CPV in B & D and CKM elements from heavy-quark decays

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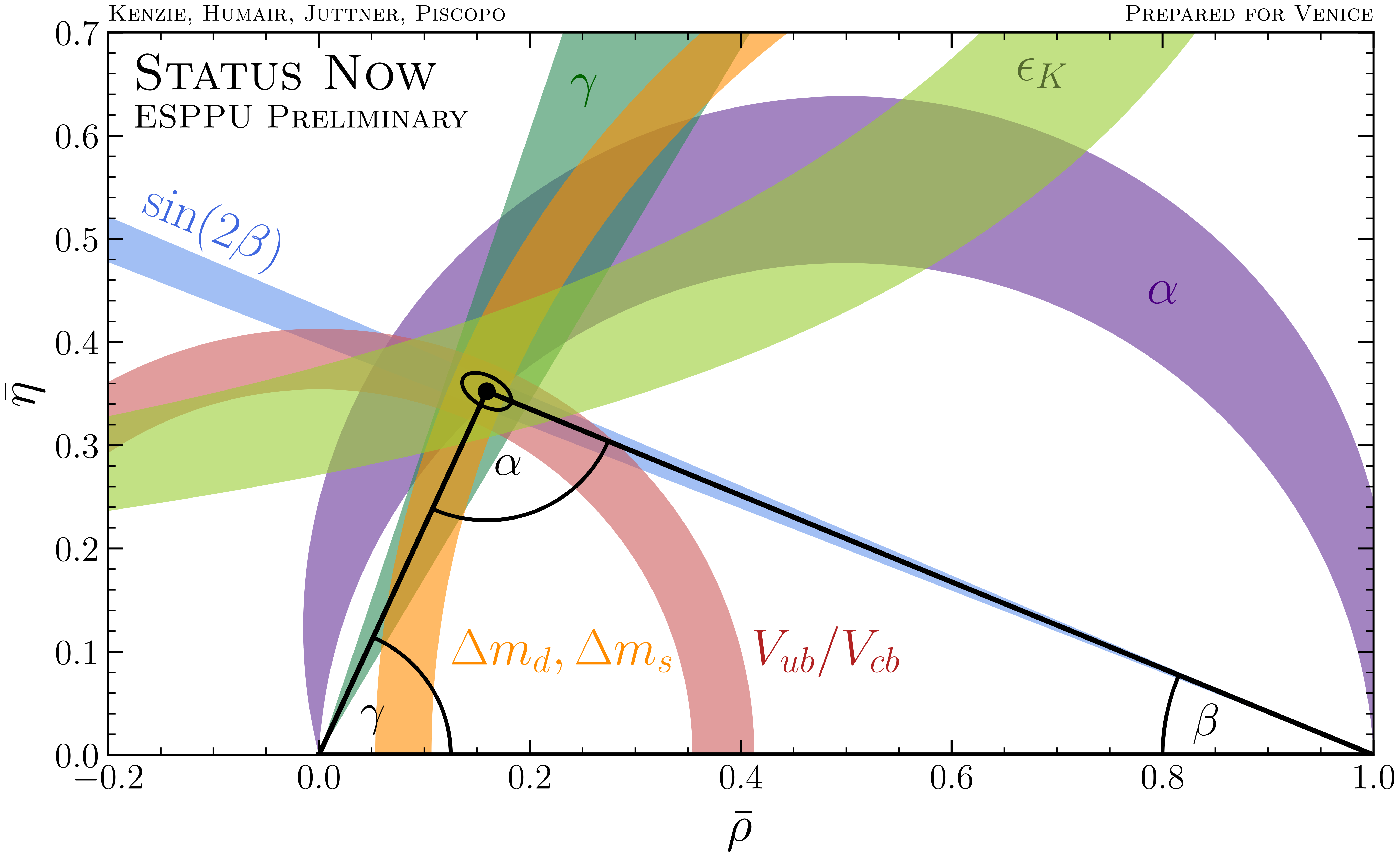
Yuval Grossman, Thibaud Humair, Andreas Jüttner, Matthew Kenzie, Maria Laura Piscopo (for the Flavour WG)

Introduction

- Study of heavy quark decays plays a fundamental role in testing the CKM matrix and CPV in the SM
- Combining constraints on the CKM Unitarity Triangle from tree-level processes (γ, $|V_{ub}|$, $|V_{cb}|$) and loop-level processes (β, Δm_d, Δm_s) could hint at NP, if tensions should emerge



Introduction

Predicted to be very small in the SM with % precision

- The CPV phase induced by B_s^0-meson mixing (ϕ_s) is highly sensitive to NP and the semileptonic CP asymmetries in B_q^0-mixing (a_d^{sl}, a_s^{sl}) provide ideal null tests of the SM

$\mathrm{Im}\left[(V_{cb}V_{ub}^*)(V_{cd}V_{ud}^*)\right] \approx 6 \times 10^{-3}$

- Charm CPV strongly suppressed in the SM due to of size of CKM elements. Theory predictions are currently limited and clear interpretation of the observation of CPV in D^0 decays, is so far missing
  - Future measurements of CPV due to D^0-meson mixing ($|q/p|$, ϕ), and of CP asymmetries in D meson decays with charged and neutral final states will be crucial to improve current the picture

Main inputs and references used

Submitted inputs

- [ID26] HFLAV input to the 2026 update of the European Strategy for Particle Physics
- [ID81] Discovery potential of LHCb Upgrade II
- [ID188] LEP3: A High-Luminosity e+e− Higgs & Electroweak Factory in the LHC Tunnel
- [ID196] Prospects in flavour physics at the FCC
- [ID205] The Belle II Experiment at SuperKEKB
- [ID223] Projections for key measurements in flavour physics
- [ID231] Super tau charm facility
- [ID241] The FCC integrated programme: a physics manifesto

Other literature

- Physics case for an LHCb Upgrade II
- The Belle II Physics Book
- CP violation studies at Super Tau-Charm Facility
- FCC Physics Opportunities - Volume 1

Important caveats

- Values used/quoted always refer to the relevant literature, *when available*
- In the absence of explicit projections for an observable, we have derived *our own estimates* taking into account quoted expected yields and reconstruction efficiencies
- Projections for future facilities such as a Tera-Z collider and STCF do not have the same level of robustness as those for the current experiments, as they depend on still unknown detector design choices

All projections for future experiments are to be seen more as an illustration of the potential of these future machines than actual precise expectations

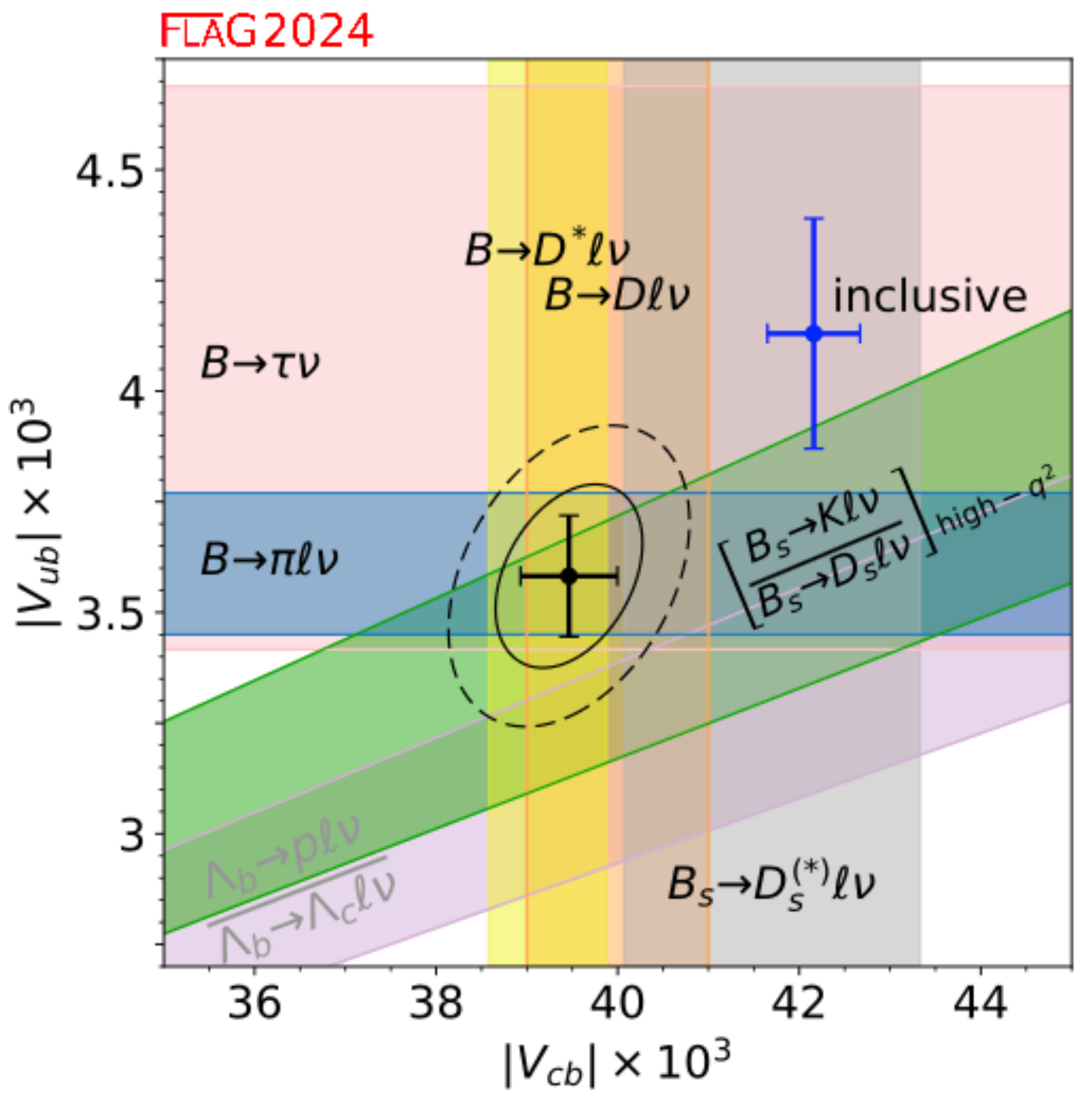
CKM angle γ

- Tree-level decays with excellent theory prediction: SM CKM benchmark
- HL-LHC (LHCb Upgrade II) plays the dominates role
- Precision currently driven by Dalitz analysis of $B^+ \to D_{CP} K^+$, with $D_{CP} \to K_S^0 \pi^+ \pi^-$
- With $D_{CP} \to K_S^0 \pi^+ \pi^-$, cross-over between beauty and charm physics
  - Strong phase inputs from BESIII, which contributes 0.4°
  - Ideally STCF improves on the strong phase measurements

