University of Zurich[UZH]

LF(U)V tests in tau decays and EW precision observables in view of FCC-ee

Fostering Swiss collaboration towards a future circular collider

Zurich, 26 August 2022

Nudžeim Selimović

University of Zurich

SM

Absence of Beyond the SM physics signals in data

The problems of the SM : Flavour?
Neutrino masses?
Dark matter?
Higgs hierarchy?
⋮

reasons to believe there is more!

Indirect observations, historically…

1970s

Indirect evidence for neutral current at Gargamelle bubble chamber

↓

Inferring the existence of Z

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SPS construction was justified and motivated

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Discovering Z and W

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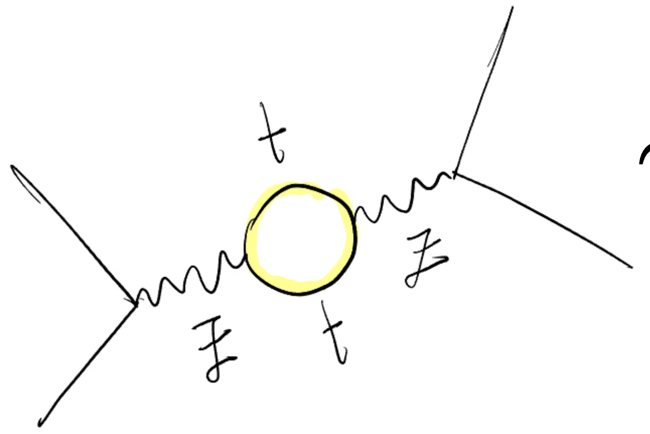
LEP construction was justified and motivated

Indirect observations, historically…



$\sim m_t^2$

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Precision measurements of Z and W properties

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Inferring

$m_{top} = 173^{+13}_{-10}\ GeV$

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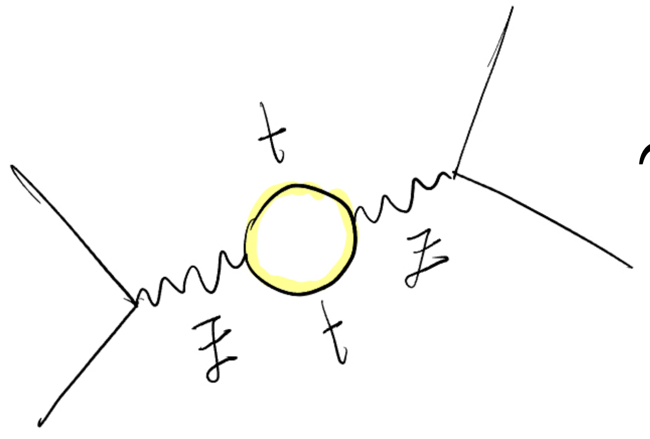

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Inferring
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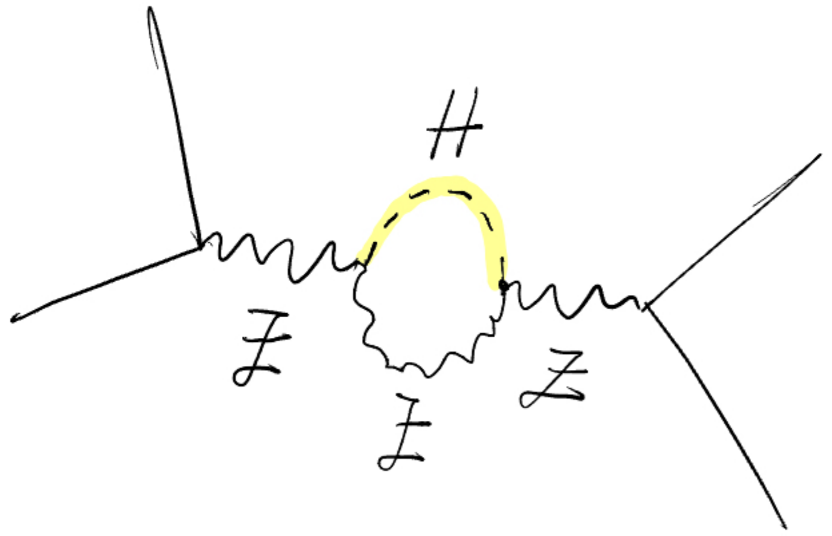

$\sim \log(m_H/m_Z)$

1995
Discovering (Tevatron) top quark in the predicted range

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Inferring
$m_H = 98^{+25}_{-21}\ GeV$

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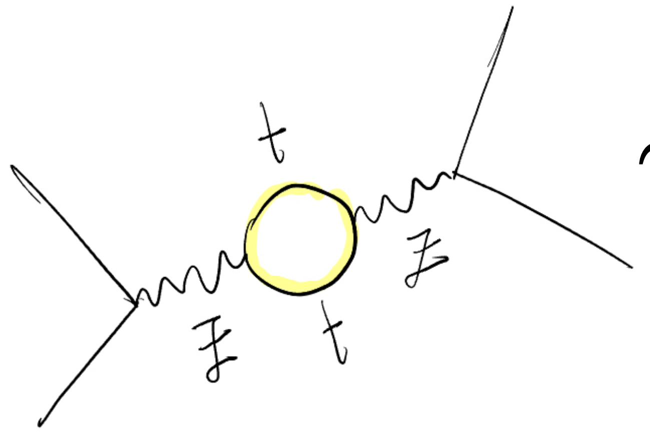

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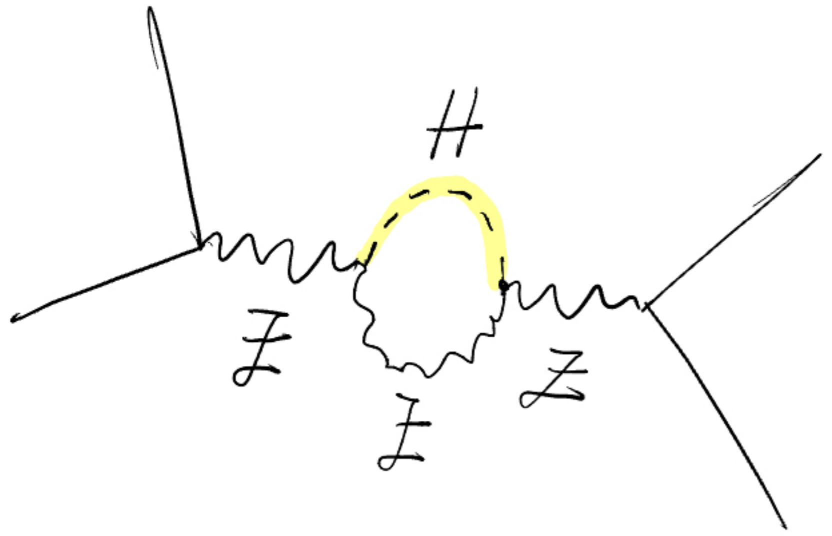


$\sim \log(m_H/m_Z)$

1995

Discovering (Tevatron) top quark in the predicted range

↓

Inferring

$m_H = 98^{+25}_{-21}\ GeV$

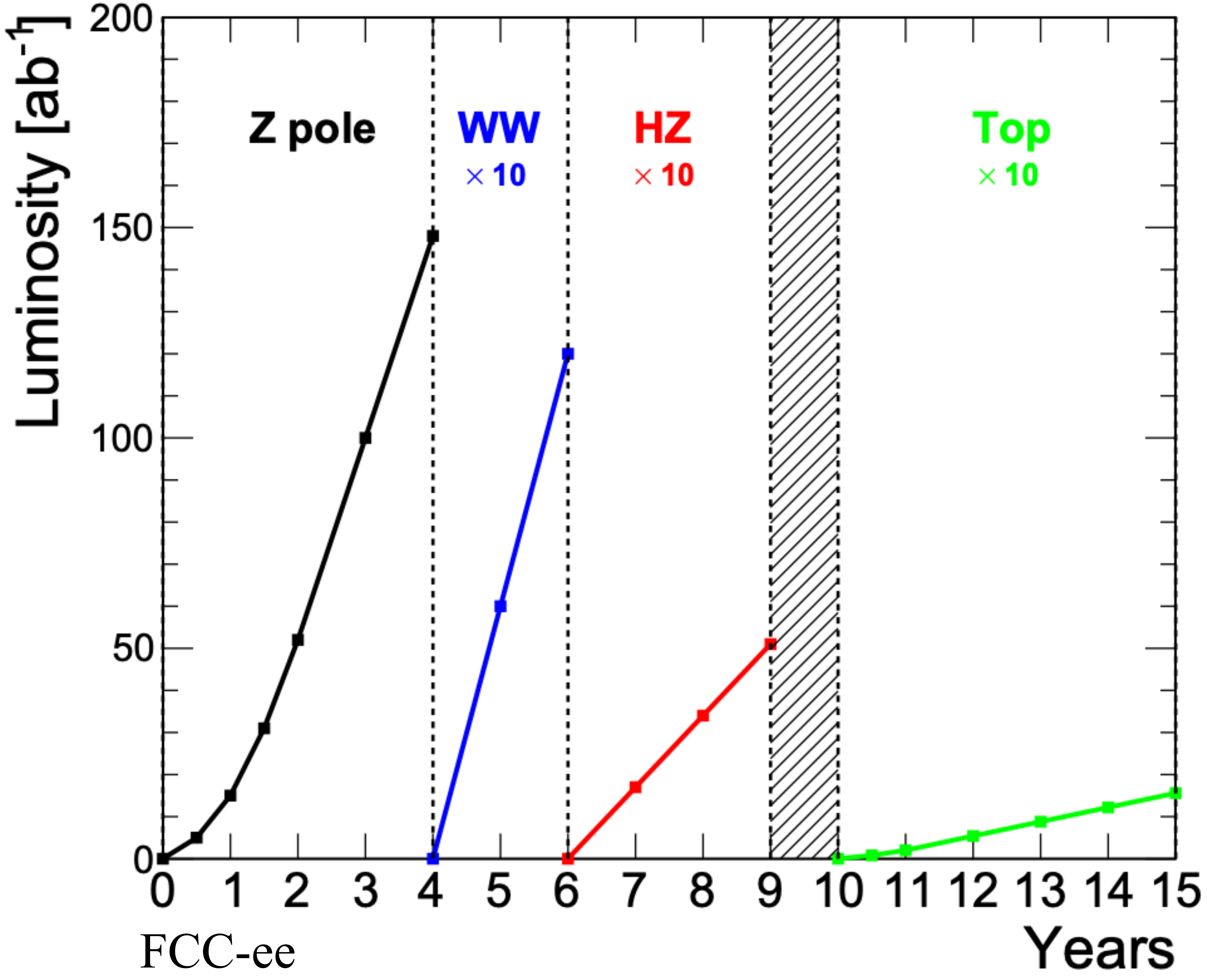
↓

2012

Discovering (LHC) Higgs in the predicted range

Indirect measurements are essential!

[Future Circular Collider Conceptual Design Report Volume 2]



	N	Precision $\sim 1/\sqrt{N}$
Z	10^{12}	10^{-6}
WW pairs	10^{8}	10^{-4}
H	10^{6}	10^{-3}
tt pairs	10^{6}	10^{-3}

SMEFT

Model independent parametrisation of the New Physics effects:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda^2}\mathcal{O}_i + O(\Lambda^{-4})$$

Example @ the Z-pole: $N_Z^{FCC-ee} = 10^5 N_Z^{LEP}$:

$$c_i^{FCC-ee} \sim 10^{-5/2} c_i^{LEP} \sim 0.003 \times c_i^{LEP}$$

or

$$\Lambda^{FCC-ee} \sim 10^{5/4} \Lambda^{LEP} \sim 18 \times \Lambda^{LEP}$$

(Neglecting theory and systematic errors)

SMEFT

Operators that can be tested at FCC-ee:

$h \to Vff$

$$\mathcal{O}_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$$
$$\mathcal{O}_{Hq}^{(3)} = (\phi^\dagger i\overleftrightarrow{D}^a_\mu H)(\bar{q}\gamma^\mu \sigma_a q)$$
$$\mathcal{O}_{H\ell}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{H\ell}^{(3)} = (\phi^\dagger i\overleftrightarrow{D}^a_\mu H)(\bar{\ell}\gamma^\mu \sigma_a \ell)$$
$$\mathcal{O}_{Hu} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$$
$$\mathcal{O}_{Hd} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$$
$$\mathcal{O}_{He} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$$

$h \to VV$

$$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$
$$\mathcal{O}_{HG} = (H^\dagger H)G_{\mu\nu}G^{\mu\nu}$$
$$\mathcal{O}_{HW} = (H^\dagger H)W_{\mu\nu}W^{\mu\nu}$$
$$\mathcal{O}_{HB} = (H^\dagger H)B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{HWB} = (H^\dagger \sigma_a H)W^a_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{HD} = |H^\dagger i D_\mu H|^2$$

$h \to ff$

$$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$
$$\mathcal{O}_{eH} = (H^\dagger H)(\bar{\ell}_L H e_R)$$
$$\mathcal{O}_{uH} = (H^\dagger H)(\bar{q}_L \tilde{H} u_R)$$
$$\mathcal{O}_{dH} = (H^\dagger H)(\bar{q}_L H d_R)$$

VV prod.

$$\mathcal{O}_{3W} = \epsilon_{abc}W^{a\nu}_\mu W^{b\rho}_\nu W^{c\mu}_\rho$$

SMEFT

Operators that can be tested at FCC-ee:

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$$\mathcal{O}_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$$
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VV prod.

$$\mathcal{O}_{3W} = \epsilon_{abc} W^{a\nu}_\mu W^{b\rho}_\nu W^{c\mu}_\rho$$

Impact τ-physics and EW precision observables

τ - physics @ FCC-ee

$N_Z = 10^{12}$ implies $1.3 \times 10^{11}\ Z \to \tau^+\tau^-$ decays

	Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.
[BESIII]	m_τ (MeV)	1776.86 ± 0.12	0.004	0.1
[LEP]	$\mathcal{B}(\tau \to e\bar{\nu}\nu)$ (%)	17.82 ± 0.05	0.0001	0.003
[LEP]	$\mathcal{B}(\tau \to \mu\bar{\nu}\nu)$ (%)	17.39 ± 0.05	0.0001	0.003
[Belle]	τ_τ (fs)	290.3 ± 0.5	0.001	0.04

