CHARM and BEAUTY

Quarks 2026, Petrozavodsk, Russia

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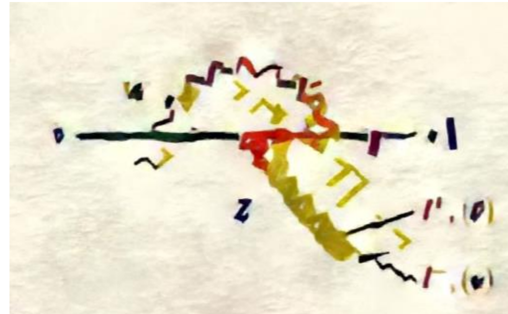
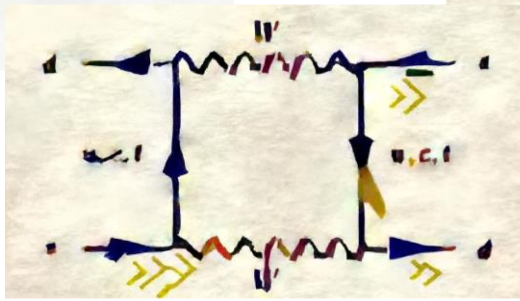
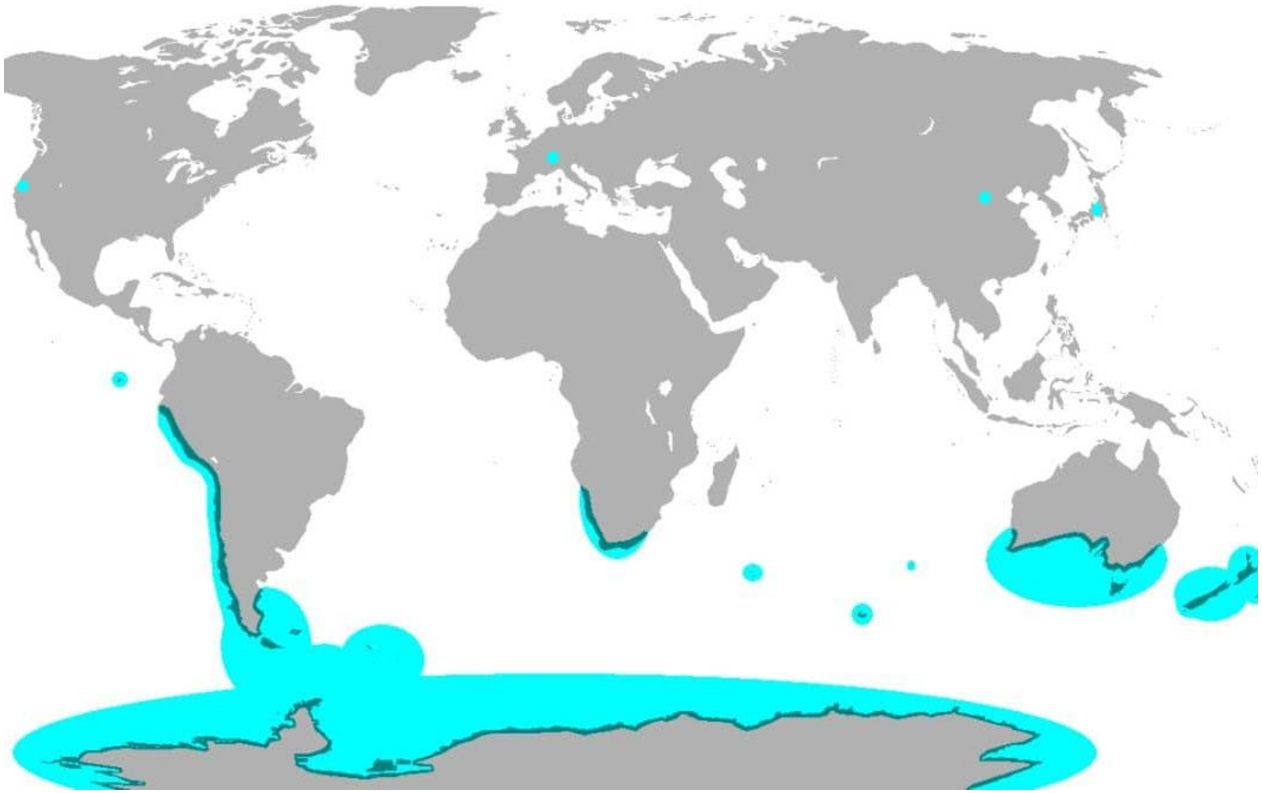


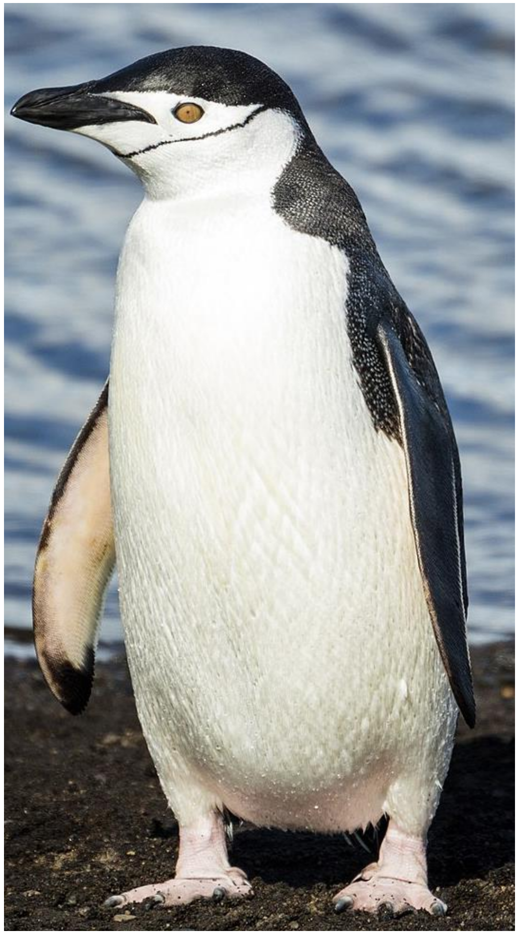


My story will be about charm boxes and beauty penguins with an ornithological focus.

Penguins

Penguins are a group of flightless semi-aquatic sea birds which live almost exclusively in the Southern Hemisphere

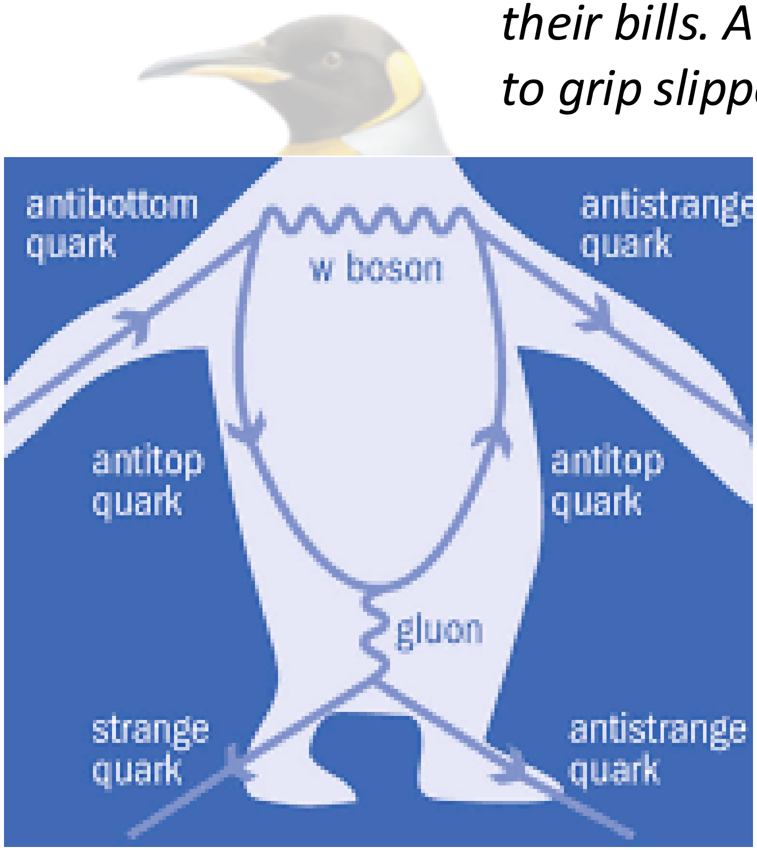




In the Northern Hemisphere, penguins are found on the Galapagos Islands, zoos, and in HEP laboratories such as KEK, SLAC, CERN (thanks to John Ellis – a father of HEP penguins)

Beauty penguins

Penguins feed on forms of sea life which they catch with their bills. A penguin has a spiny tongue and powerful jaws to grip slippery prey.



Beauty penguins born in HEP laboratories can catch, as we believe, W boson and top quark. All this digestion happens in its fat body (which it timidly hide among the cliffs). Getting in or peeking inside a silly penguin is forbidden by quantum mechanics. From the outside, one can only witness how beauty turns into strangeness.

With their ability to grasp even the slipperiest of objects, penguins appear to be, if not the only, then at least the most promising hunters of New Physics...

Heavy flavor Physics at LHC era…

…still remains interesting?

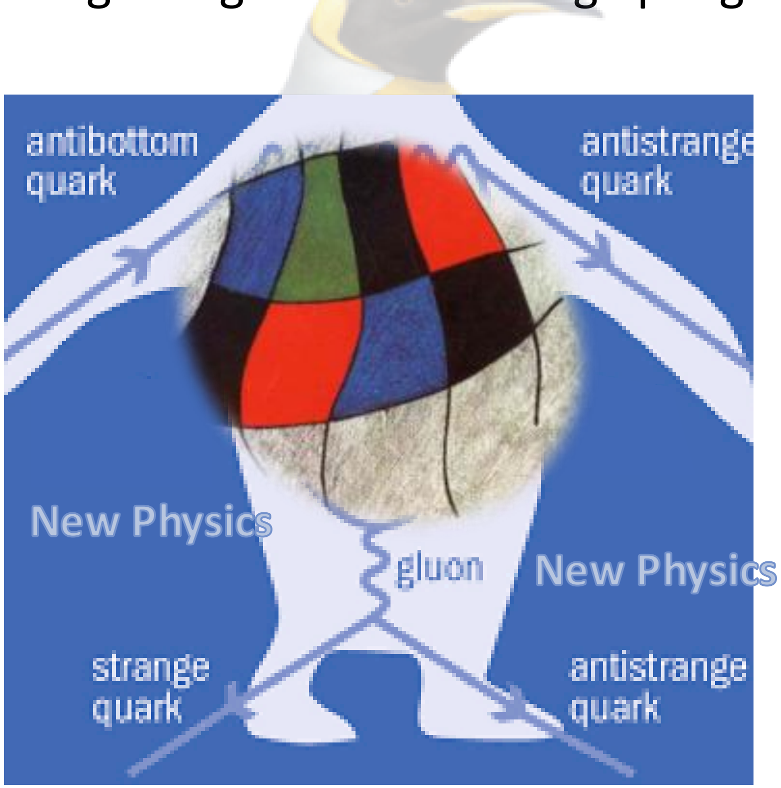
The answer is illustrated by this picture, borrowed from Avelino Vicente lecture.

Before the LHC started, we dreamed of rich new phenomenology at the energy frontier and new ideas following from its observations. So far, the LHC has delivered the Higgs boson, but nothing else. While the HL-LHC has the potential to observe new physics, the chances are slim.

But, this NP non-observation increases the prospects of discovering New Physics in precision frontier experiments.

Penguins & boxes

Beauty penguins were first observed in B-decays in 1990th by CLEO and ARGUS. In the beginning of 2000th strange penguins were observed indirectly as the direct CP violation in K0 meson system. Both measurements indicated that without the top quark, unitarity is weakly violated. Moreover, the heavier the top quark (making its direct observation less likely), the larger the penguin-diagram contribution, which increases the chances of detecting the top quark indirectly. Thus, energy and precision frontier experiments appear to be complementary.