    CPV in charm mixing from $D_{CP} \to K_S^0 \pi^+ \pi^-$ also uses these strong phases as inputs
  - If not, might use preferably $D_{CP} \to h^+ h^-$, or might be able to extract strong phases at LHCb directly
- Penguin free measurement of $\gamma + \phi_s$ with $B_s \to D_s K$
  - Expect FCC can do about as well as HL-LHC on these modes (better tagging)

    This means a penguin free measurement of ϕ_s with 15mrad precision

$|V_{ub}|/|V_{cb}|$



- Currently, precision on $|V_{ub}|$, $|V_{cb}|$ dominated by SL B decays, but longstanding tension between incl. and excl. determinations

  $|V_{cb}|$ crucial input for SM predictions of rare SL B decays

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

- Good prospects to extract $|V_{ub}|$ and $|V_{cb}|$ from leptonic $B^+_{(c)} \to \tau^+\nu_\tau$ decays with a future e^+e^- collider running at the Z pole see e.g. [Zuo, Fedele, Helsens at al '23]

  - Only one theory input, the $B_{(c)}$ decay constant—currently determined by Lattice QCD with $\%$ precision see e.g. [FLAG '24]

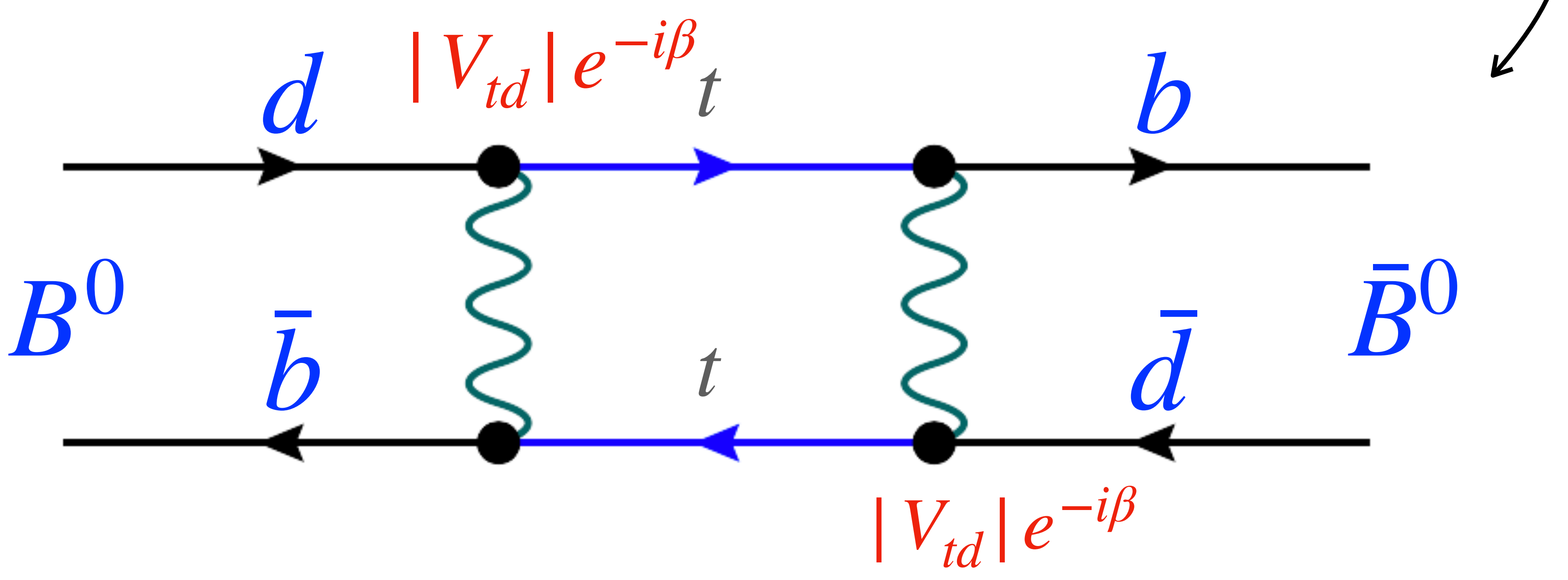
    For $B_c^+ \to \tau^+\nu_\tau$ decays, future exp. precision limited by B_c fragmentation function

  - For $|V_{ub}|$ expected precision at the level of $1\,\%$ FCC Physics Opportunities - Vol 1, but for $|V_{cb}|$ strongest constraint comes from $W^+ \to c\bar{b}$ decays, with expected sensitivity of $\sim 0.15\,\%$ ID196

See talk by P. Koppenburg

Mixing phases β and ϕ_s

Loop induced processes sensitive to virtual (off-shell) particles can probe energies much higher than those directly accessible in experiments



- Phases of B^0-$\bar{B}^0$ and B_s^0-$\bar{B}_s^0$ mixing diagrams, describing mixing-induced CPV

- Decay-time dependent analysis with tree-level, CP eigenstates decays $B^0 \to J/\psi K_S^0$, $B_s^0 \to J/\psi\phi$

- In practice, measurements of β and ϕ_s receive small bias from interference with penguin decay
  - Penguin pollution controlled with SU(3)$_F$ symmetry down to $0.1°$- $0.3°$, using control modes, e.g. $B^0 \to J/\psi\rho^0$, $B^0 \to J/\psi\pi^0$ [De Bruyn, Fleischer, Malami '25]

Penguin-free modes $B_s \to D_s^+K^-$, $B^0 \to D^0K_S^0$, $B^0 \to D^{(*)}D^{(*)}$ can also be used to extract $2\beta+\gamma$ or $\phi_s+\gamma$ with lower precision

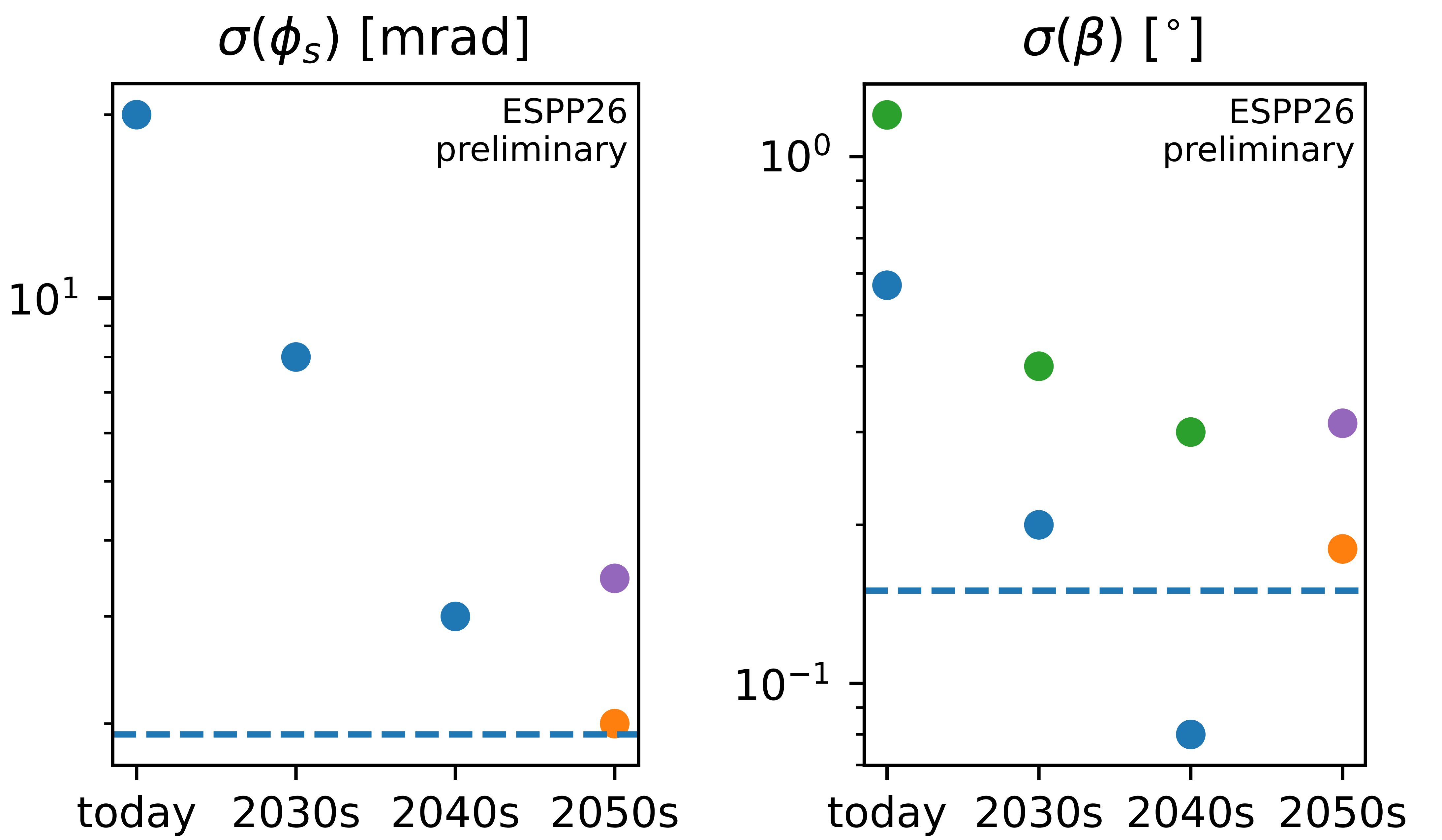
- High tagging power critical for these measurements

