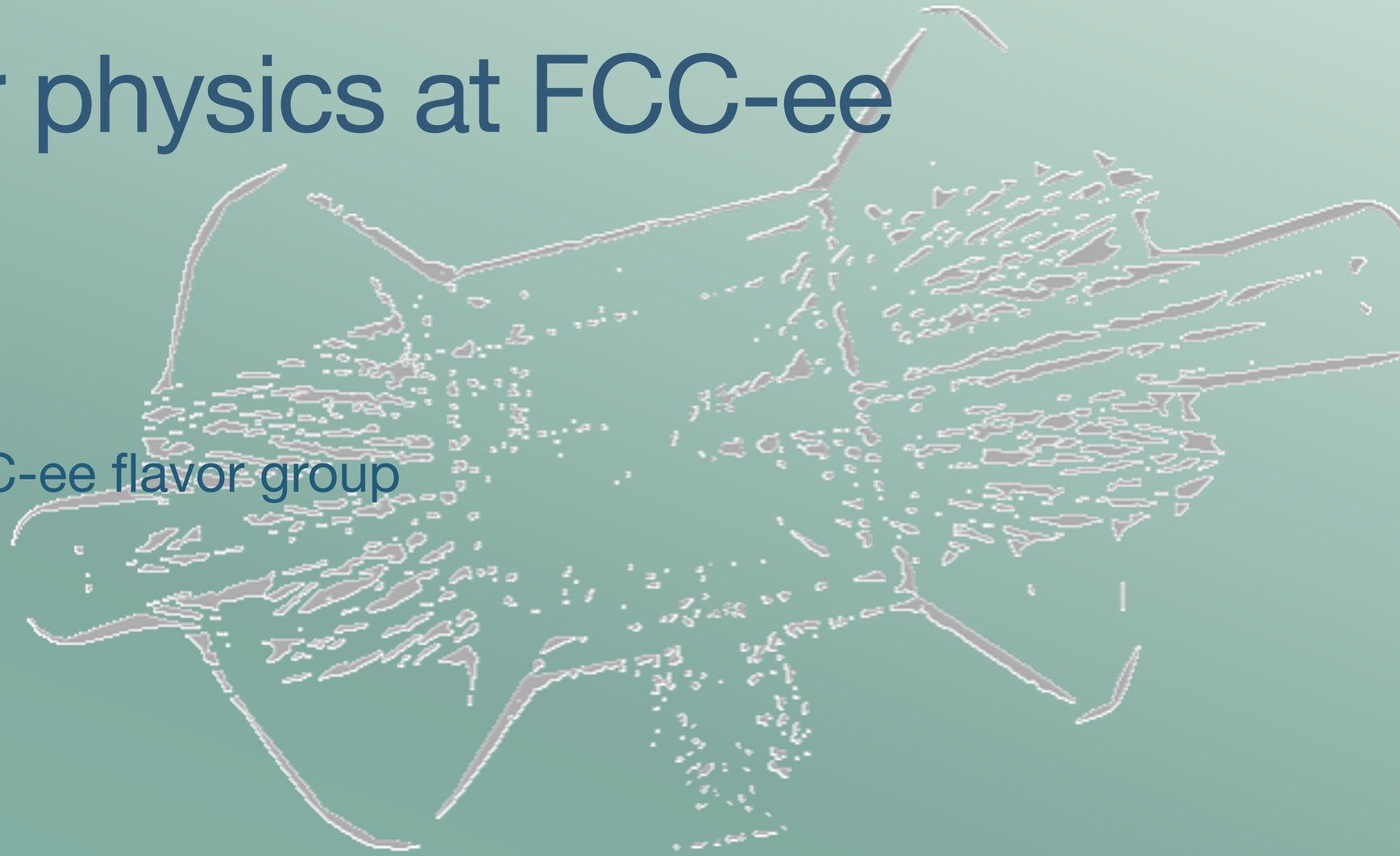
Heavy flavor physics at FCC-ee

July 09, 2022
ICHEP 2022

Xunwu Zuo for the FCC-ee flavor group



Outline

- FCC-ee dataset
- b physics program
- Charm physics program
- Tau physics program
- Other opportunities