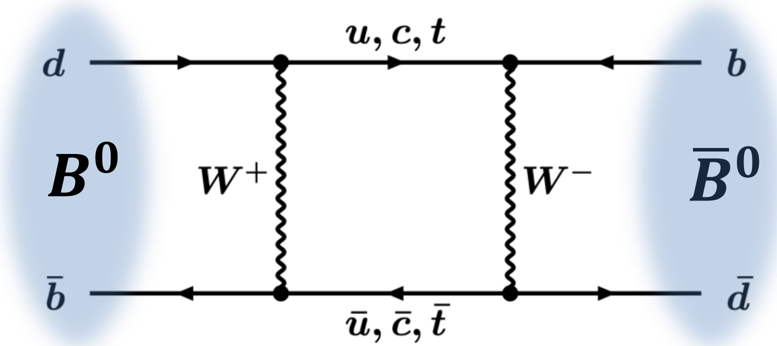
Similarly:

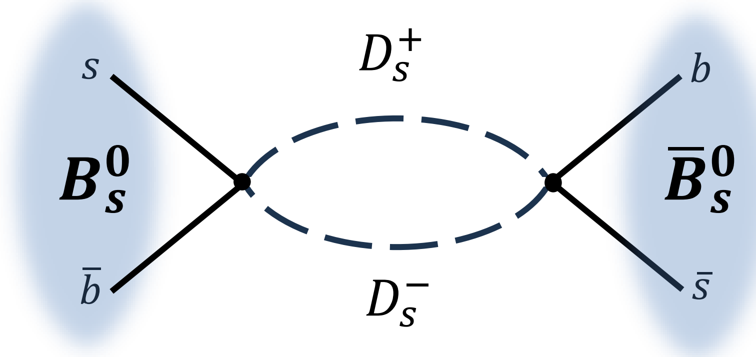
The absence of NP at the LHC supports that NP may manifest itself via loop diagrams (penguins & boxes). Such effects can only be observed as subtle deviations in loop-dominated processes (in particular, in interference with tree diagrams).

BOXES

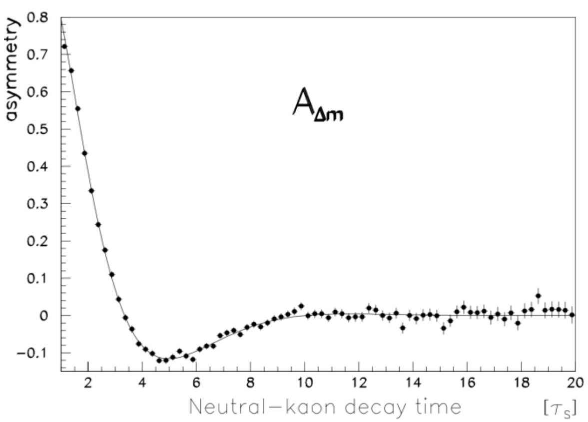
Boxes and neutral meson oscillations

Flavor oscillation, or mixing, is a crucial phenomenon studied for many years in the K^0, B_d^0, and B_s^0 systems. It is due to boxes or virtual loops.





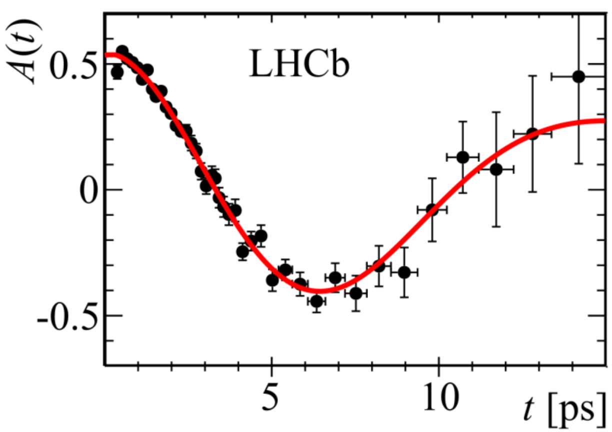
K^0 oscillations:



[CPLEAR, NuclPhys 626 (1997)]

$$x = \frac{\Delta m}{\Gamma_S} = 0.47 \quad y = \frac{\Delta\Gamma}{2\Gamma} \approx 1$$

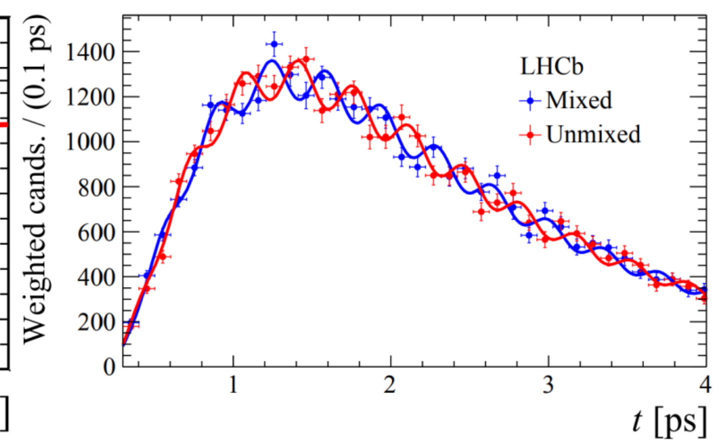
B^0 oscillations:



[LHCb, EPJC 76 (2016) 412]

$$x = \frac{\Delta m}{\Gamma} = 0.77 \quad y = \frac{\Delta\Gamma}{2\Gamma} \approx 0$$

B_s^0 oscillations:

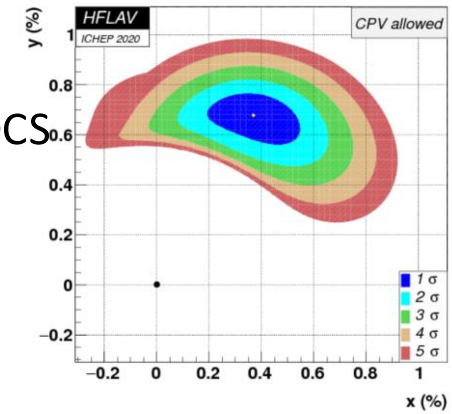


[LHCb, EPJC 79 (2019) 706]

$$x = \frac{\Delta m}{\Gamma} = 17.8 \quad y = \frac{\Delta\Gamma}{2\Gamma} \approx 0.06$$

Charm mixing

$x \sim 1\% \gg y$ would be a strong hint for NP



- D^0-mixing using $D^0 \to K^+\pi^-$:

measure x', y' rotated by $\delta_{K\pi}$ – strong phase difference between CF & DCS

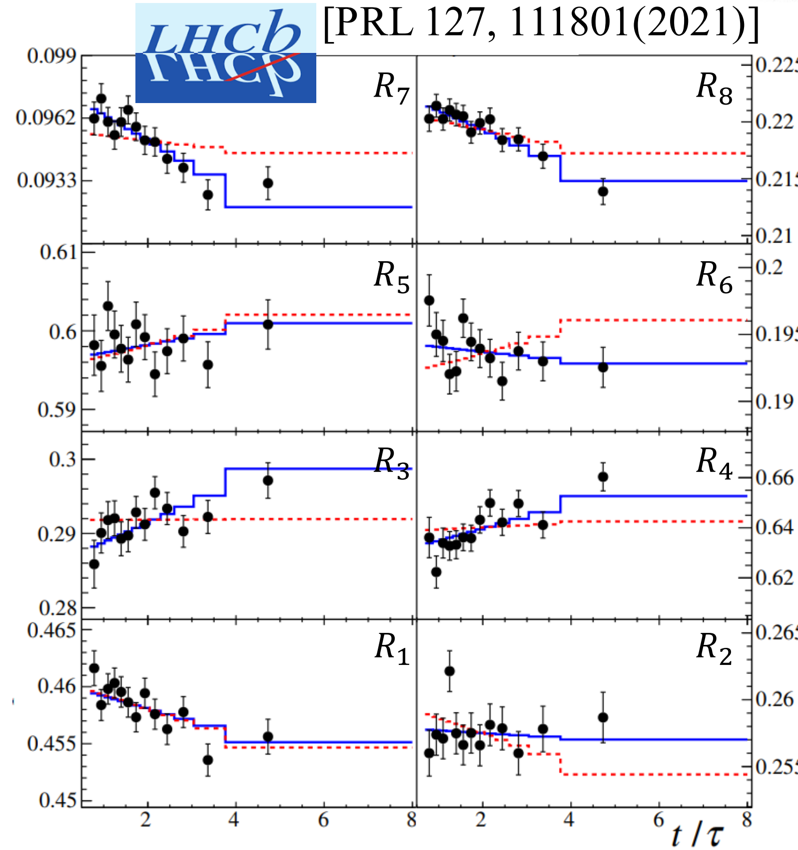
$$R(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

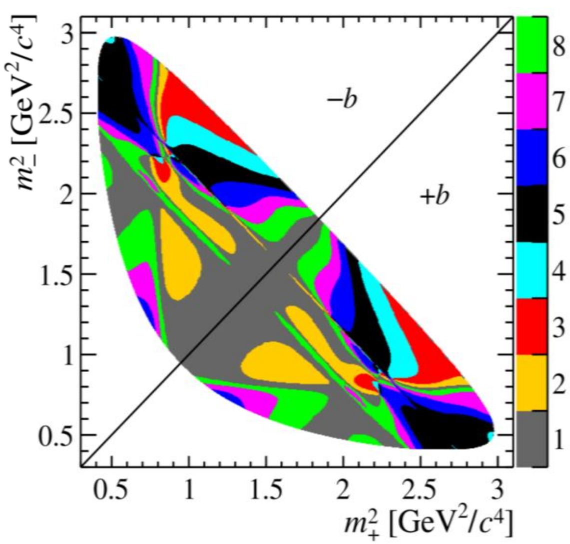
- D^0-mixing using $D^0 \to K_S^0 \pi^+\pi^-$

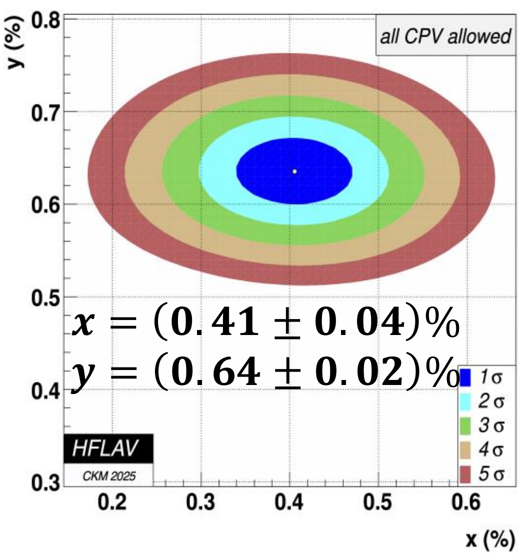
allows to extract x and y, moreover, in a model-independent way:

The Dalitz plot is partitioned into 16 bins with a constant strong-phase in each bin. The bin boundaries and their phases are done by BESIII [PRL 124, 241802 (2020)].

