Quark & Lepton flavor physics opportunities at FCC-ee

FUTURE CIRCULAR COLLIDER

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on behalf of the FCC collaboration

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CEU Universidad Cardenal Herrera

GENERALITAT VALENCIANA

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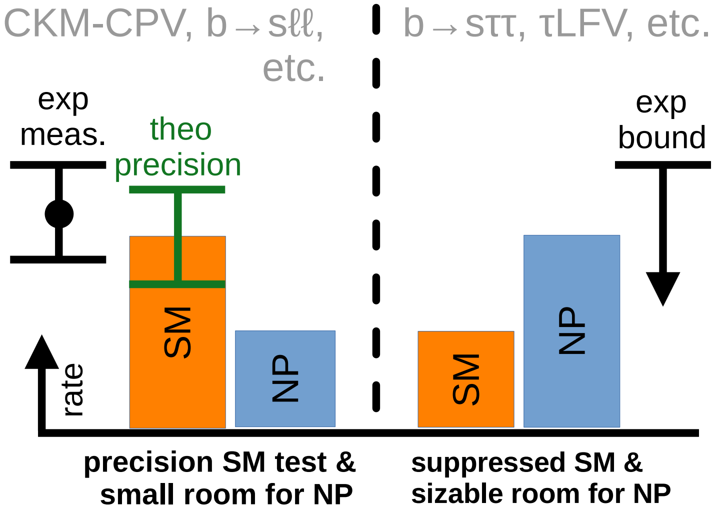
Quark & Lepton flavor physics

- Testing fundamental properties of the Standard Model (SM): GIM suppression, CKM mechanism, universality in leptonic couplings, absence of charged-lepton flavor violation, etc.

- Try to uncover New Physics (NP) from precise measurements & precise SM predictions...

- … or search for a process highly suppressed in the SM



- **Here**: potential impact of FCC-ee on the flavor physics program

FCC-ee

- Growing effort for a comprehensive and detailed assessment of future electron-positron physics cases
- Multiple aspects addressed at EPS-HEP; sessions: *T05-T09, T11, T13, Poster*
- Study full realm of SM particle spectrum, across multiple energies
- **Next**: prospects for small number of flavor cases, given <u>evolving</u> machine specifications

  Conversely, flavor sets detector requirements (vertexing, tagging, etc.)

6 x 10^{12} Z^0s — direction of this talk →

Particle species	B^0	B^+	B^0_s	Λ_b	B^+_c	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	370	370	90	80	2	720	200

[FCC Physics Opportunities CDR, arXiv:2505.00272]
[Flavour cases: EPJPlus 136, 837 arXiv:2106.01259, and EPJPlus 136, 912 arXiv:2106.12168]

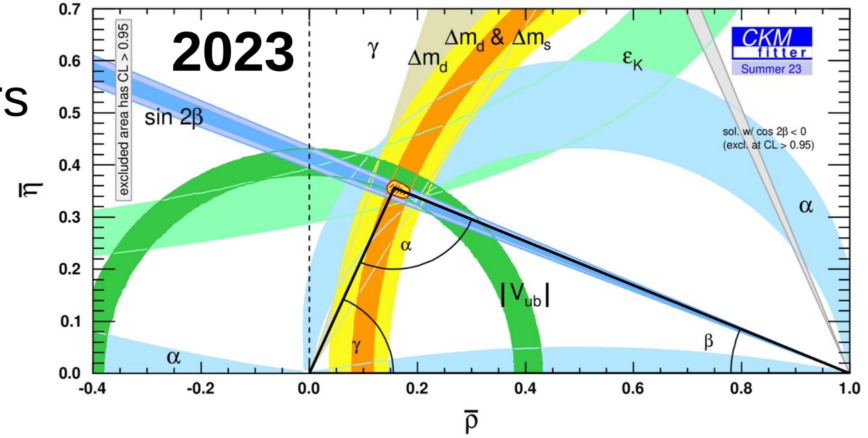
[Cobal '22 @ ICHEP]

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

Unitary Triangle (UT): the SM

- A single phase must account for CP violating phenomena across distinct quark flavor sectors
- CKM program requires accurate data: BaBar, Belle (II), LHCb, etc...

  … and an accurate description in particular of the QCD dynamics: broadly, consistent SM picture as of now



[Charles, Deschamps, Descotes-G., Monteil, Orloff, Qian, Tisserand, Trabelsi, Urquijo, LVS]

- Combined effort from the experimental and theory communities: higher exp accuracy must be matched by higher theo accuracy
- Theoretical requirements: progress will be needed!, including perturbative (i.e., hard gluons) and non-perturbative (i.e., soft gluons) QCD effects, and also EM

UT: some specific studies

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- **UT angles**, factor ~2 improvement w.r.t. LHCb 300/fb and Belle II 50/ab:
  - β from golden $B \to J/\psi\, K_S$ mode: already pressing to address penguin pollution
  - α from isospin analysis: neutral $B^0 \to \pi^0\pi^0$ mode; need to account for isospin-breaking effects, e.g., through $B \to \pi\eta^{(\prime)}$ [Wang, Descotes-G., Deschamps, Li, Chen, Zhua, Ruan '22]
  - β_s, etc.: complementary tests of CKM [Aleksan, Oliver, Perez '21; CepC: Li, Ruan, Zhao '22; Aleksan, Oliver '22, + Perez '21 '24]
- **CKM magnitudes**:
  - Novel $|V_{cx}|$ extraction from $W \to cx$, tagging efficiency (δ_ϵ) is essential
  - $W \to cb$: independent from QCD form factors
  - SτcF, $D_s \to \mu\nu$: $\delta|V_{cs}|$ stat @ 0.2%
  - $|V_{cb}|$ from $B_c \to \tau\nu$ not possible due to hadronization fraction uncertainty

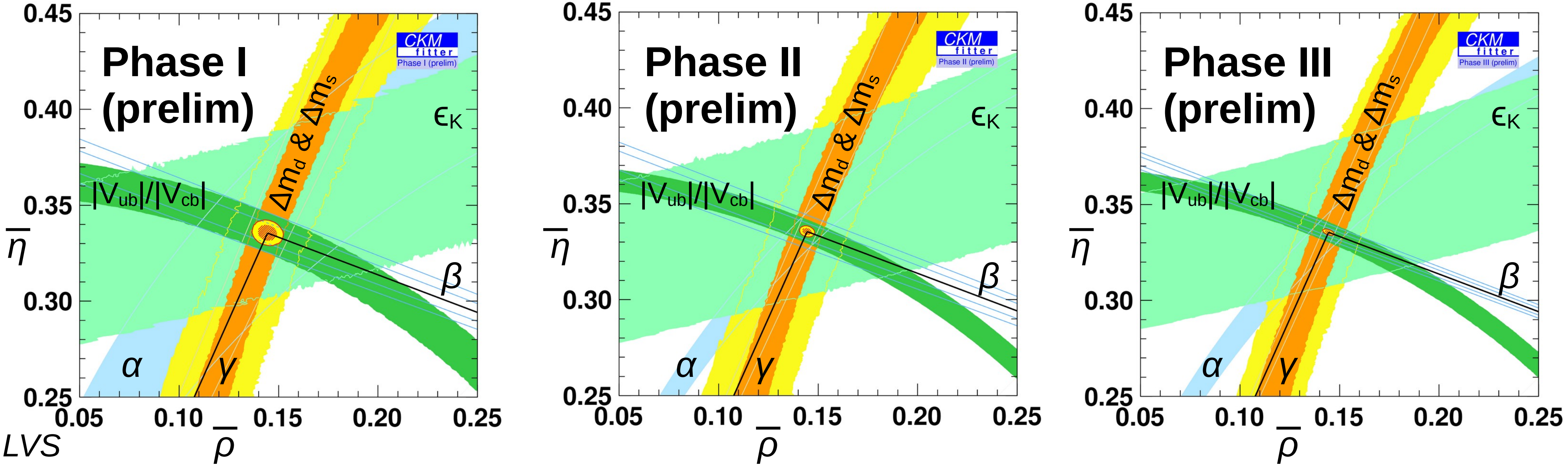
3 x 10^8 WW

$\lvert V_{ij}\rvert$	Current (PDG)		FCC-ee ($\delta_\epsilon = 1\%$)	FCC-ee ($\delta_\epsilon = 0.1\%$)	FCC-ee (Stat. only)
$\lvert V_{cs}\rvert$	0.975 ± 0.006	(0.6%)	0.36%	0.05%	0.008%
$\lvert V_{cb}\rvert$	$(40.8 \pm 1.4) \times 10^{-3}$	(3.4%)	0.52%	0.16%	0.14%

