New Physics at Tera-Z and Beyond

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Based mostly on 2411.0248, 2507.03073

BNL (Zoom)
September 4th, 2025

Outline

1. Introduction
2. Observables and BSM from the EFT viewpoint
3. Impact on selected benchmark scenarios
4. Conclusion

Particle Physics @2025

No direct signs of New Physics at LHC after Higgs boson discovery

However, we have a strong theoretical bias for expecting NP around TeV
(Naturalness, flavour anomalies, …)

Can we anticipate and guide possible future direct discoveries?

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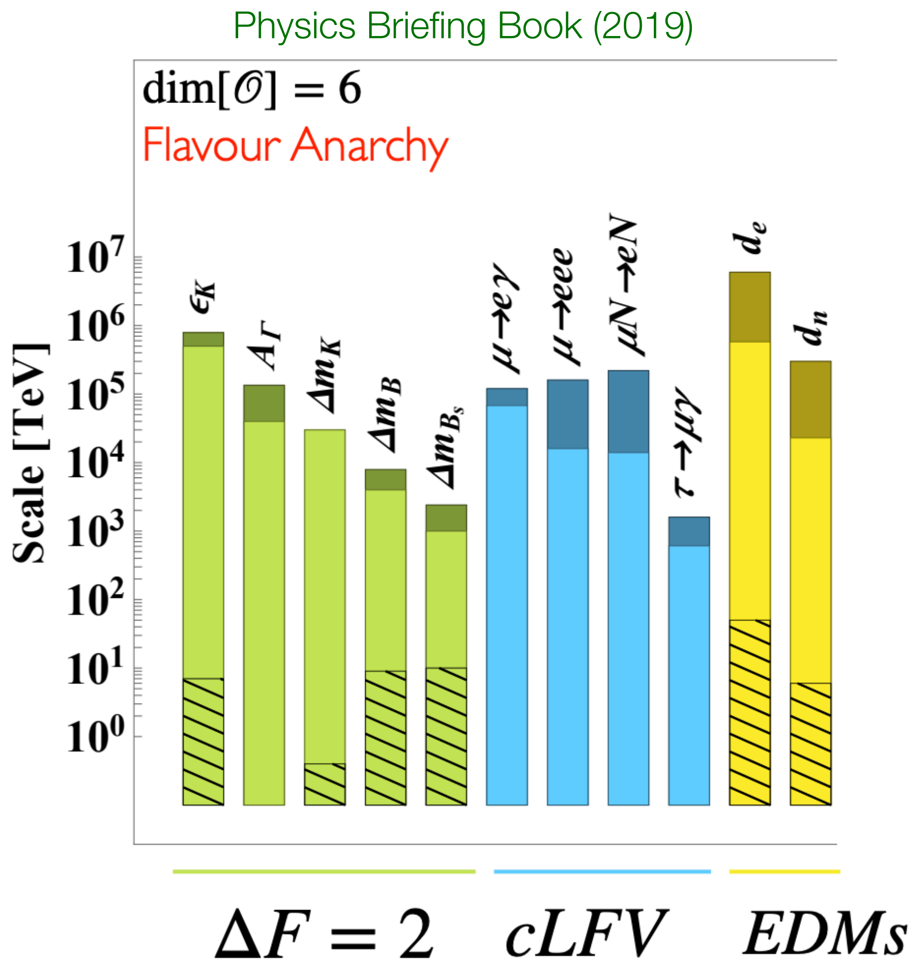


Yes, with precision!
Indirect probes can test much higher scales than TeV
Prototypical examples: flavour, CP

Electron-Positron colliders offer unique opportunities to improve
our knowledge of the EW sector of the SM and test NP at very high scales

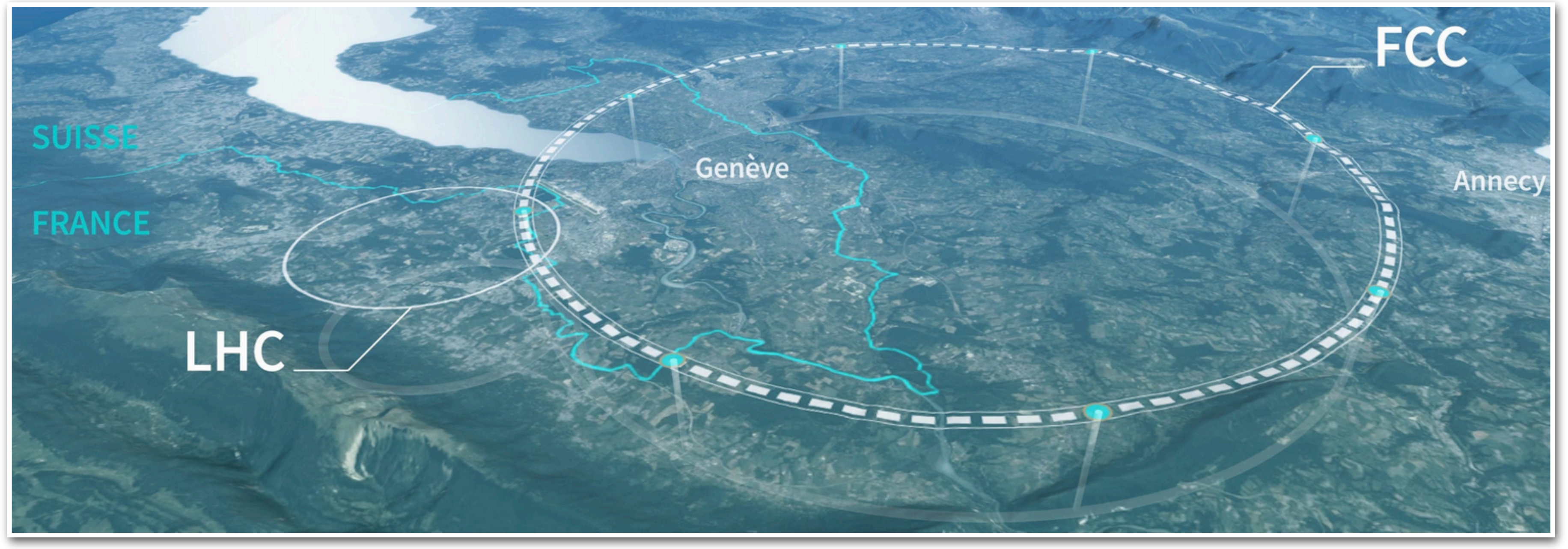
"An e^+e^- (Higgs) factory is the highest priority future collider" (Last EU Strategy)

FCC-ee

≈ 90 km circumference e^+e^-collider (start ~ 2045)

Mature and solid proposal
Lot of effort and studies into feasibility

Paves the way to ≈ 100 TeV FCC-hh collider



FSR 2025

Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^{8} WW	2.2×10^{6} ZH + 65k WW $\rightarrow$ H	2×10^{6} $t\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H	

$\approx 10^5$ *more than LEP!*

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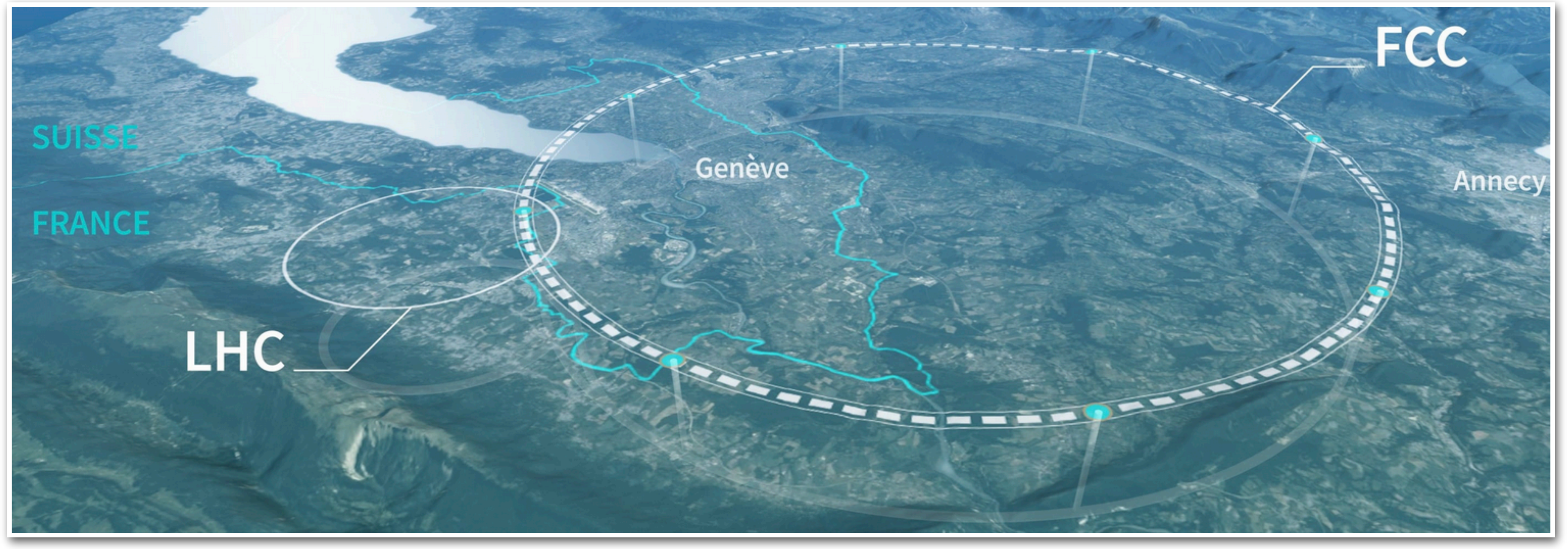

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BSM at Tera-Z

Tera-Z offers incredible *indirect* BSM opportunities

$$\frac{\delta O_Z}{O_Z} \sim 10^{-6} \qquad \text{(stat. limit)}$$

$$\frac{\delta O_Z}{O_Z} \sim \frac{g_*^2 v_{\mathrm{EW}}^2}{\Lambda^2} \implies \Lambda \sim O(100)\ \textbf{TeV} \quad \textbf{Tree-level}$$

$$(g_* = 1)$$

$$\frac{\delta O_Z}{O_Z} \sim \frac{g_*^2}{16\pi^2} \frac{g_*^2 v_{\mathrm{EW}}^2}{\Lambda^2} \implies \Lambda \sim O(10)\ \textbf{TeV} \quad \textbf{1-loop}$$

Observables: Z, W pole at FCC-ee

(Definitions in e.g. PDG EW)

FSR 2025, EW PPG 2025

Sources of uncertainty:

- real observables, experimental ("EXP")
- conversion exp.
  → EW pseudo-observables ("TH-PO")
- SM theory prediction ("TH")

We developed three benchmarks:

- **S1:** theory limited, conservative
- **S2:** theory limited, aggressive
- **S3:** exp. only

Greljo, Stefanek, Valenti (2025)

	Scenario S1	**Scenario S2**	**Scenario S3**
Observable	**TH PO+TH agg.+EXP** (10^{-5})	**TH agg.+EXP** (10^{-5})	**EXP Only** (10^{-5})
Γ_Z	1.55	0.820	0.510
σ_{had}	4.33	2.06	1.93
R_e	2.21	1.05	0.410
R_μ	2.20	1.02	0.330
R_τ	2.20	1.03	0.350
R_b	20.1	1.63	0.180
R_c	100	1.19	0.260
A_{FB}^e	126	25.7	25.2
A_{FB}^μ	125	21.1	20.6
A_{FB}^τ	126	23.3	22.8
A_{FB}^b	87.8	6.42	5.50
A_{FB}^c	89.1	10.2	9.62
A_{FB}^s	88.2	10.7	10.2
$\sin^2\theta_W$	6.87	0.780	0.730
A_e	87.9	9.78	9.20
A_μ	90.1	22.1	21.8
A_τ	90.5	23.4	23.2
A_b	11.7	10.5	10.5
A_c	16.9	9.00	8.99
A_s	14.2	13.2	13.2
M_W	0.490	0.320	0.300
Γ_W	16.1	16.1	16.1

Conservative ⟶ Aggressive

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Lot of work required to match exp. precision!

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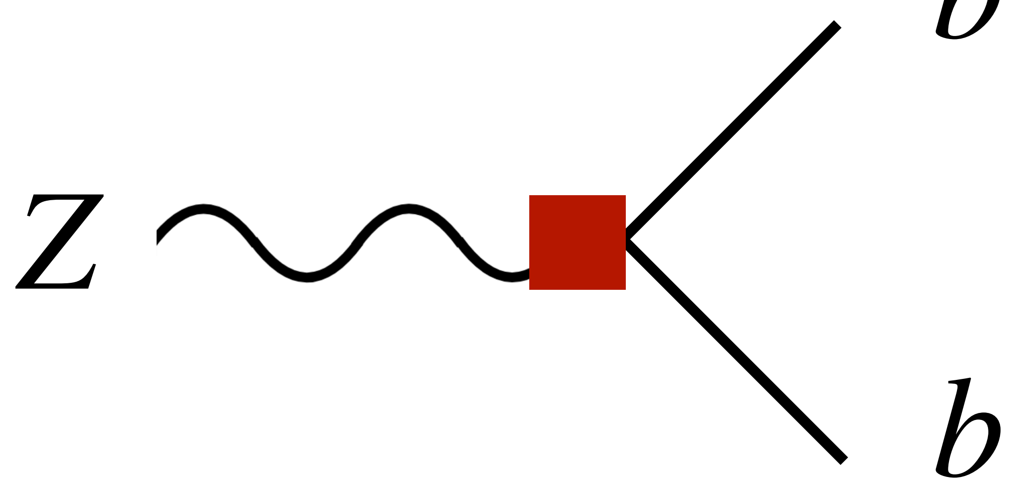
Observables: Z, W pole at FCC-ee

S1 to **S3** impact on BSM can vary significantly!

Examples

<u>Higgs-bottom current operators</u> (R_b)

$$\mathcal{L}_{\rm Warsaw} \supset [C_{Hd}]_{33}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_3\gamma^\mu d_3) + [C^{(1)}_{Hq}]_{33}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}_3\gamma^\mu q_3) + [C^{(3)}_{Hq}]_{33}(H^\dagger \overleftrightarrow{D}^I_\mu H)(\bar{q}_3\gamma^\mu \tau^I q_3)$$



$$\delta g^b_L = -\frac{v^2}{2}\left([C^{(1)}_{Hq}]_{33} + [C^{(3)}_{Hq}]_{33}\right), \quad \delta g^b_R = -\frac{v^2}{2}[C_{Hd}]_{33}$$

$$\frac{\Delta R_b}{R_b} = (1-R_b)\frac{2g_L\delta g_L + 2g_R\delta g_R}{g_L^2 + g_R^2}$$

⇒

	S1*	**S3**
$\Lambda_{Hd,33}$	7 (18) TeV	74 TeV
$\Lambda_{Hq(1,3),33}$	16 (40) TeV	173 TeV

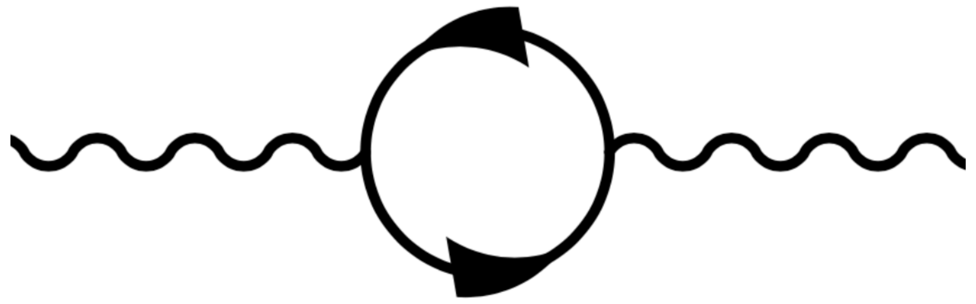
*leading bound in bracket from Γ_Z

Observables: Z, W pole at FCC-ee

S1 to **S3** impact on BSM can vary significantly!

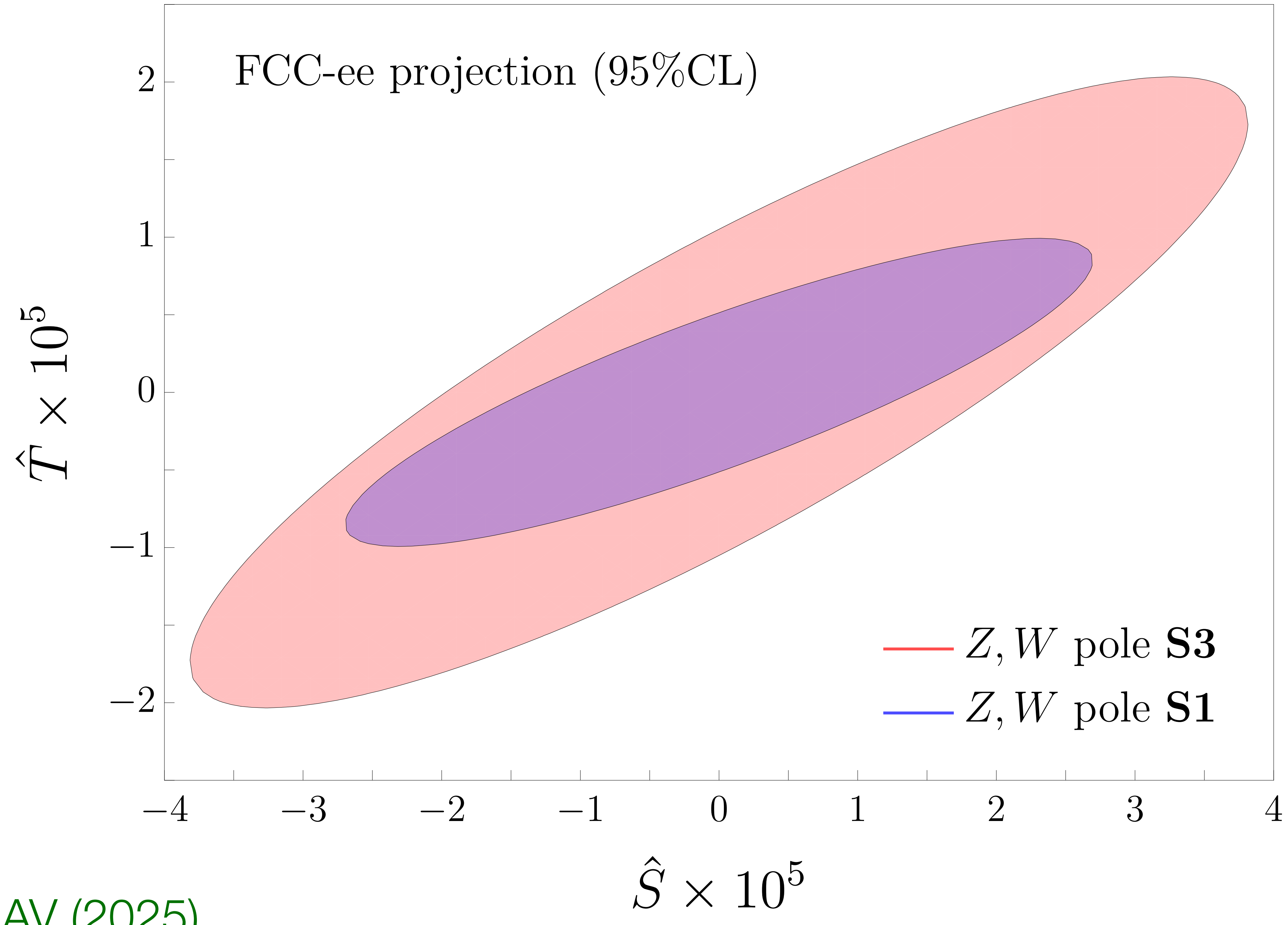
Examples

<u>S, T parameters</u>



$$\Pi_{VV}(p^2) \sim \hat{T} + p^2\hat{S} + p^4\hat{W}, \hat{Y} + \ldots$$

$$\mathcal{L}_{\rm SILH} \supset \frac{\hat{T}}{2v^2}(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger \overleftrightarrow{D}^\mu H) + \frac{\hat{S}}{4m_W^2}\left(ig'(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu} + ig(H^\dagger \overleftrightarrow{D}^I_\mu H)\partial_\nu W^{I\,\mu\nu}\right)$$



S1: $S, T = \{2.42, 1.29\} \times 10^{-5}$, $\rho = 0.856$

S3: $S, T = \{1.71, 0.63\} \times 10^{-5}$, $\rho = 0.885$

Greljo, Stefanek, AV (2025)

Observables: Z, W pole at FCC-ee

More systematically: $U(2)^5$ **SMEFT**

Credit: Ben A. Stefanek

H^6 and H^4D^2	
Q_H	$(H^\dagger H)^3$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\lvert H^\dagger D_\mu H\rvert^2$

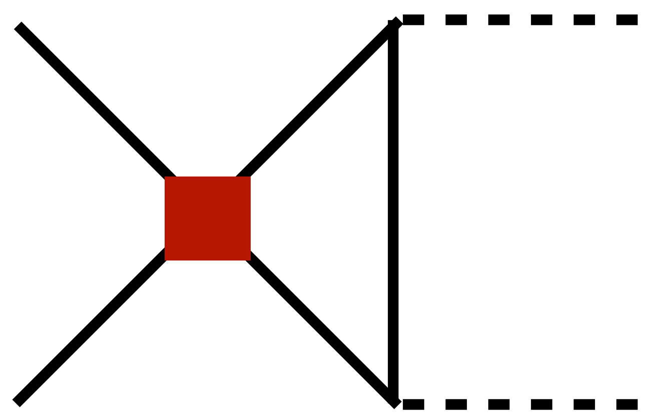
ψ^2H^2D		X^2H^2 and X^3	
$Q_{H\ell}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar\ell\gamma^\mu\ell)_{pp}$	Q_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$
$Q_{H\ell}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar\ell\tau^I\gamma^\mu\ell)_{pp}$	Q_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e\gamma^\mu e)_{pp}$	Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q\gamma^\mu q)_{pp}$	Q_{HWB}	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q\tau^I\gamma^\mu q)_{pp}$	Q_G	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u\gamma^\mu u)_{pp}$	Q_W	$\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d\gamma^\mu d)_{pp}$		

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
$Q_{\ell\ell}$	$(\bar\ell\gamma_\mu\ell)(\bar\ell\gamma^\mu\ell)_{\substack{pprr\\prrp}}$	Q_{ee}	$(\bar e\gamma_\mu e)(\bar e\gamma^\mu e)_{pprr}$	$Q_{\ell e}$	$(\bar\ell\gamma_\mu\ell)(\bar e\gamma^\mu e)_{pprr}$
$Q_{qq}^{(1)}$	$(\bar q\gamma_\mu q)(\bar q\gamma^\mu q)_{\substack{pprr\\prrp}}$	Q_{uu}	$(\bar u\gamma_\mu u)(\bar u\gamma^\mu u)_{\substack{pprr\\prrp}}$	$Q_{\ell u}$	$(\bar\ell\gamma_\mu\ell)(\bar u\gamma^\mu u)_{pprr}$
$Q_{qq}^{(3)}$	$(\bar q\gamma_\mu\tau^I q)(\bar q\gamma^\mu\tau^I q)_{\substack{pprr\\prrp}}$	Q_{dd}	$(\bar d\gamma_\mu d)(\bar d\gamma^\mu d)_{\substack{pprr\\prrp}}$	$Q_{\ell d}$	$(\bar\ell\gamma_\mu\ell)(\bar d\gamma^\mu d)_{pprr}$
$Q_{\ell q}^{(1)}$	$(\bar\ell\gamma_\mu\ell)(\bar q\gamma^\mu q)_{pprr}$	Q_{eu}	$(\bar e\gamma_\mu e)(\bar u\gamma^\mu u)_{pprr}$	Q_{qe}	$(\bar q\gamma_\mu q)(\bar e\gamma^\mu e)_{pprr}$
$Q_{\ell q}^{(3)}$	$(\bar\ell\gamma_\mu\tau^I\ell)(\bar q\gamma^\mu\tau^I q)_{pprr}$	Q_{ed}	$(\bar e\gamma_\mu e)(\bar d\gamma^\mu d)_{pprr}$	$Q_{qu}^{(1)}$	$(\bar q\gamma_\mu q)(\bar u\gamma^\mu u)_{pprr}$
		$Q_{ud}^{(1)}$	$(\bar u\gamma_\mu u)(\bar d\gamma^\mu d)_{pprr}$	$Q_{qu}^{(8)}$	$(\bar q\gamma_\mu T^A q)(\bar u\gamma^\mu T^A u)_{pprr}$
		$Q_{ud}^{(8)}$	$(\bar u\gamma_\mu T^A u)(\bar d\gamma^\mu T^A d)_{pprr}$	$Q_{qd}^{(1)}$	$(\bar q\gamma_\mu q)(\bar d\gamma^\mu d)_{pprr}$
				$Q_{qd}^{(8)}$	$(\bar q\gamma_\mu T^A q)(\bar d\gamma^\mu T^A d)_{pprr}$

Minimum order (Except $4t$)

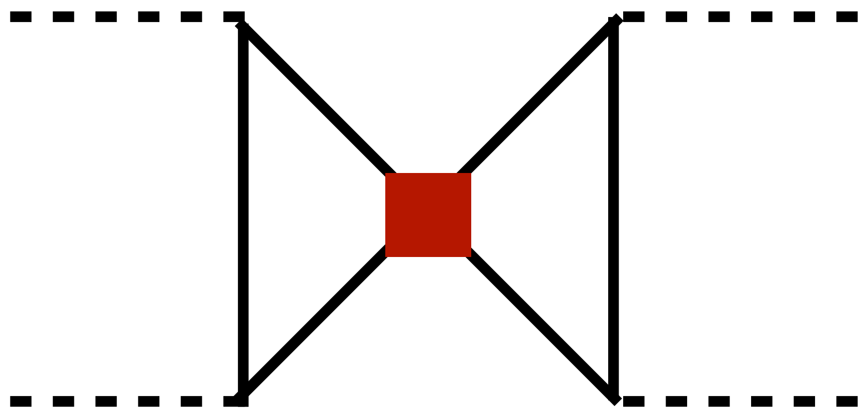
- TL
- 1-loop
- 2-loops

e.g.