[Tau-lepton Physics at the FCC-ee, Mogens Dam]

1. Tests of lepton flavour universality in τ - decays
2. Tests of charged lepton flavour violation in τ - decays

1. Tests of LFU in τ - decays

[Precision Tau Physics, Antonio Pich]

		$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$
[LEP]	$\lvert g_\mu/g_e \rvert$	1.0018 (14)

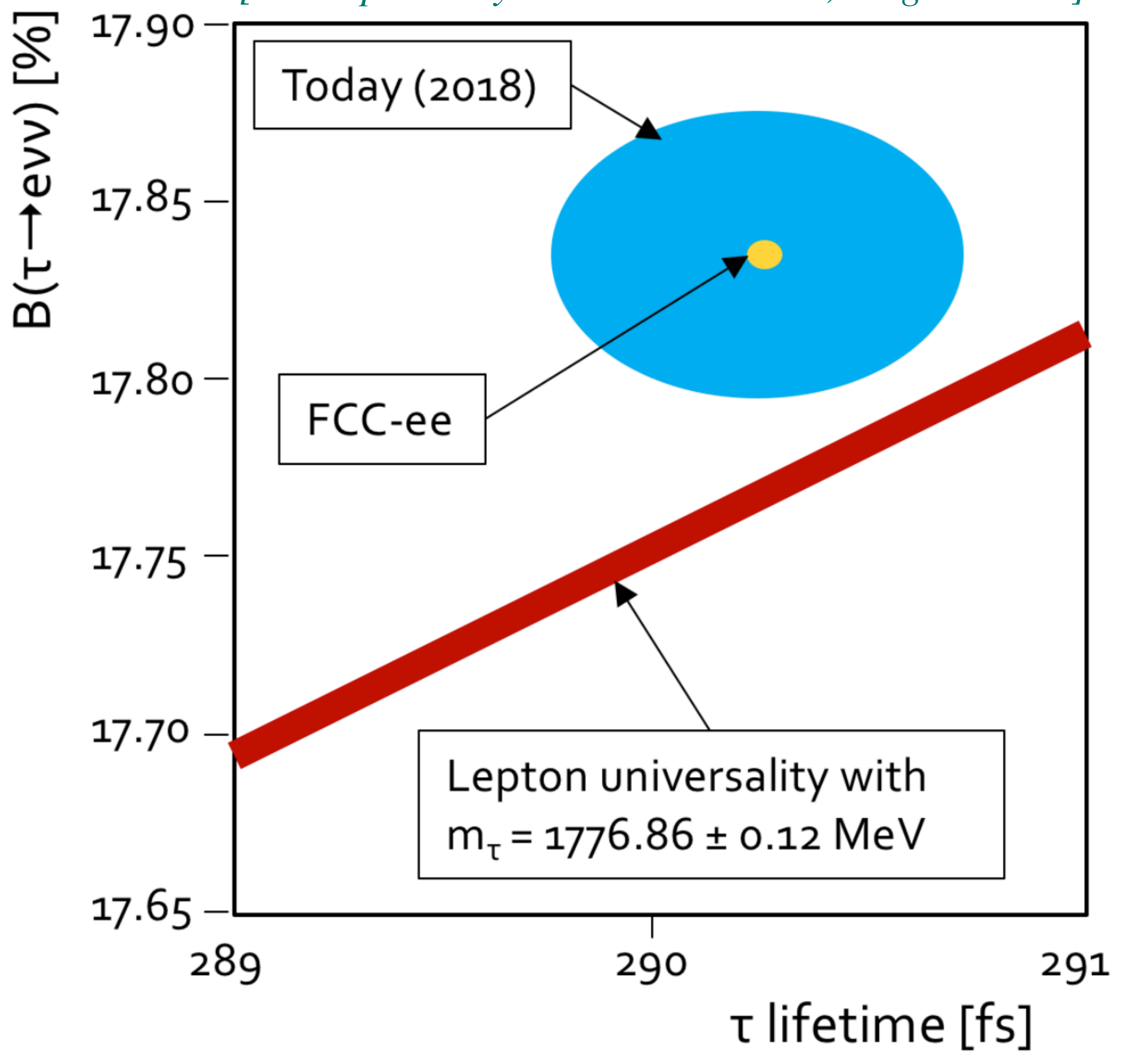
		$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$
[LEP]	$\lvert g_\tau/g_\mu \rvert$	1.0011 (15)

		$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$
[LEP]	$\lvert g_\tau/g_e \rvert$	1.0030 (15)

FCC-ee expected to go below 10^{-4} !

QED corrections known to $\mathcal{O}(\alpha^2) \lesssim 10^{-5}$

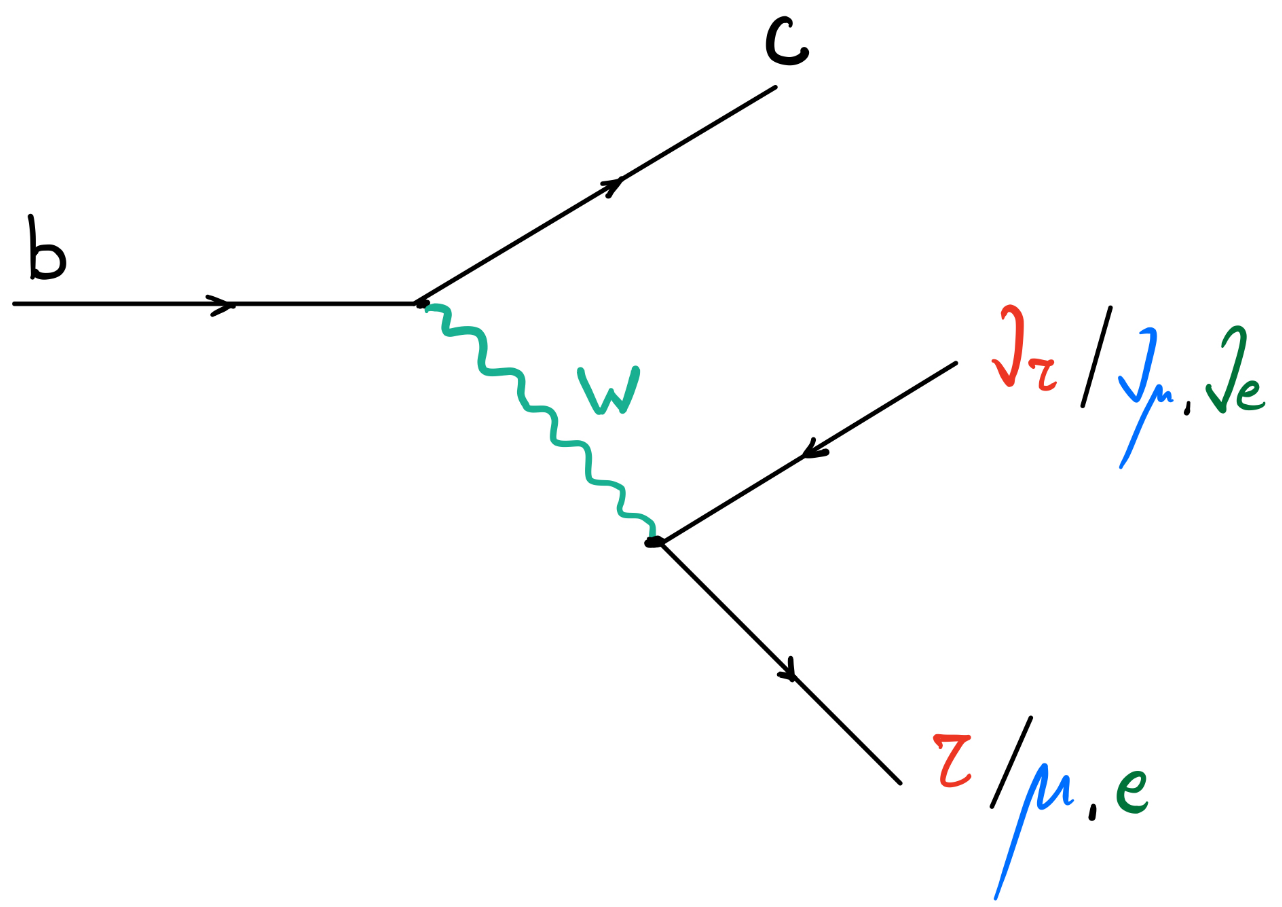
[Tau-lepton Physics at the FCC-ee, Mogens Dam]



Example: B-anomalies ↔ LFUV in τ decays

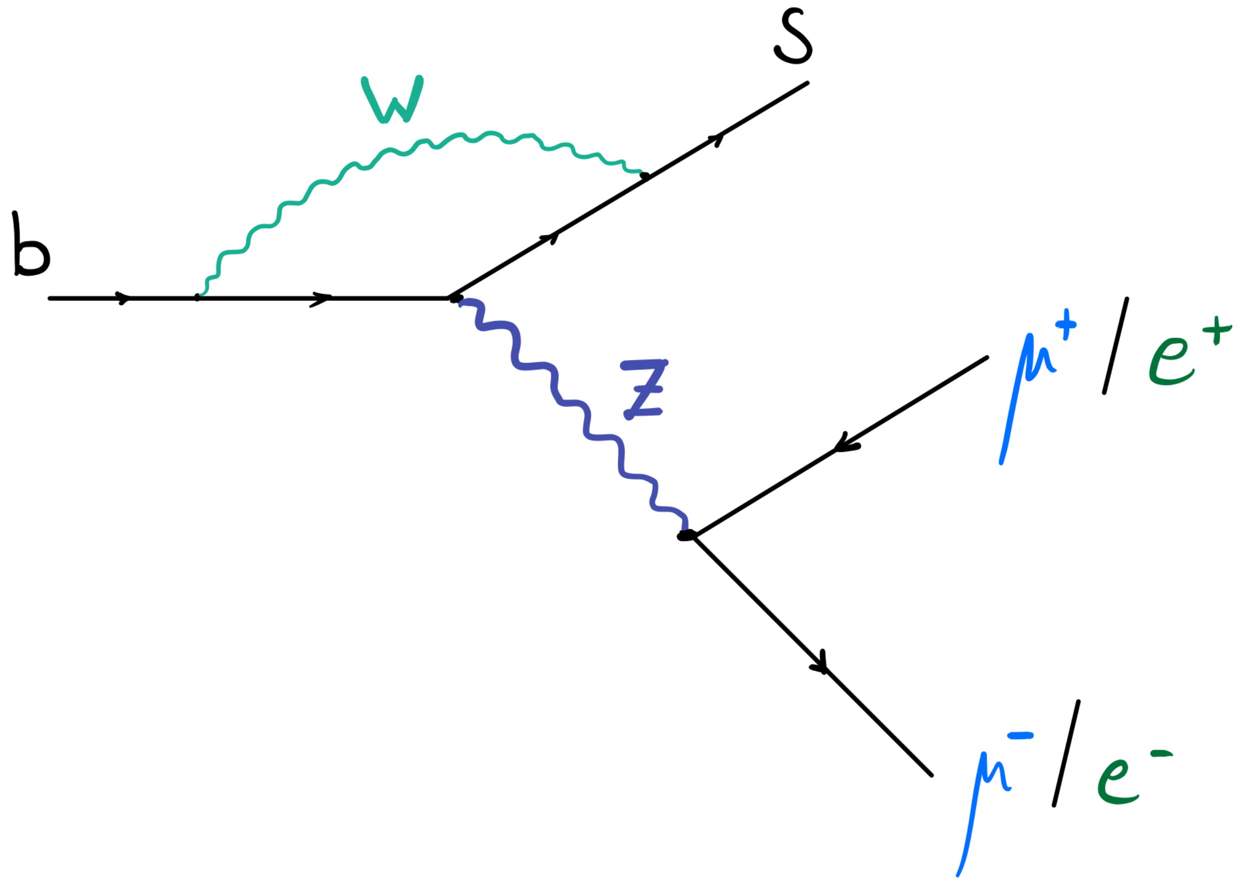
A quick review:

- τ / μ and τ / e $\sim 3\sigma$ deviation in $b \to c\tau\nu$ charged current



- *Tree* level in SM

- μ / e $\sim 4\sigma$ deviation in $b \to s\ell\ell$ neutral current



- *Loop* level in SM

Combined explanation ingredients

1. Approximate $U(2)^5$ *flavour symmetry*

[R. Barbieri, G. Isidori, J. Jones-Perez, P. Lodone and D. M. Straub, arXiv:1105.2296]

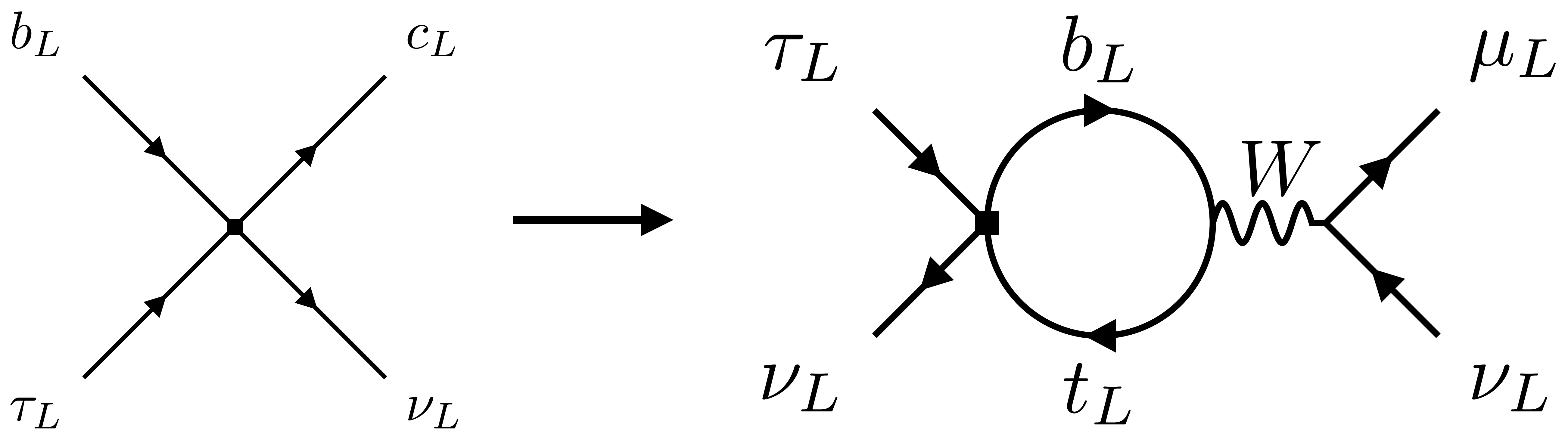
2. $U_1 \sim (3,1)_{2/3}$ *vector leptoquark*

