Higgs factory and flavor physics: theory perspective

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Flavor facrtory

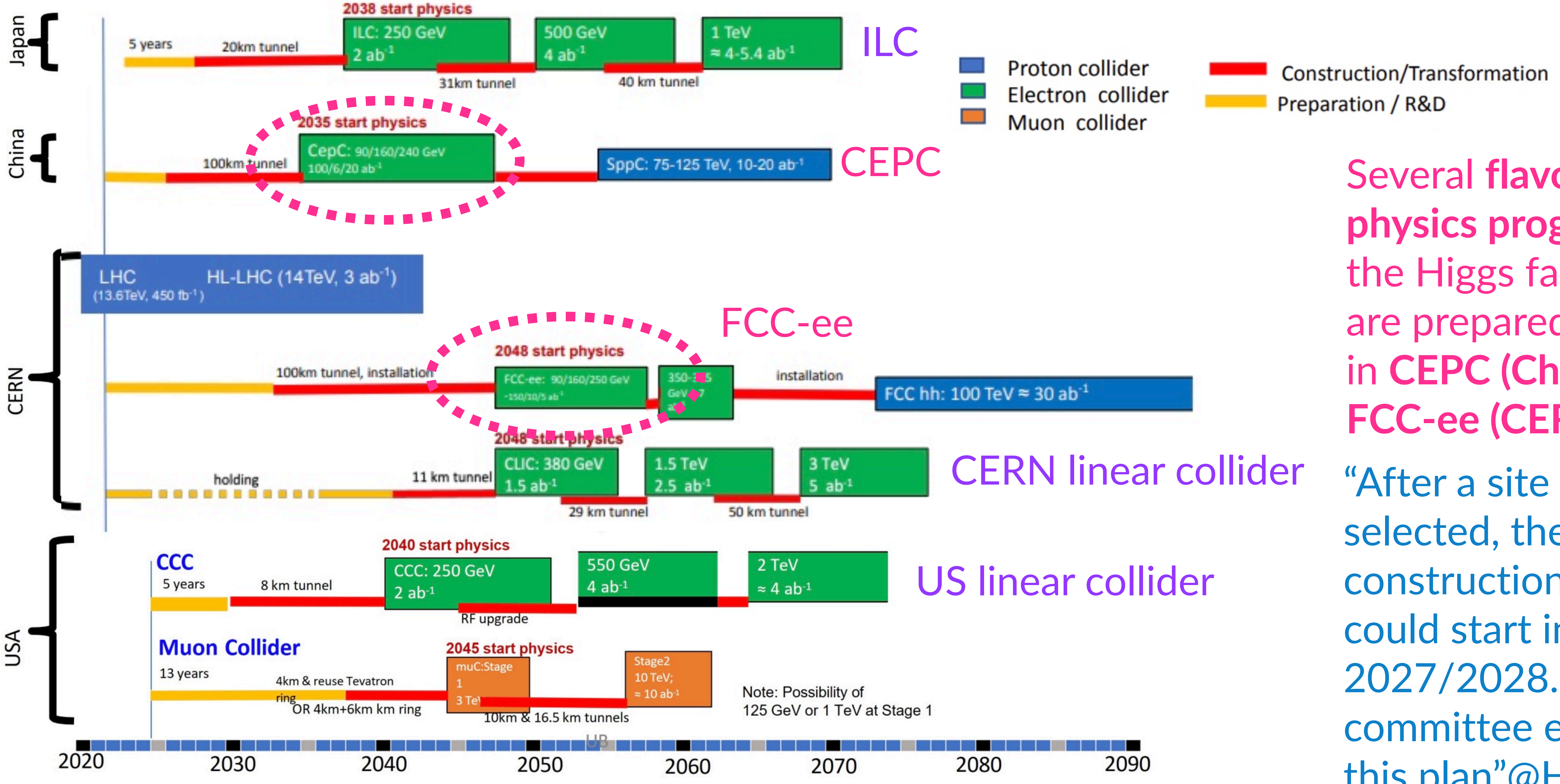
- Currently, Belle II, LHCb and BES-III experiments are the main flavor factories **with multi purposes**, and they are probing TeV scale new physics through flavor measurements
- As a next-generation experiment, Higgs factories are expected to take on the role of the flavor factory as a by-product
- Indeed, e^+e^- circular colliders can do a better job than the on-going flavor factories

Belle II LHCb BESIII

WHAT'S NEXT?

Future (e^+e^-) colliders

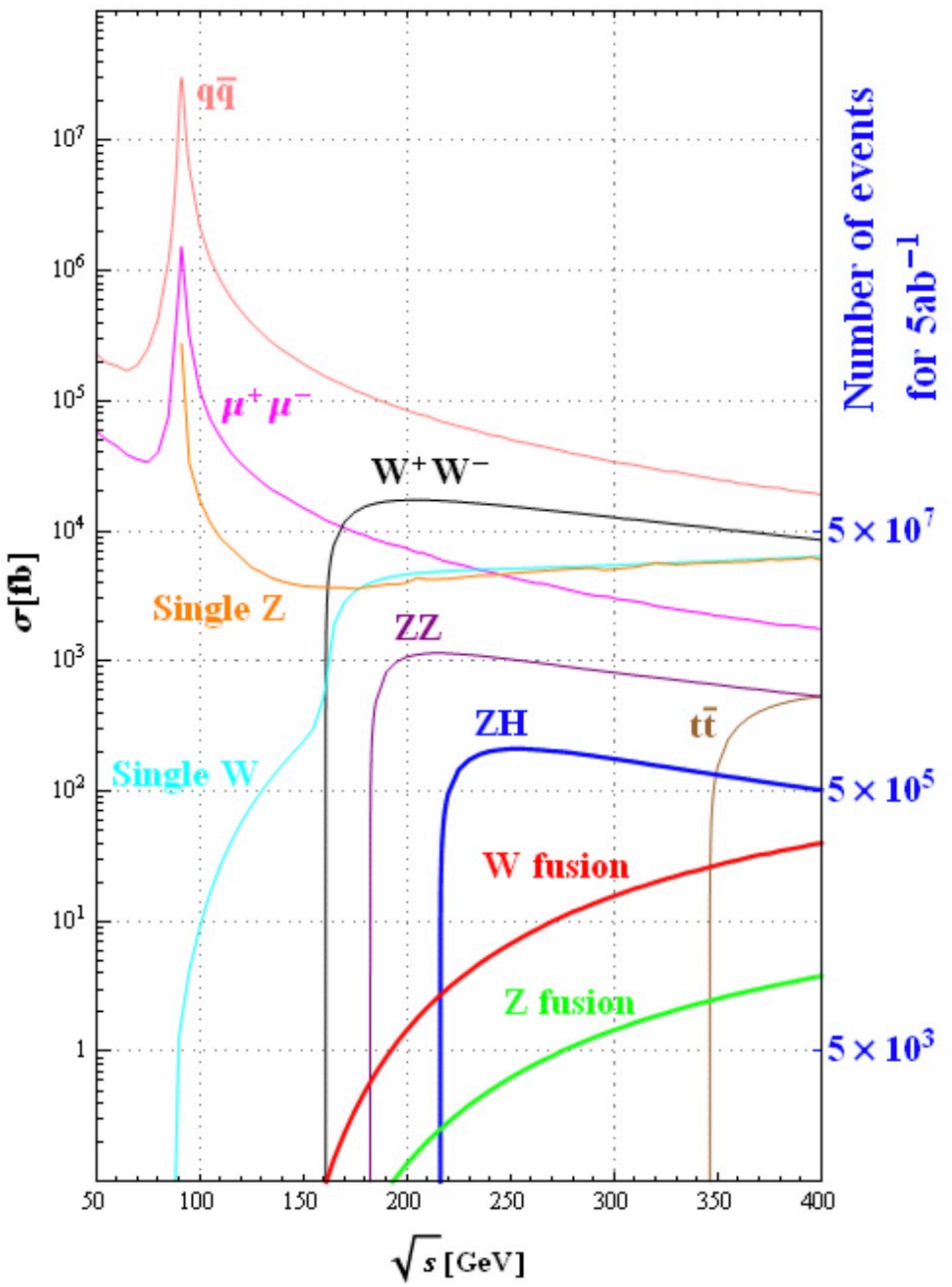
[The Snowmass 2021 Energy Frontier Report, 2211.11084]

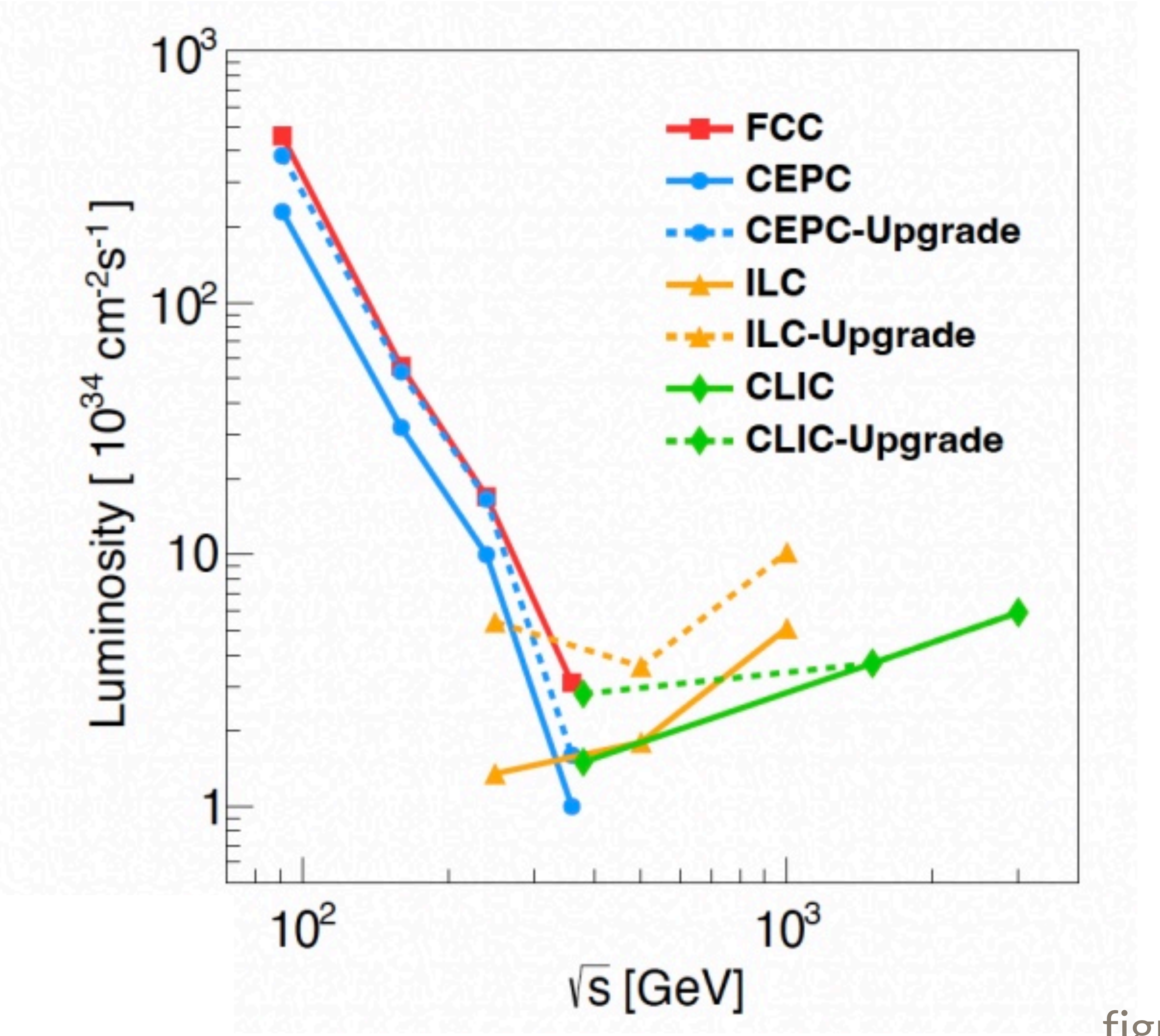


Several **flavor physics programs** in the Higgs factory are prepared in **CEPC (China)** and **FCC-ee (CERN)**

“After a site has been selected, the construction of CEPC could start in 2027/2028. The committee endorses this plan”@HIggs2023

