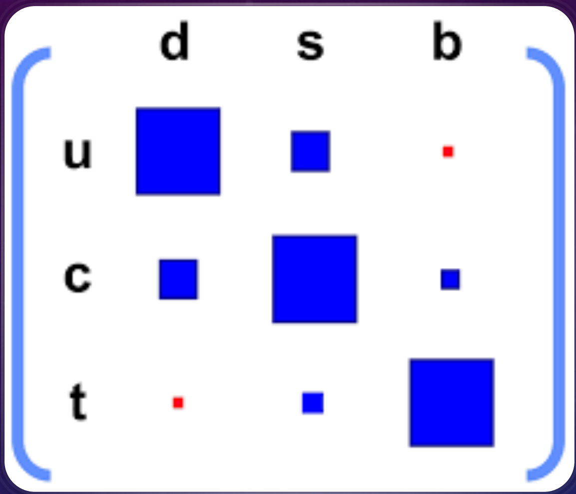
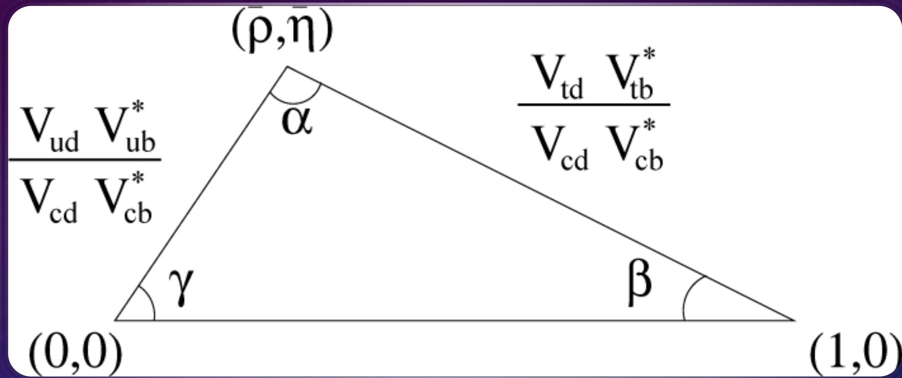
QUARK FLAVOUR PHYSICS

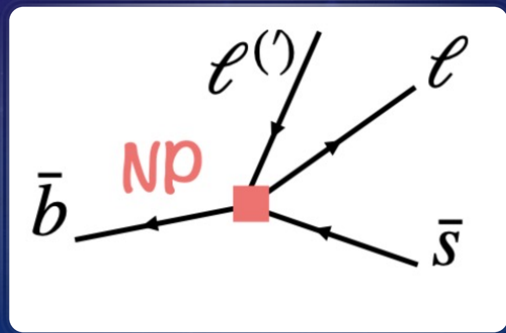
ICHEP 24TH JULY 2024, PRAGUE, CZECH REPUBLIC

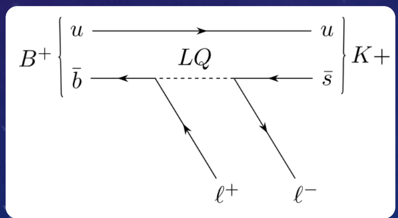
SNEHA MALDE

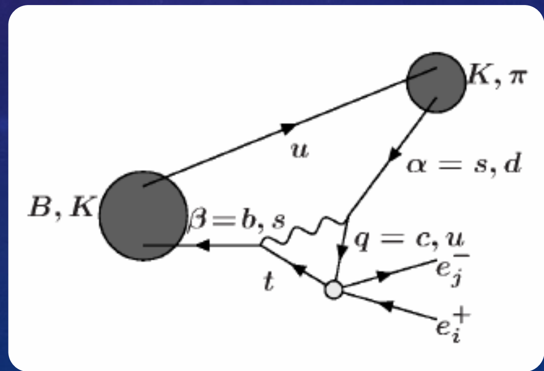
MOTIVATIONS











EXPERIMENTAL NIGGLE

- Quarks aren’t free
- In bound states
- Adds complexity to the “SM prediction” or the interpretation

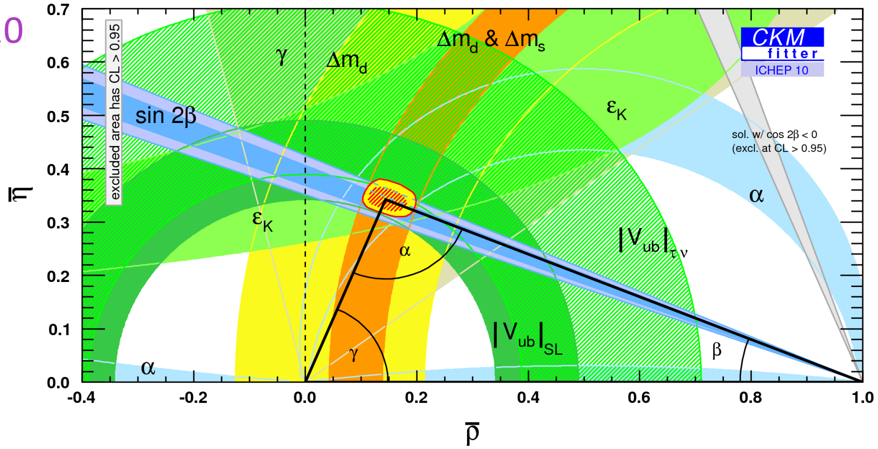
EXPERIMENTAL DIVERSITY

- Each is unique
- Different particle species are accessed
- Competitive in specific places
- Complementary in others

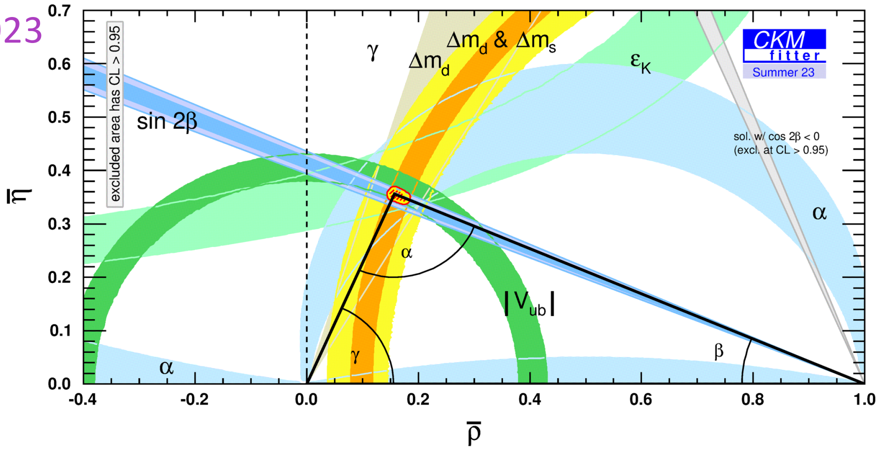
WHERE WE ARE

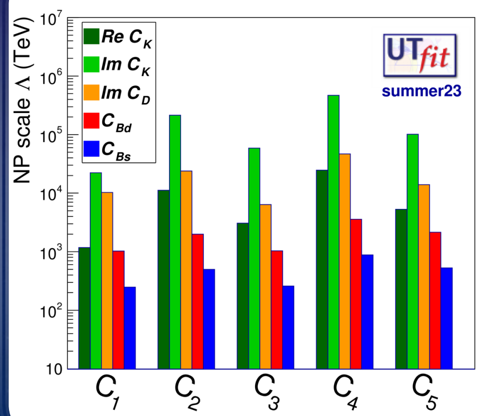
- Flavour physics can feel incremental but over the lifespan of LHCb:
- Much more is understood about CKM, rare decays, and QCD.
- Flavour physics sets scale limits on NP
- Use recent results to show where we are, and where we are headed.

2010



2023

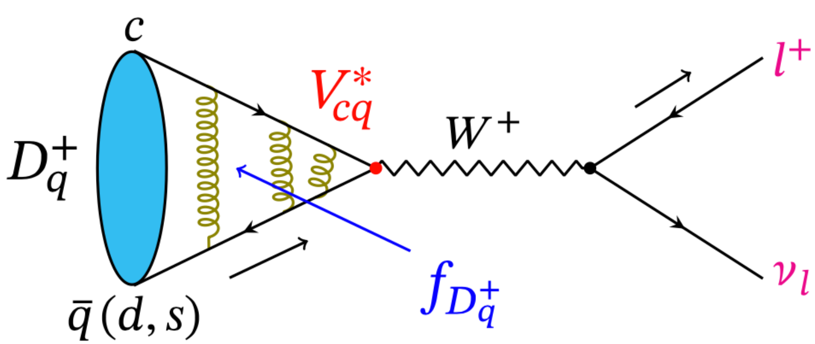




CKM ELEMENTS & FORM FACTORS

- Simple decay, QCD and weak interaction are both present
- BESIII $e^+ e^-$ collider running at a variety of energies to access light/charm hadrons
- Hermetic detector – constraints allow for missing particle (muon channel)
- Most precise BF measurement
- $f_{D_S^+}|V_{cs}|= 241.1 \pm 2.5 \pm 2.2 \pm 1.0$
- $|V_{cs}|= 0.968 \pm 0.0101_{stat} \pm 0.009_{syst}$

$D_{(s)}$ pure leptonic decay

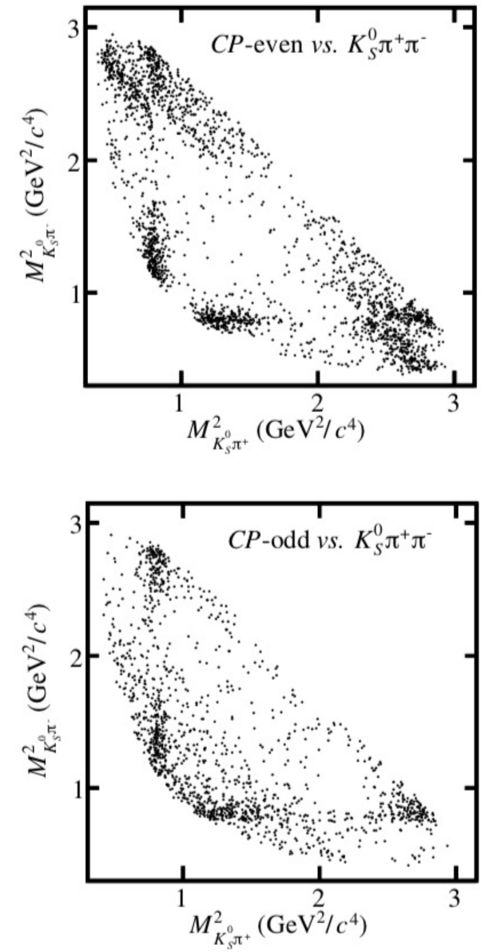


$$\Gamma(D_{(s)}^+ \to l^+\nu_l) \propto \left|f_{D_{(s)}^+}\right|^2 \cdot \left|V_{cd(s)}\right|^2$$

