Flavour physics experiments at colliders



Marcella Bona (QMUL)





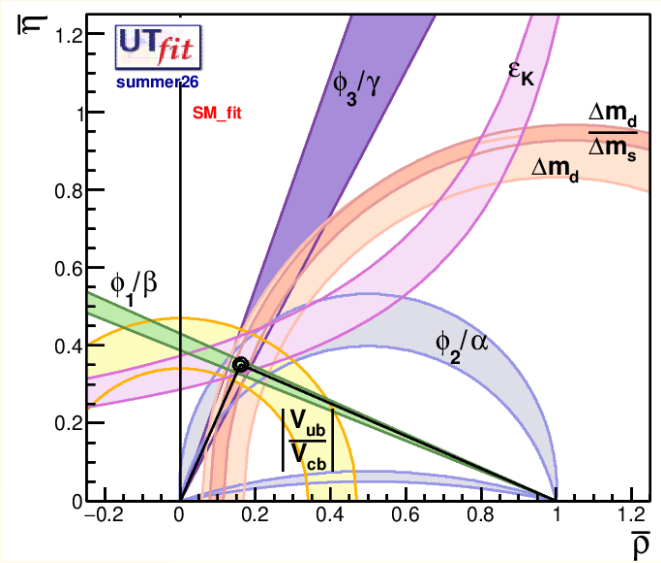




14th ICFA Seminar 2026
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The power of flavour

- Precision physics to test the Standard model
  - Over-constrain the CKM Unitarity Triangle
    - Redundancy exposes inconsistencies
    - Angles (β, γ, α, ϕ_s) and sides: $|V_{cb}|$, $|V_{ub}|$



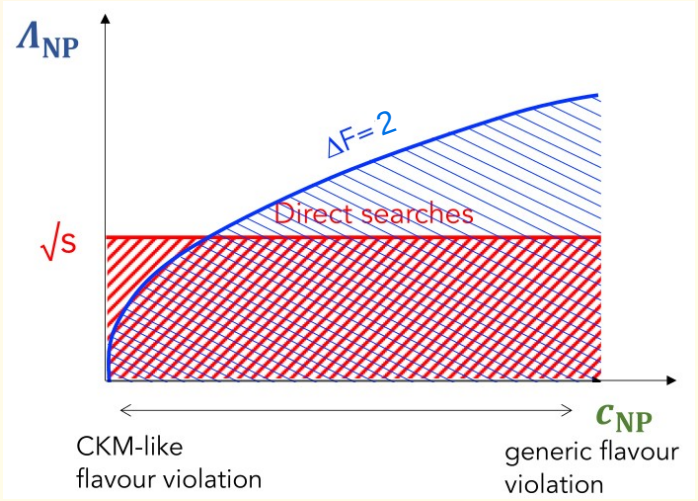
The power of flavour

- Precision physics to test the Standard model
  - Over-constrain the CKM Unitarity Triangle
    - Redundancy exposes inconsistencies
    - Angles (β, γ, α, ϕ_s) and sides: $|V_{cb}|$, $|V_{ub}|$
- Sensitivity to scales above direct reach
  - via processes mediated by box and loop diagrams (strongly suppressed in the SM)
  - New Physics can compete and modify the properties of the decays

$$\mathcal{H}_{NP} \propto \frac{c_{NP}}{\Lambda^2_{NP}}$$

NP coupling

NP scale



The power of flavour

A lesson from history:

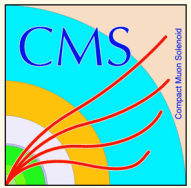
- New physics showed up at precision frontier before energy frontier
  - GIM mechanism before discovery of charm
  - CP violation / CKM before discovery of bottom & top
  - Neutral currents before discovery of Z

The experiments

- Main actors in B physics: LHCb, CMS, ATLAS, and Belle II
  - B-factory-style experiments: trigger fully efficient on B events, modes with neutrals, inclusive measurements, statistical limitation
  - Hadron collider experiments: access to tiny BRs, all b-hadrons types, LHC complex environment







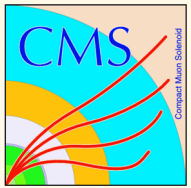


The experiments

- Main actors in B physics: LHCb, CMS, ATLAS, and Belle II
  - B-factory-style experiments: trigger fully efficient on B events, modes with neutrals, inclusive measurements, statistical limitation
  - Hadron collider experiments: access to tiny BRs, all b-hadrons types, LHC complex environment
- Charm, kaon and tau physics: adding BESIII, NA62 and KOTO to the landscape
  - complementarity with and fundamental inputs for B physics analyses and focus on charm and tau physics
  - unique access to ultra rare decays in exceptionally controlled enviroments.















CP violation and Unitarity Triangle

- CP violation is a key for the explaining matter-antimatter asymmetry.
- Experimentally established in kaon, B, and D meson systems. And in baryons!
- Its magnitute in the Standard Model is many orders of magnitude smaller than needed to account for the observed baryon asymmetry
  - pointing to new, yet undiscovered sources of CP violation beyond the SM

- In the SM formalised in the Complex phase in the quark mixing matrix
  - CKM (Cabibbo-Kobayashi-Maskawa) Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CK @ CKM2006 in Nagoya



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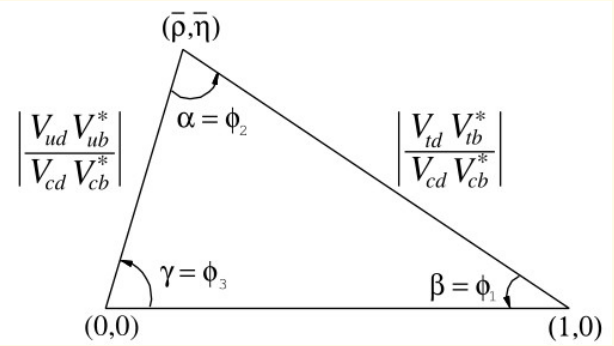
$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + (\lambda^4)$$

Almost diagonal
Almost real

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- In the SM formalised in the Complex phase in the quark mixing matrix
  - CKM (Cabibbo-Kobayashi-Maskawa) Matrix
  - Unitary relations give us handles to define many observables
  - Test the CKM paradigm through precision and redundancy
  - Assess the space left for going beyond the SM

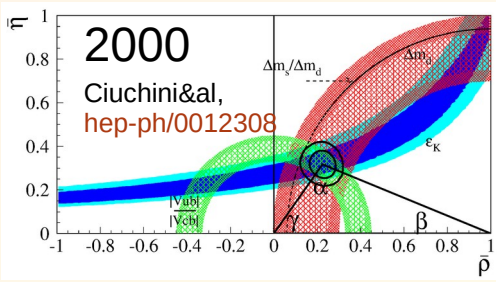


$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* \simeq \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) = 0$$

CP violation and Unitarity Triangle

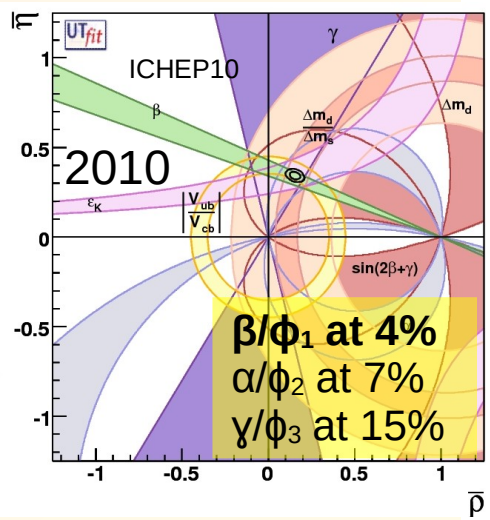
- From pre-B-factory to now
  - with lattice improvements throughout

V_{cb} at 5% and V_{ub} at 7%



$\bar{\rho}$ at 17%
$\bar{\eta}$ at 13%

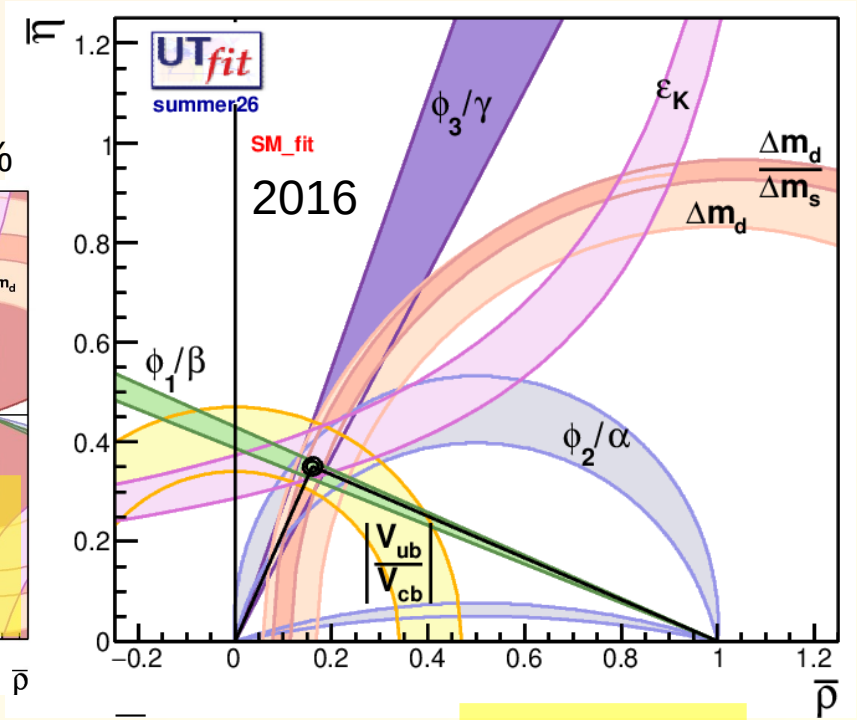
V_{cb} at 1% and V_{ub} at 5%



β/ϕ_1 at 4%
α/ϕ_2 at 7%
γ/ϕ_3 at 15%

$\bar{\rho}$ at 16%
$\bar{\eta}$ at 3%

V_{cb} at 2% and V_{ub} at 8%



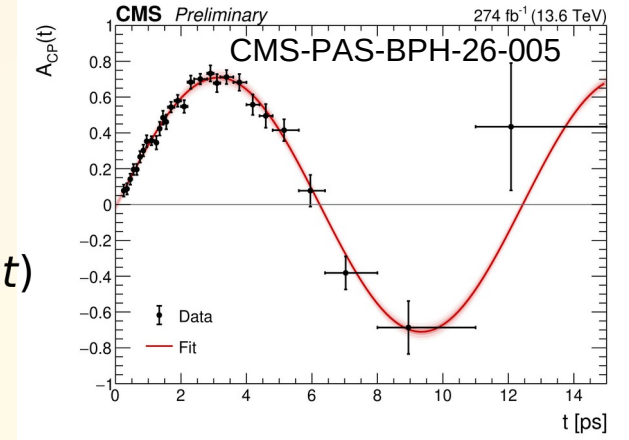
$\bar{\rho}$ at 5%
$\bar{\eta}$ at 2%

β/ϕ_1 at 1.8%
α/ϕ_2 at 5%
γ/ϕ_3 at 3%

ϕ_1/β angle

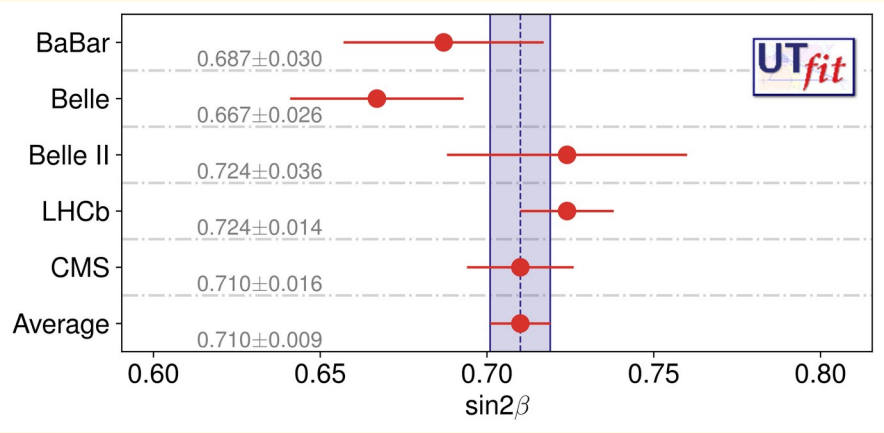
Golden mode $J/\psi K^0$ via time-dependent asymmetry measurement

$$\mathcal{A}_{CP}(t) = \frac{\Gamma(\bar{B}^0(t)\to J/\psi K_S^0) - \Gamma(B^0(t)\to J/\psi K_S^0)}{\Gamma(\bar{B}^0(t)\to J/\psi K_S^0) + \Gamma(B^0(t)\to J/\psi K_S^0)} = S\sin(\Delta m t) - C\cos(\Delta m t)$$



