Flavour physics at LHCb, Belle II and BESIII, and opportunities for a future Z factory

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CEPC Workshop 2026, Shanghai

Flavour physics probes new physics far above direct reach. Today LHCb, Belle II and BESIII explore it complementarily, each with strengths and limits. A Tera-Z has the potential to close the gaps none of them can reach alone. *(To be honest, also other important players: CMS/ATLAS and NA62.)*

Outline

- Why flavour physics
- LHCb: highlights and limits
- Belle II: the clean complement
- BESIII: charm threshold and strong phases
- The gaps none of them closes alone
- A future Z factory
- Summary

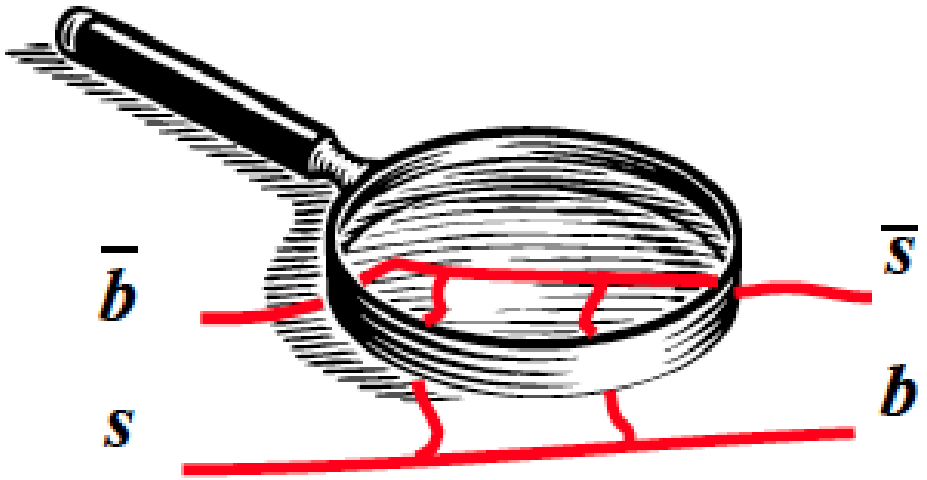
Why flavour physics: how stubborn is the SM?

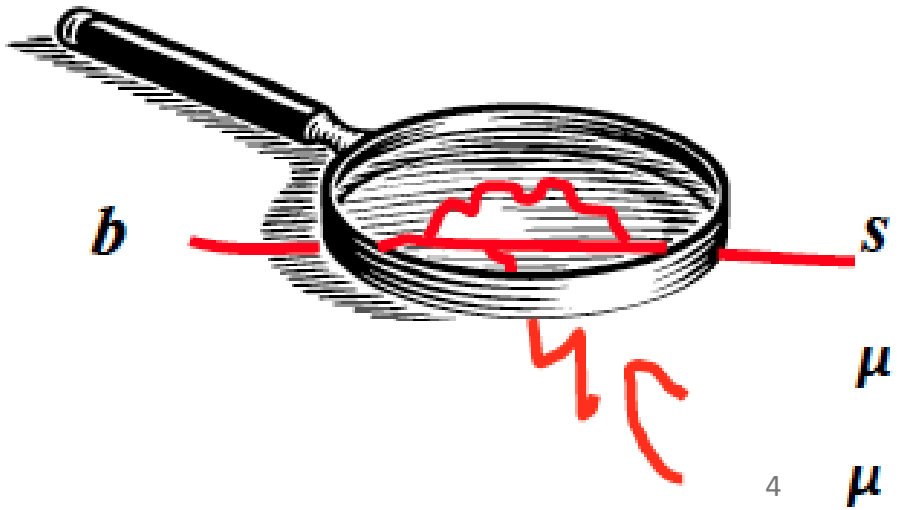
- Open questions the SM does not answer:
  - 3 generations; mass hierarchy over orders of magnitude; origin of flavour couplings
  - Baryon asymmetry of the universe (BAU)
- Can SM CP violation explain the BAU?
  - Qualitatively yes
  - Quantitatively NO: predicts baryon-to-photon number density in the universe $\eta \approx 10^{-19}$, off by ~10 orders of magnitude
  - → New sources of CP violation needed beyond the SM
- But so far, the donkey didn't move too much…



Indirect reach: low-energy vs high-energy

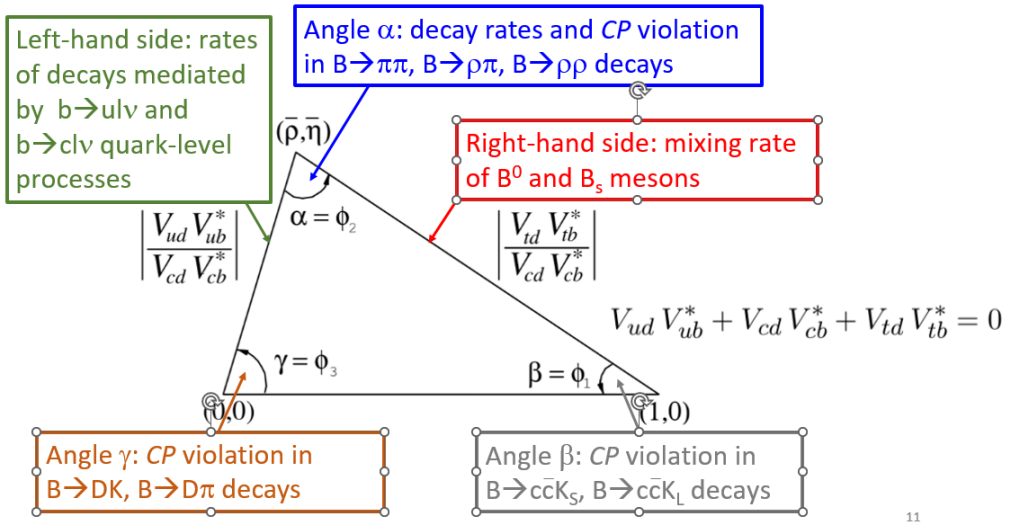
- ATLAS/CMS: direct production of new heavy states, limited by LHC energy
- Flavour (LHCb, B/charm factories): indirect, via virtual NP in loops
  - Sensitive to mass scales $\gg$ 1 TeV, beyond direct reach
  - Requires precise SM predictions to expose small NP shifts
- A second layer of complementarity, among flavour physics experiments, is discussed in this talk

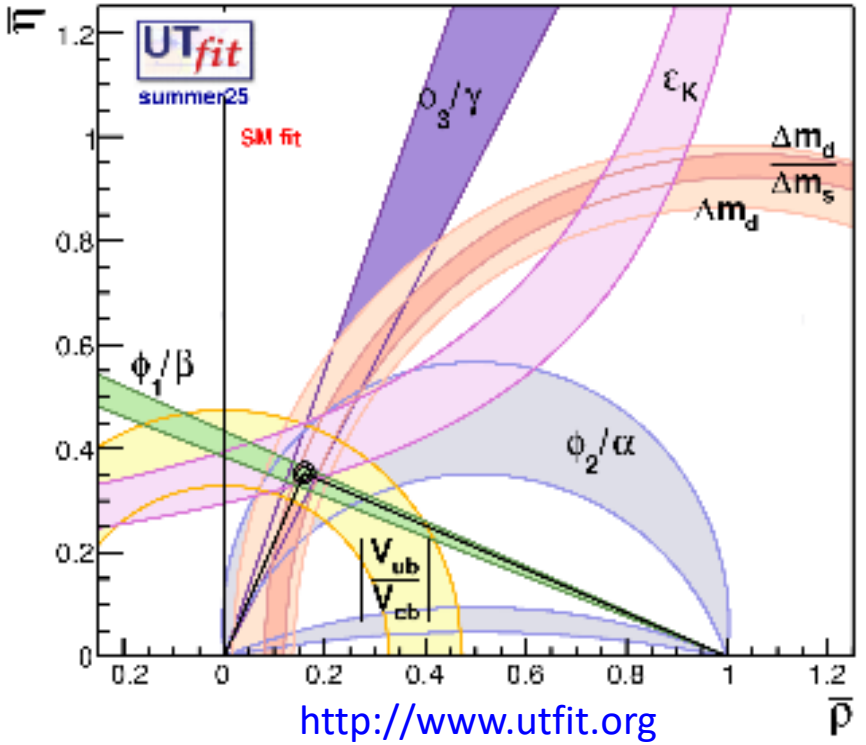




State of the CKM picture

- Unitarity triangle over-constrained by many independent processes
  - Angles α/β/γ from CP violation; sides from $|V_{ub}/V_{cb}|$ and mixing
- Global CKM fit: tremendous success of the paradigm → CKM works!
  - All contours cross in one region to current precision
- But still room for NP contributions at the ~10% level





