International CEPC Workshop 2025

Flavour physics at future e^+e^- colliders

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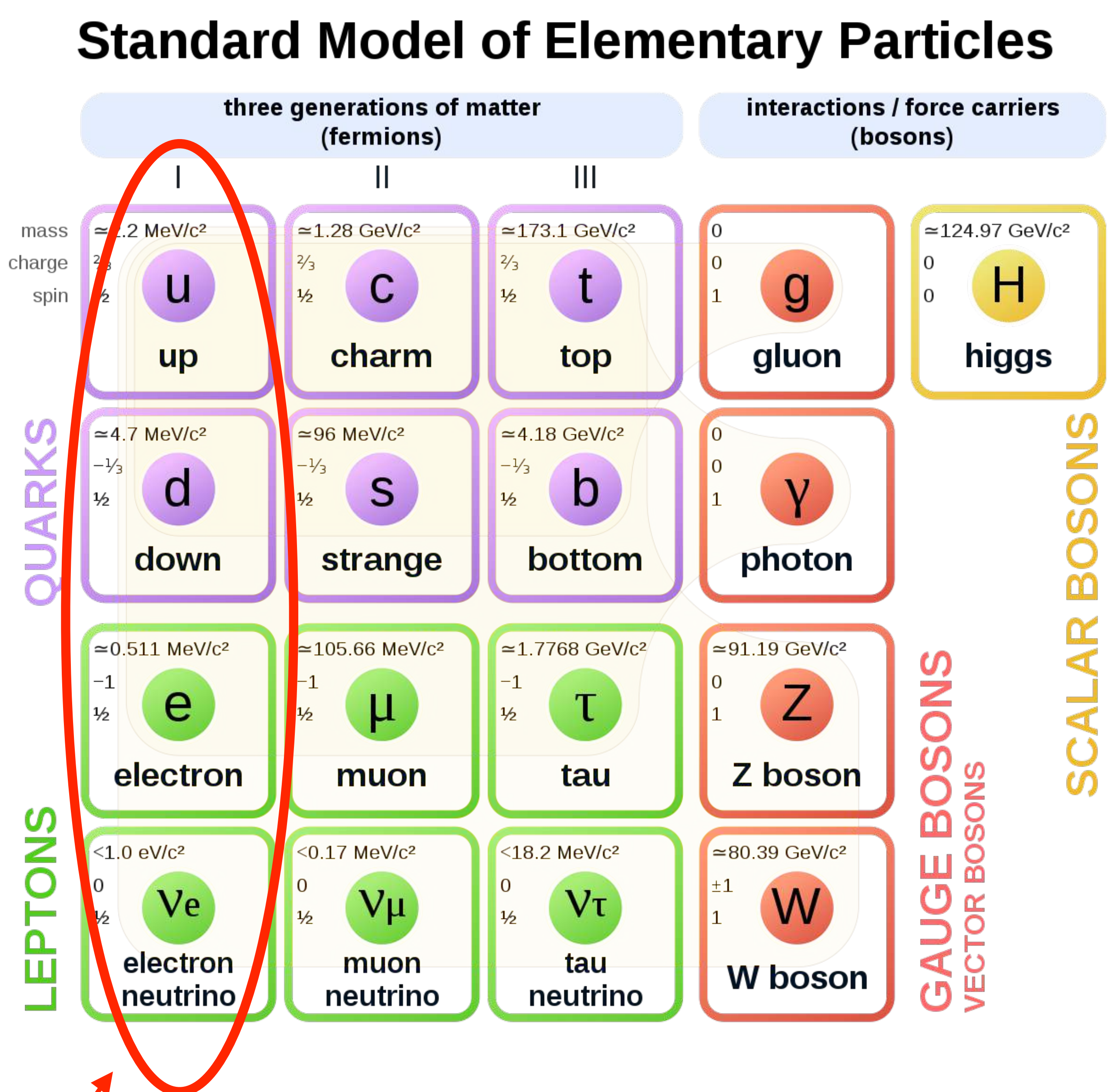
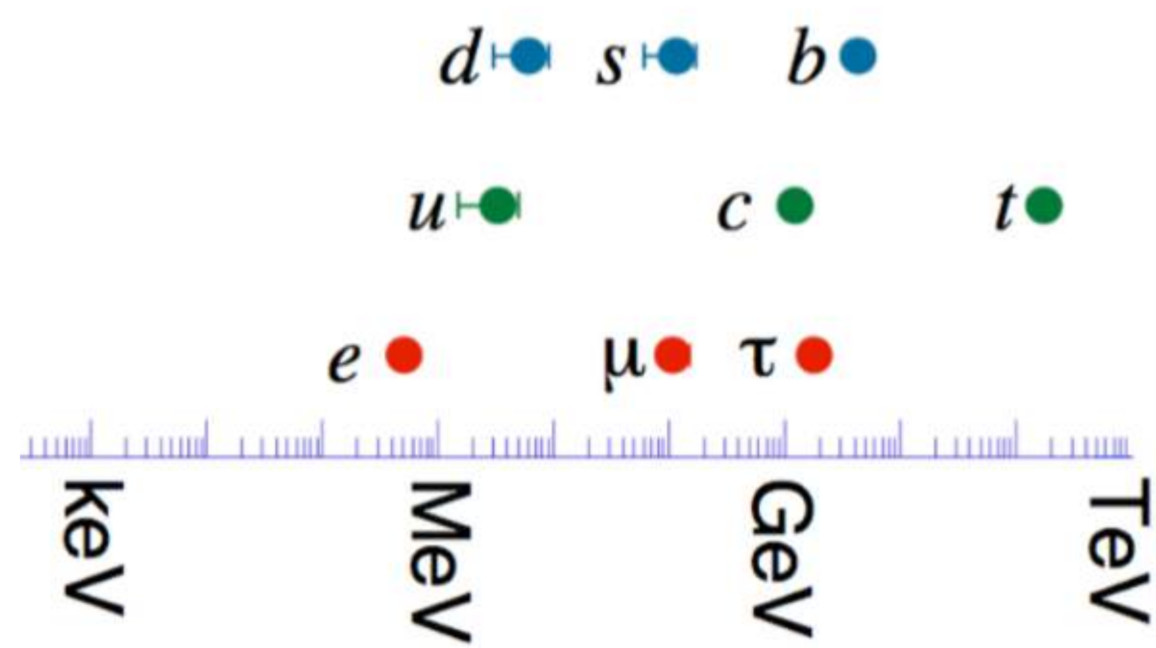
Why flavour?

see e.g. J. Zupan's review arXiv:1903.05062





3 fermion generations (or families)

Hierarchical fermion masses

You are here (why?)

(why?)

Flavor in the SM

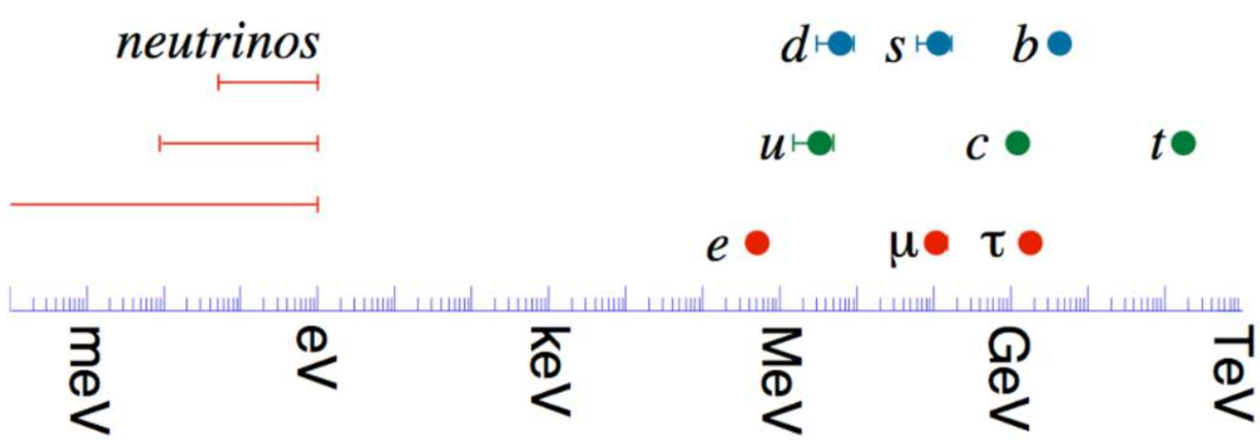
courtesy of O. Sumensari

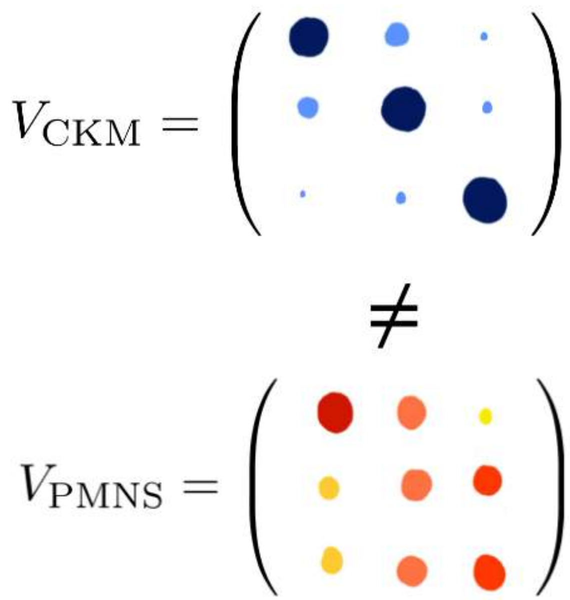
- The SM **flavor sector** is **loose**: (*even w/o considering neutrinos*)

⇒ 13 free parameters (masses and quark mixing) — *fixed by data.*

$$\mathcal{L}_{\rm Yuk} = -Y_d^{ij}\,\overline{Q}_i d_{Rj}\, H - Y_u^{ij}\,\overline{Q}_i u_{Rj}\, \widetilde{H} - Y_\ell^{ij}\,\overline{L}_i e_{Rj}\, H + \text{h.c.}$$

⇒ These (many) parameters exhibit a hierarchical structure which we do not understand.





How to **explain the observed patterns** in terms of **less** and **more fundamental parameters**?

Why is Flavour Physics important?

SM flavour puzzle

- Why three families?
- Why the hierarchies?

We need to find the scale of New Physics!

- LHC found a SM-like Higgs
- No sign of new phenomena

Do we really need New Physics?

- Hierachy Problem (?)
- Dark Matter/Dark Energy
- Inflation
- Neutrino masses
- Baryon asymmetry
- Origin of flavour hierarchies

...

Why flavour?

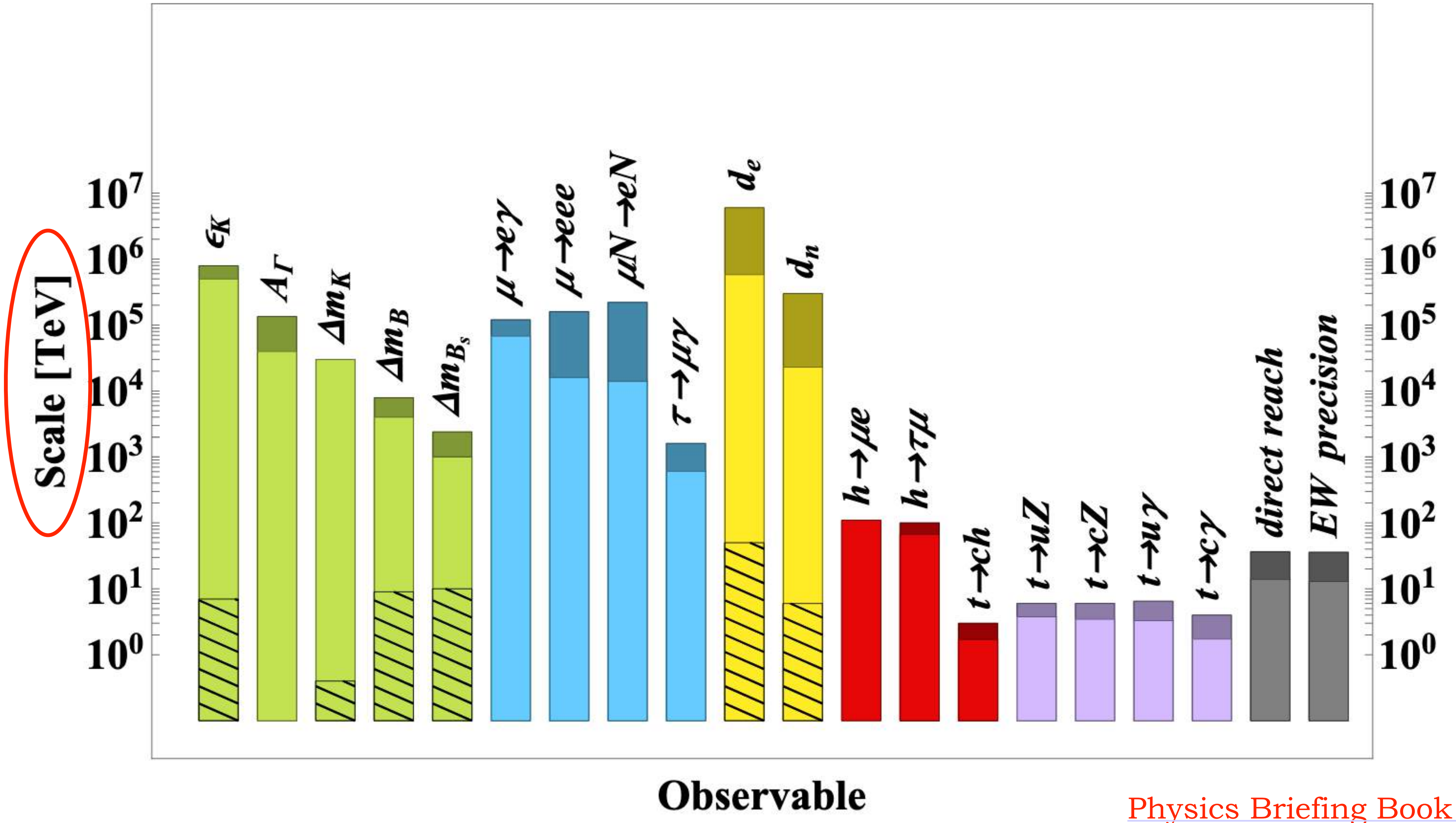
Do we really need New Physics?

- Hierachy Problem (?) → *TeV-scale New Physics?*
- Dark Matter/Dark Energy
- Inflation
- Neutrino masses → *see-saw?*
- Baryon asymmetry → *new sources of CPV? leptogenesis?*
- Origin of flavour hierarchies → *symmetries of flavour?*

...

Testable through hadronic/leptonic flavour/CP violation?

Sensitivity to new physics scale



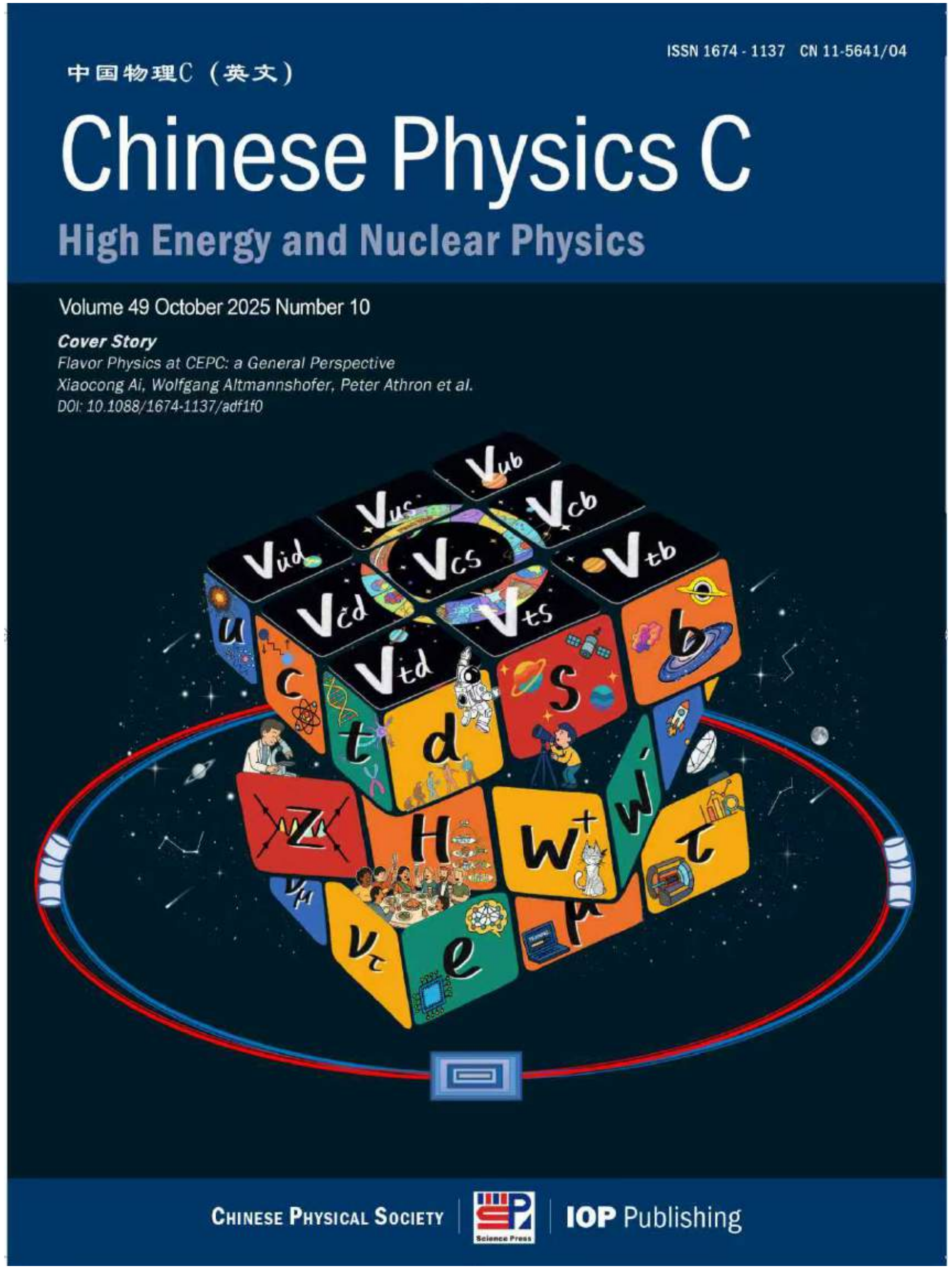
Physics Briefing Book ESPPU 2020

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \ldots$$

Tera Z as a flavour factory

Warning: here we focus on the CEPC,
but everything applies to the FCC-ee too!

Recent cover story (and editors suggestion) on CPC



Thanks to Wang Yuexin for the cover design!

