

# Belle II & European strategy

Thibaud Humair,  
Belle II Physics week, 8 October 2025



**HELMHOLTZ**

# European Strategy: how does this work?

The **European Strategy for Particle Physics (ESPP)** is a process through which the CERN Council gathers inputs from the broad community to decide the future of particle physics in Europe.

Happened first in 2005, then updates in 2013 and 2020

In the **last European Strategy update in 2020**, the main conclusions were:

- fully exploit the high-lumi LHC
- $e^+e^-$  Higgs factory is the highest-priority next collider

Now we are in the **2026 strategy update**. Goal: come up with concrete plan for next flagship project at CERN

- The broad community has submitted inputs for the CERN council, including [Belle II](#), [LHCb](#), [LHC+Belle II](#)
- Inputs were discussed in an [Open Symposium](#) in June
- The Physics Preparatory Group has summarised these inputs in a [briefing book](#), with one chapter on flavour physics
- This will be used by the CERN council to make a decision in  $\sim 2$  years or so

**Today:** based on the briefing book, discuss the Belle II interplay with ESPP

# Flavour at the $Z$ pole

## High-energy colliders considered:

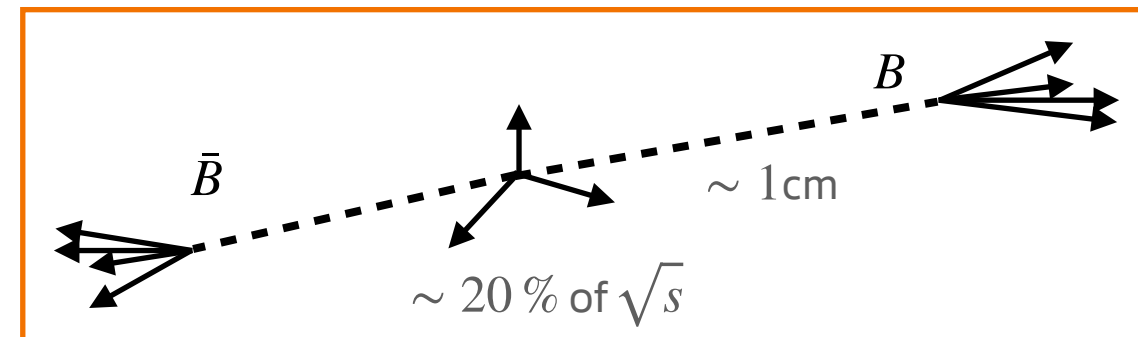
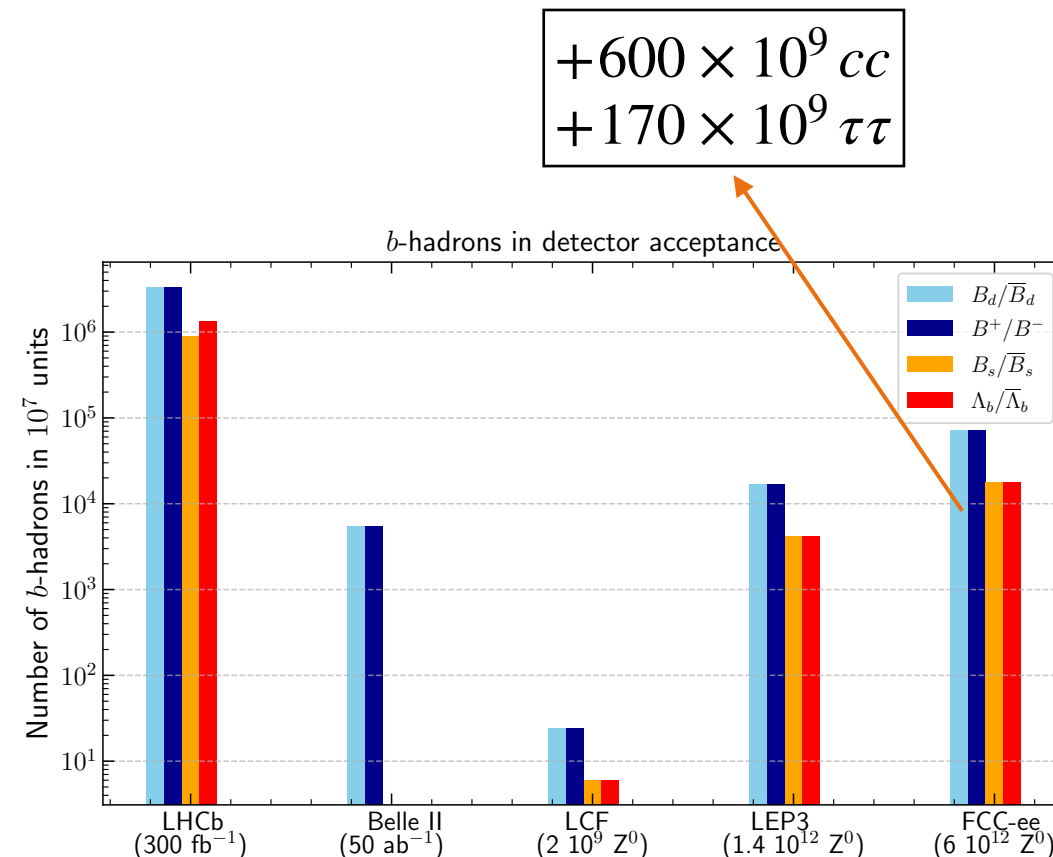
- Linear  $e^+e^-$ : CLIC, ILC...
  - Circular  $e^+e^-$ :
    - LEP3: 27 km in LHC tunnels, max  $\sqrt{s} \sim 230$  GeV
    - FCC-ee: 100 km, max  $\sqrt{s} \sim 365$  GeV
- Preferred option, potential competition from China: CEPC

## Flavour at FCC-ee or LEP 3:

- Run at the  $Z^0$ -pole to produce billions of  $b/c/\tau$
- high boost
- clean environment

Other relevant, low-energy project:

STCF: super tau charm factory (China)



# The future of flavour

Let's assume we get:

- Full LHCb and Belle II programme in the 2040s
- LEP3 or FCC-ee in the 2050s

## What does Belle II bring in this?

Some answers from the briefing book, but shortcomings:

- At best: sensitivity studies made with baseline FCC-ee detector simulation (IDEA)
- Most often: cook up some extrapolations from existing results

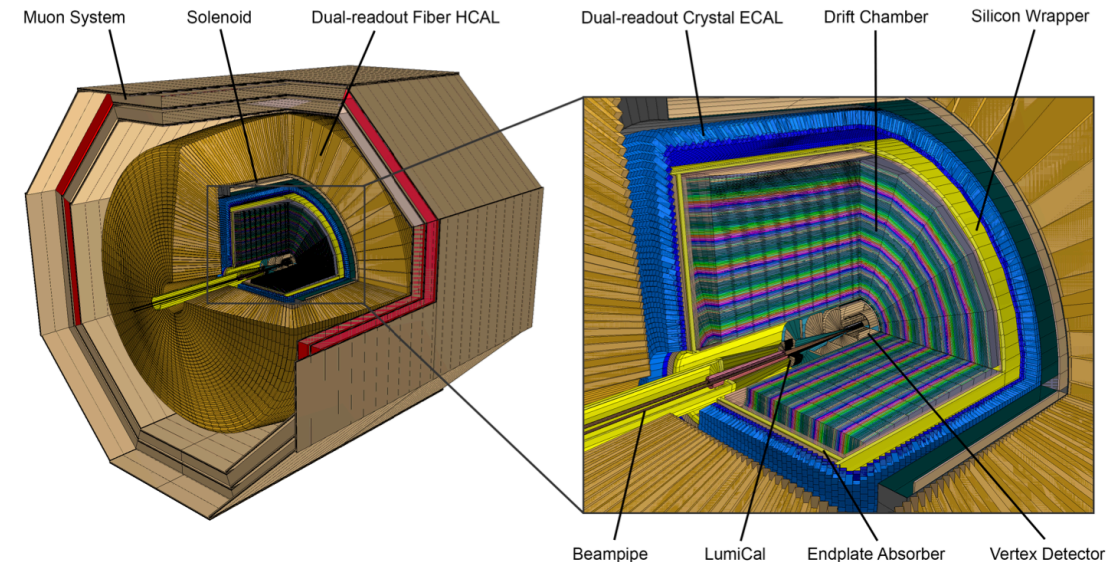
To refine the projections and detector requirements, the **Flavour at FCC workshop** was formed

From our experience at Belle II, there is a lot we can bring  
[Kick off workshop at CERN](#) on 19-21 November:

**2030s**  
Belle II  $10 \text{ ab}^{-1}$   
LHCb  $50 \text{ fb}^{-1}$

**2040s**  
Belle II  $50 \text{ ab}^{-1}$   
LHCb  $300 \text{ fb}^{-1}$

**2050s**  
LCF  $2 \cdot 10^9 \text{ Z}^0$   
LEP3  $1.4 \cdot 10^{12} \text{ Z}^0$   
FCC-ee  $6 \cdot 10^{12} \text{ Z}^0$



# CKM physics and CPV in $B$ & $D$

# The CKM triangle

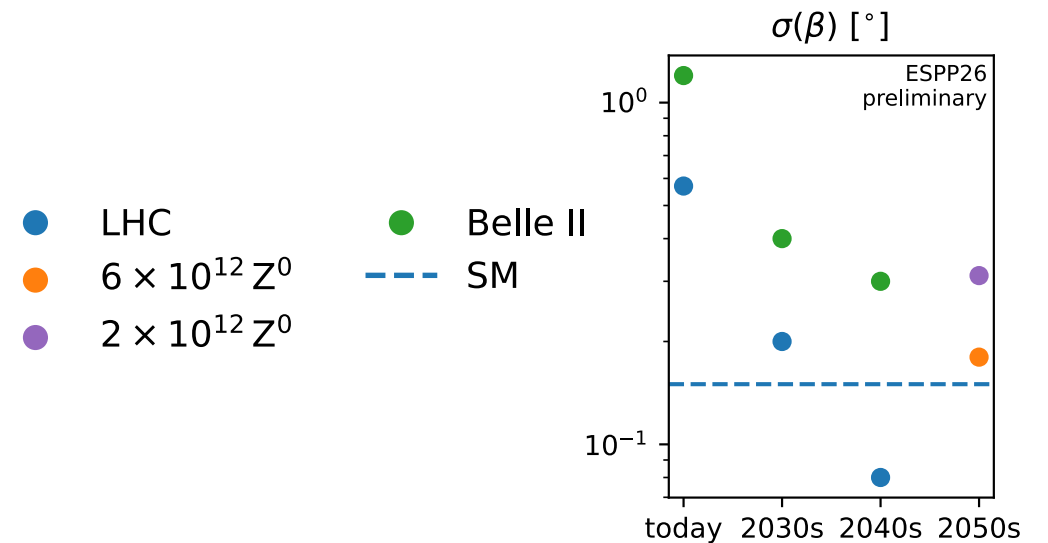
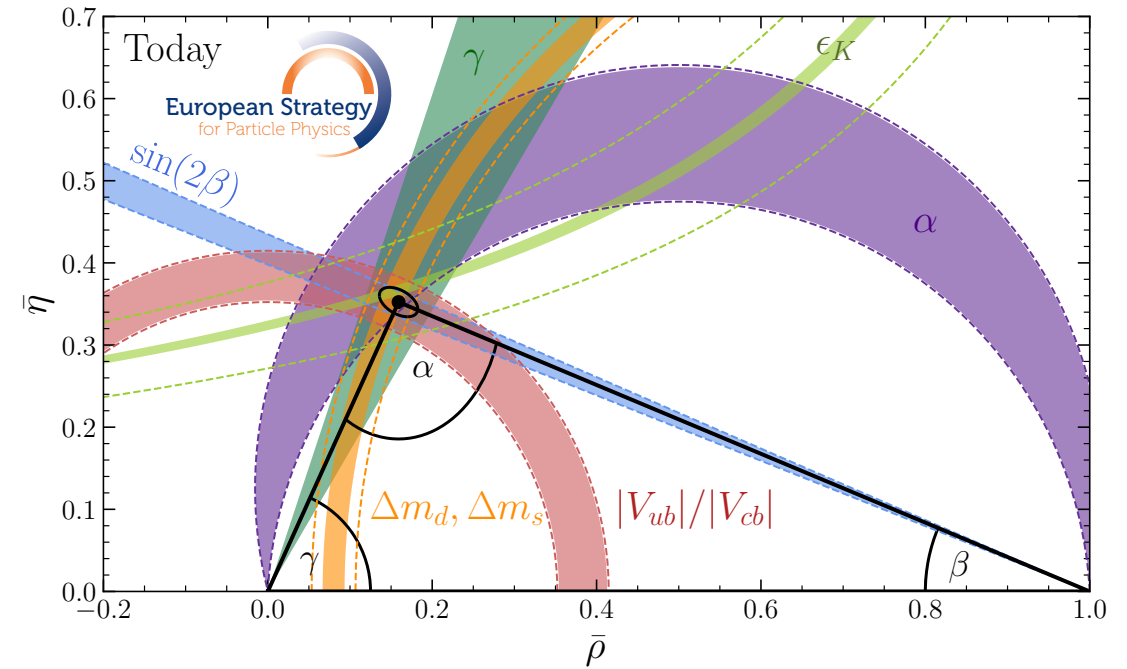
Testing the consistency of the CKM triangle will remain one central part of flavour physics in coming decades

LHCb will dominate in parameters extracted from decays to fully charged final states, even over FCC-ee:

- $\gamma$  (CPV with  $B \rightarrow DK$  & co.)
- $\beta$  (CPV with  $B \rightarrow J/\psi K^0$ )

We know that Belle II plays a central role in measurements with:

- neutrals  $\rightarrow \alpha/\phi_2$
- missing energy  $\rightarrow V_{ub}$  &  $V_{cb}$



# $|V_{ub}|, |V_{cb}|$

Currently, precision on  $|V_{ub}|, |V_{cb}|$  dominated by SL  $B$  decays

→ expect mid-term precision  $|V_{ub}|, |V_{cb}|$  by LHCb, Belle II of  $\sim 1\%$

Tensions in inclusive/exclusive determination calls for alternative measurements:

**Inclusive measurements:** Belle II is alone, no FCC-ee projections exist afaik

**Leptonic decays:** only theory input is decay constant, with % precision from lattice

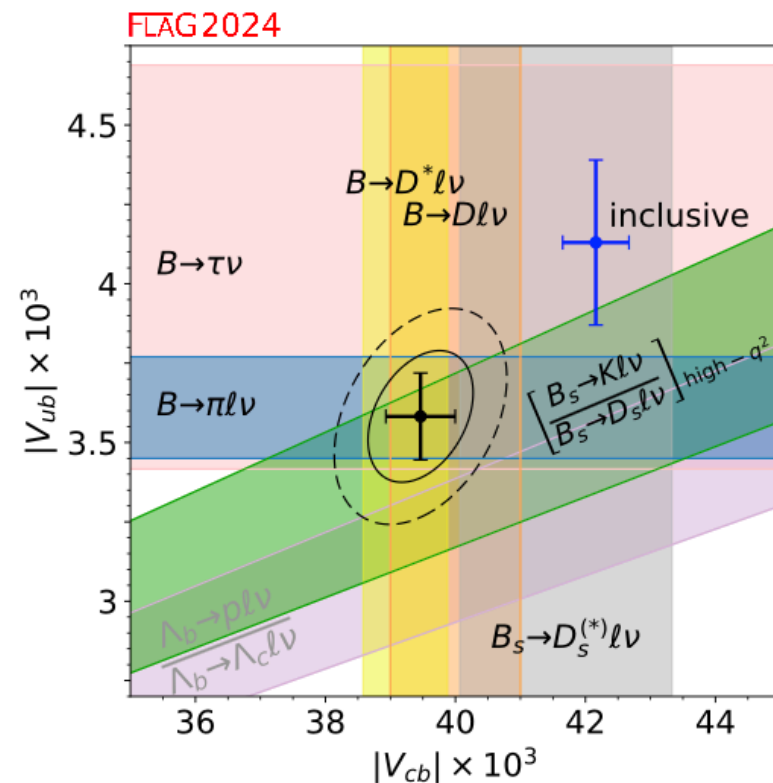
→  $V_{ub}$  with  $B^+ \rightarrow \tau\nu$ :  $\sim 3\%$  precision expected at Belle II and  $\sim 1 - 2\%$  at FCC-ee

→  $V_{cb}$  with  $B_c^+ \rightarrow \tau\nu$ , but precision limited by knowledge of fragmentation fraction (see [arXiv:2305.02998](https://arxiv.org/abs/2305.02998))

**On-shell:**  $W \rightarrow \text{jet jet}$

→ FCC-ee could measure  $|V_{cb}|$  from  $W^+ \rightarrow c\bar{b}$  with a precision of  $\sim 0.15\%$