[PRL 127, 111801(2021)]







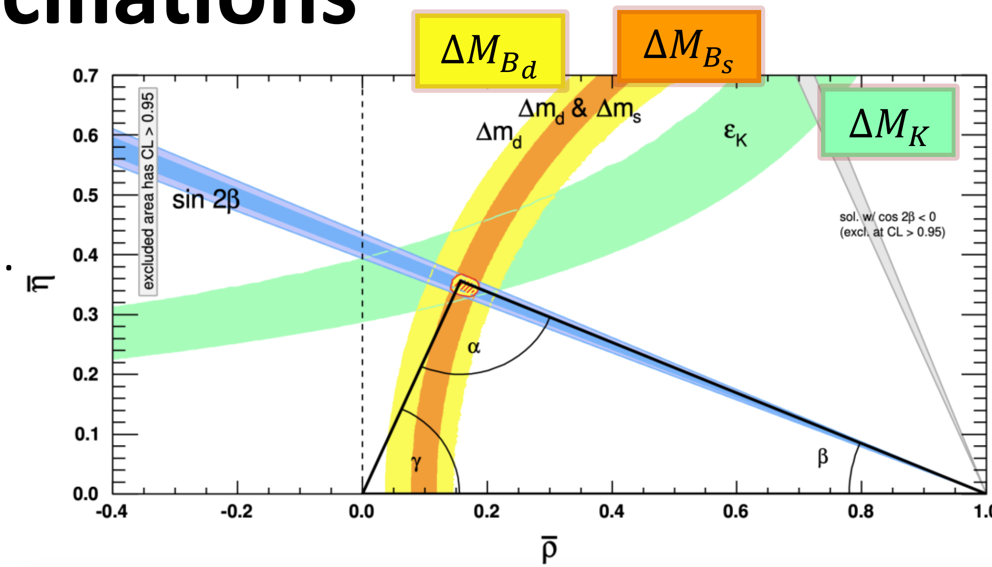
$x = (0.41 \pm 0.04)\%$
$y = (0.64 \pm 0.02)\%$

But, alas: $x \sim y \lesssim 1\%$ is consistent with SM

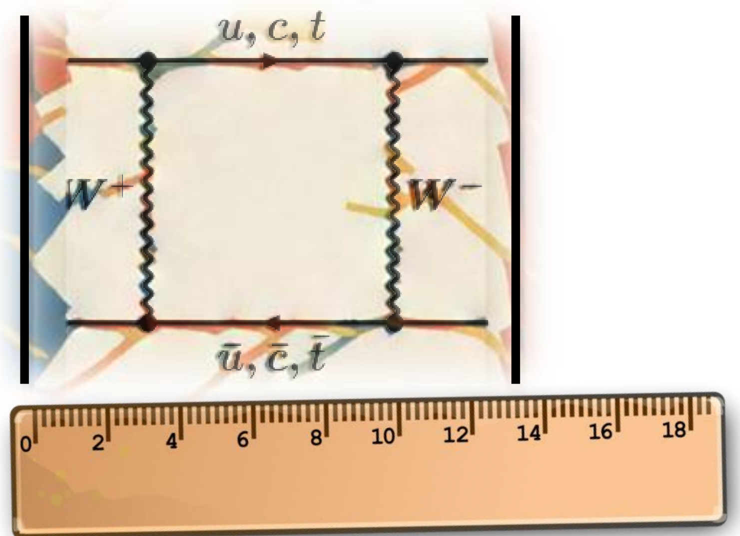
Strength of meson oscillations

The measured x and y in K^0, B_d^0, and B_s^0 systems are consistent with the SM. Moreover, x (and to a lesser extent y) constrain the SM parameters (UT triangle).

x and y in D^0 are mostly dominated by long-distance QCD effects, and their experimental values can be accommodated within SM.

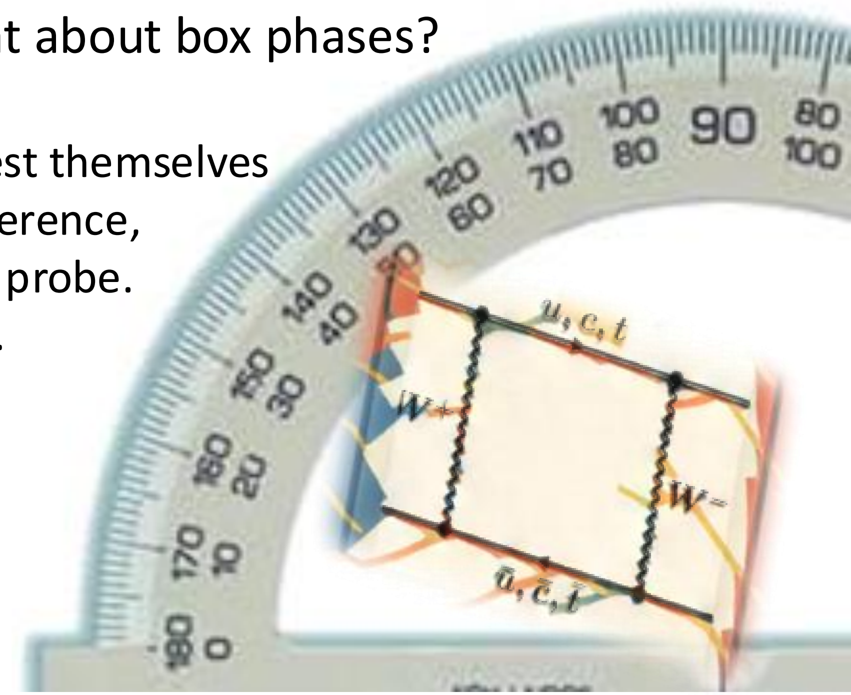


Oscillation strength measures just absolute value of the box diagram:



What about box phases?

Phases manifest themselves through interference, and their best probe. is CP violation.



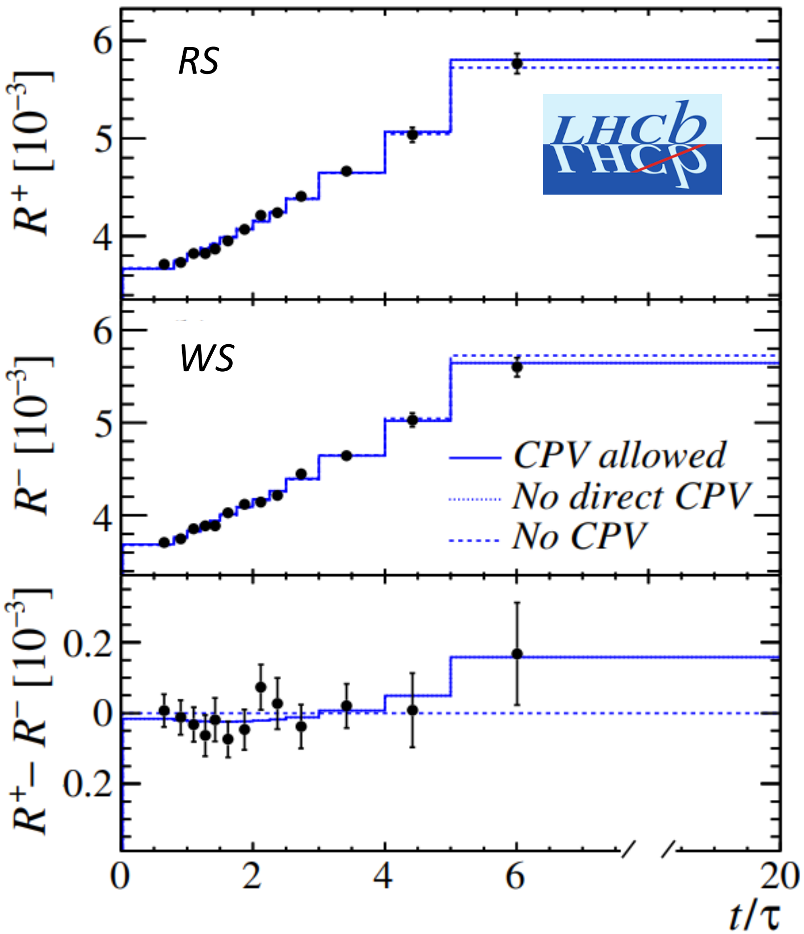
Search for CP violation in charm

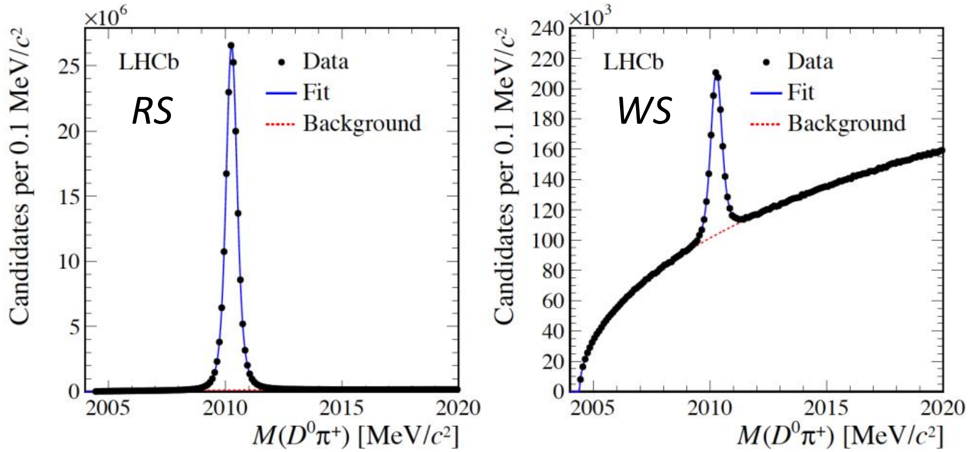
t-dependence in $D^0 \to K^+\pi^-$ Right/Wrong signs

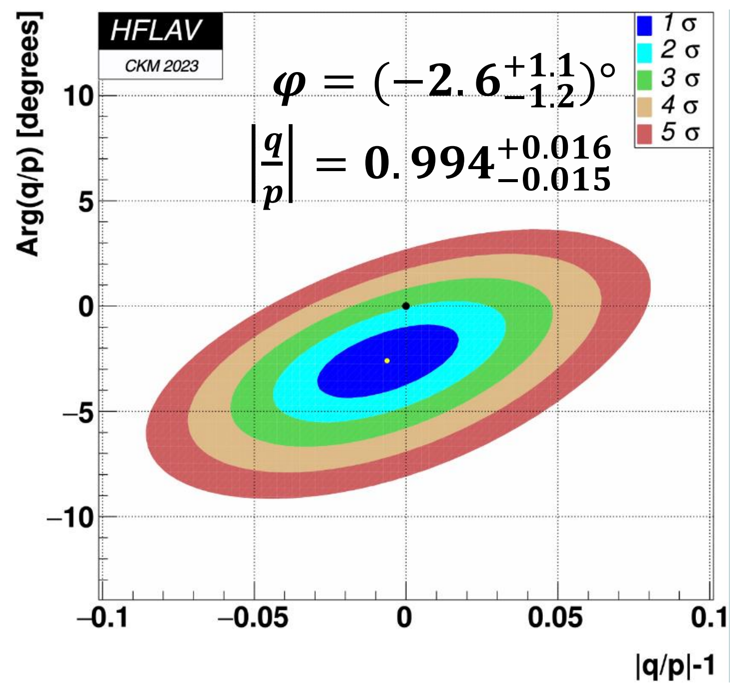
LHCb [PRD 97, 031101 (2018)]

CPV in mixing: $|D_{1,2}\rangle = p|D^0\rangle \mp q|\bar{D}^0\rangle$,

if CPV: $\left|\frac{q}{p}\right| \neq 1$,or/and $\varphi = Arg\left(\frac{q}{p}\right) \neq 0$.







