Flavor physics at future e+e- Z factories

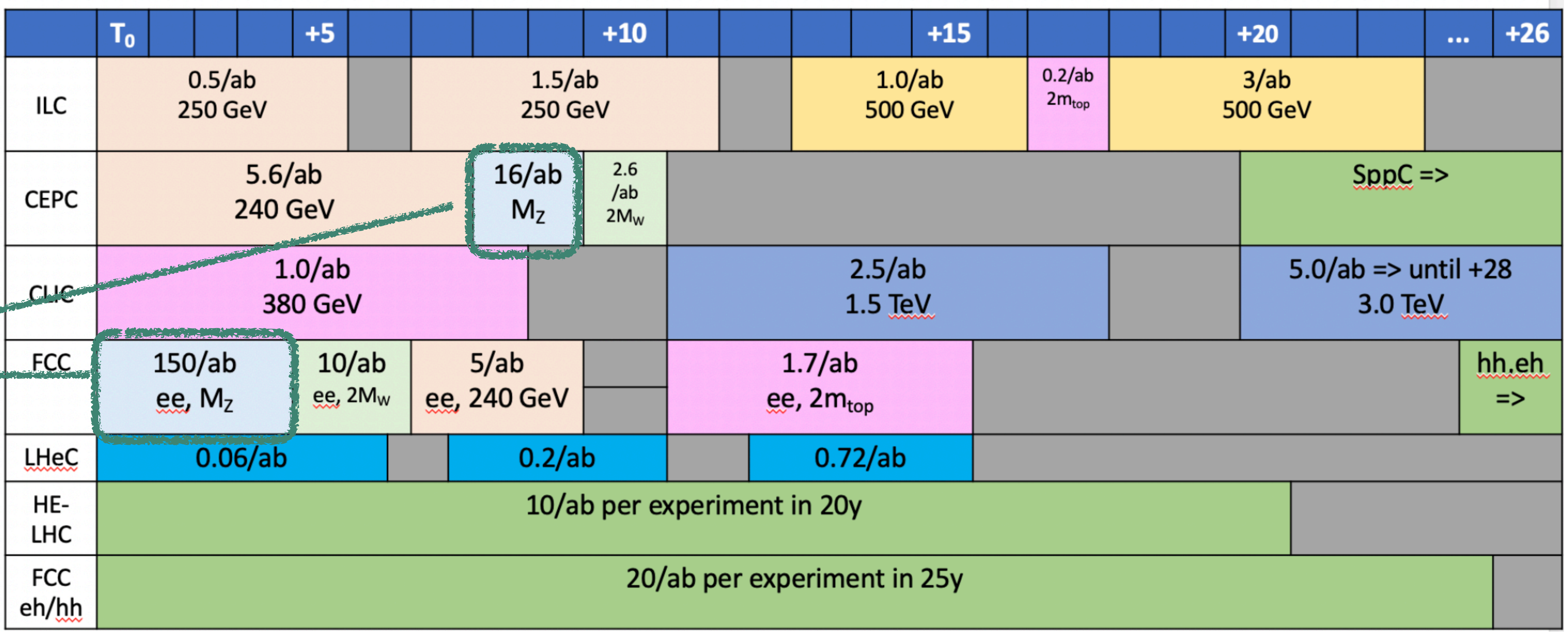
September 06, 2023
SYSU-PKU collider physics forum

左训午 (KIT)

Outline

- Z factory dataset
- b physics program
  - $b \to q\ell\nu$
  - $b \to s\ell\ell$
  - $b \to s\nu\nu$
  - B^0/B_s^0 mixing
- Non-b physics program
  - Charm physics
  - Tau physics
  - Other opportunities

Z factories



Trillions of Z bosons

— **factory!**

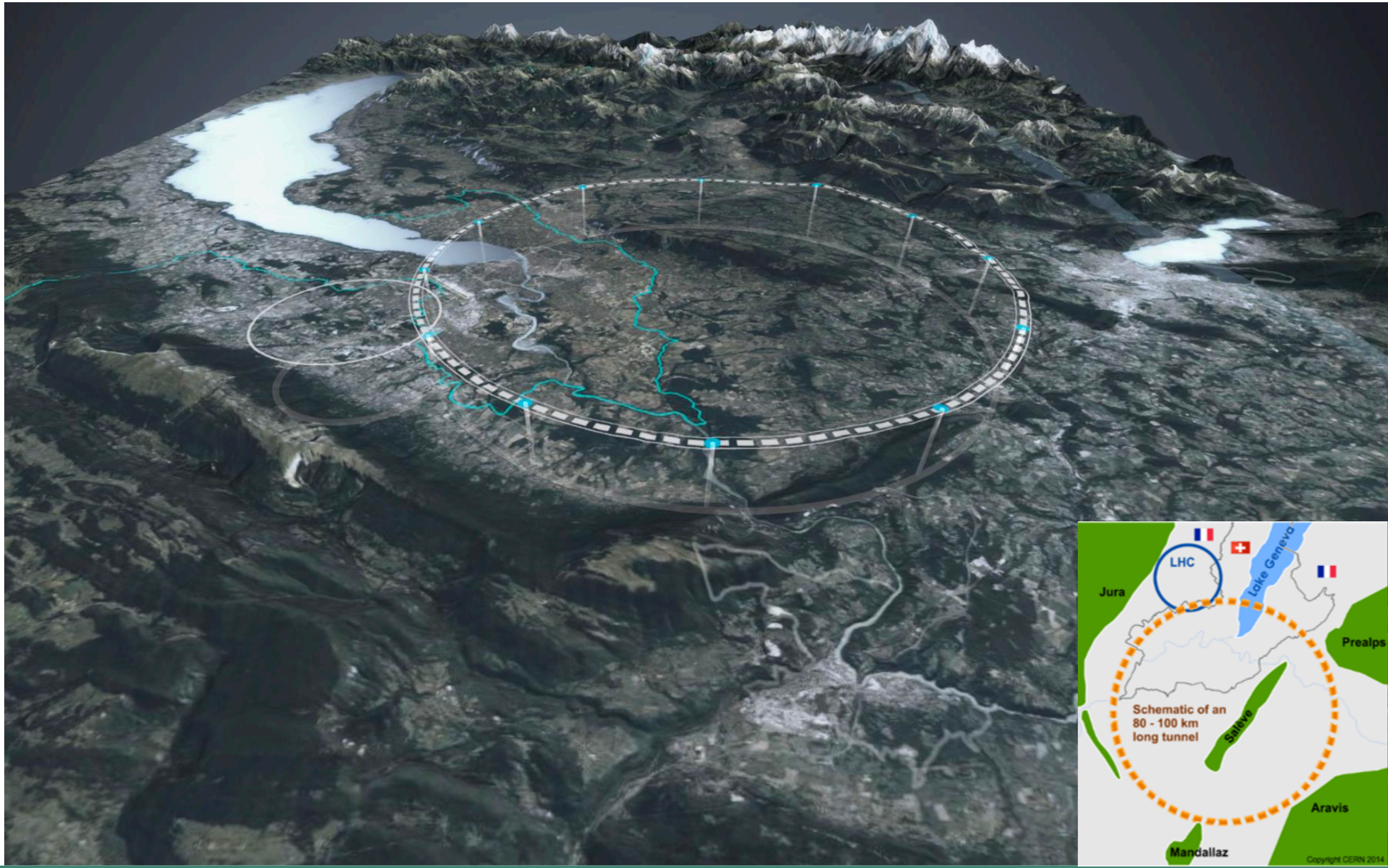
European Strategy 2020, 1910.11775

(Outdated, but enough for the purpose)

- Will use FCC-ee as the main example for the rest of this talk. All points are valid for CEPC

FCC-ee

- 91km ring near CERN
- Possibility for 4 experiment sites
- Operate at Z, WW, ZH, tt energies
- ~15 years of operation starting ~2045



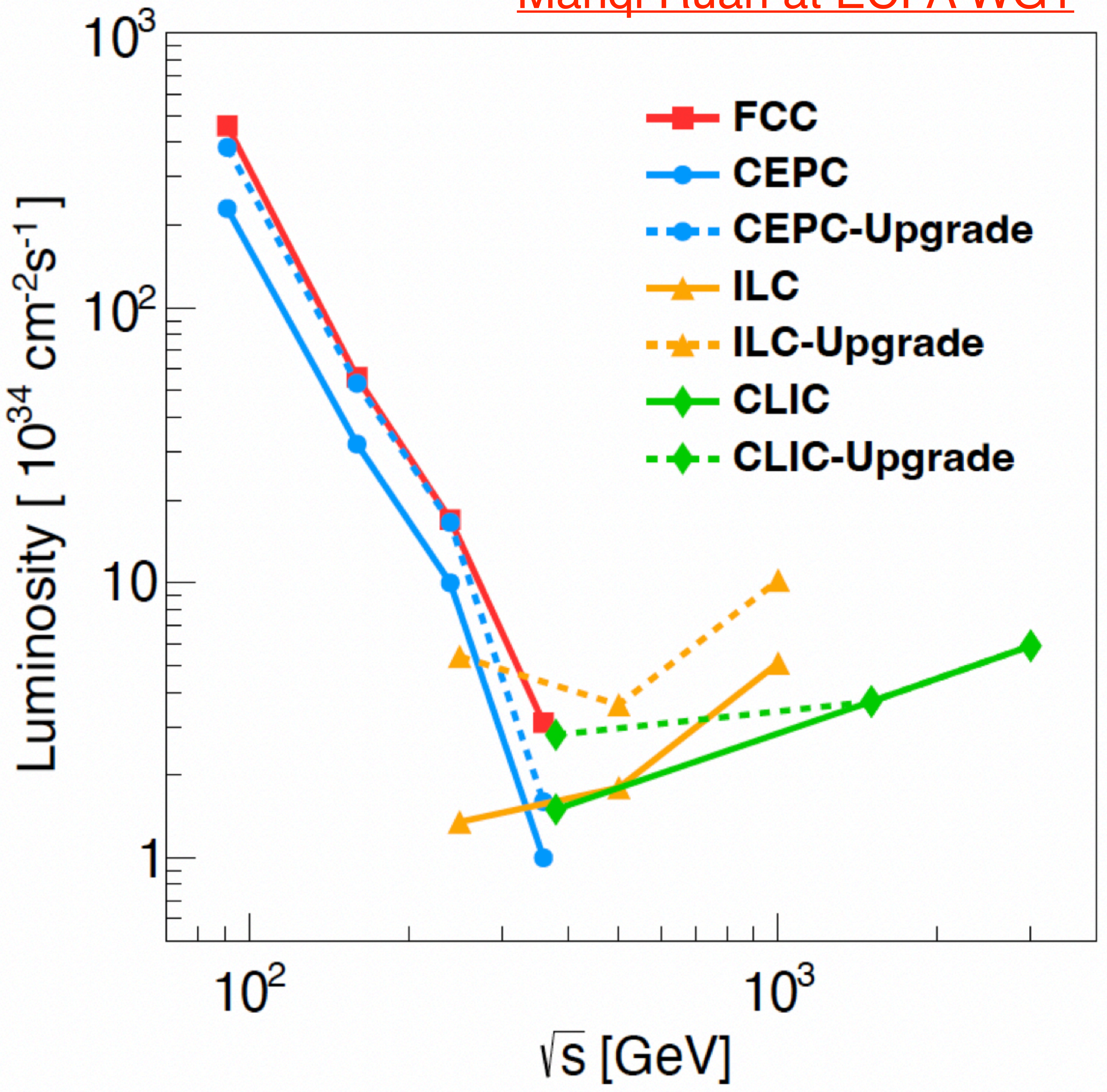
FCC-ee dataset

Much more than just "H-factory"

- Splendid datasets expected with a plethora of physics opportunities
  - EW precision measurement (Z, W, H, t)
  - QCD precision measurement (α_s)
  - Flavor physics (b, c, τ)
  - BSM particles (ALPs, dark photons, LLPs)

Dataset	Operation	Int. lumi. (ab^{-1})	Events
Z	4 years	180	6×10^{12}
WW	2 years	12	2.4×10^{8}
ZH	3 years	7	1.5×10^{6}
tt	5 years	2.5	2×10^{6}

Manqi Ruan at ECFA WG1



4 IPs assumed for FCC luminosity estimates, and the rest of the slides

FCC-ee as flavor factory

Best option for next-generation flavor machine

- FCC-ee expects to operate at Z-pole for 4 years, producing a total of 6×10^{12} Z bosons
- About 14x as many B^0/B^+ as at Belle II (50 ab^{-1})
- About 9x as many τ as Super tau-charm factory
- All species of b-hadrons are produced
- Decay products significantly boosted