Accessible to both Belle II and LHC experiments:

2001: Discovery of CP violation in $B^0 \to J/\psi KS$ (BaBar, Belle)
2001-2010: BaBar and Belle get to a 4% uncertainty
2011: first result from LHCb
2023: LHCb achieves the most precise single result at 2%
2024: Belle II perform its first measurement
2026: CMS enters the stage at 2%

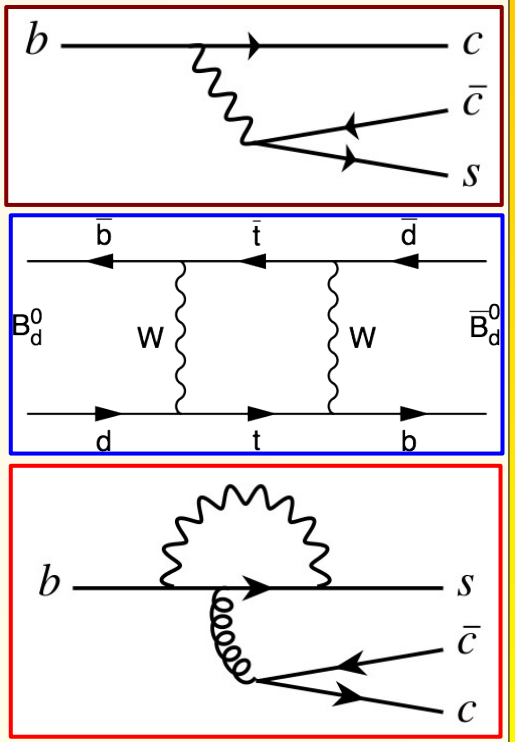


ϕ_1/β angle

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

J/ψK^0 time-dependent S parameter now a precision measurement at 1.3%.
Challenging the theoretical approximation.

Golden mode when considering the interfering between the tree diagram from the decay and the box diagram from the mixing



$$A_{ccs} \sim \underbrace{V_{cb}V^*_{cs}}_{(\lambda^2)}\left(T + P^c - P^t\right) + \underbrace{V_{ub}V^*_{us}}_{(\lambda^4)}\left(P^u - P^t\right)$$

CKM-suppressed pollution by penguins

ϕ_1/β angle

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

J/ψK^0 time-dependent S parameter now a precision measurement at 1.3%.
Challenging the theoretical approximation:

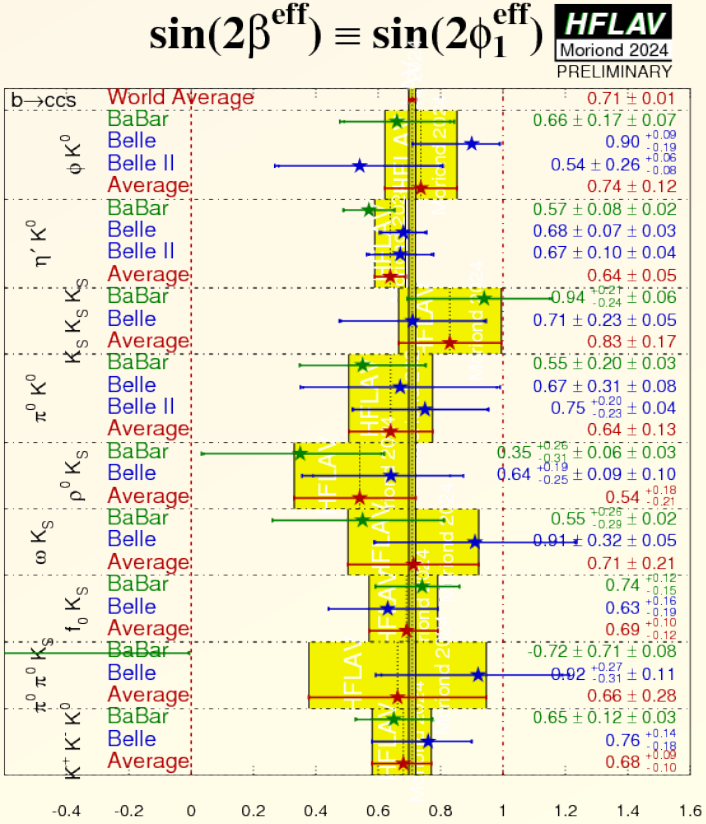
- Ciuchini &al (2005) arXiv:hep-ph/0507290:
  - updated ΔS = -0.01 ± 0.01
- De Bruyn &al (2025) arXiv:2505.06102
  - exact SU(3)
  - ΔS ~ +0.005 ± 0.005
- Ligeti &al (2025) arXiv:2506.21675:
  - leading term SU(3) breaking
  - ΔS = +0.001 ± 0.015
- Ciuchini &al (very preliminary):
  - ΔS ~ ± 0.02

courtesy of L. Silvestrini

Channel	$\widetilde{E}_2$	$\widetilde{P}_2^{GIM}$	EA_1	$\widetilde{EA}_2$	EA_2	$\widetilde{P}_4^{GIM}$
$B^+ \to \pi^+ J/\Psi$	λ_{bd}^c	λ_{bd}^u	λ_{bd}^u	0	0	0
$B^+ \to K^+ J/\Psi$	λ_{bs}^c	λ_{bs}^u	λ_{bs}^u	0	0	0
$B_d \to \pi^0 J/\Psi$	λ_{bd}^c	λ_{bd}^u	0	0	λ_{bd}^u	0
$B_d \to K^0 J/\Psi$	λ_{bs}^c	λ_{bs}^u	0	0	0	0
$B_d \to \eta_1 J/\Psi$	λ_{bd}^c	λ_{bd}^u	0	λ_{bd}^c	λ_{bd}^u	λ_{bd}^u
$B_d \to \eta_8 J/\Psi$	λ_{bd}^c	λ_{bd}^u	0	λ_{bd}^c	λ_{bd}^u	λ_{bd}^u
$B_s \to \pi^0 J/\Psi$	0	0	0	0	λ_{bs}^u	0
$B_s \to \bar{K}^0 J/\Psi$	λ_{bd}^c	λ_{bd}^u	0	0	0	0
$B_s \to \eta_1 J/\Psi$	λ_{bs}^c	λ_{bs}^u	0	λ_{bs}^c	λ_{bs}^u	λ_{bs}^u
$B_s \to \eta_8 J/\Psi$	λ_{bs}^c	λ_{bs}^u	0	λ_{bs}^c	λ_{bs}^u	λ_{bs}^u

ϕ_1/β angle from penguins

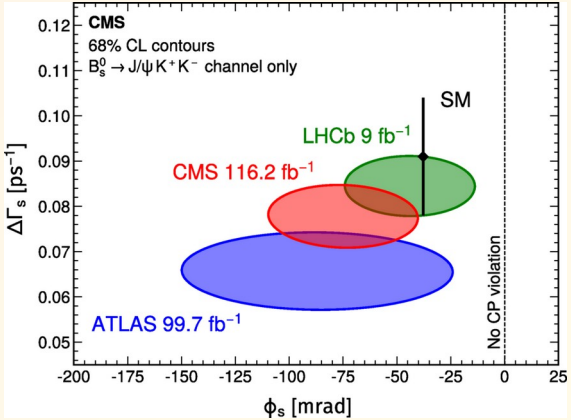
- Processes dominated by flavour-changing neutral current loop-level amplitudes
  - Sensitive to new physics
- Showing agreement with $c\bar{c}s$ value
- Calculations not really available
  - Theoretical calculations will catch up?



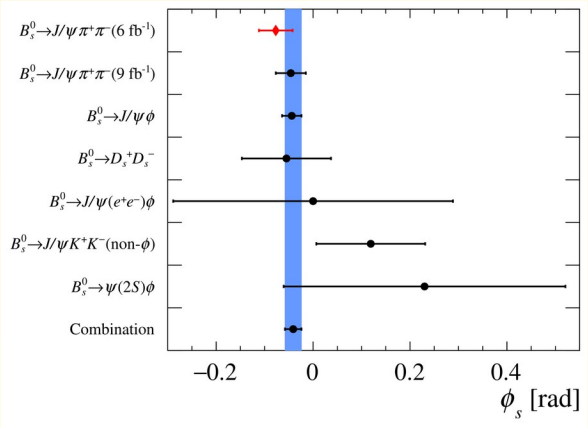
CP violation in the B_s system: ϕ_s

- Another CKM matrix unitarity relation makes a squashed triangle.
  - Expected to be a very small angle: $\phi_s = -36.7 \pm 1.0$ mrad

- J/ψϕ CMS analysis with Run 2
  - 27500 tagged B_s candidates
- With Run 1, first evidence of non-zero value: $\phi_s = (-75 \pm 23)$ mrad



- LHCb new result using J/ψππ
- New LHCb average
  - ϕs = (−41 ± 17) mrad
- Most precise at 23 mrad



HFLAV

$c\bar{c}s$ world-average:
$\phi_s = (-53 \pm 13)$ mrad

PRL 136 (2026) 181801

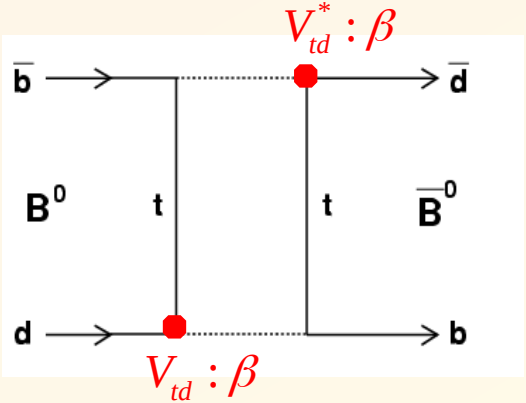
penguin pollutions to be assessed

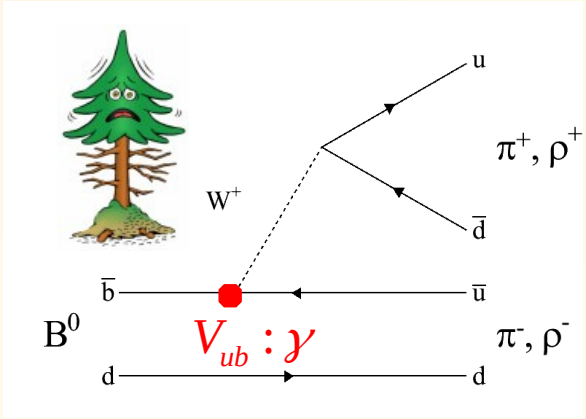
arXiv:2608.14119

ϕ_2/α angle

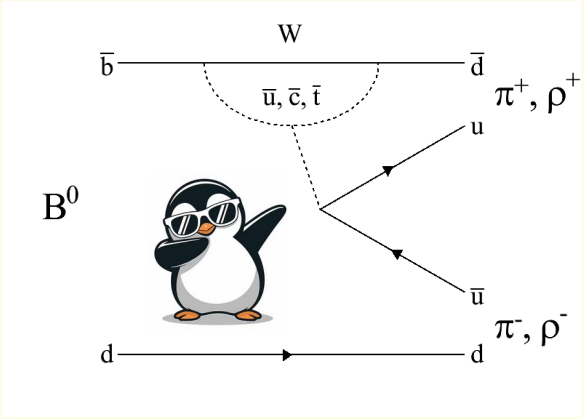
$$\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$$