→  $|V_{ub}|$  from  $W^+ \rightarrow u\bar{b}$  would be stat. limited and not competitive



# CKM angle $\alpha/\phi_2$

The CKM angle  $\alpha$  is measured using CPV in charmless decays

- $B^0 \rightarrow \pi^0 \pi^0, B^0 \rightarrow \pi^+ \pi^-, B^+ \rightarrow \pi^+ \pi^0$ : simple 2-body decays
- $B^0 \rightarrow \rho^0 \rho^0, B^0 \rightarrow \rho^+ \rho^-, B^+ \rightarrow \rho^+ \rho^0$ : complex resonance structure, so far driving precision

Need all isospin-related mode to cancel out theory uncertainties (penguin pollution)

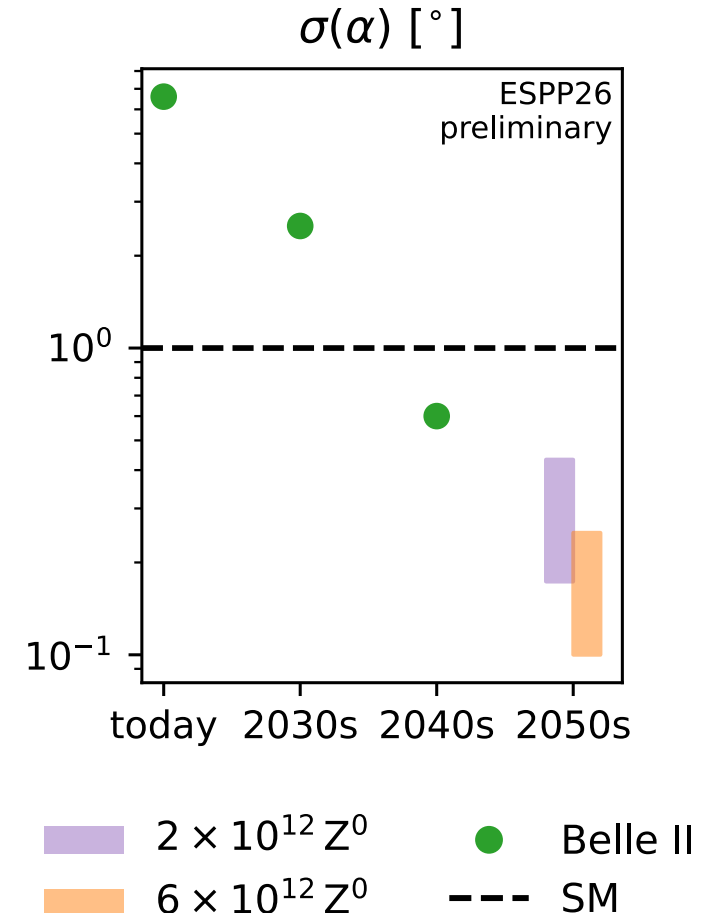
→ Multiple neutrals in the final state makes it ideal for  $e^+e^-$  environment

Detailed sensitivity study for  $B \rightarrow \pi^0 \pi^0$  in [arxiv:2208.08327](https://arxiv.org/abs/2208.08327) shows dependence of sensitivity on the precision of the calorimeter:

- $\sigma(E) \sim 17\% / \sqrt{E} \oplus 1\%$  → similar precision per Mio produced as for Belle II
- $\sigma(E) \sim 3\% / \sqrt{E} \oplus 0.3\%$  → improvement from better separation of peaking bkg

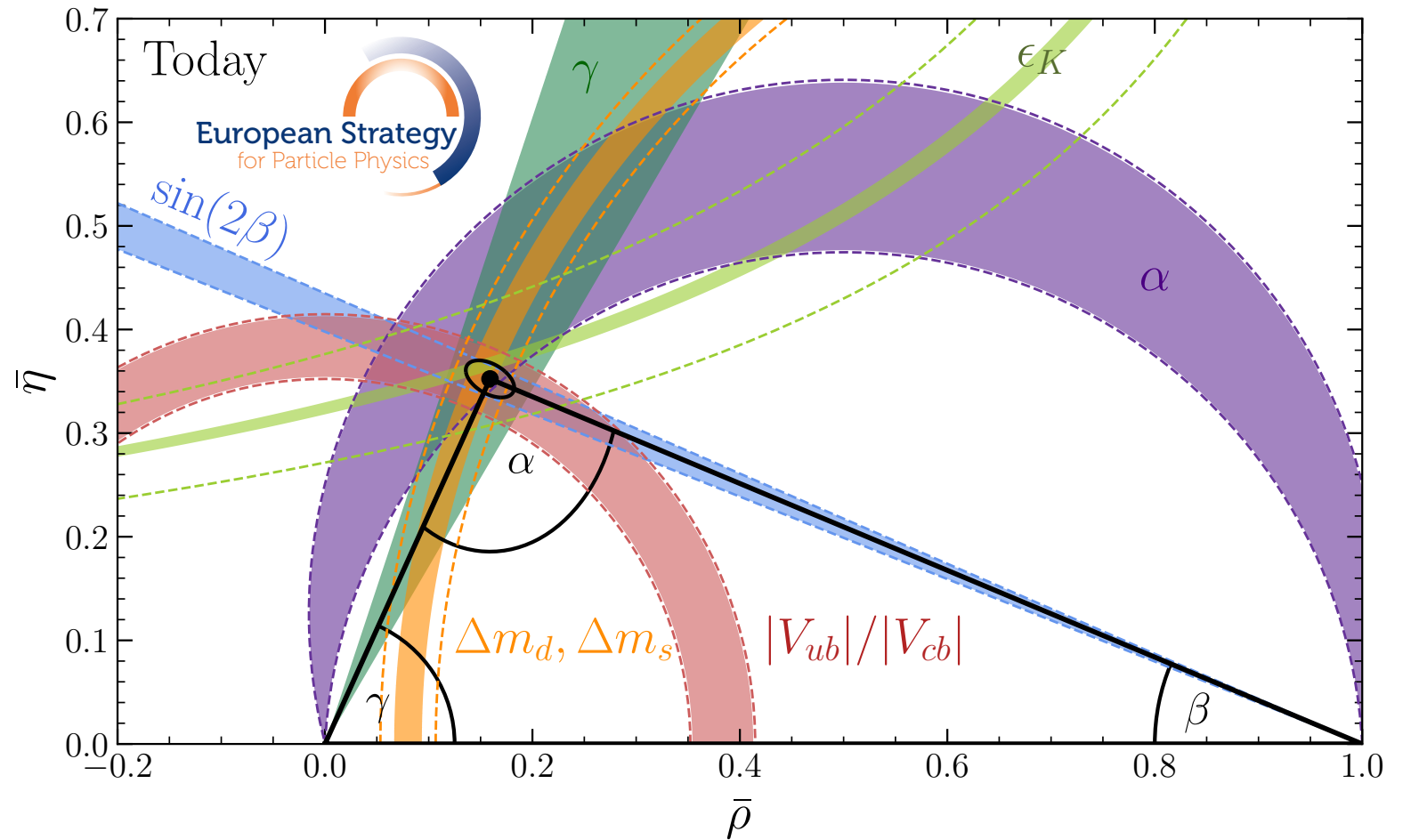
⇒ In multi-body decays with neutrals, exact precision strongly depends on the detector performances!

In any case, precision on  $\alpha$  expected to be limited by isospin-breaking effects beyond Belle II!

