is the universe made from matter and not from antimatter?
- What is the nature of dark matter?
- Why is the EW-scale so different to the Planck scale / why is the Higgs mass at the EW-scale?
- Why …

Flavour Physics lets us investigate all these questions and more.

Indirect Searches

- High Precision measurements offer an indirect search for the effects of new physics.
  - We can test if results agree with the SM.
  - Disagreement ➔ New Physics (or need for improved predictions or measurements!)
- Flavour Physics lets us study effects present at very high energies.
  - In the same way that we can see the weak force in lower energy nuclear decays, flavour physics lets us probe effects of hypothetical particles with mass ~ 100 TeV.



Key message: Flavour Physics allows sensitivity to new physics far beyond the energies of current colliders.

Selected Highlights

- This talk contains selected highlights of current flavour physics measurements.
- Not possible to include everything in 20 minutes!
- Apologies in advance for leaving out some material.

Current Experiments

Unitarity Triangle

- CKM matrix relates mass eigenstates to flavour eigenstates.
- Can be written in terms of three angles and one complex phase.
- Unitarity condition leads to ‘triangles’ in complex phase space.
- One of these has similar length sides.
- Does the triangle close? Is our description of physics consistent?

$$V_{\mathrm{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \qquad V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1 \qquad V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1 \qquad V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

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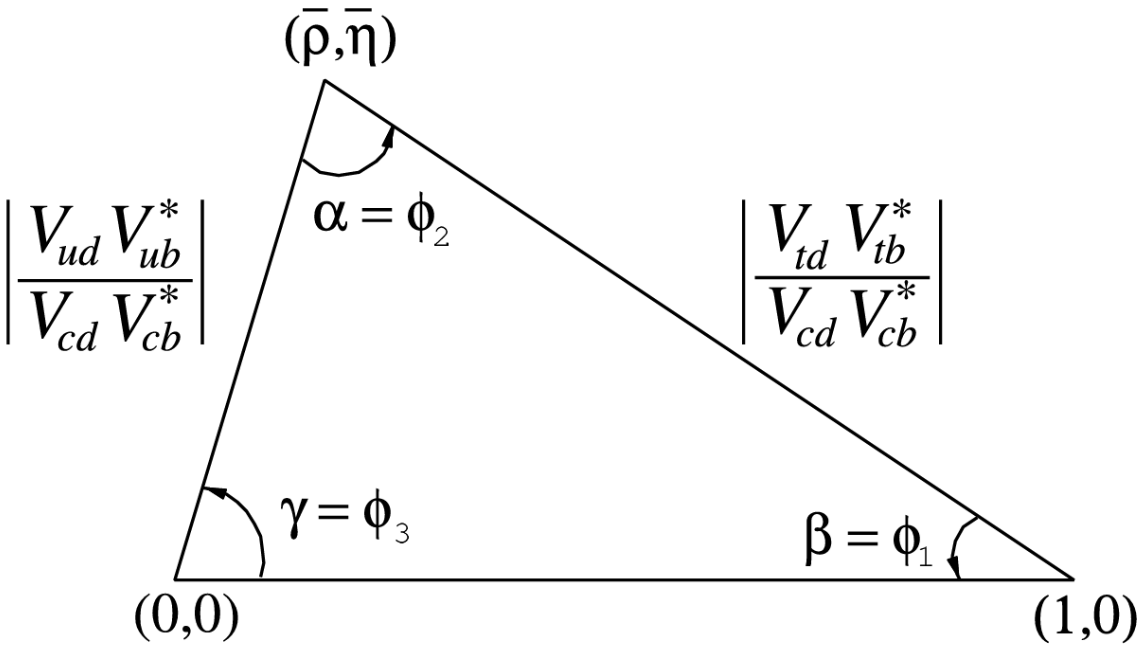
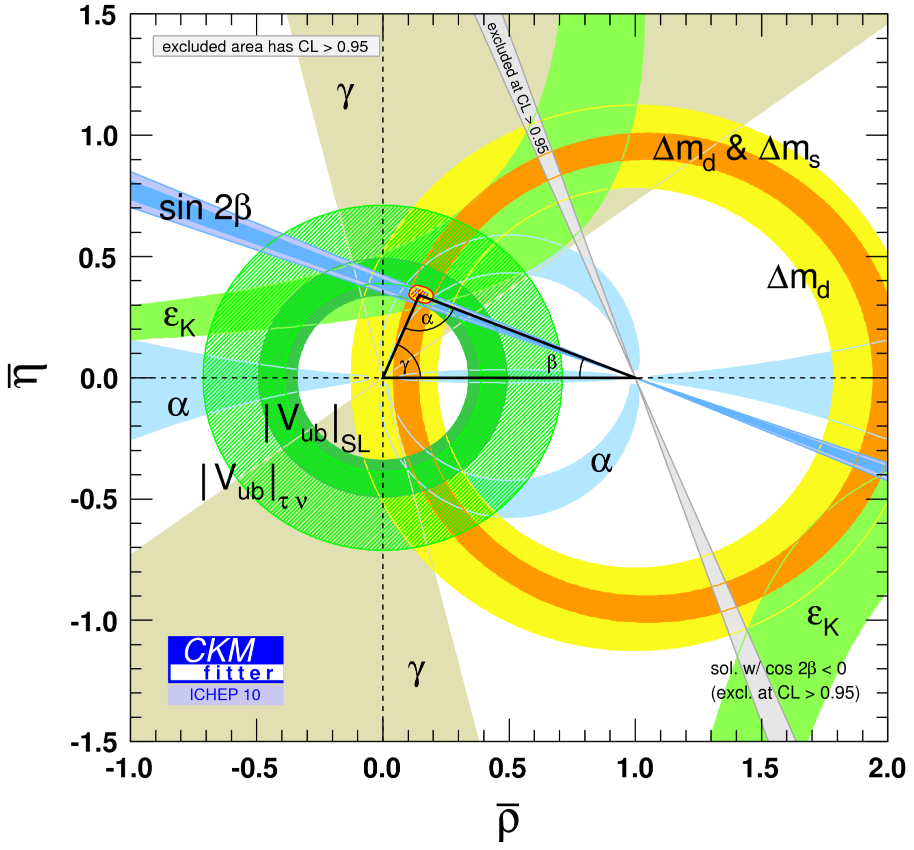
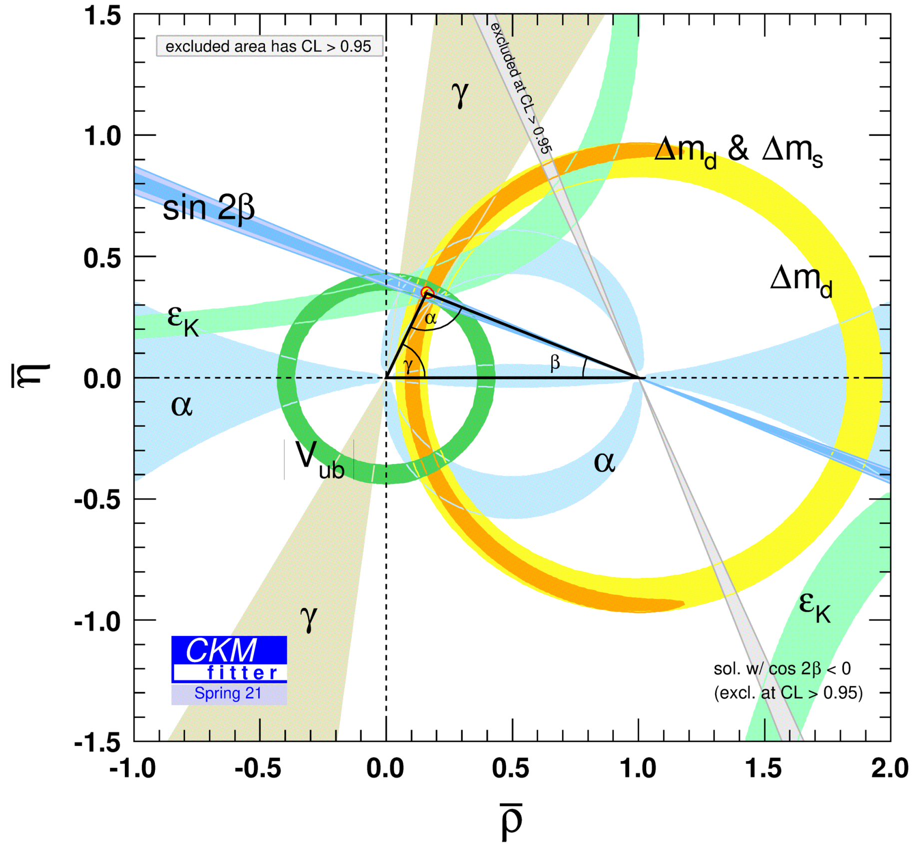