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

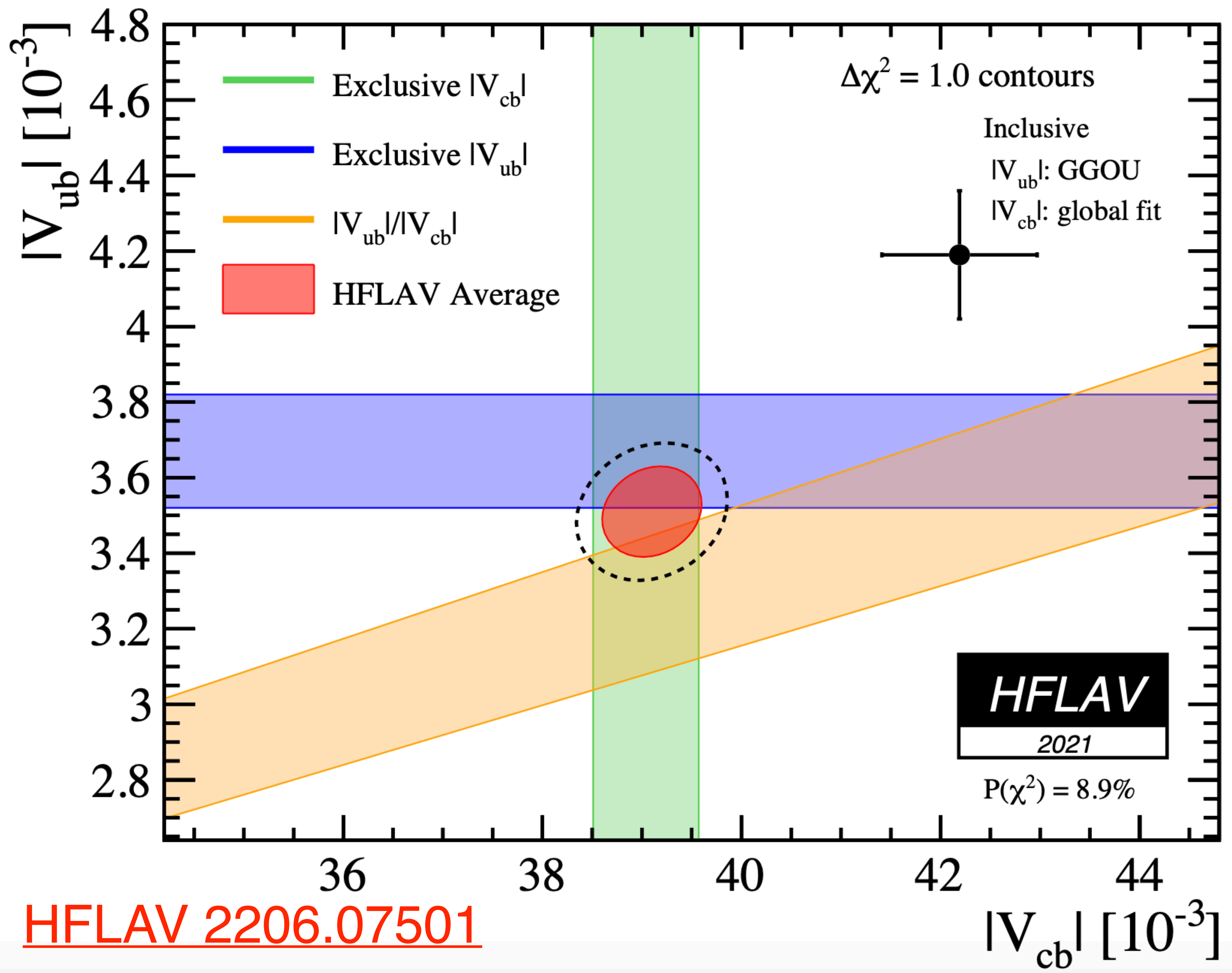
particle count $(\times 10^9)$	$B^0\ (\bar{B}^0)$	$B^\pm$	$B_s\ (\bar{B}_s)$	$B_c^\pm$	$\Lambda_b\ (\bar{\Lambda}_b)$	$c\ (\bar{c})$	$\tau^\pm$
Belle II	55	55	0.6	N.A.	N.A.	130	90
FCC-ee	770	770	170	7	150	1400	400

b physics

- $b \to q\ell\nu$
- $b \to s\ell\ell$
- $b \to s\nu\nu$
- B^0/B_s^0 mixing

$b \to q\ell\nu$ transition

- Precise determination of CKM $|V_{ub}|$ and $|V_{cb}|$
  - Long-standing discrepancy between inclusive and exclusive extractions
  - Extreme precision at FCC-ee with exclusive decays
  - Independent clean probe via $B^+ \to \tau^+\nu_\tau$ (Zuo et al. 2305.02998)



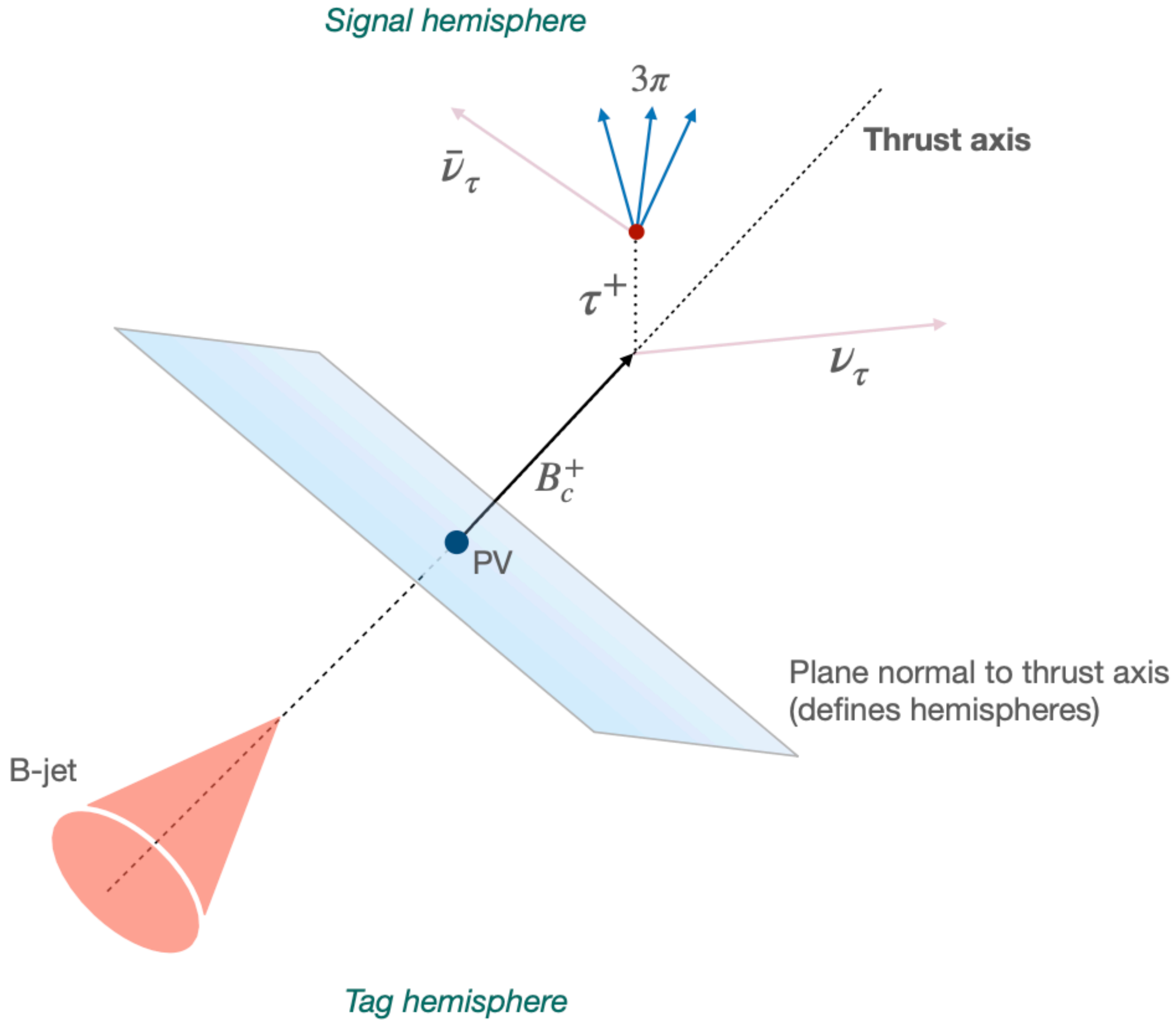
HFLAV 2206.07501

- Test of LFU with $H_b \to H_c\ell\nu$
  - $R(D)$ and $R(D^*)$ together present 3.3σ tension with SM
  - Opportunities for new $R(H_c)$ (Ho et al. 2212.02433)
  - Possibility of differential test of LFU (Ligeti et al. 2112.07685)
  - Independent probe of $b \to c\ell\nu$ through $B_c^+ \to \ell^+\nu_\ell$ (Zheng et al. 2007.08234, Zuo et al. 2305.02998)

HFLAV Summer 2023	$R(D)$	$R(D^*)$
Meas. Ave.	0.357 ± 0.029	0.284 ± 0.012
Pred. Ave.	0.298 ± 0.004	0.254 ± 0.005

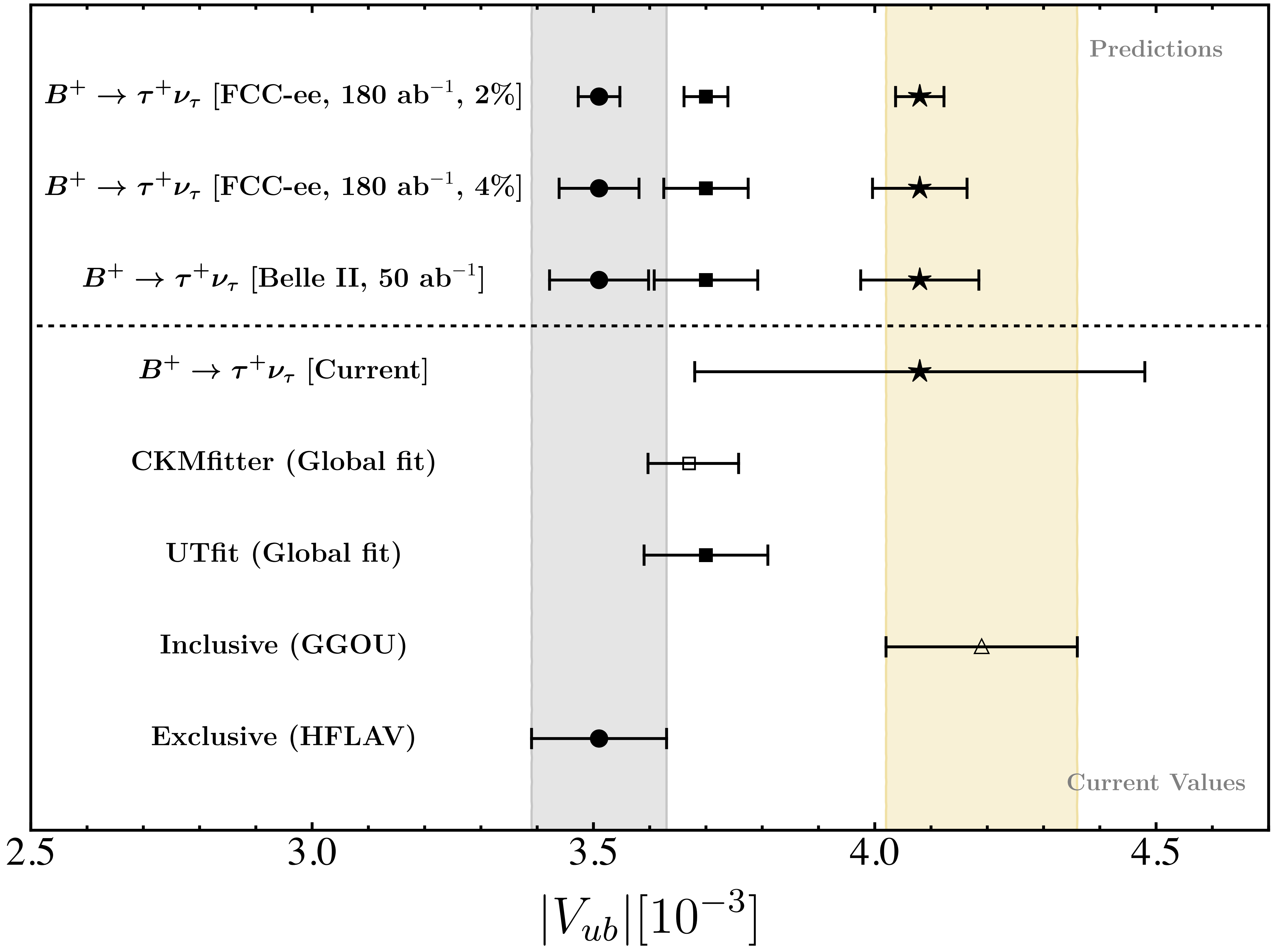
Case study - $B^+/B_c^+ \to \tau^+\nu_\tau$

- Tag 3-prong hadronic decay of τ
- MVA analysis to separate B^+, B_c^+ and backgrounds



- Measure $\mathscr{B}(B^+ \to \tau^+\nu_\tau)$ and extract $|V_{ub}|$

$$\mathscr{B}(B_q^+ \to \tau^+\nu_\tau)^{\mathrm{SM}} = \tau_{B_q^+}\frac{G_F^2\,|V_{qb}|^2 f_{B_q^+}^2\, m_{B_q^+}\, m_\tau^2}{8\pi}\left(1-\frac{m_\tau^2}{m_{B_q^+}^2}\right)^2 \quad , \quad q = u, c$$

