New Physics Through Flavor Tagging at FCC-ee

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Universität Basel

Workshop on FCC-ee and Lepton Colliders

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FCC-ee plan

Z-pole

Above the Z-pole

FCC-ee plan

Z-pole

FCC-ee report (2019)
De Blas et al (2019)
Blondel, Janot (2019, 2022)
Bernardi et al (2022)
Allwicher et al (2023, 2024)
Stefanek et al (2024)
Ge et al (2024), …

$O(10^{12})$ Z-bosons

- $\sim 10^5$ more than LEP
  $\rightarrow O(300)$ statistical improvement on EWPO
- Systematics: capped at $O(10) - O(100)$

Probe tree-level new physics up to $O(100)$ TeV

(LEP $O(10)$ TeV)

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Above the Z-pole

Reference energies:

WW	Zh	$t\bar{t}$
163 GeV	240 GeV	365 GeV
10 ab^{-1}	5 ab^{-1}	1.5 ab^{-1}

Higher energy & luminosity than LEP-II
(130-209 GeV, ~ 3 fb^{-1} tot)

What are the new physics opportunities?

Outline

1. Observables and flavor tagging above the Z-pole
2. SMEFT interpretation
3. Impact on selected models
4. Conclusion

Observables

$(\sqrt{s'} \gtrsim 0.85\sqrt{s})$

Consider inclusive, non-radiative fermion pair-production ratios:

$$R_b = \frac{\sigma(e^+e^- \to \bar{b}b)}{\sum_{q=u,d,s,c,b} \sigma(e^+e^- \to \bar{q}q)} \qquad + R_c, R_s, R_t, R_\ell$$

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- Theoretically OK: $\Delta R_b / R_b \,|_{\text{theory}} \sim 10^{-4}$ PDG EW (2024)
- Naïve stat limit: ≈ same as theory $(WW : N_{\bar{b}b} \simeq 6 \times 10^7)$
- **Systematics?**

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- **Systematics?**

Flavor tagging crucial to assess expected FCC-ee precision

Toy model: R_b

Two flavors only (b, j)

$$N_{\rm tot} = \mathcal{L} \cdot \mathcal{A} \cdot \sigma(e^+e^- \to q\bar{q})$$ → total untagged events

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Taggers:

ϵ_b^b = True positive rate (prob. tag b-jet as b) $= 1 - \epsilon_b^j$

ϵ_j^b = False positive rate (prob. tag j-jet as b) $= 1 - \epsilon_j^j$

$$\begin{cases} N(n_b = 2) \equiv N_2 = N_{\rm tot}[(\epsilon_b^b)^2 R_b + (\epsilon_j^b)^2 R_j] \,, \\ N(n_b = 1) \equiv N_1 = 2N_{\rm tot}[\epsilon_b^b(1-\epsilon_b^b)R_b + \epsilon_j^b(1-\epsilon_j^b)R_j] \\ N(n_b = 0) \equiv N_0 = N_{\rm tot}[(1-\epsilon_b^b)^2 R_b + (1-\epsilon_j^b)^2 R_j] \,. \end{cases}$$

Toy model: R_b

$$-2\log L = \sum_i \frac{(N_i^{\mathrm{exp}} - N_i)^2}{N_i^{\mathrm{exp}}} + \frac{x^2}{(\delta_\epsilon)^2}$$

- Systematic uncertainty on taggers: $\epsilon_i^j \rightarrow \epsilon_i^j(1+x)$, δ_ϵ from MC
- Fit parameters: R_b & N_{tot}, ϵ_b^b
- Asimov approximation: $N_i^{\mathrm{exp}} \rightarrow N_i^{\mathrm{nominal}}$

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- Asimov approximation: $N_i^{\text{exp}} \to N_i^{\text{nominal}}$

$$\left(\frac{\Delta R_b}{R_b}\right)^2 = \frac{1-\epsilon_b^b(2-\epsilon_b^b(2-R_b))}{N_{\text{tot}} R_b (\epsilon_b^b)^2}$$

→ **True positives stat**

False positives stat ←

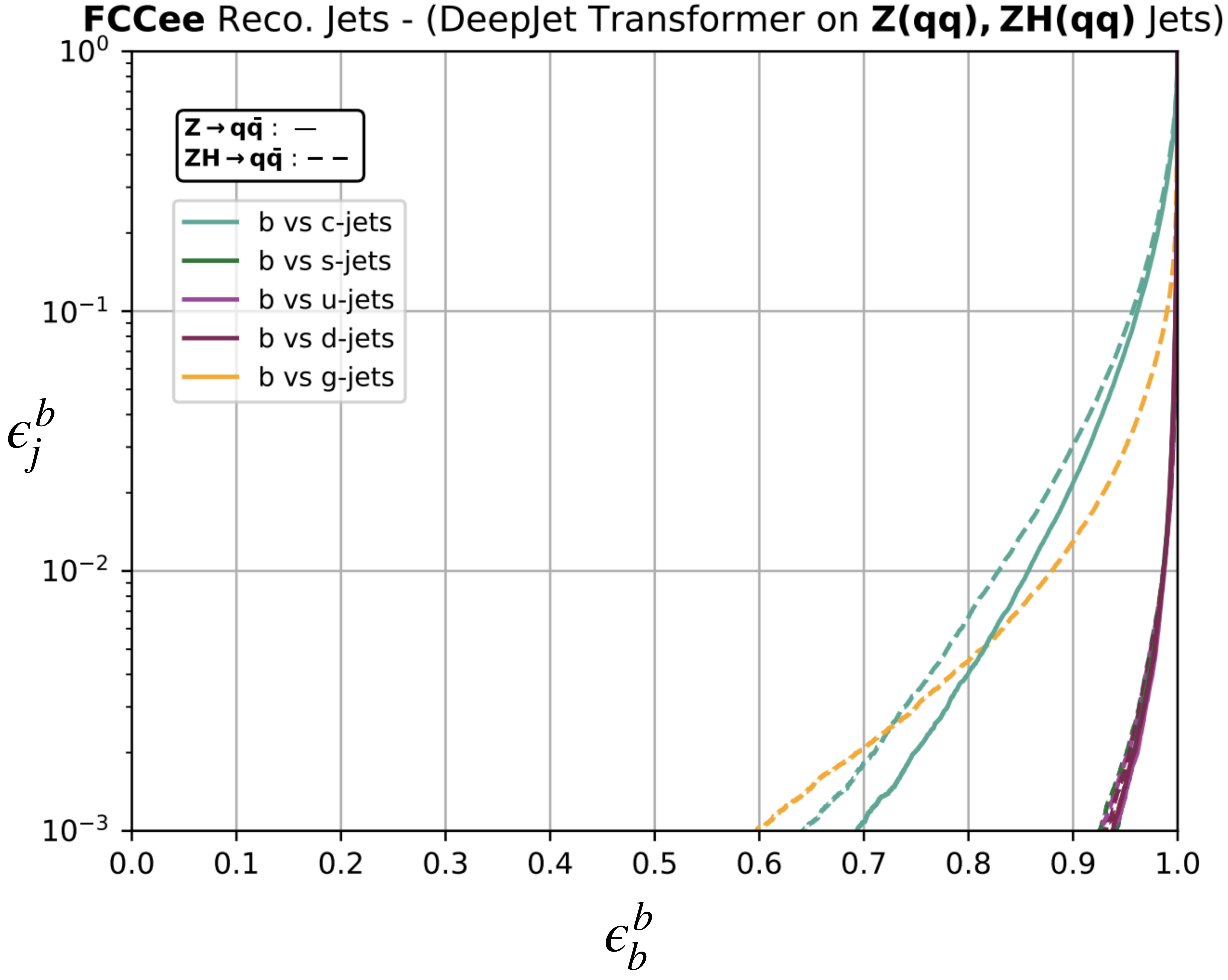
$$+ \frac{2(\epsilon_b^b - R_b(2-\epsilon_b^b)(2\epsilon_b^b - 1))}{N_{\text{tot}} R_b^2 (\epsilon_b^b)^3}\epsilon_j^b$$

False positives syst ←

$$+ \frac{4(R_b-1)^2(\epsilon_j^b)^2}{R_b^2(\epsilon_b^b)^2}(\delta_\epsilon)^2 + \mathcal{O}\left((\epsilon_j^b)^2\right)$$

Toy model: R_b

Blekmann et al (2024) *DeepJetTransformer* ROC curves at FCC-ee



- Realistic estimate $\delta_\epsilon \simeq 0.01$. Consider WW run.
- Minimize $\Delta R_b/R_b$ with $\epsilon_j^b = \epsilon_c^b(\epsilon_b^b)$ (conservative)

Toy model: R_b

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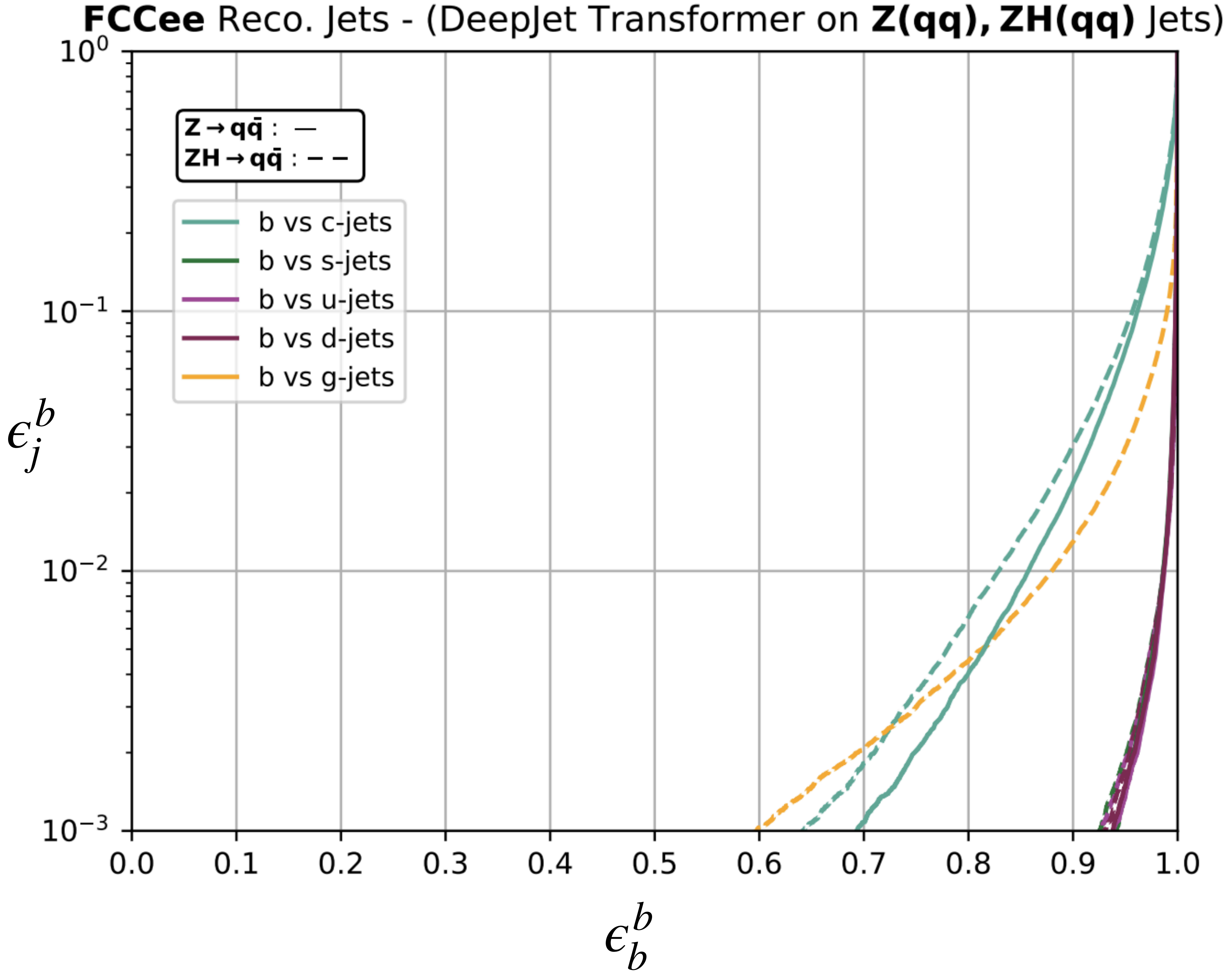

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- Minimize $\Delta R_b/R_b$ with $\epsilon_j^b = \epsilon_c^b(\epsilon_b^b)$ (conservative)

$$\frac{\Delta R_b}{R_b} \simeq 2 \times 10^{-4} \qquad \begin{pmatrix} \epsilon_b^b \simeq 0.65 \\ \epsilon_j^b \simeq 10^{-3} \end{pmatrix}$$

- Almost saturates naïve stat & theory limit
- LEP-II: $\Delta R_b/R_b \simeq O(0.05)$ LEP EW WG (2003,2013)

→ impressive $O(10^2)$ improvement!

Note: for role of additional background (e.g. collimated VV) see the paper

Realistic fit: results

Observable/FCC-ee Rel. Err. (10^{-3})	WW	Zh	$t\bar{t}$
R_b	0.17	0.36	0.96
R_s	3.7	5.8	10
R_c	0.14	0.27	0.69
R_t	-	-	1.2
$R_{\tau,\mu}$	0.16	0.35	0.97
R_e	0.50	0.52	0.64

assuming $\Delta m_t/m_t \lesssim O(0.1\%)$ from FCC-ee m_t scan

stat ← (R_t)

stat ← ($R_{\tau,\mu}$)

syst (theory) ← (R_e)

→ Fit R_b, R_s, R_c *simultaneously*

Small correlations: e.g. WW

$$\rho = \begin{pmatrix} 1 & -0.006 & -0.22 \\ -0.006 & 1 & -0.006 \\ -0.22 & -0.006 & 1 \end{pmatrix}$$

Solid (at least) $O(10^2)$ improvement compared to LEP-II

Room for improvement: s-tagging

Z-pole summary

LEP EW WG (2003,2013)
De Blas et al (2019)
Blonde, Janot (2021)
PDG (2024)

Observable	Curr. Rel. Err. (10^{-3})	FCC-ee Rel. Err. (10^{-3})	Error reduction
Γ_Z	2.3	0.1	23
σ^0_{had}	37	5	7
R^Z_b	3.06	0.3	10
R^Z_c	17.4	1.5	12
$A^{0,b}_{\text{FB}}$	15.5	1	16
$A^{0,c}_{\text{FB}}$	47.5	3.08	15
A^Z_b	21.4	3	7
A^Z_c	40.4	8	5
R^Z_e	2.41	0.3	8
R^Z_μ	1.59	0.05	32
R^Z_τ	2.17	0.1	22
$A^{0,e}_{\text{FB}}$	154	5	31
$A^{0,\mu}_{\text{FB}}$	80.1	3	27
$A^{0,\tau}_{\text{FB}}$	104.8	5	21
A^Z_e	14.3	0.11	130
A^Z_μ	102	0.15	680
A^Z_τ	102	0.3	340
N_ν	50	0.8	62

(Curr. from SLC) — applies to A^Z_e, A^Z_μ, A^Z_τ

(See PDG@EW for definitions)

W-pole $+\tau$ decays summary

LEP EW WG (2003,2013)
De Blas et al (2019)
Blonde, Janot (2021)
PDG (2024)