Unitarity Triangle

2010



Now



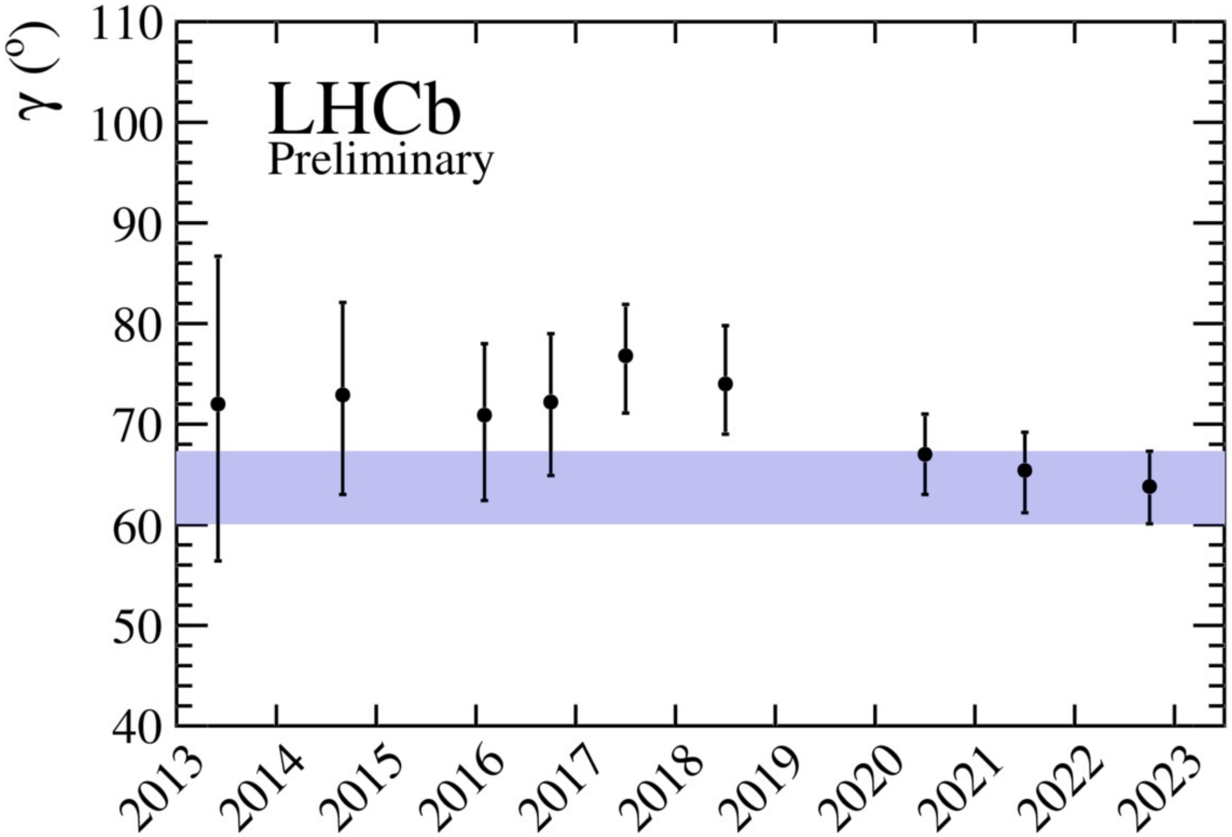
CKM Angle γ

- Only angle of the unitarity triangle determined in tree level B-decays (to open charm states).

$$\gamma \equiv \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$$

- CKM fits return a $\sim 2°$uncertainty on γ - clear need to achieve same level of precision in direct measurements.

- Incredible progress delivered by LHCb.
    - Important input from other experiments, including BESIII.



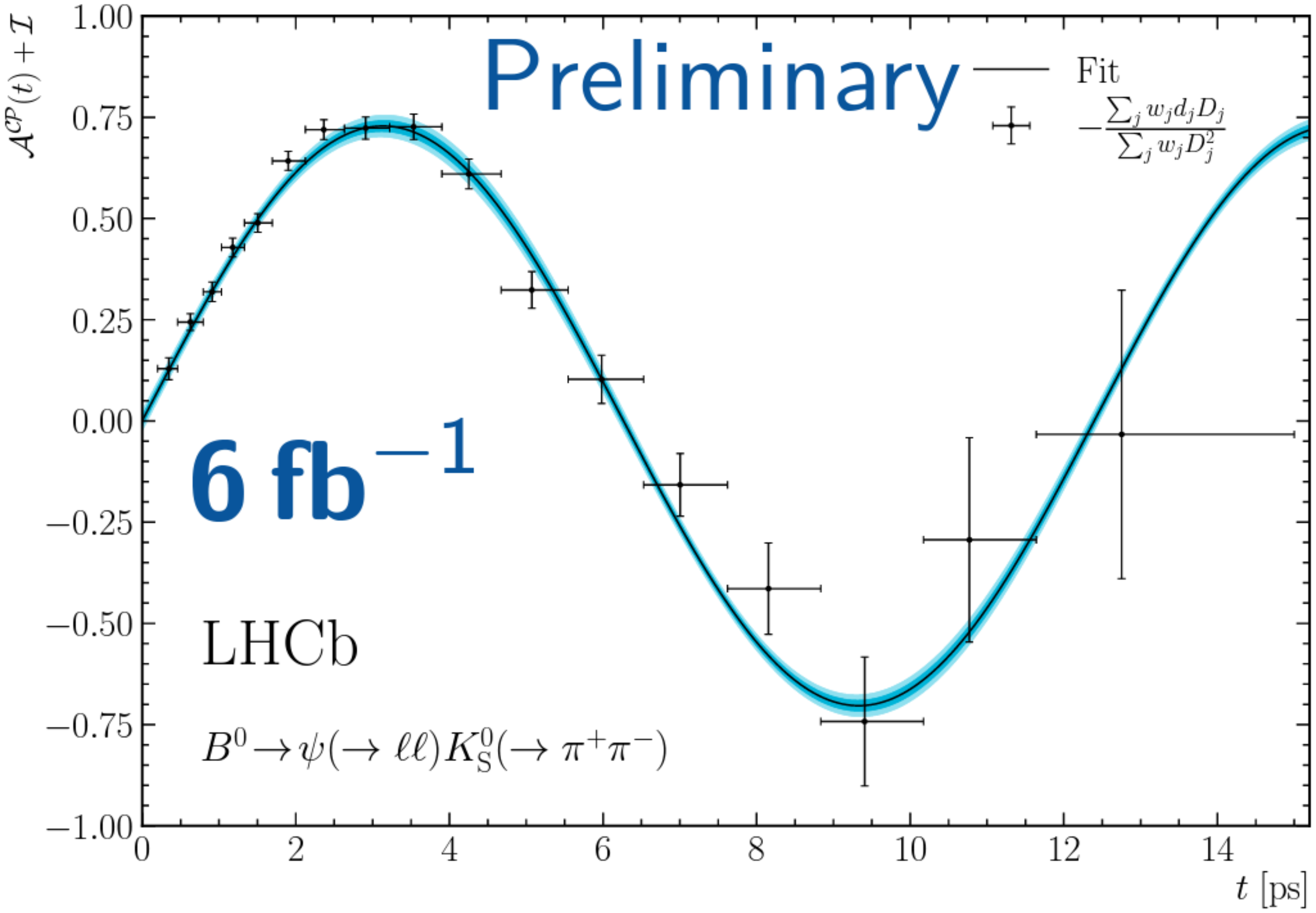
$\sin(2\beta)$

- Access angle via measurement of time-dependent CP asymmetry in $b \to c\bar{c}s$, e.g. $B \to J/\psi\, K_s$

$$\beta \equiv \arg\left[-\left(V_{cd}V_{cb}^{*}\right) / \left(V_{td}V_{tb}^{*}\right)\right]$$

sin(2β) = 0.7158 ± 0.0133 (stat) ± 0.0078 (syst)

- LHCb now dominating the world average.