[from Marzocca, Szewc, Tammaro '24; see also Liang, Li, Zhu, Shen, Ruan '24; SτcF: Liu, Shi, Li, Zhou, Zheng '21]

UT: projections

- **Phase I**, 2030's: Belle II @ 10 ab^{-1} & LHCb @ 50 fb^{-1}
- **Phase II**, 2040's: Belle II @ 50 ab^{-1} & LHCb @ 300 fb^{-1}
- **Phase III**, 2050's: Phase II & FCC-ee (6 x 10^{12} Z + 3 x 10^{8} WW)
- Central values adjusted to avoid tension among observables



Unitary Triangle: Beyond the SM

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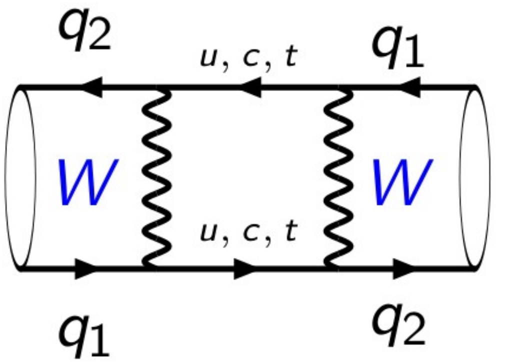
- Processes absent in the SM at the tree level play a crucial role in its tests
- Often, higher sensitivity to NP than high-energy frontier
- NP generally challenges the minimal SM picture of CP violation (CPV)
- **NP example**: consider NP only in processes that change flavor number by two units, |ΔF|=2 (F=beauty, strangeness)

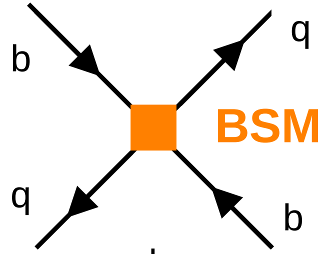
  Relative sizes h_X and extra CP violating phases σ_X (assumed here unrelated across X=B, B_s, K)



CKM (in presence of NP),
bag parameters,
↓ decay constants

$$M_{12} = M_{12}^{\mathrm{SM}} \times (1 + h\, e^{2i\sigma})$$

↑ ↗
NP parameters

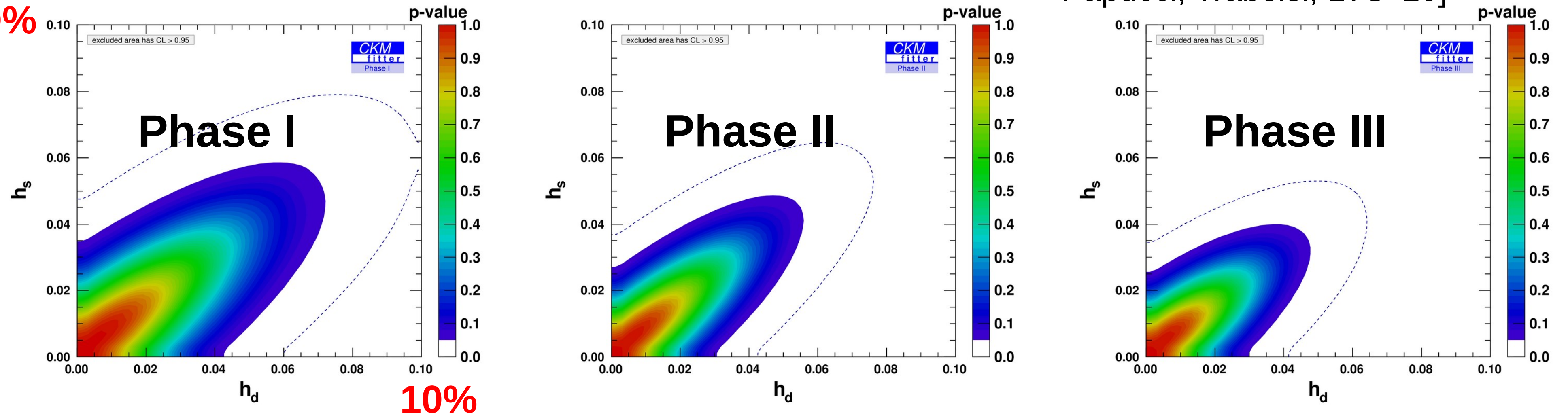


q=d, s
(can also consider loop-suppressed NP effects)

UT & BSM: projections

- Extraction of CKM parameters degrades in presence of NP
- Currently: h_d, h_s can be as high as **O(20%)**! (tree-level NP at 100's of TeV)
- Bottlenecks: QCD inputs, $|V_{cb}|$

[Charles, Descotes-G., Ligeti, Monteil, Papucci, Trabelsi, LVS '20]

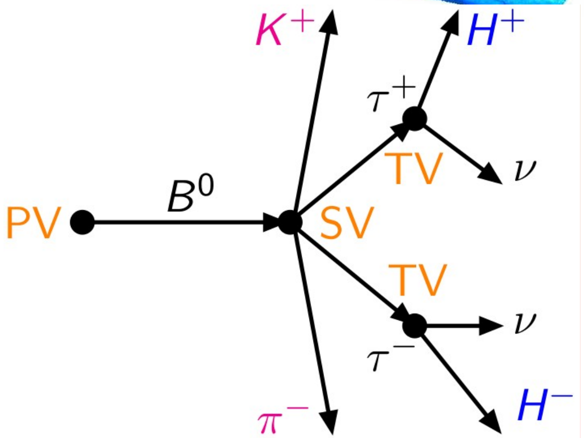


- Mixing induced semi-leptonic asymmetries play no role in the current study of heavy NP, but can have an important impact in specific NP extensions

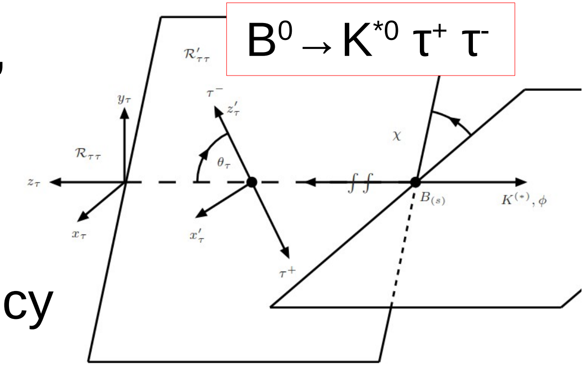
[B-mesogenesis: Miró, Escudero, Nebot '24]

Rare decays of bottom quarks

- Rare decays: GIM and CKM suppressed in the SM
- Bottom decays: consider processes relying on the third generation, generally expected to be more sensitive to NP
- **Example**: $b \to s\, \tau^+\tau^-$
  - SM: BR~O(10^{-7}) [BR~O(10^{-6}) for $B_s \to \tau^+\tau^-$]; current exp: BR~<O(10^{-5}) Belle II $B^+ \to K^+\tau^+\tau^-$ [BR~<O(10^{-3}), LHCb]
  - FCC-ee: presence of invisible particles in the final state, excellent vertexing is then required; can reach ~O(10^{-7}) [~O(10^{-5})] sensitivity
  - Multiple observables, including tau polarization observables: important for complementarity & redundancy