http://www.utfit.org

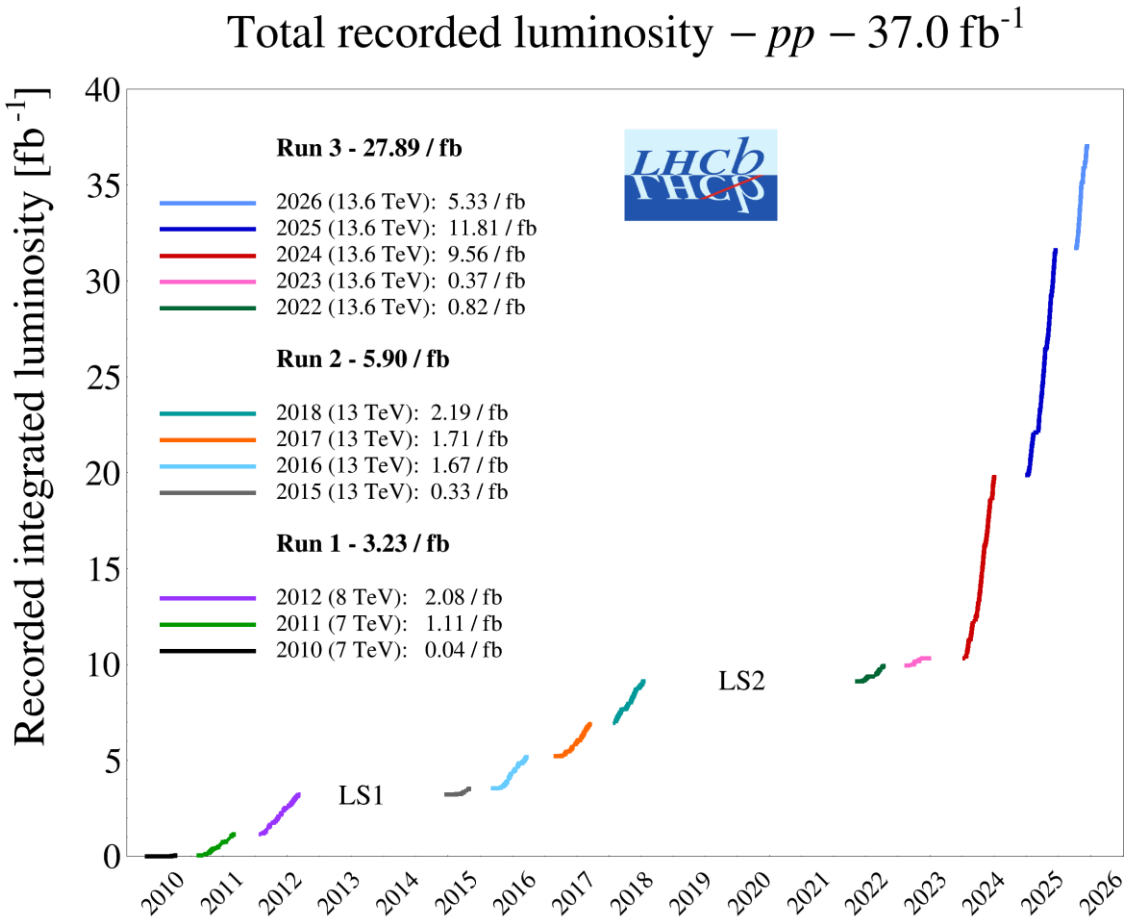
LHCb

The power of statistics

(detailed overview: see Z. Xu's parallel talk)

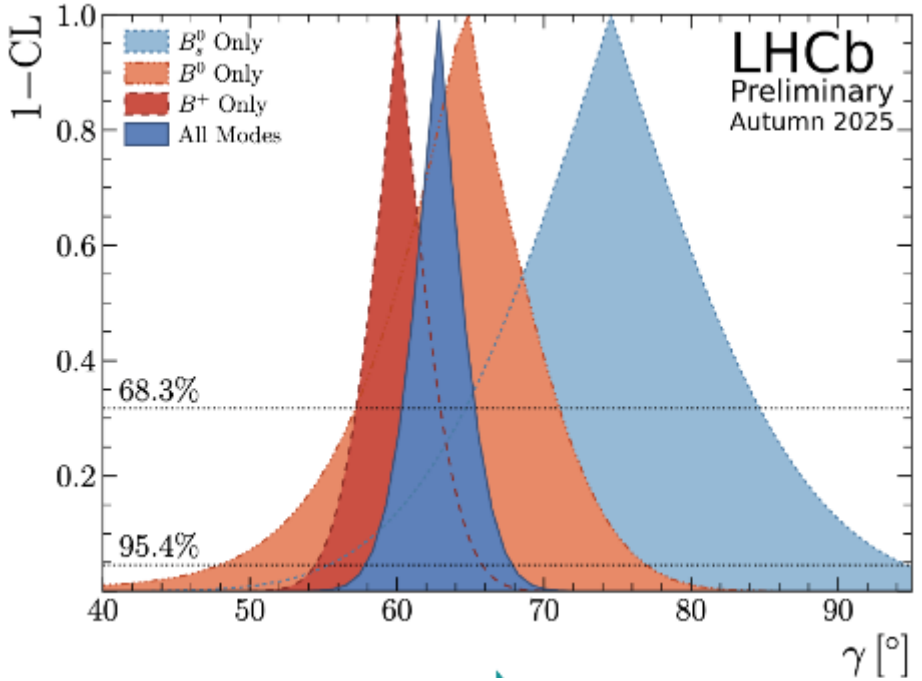
The LHCb detector and datasets

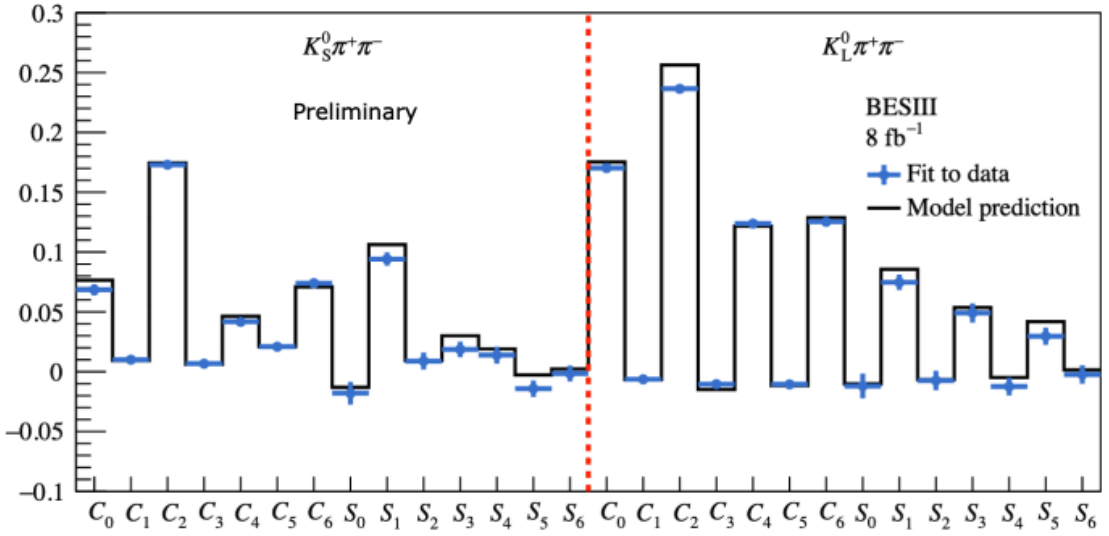
- Single-arm forward spectrometer, $2 < \eta < 5$
  - Precise vertexing (σ_τ ~45 fs), momentum, powerful PID
- A forward heavy-flavour factory: huge b and c yields → home of enormous b/c statistics, baryons, charm and all b-hadron species
- Datasets: 9 fb^{-1} (Run 1–2) + 28 fb^{-1} (Run 3), 37 fb^{-1} total



CKM angle γ: the precision frontier

- Tree-level, theoretically clean ($\delta\gamma \sim 10^{-7}$)
- 2025 LHCb average: $\gamma = (62.8 \pm 2.6)°$
  - Most precise single-experiment determination; >12 channels; ~15° pre-LHCb
- Also built on strong-phase input from BESIII (more later)
  - Joint BESIII–LHCb unbinned analysis → ~5% gain; γ strong-phase uncertainty down to 0.6°