FCC-ee

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

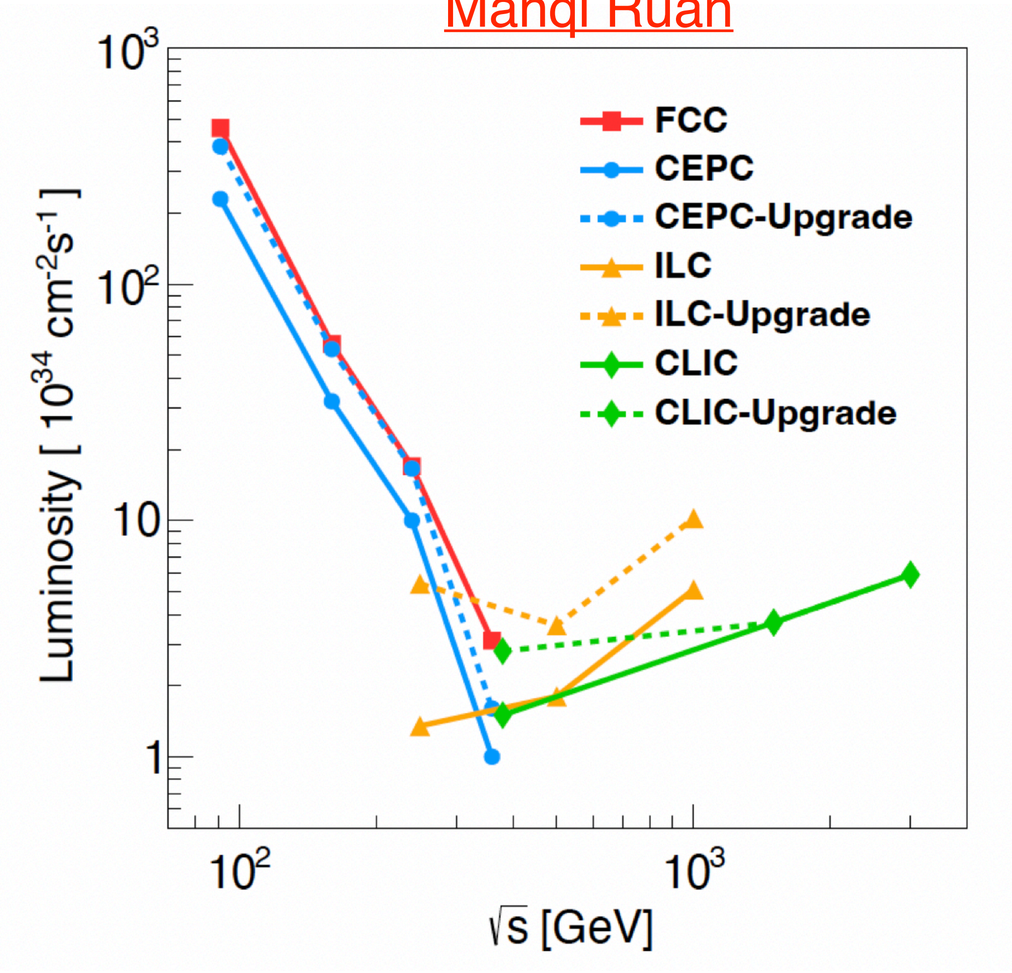
FCC-ee dataset

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)
  - Rare decay searches
  - BSM particles (ALPs, dark photons, LLPs)

Dataset	Operation	Int. lumi. (ab^{-1})	Events
Z	4 years	150	5×10^{12}
WW	2 years	12	5×10^{7}
ZH	3 years	5	$> 10^{6}$
tt	5 years	2	$> 10^{6}$

Manqi Ruan



2 IPs assumed for 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 5×10^{12} Z bosons
- About 13x as many B^0/B^+ as at Belle II (50 ab^{-1})
- About 8x 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	✓		(✓)

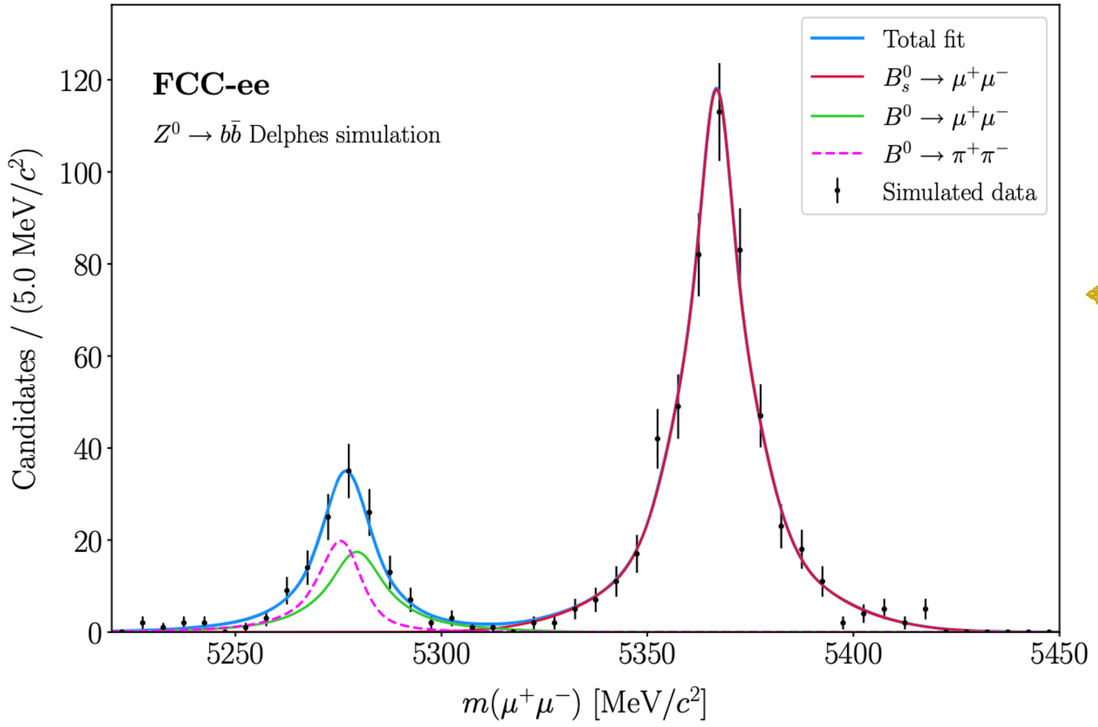
Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B_s^0 / $\overline{B}_s^0$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	300	300	80	80	600	150