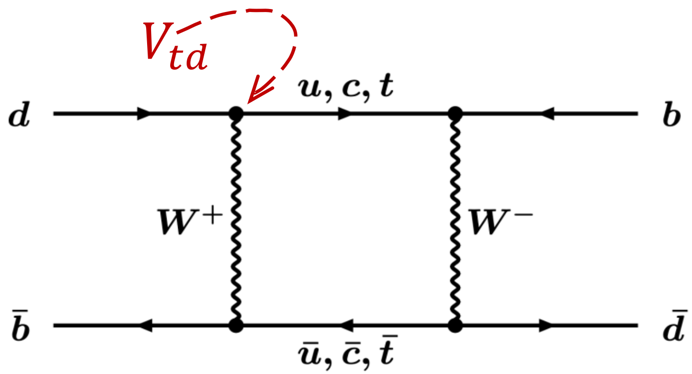
no evidence for CP violation; the current most stringent bounds on the CPV parameters

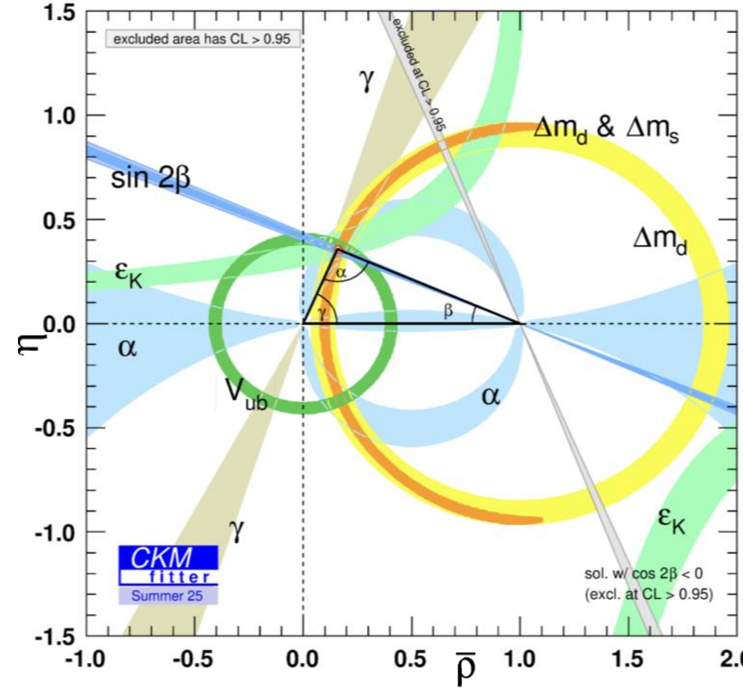
CP violation in beauty

Box's phases are measured in CPV in mixing:

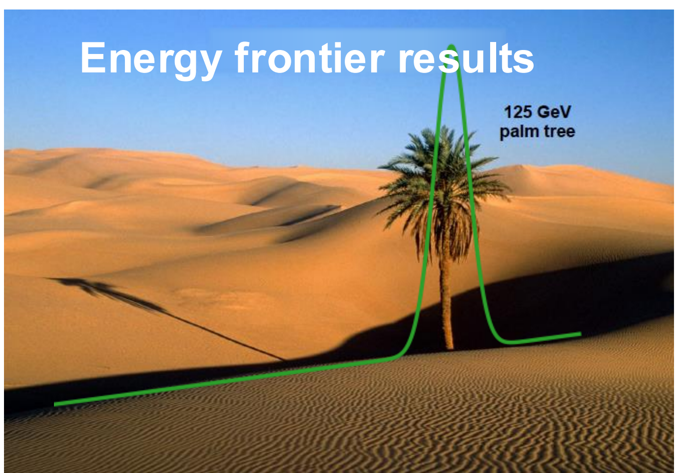
- angles α and β are related to phase of V_{td};
- angle γ is being measured at LHCb in $B_s^0 \to D_s^{\pm} K^{\mp}$

related to V_{ts}

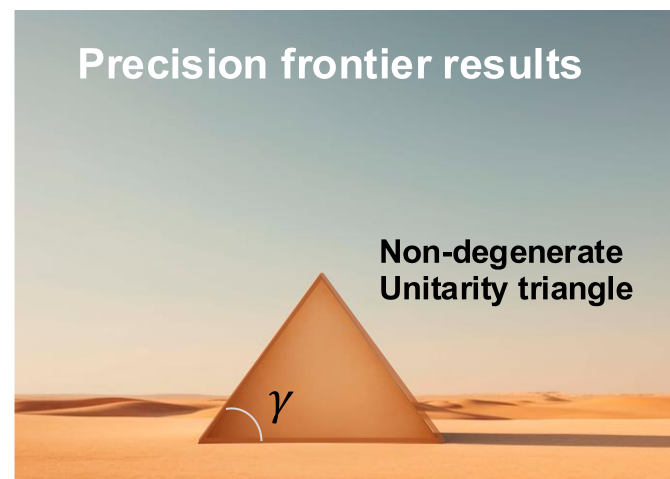




In recent years, the accuracy has been improving, the allowed area (of the upper apex of the Unitarity triangle) is becoming smaller and smaller,

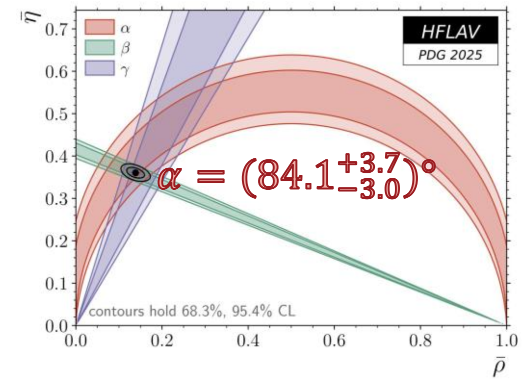


but there are no contradictions indicating the failure of the SM.

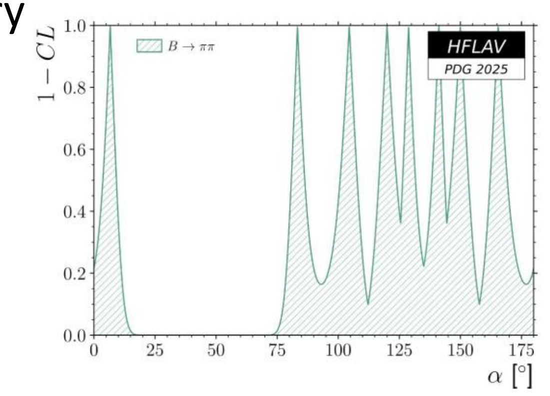


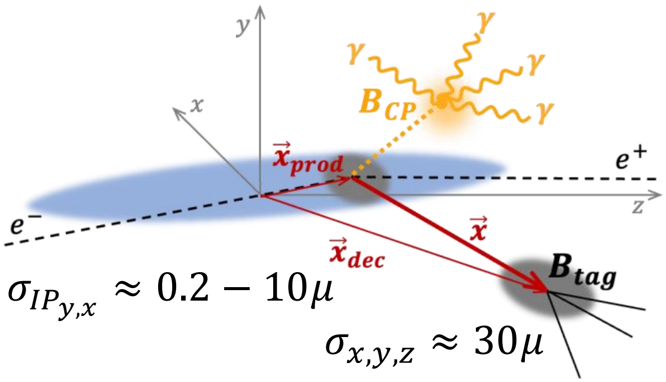
CP violation in $B^0 \to \pi^0\pi^0$

α is the least precisely known angle of the UT. It is best measured through an isospin analysis of both direct and indirect CPV in $B \to \pi\pi$. But this requires resolving a system of trigonometric equations with an eightfold ambiguity. Missing indirect CPV measurement in $B^0 \to \pi^0\pi^0$ would help, but requires B^0 vertex measurement.



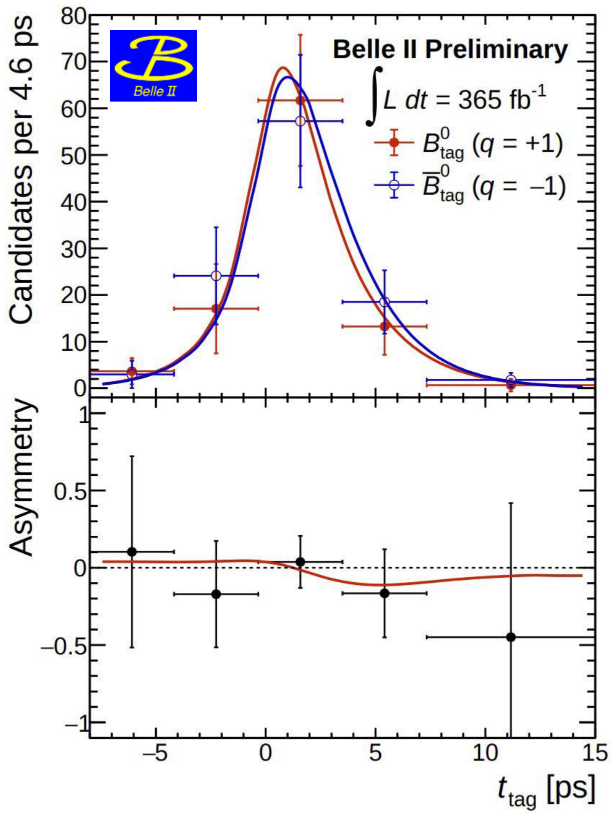
Thanks to $B^0\bar{B}^0$ quantum entanglement, time-dependent asymmetry arises even when measuring a single decay time of the tag-B meson decay time $t_{tag} = x/v$.





$\sigma_{IP_{y,x}} \approx 0.2 - 10\mu$

$\sigma_{x,y,z} \approx 30\mu$



$$S = 0.61^{+0.75}_{-0.79} \pm 0.11$$
$$C = 0.05 \pm 0.28 \pm 0.07$$

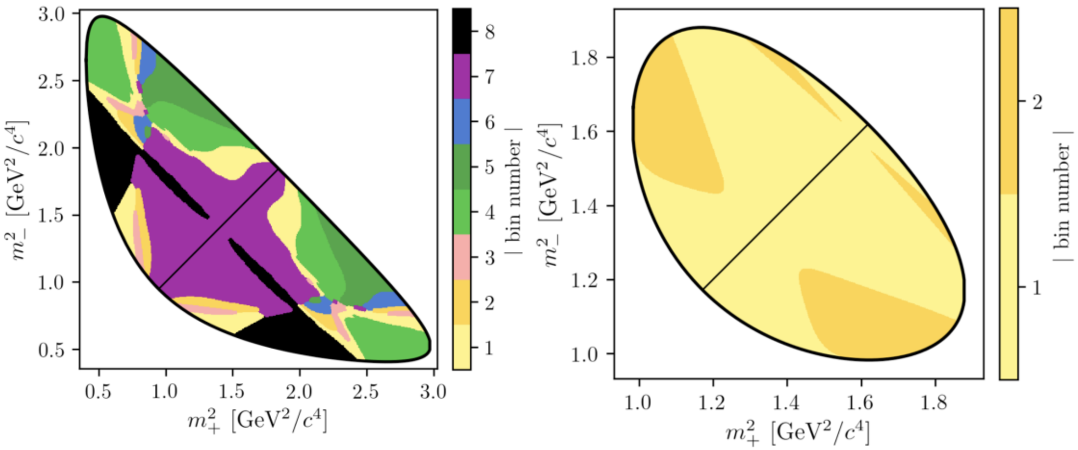
But t_{tag} resolution is crucial

Requires unprecedented vertex resolution achievable at Belle II only: both IP and tag-B vertex resolutions are ~5 times better than at Belle.

Mixing induced CPV in $B^0 \to \pi^0\pi^0$ measured for the first time!