- b → uud transitions with possible loop contributions
  - CP violation in interference between mixing and decay
  - time-dependent analyses
  - looking at ππ, ρρ, πρ final states





(λ^3)



(λ^3)

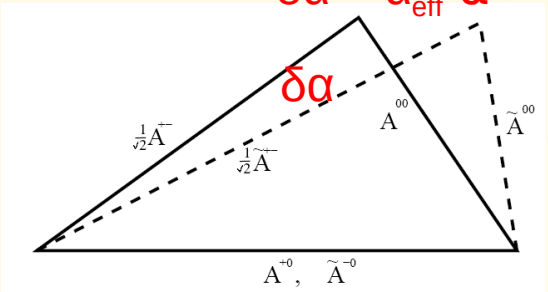
ϕ_2/α angle

$$\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$$

- b → uud transitions with possible loop contributions
  - looking at ππ, ρρ, πρ final states
- Extract α using precise measurements of all isospin-related decay modes, including neutral final states
  - SU(2) Isospin relations.
  - SU(3) flavour related processes

  to disentagle the penguin contributions

$\delta\alpha = \alpha_{eff} - \alpha$



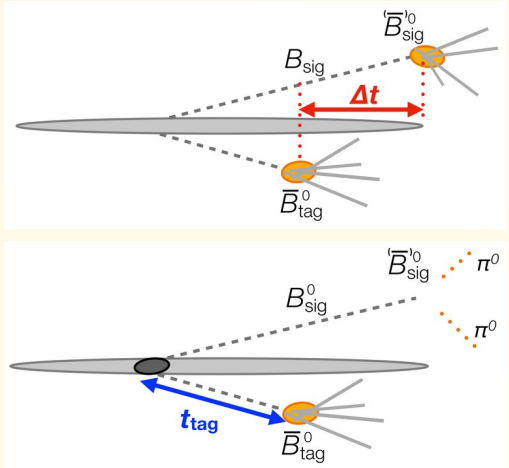
- Belle II (B factories) is crucial for this:
  - clean e^+e^- environment
  - excellent neutral-particle reconstruction

ϕ_2/α angle

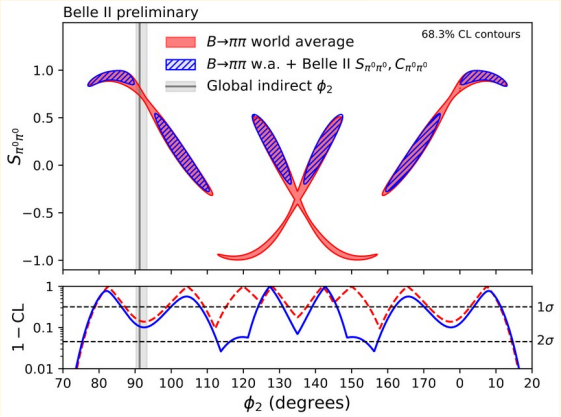
arXiv:2606.20797

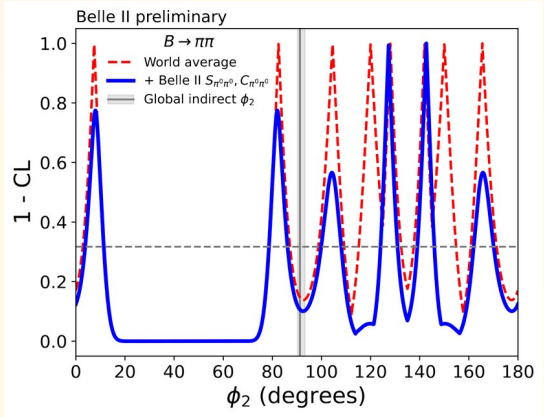
$$\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$$

- World first: $B^0 \to \pi^0\pi^0$ mixing-induced CP asymmetry
  - No tracks
  - Exploit quantum entanglement of the B^0–$\bar{B}^0$ pair, the smaller interaction region and the improved (x4) resolution on the tag side in Belle II
  - Decay-time evolution inferred from the tagged-B



Conventional time-dependent analysis would need 20× more data for same precision!



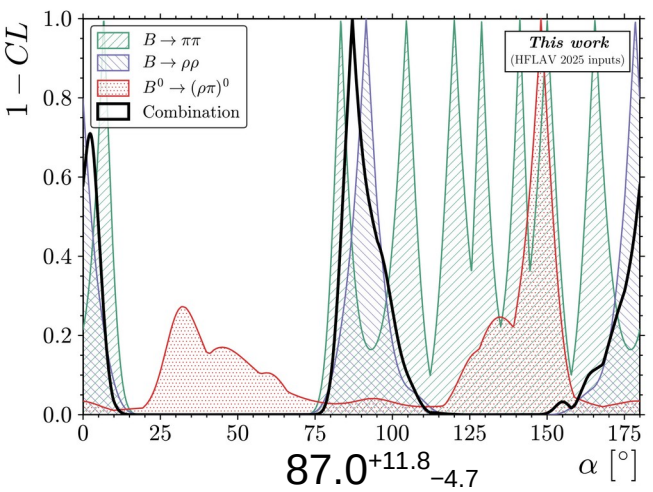


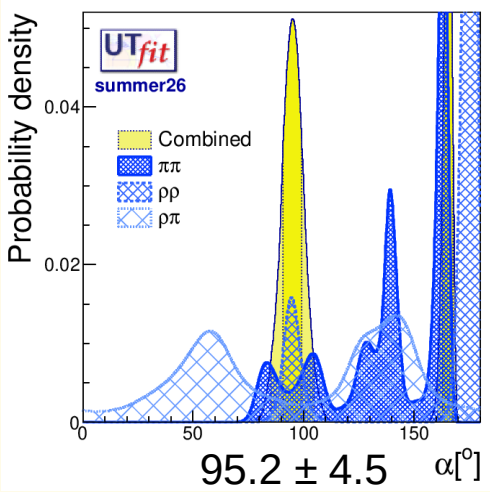
Reduces α ambiguities

ϕ_2/α angle

$$\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$$

- Less known among the angles
  - ππ/ρρ systems updated
  - ρπ results still from B factories with big uncertainties
- At the level 5º-8º when considering the UT picture



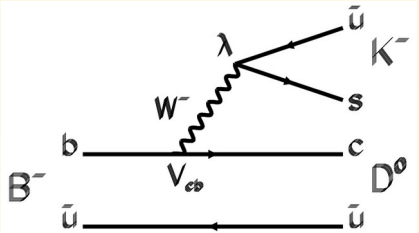


Žlebčík arXiv:2609.31828

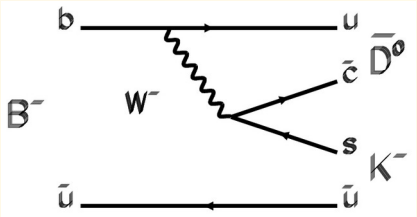
ϕ_3/γ angle

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

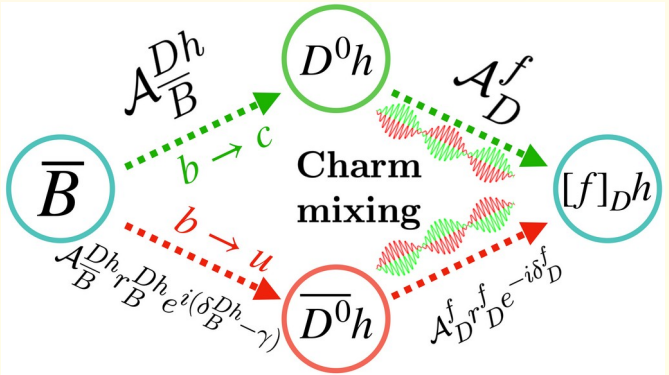
- Only UT angle from tree-level processes
  - theoretically clean, reference for model building
- Measured in decays which are sensitive to interference between favoured b → c and suppressed b → u quark transition amplitudes that are proportional to V_{cb} and V_{ub}.



V_{cb} (~λ^2)



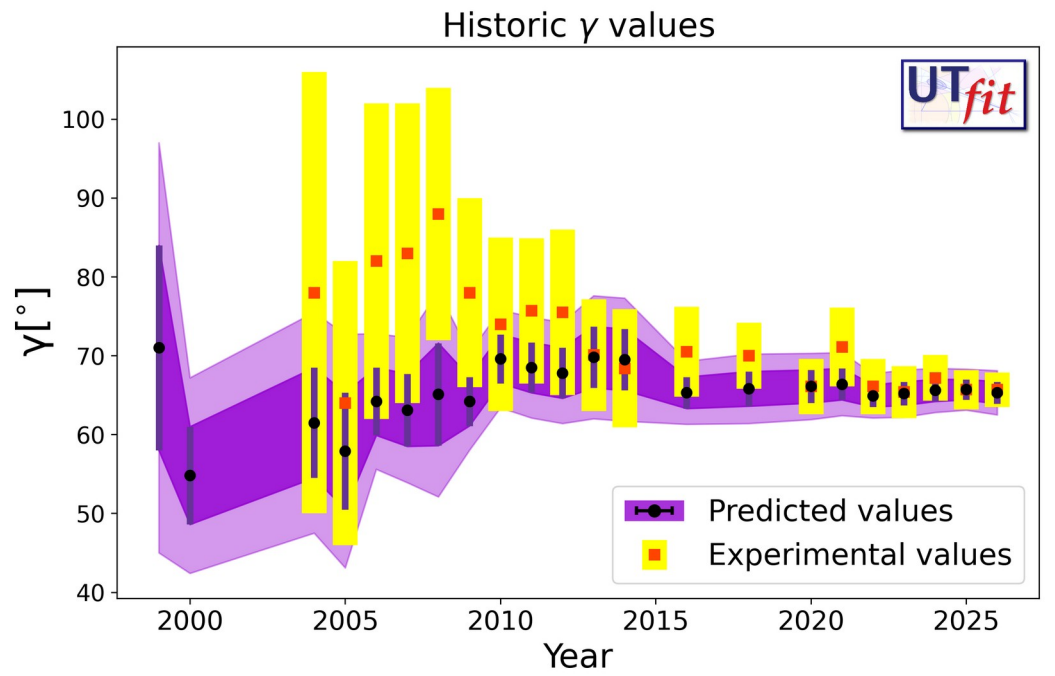
$V_{ub}=|V_{ub}|e^{-i\gamma}$ (~λ^3)