Phys.Rev.D 108 (2023) 11, 112001

BESIII & QUANTUM CORRELATION

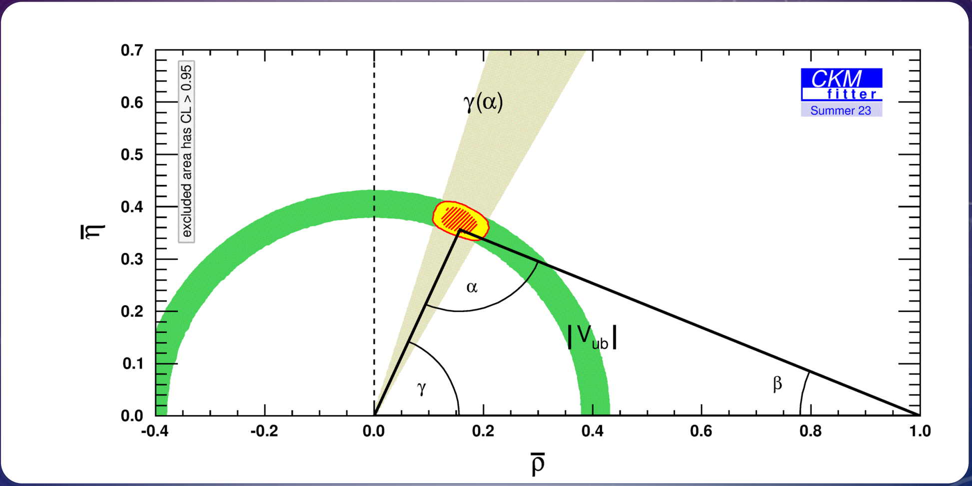
- Charm mesons are produced quantum-entangled at ψ''
- Difference in two plots is a clear sign of quantum-entanglement
- Source of interference, and can be used to measure the parameters of the strong interaction in charm decays
    - Key input to CPV at LHCb and BELLE2



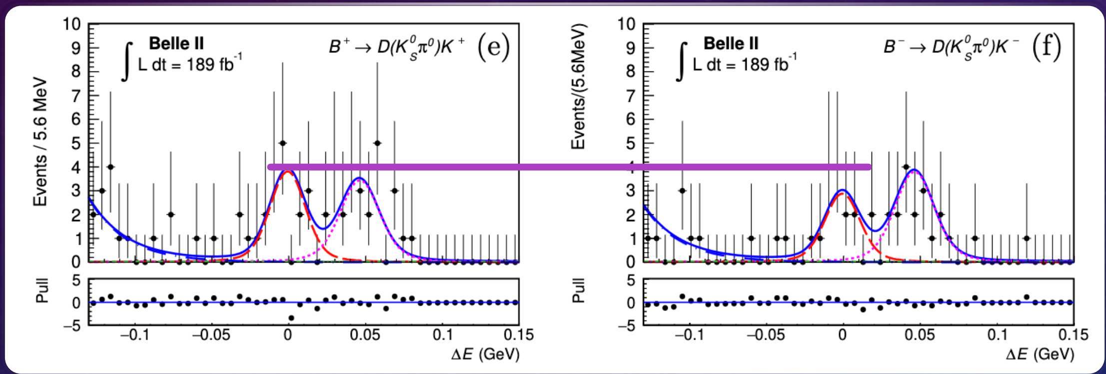
Phys. Rev. Lett. 124, 241802

CKM ANGLE γ

- Measured in tree level B→DK like decays
- Hadronic physics part is directly measured
  - The "B" part in the B factories directly alongside γ
  - The "D" part from charm factories where necessary, e.g BESIII
- Lack of LQCD input needs leads to one of the most pristine observables in flavour physics
- Fully hadronic decays requiring kaon/pion separation → LHCb & BELLE2



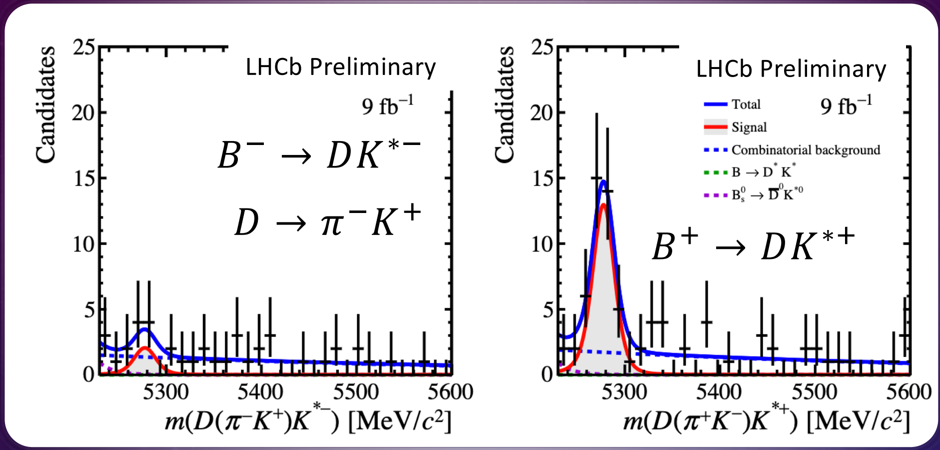
PROGRESS FROM Belle/Belle II

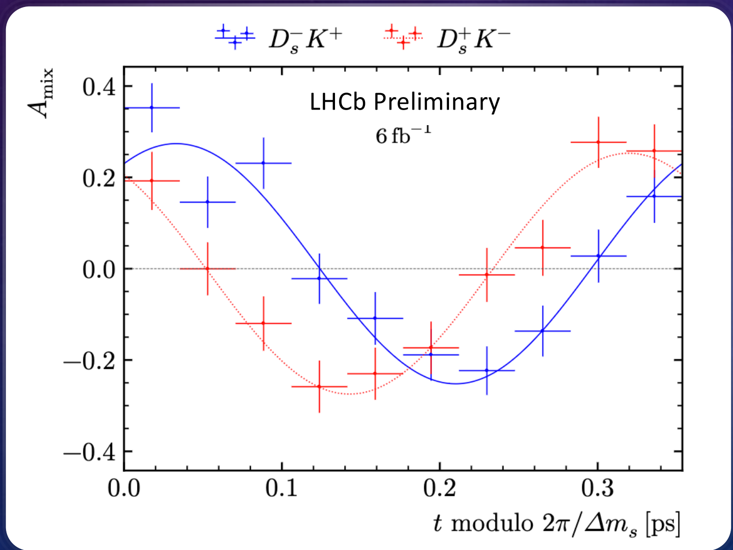


- $B^+ \to DK^+$; The golden channel
- Many D decays used
- Belle data often reanalysed using new techniques and common framework for Belle II.
- CPV in this particular channel ~ 10%

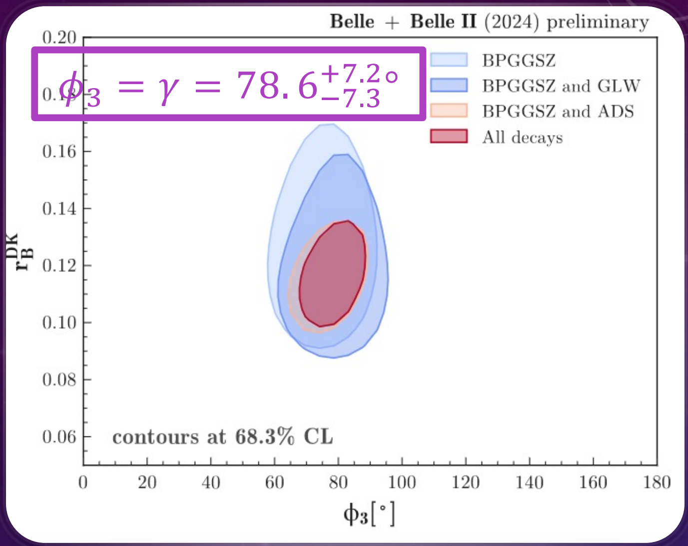
JHEP05(2024)212

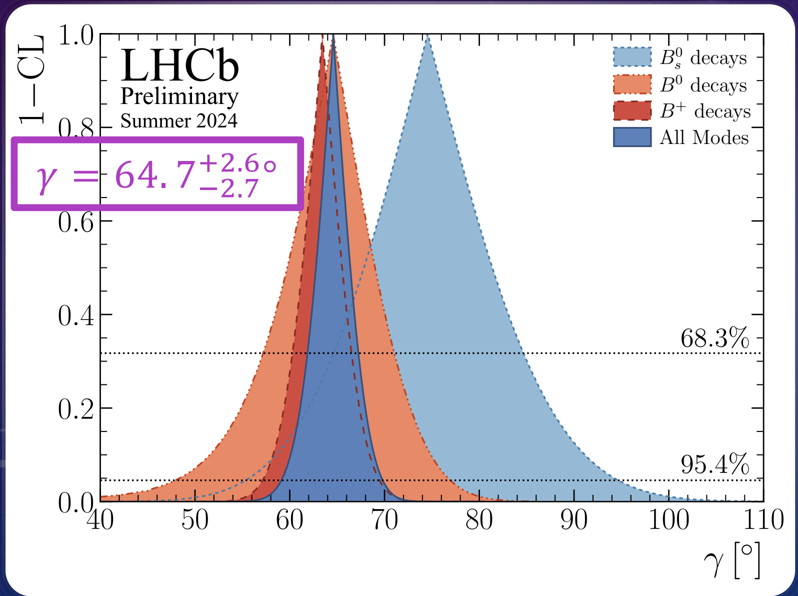
PROGRESS FROM LHCb





- Recent focus has been on other B decays
- $B^0 \to DK^{*0}, B^+ \to DK^{*+},\ B^+ \to D^*K^+$
- Some large asymmetries ~70%
- $B_S^0 \to D_S^{\mp} K^{\pm}$: time dependent analysis
- Tagging power 6.1%
- Asymmetry to charge conjugate final states