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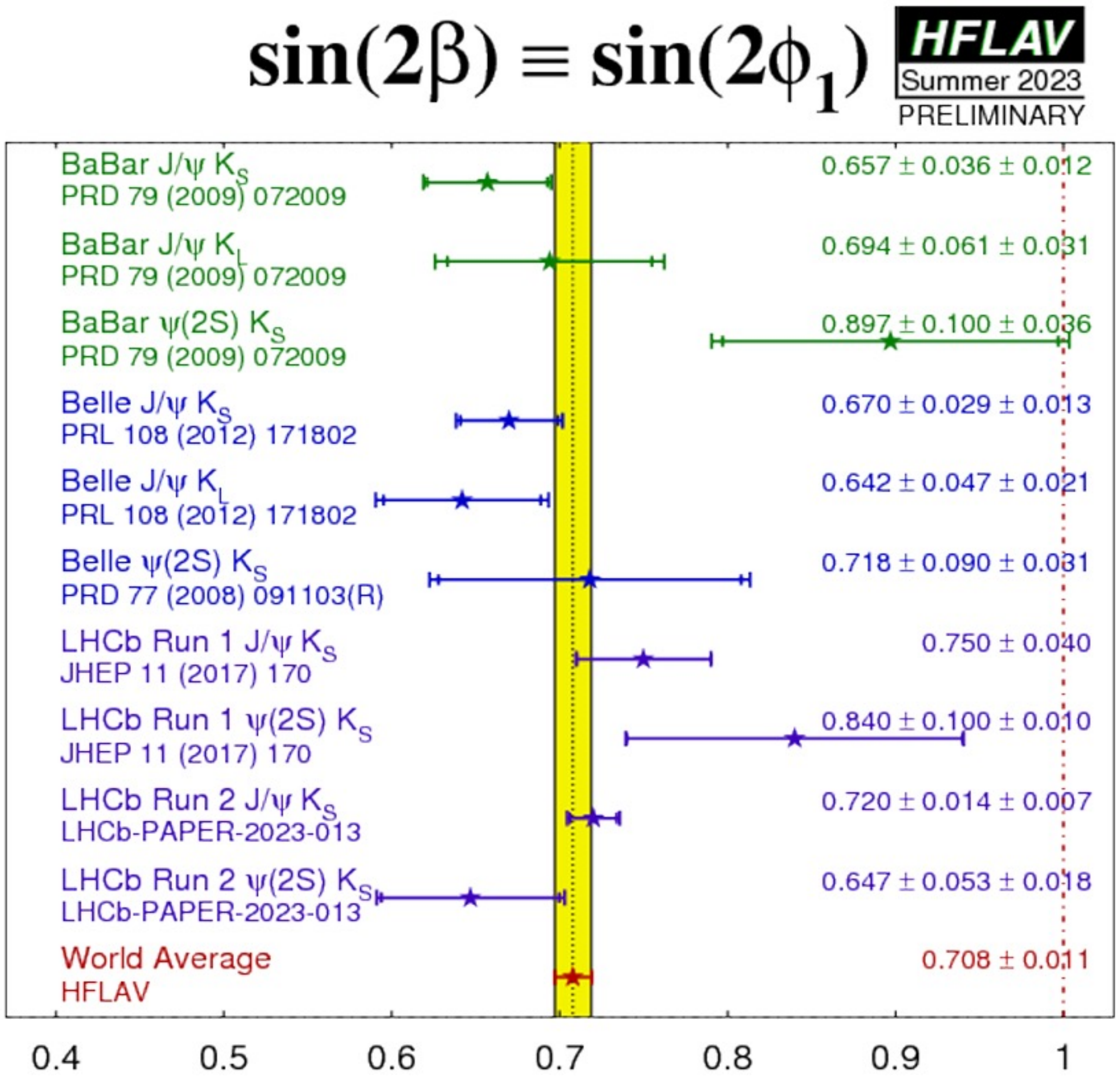
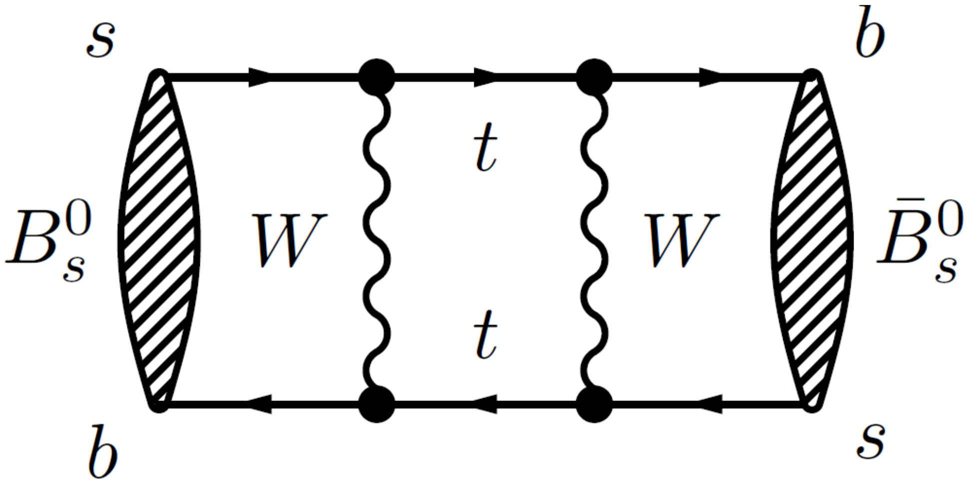
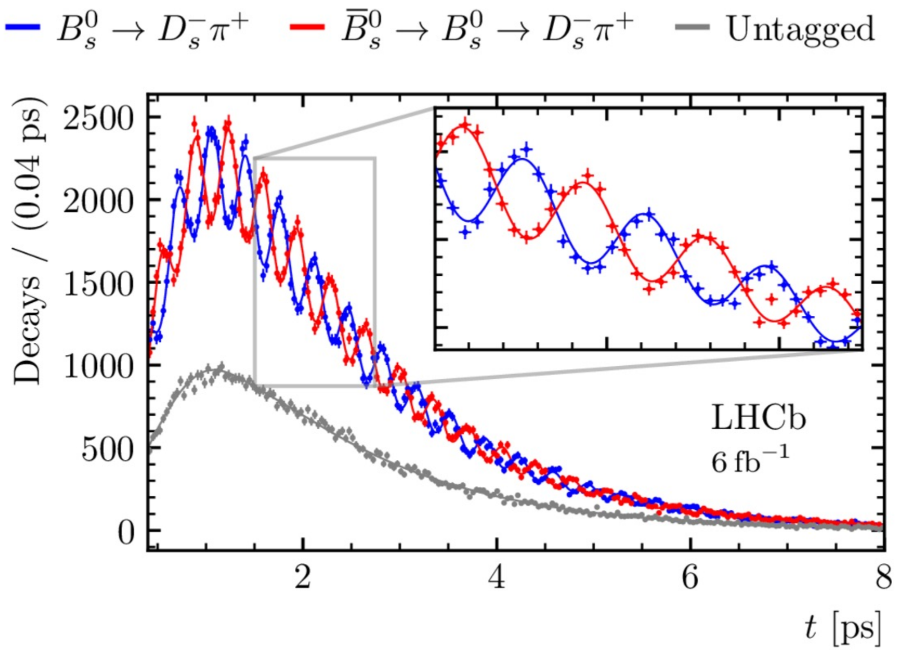


B_s oscillations



- Rich programme studying B_s oscillations.
- LHCb delivered world's best measurement of mass difference between heavy and light B_s states.
- Requires precise flavour tagging – incredibly challenging measurement.

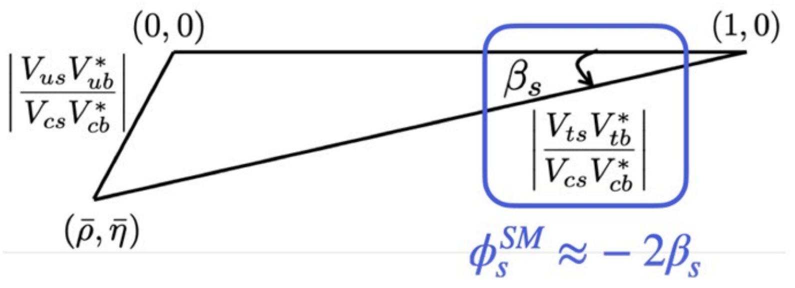
$$\Delta m_s = 17.7656 \pm 0.0057\,\mathrm{ps}^{-1}$$



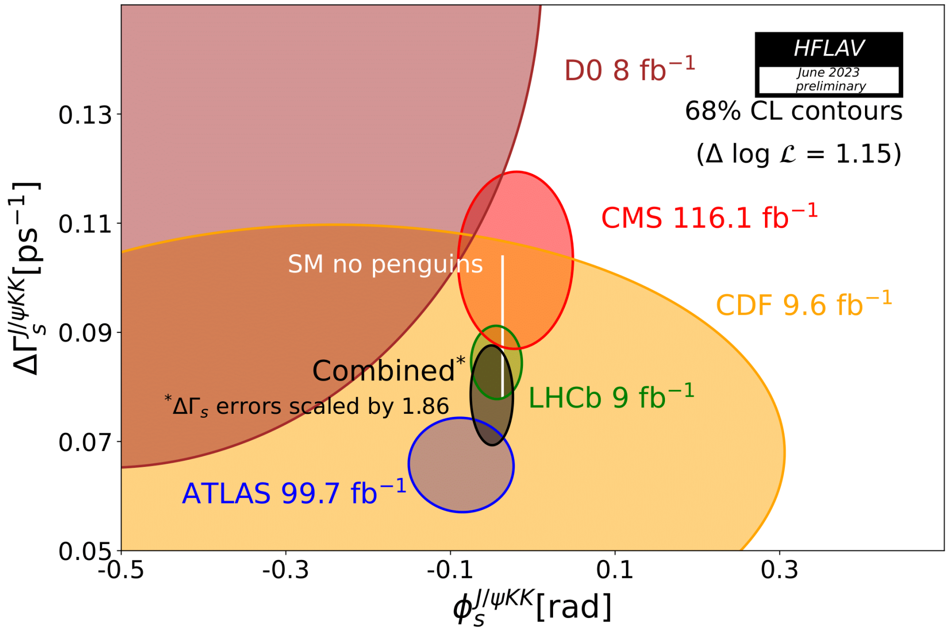
V. Jevtic and P. Li; HFLAV

ϕ_s

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



- Probe B_s meson decays via $b \to c\bar{c}s$, as a function of decay time, picking out potential CP-violation in the interference between mixing and decay.
  - Dominated by $B_s \to J/\psi\,\phi$
- Important contributions from all the LHC experiments.
  - New contribution from LHCb forthcoming [LHCb-PAPER-2023-016].
  - High precision also from CMS [PLB 816 (2021) 136188], ATLAS [EPJC 81 (2021) 342]
- LHCb also has a recent measurement of ϕ_s in $b \to s\bar{s}s$ [arxiv:2304.06198]