ϕ_3/γ angle

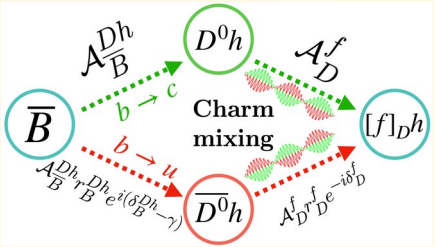
$$\gamma \equiv \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$$

- Until 2012, uncertainty at 11º
- LHCb-era took it down to 3º



ϕ_3/γ angle

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



$$\Gamma(B^{\pm} \to Dh^{\pm}) \propto |r_D e^{-i\delta_D} + r_B e^{i(\delta_B \pm \gamma)}|^2 \Rightarrow r_D^2 + r_B^2 + 2\kappa_D\kappa_B r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$

- The hadronic parameters (r_B , δ_B , r_D, δ_D) are specific to each B and D decay.
- The CP-violating weak phase difference (γ) is shared by all.
- Need the combination of the results from many different decay modes.
- The D parameters can be determined including charm and mixing observables.

$$\begin{aligned}\Gamma(B^{\pm} \to Dh^{\pm}) \propto\ & r_D^2 + r_B^2 + 2\kappa_D\kappa_B r_D r_B \cos(\delta_B + \delta_D \pm \gamma) \\ & - \alpha\left[(1 + r_B^2)\kappa_D r_D \cos(\delta_D) + (1 + r_D^2)\kappa_B r_B \cos(\delta_B \pm \gamma)\right] y \\ & + \alpha\left[(1 - r_B^2)\kappa_D r_D \sin(\delta_D) - (1 - r_D^2)\kappa_B r_B \sin(\delta_B \pm \gamma)\right] x\end{aligned}$$

LHCb arXiv:2110.02350

ϕ_3/γ angle

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

LHCb arXiv:2110.02350

Betti&al arXiv:2409.06449

$B^\pm$ Decays

Decay mode	Experiments
$B^\pm \to DK^\pm$, $D \to KK/\pi\pi$ (GLW)	BaBar, Belle, CDF, LHCb
$B^\pm \to DK^\pm$, $D \to K\pi$ (ADS)	BaBar, Belle, CDF, LHCb
$B^\pm \to DK^\pm$, $D \to \pi^+\pi^-\pi^0$ (GLW)	BaBar
$B^\pm \to DK^\pm$, $D \to K\pi\pi^0$ (ADS)	BaBar, Belle
$B^\pm \to DK^\pm$, $D \to KK\pi\pi/4\pi$ (GLW)	Belle, LHCb
$B^\pm \to DK^\pm$, $D \to \pi\pi\pi^0/KK\pi^0/K\pi\pi^0$ (GLW)	LHCb
$B^\pm \to DK^\pm$, $D \to K_s^0K\pi$ (ADS)	Belle, LHCb
$B^\pm \to DK^\pm$, $D \to K3\pi$ (GGSZ)	LHCb
$B^\pm \to DK^\pm$, $D \to K_s^0\pi\pi/K_s^0KK$ (GGSZ)	BaBar, Belle, LHCb
$B^\pm \to DK^\pm$, $D \to K_s^0\pi\pi\pi^0$ (GGSZ)	Belle
$B^\pm \to D^*K^\pm$, $D \to KK/\pi\pi + f_{CP^-}$ (GLW)	BaBar, LHCb
$B^\pm \to D^*K^\pm$, $D \to K_s^0\pi\pi/K_s^0KK$ (GGSZ)	LHCb
$B^\pm \to DK^{*\pm}$, $D \to KK/\pi\pi/f_{CP^-}$ (GLW)	BaBar, Belle
$B^\pm \to D\pi^\pm/D^*\pi^\pm$ (rate)	BaBar
$B^\pm \to Dh\pi\pi$, $D \to KK/\pi\pi/K\pi$ (GLW+ADS)	LHCb

B^0 Decays

Decay mode	Experiments
$B^0 \to DK^{*0}$, $D \to \pi\pi/KK/4\pi/K\pi/K3\pi$ (GLW+ADS)	LHCb
$B^0 \to DK^{*0}$, $D \to K_s^0\pi\pi/K_s^0KK$ (GGSZ)	Belle, LHCb
$B^0 \to D^-\pi^+/D^*(\text{full})\pi/D\rho$ (time-dep.)	BaBar, Belle
$B^0 \to D^{*-}\pi^+$ partial rec. (time-dep.)	BaBar, Belle
$B^0 \to D\pi$ time-dep. rates, $D \to K\pi\pi$	LHCb

B_s Decays

Decay mode	Experiments
$B_s \to D\bar{K}^{*0}$, $D \to \pi\pi/KK/4\pi/K\pi/K3\pi$ (GLW+ADS)	LHCb
$B_s \to D_sK\pi\pi$ (time-dep.)	LHCb

D Mixing & CP Asymmetries

Decay / observable	Experiments
$D \to KK/\pi\pi$ ΔA_{CP}, A_{CP} (CPV)	BaBar, Belle, CDF, LHCb
$D \to KK/\pi\pi$ ΔY, A_γ (mixing)	CDF, LHCb
$D \to KK/\pi\pi$ $y_{CP} - y_{CP}(K\pi)$ (mixing)	LHCb, HFLAV
$D \to KK/\pi\pi$ t/τ_D	CDF, LHCb
$D \to K\pi$ (WS/RS) r_D, x'^2, y', c', $\delta_{K\pi}$ (mixing)	BaBar, Belle, BESIII, LHCb
$D \to K_s^0\pi\pi$ (& K_s^0KK)	BaBar, Belle, LHCb
x_{CP}, y_{CP}, Δx, Δy; x, y, $\lvert q/p\rvert$, ϕ (mixing)	
$D \to K_s^0K\pi$ $\mathcal{B}(D^0)/\mathcal{B}(\bar{D}^0)$ in $K^{*\pm}$ region	Belle
$D \to K\pi\pi^0$ $x'^\pm$, $y'^\pm$ (mixing)	BaBar
$D \to \pi\pi\pi^0$ x, y no CPV (mixing)	BaBar
$D \to K3\pi$ $x^2 + y^2$; decay params κ, R, δ	LHCb,
(mixing+params)	LHCb+BESIII+CLEO-c
$D \to K\ell\nu_\ell$ $(x^2 + y^2)/2$ (mixing)	HFLAV

Auxiliary Inputs

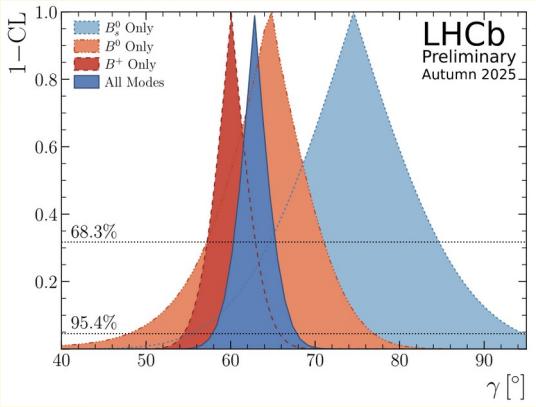
Quantity	Source
CP-even fractions F_{CP} ($D \to 4\pi$, $hh\pi^0$, $KK\pi\pi$)	CLEO-c, BESIII
DCS/CF branching ratios	BESIII
Coherence factor κ ($B \to DK^{*\pm}$)	CLEO-c, theory
Coherence factor κ_B ($B^0 \to DK^{*0}$)	LHCb

Thanks LLMs

ϕ_3/γ angle

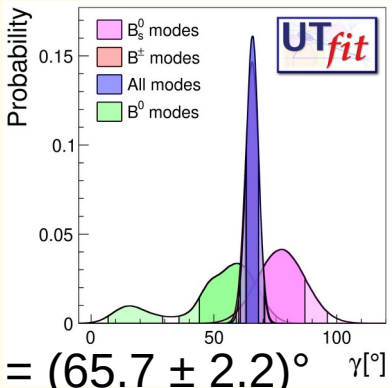
$$\gamma \equiv \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$$

LHCb LHCb-CONF-2025-003
Betti&al arXiv:2409.06449



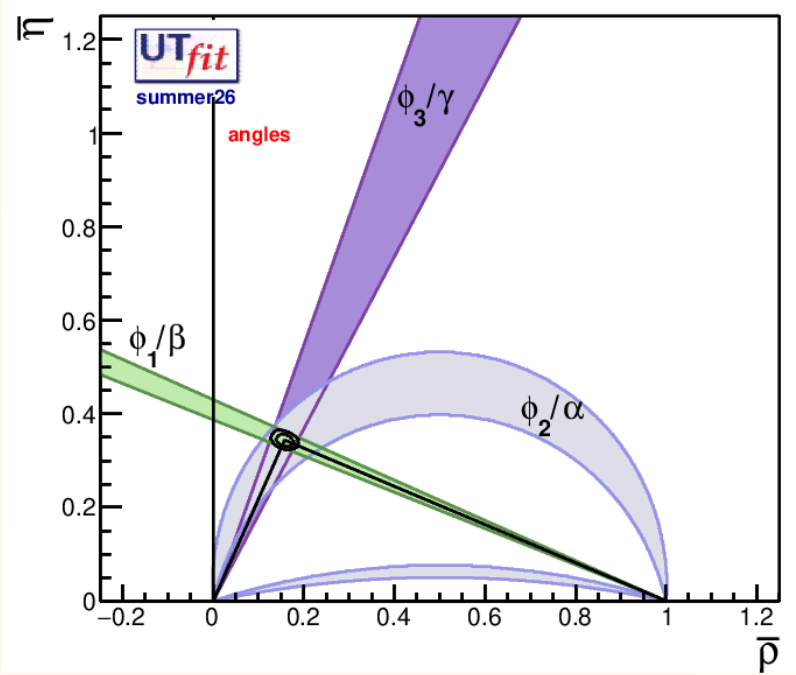
Latest

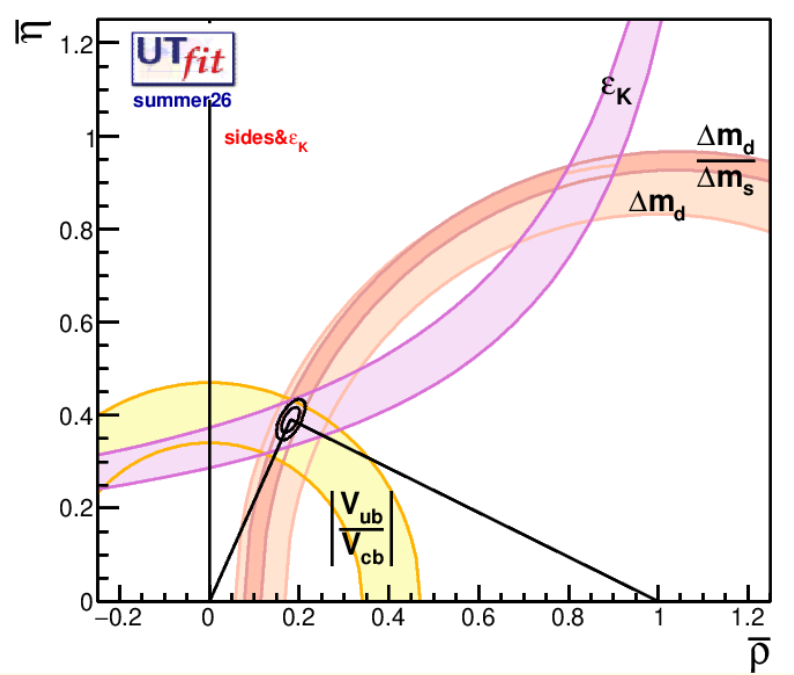
- LHCb combined Run 1+2 [LHCb-CONF-2025-003]
  - **γ = (62.8 ± 2.6)°** → ×5 improvement in 15 years
- LHCb + BESIII joint fit (Fourier basis, no binning) [arXiv:2604.05701/05712]:
  - γ = (71.3 ± 5.0)° → best single measurement of γ
  - exploits BESIII $\psi(3770) \to D\bar{D}$ strong-phase inputs
- Belle II combined with Belle [arXiv:2308.05048]:
  - **ϕ_3 = (78.6 ± 7.3)°**



γ/ϕ_3 = (65.7 ± 2.2)°

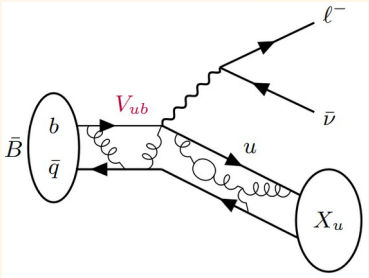
On the sides..