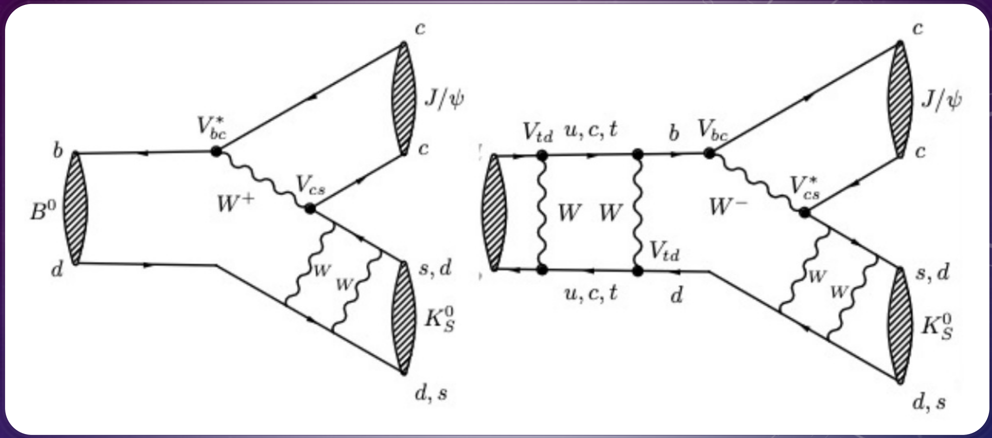
COMBINATIONS

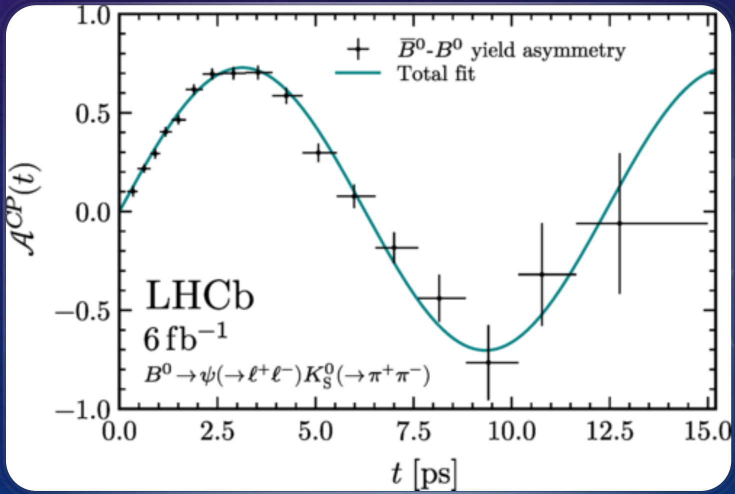
- Many decays → combinations
- Charm input from BESIII/CLEO is critical
- LHCb has far surpassed target goal for Run2
- Compare to combination of other sides and angles of CKM triangle assuming unitarity:
  - $\gamma = 66.3^{+0.7\circ}_{-1.9}$ from CKM fitter
  - Consistency with unitarity. Will take effort to drive precision down significantly further to look for inconsistencies

arXiv:2404.12817
LHCb-CONF-2024-004
CKMFitter
UTFIt

$\boldsymbol{\beta}$

- $\boldsymbol{\beta}$ in $B^0 \to J/\psi K_S^0$
- Decay time dependent CPV of B^0 and $\overline{B^0}$ decay rates
- Observables are
  - C: direct CP
  - S: mixing induced CP asymmetries
- LHCb → most precise measurement to date



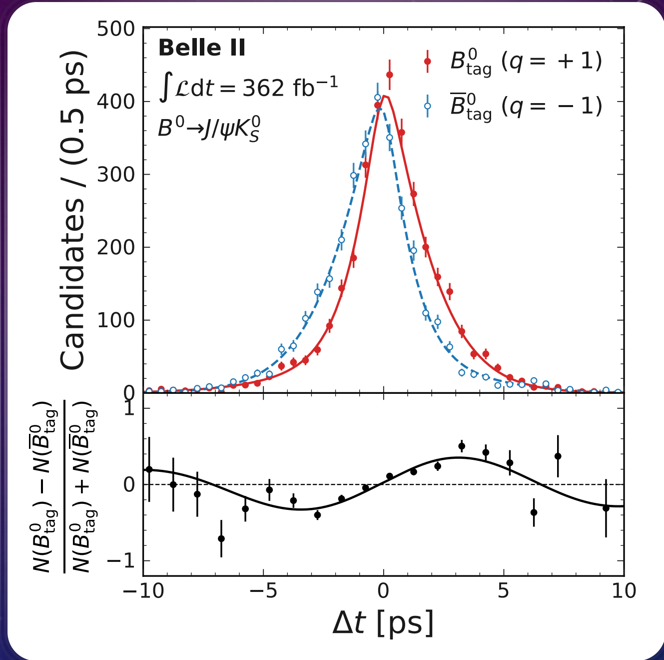


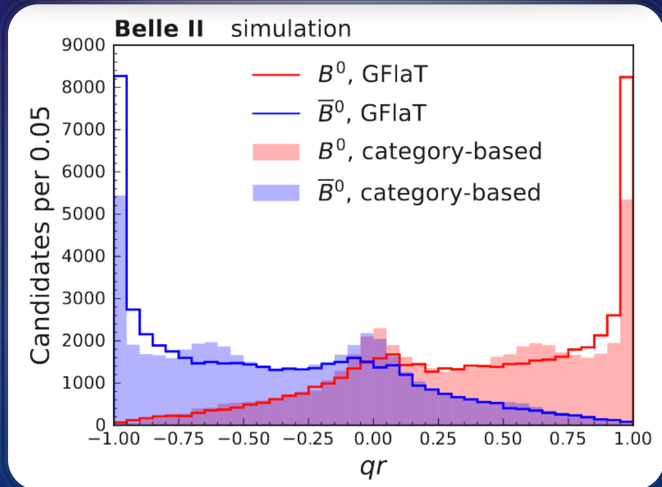
- S=0.724 ± 0.014 ~$\sin(2\beta)$
- C=0.004 ± 0.012

PRL. 132 (2024) 021801

UPDATED RESULT FROM Belle II

- Improvements from FT algorithm based on Graph neural network (increase of 18%)
- Tagging power of 37.4%
- $S = 0.724 \pm 0.035 \pm 0.009$
- $C = -0.035 \pm 0.026 \pm 0.029$

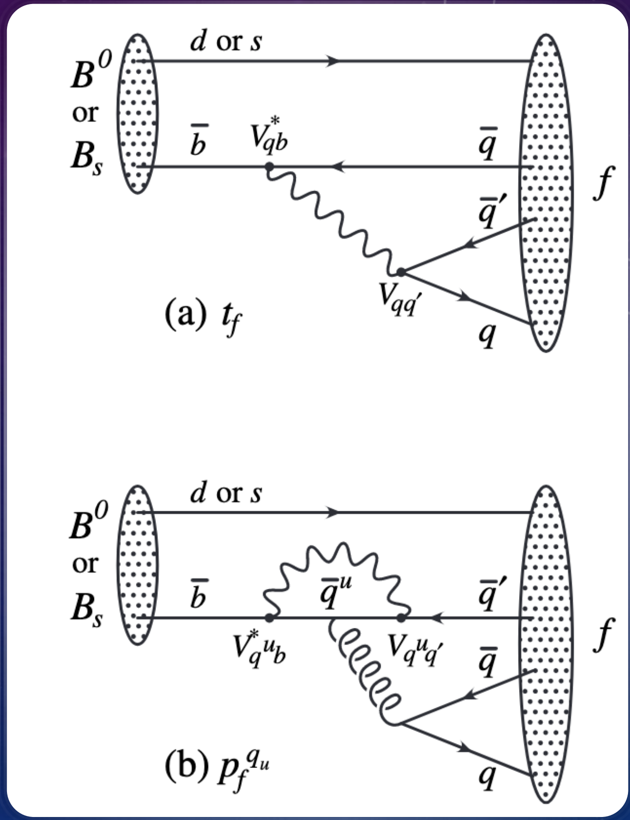




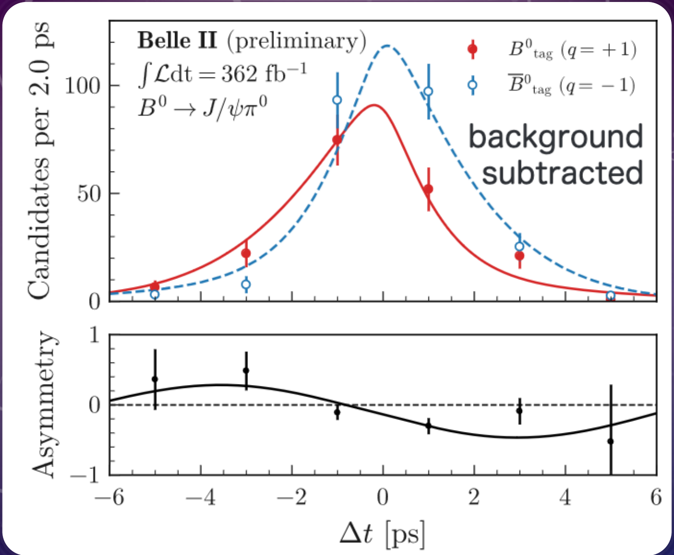
PRD 110 012001

PENGUINS IN B DECAYS

- In $B^0 \to J/\psi K_S^0$ the tree amplitude is dominant
- Other $b \to sq\bar{q}$ larger penguin contributions
- Sensitive to possible NP particles
- Measurements of CPV in B decays with large penguin contributions
  - Further understanding of the penguin amplitudes
  - Search for the effect of NP

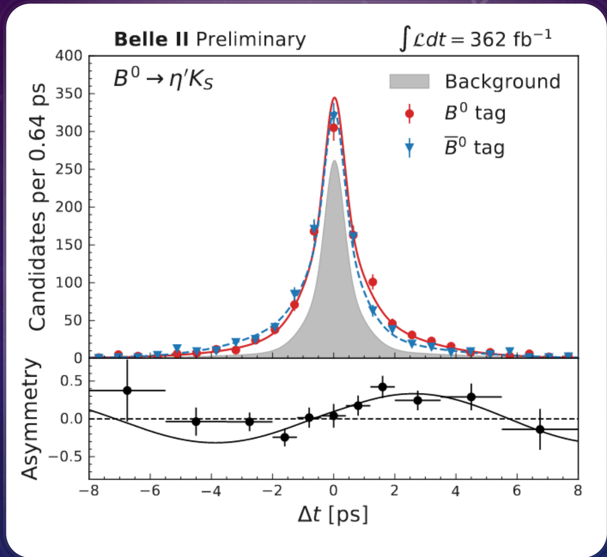


RECENT RESULTS IN DECAYS WITH PENGUIN CONTRIBUTIONS



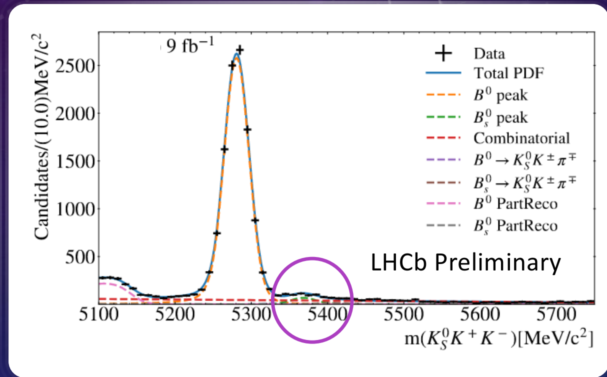
$$S = -0.88 \pm 0.17 \pm 0.03$$
$$C = 0.39 \pm 0.12 \pm 0.03$$