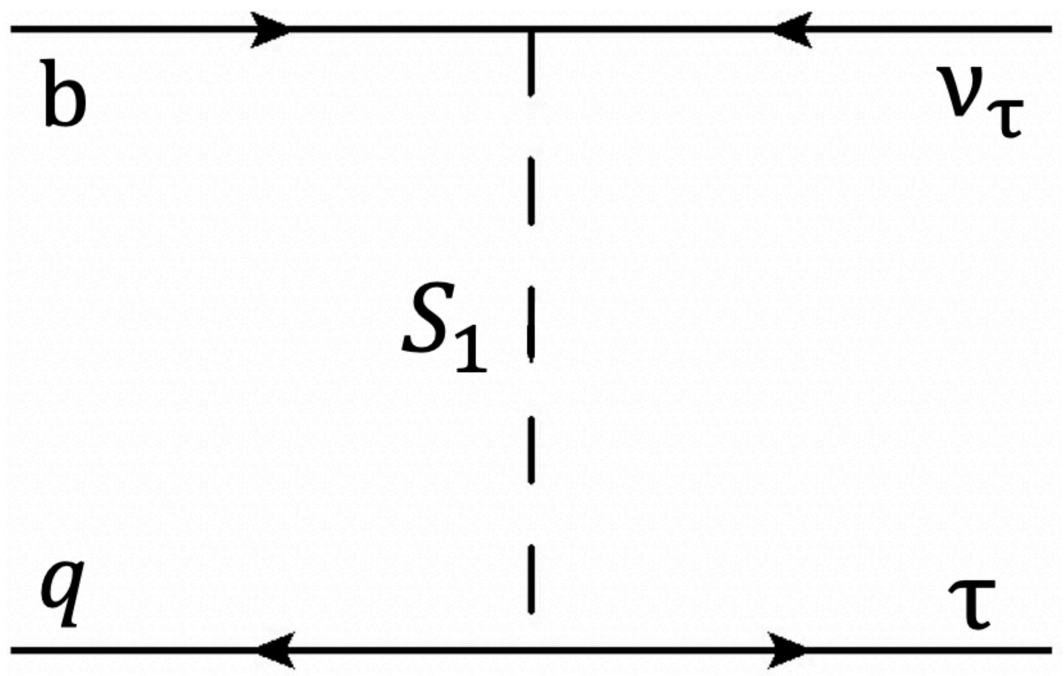


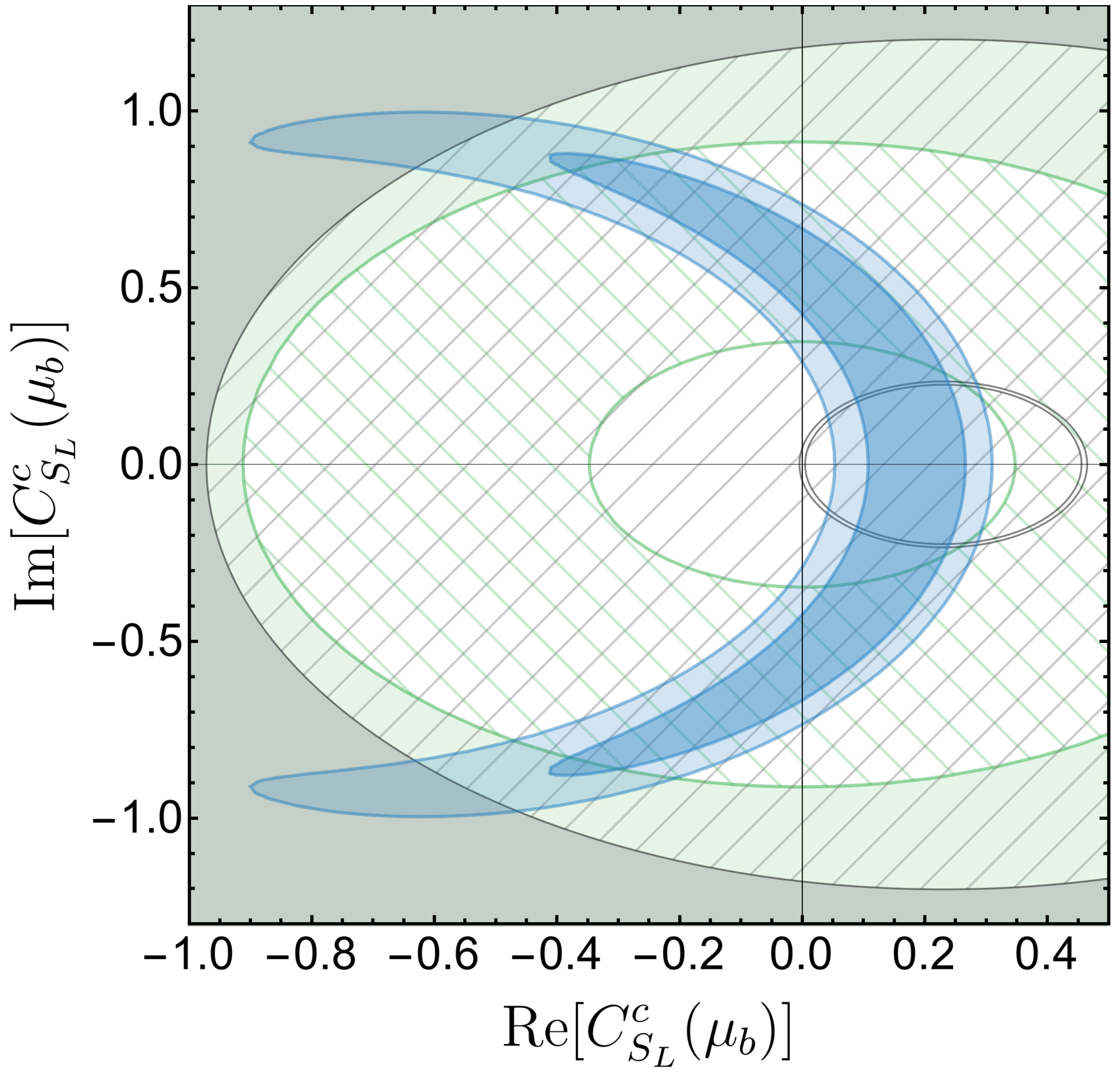
Case study - $B^+/B_c^+ \to \tau^+\nu_\tau$

- Consider a generic EFT Hamiltonian that affects the $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ and $\mathcal{B}(B_c^+ \to \tau^+\nu_\tau)$

$$\mathcal{H}_{\rm eff} = 2\sqrt{2}G_F \sum_{q=u,c} V_{qb}\Big[\left(1 + C_{V_L}^q\right) \left(\bar{q}_L\gamma_\mu b_L\right)\left(\bar{\tau}_L\gamma^\mu\nu_L\right) + C_{V_R}^q \left(\bar{q}_R\gamma_\mu b_R\right)\left(\bar{\tau}_L\gamma^\mu\nu_L\right)$$
$$+ C_{S_L}^q \left(\bar{q}_R b_L\right)\left(\bar{\tau}_R\nu_L\right) + C_{S_R}^q \left(\bar{q}_L b_R\right)\left(\bar{\tau}_R\nu_L\right) + C_T^q \left(\bar{q}_R\sigma_{\mu\nu}b_L\right)\left(\bar{\tau}_R\sigma^{\mu\nu}\nu_L\right)\Big] + \text{h.c.}\,,$$

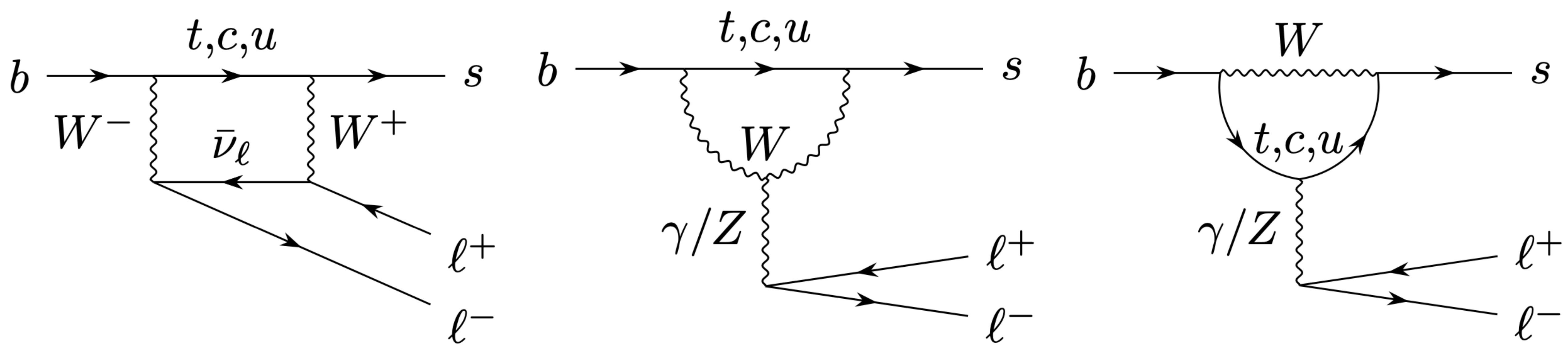
- As an example, showing the interpretation of $B_c^+ \to \tau^+\nu_\tau$ in the scalar leptoquark model



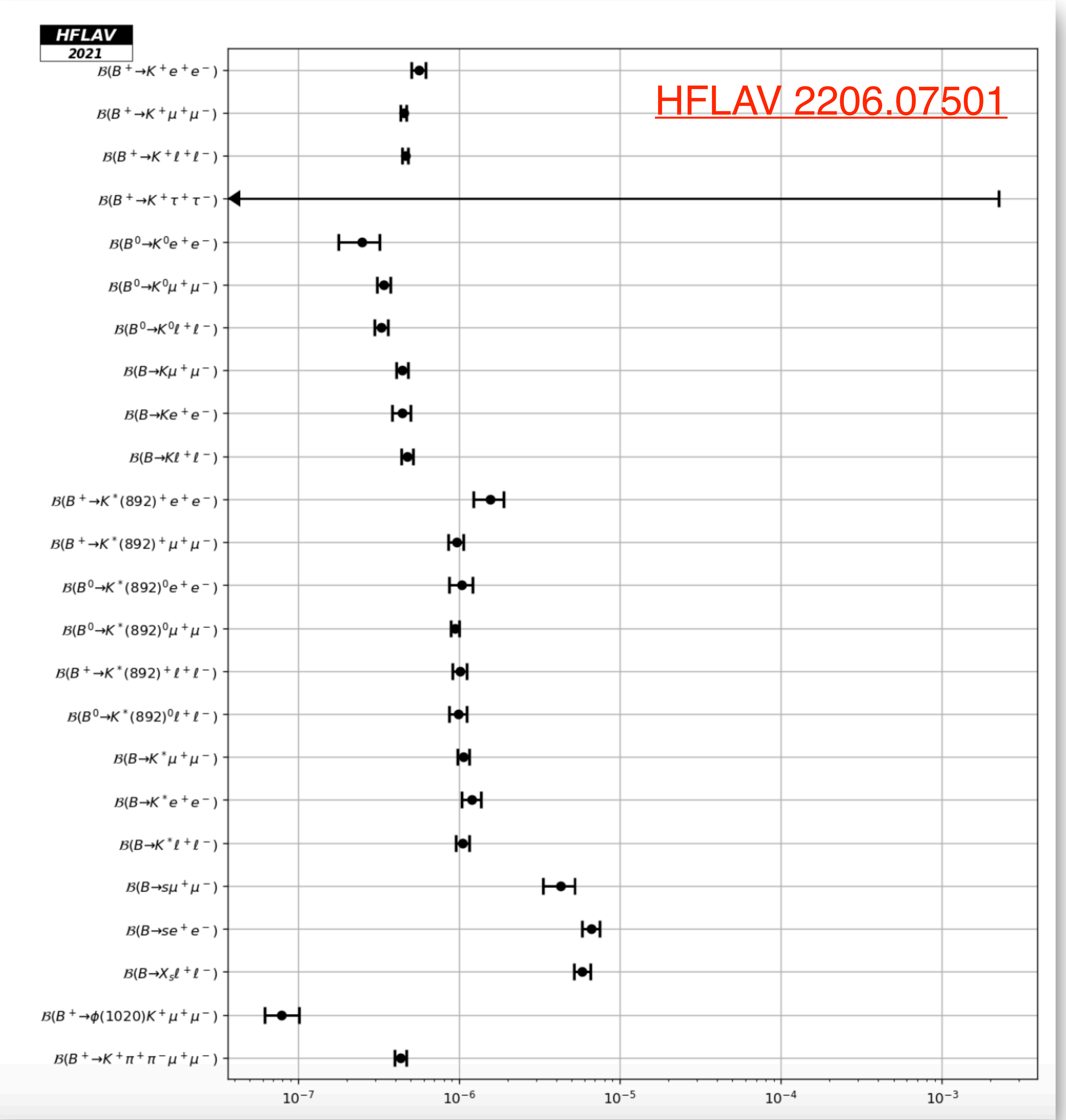


- Grey shade is the exclusion by current results
- Green hash is the exclusion expected for HL-LHC
- Grey hash is the exclusion by FCC-ee (the thin annulus survives)
- Blue shades are 1σ,2σ,3σ bands from current $b \to c$ anomalies