$\propto O_{Hf}$

$(Z \to f\bar f)$



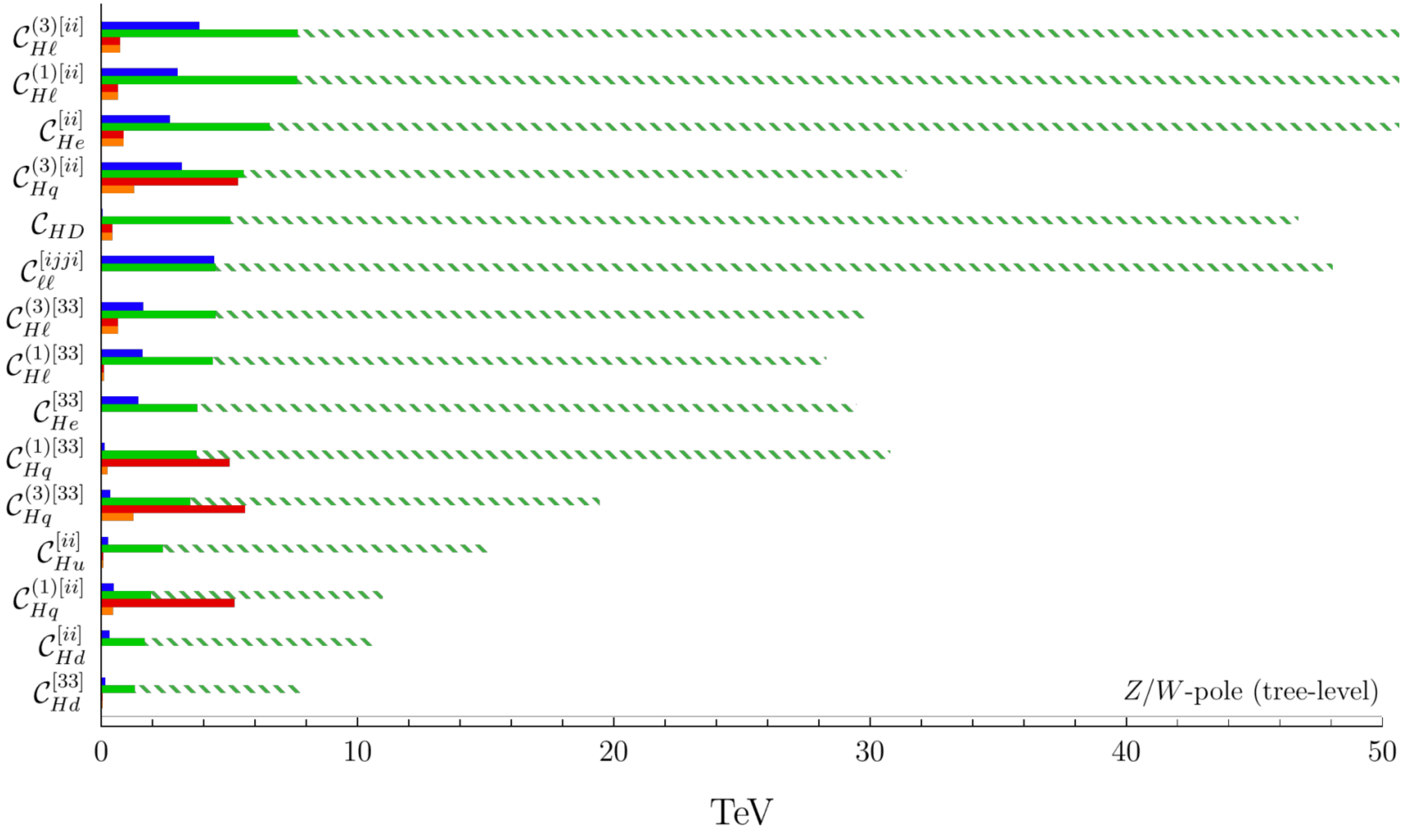
$\propto O_{HD}$

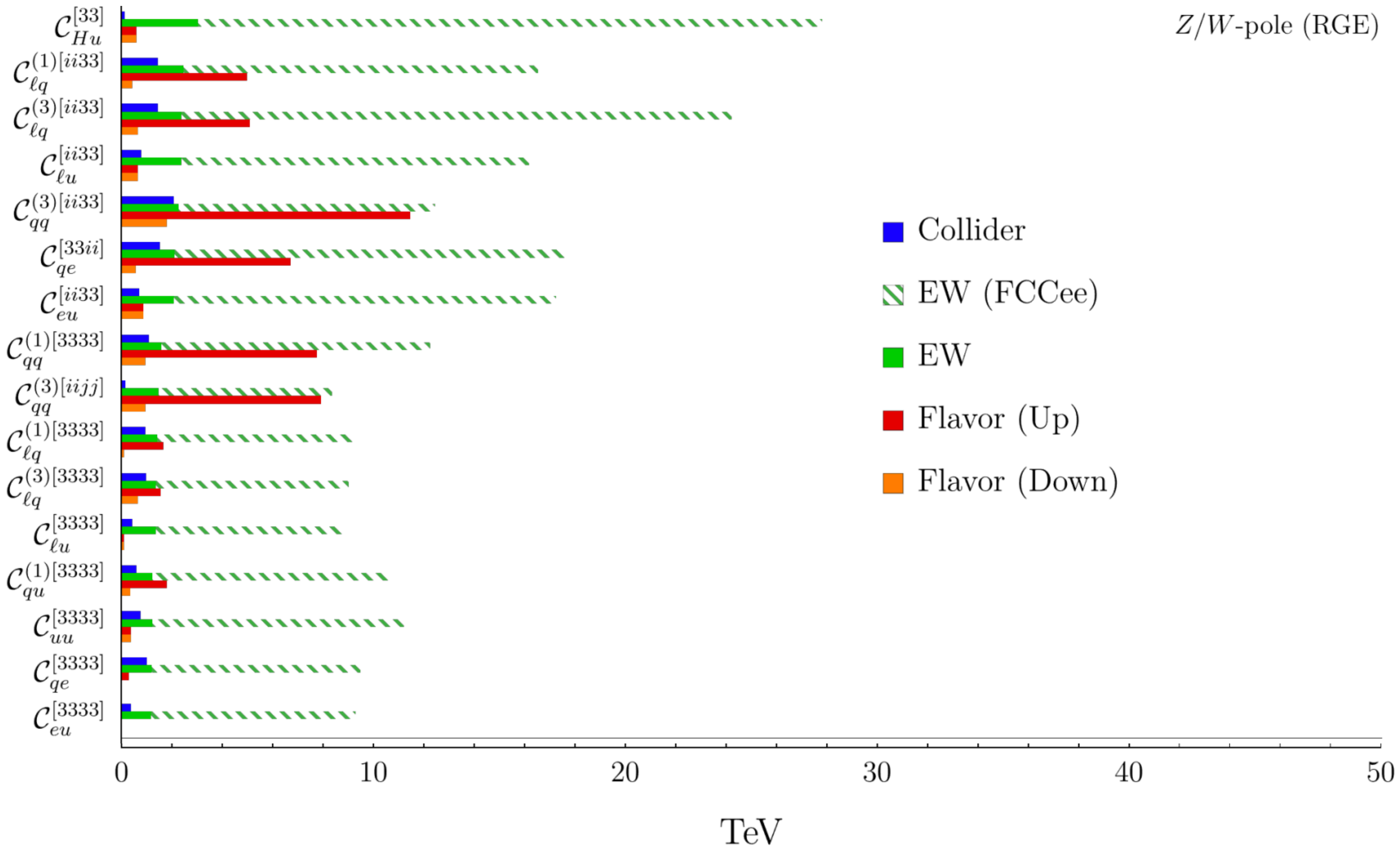
(δm_W)

Observables: Z, W pole at FCC-ee

More systematically: $U(2)^5$ **SMEFT**

Allwicher, Cornella, Isidori, Stefanek (2023)





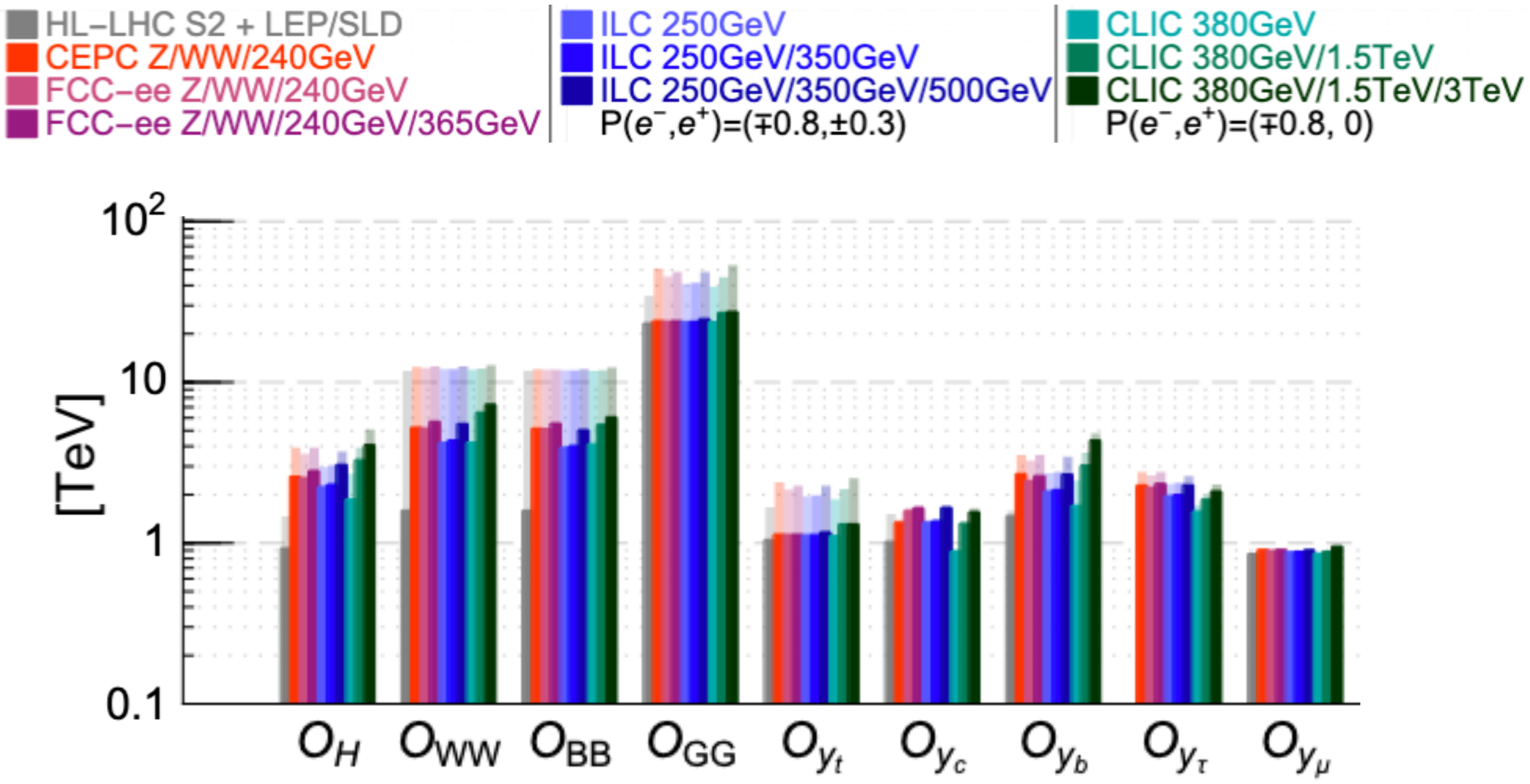
Note: observables from FCC-ee FSR 2019 ~ **S1,** conservative

Observables: Higgs couplings

FSR 2025

Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.38 / 0.49
κ_g (%)	2*	0.49 / 0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	–	0.70 / 0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$
Γ_H (%)	–	0.78
$\mathcal{B}_{\rm inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}
$\mathcal{B}_{\rm unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}

Sources of uncertainty mainly experimental, not theory limited



de Blas, Durieux, Grojean, Gu, Paul (2019)

Fermion pair production above the Z pole

Opportunity to probe new **4F** operators at ***tree-level***

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

- Theory uncertainty: $\Delta R_b^{ff}/R_b^{ff}|_{\text{theory}} < 10^{-4}$ @FCC (same as Z pole)
- Experimental stat: $O(10^{-4})$ $(WW : N_{\bar{b}b} \simeq 6 \times 10^7)$
- Experimental systematics?

No dedicated study yet → No problem! We assessed it   Greljo, Tiblom, Valenti (2024)

Fermion pair production above the Z pole

Mean number of events per bin ($ij \equiv q_i\, q_j$) ⟵

$$N_{ij} = N_{\text{tot}} \sum_z \frac{2}{1+\delta_{ij}} R_z^{ff} \epsilon_z^i \epsilon_z^j$$

N_{tot}: total untagged events

R_z^{ff}: Hadronic ratios

Taggers

ϵ_i^j = prob. tagging flavour i as j

$i = j \Rightarrow$ True Positive rate

$i \neq j \Rightarrow$ False Positive (mistag)

$$-2\log L = \sum_{ij} \frac{\left(N_{ij} - N_{ij}^{\text{exp}}\right)^2}{N_{ij}^{\text{exp}}} + \sum_{i \neq j} \frac{x_{ij}^2}{\delta_\epsilon^2}$$

- Systematic uncertainty on taggers: $\epsilon_i^j \to \epsilon_i^j(1+x_i^j)$, δ_ϵ from MC/exp. det (identical for simplicity)
- Fit parameters: $R_z^{ff} + N_{\text{tot}}, \epsilon_i^i$ → avoid unnecessary uncertainties (e.g. precise luminosity knowledge)
- Other relevant background: collimated jets ($e^+e^- \to VV \to 4f$). Ok if known at percent level (MC)

Results

FCC-ee taggers from Blekman et al. (2024) , $\delta_\epsilon = 1\,\%$

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

stat ← ($R_{\tau,\mu}^{ff}$)

syst (theory) ← (R_e^{ff})

→ Fit $R_b^{ff}, R_s^{ff}, R_c^{ff}$ *simultaneously*

Small correlations: e.g. WW

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

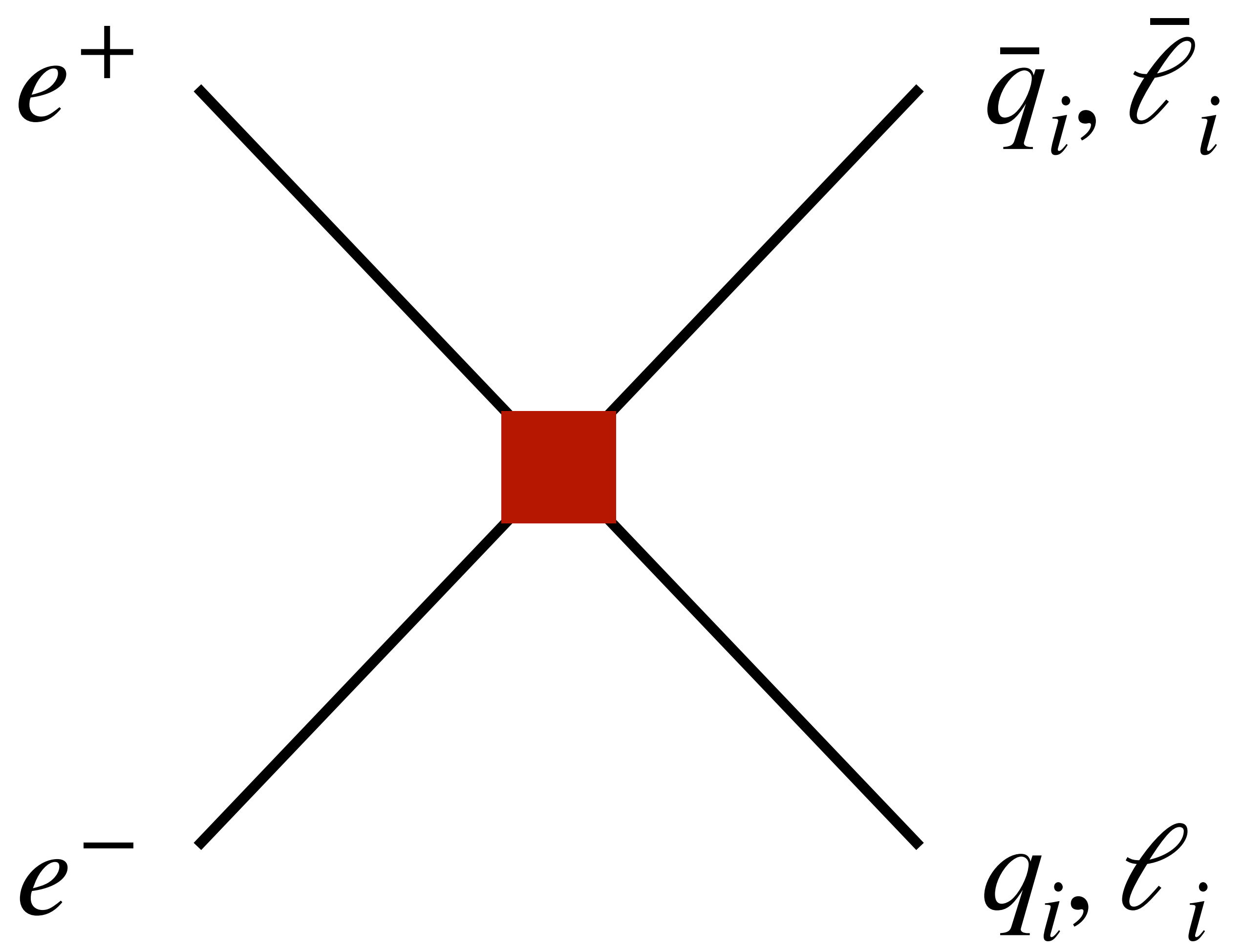
$O(10^2)$ improvement compared to LEP-II

Room for further improvement: s-tagging

2. Observables and BSM from EFT viewpoint

BSM impact: ***flavour conserving, non-universal* 4F** interactions (SMEFT)

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



$$
2q2\ell \left\{ \begin{array}{c|c}
\mathcal{O}_{\ell q}^{(1)} & (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{q}_s \gamma^\mu q_t) \\
\mathcal{O}_{\ell q}^{(3)} & (\bar{\ell}_p \gamma_\mu \tau^I \ell_r)(\bar{q}_s \gamma^\mu \tau_I q_t) \\
\mathcal{O}_{eu} & (\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t) \\
\mathcal{O}_{ed} & (\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t) \\
\mathcal{O}_{\ell u} & (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{u}_s \gamma^\mu u_t) \\
\mathcal{O}_{\ell d} & (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{d}_s \gamma^\mu d_t) \\
\mathcal{O}_{qe} & (\bar{e}_p \gamma_\mu e_r)(\bar{q}_s \gamma^\mu q_t) \\
\mathcal{O}_{\ell edq} & (\bar{\ell}_p^j e_r)(\bar{d}_s q_t^j) \\
\mathcal{O}_{\ell equ}^{(1)} & (\bar{\ell}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t) \\
\mathcal{O}_{\ell equ}^{(3)} & (\bar{\ell}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)
\end{array} \right.
$$

$$
4\ell \left\{ \begin{array}{c|c}
\mathcal{O}_{\ell\ell} & (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{\ell}_s \gamma^\mu \ell_t) \\
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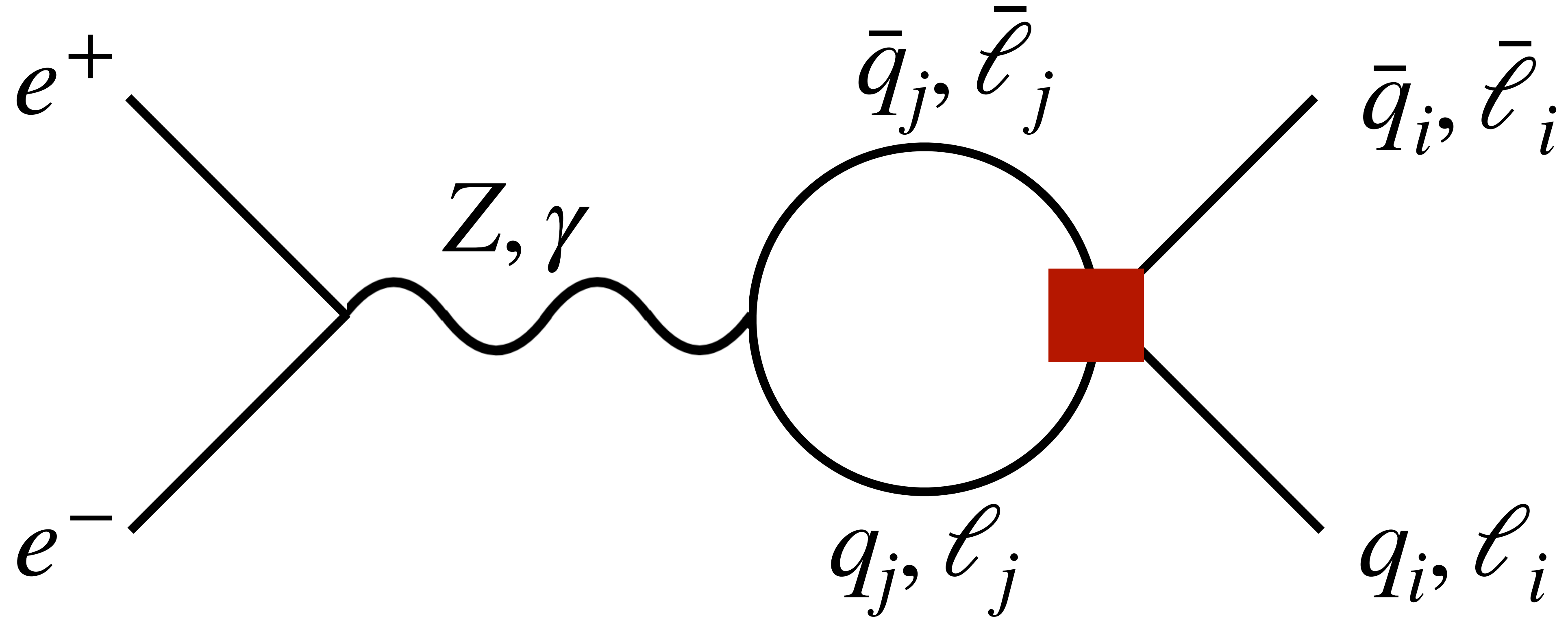
- Tree-level: $2q2\ell + 4\ell$ operators involving e^+e^- $(prst = 11ii)$
- 1-loop: $2q2\ell + 4\ell + 4q$, all indices $prst = iijj$ (gauge running)



$4q$

$4q$	$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
	$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\tau^I\gamma_\mu q_r)(\bar{q}_s\tau_I\gamma^\mu q_t)$
	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
	$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$

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

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- 1-loop: $2q2\ell + 4\ell + 4q$, all indices $prst = iijj$ (gauge running)
- Likelihood including the 3 runs, one operator at a time

$\rightarrow \Delta R_a^{ff}/(R_a^{ff})^{\rm SM} \sim s/\Lambda^2$: growth compensates precision deterioration!