[D. Buttazzo, A. Greljo, G. Isidori and D. Marzocca, arXiv:1706.07808]

Example: B-anomalies ↔ LFUV in τ decays

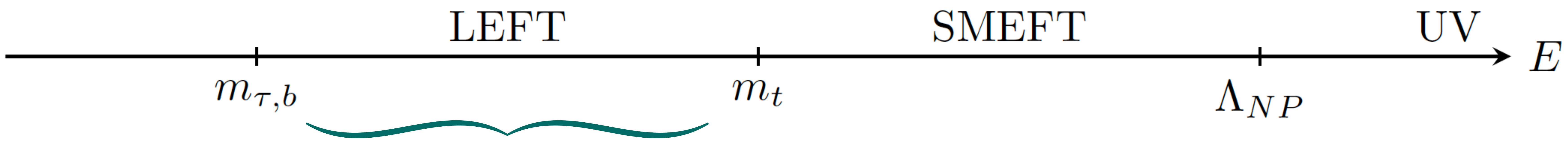
$$[O_{\ell q}^{(1)}]_{\alpha\beta ij} = (\bar{\ell}_L^\alpha \gamma_\mu \ell_L^\beta)(\bar{q}_L^i \gamma^\mu q_L^j)$$

$$[O_{\ell q}^{(3)}]_{\alpha\beta ij} = (\bar{\ell}_L^\alpha \sigma^I \gamma_\mu \ell_L^\beta)(\bar{q}_L^i \sigma^I \gamma^\mu q_L^j)$$



[F. Feruglio, P. Paradisi, A. Pattori arXiv: 1606.00524]

EFT for τ decays



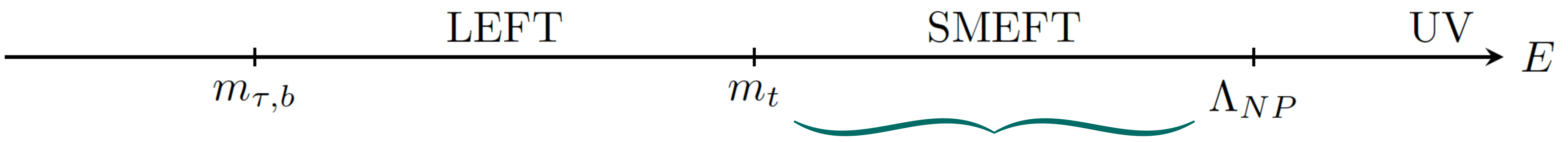
$$\boxed{\mathcal{L}_{\text{LEFT}} = -\frac{2}{v^2}\left[L_{\nu e}^{V,LL}\right]^{\alpha\beta\gamma\delta}\left(\bar{\nu}_L^{\alpha}\gamma_\mu \nu_L^{\beta}\right)\left(\bar{e}_L^{\gamma}\gamma^\mu e_L^{\delta}\right)}$$

In the SM: $\left[L_{\nu e}^{V,LL}\right]^{\alpha\beta\beta\alpha}_{SM} = 1$

Deviation parametrised by:

$$R_{\beta\alpha} \equiv \frac{\Gamma(\ell_\beta \to \ell_\alpha \nu\bar{\nu})}{\Gamma_{\text{SM}}(\ell_\beta \to \ell_\alpha \nu\bar{\nu})} \equiv 1 + \delta R_{\beta\alpha} \approx 1 + 2\,\text{Re}[L_{\nu e}^{V,LL}]^{\text{NP}}_{\alpha\beta\beta\alpha}$$

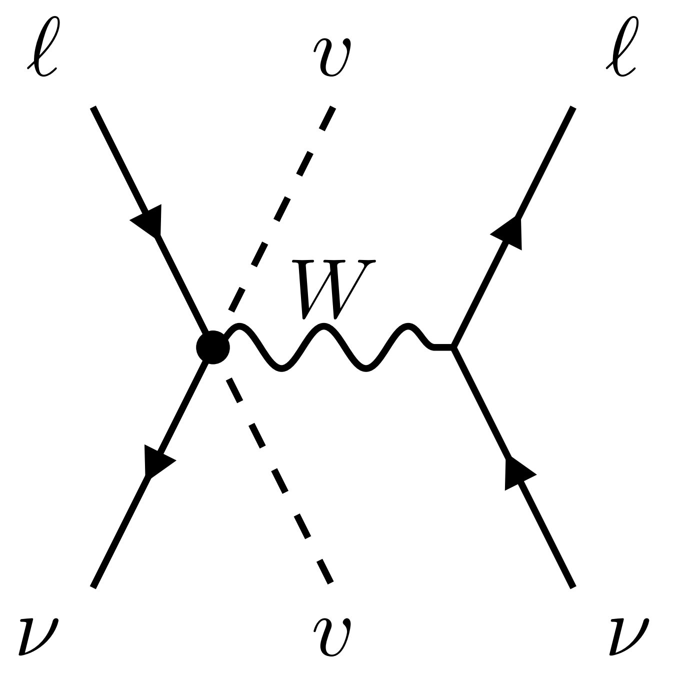
EFT for τ decays



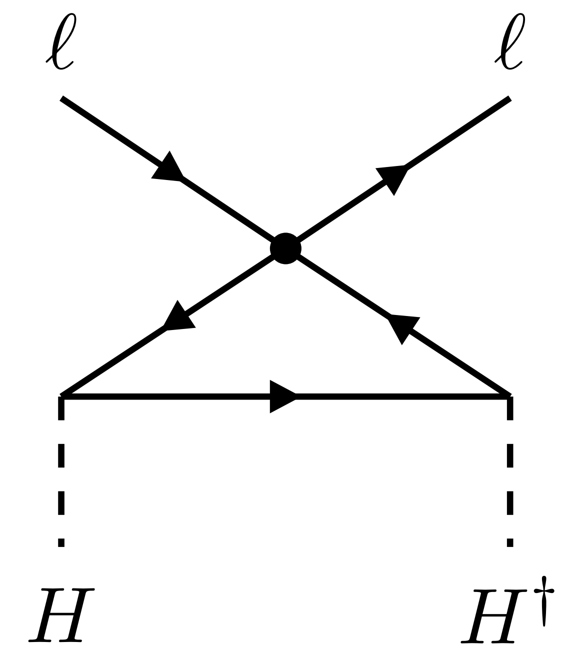
$$\mathcal{L}_{\text{SMEFT}} = -\frac{2}{v^2}\left[C_{\ell q}^{(3)}\right]^{\alpha\beta ij}\left(\bar{\ell}^{\alpha}\gamma_{\mu}\sigma^{I}\ell^{\beta}\right)\left(\bar{q}^{i}\gamma^{\mu}\sigma^{I}q^{j}\right)$$

LEFT - SMEFT matching (tree-level):

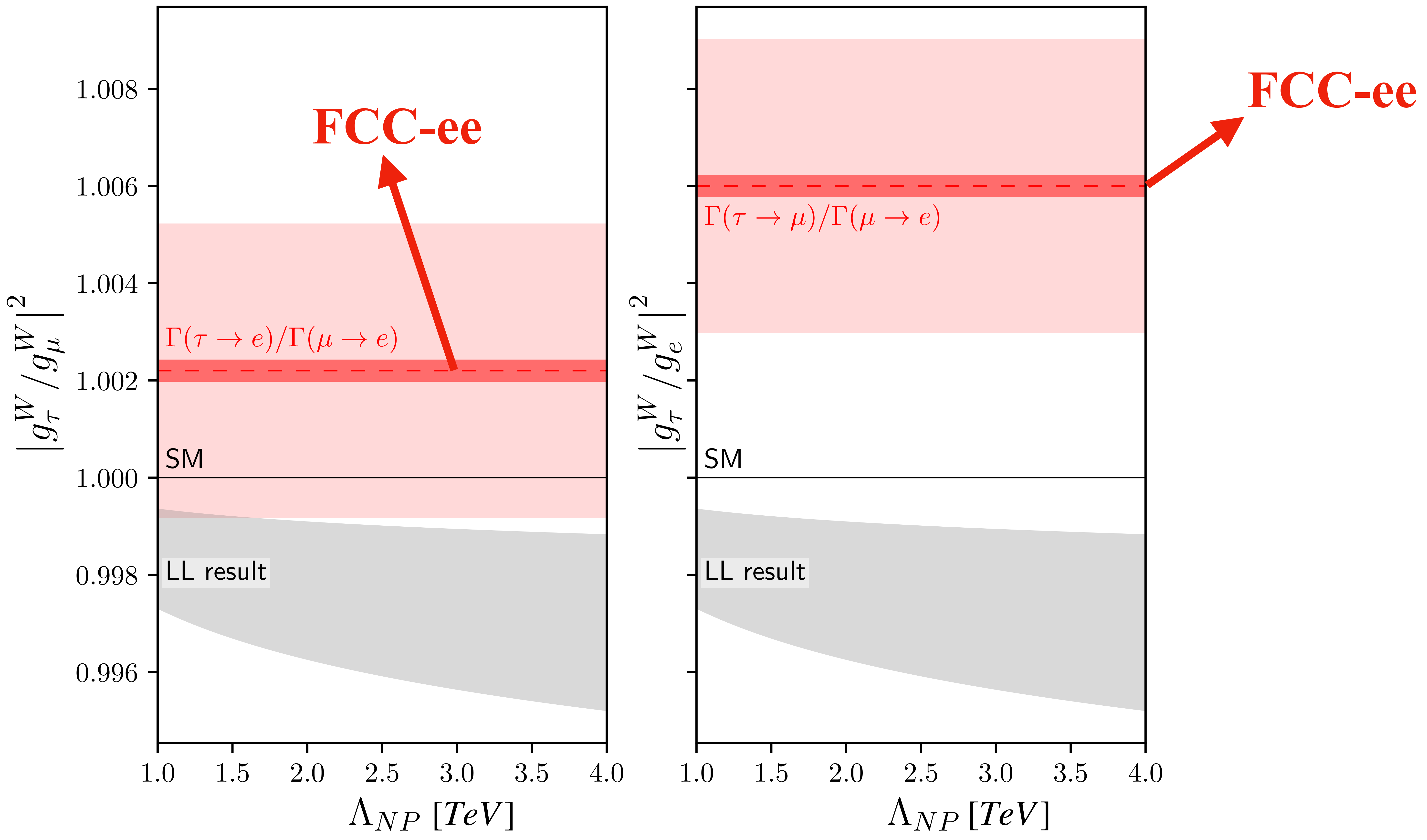
$$[L_{\nu e}^{V,LL}]^{\alpha\beta\beta\alpha}_{\text{NP}-\text{LL}} = -2\sum_{\gamma=\alpha,\beta}\left[C_{H\ell}^{(3)}\right]_{\gamma\gamma}(m_t) = -\frac{y_t^2 N_c}{8\pi^2}\log\frac{\Lambda_{\text{NP}}^2}{m_t^2}\sum_{\gamma=\alpha,\beta}[C_{\ell q}^{(3)}]_{\gamma\gamma 33}$$



$$[O_{H\ell}^{(3)}]_{\alpha\beta} = (\bar{\ell}^{\alpha}\gamma_{\mu}\sigma^{I}\ell^{\beta})(H^{\dagger}i\overleftrightarrow{D}^{\mu}\sigma^{I}H)$$



$$|g_\tau^W/g_\mu^W|^2 \equiv \frac{\Gamma(\tau\to e\nu\bar\nu)}{\Gamma(\mu\to e\nu\bar\nu)}\left[\frac{\Gamma_{\rm SM}(\tau\to e\nu\bar\nu)}{\Gamma_{\rm SM}(\mu\to e\nu\bar\nu)}\right]^{-1} = 1 + 2{\rm Re}[L_{\nu e}^{V,LL}]^{\rm NP}_{\mu\tau\tau\mu} - 2{\rm Re}[L_{\nu e}^{V,LL}]^{\rm NP}_{e\mu\mu e}$$



[LFU violations in leptonic τ decays and B-physics anomalies, Lukas Allwicher, Gino Isidori, NS]

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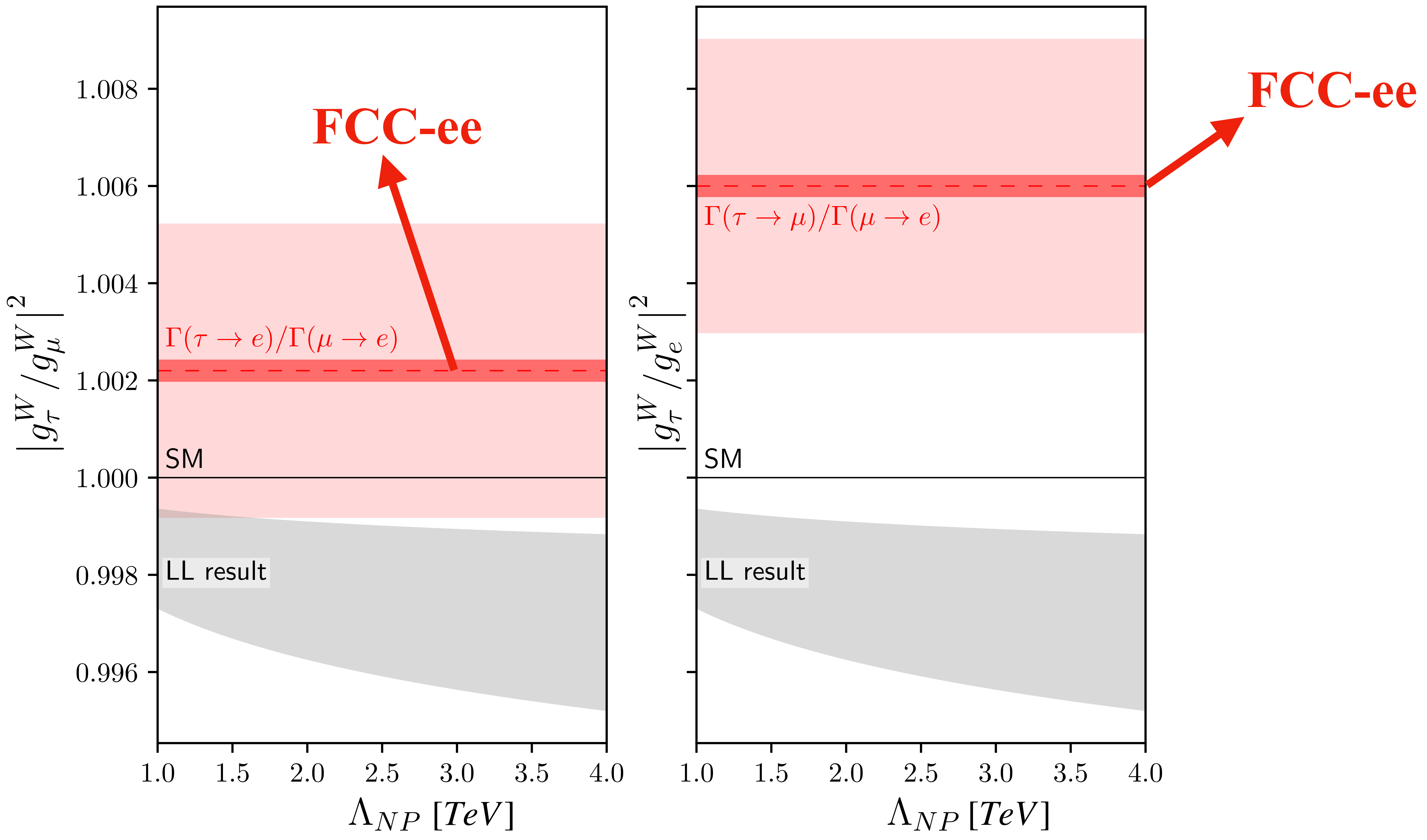

Full model computations are important!