σ * Luminosity * run-time = event numbers





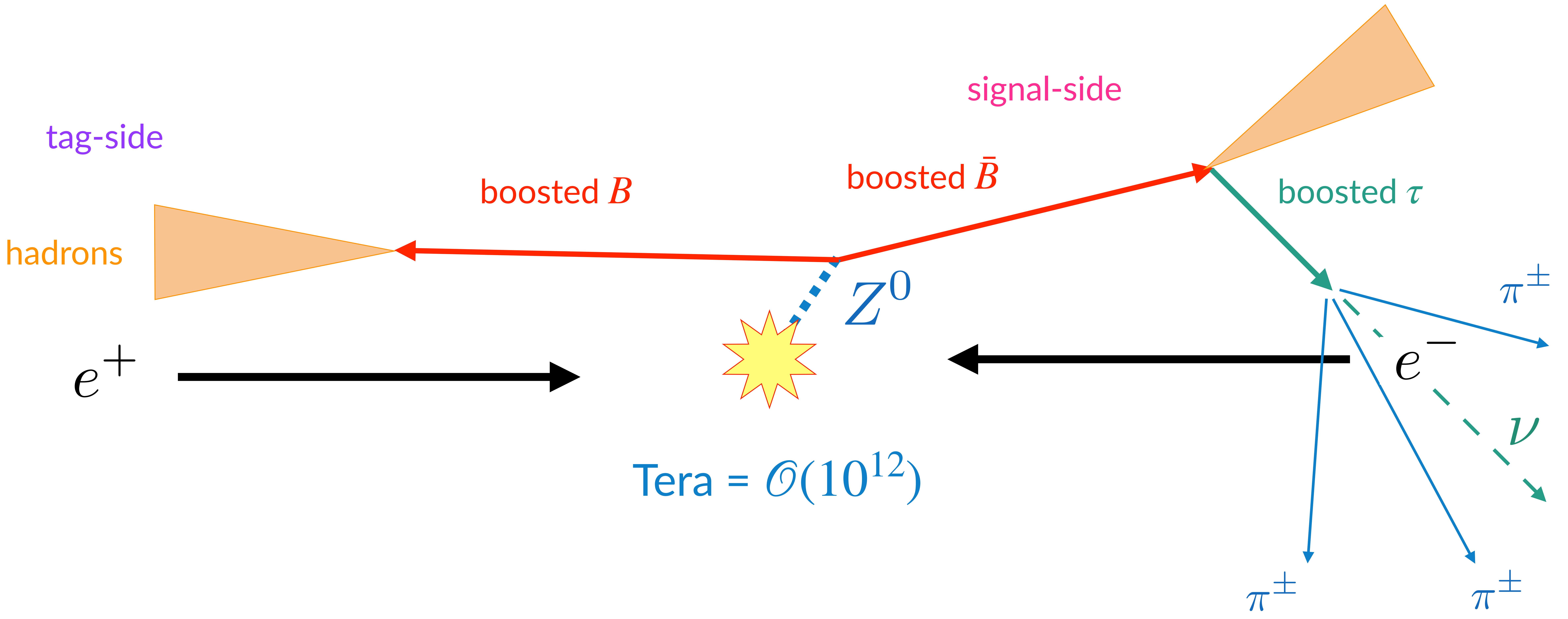
CEPC and FCC-ee are the best environments **to probe Z-pole physics, which is new flavor factory**

CPEC/FCC-ee plan **4Tera/5Tera Z** productions
→ similar sensitivity

Note: both are **unpolarized** circular colliders

figures from slide of Manqi Ruan

Flavor physics at Z-pole



Expected yields and advantages

- Expected yields at FCC-ee for 5×10^{12} Z decays [Monteil, Wilkinson, 2106.01259]

Yields (×10^9)	B^0	B^+	B_s^0	Λ_b^0	B_c^+	$c\bar{c}$	$\tau^+\tau^-$
FCC-ee Z-pole	310*2	310*2	75*2	65*2	1.5*2	600	170
Belle II 50 ab^{-1}	26*2	26*2	0.3*2	—	—	65	46

- The expected yields of b and c are one order of magnitude larger than Belle II
  τ is larger by a factor
- Heavier flavor species (B_s, Λ_b, B_c^+) than Belle II
- More boosted than Belle II, providing more accurate tracking reconstruction

Flavor Physics at CEPC: a General Perspective

Contents

Source by slide of Manqi Ruan at Higgs2023

CEPC collaboration is currently writing a White Paper for the flavor physics

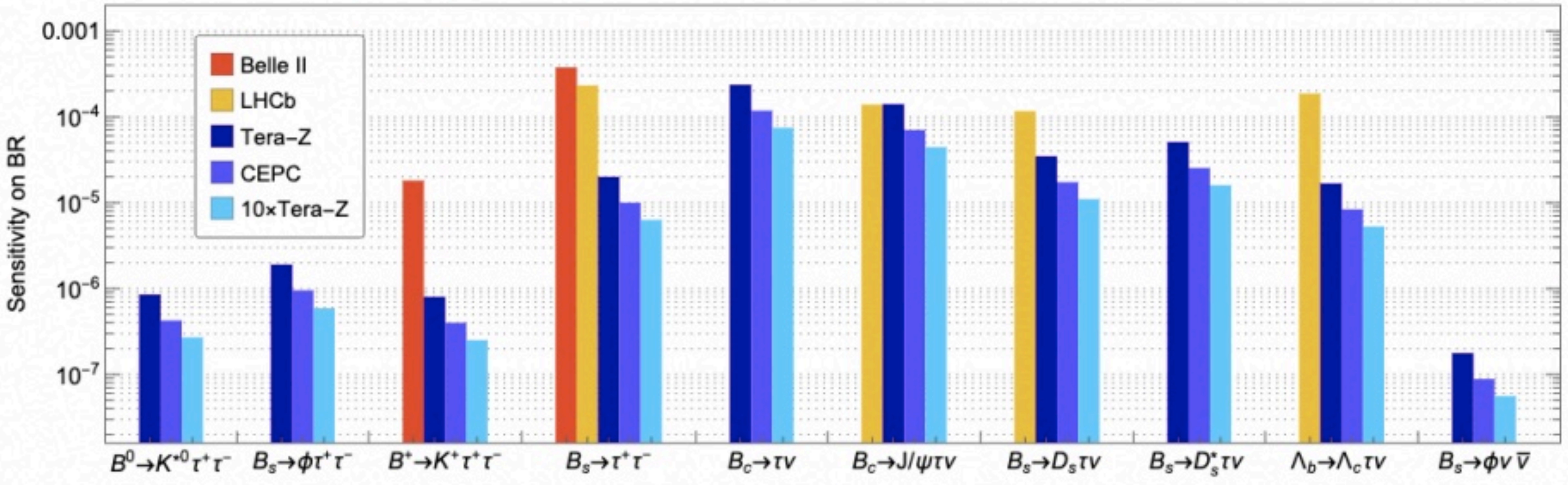


Figure 18: Projected sensitivities of measuring the $b\to s\tau\tau$ [70], $b\to s\nu\bar{\nu}$ [34] and $b\to c\tau\nu$ [35, 62] transitions at the Z pole. The sensitivities at Belle II @ 50 ab^{-1} [6] and LHCb Upgrade II [17, 71] have also been provided as a reference. Note, the LHCb sensitivities are generated by combining the analyses of $\tau^+\to\pi^+\pi^-\pi^-(\pi^0)\nu$ and $\tau\to\mu\nu\bar{\nu}$. This plot is adapted from [35].

Other available documents:

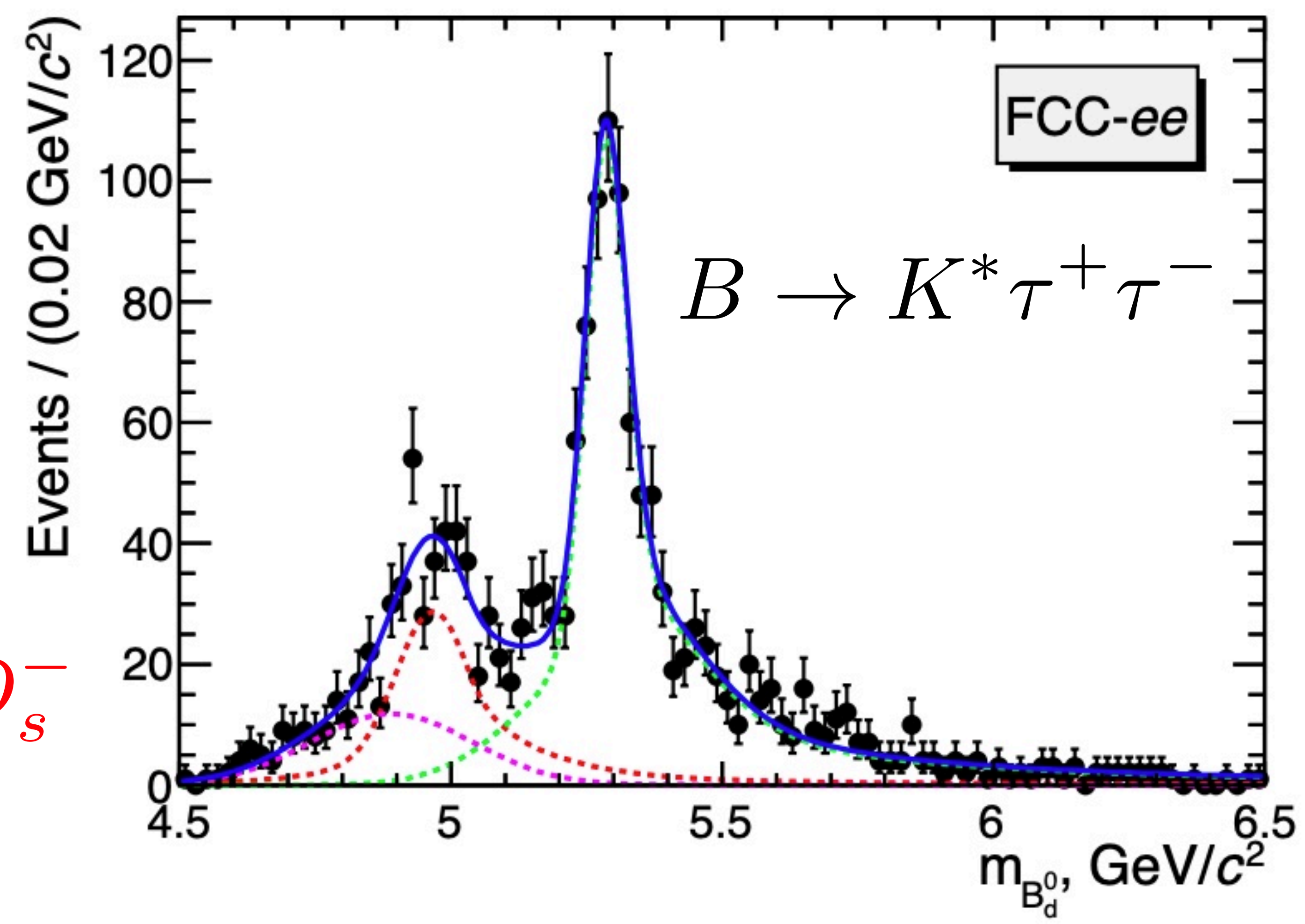
- CEPC Conceptual Design Report (CDR), 1811.10545
- FCC-ee Conceptual Design Report (CDR), inspire1, 2

$$e^+e^- \rightarrow Z \rightarrow b\bar{b}$$

Two-taus mode

- $B_s \to \tau^+\tau^-$ and $B \to K^{(*)}\tau^+\tau^-$ are candidates to study the LFU-violating new physics, which is motivated by the B anomalies. First measurement of $B_s \to \phi\tau^+\tau^-, \Lambda_b \to \Lambda\tau^+\tau^-$
- Boosted τ with $\tau \to 3\pi^\pm + \nu_\tau$ can reconstruct neutrino momentum, and hence the decay kinematics of $B_{(s)}$-meson is fully solvable even if two-tau modes

[FCC-ee CDR]



Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$
Belle II	$\sim 2\,000$	~ 10
LHCb Run I	150	-
LHCb Upgrade	~ 5000	-
FCC-ee	~ 200000	~ 1000