UTfit
summer26
angles
ϕ_3/γ
ϕ_1/β
ϕ_2/α
$\bar{\eta}$
$\bar{\rho}$


UTfit
summer26
sides&ε_K
ε_K
$\frac{\Delta m_d}{\Delta m_s}$
Δm_d
$\left|\frac{V_{ub}}{V_{cb}}\right|$
$\bar{\eta}$
$\bar{\rho}$

On the sides..

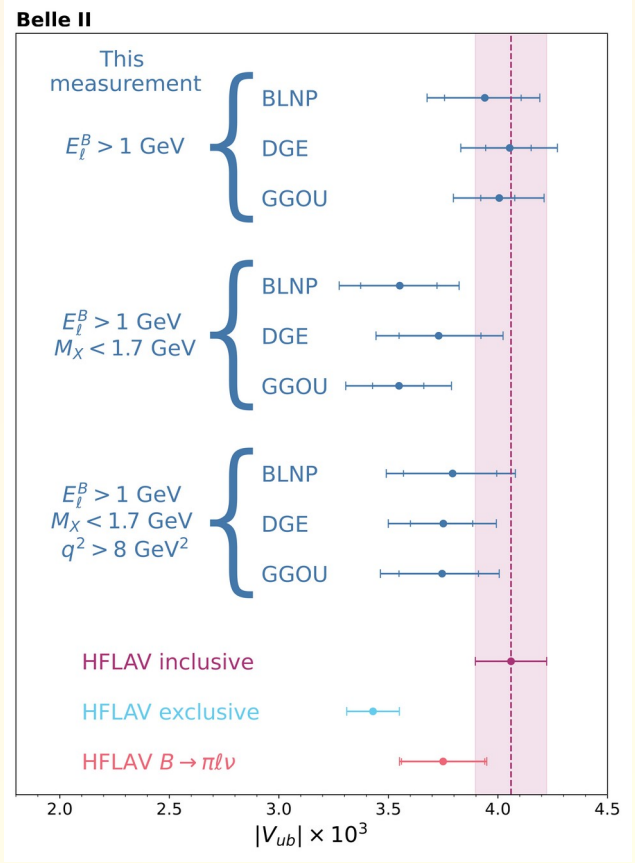
- Semileptonic decays:
  - tree-level dominated
  - reference for model building



- New inclusive Belle-II $B \to X_u \ell \nu$ measurement
  - $|V_{ub}| = (4.01 \pm 0.11 \pm 0.16 \pm 0.08) \times 10^{-3}$
  - compatible with inclusive average
- single measurements with uncertainties competing with those of the averages

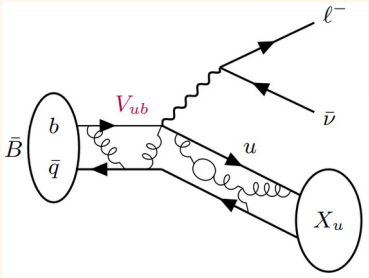
Belle II

~5%



PRD 113 (2026) 032004

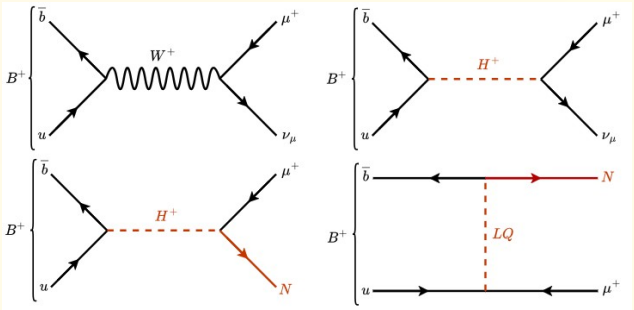
On the sides..



- Semileptonic decays:
  - tree-level dominated
  - reference for model building

- New inclusive Belle-II $B \to X_u \ell \nu$ measurement
  - $|V_{ub}| = (4.01 \pm 0.11 \pm 0.16 \pm 0.08) \times 10^{-3}$
  - compatible with inclusive average
- single measurements with uncertainties competing with those of the averages

- $B \to \mu\nu/\tau\nu$ decays depends on V_{ub}
  - sensitive to NP

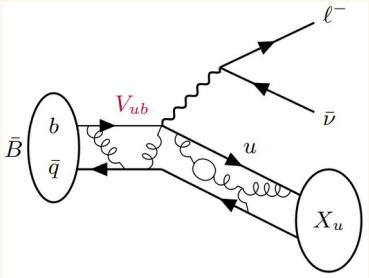


$$\mathcal{B}(B^+ \to \mu^+ \nu_\mu) = \frac{G_F^2 m_B m_\mu^2}{8\pi} \left(1 - \frac{m_\mu^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_{B^+}$$

$|V_{ub}| = (3.92\ ^{+0.77}_{-0.96}\ ^{+0.44}_{-0.49} \pm 0.03) \times 10^{-3}$

~25%

On the sides..



- Semileptonic decays:
  - tree-level dominated
  - reference for model building

- New inclusive Belle-II $B \to X_u \ell \nu$ measurement
  - $|V_{ub}| = (4.01 \pm 0.11 \pm 0.16 \pm 0.08) \times 10^{-3}$
  - compatible with inclusive average
- single measurements with uncertainties competing with those of the averages

- On-shell determinations: $W \to bc$ in top-pair events
  - ATLAS: $|V_{cb}| = (50 \pm 9 \pm 10) \times 10^{-3}$
  - CMS: $|V_{cb}| = (45.9 \pm 4.8 \pm 7.6) \times 10^{-3}$
  - overall uncertainties are large, sys>stat ($t\bar{t}$ modelling in simulation)

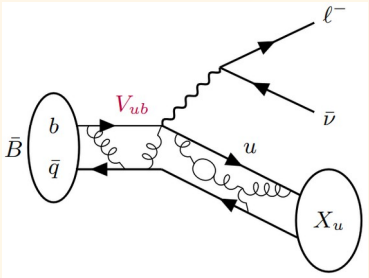
~20-27%

arXiv:2603.16414

CMS PAS TOP-26-001

On the sides..

- Semileptonic decays:
  - tree-level dominated
  - reference for model building



- (very) Long standing discrepancy between inclusive and exclusive measurements
  - V_{cb} enters everywhere in CKM fits
  - reduced tension in V_{ub}

~1.2%

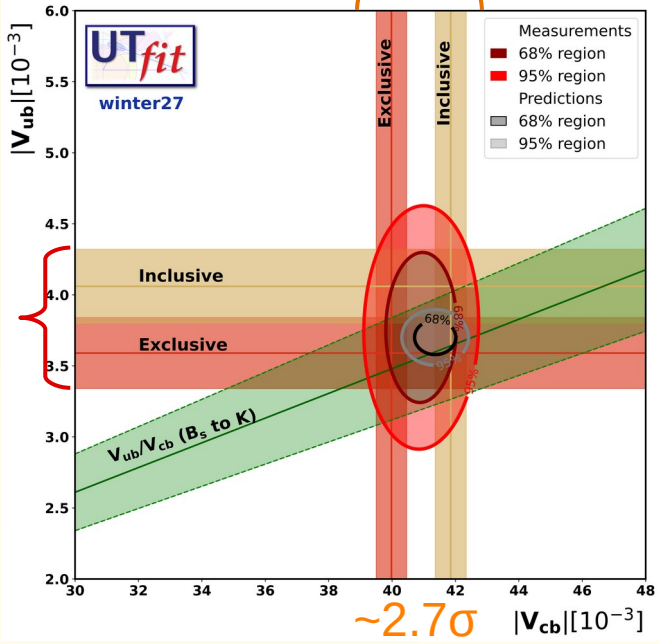
$|V_{cb}|$ *(excl)* = (39.98 ± 0.48) 10^{-3}
$|V_{cb}|$ *(incl)* = (41.85 ± 0.49) 10^{-3}

$|V_{ub}|$ *(excl)* = (3.59 ± 0.25) 10^{-3}
$|V_{ub}|$ *(incl)* = (4.06 ± 0.26) 10^{-3}

~6-7%

~9%

~1.8%



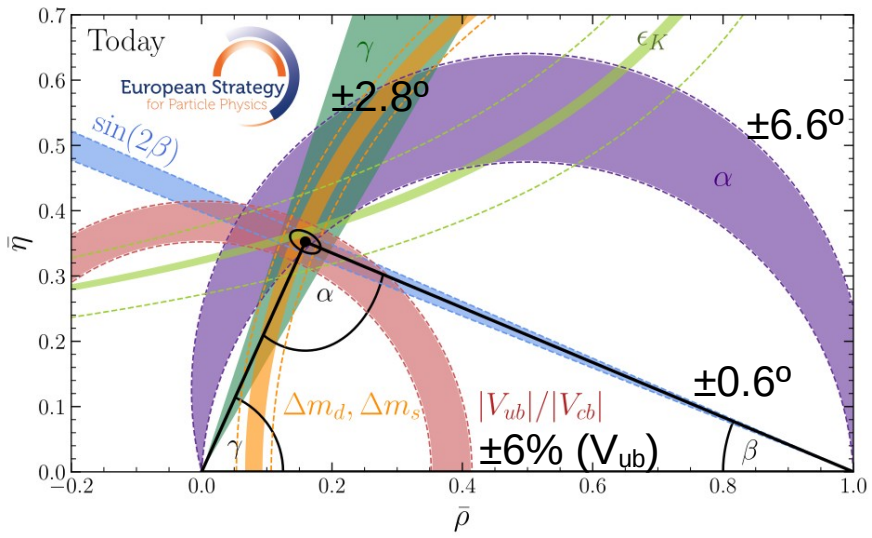
~2.7σ

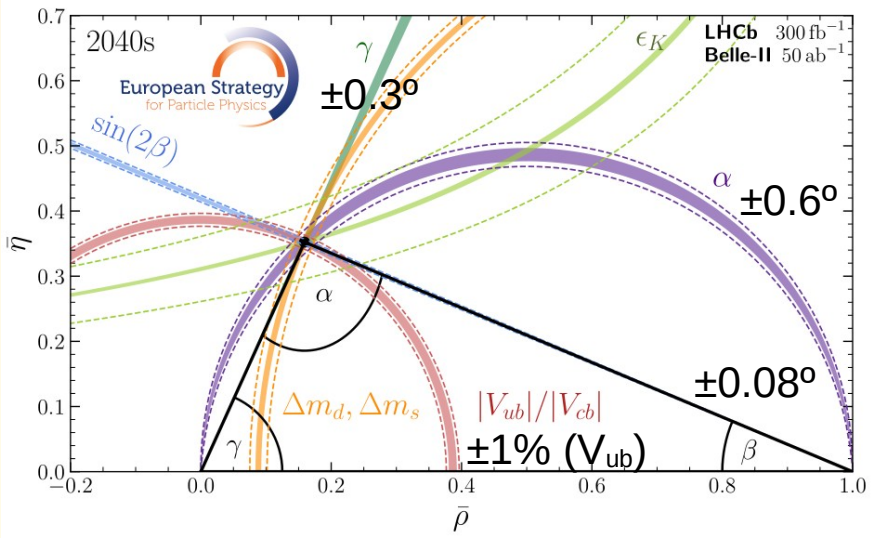
The future of the Unitarity Triangle

2030-2040:
arXiv:2503.24346

Improvements by:

ϕ_1/β → 3x (2030), 7x (2040) → but penguin pollution
ϕ_2/α → 3x (2030), 12x (2040)
ϕ_3/γ → 3.5x (2030), 9x (2040)
V_{ub}/V_{cb} → 3x (2030), 6x (2040) → but lattice/theory/(radiative correction)

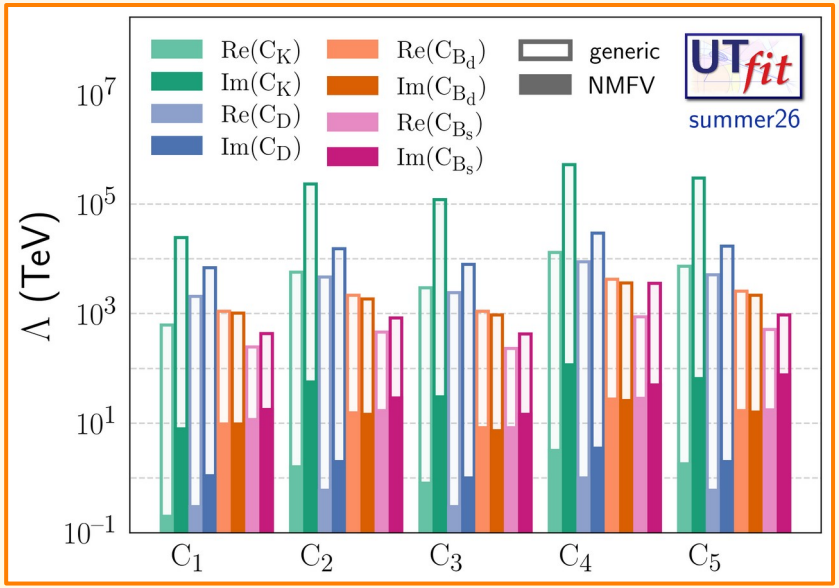




nightmare scenario

Glimpse into new physics

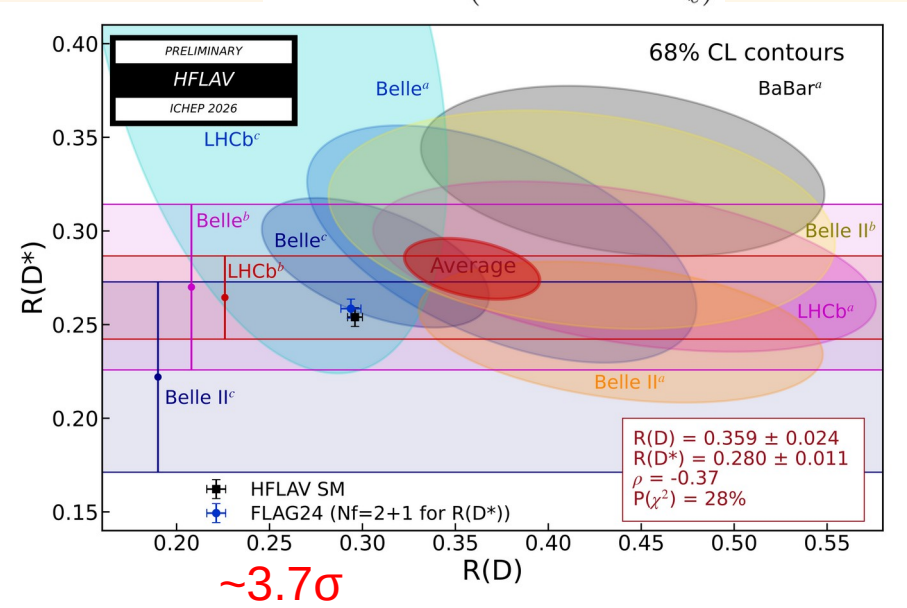
- "Extreme" tests of the Standard Model due to precision predictions
  - testing SM accidental symmetries like Lepton Flavour Universality
  - testing scales not directly accessible



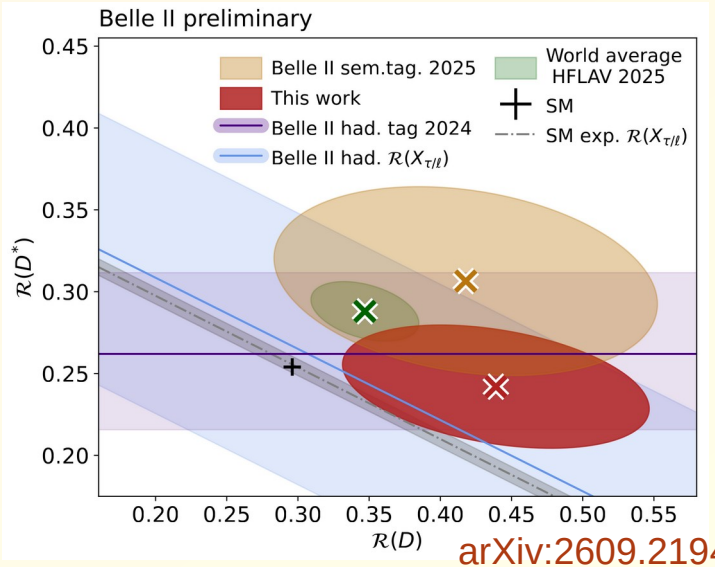
Glimpse into new physics

- testing SM accidental symmetries like Lepton Flavour Universality

$$R(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell)}$$



- New Belle II analysis
  - most precise with hadronic tag
  - overall agreement

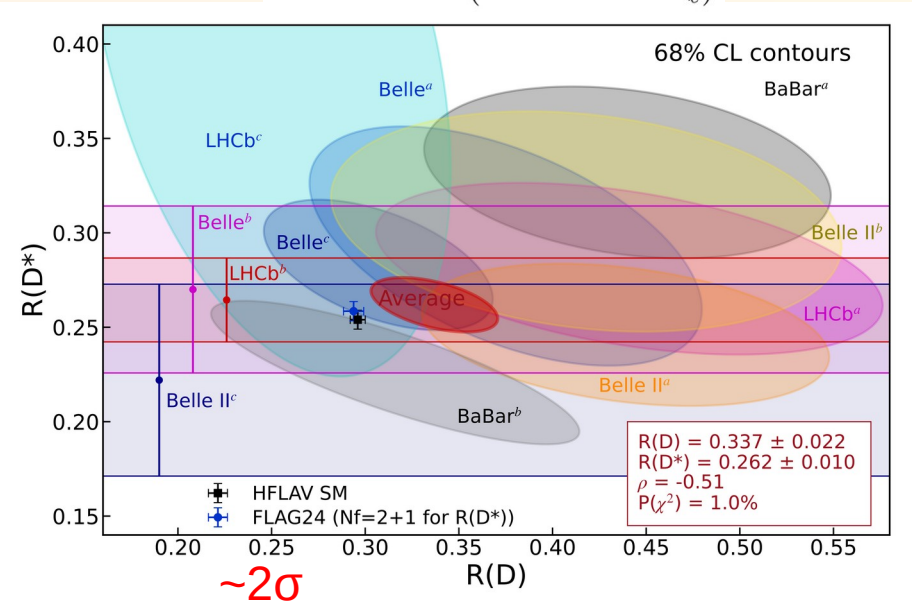


arXiv:2609.21947

Glimpse into new physics

- testing SM accidental symmetries like Lepton Flavour Universality

$$R(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell)}$$



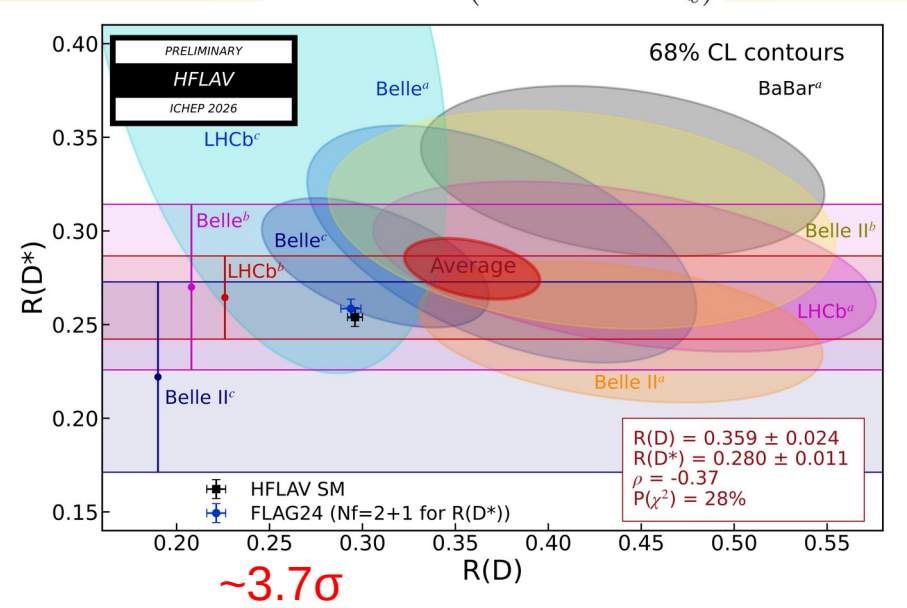
- Preliminary BaBar analysis
  - previous (2012) analysis with hadronic tags
  - now (2025) with semileptonic tags
  - statistically independent
  - consistent with SM at ~1.5σ
  - world average consistent with SM at ~2σ



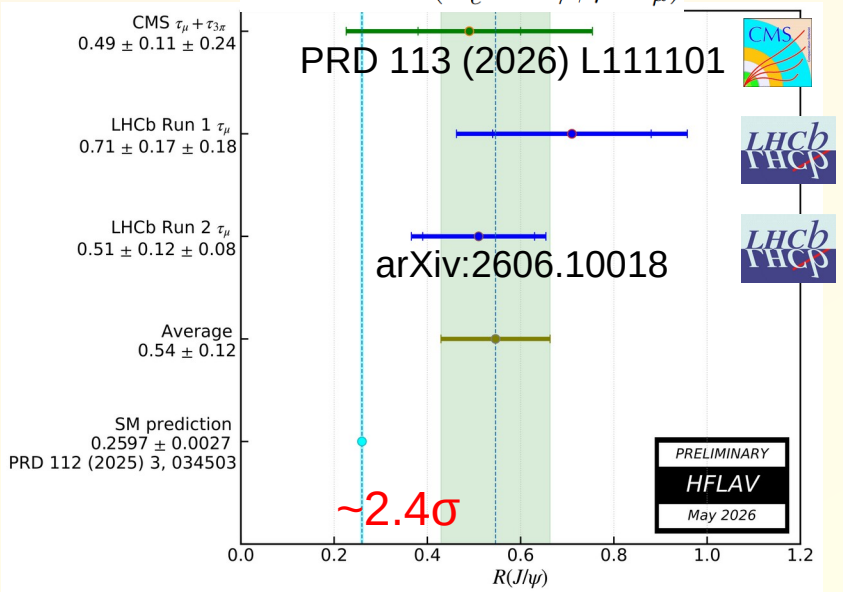
Glimpse into new physics

- testing SM accidental symmetries like Lepton Flavour Universality

$$R(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell)}$$



$$\mathcal{R}(J/\psi) \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$

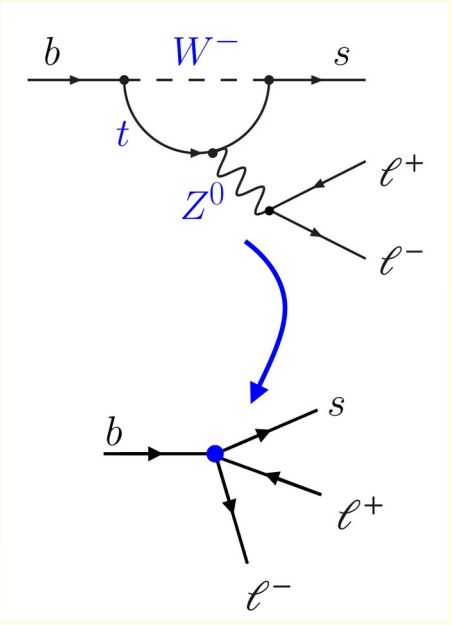


Give new physics a chance: FCNC

- Flavour-Changing Neutral Currents are the perfect ground
  - a lot of measurements