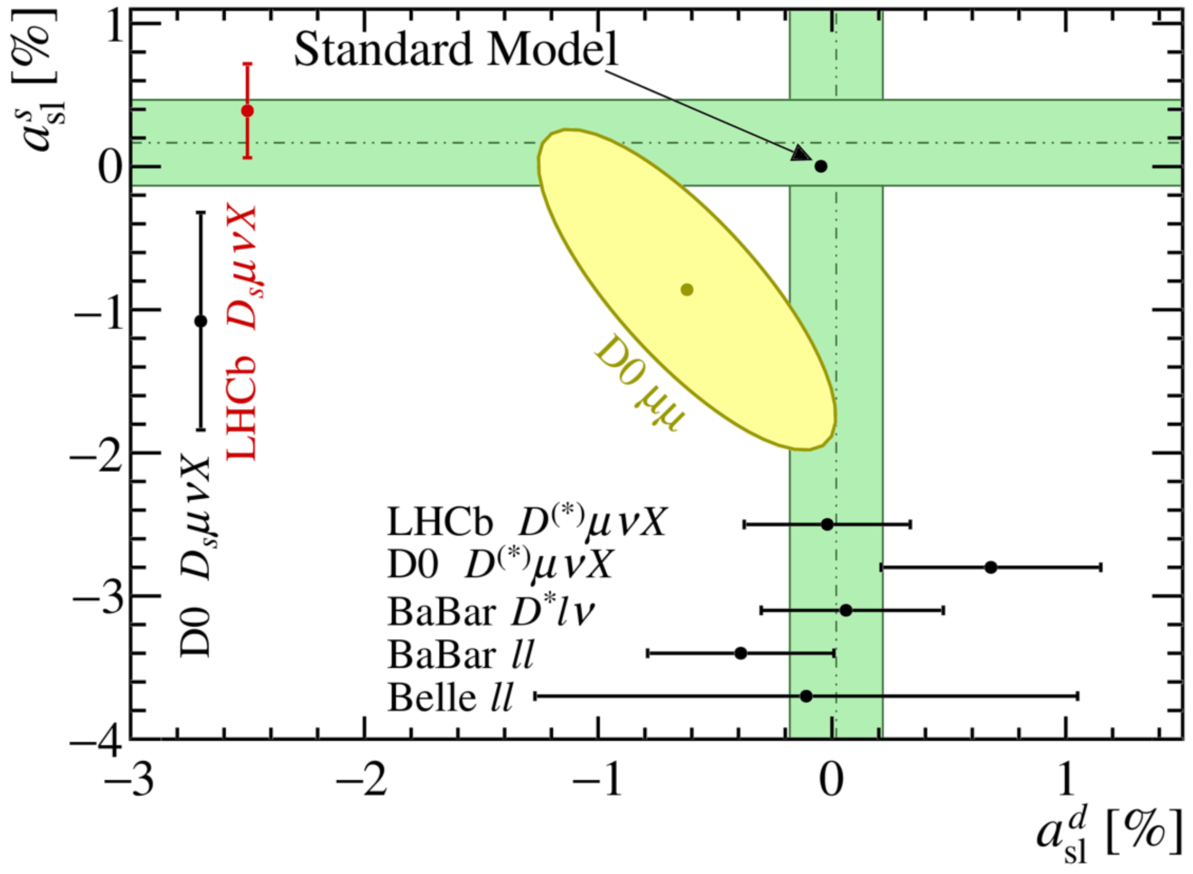


Semileptonic Asymmetries

- Measurement of relative rate of flavour specific decays to final states only accessible after mixing.

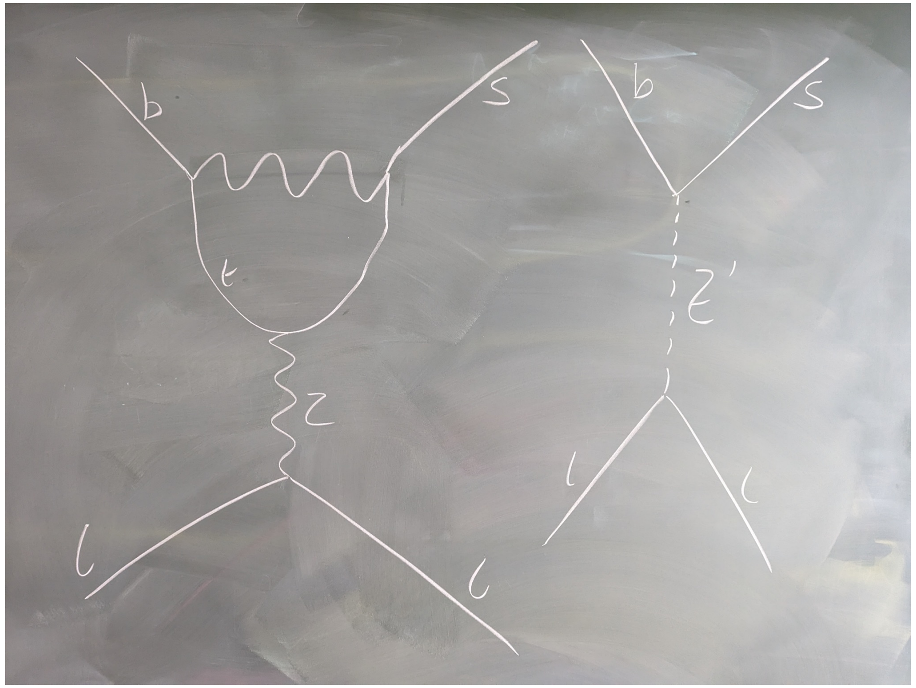
$$a_{\rm sl} \equiv \frac{\Gamma(\overline{B} \to f) - \Gamma(B \to \bar{f})}{\Gamma(\overline{B} \to f) + \Gamma(B \to \bar{f})}$$

- Asymmetries tiny in SM, but enhanced in many NP models.
- LHCb measurements to date only use Run 1 data.



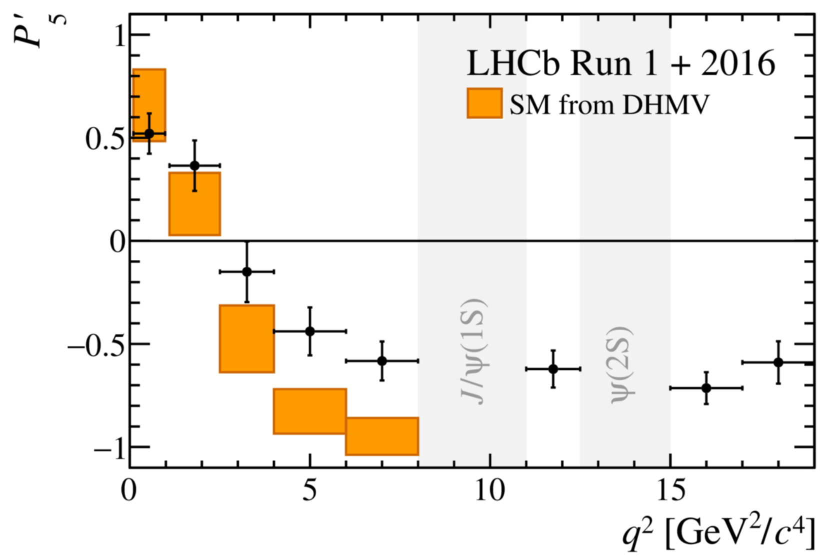
Rare Decays: $b \to s\mu\mu$

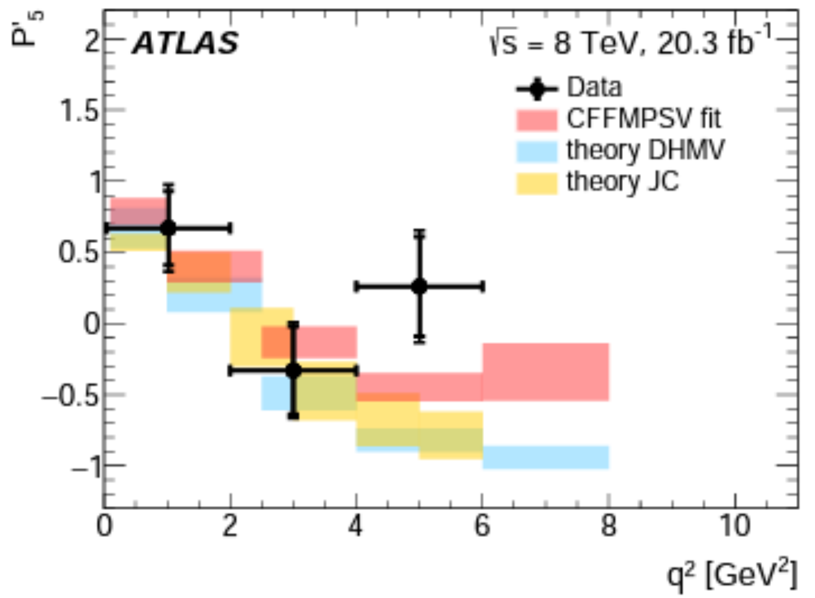
- FCNC in SM only occur at loop level.
- Measurements of $b \to sll$ transitions therefore probe (tree-level) new physics at high energy scales.
- New Physics effects often described via Wilson Coefficients:
  e.g. C9 (vector) and C10 (axial-vector).
- Global fits to data in different channels seek a unified explanation of results.



$B \to K^{*}\mu\mu$ angular analysis

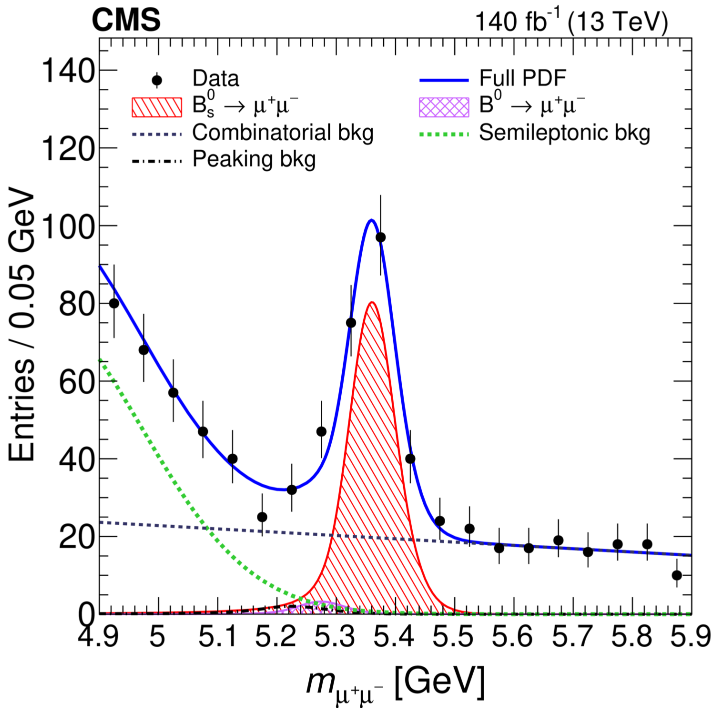
- Measure angular distribution of $B \to K^{*}\mu\mu$ decays.
- LHCb measure multiple 3σ deviations in neighbouring bins; overall global fit shows significant deviation from SM.
- Deviations largest in bins closest to the J/ψ.
- Other LHC experiments also delivering measurements that show similar tension.