b physics

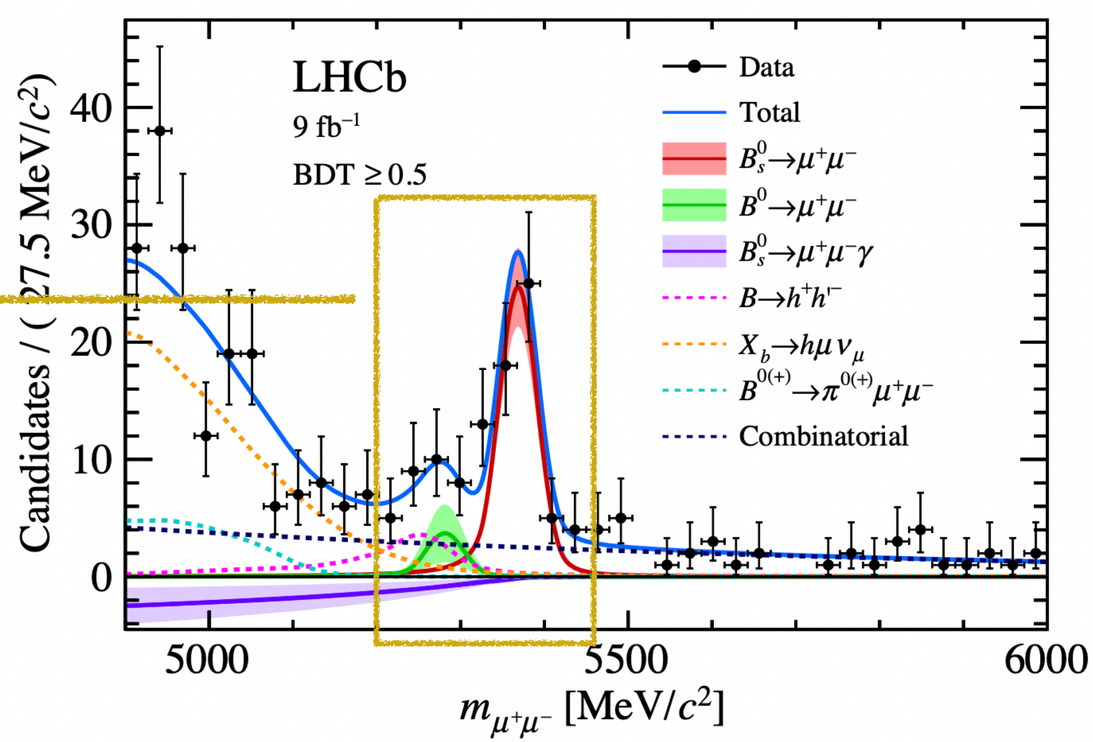
$B^0/B_s^0 \to \mu^+\mu^-$

- 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

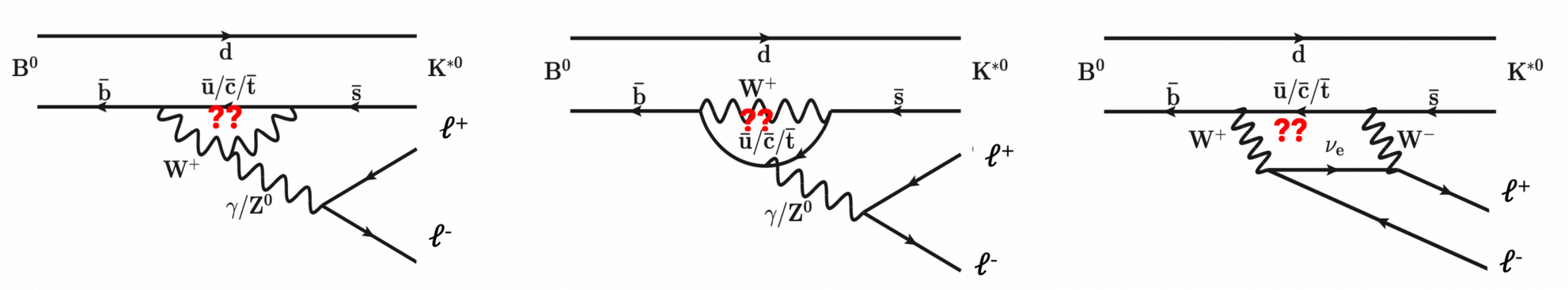
Eur. Phys. J. Plus (2021) 136:837



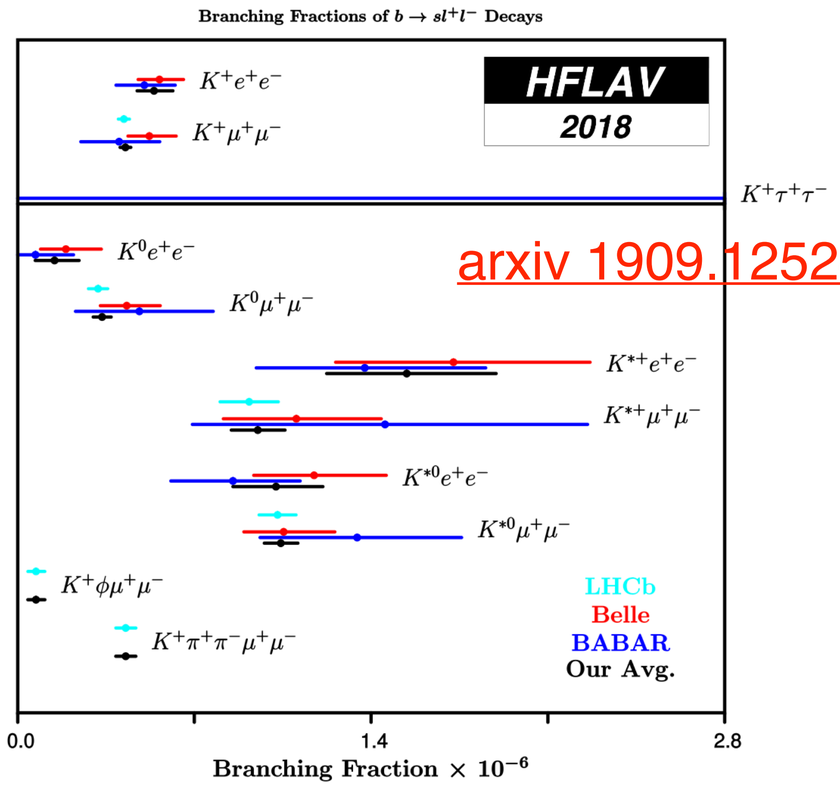
Phys. Rev. Lett. 128, 041801



$b \to s\ell\ell$ transition

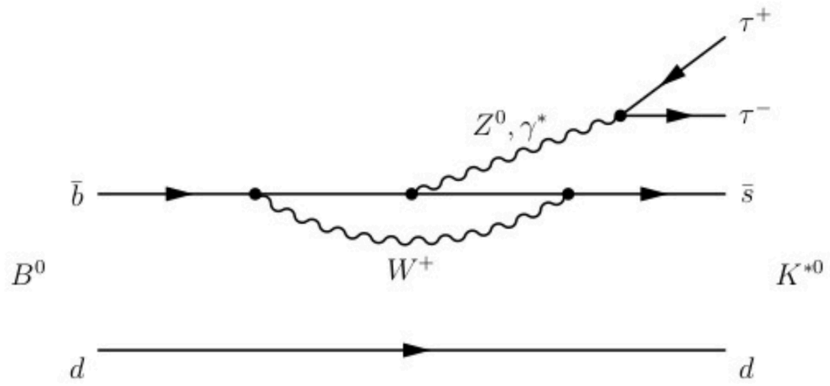


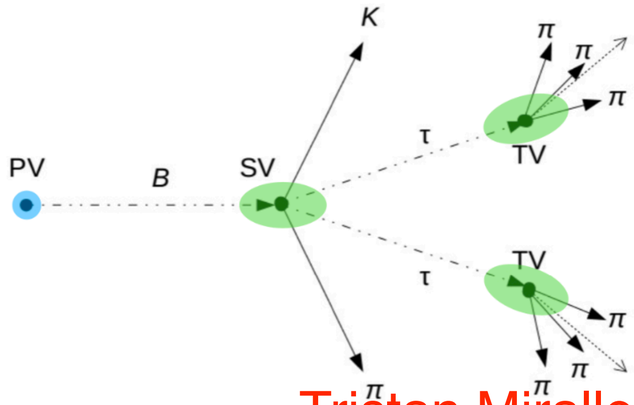
- $b \to s\ell\ell$ is mediated by different diagrams in SM, with their relative importance varying with $q^2 = M_{ll}^2$
- BR highly sensitive to BSM modification (and also have large uncertainties due to non-perturbative QCD)
- Hints of LFUV seen in R_K and R_{K^*} between e and μ
- $b \to s\ell\ell$ not yet established for τ
  - Expected $BR_{SM} \sim O(10^{-7})$