Example: 4321 Models

[L. Di Luzio, A. Greljo and M. Nardecchia, arXiv: 1708.08450]
[L. Di Luzio, J. Fuentes-Martin, A. Greljo, M. Nardecchia, S. Renner, arXiv: 1808.00942]
[M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, arXiv: 1712.01368, 1805.09328]
[H. Georgi, Y. Nakai, arXiv: 1606.05865] [J. Fuentes-Martın, P. Stangl, arXiv: 2004.11376]
[D. Guadagnoli, M. Reboud, P. Stangl, arXiv: 2005.10117] …

$$\underset{g_4}{SU(4)_3} \times \underset{g_3}{SU(3)_{1+2}} \times SU(2)_L \times U(1)'$$

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
$\psi_L = (q_L^3\ \ell_L^3)^T$	**4**	**1**	**2**	0
$\psi_R^+ = (u_R^3\ \nu_R^3)^T$	**4**	**1**	**1**	1/2
$\psi_R^- = (d_R^3\ e_R^3)^T$	**4**	**1**	**1**	−1/2

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$\psi_R^- = (d_R^3\ e_R^3)^T$	**4**	**1**	**1**	−1/2
$q_L'^i$	**1**	**3**	**2**	1/6
u_R^i	**1**	**3**	**1**	2/3
d_R^i	**1**	**3**	**1**	−1/3
$\ell_L'^i$	**1**	**1**	**2**	−1/2
e_R^i	**1**	**1**	**1**	−1

$i = 1,2$

$U(2)^5$: *1st ingredient*

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$$\underset{g_4}{SU(4)_3} \times \underset{g_3}{SU(3)_{1+2}} \times SU(2)_L \times U(1)'$$

$< \Omega_1 >$ $< \Omega_3 >$ $\longrightarrow$ U_μ $(+\, G'_\mu,\, Z'_\mu)$

U_1 LQ: 2nd ingredient

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
$\psi_L = (q_L^3\ \ell_L'^3)^T$	**4**	**1**	**2**	0
$\psi_R^+ = (u_R^3\ \nu_R^3)^T$	**4**	**1**	**1**	1/2
$\psi_R^- = (d_R^3\ e_R^3)^T$	**4**	**1**	**1**	−1/2
$q_L'^i$	**1**	**3**	**2**	1/6
u_R^i	**1**	**3**	**1**	2/3
d_R^i	**1**	**3**	**1**	−1/3
$\ell_L'^i$	**1**	**1**	**2**	−1/2
e_R^i	**1**	**1**	**1**	−1
Ω_3	$\bar{\mathbf{4}}$	**3**	**0**	1/6
Ω_1	$\bar{\mathbf{4}}$	**1**	**0**	−1/2

$i = 1,2$

$U(2)^5$: 1st ingredient

Example: 4321 Models

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$\underset{g_4}{SU(4)_3} \times \underset{g_3}{SU(3)_{1+2}} \times SU(2)_L \times U(1)'$

$<\Omega_1>$ $<\Omega_3>$ $\longrightarrow$ U_μ $(+\, G'_\mu,\, Z'_\mu)$

U_1 LQ: 2nd ingredient

$SU(3)_c \times SU(2)_L \times U(1)_Y$

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
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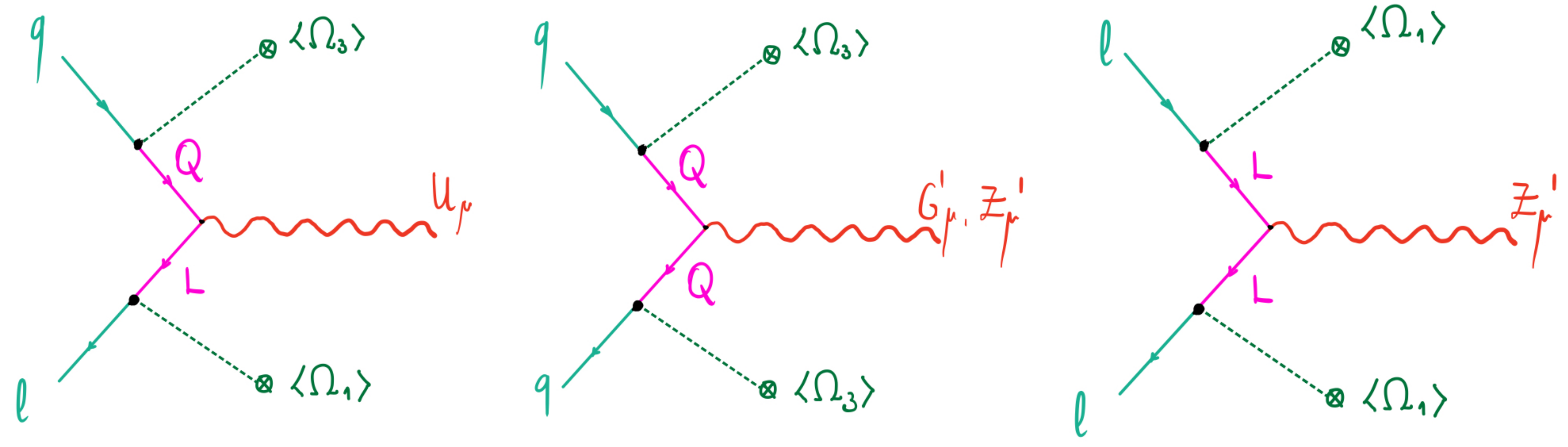
$\ell_L'^i$	**1**	**1**	**2**	−1/2
e_R^i	**1**	**1**	**1**	−1
Ω_3	$\bar{\mathbf{4}}$	**3**	**0**	1/6
Ω_1	$\bar{\mathbf{4}}$	**1**	**0**	−1/2

$i = 1,2$

$U(2)^5$: 1st ingredient

$+$ Vector-like fermions: $U(2)^5$ breaking

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
$\chi_L = (Q'_L\ L'_L)^T$	**4**	**1**	**2**	0
$\chi_R = (Q_R\ L_R)^T$	**4**	**1**	**2**	0



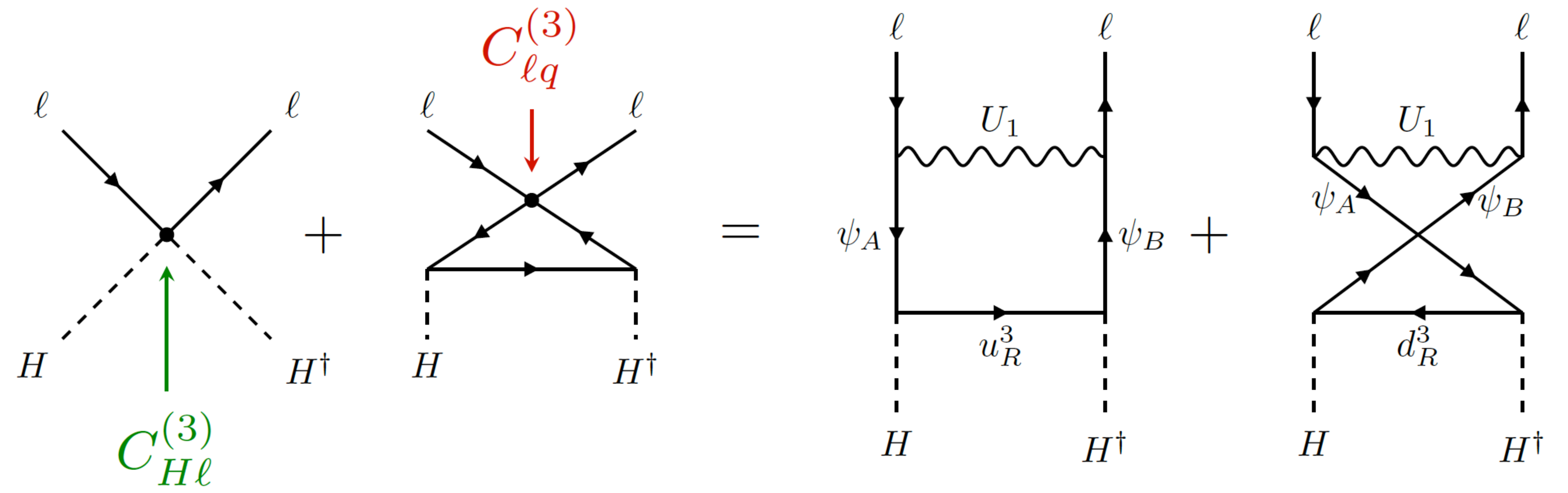
$$\mathcal{L} \supset M_q \bar{Q}_R q_L^2 + M_\ell \bar{L}_R \ell_L^2$$

4321 - SMEFT matching @ 1-loop

Contribution to $C_{H\ell}^{(3)}$: $\langle \ell_\beta^b(0)\bar{\ell}_\alpha^a(0)H^c(q)H^{\dagger d}(-q)\rangle$

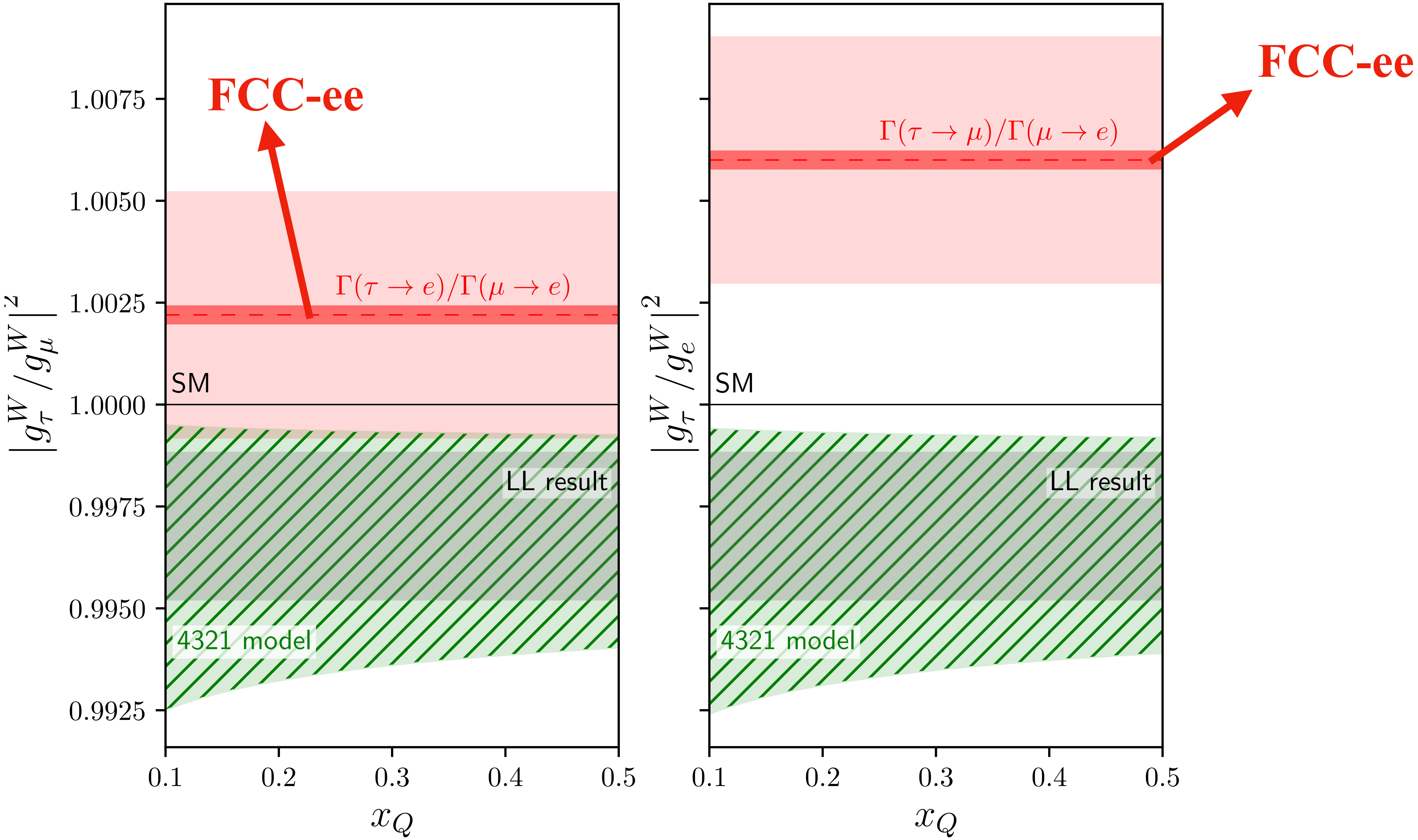
$\left[O_{H\ell}^{(3)}\right]^{\alpha\beta} = (\bar{\ell}^\alpha\gamma_\mu\sigma^I\ell^\beta)\left(H^\dagger i\overleftrightarrow{D}^\mu\sigma^I H\right)$