LHCb: $\sim 5\,\%$ Belle II: $30\,\%$ FCC-ee: $25\,\%$ (similar to LEP)

Mixing phases: projections

- $B^0 \to J/\psi K^0_S$, $B^0_s \to J/\psi\phi$ are fully charged final states with di-leptons ⇒ FCC-ee and HL-LHC reach comparable precisions

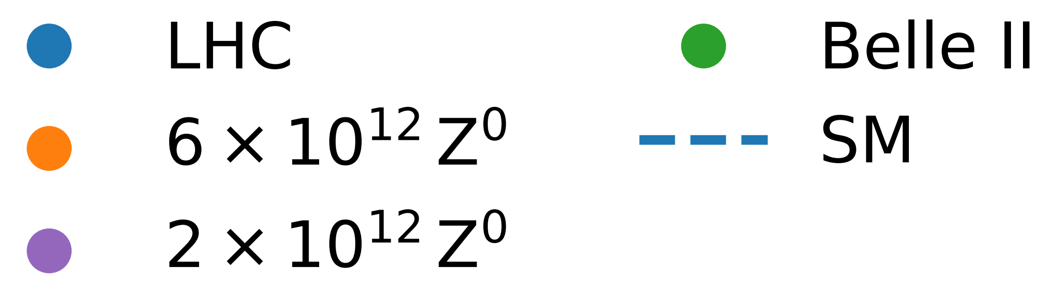
- Precision of a few 0.1°, comparable to SU(3)$_F$ limit

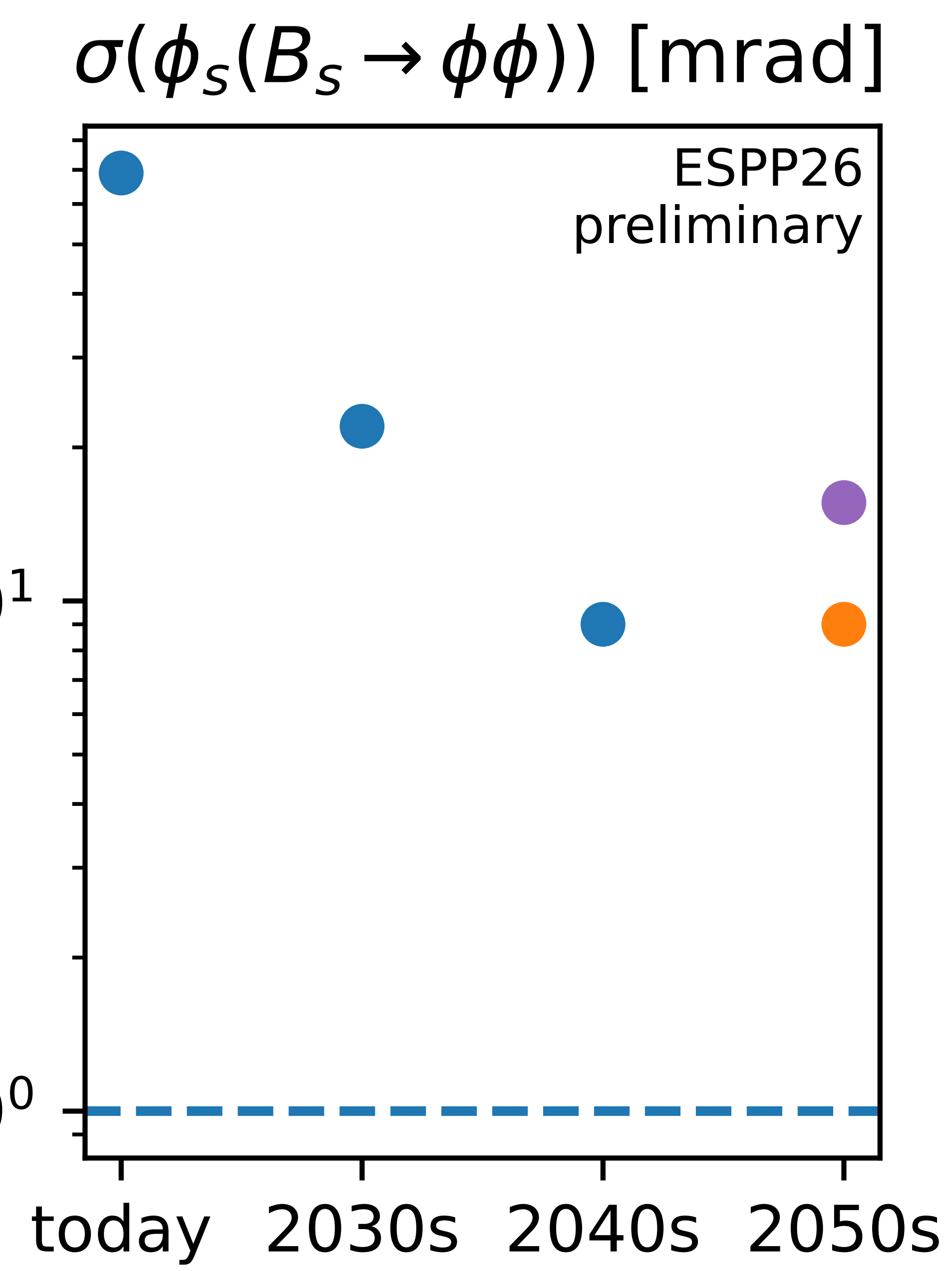


- Mixing-phase also measured in penguin-mediated decays, sensitive to phases beyond the SM

- Here $B^0_s \to \phi\phi$: comparable precision between FCC-ee and HL-LHC [Aleksan, Oliver '22]

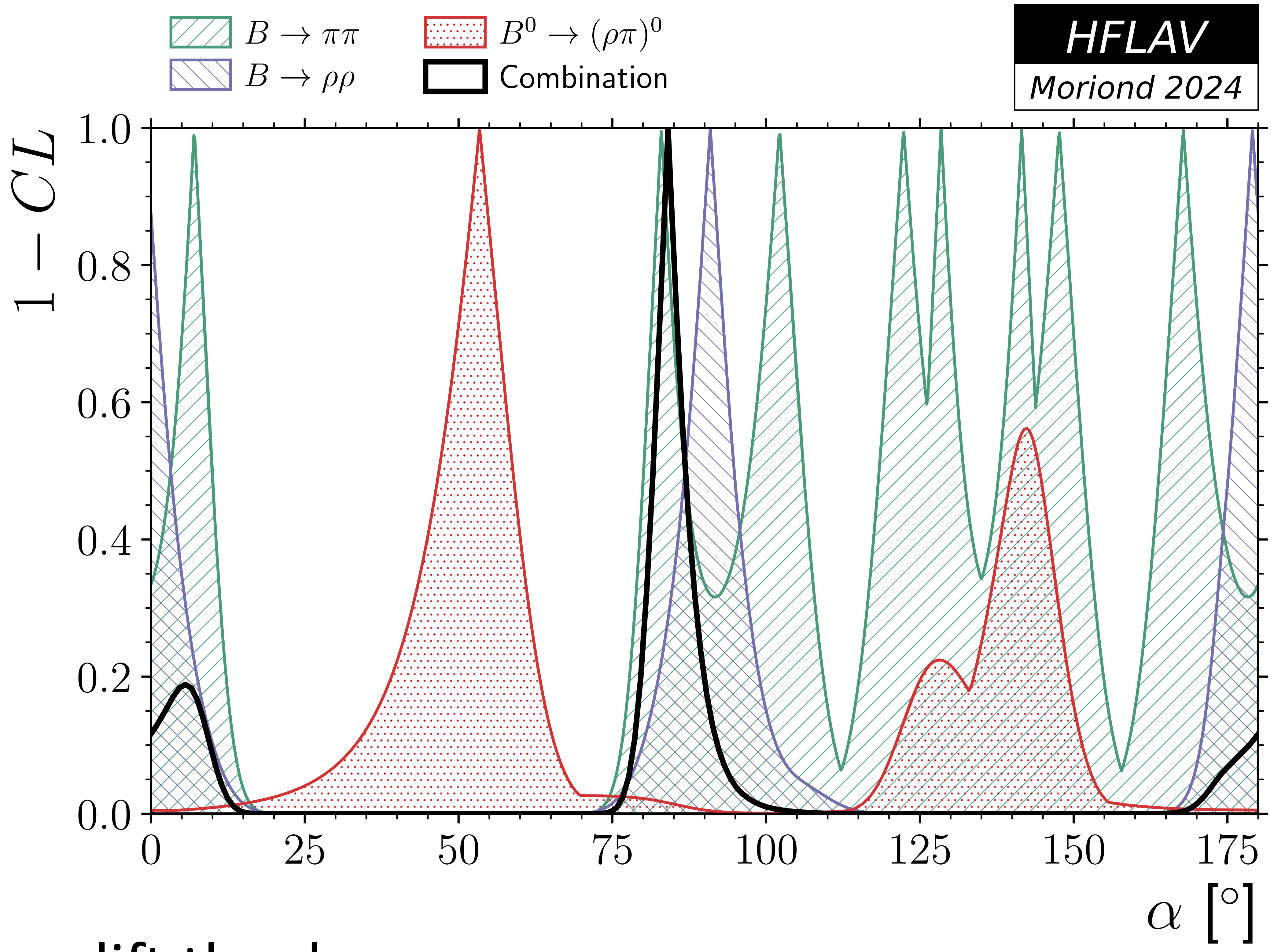
- Not expected to hit theory limit from QCD factorisation





Other penguin modes not shown here, e.g. $B^0_s \to K^*K^*$, $B^0 \to \eta' K^0_S$, also of interest