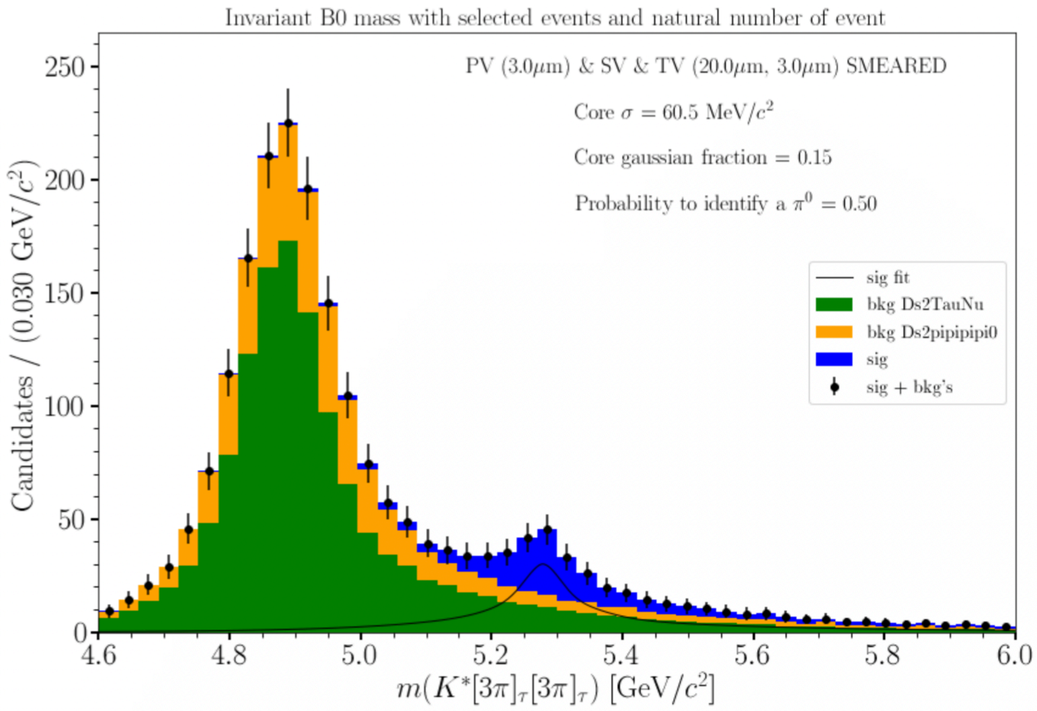
arxiv 1909.12524

$b \to s\ell\ell$ transition





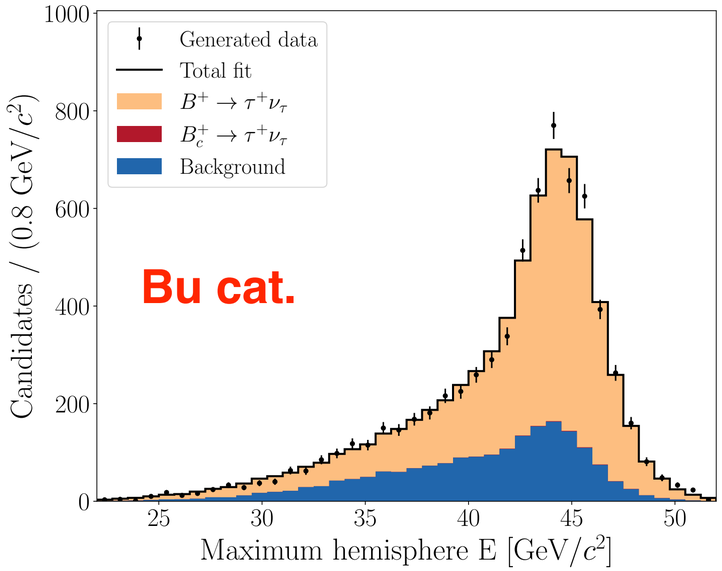
Tristan Miralles at FCC Week

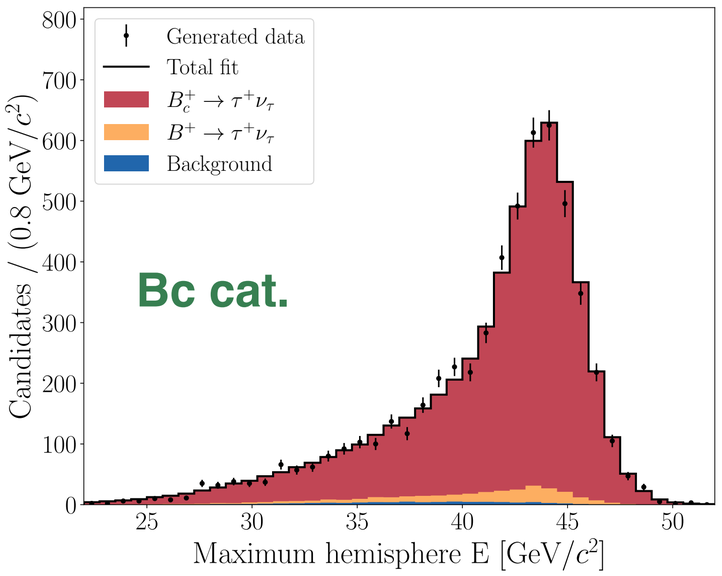


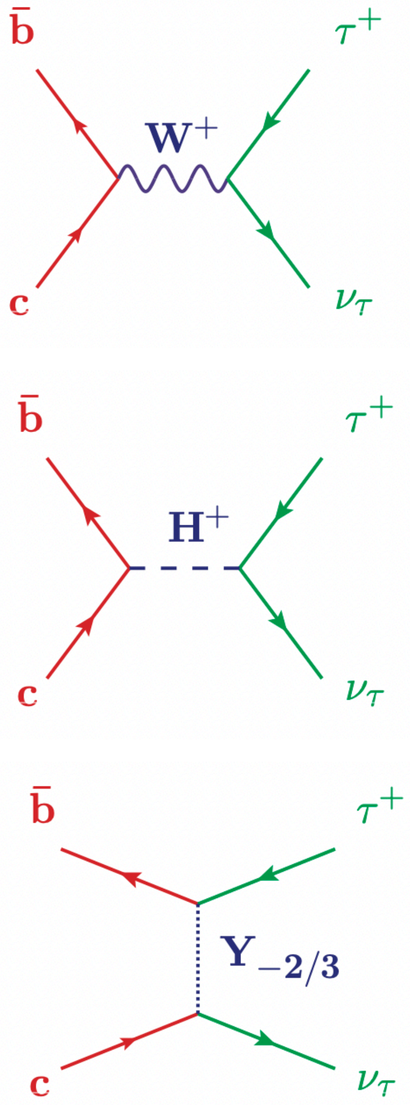
- Additional test of LFV in $b \to s\tau\tau$
- Background with the same final state can be separated by kinematic properties
  - More ongoing studies on comprehensive backgrounds toward a full analysis
- The goal is to understand the performance/ requirements for vertex detectors (backup for π^0 ID)

$B^+/B_c^+ \to \tau^+\nu_\tau$

- Not possible to study $B_c^+ \to \tau^+\nu_\tau$ at LHCb or Belle
- Decays suppressed by CKM
  - Still, millions of signals at FCC-ee
- Highly pure selections can be achieve for both signal modes
  - 2%-3% statistical uncertainties on signal yields