Flavor Physics at the CEPC: a General Perspective

Xiaocong Ai[1], Wolfgang Altmannshofer[2], Peter Athron[3], Xiaozhi Bai[4], Lorenzo Calibbi[5*], Lu Cao[6,7], Yuzhi Che[8,9], Chunhui Chen[10], Ji-Yuan Chen[31], Long Chen[11], Mingshui Chen[8,9,77], Shanzhen Chen[8,9,77†], Xuan Chen[11], Shan Cheng[12], Cheng-Wei Chiang[13], Andreas Crivellin[14,15], Hanhua Cui[8,9], Olivier Deschamps[16], Sébastien Descotes-Genon[17], Xiaokang Du[18], Shuangshi Fang[8,9], Yu Gao[8,9], Yuanning Gao[46], Li-Sheng Geng[19], Pablo Goldenzweig[20], Jiayin Gu[21,22,23], Feng-Kun Guo[24,9,25†], Yuchen Guo[26,27], Zhi-Hui Guo[28†], Tao Han[29], Hong-Jian He[30,31], Jibo He[9], Miao He[8,9], Xiaogang He[30,31,65] Yanping Huang[8,9], Gino Isidori[15], Quan Ji[8,9], Jianfeng Jiang[8,9], Xu-Hui Jiang[8,32,33], Jernej F. Kamenik[34,35], Tsz Hong Kwok[33†], Gang Li[8,9], Geng Li[36], Haibo Li[8,9], Haitao Li[11], Hengne Li[37], Honglei Li[38], Liang Li[31,65,66], Lingfeng Li[39,33*], Qiang Li[40], Qiang Li[46], Shu Li[30,31], Xiaomei Li[41], Xin-Qiang Li[42†], Yiming Li[8,9], Yubo Li[43], Yuji Li[6], Zhao Li[8,9], Hao Liang[8,9], Zhijun Liang[8,9], Libo Liao[44], Zoltan Ligeti[45], Jia Liu[46], Jianbei Liu[75,76], Tao Liu[33*], Yi Liu[1], Yong Liu[8,9], Zhen Liu[47], Xinchou Lou[8,77,78], Peng-Cheng Lu[11], Alberto Lusiani[48], Hong-Hao Ma[49], Kai Ma[50], Farvah Mahmoudi[79,80,81], Yajun Mao[46], Yaxian Mao[42], David Marzocca[51], Juan-Juan Niu[49], Soeren Prell[10], Huirong Qi[8,9], Sen Qian[8,9], Zhuoni Qian[52], Qin Qin[53†], Ariel Rock[33], Jonathan L. Rosner[54,55], Manqi Ruan[8,9,77*], Dingyu Shao[6], Chengping Shen[56,23], Xiaoyan Shen[8,9], Haoyu Shi[8,9], Liaoshan Shi[57†], Zong-Guo Si[11], Cristian Sierra[3], Huayang Song[24], Shufang Su[58], Wei Su[44], Zhijia Sun[8,9,62] Michele Tammaro[59], Dayong Wang[46], En Wang[1], Fei Wang[1], Hengyu Wang[8,9], Jian Wang[11], Jianchun Wang[8,9,77], Kun Wang[74], Lian-Tao Wang[54], Wei Wang[31,60], Xiaolong Wang[56], Xiaoping Wang[19], Yadi Wang[61], Yifang Wang[8,9,77], Yuexin Wang[8,62†], Xing-Gang Wu[63], Yongcheng Wu[3], Rui-Qing Xiao[30,31,64], Ke-Pan Xie[19], Yuehong Xie[42], Zijun Xu[8,9], Haijun Yang[30,31,65,66], Hongtao Yang[4], Lin Yang[30], Shuo Yang[26,27], Zhongbao Yin[42], Fusheng Yu[67], Changzheng Yuan[8,9], Xing-Bo Yuan[42], Xuhao Yuan[8,9], Chongxing Yue[26,27], Xi-Jie Zhan[68], Hong-Hao Zhang[82] Kaili Zhang[8,62], Liming Zhang[69], Xiaoming Zhang[42], Yang Zhang[1], Yanxi Zhang[46], Ying Zhang[83] Yongchao Zhang[70], Yu Zhang[71], Zhen-Hua Zhang[72], Zhong Zhang[57,70], Mingrui Zhao[41], Qiang Zhao[8,9], Xu-Chang Zheng[63], Yangheng Zheng[9], Chen Zhou[46], Daicui Zhou[42], Pengxuan Zhu[24], Yongfeng Zhu[46], Xuai Zhuang[8,9], Xunwu Zuo[20†], Jure Zupan[73]

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You can find it here:
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~150 authors/endorsers

~80 institutions

~70 pages (+biblio)

CEPC flavour white paper

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A vast subject: today, I can only mention
a few selected topics (guided by personal bias)

Nominal operation scheme (50 MW) as in the CEPC Accelerator TDR:

Operation mode	Z factory	WW threshold	Higgs factory	$t\bar{t}$
$\sqrt{s}$ (GeV)	91.2	160	240	360
Run time (year)	2	1	10	5
Instantaneous luminosity ($10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, per IP)	191.7	26.7	8.3	0.83
Integrated luminosity (ab^{-1}, 2 IPs)	100	6.9	21.6	1
Event yields	4.1×10^{12}	2.1×10^{8}	4.3×10^{6}	0.6×10^{6}

The Z-peak run is expected to deliver a few $\times 10^{12}$ visible Z decays

$$\mathrm{BR}(Z \to b\bar{b}) \approx 15\% \,,\; \mathrm{BR}(Z \to c\bar{c}) \approx 12\% \,,\; \mathrm{BR}(Z \to \tau^+\tau^-) \approx 3\%$$

⇩

Plenty of flavour physics opportunities from $Z \to bb$, $Z \to cc$, $Z \to \tau\tau$

Particle	BESIII	Belle II (50 ab^{-1} on $\Upsilon(4S)$)	LHCb (300 fb^{-1})	CEPC (4×Tera-Z)
B^0, $\bar{B}^0$	-	5.4×10^{10}	3×10^{13}	4.8×10^{11}
$B^{\pm}$	-	5.7×10^{10}	3×10^{13}	4.8×10^{11}
B_s^0, $\bar{B}_s^0$	-	6.0×10^8 (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	1.2×10^{11}
$B_c^{\pm}$	-	-	1×10^{11}	7.2×10^8
Λ_b^0, $\bar{\Lambda}_b^0$	-	-	2×10^{13}	1×10^{11}
D^0, $\bar{D}^0$	1.2×10^8	4.8×10^{10}	1.4×10^{15}	8.3×10^{11}
$D^{\pm}$	1.2×10^8	4.8×10^{10}	6×10^{14}	4.9×10^{11}
$D_s^{\pm}$	1×10^7	1.6×10^{10}	2×10^{14}	1.8×10^{11}
$\Lambda_c^{\pm}$	0.3×10^7	1.6×10^{10}	2×10^{14}	6.2×10^{10}
$\tau^+\tau^-$	3.6×10^8	4.5×10^{10}		1.2×10^{11}

Advantages of a high-energy e^+e^- collider as flavour factory:

Luminosity

$\mathcal{L}$=100/ab, O(10^{12}) Z decays ⇒ O(10^{11}) *bb*, *cc*, and $\tau\tau$ pairs

Energy

besides producing states unaccessible, *e.g.*, at Belle II
$M_Z \gg 2m_b, 2m_\tau, 2m_c$ ⇒ surplus energy, boosted decay products
(better tracking and tagging, lower vertex uncertainty etc.)

Cleanliness

as for any leptonic machine, full knowledge of the initial state
(e.g. *Z* mass constraint on invariant masses more powerful)
⇒ it enables searches involving neutral/invisible particles

What flavour physics can we study at a Tera Z?

flavour-violating Z decays

forbidden processes [lepton flavour (universality) violation, lepton/baryon number violation…]

precise measurements [CKM UT angles, CPV…]

rare decays [(semi-)leptonic B decays…]

charm physics

exotic hadrons spectroscopy

tau physics

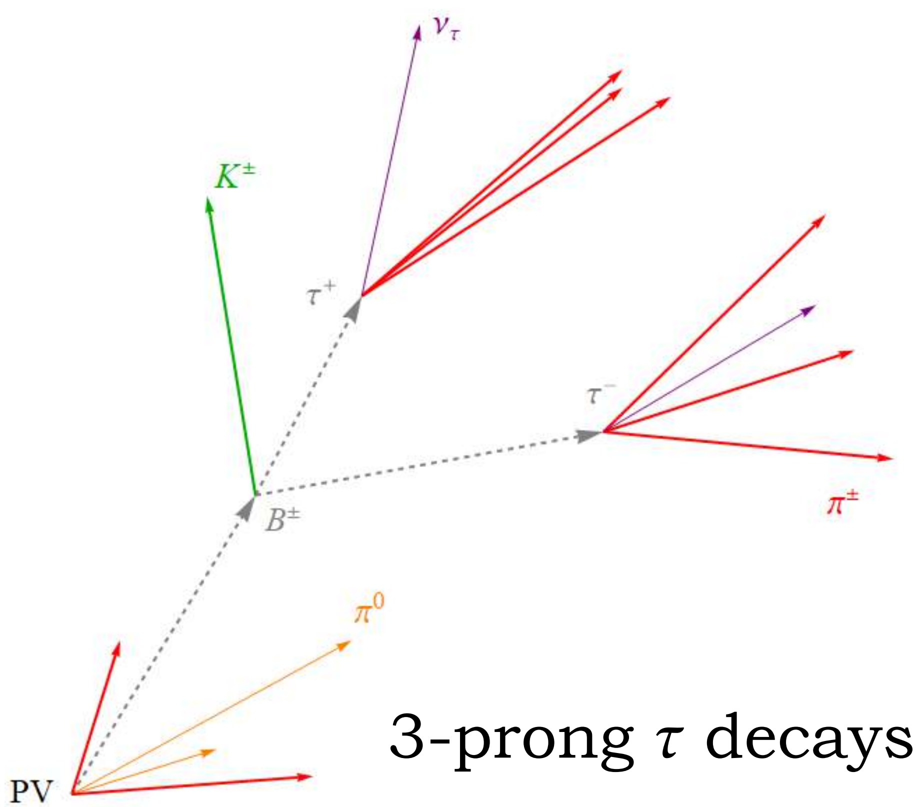
… in one word (almost) *everything*

$b \to s\tau\tau$

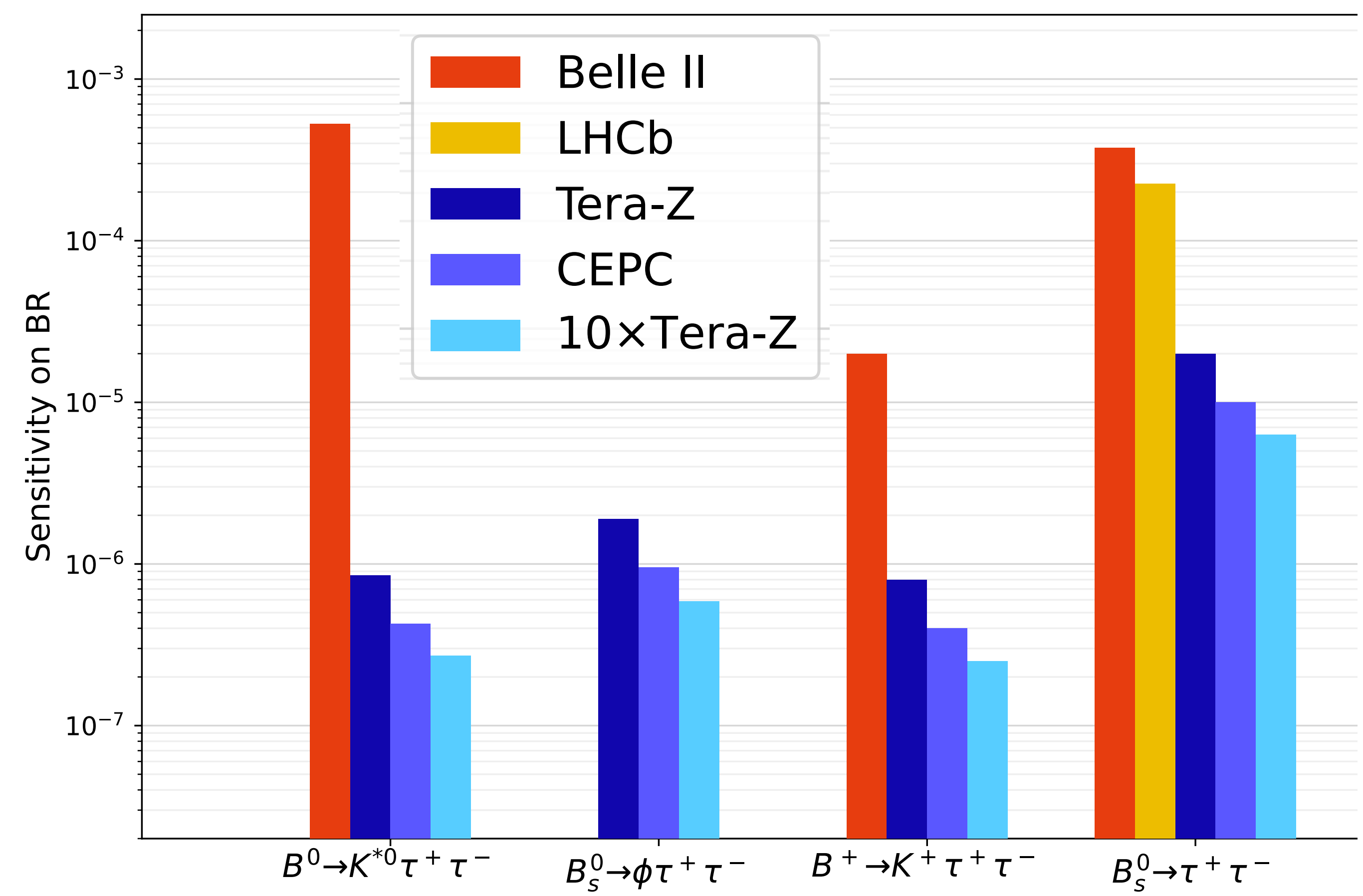
$$\text{BR}(B_s \to \tau\tau)_{\text{SM}} = (7.7 \pm 0.5) \times 10^{-7}$$ (Bobeth et al. 1311.0903)

$$\text{BR}(B \to K\tau\tau)_{\text{SM}} = (1.2 \pm 0.1) \times 10^{-7}$$ (Du et al. 1510.02349)

- Unobserved, weakly constrained (~10^{-4}-10^{-3} by Belle, Belle II can provide an O(10) increased sensitivity)
- They can have huge new-physics enhancement (especially in theories preferably coupling to third generation fermions)
- CEPC prospect:



3-prong τ decays



updated from Li Lingfeng and Liu Tao '20

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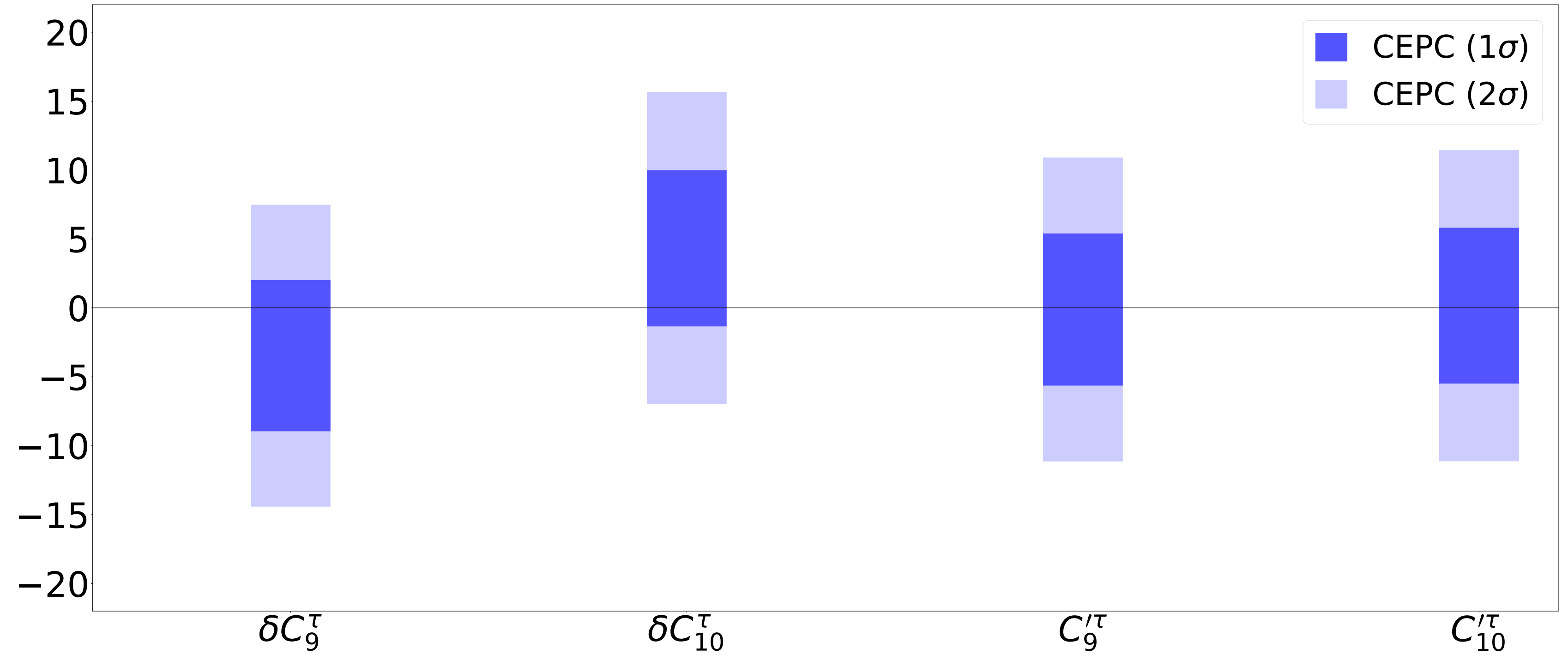
CEPC bounds on new physics contributions:

$$\mathcal{H}^{\text{eff}}_{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb}V^*_{ts}\frac{\alpha}{4\pi}\sum_j (C_j O_j + C'_j O'_j) + (C_L O_L + C_R O_R) + \text{h.c.},$$