CKM angle α



- Currently least known CKM angle

- Measured from combination of branching fractions and CPV observables in isospin-related charmless B decays:

  - $B^0 \to \pi^0\pi^0, B^0 \to \pi^+\pi^-, B^+ \to \pi^+\pi^0$: simpler two-body decays but lead to degenerate solutions for α.
    $\to$ Only a decay-time-dependent analysis of $B^0 \to \pi^0\pi^0$ can lift the degeneracy

  - $B^0 \to \rho^0\rho^0, B^0 \to \rho^+\rho^-, B^+ \to \rho^+\rho^0$: more challenging multi-body decay modes, with complex resonant structures. So far driving the overall precision

- An e^+e^- environment is the best suited, combining good neutral detection, high tagging efficiencies, reasonably flat efficiency profile

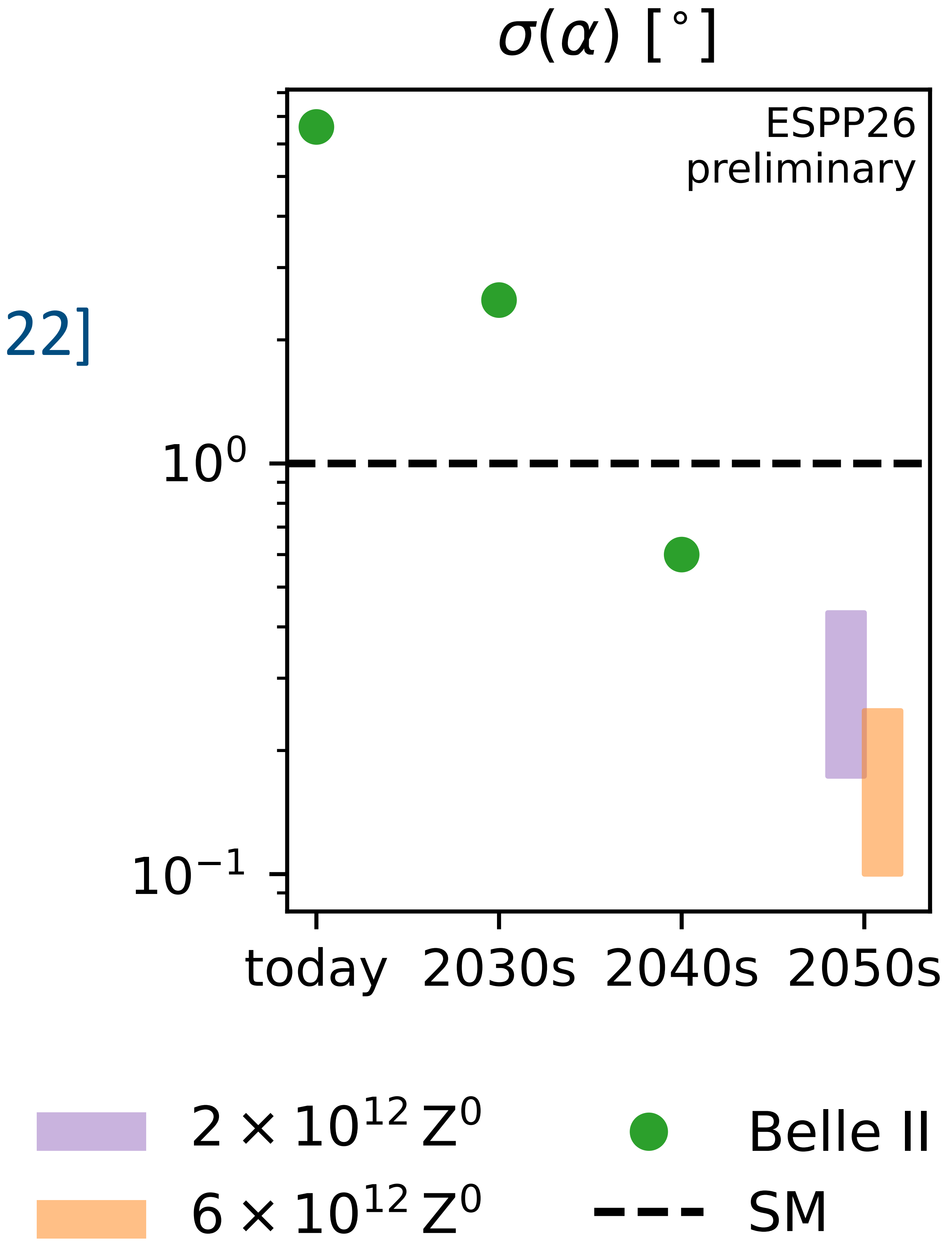
CKM angle α: projections

- Expected sensitivities at Tera-Z from $B \to \pi^0\pi^0$ studied in [Wang, Descotes-Genon et al '22]
  - Precision on $\alpha(\pi\pi)$ estimated with detector simulations. *Assumed* same improvement on $\alpha(\rho\rho)$
  - Projections obtained using *different* electromagnetic calorimeter resolutions:

    - $\sigma(E) \sim \frac{3\,\%}{\sqrt{E}} \oplus 0.3\,\%$ → similar precision per Mio B^0 produced as for Belle II

    - $\sigma(E) \sim \frac{17\,\%}{\sqrt{E}} \oplus 1\,\%$ → ~ 2.5 improvement, from better separation from $B_s \to \pi^0\pi^0$ and mis-reconstructed decays

  - No decay-time-dependent analysis of $B \to \pi^0\pi^0$

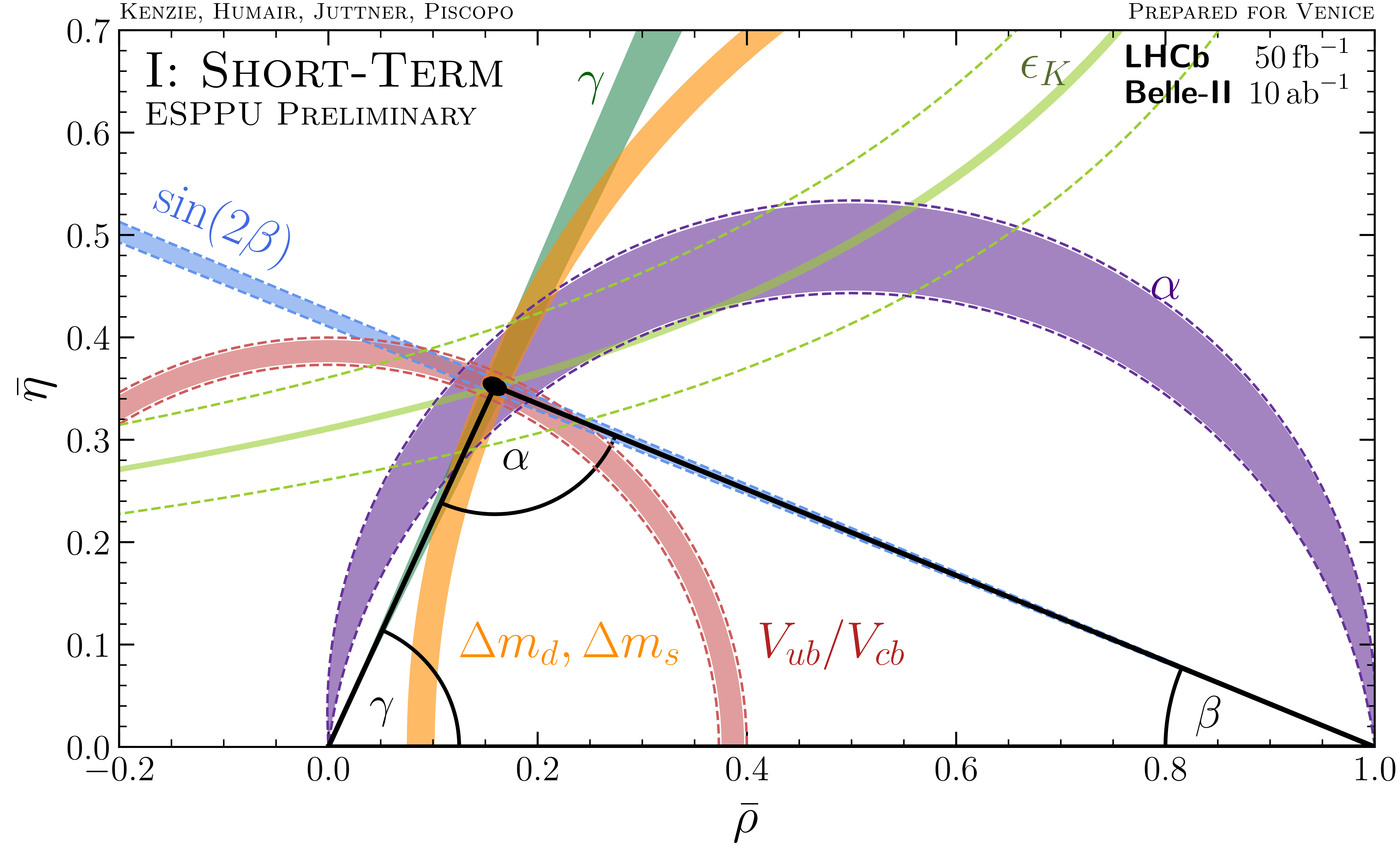


Improved theory prediction needed to beat Isospin-breaking limit, today $\sim 1^\circ$

- A Tera-Z machine is expected to dominate in multi-body decays with neutrals. However, exact precision strongly depends on the detector performances!