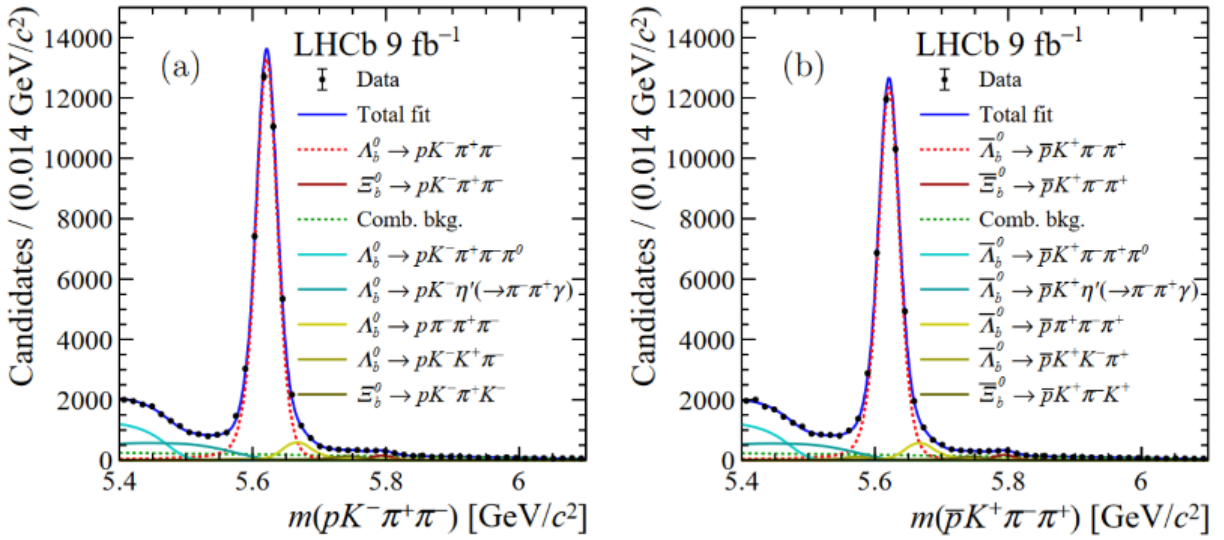


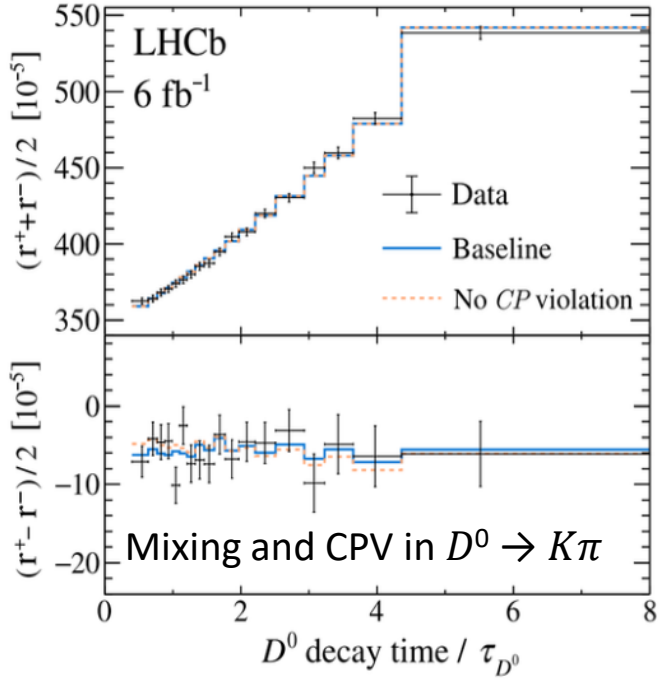


Refs: LHCb-CONF-2025-003, LHCb-PAPER-2025-063, LHCb-PAPER-2025-064, arXiv:2604.05712, arXiv:2604.05701

CP violation unique to LHCb: baryons and charm

- First observation of CPV in baryon decays (2025)
  - ΔA_{CP} = (2.45 ± 0.46 ± 0.10)%, 5.2σ
- Charm: first direct CPV (2019); mixing and CPV still consistent with CP symmetry
- Baryons and charm statistics: the hadron collider's comfort zone!



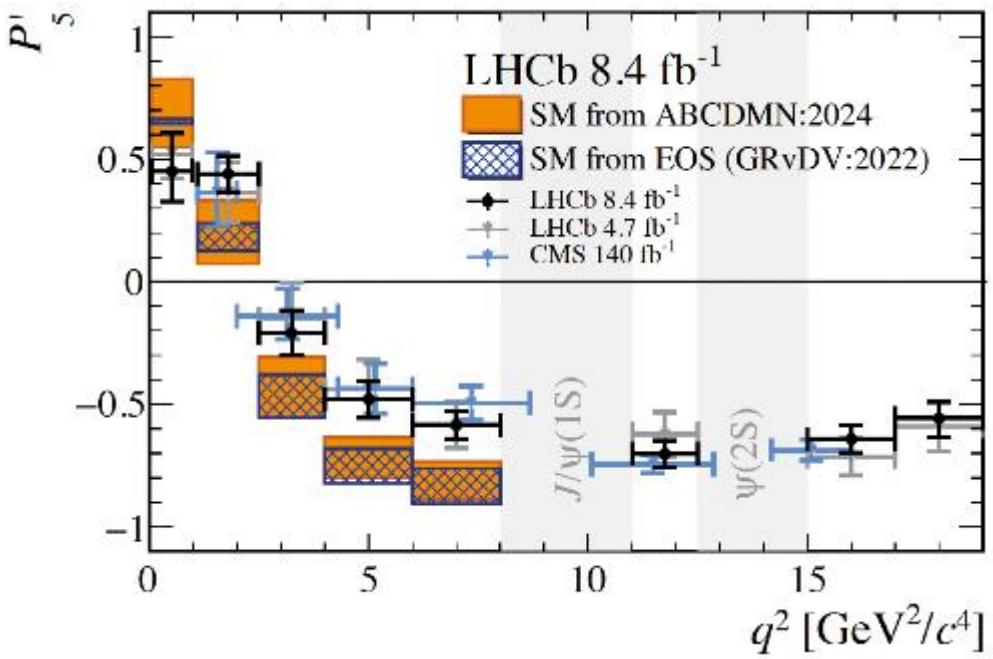


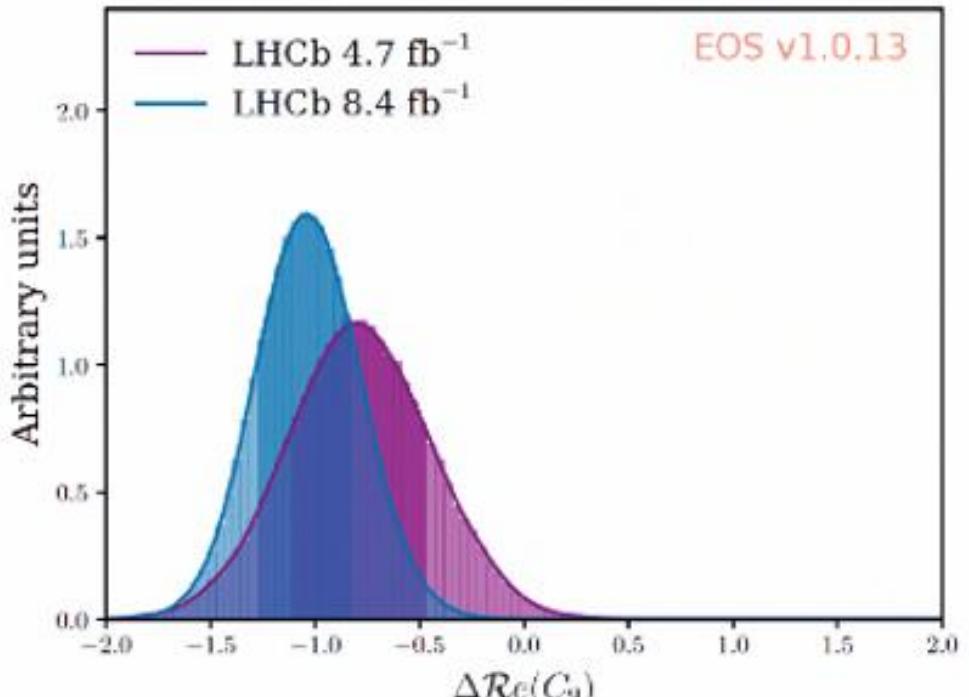
Refs: Nature 643 (2025) 1223, PRD 111 (2025) 012001, JHEP 12 (2025) 153

Rare decays b → sμμ

- Branching fractions consistently below SM (1–3σ)
- Angular analysis $B^0 \to K^{*0}\mu^+\mu^-$, full Run 1–2 (8.4 fb^{-1})
  - Favoured shift in vector coupling (C9), consistent LHCb–CMS pattern
  - Tension ~4σ in optimised observables
- NP, or underestimated hadronic / charm-loop effects? → tantalising but hadronically limited, not yet a clean NP signal

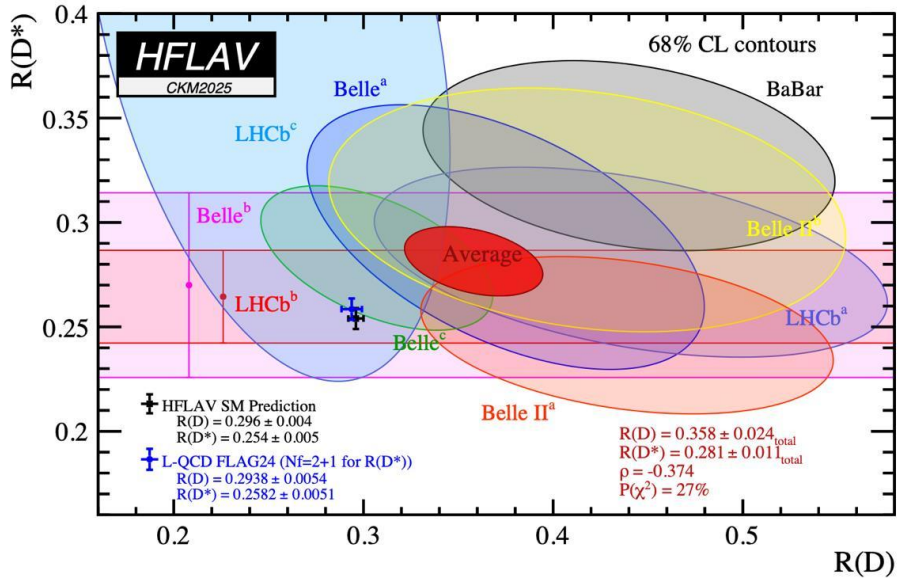
Refs: arXiv:2512.18053



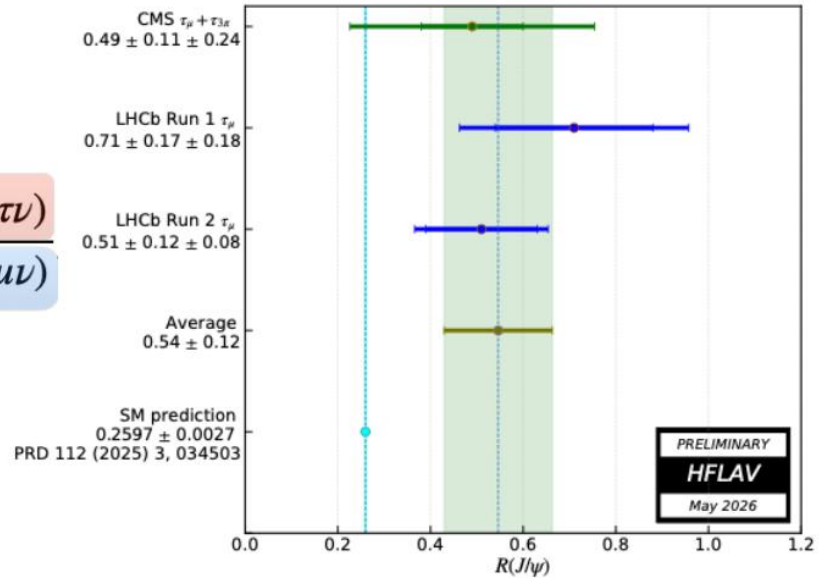


LFU and b → cτν: where LHCb starts to suffer, although still competitive

- R(D*) world average: 3.8σ from SM (HFLAV 2025)
- LHCb R(J/ψ) = 0.51 ± 0.12 ± 0.08 (1.8σ, world-leading, stat-limited)
- Common feature: τ and ν in the final state
  - Hard to reconstruct at a hadron collider → a structural limit: neutrinos and missing energy are LHCb's hard edge