e.g. $\Lambda_{qe,3311} = \{17.8, 17.4, 16.6\}$ TeV

$WW \quad ZH \quad t\bar{t}$

	Operator	Definition
$2q2\ell$	$\mathcal{O}_{\ell q}^{(1)}$	$(\bar{\ell}_p\gamma_\mu\ell_r)(\bar{q}_s\gamma^\mu q_t)$
	$\mathcal{O}_{\ell q}^{(3)}$	$(\bar{\ell}_p\gamma_\mu\tau^I\ell_r)(\bar{q}_s\gamma^\mu\tau_I q_t)$
	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
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	$\mathcal{O}_{qe}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{q}_s\gamma^\mu q_t)$
	$\mathcal{O}_{\ell edq}$	$(\bar{\ell}_p^j e_r)(\bar{d}_s q_t^j)$
	$\mathcal{O}_{\ell equ}^{(1)}$	$(\bar{\ell}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
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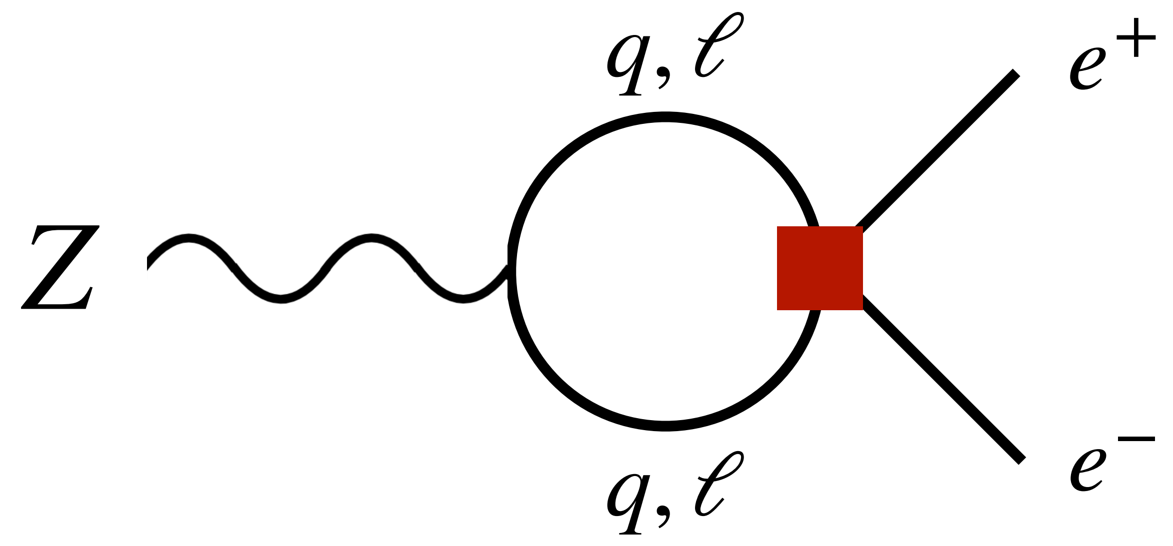
2. Observables and BSM from EFT viewpoint

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

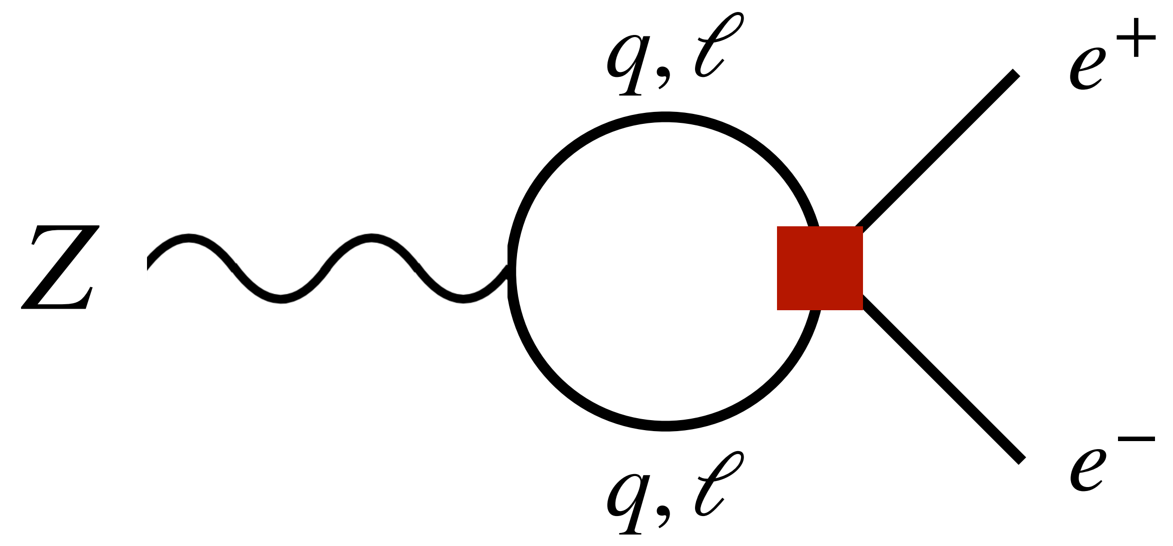


(y_t^2 for top, gauge others)

Note: Z, W pole from FSR 2019 ~ **S1**

2. Observables and BSM from EFT viewpoint

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

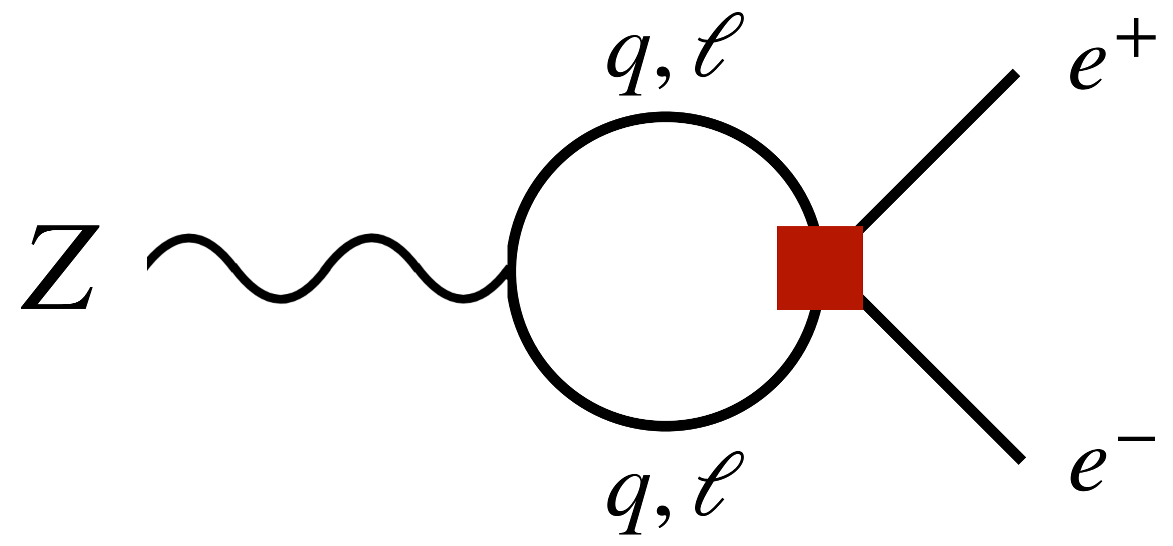


(y_t^2 for top, gauge others)

Note: Z, W pole from FSR 2019 ~ **S1**

2. Observables and BSM from EFT viewpoint

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



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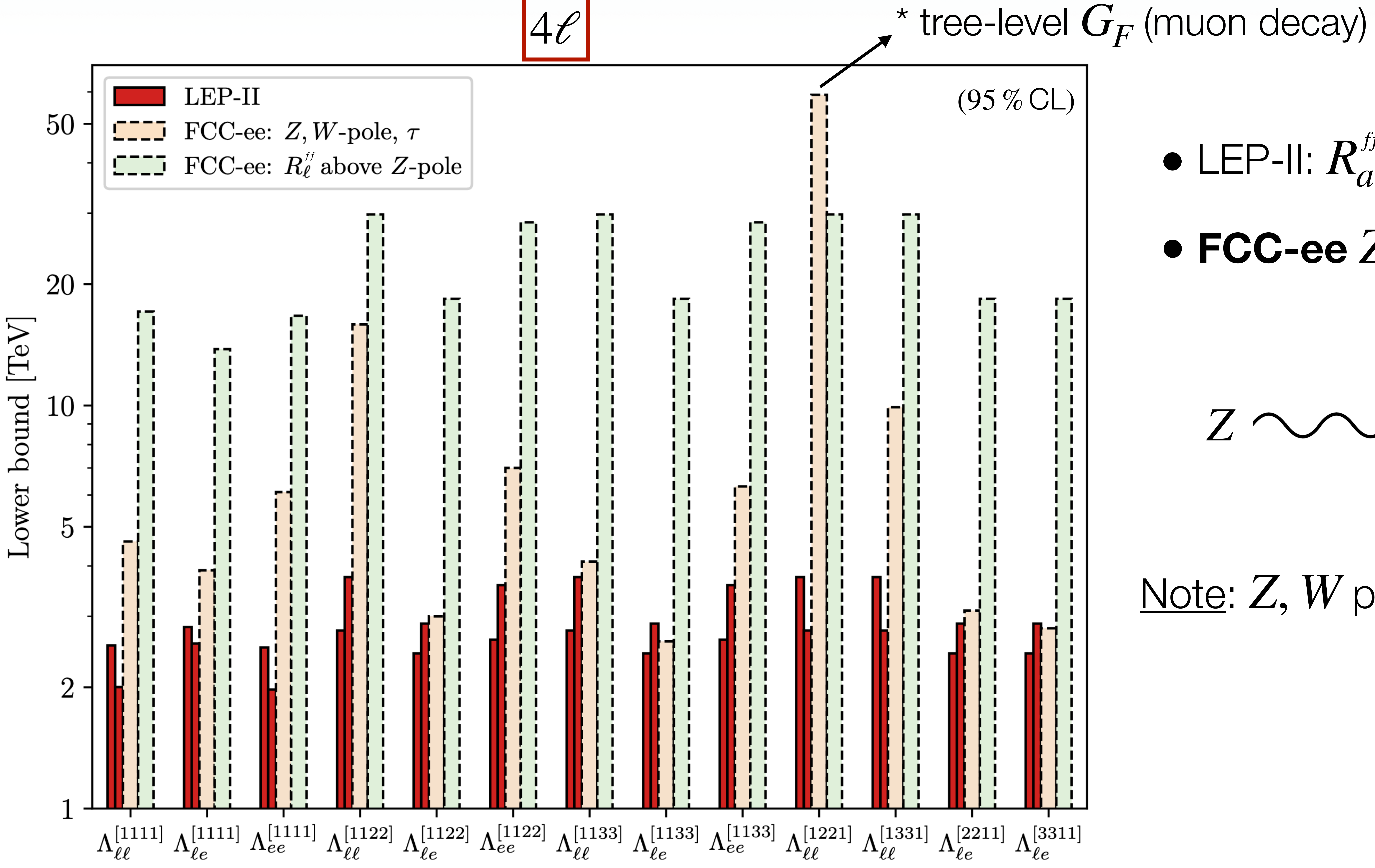
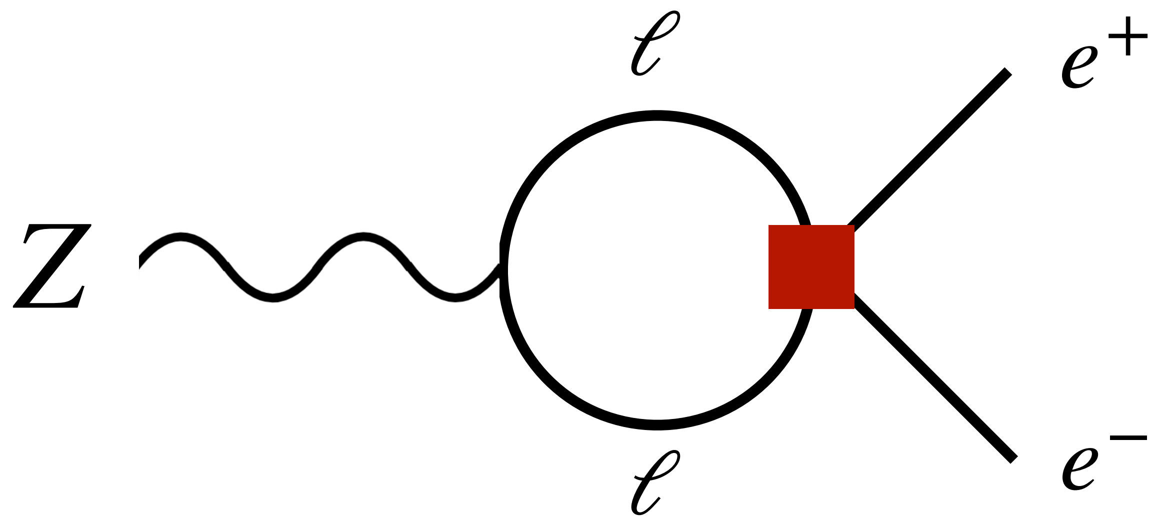
2. Observables and BSM from EFT viewpoint

4ℓ



- LEP-II: R_a^{ff} ratios
- **FCC-ee Z-pole: 1-loop RGE***



Note: Z, W pole from FSR 2019 ~ **S1**

Oblique corrections

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

EoM:

flavour conserving, non-universal 4F

(TL in fermion pair-prod.)

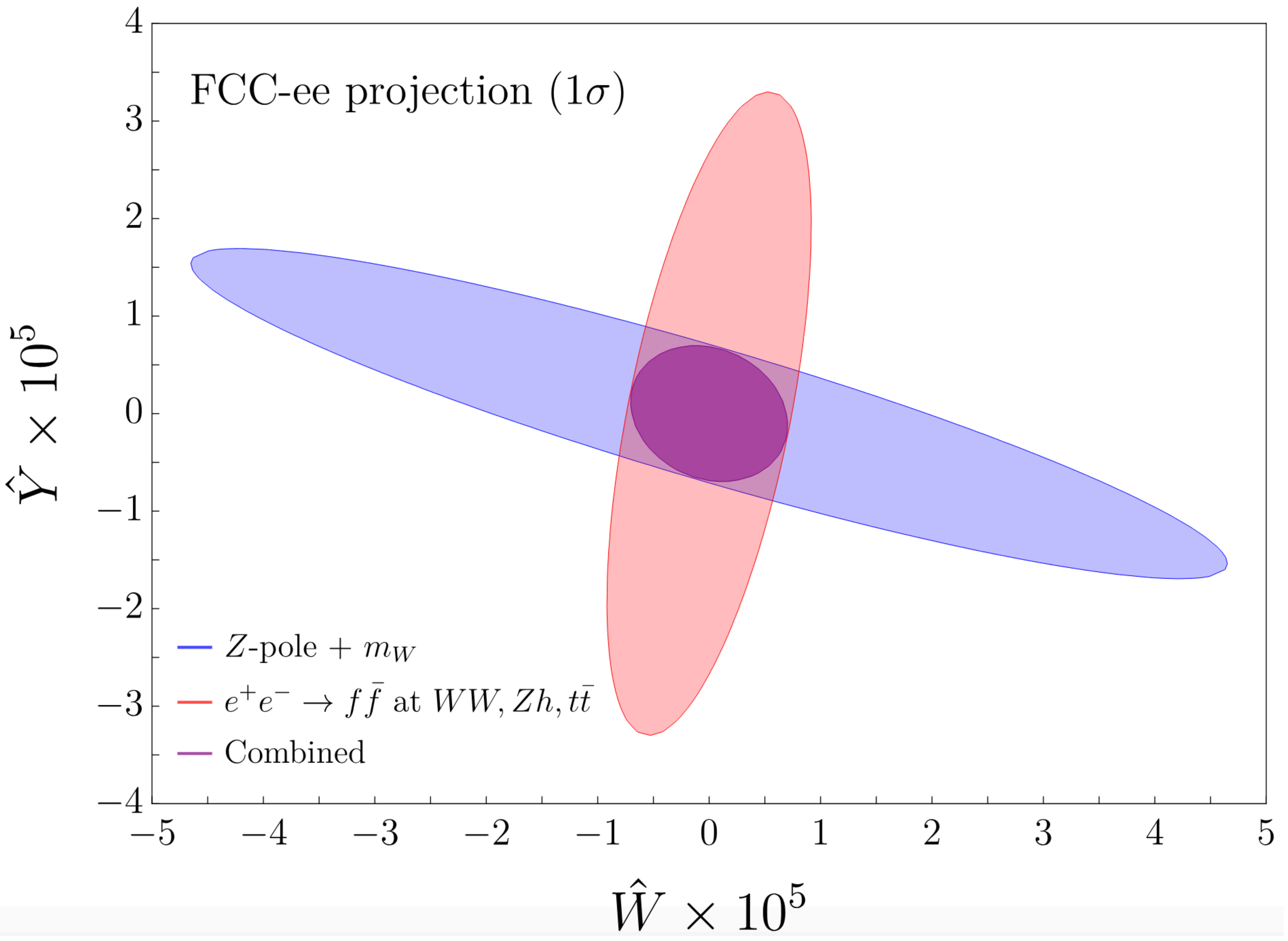
+

Higgs-fermion current operators

(TL at Z-pole)

	$\hat{W}\times 10^5$	$\hat{Y}\times 10^5$
Current (LHC)	$[-19, 5]$	$[-31, 14]$
HL-LHC	$[-4.5, 6.9]$	$[-6.4, 8.0]$
FCC-ee pole observables	$[-3.1, 3.1]$	$[-1.1, 1.1]$
FCC-ee above the pole	$[-0.60, 0.60]$	$[-2.2, 2.2]$

Note: Z, W pole from FSR 2019 $\sim$ **S1**

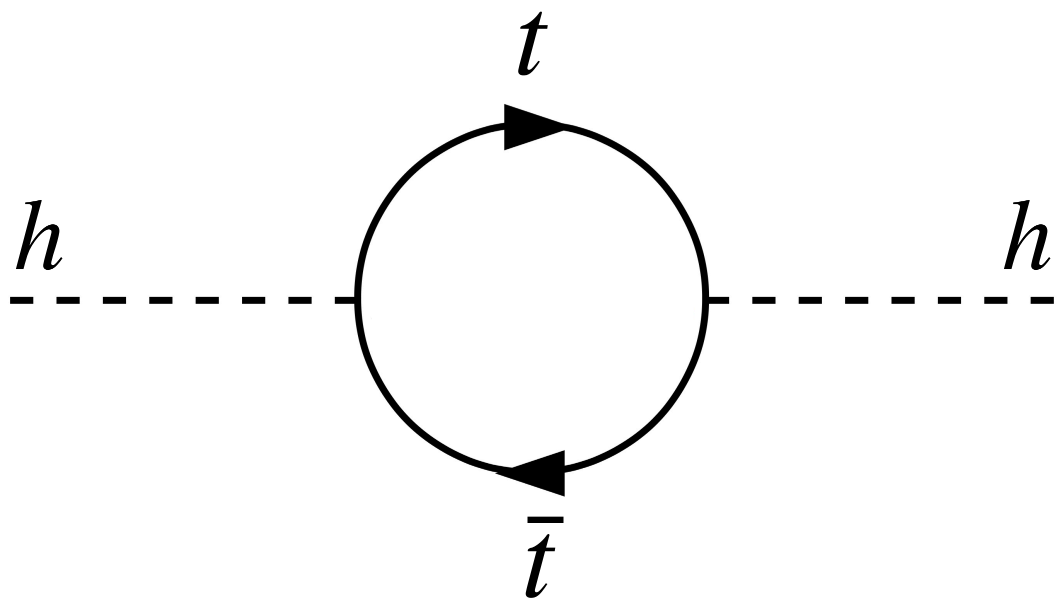


Beyond SMEFT: naturalness

Recall Tera-Z allows in-depth exploration of the TeV scale at *loop-level*

LEP+ LHC

Naturalness is ***the*** motivation for expecting loop-level NP at (~~sub~~-)TeV



$$\delta m_h^2 = \frac{3y_t^2}{4\pi^2}\Lambda_{\rm NP}^2 \qquad \Lambda_{\rm NP} \gtrsim \text{TeV's} \Longleftrightarrow \left(\frac{\delta m_h^2}{m_h^2}\right)^{-1} \lesssim 1\,\%$$

Naturalness models are key benchmarks for FCC-ee!

Natural SUSY

Natural SUSY remains one of the most motivated naturalness frameworks. Our focus.

(For CHM see Rattazzi et al (2024), Stefanek (2024))

1. Pick concrete natural SUSY scenario:

   → **R-parity conserving MSSM with MFV** See e.g. Martin (1997)

   Well-known, simple, allows focusing on Z and Higgs factory physics

2. Employ realistic set of observables:

   → **FCC-ee: Scenarios S1 to S3**

3. Identify and study key sectors efficiently probed at these facilities:

   → **Heavy Higgs doublet, Stops, Higgsino & Gauginos**

3. Impact on selected benchmark scenarios

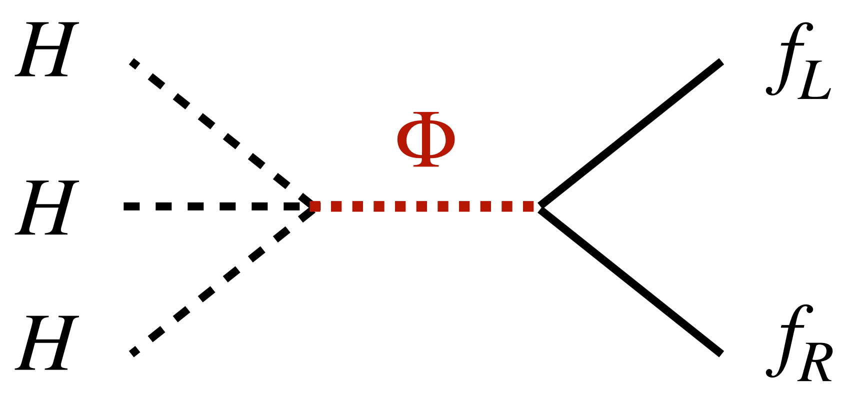
Heavy Higgs doublet

Constrained Type-II 2HDM. Only field coupling linearly to SM: **TL + 1-loop effects**

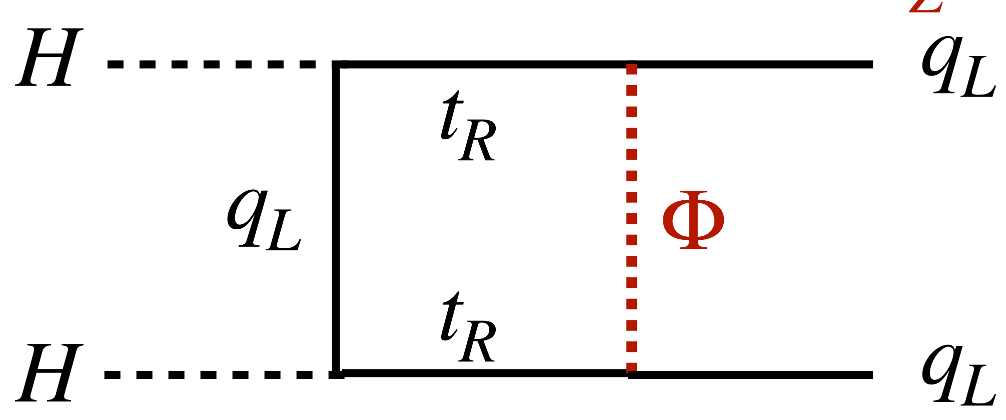
$$\mathcal{L}_\Phi \supset -\bar{q}_L \widetilde{\Phi}(\cot\beta\, Y_u^{\rm SM})u_R + \bar{q}_L \Phi(\tan\beta\, Y_d^{\rm SM})d_R + \bar{\ell}_L \Phi(\tan\beta\, Y_e^{\rm SM})e_R - \frac{g_Z^2}{8}\sin 4\beta |H|^2 \Phi^\dagger H + \text{h.c.}$$

Decoupling limit: $m_A \gg m_Z$, match to dim-6 SMEFT

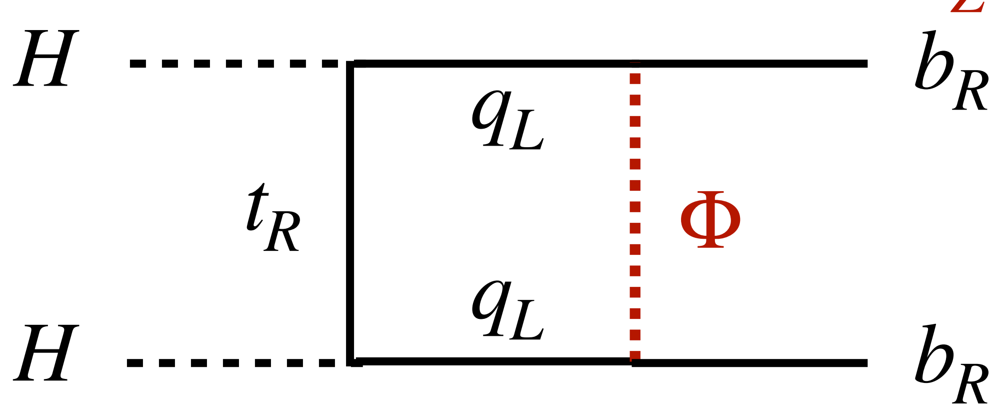
$$C_{fH} \propto g_Z^2 Y_f^{\rm SM} \sin 4\beta \tan\beta$$



$$[C_{Hq}^{(1)}]_{33} \propto \frac{y_t^4}{32\pi^2}\cot^2\beta \log\frac{m_\Phi^2}{m_Z^2}$$



$$[C_{Hd}]_{33} \propto \frac{y_t^2 y_b^2}{32\pi^2}\tan^2\beta \log\frac{m_\Phi^2}{m_Z^2}$$