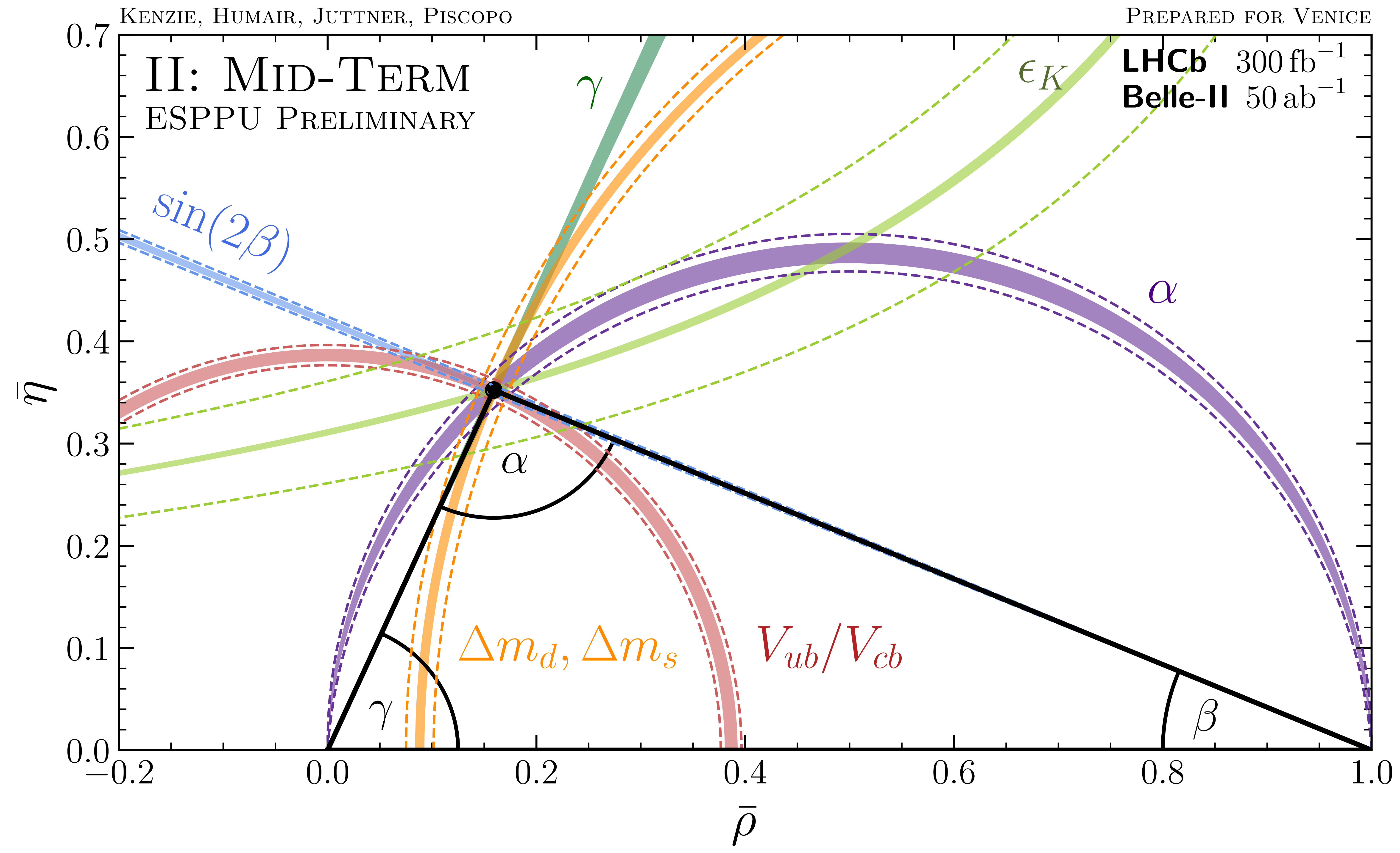
CKM status: Milestone I

Solid bands only account for experimental uncertainties
Dashed lines refer to combined theory and exp. uncertainties



CKM status: Milestone II

Solid bands only account for experimental uncertainties
Dashed lines refer to combined theory and exp. uncertainties



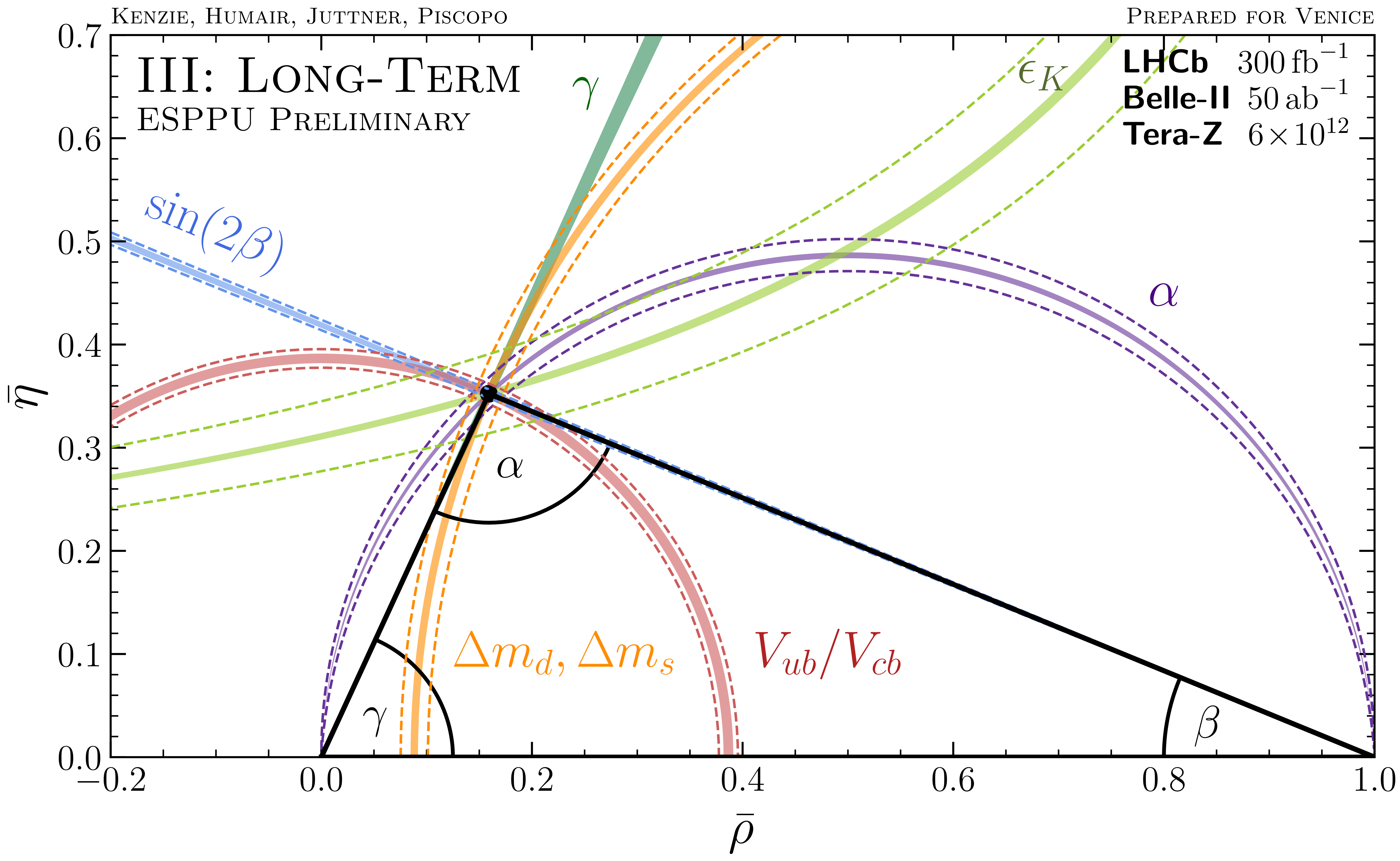
CKM status: Milestone III

Solid bands only account for experimental uncertainties
Dashed lines refer to combined theory and exp. uncertainties

- Improvement from Tera-Z mostly visible on α

- This assumes that the tensions between inclusive and exclusive measurements of $|V_{ub}|$, $|V_{cb}|$ resolve
  $\rightarrow$ benefit from e^+e^- environment

- Theory improvements are crucial



Semileptonic CP asymmetries

- Encode CPV in in $B^0_{(s)} - \bar{B}^0_{(s)}$ mixing. Currently, exp. limited:

In the SM:	HFLAV:
$a_d^{sl} = (-5.1 \pm 0.5) \times 10^{-4}$	$a_d^{sl} = -21(14) \times 10^{-4}$
$a_s^{sl} = (2.2 \pm 0.2) \times 10^{-5}$	$a_s^{sl} = -60(280) \times 10^{-5}$

[Albrecht, Bernlochner, Lenz, Rusov '24]

$$a_q^{sl} = \frac{\Gamma(\bar{B}^0_q \to f) - \Gamma(B^0_q \to \bar{f})}{\Gamma(\bar{B}^0_q \to f) + \Gamma(B^0_q \to \bar{f})}$$