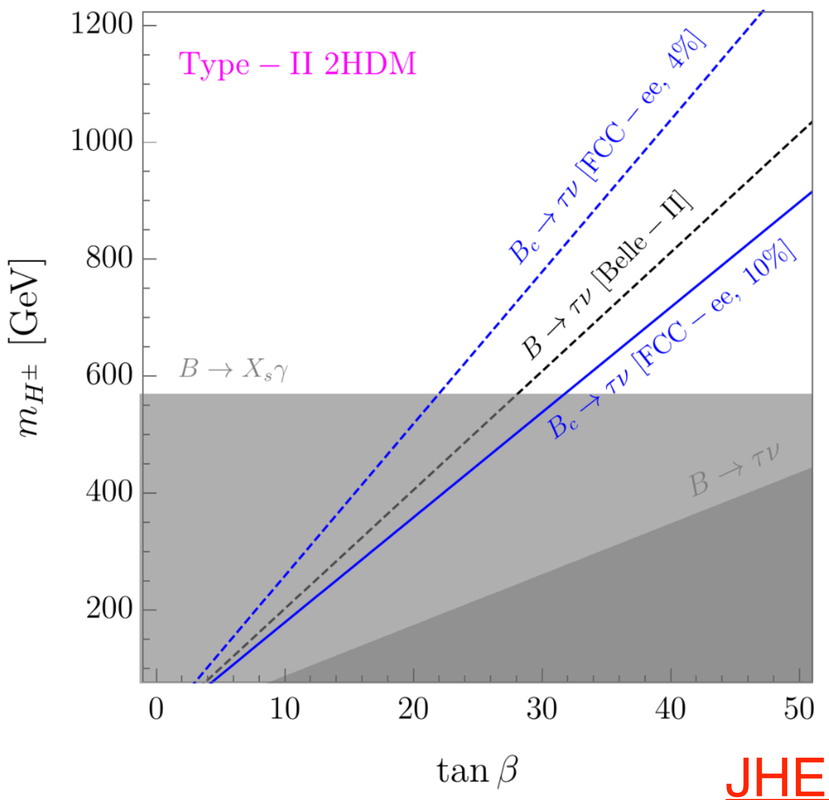


Flavor case - $B^+/B_c^+ \to \tau^+\nu_\tau$

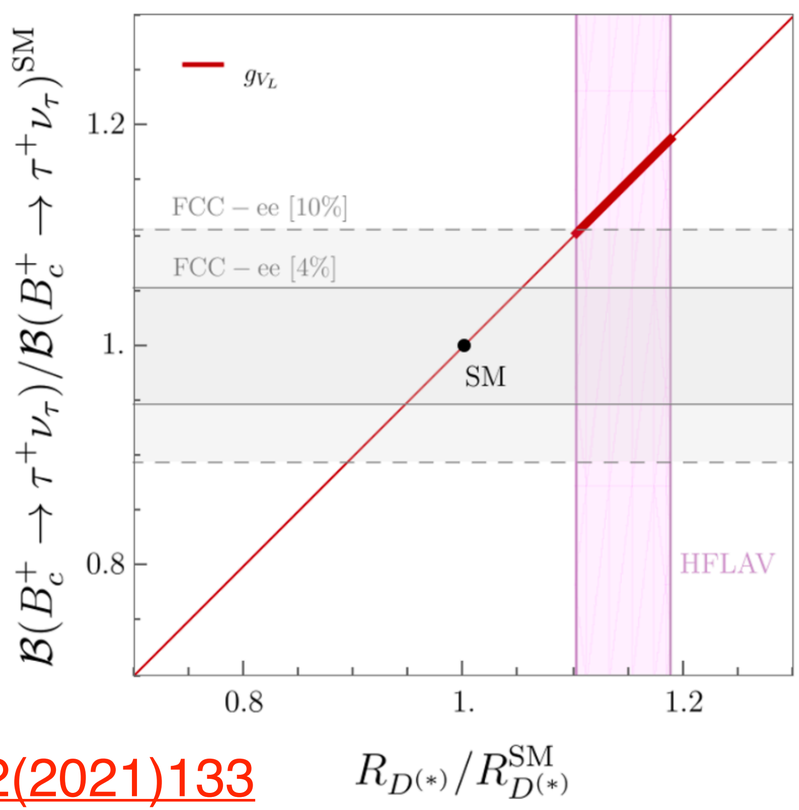
Results can be interpreted in two ways

- Measure $|V_{cb}|$ and $|V_{ub}|$
  - Depends on the theoretical expectation of $f(B_c^+)$ and $\mathscr{B}(B^+ \to \tau^+\nu_\tau)$
- Constrain BSM models
  - Measure ratio relative to a normalization mode $B_c^+ \to j/\psi\mu^+\nu_\mu$ to decoupled from $|V_{cb}|$ and $f(B_c^+)$

2HDM



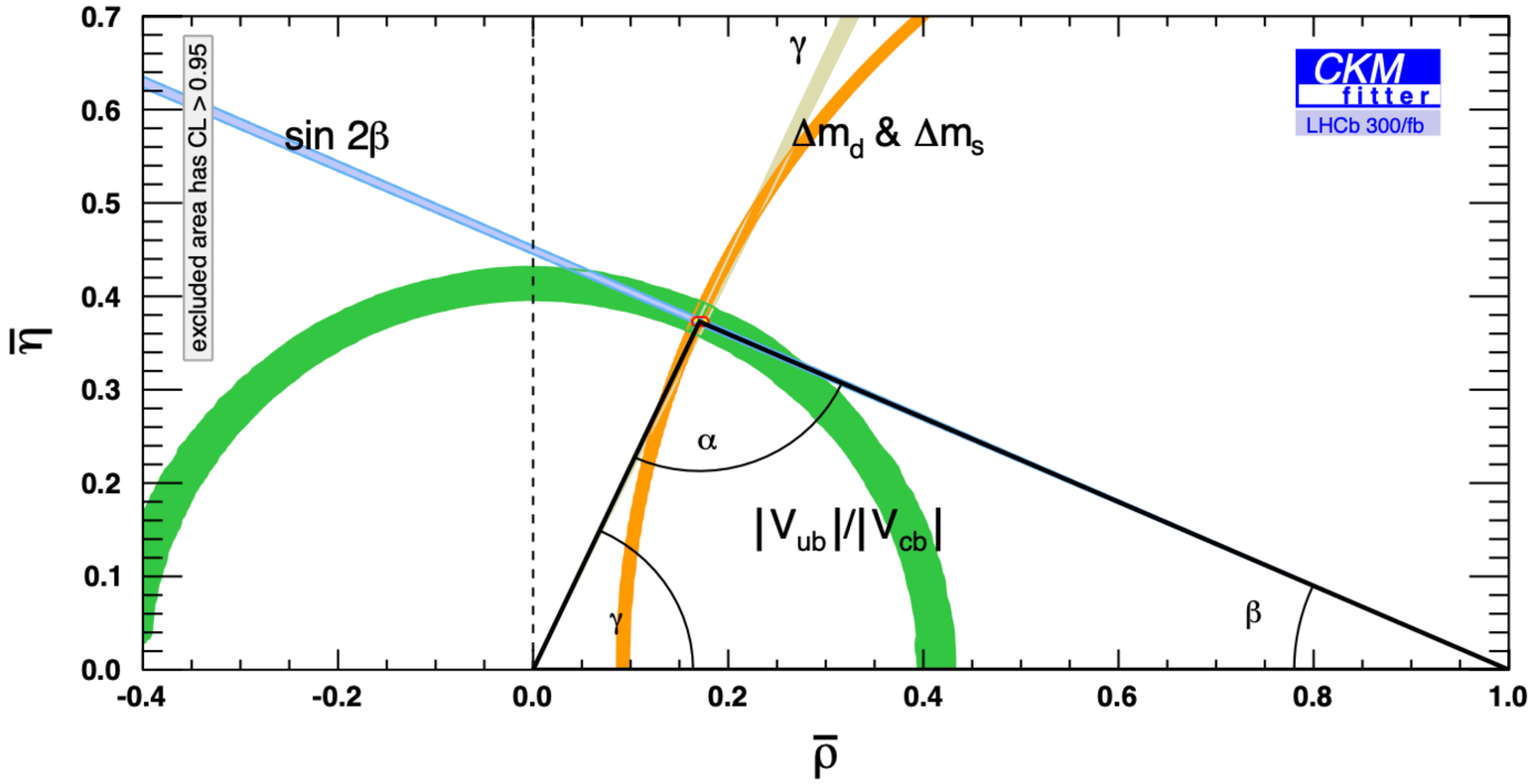
lepto-quark model



JHEP12(2021)133

CMK fit

- Potential status of the unitary triangle in 2030s based on LHCb measurements and improved lattice QCD calculations
- Complementary measurement of $|V_{ub}|/|V_{cb}|$ to be added by Belle and FCC-ee