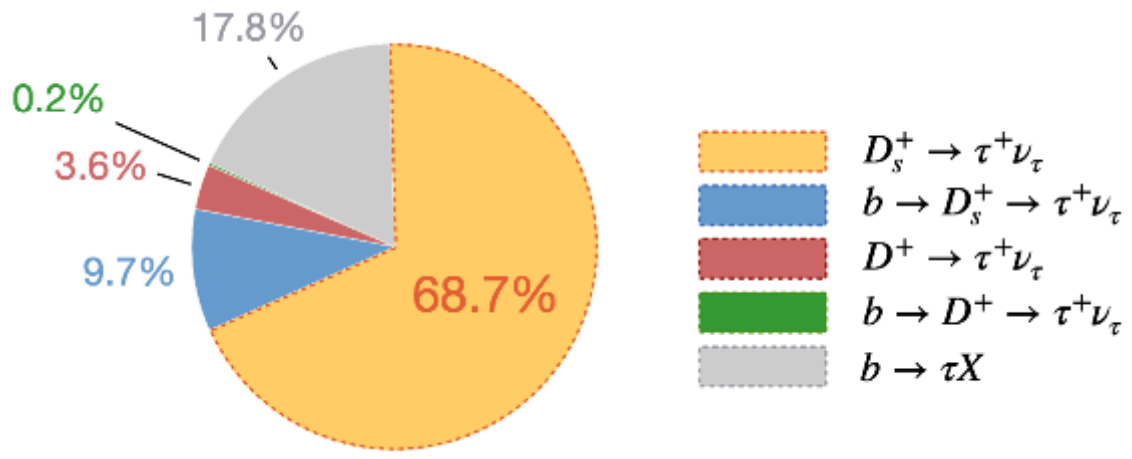


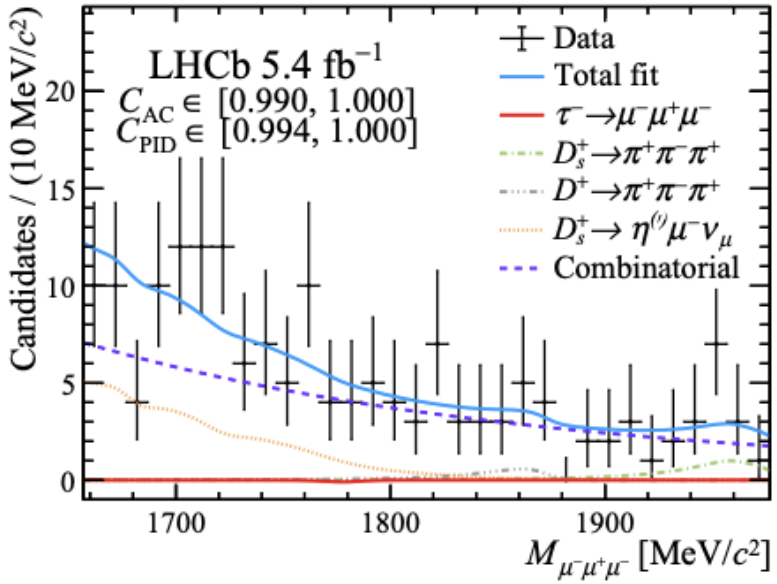
$$\frac{\mathcal{B}(B_c \to J/\psi\tau\nu)}{\mathcal{B}(B_c \to J/\psi\mu\nu)}$$



Refs: HFLAV 2025, PRL 137 (2026) 141801

Charged LFV: a null-test for New Physics





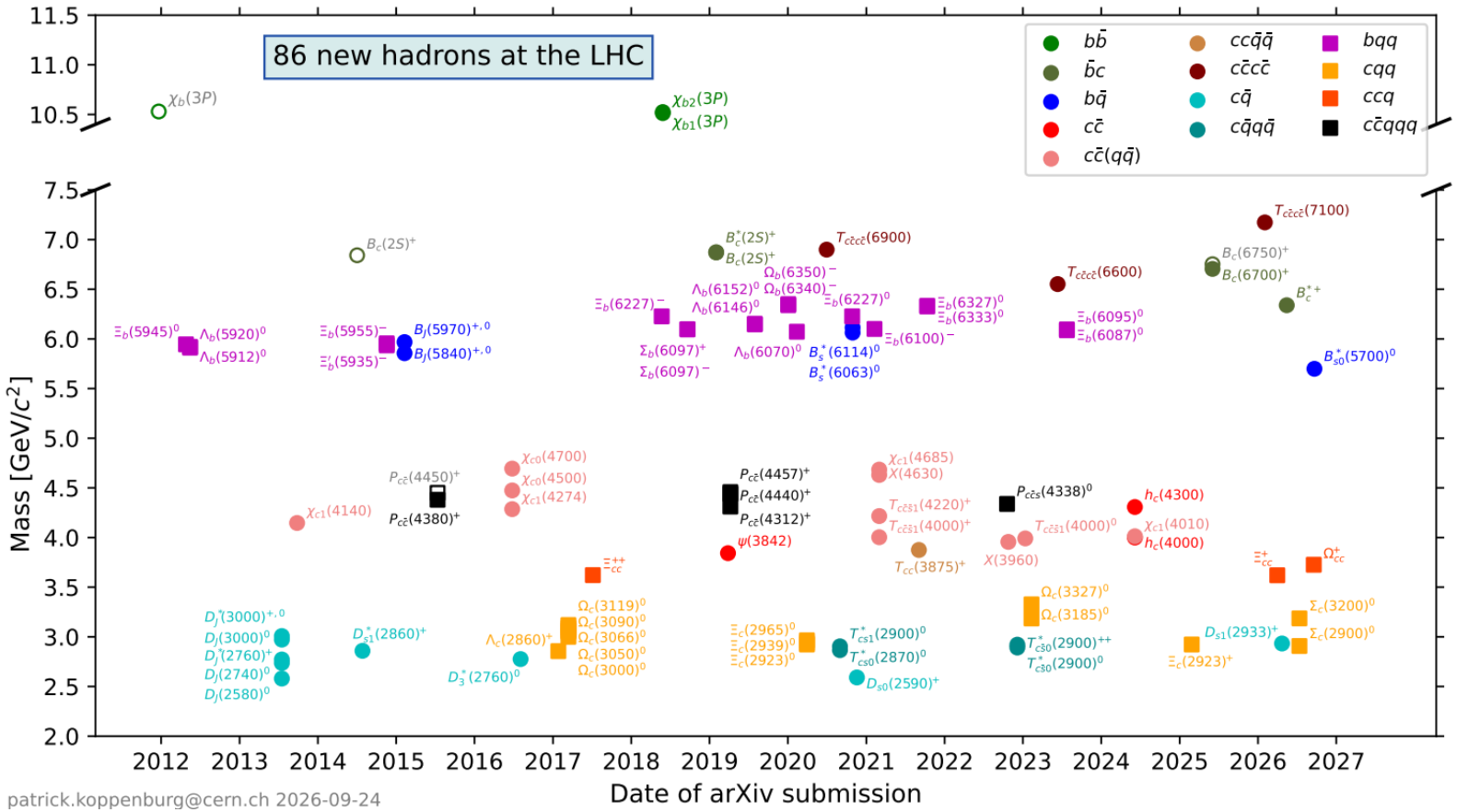
- cLFV essentially forbidden in the SM (ν-oscillation level, unobservable)
- Enhanced in many NP models, an observation would be unambiguous NP
- LHCb search $\tau^- \to \mu^-\mu^-\mu^+$ (τ produced ~10^{11}/fb^{-1})

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 1.9 \times 10^{-8}\ (90\%\ \mathrm{CL}), \quad < 2.3 \times 10^{-8}\ (95\%\ \mathrm{CL})$$

Refs: arXiv:2601.20785

New hadrons budget at the LHC

- Out of 86 new hadrons observed at the LHC, 76 were observed by LHCb
- Although not built with this in mind, this is an important by-product of LHCb detector's features, comprising a flexible trigger and hadron PID capabilities with its two RICH subdetectors