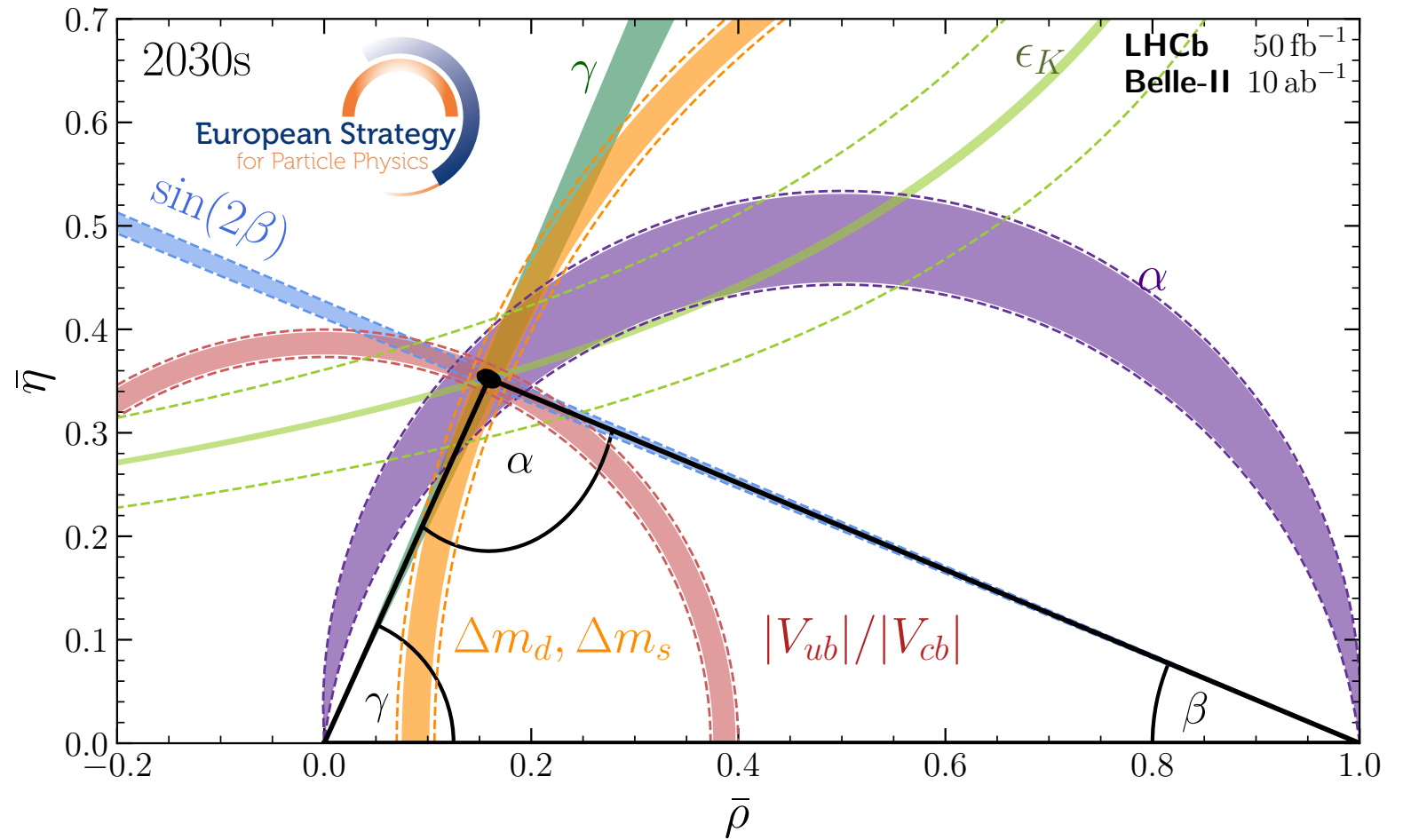




# CKM triangle: today

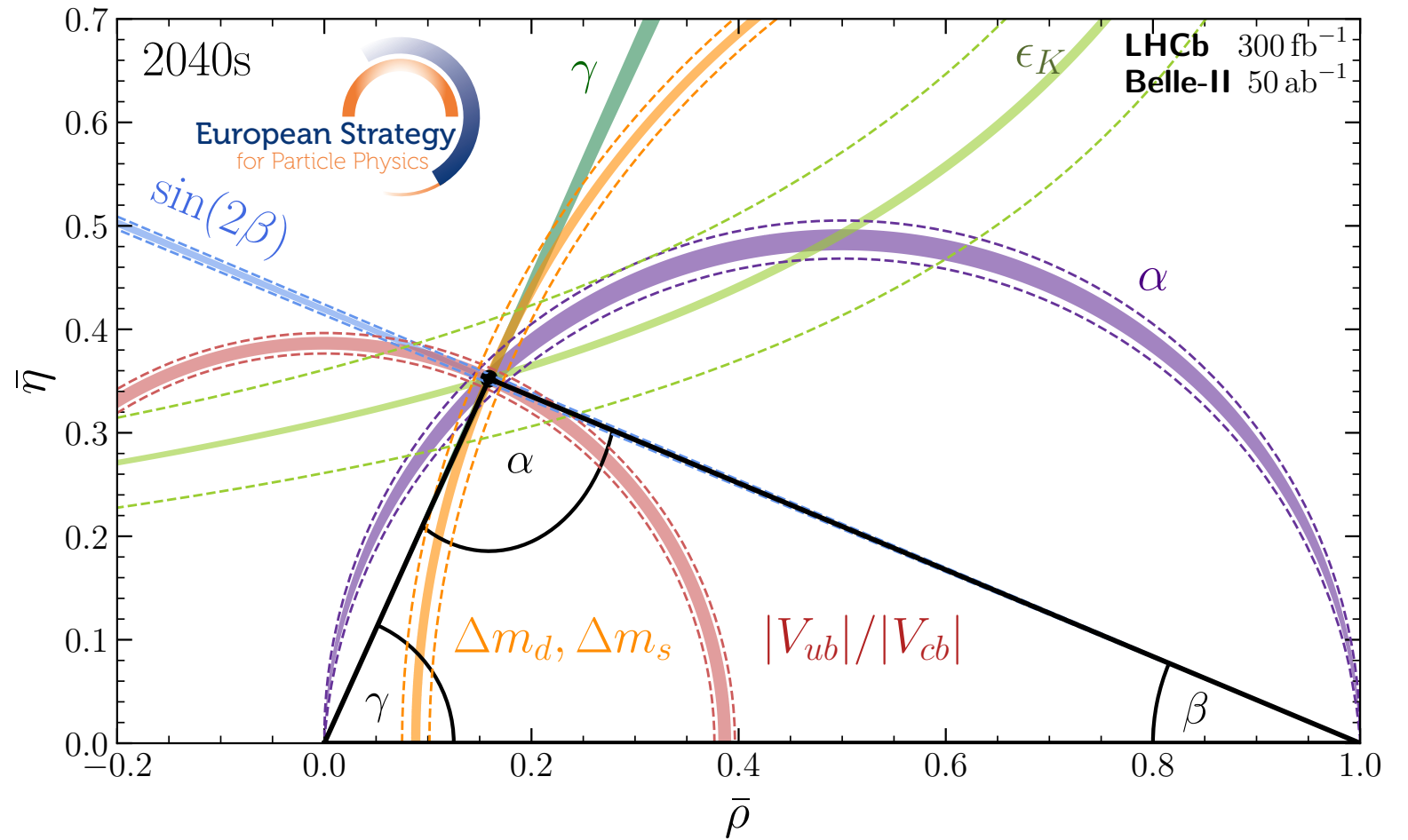


# CKM triangle: 2030s



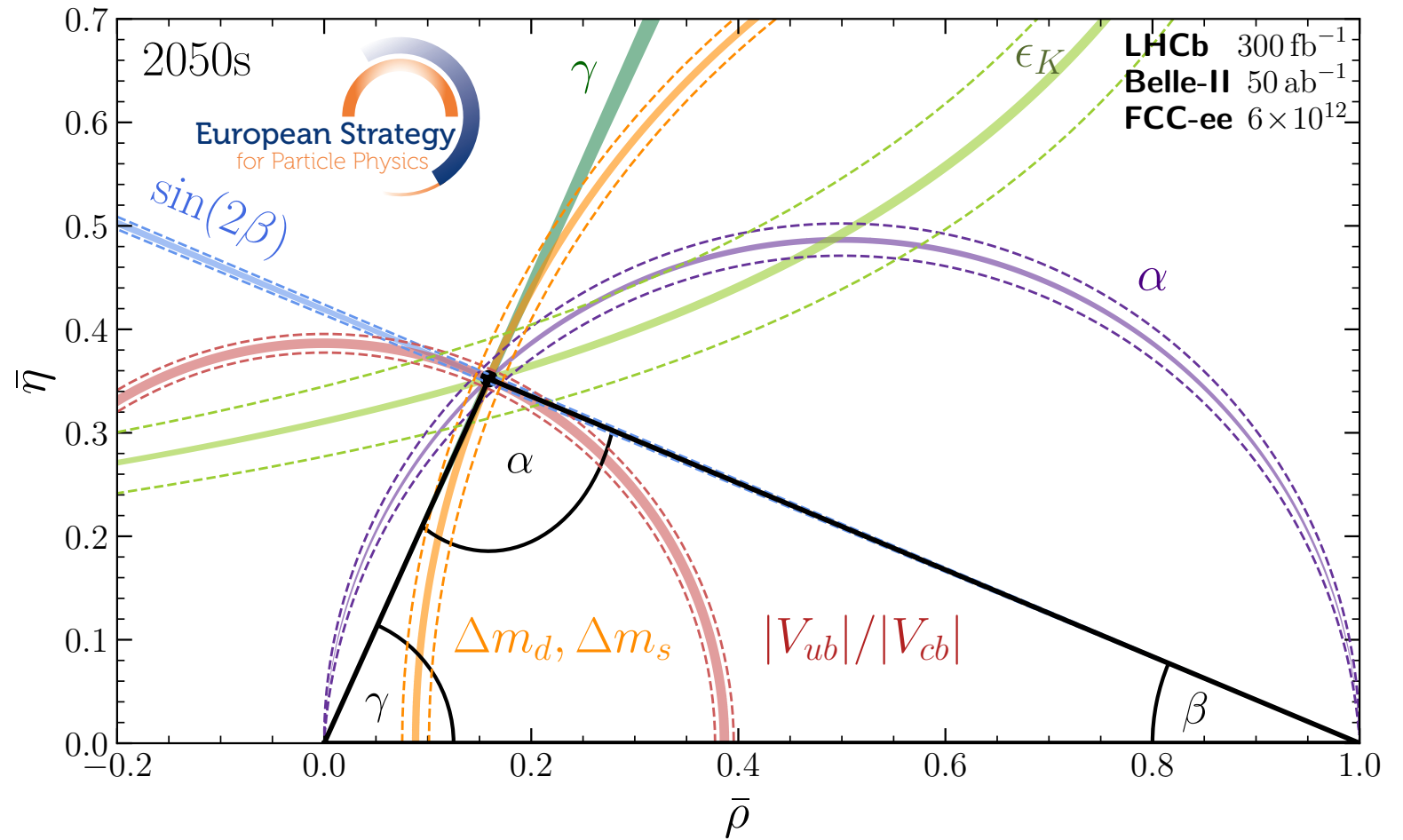
# CKM triangle: 2040s

Uncertainty on  $V_{cb}$  also enters in th. uncertainties of  $\epsilon_K$



# CKM triangle: 2050s

Limitations will come mostly from theory uncertainties

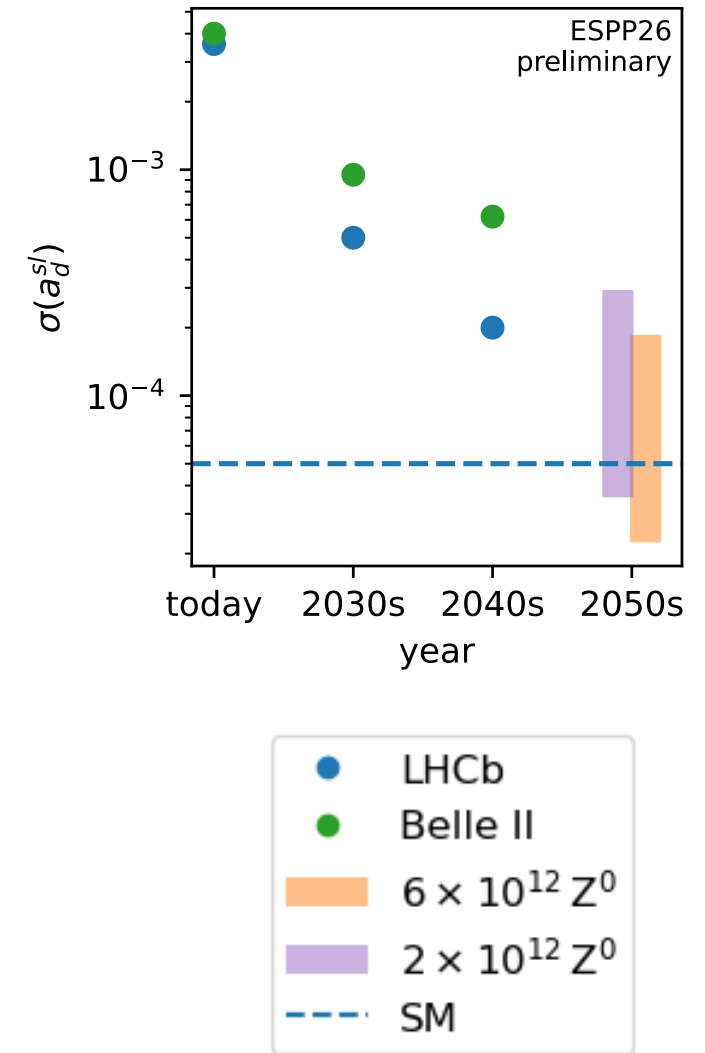


# Semileptonic asymmetries

Encode CPV in  $B^0$ - $\bar{B}^0$  mixing, measured as asymmetry in number of observed  $B^0 \rightarrow D^{(*)}\ell^+\nu$  vs  $B^0 \rightarrow \bar{D}^{(*)}\ell^-\nu$  decays

Very small in SM, but enhancement expected

- Large asymmetry