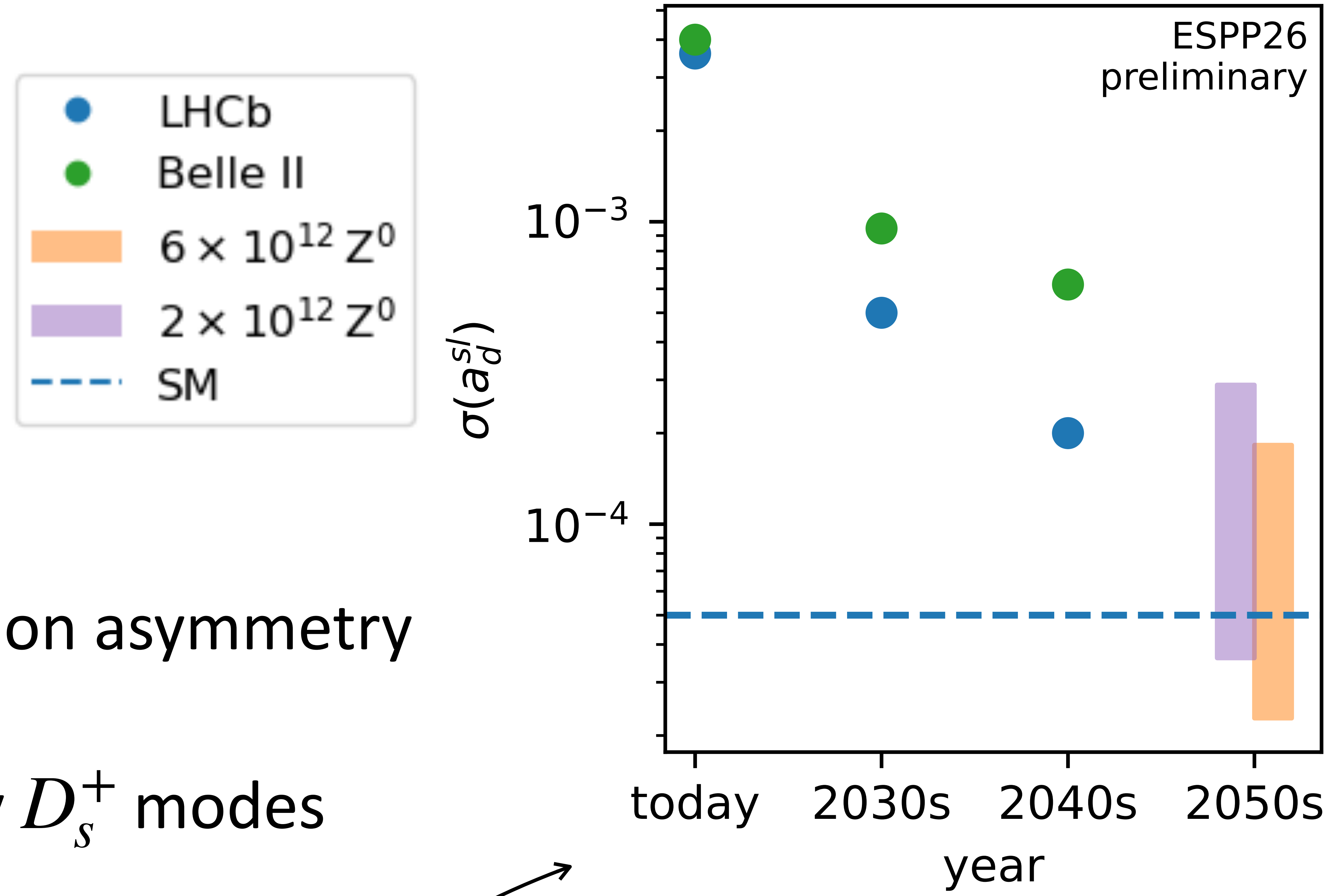
f is flavour specific: it can only be accessed via the decay of B^0_q but not of $\bar{B}^0_q$. Mixing is required to allow the decay via $\bar{B}^0_q \to B^0_q \to f$

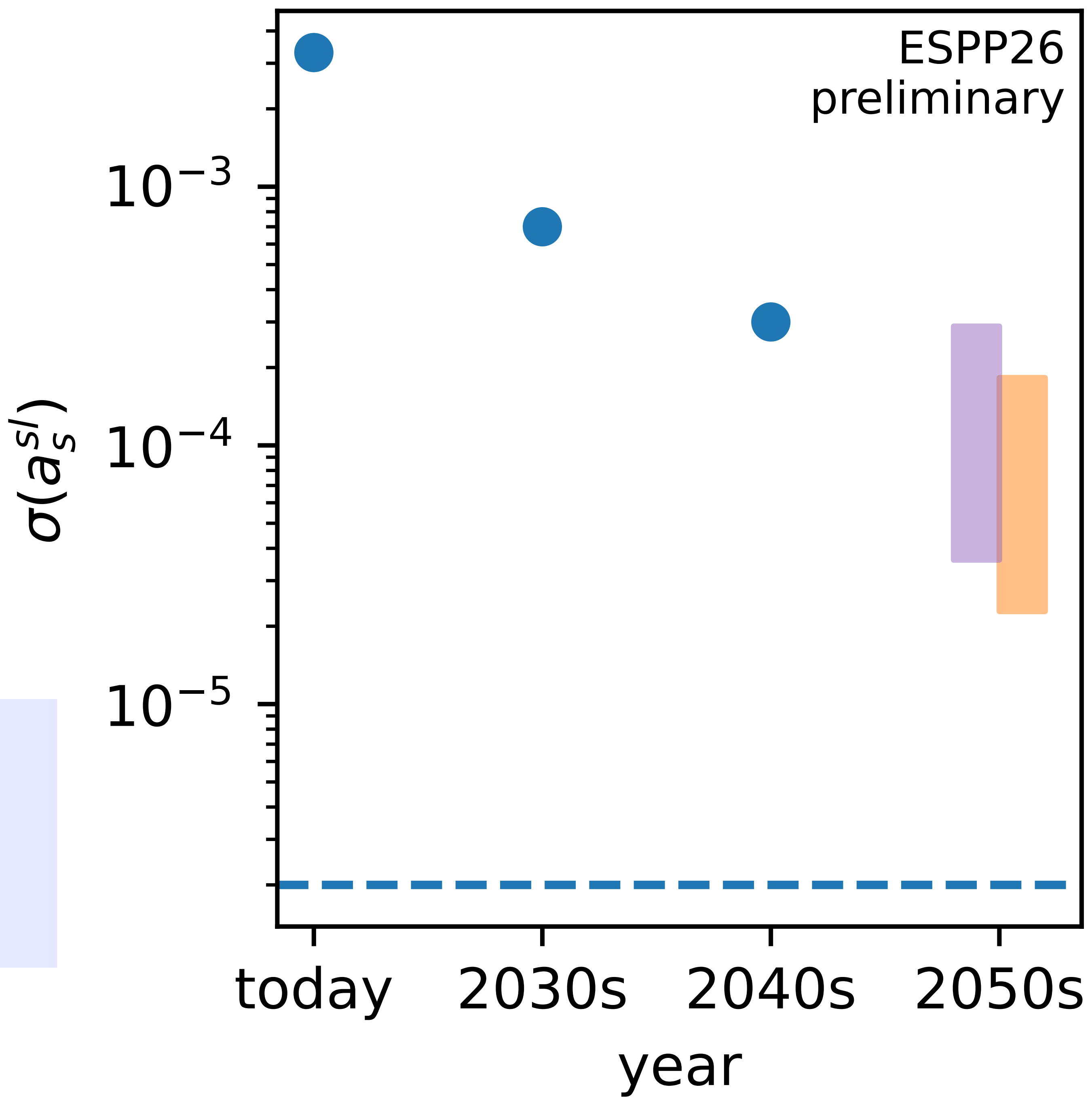
- Comparatively clean theoretical predictions, powerful SM null tests
- Various experimental techniques:
  - Asymmetries between number of same-sign lepton pairs, $N(\ell^+\ell^+)$ vs $N(\ell^-\ell^-)$, at Belle II
  - Decay-time-dependent analysis in proton-proton environment
- For LHCb and Belle II: uncertainties scaled down from existing measurements, assuming detector asymmetries controlled at the 10^{-4} level

Rely on control samples

SL CP asymmetries: projections

- Several advantages of a Tera-Z facility:
  - Unlike at LHC, no production asymmetries
  - Light tracking detector (low material) helps reducing detection asymmetry
  - For a_s^{sl} , good neutrals reconstruction allows to access many D_s^+ modes
- However, challenging measurement and reliable estimates would require sensitivity studies with accurate detector simulation
- But potential to push precision significantly higher than at LHC
  - Might even observe CPV in B_d^0-meson mixing for the first time





For Tera-Z :
Upper limit from [Charles, Descotes-Genon et al. '20]
Lower limit from FCC Physics Opportunities - Volume 1

Indirect CPV in charm: $|q/p|$ and ϕ

- Describe CPV in D^0 mixing and in the interference of mixing and decay
    - Important null tests of the SM

CPV in mixing expected to be very small in the SM, but precise predictions are challenging

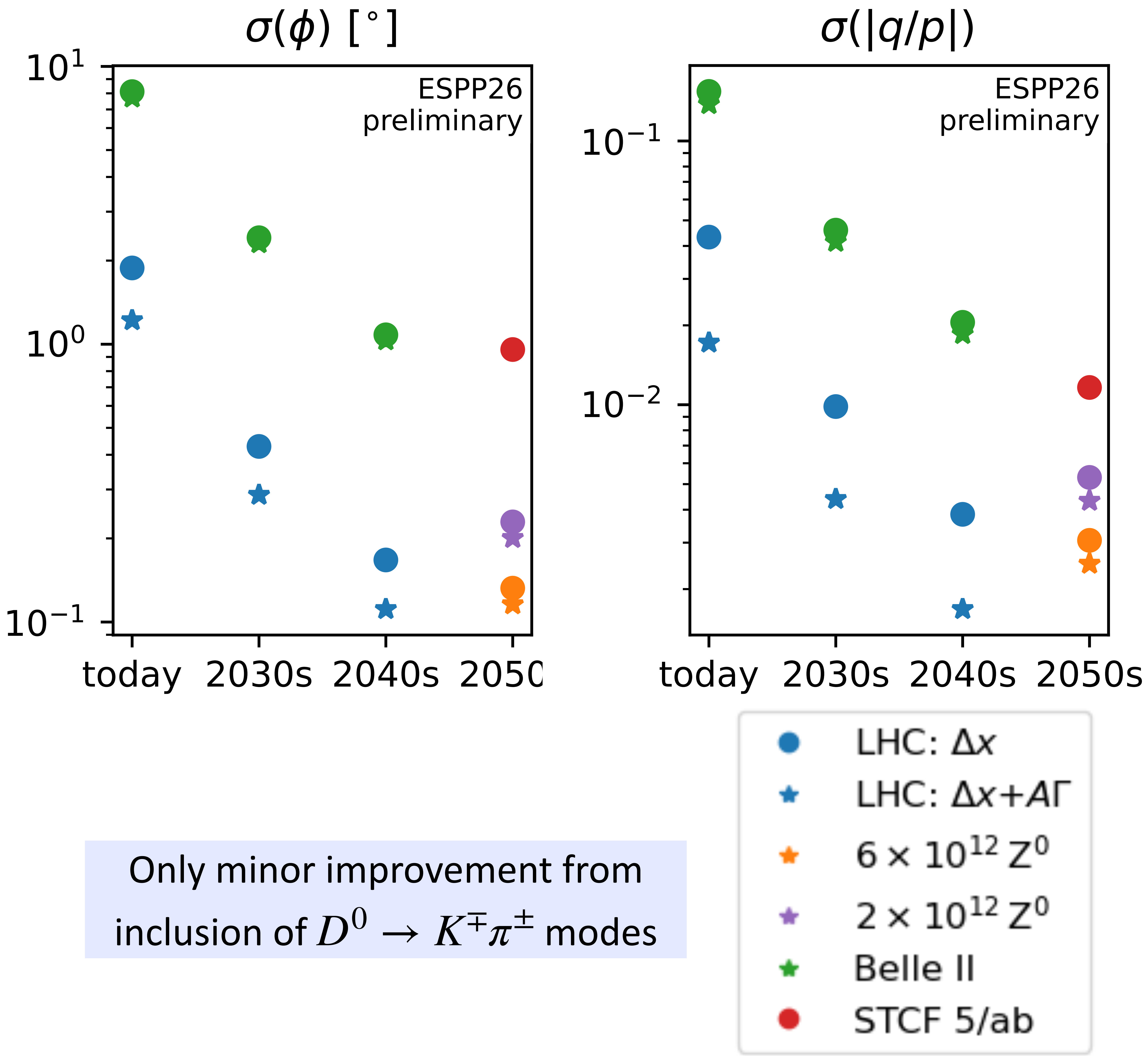
see e.g. [Kagan, Silvestrini '20]