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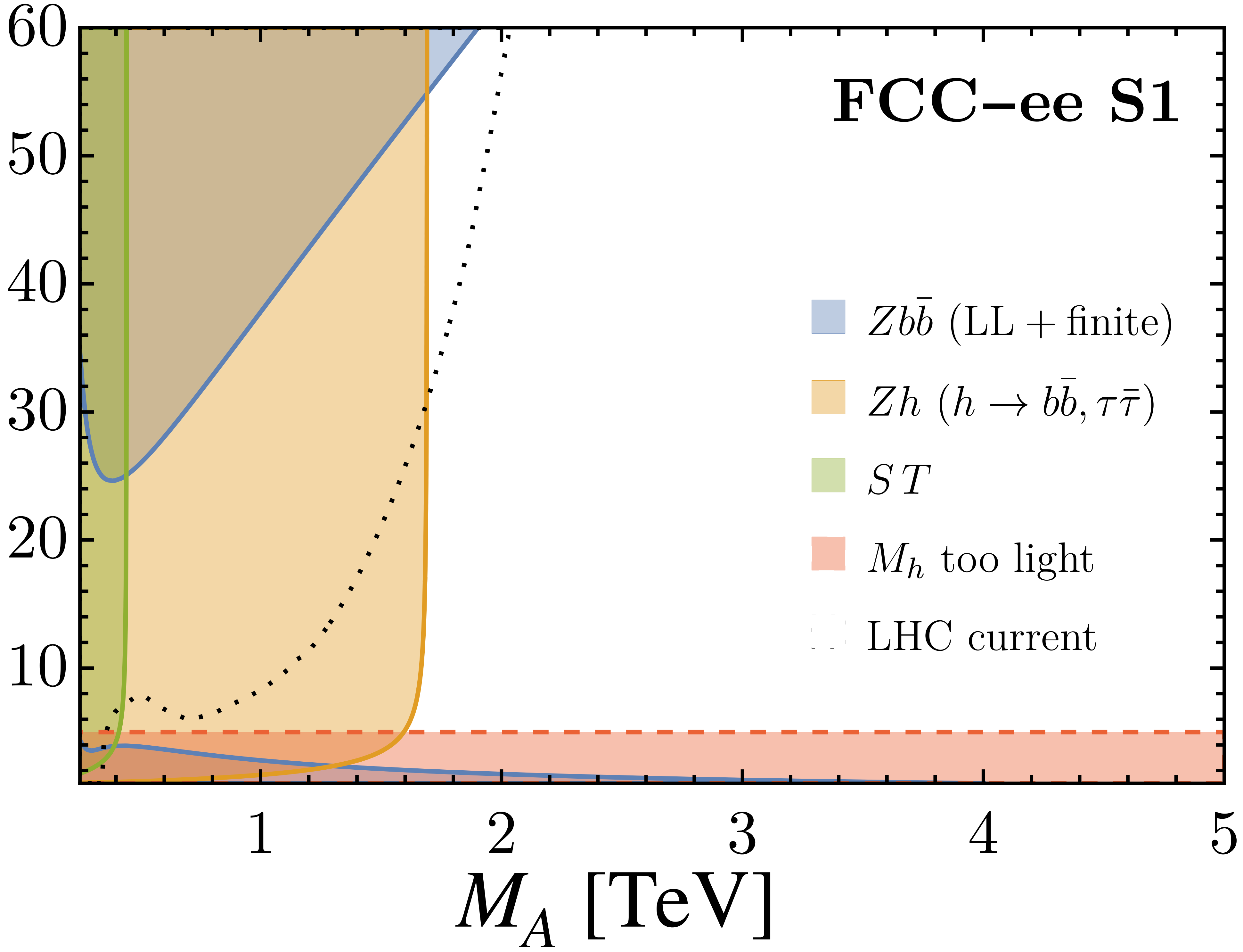
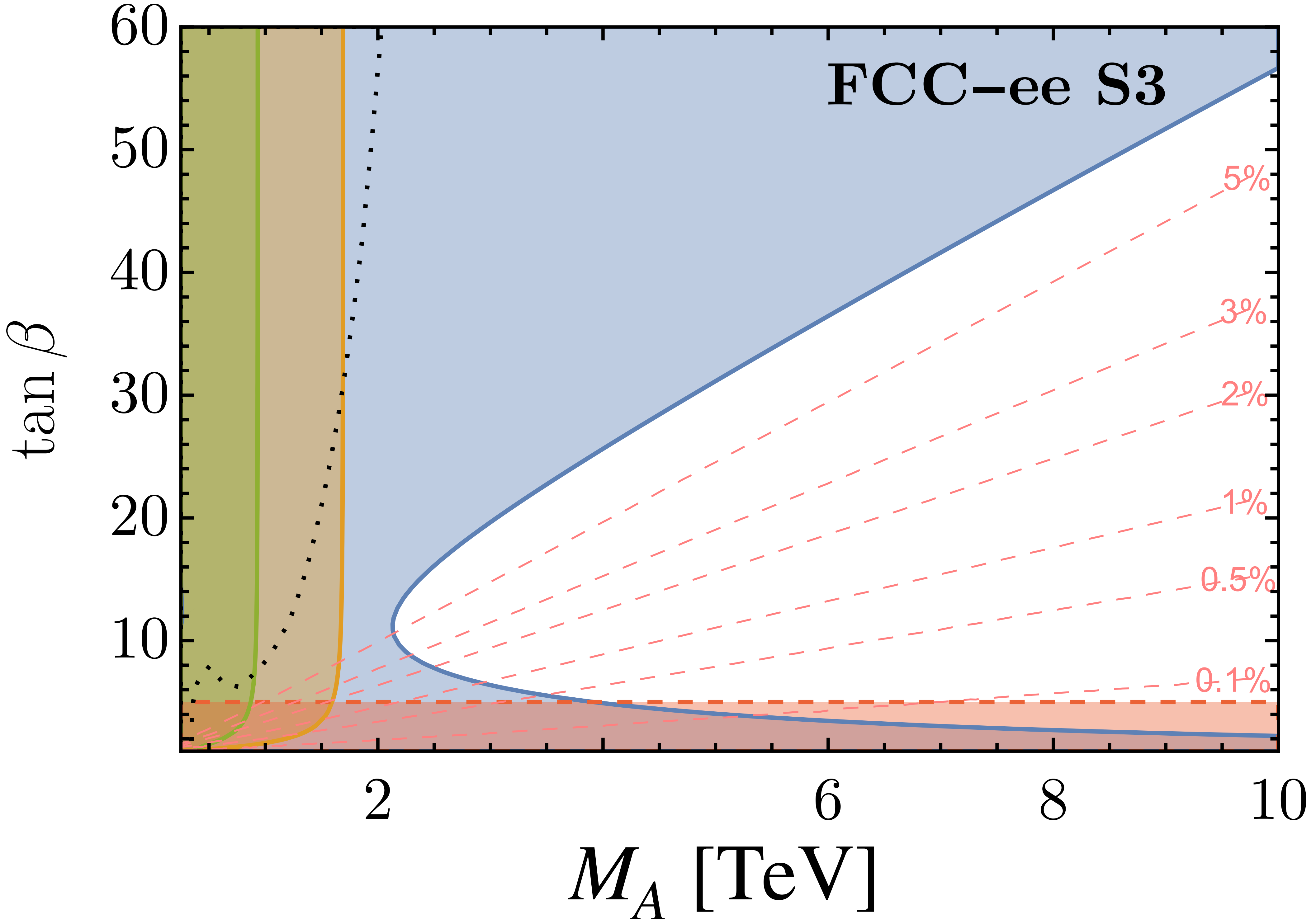
$C_{fH} \propto g_Z^2 Y_f^{\rm SM} \sin 4\beta \tan\beta$ $\quad [C_{Hq}^{(1)}]_{33} \propto \frac{y_t^4}{32\pi^2}\cot^2\beta \log\frac{m_\Phi^2}{m_Z^2}$ $\quad [C_{Hd}]_{33} \propto \frac{y_t^2 y_b^2}{32\pi^2}\tan^2\beta \log\frac{m_\Phi^2}{m_Z^2}$

($1 \lesssim \tan\beta \lesssim 60$ from perturbativity)





3. Impact on selected benchmark scenarios

Stops

(MSSM TL: $m_h \leq m_Z$)

Crucial to accomodate $m_h \simeq 125$ GeV: need $m_{\tilde{t}_{1,2}} \gtrsim 1$ TeV and $X_t \simeq X_t^{\max}$

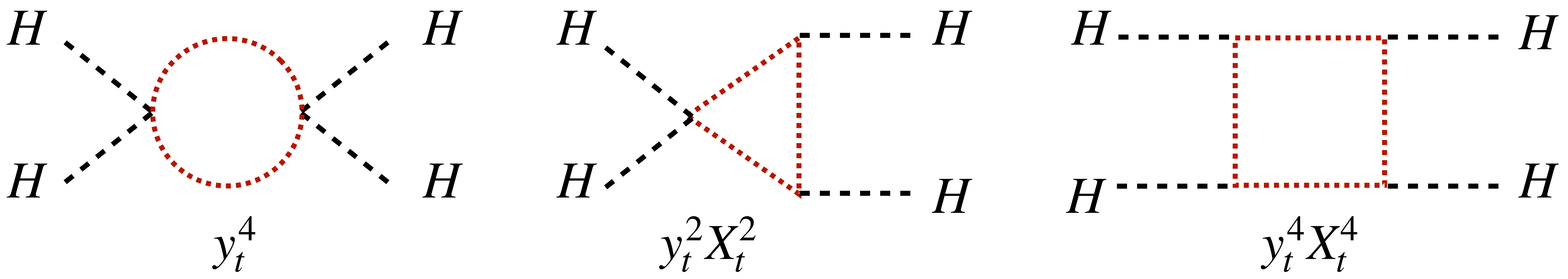
See e.g.
Carena, Haber (2002)

Primary source of fine-tuning within MSSM (little hierarchy)

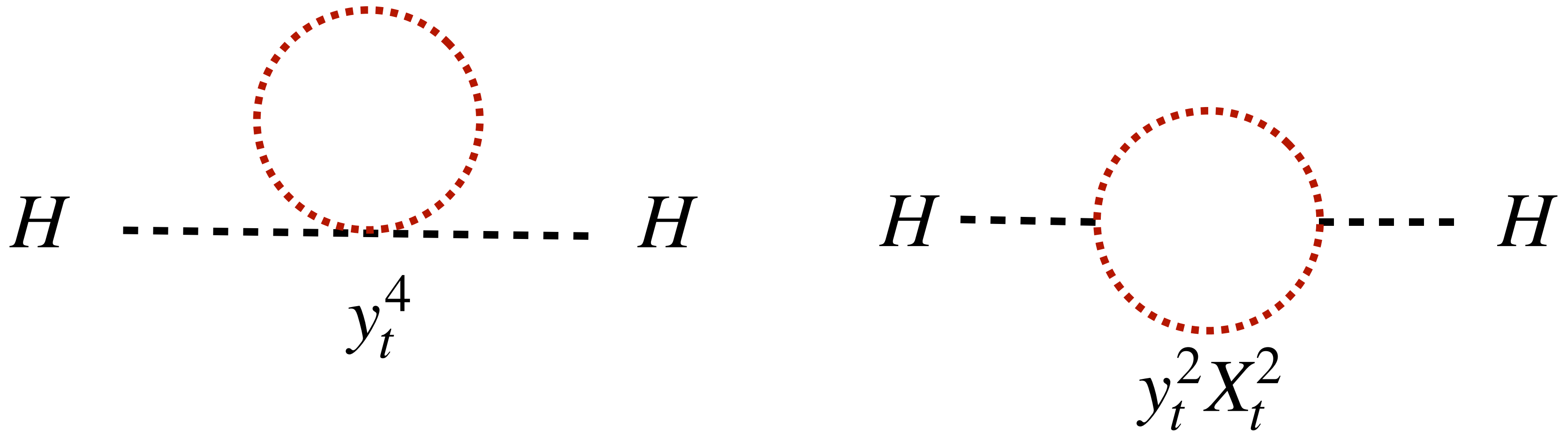
$$\mathcal{L}_{\rm stop} \supset \boldsymbol{y_u} X_u\, \tilde{u}_R^\dagger H_u \tilde{q}_L - \boldsymbol{y_u}\boldsymbol{y_u}^\dagger (H_u\tilde{q}_L)^\dagger (H_u \tilde{q}_L)$$

$$X_t^{\max} = \sqrt{6 m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

$\delta\lambda_H \propto$



$\delta v_{\rm EW}^2 \propto$



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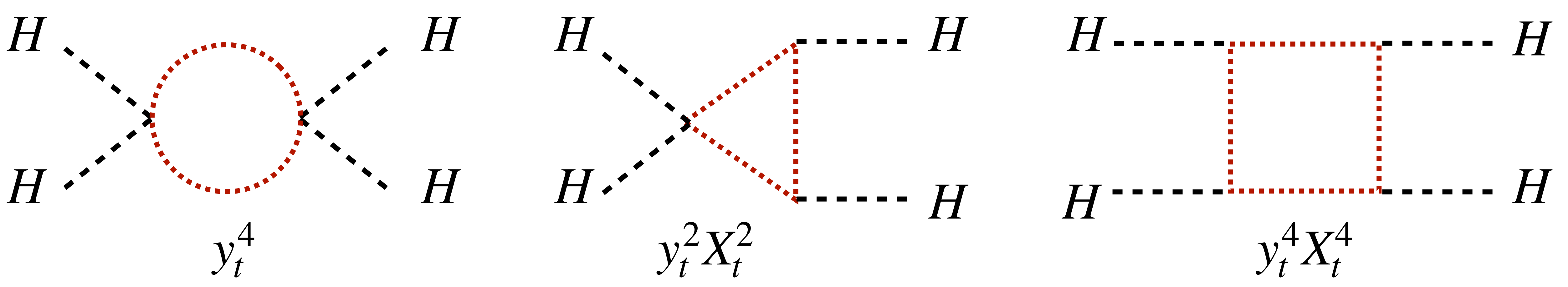
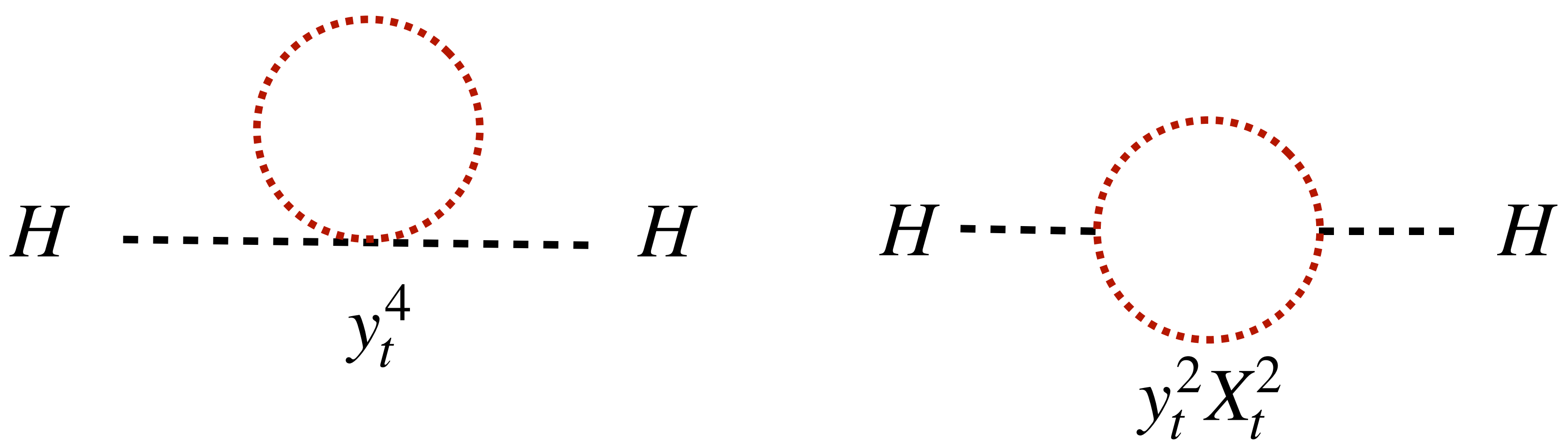
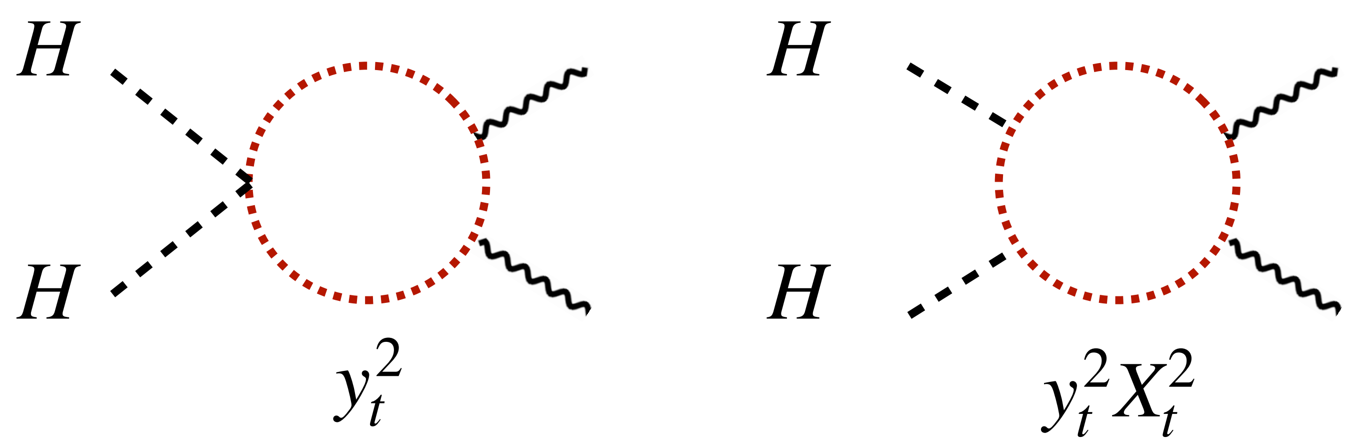


$\Longrightarrow \hat{T}!$ (C_{HD})

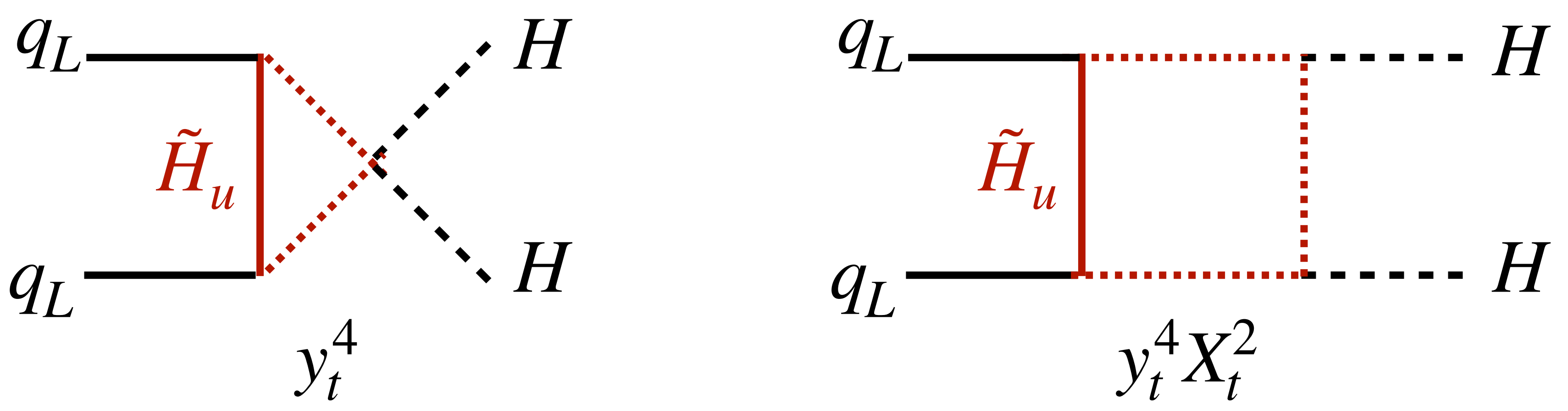
$\delta v_{\rm EW}^2 \propto$



$\kappa_{g,\gamma} \propto$ $(C_{Hg,HB,HW})$



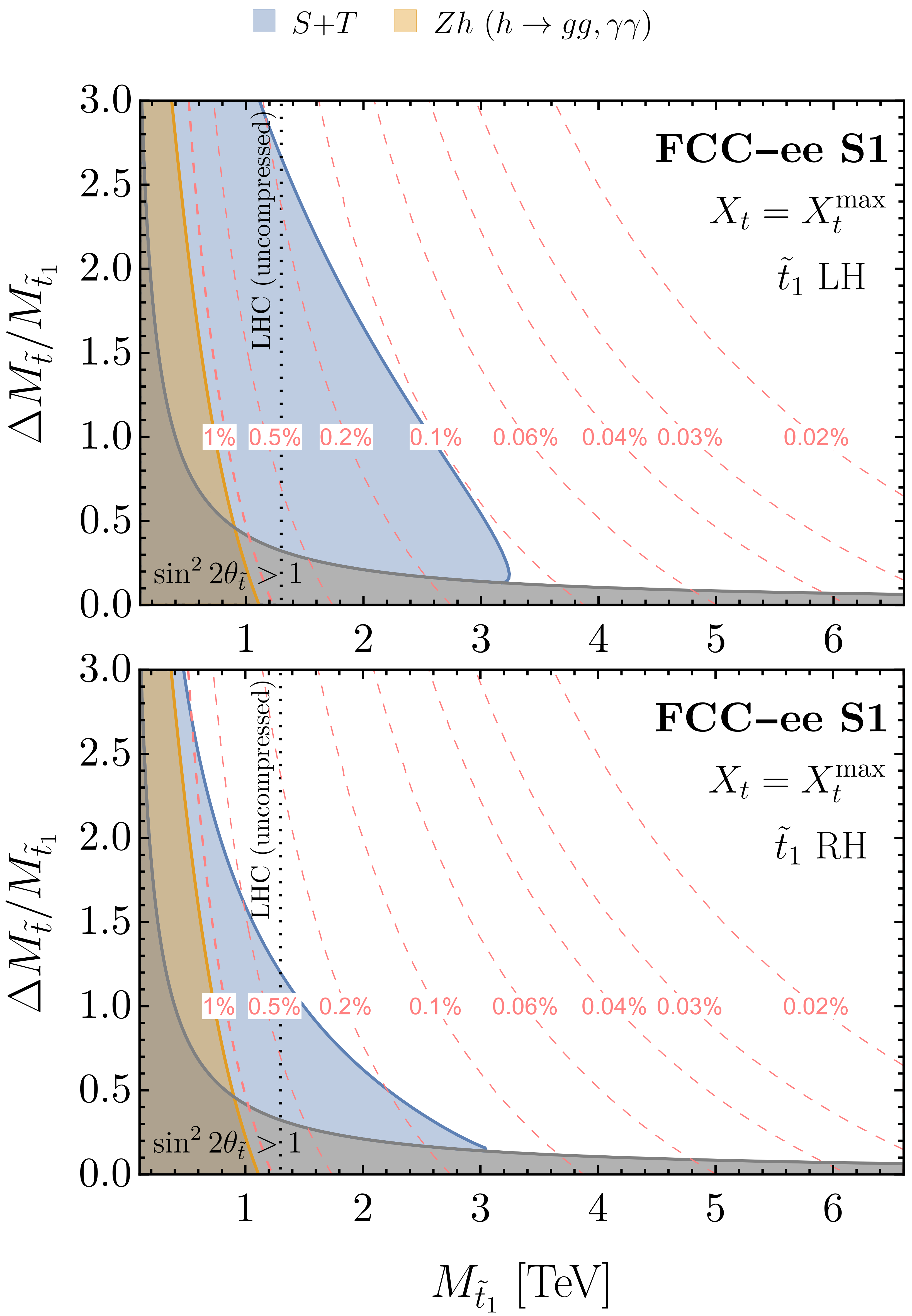
$R_b \propto$ $(C_{Hq}^{(1,3)})$

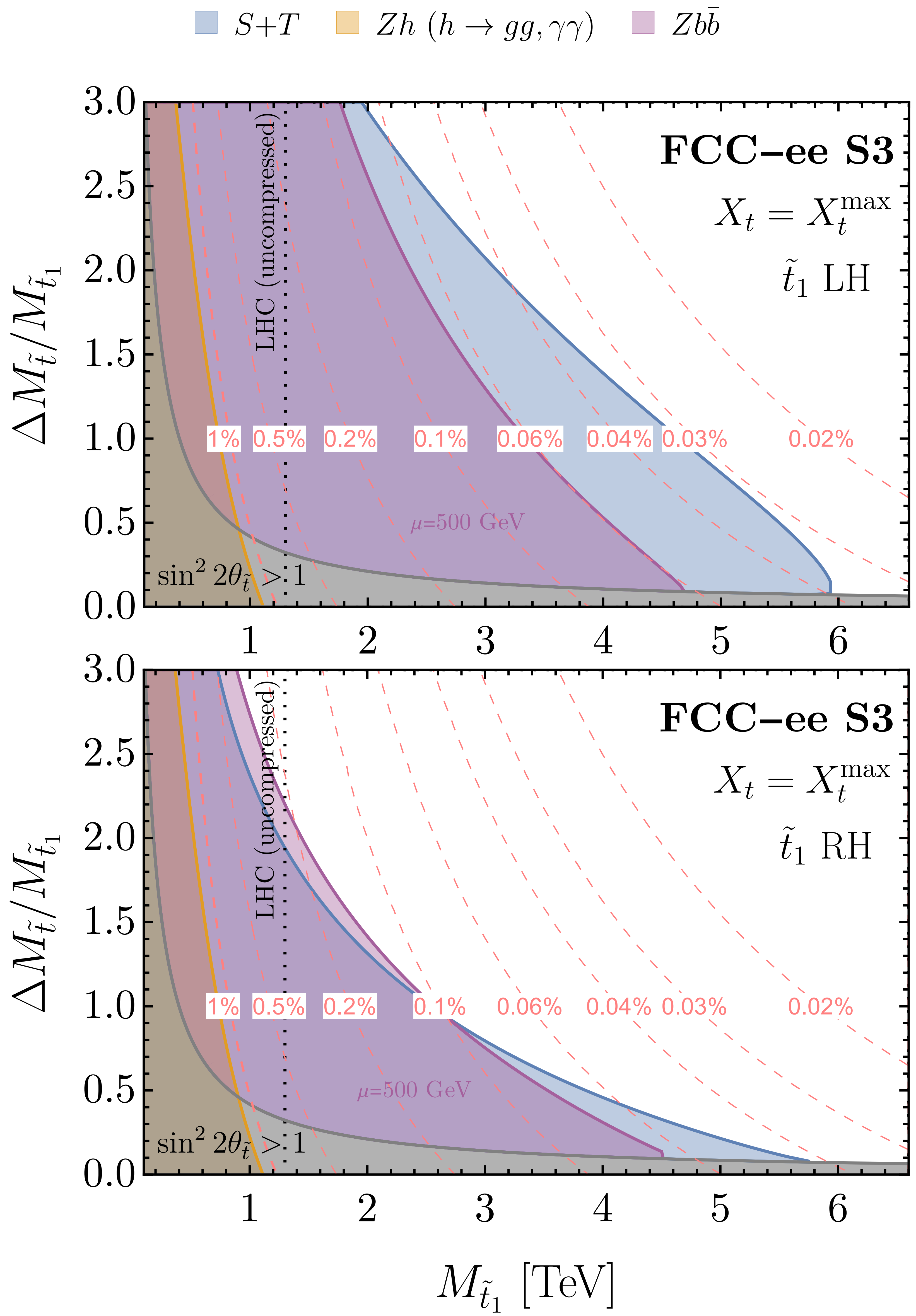


(Higgsino mass depedence via μ)