Observable	Value	Error	FCC-ee Tot.	Error reduction
Γ_W [MeV]	2085	42	1.24	34
m_W [MeV]	80350	15	0.39	38
$\mathrm{Br}(W \to e\nu)(\%)$	10.71	0.16	0.0032	50
$\mathrm{Br}(W \to \mu\nu)(\%)$	10.63	0.15	0.0032	47
$\mathrm{Br}(W \to \tau\nu)(\%)$	11.38	0.21	0.0046	46
$\tau \to \mu\nu\nu(\%)$	17.39	0.04	0.003	13
$\tau \to e\nu\nu(\%)$	17.82	0.04	0.003	13

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2. SMEFT interpretation
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2. SMEFT interpretation

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Consider ***flavor conserving, non-universal*** **4F** interactions

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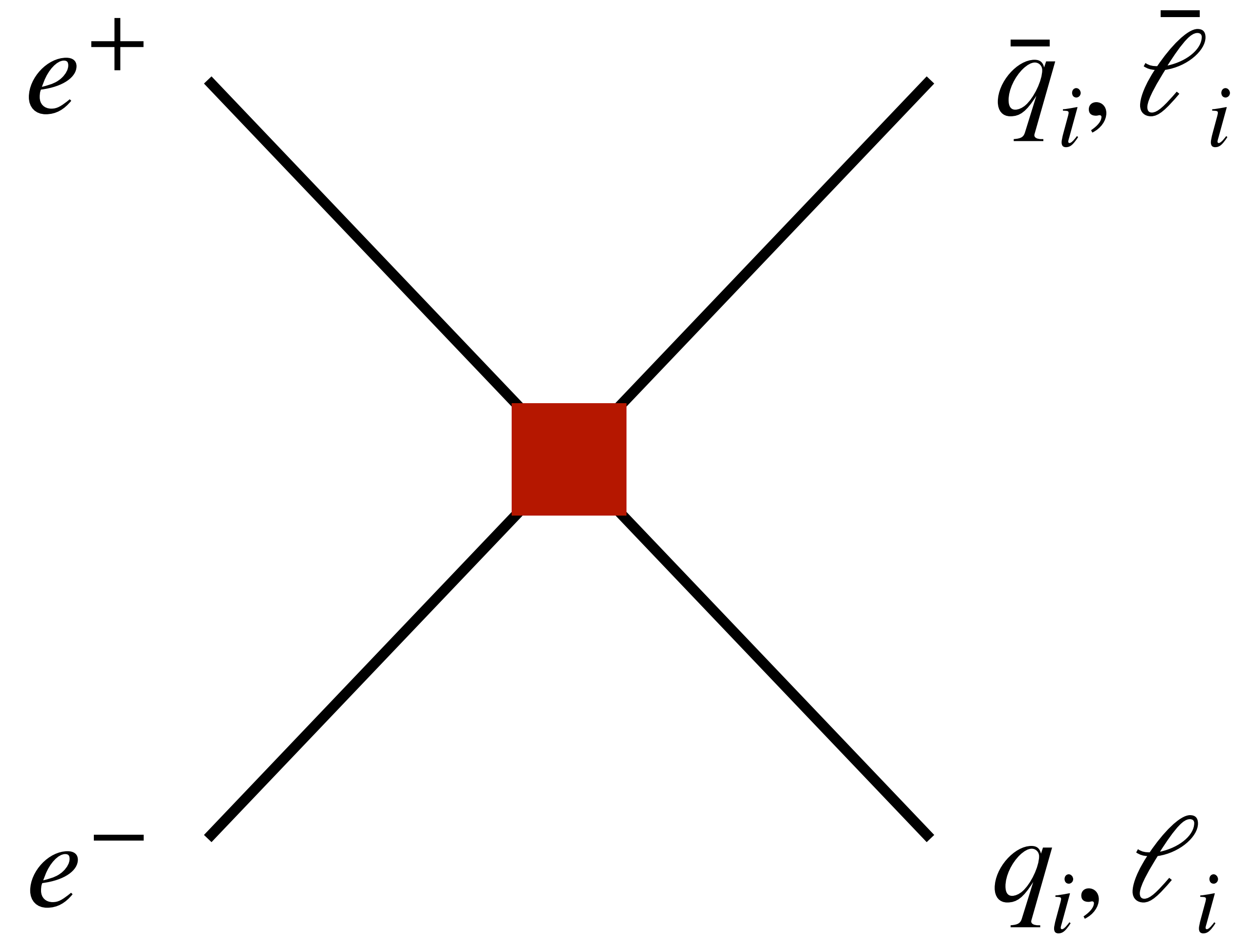
$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathscr{O}_i$$

Consider ***flavor conserving, non-universal* 4F** interactions

Above the pole

- Tree-level: $2q2\ell + 4\ell$ operators involving e^+e^- $(prst = 11ii)$



$2q2\ell$	$\mathcal{O}_{\ell q}^{(1)}$	$(\bar{\ell}_p\gamma_\mu\ell_r)(\bar{q}_s\gamma^\mu q_t)$
	$\mathcal{O}_{\ell q}^{(3)}$	$(\bar{\ell}_p\gamma_\mu\tau^I\ell_r)(\bar{q}_s\gamma^\mu\tau_I q_t)$
	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
	$\mathcal{O}_{\ell u}$	$(\bar{\ell}_p\gamma_\mu\ell_r)(\bar{u}_s\gamma^\mu u_t)$
	$\mathcal{O}_{\ell d}$	$(\bar{\ell}_p\gamma_\mu\ell_r)(\bar{d}_s\gamma^\mu d_t)$
	$\mathcal{O}_{qe}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{q}_s\gamma^\mu q_t)$
	$\mathcal{O}_{\ell eqd}$	$(\bar{\ell}_p^j e_r)(\bar{d}_s q_t^j)$
	$\mathcal{O}_{\ell equ}^{(1)}$	$(\bar{\ell}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
	$\mathcal{O}_{\ell equ}^{(3)}$	$(\bar{\ell}_p^j\sigma_{\mu\nu}e_r)\epsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$
4ℓ	$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}_p\gamma_\mu\ell_r)(\bar{\ell}_s\gamma^\mu\ell_t)$
	$\mathcal{O}_{\ell e}$	$(\bar{\ell}_p\gamma_\mu\ell_r)(\bar{e}_s\gamma^\mu e_t)$
	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$

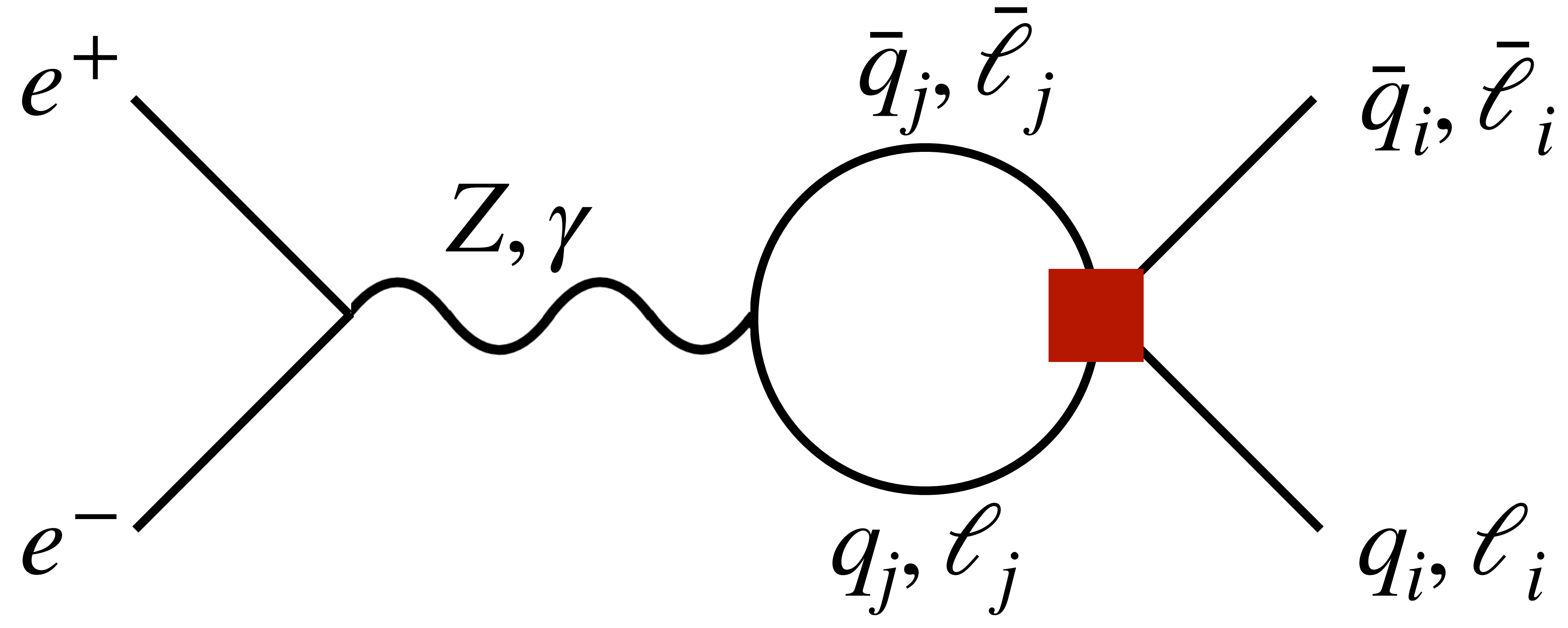
2. SMEFT interpretation

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Consider ***flavor conserving, non-universal* 4F** interactions

Above the pole

- Tree-level: $2q2\ell + 4\ell$ operators involving e^+e^- $(prst = 11ii)$
- 1-loop: $2q2\ell + 4\ell + 4q$, all indices $prst = iijj$ (gauge running)



$2q2\ell$:

$\mathcal{O}_{\ell q}^{(1)}$	$(\bar{\ell}_p\gamma_\mu \ell_r)(\bar{q}_s\gamma^\mu q_t)$
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$\mathcal{O}_{qe}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{q}_s\gamma^\mu q_t)$
$\mathcal{O}_{\ell edq}$	$(\bar{\ell}_p^j e_r)(\bar{d}_s q_t^j)$
$\mathcal{O}_{\ell equ}^{(1)}$	$(\bar{\ell}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$\mathcal{O}_{\ell equ}^{(3)}$	$(\bar{\ell}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

$4q$:

$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\tau^I\gamma_\mu q_r)(\bar{q}_s\tau_I\gamma^\mu q_t)$
$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$

4ℓ:

$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}_p\gamma_\mu \ell_r)(\bar{\ell}_s\gamma^\mu \ell_t)$
$\mathcal{O}_{\ell e}$	$(\bar{\ell}_p\gamma_\mu \ell_r)(\bar{e}_s\gamma^\mu e_t)$
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2. SMEFT interpretation

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Consider ***flavor conserving, non-universal* 4F** interactions

Above the pole

Build likelihood with the 3 runs, one operator at a time

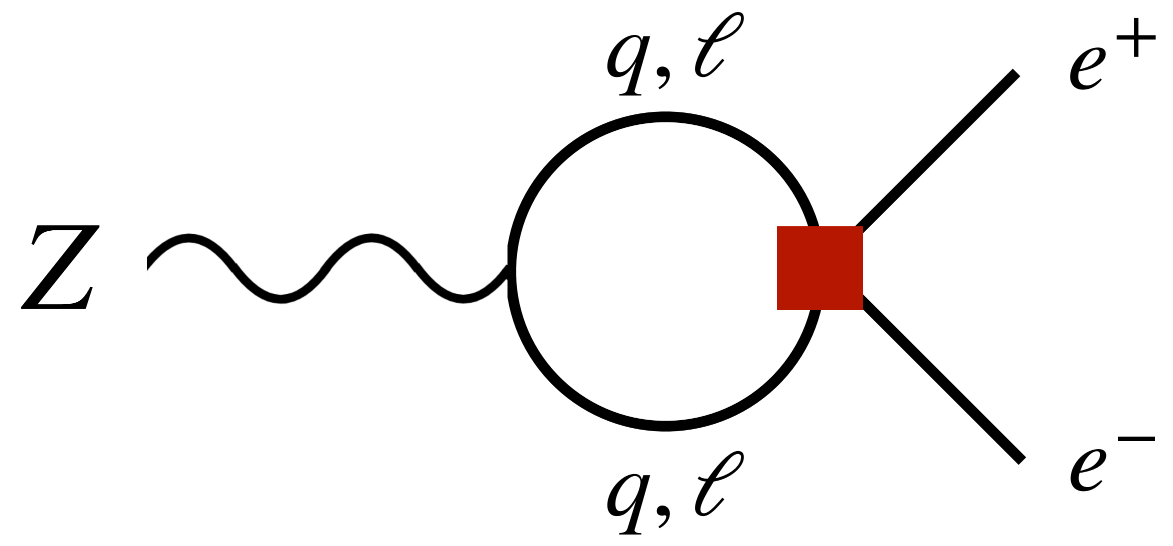
→ set $c_i = 1 \Rightarrow$ lower bound on Λ

→ $\Delta R_a / R_a^{\text{SM}} \sim s/\Lambda^2$: growth compensates precision deterioration!

→ Alternative: pair-production *around* the Z-pole ⇒ See Ge et al (2024)

2. SMEFT interpretation

- LEP-II: R_a ratios
- (HL-)LHC: high-p_T $\bar{q}q \to e^+e^-$ tails
- **FCC-ee Z-pole**: **1-loop RGE** ⟶



(y_t^2 for top, gauge others)

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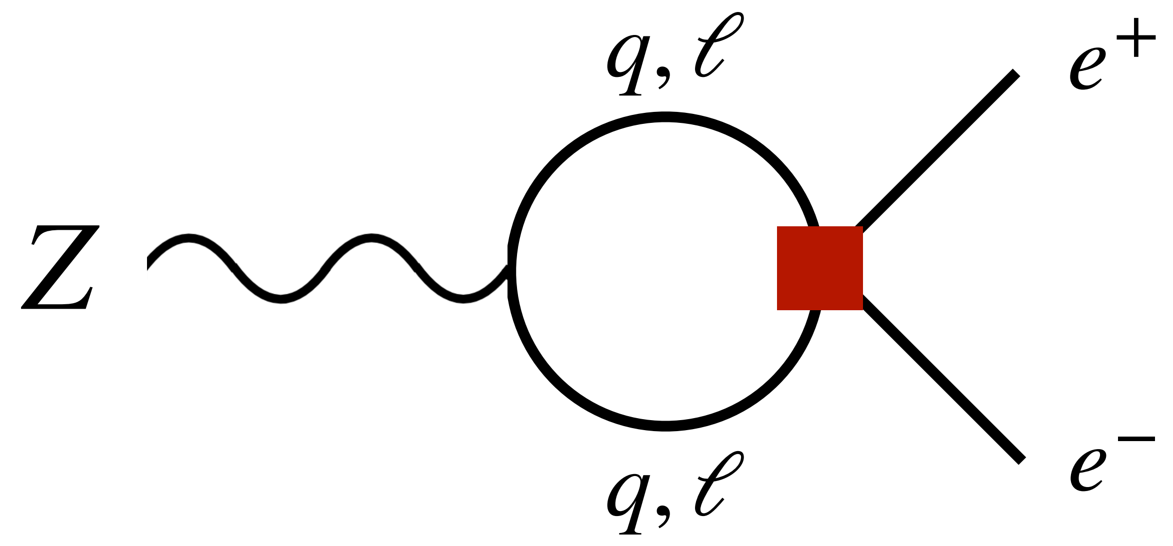
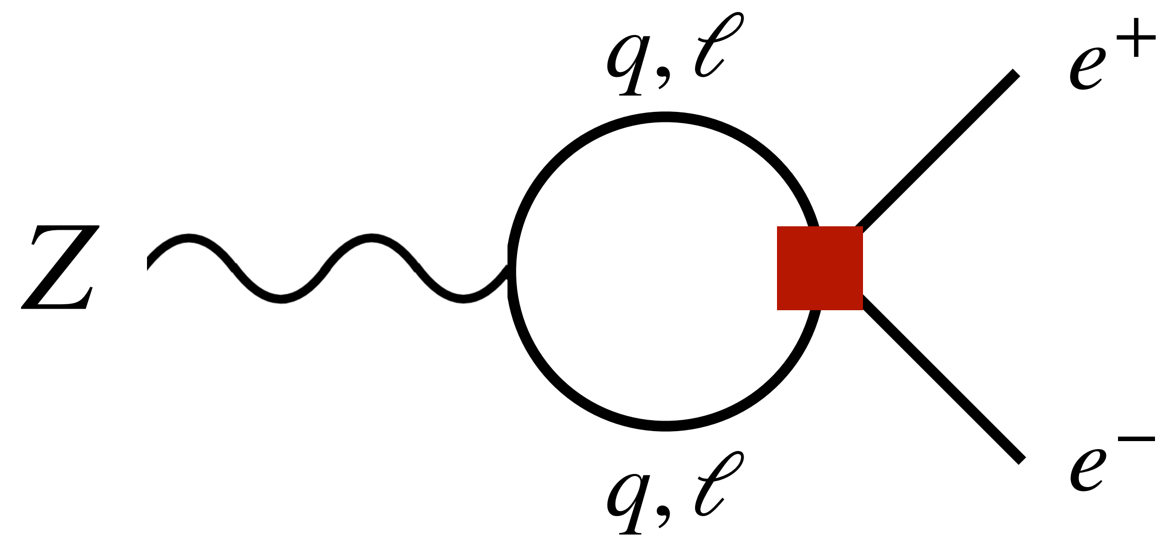