# CPV in charm: mixing

CPV has been observed in charm decays but its origin is unclear  
Would like to disentangle more precisely:

- indirect CPV: mixing-induced, parameterised by  $|q/p|$  and  $\phi$
- direct CPV

## Indirect CPV:

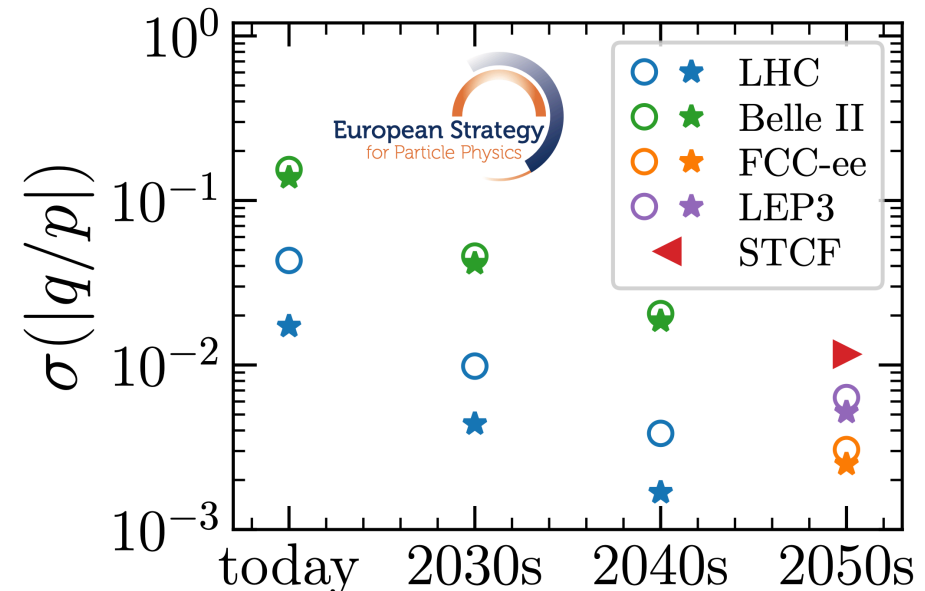
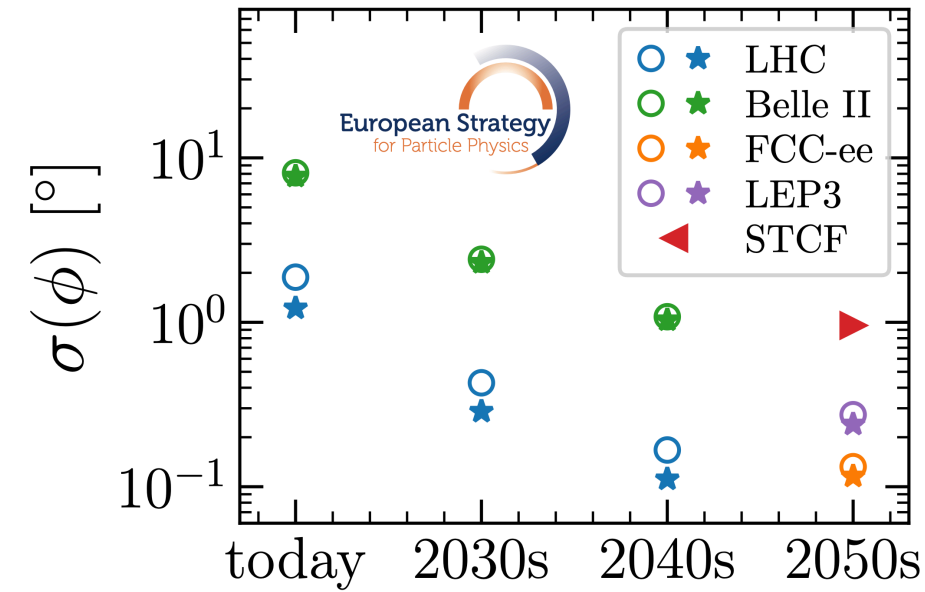
most precise way to measure it:

- $D^0 \rightarrow K_S \pi^+ \pi^- (\pi^0)$  time-dependent analysis
- Get extra constraint by measuring CPV in  $D^0 \rightarrow \pi^+ \pi^-$

Simple extrapolation scaling LHCb results to expected yields

⇒ Sensitivities at FCC-ee comparable to LHCb Upgrade II

Many caveats due to simple extrapolation!