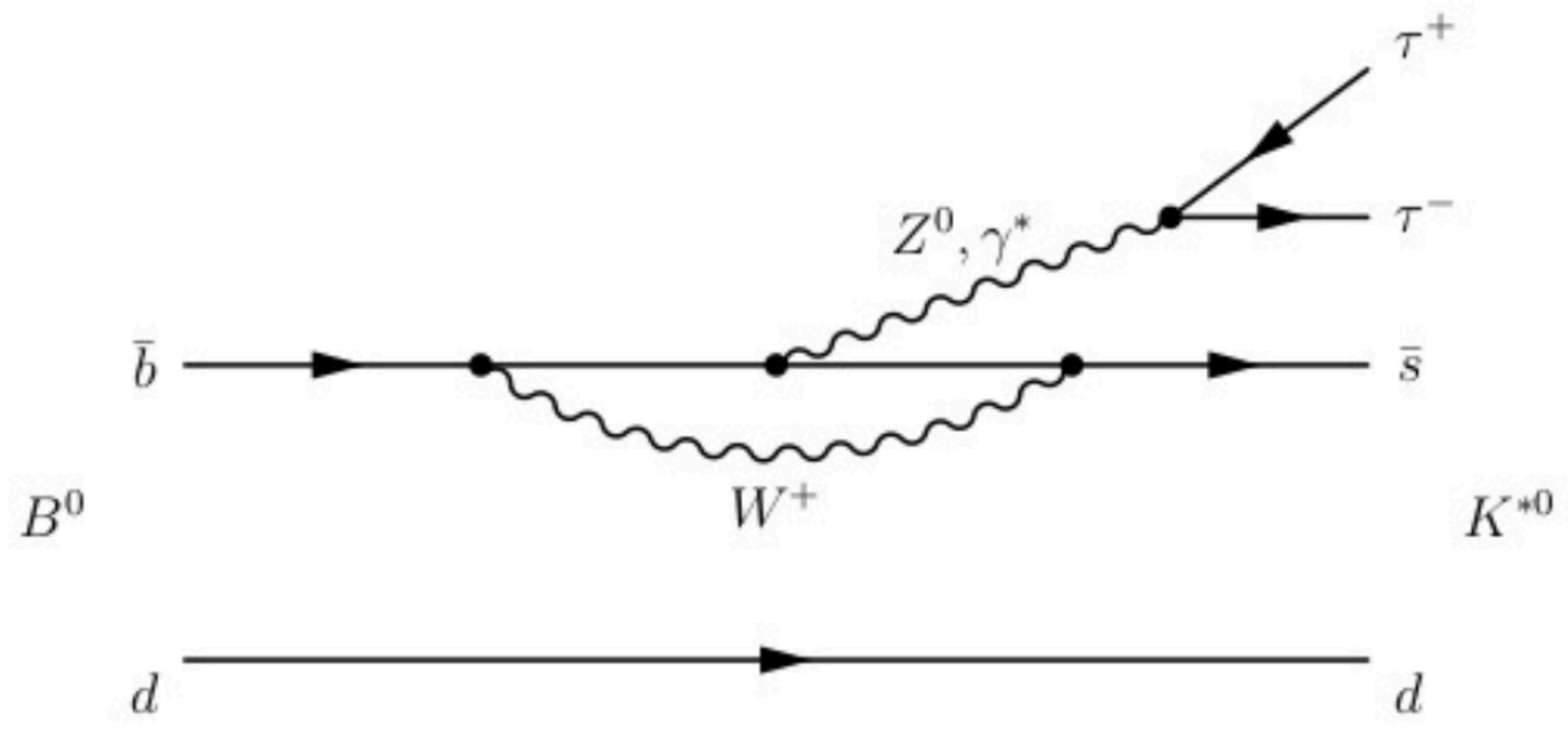
$b \to s\ell\ell$ transition

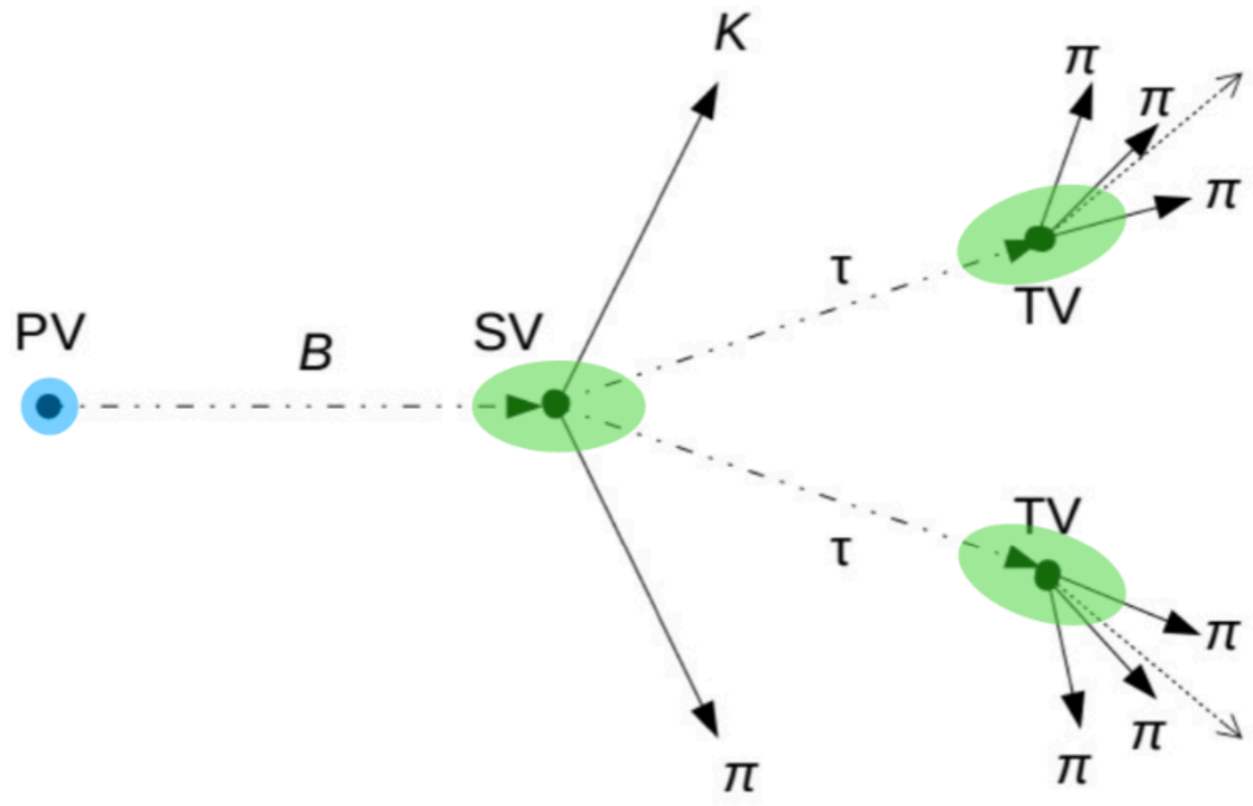


- Mediated by different diagrams in SM, with their relative importance varying with $q^2 = M_{ll}^2$
- Highly sensitive to BSM modification (also with large uncertainties due to non-perturbative QCD)
- R_K and R_{K*} to be tested at higher precision
- $b \to s\ell\ell$ not yet established for τ
  - Expected $BR_{\mathrm{SM}}(B \to K\tau\tau) \sim$ O(10^{-7})

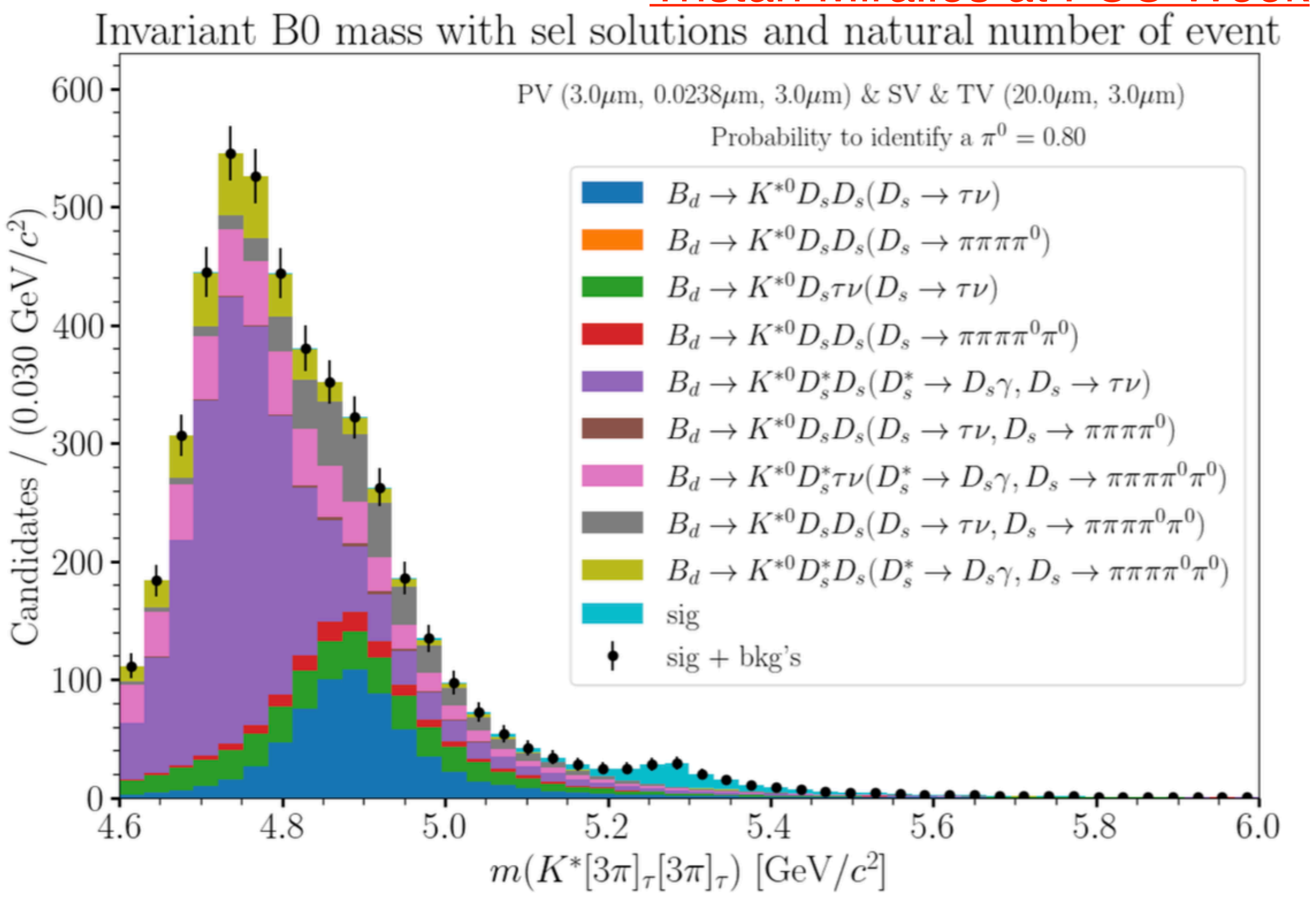


Case study - $B^0 \to K^{*0}\tau^+\tau^-$





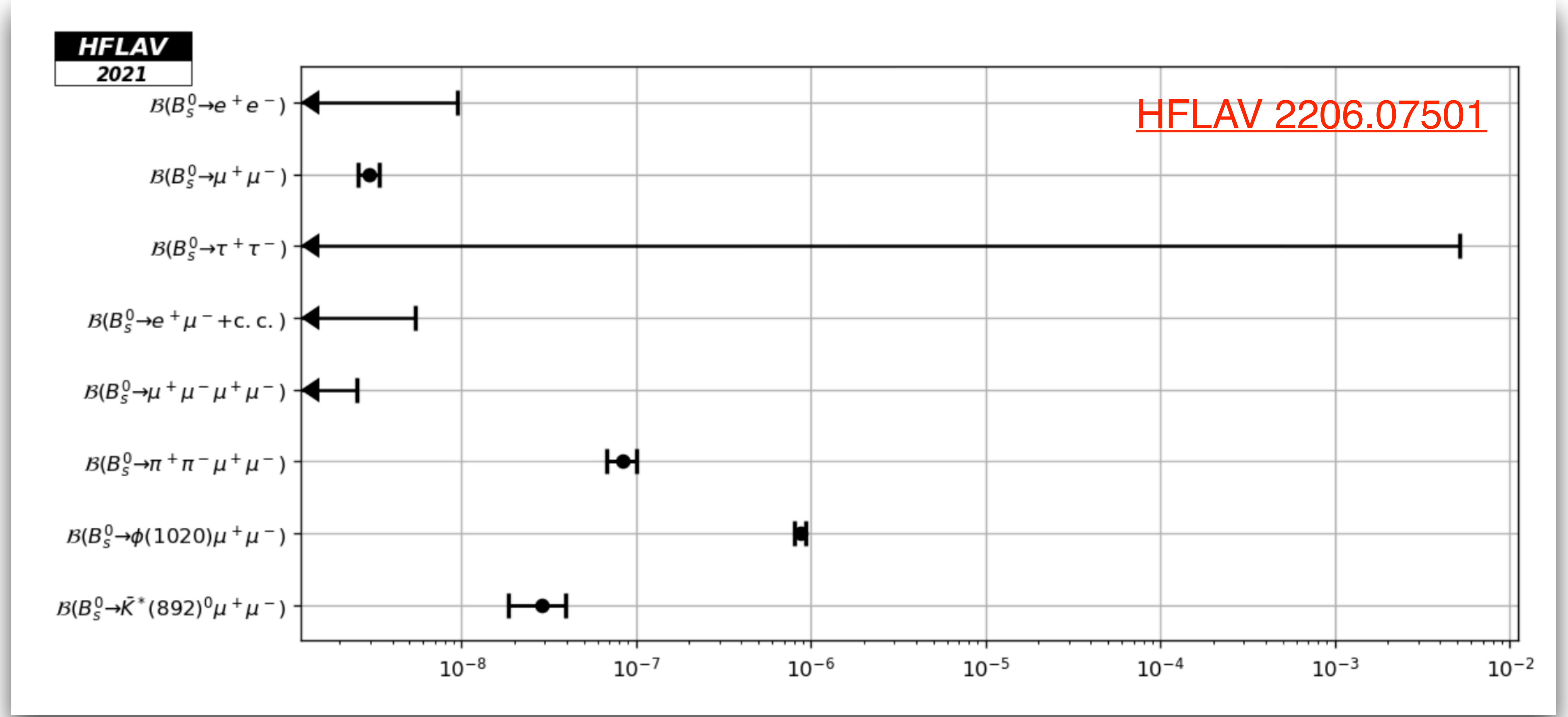
[Tristan Miralles at FCC Week]



- Event kinematics fully reconstructable
- Background with the same final state can be separated by kinematic properties
  - More ongoing studies on comprehensive backgrounds toward a full analysis
- The goal is to understand the performance/ requirements for vertex detectors (backup for π^0 ID)

$b \to s\ell\ell$ transition

- Purely leptonic $B_s \to \ell^+\ell^-$ are clean probes for theory interpretations.
- SM expectation for $\mathscr{B}(B_s \to \tau^+\tau^-) \approx 200 \times \mathscr{B}(B_s \to \mu^+\mu^-)$
  - Difficult at LHCb and Belle II, well-identifiable at FCC-ee.
  - New probe of CP structure through τ polarization.