UT angle γ

[LHCb-PAPER-2026-010]



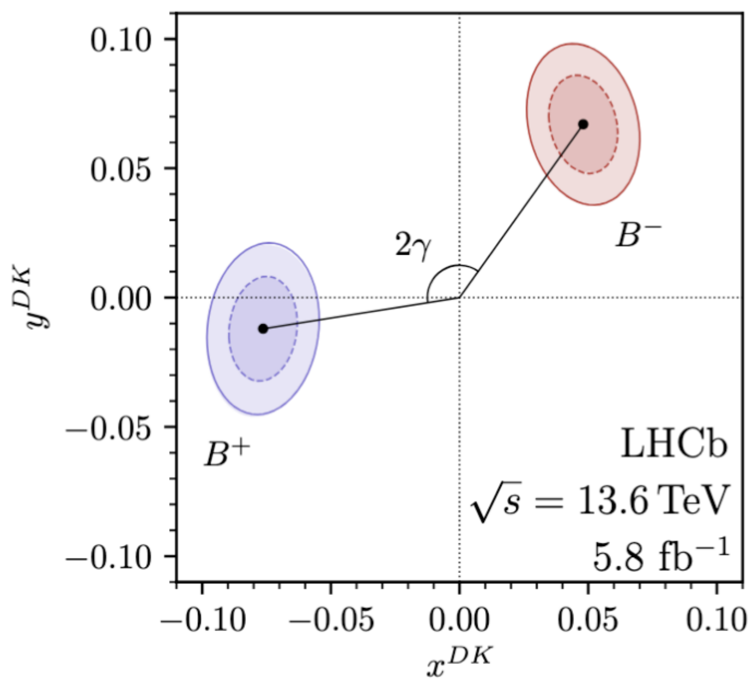
Measurement of γ using $B^+ \to DK^+; D \to K_S\pi^+\pi^-$ ($K_SK^+K^-$)

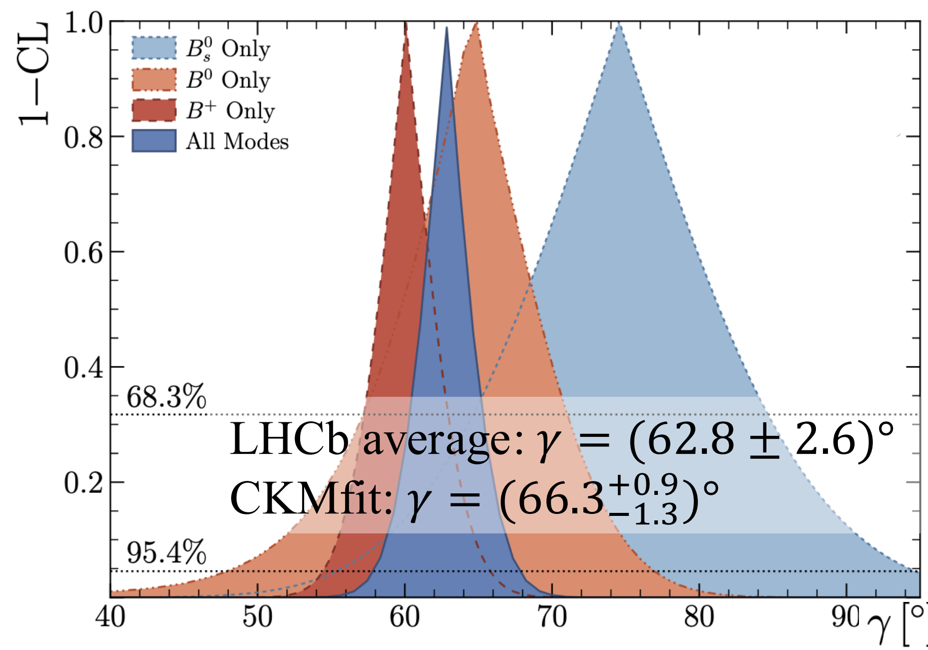
Signal yields of in the j-bin dependent on the CP-violating observables

$$\boldsymbol{x_\pm + iy_\pm = r_B e^{i(\delta_B+\gamma)}}$$

$$N_j(B^\pm) \sim F_{\mp j} + (x_\pm^2 + y_\pm^2)F_j + 2\sqrt{F_j F_{-j}}(x_\pm c_j \mp y_\pm s_j)$$

$\boldsymbol{c, s_j}$ inputs (strong-phase parameters of $K_S h^+h^-$) taken from combined measurement of BESIII and CLEO

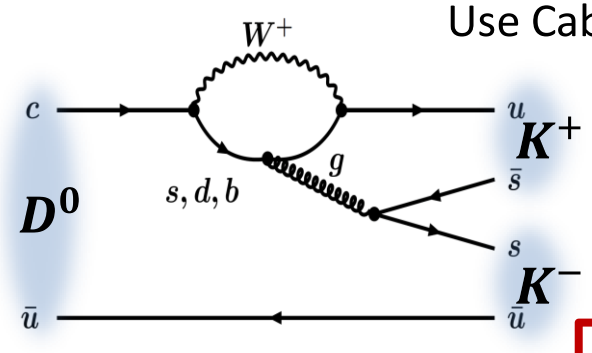





PENGUINS

Penguins and boxes in charm are tiny

Charm only has penguin diagram with down-type quarks in the loop. In SM they are strongly suppressed ($M_b \ll M_W$, $V_{ub} \ll V_{cb} \ll 1$), thus any sizeable penguin is a hint for NP. They can be seen in direct CP violation, as only penguin can bear complex phase with respect to tree.



Use Cabibbo suppressed decays: $D^0 \to K^+K^-$ or $\pi^+\pi^-$, and look for:

$$A_{CP} = \frac{\Gamma(D^0 \to K^+K^-) - \Gamma(\bar{D}^0 \to K^+K^-)}{\Gamma(D^0 \to K^+K^-) + \Gamma(\bar{D}^0 \to K^+K^-)}$$

Due to detector/production asymmetry LHCb measured $\Delta A_{CP} = A_{CP}^{KK} - A_{CP}^{\pi\pi}$, where many effects cancels out

$$\Delta A_{CP} = (-15.5 \pm 2.9) \times 10^{-4} \ \mathbf{(5.3\ \sigma)}$$

[PLB 774, 235 (2017)]

[PRL 122, 211803 (2019)]

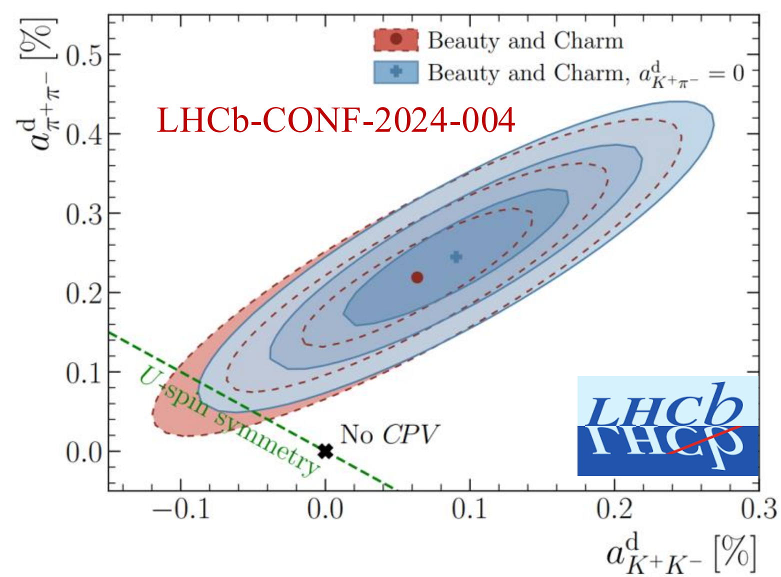
Much higher than predicted $A_{CP}^{KK,\pi\pi} \lesssim 2 \times 10^{-4}$:

NP or long-distance QCD?

New LHCb measurement of K^+K^- and $\pi^+\pi^-$ separately with detailed study of all detector effects:

$$a^d_{\pi^+\pi^-} = (23.2 \pm 6.1) \times 10^{-4} \ (3.8\ \sigma)$$
$$a^d_{K^+K^-} = (7.7 \pm 5.7) \times 10^{-4} \ (1.4\ \sigma)$$

[PRL 131, 091802 (2023)]



Search for direct CP violation in charm

Belle II has significantly smaller sample of charm mesons, but can test modes with K^0 or π^0, mostly unreachable for LHCb

$D^+ \to \pi^+\pi^0$: $A_{CP} = (-1.8 \pm 0.9 \pm 0.1)\%$

[PRD112, 031101(2025)]

$D^0 \to \pi^0\pi^0$: $A_{CP} = (0.30 \pm 0.72 \pm 0.20)\%$

[PRD 12, 012006 (2025)]

$D^0 \to K_S^0 K_S^0$: $A_{CP} = (-0.6 \pm 1.1 \pm 0.6)\%$

[PRD112, 012017 (2025)]

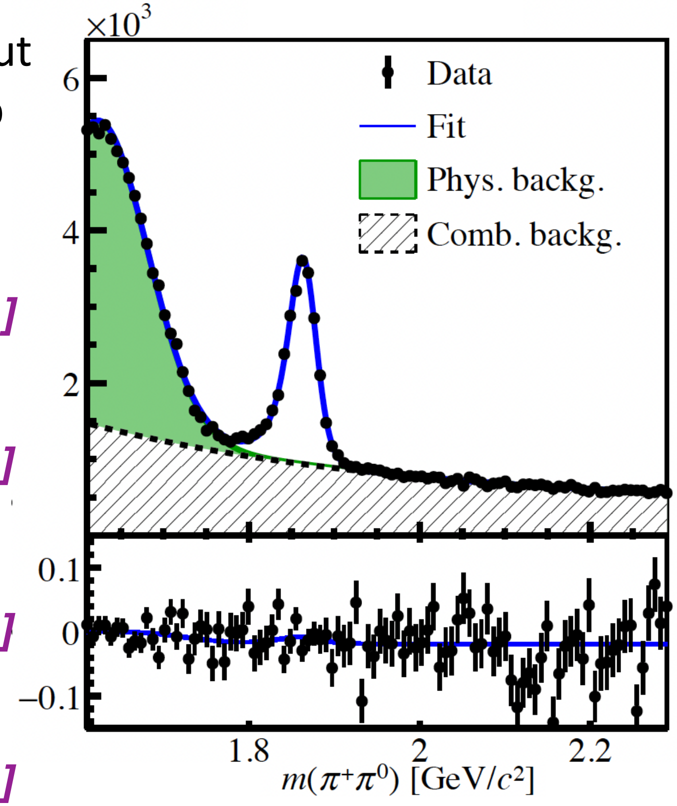
$D^0 \to K_S^0 K_S^0$: $A_{CP} = (1.86 \pm 1.04 \pm 0.41)\%$

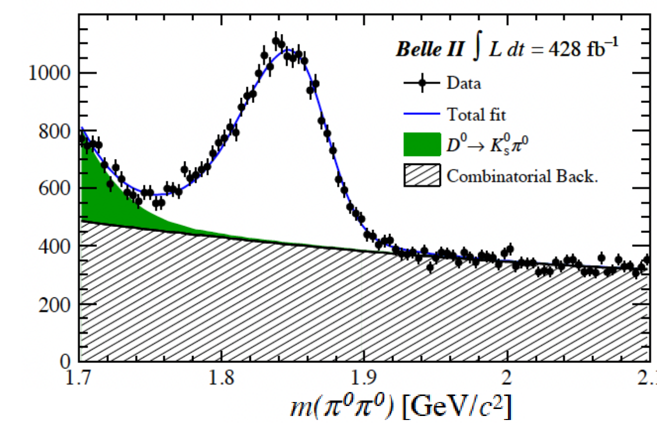
[JHEP02, 253 (2026)]

$D^0 \to \pi^+\pi^-\pi^0$: $A_{CP} = (0.29 \pm 0.27 \pm 0.13)\%$

[PRD113, 052006 (2026)]

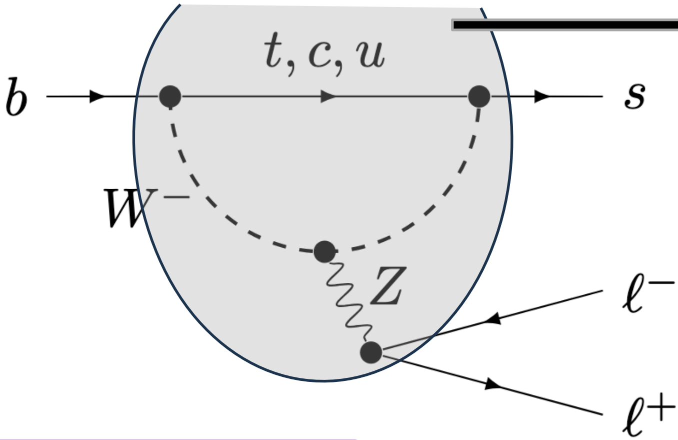
To date, no CPV has been observed in any channel. The measurement reaches a precision at the $\lesssim 1\%$ level, setting the most stringent world limits for these modes