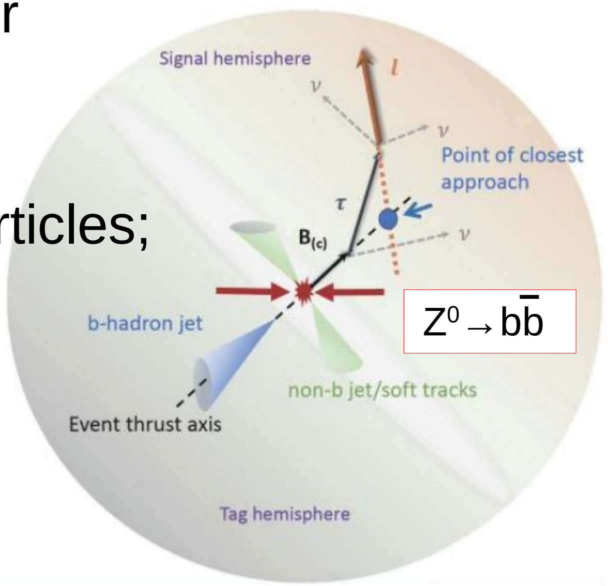


[Kamenik, Monteil, Semkiv, LVS ‘17, Li, Liu ‘20, Miralles ‘23, Miralles, Monteil ‘25]



Other bottom-meson decays

- Other modes with invisibles also accessible; example: $b \to s\, \nu_? \nu_?$ (any neutrino flavors, may relate to charged leptons via SU(2)$_L$), expected accuracy of O(1%) in BRs; study time-dependent/integrated CPV
- Light charged leptons, $b \to s\, \ell^+ \ell^-$; HL-LHC and FCC-ee perform similarly for muons, while FCC-ee does much better for electrons; improve on lepton flavor universality (LFU) tests (no theo uncertainty)
- $b \to c\, \tau\, \nu$ & $b\, c(u) \to \tau\, \nu$: require dealing with invisible particles; LFU anomalies: Tera-Z gives an additional picture



[νν: Amhis, Kenzie, Reboud, Wiederhold ‘23; B_s to ϕ νν BRs, CPV: Kwok, Polonsky, Lukashenko, Aebischer, Kilminster ‘25; CepC: Li, Ruan, Wang, Wang ‘22]

[ℓℓ: Bordone, Cornella, Davighi ‘25]

[τν: Zheng, Xu, Cao, Yu, Wang, Prell, Cheung, Ruan ‘20, Amhis, Hartmann, Helsens, Hill, Sumensari ‘21, Zuo, Fedele, Helsens, Hill, Iguro, Klute ‘23]

Charm physics

- Complementary sector to down-type physics
- $Z \to cc$ yields comparable to $Z \to bb$ at FCC-ee
- **Direct CPV** discovered by LHCb: whether ΔA_{CP} is consistent with the KM mechanism is still unknown, due to the difficulty in describing the underlying soft-QCD dynamics

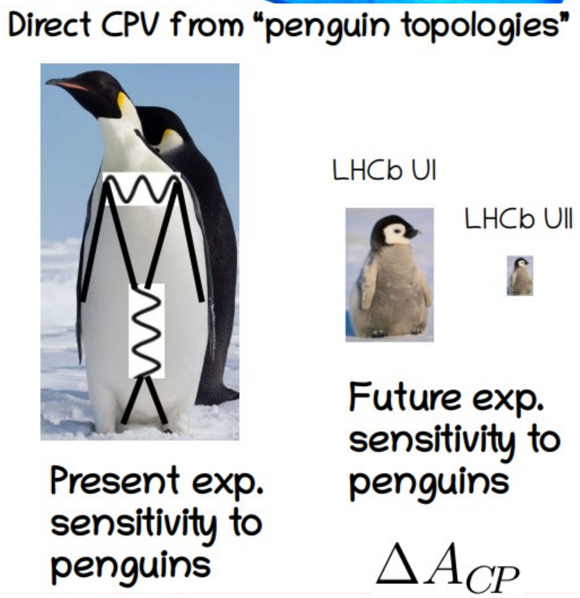
  e^+e^-: no asymmetry production syst, ideal given small CPV of ~0.1%

  FCC-ee can look for complementary signs of CPV, e.g., in charm-meson decays having π^0s in the final state
- **Rare charm decays**: τs are not kinematically accessible

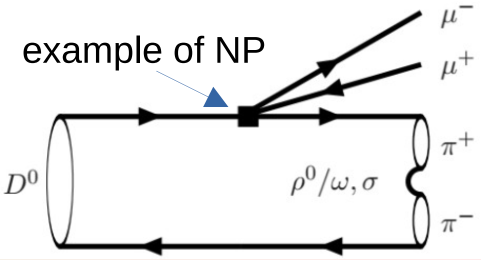
  FCC-ee can address $c \to u\, e^+e^-$ and $c \to u\, \nu\nu$ transitions; modes with neutrals (e.g., π^0s) in $D \to hh\ell^+\ell^-$ final states help in controlling SM soft-QCD dynamics

  $D^0 \to \pi^0\nu\nu$ at ~<O(10^{-4}) BESIII: improve by > 100x at FCC-ee (naive luminosity scaling)

[νν: Bause, Gisbert, Golz, Hiller '20]



very rich LHCb dataset on $D^0 \to \pi^+\pi^-\mu^+\mu^-$



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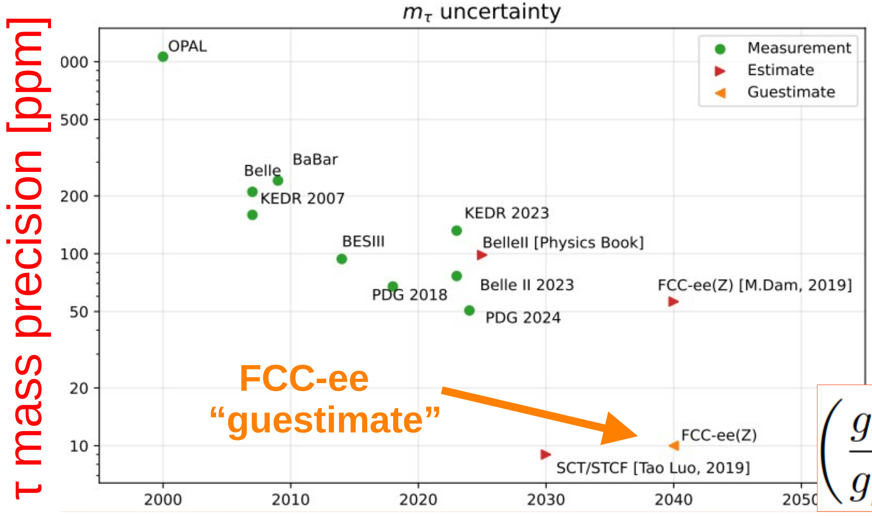
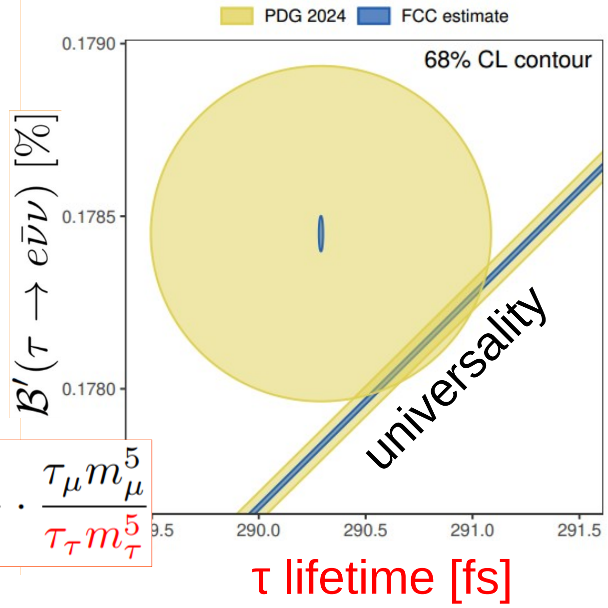
τ physics