Can constrain the penguin contribution in $B^0 \to J/\psi K_S^0$.
1st observation of CPV in this channel



$$S = 0.67 \pm 0.10 \pm 0.04$$
$$C = -0.19 \pm 0.08 \pm 0.03$$

Limit tree contribution, results compatible with SM



$B^0_{(S)} \to K_S^0 hh'$ BF measurements

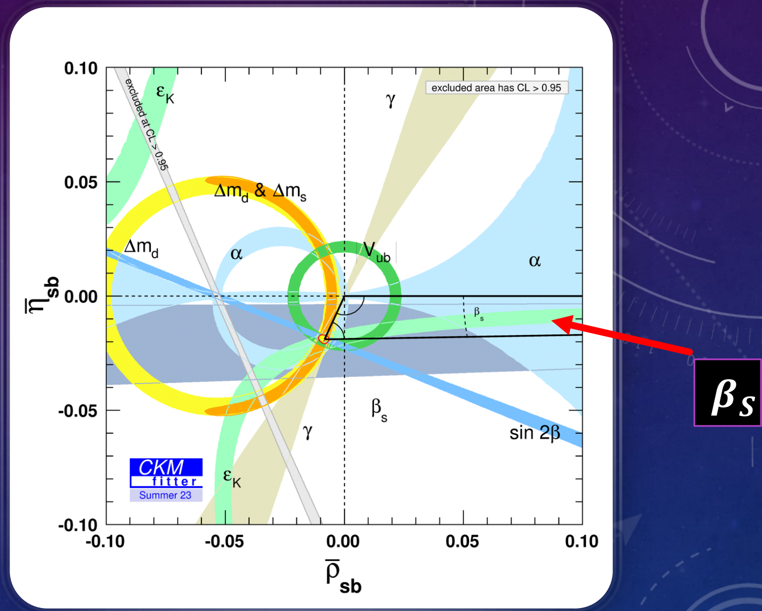
Refine QCD predictions for these and other charmless decay modes

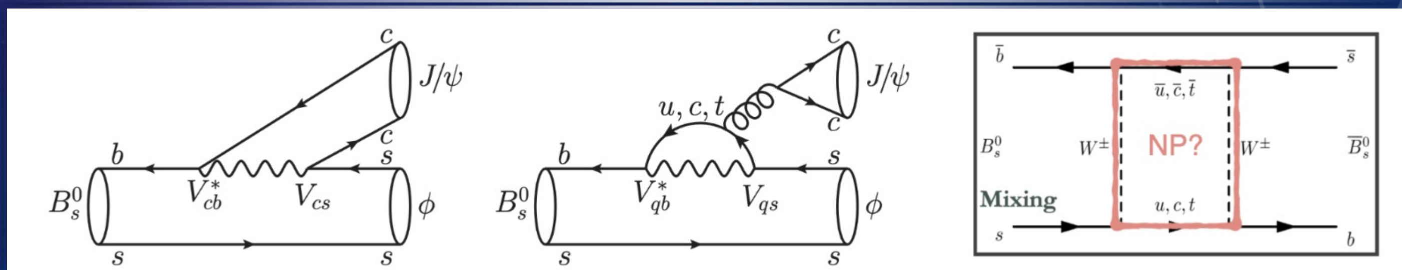
First observation of $B_S^0 \to K_S^0 KK$

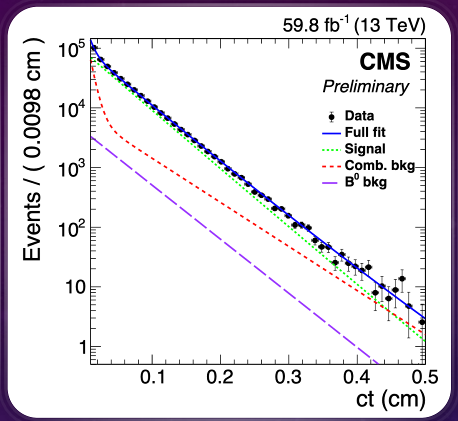
Belle preprint 2024-018 in prep
arXiv:2402.03713
LHCb-PAPER-2024-029

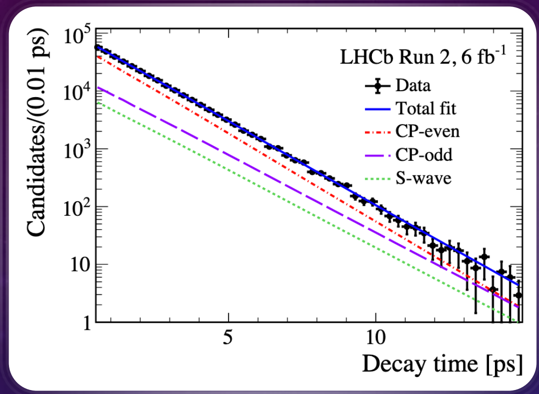
CPV IN $B_s^0 \to J/\psi\phi$

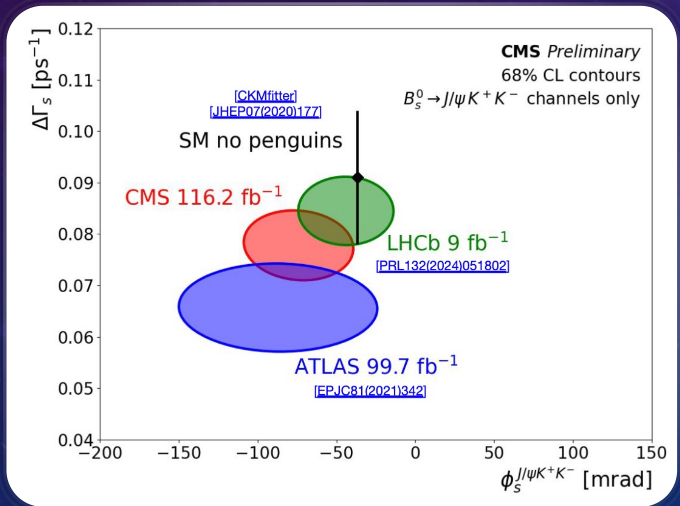
- SM prediction is small and accurate
- NP contribution in mixing can cause significant alterations
- Requires full angular fit to fully characterize the CP-even and CP-odd amplitudes.
- Non-zero width difference of the two B_S eigenstates











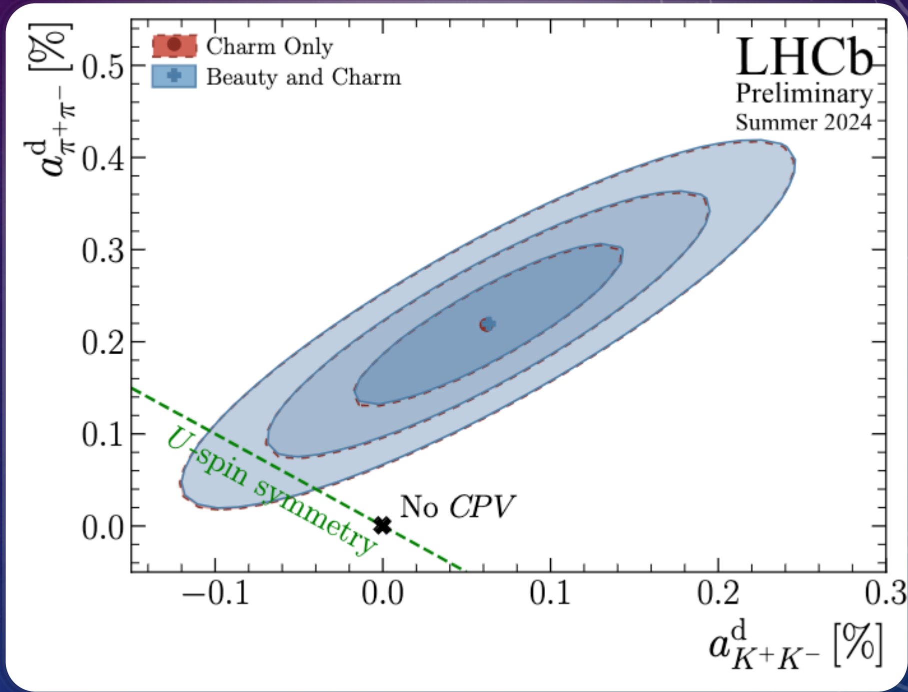
RECENT UPDATES FROM LHCb AND CMS

- CMS final tagging power averages at 5.6%. Cutting edge ML techniques
  - (LHCb comparison ~4.2%)
- Competitive measurement from CMS -First evidence of CPV in this channel
- Measurements of the $\tau_L\left(B_S^0 \to J/\psi\eta'\right)$ and $\tau_H\left(B_S^0 \to J/\psi\pi^+\pi^-\right)$ from other decays lead to $\Delta\Gamma_S$ consistent with SM.
- As these measurements of ϕ_S become more precise understanding the penguin amplitudes becomes more important

CMS-PAS-BPH-23-004
PRL 132 (2024) 051802
JHEP (2024) 253

CHARM CPV

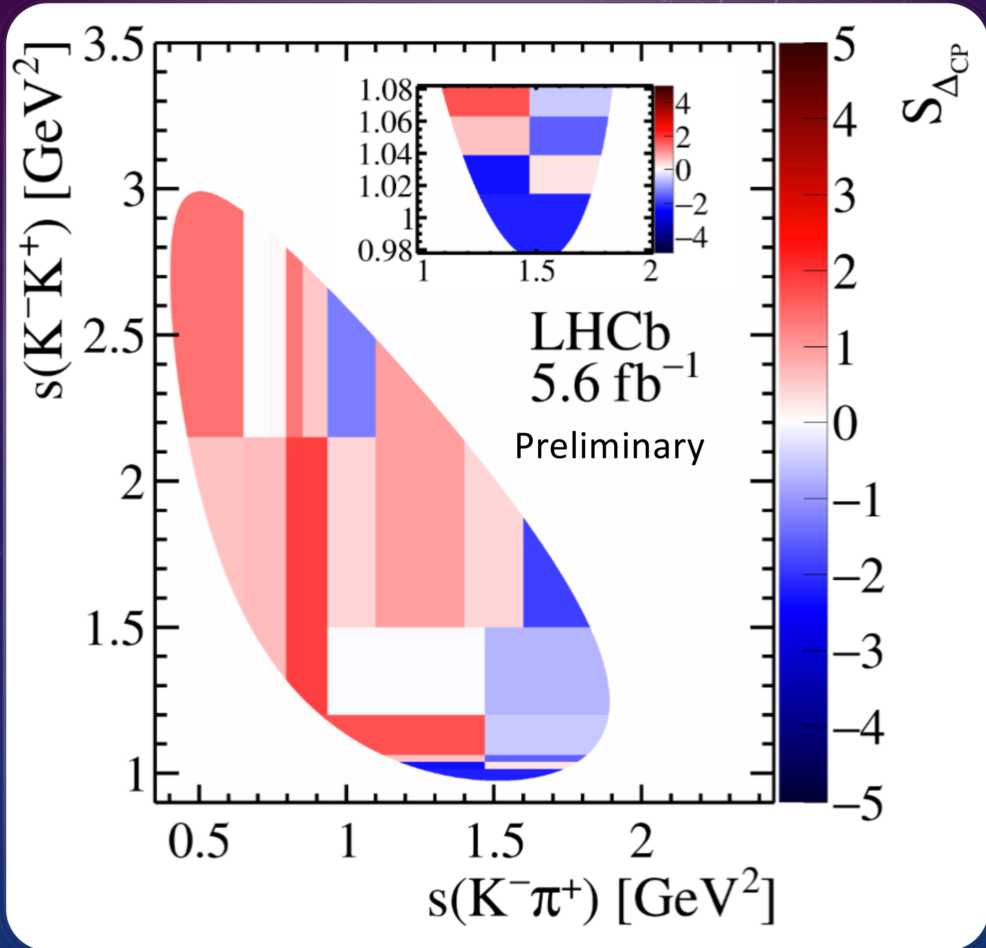
- Up sector CPV
- SM prediction difficult
- Small – disentangling detector effects crucial
- Single mode evidence only in $D^0 \to \pi^+ \pi^-$ decays – search elsewhere