$\left[O_{\ell q}^{(3)}\right]^{\alpha\beta ij} = (\bar{\ell}^\alpha\gamma_\mu\sigma^I\ell^\beta)(\bar{q}^i\gamma^\mu\sigma^I q^j)$



$\psi_{A,B} = q, Q$

$$|g_\tau^W/g_\mu^W|^2 \equiv \frac{\Gamma(\tau\to e\nu\bar{\nu})}{\Gamma(\mu\to e\nu\bar{\nu})}\left[\frac{\Gamma_{\rm SM}(\tau\to e\nu\bar{\nu})}{\Gamma_{\rm SM}(\mu\to e\nu\bar{\nu})}\right]^{-1} = 1 + 2{\rm Re}[L_{\nu e}^{V,LL}]^{\rm NP}_{\mu\tau\tau\mu} - 2{\rm Re}[L_{\nu e}^{V,LL}]^{\rm NP}_{e\mu\mu e}$$



[LFU violations in leptonic τ decays and B-physics anomalies, Lukas Allwicher, Gino Isidori, NS]

2. Tests of cLFV in τ - decays

Decay	Present bound	FCC-ee sensitivity
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}

Example: Type-I seesaw (symmetry protected)

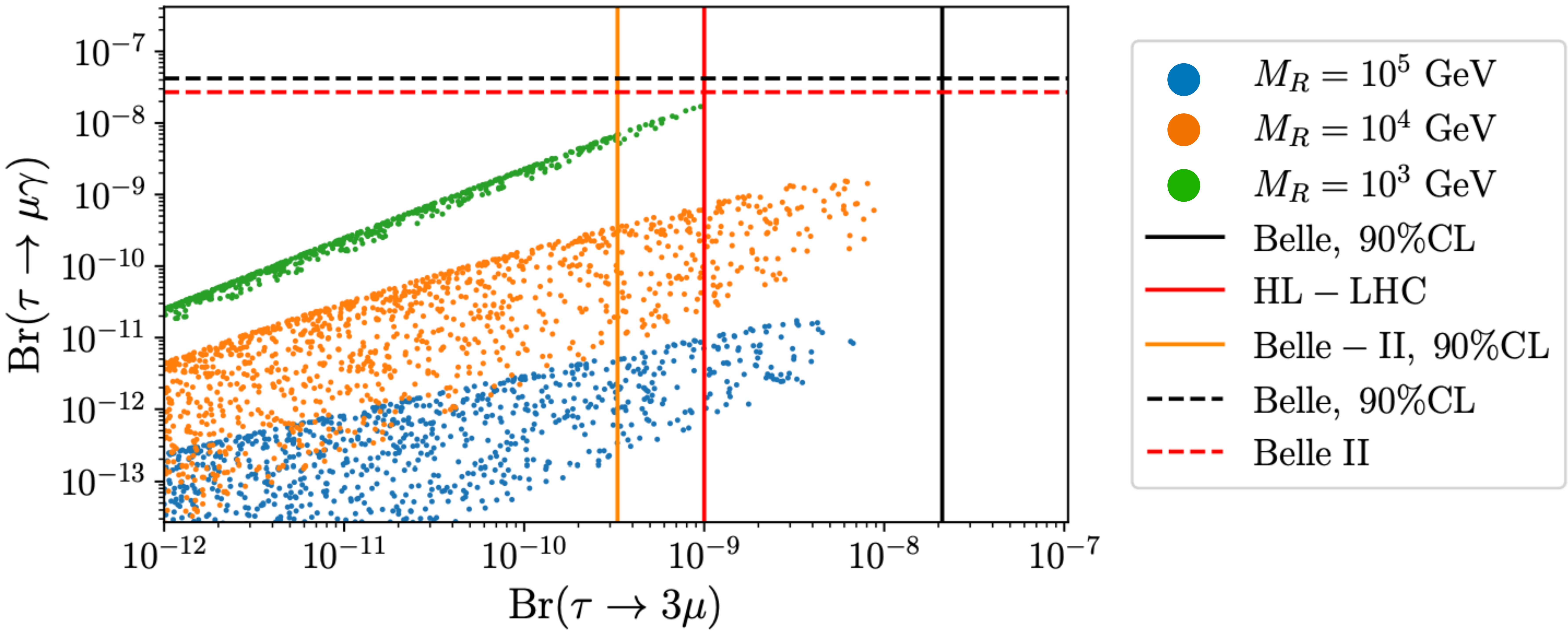
[Comprehensive Analysis of Charged Lepton Flavour Violation in the Symmetry Protected Type-I Seesaw, Andreas Crivellin, Fiona Kirk, Claudio Andrea Manzari]

$$\mathscr{L} = -\frac{1}{2}(\bar{\nu}_L \, \bar{N}_R^c) \, M_\nu \, (\nu_L^c \, N_R)^T$$

$$M_\nu = \begin{pmatrix} O_{3\times3} & \frac{v}{\sqrt{2}} Y^\nu \\ \frac{v}{\sqrt{2}} Y^\nu & M_R \end{pmatrix}$$

$$m_{\nu_L} = -\frac{v^2}{2} Y^\nu M_R^{-1} Y^{\nu\,T} \equiv 0$$

$$m_{N_R} = M_R + \mathcal{O}\left(\frac{v^2}{m_R^2}\right)$$



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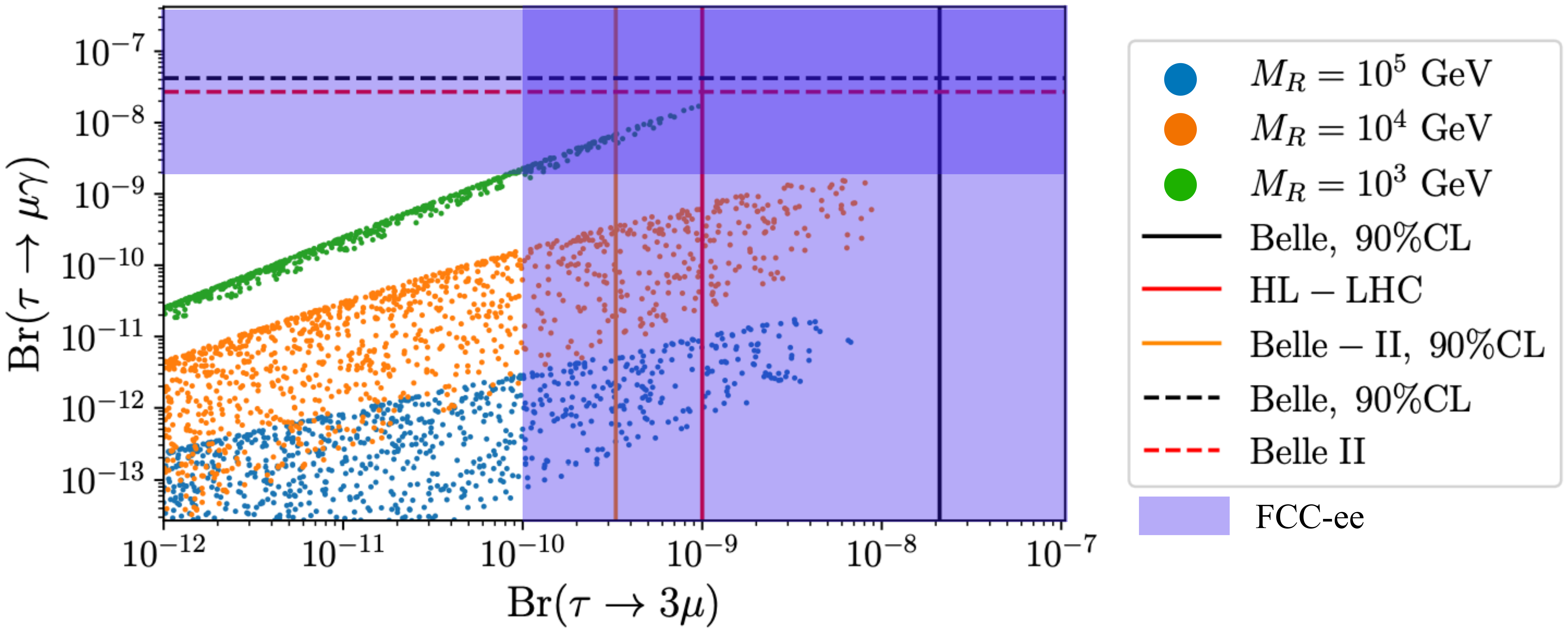

Z LFV couplings

Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	10^{-10}–10^{-8}
$Z \to \tau\mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}

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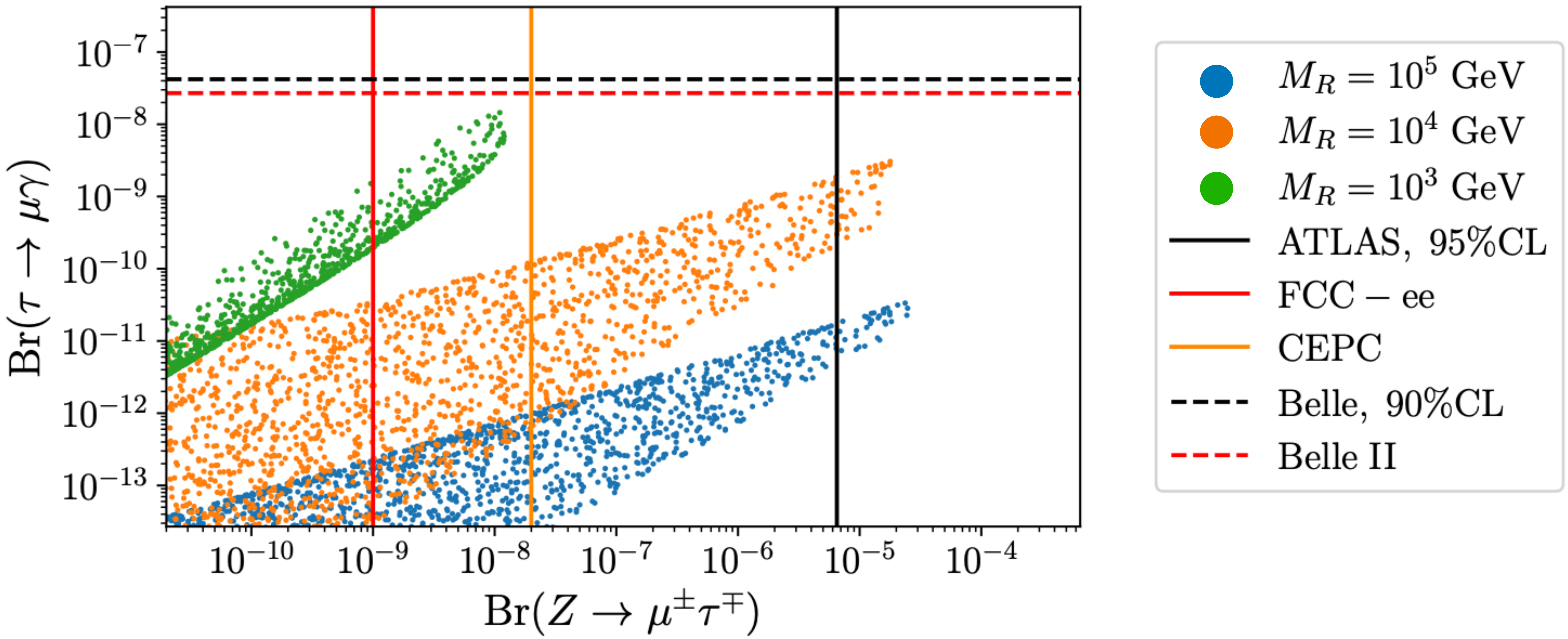

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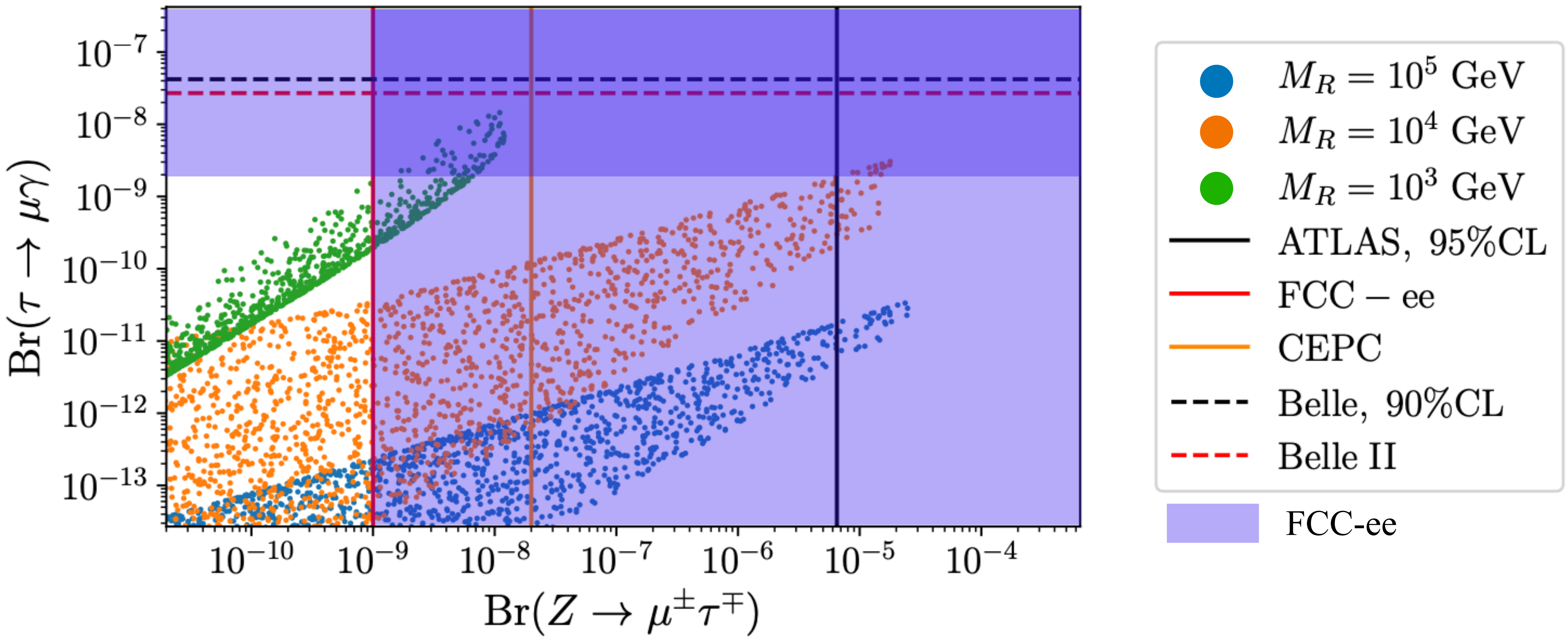

Electroweak physics @ FCC-ee

[Future Circular Collider Conceptual Design Report Volume 1]

Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and dominant exp. error
m_Z (keV/c^2)	$91{,}186{,}700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	$2{,}495{,}200 \pm 2300$	8	100	From Z line shape scan beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20{,}767 \pm 25$	0.06	0.2–1	Ratio of hadrons to leptons acceptance for leptons
α_s (m_Z) ($\times 10^4$)	1196 ± 30	0.1	0.4–1.6	From R_ℓ^Z above
R_b ($\times 10^6$)	$216{,}290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
σ_{had}^0 ($\times 10^3$) (nb)	$41{,}541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement
N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	$231{,}480 \pm 160$	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}$ (m_Z) ($\times 10^3$)	$128{,}952 \pm 14$	4	Small	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics
m_W (MeV/c^2)	$80{,}350 \pm 15$	0.5	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan beam energy calibration
α_s (m_W) ($\times 10^4$)	1170 ± 420	3	Small	From R_ℓ^W
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	$172{,}740 \pm 500$	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	$\pm 30\%$	0.5–1.5%	Small	From $E_{CM} = 365$ GeV run

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Great theory effort needed to match the experimental precision!