# Direct CPV in charm

We want to be able to measure CPV in several isospin-related decays to cancel out theory uncertainties, e.g.:

$$D^0 \rightarrow \pi^+ \pi^-, D^0 \rightarrow \pi^0 \pi^0, D^+ \rightarrow \pi^+ \pi^0$$

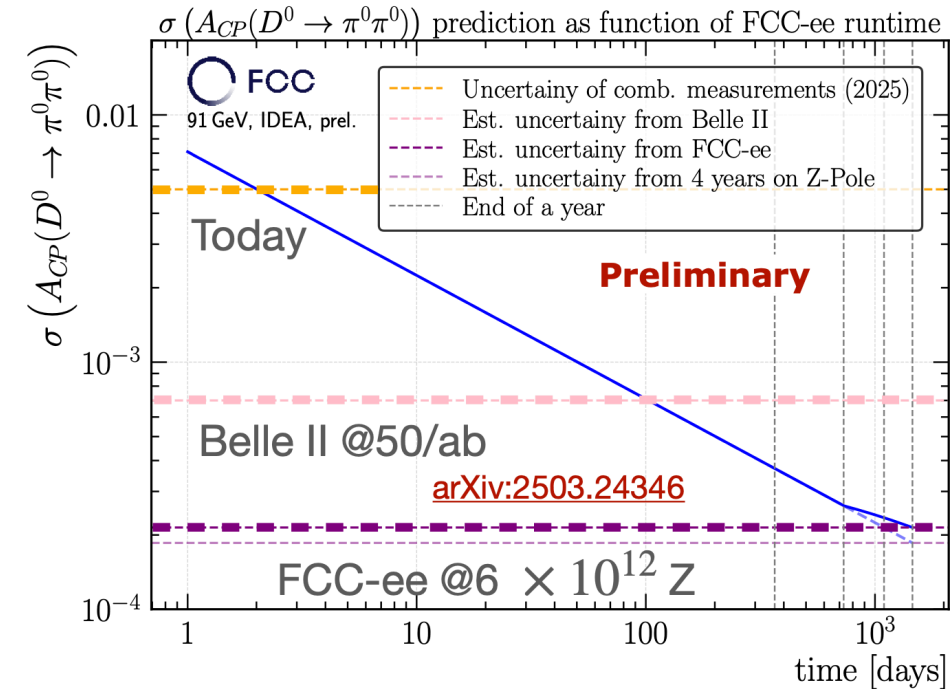
Projections with  $D^0 \rightarrow \pi^0 \pi^0$  ongoing

⇒ Good chance that FCC-ee makes the most precise measurement, improvement of factor  $\sim 5$  wrt Belle II expectation

Many caveats:

- proper estimates of systematics would need full simulation
- possible improvement from opposite-side tagging
- ...

W.Weber, S. Monteil, R.Madar, K.Kröniger, work in progress



# Rare $B$ & $D$ decays



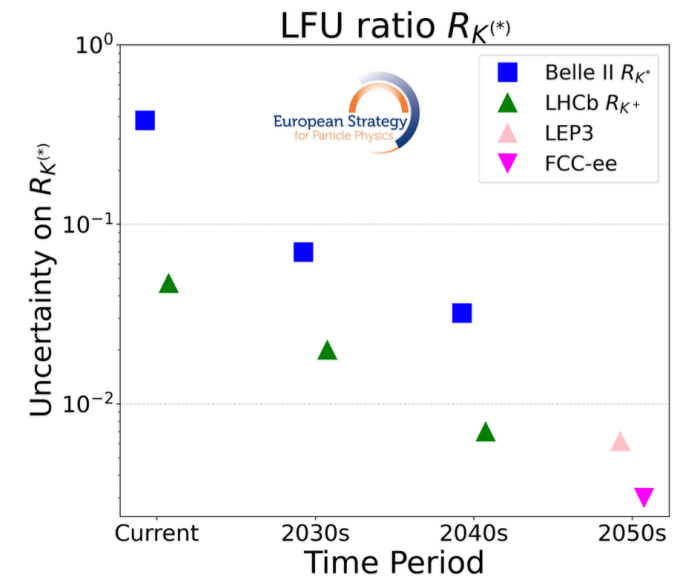
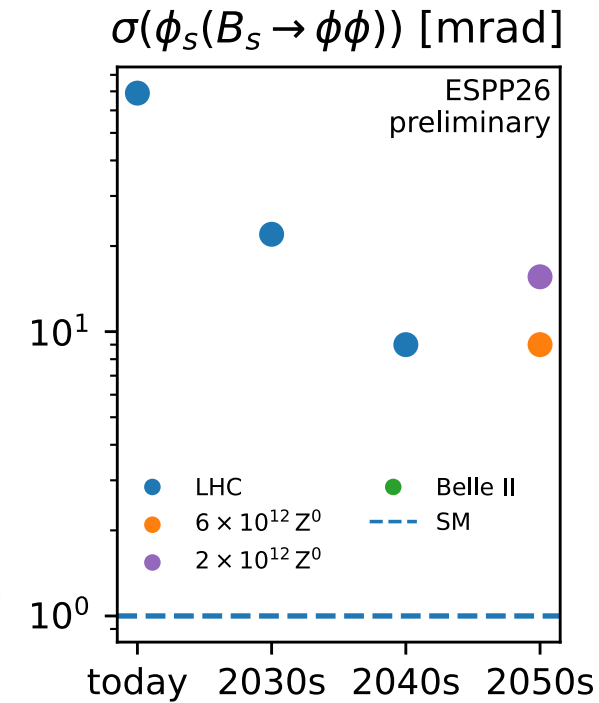
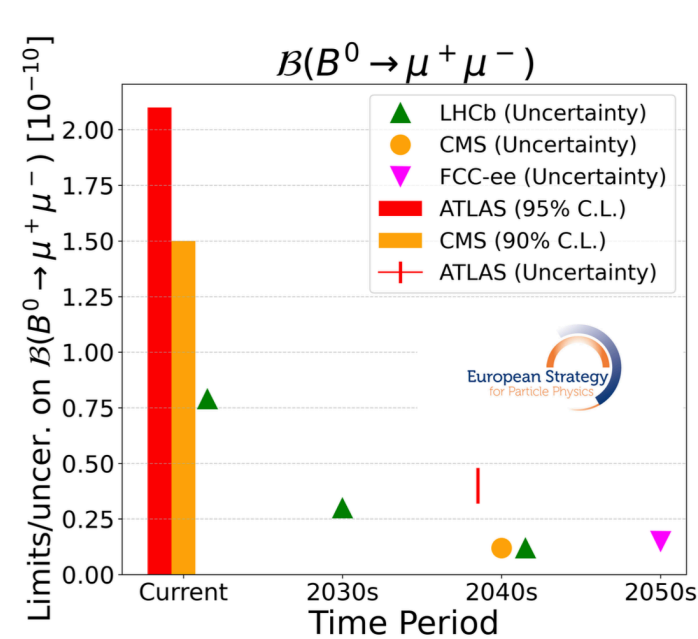
# Rare decays

LHCb upgrade expected to dominate in the study of penguin decays with fully charged final states

Possible exceptions:

- LFU ratios  $R_{K^*}$
- exploit polarised  $\Lambda_b$ 's in  $\Lambda_b \rightarrow \Lambda \mu \mu$  analysis ([arxiv:2510.02225](https://arxiv.org/abs/2510.02225))

Again, expect more significant improvements in decays with neutrals and missing energy



# $b \rightarrow s\nu\nu$

Existing FCC-ee sensitivity study for  $B^0 \rightarrow K^+\pi^-\nu\nu$ : [arxiv:2309.11353](https://arxiv.org/abs/2309.11353)

- using IDEA detector simulation
- perfect vertex seeding and PID, but expected to have small impact

Discriminate from backgrounds using mainly:

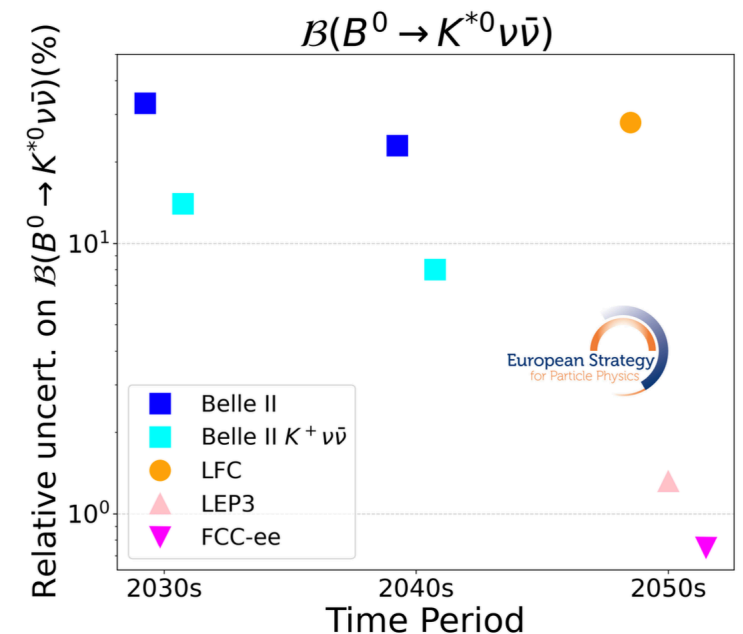
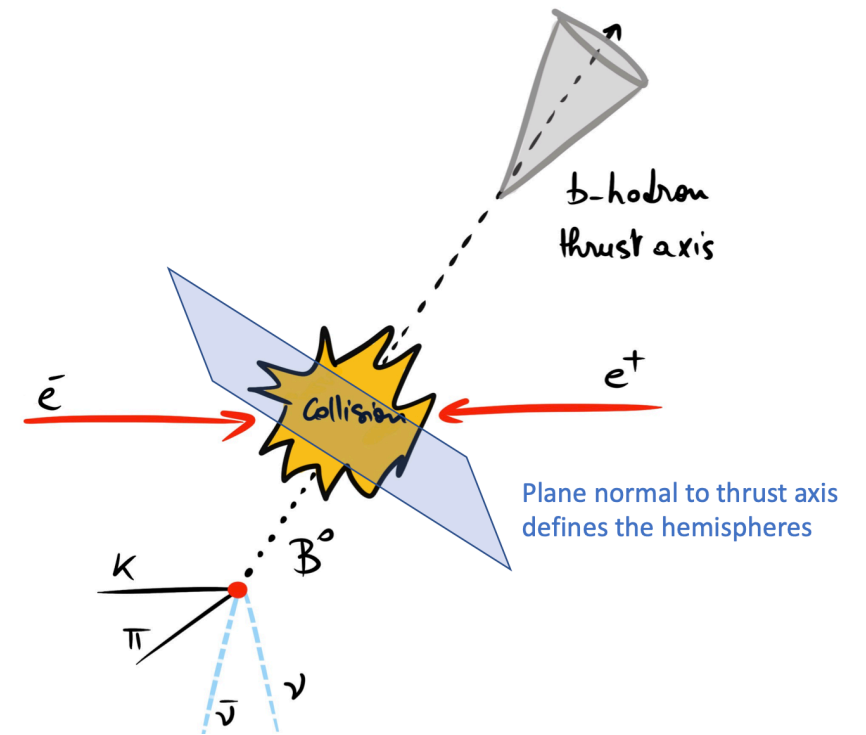
- detached  $K^+\pi^-$  vertex
- missing energy in signal hemisphere

Expected precisions on BF substantially better than Belle II:

|                               |              |
|-------------------------------|--------------|
| Belle II $50 \text{ ab}^{-1}$ | $\sim 10\%$  |
| FCC-ee:                       | $\sim 0.5\%$ |

(Note: note sure of how Belle II extrapolation is done here)

- Would allow more refined analysis to extract additional observables ( $f_L, d\Gamma/dq^2 \dots$ )



# $b \rightarrow s\tau\tau$

Current limits on  $B \rightarrow K^{(*)}\tau\tau$  at the level of  $10^{-3}$

⇒ can expect to reach  $10^{-4}$  with  $50 \text{ ab}^{-1}$

Ongoing FCC-ee  $B^0 \rightarrow K^{*0}\tau^+\tau^-$  study using IDEA simulation

- use  $\tau \rightarrow 3\pi\nu$  decays for both  $\tau$ s
- 3 vertices provide kin. constraint to get approximate  $B$  mass

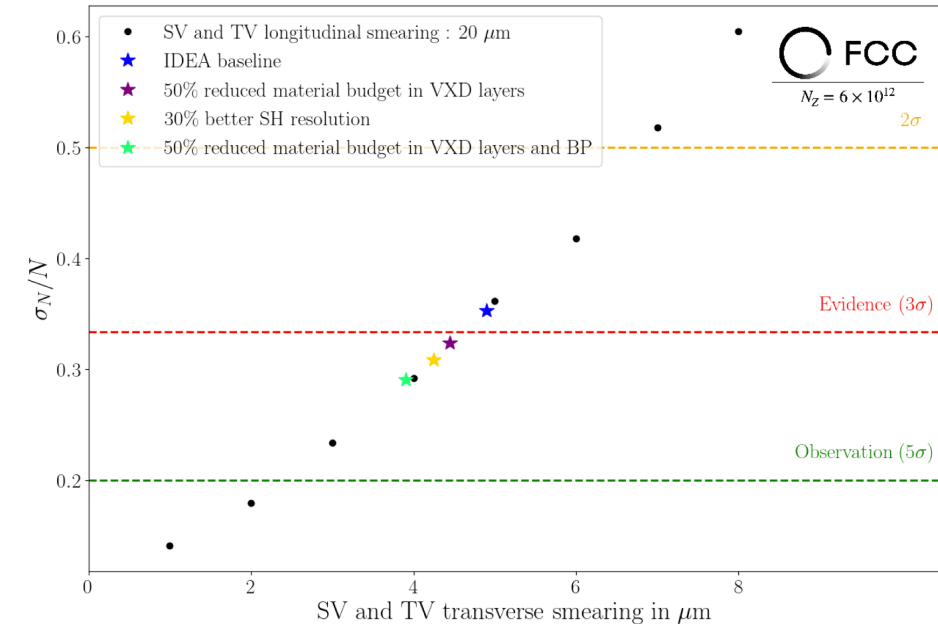
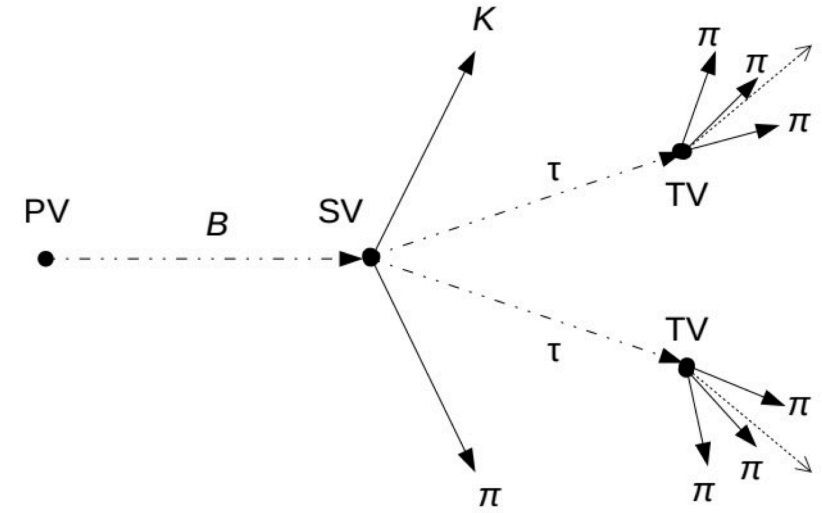
⇒ can get more than two order of magnitude improvement wrt full Belle II,

down to SM level:  $\sim 10^{-7}$  with  $6 \times 10^{12} Z$

... but depends heavily on material budget and vertex resolution

This does not include the new LHCb result  $B(B^0 \rightarrow K^{*}\tau\tau) < 2.8 \times 10^{-4}$  with  $5.4 \text{ fb}^{-1}$  ...