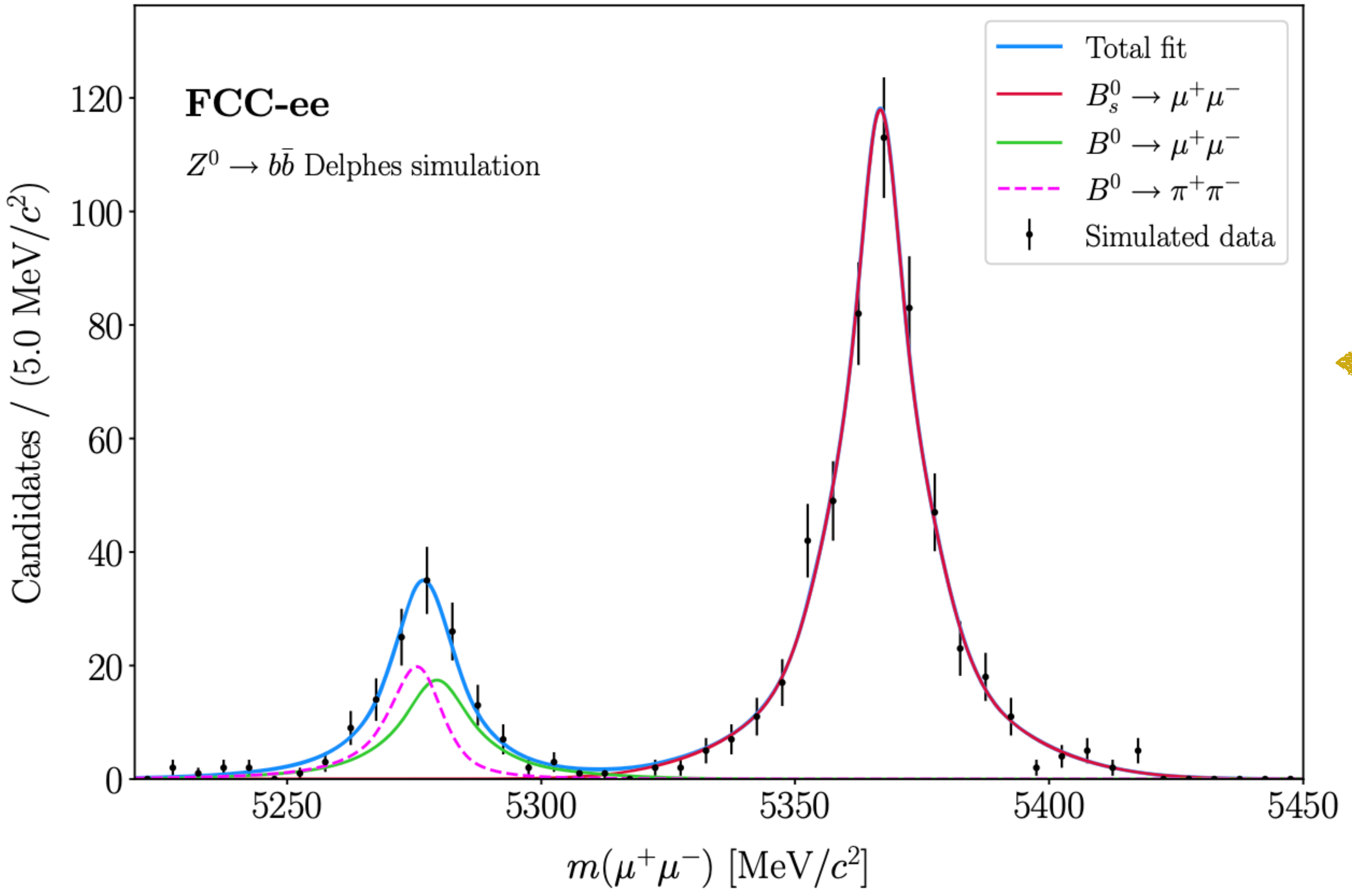


- Additional tests of CLFV decays of $B_s \to \tau\mu$ and $B_s \to \tau e$ at extreme precisions
  - Still room for large NP effects

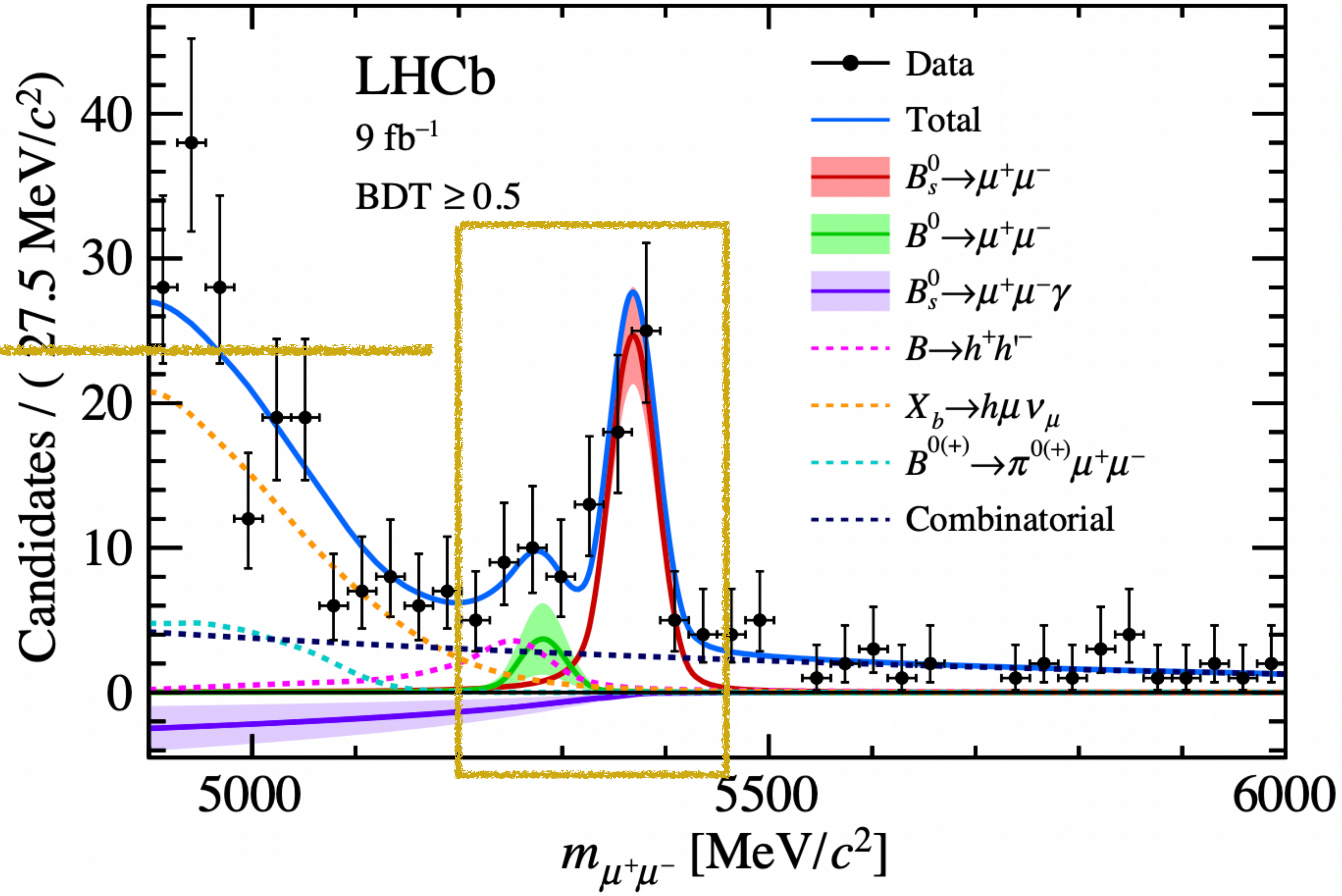
Case study - $B^0/B_s^0 \to \mu^+\mu^-$

- Measurements of ultra-rare $B \to \mu^+\mu^-$, some unique at FCC-ee
- High invariant-mass resolution expected from excellent tracking performance
- Controlling the misidentification of π^+ as μ^+ is a important consideration in detector design

Eur. Phys. J. Plus (2021) 136:837

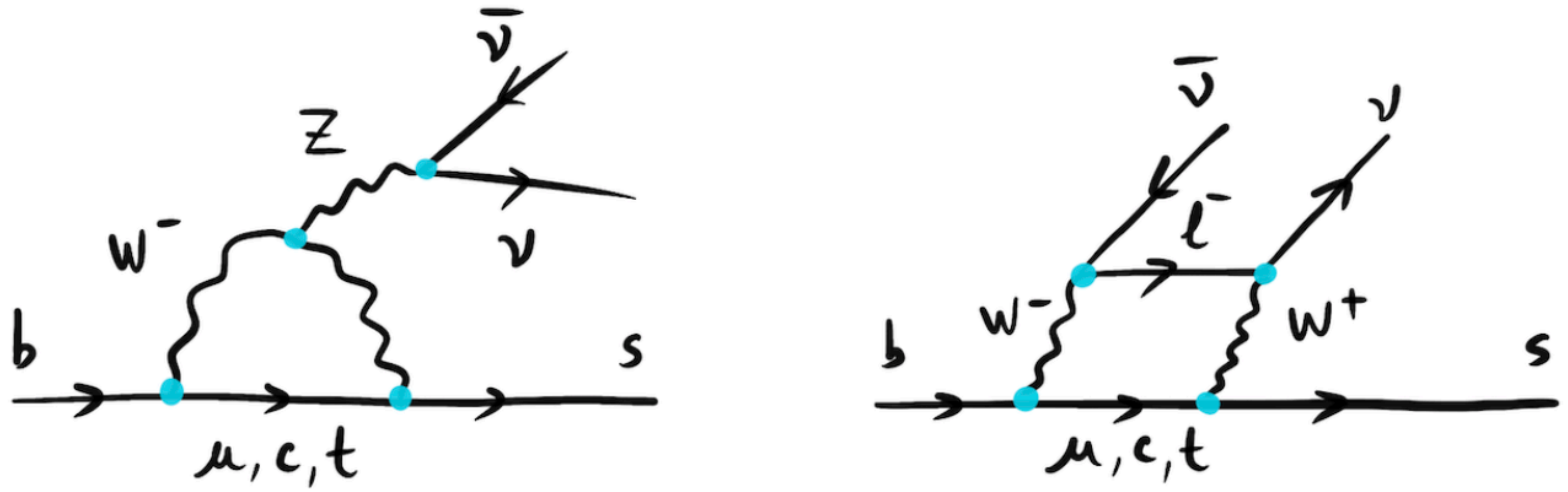


Phys. Rev. Lett. 128, 041801



$b \to s\nu\nu$ transition

- Probe of NP complementary to $b \to c\ell\nu$ and $b \to s\ell\ell$



- SM $\mathscr{B}(b \to s\nu\nu) \approx 10^{-5}$
  - First evidence of $B^+ \to K^+\nu\nu$ (Eldar Ganiev at EPS2023)
  - Belle II expect 10% precision on $B \to K^{(*)}\nu\nu$ (projection to be updated)
  - Unique opportunities for $B_s \to \phi\nu\nu,\ \Lambda_b \to \Lambda\nu\nu$, and $B_c \to D_s\nu\nu$ at FCC-ee

- Low energy Hamiltonian written as

in which SM corresponds to $C_L = -6.35,\ C_R = 0$

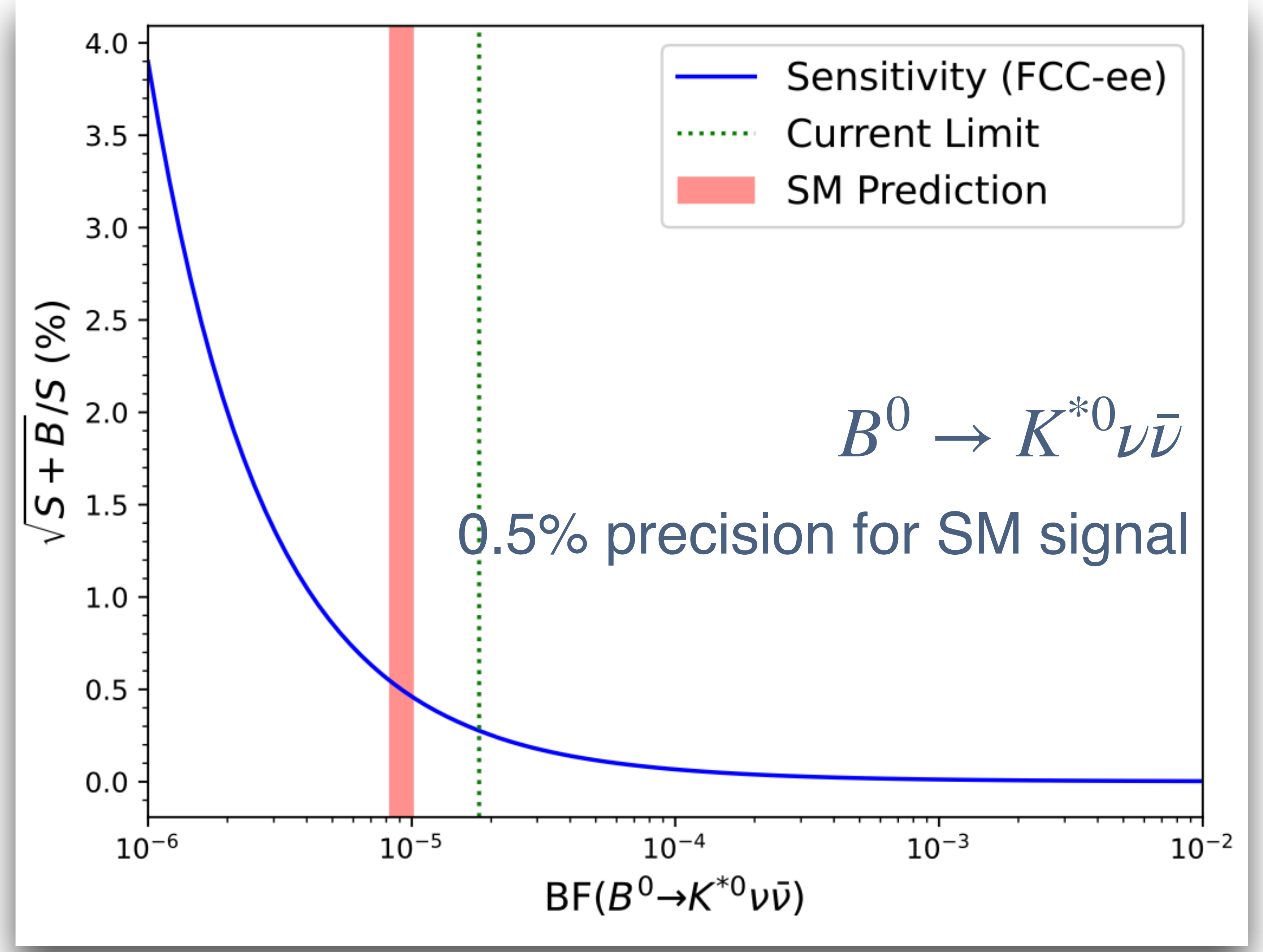
$$H_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{tb}V_{ts}^*(C_L O_L + C_R O_R) + \text{h.c.}$$