PRD 101 (2020) 012005
PRL 131 (2023) 091802
LHCb-CONF-2024-004

$D^{\pm} \to K^{+}K^{-}\pi^{\pm}$

- CPV in this channel could be linked to the same mechanism as $D^0 \to hh$
- Look for local CPV
- Signal yield 135M
- Control channel $D_S^{\pm} \to K^{+}K^{-}\pi^{\pm}$ where no CPV expected
- Scale is the significance of the local CPV
- Data consistent with CP symmetry P=8.1%

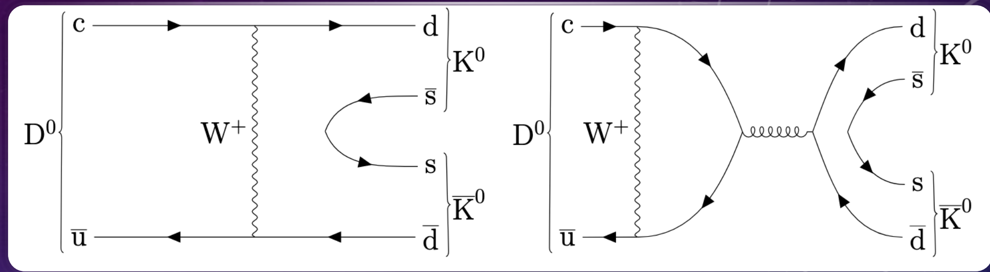


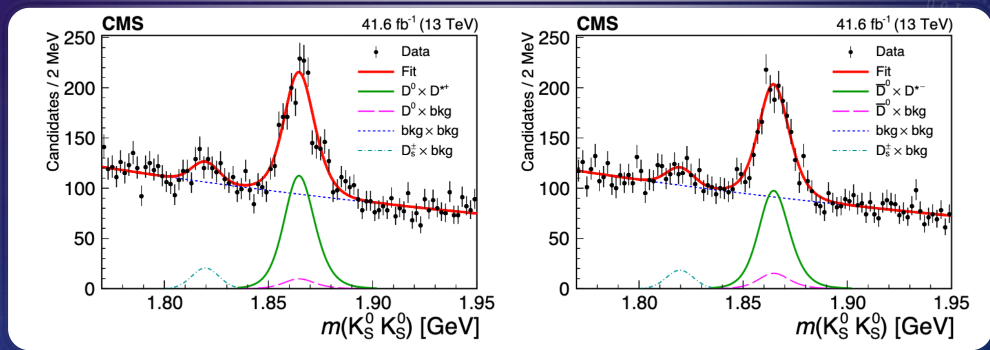
$D^0 \rightarrow K_S^0 K_S^0$

- Both diagrams have similar contributions but different phases – hence CPV may be large in this decay channel
- First charm CPV result from CMS from a dedicated dataset collected for heavy flavour physics

- $D^{*+} \rightarrow D^0\pi^+$ tags the flavour of D meson
- Subtract asymmetries from $D^0 \rightarrow K_S^0\pi\pi$ to remove production and detection asymmetries.
- Results $A_{CP(KsKs)} = 6.2 \pm 3.0 \pm 0.2 \pm 0.8$ %

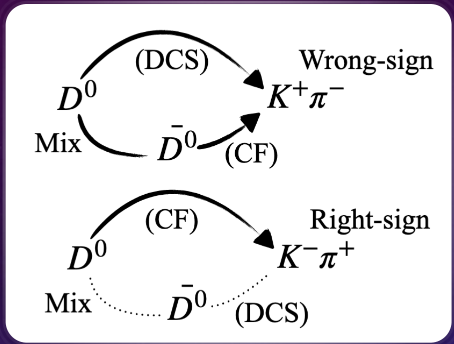
cf LHCb: $A_{CP(KsKs)} = -3.1 \pm 1.2 \pm 0.4 \pm 0.2$ %

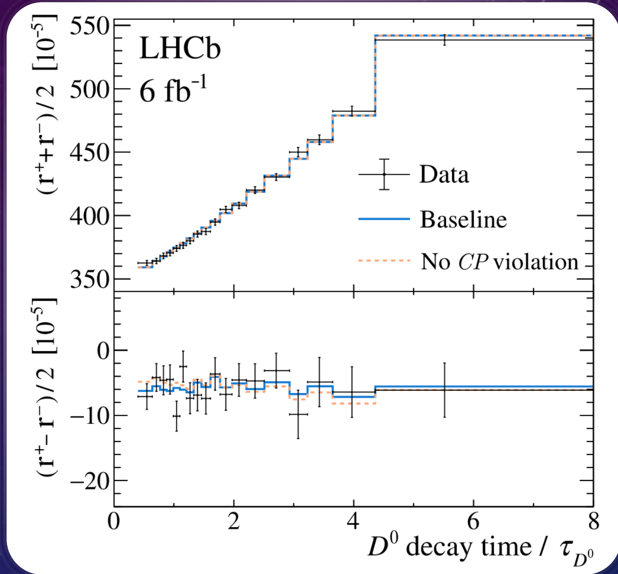




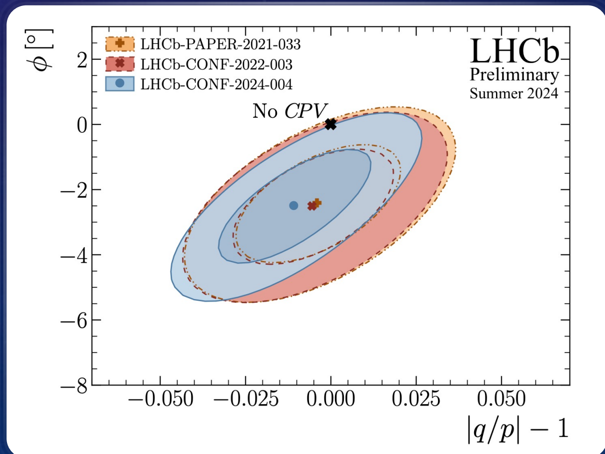
arXiv:2405.11606
PRD 104 031102 (2021)

CHARM CPV IN INTERFERENCE OF DECAY AND MIXING





- Yet to be observed
- Significant improvement in the mixing parameters
- No evidence of any CPV
- Allowed parameter space consistent with no CPV continues to shrink

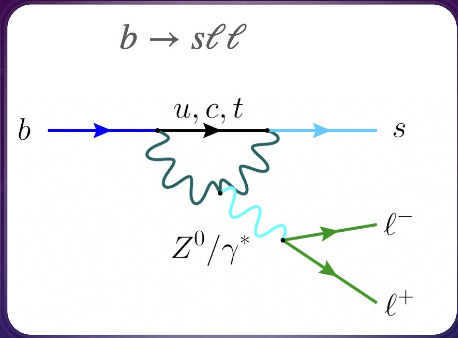


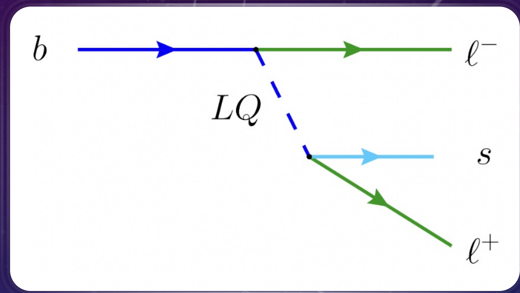
LHCb-PAPER-2024-008

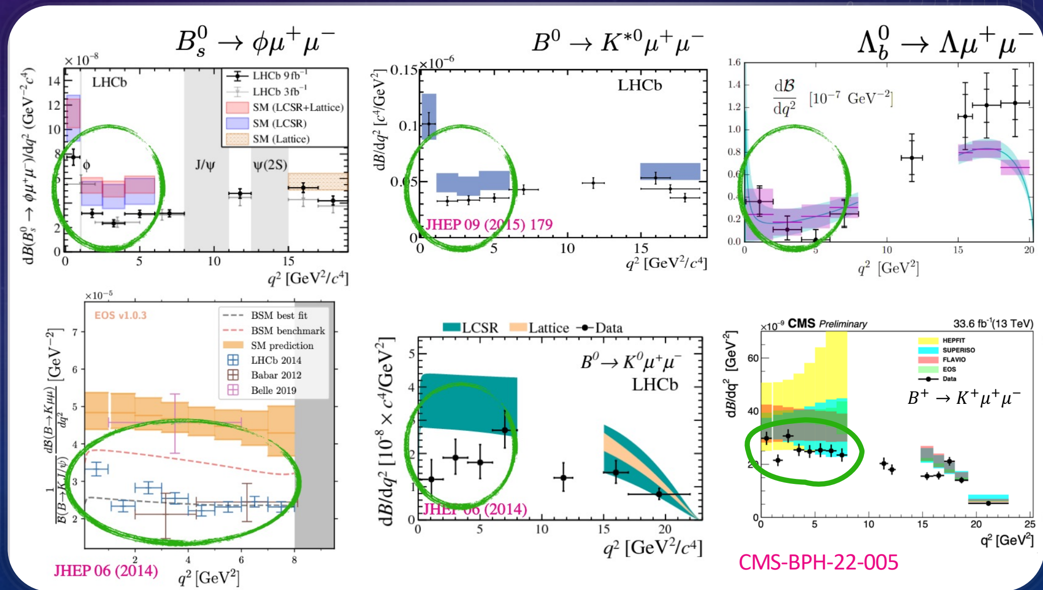
FCNC

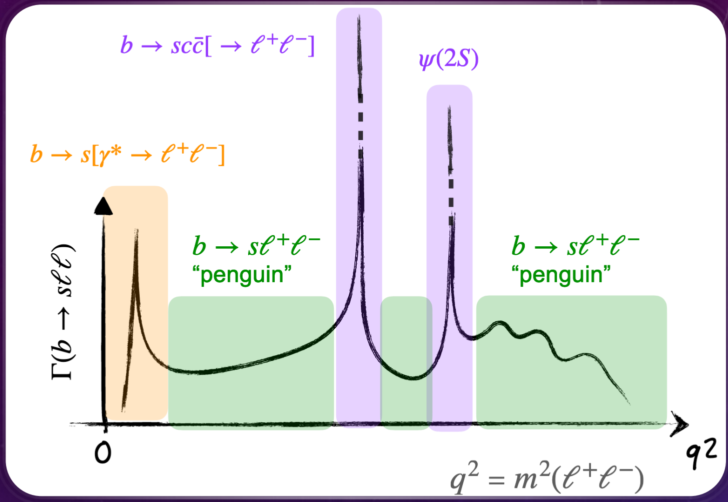
- FCNC suppressed in the SM
- Can be enhanced by NP
- $b \to sll$ transitions have a consistent pattern of the rate being too low in certain regions across many channels