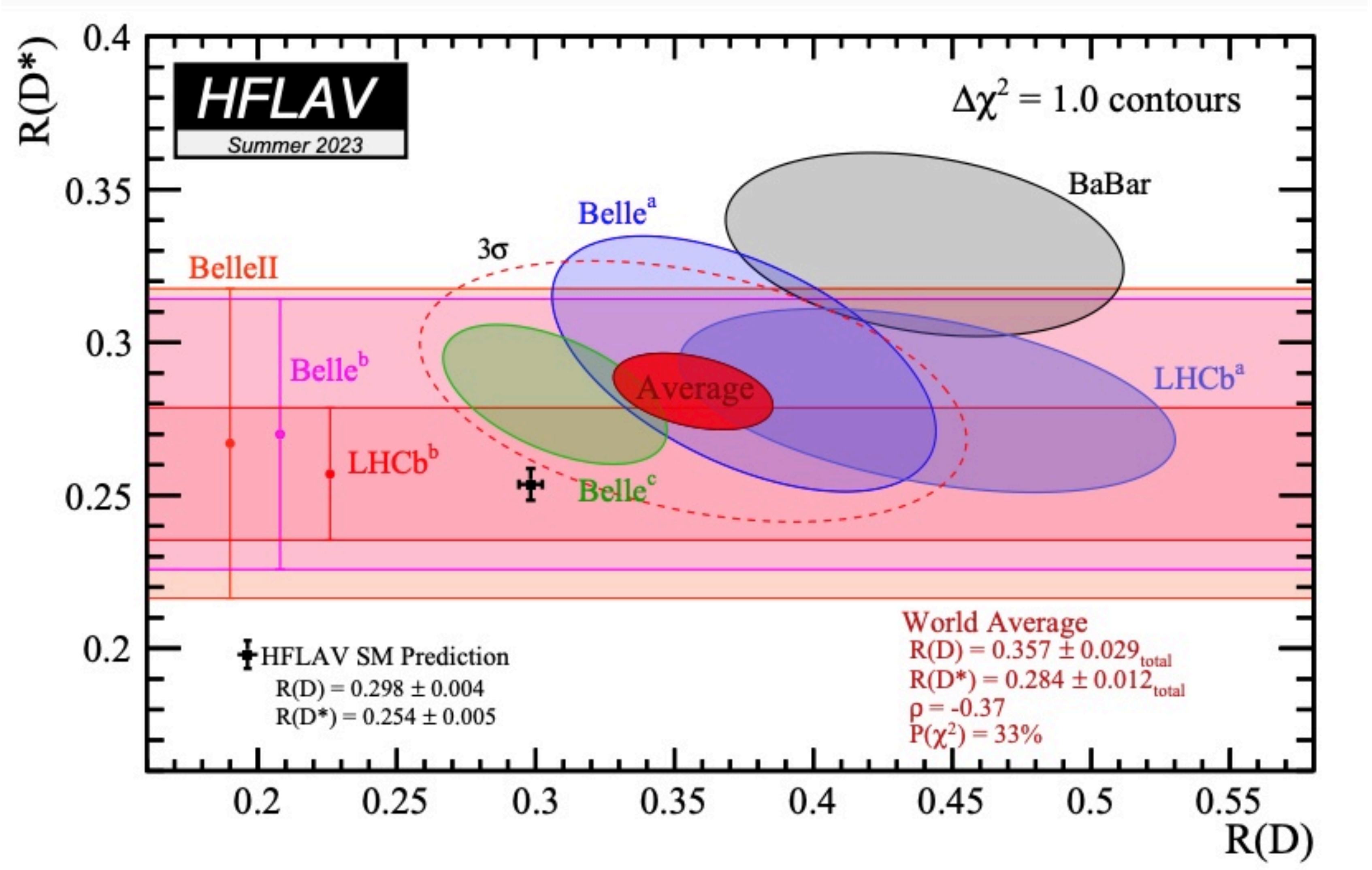
$$\mathrm{BR}(B \to \tau^+\tau^-)_{\mathrm{CEPC}} < 4 \times 10^{-6}$$
$$\mathrm{BR}(B_s \to \tau^+\tau^-)_{\mathrm{CEPC}} < 2 \times 10^{-5}$$

[CEPC CDR]

New physics search

- New physics motivated by the B anomaly can be probed by two-taus mode [Capdevila, et al, 1712.01919]

[HFLAV summer2023]

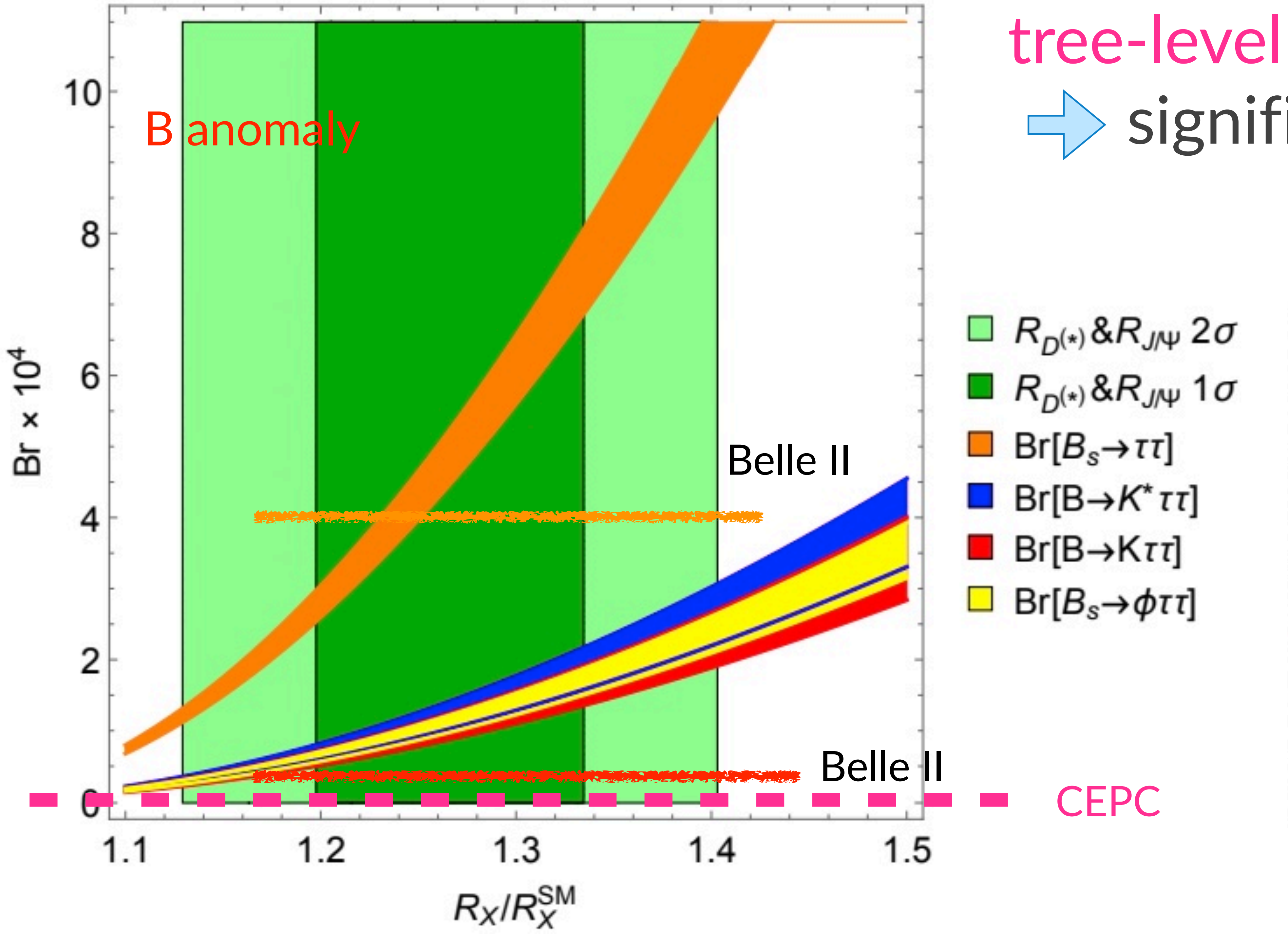


currently,
3.3σ deviation

$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\bar{\tau}\nu_\tau)}{\mathrm{BR}(B \to D^{(*)}\bar{\ell}\nu_\ell)}$$

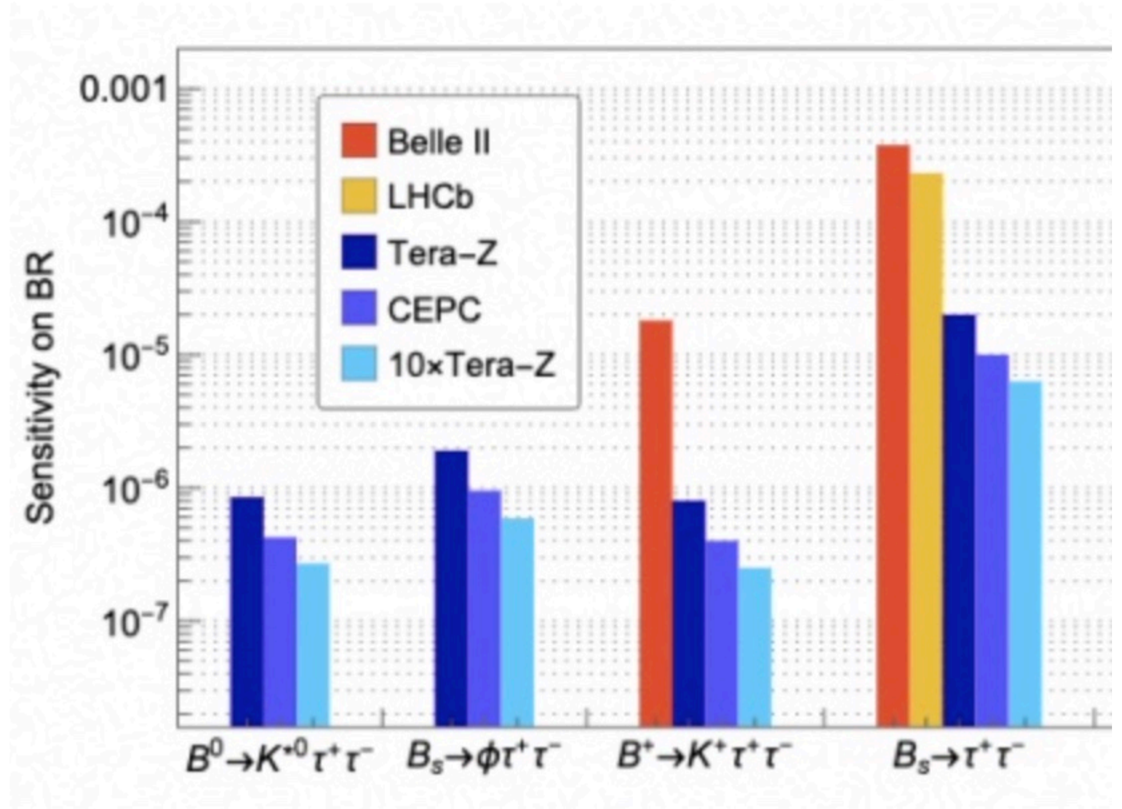
Naive SU(2)L relation in NP sector

$$b \to c\tau\nu_\tau \approx b \to s\tau\tau$$



tree-level NP vs loop+GIM SM
⇨ significantly sensitive to NP

[CEPC White Paper]



Single tau: $B_c^+ \to \tau\nu$ and $B^+ \to \tau\nu$

- $B_c^+ \to \tau\nu$ is unobserved channel, while $B^+ \to \tau\nu$ was measured by Belle and BaBar with 30% precision
- Theoretical clean channels and one can in principal extract $|V_{cb}|$ and $|V_{ub}|$
- $B_c^+ \to \tau\nu$ is sensitive to $(bc\tau\nu)$ scalar interactions, amplified by $m_{B_c}^2/m_\tau^2$, which are directly correlated to the B-anomaly $[R(D^{(*)}); b \to c\tau\nu$; LFU violation $(\tau/\ell)]$
- CEPC Tera-Z simulation [Zheng, et al, 2007.08234], and FCC-ee Tera-Z [Amhis, et al, 2105.13330; Fedele, et al, 2305.02998]
- The BDT classification is possible for $B_c^+ \to \tau\nu$ and $B^+ \to \tau\nu$ signals at Z-pole decay

Process	Bc category	Bu category
$N(B_c^+ \to \tau^+\nu_\tau)$	10000.7	474.2
$N(B^+ \to \tau^+\nu_\tau)$	1144.7	10009.5
$N(Z \to b\bar{b})$	364.5	2778.8
$N(Z \to c\bar{c})$	83.9	28.5

Expected yield of different processes in both Bc and Bu categories.