- The projections for the sensitivities have been derived using:
    - $D^0 \to K_S\pi^+\pi^-(\pi^0)$ — corresponding to 4 observables: $x_{CP}, y_{CP}, \Delta x, \Delta y$
    - $D^0 \to h^+h^-$ — corresponding to 1 observable A_Γ
    - $D^0 \to K^\pm\pi^\mp$ — corresponding to 4 observables: x'_+, x'_-, y'_+, y'_-
- Note that for STCF we assume 5 years of running at the $\psi(4010)$ resonance

Values obtained might change, also following the new BESIII study

$|q/p|$ and ϕ: projections

- With $D^0 \to K_S^0\pi^+\pi^-(\pi^0)$ decays, precision with 6 Tera-Z competitive with that of LHCb Upgrade II
- Adding constraints from $D^0 \to \pi^+\pi^-$, highest precision reached with LHCb Upgrade II
- However, many caveats e.g.:
  - Assuming D^*-tagging only (possible to tag using other c-quark in event)
  - No limitation from strong-phase measurements



Only minor improvement from inclusion of $D^0 \to K^\mp\pi^\pm$ modes

CPV in the decay: isospin sum-rules

- Theory interpretations of CPV in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ not yet clear
  - In the absence of direct computations, the hadronic structure of the decays can be analysed resorting to symmetries of the SM, such as isospin
- In the *isospin limit,* the decay amplitudes for $D^0 \to \pi^+\pi^-$, $D^0 \to \pi^0\pi^0$ and $D^+ \to \pi^+\pi^0$ satisfy the sum rule

$$(1/\sqrt{2})\mathscr{A}^{+-} + \mathscr{A}^{00} = \mathscr{A}^{+0}$$

e.g. [Grossman, Kagan, Zupan '12]

- Precise measurements of the CP asymmetries in isospin partners modes will be extremely beneficial to get insight into their hadronic structure and test the SM

CPV in $D^0 \to \pi^0\pi^0$

- Projections on $D \to \pi\pi$ sum-rule expected to scale similarly as $A_{CP}(D^0 \to \pi^0\pi^0)$

- For Belle II: most recent measurement with 428/fb, 26k D^{*+}-tagged events leads to

$$A_{\mathrm{CP}}(\pi^0\pi^0) = (0.30 \pm 0.72 \pm 0.20)\,\%$$

- Belle II Upgrade with 50/ab: expected precision on A_{CP} of 0.07%

- With 6 Tera Z: expected 107 Mio of $D^{*+} \to (D^0 \to \pi^0\pi^0)\pi^+$ events
  - *Naive scaling* from Belle II yields to a precision on A_{CP} of 0.012%
  - Precise extrapolation would require proper sensitivity study. But similarly to α: an e^+e^- environment is best suited for null tests from isospin sum rules

Summary

- For the CKM fit as well as charm mixing, future precision will mostly by driven by LHCb upgrade II, with theory improvements being crucial to be able to fully exploit the experimental results

- For a Tera-Z factory to become competitive, it must exploit either

    - Modes with neutrals, which provide fundamental *complementarity* to the LHCb programme

    - Modes which require tagging, benefitting from the clean e^+e^- environment

- A particularly interesting case is that of the semileptonic CP asymmetries a_d^{sl}, a_s^{sl}. Clean observables where a Tera-Z facility could set the precision frontier