- Large Z→ττ yields. Z factories are **ideal** for studying many τ properties, as illustrated by **LEP**; better τ vs. hadrons separation, better τ hemispheres separation, momentum perfectly known, higher momentum tracks
- τ physics offers unique conditions for studying soft QCD at intermediate energies
- τ mass at ~10 ppm; τ lifetime at ~22 ppm; τ→ℓνν BRs at 0.02%; test of W-leptons coupling universality: g_τ/g_ℓ (ℓ=e, μ)



[Lusiani '24; also, Dam '19, Pich '21]

$$\left(\frac{g_\tau}{g_\mu}\right)^2 \propto \frac{\mathcal{B}(\tau \to e\bar{\nu}\nu)}{\mathcal{B}(\mu \to e\bar{\nu}\nu)} \cdot \frac{\tau_\mu m_\mu^5}{\tau_\tau m_\tau^5}$$

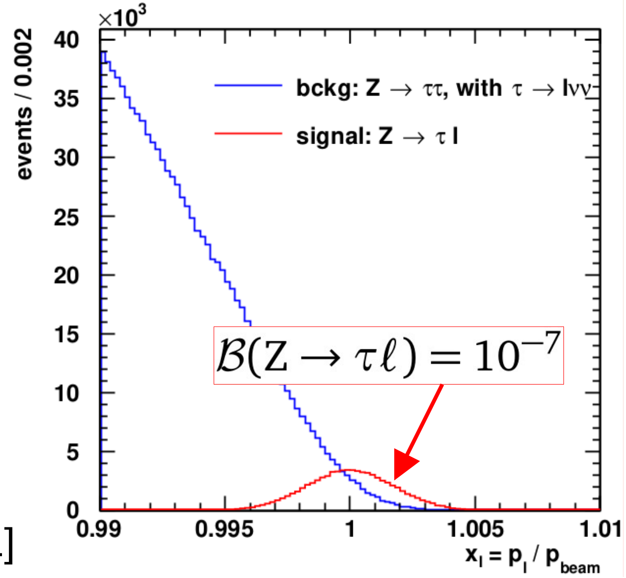


Charged-Lepton Flavor Violation

- Accidental symmetry of the SM, tied to the smallness of neutrino masses
- **LFV τ decays**: exp advantage of neutrinoless final states; $\tau\to\mu\gamma$ at ~O(10^{-9}) & $\tau\to\mu\mu\mu$ at ~O(10^{-11}), ~5x better than projected for other machines (i.e., Belle II, SτcF)
- Tera-Z: look for **LFV Z decays**; $Z\to\tau\ell$ at ~O(10^{-9}); also, $Z\to\mu e$ at ~O($10^{-(8-10)}$) (depending on μ/e ID)

[Lusiani '24, Dam '19]

[Novotny '22; Qin, Li, Lu, Yu, Zhou '17] [Chrzaszcz, Gonzalez S., Monteil '21]



- **LFV Higgs decays**: ~10^6 Higgses in association with Z; similar sensitivity to $H\to\mu e$ w.r.t. HL-LHC, ~2x better sensitivity to $H\to\tau\ell$
- **Heavy quark decays**, e.g.: $b\to s\,\tau\mu$ current exp LHCb bound of ~<O(10^{-5}), down to ~<O(10^{-6}) at HL-LHC; easier reconstruction than $b\to s\,\tau\tau$ at FCC-ee

Conclusions

- Flavor played a crucial role in the building of the Standard Model
- **FCC-ee also a machine for quark & lepton flavors!**

  Subset of cases (apologies for omissions!): rich variety of processes

  Can complement & improve projections of other machines
- **Quark physics**: broad scope of applications, CKM, rare decays, etc.; needs continuous effort from the theory community
- **Lepton physics**: strong physics cases in the τ physics, e.g., testing symmetries in the leptonic sector

THANKS!

237	Absolute Higgs boson cross section, mass, and width at FCC-ee	T08
239	Higgs boson couplings to hadrons, invisible, and rare decays at FCC-ee	T08
246	Progress in the center-of-mass energy calibration at FCC-ee	T13
248	The IDEA detector concept for FCC-ee	T11
255	High-precision QCD physics at FCC-ee	T05
257	BSM physics opportunities at the FCC-ee	T09
259	Electroweak Precision Physics at the FCC-ee	T06
261	Quark & Lepton flavour physics opportunities at FCC-ee	T07
264	Design, performance and future prospects of vertex detectors at the FCC-ee	T11
778	Status and Perspectives for FCC-ee Detector Background Studies	T11
798	Enhancing Particle Identification for Future Circular Collider Experiments using Cluster Counting Technique	Poster

240 Higgs precision at FCC-hh
242 Top quark physics at FCC-ee and FCC-hh

	Central values	Uncertainties ~Current	Phase I	Phase II	Phase III
$\lvert V_{ud}\rvert$	0.97437	±0.00054	id	id	id
$\lvert V_{us}\rvert\, f_+^{K\to\pi}(0)$	0.2177	±0.00038	id	id	id
$\lvert V_{cd}\rvert$	0.2248	±0.0043	±0.003	id	id
$\lvert V_{cs}\rvert$	0.9735	±0.0094	id	id	±0.0035
$\lvert\epsilon_K\rvert \times 10^3$	2.240	±0.011	id	id	id
Δm_d [ps^{-1}]	0.5065	±0.0019	id	id	id
Δm_s [ps^{-1}]	17.757	±0.006	id	id	id
$\lvert V_{cb}\rvert_{\mathrm{SL}} \times 10^3$	42.26	±0.58	±0.42	±0.42	id
$\lvert V_{cb}\rvert_{W\to cb} \times 10^3$		—	—	—	±0.22
$\lvert V_{ub}\rvert_{\mathrm{SL}} \times 10^3$	3.56	±0.22	±0.048	±0.027	id
$\lvert V_{ub}/V_{cb}\rvert$ (from Λ_b)	0.0842	±0.0050	±0.0025	±0.0008	id
$\mathcal{B}(B\to\tau\nu)\times 10^4$	0.83	±0.24	±0.083	±0.050	±0.033
$\mathcal{B}(B\to\mu\nu)\times 10^6$	0.37	—	±0.041	±0.02	id
$\sin 2\beta$	0.680	±0.017	±0.005	±0.002	±0.0008
α [°] (mod 180°)	91.9	±4.4	±2.5	±0.6	±0.4
γ [°] (mod 180°)	66.7	±5.6	±0.8	±0.3	±0.2
$-2\beta_s$ [rad]	−0.035	±0.021	±0.008	±0.002	±0.0012
$A^d_{\mathrm{SL}} \times 10^4$	−6	±19	±5	±2	±0.25
$A^s_{\mathrm{SL}} \times 10^5$	3	±300	±70	±30	±2.5

FCC-ee projection reaches SM level, Monteil @ 4th FCC Week

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Phase I, 2030's: Belle II @ 10 ab^{-1} & LHCb @ 50 fb^{-1}
Phase II, 2040's: Belle II @ 50 ab^{-1} & LHCb @ 300 fb^{-1}
Phase III, 2050's: as above + FCC-ee (6×10^{12} Z + 3×10^8 WW)

$\bar{m}_t$ [GeV]	165.30	± 0.32	id	id	± 0.020
$\alpha_s(m_Z)$	0.1185	± 0.0009	id	id	± 0.00003
$f_+^{K\to\pi}(0)$	0.9681	± 0.0026	± 0.0012	id	id
f_K [GeV]	0.1552	± 0.0006	± 0.0005	id	id
B_K	0.774	± 0.012	± 0.005	± 0.004	id
f_{B_s} [GeV]	0.2315	± 0.0020	± 0.0011	id	id
B_{B_s}	1.219	± 0.034	± 0.010	± 0.007	id
f_{B_s}/f_{B_d}	1.204	± 0.007	± 0.005	id	id
B_{B_s}/B_{B_d}	1.054	± 0.019	± 0.005	± 0.003	id
$\tilde{B}_{B_s}/\tilde{B}_{B_d}$	1.02	± 0.05	± 0.013	id	id
$\tilde{B}_{B_s}$	0.98	± 0.12	± 0.035	id	id
η_B	0.5522	± 0.0022	id	id	id
$\eta_K^{(tt)}$	0.545	± 0.026	id	id	id
$\eta_K^{(ut)}$	0.4040	± 0.0069	id	id	id