Electroweak physics @ FCC-ee

[Standard Model Theory for the FCC-ee Tera-Z stage,
Report on the Mini Workshop: Precision EW and QCD Calculations for the FCC Studies: Methods and Tools]

Example: Z width

Observable	Present value	±	error	FCC-ee (statistical)	FCC-ee (systematic)	Source and dominant experimental error
Γ_Z (keV)	2 495 200	±	2300	8	100	Z line shape scan
					0.1 MeV	Beam energy calibration

Current status:

Γ_i (MeV)	Γ_Z
$\mathcal{O}(\alpha)$	60.22
$\mathcal{O}(\alpha\alpha_s)$	9.11
$\mathcal{O}(\alpha_t\alpha_s^2,\ \alpha_t\alpha_s^3,\ \alpha_t^2\alpha_s,\ \alpha_t^3)$	1.20
$\mathcal{O}(N_f^2\alpha^2)$	5.13
$\mathcal{O}(N_f\alpha^2)$	3.04
$\mathcal{O}(\alpha_{bos}^2)$	0.51

[Complete electroweak two-loop corrections to Z boson production and decay,
I. Dubovyk et al., Phys. Lett. B783 (2018) 86]

Electroweak physics @ FCC-ee

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Compare with $\delta\Gamma_Z = 2.3$ MeV

Electroweak physics @ FCC-ee

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				0.1 MeV	Beam energy calibration

Theory error estimates:

δ_1	δ_2	δ_3	δ_4	δ_5	$\delta\Gamma_Z$ (MeV)
$\mathcal{O}(\alpha^3)$	$\mathcal{O}(\alpha^2\alpha_s)$	$\mathcal{O}(\alpha\alpha_s^2)$	$\mathcal{O}(\alpha\alpha_s^3)$	$\mathcal{O}(\alpha_{bos}^2)$	$=\sqrt{\sum_{i=1}^5 \delta_i^2}$
TH1 (estimated error limits from geometric series of perturbation)					
0.26	0.3	0.23	0.035	0.1	0.5
TH1-new (estimated error limits from geometric series of perturbation)					
0.2	0.21	0.23	0.035	$< 10^{-4}$	0.4

δ_1'	δ_2'	δ_3'	δ_4		$\delta\Gamma_Z$ (MeV)
$\mathcal{O}(N_f^{\leq 1}\alpha^3)$	$\mathcal{O}(\alpha^3\alpha_s)$	$\mathcal{O}(\alpha^2\alpha_s^2)$	$\mathcal{O}(\alpha\alpha_s^3)$		$=\sqrt{\delta_1'^2+\delta_2'^2+\delta_2'^3+\delta_4^2}$
TH2 (extrapolation through prefactor scaling)					
0.04	0.1	0.1	0.035	10^{-4}	0.15

Missing 3-loop contributions

Missing 4-loop contributions

Electroweak physics @ FCC-ee

10 operators modifying EWPOs:

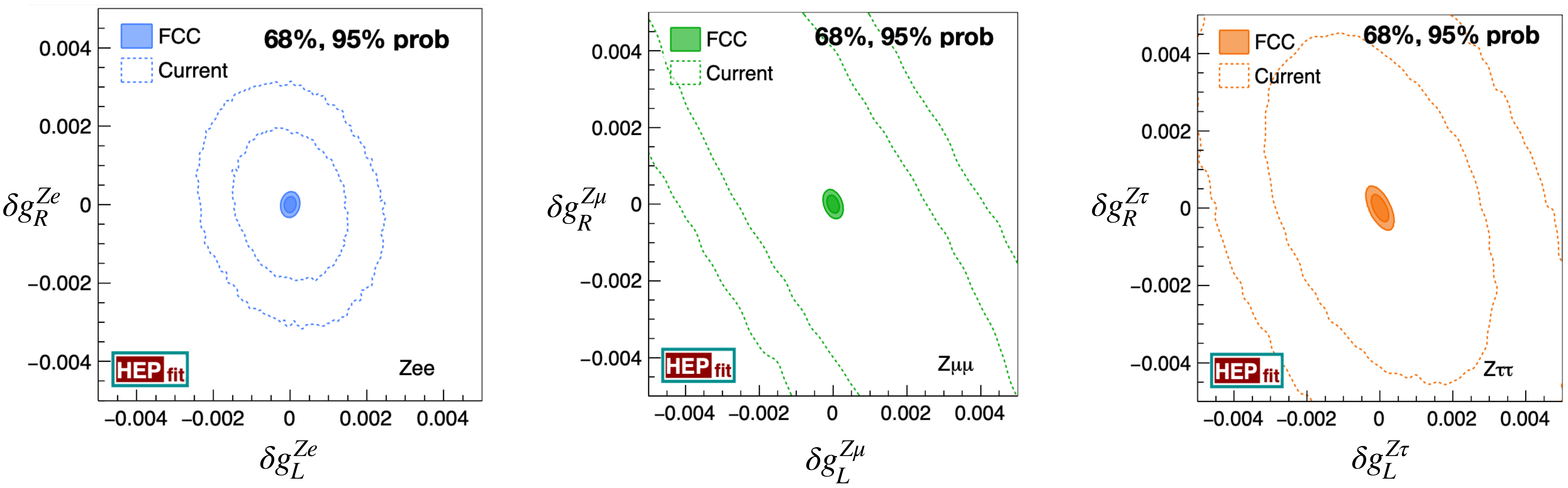
$$\left.\begin{aligned}
\mathcal{O}_{Hq}^{(1)} &= (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)\\
\mathcal{O}_{Hq}^{(3)} &= (\phi^\dagger i\overleftrightarrow{D}^a_\mu H)(\bar{q}\gamma^\mu \sigma_a q)\\
\mathcal{O}_{H\ell}^{(1)} &= (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu \ell)\\
\mathcal{O}_{H\ell}^{(3)} &= (\phi^\dagger i\overleftrightarrow{D}^a_\mu H)(\bar{\ell}\gamma^\mu \sigma_a \ell)\\
\mathcal{O}_{Hu} &= (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)\\
\mathcal{O}_{Hd} &= (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)\\
\mathcal{O}_{He} &= (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)\\
\mathcal{O}_{HWB} &= (H^\dagger \sigma_a H)W^a_{\mu\nu}B^{\mu\nu}\\
\mathcal{O}_{HD} &= |H^\dagger i D_\mu H|^2\\
\mathcal{O}_{\ell\ell} &= (\bar{\ell}_L\gamma_\mu \ell_L)(\bar{\ell}_L\gamma^\mu \ell_L)
\end{aligned}\right\}$$

Neutral current couplings modifications:

$$\mathcal{L}_Z = -\frac{e}{s_W c_W}(1+\delta g_Z)Z_\mu\left\{\sum_{\psi=q,\ell}\bar{\psi}^i\gamma^\mu\left(g_L^\psi\delta_{ij}+\delta g^\psi_{Lij}\right)\mathrm{P_L}\psi^j+\sum_{\psi=u,d,e}\bar{\psi}^i\gamma^\mu\left(g_R^\psi\delta_{ij}+\delta g^\psi_{Rij}\right)\mathrm{P_R}\psi^j\right\}$$

δg_L^{Zu}	$-\frac{v^2}{2\Lambda^2}\left(C_{Hq}^{(1)}-C_{Hq}^{(3)}\right)+\frac{1}{2}\delta g_Z+\frac{2}{3}\left(\delta s_W^2-s_W^2\delta g_Z\right)$
δg_L^{Zd}	$-\frac{v^2}{2\Lambda^2}\left(C_{Hq}^{(1)}+C_{Hq}^{(3)}\right)-\frac{1}{2}\delta g_Z-\frac{1}{3}\left(\delta s_W^2-s_W^2\delta g_Z\right)$
$\delta g_L^{Z\nu}$	$-\frac{v^2}{2\Lambda^2}\left(C_{Hl}^{(1)}-C_{Hl}^{(3)}\right)+\frac{1}{2}\delta g_Z$
δg_L^{Ze}	$-\frac{v^2}{2\Lambda^2}\left(C_{Hl}^{(1)}+C_{Hl}^{(3)}\right)-\frac{1}{2}\delta g_Z-\left(\delta s_W^2-s_W^2\delta g_Z\right)$
δg_R^{Zu}	$-\frac{v^2}{2\Lambda^2}C_{Hu}+\frac{2}{3}\left(\delta s_W^2-s_W^2\delta g_Z\right)$
δg_R^{Zd}	$-\frac{v^2}{2\Lambda^2}C_{Hd}-\frac{1}{3}\left(\delta s_W^2-s_W^2\delta g_Z\right)$
δg_R^{Ze}	$-\frac{v^2}{2\Lambda^2}C_{He}-\left(\delta s_W^2-s_W^2\delta g_Z\right)$
δg_Z	$-\frac{v^2}{\Lambda^2}\left(\delta v+\frac{1}{4}C_{HD}\right)$
δv	$C_{Hl}^{(3)}-\frac{1}{2}C_{ll}$
δs_W^2	$-\frac{v^2}{\Lambda^2}\frac{s_W c_W}{c_W^2-s_W^2}\left[2s_W c_W\left(\delta v+\frac{1}{4}C_{HD}\right)+C_{HWB}\right]$

Leptonic Z-coupling modifications:



$|\delta g_L^{Ze}| < 2.5 \times 10^{-4}$ (2.5×10^{-3})
$|\delta g_R^{Ze}| < 3 \times 10^{-4}$ (3×10^{-3})

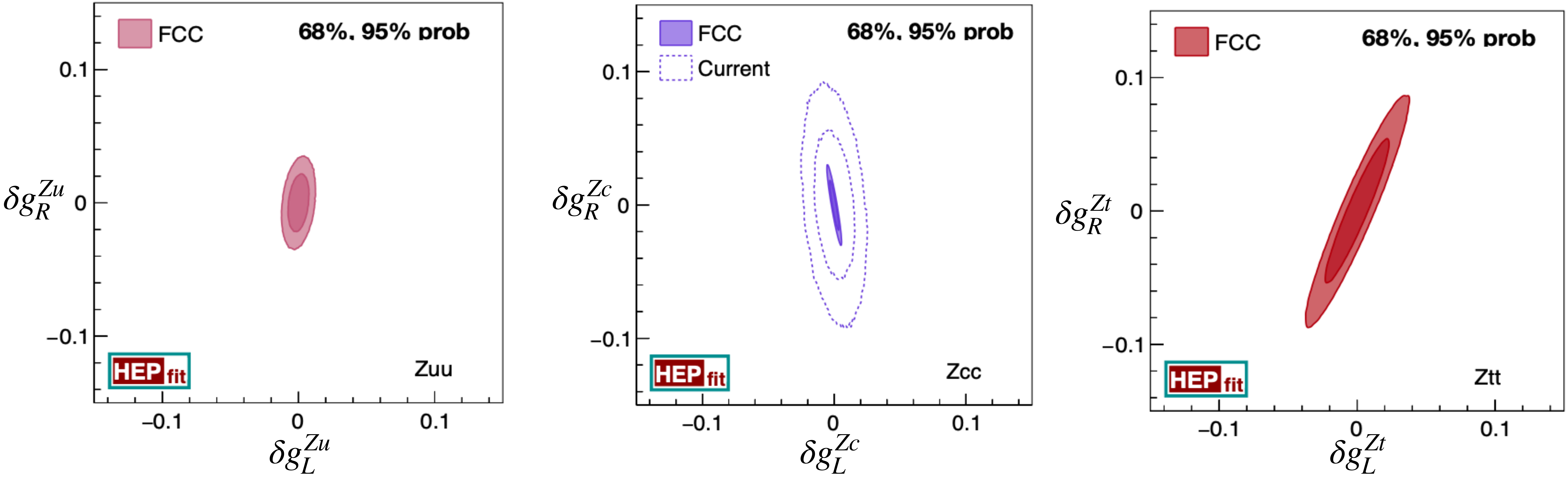
$|\delta g_L^{Z\mu}| < 2.5 \times 10^{-4}$
$|\delta g_R^{Z\mu}| < 4 \times 10^{-4}$

$|\delta g_L^{Z\tau}| < 4 \times 10^{-4}$ (4×10^{-3})
$|\delta g_R^{Z\tau}| < 5.5 \times 10^{-4}$ (5.5×10^{-3})

[11th FCC-ee workshop: Theory and Experiments CERN, Jan 9, 2019, Jorge de Blas]

Electroweak physics @ FCC-ee

Up-type Z-coupling modifications:



$|\delta g_L^{Zu}| < 1.5 \times 10^{-2}$

$|\delta g_R^{Zu}| < 3 \times 10^{-2}$

$|\delta g_L^{Zc}| < 6 \times 10^{-3}$ (2.5×10^{-2})

$|\delta g_R^{Zc}| < 3 \times 10^{-2}$ (9×10^{-2})

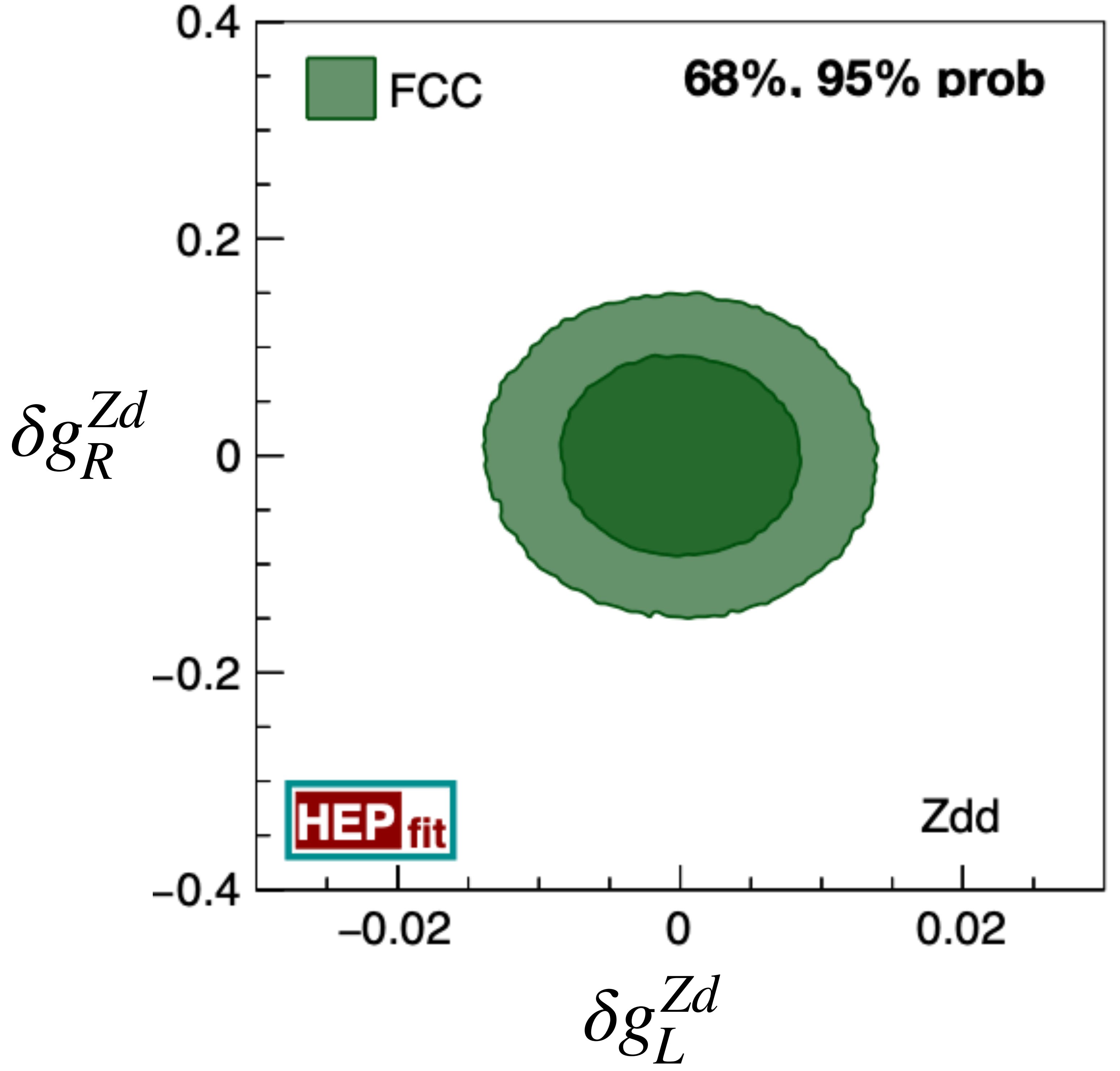
$|\delta g_L^{Zt}| < 4 \times 10^{-2}$

$|\delta g_R^{Zt}| < 9 \times 10^{-2}$

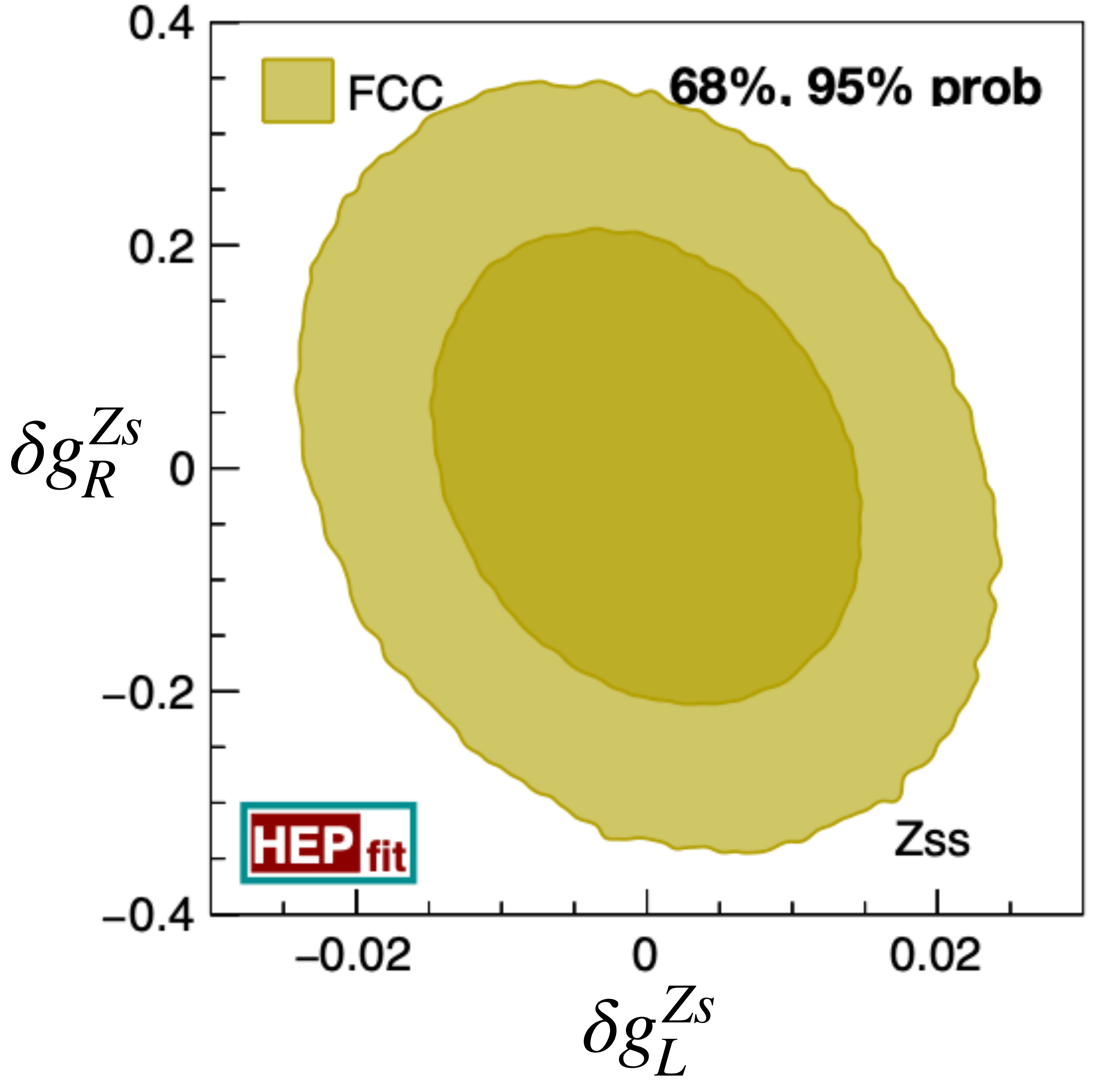
[11th FCC-ee workshop: Theory and Experiments CERN, Jan 9, 2019, Jorge de Blas]

Electroweak physics @ FCC-ee

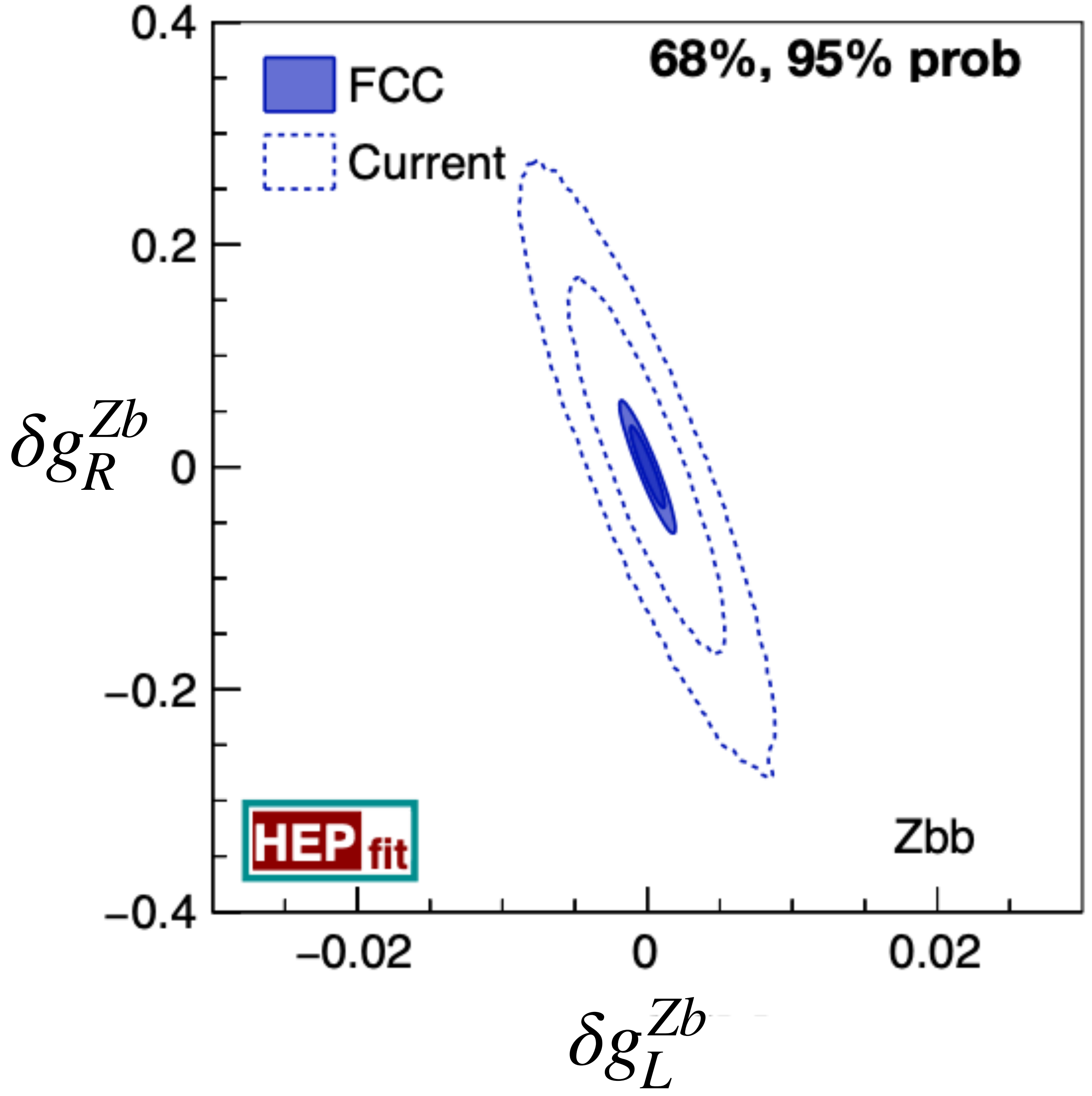
Down-type Z-coupling modifications:



$|\delta g_L^{Zd}| < 1.5 \times 10^{-2}$
$|\delta g_R^{Zd}| < 1.5 \times 10^{-1}$



$|\delta g_L^{Zs}| < 2.5 \times 10^{-2}$
$|\delta g_R^{Zs}| < 3.5 \times 10^{-1}$



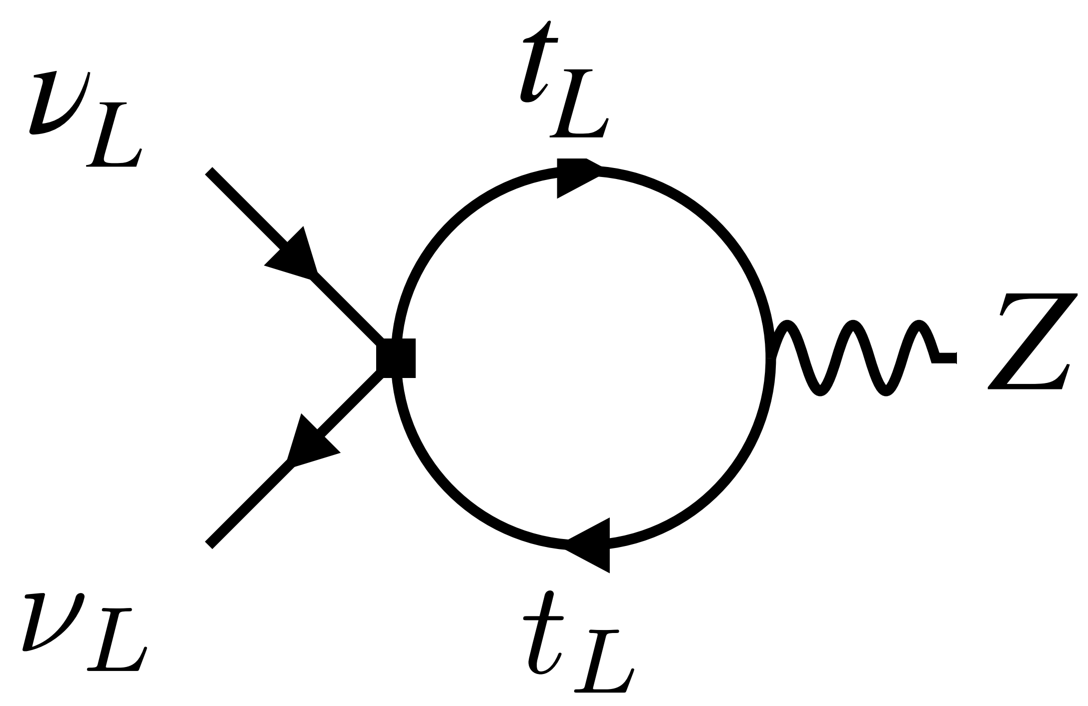
$|\delta g_L^{Zb}| < 2 \times 10^{-3}$ (1×10^{-2})
$|\delta g_R^{Zb}| < 6 \times 10^{-2}$ (2.5×10^{-1})