Before FCC-ee, precision might be driven both by LHCb and Belle II



# Other electroweak penguin decays<sup>c</sup>

## Invisible decays:

Due to helicity suppression,  $B \rightarrow \nu\nu$  is essentially non existent in the SM

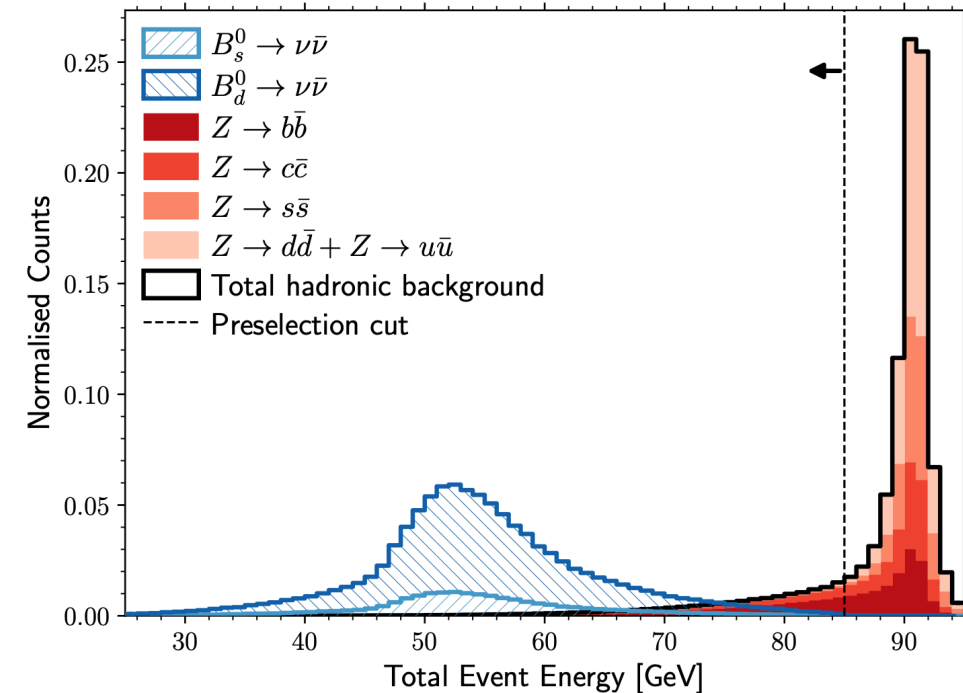
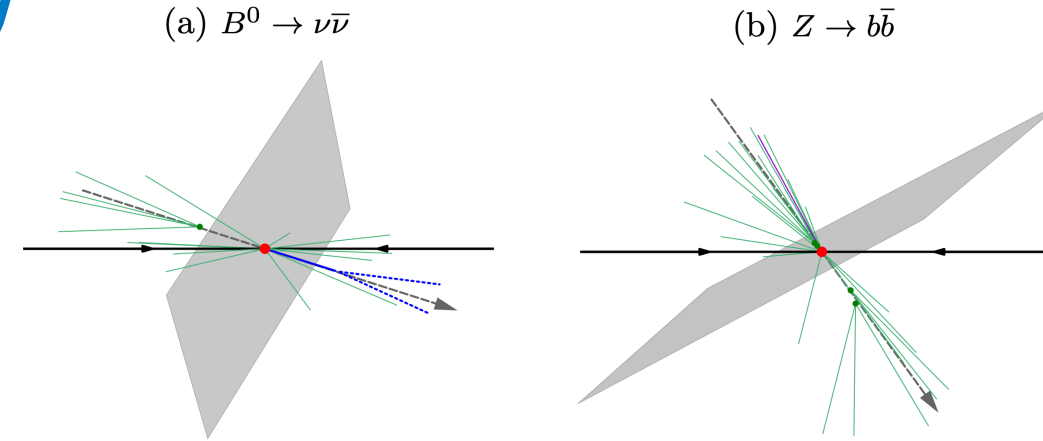
Current best limit from BaBar:  $B(B \rightarrow \text{invisible}) < 2.4 \times 10^{-5}$  90% C.L  
 $\Rightarrow 10^{-6}$  seems within reach with full Belle II lumi

Recent FCC-ee study shows  $B(B \rightarrow \text{invisible}) < 7.2 \times 10^{-9}$  90% C.L  
with  $6 \times 10^{12}$  Zs [arxiv2508.04471](https://arxiv.org/abs/2508.04471)

Again, combine vertex information & missing energy

## Inclusive decays:

Projections for inclusive  $B \rightarrow X_s \ell \ell$  decays have not yet been studied.  
However, could expect good performance using, again, vertex info



$$c \rightarrow u\nu\nu$$

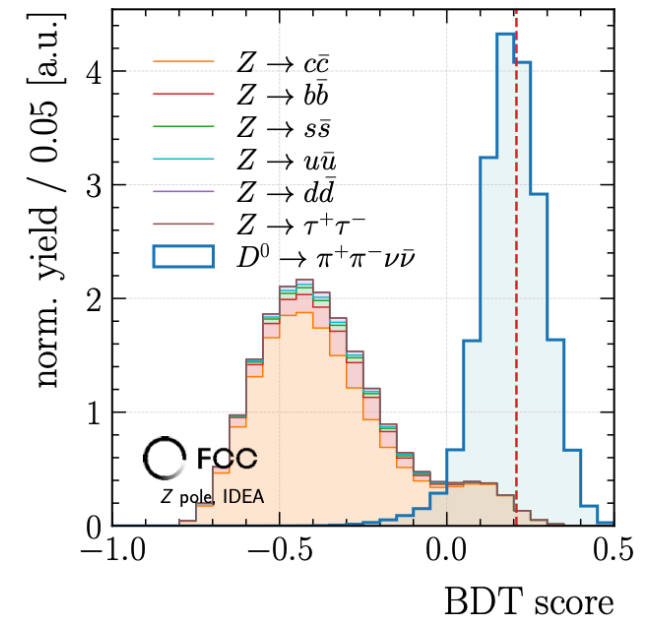
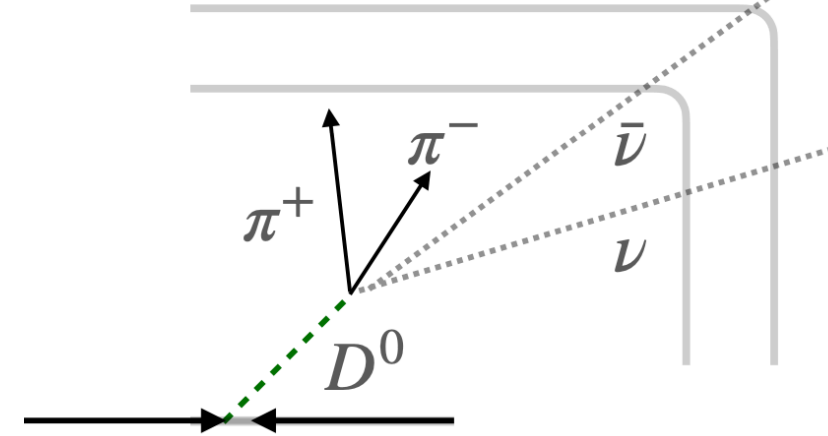
$c \rightarrow u\nu\nu$  is a clean way to study EW penguin with up-type quarks, as  $c \rightarrow u\ell\ell$  is dominated by long distance (resonances, e.g.,  $\phi$ )

Only existing limit is from BESIII:  $\mathcal{B}(D^0 \rightarrow \pi^0\nu\nu) < 2.1 \times 10^{-4}$  90% CL

Recent FCC-ee study of  $D^0 \rightarrow \pi^+\pi^-\nu\nu$   $3\sigma$  can be reached for  $\mathcal{B} \sim 2 \times 10^{-7}$  with  $6 \times 10^{12}$   $Z$ s

Searches for these decays are being prepared at Belle II  
Competition from BES III and (later) STCF to be expected!

D.Suelmann, T.Hacheney, S.Monteil, A.Di Canto,  
L.Röhrig, G.Hiller, D.M., arXiv:2509.10447



# Conclusions

Several interesting and important topics missing from my talk:

- Radiative  $B$  and  $D$  decays
- $\tau$  physics (LFV, EDM,  $V_{us}$ ...)
- $R(D^{(*)})$
- ....

But one can extrapolate some general-ish conclusions from what I presented:

- $B$  &  $D$  decays to charged final states will remain dominated by LHCb upgrade II
- The gain of a Tera-Z programme is mostly seen in decays with  $\tau$ 's,  $\nu$ 's,  $\gamma$ 's
  - the gain wrt Belle II with  $50 \text{ ab}^{-1}$  can be moderate ( $B^0/D^0 \rightarrow \pi^0\pi^0$ ) or larger if vertex information can be exploited ( $b \rightarrow s\tau\tau$ )

⇒ until, the 2050s We have a big void to fill up