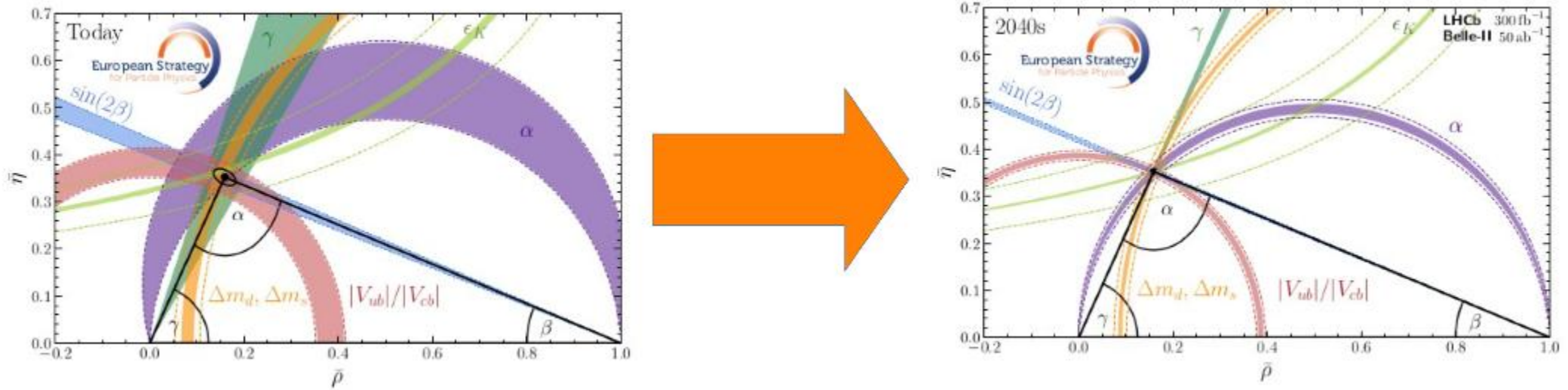


https://koppenburg.ch/particles.html

ESPPU Physics Briefing Book

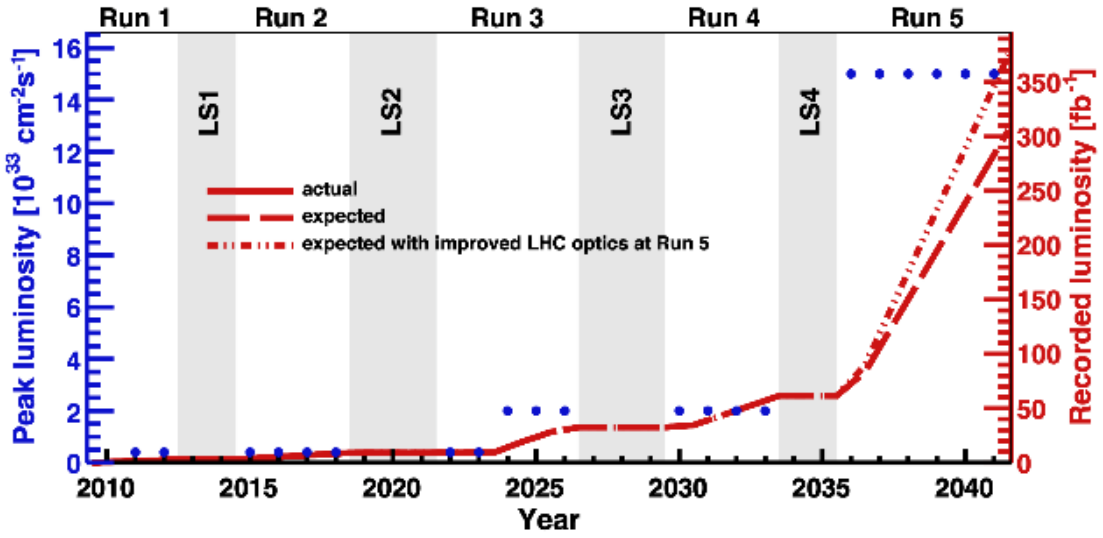
https://cds.cern.ch/record/2944678

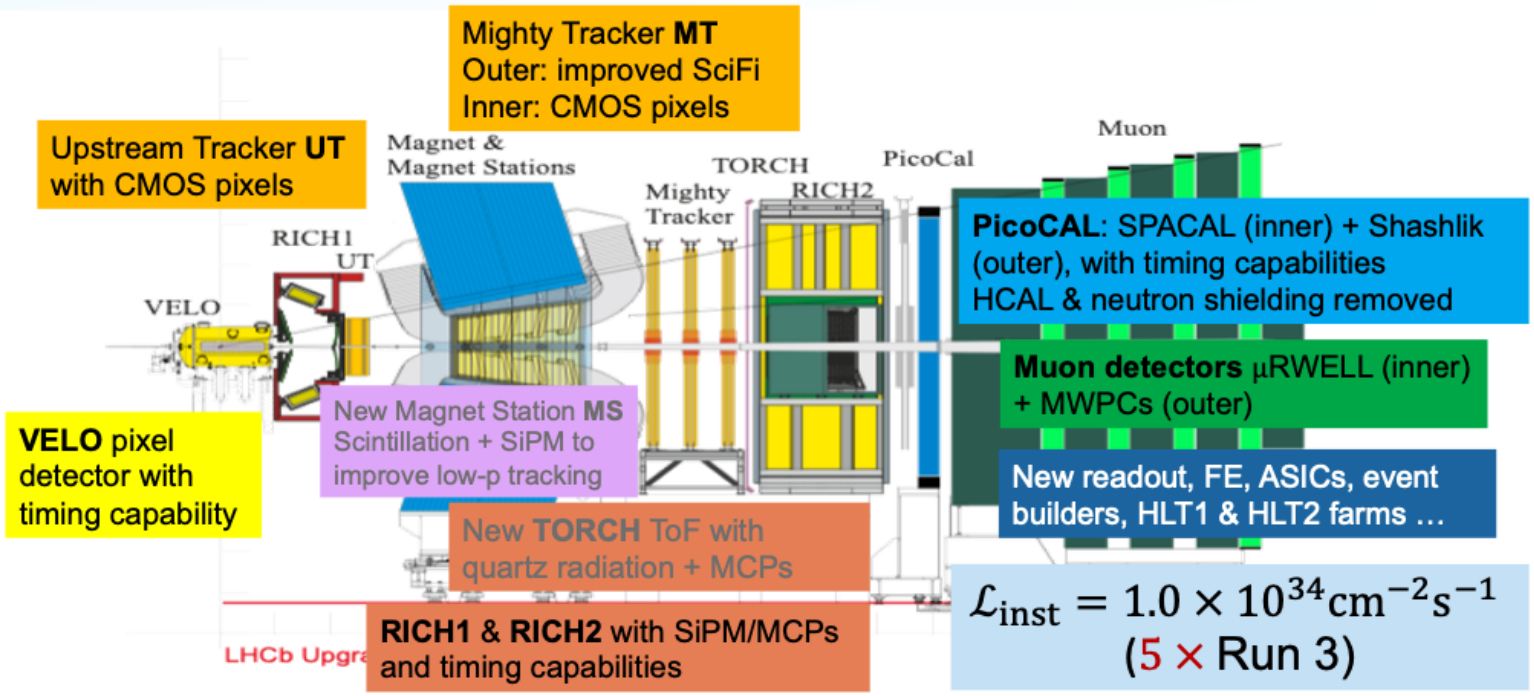
- It is only through the combined exploration of flavour, Higgs and electroweak domains that the structure of physics beyond the SM can be uncovered via indirect searches
- [In flavour] major progress is anticipated through the full exploitation of existing experimental facilities up to the 2040s, **particularly of LHCb Upgrade II** ... this is one of the areas of particle physics where the largest gain ... is expected in the next 20 years



LHCb Upgrade II

- $L_{inst} = 1.0\times10^{34}\ cm^{-2}s^{-1}$ (5 × Run 3)
  → goal 300 fb^{-1}
- New timing-capable detectors throughout
- More statistics, same environment





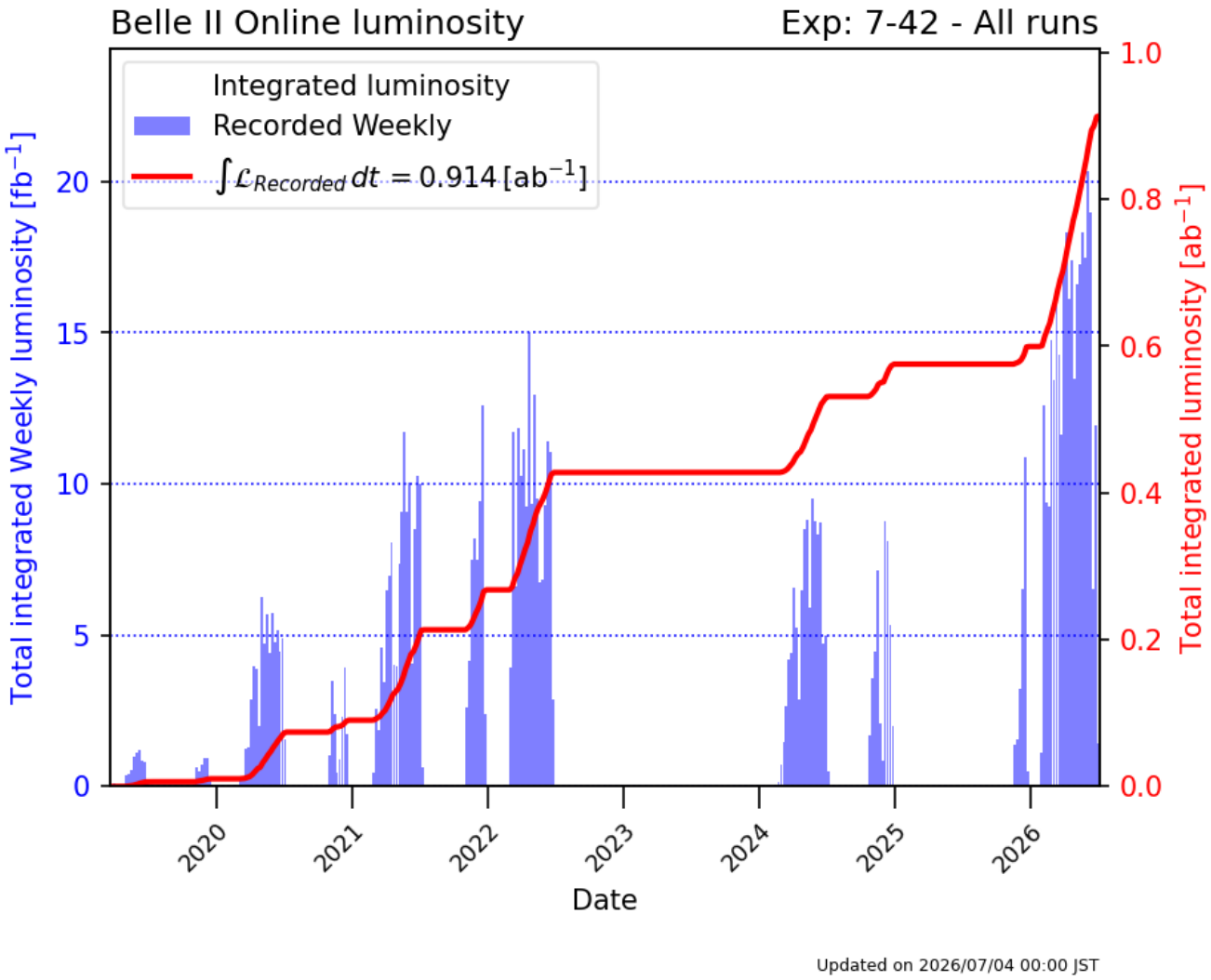
- The project was approved by the CERN Research Board on June 2026, and the collaboration is now working on the detector TDRs