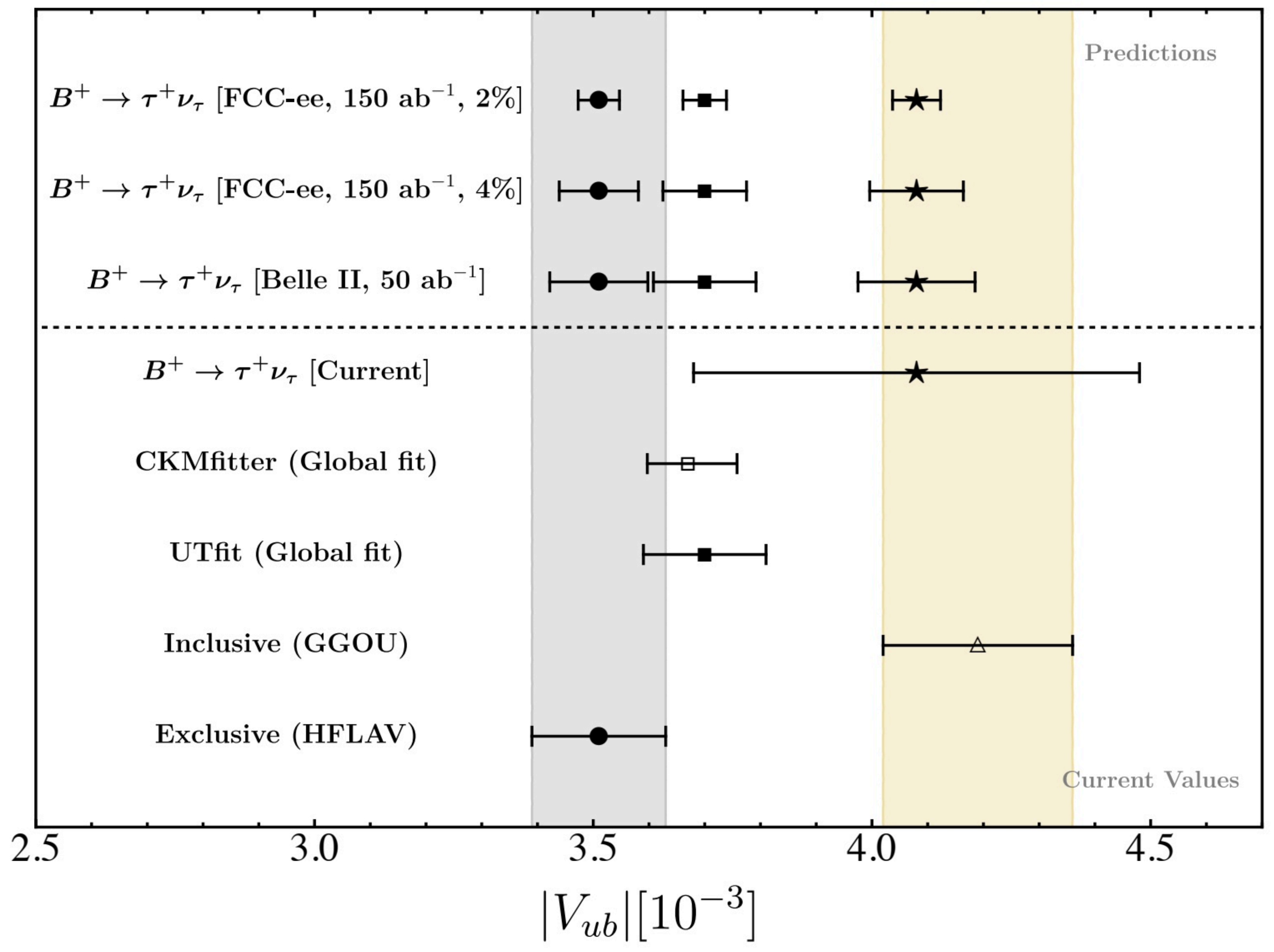
New physics search

- FCC-ee sensitivity (5 Tera-Z): [Amhis, et al, 2105.13330; Fedele, et al, 2305.02998]

  $\mathrm{BR}(B_c^+ \to \tau\nu)$: 1.7%—2.6% precision for idealistic/pessimistic

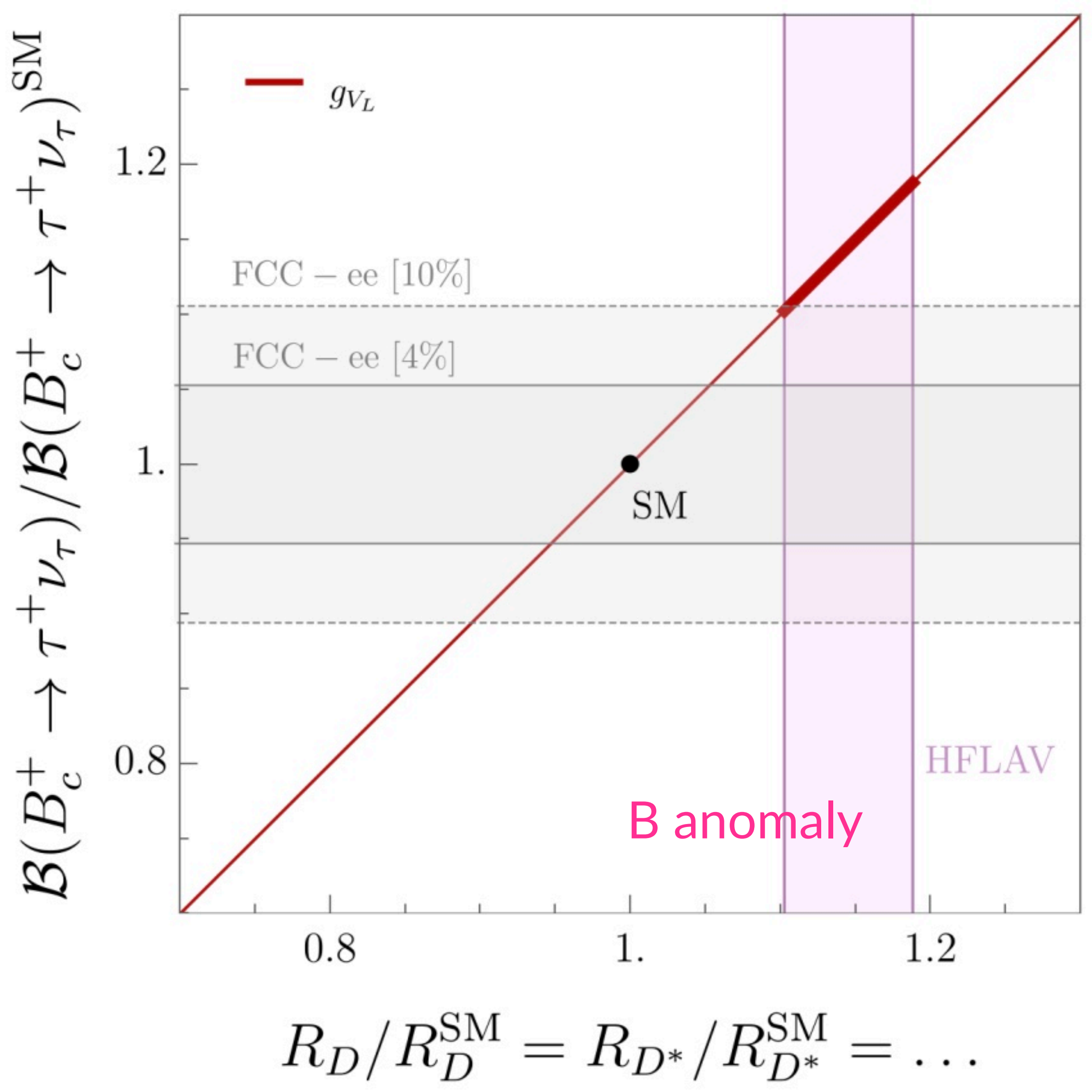
  $\mathrm{BR}(B^+ \to \tau\nu)$: 1.9%—4.0% precision

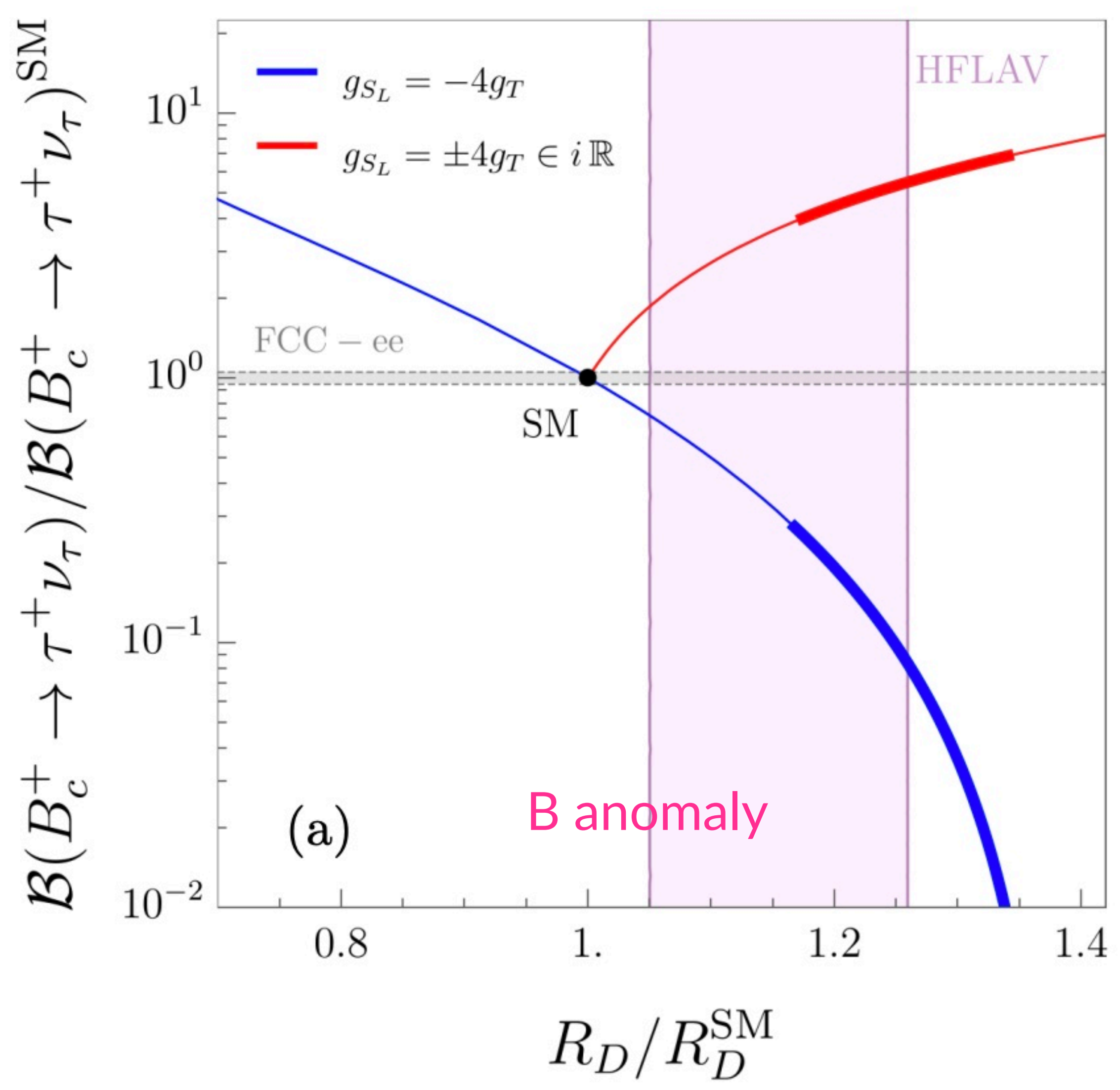
|Vub| extraction



$B^+ \to \tau\nu$ will be a new method for |Vub|

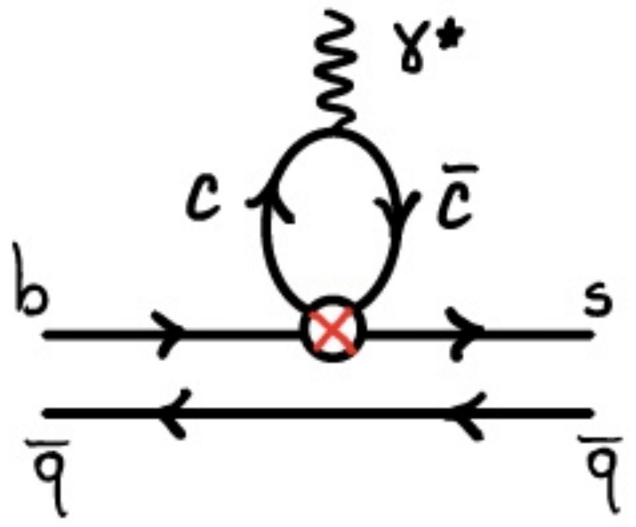
correlation to the B anomaly



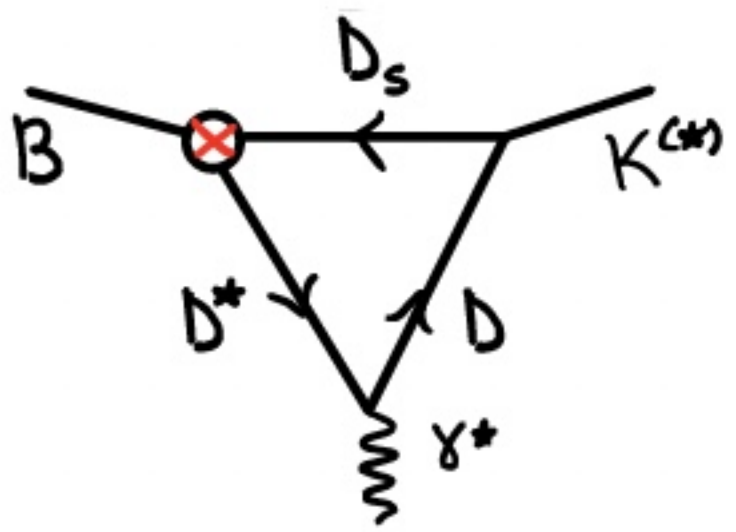


Data-driven determination of non-perturbative QCD

- Understanding of the non-perturbative charm-quark contribution to $b \to s\ell^+\ell^-$, which is LFU, is needed in light of $b \to s\mu^+\mu^-$ anomaly
- Large statistics allows precise measurement of $B \to K^* e^+ e^-$ with angular analysis, and one can determine the non-perturbative effect