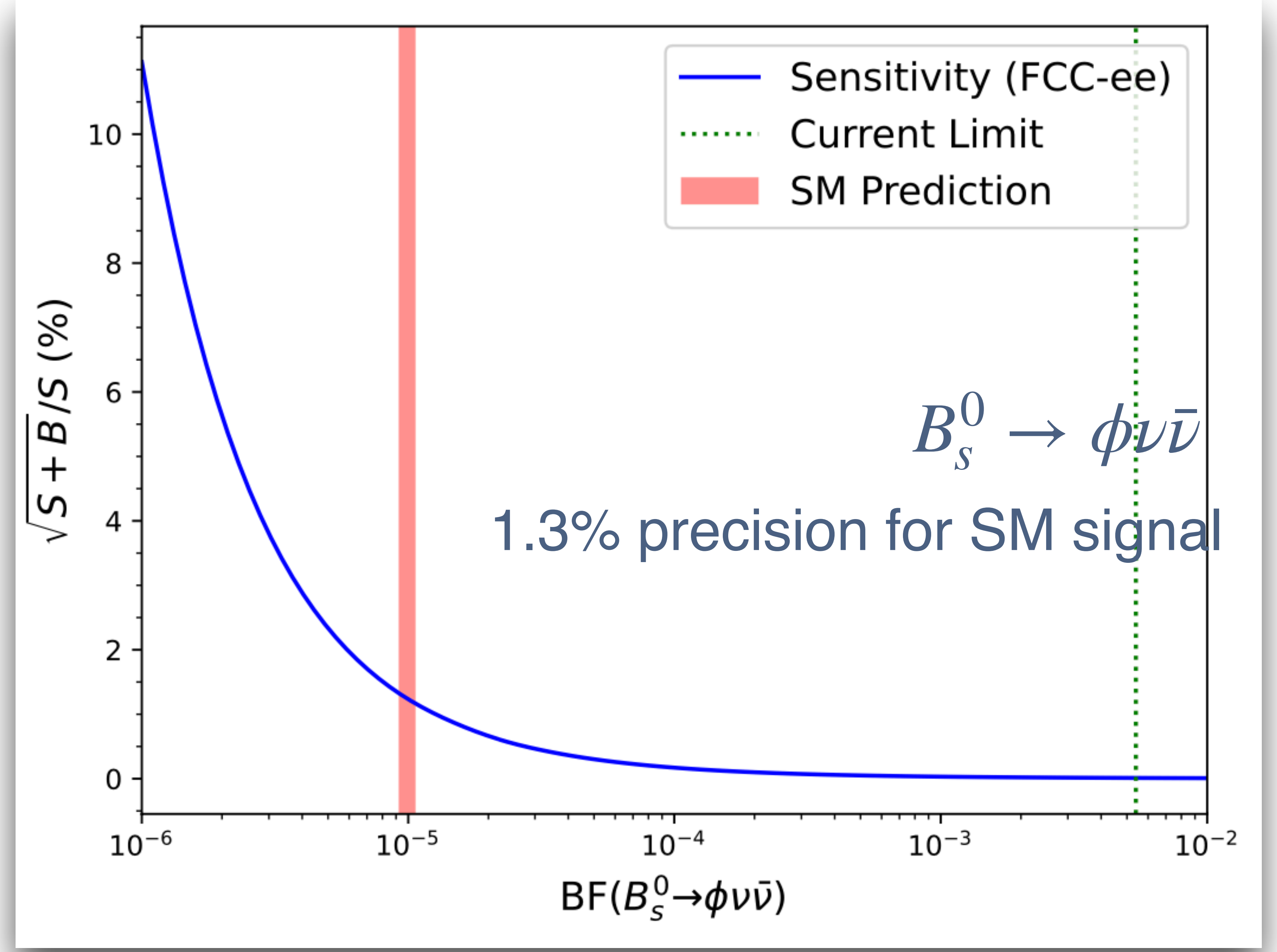
$$O_{L(R)} = \frac{e^2}{2\pi^2}(\bar{s}\gamma^\mu P_{L(R)} b)(\bar{\nu}_l \gamma_\mu P_L \nu_l)$$

Case study - $b \to s\nu\nu$

- (Preliminary) expect O(1%) precision for $B^0 \to K^{*0}\nu\bar{\nu}$ and $B^0_s \to \phi\nu\bar{\nu}$
  - Requires excellent vertex resolution and particle identification

Matthew W. Kenzie at FCC Week





- Study at CEPC with similar performance (Li et al. 2201.07374)
- Proposal for studies of time-dependent CP asymmetry (Descotes-Genon et al. 2208.10880)

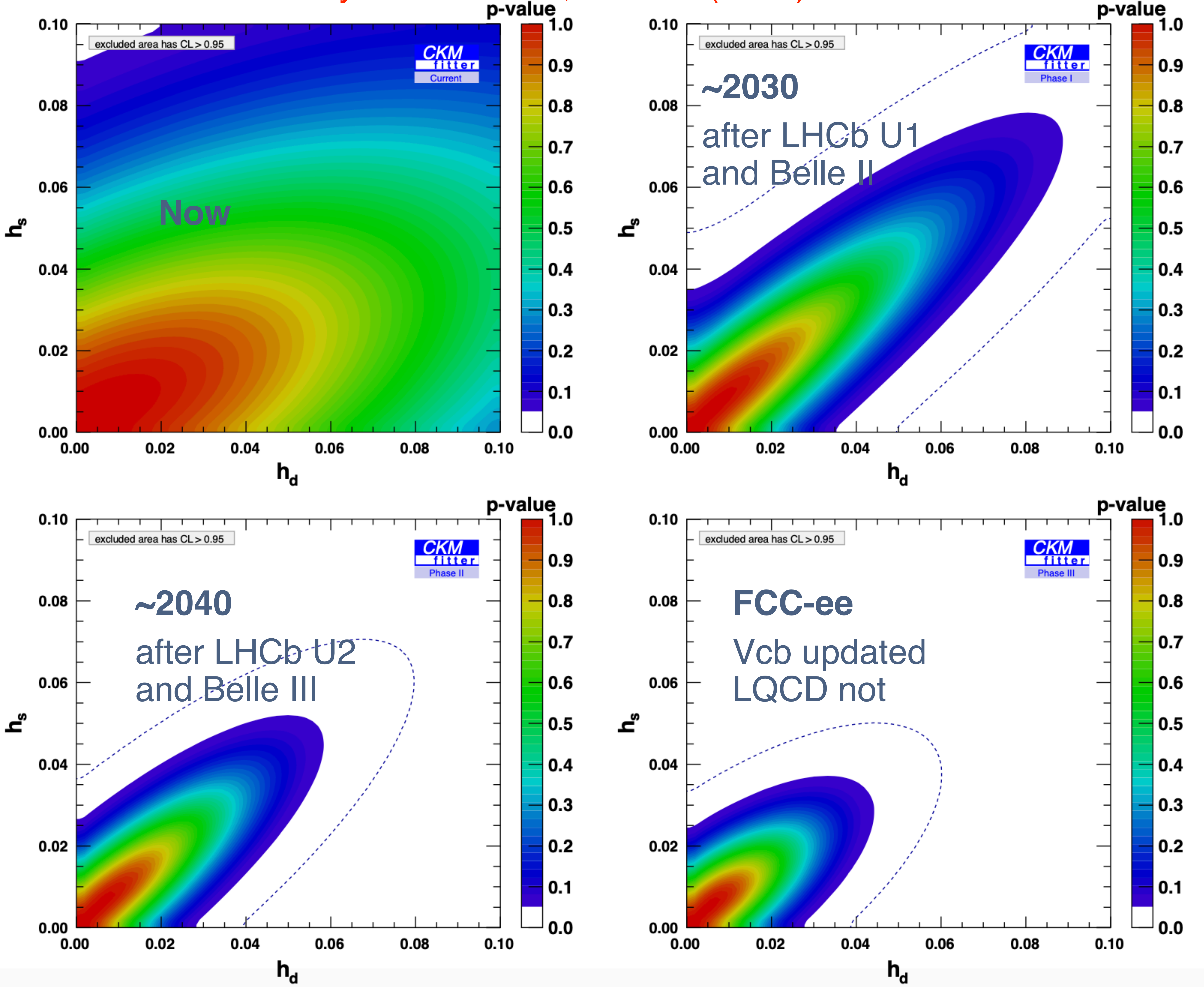
B^0/B_s^0 mixing

Phys. Rev. D 102, 056023 (2020)

- Model-independent search for CPV in the $B^0-\bar{B}^0$ and $B_s^0-\bar{B}_s^0$ mixings

$$M_{12} = M_{12}^{\mathrm{SM}} \times (1 + h_{d,s}e^{2i\sigma_{d,s}})$$

- $|V_{cb}|$ precision and LQCD mixing parameters are main sources of uncertainty.
  - $|V_{cb}|$ will be greatly improved at FCC-ee with on-sell W decays



non-b flavor physics

- Charm physics
- tau physics
- Other flavor physics with Z, W, H, t

charm physics

Appealing opportunities. Experimental performance to be studied

- FCNC $c \to u\nu\nu$ decay

  Phys. Rev. D 103, 015033

  - $D \to \pi\nu\nu$, $D_s \to K\nu\nu$, $\Lambda_c^+ \to p\nu\nu$, etc.
  - Complementary to $c \to ull$ channels
  - Clean null tests of SM, only exp result to date $\mathscr{B}(D \to \pi\nu\nu) < 2.1 \times 10^{-4}$@90% CL (Phys. Rev. D 105, L071102)
  - BR can be probed down to 10^{-6} level at FCC-ee
- Pure leptonic $D^0 \to l^+l^-$ decay

  Belle II physics book

  - Very little SM contribution
  - NP that contributes to $c \to ull$ would also have effect on $D^0 \to l^+l^-$
- CP asymmetry in $D^+ \to \pi^+\pi^0$ and $D^0 \to K_s^0K_s^0$ decays
  - CP violation for $D^0 \to K_s^0K_s^0$ may be ~1% in SM, could become the first evidence of CP violation in charm sector
  - CP violation for $D^+ \to \pi^+\pi^0$ is 0 in SM, good null test

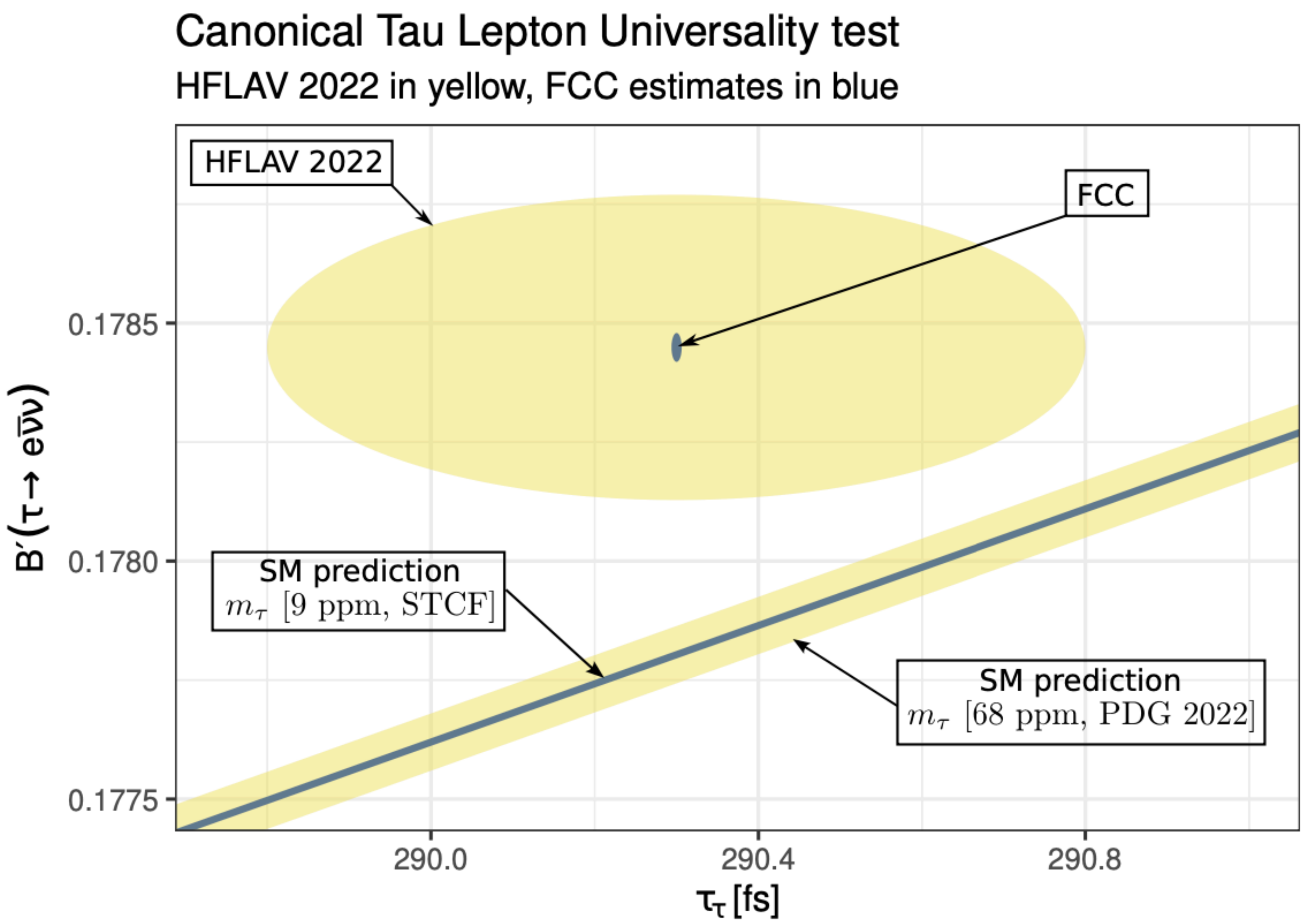
  Phys. Rev. D 92, 054036

tau properties

- High precision on tau properties (complementary to STCF)
  - Lifetime measurement benefits from high boost in $Z \to \tau\tau$ decays
  - LFU test of $\mathscr{B}(\tau \to e\nu\nu)/\mathscr{B}(\tau \to \mu\nu\nu)$
  - Need m_τ input from future τ-factories
  - Systematic uncertainties to be studied and improved