Belle II

The clean complement: neutrals and neutrinos

Belle II at SuperKEKB

- e^+e^- at the Y(4S): clean, known initial-state kinematics
  - Missing-momentum reconstruction for decays with neutrinos
- Coherent $B^0\bar{B}^0 \rightarrow$ time-dependent CP; efficient with neutrals (π^0, γ)
- ~914 fb^{-1} at Y(4S) (Run 1 + Run 2), now exceeding Belle
- Trade-off: lower rates; no B_s, B_c, Λ_b at the Y(4S)



Time-dependent CPV with photons and $\pi^0\pi^0$

- $S(K_S\pi^+\pi^-\gamma)$ → most precise in any $b\to s\gamma$
  - Probes right-handed currents; consistent with SM so far

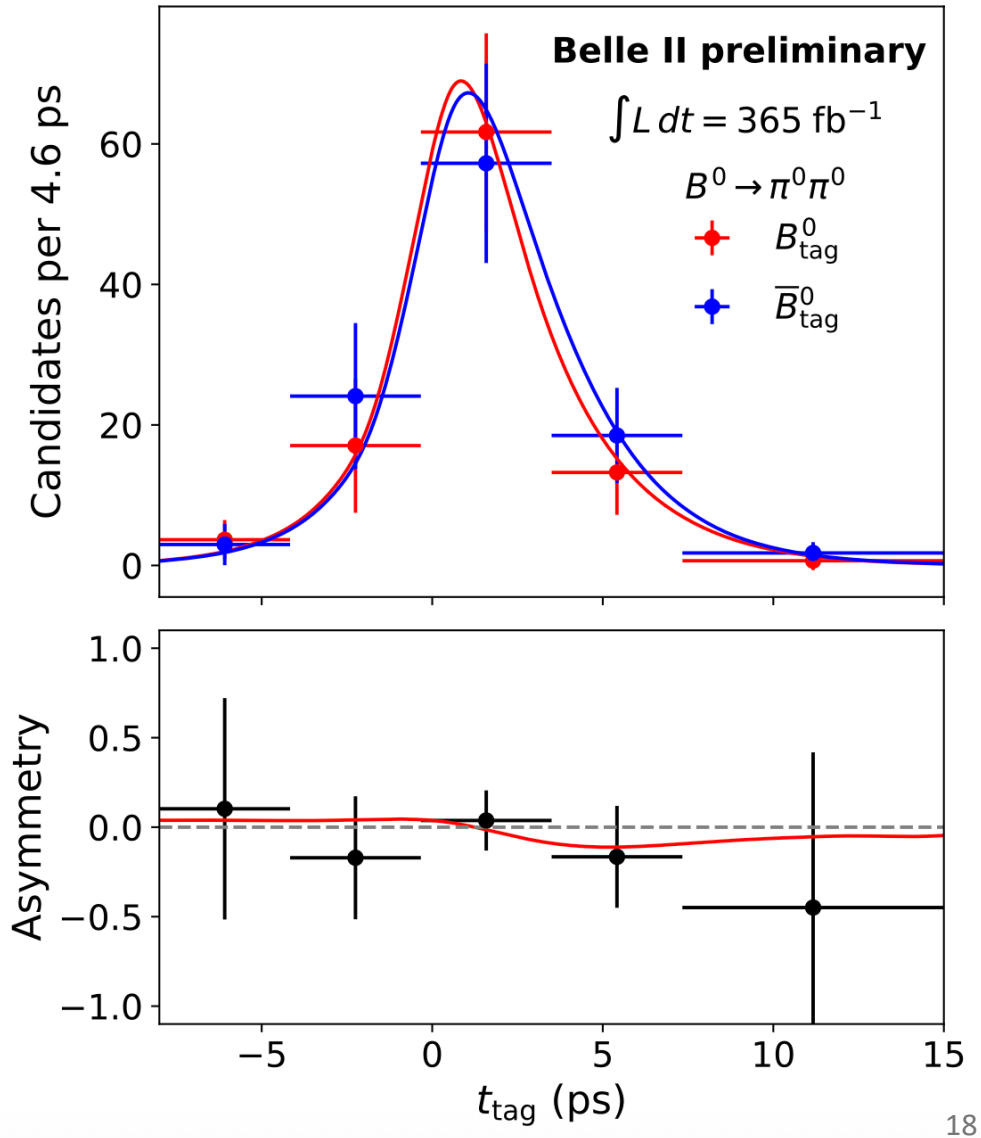
    $S = -0.29 \pm 0.11\ (stat) \pm 0.05\ (syst)$

    $C = -0.17 \pm 0.09\ (stat) \pm 0.04\ (syst)$

- $B^0\to\pi^0\pi^0$: first mixing-induced CPV measurement with a $\pi^0\pi^0$ final state
  - Improves the isospin constraint on ϕ_2 (α)

    $S = 0.61–0.79\ (stat) \pm 0.11\ (syst)$

    $C = 0.05 \pm 0.28\ (stat) \pm 0.07\ (syst)$

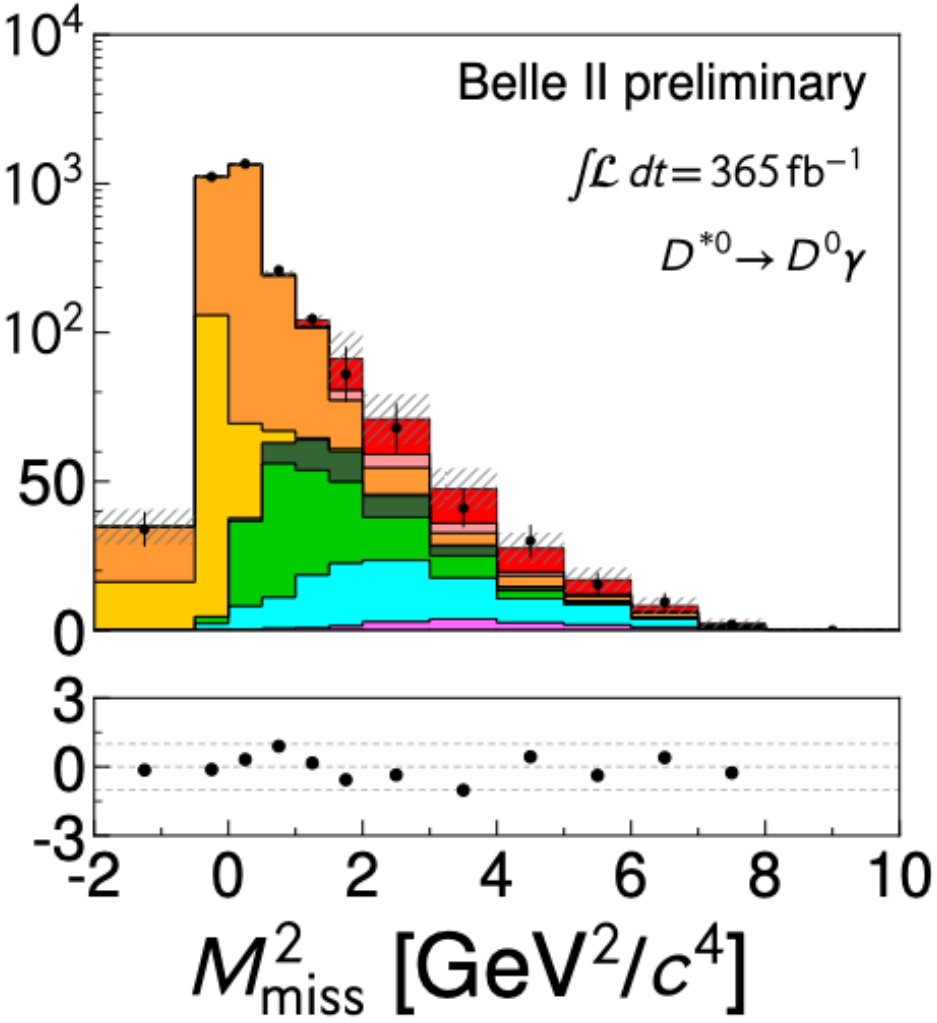


Refs: arXiv:2510.01331, arXiv:2606.20797

LFU with neutrinos: R($D^{(*)}$)