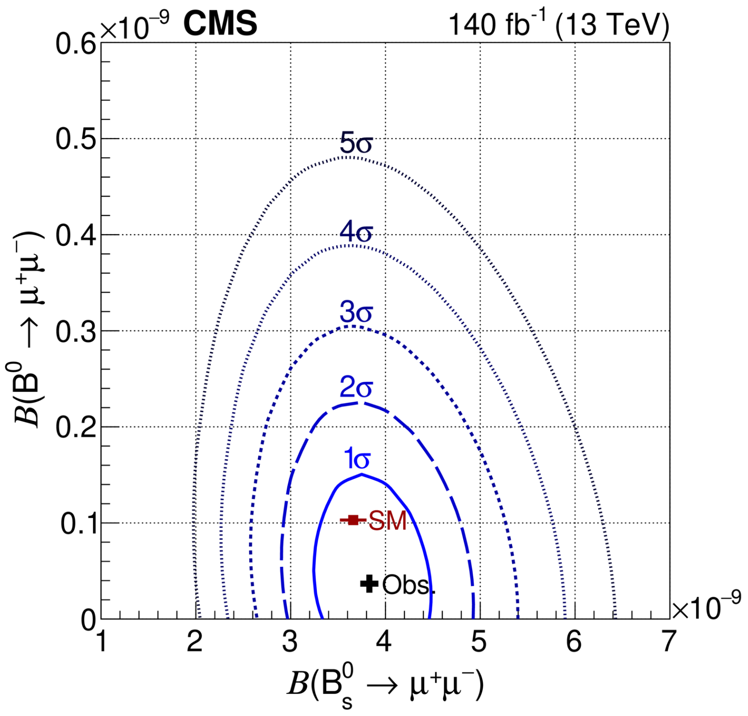




$B_s \to \mu\mu$ branching fraction

- Measure the rate of the $B_s \to \mu\mu$ decay (probes C10 coefficient).
- New measurement from the CMS collaboration – in excellent agreement with the SM.

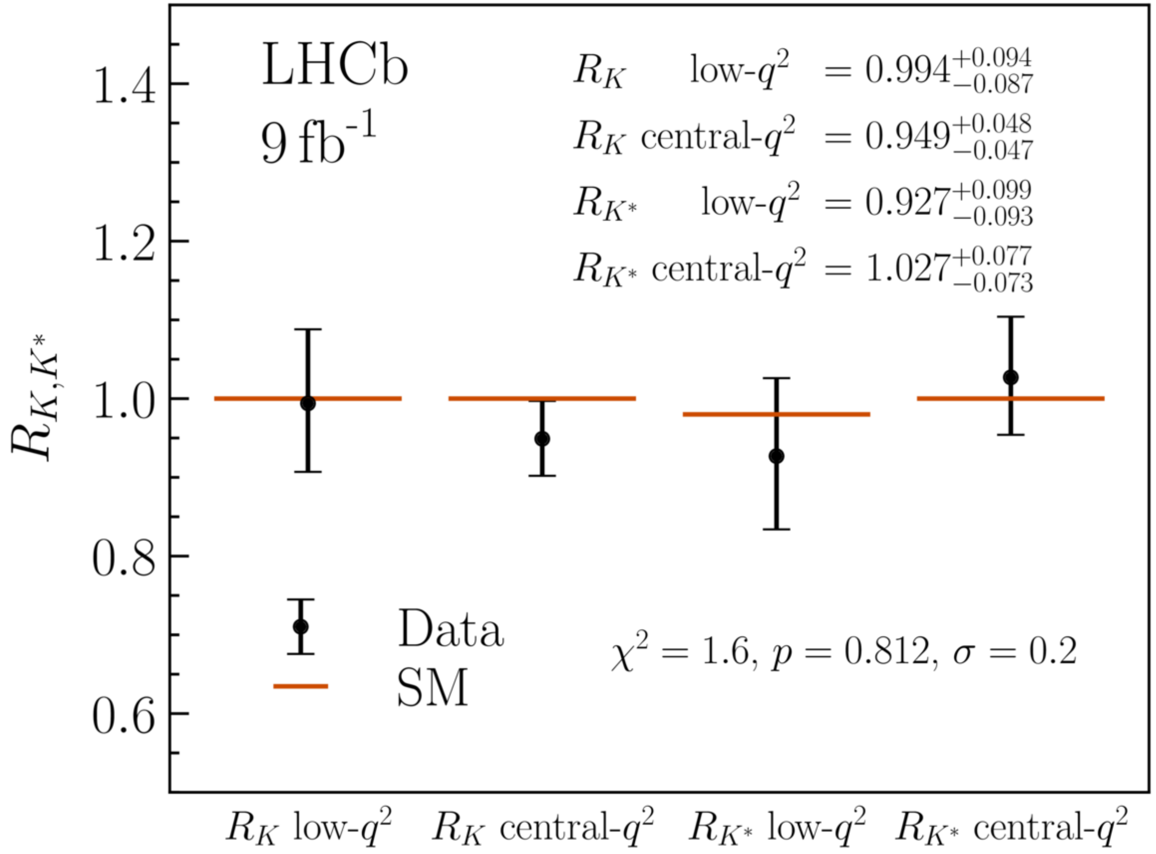




$b \to sll$: Lepton Universality Tests

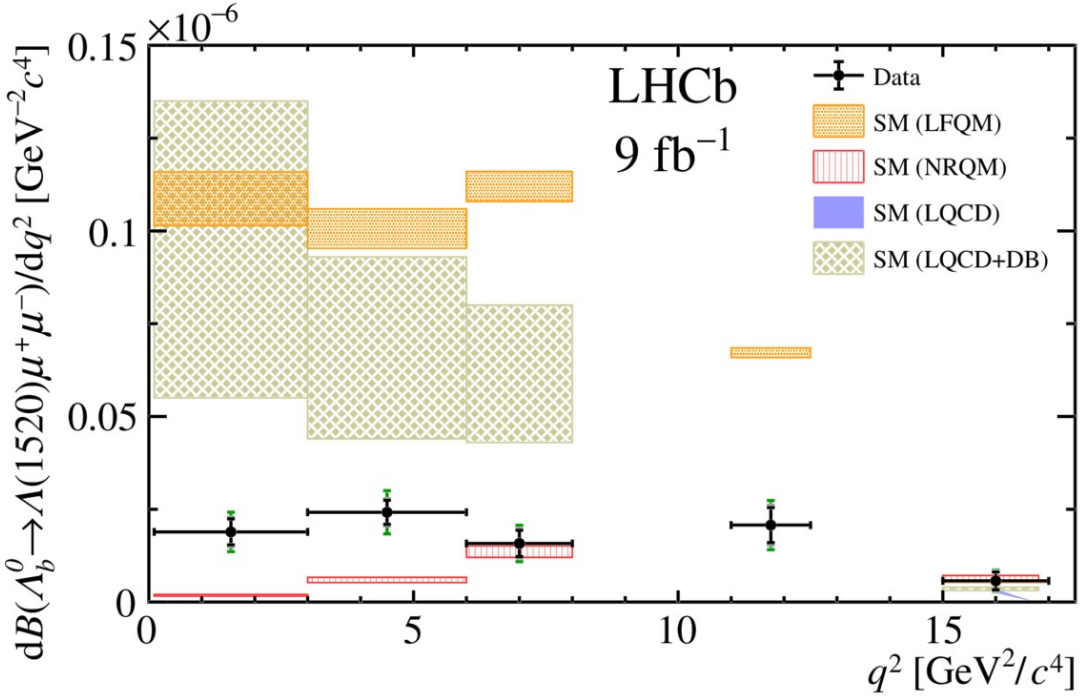
- LHCb measure relative rate of $b \to s\mu\mu$ and $b \to see$ transitions.
  - Electron channel features 'difficult' backgrounds that hampered previous measurements.

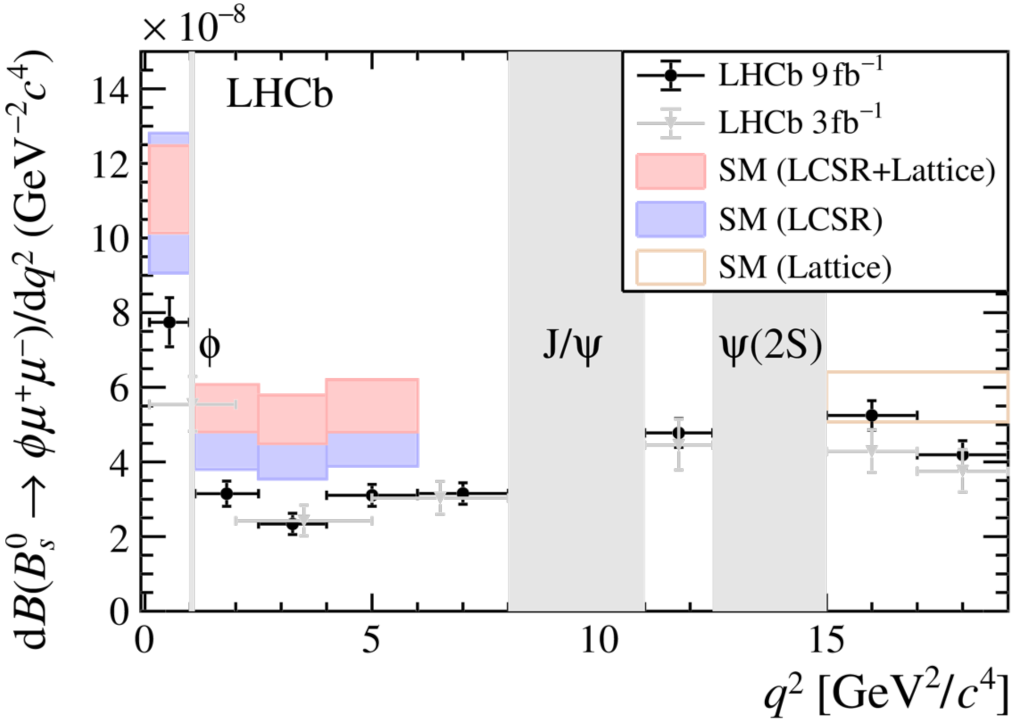
- Results in excellent agreement with unity (and SM predictions).