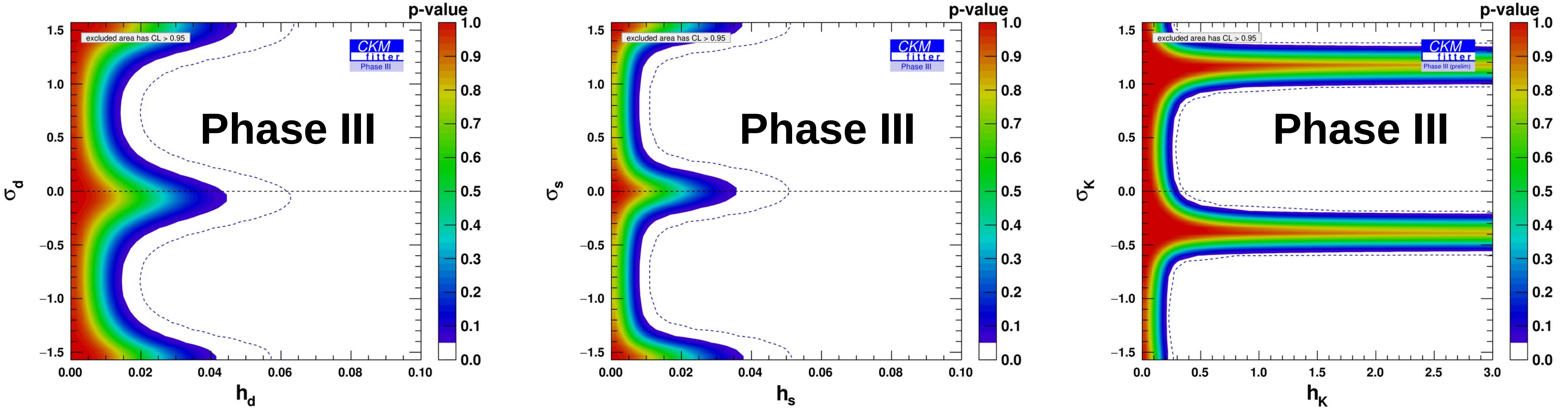
Table 1: Central values and uncertainties used in our analysis. Central values have been adjusted to eliminate tensions when moving to the smaller uncertainties typical of the future projections. The entries "id" refer to the value in the same row in the previous column. The assumptions entering Phase I, Phase II and Phase III estimates are described in the text.

[More details and references: see future proceedings to this talk;
Phases I & II: includes 2503.24346v1;
Lattice QCD projections: 1812.07638, 1808.10567; precision in decay constants and bag parameters substantially better than 1%; Phase II: w/ EM corrections]

UT & BSM: projections

- CP phases σ_X largely unconstrained
- Kaons: marginal change Phase I → III

  (ϵ_K: no constraint on h_K when σ_K from heavy NP is aligned to $V_{td}V_{ts}^*$)



[Charles, Descotes-G., Ligeti, Monteil, Papucci, Trabelsi ‘13, + LVS '20]

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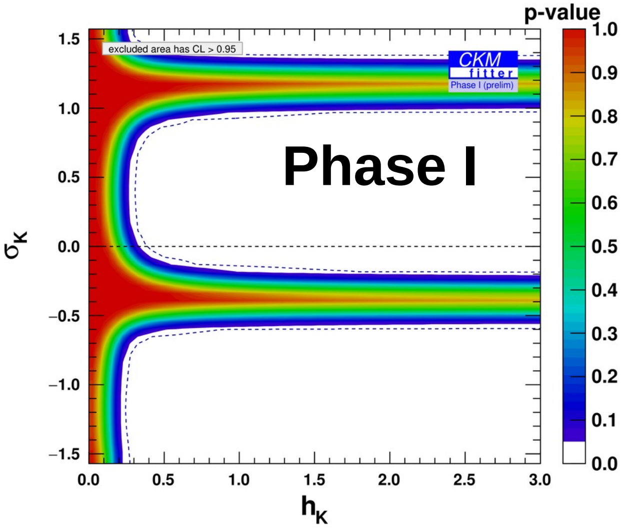
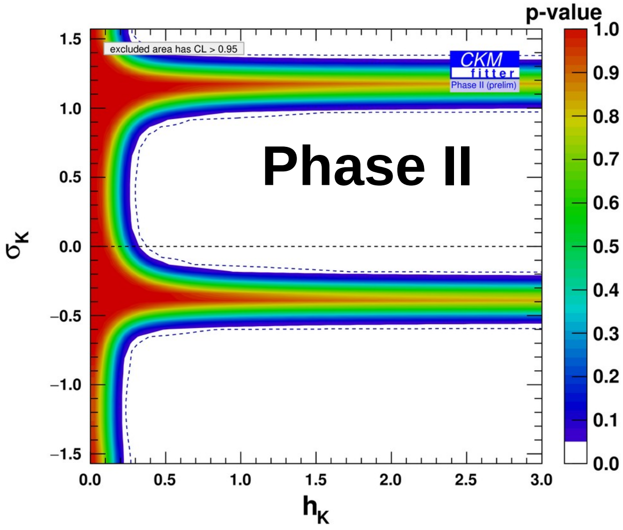
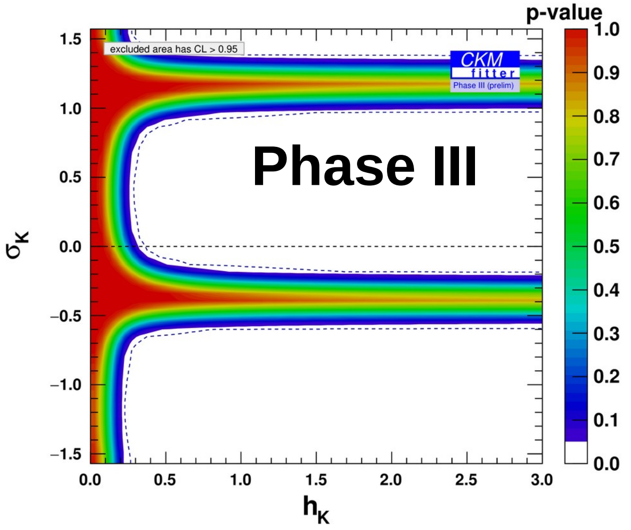
UT & BSM: projections

Presently working on current status, with current central values for the various observables







Barely perceptible progress reflects $\delta|V_{cb}|$ ~ constant across Phases I-III