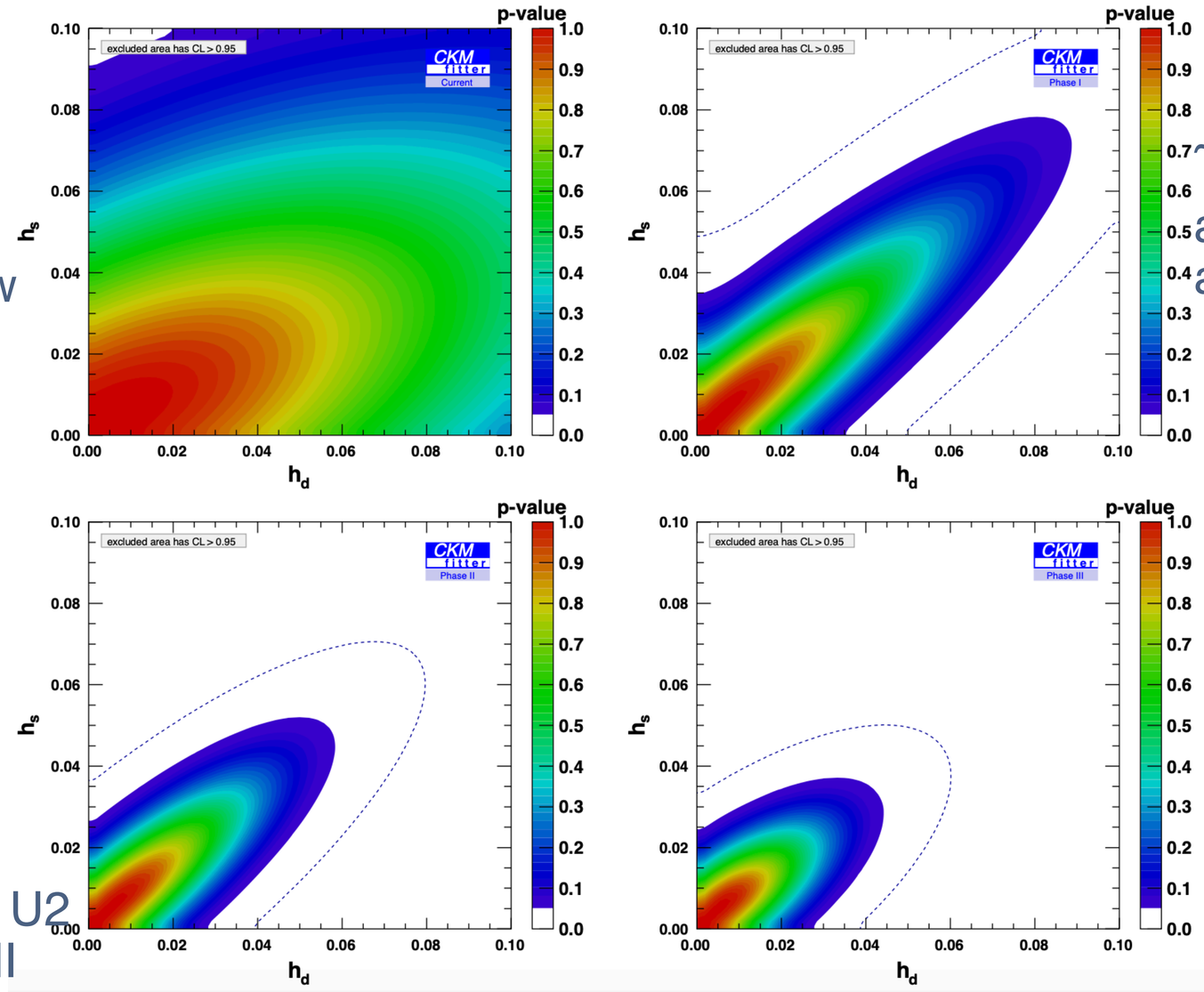
arxiv 1808.08865

b physics

- Model-independent search for CPV in the $B^0 - \bar{B}^0$ and $B_s^0 - \bar{B}_s^0$ mixings
- $|V_{cb}|$ precision and LQCD mixing parameters are main sources of uncertainty.
  - $|V_{cb}|$ will be greatly improved at FCC-ee with on-sell W decays

Phys. Rev. D 102, 056023 (2020)

Now



~2030

after LHCb U1 and Belle II

~2040

after LHCb U2 and Belle III

FCC-ee

Vcb updated LQCD not

non-b flavor physics

charm physics

Appealing opportunities. Experimental performance to be studied

- FCNC $c \to u\nu\nu$ decay
  - $D \to \pi\nu\nu$, $D_s \to K\nu\nu$, $\Lambda_c^+ \to p\nu\nu$, etc.
  - Complementary to $c \to ull$ channels
  - Clean null tests of SM, no experimental limits at the moment
  - BR can be probed down to 10^{-6} level at FCC-ee

Phys. Rev. D 103, 015033

- Pure leptonic $D^0 \to l^+l^-$ decay
  - Very little SM contribution
  - NP that contributes to $c \to ull$ would also have effect on $D^0 \to l^+l^-$