(y_t^2 for top, gauge others)

2. SMEFT interpretation

- Cs: atomic parity violation
- (HL-)LHC: high-p_T $\bar{q}q \to e^+e^-$ tails
- **FCC-ee Z-pole**: **1-loop RGE** →

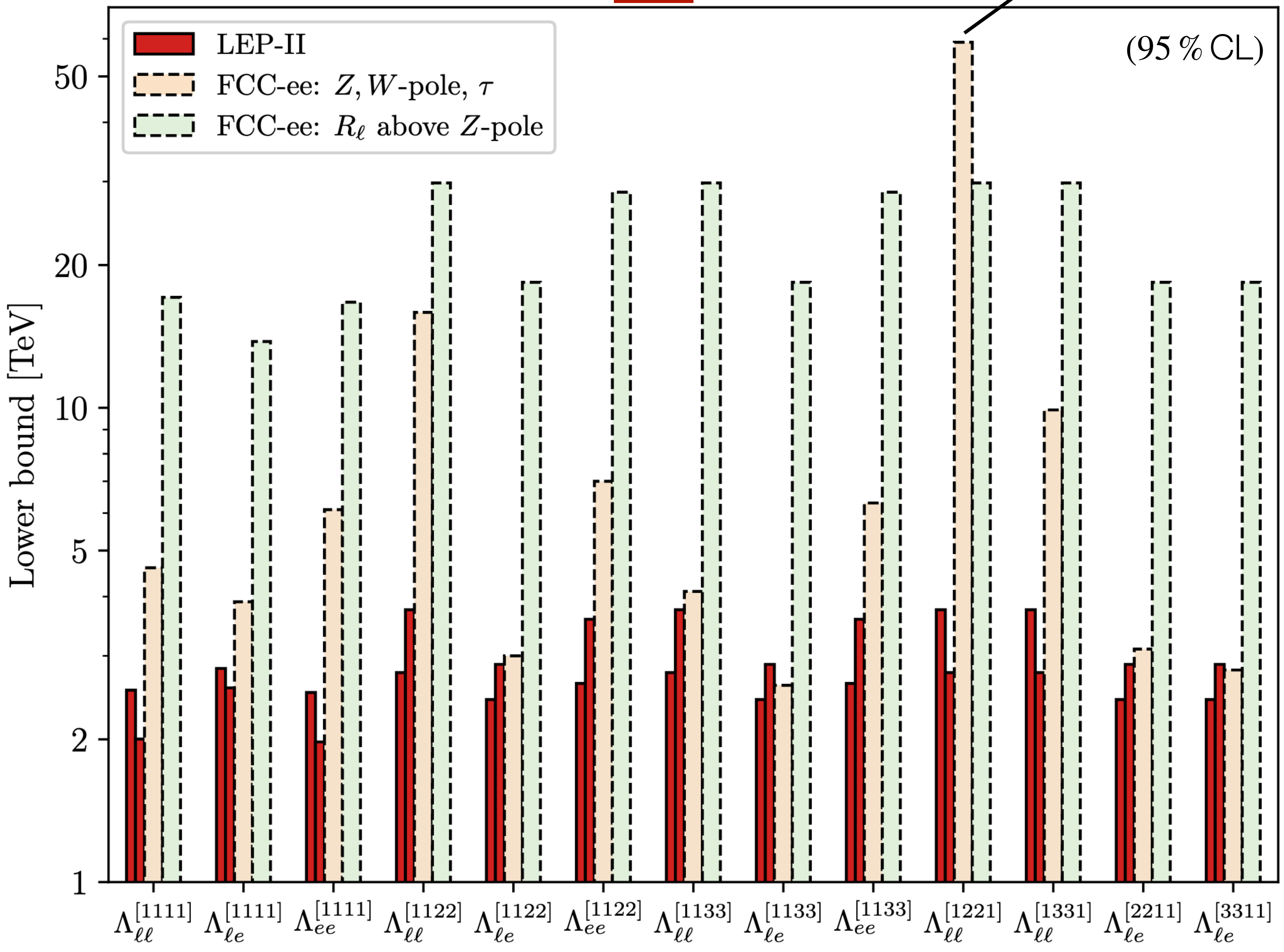


(y_t^2 for top, gauge others)

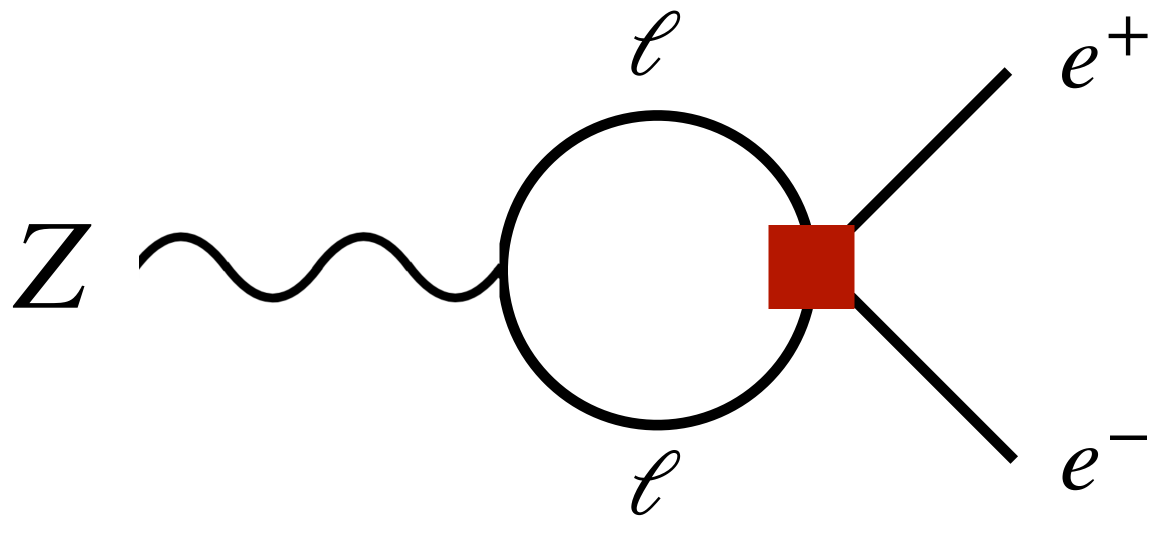
2. SMEFT interpretation

4ℓ

* tree-level G_F (muon decay)



- LEP-II: R_a ratios
- **FCC-ee Z-pole**: **1-loop RGE***



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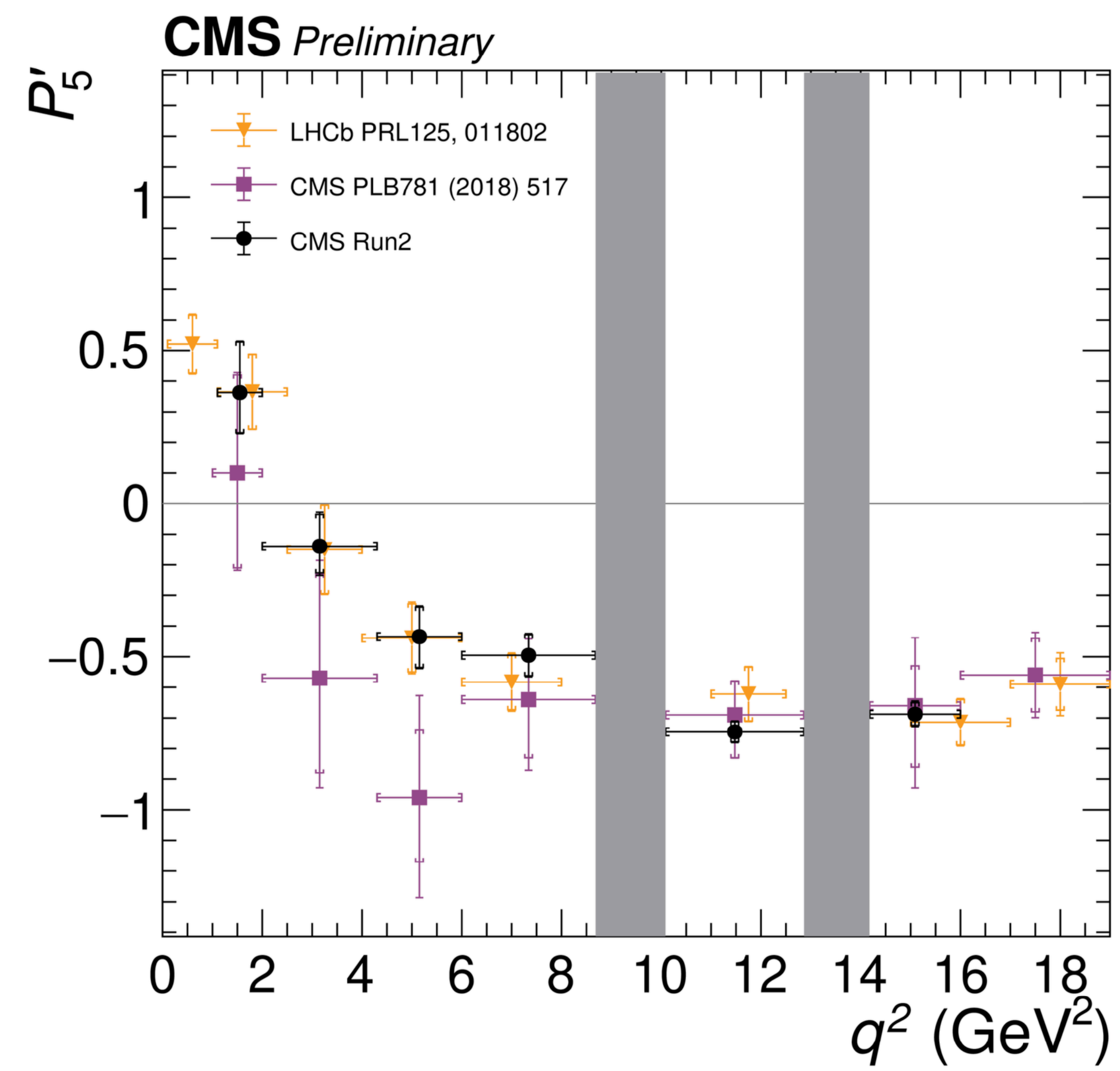
Motivation: B anomalies

$b \to s\ell\ell$

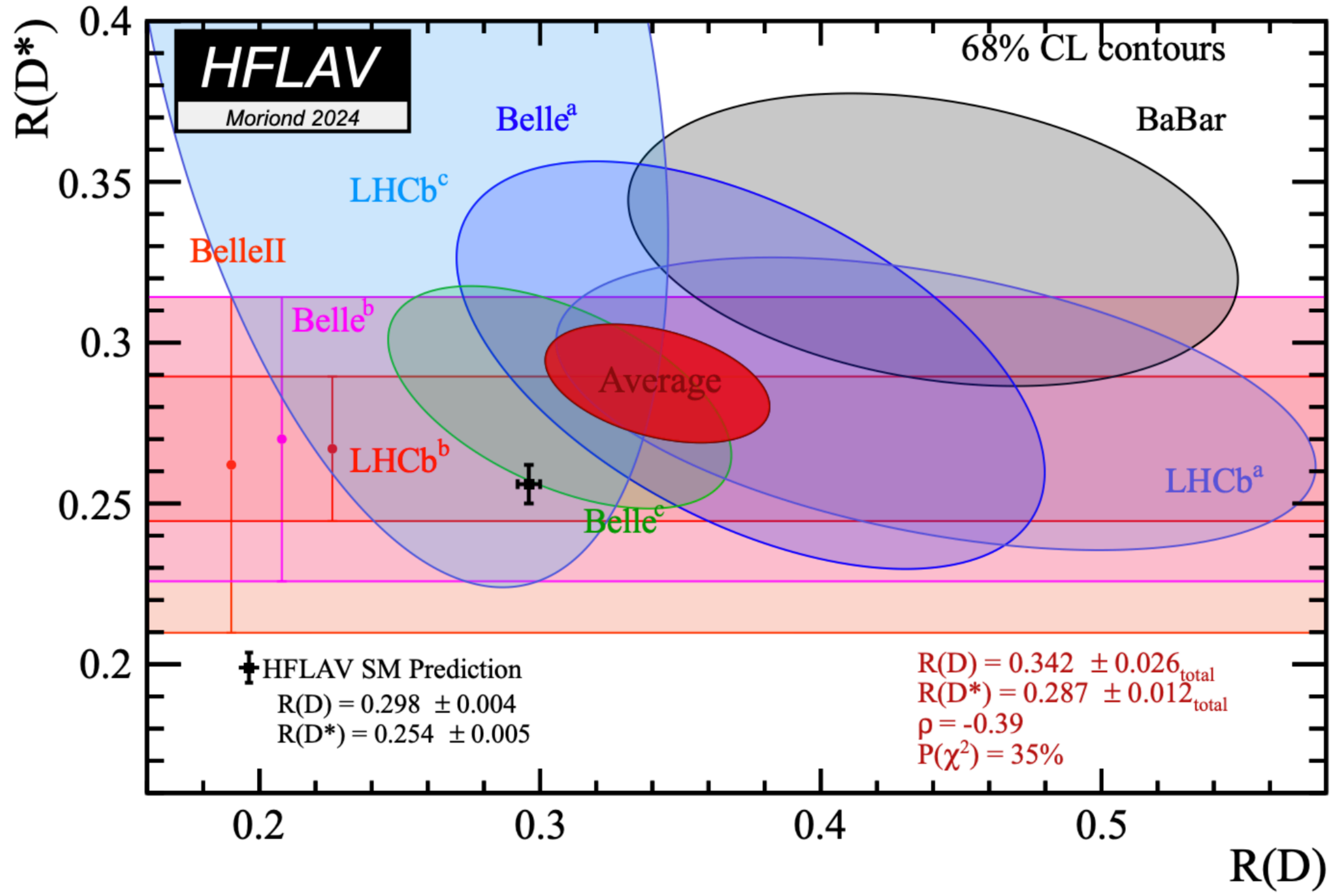
CMS+LHCb tension with (some) SM calculations