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_τ [MeV]	Threshold / inv. mass endpoint	1776.86 ± 0.12	0.005	0.12	Mass scale
τ_τ [fs]	Flight distance	290.3 ± 0.5 fs	0.005	< 0.040	Vertex detector alignment
$B(\tau \to e\nu\nu)$ [%]	Selection of $\tau^+\tau^-$, identification of final state	17.82 ± 0.05	0.0001	No estimate; possibly 0.003	Efficiency, bkg, Particle ID
$B(\tau \to \mu\nu\nu)$ [%]		17.39 ± 0.05			

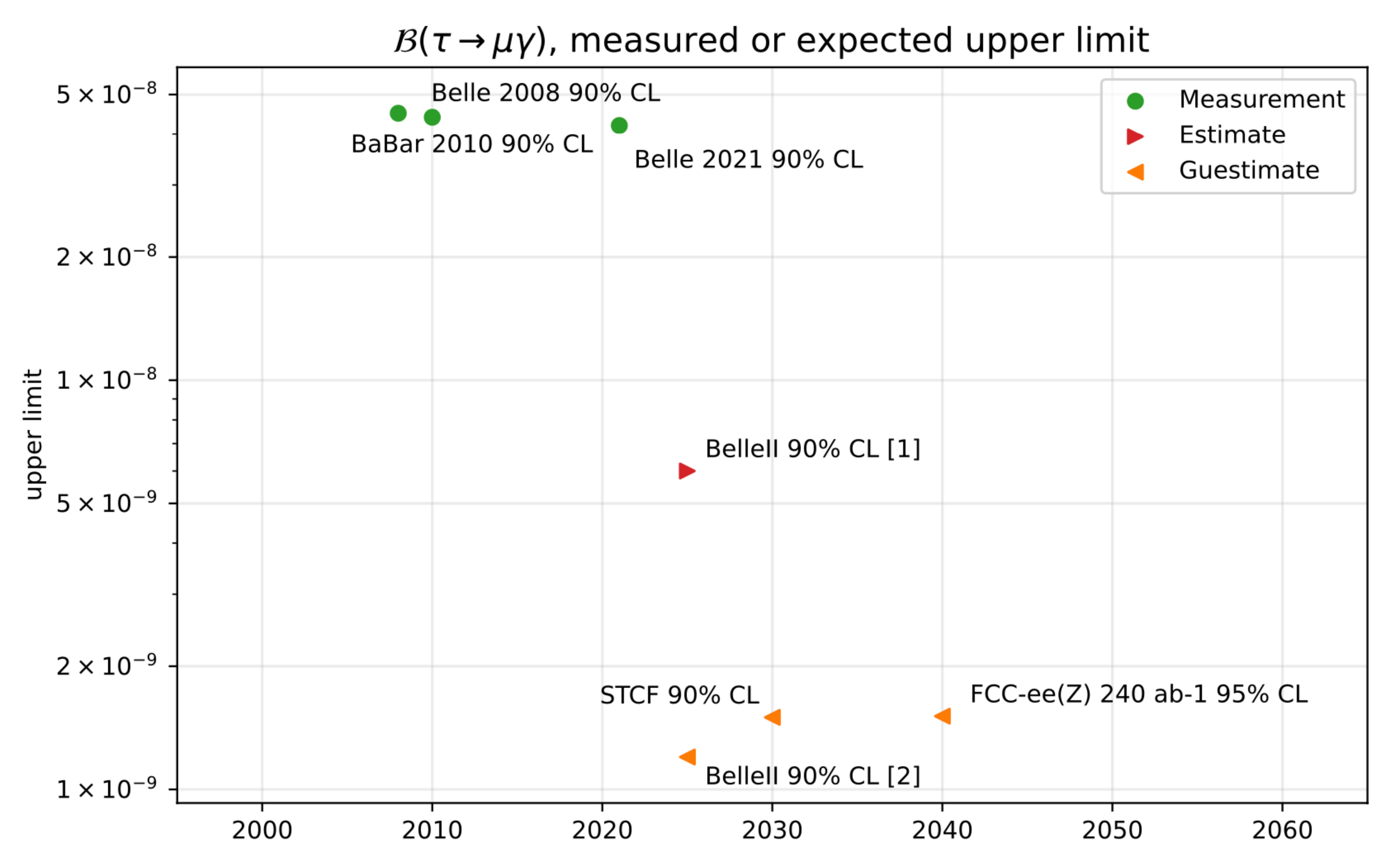
Mogens Dam at WS TAU

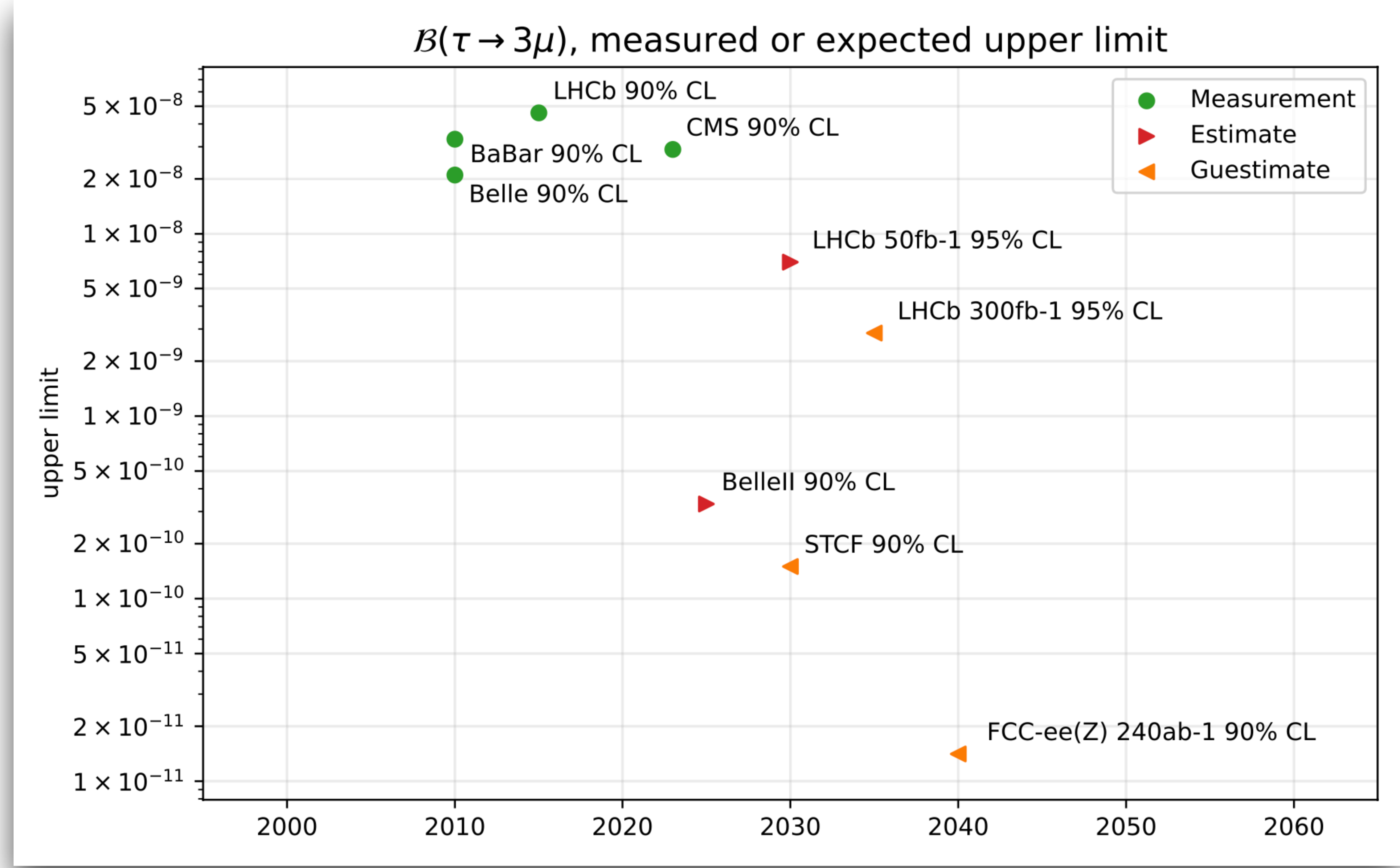


Alberto Lusiani at CLFV2023

CLFV tau decays

- All NP introducing $\mu \leftrightarrow e$ also call for $\tau \leftrightarrow \mu/e$
  - Usually more pronounced from m_τ/m_μ
  - Potential indirect constraint on $\mu \leftrightarrow e$ through $\mu \to \tau^* \times \tau^* \to e$ (Ardu et al. 2202.09246)
- Precision at FCC-ee benefit from high efficiency and copious events