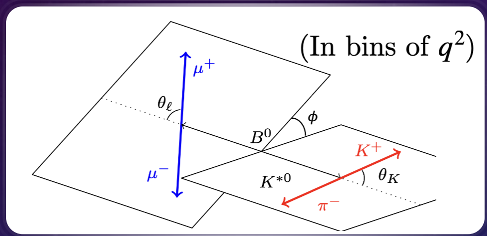
- Selection of results (there are more)











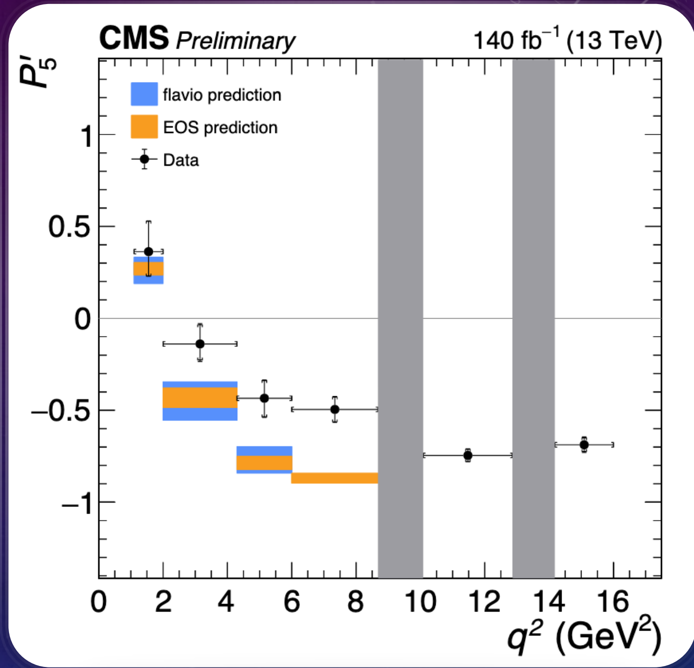
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \big(\frac{1}{4}(1-F_L)\sin^2\theta_K - F_L\cos^2\theta_K\big)\cos 2\theta_l + \frac{1}{2}P_1(1-F_L)\sin^2\theta_K\sin^2\theta_l\cos 2\phi + \sqrt{(1-F_L)F_L}\big(\frac{1}{2}P_4'\sin 2\theta_K\sin 2\theta_l\cos\phi + P_5'\sin 2\theta_K\sin\theta_l\cos\phi\big) - \sqrt{(1-F_L)F_L}\big(P_6'\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}P_8'\sin 2\theta_K\sin 2\theta_l\sin\phi\big) + 2P_2(1-F_L)\sin^2\theta_K\cos\theta_l - P_3(1-F_L)\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

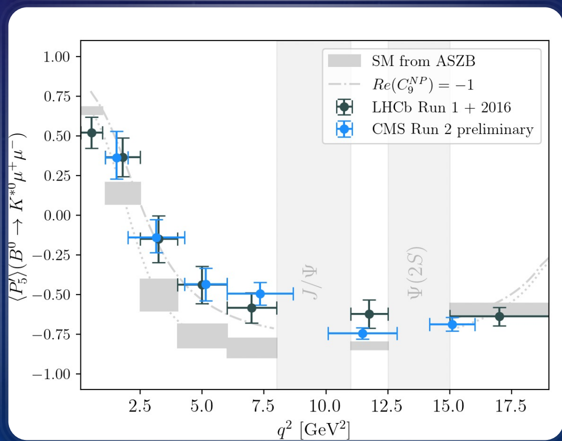
$B^0 \to K^{*0}\mu^+\mu^-$

- Study the differential branching fraction
- 3 angles and q^2
- To reduce dependence on hadronic form factors the differential BF can be built in terms of optimised observables
- P_5' is one of these

NEW CMS ANALYSIS

- Comparable sensitivity to the LHCb results
- Confirms the differences between the SM prediction and data from LHCb Run1+2016 data



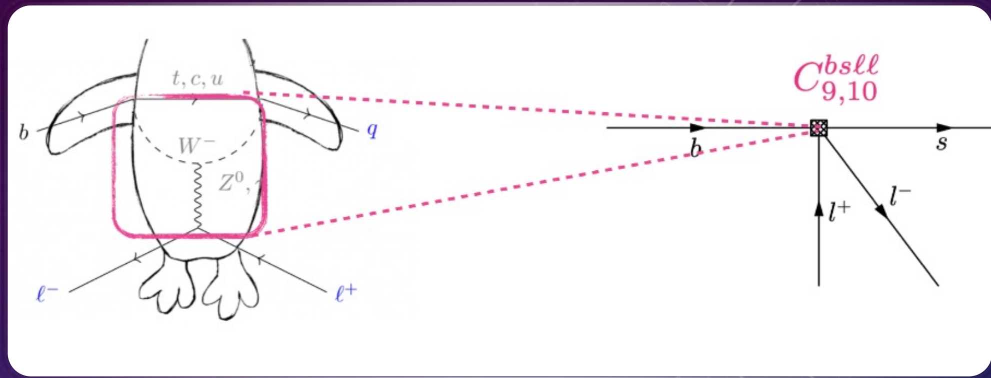


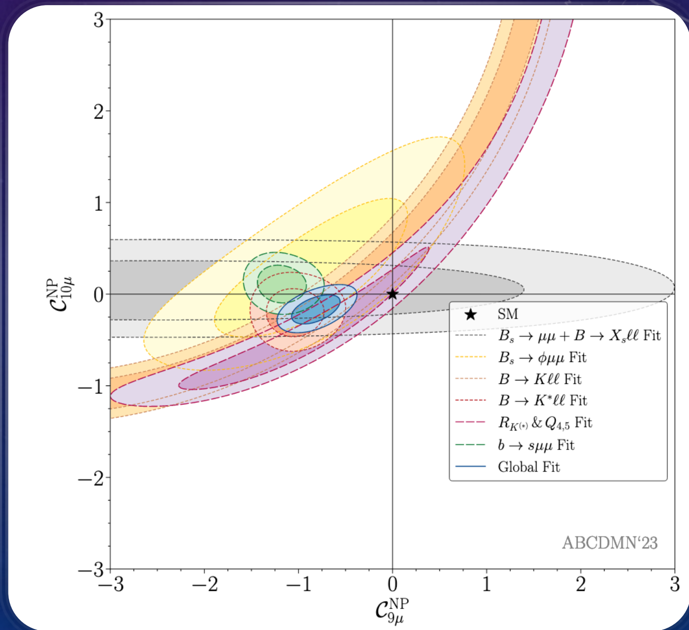
CMS-PAS-BPH-21-002
Phys. Rev. Lett. 125, 011802

WILSON COEFFICIENTS

- EW scale >>m_b
- Replace the loop with effective couplings

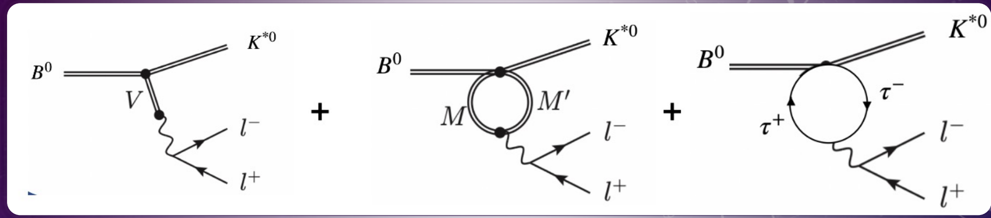
- Global fit of all BF and angular analysis of $b \to sll$ transitions (not yet the new CMS result)
- Discrepancy with the SM value
- NP or lack of understanding of hadronic effects [charm-loops and similar]