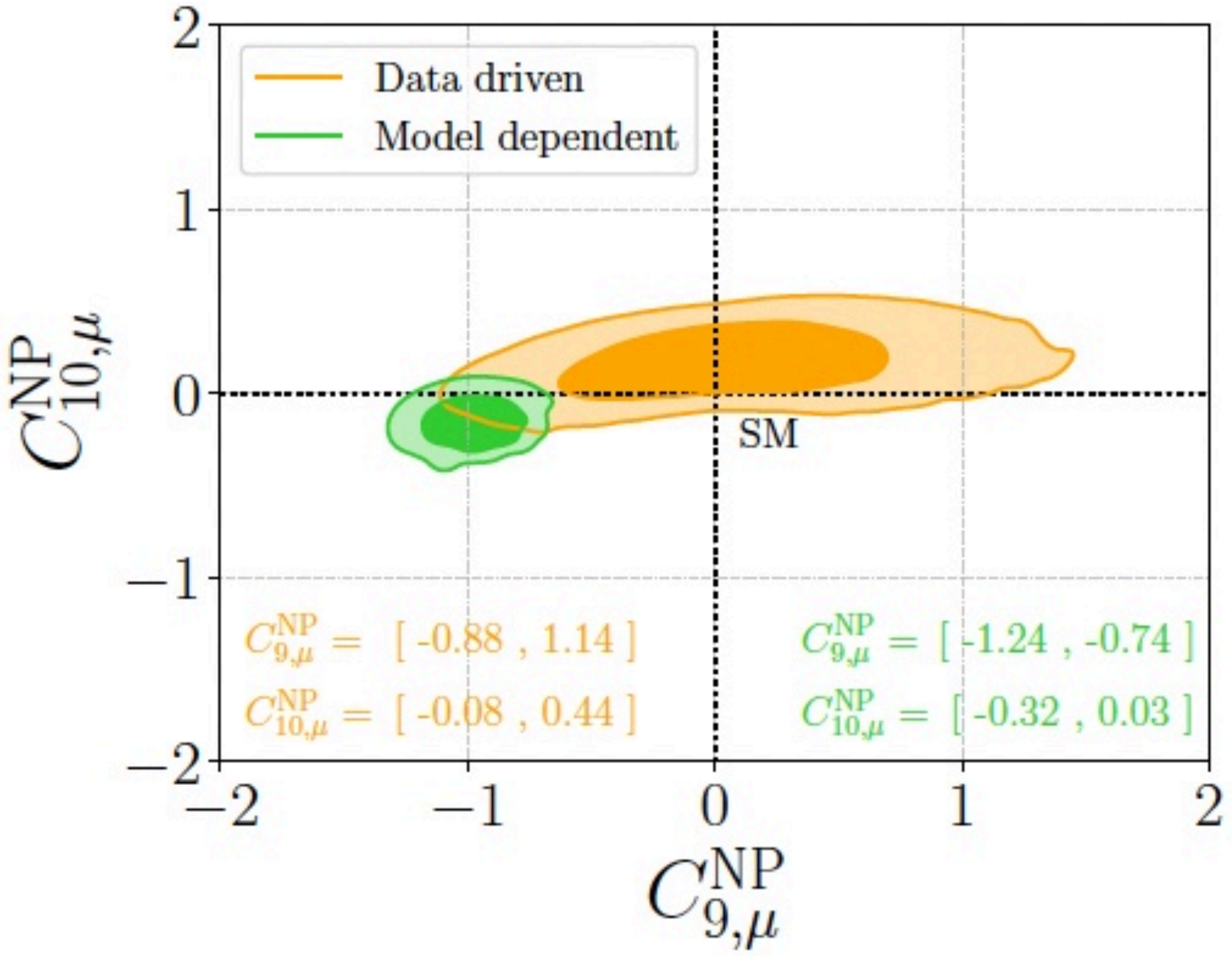
off-shell J/Ψ charm-penguin



rescattering effect

[Ciuchini, et al, 2212.10516]

$b \to s\mu^+\mu^-$ anomaly



Decay mode	$B^0 \to K^*(892)e^+e^-$
Belle II	$\sim$ 2 000
LHCb Run I	150
LHCb Upgrade	$\sim$ 5000
FCC-ee	$\sim$ 200000

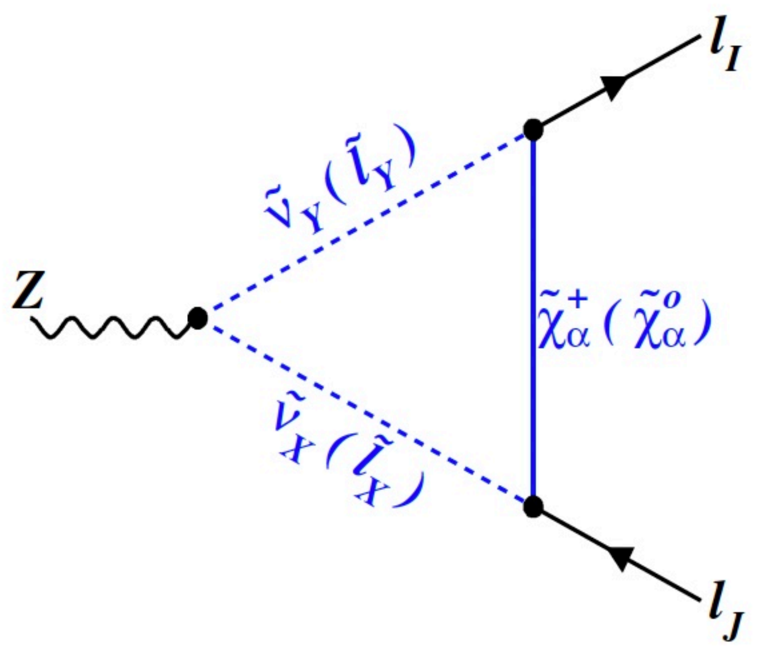
$$e^+e^- \to Z \to \ell_I^+\ell_J^-$$

Z-FCNC

- Leptonic Z-FCNC decay ($Z \to \ell_I^+ \ell_J^-$) never occurs within the SM (m_ν suppression).
  Therefore, Tera-Z physics provides a great opportunity to search LFV new physics

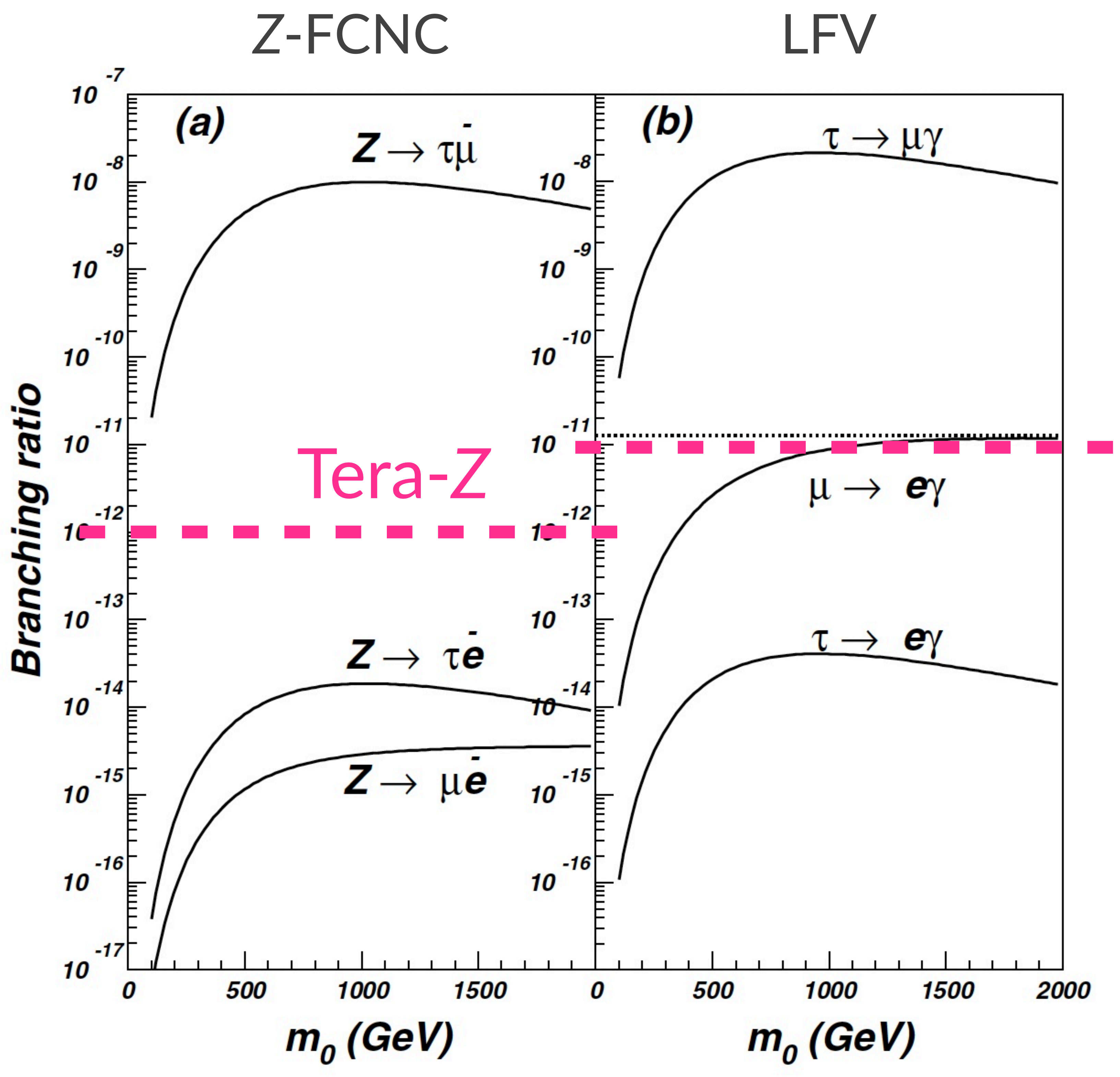
- Supersymmetric seesaw model (MSSM+heavy right–handed Majorana mass) is a good target; The LFV is inevitable through the renormalization group equation

$$\delta(\mathbf{m}^2_{\tilde{L}})_{IJ} \simeq -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)(\mathbf{Y}_\nu^{0\dagger}\mathbf{Y}_\nu^0)_{IJ} \ln\left(\frac{M_P}{M_M}\right)$$



$Z \to \tau\mu$ and $\tau \to \mu\gamma$ are most sensitive; and accessible

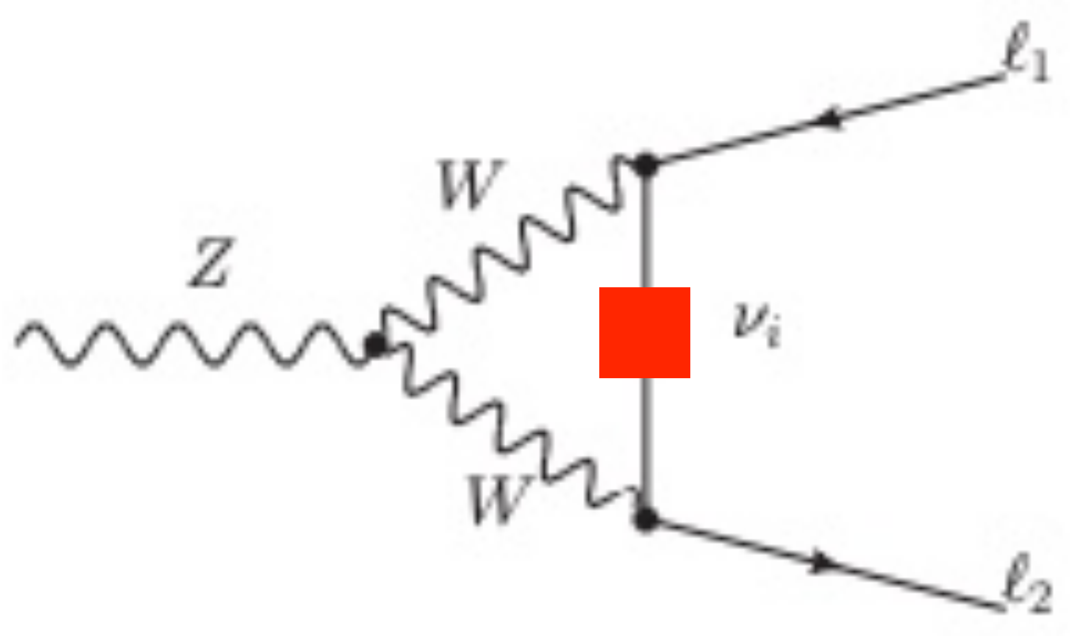
[Cao, Xiong, Yang, hep-ph/0307126]