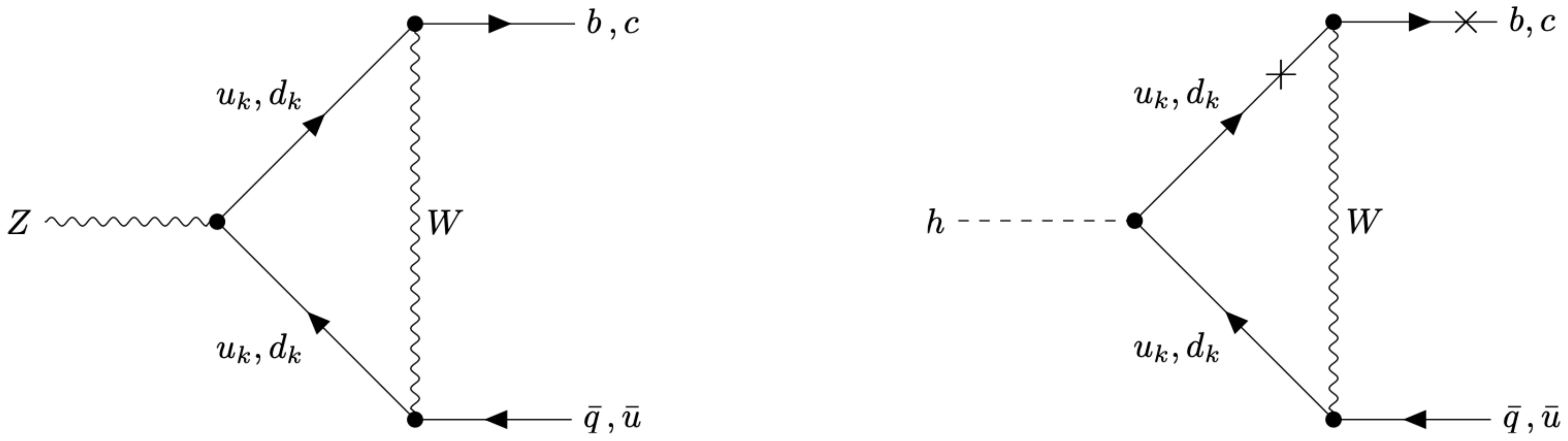




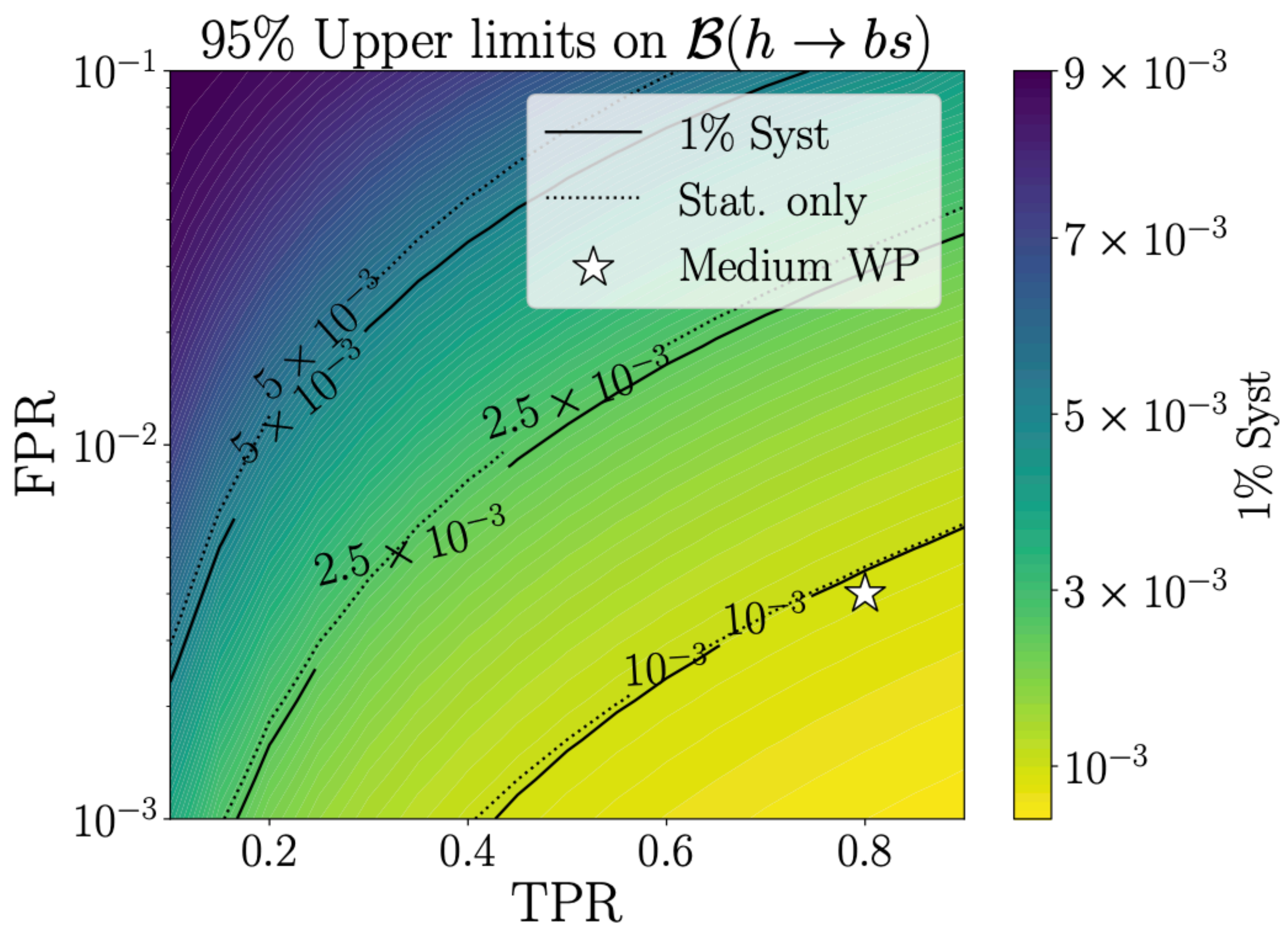
Alberto Lusiani at CLFV2023

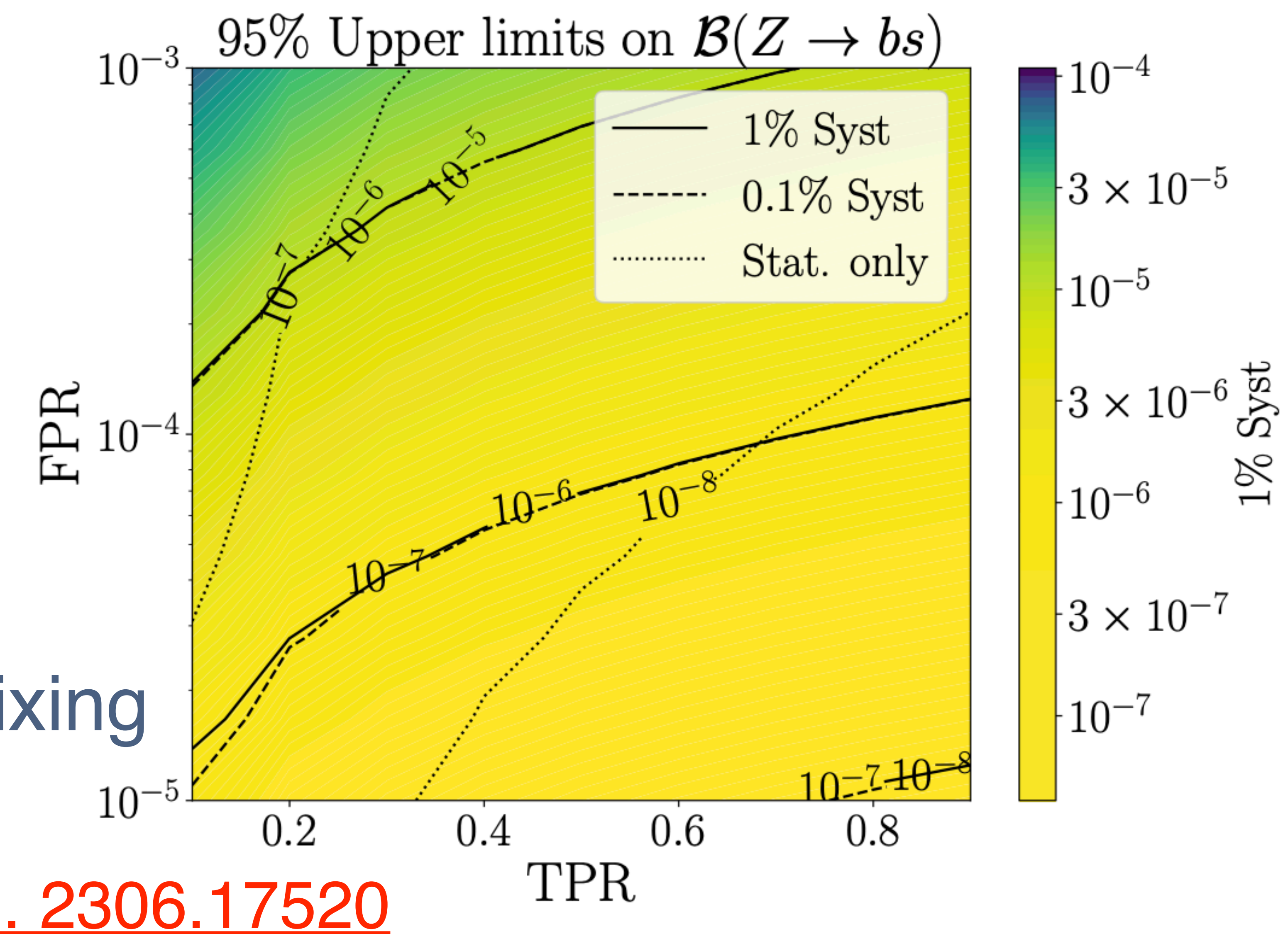
Other opportunities

- Flavor changing decays of Z and H non-vanishing in SM
  - $\mathcal{B}(Z \to bs)^{\mathrm{SM}} = (4.2 \pm 0.7) \times 10^{-8}$
  - $\mathcal{B}(H \to bs)^{\mathrm{SM}} = (8.9 \pm 1.5) \times 10^{-8}$



- With BSM modification
  - $\mathcal{L} \supset g^L_{sb}(\bar{s}_L\gamma_\mu b_L)Z^\mu + g^R_{sb}(\bar{s}_R\gamma_\mu b_R)Z^\mu + y_{sb}(\bar{s}_L b_R)h + y_{bs}(\bar{b}_L s_R)h + \mathrm{h.c.}$
- Requires excellent flavor tagging efficiency and fake rate
  - Potential to probe Z-FCNC at SM level
  - $H \to qq'$ complementary to indirect constraints from $B^0_s - \bar{B}^0_s$ or $D - \bar{D}$ mixing



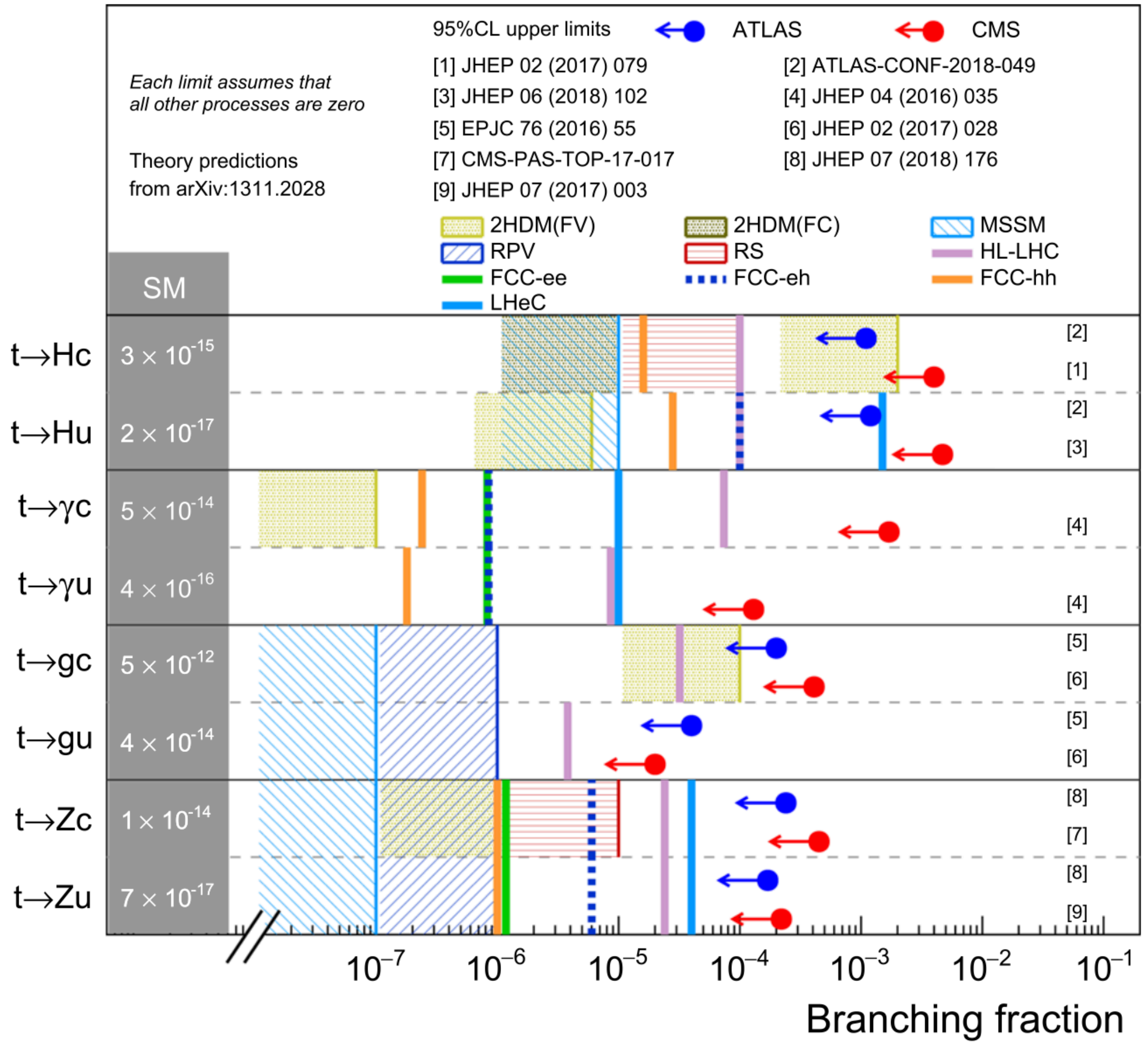


J. F. Kamenik et al. 2306.17520

Other opportunities

- Test CLFV in $Z \to \tau\mu$, $Z \to \tau e$ decays and $H \to ll'$ decays
  - Probe BR down to $10^{-8} - 10^{-10}$ ([SciPost Phys. Proc. 1, 041 (2019)](#))
- FCNC in top quark decays
  - Advantage in $t \to \gamma q$ and $t \to Zq$ at FCC-ee
  - distinguish c from u
- Measure CMK elements with on-shell $W \to bc, W \to cs$ decays
  - Expect excellent vertexing and flavor tagging efficiencies
  - Direct (theory-free) determination.
  - (Preliminary) expect $|V_{cb}|$ precision at 0.4%

[FCC CDR](#)



Summary

Backup

b physics

Phys. Rev. D 102, 056023 (2020)

	Central values	Uncertainties				Reference Phases I–III
		Current [28]	Phase I	Phase II	Phase III	
$\lvert V_{ud}\rvert$	0.97437	±0.00021	id	id	id	[28]
$\lvert V_{us}\rvert f_+^{K\to\pi}(0)$	0.2177	±0.0004	id	id	id	[28]
$\lvert V_{cd}\rvert$	0.2248	±0.0043	±0.003	id	id	[40,41]
$\lvert V_{cs}\rvert$	0.9735	±0.0094	id	id	id	[28,40,41]
Δm_d [ps^{-1}]	0.5065	±0.0019	id	id	id	[17]
Δm_s [ps^{-1}]	17.757	±0.021	id	id	id	[17]
$\lvert V_{cb}\rvert_{\mathrm{SL}} \times 10^3$	42.26	±0.58	±0.60	±0.44	id	[29]
$\lvert V_{cb}\rvert_{W\to cb} \times 10^3$		…	…	…	±0.17	[34–36]
$\lvert V_{ub}\rvert_{\mathrm{SL}} \times 10^3$	3.56	±0.22	±0.042	±0.032	id	[29]
$\lvert V_{ub}/V_{cb}\rvert$ (from Λ_b)	0.0842	±0.0050	±0.0025	±0.0008	id	[30]
$\mathcal{B}(B\to\tau\nu)\times 10^4$	0.83	±0.24	±0.04	±0.02	±0.009	[29,34]
$\mathcal{B}(B\to\mu\nu)\times 10^6$	0.37	…	±0.03	±0.02	id	[29]
$\sin 2\beta$	0.680	±0.017	±0.005	±0.002	±0.0008	[29,30,34]
$\alpha[°]$ (mod 180°)	91.9	±4.4	±0.6	id	id	[29]
$\gamma[°]$ (mod 180°)	66.7	±5.6	±1	±0.25	±0.20	[29,30,34]
β_s[rad]	−0.035	±0.021	±0.014	±0.004	±0.002	[30,34]
$A_{\mathrm{SL}}^d \times 10^4$	−6	±19	±5	±2	±0.25	[14,17,34,37]
$A_{\mathrm{SL}}^s \times 10^5$	3	±300	±70	±30	±2.5	[14,17,34,37]
$\bar{m}_t$ [GeV]	165.30	±0.32	id	id	±0.020	[28,34]
$\alpha_s(m_Z)$	0.1185	±0.0011	id	id	±0.00003	[28,34]
$f_+^{K\to\pi}(0)$	0.9681	±0.0026	±0.0012	id	id	[30]
f_K [GeV]	0.1552	±0.0006	±0.0005	id	id	[30]
f_{B_s} [GeV]	0.2315	±0.0020	±0.0011	id	id	[30]
B_{B_s}	1.219	±0.034	±0.010	±0.007	id	[30]
f_{B_s}/f_{B_d}	1.204	±0.007	±0.005	id	id	[30]
B_{B_s}/B_{B_d}	1.054	±0.019	±0.005	±0.003	id	[30]
$\tilde{B}_{B_s}/\tilde{B}_{B_d}$	1.02	±0.05	±0.013	id	id	[30,42,43]
$\tilde{B}_{B_s}$	0.98	±0.12	±0.035	id	id	[30,42,43]
η_B	0.5522	±0.0022	id	id	id	[44]

π^0 identification

- Need exquisite EM calorimetry for pi0 identification
  - $3\,\%/\sqrt{E}$ expected

JINST 15 P11005