→ sensitivity to new physics scales up to ~ 10 TeV

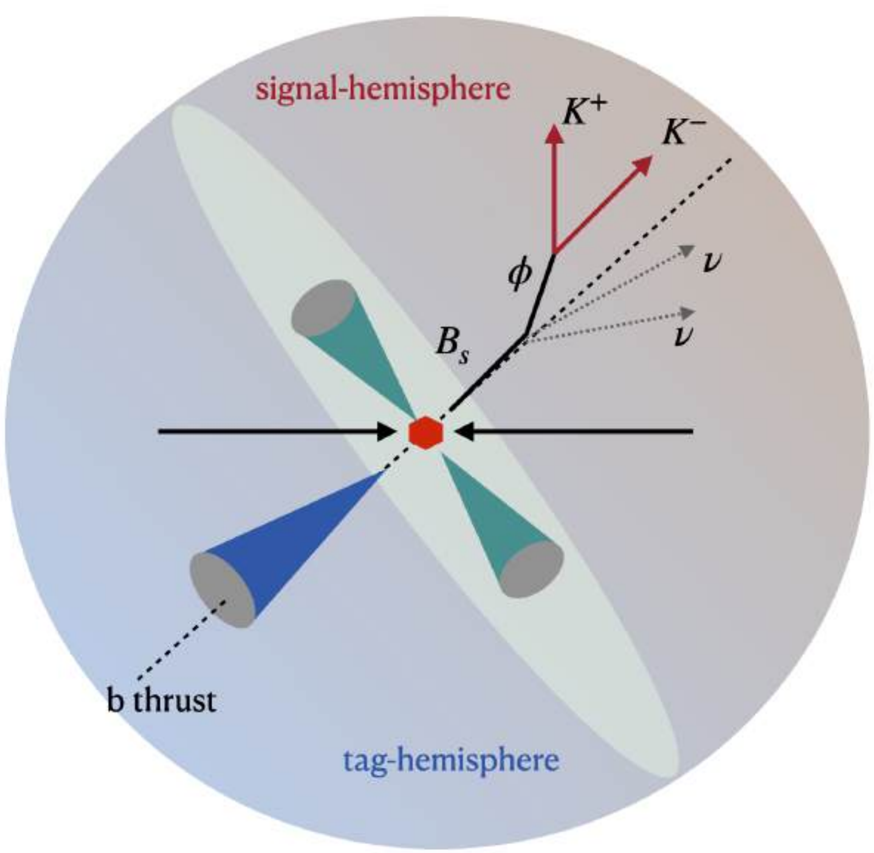
$B^0 \to K^{*0}\tau^+\tau^-$ $B_s^0 \to \phi\tau^+\tau^-$ $B^+ \to K^+\tau^+\tau^-$ $B_s^0 \to \tau^+\tau^-$

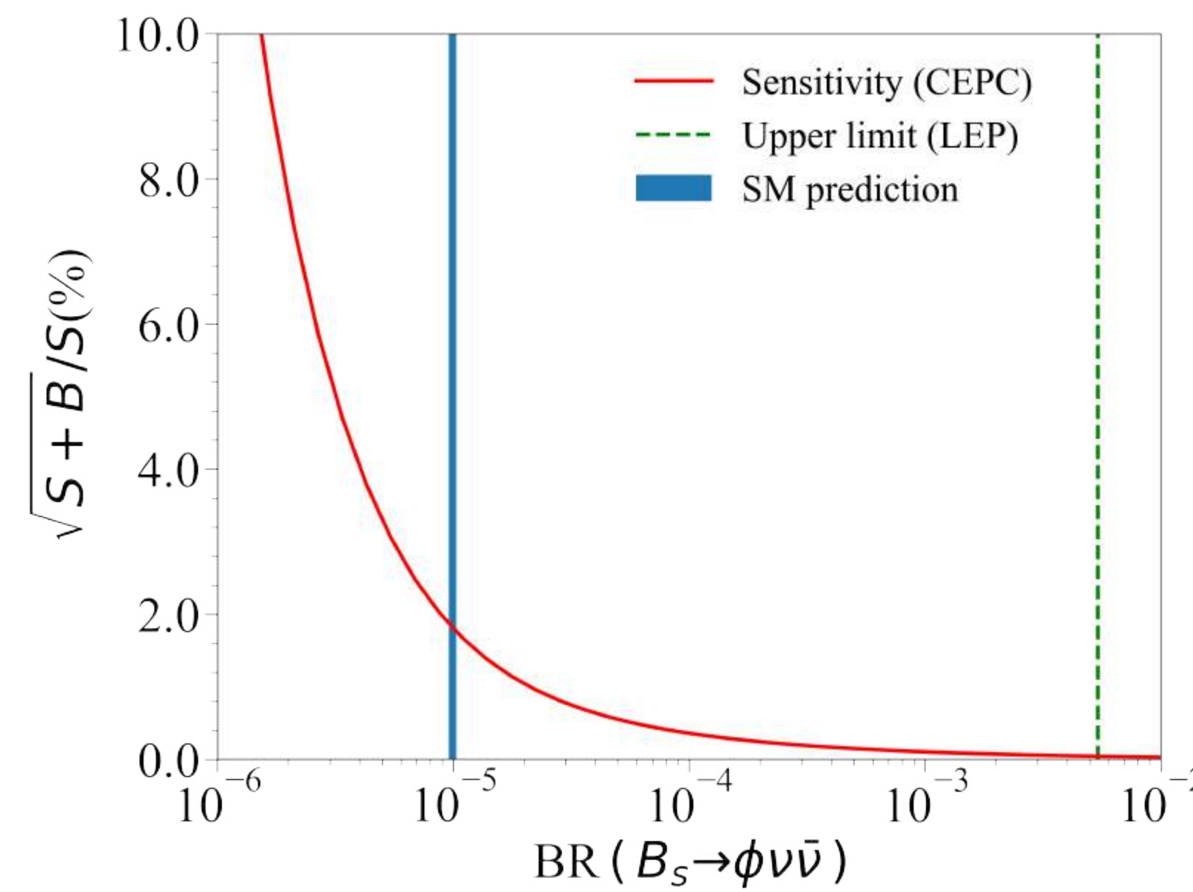
updated from Li Lingfeng and Liu Tao '20

$b \to s\nu\nu$

	Current Limit	Detector	SM Prediction
$\mathrm{BR}(B^0 \to K^0 \nu\bar{\nu})$	$< 2.6 \times 10^{-5}$ [3]	BELLE	$(3.69 \pm 0.44) \times 10^{-6}$ [1]
$\mathrm{BR}(B^0 \to K^{*0} \nu\bar{\nu})$	$< 1.8 \times 10^{-5}$ [3]	BELLE	$(9.19 \pm 0.99) \times 10^{-6}$ [1]
$\mathrm{BR}(B^\pm \to K^\pm \nu\bar{\nu})$	$(2.7 \pm 0.7) \times 10^{-5}$	Belle II '23	$(3.98 \pm 0.47) \times 10^{-6}$ [1]
$\mathrm{BR}(B^\pm \to K^{*\pm} \nu\bar{\nu})$	$< 4.0 \times 10^{-5}$ [5]	BELLE	$(9.83 \pm 1.06) \times 10^{-6}$ [1]
$\mathrm{BR}(B_s \to \phi \nu\bar{\nu})$	$< 5.4 \times 10^{-3}$ [6]	DELPHI	$(9.93 \pm 0.72) \times 10^{-6}$

- Also these modes can be greatly enhanced by new physics e.g. LC Crivellin Ota '15
- A Tera Z can measure $B_s \to \phi\nu\nu$ with a percent level precision: Li et al. '22





- Similar precision is expected for the other $b \to s\nu\nu$ modes Ahmis et al. (FCC-ee) '23

$B_c \to \tau\nu$

- Key observable to test possible LFU anomalies in charged-current B decays

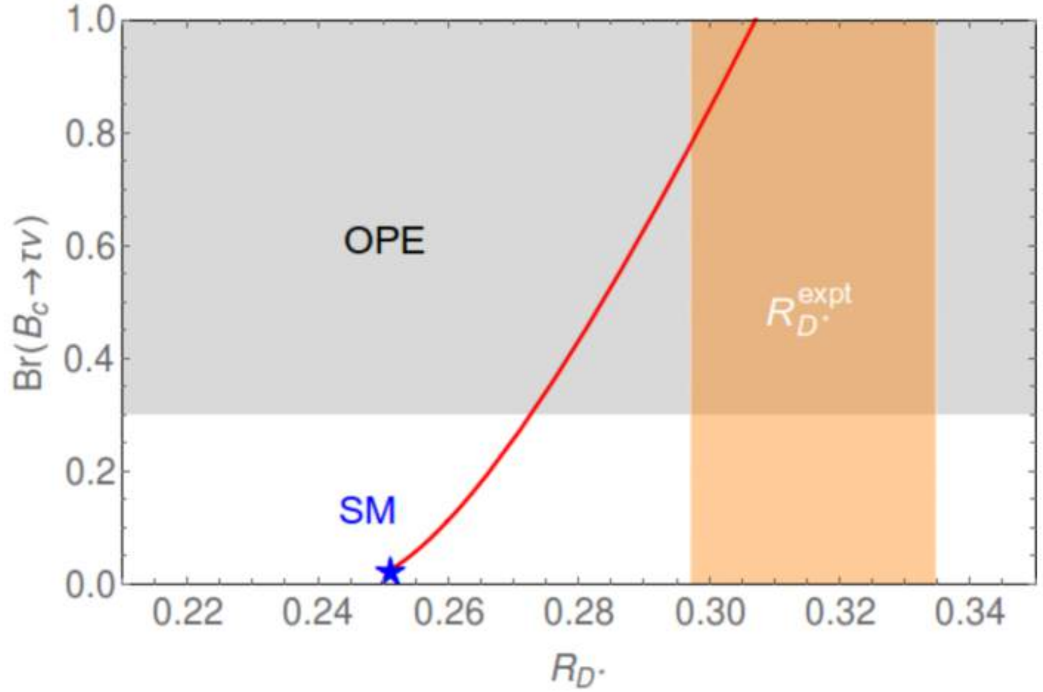
Alonso et al. '16

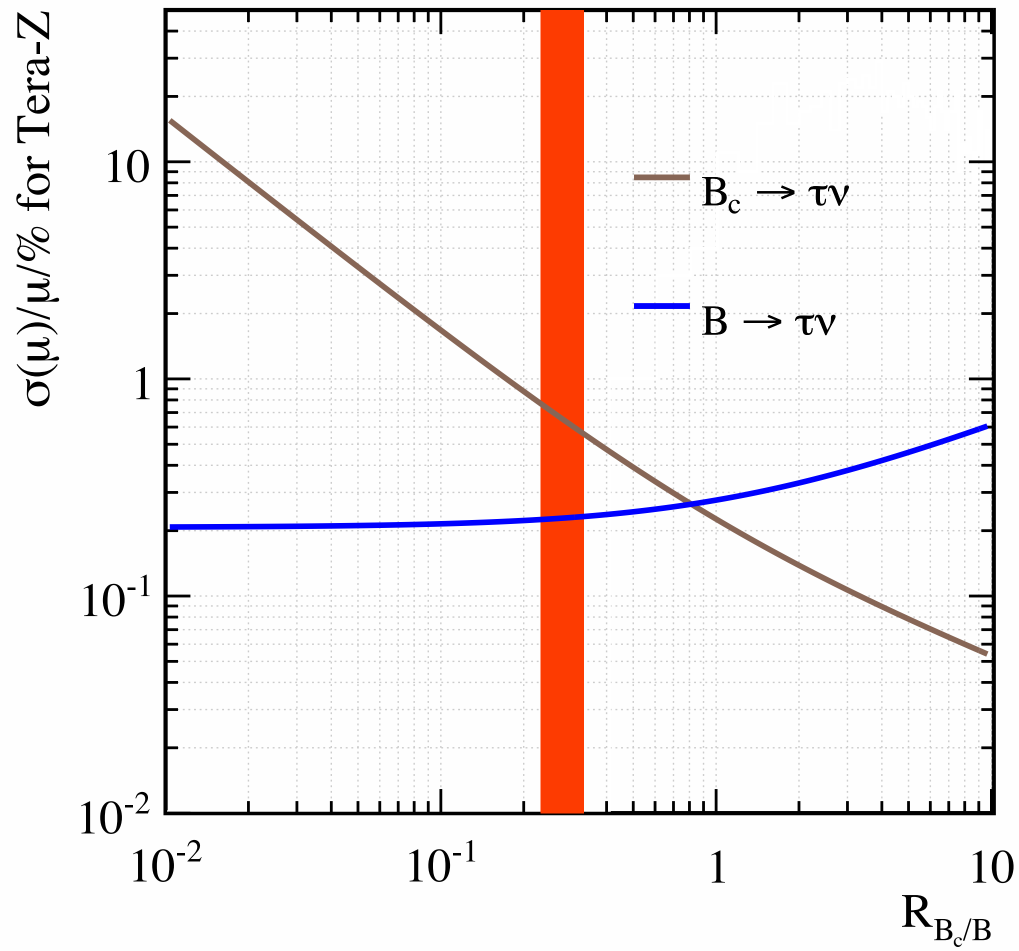
- SM prediction for the BR ~ 2%, beyond the reach of LHCb

- Tera Z could measure it with percent accuracy (hence providing a percent level measurement of V_{cb})

Zheng et al. '20

Paradigmatic example:
too heavy for Belle II,
too “elusive” for LHCb!





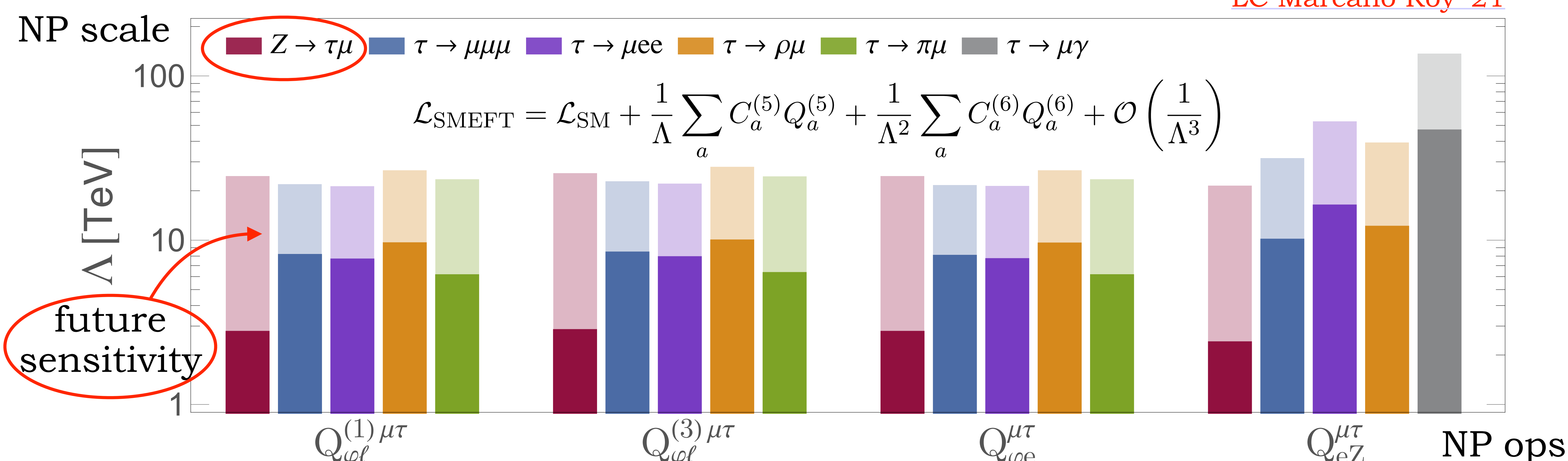
Lepton Flavour Violation in Z decays

Measurement	Current	HL-LHC	FCC	CEPC prelim.
$\mathrm{BR}(Z \to \tau\mu)$	$< 6.5 \times 10^{-6}$	1.4×10^{-6}	10^{-9}	10^{-9}
$\mathrm{BR}(Z \to \tau e)$	$< 5.0 \times 10^{-6}$	1.1×10^{-6}	10^{-9}	
$\mathrm{BR}(Z \to \mu e)$	$< 2.62 \times 10^{-7}$	5.7×10^{-8}	$10^{-8} - 10^{-10}$	10^{-9}

M. Dam '18

- LHC searches limited by backgrounds (in particular $Z \to \tau\tau$): max ~10 improvement can be expected at HL-LHC (3000/fb)
- A Tera Z can test LFV new physics searching for $Z \to \tau\ell$ at the level of what Belle II (50/ab) will do through LFV tau decays (or better)