Branching ratios,
Angular analyses
SM symmetry tests

$$B_s \to \ell^+\ell^-, B \to K\ell^+\ell^-,$$
$$B \to K^*\ell^+\ell^-, B_s \to \phi\ell^+\ell^-,$$
$$\Lambda_b \to pK^-\ell^+\ell^-, \ldots$$



Problem of hadronic uncertainties

Increasing precision of the SM prediction

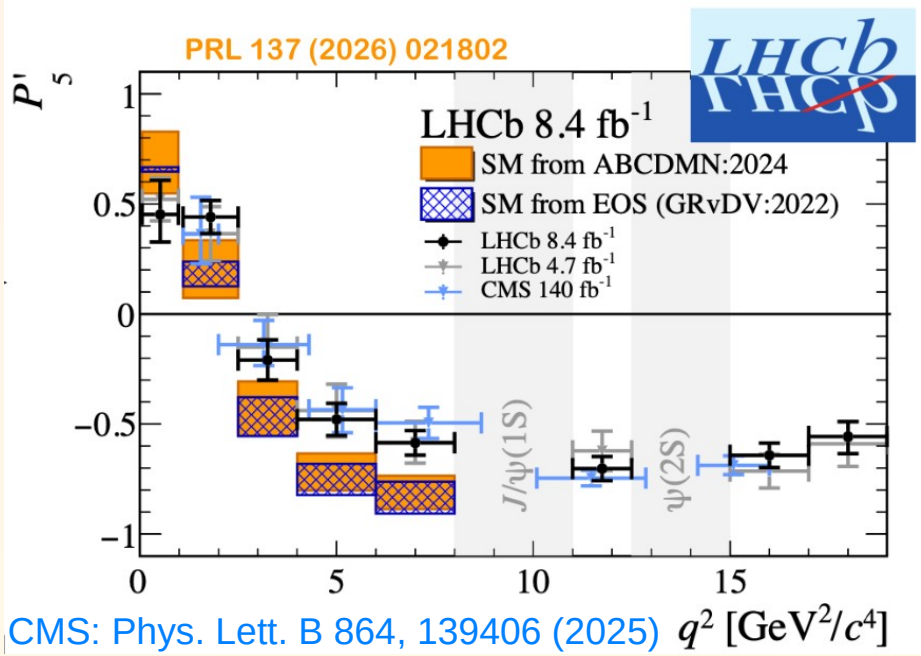
- Semileptonic $b \to s\mu\mu$
- Leptonic $B_s \to \mu\mu$
- Lepton universality

Weak effective theory: four-fermion interaction with effective couplings: Wilson coefficients $C_i = C_i^{SM} + C_i^{NP}$

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$$

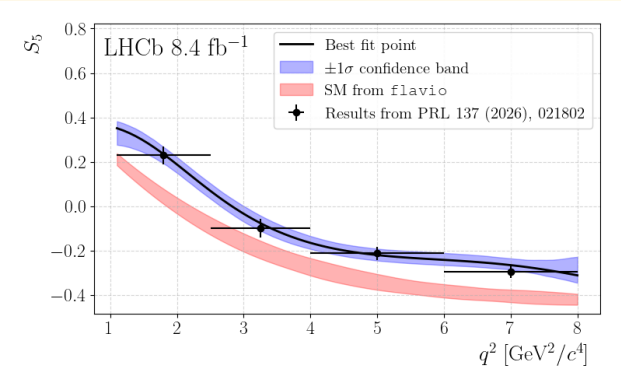
Give new physics a chance: FCNC

- Amplitude analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay

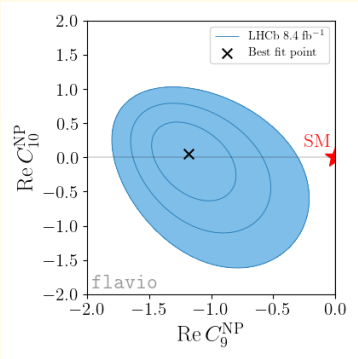


CMS: Phys. Lett. B 864, 139406 (2025)

arXiv:2608.12215



- Unbinned, model-independent amplitude analysis
- q^2 dependence in terms of Legendre polynomials
- tensions at the level of 4.3 to 4.8σ

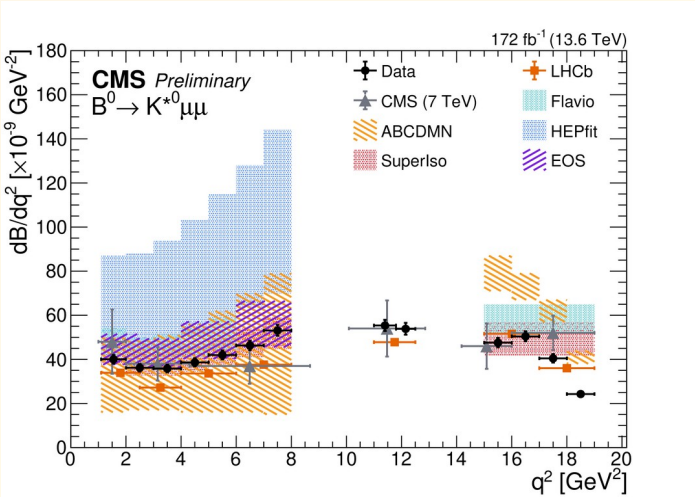


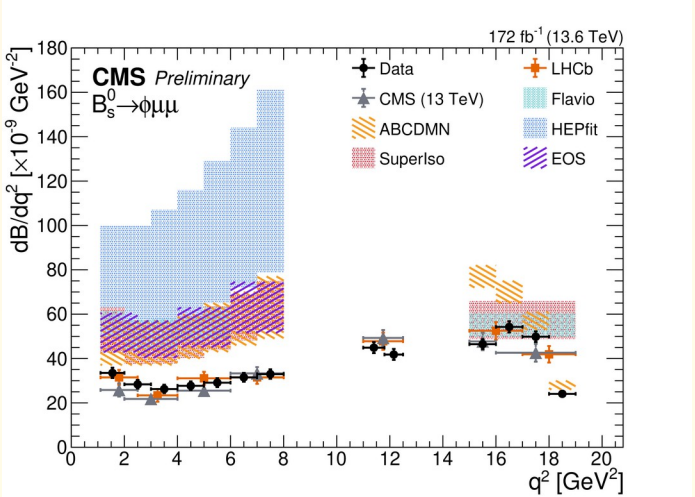
Give new physics a chance: FCNC

- CMS simultaneous differential branching fraction and isospin asymmetry measurements of rare b→sμμ decays

CMS-PAS-BPH-24-005

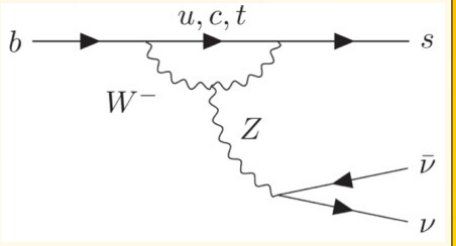
- Results in agreement with previous CMS & LHCb results
- Relative suppression wrt theory in all 6 b→sμμ decays

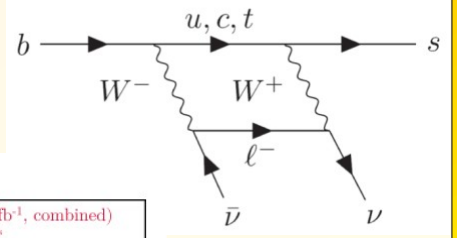




Give new physics a chance: FCNC

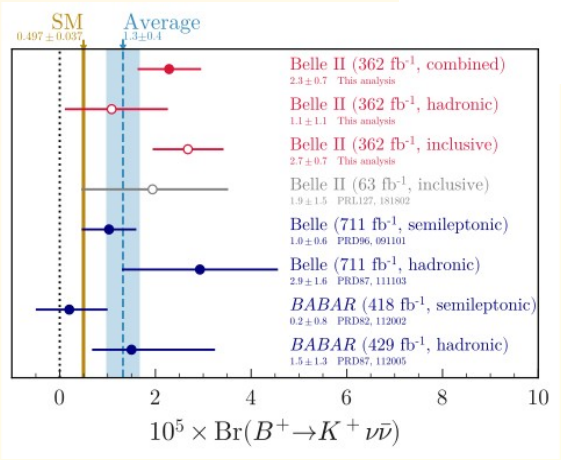
- Flavour-Changing Neutral Currents are the perfect ground
  - **b → sνν̄** measurements at Belle II
  - Theoretically clean: no γ*, no charm loops or resonances





- Evidence for $B^+ \to K^+ \nu\bar{\nu}$
  - BR ~2.7σ larger than SM expectations
  - *PRD 109 (2024) 112006*

- First inclusive search
  - $BR(B \to X_s \nu\bar{\nu}) < 3.3 \times 10^{-4}$ @90 % CL
  - SM prediction $(2.9 \pm 0.3) \times 10^{-5}$
  - *PRL 136 (2026) 231801*



PRD 109 (2024) 112006

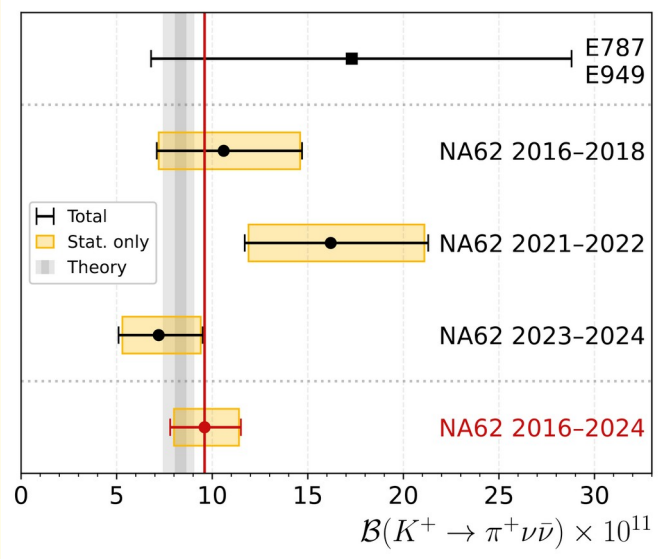
Give new physics a chance: FCNC

- Flavour-Changing Neutral Currents are the perfect ground
  - **s → dνν̄** golden modes
  - highly suppressed in the SM and highly sensitive to NP