$(R_{K^{(*)}} \simeq 1)$



$b \to c\tau\nu$

$\sim 3.3\sigma$ tension with SM



Benchmark = BSM models accounting one/both discrepancies

I) Vector LQ for $b \to s\ell\ell$ and $b \to c\tau\nu$

$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_\mu \left(\bar{q}_L^3 \gamma^\mu \ell_L^3 + \beta_{s\tau}\, \bar{q}_L^2 \gamma^\mu \ell_L^3\right) + \text{h.c.}$$

$U_\mu \sim (\mathbf{3}, 1, 2/3)$

Parameters: $r_U \equiv g_U / M_U$ & $\beta_{s\tau}$

Buttazzo, Greljo, Isidori, Marzocca (2017)
Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert (2019, 2021)

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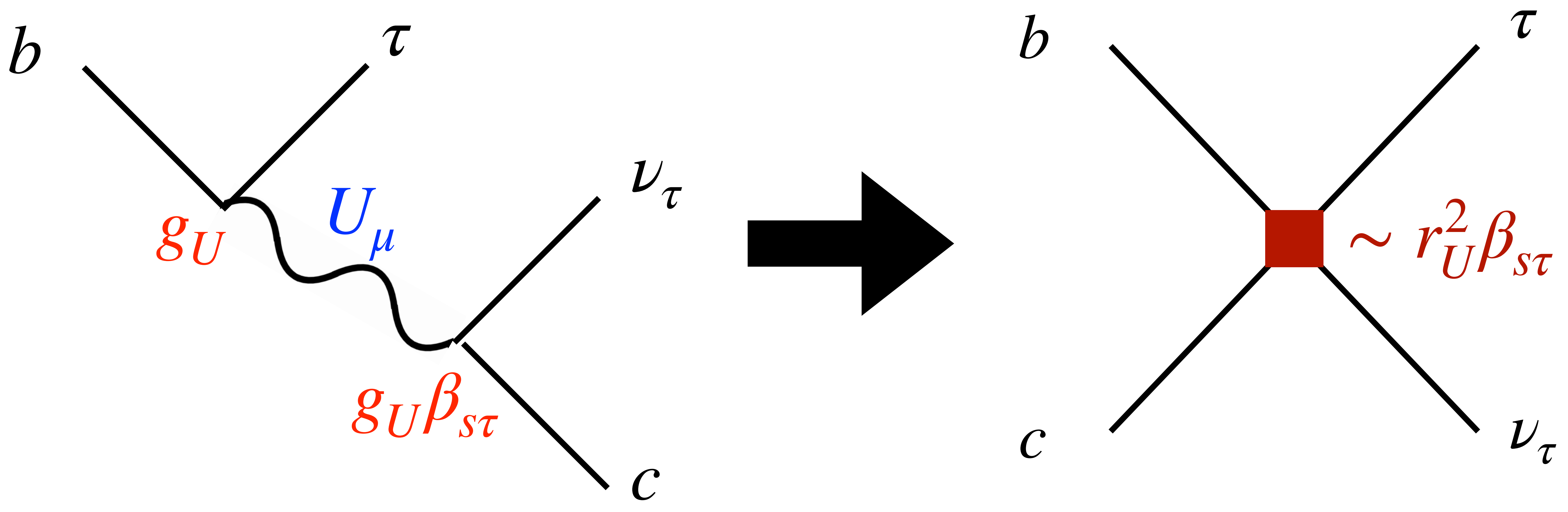
- TL contrib. to $b \to c\tau\nu$



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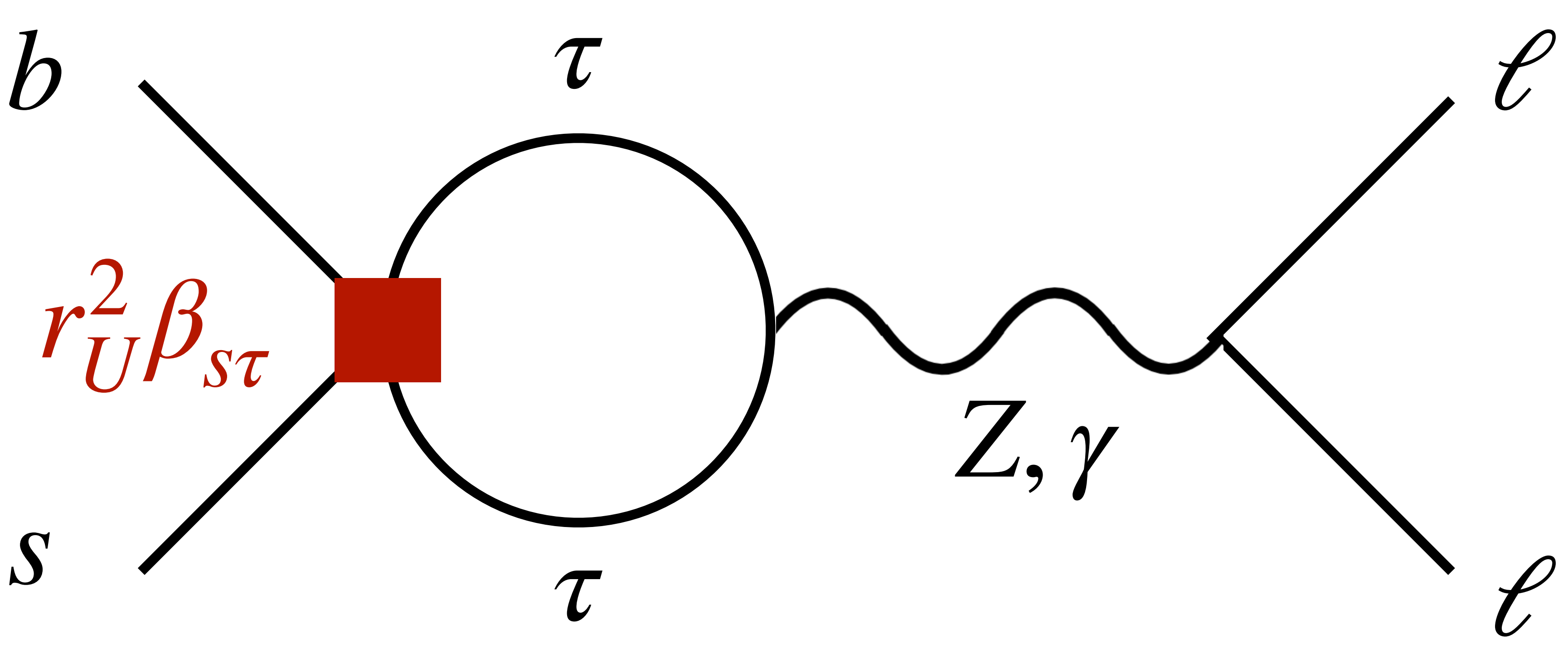
- TL contrib. to $b \to c\tau\nu$
- 1-loop to $b \to s\ell\ell$



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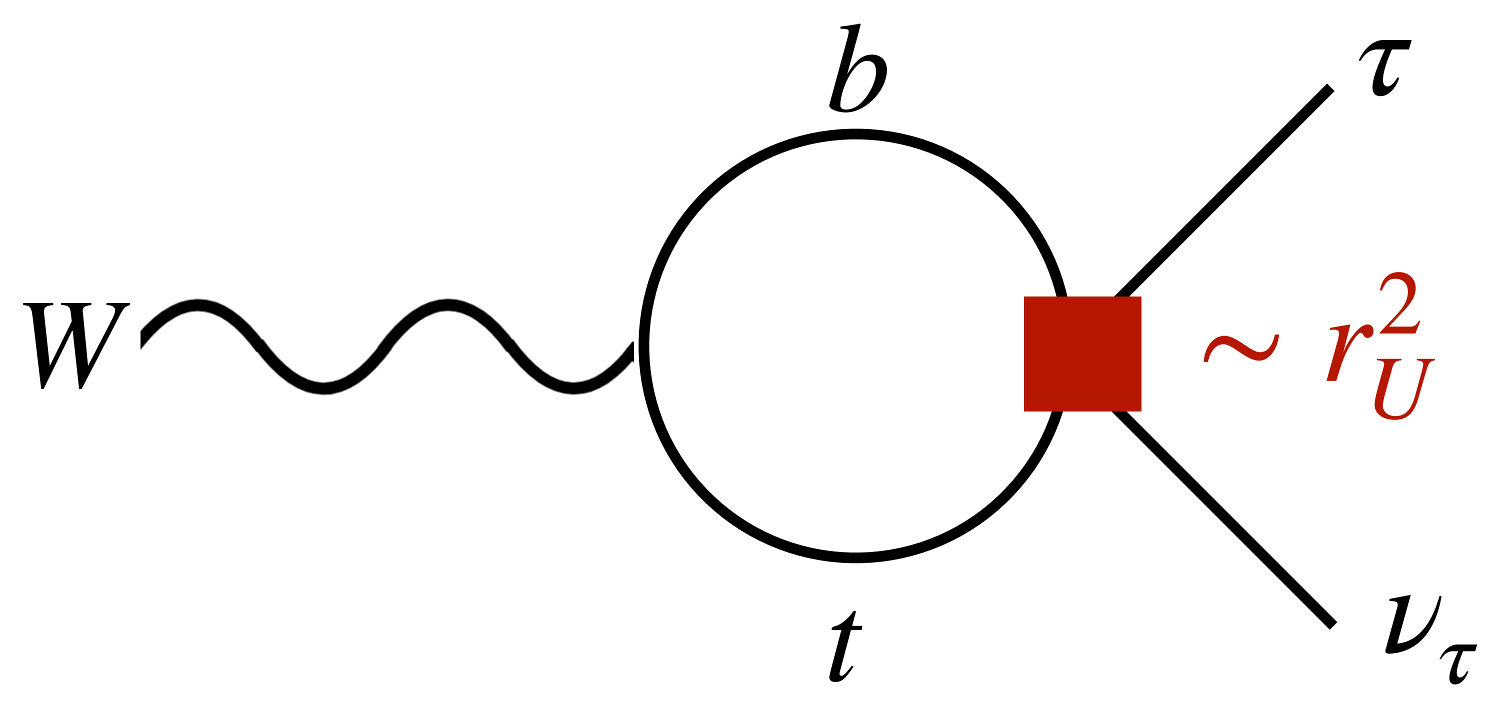
- TL contrib. to $b \to c\tau\nu$
- 1-loop to $b \to s\ell\ell$
- 1-loop to $\tau \to \mu\nu\nu$



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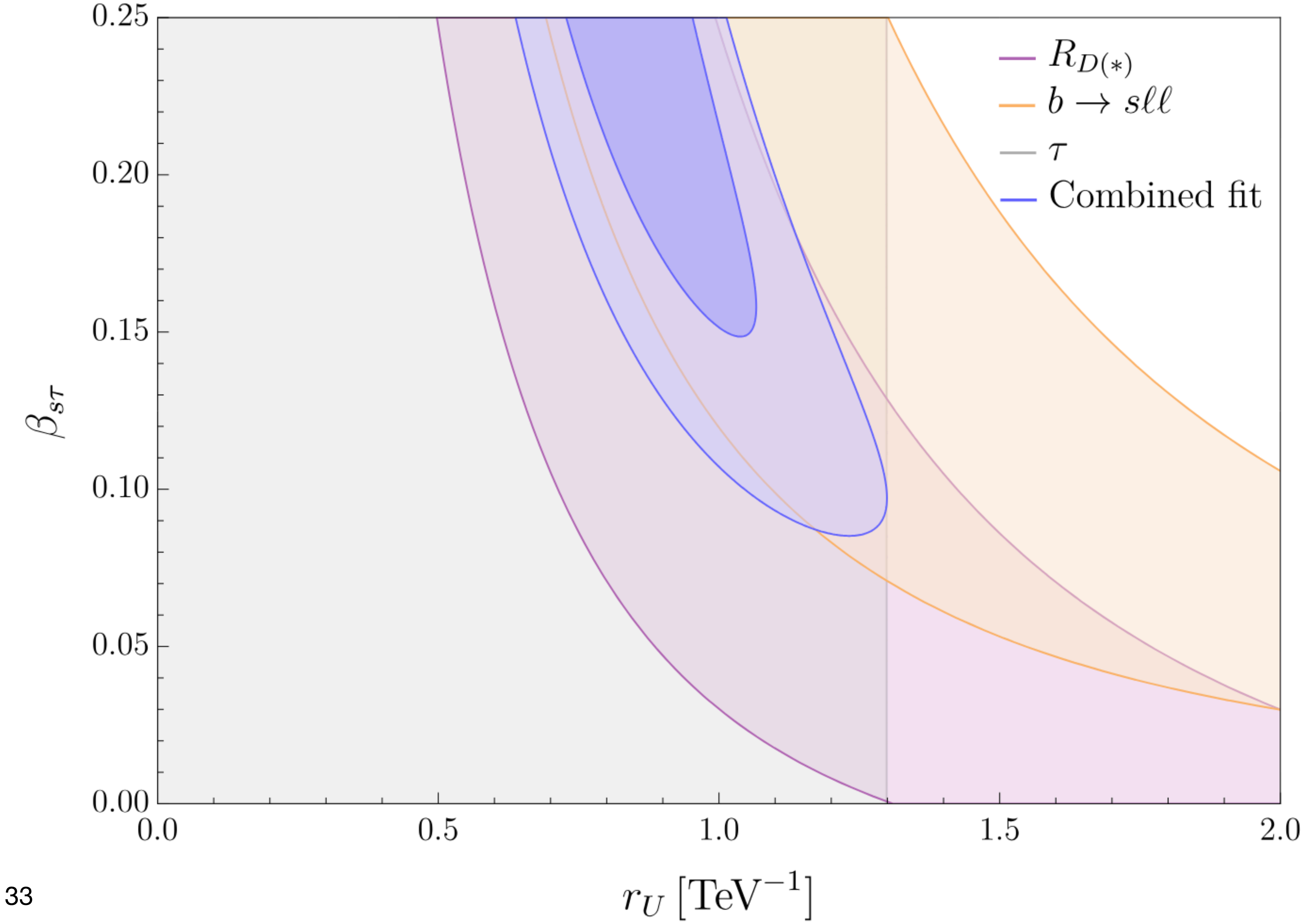
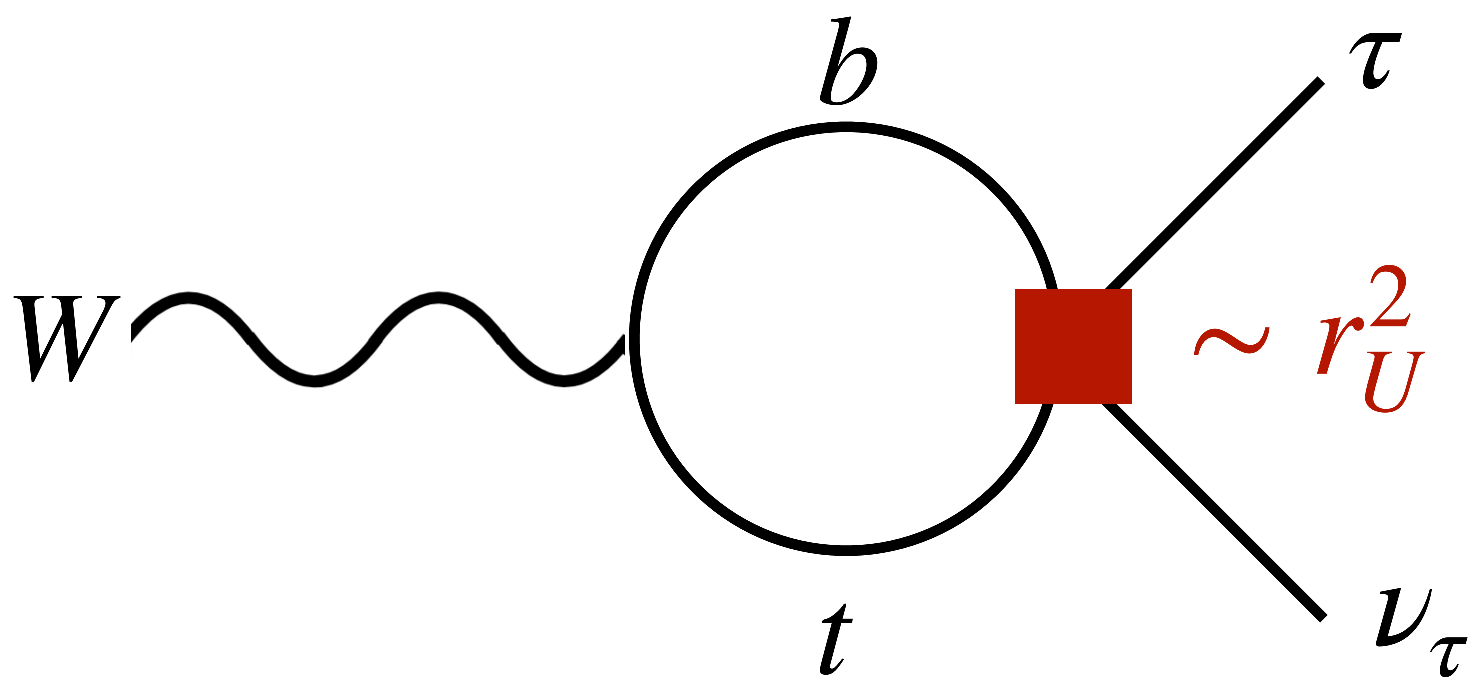