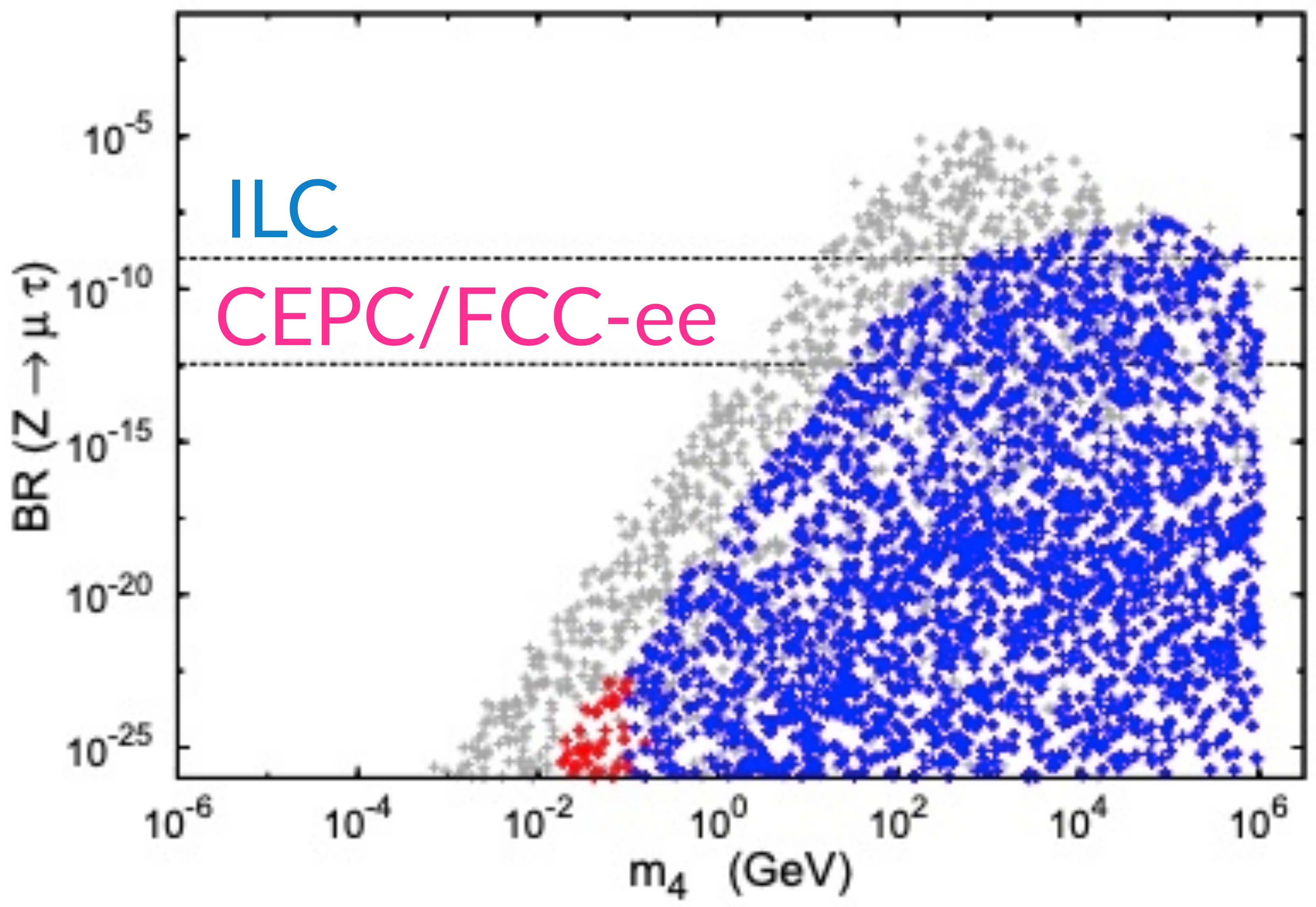
Z-FCNC

- Leptonic Z-FCNC decay ($Z \to \ell_I^+ \ell_J^-$) can also probe sterile neutrino indirectly
- $m_4 \gtrsim 100$ GeV region is accessible in Tera-Z factory

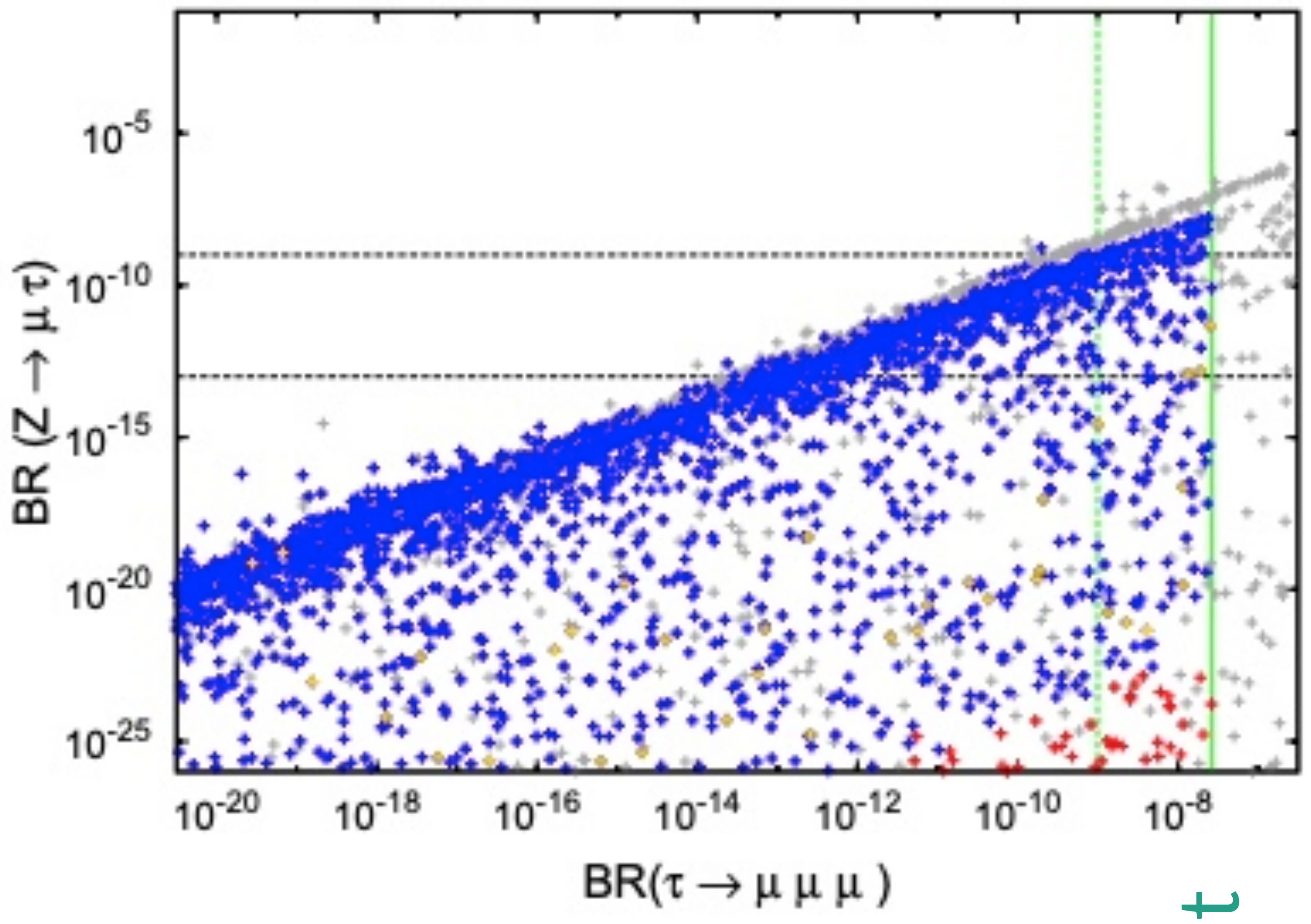
[Abada, et al., 1412.6322]



sterile neutrino mass



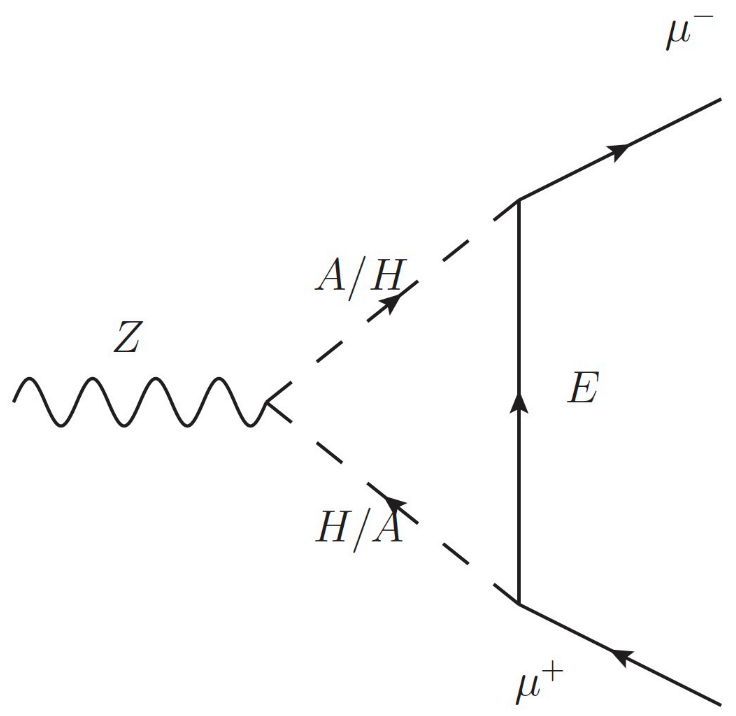
blue: standard cosmology
red: non-standard
gray: excluded



Electroweak phase transition at Z-pole

- The BAU can be explained by electroweak baryogenesis, which requires a strong 1st-order phase transition and additional CP violation

- In the additional Higgs sector, a large mass difference between M_H and M_A is needed for the strong 1st-order phase transition [Huang, Senaha, 1905.10283]

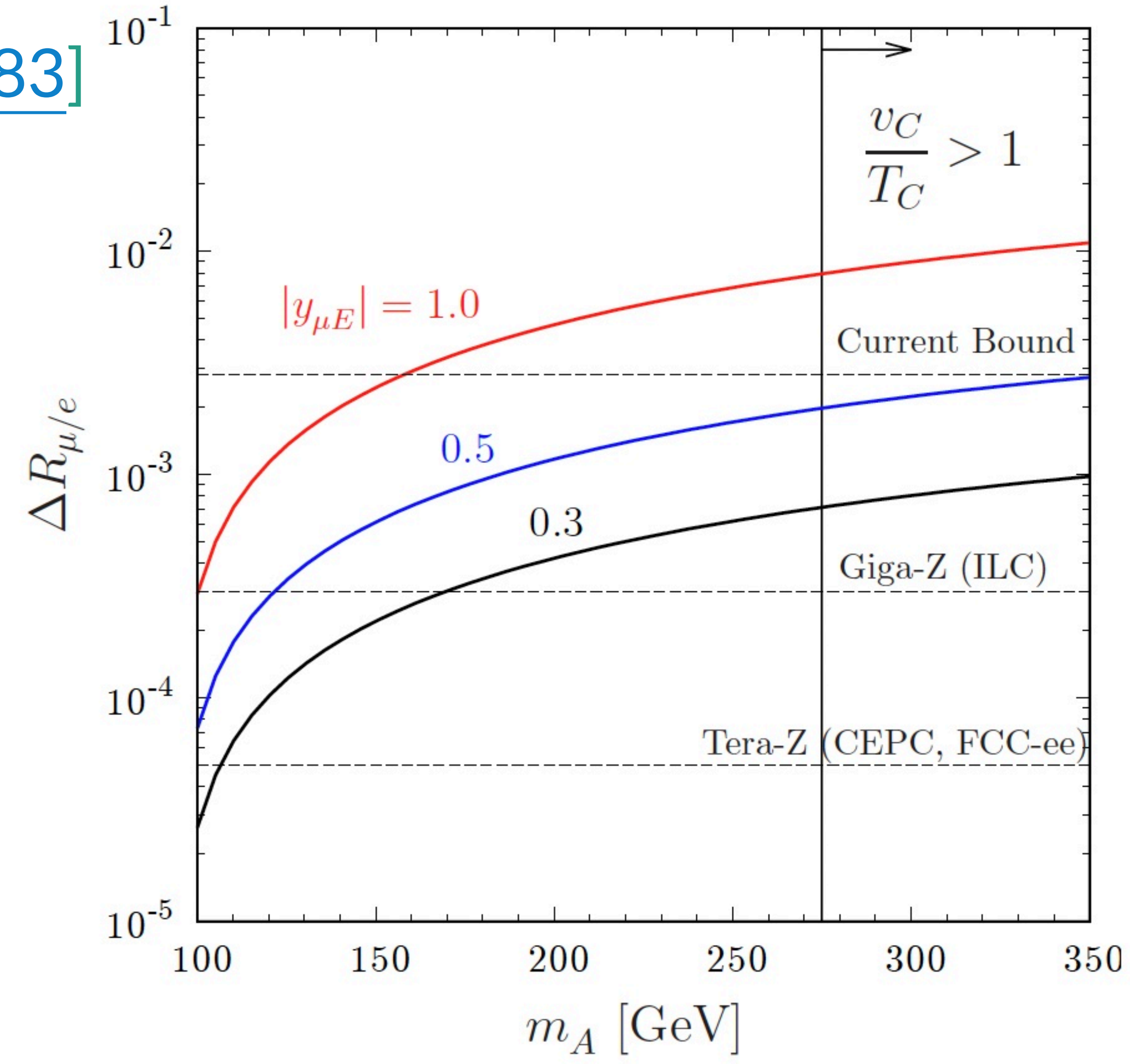


enhanced by $\log(M_A^2/M_H^2)$

For the CP violation, additional fermion would be needed

When it is muophilic fermion (motivated by muon g-2 anomaly)

$$R_{\mu/e} = \frac{\Gamma(Z \to \mu^+\mu^-)}{\Gamma(Z \to e^+e^-)}$$



$$e^+e^- \to W^+W^-,\ W \to q\bar{q}'$$

W inclusive-hadronic decay

- Inclusive hadronic decay of W boson, $W \to q\bar{q}'$, is proportional to (in the massless q limit)

$$\propto |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 + |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2$$