3. Impact on selected benchmark scenarios

Stops





Higgsinos & EW Gauginos

Naturally light ($\Delta(\mu) = 4\mu^2/m_Z^2$), classical DM candidate (LSP)

Easily evade direct searches (compressed spectra): typical LCF benchmark

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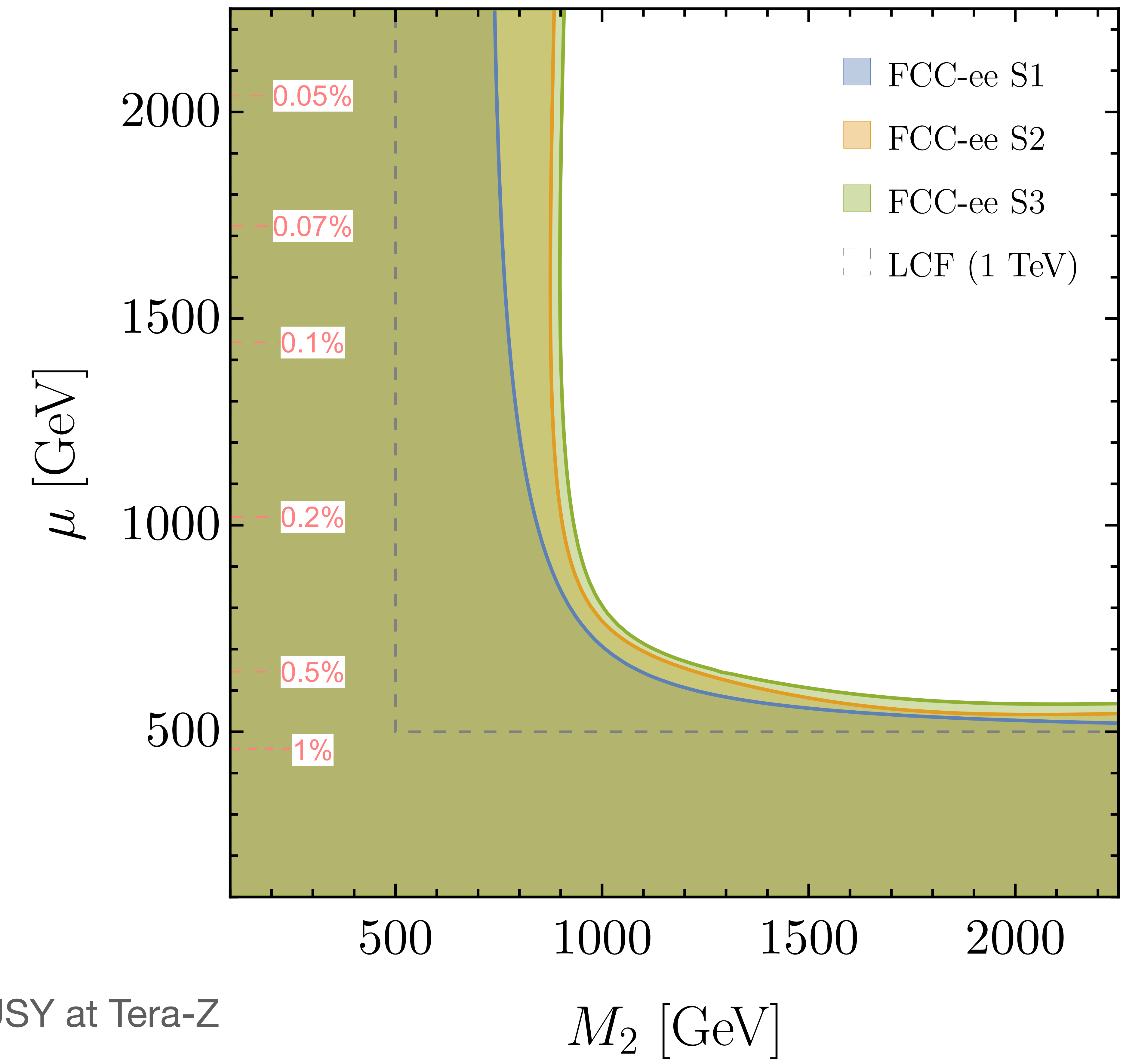
Easily evade direct searches (compressed spectra): typical LCF benchmark



Tera-Z: S, T, W, Y

$$\hat{W} = \frac{\alpha_L m_W^2}{30\pi}\left(\frac{1}{\mu^2} + \frac{2}{M_2^2}\right)$$

leading and ***additive:***

inescapable reach on μ, M_2 up to 500 GeV!

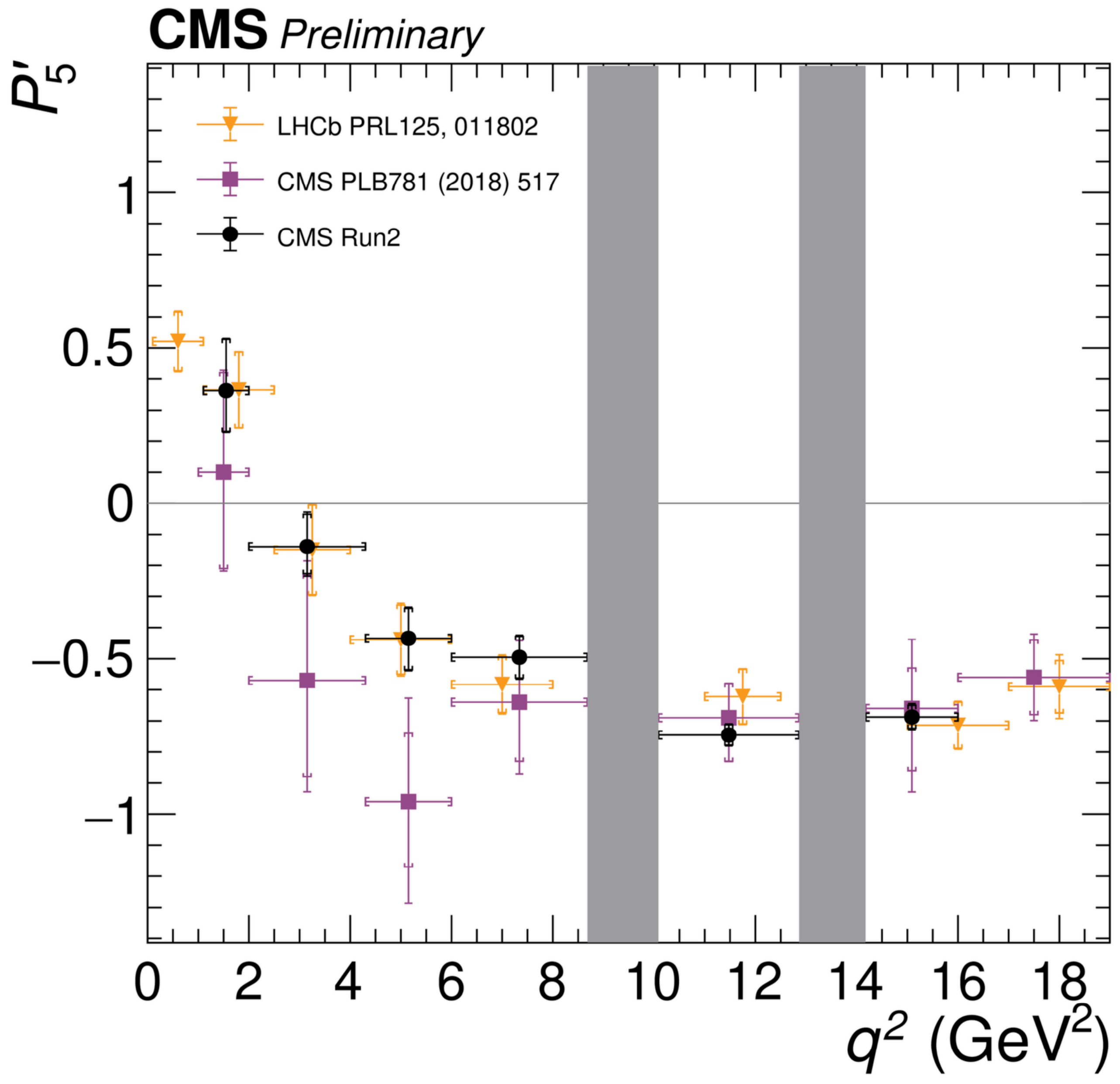
- Closes compressed gaps (uncompressed LHC $M_2 \gtrsim$ TeV)
- Greater reach than direct searches of 1 TeV LCF!

Beyond SMEFT: B anomalies

$b \to s\ell\ell$

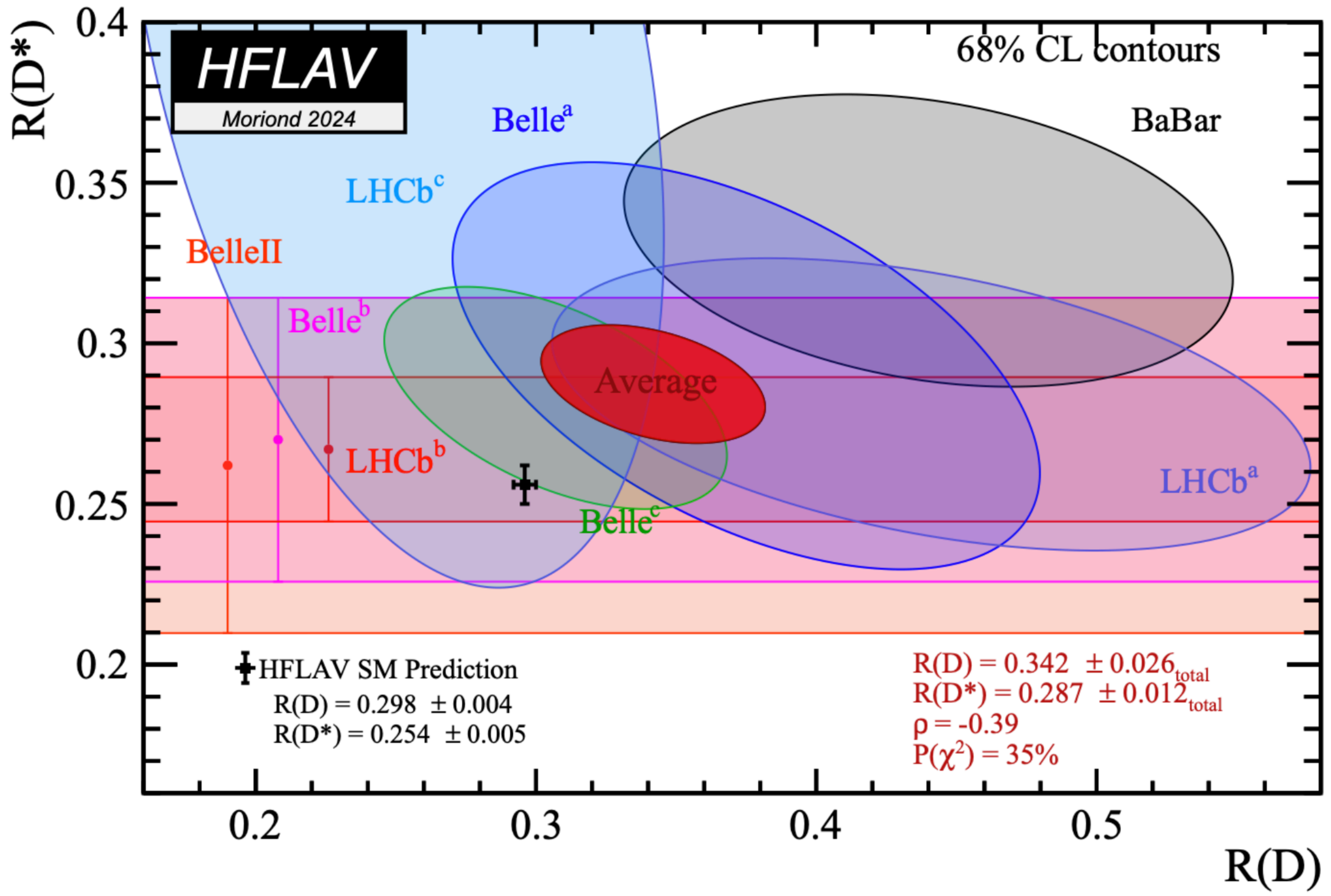
CMS+LHCb $(3 \div 4)\sigma$ tension (actually open debate)

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



$b \to c\tau\nu$

$\sim 3.1\sigma$ tension (HFLAV FF)



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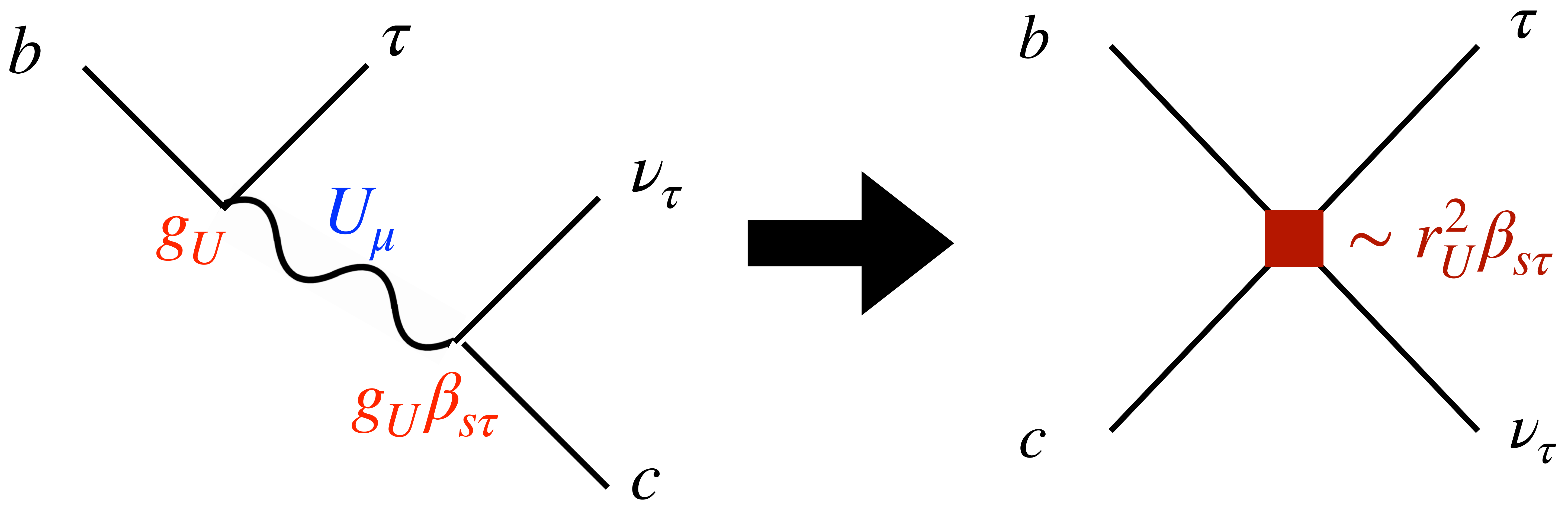
- TL contrib. to $b \to c\tau\nu$



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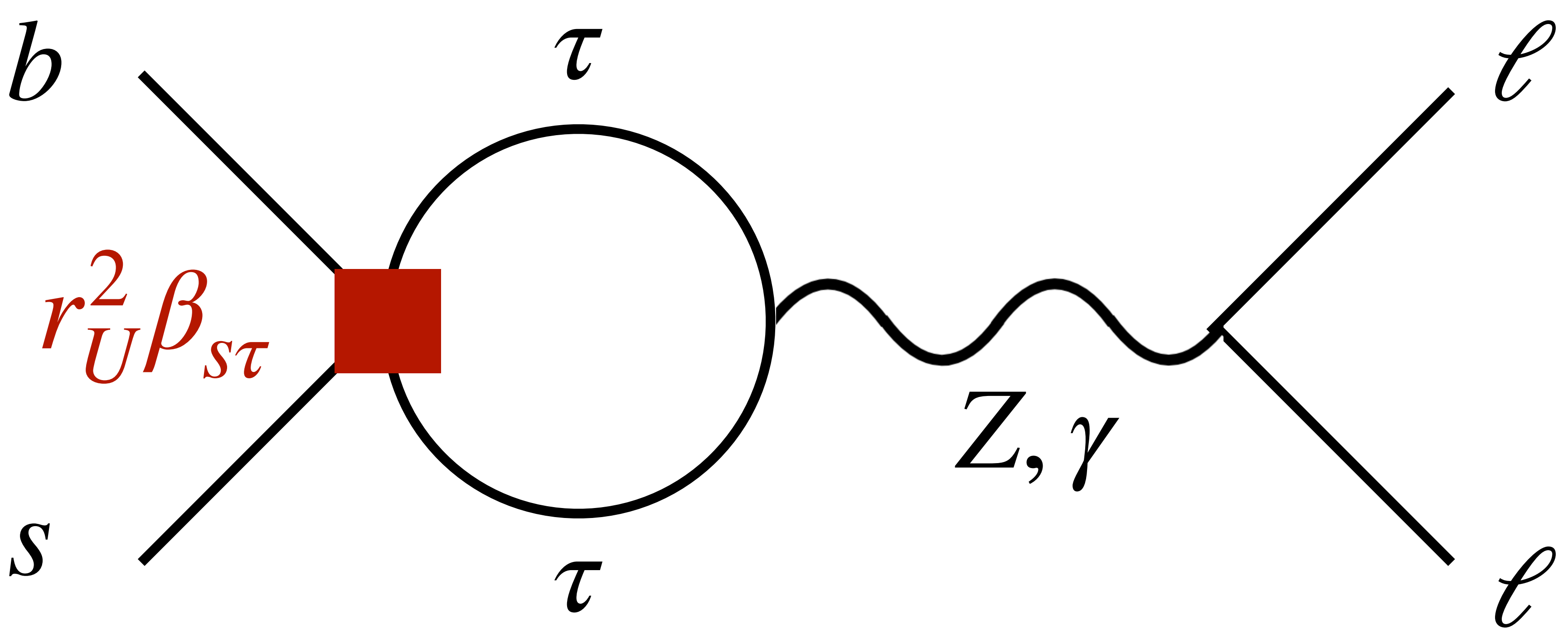
- TL contrib. to $b \to c\tau\nu$
- 1-loop to $b \to s\ell\ell$



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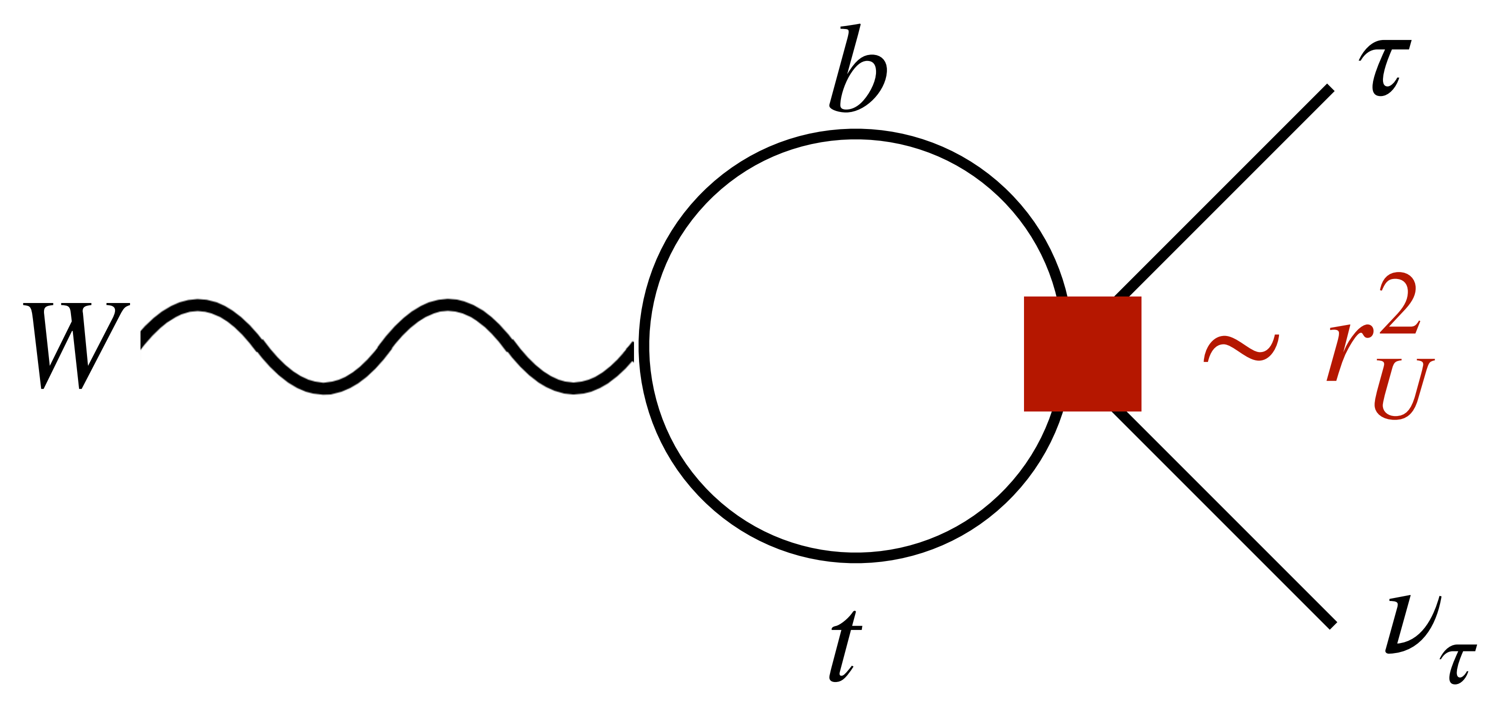
- 1-loop to $\tau \to \mu\nu\nu$