LC Marcano Roy '21

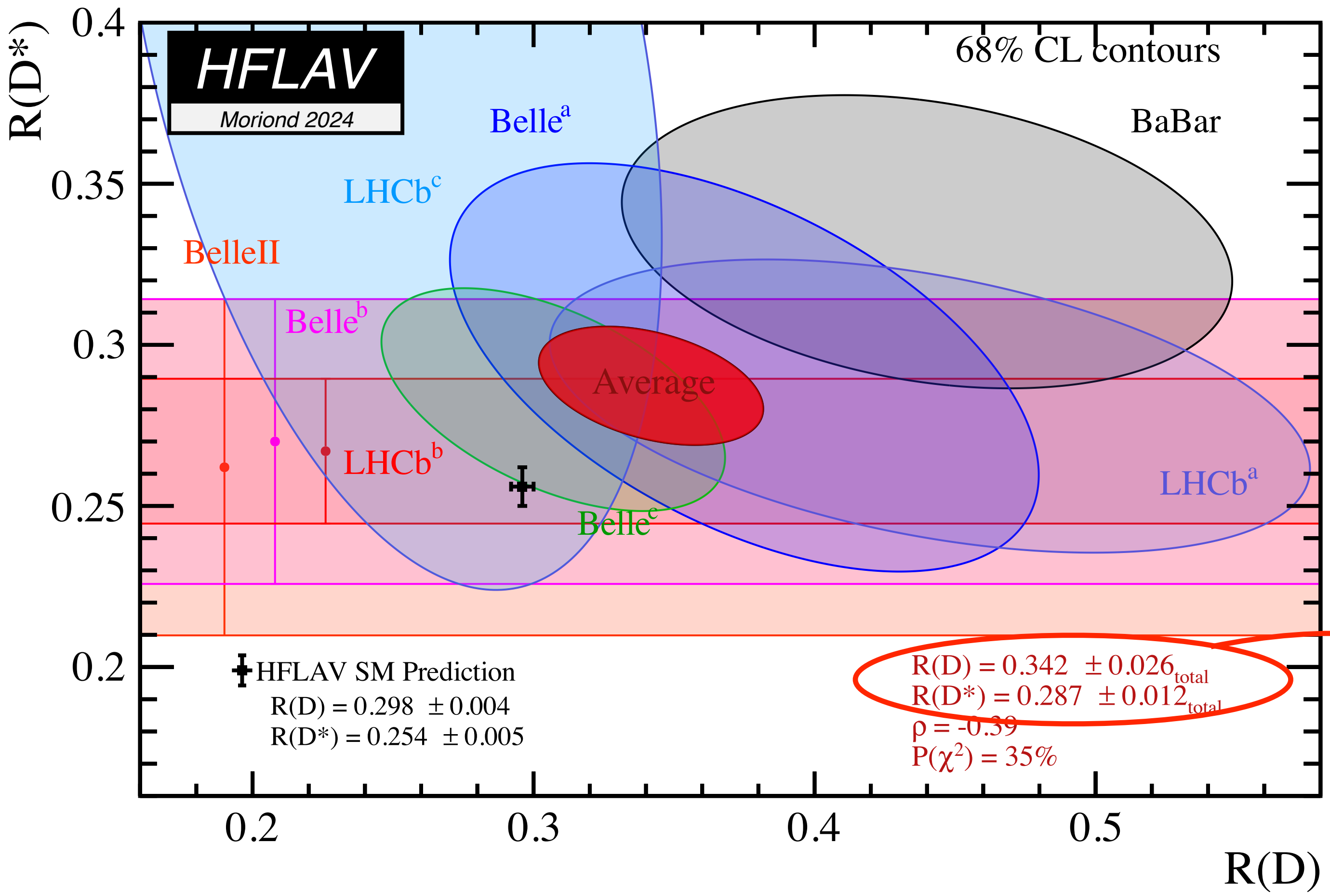


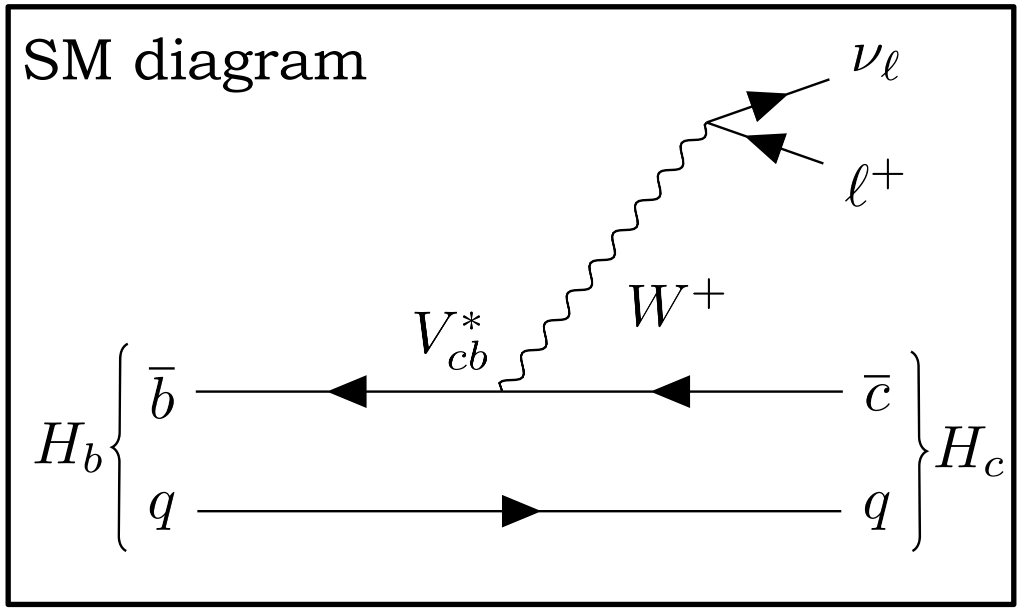
Gauge interactions are flavour blind: the SM predicts
Lepton Flavour Universality (LFU) EW interactions

⇨ any deviation from LFU would be a clear indication of NP

Example: LFU tests in semileptonic (charged-current) B decays

$$R_{D^{(*)}} \equiv \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)}, \;\; \ell = e,\, \mu$$





Current precision: ~5-10%
World average still somewhat in tension with the SM prediction

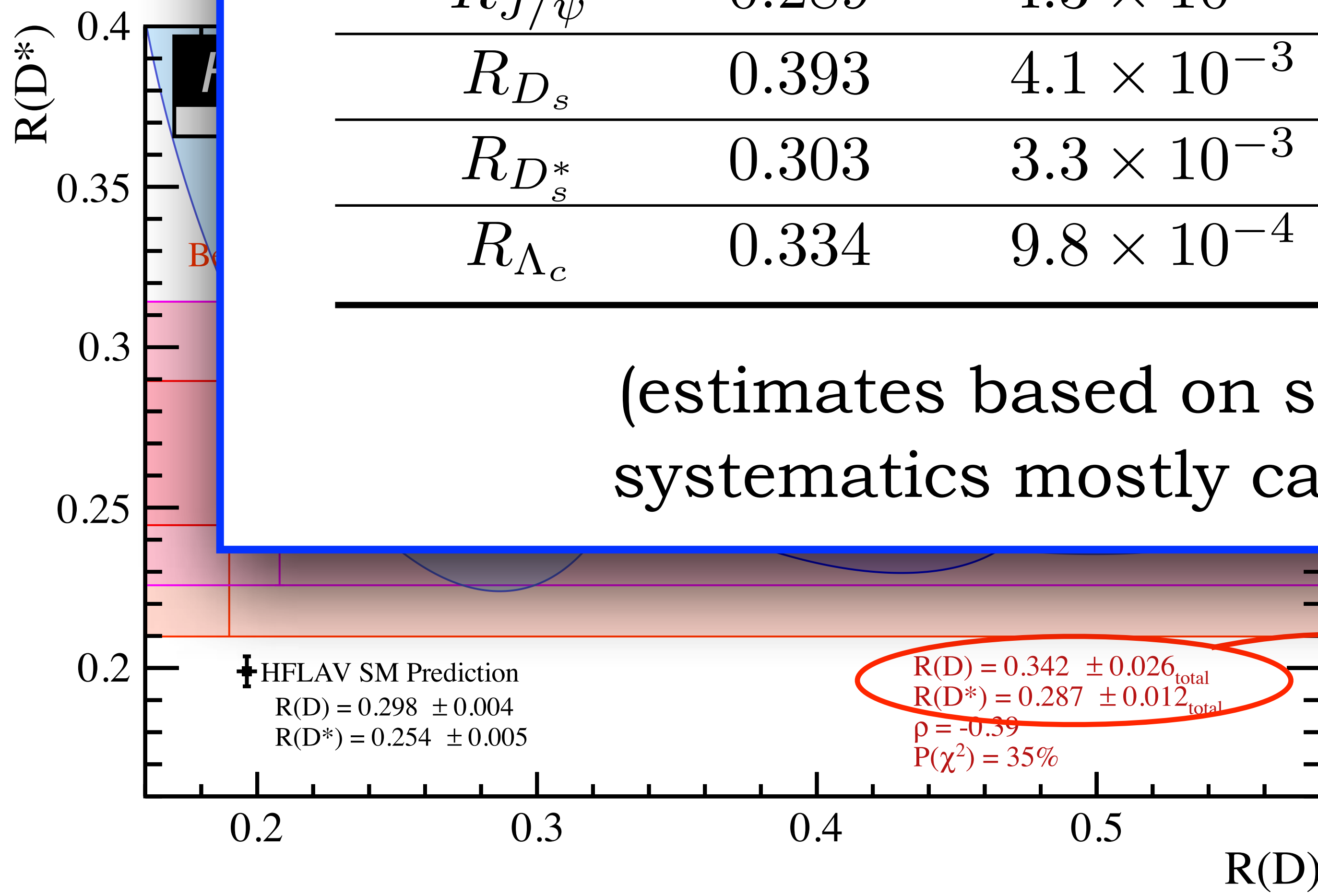
Gauge interactions are flavour blind: the SM predicts Lepton Flavour Universality (LFU) EW interactions

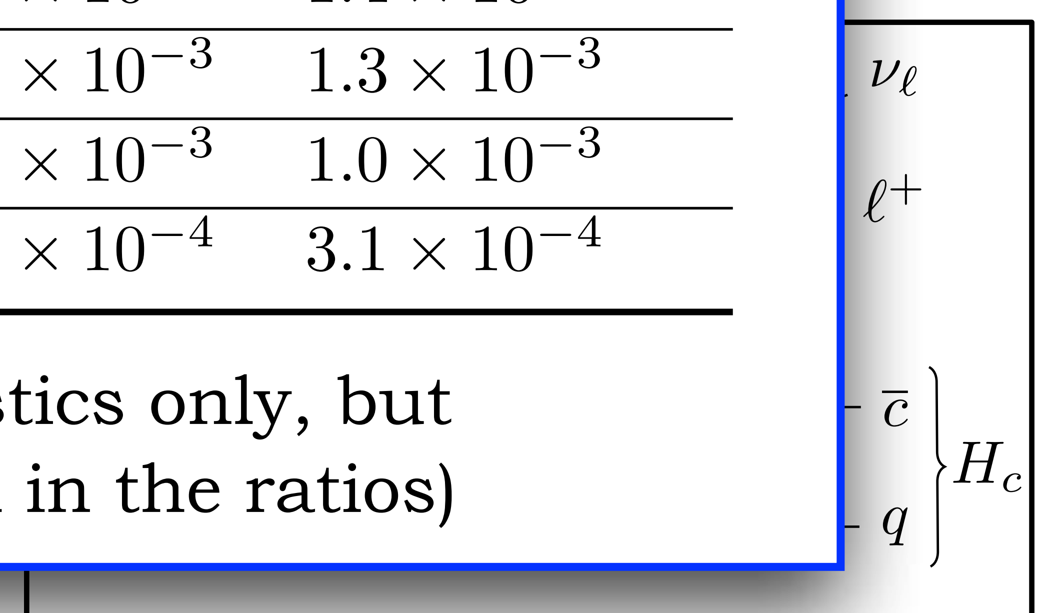
⇨ any deviation from LFU would be a clear indication of NP

CEPC could achieve a precision below 1% on the LFU tests in $b \to c\tau\nu$ decays:

R_{H_c}	SM Value	Tera-Z	4×Tera-Z	10×Tera-Z
$R_{J/\psi}$	0.289	4.3×10^{-2}	2.1×10^{-2}	1.4×10^{-2}
R_{D_s}	0.393	4.1×10^{-3}	2.1×10^{-3}	1.3×10^{-3}
$R_{D_s^*}$	0.303	3.3×10^{-3}	1.6×10^{-3}	1.0×10^{-3}
R_{Λ_c}	0.334	9.8×10^{-4}	4.9×10^{-4}	3.1×10^{-4}

(estimates based on statistics only, but systematics mostly cancel in the ratios)



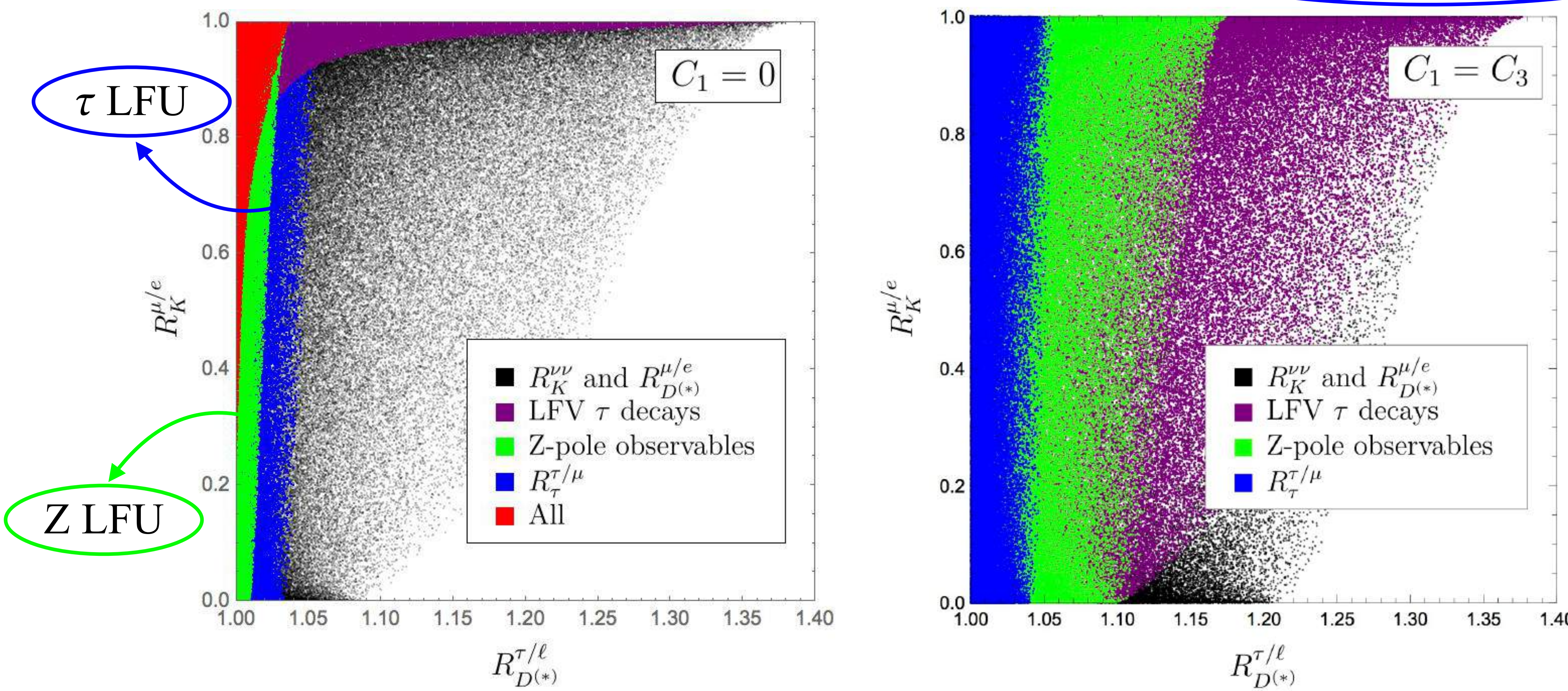


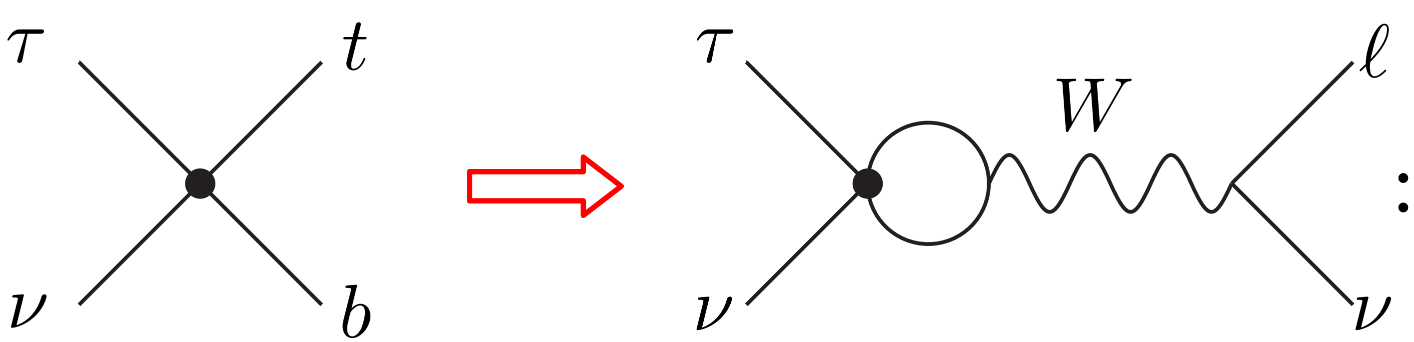
Current precision: ~5-10%
World average still somewhat in tension with the SM prediction

Constraints on B LFU from tau LFU

New physics inducing operators involving mainly 3rd family fermions

Ops with only 3rd family: $Q_{\ell q}^{(1)} = (\bar{L}_3 \gamma^\mu L_3)(\bar{Q}_3 \gamma_\mu Q_3)$, $Q_{\ell q}^{(3)} = (\bar{L}_3 \gamma^\mu \tau_I L_3)(\bar{Q}_3 \gamma_\mu \tau^I Q_3)$

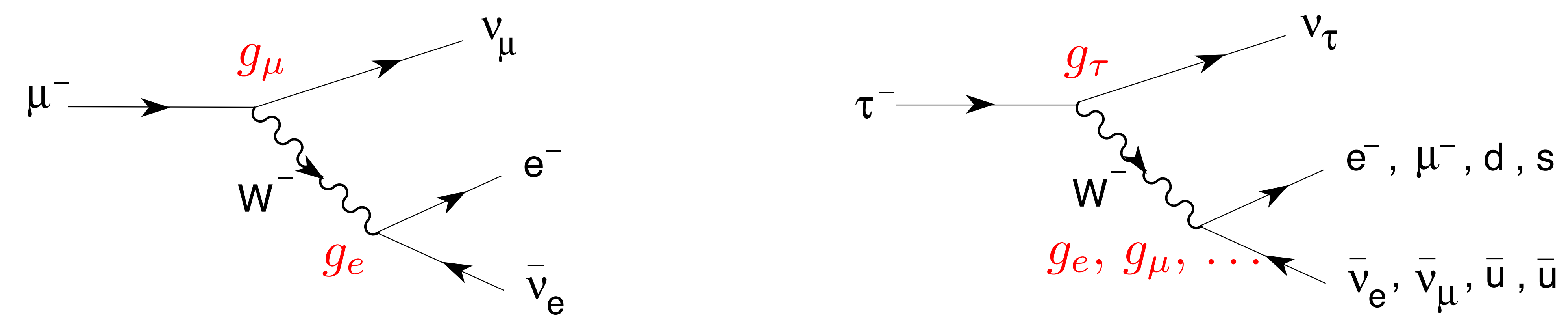




$$\frac{\mathrm{BR}(\tau \to \ell \nu \bar{\nu})}{\mathrm{BR}(\mu \to e \nu \bar{\nu})} \quad \tau \text{ LFU}$$

Feruglio Paradisi Pattori ’16, ’17

LFU tests in tau decays



phase-space factors

radiative corrections

$$\left(\frac{g_\mu}{g_e}\right)^2 = \frac{\mathrm{BR}(\tau\to\mu\nu\bar\nu)}{\mathrm{BR}(\tau\to e\nu\bar\nu)}\,\frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}\,\frac{R_W^{\tau e}}{R_W^{\tau\mu}}\,,$$

$$\left(\frac{g_\tau}{g_\ell}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5\frac{\mathrm{BR}(\tau\to\ell\nu\bar\nu)}{\mathrm{BR}(\mu\to e\nu\bar\nu)}\,\frac{f(m_e^2/m_\mu^2)}{f(m_\ell^2/m_\tau^2)}\,\frac{R_W^{\mu e}R_\gamma^{\mu}}{R_W^{\tau\ell}R_\gamma^{\tau}}\,,\qquad (\ell = e,\mu)$$

Currently LFU tested with per mil level precision:

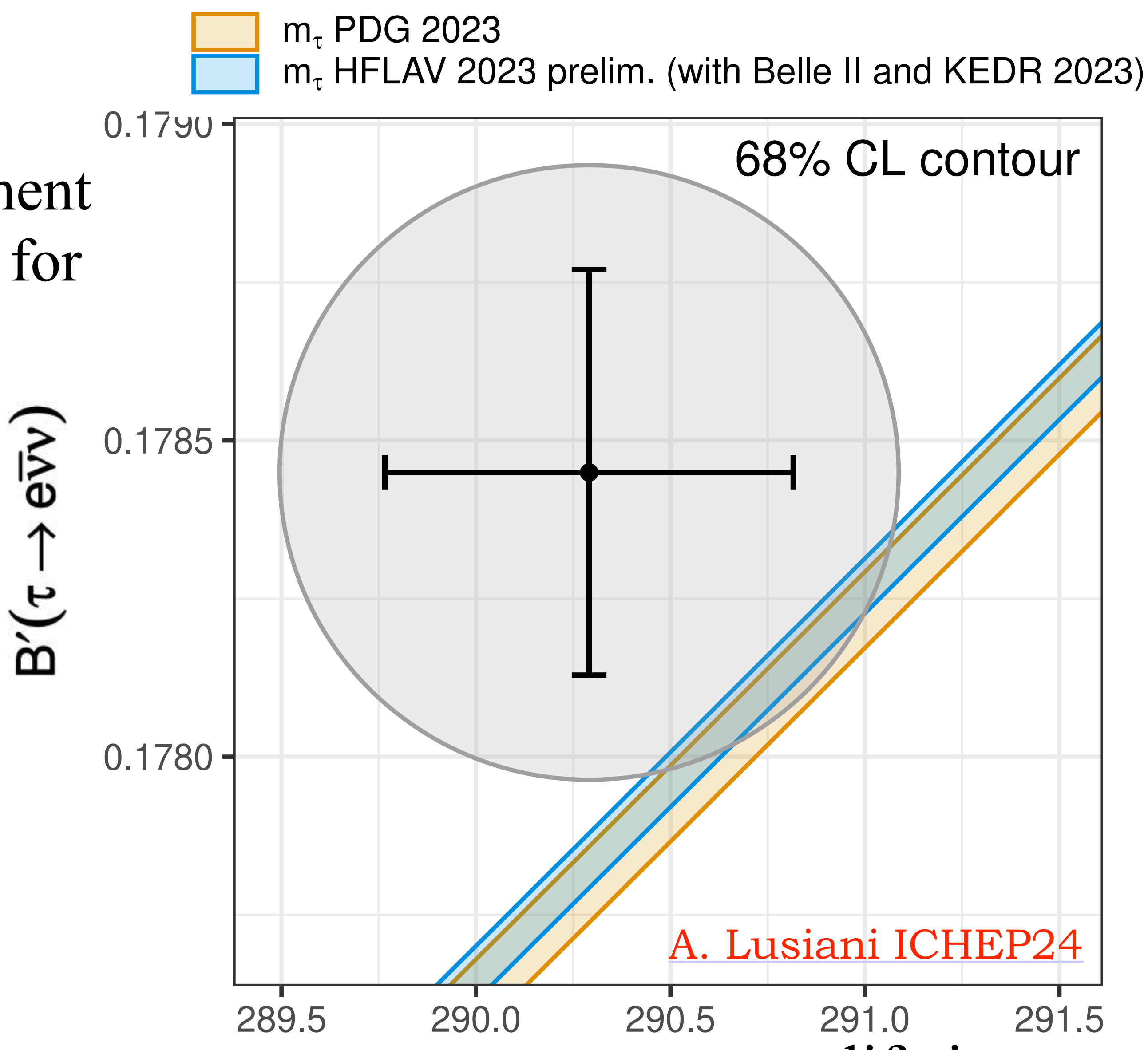
$$\frac{g_\mu}{g_e} = 1.0002\pm0.0011\,,\quad \frac{g_\tau}{g_e} = 1.0018\pm0.0014\,,\quad \frac{g_\tau}{g_\mu} = 1.0016\pm0.0014$$

HFLAV, A. Lusiani ICHEP24

[error budget: 1.1‰ from BRs, 0.9‰ from τ_τ, 0.2‰ from m_τ]

LEP & Belle II   Belle   BESIII & Belle II

Average of measurement and g_μ=g_e prediction for $\mathrm{BR}(\tau \to e\nu\bar{\nu})$



tau lifetime

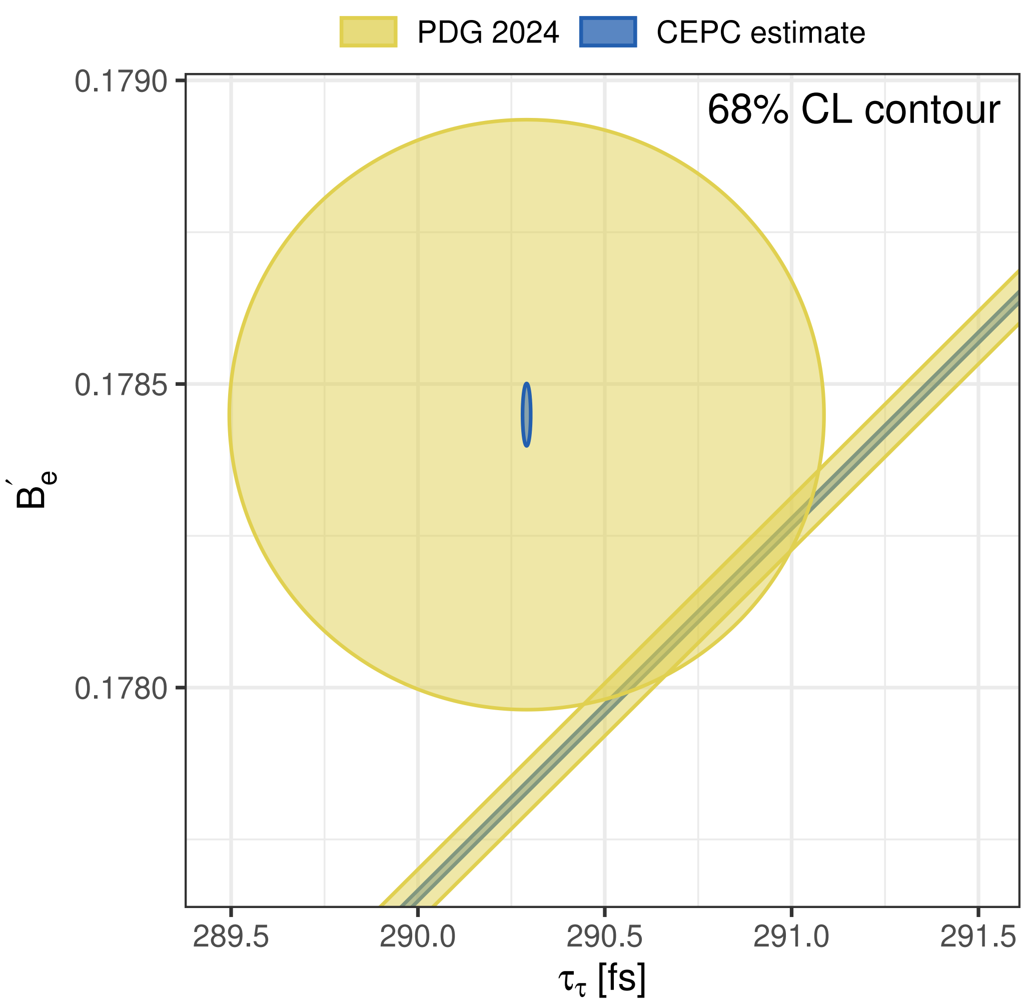
Test of new physics! Example, 3rd generation lepton-Higgs operator:

$$\frac{1}{\Lambda^2} i(\Phi^\dagger \tau^I \overleftrightarrow{D}_\mu \Phi)(\bar{L}_3 \tau^I \gamma^\mu L_3) \quad \Rightarrow \quad g_e = g_\mu = g, \quad g_\tau = g\left(1 + \frac{v^2}{\Lambda^2}\right)$$

Current LFU limits set a bound on the NP scale of Λ > 8 TeV

Preliminary studies show that a 10-fold improvement of the systematics is possible:

Measurement	Current	Belle II	FCC	CEPC prelim.
Lifetime [sec]	$(2903 \pm 5) \times 10^{-16}$		$\pm\, 6 \times 10^{-18}$	$\pm\, 7 \times 10^{-18}$
$\mathrm{BR}(\tau \to e\nu\bar{\nu})$	$(17.82 \pm 0.04)\%$		$\pm\, 0.003\%$	$\pm\, 0.003\%$
$\mathrm{BR}(\tau \to \mu\nu\bar{\nu})$	$(17.39 \pm 0.04)\%$		$\pm\, 0.003\%$	$\pm\, 0.003\%$
m_τ [MeV]	1776.93 ± 0.09		$\pm\, 0.0016$ (stat.) $\pm\, 0.018$ (syst.)	

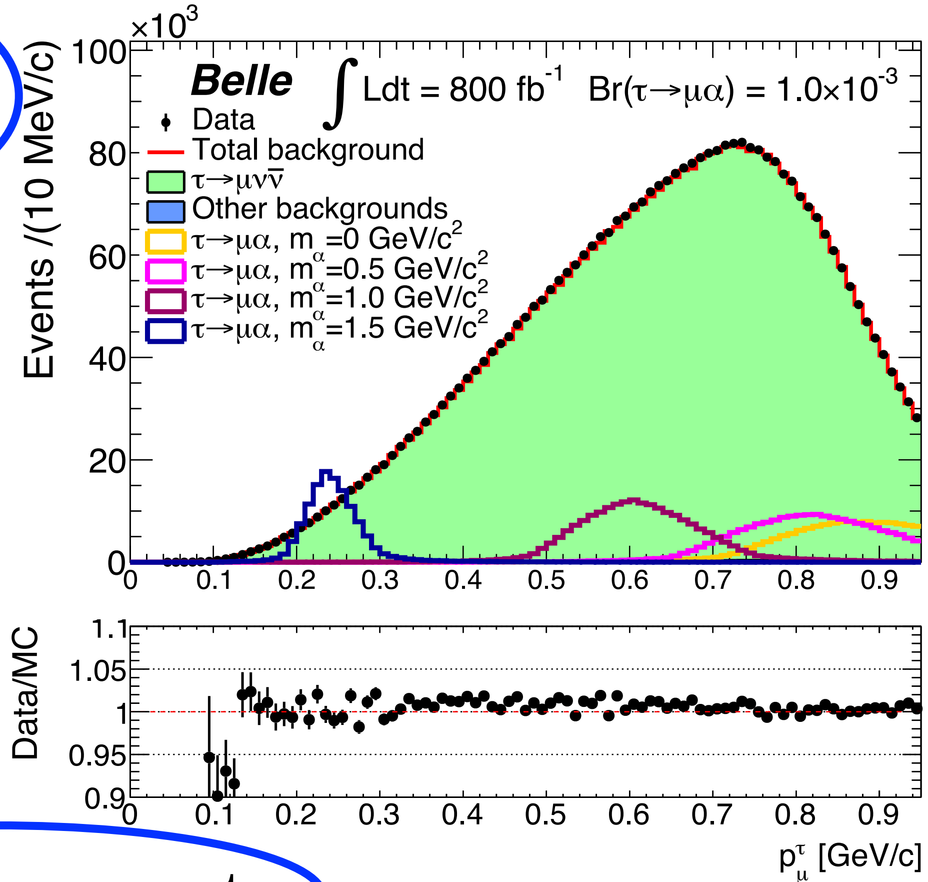


Tera-Z factories could test tau LFU at the 0.1‰ level

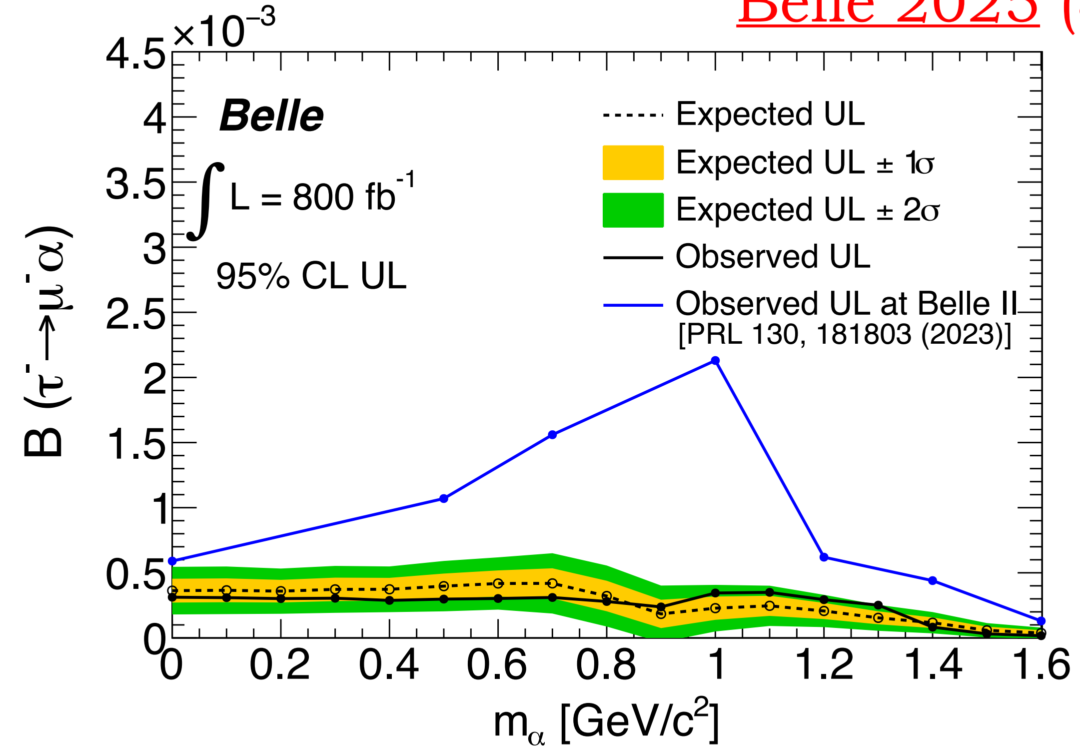
This translates to a sensitivity to LFU new-physics operators up to scales ~20 TeV

Light invisible NP boson in LFV tau decays, $\tau \to \ell X$

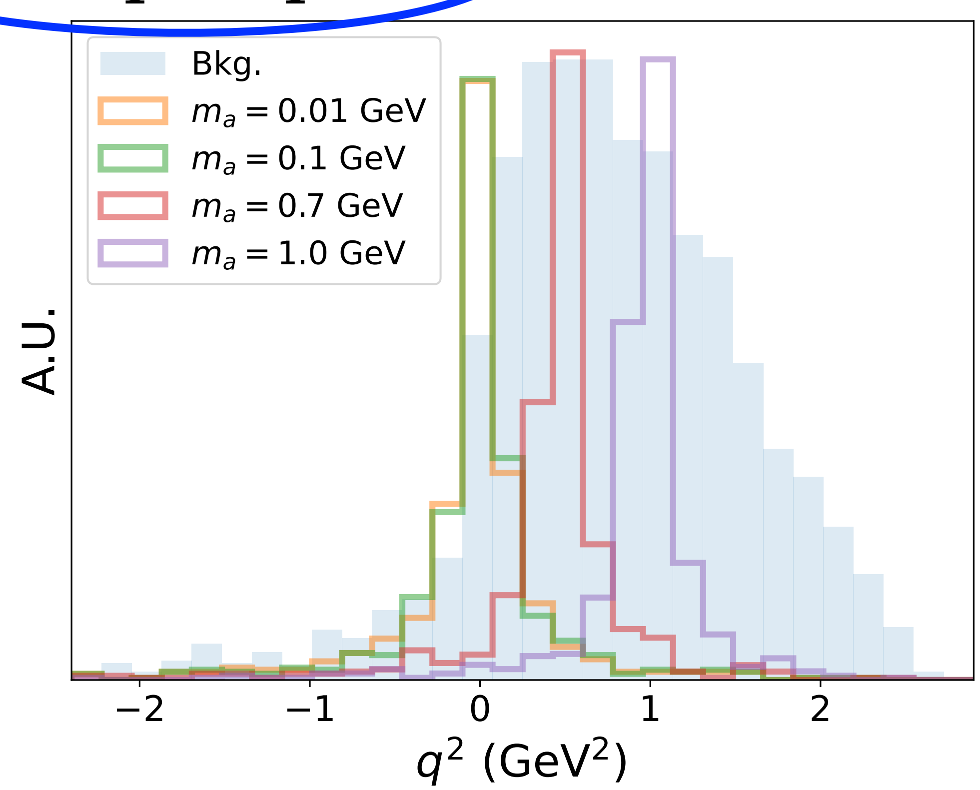
Current best

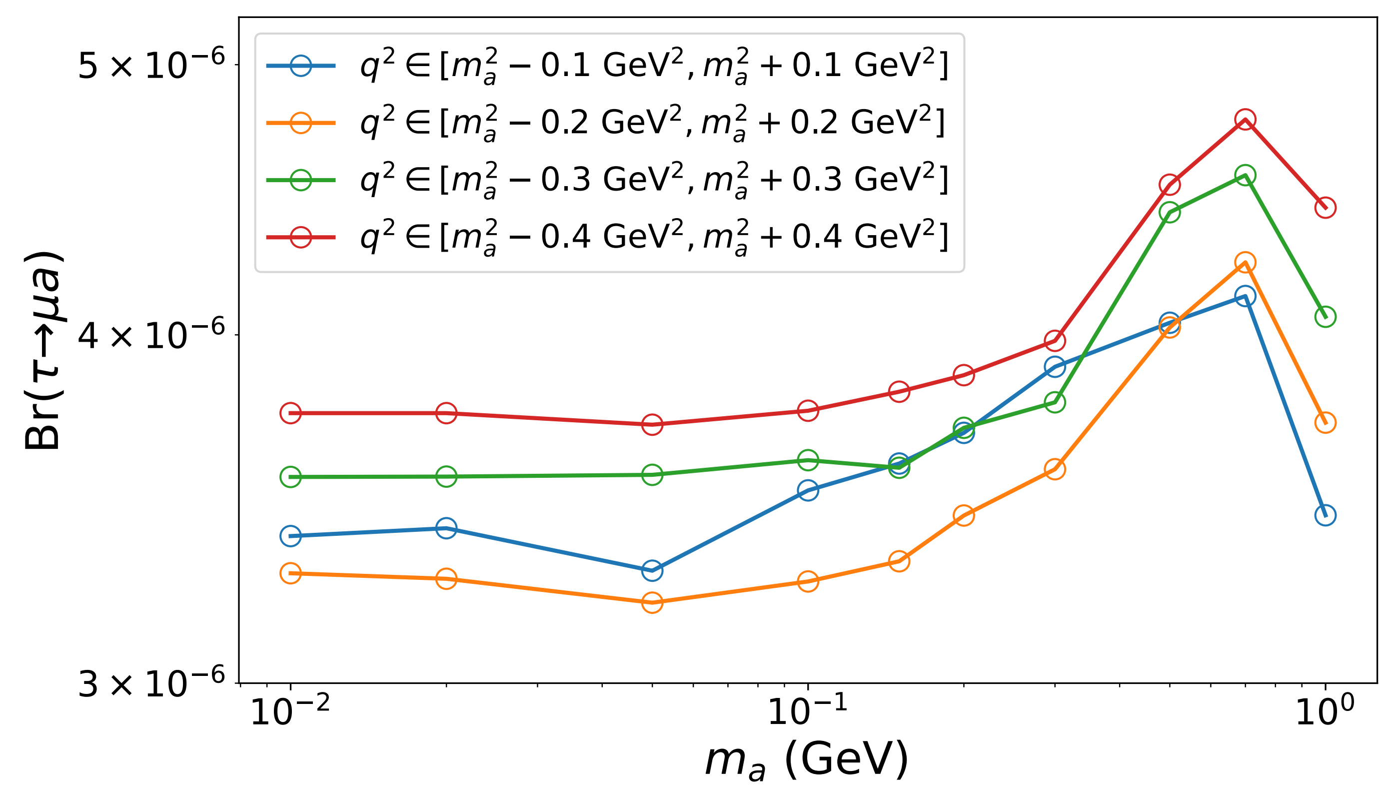


Belle 2025 (800 fb^{-1})