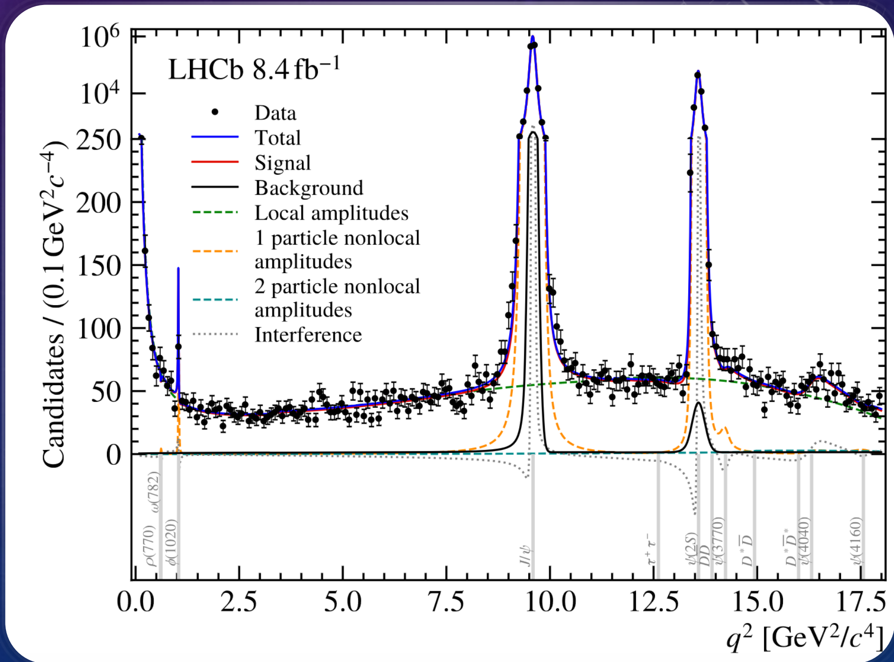


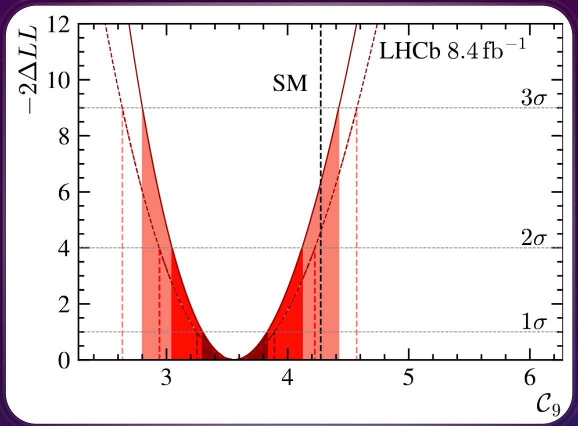
arXiv:2304.07330

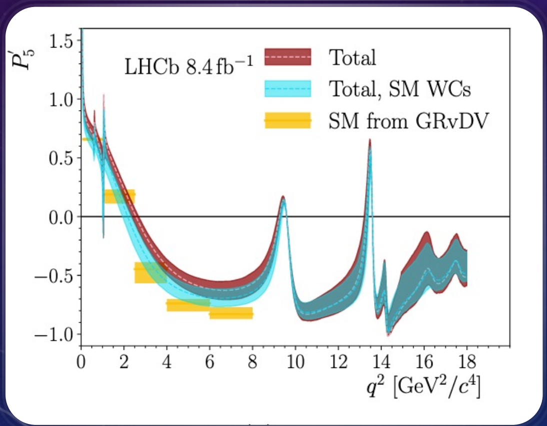
$B^0 \to K^{*0}\mu^+\mu^-$ NON-LOCAL AMPLITUDES



- Amplitude analysis of the full q^2 spectrum
- Include all resonances
  - Light hadrons $\omega, \rho, \phi\ etc$
  - Charmonia
  - Double Charm
  - τ loops







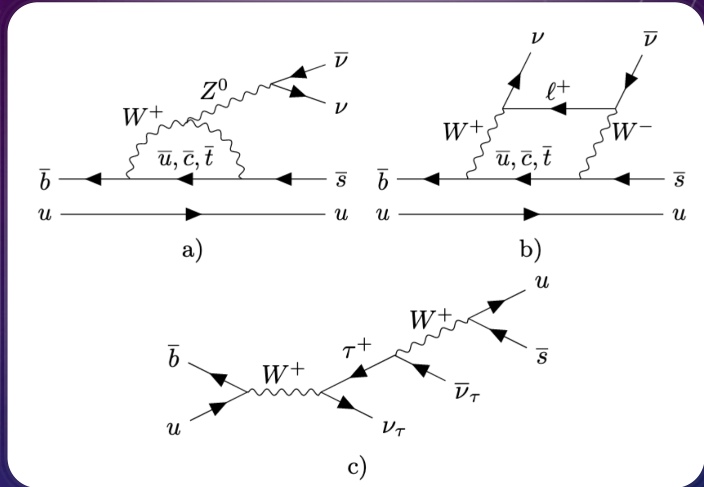
INTERPRETATION

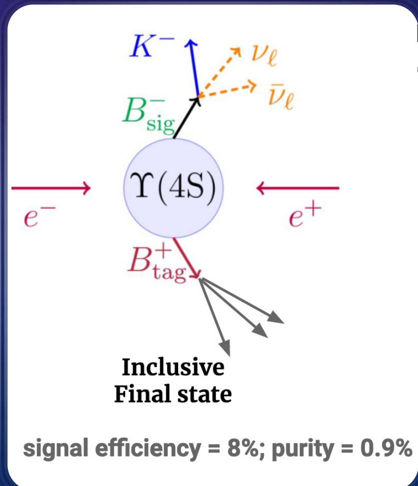
- There is some contribution of non-local amplitudes leaking into the binned analysis
- However, there is still preference for a result for C_9 value shifted from the SM model 2.1 σ
- Data prefers larger P_5' values even with WC set to SM parameters

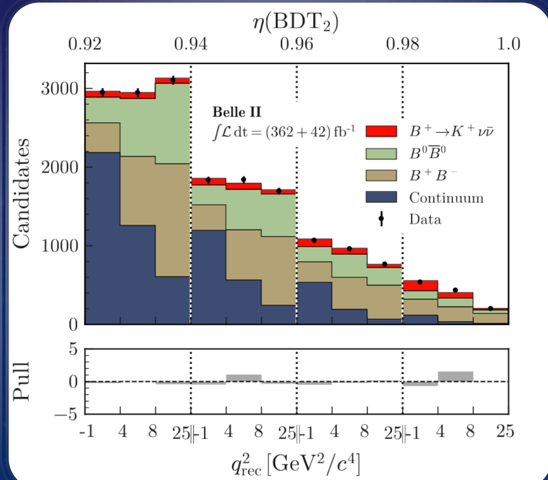
arXiv:2405.17347

$B^+ \to K^+\nu\bar{\nu}$

- Predictions are relatively more precise; than due to no hadronic uncertainties beyond form factors unlike $b \to sll$
- However extremely challenging signature
- Full reconstruction of the tag-side B
- New inclusive tagging method
- First evidence of the decay
- BF:$(2.3 \pm 0.7)\times10^{-5}$
- 2.7σ sigma from SM prediction

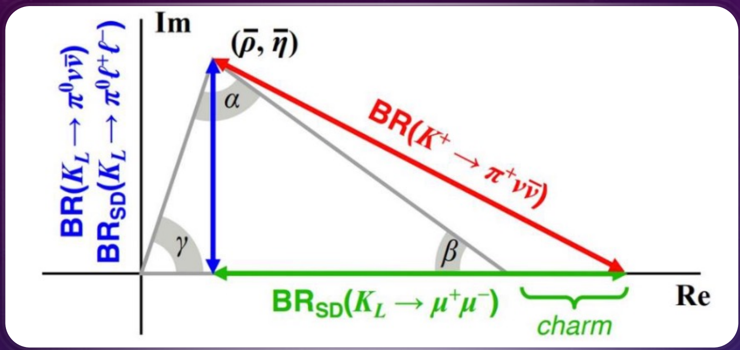




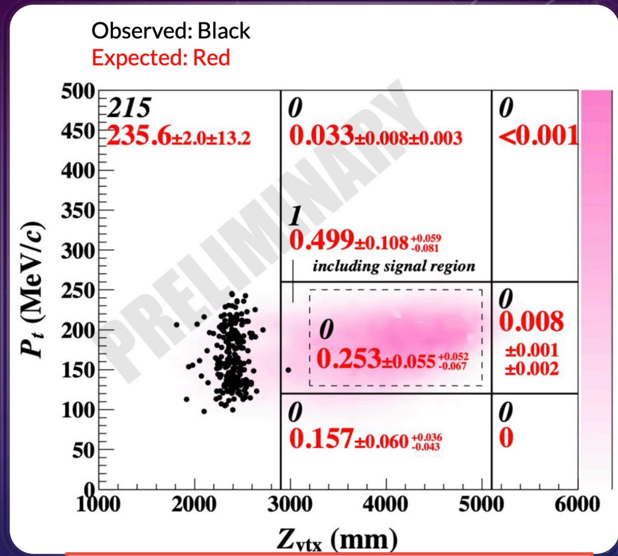


PRD 109 112006 (2024)

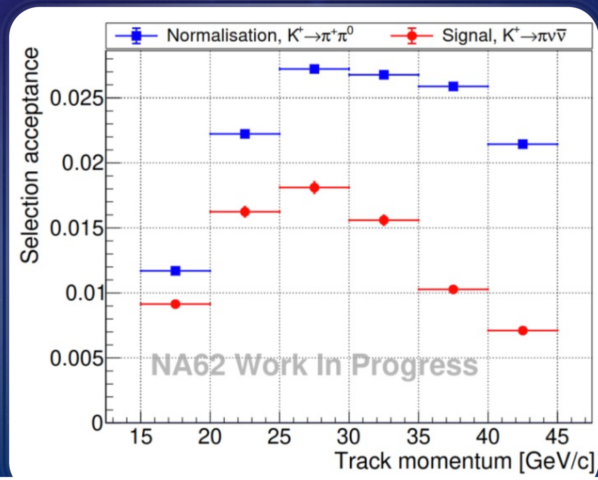
FCNC IN KAONS



- Kaon physics can constrain the UT on its own
- CKM parameters are larger source of SM uncertainty
- New preliminary result from KOTO on $K_L^0 \to \pi^0 \nu\bar{\nu}$
- Charged kaon bkg reduced with new upstream veto detector
- New detectors and analysis techniques reduce bkg by factor 5



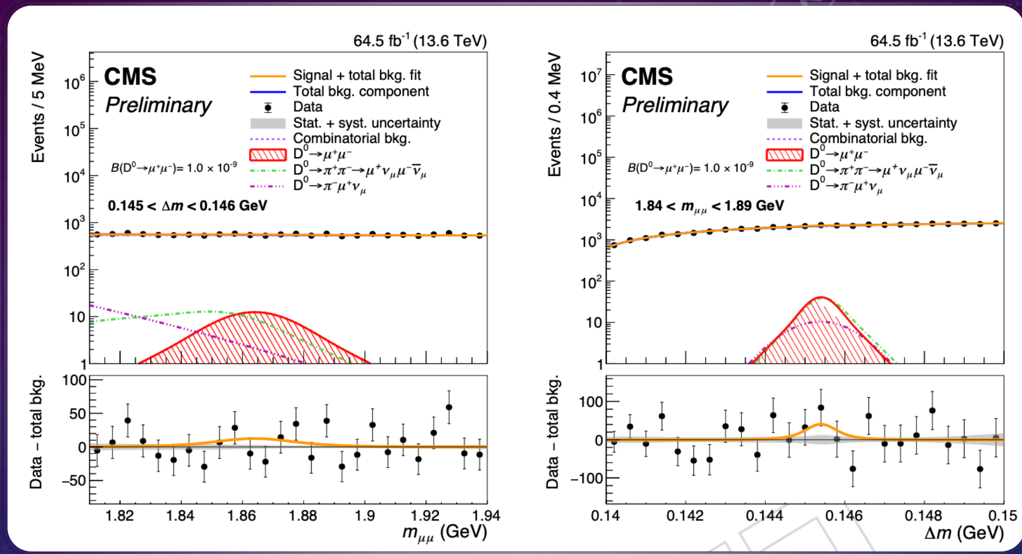
BF: $K_L^0 \to \pi^0 \nu\bar{\nu} < 2\times10^{-9}$