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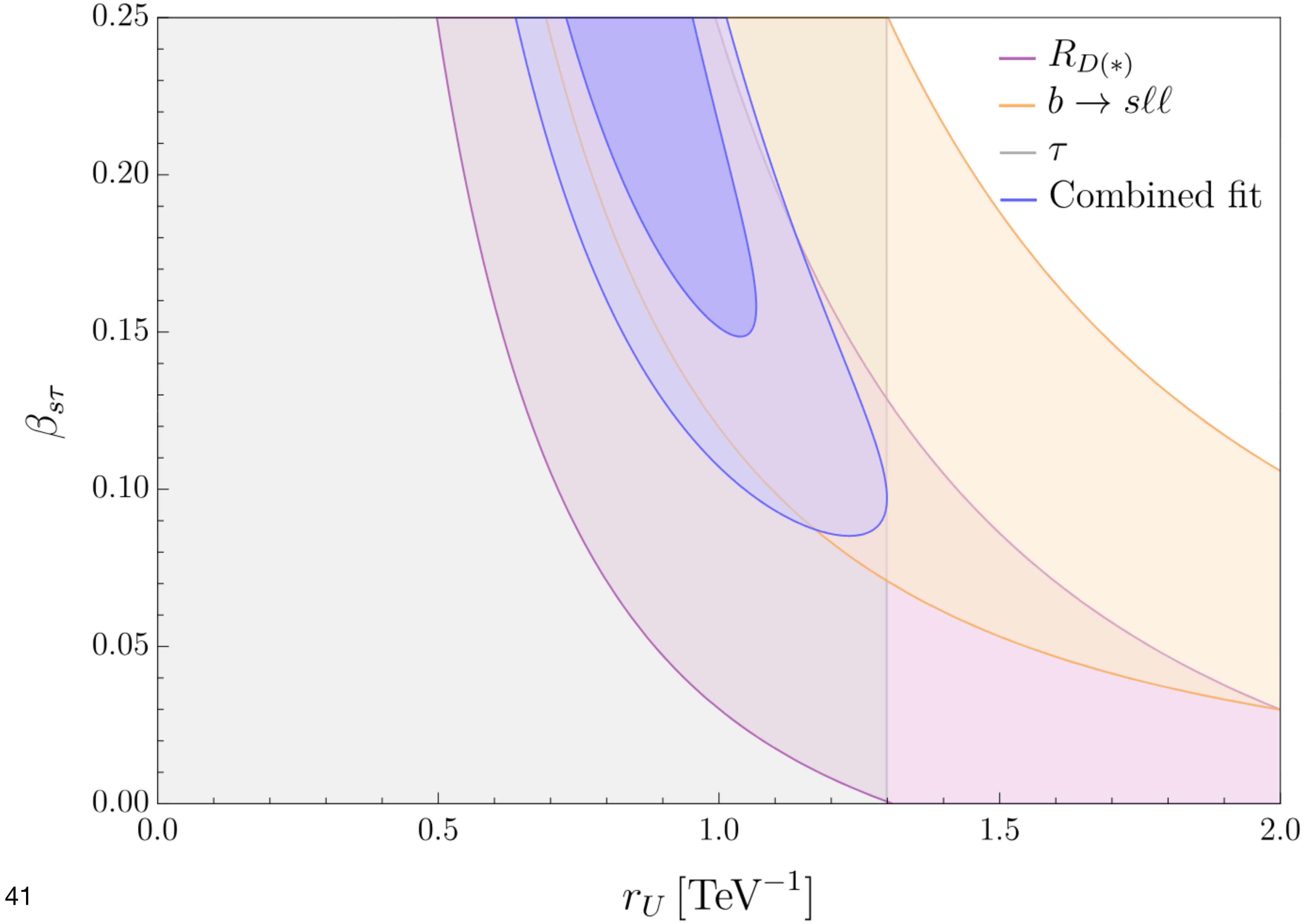
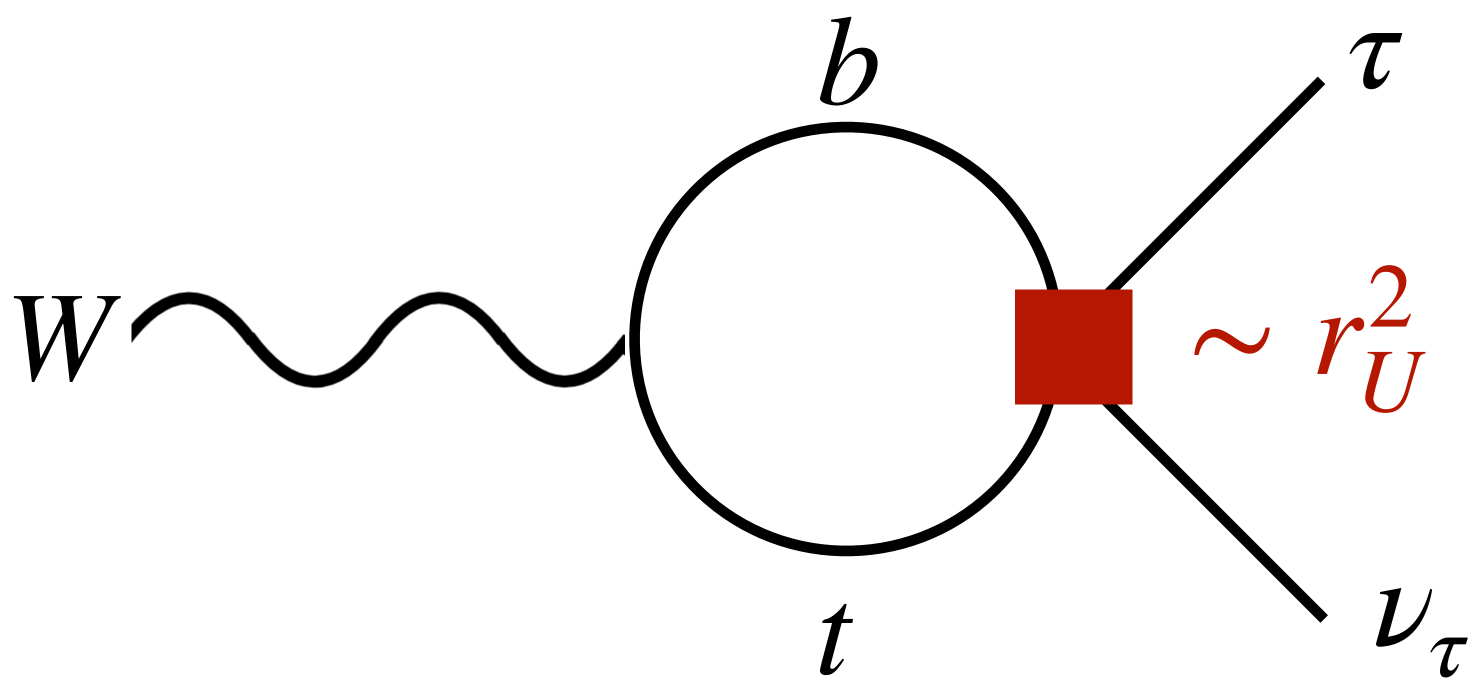
- 1-loop to $b \to s\ell\ell$
- 1-loop to $\tau \to \mu\nu\nu$



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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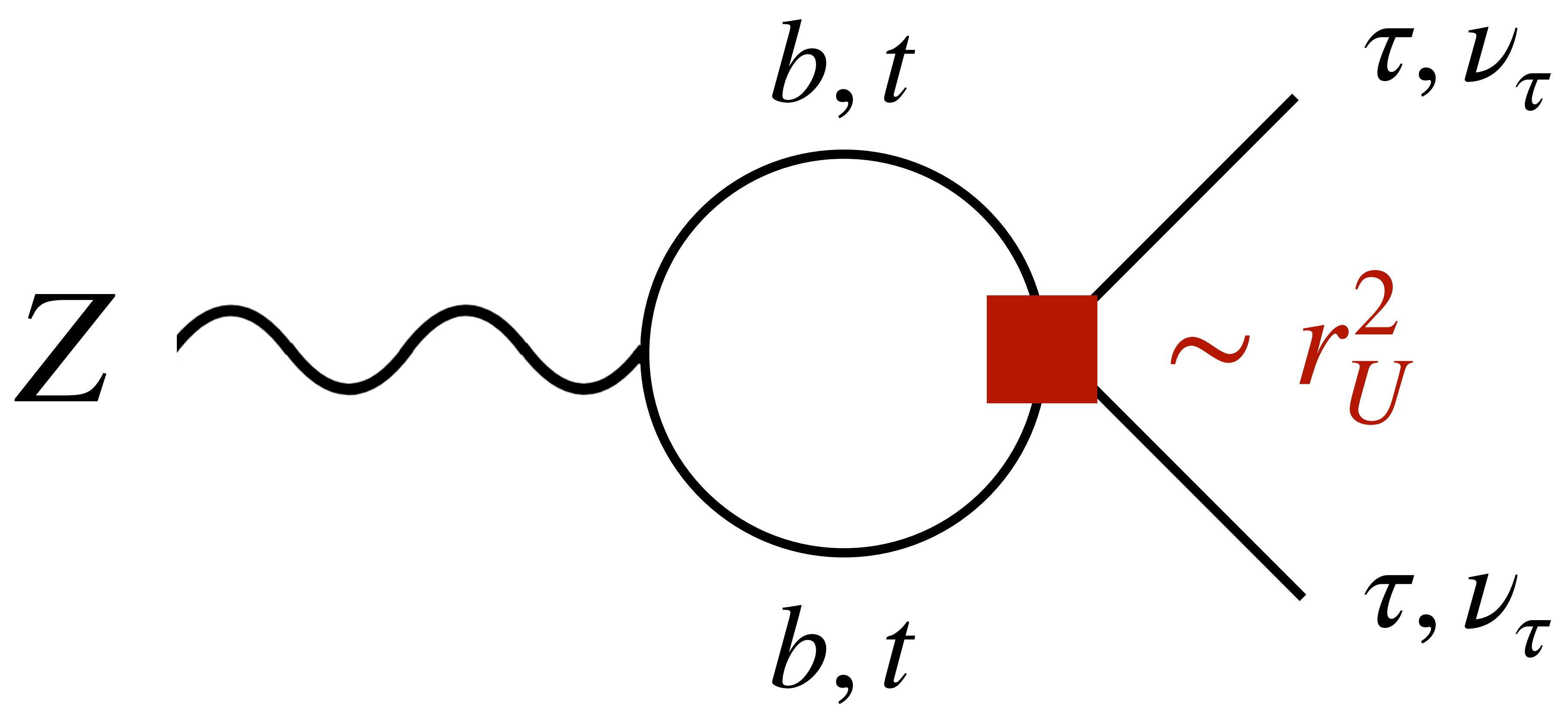

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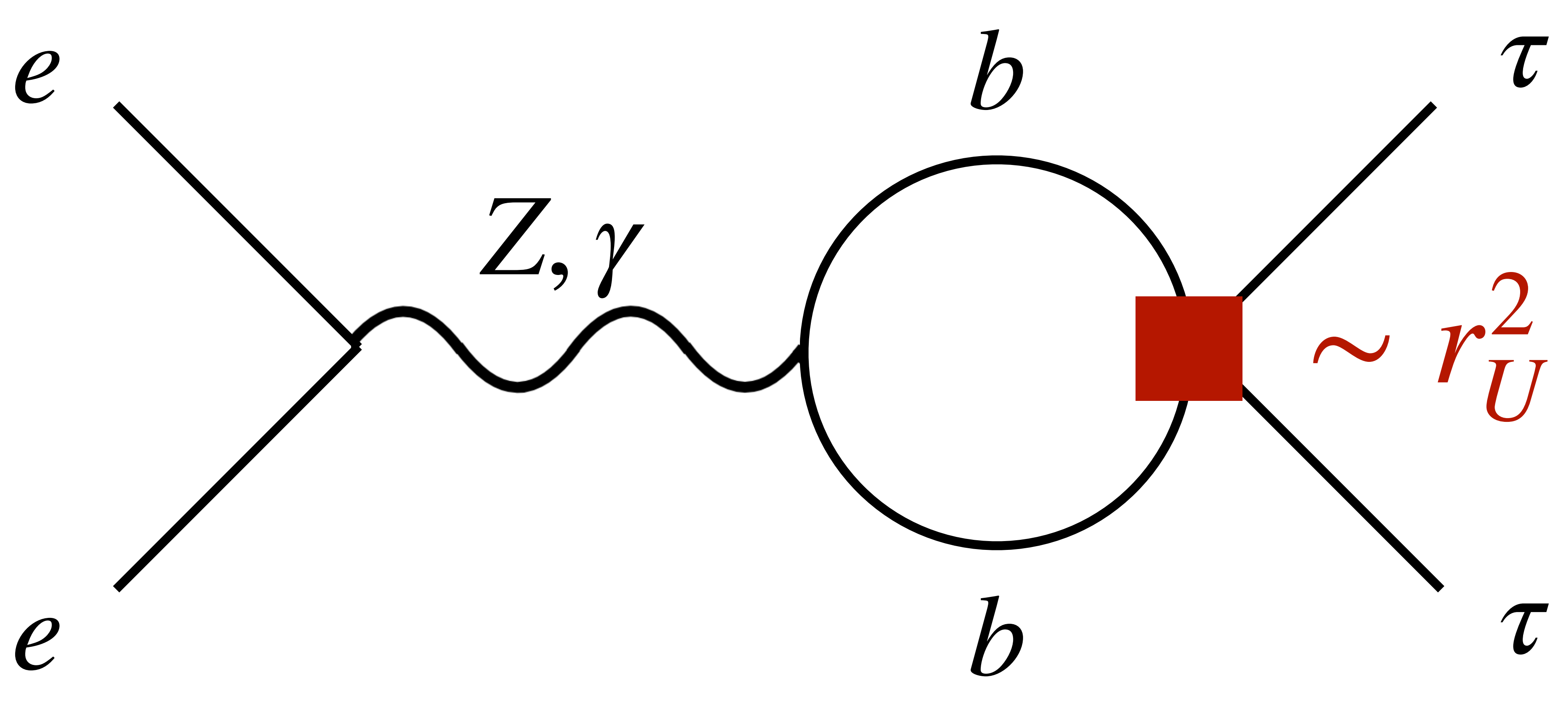
- **Fermion pair-prod.**: 1-loop contrib.
  to $e^+e^- \to \tau\tau, e^+e^- \to \bar{q}q$



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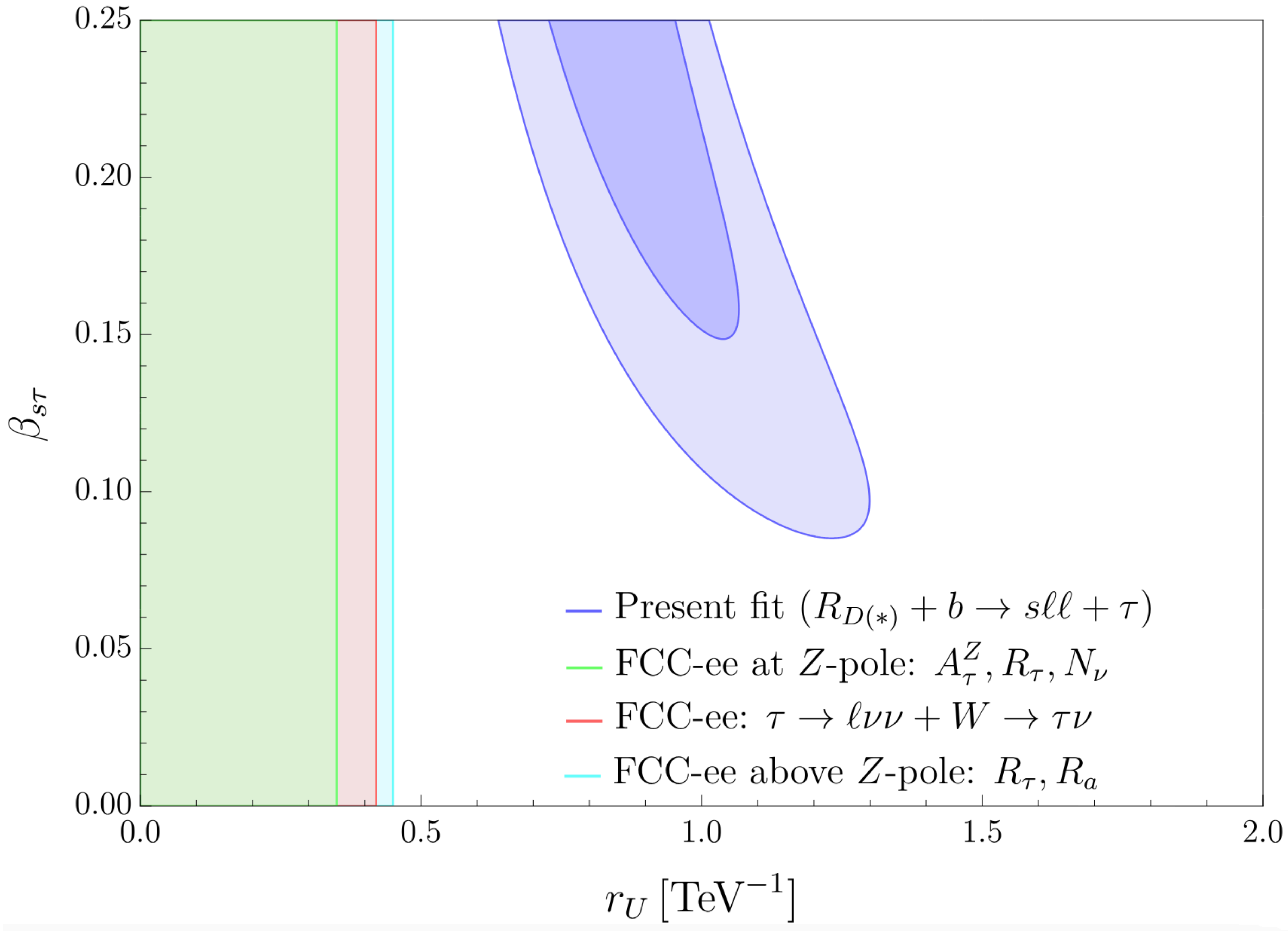

3. Impact on selected benchmark scenarios

II. Z' for $b \to s\ell\ell$

Greljo et al (2022)
Allanach et al (2023, 2024)
…

$$\mathcal{L} \supset g_{ij} Z_\mu{}' \left(\bar{q}_L^i \gamma^\mu q_L^j \right) + g_\ell Z_\mu{}' \sum_{e,\mu,\tau} \left(\bar{\ell}_L \gamma^\mu \ell_L + \bar{e}_R \gamma^\mu e_R \right) + \text{h.c.}$$

Parameters: $r_x \equiv g_x / M_{Z'}$

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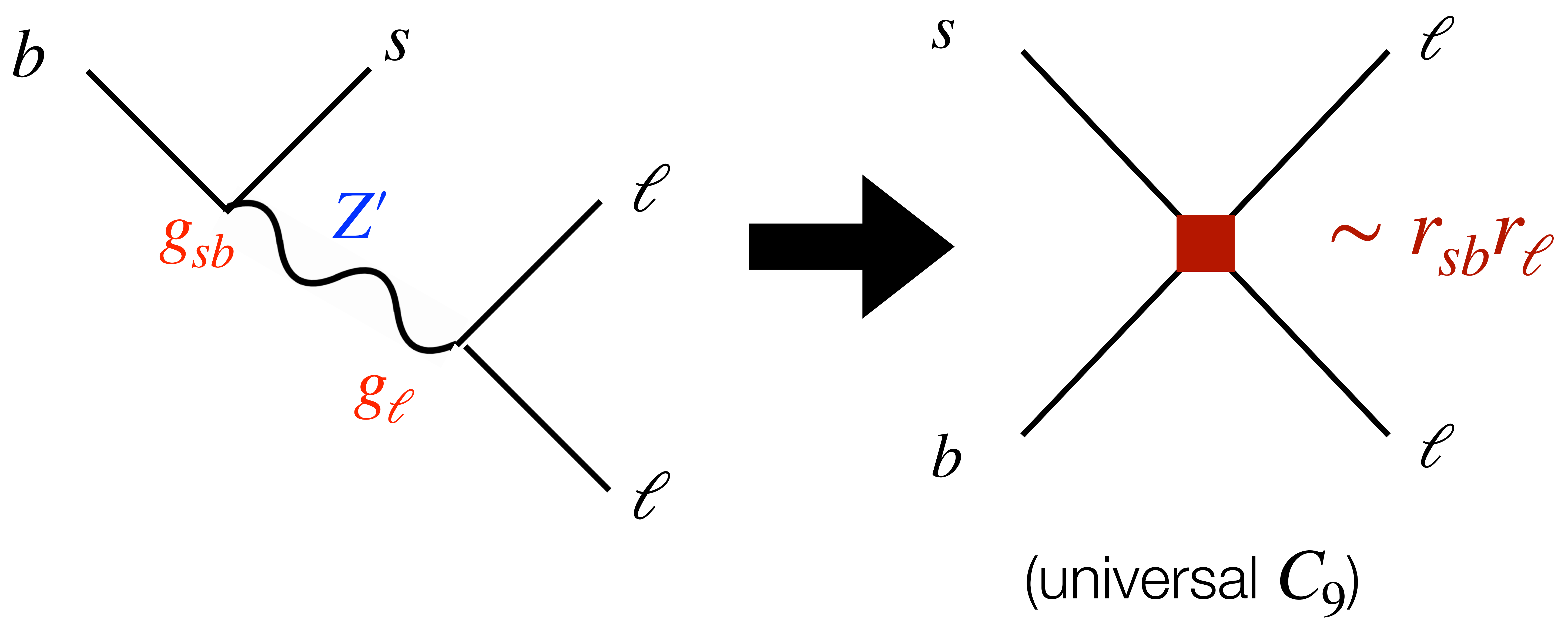
- TL contrib. to $b \to s\ell\ell$



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Parameters: $r_x \equiv g_x / M_{Z'}$

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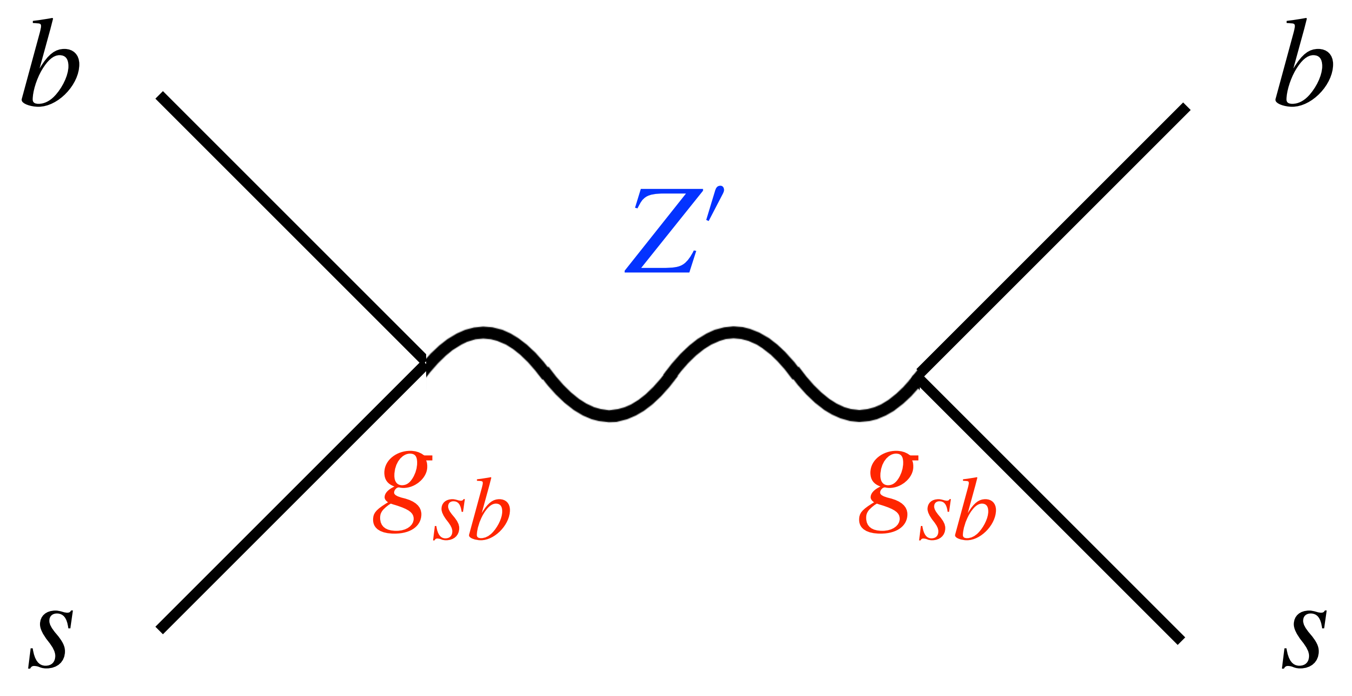