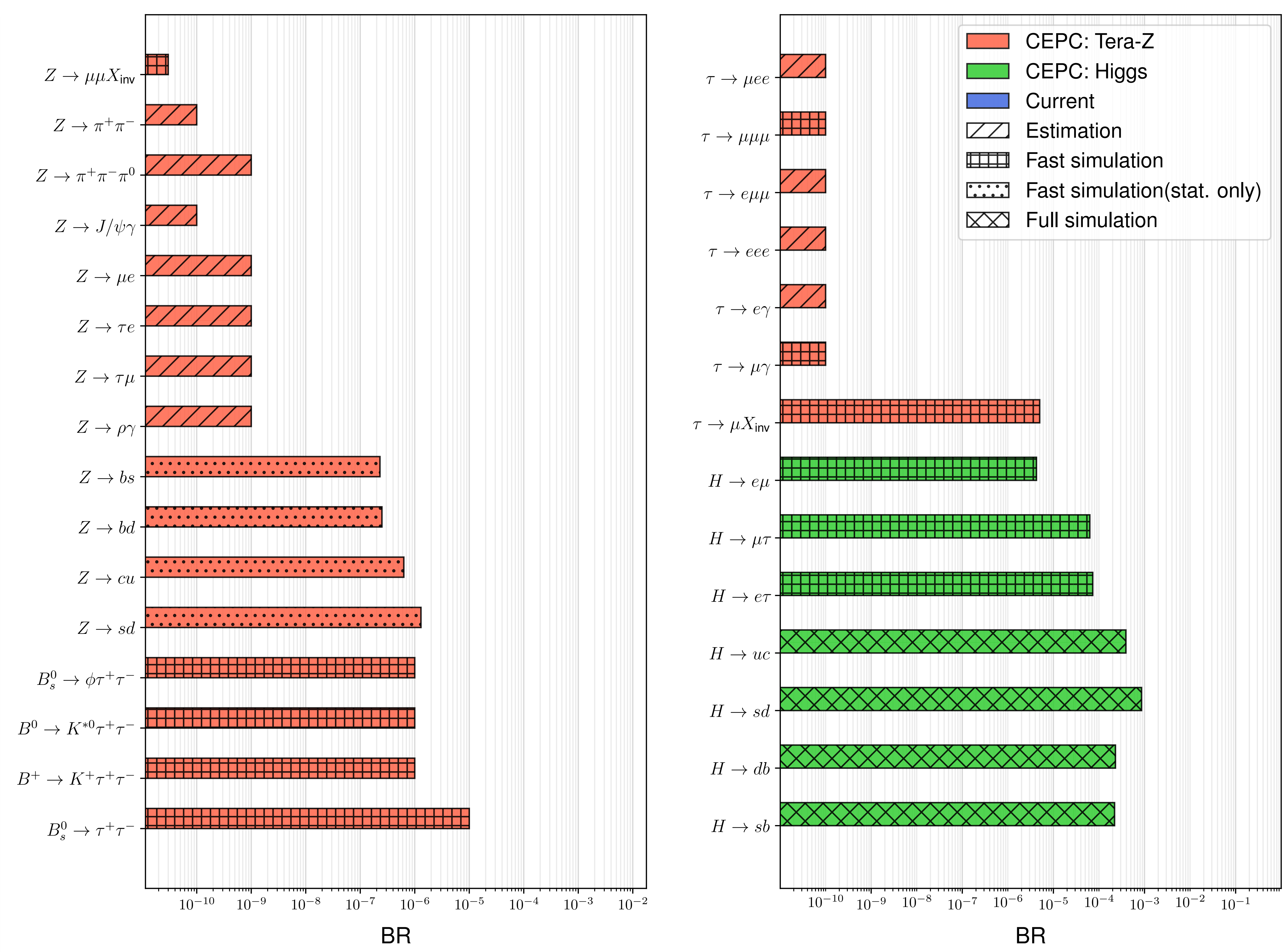


CEPC prospect

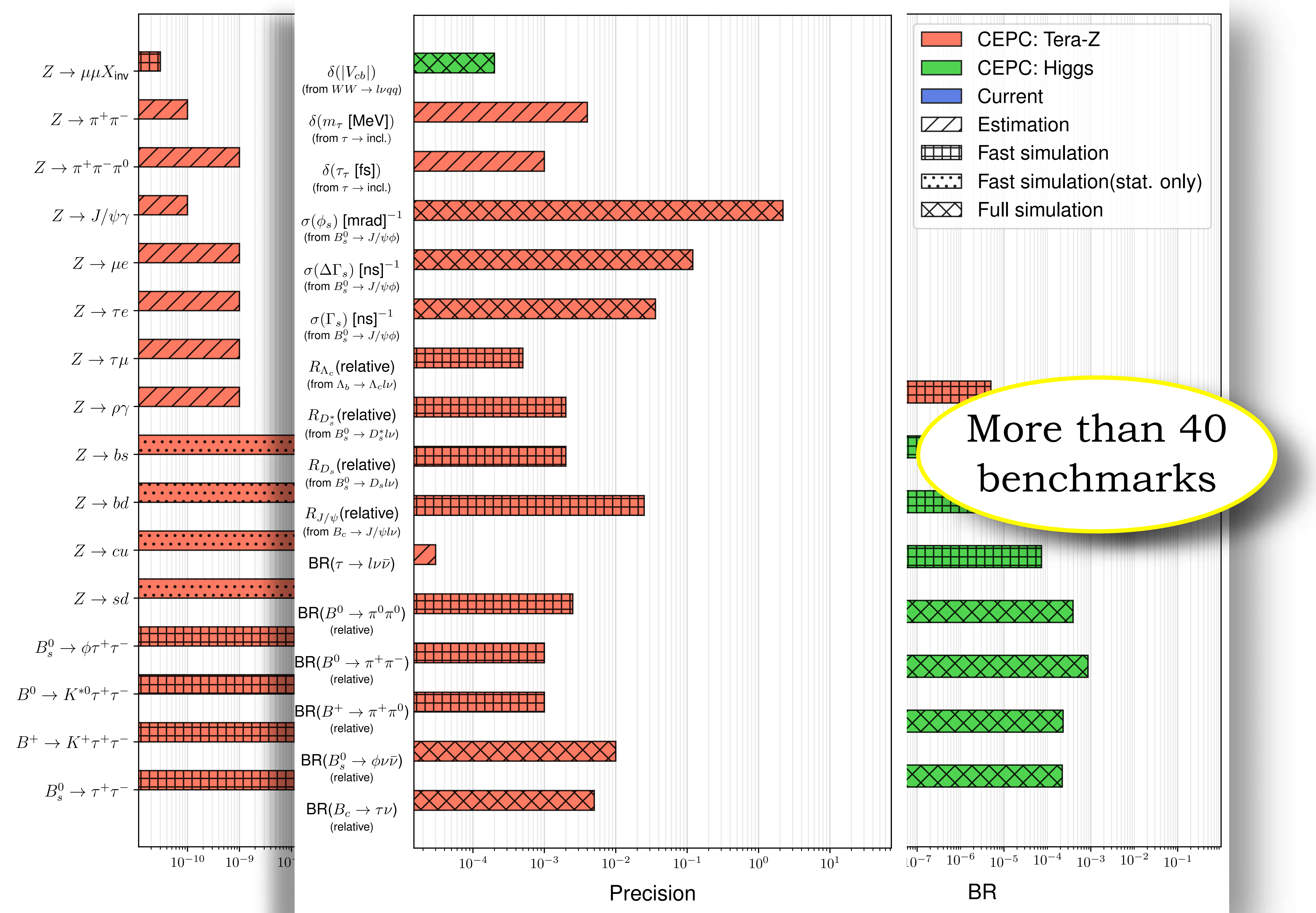




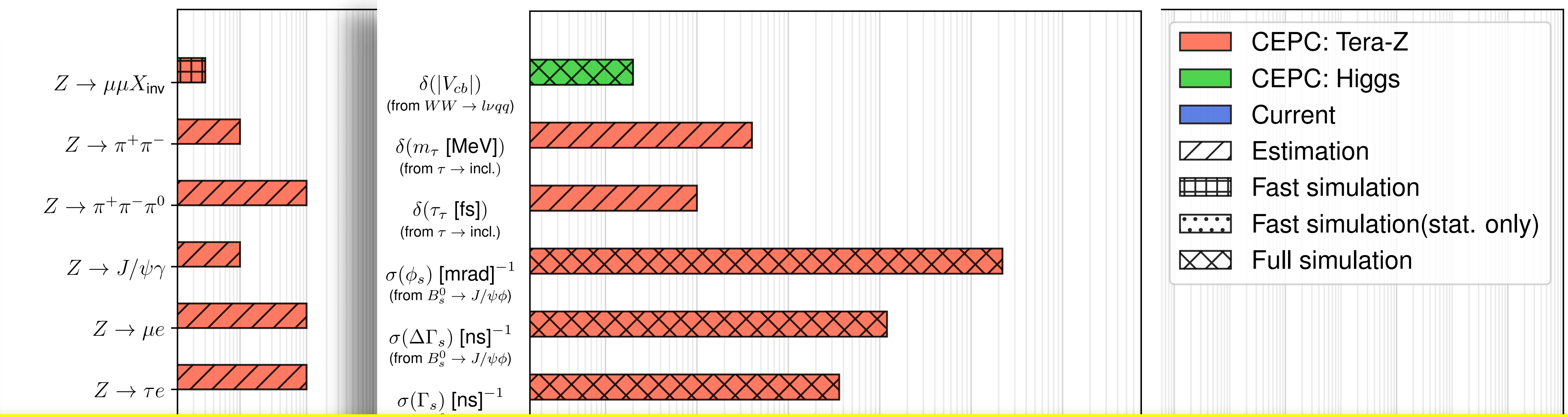
Summary: benchmark searches and measurements



Summary: benchmark searches and measurements



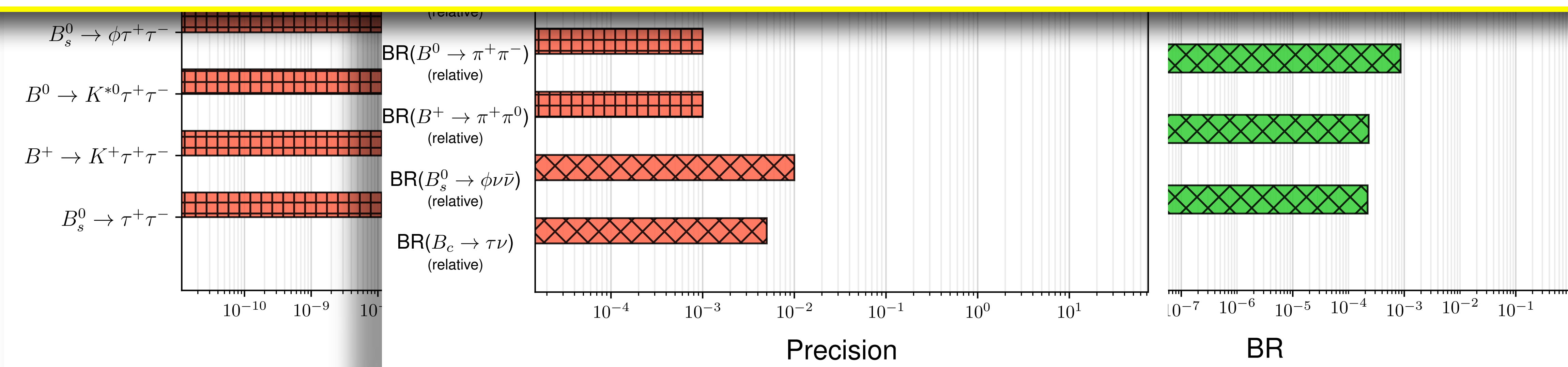
Summary: benchmark searches and measurements



In the white paper there is much more than what I could mention:

- opportunities beyond Z pole (top/Higgs FCNCs, CKM entries measurements from W decays etc.)
- detector performance requirements for such an ambitious program

…



Final remarks

Plenty of mystery (hence of opportunities to learn something) in the flavour sector of the Standard Model

Through flavour observables, one can probe some of the highest energy scales accessible in laboratory experiments

The Z-pole run of the CEPC would offer plenty of flavour physics opportunities, summarised in our white paper

O(10^{12}) Z decays would enable us to study many processes with a much higher precision than (or inaccessible to) other experiments

Examples of unique opportunities at Tera Z: rare B decays, Z LFV decays, tests of LFU in tau decays or B_c decays etc.

It is not over: there is much more to study!

The "wish list" is long, here some examples:

- CKM: summarize the prospects for CKM measurements (especially the new methodology of determine it directly from W and top decay)
- CPV: explore conventional CPV observation channels (including baryons like Λ_b), and discuss new methods
- Possible to probe matter origin? Any sensitivity to *e.g.* leptogenesis (heavy sterile neutrinos?) and relevant physics processes (EWPT, QCD phase transition, etc.)
- Interplay between Flavour & QCD: (i) hadronization, (ii) form factors, (iii) QCD effects & B-anomalies …
- Dedicated studies on charm (D, Λ_c) and strange hadrons
- Light new physics particles (X) in hadrons decays? $D \to \pi X$, $B \to K X$ etc.

…

Everyone is welcome to join these efforts and share their insight!


谢谢大家!
有问题吗?

Additional slides

Z LFV prospects

A study in the context of the FCC-ee (5×10^{12} Zs):

- $Z \to \mu e$:

M. Dam @ Tau '18 & 1811.09408

In contrast to the LHC, no background from $Z \to \tau\tau$:

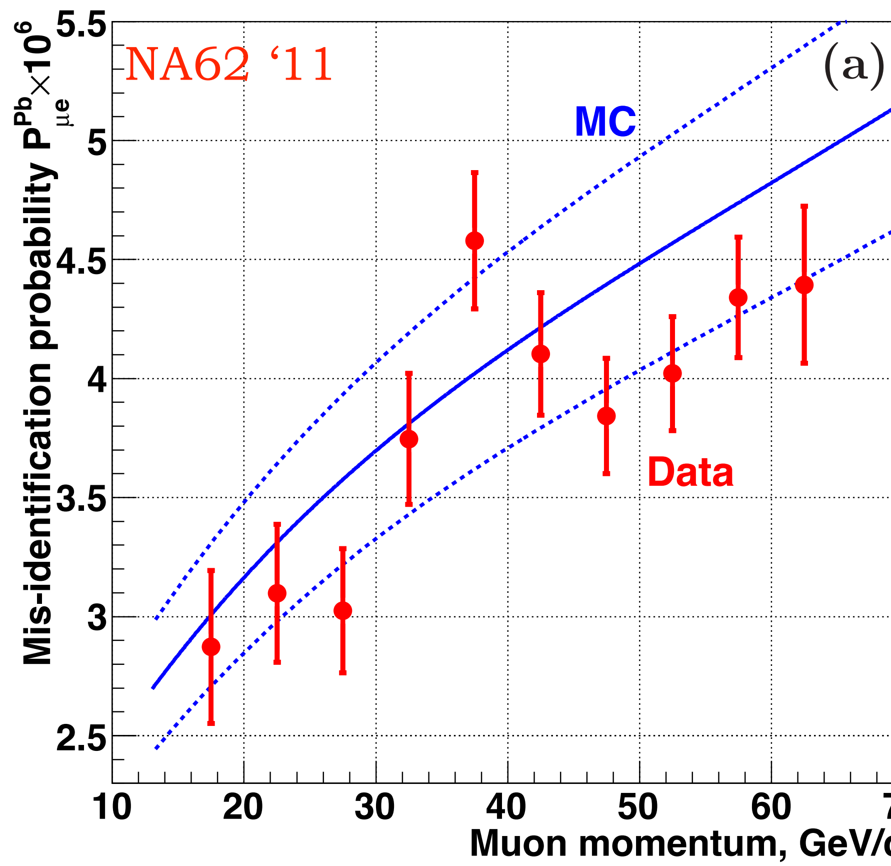
Z mass constraint much more effective (collision energy is known)

→ background rate < 10^{-11} (with a 0.1% momentum resolution at ~45 GeV)

Main issue: muons can release enough brems. energy in the ECAL to be mis-id as electrons. Mis-id probability measured by NA62 for a LKr ECAL: 4×10^{-6} (for p_μ~45 GeV)

Bg. from $Z \to \mu\mu$ + mis-id μ

(3×10^{-7} of all Z decays)



Sensitivity limited to: $\mathrm{BR}(Z \to \mu e) \sim 10^{-8}$

(Improved e/μ separation? Down to 10^{-10})