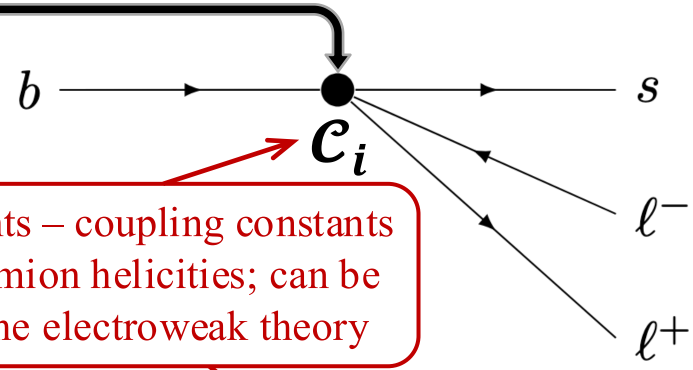




Electroweak penguins

Electroweak penguins model-independent description: factorization short & long distances





Wilson coefficients – coupling constants with different fermion helicities; can be calculated from the electroweak theory

$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} \mathcal{C}_i(\mu)\, \mathcal{O}_i(\mu)$$

Local operators account for hadron formation; universal across different processes

FC coupling of NP: we know nothing of it

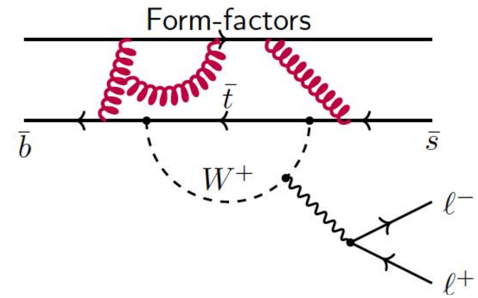
NP: $\Delta\mathcal{H}_{NP} = -\frac{\kappa}{\Lambda_{NP}} \mathcal{C}_{NP}\, \mathcal{O}_j$

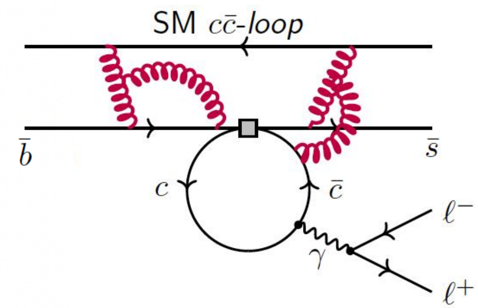
Scale of NP up to ~100 TeV reachable: JHEP 11 (2014), 121

Wilson coefficient		Operator
γ-penguin[1]	$\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
ew. penguin	$\mathcal{C}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$
	$\mathcal{C}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$
scalar	$\mathcal{C}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$
pseudoscalar	$\mathcal{C}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$

Penguin's observables

Observables in $b \to s\ell^\pm\ell^\mp$ are affected by poorly computable QCD…

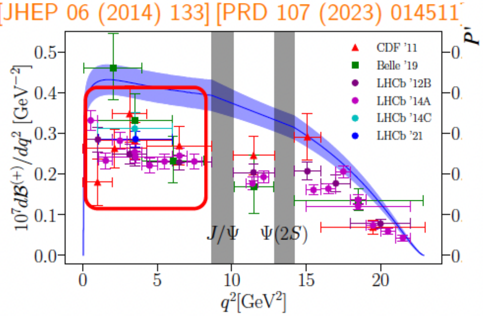




Observables in $b \to s\ell^\pm\ell^\mp$	Experiment	Theory
Branching fractions		
Angular distributions		
CP violation		
Lepton universality		

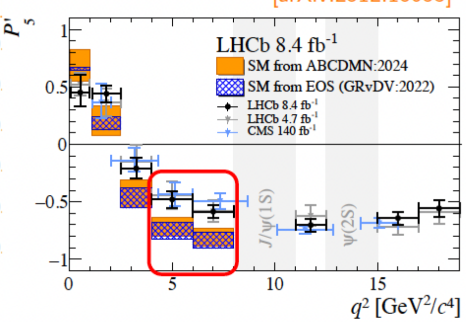
At experiment it is the simplest to measure the branching fraction: just count the number of signal events, but for theory it is the most difficult to predict this

[JHEP 06 (2014) 133] [PRD 107 (2023) 014511]



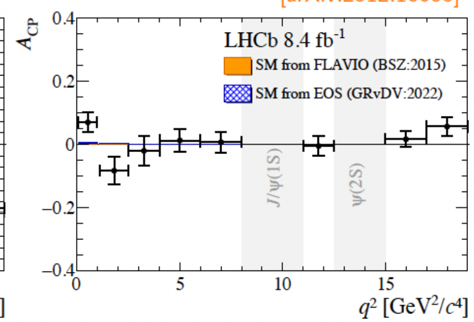
BR: affected by FF and $c\bar{c}$ loops

[arXiv:2512.18053]

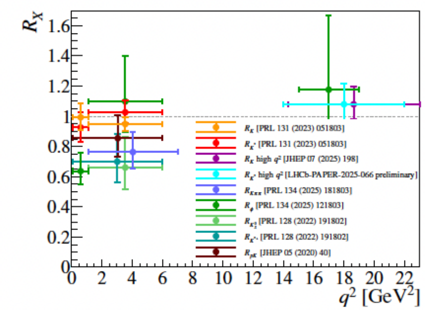


Angular observables: affected by $c\bar{c}$ loops

[arXiv:2512.18053]



CP-asymmetries: clean

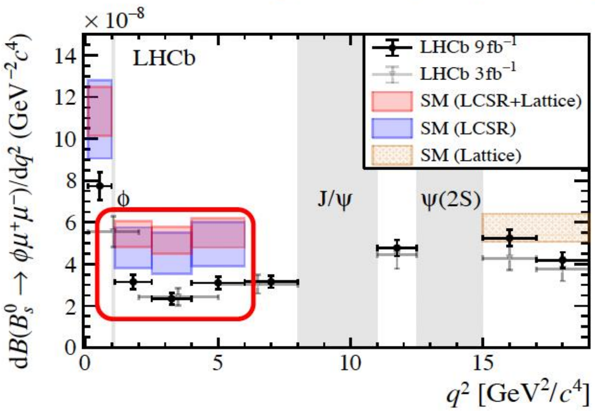


Lepton universality: clean

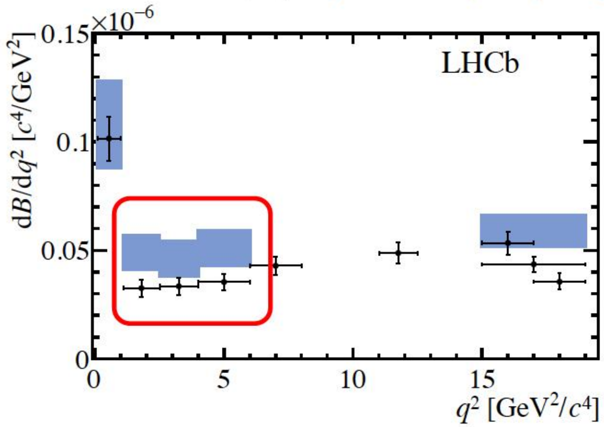
What is simpler experimentally is more challenging theoretically, and vice versa

Branching fractions

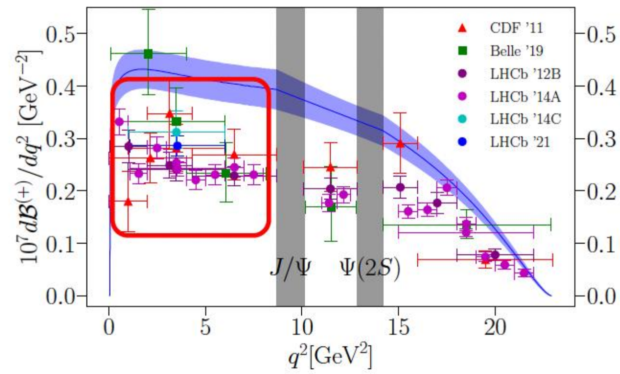
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127 (2021) 151801]



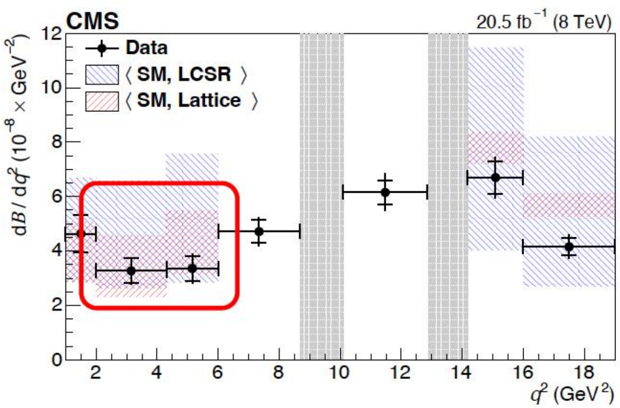
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



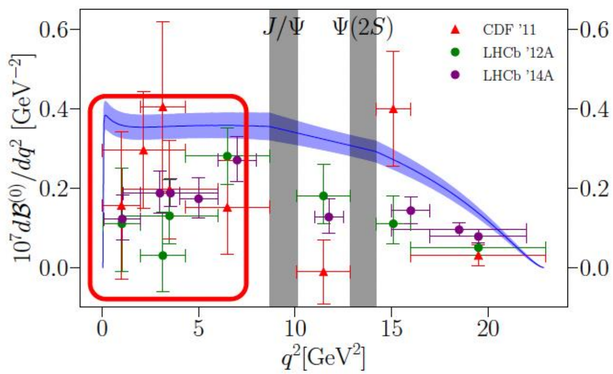
$B^+ \to K^+\mu^+\mu^-$ [HPQCD, PRD 107 (2023) 1]



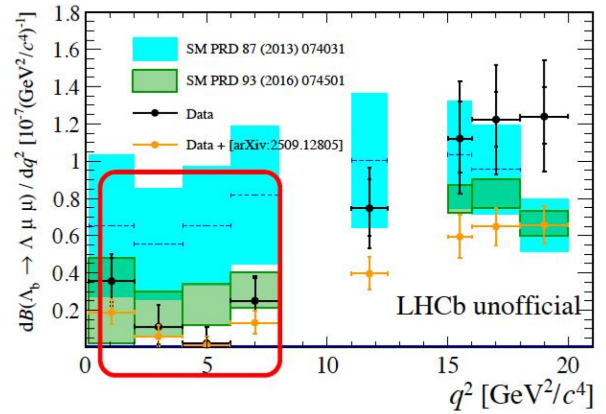
CMS $B^0 \to K^{*0}\mu^+\mu^-$ [PLB 753 (2016) 424]



$B^0 \to K^0\mu^+\mu^-$ [HPQCD, PRD 107 (2023) 1]

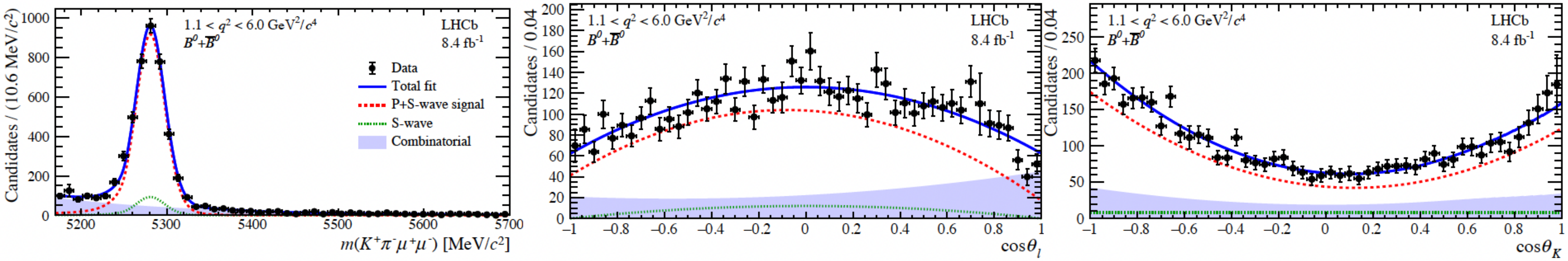


LHCb $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



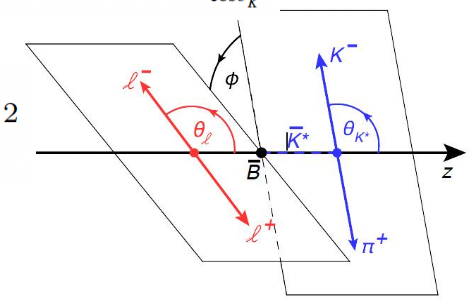
- Data typically below SM predictions: tension $1-3\sigma$ level, but significant hadronic uncertainties from form-factors and charm-loop;
- Important result from Lattice QCD: *PRD 107,1 (2023)*