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$: 1

$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2$: 1

= 2 in the CKM unitarity

= 2.002(27) from flavor

uncertainty comes from $|V_{cs}|$

O(1%) precision

- Inclusive hadronic decay can determine $|V_{cs}|$ and direct test the CKM unitarity
[d'Enterria, Srebre, 1603.06501; CMS, 2201.07861]

CMS Run2 35.9fb-1 result:

$$\mathrm{BR}(W \to q\bar{q}') = (67.46 \pm 0.04_{\mathrm{stat}} \pm 0.28_{\mathrm{syst}})\ \%$$

direct measurement

$$\mathrm{BR}(W \to q\bar{q}') = (67.32 \pm 0.02_{\mathrm{stat}} \pm 0.23_{\mathrm{syst}})\ \%$$

assuming LFU

	$\lvert V_{cs}\rvert$	unitarity test
CMS Run2	0.967 (11)	1.984 (21)
flavor	0.987 (11)	2.002 (27)

Syst. error budget for *W* inclusive-hadronic decay [CMS, 2201.07861]

	$W \to e\bar{\nu}_e$	$W \to \mu\bar{\nu}_\mu$	$W \to \tau\bar{\nu}_\tau$	$W \to q\bar{q}'$
Pileup	20	6	11	14
Luminosity	5	14	5	7
JES/JER	3–17	5–21	4–11	4–21
b tagging	<1–19	<1–25	<1–5	<1–17
tW normalization	35	43	27	46
WW normalization	8	9	5	9
WW p_T	1–2	1–2	<1–5	<1–4
W+jets normalization	<1–6	<1–7	<1–13	<1–10
γ+jets normalization	1	2	5	4
WZ, ZZ normalization	<1	1	<1	<1
$t\bar{t}$ production:				
QCD scale	32	47	25	45
top quark p_T	16	24	7	18
ISR	10	16	37	37
FSR	3	4	9	5
PDF	4	5	3	4
α_S	5	5	3	6
PYTHIA 8 UE tune	1	5	7	7
hdamp parameter	3	3	2	4
Drell–Yan background:				
QCD scale	2–24	10–27	5–20	8–30
PDF	3	5	2	4
QCD multijet background:				
$e\mu$	5	12	12	6
eh	3–4	11–17	6–7	6–10
μh	10–11	10–13	5–13	2–3
$e\tau_h$	<1–5	<1–8	<1–9	<1–7
$\mu\tau_h$	<1–12	<1–10	<1–9	<1–10
e measurement:				
Reconstruction efficiency	50	13	3	15
Identification efficiency	<1–14	1–8	<1–10	<1–5
Trigger (prefiring)	29	2	1	9
Trigger	<1–27	<1–4	<1–13	<1–9
Energy scale	7	6	<1	4
μ measurement:				
Reconstruction efficiency	<1–2	<1–5	<1–6	<1–6
Trigger	8	26	3	7
Energy scale	1	<1	3	2
τ_h measurement:				
Reconstruction efficiency	2–14	7–17	21–46	14–24
Energy scale	9	5	14	6
Jet misidentification	1–14	<1–10	1–24	<1–10
e misidentification	<1	<1	2	1
$\tau \to e, \mu, h$	<1	<1	<1–2	<1–1

CMS Run2 35.9fb-1 result:

$$\mathrm{BR}(W \to q\bar{q}') = (67.46 \pm 0.04_{\mathrm{stat}} \pm 0.28_{\mathrm{syst}})\,\%$$

direct measurement

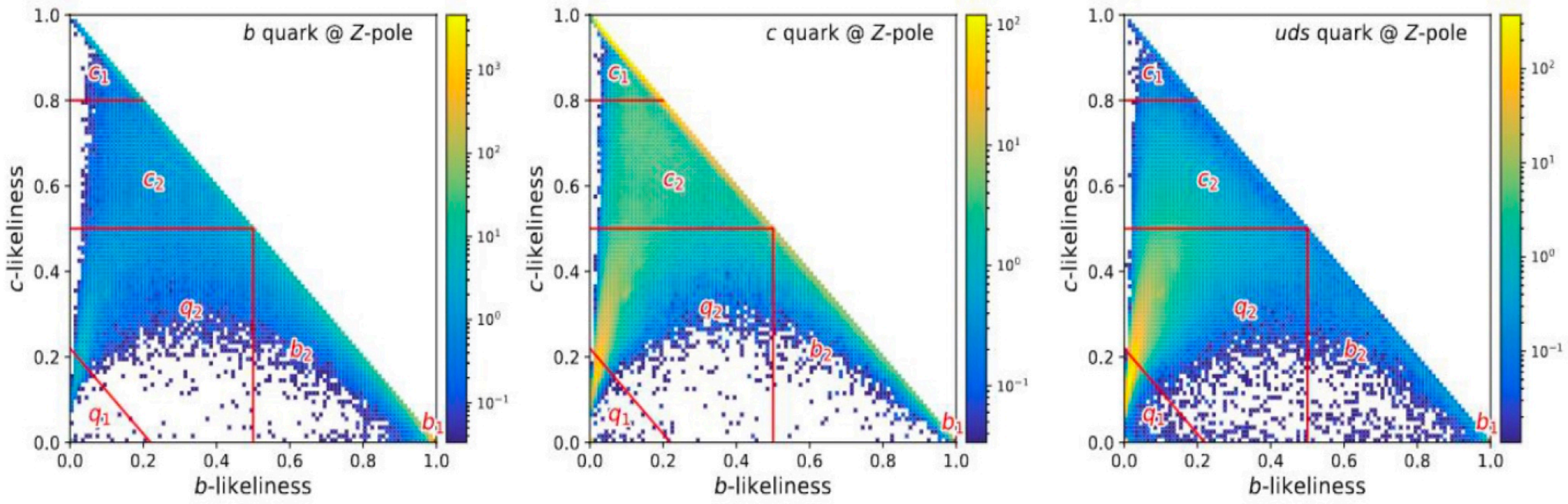
$$\mathrm{BR}(W \to q\bar{q}') = (67.32 \pm 0.02_{\mathrm{stat}} \pm 0.23_{\mathrm{syst}})\,\%$$

assuming LFU

Syst. errors are dominated by the theoretical error of the top-associated *W* production cross section

$|V_{cb}|$ from W decay

- CEPC plans to probe $|V_{cb}|$ from $e^+e^- \to W^+W^-, W \to bc, W \to \ell\nu$

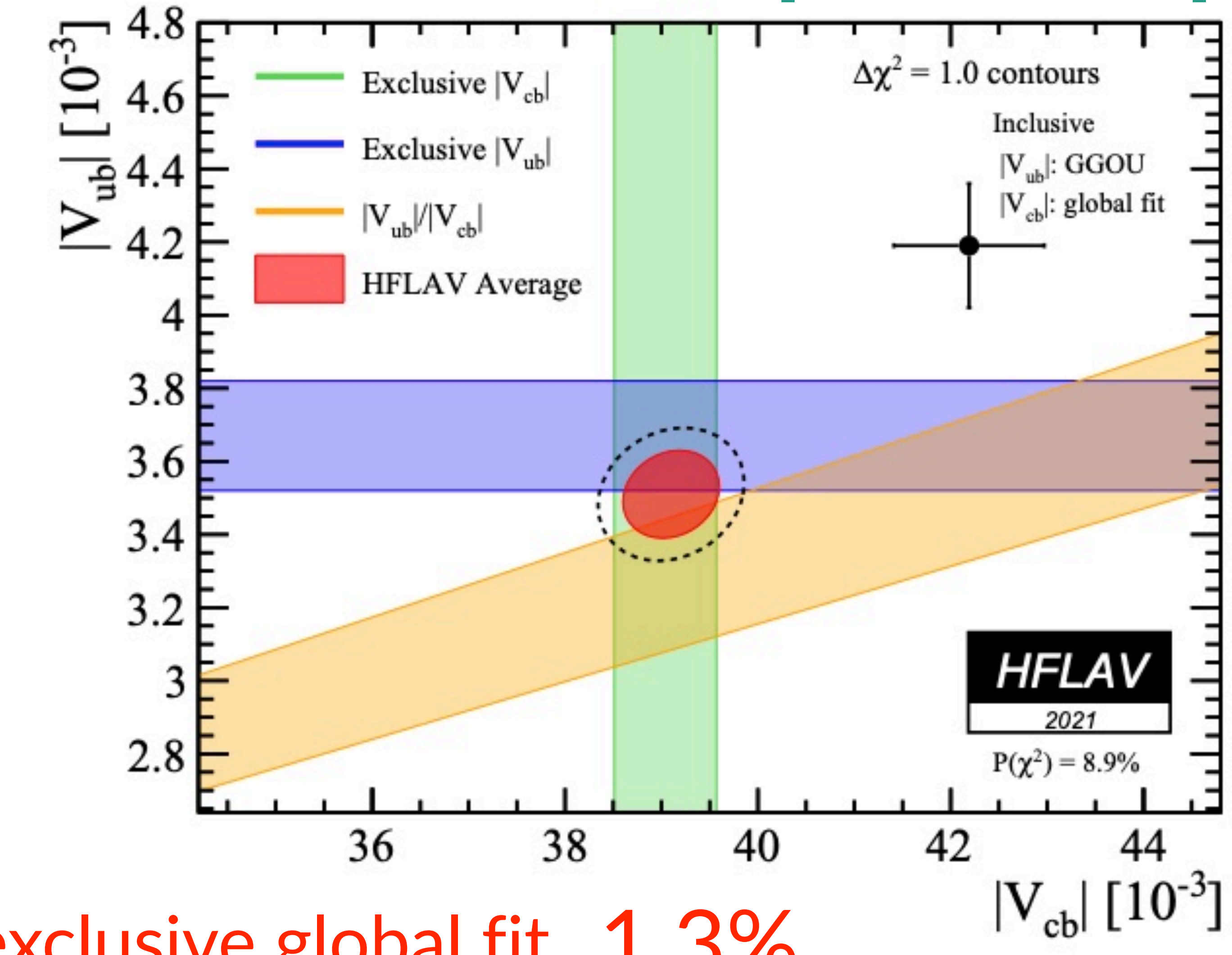


quark \ tag	b_1	b_2	c_1	c_2	q_1	q_2
b	0.47	0.378	0.0197	0.0965	0.00397	0.0315
c	0.00042	0.078	0.298	0.373	0.0682	0.182
uds	0.000104	0.00477	0.00145	0.054	0.538	0.401

Source by slide of Manqi Ruan at Higgs2023

$|V_{cb}|$ could be measured to a relative uncertainty of 0.4% at CEPC nominal set up

[HFLAV2021]