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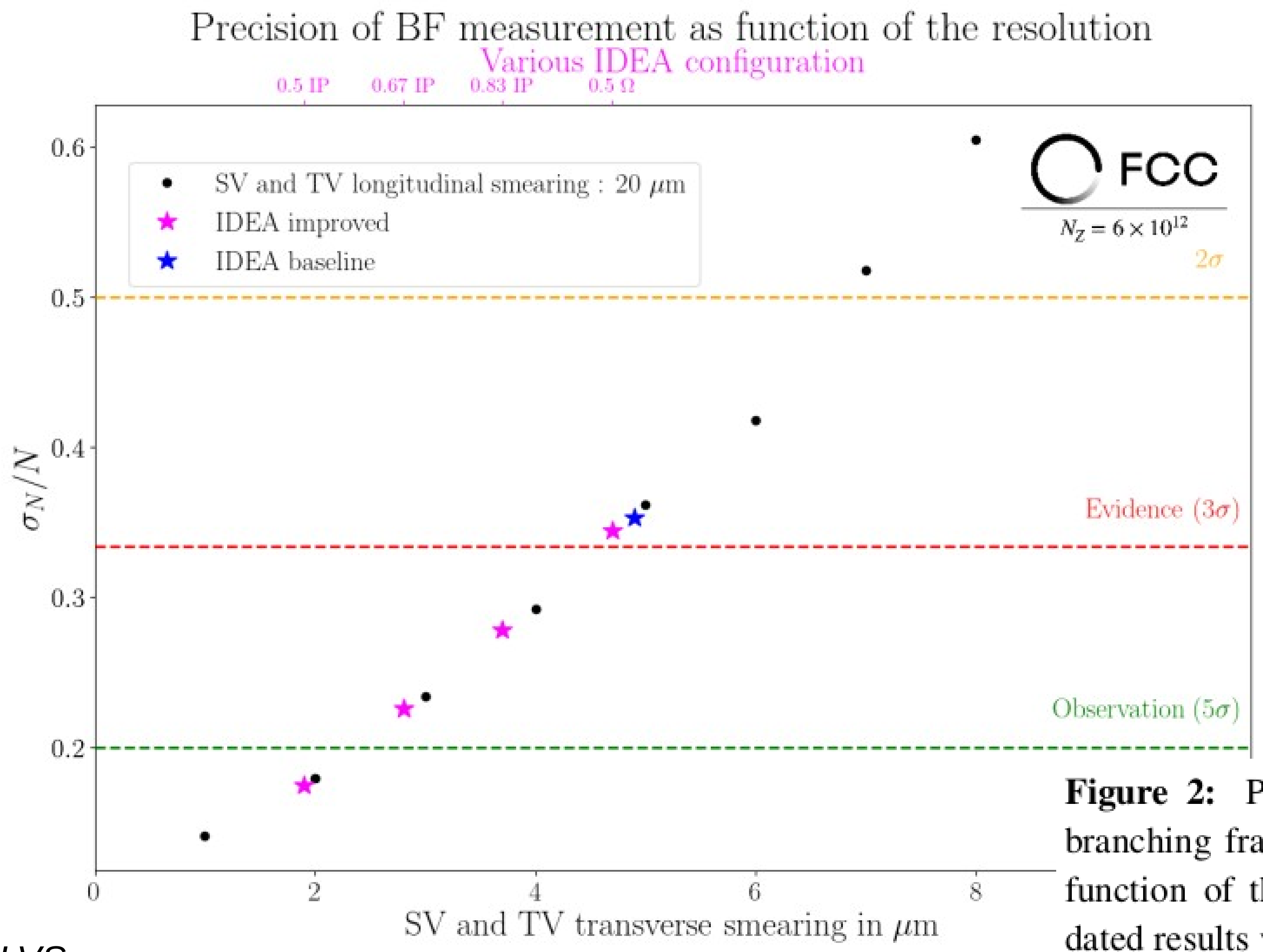

[Miralles @ Beauty 2023;
see also Miralles, Monteil '25]

Figure 2: Precision of the $B^0 \to K^{*0}\tau^+\tau^-$ branching fraction measurement at FCC-*ee* as function of the vertexing performances. Updated results w.r.t. Beauty talk.

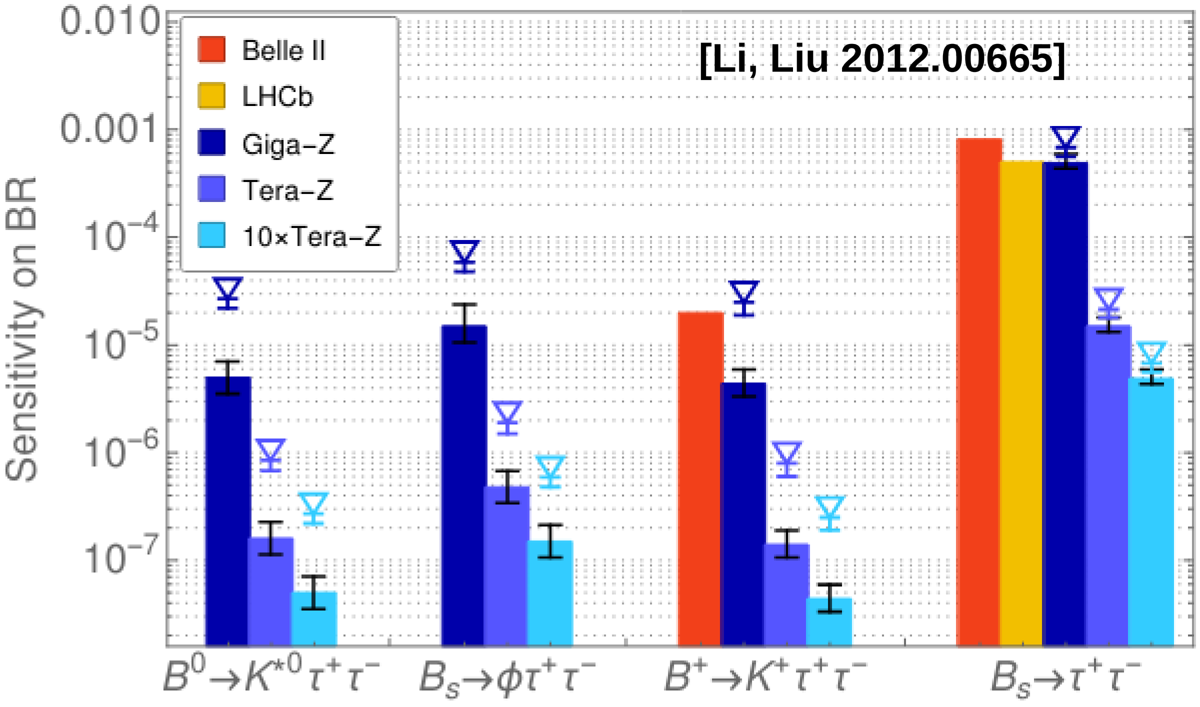

Figure 7: Expected precisions (@1σ C.L.) for the measurements of $B^0 \to K^{*0}\tau^+\tau^-$, $B_s \to \phi\tau^+\tau^-$, $B^+ \to K^+\tau^+\tau^-$ and $B_s \to \tau^+\tau^-$ at Belle II, LHCb and the future Z factories. The error bars represent the precisions obtained by varying the experimentally measured backgrounds by one sigma and the semi-quantitatively estimated ones by a factor of two, upward and downward respectively. The double bars below the inverted triangle denote the sensitivities with a finite spatial resolution, *i.e.*, 5μm and 10μm respectively, for the tracker.

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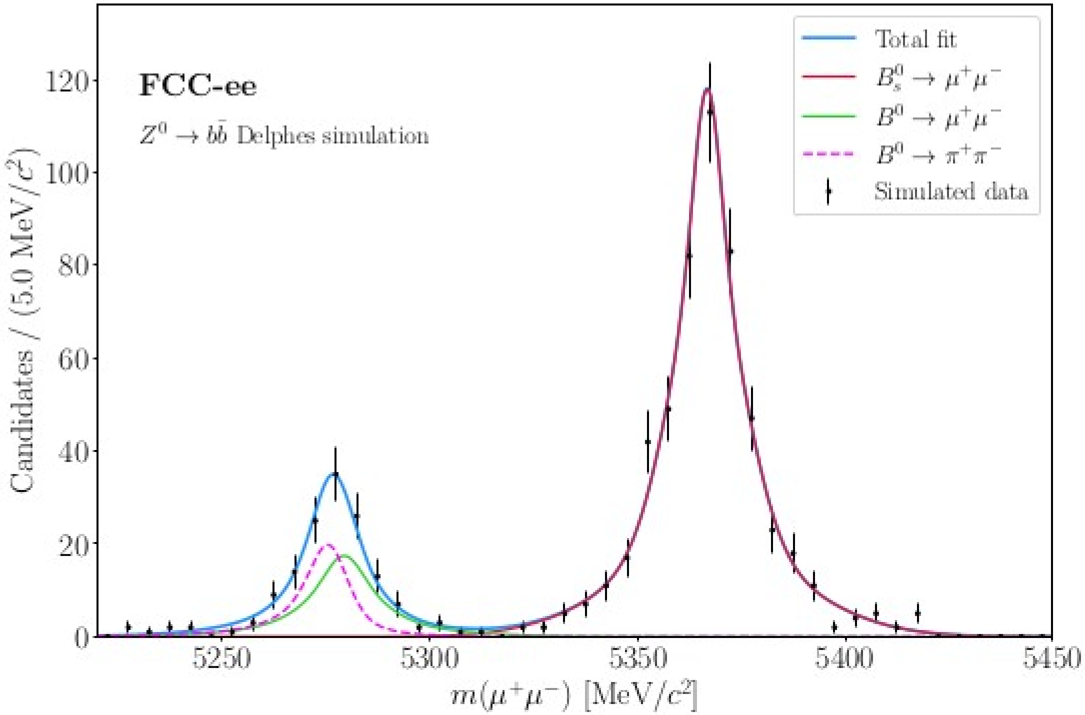