I) Vector LQ for $b \to s\ell\ell$ and $b \to c\tau\nu$

FCC-ee:

- $\mathcal{O}(10)$ improvement in $\tau \to \mu\nu\nu$ & $\mathcal{O}(50)$ $W \to \tau\nu$



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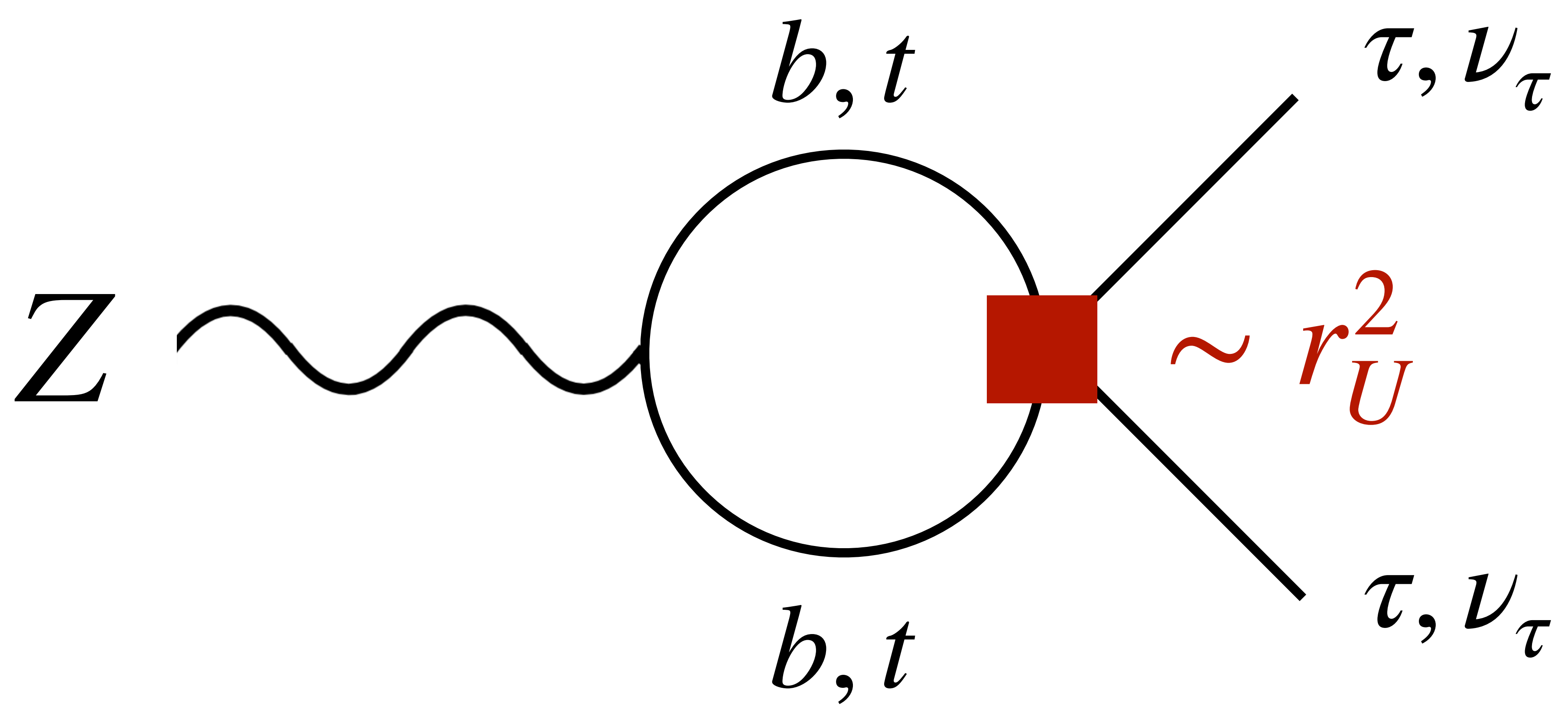

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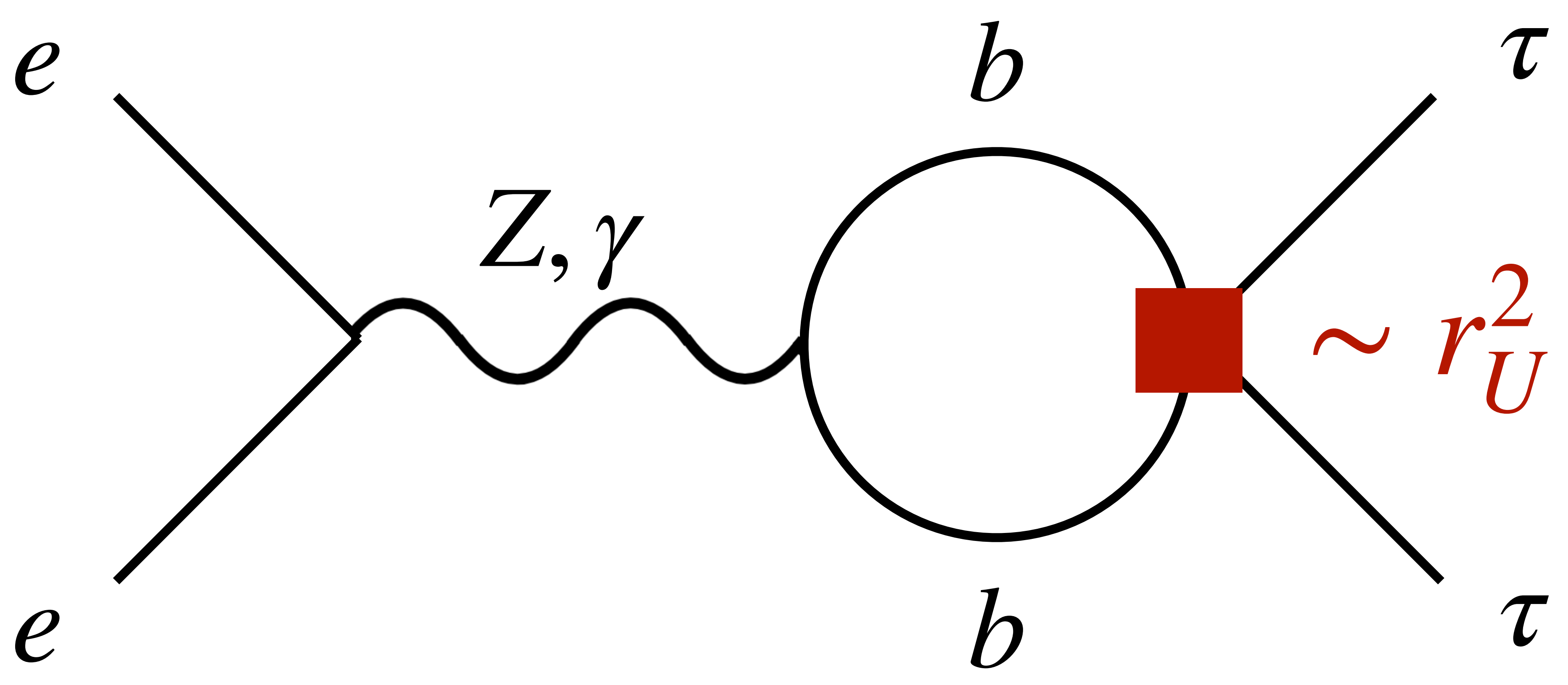
  to $e^+e^- \to \tau\tau, e^+e^- \to \bar{q}q$



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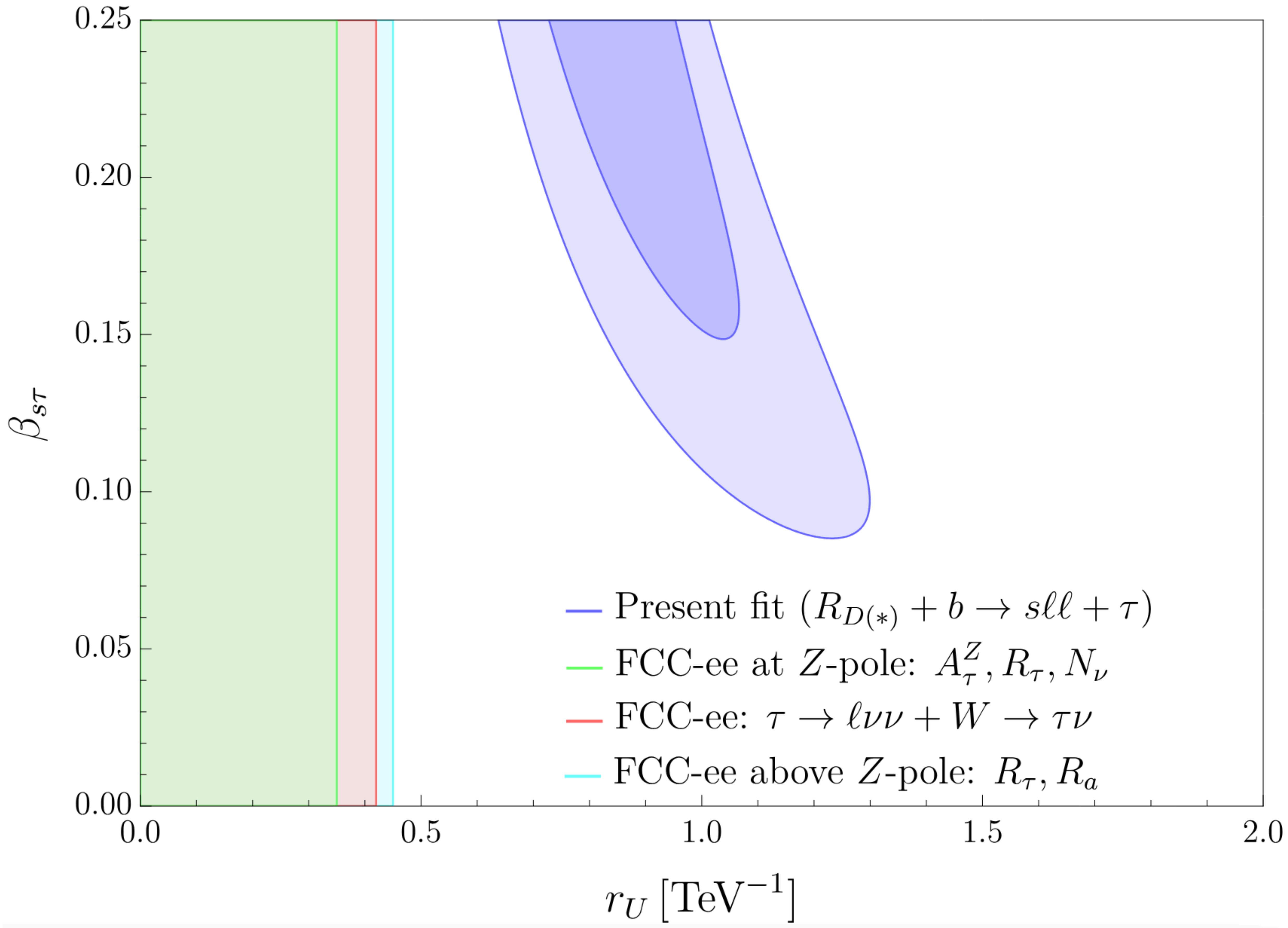

II) Scalar LQ for $b \to s\ell\ell$

Greljo, Salko, Smolkovic, Stangl (2022)

$$\mathscr{L} \supset \sum_{\alpha=e,\mu} S_\alpha \, \ell_L^\alpha \left(\lambda_b \, \bar{q}_L^{c,3} + \lambda_s \, \bar{q}_L^{c,2} \right)$$