Belle II physics book

- CP asymmetry in $D^+ \to \pi^+\pi^0$ and $D^0 \to K_s^0 K_s^0$ decays
  - CP violation for $D^0 \to K_s^0 K_s^0$ 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

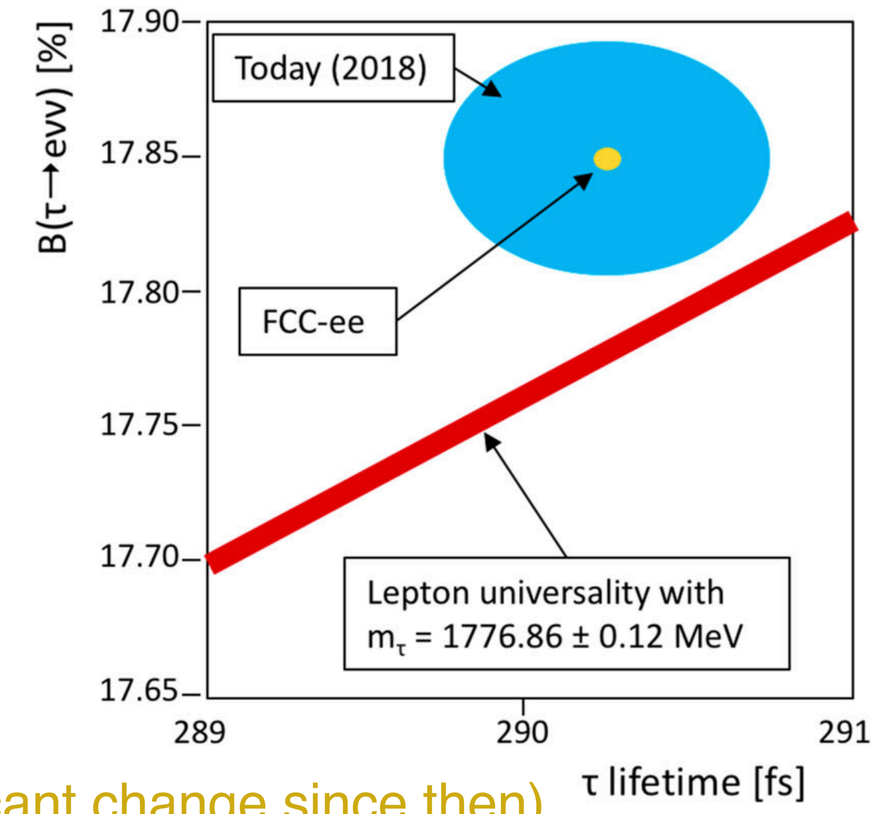
tau physics

- High precision on tau properties (complementary to STCF)
  - Lifetime measurement benefits from high boost in $Z \to \tau\tau$ decays
  - Systematic uncertainties to be studied and improved
- Probe CLFV $\tau \to 3\mu$ decay
  - Higher efficiency than the LHC and Belle
  - Essentially background free

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

FCC CDR

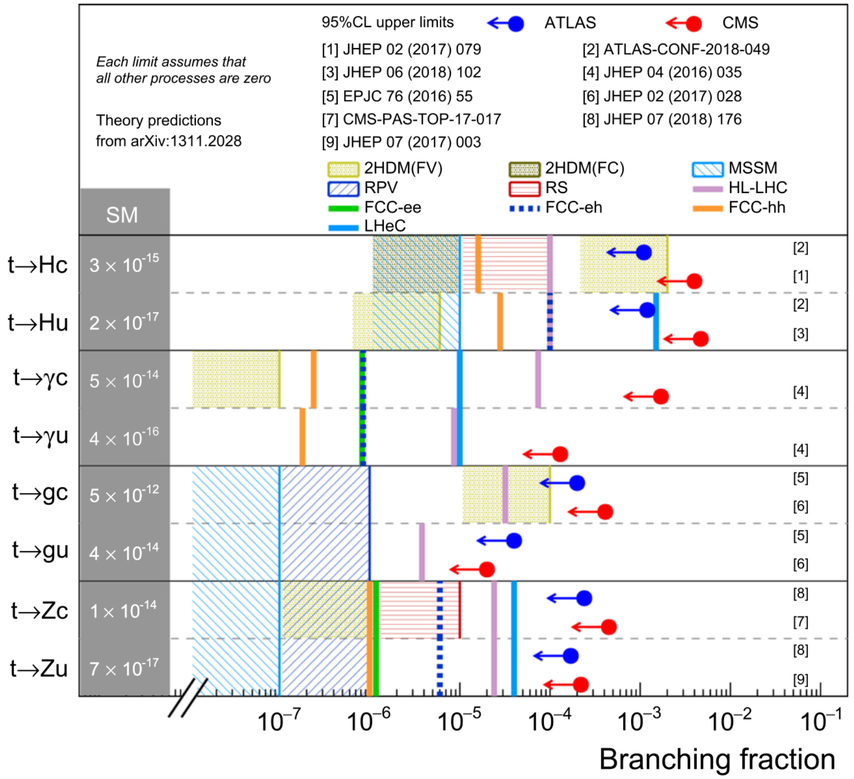


(Estimates made in 2018, no significant change since then)

Other opportunities

- Test LFV 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



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]
$\lvert V_{cb}\rvert_{\rm SL} \times 10^3$	42.26	±0.58	±0.60	±0.44	id	[29]
$\lvert V_{cb}\rvert_{W\to cb} \times 10^3$		…	…	…	±0.17	[34–36]
$\lvert V_{ub}\rvert_{\rm SL} \times 10^3$	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]
α[°] (mod 180°)	91.9	±4.4	±0.6	id	id	[29]
γ[°] (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]
$A_{\rm SL}^d \times 10^4$	−6	±19	±5	±2	±0.25	[14,17,34,37]
$A_{\rm SL}^s \times 10^5$	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