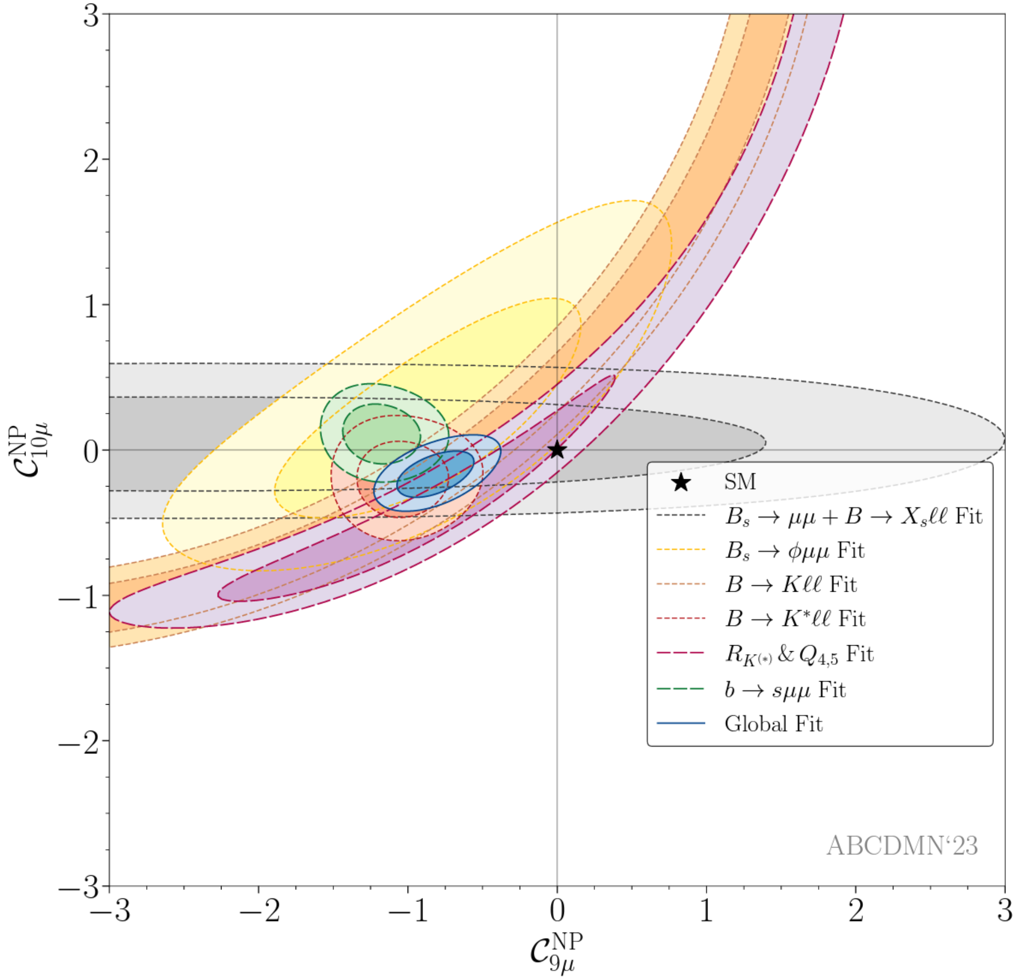
$b \to sll$: Branching Fractions

- Multiple FCNC B-meson decays show significant disagreement between SM predictions and data at the 2-3σ level.
- However, branching fraction predictions suffer from large QCD uncertainties.





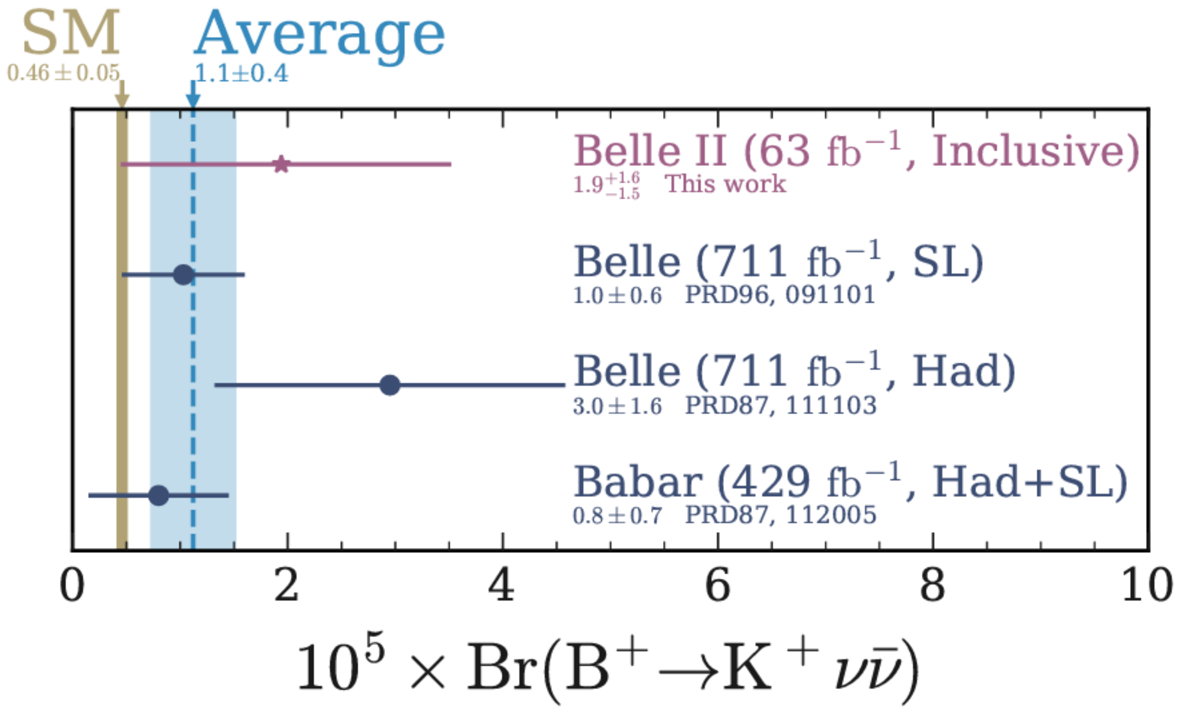
$b \to sll$: Global Fits and Related Searches



- Overall SM tension with data remains at a level >4σ (but decreased from 6-7σ about 1 year ago).
- NP mostly expressed via C9 (vector) Wilson coefficient.
- But no observation of LFV ($b \to s\tau\mu$, $b \to s\tau e$, $b \to s\mu e$) that would naturally occur in many models of NP. Many limits set by different experiments.

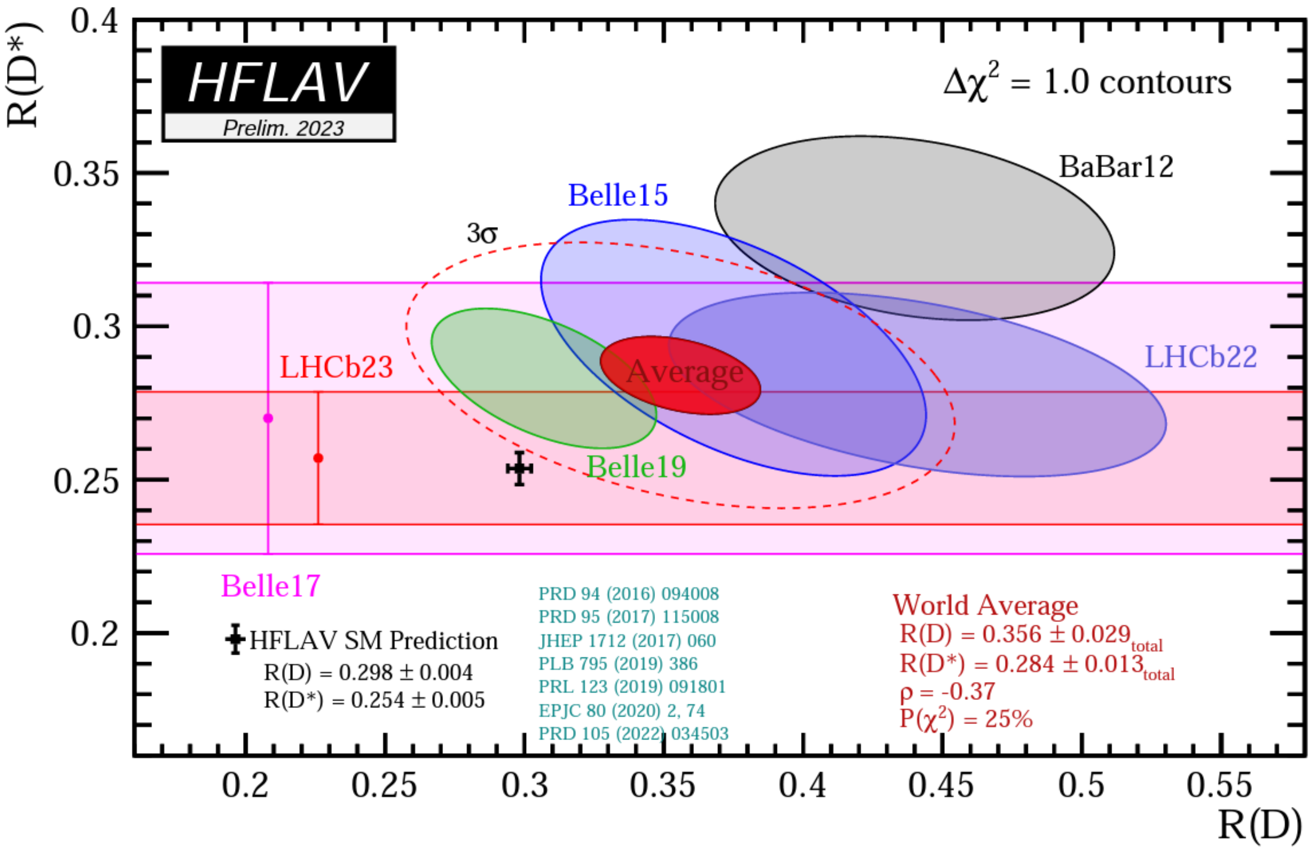
$B \to K\upsilon\upsilon$

- First Belle II data already provides competitive limit on $B(B \to K\upsilon\upsilon)$.
- Measurement accessible at Belle II; not possible at hadron collider experiments.
- Much more to come.