Z LFV prospects

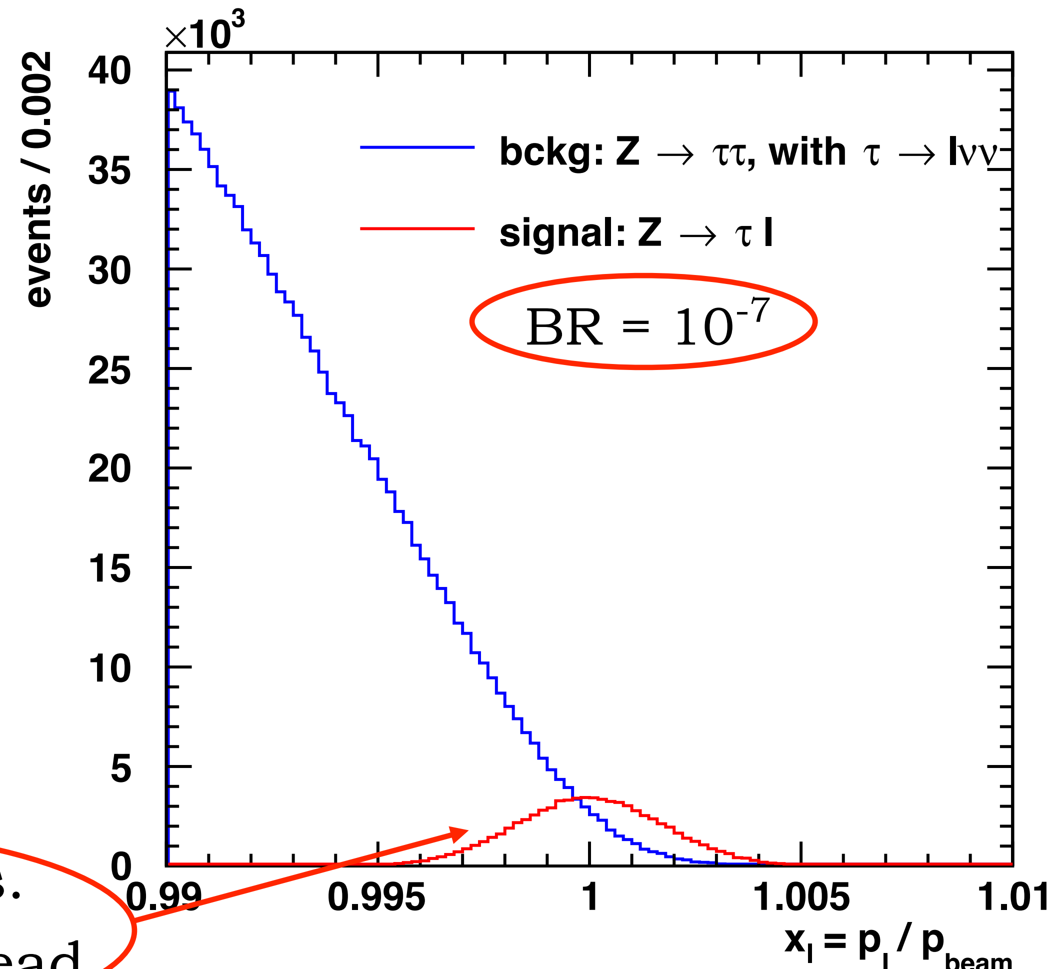
A study in the context of the FCC-ee (5×10^{12} Zs):

- $Z \to \ell\tau$: M. Dam @ Tau '18 & 1811.09408

To avoid mis-id, select one hadronic τ ($\geq$3 prong, or reconstructed excl. mode)

Main background from $Z \to \tau\tau$ (with one leptonic τ decay)

Simulated signal & background:



~10^{-3} momentum res.
& ~10^{-3} collision E spread

Sensitivity:
$\mathrm{BR}(Z \to \ell\tau) \sim 10^{-9}$

Z LFV prospects

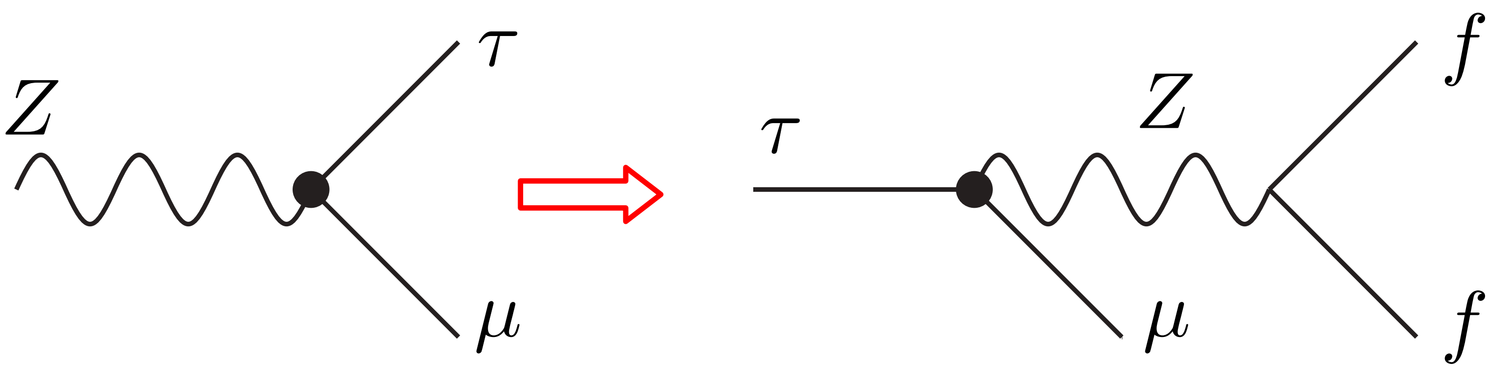
- CEPC can improve on present LHC (future HL-LHC) bounds up to 4 (3) orders of magnitude, at least for the $Z \to \tau\ell$ modes

- The question is: can CEPC searches find new physics with these modes?

- It depends on the indirect constraints from other processes

- In particular low-energy LFV processes are unavoidably induced

e.g. :



$\tau \to \mu\,\ell\ell$

$\tau \to \mu\,\pi$

$\tau \to \mu\,\rho$

$\ldots$

Previous model-independent studies:

Nussinov Peccei Zhang '00; Delepine Vissani '01; Gutsche et al. '11; Crivellin Najjari Rosiek '13; ...

If NP scale $\boldsymbol{\Lambda} \gg m_W$: $\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2} \sum_a C_a^{(6)} Q_a^{(6)} + \ldots$

Dimension-6 effective operators that can induce CLFV

4-leptons operators		Dipole operators	
$Q_{\ell\ell}$	$(\bar{L}_L \gamma_\mu L_L)(\bar{L}_L \gamma^\mu L_L)$	Q_{eW}	$(\bar{L}_L \sigma^{\mu\nu} e_R) \tau_I \Phi W_{\mu\nu}^I$
Q_{ee}	$(\bar{e}_R \gamma_\mu e_R)(\bar{e}_R \gamma^\mu e_R)$	Q_{eB}	$(\bar{L}_L \sigma^{\mu\nu} e_R) \Phi B_{\mu\nu}$
$Q_{\ell e}$	$(\bar{L}_L \gamma_\mu L_L)(\bar{e}_R \gamma^\mu e_R)$		
2-lepton 2-quark operators			
$Q_{\ell q}^{(1)}$	$(\bar{L}_L \gamma_\mu L_L)(\bar{Q}_L \gamma^\mu Q_L)$	$Q_{\ell u}$	$(\bar{L}_L \gamma_\mu L_L)(\bar{u}_R \gamma^\mu u_R)$
$Q_{\ell q}^{(3)}$	$(\bar{L}_L \gamma_\mu \tau_I L_L)(\bar{Q}_L \gamma^\mu \tau_I Q_L)$	Q_{eu}	$(\bar{e}_R \gamma_\mu e_R)(\bar{u}_R \gamma^\mu u_R)$
Q_{eq}	$(\bar{e}_R \gamma^\mu e_R)(\bar{Q}_L \gamma_\mu Q_L)$	$Q_{\ell edq}$	$(\bar{L}_L^a e_R)(\bar{d}_R Q_L^a)$
$Q_{\ell d}$	$(\bar{L}_L \gamma_\mu L_L)(\bar{d}_R \gamma^\mu d_R)$	$Q_{\ell equ}^{(1)}$	$(\bar{L}_L^a e_R) \epsilon_{ab} (\bar{Q}_L^b u_R)$
Q_{ed}	$(\bar{e}_R \gamma_\mu e_R)(\bar{d}_R \gamma^\mu d_R)$	$Q_{\ell equ}^{(3)}$	$(\bar{L}_i^a \sigma_{\mu\nu} e_R) \epsilon_{ab} (\bar{Q}_L^b \sigma^{\mu\nu} u_R)$
Lepton-Higgs operators			
$Q_{\Phi\ell}^{(1)}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{L}_L \gamma^\mu L_L)$	$Q_{\Phi\ell}^{(3)}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu^I \Phi)(\bar{L}_L \tau_I \gamma^\mu L_L)$
$Q_{\Phi e}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_R \gamma^\mu e_R)$	$Q_{e\Phi 3}$	$(\bar{L}_L e_R \Phi)(\Phi^\dagger \Phi)$

Grzadkowski et al. ’10; Crivellin Najjari Rosiek ‘13

The couplings of Z to leptons are protected by the SM gauge symmetry
→ LFV effects must be proportional to the EW breaking:

$$\mathrm{BR}(Z \to \ell\ell') \sim \mathrm{BR}(Z \to \ell\ell) \times C_{\mathrm{NP}}^2 \left(\frac{v}{\Lambda_{\mathrm{NP}}}\right)^4$$

In the SM EFT, only 5 operators contribute at the tree level:

$$Q_{\Phi\ell}^{(1)} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{\ell}_L \gamma^\mu \ell'_L), \qquad Q_{\Phi\ell}^{(3)} = (\Phi^\dagger i \overleftrightarrow{D}_\mu^I \Phi)(\bar{\ell}_L \tau_I \gamma^\mu \ell'_L), \qquad Q_{\Phi e} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{\ell}_R \gamma^\mu \ell'_R)$$

$$Q_{eW} = (\bar{\ell}_L \sigma^{\mu\nu} \ell'_R) \tau_I \Phi W_{\mu\nu}^I, \qquad Q_{eB} = (\bar{\ell}_L \sigma^{\mu\nu} \ell'_R) \Phi B_{\mu\nu}$$

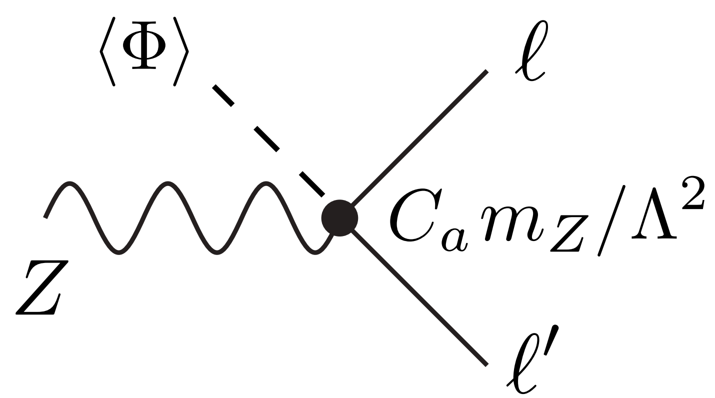
$$\mathrm{Br}\left[Z^0 \to \ell_f^\pm \ell_i^\mp\right] = \frac{m_Z}{24\pi\Gamma_Z}\left[\frac{m_Z^2}{2}\left(\left|C_{fi}^{ZR}\right|^2 + \left|C_{fi}^{ZL}\right|^2\right) + \left|\Gamma_{fi}^{ZL}\right|^2 + \left|\Gamma_{fi}^{ZR}\right|^2\right]$$

$$\Gamma_{fi}^{ZL} = \frac{e}{2 s_W c_W}\left(\frac{v^2}{\Lambda^2}\left(C_{\varphi l}^{(1)fi} + C_{\varphi l}^{(3)fi}\right) + \left(1 - 2 s_W^2\right)\delta_{fi}\right) \qquad \Gamma_{fi}^{ZR} = \frac{e}{2 s_W c_W}\left(\frac{v^2}{\Lambda^2} C_{\varphi e}^{fi} - 2 s_W^2 \delta_{fi}\right)$$

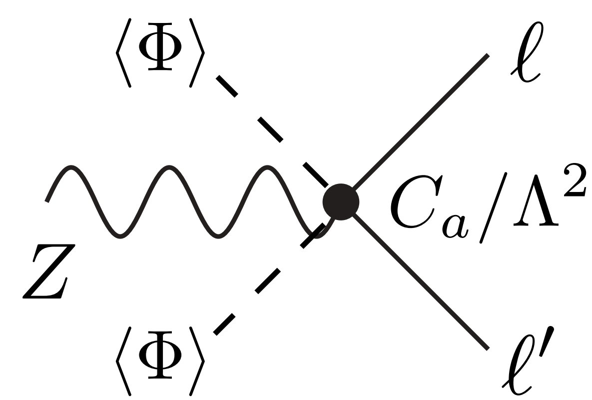
$$C_{fi}^{ZR} = C_{if}^{ZL\star} = -\frac{v}{\sqrt{2}\Lambda^2} = \left(s_W C_{eB}^{fi} + c_W C_{eW}^{fi}\right)$$

Crivellin Najjari Rosiek 1312.0634

Dipole operators:



Higgs-lepton operators:



$$Q^{(1)}_{\Phi\ell} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar\ell_L\gamma^\mu \ell'_L), \qquad Q^{(3)}_{\Phi\ell} = (\Phi^\dagger i \overleftrightarrow{D}^I_\mu \Phi)(\bar\ell_L\tau_I\gamma^\mu\ell'_L), \qquad Q_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar\ell_R\gamma^\mu\ell'_R)$$

$$Q_{eW} = (\bar\ell_L\sigma^{\mu\nu}\ell'_R)\tau_I\Phi\, W^I_{\mu\nu}, \qquad Q_{eB} = (\bar\ell_L\sigma^{\mu\nu}\ell'_R)\Phi\, B_{\mu\nu}$$

If a single operator dominates, $Z\to\ell\ell'$ constrain NP scales up to

$$C_a = 1: \quad \Lambda \gtrsim 5\ \text{TeV} \ \ (\text{Z}\to\mu\text{e}), \quad \Lambda \gtrsim 3\ \text{TeV} \ \ (\text{Z}\to\tau\ell)$$

$$\Gamma^{ZL}_{fi} = \frac{e}{2s_W c_W}\left(\frac{v^2}{\Lambda^2}\left(C^{(1)fi}_{\varphi l} + C^{(3)fi}_{\varphi l}\right) + \left(1-2s^2_W\right)\delta_{fi}\right) \qquad \Gamma^{ZR}_{fi} = \frac{e}{2s_W c_W}\left(\frac{v^2}{\Lambda^2}C^{fi}_{\varphi e} - 2s^2_W\delta_{fi}\right)$$

$$C^{ZR}_{fi} = C^{ZL\star}_{if} = -\frac{v}{\sqrt{2}\Lambda^2} = \left(s_W C^{fi}_{eB} + c_W C^{fi}_{eW}\right)$$

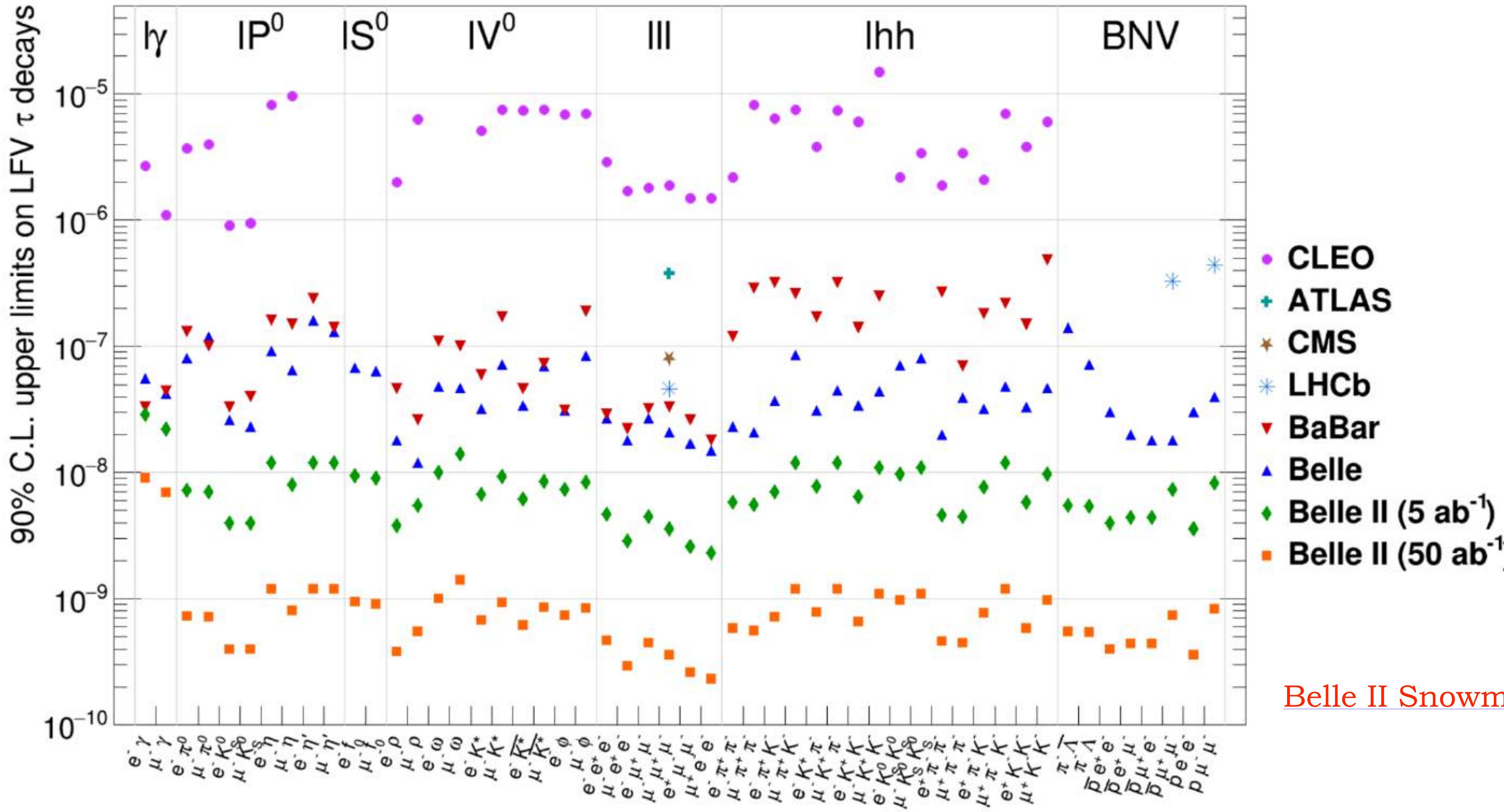
Crivellin Najjari Rosiek 1312.0634

Model-independent indirect limits on Z LFV decays

Observable	Operator	Indirect Limit on LFVZD	Strongest constraint
lepton-Higgs ops	$(Q_{\varphi\ell}^{(1)} + Q_{\varphi\ell}^{(3)})^{e\mu}$	3.7×10^{-13}	$\mu \to e$, Au
$\mathrm{BR}(Z \to \mu e)$	$Q_{\varphi e}^{e\mu}$	9.4×10^{-15}	$\mu \to e$, Au
dipole ops	$Q_{eB}^{e\mu}$	1.4×10^{-23}	$\mu \to e\gamma$
	$Q_{eW}^{e\mu}$	1.6×10^{-22}	$\mu \to e\gamma$
$\mathrm{BR}(Z \to \tau e)$	$(Q_{\varphi\ell}^{(1)} + Q_{\varphi\ell}^{(3)})^{e\tau}$	6.3×10^{-8}	$\tau \to \rho\, e$
	$Q_{\varphi e}^{e\tau}$	6.3×10^{-8}	$\tau \to \rho\, e$
	$Q_{eB}^{e\tau}$	1.2×10^{-15}	$\tau \to e\gamma$
	$Q_{eW}^{e\tau}$	1.3×10^{-14}	$\tau \to e\gamma$
$\mathrm{BR}(Z \to \tau\mu)$	$(Q_{\varphi\ell}^{(1)} + Q_{\varphi\ell}^{(3)})^{\mu\tau}$	4.3×10^{-8}	$\tau \to \rho\, \mu$
	$Q_{\varphi e}^{\mu\tau}$	4.3×10^{-8}	$\tau \to \rho\, \mu$
	$Q_{eB}^{\mu\tau}$	1.5×10^{-15}	$\tau \to \mu\gamma$
	$Q_{eW}^{\mu\tau}$	1.7×10^{-14}	$\tau \to \mu\gamma$