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ *[arXiv:2512.18053]*



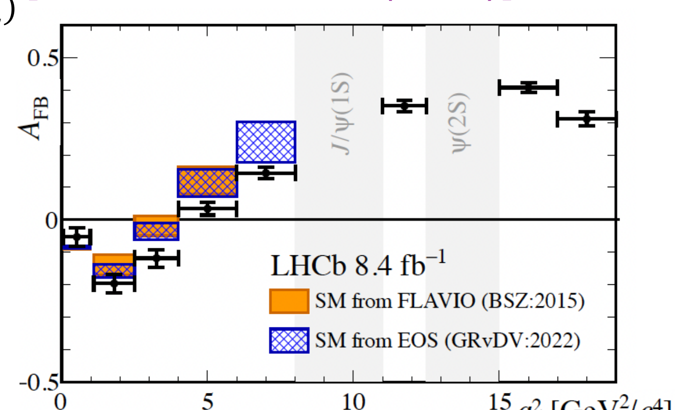
5D fit: 3 angular variables $(\theta_\ell, \theta_{K^*}, \varphi)$, q^2, $M_{K\pi}$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^5\overleftrightarrow{\Gamma}}{\mathrm{d}q^2\mathrm{d}m_{K\pi}\mathrm{d}\vec{\Omega}} = (1-\hat{F}_S)\frac{9}{64\pi}\sum_i (S_i \pm A_i) f_i(\vec{\Omega})|\mathcal{BW}_P(m_{K\pi})|^2 + \frac{1}{8\pi}\sum_j (\tilde{S}_j \pm \tilde{A}_j) f_j(\vec{\Omega}) F(m_{K\pi})$$

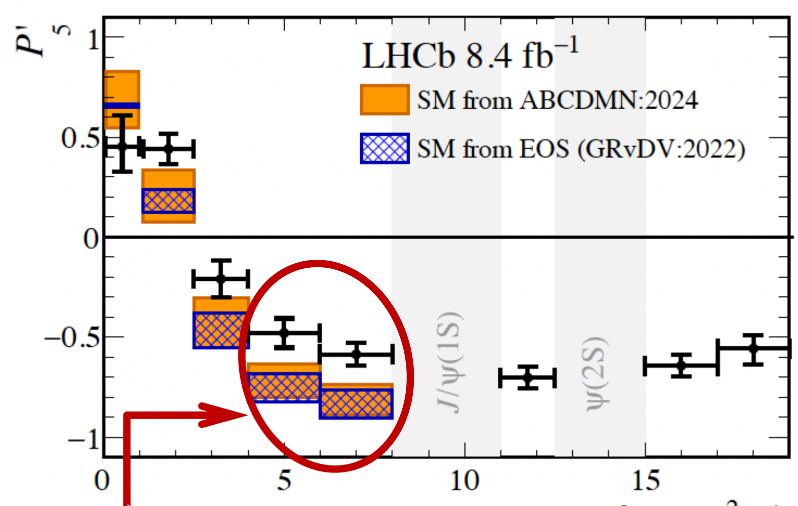


Perform ratios of observables where form factors cancel at leading order, *e.g.*

$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$ *[JHEP, 1305, 137, (2013)]*



in agreement with CMS and previous LHCb

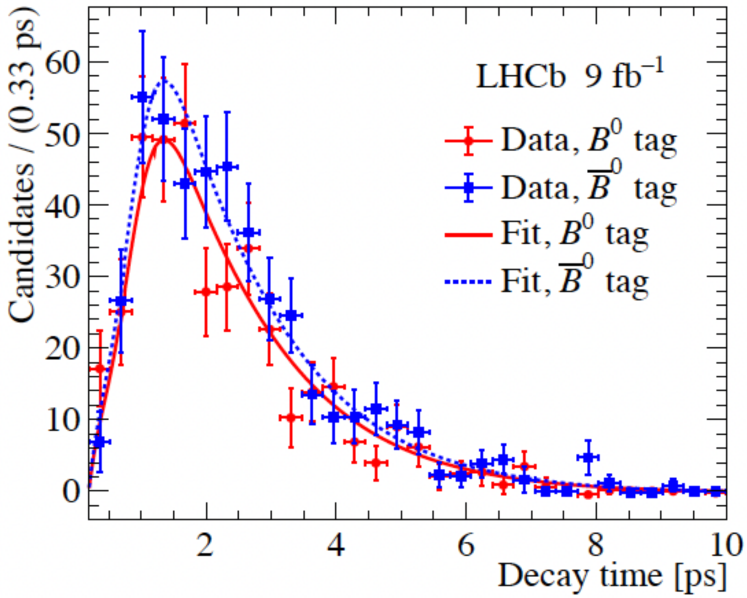


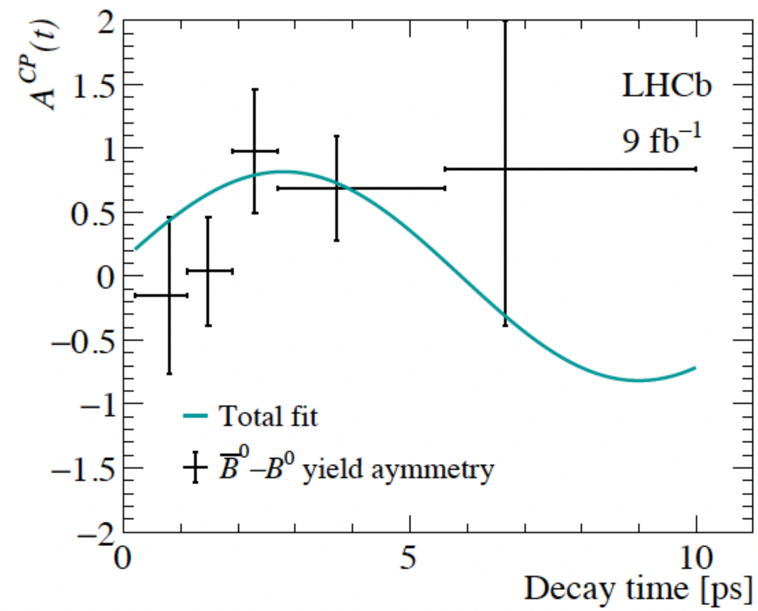
$\sim 2.7\sigma$ disagreement with SM

CP violation in $B^0 \to K^0_S \mu^+ \mu^-$

[LHCb-PAPER-2025-062, in preparation]

First time-dependent measurement of CPV in $b \to s\ell^+\ell^-$ – processes using Run 1+2 data



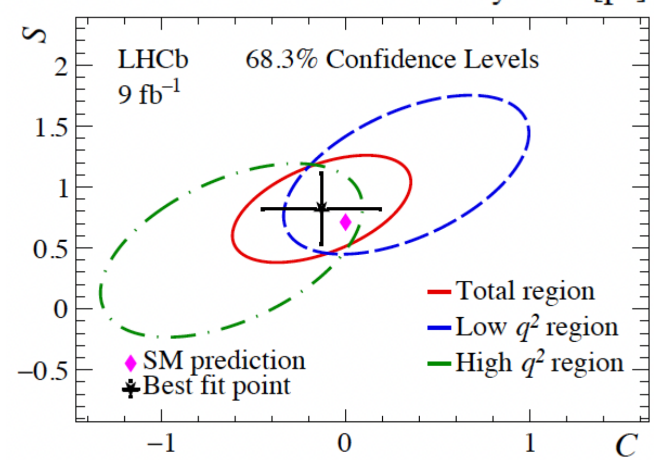


$$S = +0.82 \pm 0.29 \pm 0.05$$

$$C = -0.13 \pm 0.32 \pm 0.04$$

SM expectation $S = \sin 2\beta, C = 0$

in good agreement with SM prediction

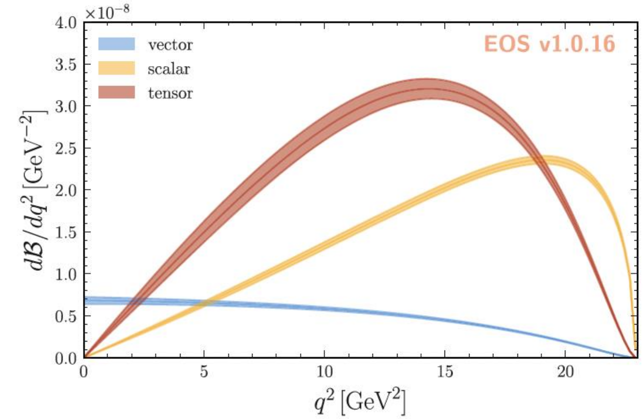


Evidence for $B^+ \to K^+ \nu\bar{\nu}$

[PRD 112, 092016 (2025)]

$$\frac{d\mathcal{B}}{dq^2} = 3\tau_B \left(\frac{4G_F}{\sqrt{2}}\frac{\alpha}{2\pi}\right)^2 |V_{ts}^* V_{tb}|^2 \frac{\sqrt{\lambda_{BK}}q^2}{(4\pi)^3 M_B^3} \left[\frac{\lambda_{BK}}{24q^2}|f_+(q^2)|^2 |C_{VL}+C_{VR}|^2 + \frac{(M_B^2-M_K^2)^2}{8(m_b-m_s)^2}|f_0(q^2)|^2 |C_{SL}+C_{SR}|^2 + \frac{2\lambda_{BK}}{3(M_B+M_K)^2}|f_T(q^2)|^2 |C_{TL}|^2\right]$$

$$\mathcal{B}_{SM}(B \to K\nu\bar{\nu}) = (5.6 \pm 0.4)\times 10^{-6}$$



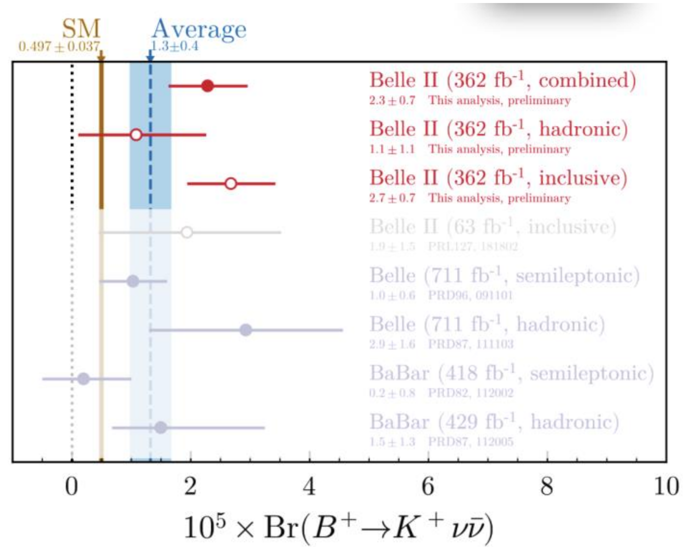
Two methods:

- One (tagging) B^--meson in the event is reconstructed fully in hadronic modes (*hadronic*);
- Tagging B^--meson is all particles in event, except for K^+ from the signal side (*inclusive*).