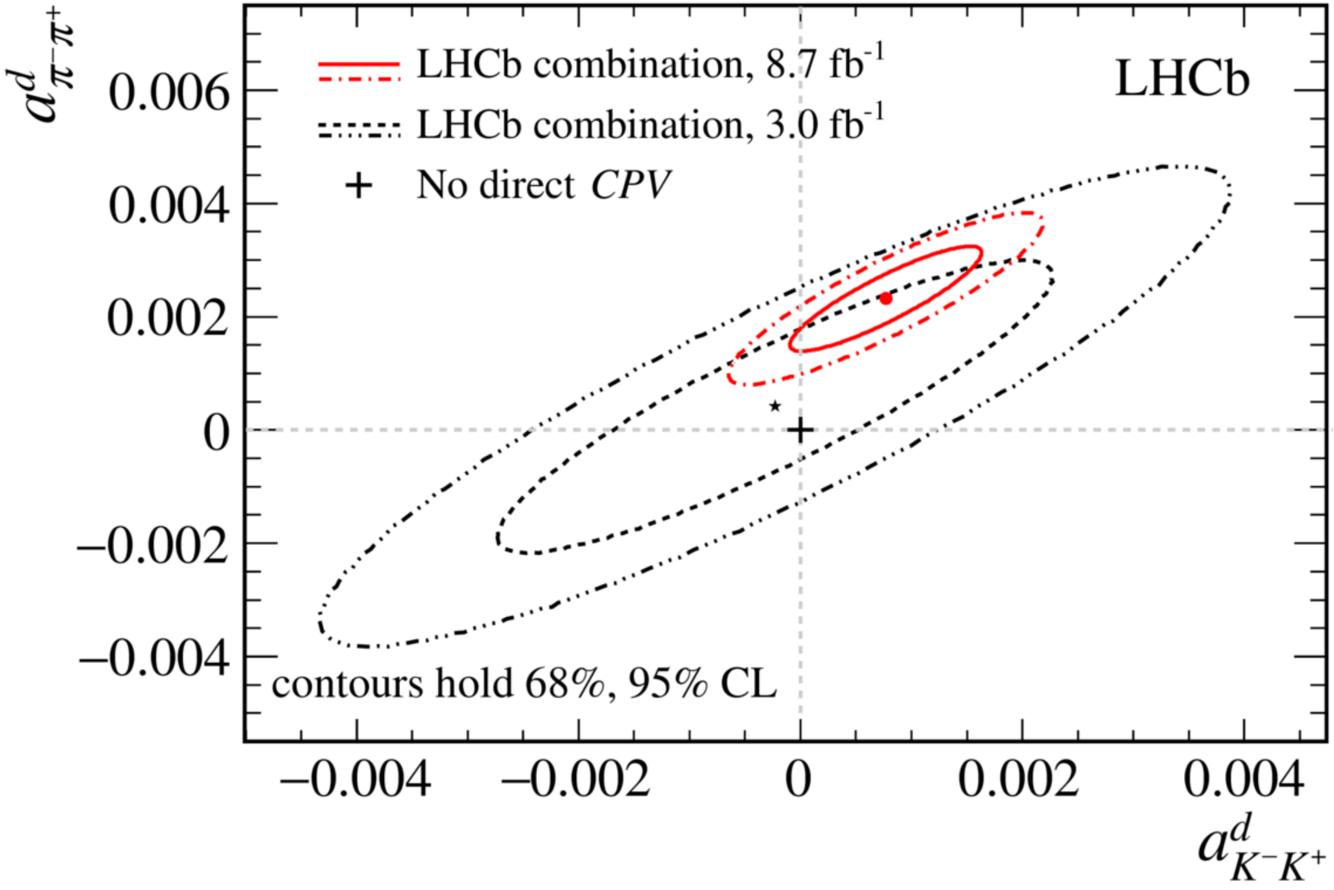
R(D*)

- $R(D^{(*)}) = \frac{B(B \to D^{(*)}\tau\upsilon)}{B(B \to D^{(*)}\mu\upsilon)}$
- Many models of NP exhibit large couplings to 3rd generation particles.
- LHCb has recently reported 2 new measurements:
    - 2D measurement using muonic τ decays, with Run 1 data.
    - R(D*) measurement using 3h τ decays, with Run 2 data (2015+2016).
- Global Fit to data exhibits 3.2 σ tension with SM prediction.



Charm CPV

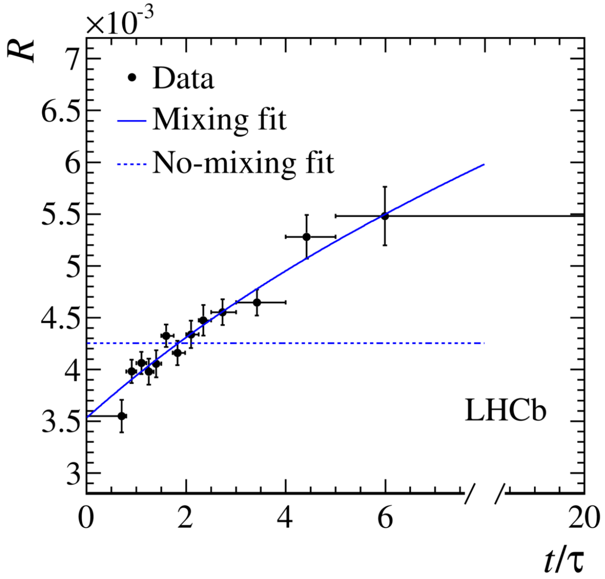
- Direct CPV observed in charm at LHCb.
- Effect ~7× larger than expected in the SM (LCSR). Might be rescattering effects.
- U-spin predicts that $a^d_{\pi\pi} = -a^d_{KK}$; data disagrees at 2σ level.
- More measurements crucial to determine if CPV in charm consistent with SM.



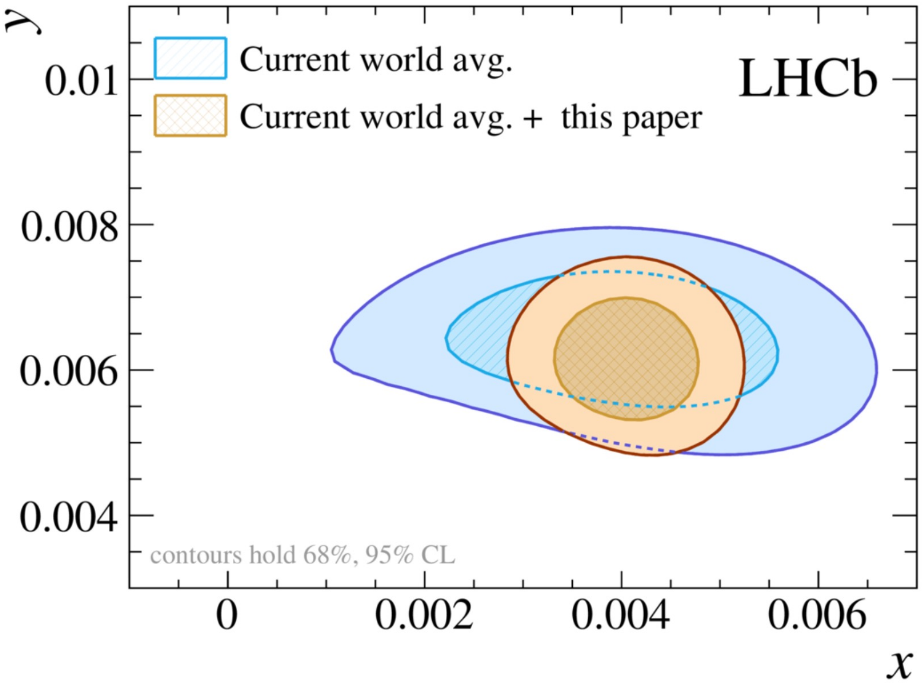
Charm Mixing

- Charm Mixing observed for the first time at LHCb (2012).
- LHCb now exploring charm mixing parameters – measured non-zero mass difference between neutral D mesons.
- Still no evidence for mixing-induced CPV.