$S_\alpha \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

Parameters: $r_{b,s} \equiv \lambda_{b,s}/M_S$

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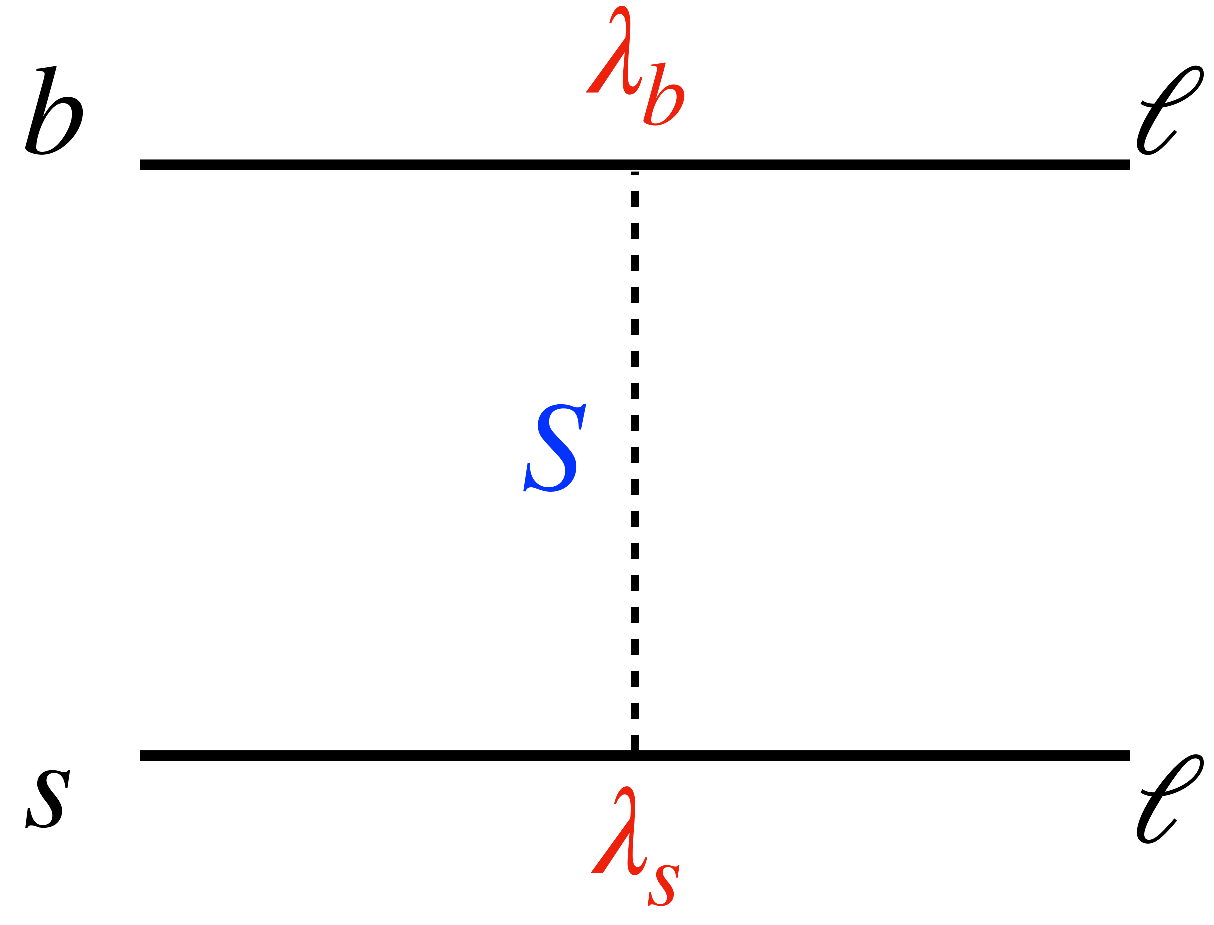

$\sim r_b \, r_s$

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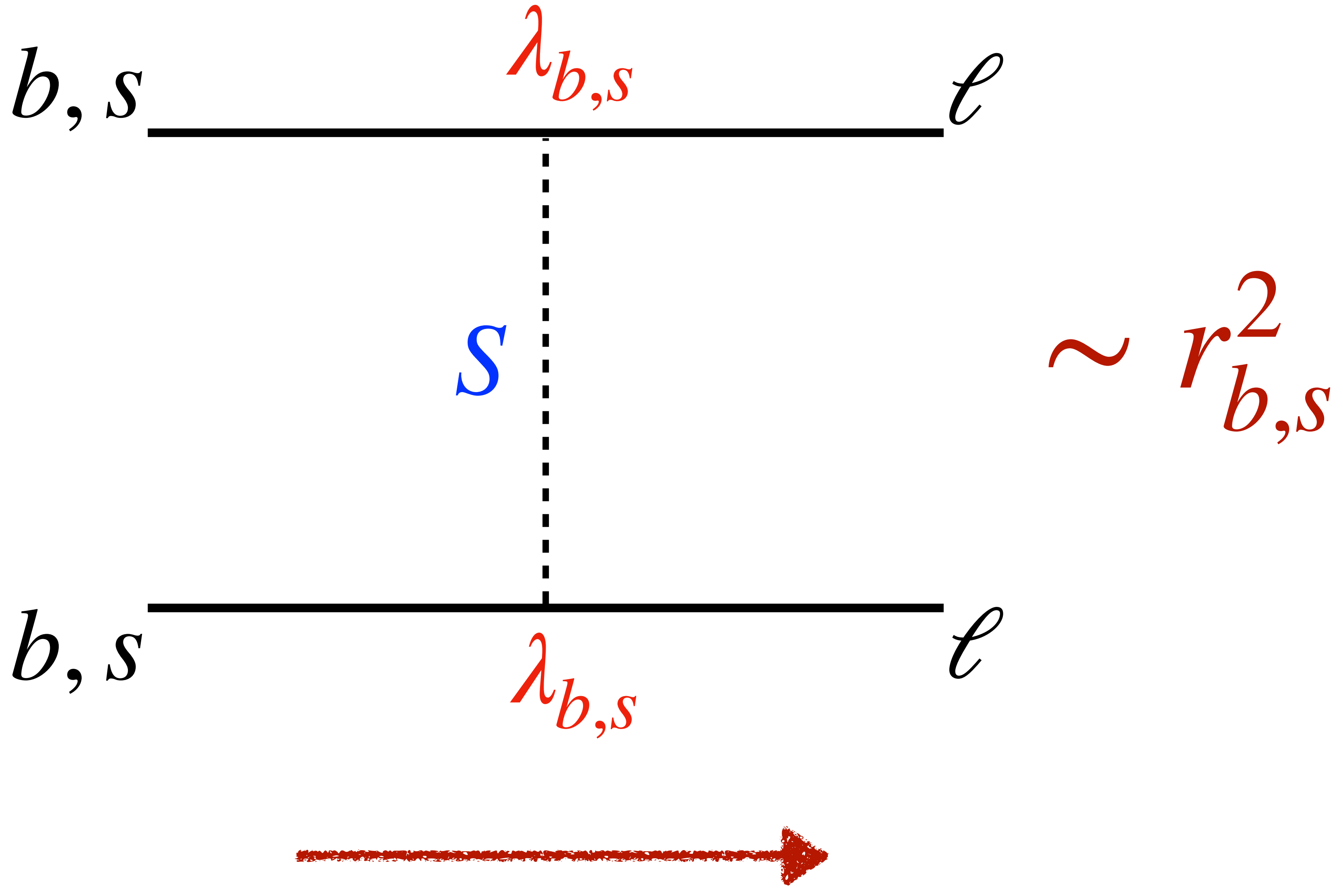

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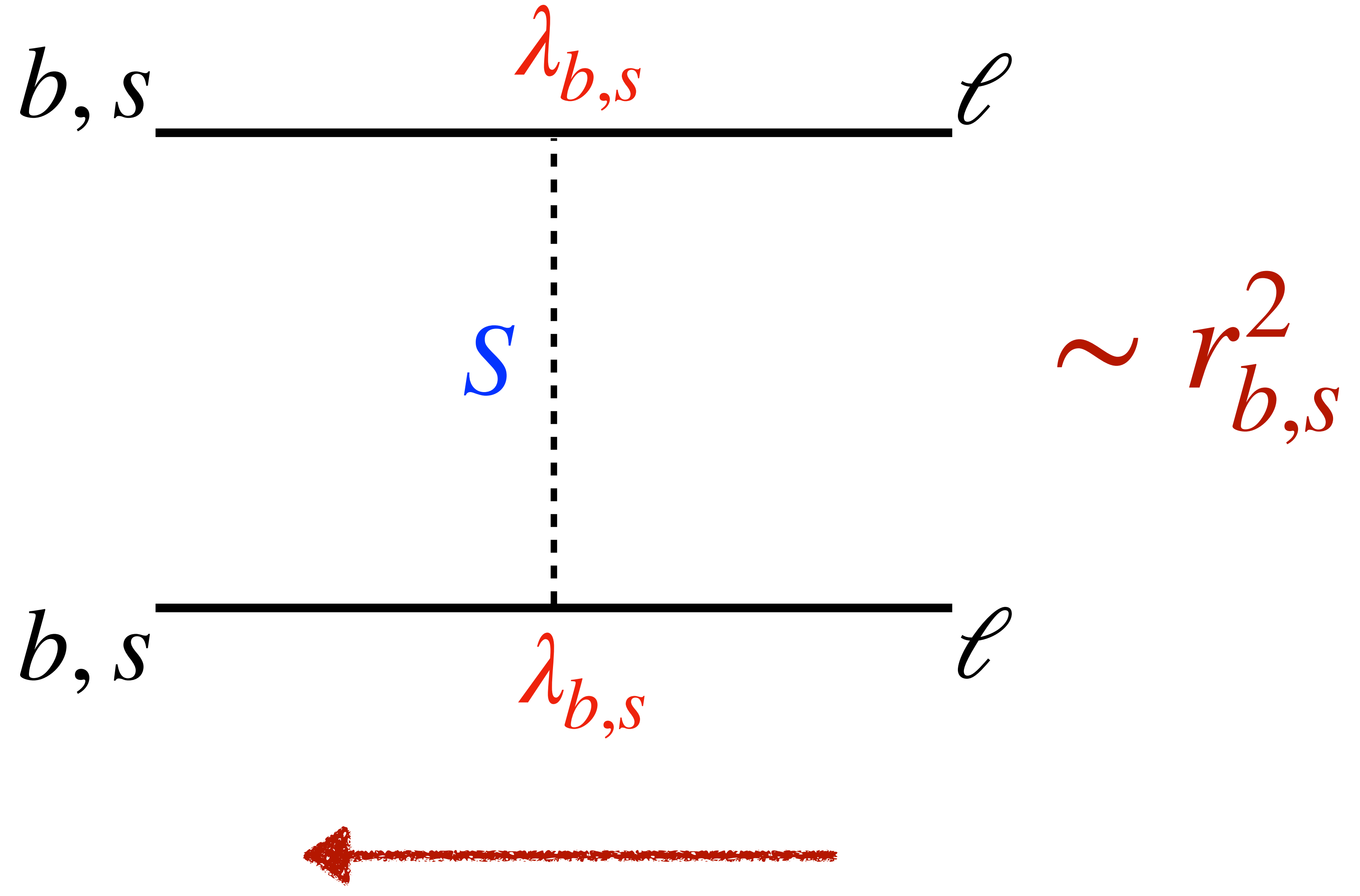

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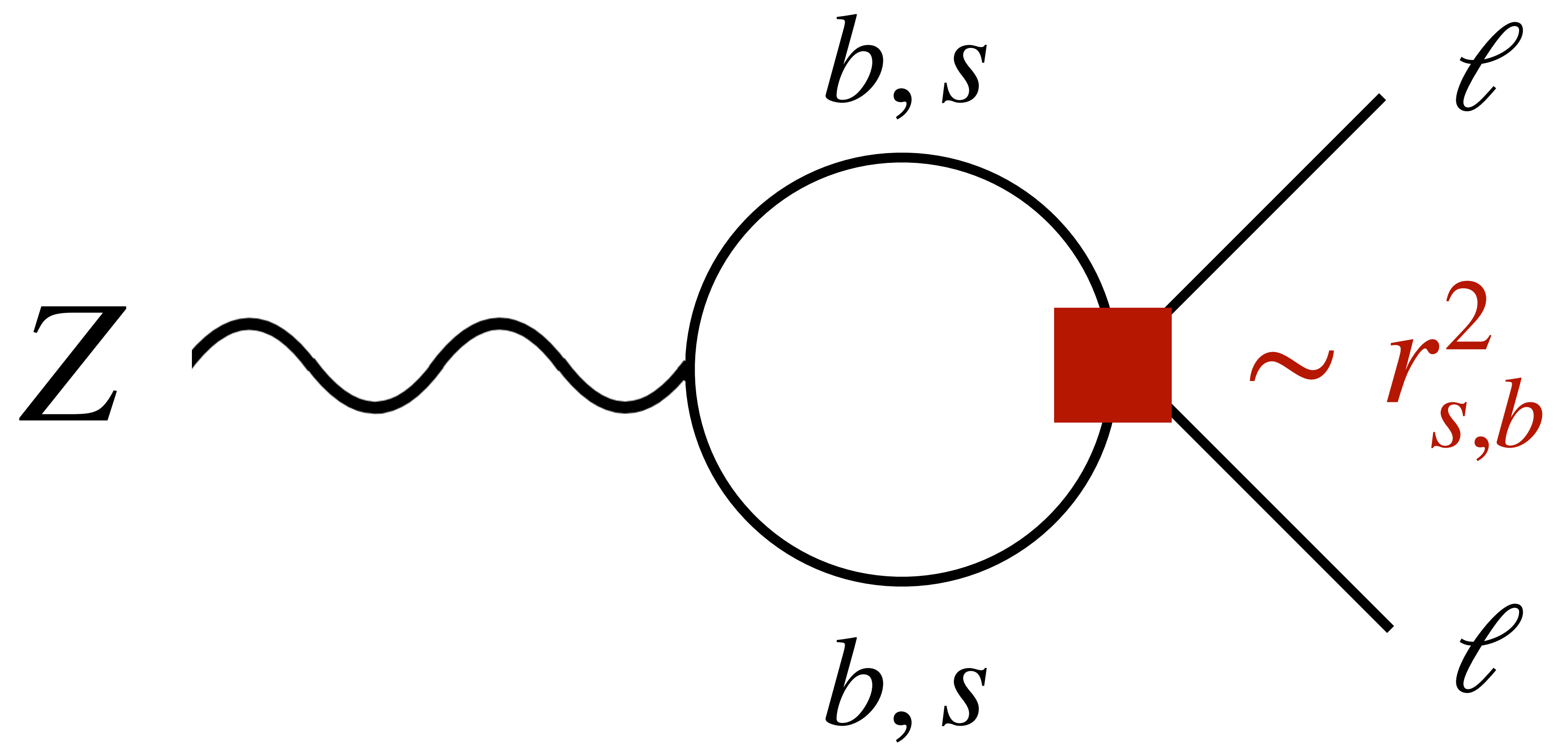

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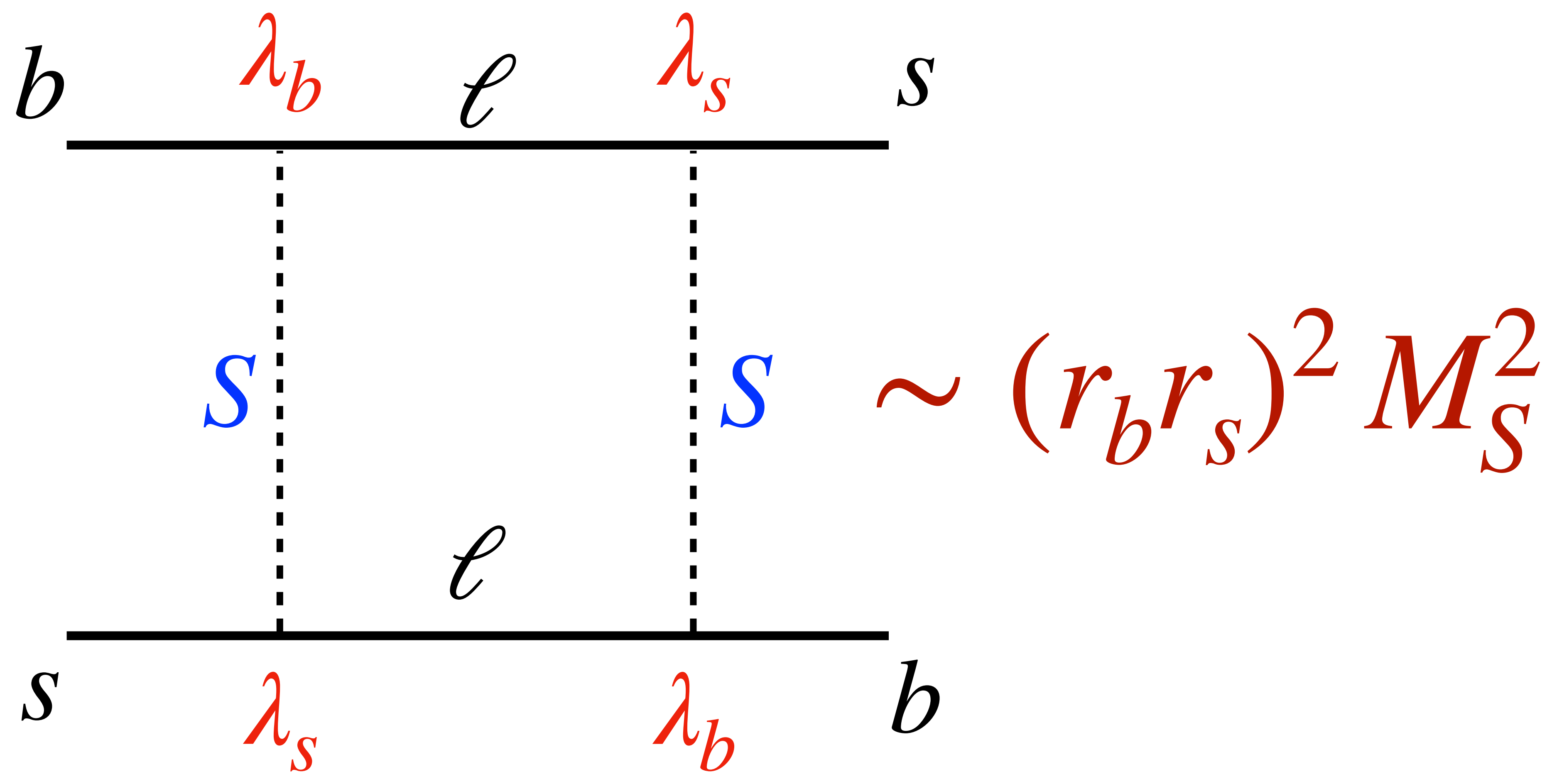