$\sim (r_{sb})^2$

3. Impact on selected benchmark scenarios

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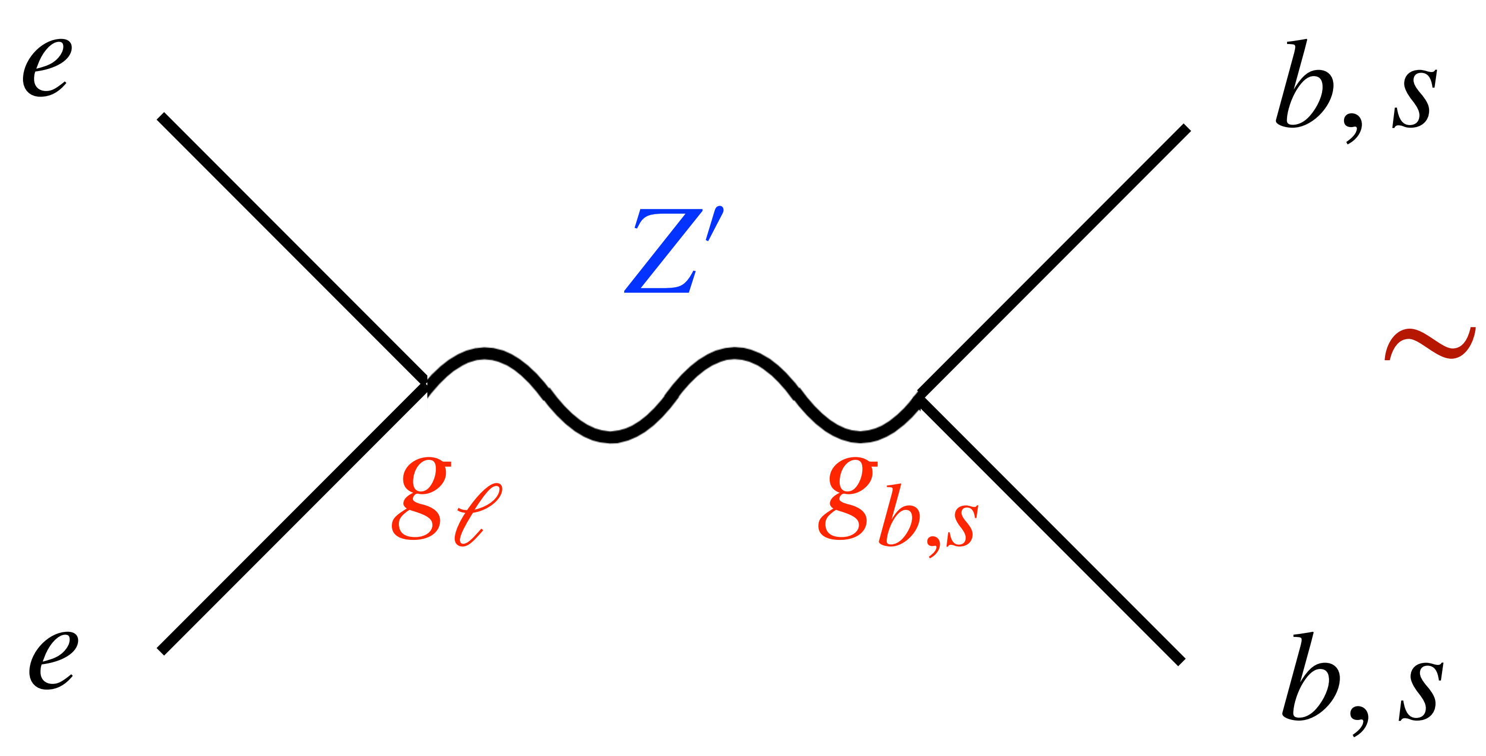
↑

LEP-II, **FCC-ee!**



$\sim r_\ell r_{b,s}$

UV models: $(r_{sb} r_\ell)^2 \leq \frac{1}{2}\left((r_s r_\ell)^2 + (r_b r_\ell)^2\right)$

Altmannshofer et al (2023)

3. Impact on selected benchmark scenarios

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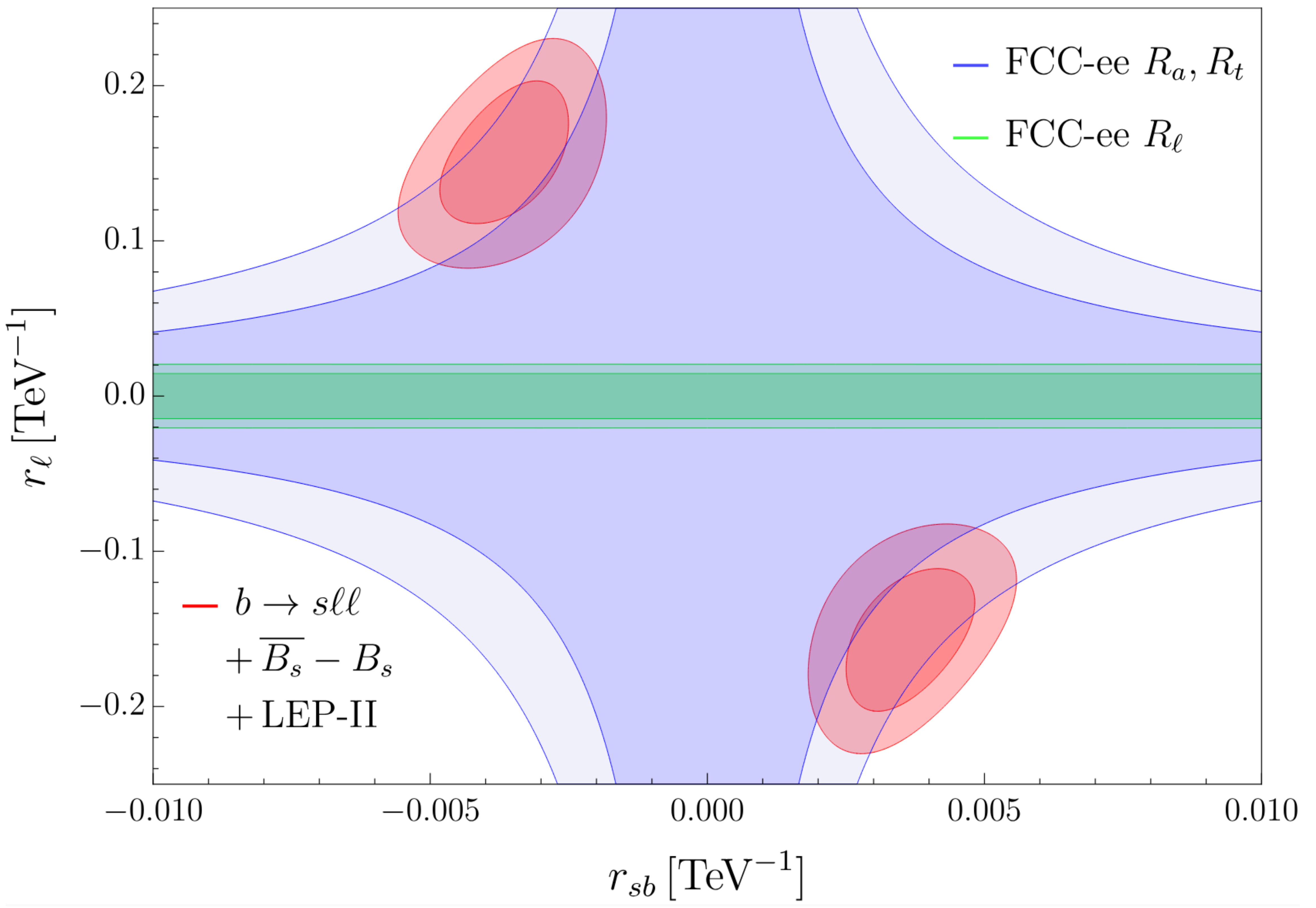

III. Scalar LQ for $b \to s\ell\ell$

Sakaki et al (2013)
Dorsner et al (2016)
....

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

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

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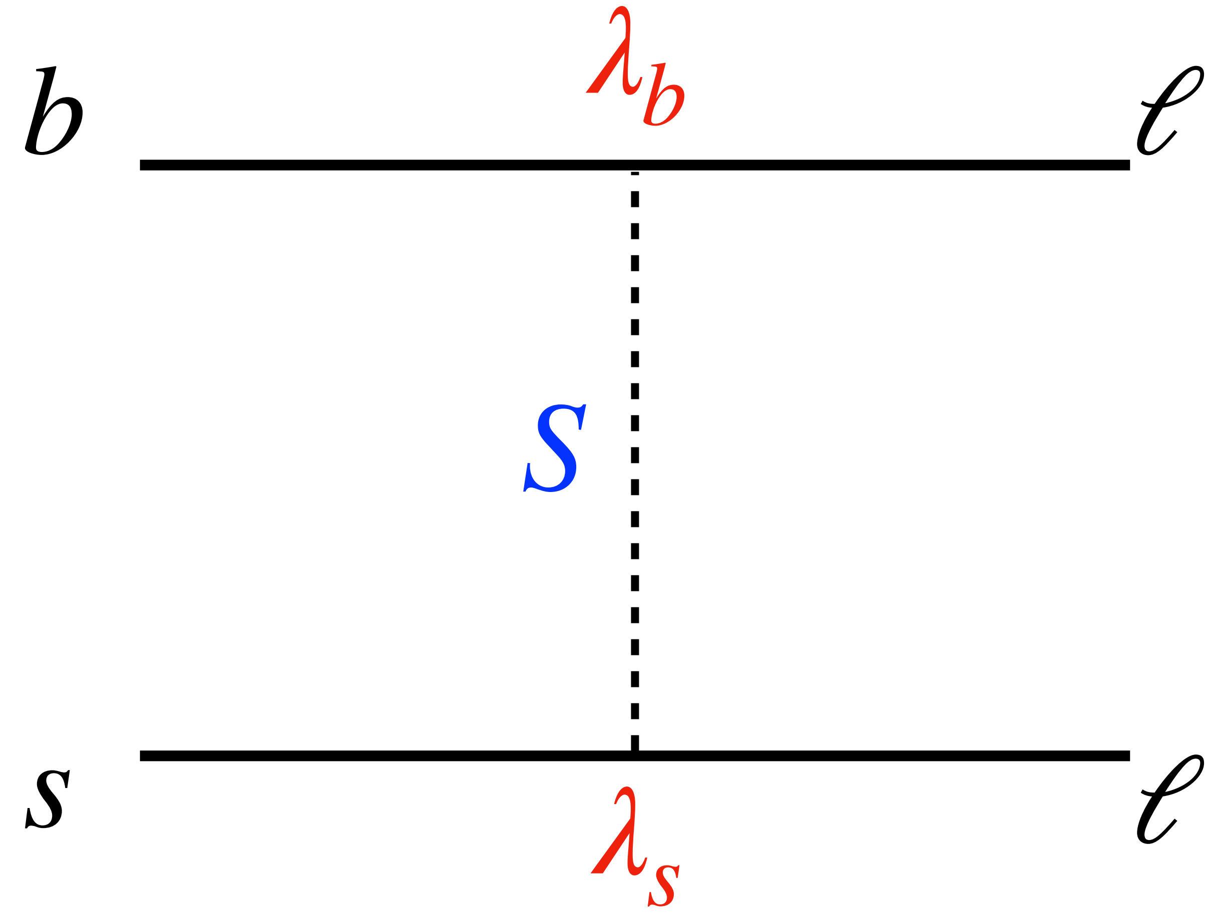

$\sim r_b \, r_s$

- TL contrib. to $b \to s\ell\ell$

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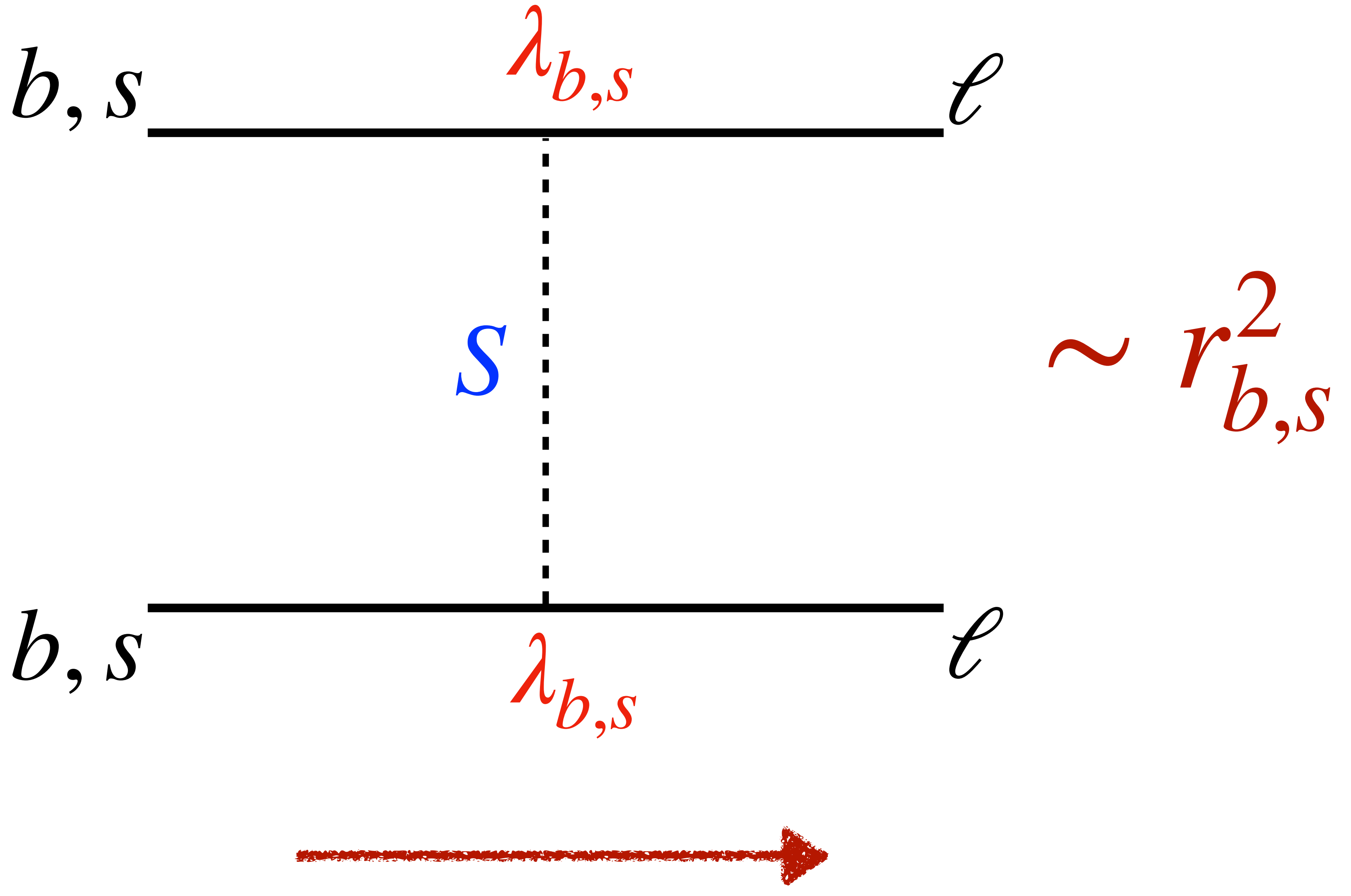

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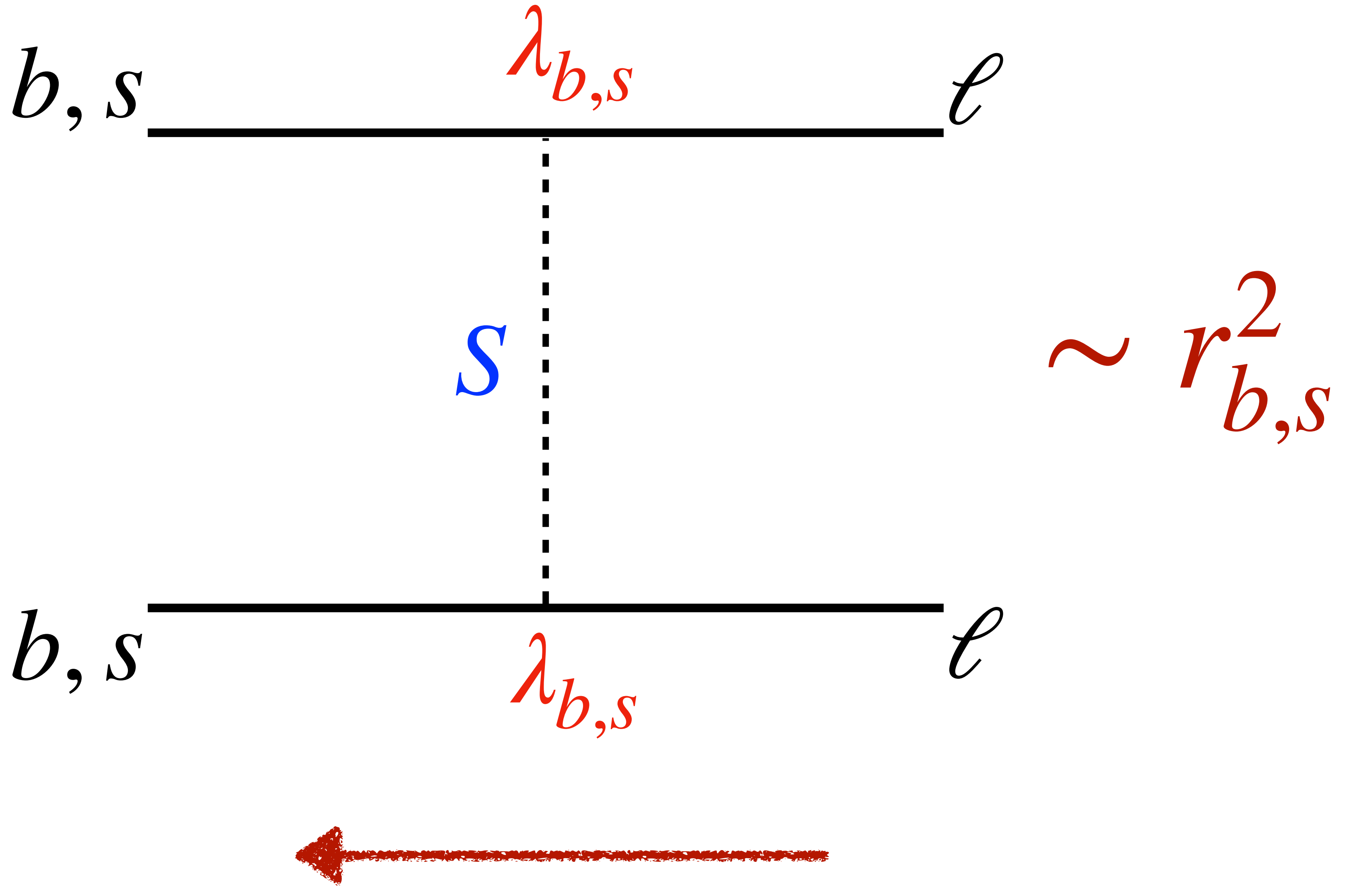

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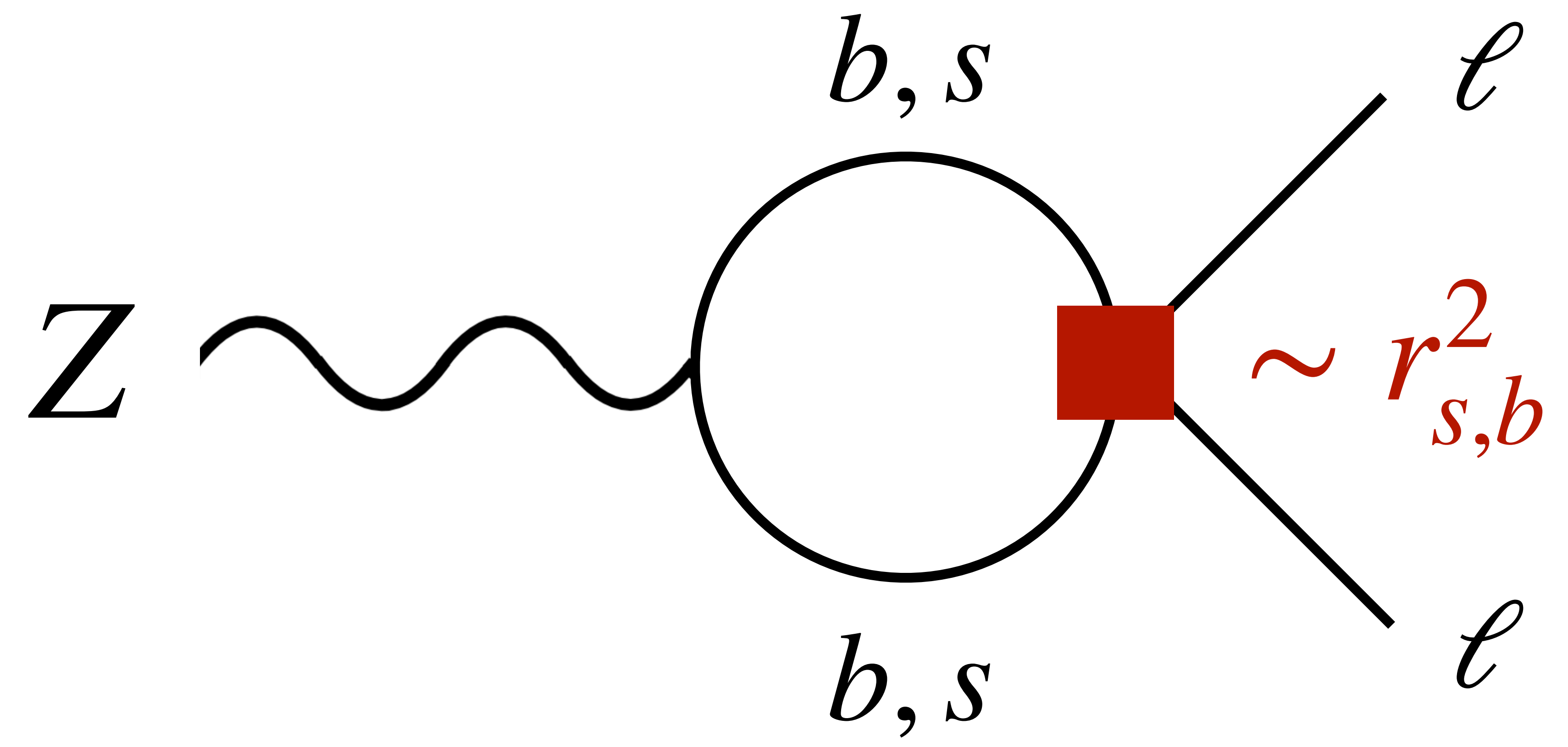

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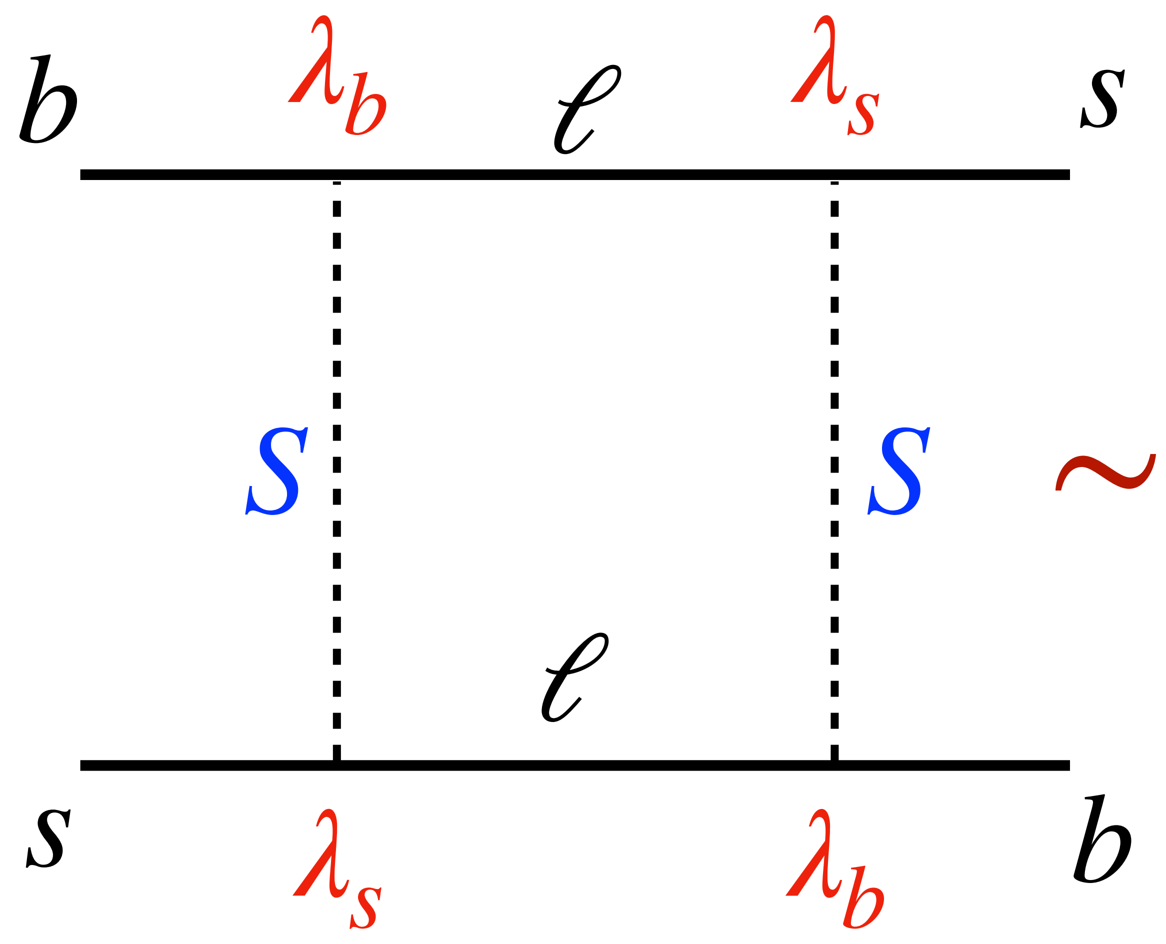