Refs: arXiv:2609.21947

- Hadronic B-tagging constrains kinematics for ν final states
  - Tagging efficiency < 1%, powerful but statistics-starved
- R(D*) = 0.242 ± 0.019 ± 0.016
  R(D) = 0.439 ± 0.055 ± 0.046
  (most precise to date)
- $|V_{ub}|$ inclusive vs exclusive: persistent ~3σ puzzle

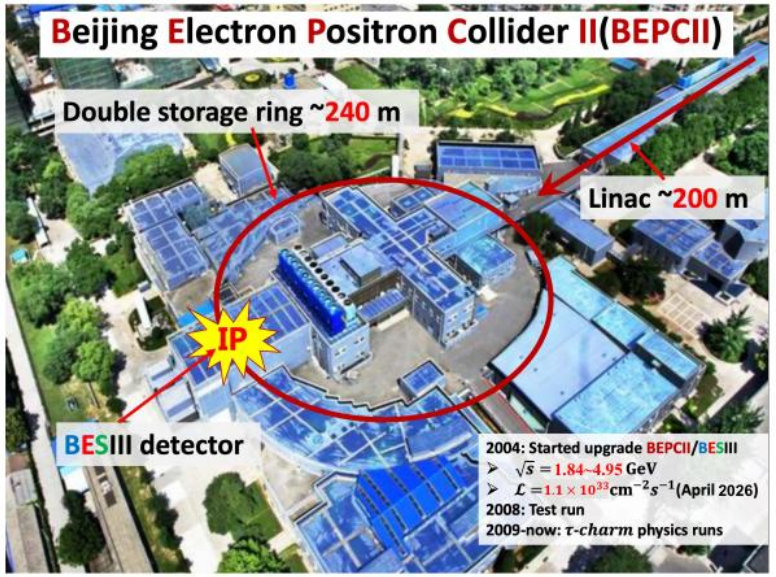


BESIII

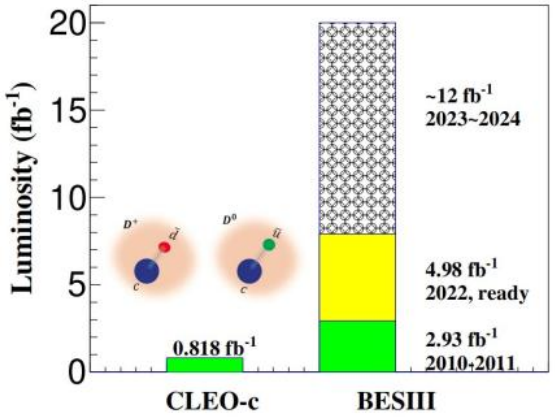
Charm threshold: strong phases and precision
(detailed overview: see L. Sun's parallel talk)

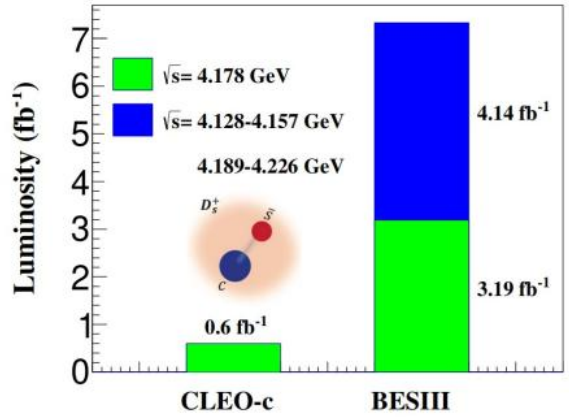
BESIII at BEPCII

- e^+e^- at charm threshold; world's largest near-threshold charm samples
- Charm hadrons produced in pairs, quantum-correlated
- 93% coverage, sensitive to missing particles (ν, K_L)
- Double-tag method → clean, absolute branching fractions



Near-threshold open charm datasets





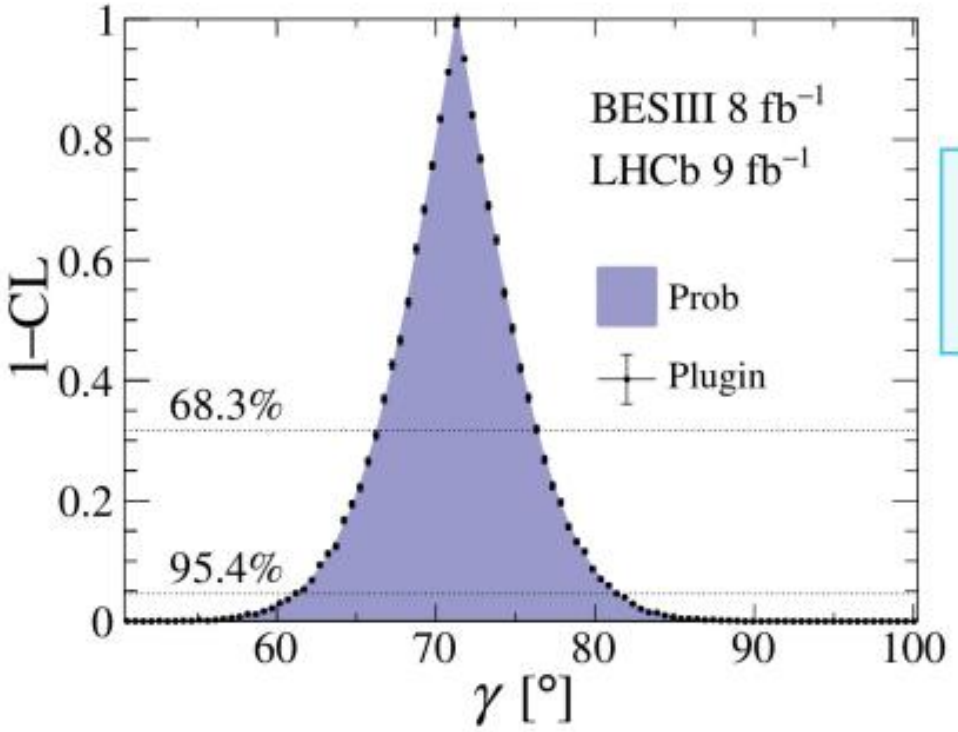
A clean e^+e^- environment with missing-mass access at the charm scale

BESIII: strong phases, the other side of γ

- Strong-phase inputs from quantum-correlated $D \to K_{S/L}\pi\pi$, $K_{S/L}KK$
- Direct input to the LHCb γ determination

Refs: arXiv:2604.05712, arXiv:2604.05701

  - Joint fit reduces the γ strong-phase uncertainty to 0.6°
- Precious input from BESIII to improve the precision of LHCb's γ