- expected BR
  - $BR(K^+ \to \pi^+ \nu\bar{\nu})_{SM} \approx 8.5 \times 10^{-11}$ (±5%) ~5%
  - $BR(K_L \to \pi^0 \nu\bar{\nu})_{SM} \approx 3 \times 10^{-11}$ (±6%)
  - error dominated by the CKM parameters

- $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (9.6\ ^{+1.9}_{-1.8}) \times 10^{-11}$ ~20%
  - smallest BR ever measured
  - En route to 15% by the end of the data taking and that will be all for this decay..

arXiv:2607.16413



Give new physics a chance: FCNC

- Flavour-Changing Neutral Currents are the perfect ground
  - **s → dνν̄** golden modes
  - highly suppressed in the SM and highly sensitive to NP



arXiv:2607.16413

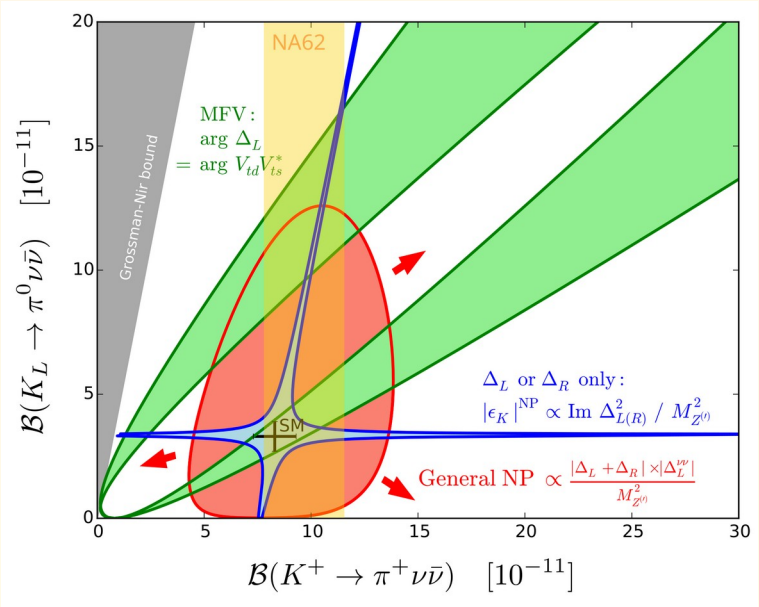
- expected BR
  - $BR(K^+ \to \pi^+ \nu\bar{\nu})_{SM} \approx 8.5 \times 10^{-11}$ (±5%) ~5%
  - $BR(K_L \to \pi^0 \nu\bar{\nu})_{SM} \approx 3 \times 10^{-11}$ (±6%)
  - error dominated by the CKM parameters
- $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (9.6\ ^{+1.9}_{-1.8}) \times 10^{-11}$ ~20%
  - smallest BR ever measured
  - En route to 15% by the end of the data taking and that will be all for this decay..
- The neutral decay is looked at by KOTO with 2021 data:
  - $BR(K_L \to \pi^0 \nu\bar{\nu}) < 2.2 \times 10^{-10}$ @90 % CL
  - getting to SM levels by the end of the run in 2030



Phys. Rev. Lett. 134, 081802

Give new physics a chance: FCNC

- Flavour-Changing Neutral Currents are the perfect ground
  - **s → dνν̄** golden modes
  - highly suppressed in the SM and highly sensitive to NP



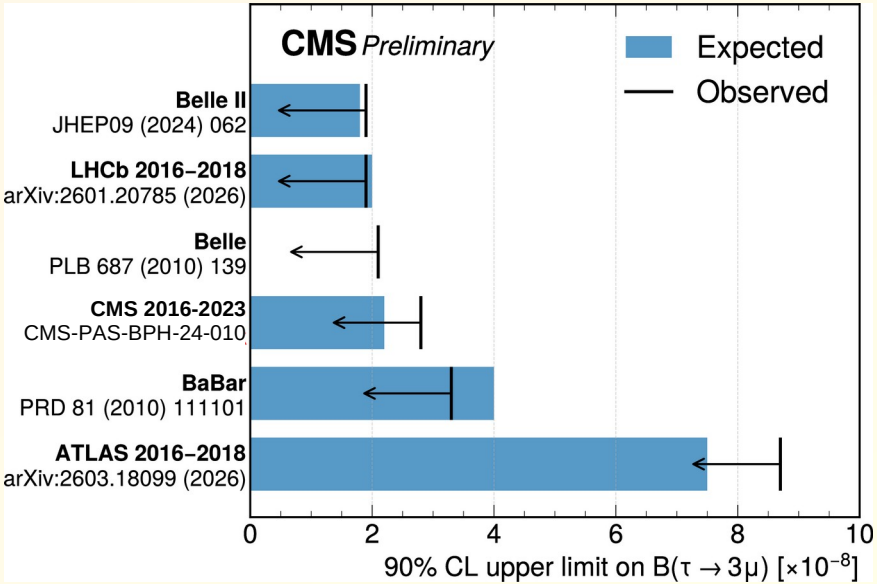
Blanke&al arXiv:2607.19055

Give new physics a chance: LFV

- Flavour violation observed in quarks and neutrinos, but not in charged leptons
- Charged lepton flavour violation related to neutrino oscillations is unobservably small in the SM: on $\tau \rightarrow 3\mu$ is $\boldsymbol{O(10^{-55})}$

- any non-zero measurement would be an unambiguous sign of physics beyond the SM.
- Upper limits on branching fractions such as BR($\tau \rightarrow \mu\gamma$) and BR($\tau \rightarrow 3\mu$) provide stringent constraints on possible SM extensions.

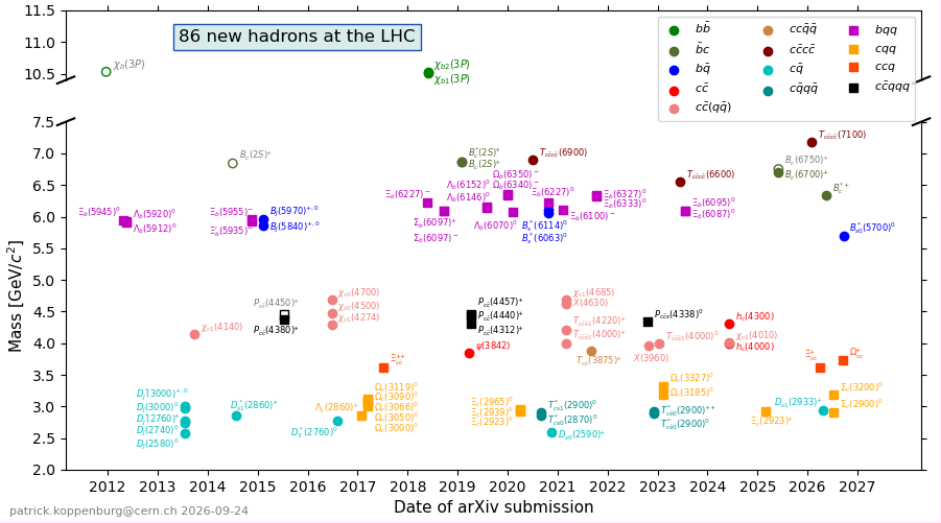
CMS-PAS-BPH-24-010



What I have left out.. and conclusions

- A lot of rare decays of beauty and charm mesons and baryons
- Spectroscopy: the new zoo
- Most of tau physics and decays

- All testing the SM to fill in its gaps and until a fracture shows to give us the direction towards the new physics
- More statistics from the experiments and theory/lattice work to match it will clarify the tensions.. (one way or hopefully another..)
- Complementarity is key



backup slides

The future of the Unitarity Triangle

2030-2040
arXiv:2503.24346

Obser-vable	Unit	Current				~2030s		~2040s (Final)			
		ATLAS	CMS	LHCb	Belle II	LHCb	Belle II	ATLAS	CMS	LHCb	Belle II
ϕ_1/β	(°)	—	—	0.57	1.2	0.20	0.4	—	—	0.08	0.3
ϕ_2/α	(°)	—	—	—	6.6	—	2.5	—	—	—	0.6
ϕ_3/γ	(°)	—	—	2.8	13	0.8	2.2	—	—	0.3	1.0
ϕ_s	(mrad)	42	23	20	—	8	—	4–9	3	3	—
$\lvert V_{cb}\rvert$	(rel. %)	—	—	—	1.7	—	1.0	—	—	—	1.0
$\lvert V_{ub}\rvert$	(rel. %)	—	—	6	6.3	2	1.8	—	—	1	1.2

Current: ATLAS/CMS Run1–3 · LHCb 2–9 fb^{-1} · Belle II ~428 fb^{-1} | ~2030s: LHCb 50 fb^{-1} · Belle II 10 ab^{-1}
~2040s: ATLAS/CMS 3000 fb^{-1} · LHCb 300 fb^{-1} · Belle II 50 ab^{-1}

The future of the Unitarity Triangle

2030-2040: arXiv:2503.24346
FCC era: CERN-2025-008

- **ϕ_1/β** considering the experimental observable (S):
  - 3x (2030), 7x (2040)→ **with all the experiments > 10x error reduction**
  - FCCee precision comparable to HL-LHC
  - **all corollary modes needed for the penguin pollution!**
- **ϕ_2/α** needs statistics in all isospin related mode: better at e^+e^- colliders
  - 3x (2030), **12x (2040) with sub-deg precisions**
  - >30x (FCCee) with 0.2º uncertainty
- **ϕ_3/γ** needs all the modes discussed and synergy with charm factories
  - 3.5x (2030), **9x (2040) getting to 0.3º uncertainty**
- **ϕ_s** improvement in precisions depends also on improvement on tagging
  - 2.5x (2030), 6x (2040) getting to **3 mrad uncertainty**
  - FCC-ee giving an additional 2x improvement
- **Vub/Vcb** more data and improved theory and lattice inputs
- FCCee: running at the Z pole and WW threshold, 15% (12% and 3.4%) branching fraction of Z decays into bb (cc and ττ) pairs

Give new physics a long term chance

arXiv:2503.24346

Observable	Unit	Current				~2030s		~2040s (Final)			
		ATLAS	CMS	LHCb	Belle II	LHCb	Belle II	ATLAS	CMS	LHCb	Belle II
Leptonic B decays											
$B(B^0_s \to \mu^+\mu^-)$	$[10^{-9}]$	+0.8/–0.7	0.45	0.48	—	0.23	—	0.33–0.40	0.22	0.16	—
$B(B^+ \to \tau^+\nu\tau)$ $B(B^+ \to \mu^+\nu\mu)$	(rel. %)	—	—	—	34 41	—	10 11	—	—	—	6 5
FCNC b → sℓℓ decays											
$P'_5(B^0 \to K^{*0}\mu^+\mu^-)$	$[10^{-3}]$	390	100	111	—	29	—	47–82	23	12	—
$B(B^+ \to K^+\nu\bar{\nu})$ $B(B^0 \to K^{*0}\nu\bar{\nu})$	(rel. %)	—	—	—	57 110	—	14 33	—	—	—	8 23
$B(B^+ \to K^+\tau^+\tau^-)$ $B(B^0 \to K^{*0}\tau^+\tau^-)$	$[10^{-4}]$	—	—	—	<10 <18	—	<1.9 <3.4	—	—	—	<0.9 <1.5
Lepton flavour violation in τ decays											
$B(\tau^+ \to \mu^+\mu^+\mu^-)$	$[10^{-8}]$	<37.6	<2.9	<4.6	<1.8	<0.64	<(0.08–0.37)	<(0.13–0.64)	<0.39	<0.26	<(0.02–0.17)