LC Marcano Roy '21

LFV tau decays:



Belle II Snowmass

Measurement	Current	Belle II	FCC	CEPC prelim.
$\mathrm{BR}(\tau \to \mu\mu\mu)$	$< 2.1 \times 10^{-8}$	3.6×10^{-10}	1.4×10^{-11}	10^{-10}
$\mathrm{BR}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	6.9×10^{-9}	1.2×10^{-9}	10^{-10}

LFU tests in Z decays

Universality presently tested at the per-mil level

LEP exps/SLD combination: hep-ex:0509008

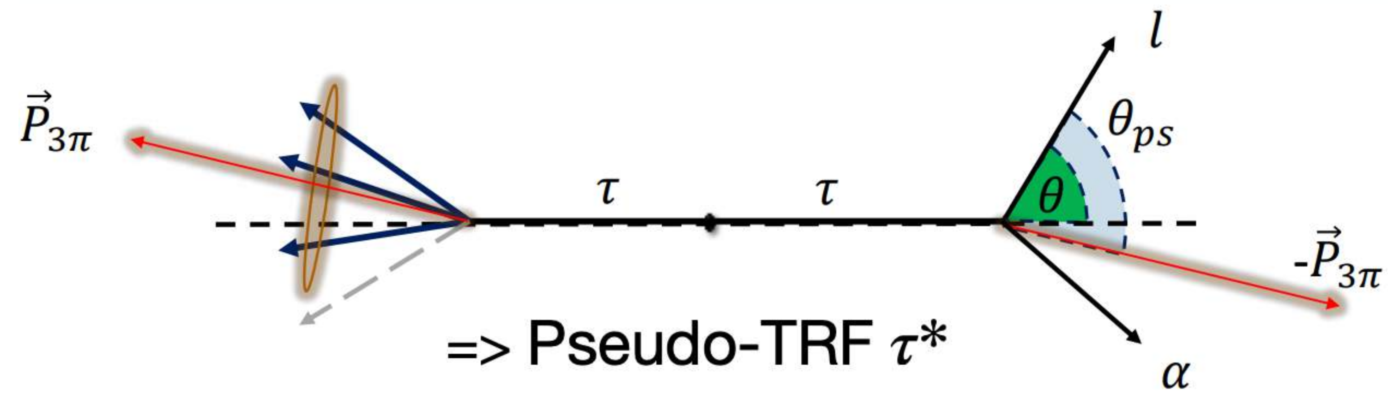
$$\frac{\mathrm{BR}(Z\to\mu^+\mu^-)}{\mathrm{BR}(Z\to e^+e^-)} = 1.0009 \pm 0.0028\,, \qquad \frac{\mathrm{BR}(Z\to\tau^+\tau^-)}{\mathrm{BR}(Z\to e^+e^-)} = 1.0019 \pm 0.0032$$

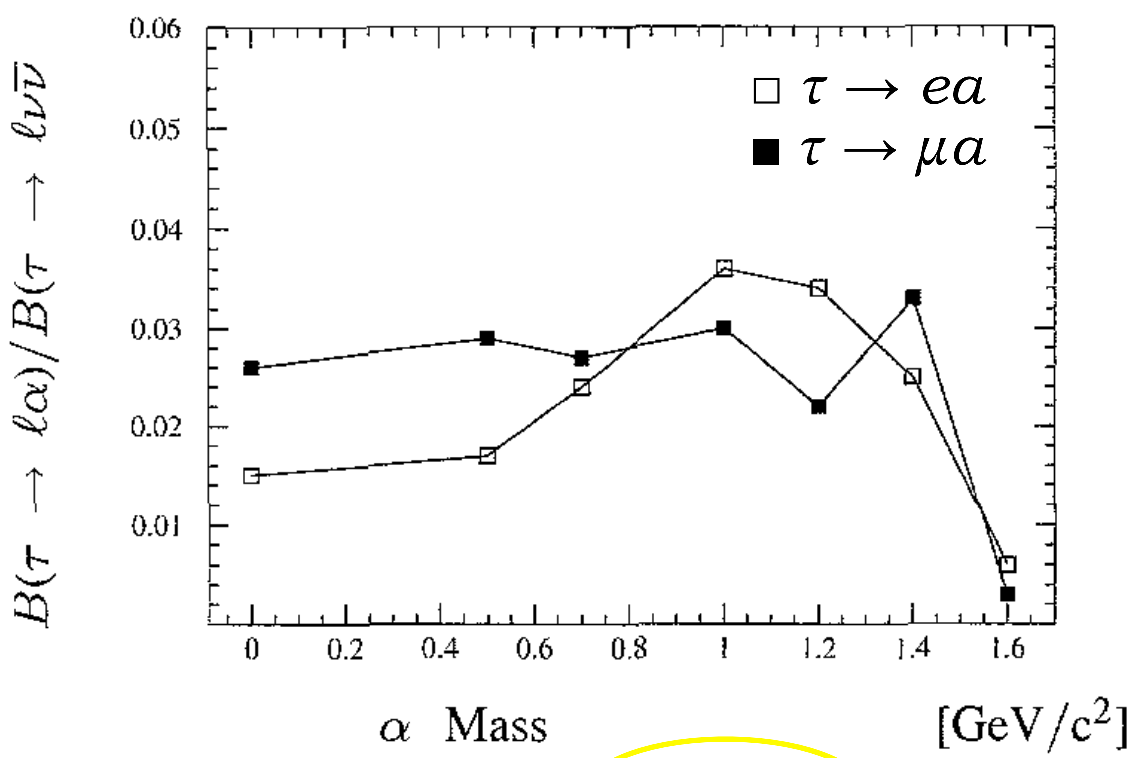
(1.7×10^7 Z decays at LEP + 6×10^5 Z decays with polarised beams at SLC)

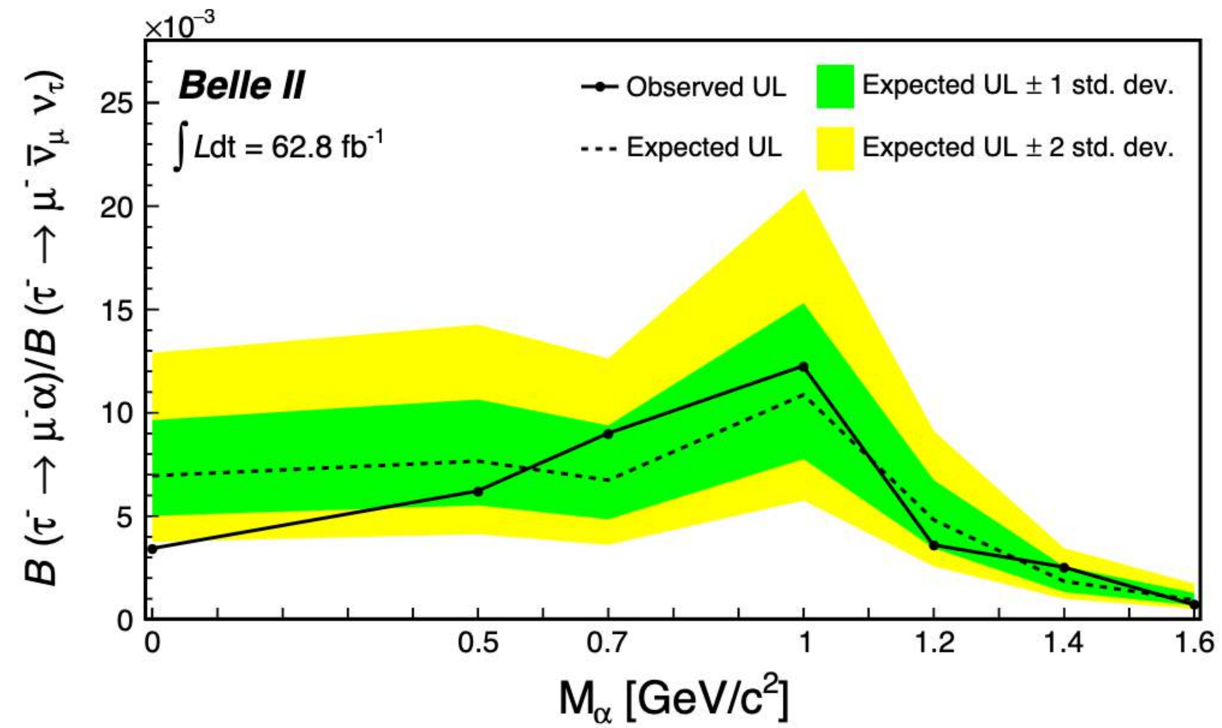
- Very important test in view of the LFU anomalies in B decays
- At LEP statistical and systematic uncertainties of the same order
- With 10^{12} Z, CEPC has no problem of statistics
- Can systematics be controlled e.g. at the 10^{-4} level?
- This would test new physics coupling preferably to tau up to scales of the order of 10-20 TeV

Present limits on $\tau \to e\, a$, $\tau \to \mu\, a$ (invisible a)

A challenging search:
tau momentum / rest frame
cannot be exactly reconstructed
BG: ordinary $\tau \to \ell\nu\bar{\nu}$







ARGUS 1995 (472 pb^{-1}) → Belle II 2023 (62.8 fb^{-1})

up to O(10) improvement!

$m_a \approx 0$:

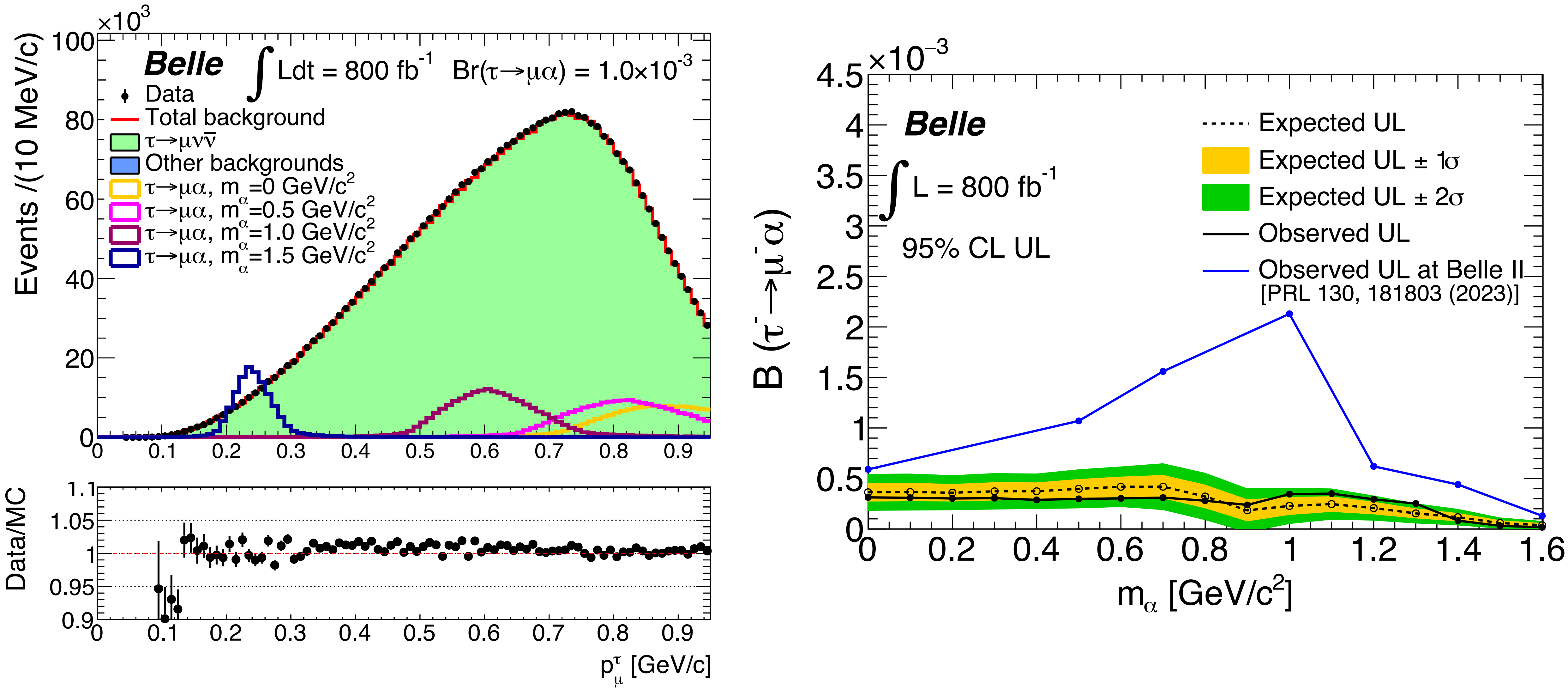
$$\mathrm{BR}(\tau \to \mu\, a) < 4.7 \times 10^{-4}\ (90\%\ \mathrm{CL}) \quad \Rightarrow \quad f_a/C^{V,A}_{\mu\tau} > 5.1 \times 10^6\ \mathrm{GeV}$$

$$\mathrm{BR}(\tau \to e\, a) < 7.6 \times 10^{-4}\ (90\%\ \mathrm{CL}) \quad \Rightarrow \quad f_a/C^{V,A}_{e\tau} > 4.0 \times 10^6\ \mathrm{GeV}$$

Present limits on $\tau \to e\, a$, $\tau \to \mu\, a$ (invisible a)

A challenging search:

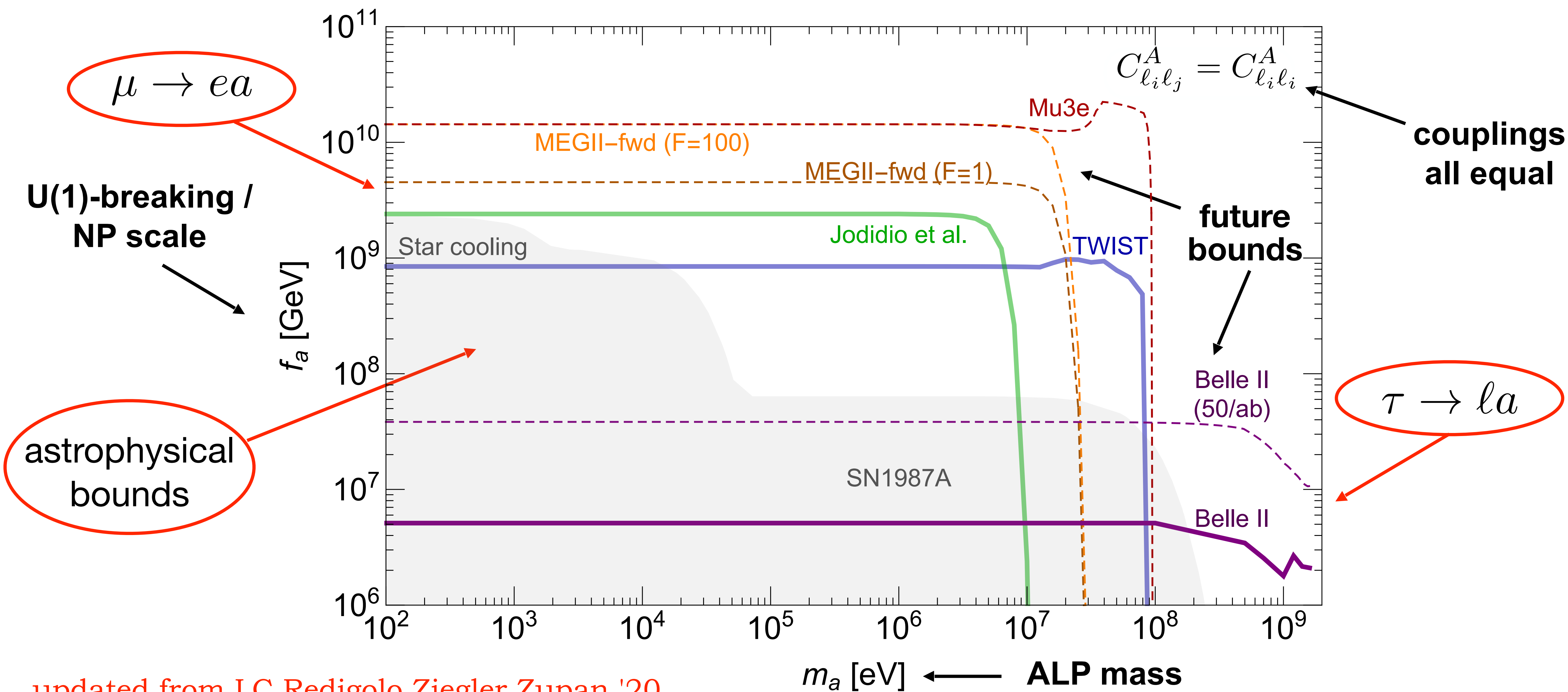
- NEW! Belle 2025 (800 fb^{-1})



$m_a \approx 0$: $\quad \mathrm{BR}(\tau \to e\, a) < 7.6 \times 10^{-4}$ (90% CL) $\Rightarrow$ $f_a/C^{V,A}_{e\tau} > 4.0 \times 10^6$ GeV

Summary of searches for light *invisible* LFV ALPs

$$\mathcal{L}_{a\ell\ell} = \frac{\partial^\mu a}{2f_a}\left(C^V_{ij}\,\bar{\ell}_i\gamma_\mu\ell_j + C^A_{ij}\,\bar{\ell}_i\gamma_\mu\gamma_5\ell_j\right) \Rightarrow \Gamma(\ell_i \to \ell_j\, a) = \frac{1}{64\pi}\frac{m^3_{\ell_i}}{f_a^2}\left(|C^V_{\ell_i\ell_j}|^2 + |C^A_{\ell_i\ell_j}|^2\right)\left(1-\frac{m_a^2}{m_{\ell_i}^2}\right)^2$$



updated from LC Redigolo Ziegler Zupan '20

- Decays mediated by dimension-5 operators: much larger NP scales can be reached than with $\mu \to e\,\gamma$, $\mu \to eee$ etc. (from dim-6 operators)
- Mu/tau/astro interplay: if $m_a > m_\mu$ constraints mainly come from τ decays