Back-up

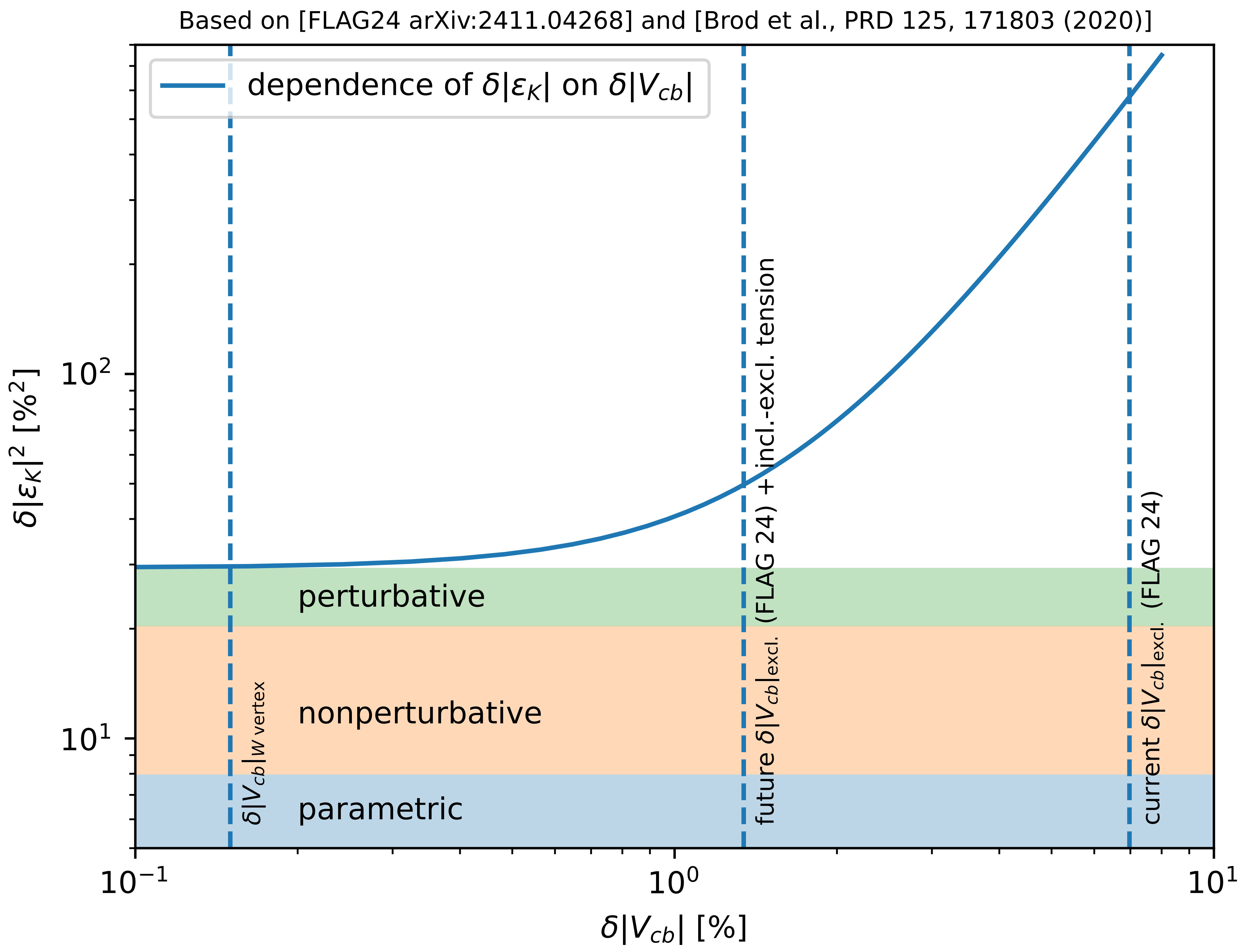
CKM apex fit

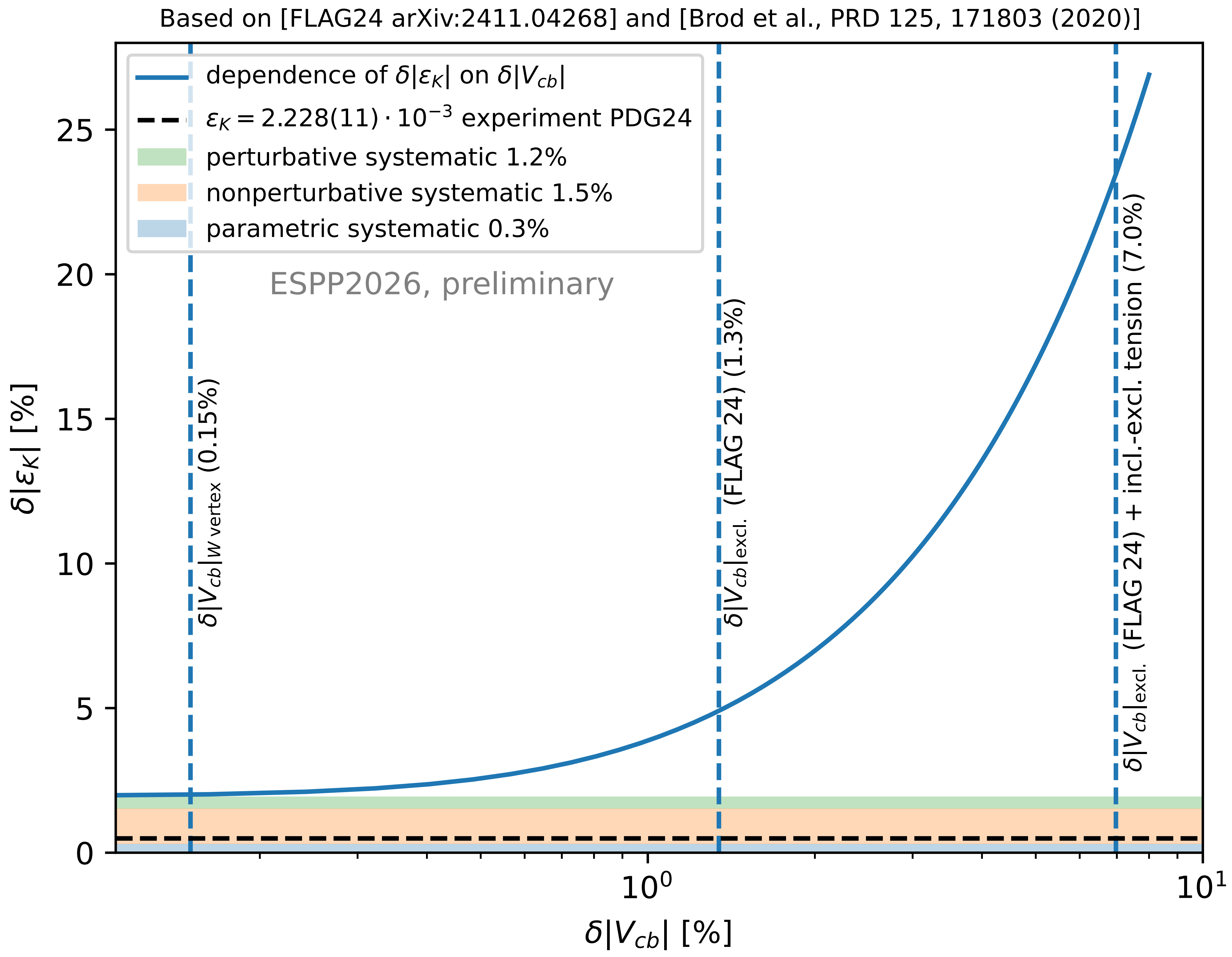
- V_{cb} tension essentially assumed to resolve
- V_{ub} has 1% irreducible
- ϵ_K has 5.4% from QCD (see plot on next slide). Perturbative part likely to improve near team, lattice near/medium term
- γ hits no theory limit
- β hits 0.1° from penguins
- α hits 0.9° from SU(3)f-breaking
- $|V_{td}/V_{ts}|$ is fixed at the current knowledge of decay constant and bagging fraction ratio

	rho	eta
Now	0.0094	0.0072
short term	0.0039	0.0029
short term (w/ th err)	0.0042	0.0033
mid term	0.0014	0.0012
mid term (w/ th err)	0.0019	0.0019
long term	0.0010	0.0009
long term (w/ th err)	0.0018	0.0018

CKM apex fit

rho eta





LHCb projections

- For "today" values:
  - $D^0 \to K_S^0\pi^+\pi^-$: 2106.03744 LHCb $D*$ tag 5.4/fb
  - $D^0 \to h^+h^-$: 2105.09889 LHCb $D*$ and B tag, 6/fb
  - $D^0 \to K^+\pi^-$: 1712.03220 LHCb $D*$ tag 5/fb
- Scaling for projections:
  - For $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to h^+h^-$, use the projections for A_Γ and Δx and scale all other uncertainties by the same factor
  - $D^0 \to K^+\pi^-$: "today" result has 0.72M WS signal decays. Then scale using yield projections in upgrade paper: 25M for 50/fb, 170M for 300/fb
- Final sensitivities for 300/fb are $\sigma(|q/p|) \approx 0.0017$, $\sigma(\phi) = 0.11^\circ$
  - Upgrade paper 1808.08865: $\sigma(|q/p|) \approx 0.001$, $\sigma(\phi) = 0.1^\circ$, reasonable agreement

Belle II projections

- For "today" values:
  - $D^0 \to K_S^0\pi^+\pi^-$: 2410.22961 Belle I+II D^* tag 1.36/ab. As this is a CP average measurement, scale down the error on x by $1/0.707$ to get uncertainty on Δx. This yields $\sigma(\phi) \sim 8\,\mathrm{deg}$, $\sigma(|q/p|) \sim 0.15$, about 50% better than the measurement in 1404.2412 using 0.9/ab of Belle data and getting $\sigma(\phi) \sim 13\,\mathrm{deg}$, $\sigma(|q/p|) \sim 0.2$
  - $D^0 \to h^+h^-$: 1509.08266 Belle D^* tag, 0.976/ab
  - $D^0 \to K^+\pi^-$: hep-ex/0601029 Belle D^* tag 0.4/ab
- Scaling for projections:
  - For $D^0 \to K_S^0\pi^+\pi^-$: add $50\,\%$ more data (scale precision down by $1/\sqrt{1.5}$) to account for adding $D^0 \to K_S^0\pi^+\pi^-\pi^0$, with yields estimated from 1703.05721
  - All: scale by $\sqrt{\ }$ lumi

FCC projections

- Projections are for 6×10^{12} Z^0's

- $\boldsymbol{D^0 \to K_S\pi^+\pi^-}$: take the reco+tagged event yields for $D^0 \to K_S\pi^+\pi^-(\pi^0)$ from the FCC submission: 6800 Mio tot
  Compare to LHCb yield in 2106.03744 : 30.6 Mio with 5.4/fb
  Take LHCb result and scale down by $\sqrt{6800/30.6}$

- $\boldsymbol{D^0 \to h^+h^-}$: take the reco $D^{*+} \to (D^0 \to h^+h^-)\pi^+$ yield from Stephane's table (see next slide): 800M
  Compared to LHCb yield in 2105.09889: 76M
  Take the LHCb result in 2105.09889 and scale down by $\sqrt{800/76}$

- $\boldsymbol{D^0 \to K^+\pi^-}$: take the reco $D^{*+} \to (D^0 \to K^+\pi^-)\pi^+$ yield from Stephane's table: 22M
  Compare to LHCb yield in 1712.03220: 0.72 M.
  Take the LHCb result in 1712.03220 and scale down by $\sqrt{22/0.72}$

- Final sensitivity: $\sigma(|q/p|) \approx 0.0024$, $\sigma(\phi) = 0.11°$.

$D^0 \to \pi^+\pi^-$ projections

- Most recent Belle II measurement: 2505.02912 with 428/fb, 26k D^*-tagged events, $A_{CP} = (0.30 \pm 0.72 \pm 0.20)\,\%$

- Belle II: expected precision on ACP: 0.09% with 50/ab from 1808.10567

- FCC-ee projection:

  - $2 \cdot 720 \cdot 10^9$ c-jets

  - $23\,\%$ fragmentation fraction to D^{*+}

  - $B(D^0 \to \pi^0\pi^0) = 8.26 \cdot 10^{-4},\ B(D^{*+} \to D^0\pi^+) = 60\,\%$

  - 80% reco eff for π^0, 90% for slow π^+

  - $\Longrightarrow$ expect 107 M $D^{*-} \to (D^0 \to \pi^0\pi^0)\pi^+$ events, precision on ACP: 0.012%

CPV in charm: expected yields

Yields at STCF not provided

- Comparison of yields for selected benchmark channels for mixing-related and direct CPV studies

	2030's		2040's		2050's
Benchmark channels	**Belle II (10 ab-1)**	**LHCb (50 fb-1)**	**Belle II (50 ab-1)**	**LHCb (300 fb-1)**	**6 TeraZ**
$D^0 \to K_S\pi^+\pi^-$	14	520	71	3500	2400
$D^0 \to K_S\pi^+\pi^-\pi^0$	8	–	38	–	4400
$D^0 \to \pi^+\pi^-$	1	236	5	1600	200
$D^0 \to \pi^0\pi^0$	0.6	–	3	–	100

Values are in units of 10^6

CKM summary

		$\alpha(^\circ)$	$\beta(^\circ)$	$\gamma(^\circ)$	V_{ub}/V_{cb}	V_{td}/V_{ts}
2030's	Belle II (10 ab-1)	2.5	0.4	2.2	2 %	—
	LHCb (50 fb-1)	—	0.2	0.8	2 %	0.0015
2040's	Belle II (50 ab-1)	0.6	0.3	1	1.6%	
	LHCb (300 fb-1)	—	0.08	0.3	1 %	0.0015
2050's	2 TeraZ	—	—	—		
	6 TeraZ	0.175	0.18	—	1 %	0.0015

Hit Lattice Limits

- Relevant errors are combined for CKM plots on next slides
- Assumed all central to "line-up"

CPV in the decay: projections

Expected statistical sensitivities in units of 10^{-5}

	2030's		2040's	
Benchmark observable	**Belle II (10 ab-1)**	**LHCb (50 fb-1)**	**Belle II (50 ab-1)**	**LHCb (300 fb-1)**
$A_{CP}(D^0 \to \pi^+\pi^-)$	130	8	60	**3.3**
$A_{CP}(D^0 \to \pi^0\pi^0)$	150	—	**70**	—
$A_{CP}(D^+ \to \pi^+\pi^0)$	200	260	130	**100**