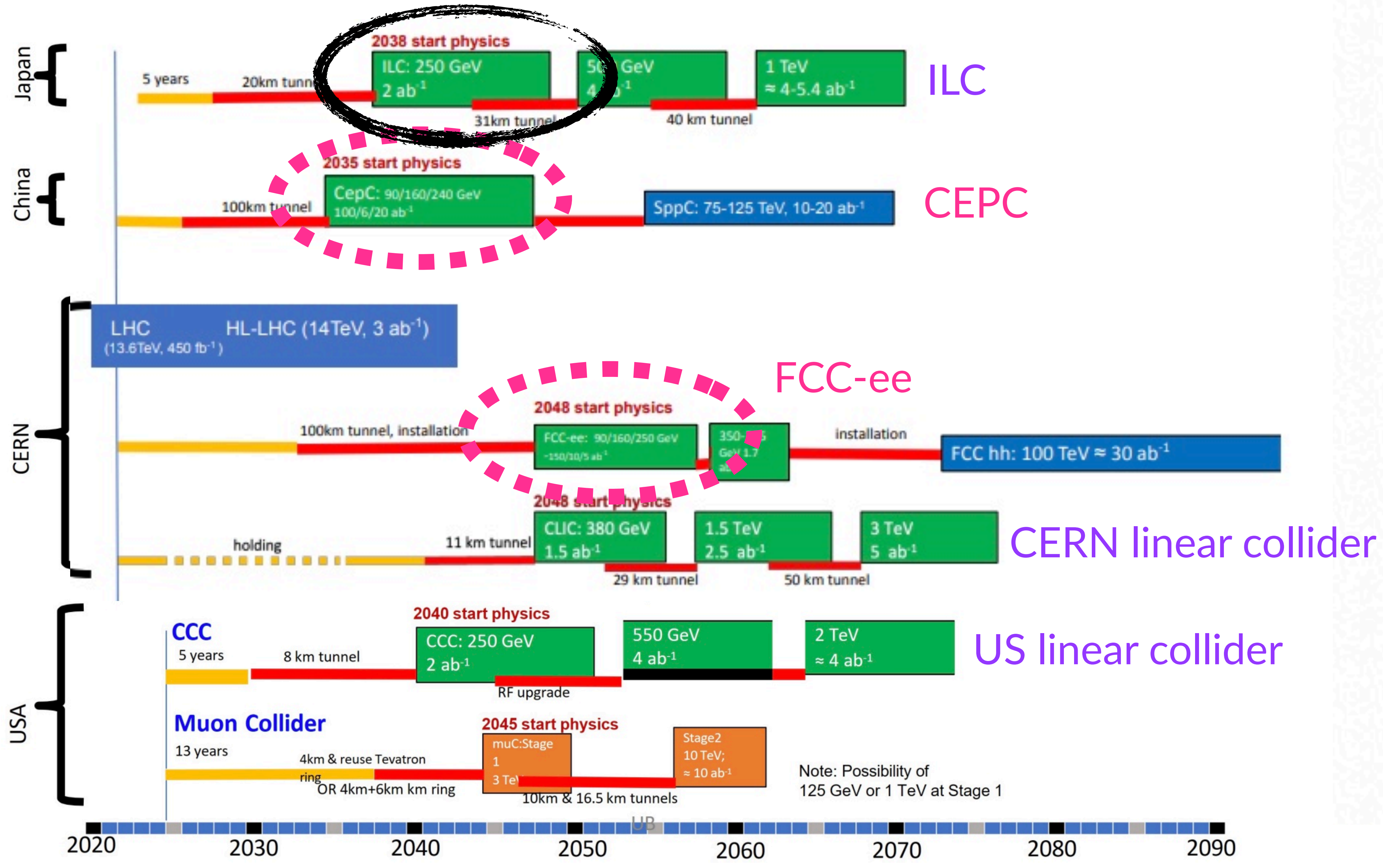
1.8% inclusive global fit

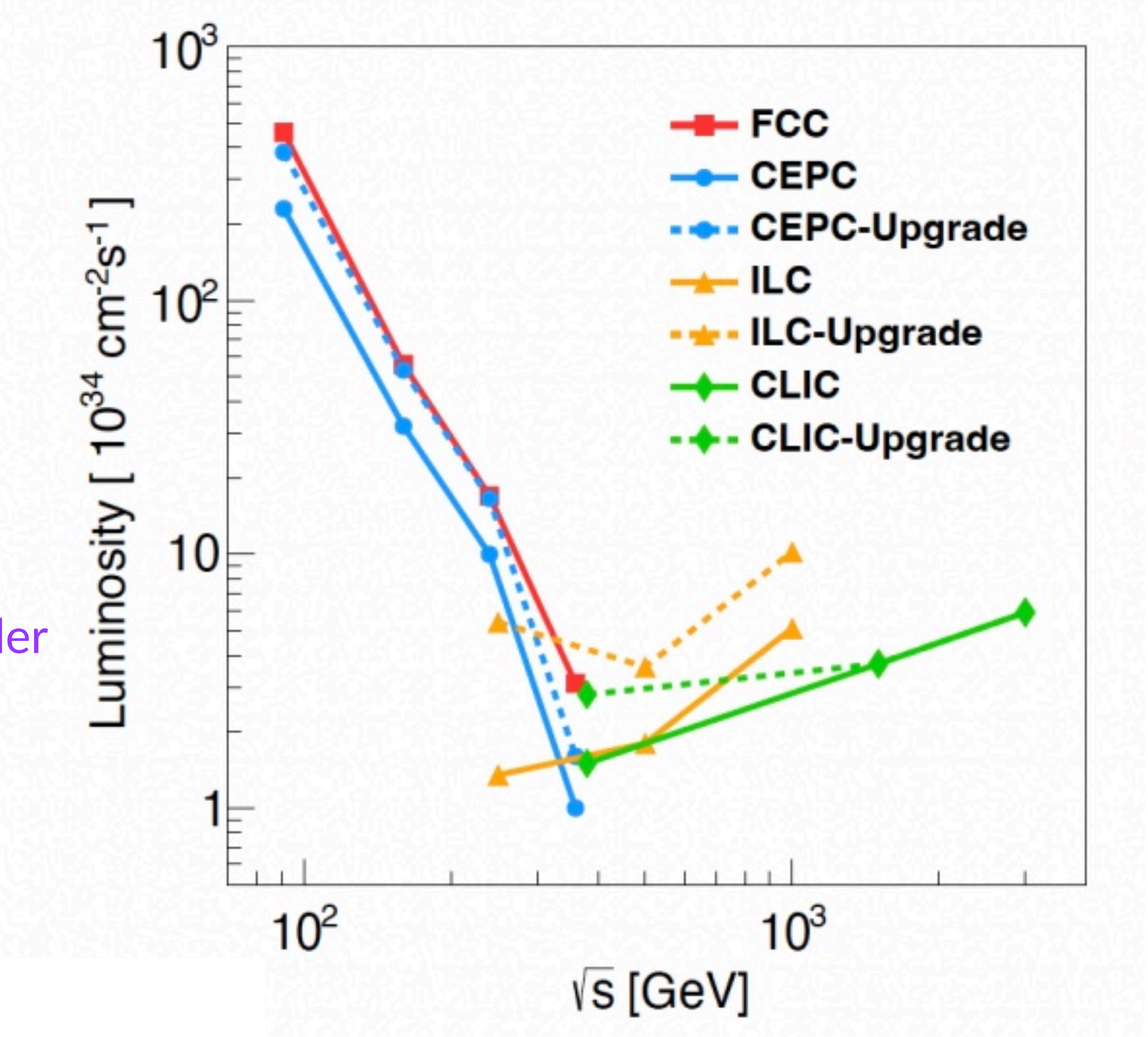
exclusive global fit 1.3%

What is the role of the linear colliders?

- Linear colliders are one and two orders of magnitude smaller statistics than Belle II and CEPC/FCC-ee setups, respectively

- If the construction of CEPC is postponed, B_s, B_c^+, Λ_b, Z-FCNC, W-hadronic decays are promising at the ILC





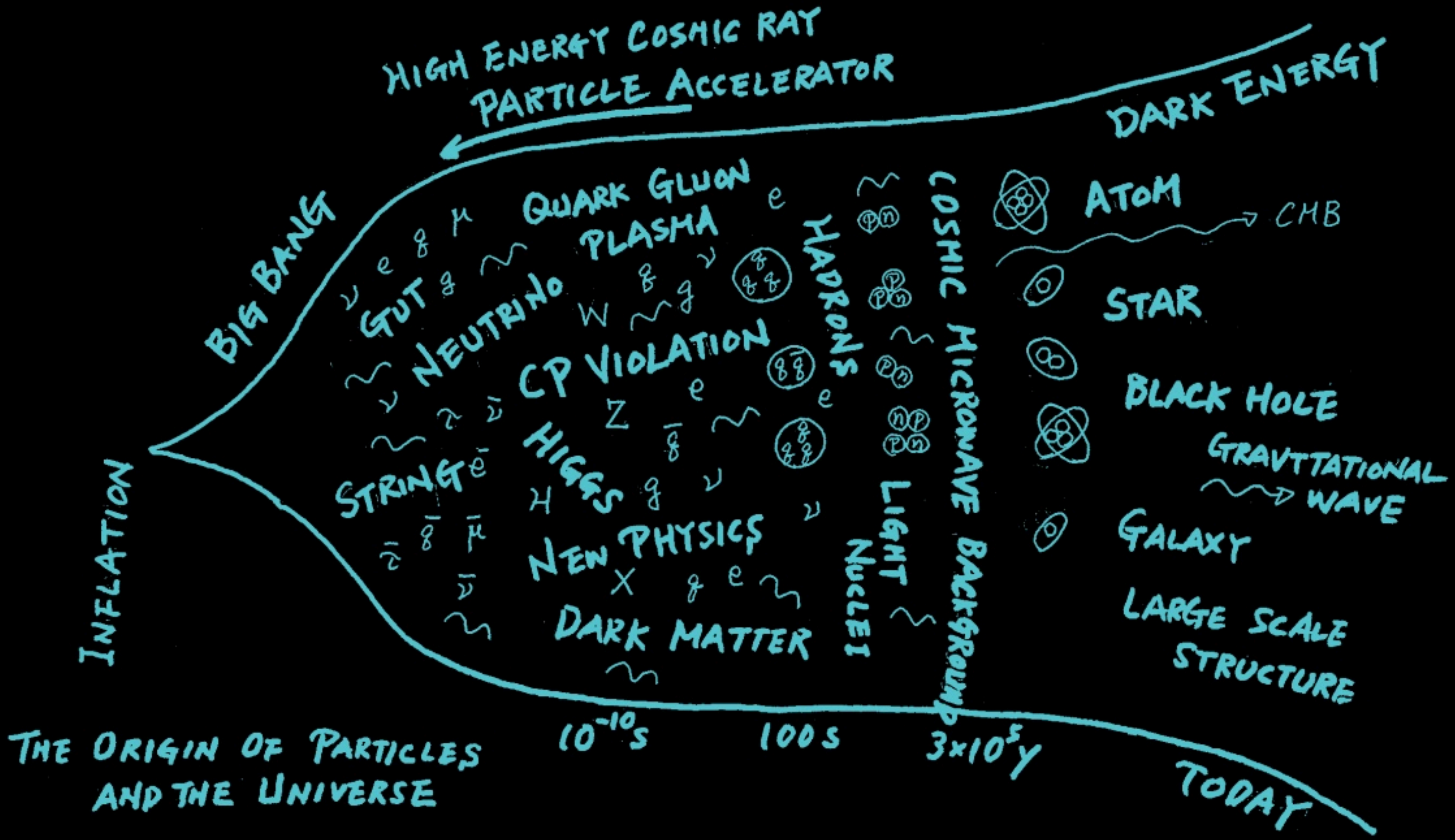
open question:

Do beam polarizations at the ILC provide any help?

Summary

- The e^+e^- Higgs factories can also be utilized as the flavor factories on Z and W decays
- 10 times statistics and better efficiency at Tera-Z factory allow to improve the precision in many flavored channels
- NP motivated by the B anomaly can be probed through two-taus and single-tau modes
- Data-driven determination of non-perturbative QCD effect is possible
- Z-FCNC search is complementary to the ongoing LFV search experiments
- W-hadronic decays provide new information of the CKM components

Backup slides



(c) KMI/Nagoya-U

[CEPC CDR]

Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
$\mathrm{BR}(B_s \to ee)$	2.8×10^{-7} (CDF) [438]	$\sim 7 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \mu\mu)$	0.7×10^{-9} (LHCb) [437]	$\sim 1.6 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \tau\tau)$	5.2×10^{-3} (LHCb) [441]	$\sim 5 \times 10^{-4}$ (LHCb) [435]	$\sim 10^{-5}$
R_K, R_{K^*}	$\sim 10\%$ (LHCb) [443, 444]	$\sim$few% (LHCb/Belle II) [435, 442]	$\sim$few %
$\mathrm{BR}(B \to K^*\tau\tau)$	–	$\sim 10^{-5}$ (Belle II) [442]	$\sim 10^{-8}$
$\mathrm{BR}(B \to K^*\nu\nu)$	4.0×10^{-5} (Belle) [449]	$\sim 10^{-6}$ (Belle II) [442]	$\sim 10^{-6}$
$\mathrm{BR}(B_s \to \phi\nu\bar{\nu})$	1.0×10^{-3} (LEP) [452]	–	$\sim 10^{-6}$
$\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})$	–	–	$\sim 10^{-6}$
$\mathrm{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar) [475]	$\sim 10^{-9}$ (Belle II) [442]	$\sim 10^{-9}$
$\mathrm{BR}(\tau \to 3\mu)$	2.1×10^{-8} (Belle) [476]	$\sim$ few $\times 10^{-10}$ (Belle II) [442]	$\sim$ few $\times 10^{-10}$
$\frac{\mathrm{BR}(\tau\to\mu\nu\bar{\nu})}{\mathrm{BR}(\tau\to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar) [464]	$\sim 10^{-3}$ (Belle II) [442]	$\sim 10^{-4}$
$\mathrm{BR}(Z \to \mu e)$	7.5×10^{-7} (ATLAS) [471]	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9} - 10^{-11}$
$\mathrm{BR}(Z \to \tau e)$	9.8×10^{-6} (LEP) [469]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-11}$
$\mathrm{BR}(Z \to \tau\mu)$	1.2×10^{-5} (LEP) [470]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-10}$

Table 2.5: Order of magnitude estimates of the sensitivity to a number of key observables for which the tera-Z factory at CEPC might have interesting capabilities. The expected future sensitivities assume luminosities of $50\,\mathrm{fb}^{-1}$ at LHCb, $50\,\mathrm{ab}^{-1}$ at Belle II, and $3\,\mathrm{ab}^{-1}$ at ATLAS and CMS. For the tera-Z factory of CEPC we have assumed the production of 10^{12} Z bosons.