$\sim (r_b r_s)^2 M_S^2$

- TL contrib. to $b \to s\ell\ell$
- TL to $\bar{q}q \to \ell\ell$ **high-p_T** tails (LHC & HL-LHC)
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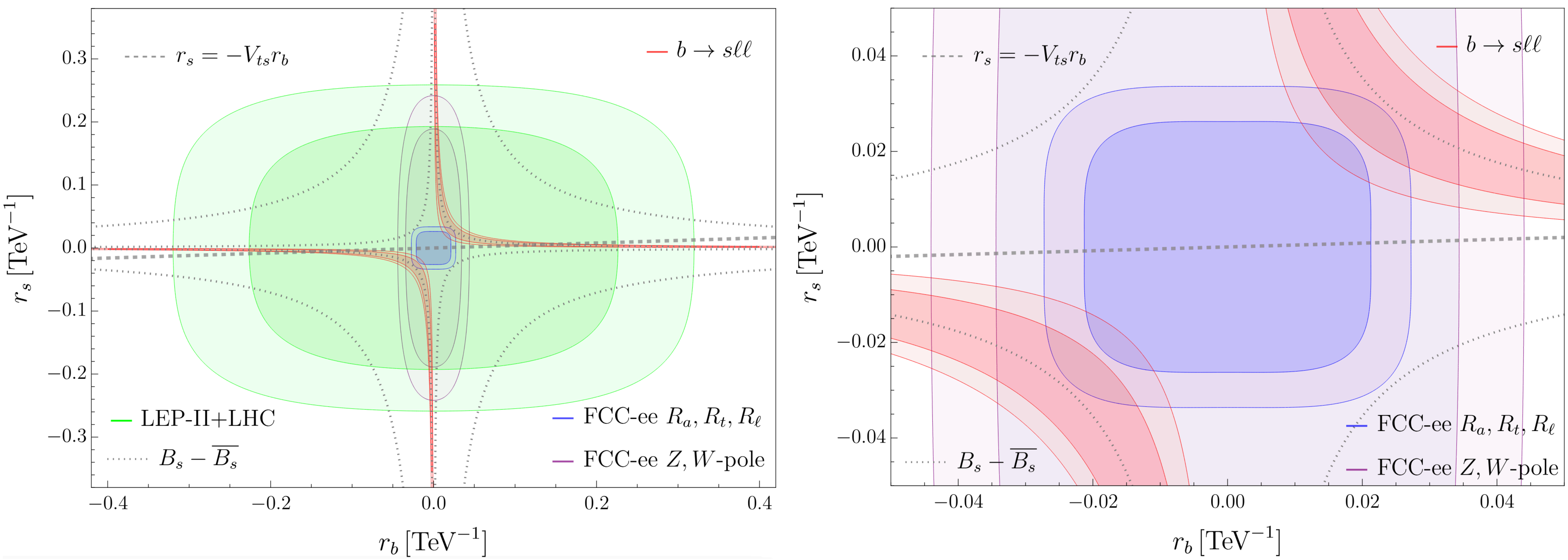
- 1-loop to **Z-pole** EWPO (LEP & **FCC-ee**)
- 1-loop (box) to $B_s - \bar{B}_s$ **oscillations**

III. Scalar LQ for $b \to s\ell\ell$



4. Conclusion

- Tera-Z unprecedented precision enables to test new physics up to $O(100)$ TeV

  This requires significant improvement in SM predictions, target for the next 2 decades

- Lots of other interesting possibilities away from the pole complementing Tera-Z

  E.g. R_a, R_ℓ above the Z-pole probe 4F up to $\mathcal{O}(50)$ TeV!

- FCC-ee impact on some concrete benchmarks:

  - probe the hierarchy problem at multi-TeV (MSSM), testing sub-permille naturalness

  - guaranteed rule out/discovery of models for currently standing B anomalies!

Thank you for your attention!

BACKUP

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

Above pole R_b toy model

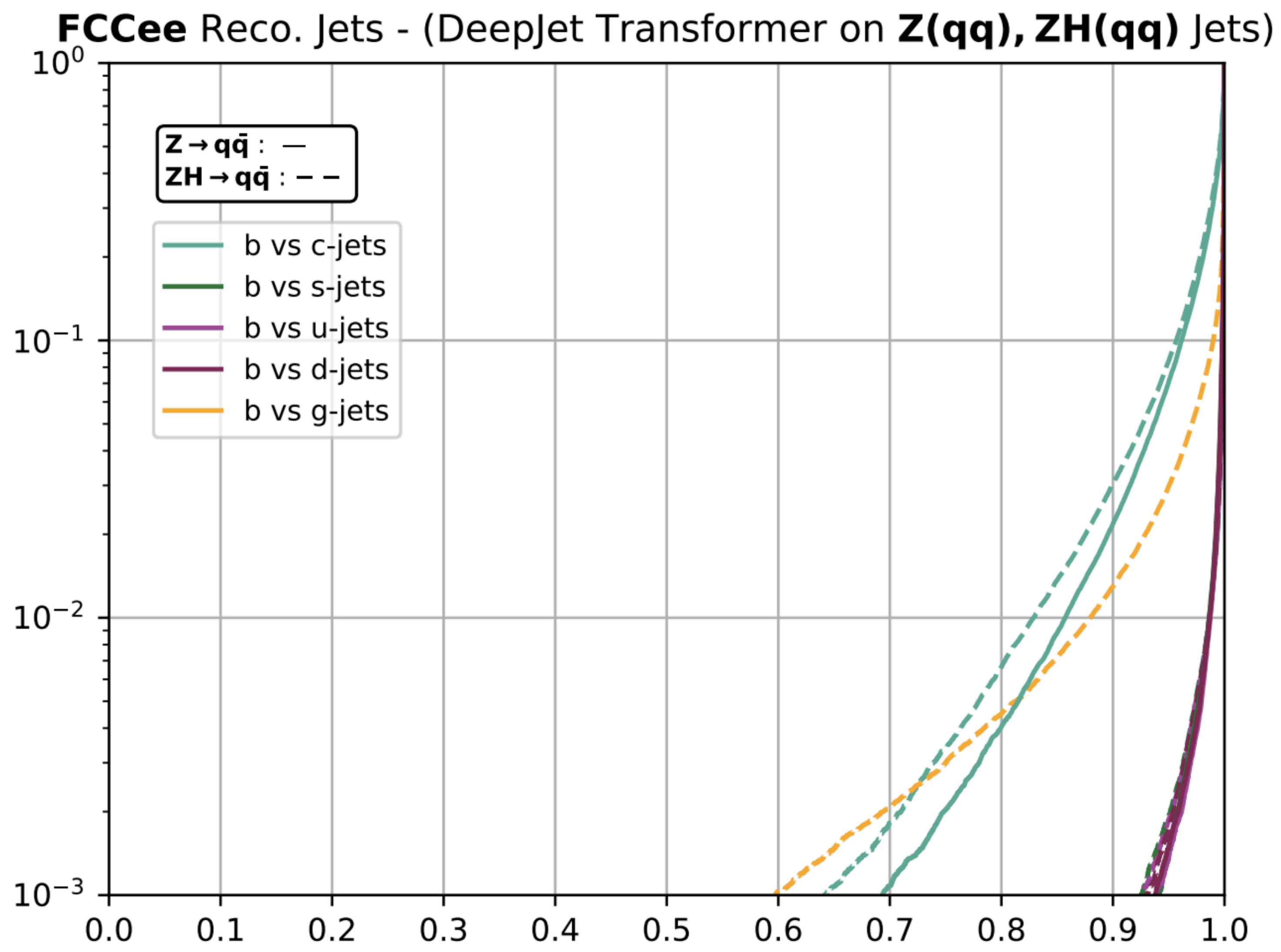
Two flavours only: b, j

$$\left(\frac{\Delta R_b}{R_b}\right)^2 = \frac{1-\epsilon_b^b(2-\epsilon_b^b(2-R_b))}{N_{\rm tot} R_b (\epsilon_b^b)^2}$$ → **True positives stat**

$$+ \frac{2(\epsilon_b^b - R_b(2-\epsilon_b^b)(2\epsilon_b^b-1))}{N_{\rm tot} R_b^2 (\epsilon_b^b)^3}\epsilon_j^b$$ → **False positives stat**

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

Blekmann et al (2024)



- *DeepJetTransformer* ROC curves at FCC-ee
- Realistically $\delta_\epsilon \simeq 0.01$, consider WW run
- Minimize $\Delta R_b / R_b$ with $\epsilon_j^b = \epsilon_c^b(\epsilon_b^b)$ (conservative)

$$\begin{pmatrix} \epsilon_b^b \simeq 0.65 \\ \epsilon_j^b \simeq 10^{-3} \end{pmatrix}$$

$$\frac{\Delta R_b}{R_b} \simeq 2 \times 10^{-4}$$

Basically saturates exp. stat limit!

Reminder LEP-II: $\Delta R_b / R_b \sim 10^{-2}$ LEP EW WG (2003,2013)

FB asymmetries above the pole

$$A_\ell = \frac{\sigma_F(e^+e^- \to \ell^+\ell^-) - \sigma_B(e^+e^- \to \ell^+\ell^-)}{\sigma_F(e^+e^- \to \ell^+\ell^-) + \sigma_B(e^+e^- \to \ell^+\ell^-)}$$

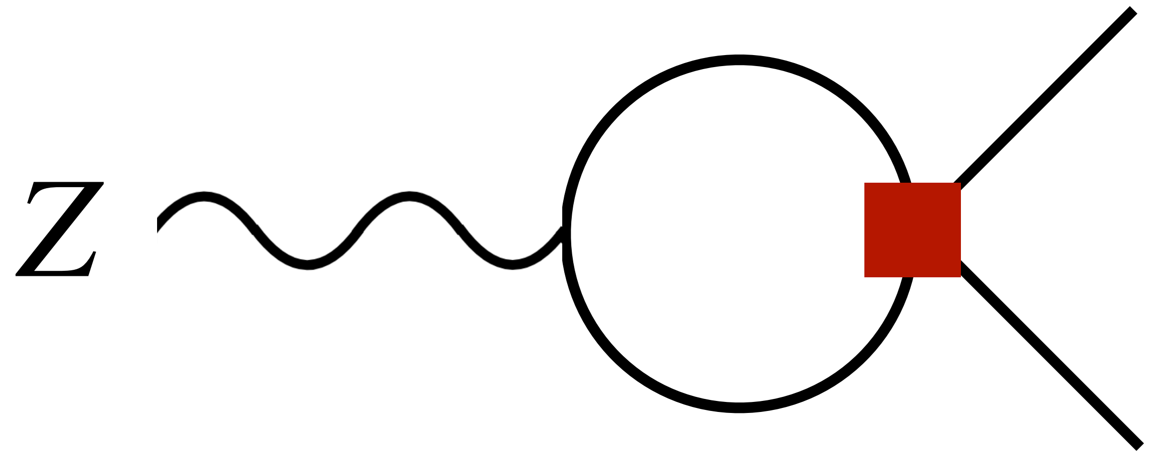
$$\left.\frac{\Delta A_\ell}{A_\ell}\right|_{\rm stat} = \sqrt{\frac{4N_F N_B}{(N_F - N_B)^2(N_F + N_B)}} = \{3.3, 8.8, 27\} \times 10^{-4}$$

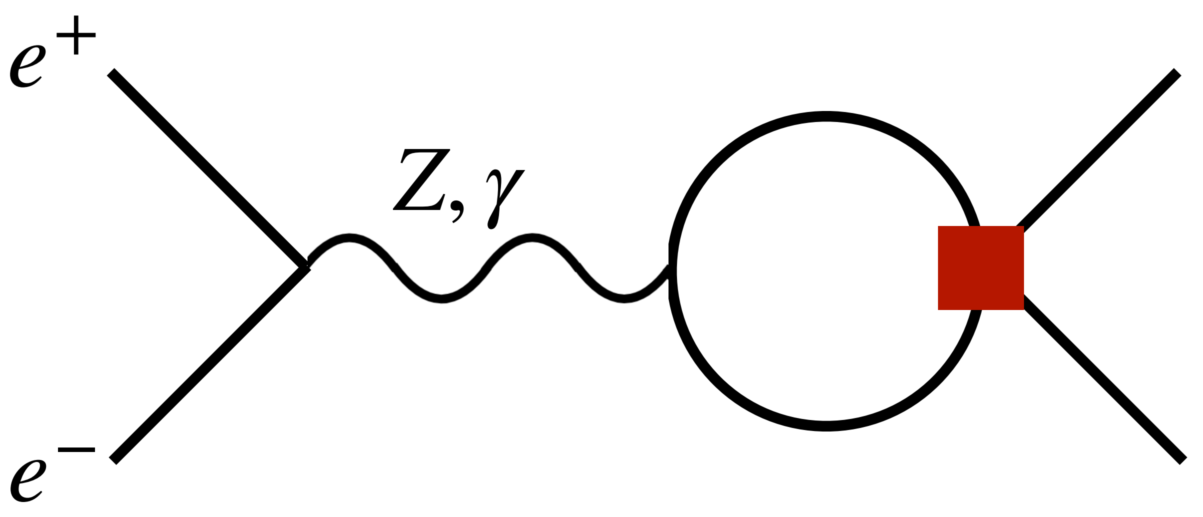
Observable/Λ [TeV]	$\Lambda_{\ell\ell,11xx}(\Lambda_{\ell\ell,1xx1})$	$\Lambda_{\ell e,11xx}(\Lambda_{\ell e,xx11})$	$\Lambda_{ee,11xx}$
R_ℓ	29.8	18.4	28.5
A_ℓ	11.7	18.1	11.2

- Bounds comparable to R_ℓ or weaker, irrelevant for us (but can lift flat dir. in global fits)
- Requires realistic detector geometry for syst. uncertainties estimation

3rd-gen only new physics

Pure RG effect,
both at Z/W and
in fermion pair-prod.





$\Lambda^{[3333]}$ [TeV]	FCC-ee Z, W-pole+τ	FCC-ee above Z-pole	
$\Lambda_{\ell q}^{(1)}$	15.7	1.1	$2q2\ell$
$\Lambda_{\ell q}^{(3)}$	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	4ℓ
$\Lambda_{\ell e}$	2.1	1.5	
Λ_{ee}	3.5	2.4	
$\Lambda_{qq}^{(1)}$	13.1	2.4	$4q$
$\Lambda_{qq}^{(3)}$	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	

- Z/W: bounds stronger for q, u ($\sim y_t^2$ running)
- Above pole: stronger for $\mathrm{SU}(2)_\mathrm{L}$ currents ($g^2 > g'^2$)

Flavour violation above pole? $(\Delta F = 1)$

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

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

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

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

$$R_{ij} \lesssim 1.645 \frac{\sigma_b}{N_{\text{tot}} \epsilon_i^i \epsilon_j^j}$$ (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	$2.70 \cdot 10^{-4}$

Flavour violation above pole? $(\Delta F = 1)$

SMEFT interpretation: $2q2\ell$ tree-level, $\Delta R_{ij} \sim s^2/\Lambda^4$

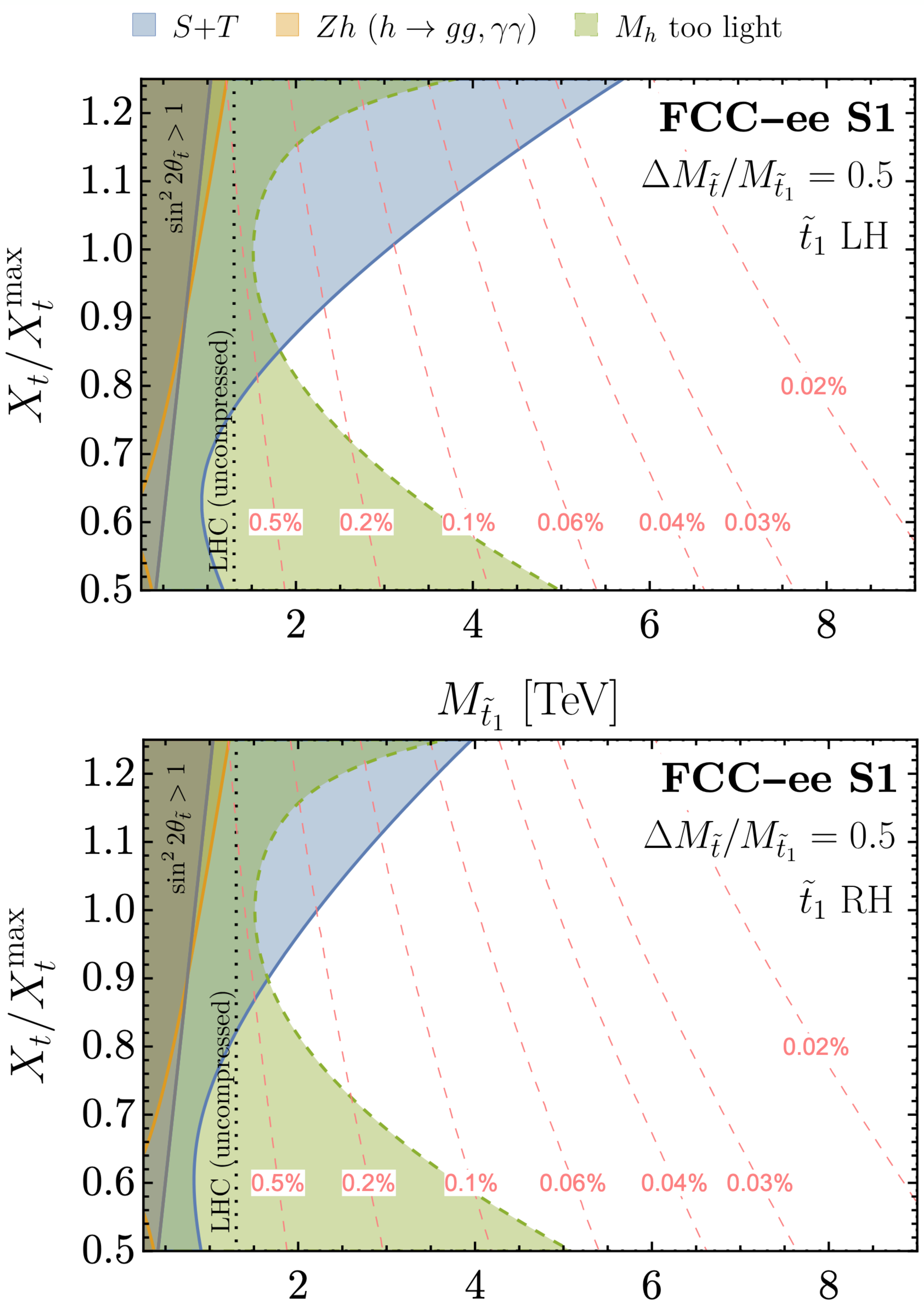
$$|\Lambda_{1123}| > 16\,\text{TeV for } \mathcal{O}^{(1)}_{\ell q}, \mathcal{O}^{(3)}_{\ell q}, \mathcal{O}_{\ell d}, \mathcal{O}_{ed}, \mathcal{O}_{qe},$$

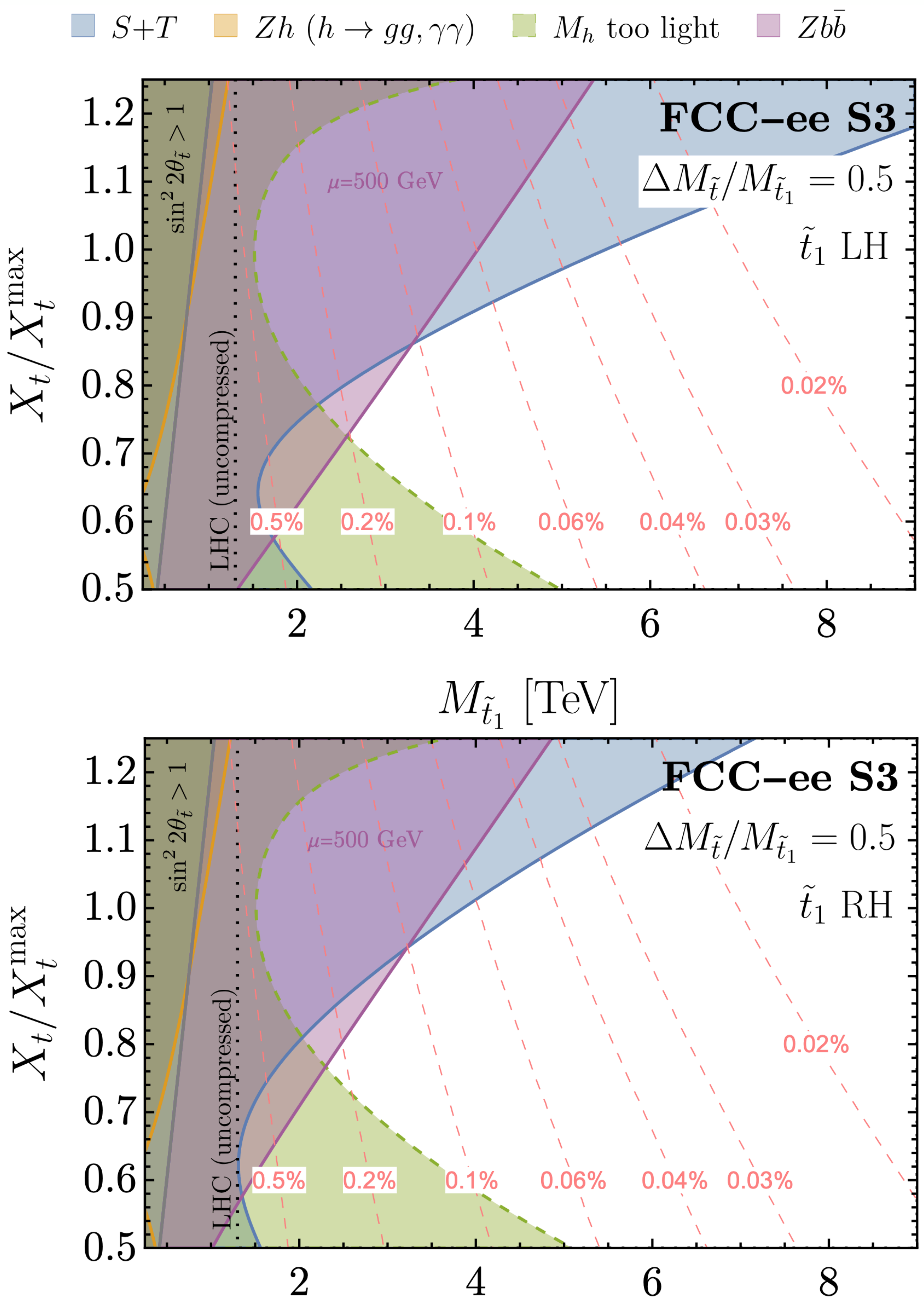
$$|\Lambda_{1113}| > 9.4\,\text{TeV for } \mathcal{O}^{(1)}_{\ell q}, \mathcal{O}^{(3)}_{\ell q}, \mathcal{O}_{\ell d}, \mathcal{O}_{ed}, \mathcal{O}_{qe}$$

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

Bounds weaker than current ones from $q_i \to q_j e^+ e^-$(hadronic decays)

(Exception: $\mathcal{O}_{eu}$, $c \to u$ high-p_T currently comparable)


$S+T$
$Zh\ (h \to gg, \gamma\gamma)$
M_h too light
FCC-ee S1
$\Delta M_{\tilde{t}}/M_{\tilde{t}_1} = 0.5$
$\tilde{t}_1$ LH
$\tilde{t}_1$ RH
$\sin^2 2\theta_{\tilde{t}} > 1$
LHC (uncompressed)
0.5%
0.2%
0.1%
0.06%
0.04%
0.03%
0.02%
$X_t/X_t^{\max}$
$M_{\tilde{t}_1}$ [TeV]


$S+T$
$Zh\ (h \to gg, \gamma\gamma)$
M_h too light
$Zb\bar{b}$
FCC-ee S3
$\Delta M_{\tilde{t}}/M_{\tilde{t}_1} = 0.5$
$\tilde{t}_1$ LH
$\tilde{t}_1$ RH
μ=500 GeV
$\sin^2 2\theta_{\tilde{t}} > 1$
LHC (uncompressed)
0.5%
0.2%
0.1%
0.06%
0.04%
0.03%
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$X_t/X_t^{\max}$
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