[Monteil, Wilkinson '21, + Hill (2106.01259), illustrating mass resolution]

Figure 3: Reconstructed invariant mass of $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ signals for 5×10^{12} Z^0 decays. Also shown is the background contribution from misidentified $B^0 \to \pi^+\pi^-$ events [25].

$$\sigma^{\rm HL}_{\rm LHCb+CMS} = \frac{1}{\sqrt{2}}\sigma^{\rm HL}_{\rm LHCb} \approx 0.06 \times 10^{-9} \qquad \sigma_{\rm FCC} = \frac{1}{\sqrt{\mathcal{N}_{\bar{B}_s \to \mu\mu}}}\mathcal{B}(\bar{B}_s \to \mu^+\mu^-) \approx 0.16 \times 10^{-9}$$

[2106.01259]

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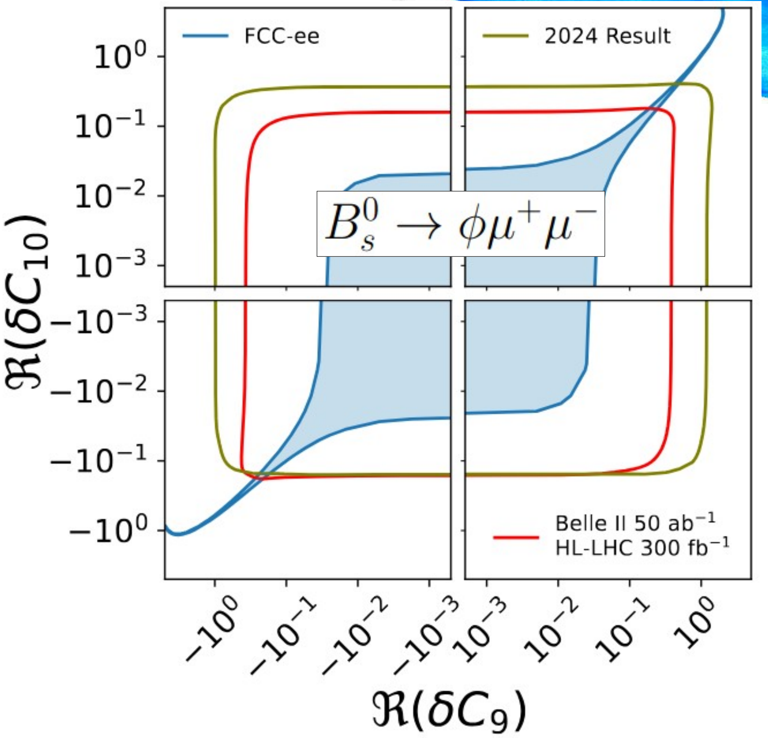
[2506.08089]



[2309.11353]

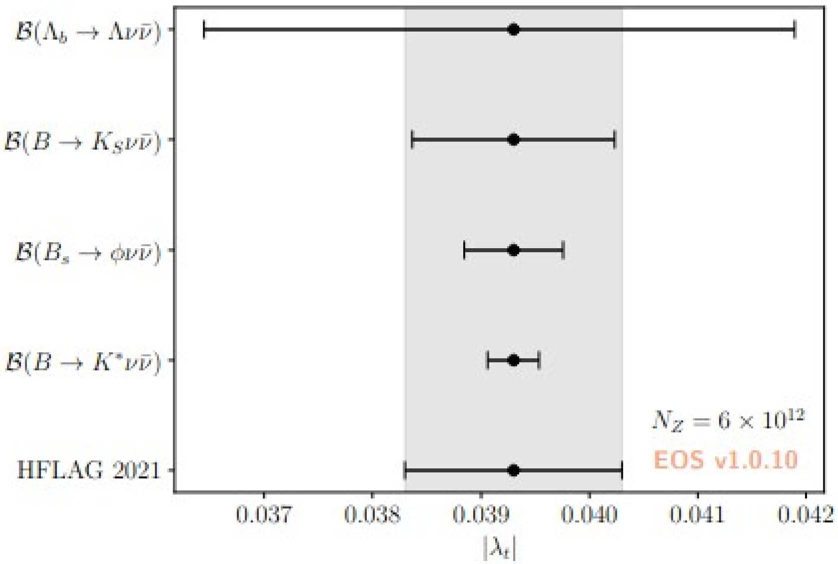
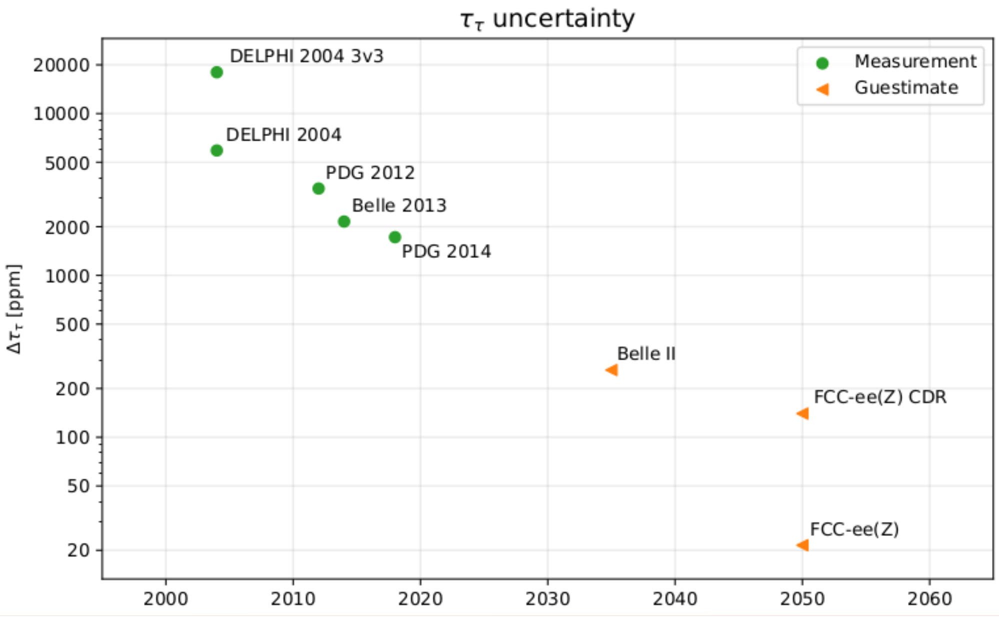
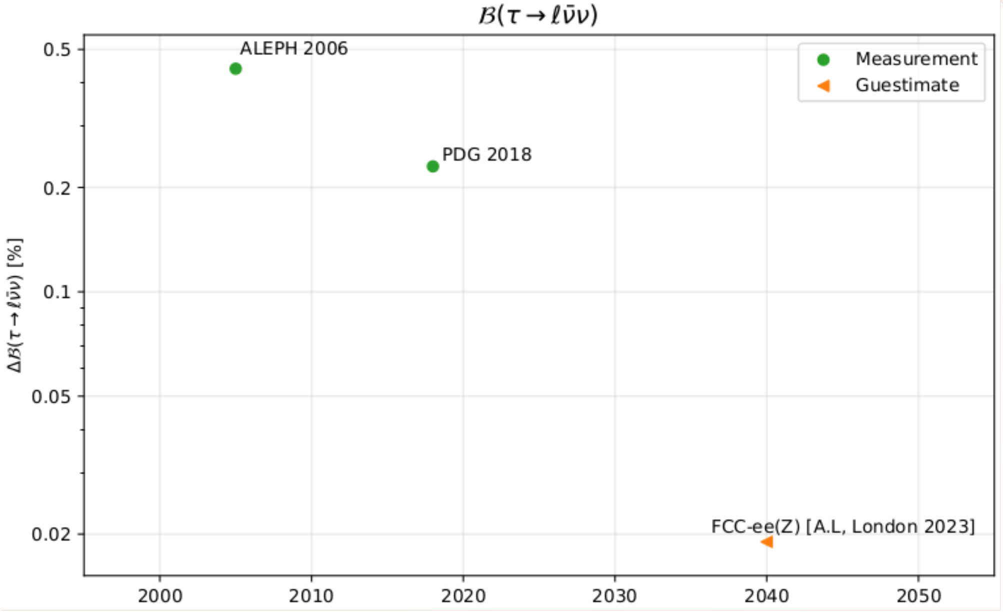