[11th FCC-ee workshop: Theory and Experiments CERN, Jan 9, 2019, Jorge de Blas]

Example: B-anomalies ↔ Z → invisibles

$$[O_{\ell q}^{(1)}]_{\alpha\beta ij} = (\bar{\ell}_L^\alpha \gamma_\mu \ell_L^\beta)(\bar{q}_L^i \gamma^\mu q_L^j)$$

$$[O_{\ell q}^{(3)}]_{\alpha\beta ij} = (\bar{\ell}_L^\alpha \sigma^I \gamma_\mu \ell_L^\beta)(\bar{q}_L^i \sigma^I \gamma^\mu q_L^j)$$



Changing the effective number of LH neutrinos: N_ν^{eff}

[F. Feruglio, P. Paradisi, A. Pattori arXiv: 1606.00524]

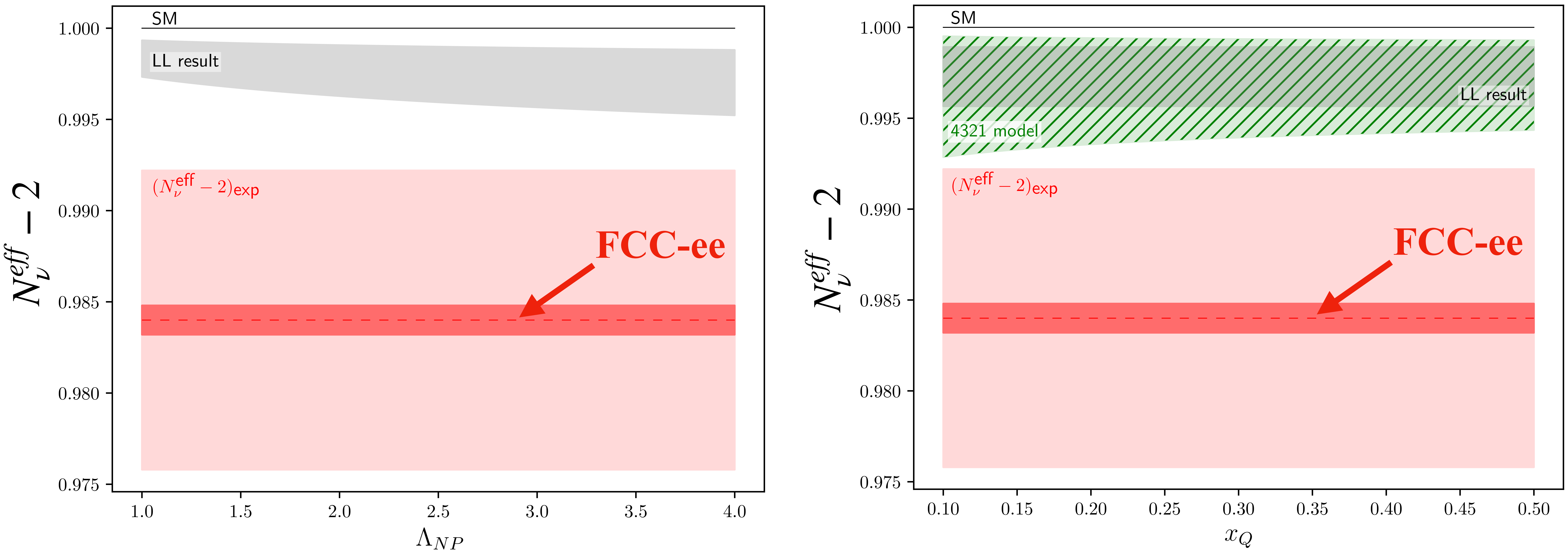
Example: B-anomalies ↔ Z → invisibles

$$[C_{H\ell}^{(1,3)}]_{\alpha\beta} = \mp \frac{y_t^2 N_c}{16\pi^2} \log \frac{\Lambda_{\rm NP}^2}{m_t^2} [C_{\ell q}^{(1,3)}]_{\alpha\beta 33}$$

$$\delta g_{\nu_\ell}^Z(\mu) = -\frac{v^2}{2}\left\{[C_{H\ell}^{(1)}]_{\ell\ell}(\mu) - [C_{H\ell}^{(3)}]_{\ell\ell}(\mu)\right\}$$

$$\delta g_{\ell_L}^Z(\mu) = -\frac{v^2}{2}\left\{[C_{H\ell}^{(1)}]_{\ell\ell}(\mu) + [C_{H\ell}^{(3)}]_{\ell\ell}(\mu)\right\}$$

$$\left|\frac{g_{\nu_\tau}^Z}{g_{\nu_\tau}^{Z,\rm SM}}\right|^2_{N_\nu^{\rm eff}} = N_\nu^{\rm eff} - 2$$



[LFU violations in leptonic τ decays and B-physics anomalies, Lukas Allwicher, Gino Isidori, NS]

Example: Inverse seesaw mechanism

$$SU(4)_3 \times SU(3)_{1+2} \times SU(2)_L \times U(1)'$$

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
$\psi_L = (q_L'^3\ \ell_L'^3)^T$	**4**	**1**	**2**	0
$\psi_R^+ = (u_R^3\ \nu_R^3)^T$	**4**	**1**	**1**	$1/2$
$\psi_R^- = (d_R^3\ e_R^3)^T$	**4**	**1**	**1**	$-1/2$

$$\mathscr{L} = -\, Y_H \, \bar{\Psi}_L \, \tilde{H} \, \Psi_R^+$$

predicting $m_t \simeq m_{\nu_\tau}$

Inverse seesaw mechanism:

$$\mathscr{L} = -\, \lambda_R \, \bar{S}_R^c \, \Omega_1^T \, \Psi_R^+ + \frac{1}{2} \mu \, \bar{S}_R^c \, S_R$$

$$\to m_R \sim \lambda_R \langle \Omega_1 \rangle \ \pm \ \mu$$

$$\to m_{\nu_\tau} \sim Y_H^\nu \langle H \rangle \mu \, / \, m_R$$

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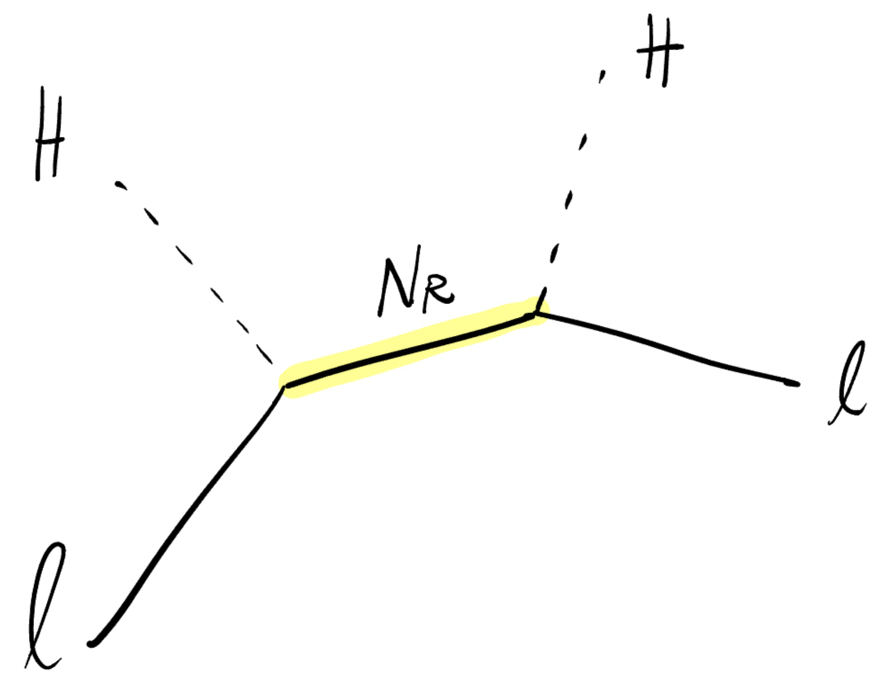
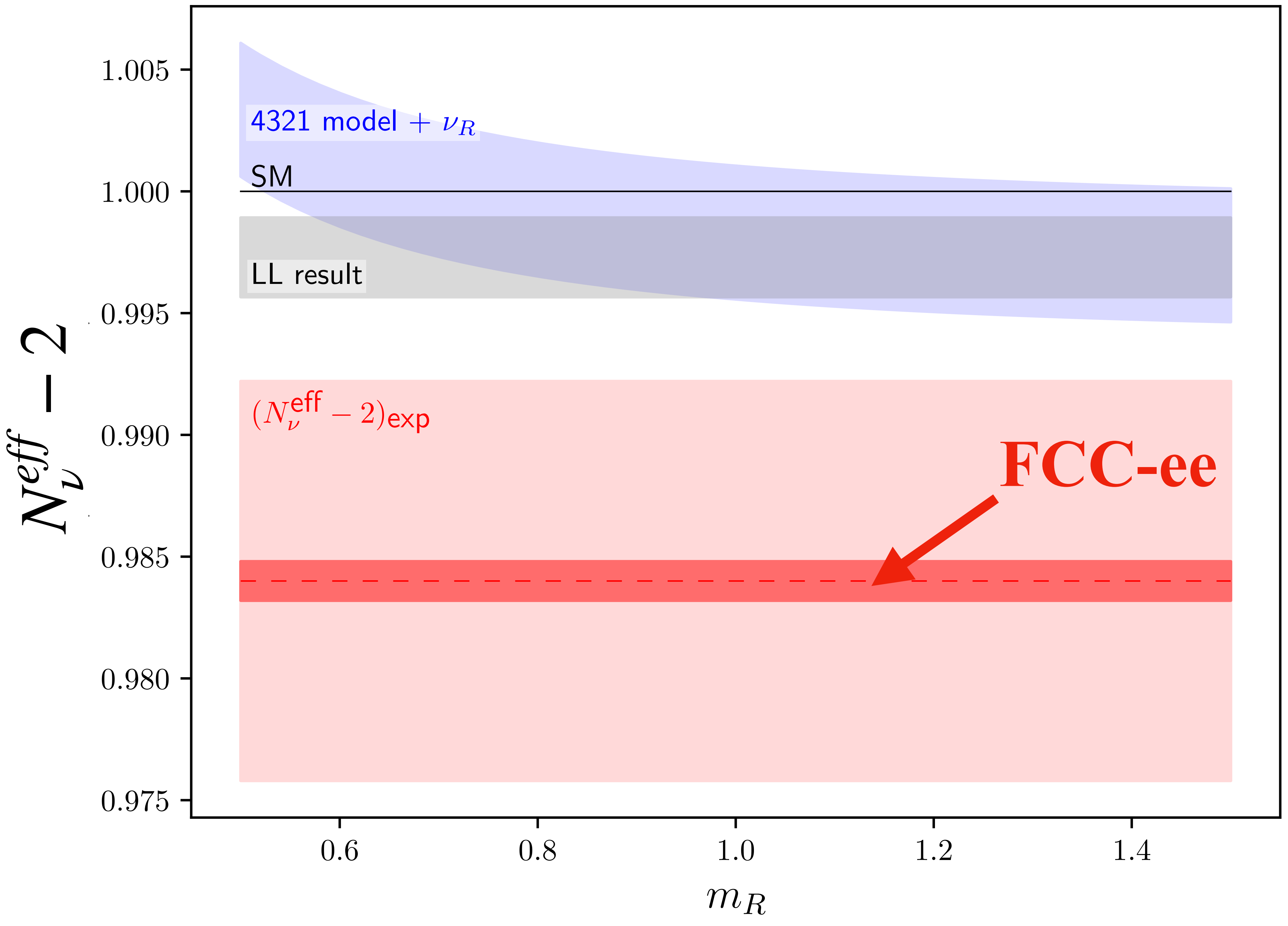
[WIP, Lukas Allwicher, Gino Isidori, Javier Lizana, Ben Stefanek, NS]

$$[C_{H\ell}^{(1)}]_{33} = -[C_{H\ell}^{(3)}]_{33} = -\frac{|Y_H^\nu|^2}{4m_R^2}$$

m_R is tied to the TeV scale

→ FCC-ee opportunity





Example: Vector-like Quarks

[Large t→cZ as a sign of vectorlike quarks in light of the W mass,
Andreas Crivellin, Matthew Kirk, Teppei Kitahara, Federico Mescia]

	u	d	q	H	U	D	Q_1	Q_5	Q_7	T_1	T_2
$SU(3)_C$	3	3	3	1	3	3	3	3	3	3	3
$SU(2)_L$	1	1	2	2	1	1	2	2	2	3	3
$U(1)_Y$	$2/3$	$-1/3$	$1/6$	$1/2$	$2/3$	$-1/3$	$1/6$	$-5/6$	$7/6$	$-1/3$	$2/3$

	U	D	Q_1	Q_5	Q_7	T_1	T_2
δg_L^{Zu}	✓	✗	✗	✗	✗	✓	✓
δg_L^{Zd}	✗	✓	✗	✗	✗	✓	✓
δg_R^{Zu}	✗	✗	✓	✗	✓	✗	✗
δg_R^{Zd}	✗	✗	✓	✓	✗	✗	✗
δg_L^{Wq}	✓	✓	✗	✗	✗	✓	✓

Conclusions

- FCC-ee will provide unrivalled test of the SM: 1 LEP / min

- 1-2 orders of magnitude improvement in precision across multitude of observables

- Theory effort needed to match great statistics:

  - computing higher order corrections
  - looking for new “clean” observables
  - doing NP sensitivity studies

THANK YOU!