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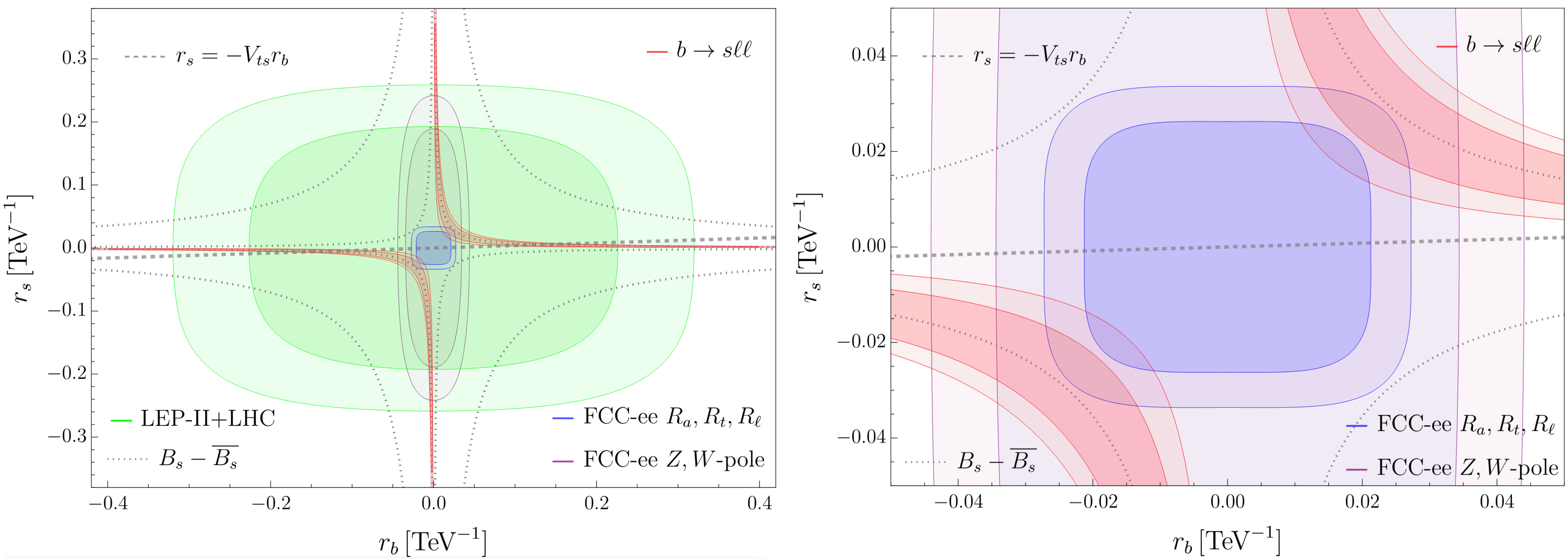
- 1-loop (box) to $B_s - \bar{B}_s$ **oscillations**

II) Scalar LQ for $b \to s\ell\ell$



Outline

1. Observables and flavor tagging above the Z-pole
2. SMEFT interpretation
3. Impact on selected models
4. Conclusion

4. Conclusion

- Current results in flavor tagging at FCC-ee allow saturation of the naïve stat limit on R_b, R_c (for R_s improvement needed)
- R_a above the Z-pole at FCC-ee:
  probe flavor conserving, non-universal 4F (also 3rd gen!) up to $\mathcal{O}(50)$ TeV!
- SMEFT RG:
  Interplay/complementarity between Z-pole EWPO (1-loop) and above the pole (TL)
- FCC-ee may rule out/discover models for current B anomalies!

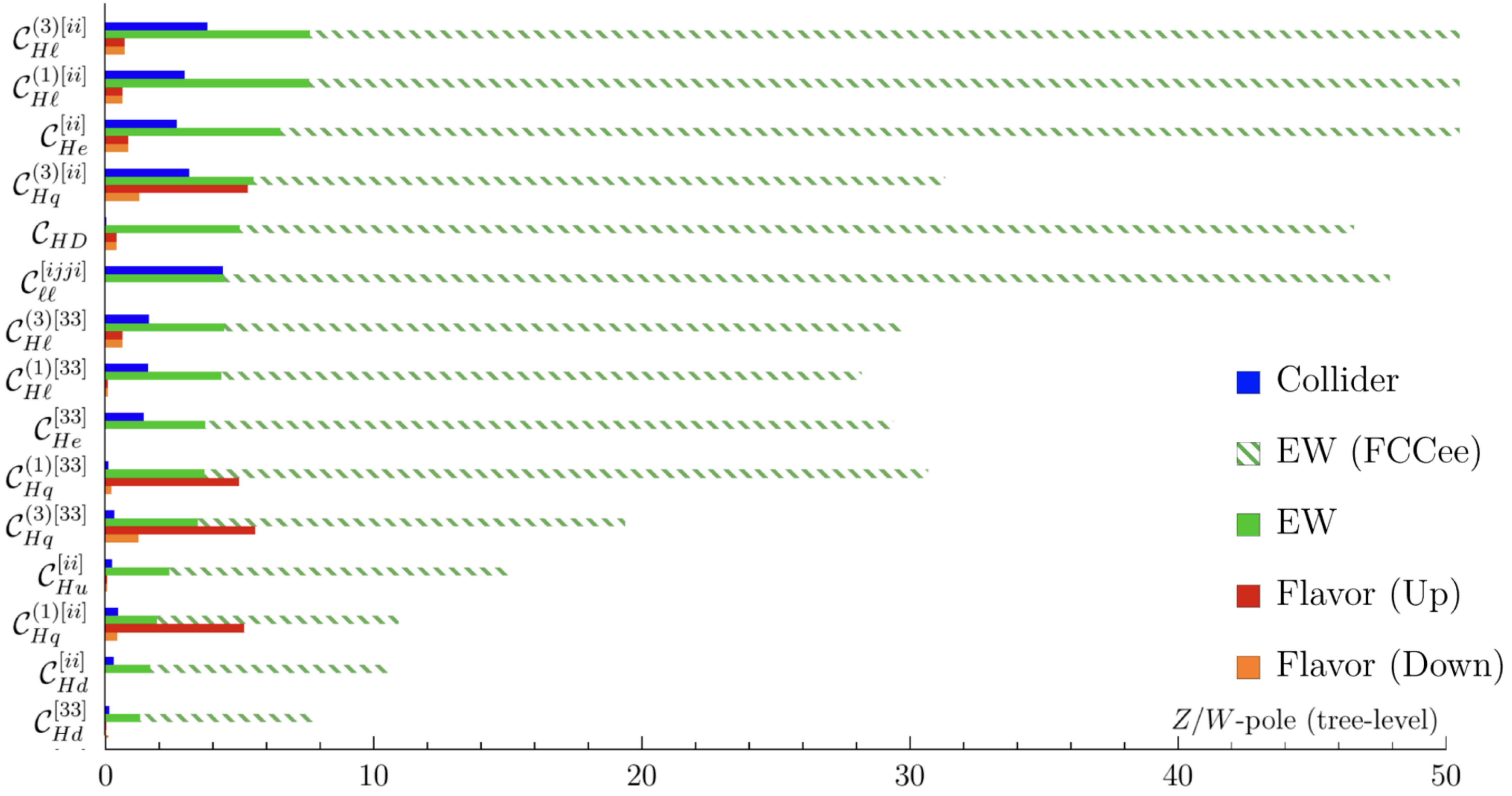
Thank you for your attention!

BACKUP

Z-pole

$[\mathcal{O}^{(1)}_{H\ell}]_{pr} =$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\ell}_p \gamma^\mu \ell_r)$	$[\mathcal{O}_{Hu}]_{pr} =$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
$[\mathcal{O}^{(3)}_{H\ell}]_{pr} =$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{\ell}_p \tau^I \gamma^\mu \ell_r)$	$[\mathcal{O}_{Hd}]_{pr} =$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$[\mathcal{O}^{(1)}_{Hq}]_{pr} =$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	$\mathcal{O}_{HD} =$	$\lvert H^\dagger D_\mu H\rvert^2$
$[\mathcal{O}^{(3)}_{Hq}]_{pr} =$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	$\mathcal{O}_{HWB} =$	$(H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$
$[\mathcal{O}_{He}]_{pr} =$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	$[\mathcal{O}_{\ell\ell}]_{1221} =$	$(\bar{\ell}_1 \gamma^\mu \ell_2)(\bar{\ell}_2 \gamma^\mu \ell_1)$

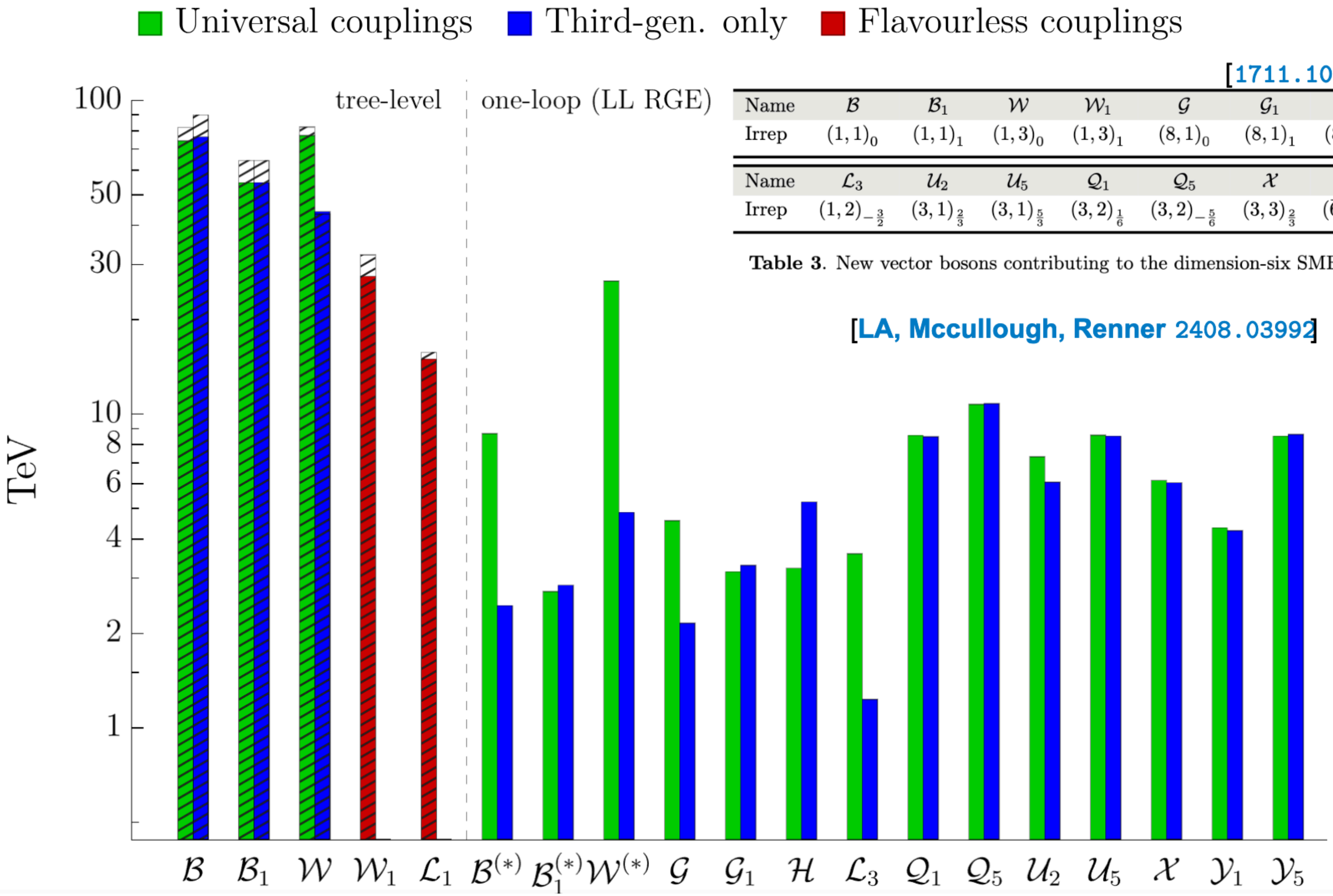
$U(2)$ limit



Allwicher et al (2023)

Z-pole

VECTORS



[1711.10391]

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

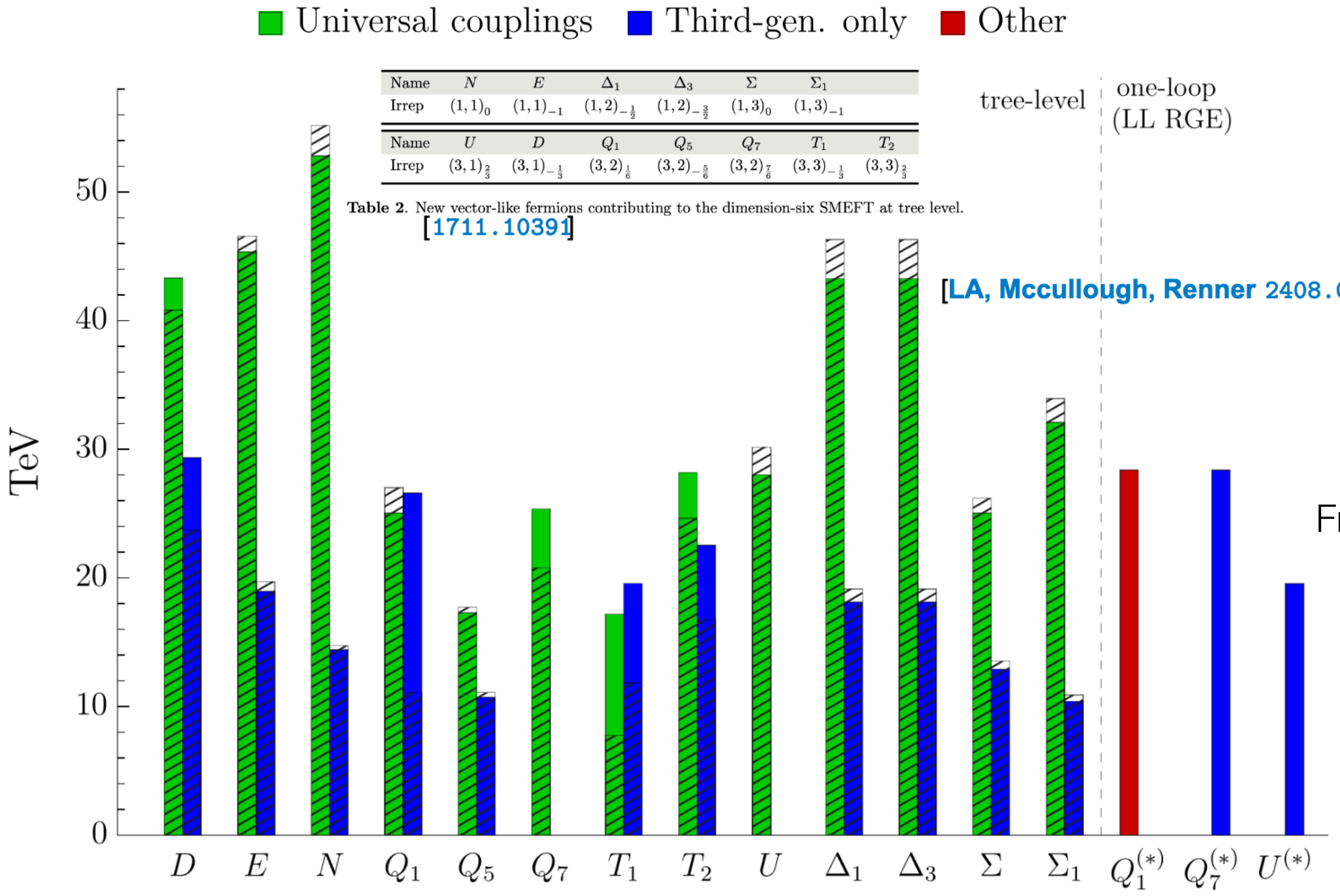
Table 3. New vector bosons contributing to the dimension-six SMEFT at tree level.