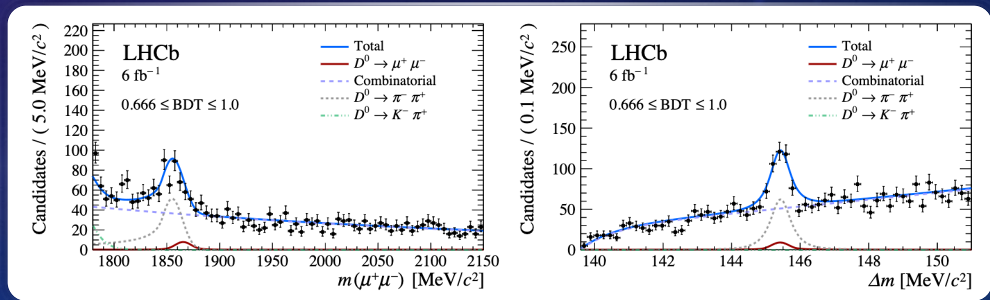
New hardware at NA62 – analysis of Run 2 data underway

$D^0 \to \mu^+\mu^-$

- SM BF ~ 10^{-13}
- Long distance effects are dominant
- One of the most sensitive FCNC in the up sector
- BF is a primary building block of NP models
- Also correlated to the mixing rate in NP models

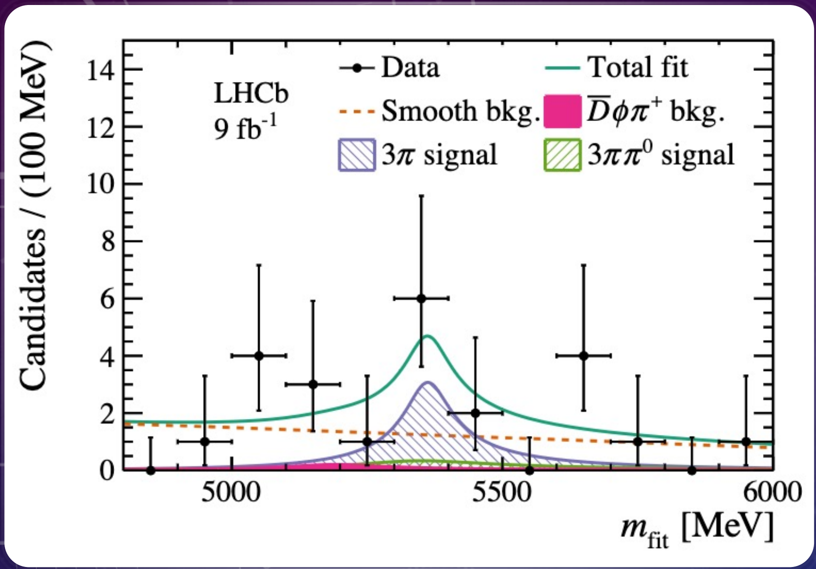


- CMS: 2022-2023 data. Low mass di-muon trigger strongly enhances the experiment capabilities
- CMS: BF $D^0 \to \mu^+\mu^- < 2.6\times10^{-9}$ @95% CL
- LHCb: BF $D^0 \to \mu^+\mu^- < 3.5\times10^{-9}$ @95% CL



CMS-BPH-2023-008
PRL131 041804 (2023)

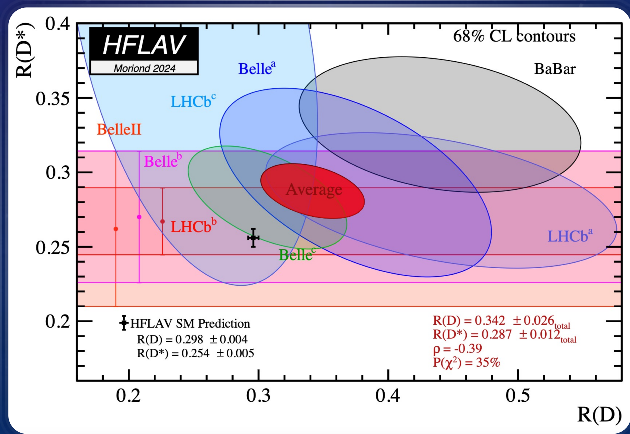
CLFV – UNAMBIGUOUS SIGNS OF NP



- Lepton Flavour Violation is forbidden in the SM
- If the hints of nonuniversality in charged current in $b \to c l^- \bar{\nu}\ (l = \tau, \mu)$ are real then likely to have cLFV
- The excess in $B^+ \to K^+ \nu\bar{\nu}$ decays points to similar NP models
- Coupling to 3rd generation larger in many models (both b and tau present here)

BF $B_S^0 \to \phi\mu^\pm \tau^\mp < 1.1\times10^{-5}$ @ 95% CL

Direction and mass constraints used to account for the missing neutrino

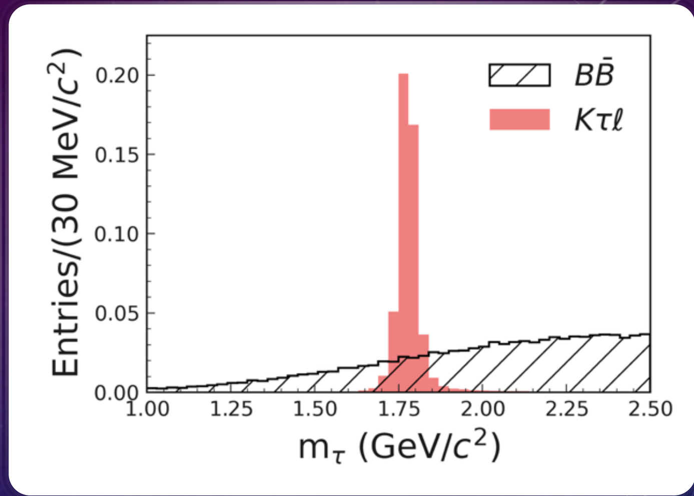


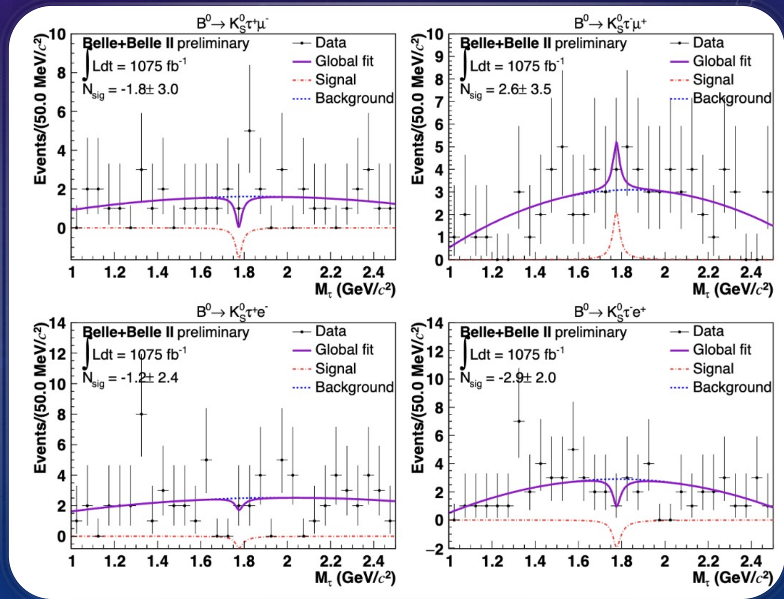
arXiv:2405.13103

$B^0 \to K_S^0 \tau^\pm l^\mp$

- Similar motivation for these decays
- Compute the recoil mass of the $\tau^\pm$ lepton
- Suppresses background
- No signal, 90% CL are set

$$\mathcal{B}(B^0 \to K_S^0 \tau^+ \mu^-) < 1.1 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^- \mu^+) < 3.6 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^+ e^-) < 1.5 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^- e^+) < 0.8 \times 10^{-5}$$

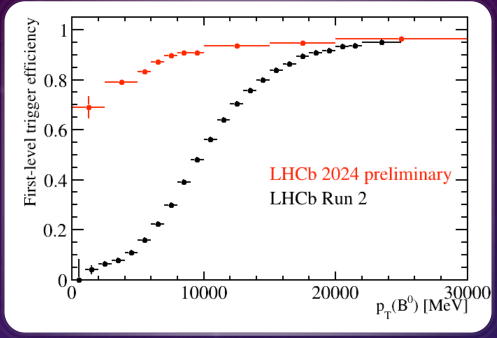


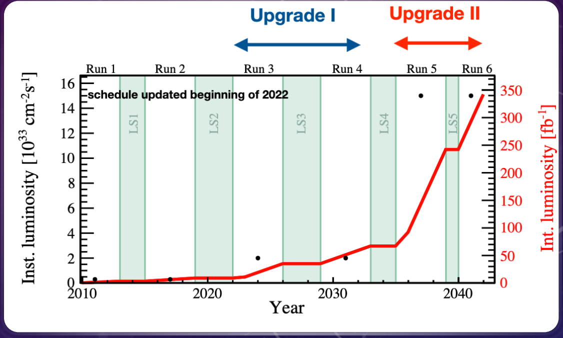


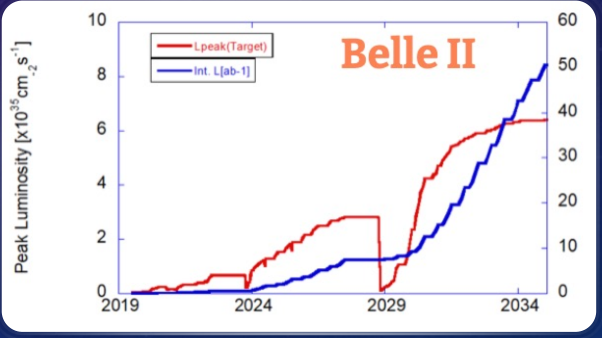
Belle & Belle II new result

INCOMING/FUTURE DATA

- LHCb
  - Substantial upgrade I, increased data taking rate and hadronic trigger efficiency
  - Ambitious further upgrade 2 in 2030s
- Belle II taking data
  - Improvement plans evolving for interaction region and detector
- BESIII charm dataset increased x7
  - Super Tau Charm Factory plans
- NA62, CMS, ATLAS, KOTO all have more data incoming
  - HL-LHC, KOTO II plans







LHCB-TDR-023
2406.19421
2303.15790

CONCLUDING THOUGHTS

- No obligation for NP discovery to be easy
- We can do complicated things
  - Multibody decays, time dependence, FT, amplitude analysis, challenging final states
  - Maximising current data through cutting edge techniques, pushing experiments beyond design, exploiting synergies between experiments
- Interpreting results across the board of quark flavour requires better understanding of things like penguin amplitudes, form factors, hadronic uncertainties.
  - Progress is ongoing and we will get there
- Powerful datasets on their way – this is an exciting way to understand the SM search for NP