Strategy for backgrounds suppression:

- Apply machine learning to check the consistency of tagging with being real B^--meson;
- Require no activity in the detector.

$$\mathcal{B} = (1.1^{+1.2}_{-1.0})\times 10^{-5} \text{ (hadronic)}$$
$$\mathcal{B} = (2.7 \pm 0.7)\times 10^{-5} \text{ (inclusive)}$$
$$\boldsymbol{\mathcal{B} = (2.3 \pm 0.7)\times 10^{-5}} \textbf{ (combined)}$$



First evidence of $b \to s\nu\bar{\nu}$ mode;
2.7σ deviation from the SM

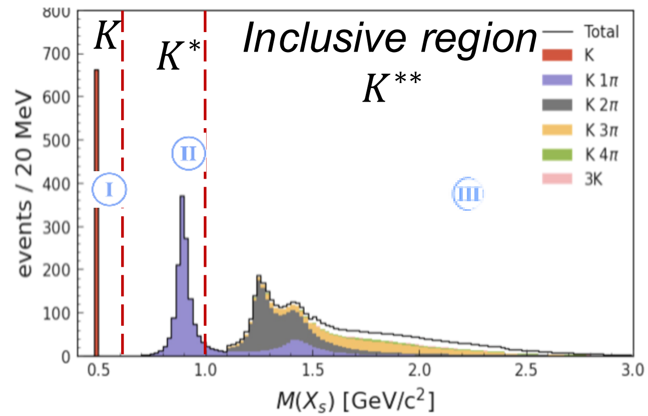
Search for $b \to s\nu\bar{\nu}$

[arXiv:2512.19138], accepted by PRL

Theoretically clean and sensitive to several possible sources of NP *[arXiv:2512.19138]*

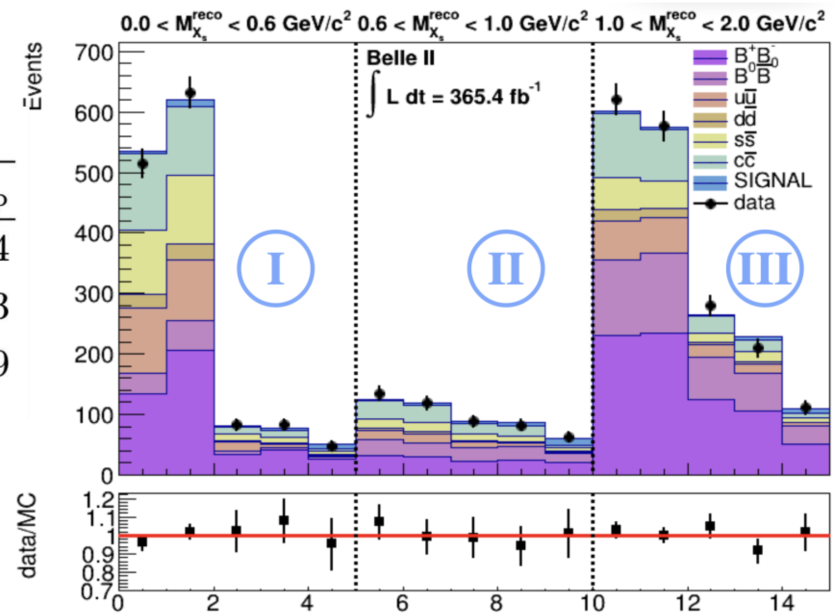
$$\mathcal{B}_{SM}(B \to X_s\nu\bar{\nu}) = (3.35 - 3.62)\times 10^{-6}$$

One B -meson in the event is reconstructed fully (hadronic tag); in the second B reconstruct s-hadrons semi inclusively ($\equiv$sum-of-exclusive = $\sum K n\pi$).



Multiple samples used to calibrate simulations and obtain systematic uncertainties

M_{X_s} [GeV/c^2]	ϵ	$N_{\rm sig}$	$\mathcal{B}$ [10^{-5}] Central value	$\mathrm{UL_{obs}}$	$\mathrm{UL_{exp}}$
[0, 0.6]	0.26%	10^{+18+18}_{-17-16}	$0.5^{+0.9+0.9}_{-0.8-0.8}$	2.5	2.4
[0.6, 1.0]	0.12%	37^{+27+31}_{-25-26}	$3.8^{+2.8+3.3}_{-2.6-2.7}$	10.1	7.3
[1.0, m_B]	0.06%	33^{+44+63}_{-42-53}	$7.3^{+9.6+13.8}_{-9.2-11.5}$	35.1	27.9



BDT output in bins of M_{X_s}

$$\boldsymbol{\mathcal{B} = \left(11.6^{+8.9}_{-8.6}(stat)^{+13.5}_{-11.3}(syst)\right)\times 10^{-5}}$$

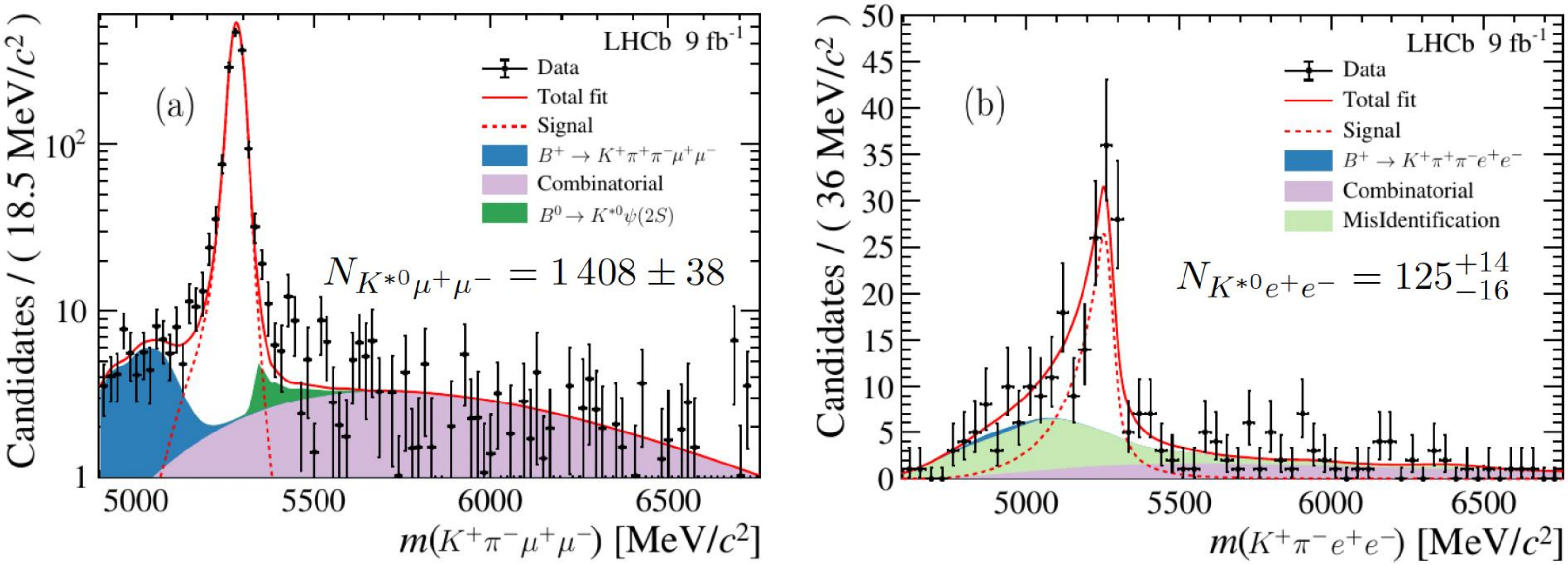
$$\boldsymbol{< 3.6\times 10^{-4}\ @90\%\ CL}$$

First/Most stringent UL on the inclusive rate

Lepton universality

Recent LHCb $B \to K^{(*)}\ell\ell$ measurements resolved previous tensions ($> 3\sigma$), confirming lepton flavor universality. Updated analysis implemented more stringent background controls. Past discrepancies are attributed to underestimated systematics in electron efficiency.

[LHCb-PAPER-2025-066] in preparation

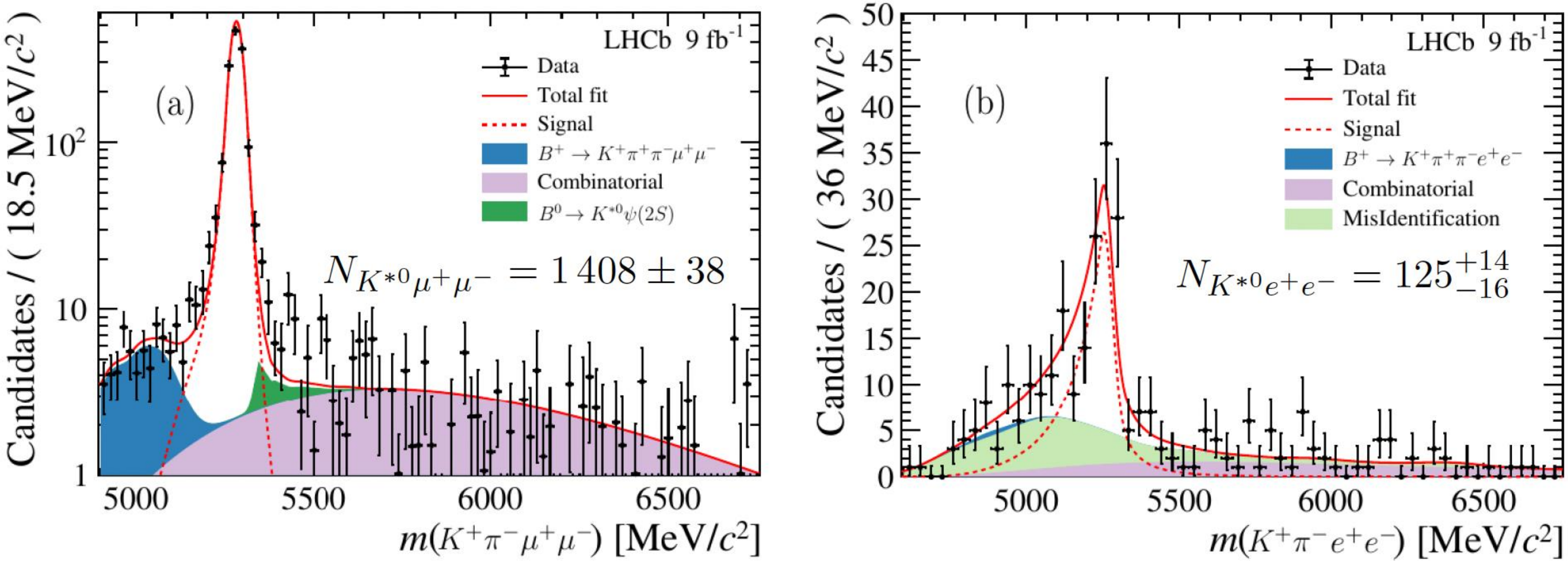


$R(K^{*0}) = 1.08^{+0.14}_{-0.13} \pm 0.07$ in excellent agreement with SM prediction

$B \to D^{(*)}\ell\upsilon$ ($\ell = \tau, \mu, e$). The discrepancy (excess of decays to τ) persists, but its significance has decreased to around $\sim 3.2\sigma$ down from 4σ.

Lepton universality

Recent LHCb $B \to K^{(*)}\ell\ell$ measurements resolved previous tensions ($> 3\sigma$), confirming lepton flavor universality. Updated analysis implemented more stringent background controls. Past discrepancies are attributed to underestimated systematic uncertainties in electron efficiency.



[arXiv:2512.19138], accepted by PRL

$$\mathcal{B} = \left(11.6^{+8.9}_{-8.6}(stat)^{+13.5}_{-11.3}(syst)\right)\times 10^{-5}$$
$$< 3.6 \times 10^{-4} \text{ @}90\%\ CL$$

First/Most stringent UL on the inclusive rate

Summary

- LHCb is successfully collecting data during Run 3, which will last until the end of June 2026. A huge Run 3 data sample ($22/fb$) available for analysis but good understanding of data from [Upgrade I] detector required
- Belle II successfully collected data, the SuperKEKb is operating in a stable mode after technical issues were resolved: $L_{peak} = 5.24 \times 10^{34}/cm^2/s$ (March 2026); $L_{day} \approx 3/fb$. The current run will last until June 2026 and will be resumed in the fall 2026.
- BESIII continues to collect data; the most interesting aspect is the quantum entanglement of $D^0\overline{D}^0$ in C=- and C=+ states.
- The SCTF project is under active development in China.
- We remain hopeful that either energy frontier or precision frontier experiments will deliver surprises in the coming years.

THANKS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