Figure 12: 68% probability ranges assuming the branching ratios to be SM-like. We used the experimental uncertainties of Sec. 4 and the **Future** form factors uncertainties described in Sec. 2. The results are compared with the value derived from $|V_{cb}| = (40.0 \pm 1.0) \times 10^{-3}$, extracted from $B \to D\ell\nu$ decays [26].

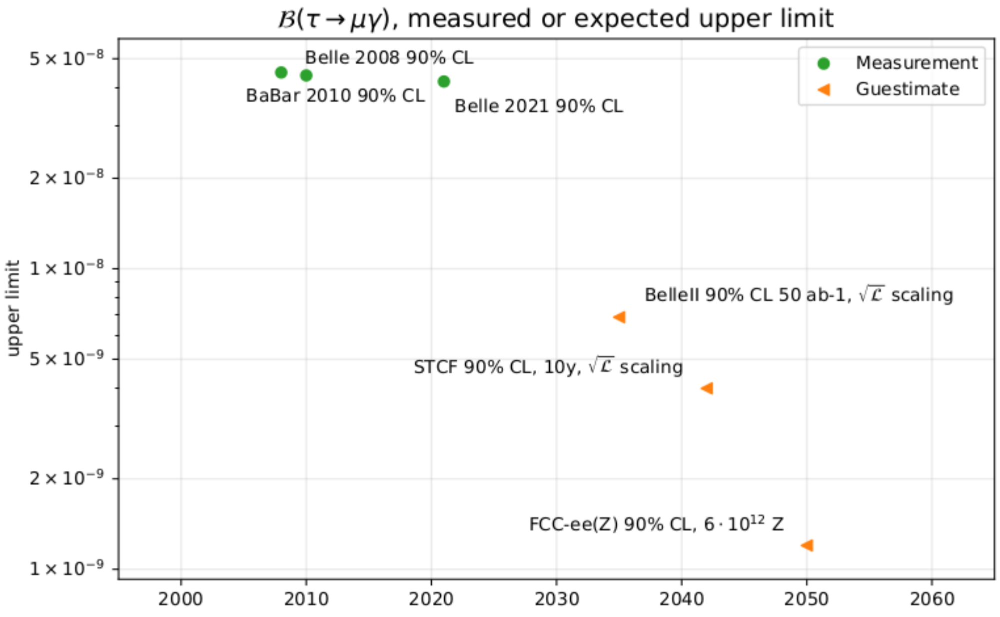
LVS

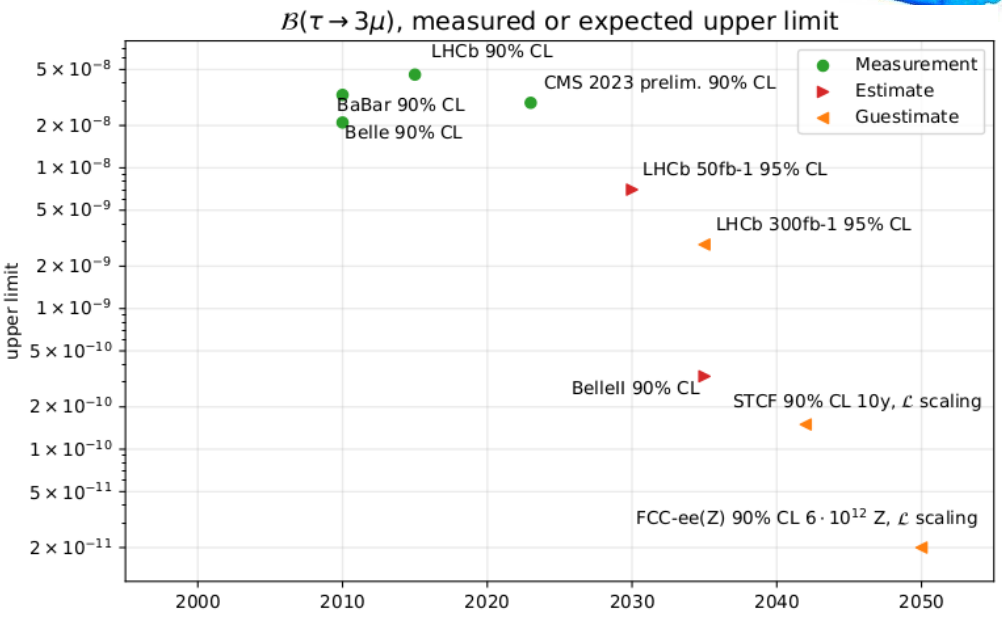




[Lusiani '24]

LVS


$\mathcal{B}(\tau \to \mu\gamma)$, measured or expected upper limit
Measurement
Guestimate
Belle 2008 90% CL
BaBar 2010 90% CL
Belle 2021 90% CL
BelleII 90% CL 50 ab-1, $\sqrt{\mathcal{L}}$ scaling
STCF 90% CL, 10y, $\sqrt{\mathcal{L}}$ scaling
FCC-ee(Z) 90% CL, $6 \cdot 10^{12}$ Z
upper limit
5×10^{-8}
2×10^{-8}
1×10^{-8}
5×10^{-9}
2×10^{-9}
1×10^{-9}
2000
2010
2020
2030
2040
2050
2060


$\mathcal{B}(\tau \to 3\mu)$, measured or expected upper limit
Measurement
Estimate
Guestimate
LHCb 90% CL
CMS 2023 prelim. 90% CL
BaBar 90% CL
Belle 90% CL
LHCb 50fb-1 95% CL
LHCb 300fb-1 95% CL
BelleII 90% CL
STCF 90% CL 10y, $\mathcal{L}$ scaling
FCC-ee(Z) 90% CL $6 \cdot 10^{12}$ Z, $\mathcal{L}$ scaling
upper limit
5×10^{-8}
2×10^{-8}
1×10^{-8}
5×10^{-9}
2×10^{-9}
1×10^{-9}
5×10^{-10}
2×10^{-10}
1×10^{-10}
5×10^{-11}
2×10^{-11}
2000
2010
2020
2030
2040
2050

[Lusiani ‘24]

Not discussed

- Any possible contribution to kaon physics, *à la* K_S to $\mu^+\mu^-$ at LHCb?
- Any possible contribution to BNV tests, e.g., $\tau \rightarrow$ proton decays?
- Heavy quark spectroscopy?
- Advantage of baryon decays: carry the polarization erased by the hadronization into mesons (2106.12168)
- Other flavor-like physics cases: EWPOs (e.g., 2411.02485, 2502.17281); quark FCNC Higgs and Z couplings (e.g., 2306.17520, 2507.01141); dedicated FCC-ee EPS-HEP talk to top
- Long-lived particles (e.g., HNLs): lifetime frontier, specific detector requirements (e.g., 2106.15459)