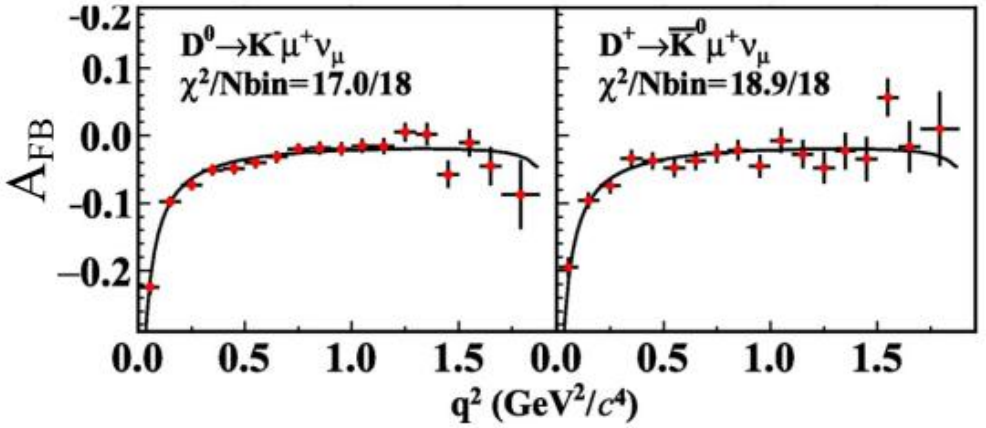


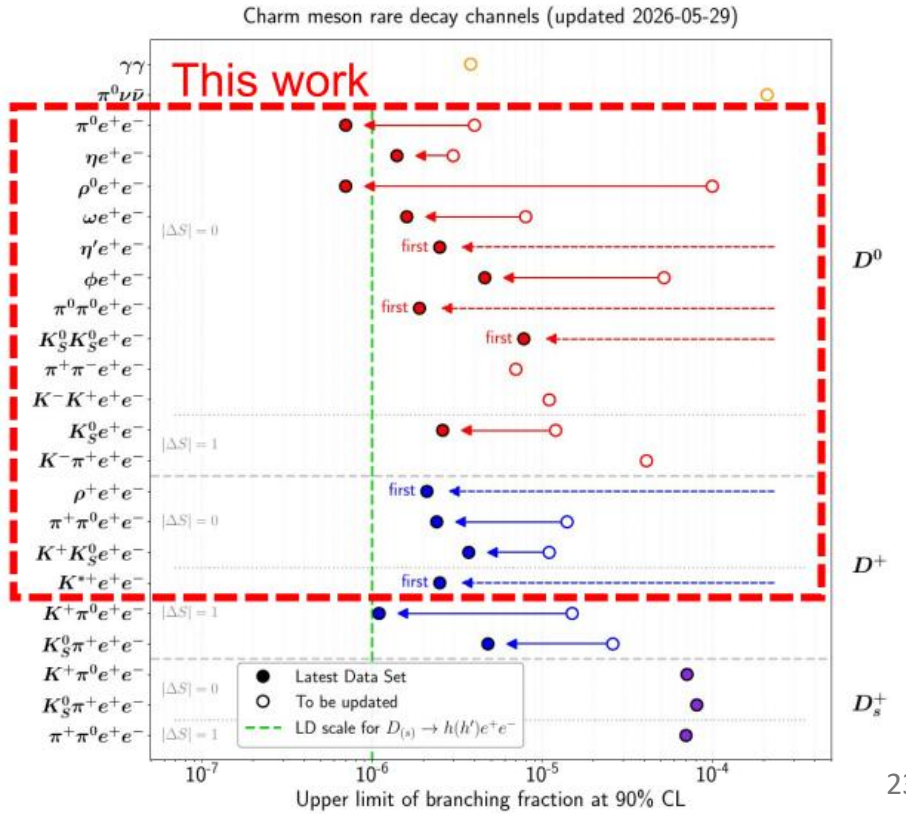
$$\gamma = (71.3 \pm 5.0)^\circ$$

most precise single measurement to date

BESIII: charm precision and clean tests

- Semileptonic D→Kℓν, D→πℓν: $f_+(0)|V_{cs}|$, $|V_{cd}|$, LFU $R_{\mu/e}$
  - First constraints on scalar currents (A_{FB} deviation ~2.3σ)
- $D^+_s \to K^0\mu\nu$ and other first observations; rare D→hhℓℓ UL at 10^{-6}–10^{-7}
- Λ^+_c programme: BFs, polarisation, CPV searches





Refs. PRL 137 (2026) 091803, PRD 114 (2026) 033008, arXiv:2607.23949, arXiv:2607.23945, PRL 136 (2026) 161802, PRD 113 (2026) 092010

The gaps

What none of the three closes alone

The gaps none of them closes alone

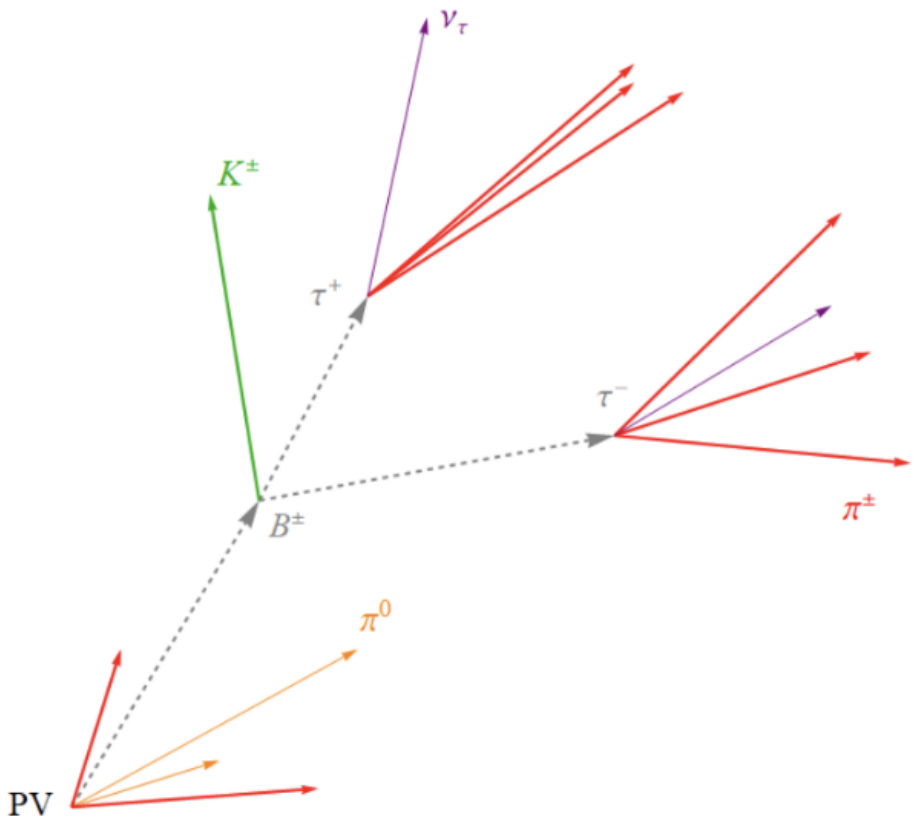
- b→sττ and b→sνν: τ/ν final states →hard everywhere today
- LHCb: huge statistics, but ν and neutrals hard
- Belle II: clean, but lower rates, no B_s/Λ_b, tagging < 1%
- BESIII: clean + missing mass, but charm threshold only
- Ultimate precision needs BOTH huge statistics AND a clean environment!

Why the Z pole for flavour

- Some 10^{12} Z (Tera-Z): enormous b, c, τ in a clean e^+e^- environment
- Boost (unlike threshold) → vertexing, lifetimes, time-dependent CPV
- All b-hadron species produced: B_s, Λ_b, B_c (unlike Y(4S))
- Missing-momentum reconstruction for ν / neutral modes
  - Combines LHCb's all species + boost with Belle II's clean + missing momentum

Z factory: the key flavour channels

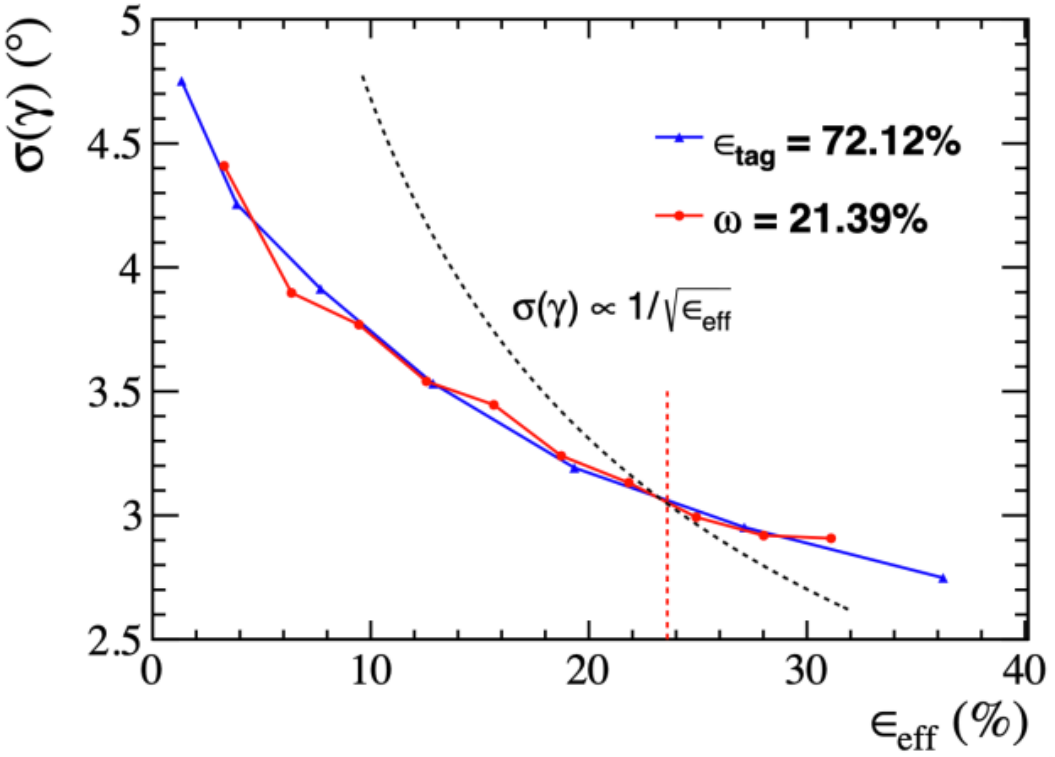
- b→sττ: the clean-environment flagship
  - absolute BF reach 10^{-7}
  - B_s→ττ approaching SM sensitivity; B→K*ττ full-sim benchmark now in place
- b→sνν: missing-energy modes
  - B_s→ϕνν ≤2% relative precision
  - Λ_b→Λνν
- Rare charm, new territory: D→πνν, D^0→γγ, D^0→invisible, Λ_c→pνν
- τ programme: LFV, mass/lifetime, LFU



Exactly the τ/ν channels that are structurally difficult or closed at today's experiments

Z factory: enabling capabilities

- Flavour-tagging power >35% at reach (fast-sim, Belle II-inspired)
- $|V_{cb}|$, $|V_{cs}|$ from on-shell and boosted W decays: ~0.15% statistical
- CKM γ: time-dependent modes improve, at / below LHCb-U2 (~0.3°)
- All b-hadron species + boost + missing-momentum reconstruction



Effective tagging efficiency of 25% already achieved by LEP → Modern techniques will increase it

Z factory: honest complementarity

- Not a replacement, but an addition:
  - Belle II keeps the lead on Y(4S)-specific modes ($\pi^0\pi^0$, etc.)
  - LHCb keeps CPV/rare in charged modes and charm statistics
  - BESIII keeps charm-threshold strong phases
- The Tera-Z adds the unique combination none of them has

Statistics alone are not enough → the case is complementarity, not supremacy

Summary

- LHCb: world-leading CKM/γ; CPV in baryons and charm; b→sμμ tensions
- Belle II: neutrals and neutrinos, photon helicity, ϕ_2, R($D^{(*)}$)
- BESIII: charm-threshold strong phases (feeding γ) and precision
- Today: all SM-consistent except persistent anomalies
- The three are deeply complementary, a Tera-Z closes the remaining gaps

Flavour physics is complementarity in action → the Z factory is its natural next step! Fundamental detectors: Vertex detector with excellent IP resolution, RICH, ECAL capable of neutral pion reconstruction