[relative rate of flavour specific WS decays]



[width difference of eigenstates]



[mass difference of eigenstates]

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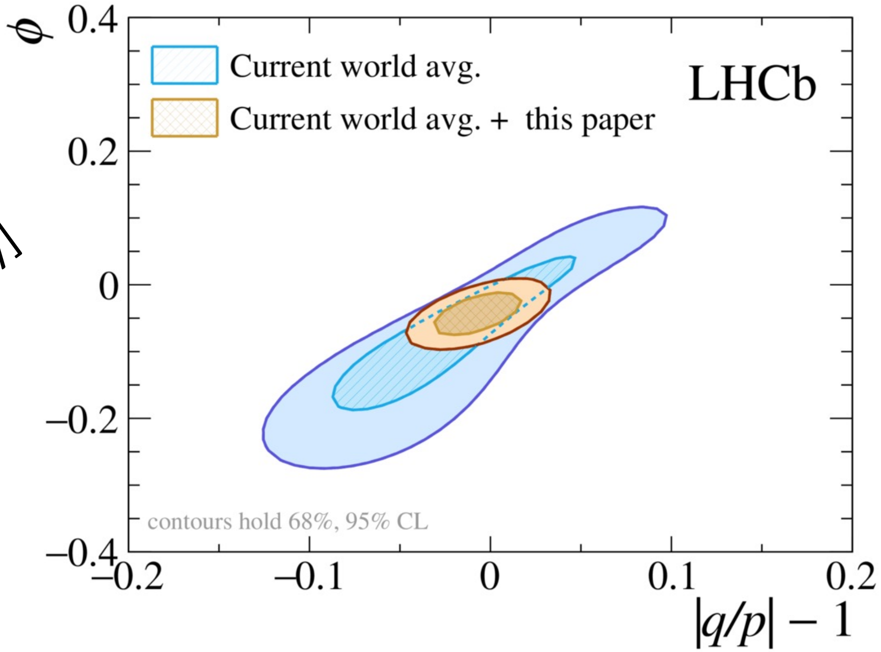
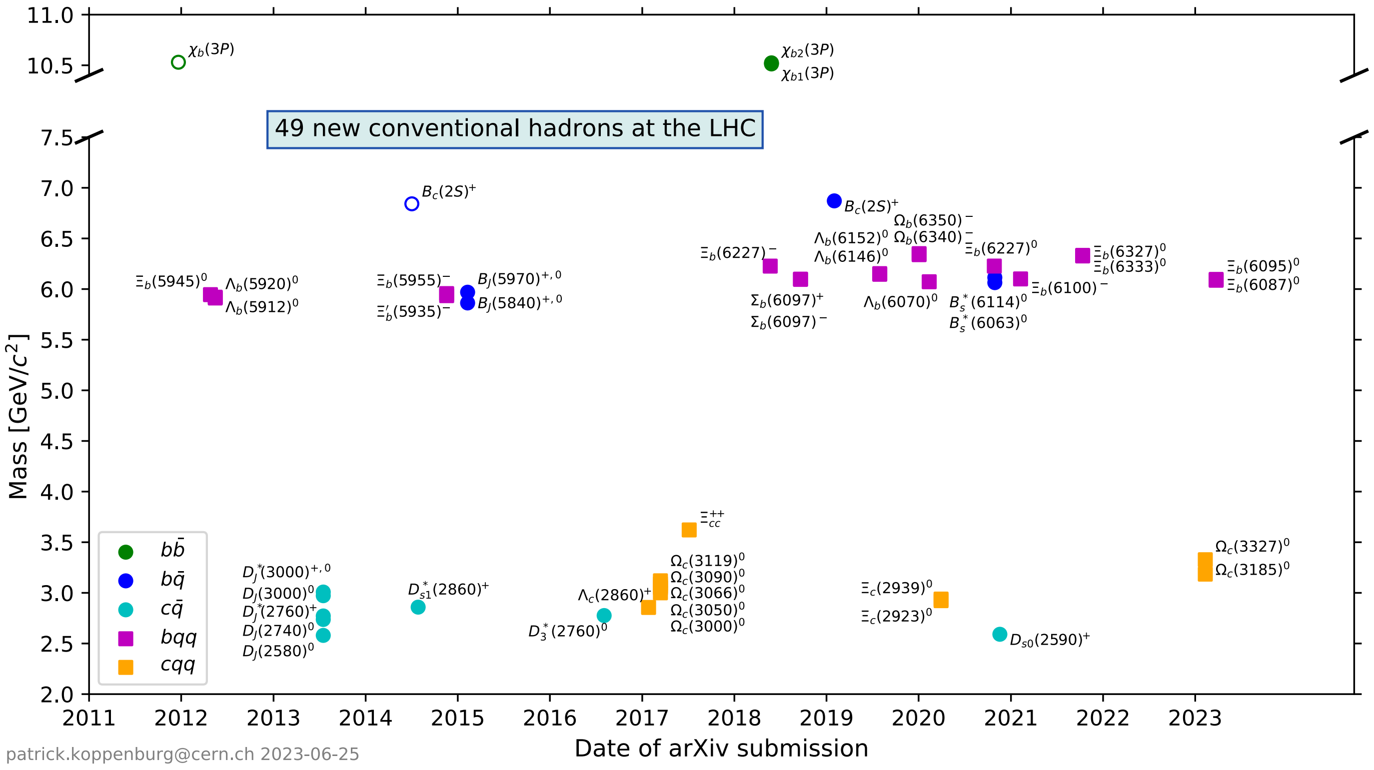
[CPV in the interference of mixing and decay]



[CPV in mixing]

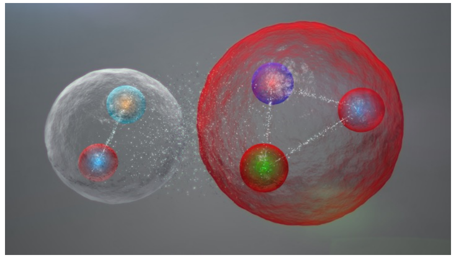
Conventional Spectroscopy

- LHC has discovered 49 new conventional hadron states.
- Experiments also testing QCD with precise measurements of masses, widths, and lifetimes.
- A wide variety of QCD measurements are possible.

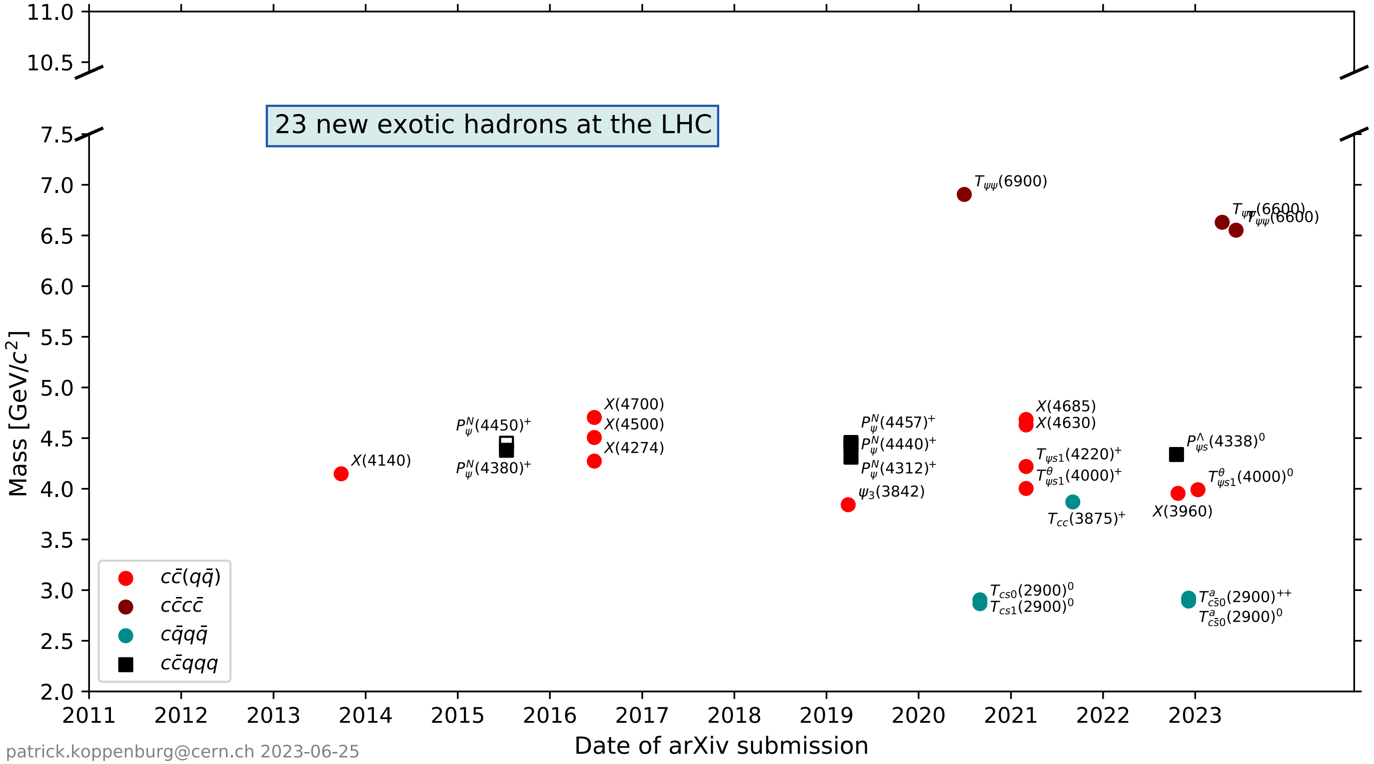


Exotic Spectroscopy

- LHC has discovered 23 new exotic hadron states.
  - Resonances consistent with tetraquarks or pentaquarks.
  - Molecular and tightly-bound hypotheses still an open-question.



- Most tetraquark and pentaquark candidates appear close to threshold of combined states, e.g. $P_{\psi}^{N}(4312)$ is close to $\Sigma_c \overline{D^0}$ threshold.



NOTE: other pre-LHC experiments have also made discoveries of potential exotic candidates e.g. X(3872)

Summary

- Selected highlights of current flavour physics.
  - Not space for everything – e.g. measurements of α or of $|V_{ub}|/|V_{cb}|$

- Heavy flavour physics studies probe new physics in a wide variety of ways:
  - Searches for new sources of CP violation.
  - Searches for enhancements / reductions in the rates of rare and forbidden decays.

- And has led to the discovery of other new phenomena, e.g. pentaquarks and tetraquarks.

- Despite recent challenges, field is living through an exciting time.

- Crucial to continue to address fundamental questions with flavour physics studies.