[**LA, Mccullough, Renner** 2408.03992]

From L. Allwicher talk

Z-pole

FERMIONS



Name	N	E	Δ_1	Δ_3	Σ	Σ_1	
Irrep	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$	
Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

Table 2. New vector-like fermions contributing to the dimension-six SMEFT at tree level.

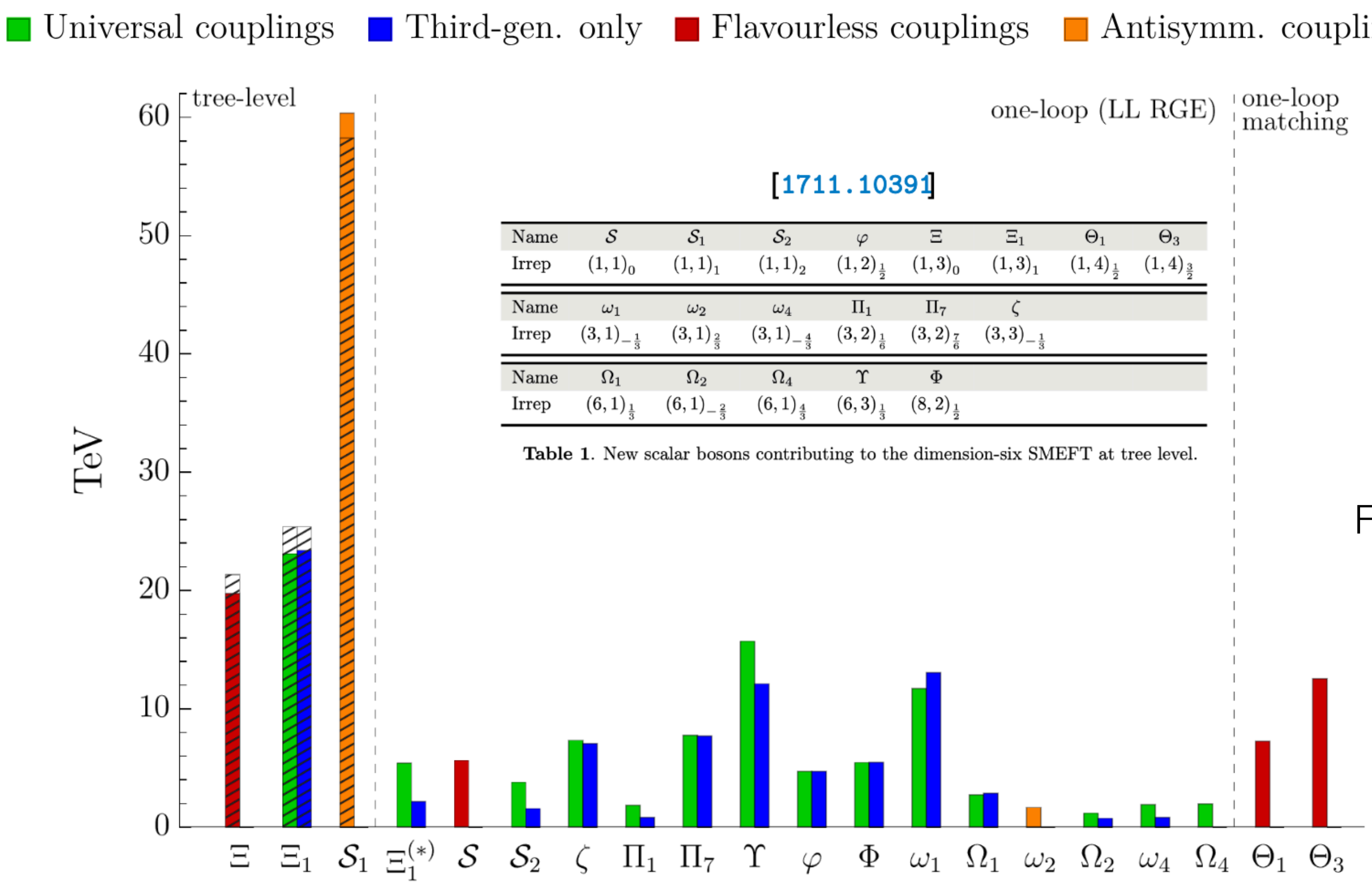
[1711.10391]

[**LA, Mccullough, Renner** 2408.03992]

From L. Allwicher talk

Z-pole

SCALARS



[1711.10391]

Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$
Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$		
Name	Ω_1	Ω_2	Ω_4	Υ	Φ			
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$			

Table 1. New scalar bosons contributing to the dimension-six SMEFT at tree level.

From L. Allwicher talk

Other bounds

Oblique corrections

$$\mathcal{L}_{\text{SMEFT}} \supset -\frac{\hat{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 - \frac{\hat{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

EoM:

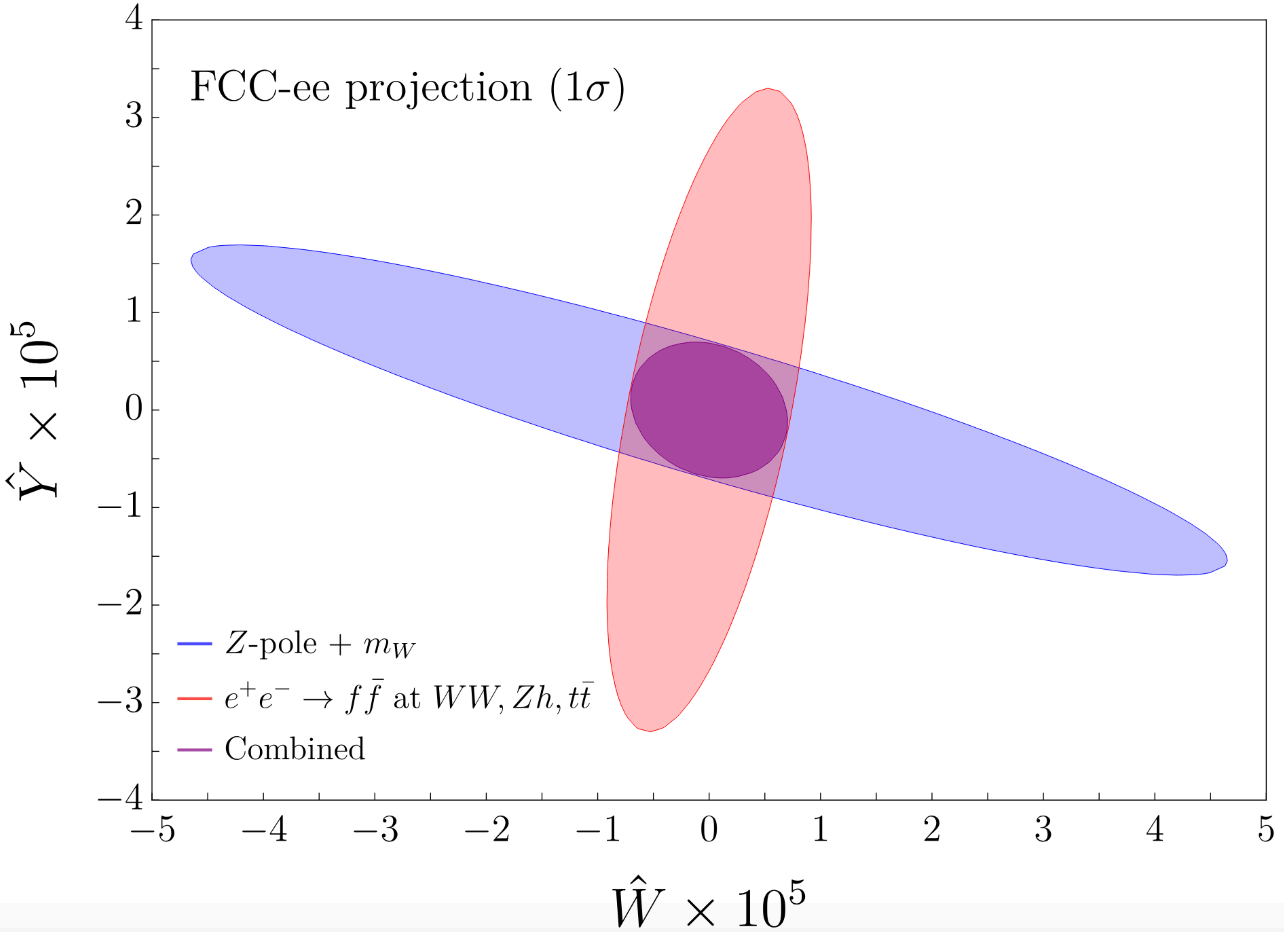
flavor conserving, non-universal 4F

(TL *above* the Z-pole)

+

Higgs-fermion current operators

(TL *at* the Z-pole)



Other bounds

3rd gen only:

Pure RG effect,
both at Z and above

$\Lambda^{[3333]}$ [TeV]	FCC-ee Z, W-pole+τ	FCC-ee above Z-pole
$\Lambda_{\ell q}^{(1)}$	15.7	1.1
$\Lambda_{\ell q}^{(3)}$	14.0	5.1
Λ_{eu}	16.2	1.6
Λ_{ed}	1.5	1.3
$\Lambda_{\ell u}$	15.4	1.5
$\Lambda_{\ell d}$	1.5	1.3
Λ_{qe}	16.7	1.1
$\Lambda_{\ell\ell}$	1.0	1.0
$\Lambda_{\ell e}$	2.1	1.5
Λ_{ee}	3.5	2.4
$\Lambda_{qq}^{(1)}$	13.1	2.4
$\Lambda_{qq}^{(3)}$	8.4	7.1
$\Lambda_{qu}^{(1)}$	9.4	1.4
$\Lambda_{qd}^{(1)}$	3.1	0.9
Λ_{uu}	12.1	1.9
Λ_{dd}	0.4	2.3
$\Lambda_{ud}^{(1)}$	2.8	1.9

4F operators *around* the Z-pole?

Ge et al (2024)

Key: $\sigma_{Z,SM} \sim \frac{s}{(s-m_Z^2)^2 + m_z^2\Gamma_Z^2} \longrightarrow \frac{\sigma_{BSM}}{\sigma_{SM,Z}} \sim \frac{s-m_Z^2}{\Lambda^2}$

$\sqrt{s} \supset m_z \pm 5$ GeV: larger stat but relative effect suppressed

Comparing results: stronger bounds above the pole

Flavor-violating ratios

$$R_{ij} = \frac{\sigma(e^+e^- \to \bar{q}_i q_j) + \sigma(e^+e^- \to \bar{q}_j q_i)}{\sum_{k,l}\sigma(e^+e^- \to \bar{q}_k q_l)}$$

Consider only N_{ij}
(contrib. to other bins negligible)

$$E[S] = s/\sigma_b$$

$$\sigma_b \simeq (b + \sum_k \sigma_{b,k})^{1/2}$$

$$R_{ij} \lesssim 1.645 \frac{\sigma_b}{N_{\text{tot}}\epsilon_i^i \epsilon_j^j}$$ (95% CL)

Result →

Energy	ij	R_{ij}
WW	bs	$2.80 \cdot 10^{-6}$
	bd	$3.44 \cdot 10^{-5}$
	cu	$5.28 \cdot 10^{-5}$
Zh	bs	$6.37 \cdot 10^{-6}$
	bd	$6.58 \cdot 10^{-5}$
	cu	$1.10 \cdot 10^{-4}$
$t\bar{t}$	bs	$1.79 \cdot 10^{-5}$
	bd	$1.53 \cdot 10^{-4}$
	cu	$2.70 \cdot 10^{-4}$

Flavor-violating ratios

SMEFT interpretation:

$$|\Lambda_{1123}| > 16\,\mathrm{TeV} \;\; \text{for}\;\; \mathcal{O}_{\ell q}^{(1)}, \mathcal{O}_{\ell q}^{(3)}, \mathcal{O}_{\ell d}, \mathcal{O}_{ed}, \mathcal{O}_{qe},$$

$$|\Lambda_{1113}| > 9.4\,\mathrm{TeV} \;\; \text{for}\;\; \mathcal{O}_{\ell q}^{(1)}, \mathcal{O}_{\ell q}^{(3)}, \mathcal{O}_{\ell d}, \mathcal{O}_{ed}, \mathcal{O}_{qe}$$

$$|\Lambda_{1112}| > 8.1\,\mathrm{TeV} \;\; \text{for}\;\; \mathcal{O}_{\ell q}^{(1)}, \mathcal{O}_{\ell q}^{(3)}, \mathcal{O}_{\ell u}, \mathcal{O}_{eu}, \mathcal{O}_{qe}$$

Bounds generally weaker/comparable with ones from hadronic decays

III) Z' for $b \to s\ell\ell$

$$\mathscr{L} \supset g_{sb} Z'_\mu \left(\bar{q}_L^3 \gamma^\mu q_L^2\right) + g_\ell Z'_\mu \sum_{\ell=e,\mu,\tau} \left(\bar{\ell}\gamma^\mu \ell\right) + \text{h.c.}$$

Parameters: $r_{sb} \equiv g_{sb}/M_{Z'}$ & $r_\ell \equiv g_\ell/M_{Z'}$

- TL contrib to $b \to s\ell\ell$
- TL contrib to $B_s - \bar{B}_s$ mixing
- TL contrib to $e^+e^- \to f\bar{f}$