New Physics Through Flavor Tagging at FCC-ee

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Based on 2411.02485 in collaboration with Admir Greljo, Hector Tiblom

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FCC-ee runs

Z-pole

Above the Z-pole

FCC-ee runs

Z-pole

FCC-ee report (2019)
De Blas et al (2019)
Blondel, Janot (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:

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

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

What are the
new physics opportunities?

Outline

1. Observables and flavor tagging above the Z-pole
2. SMEFT interpretation
3. Conclusion

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Observables

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

Focus on 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)

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

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Taggers:

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

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

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

$(R_j = 1 - R_b)$

Toy model: R_b

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

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

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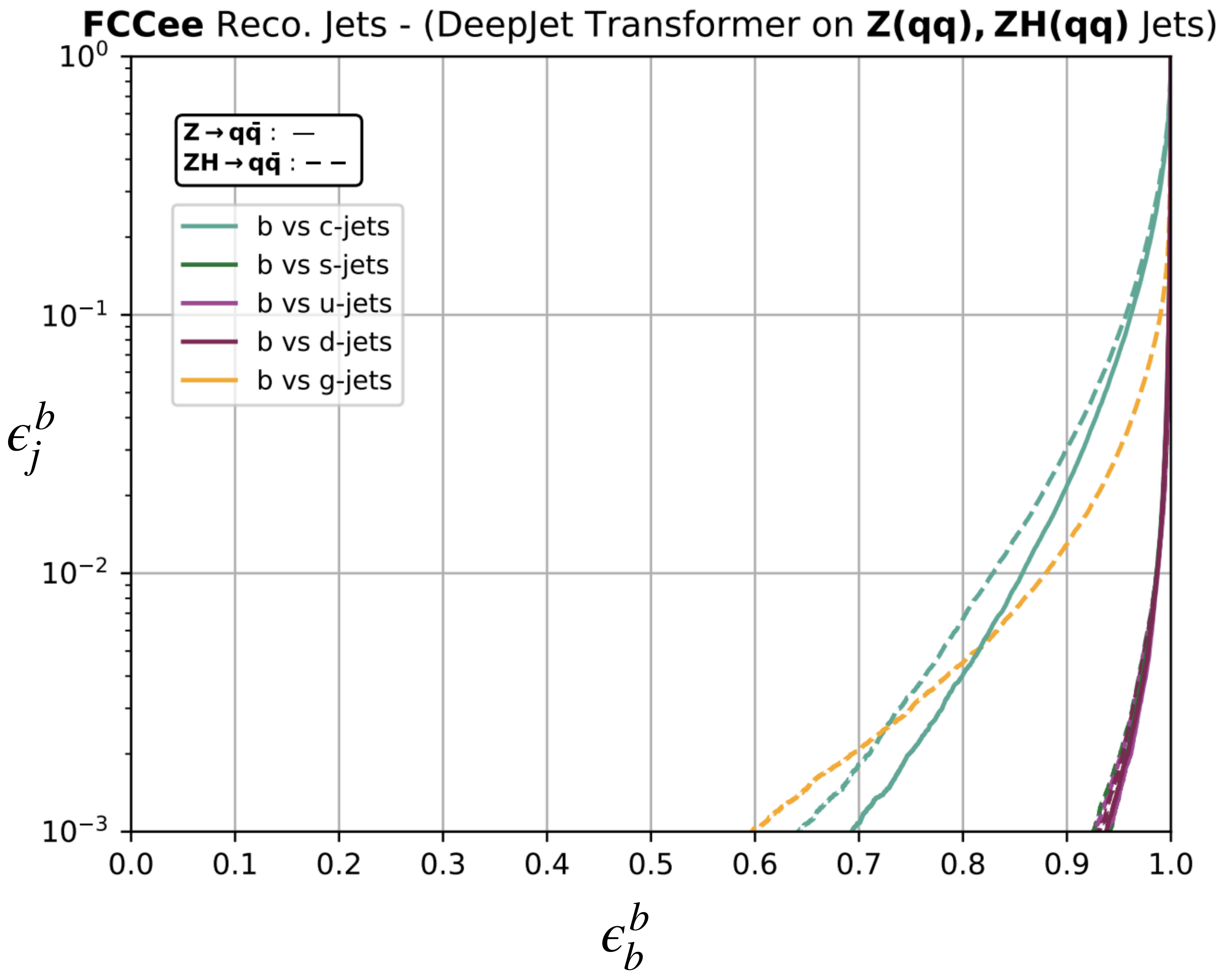
$$\left(\frac{\Delta R_b}{R_b}\right)^2 = \frac{1-\epsilon_b^b(2-\epsilon_b^b(2-R_b))}{N_{\text{tot}}R_b(\epsilon_b^b)^2}$$ → **True positives stat**

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



- 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)

Toy model: R_b

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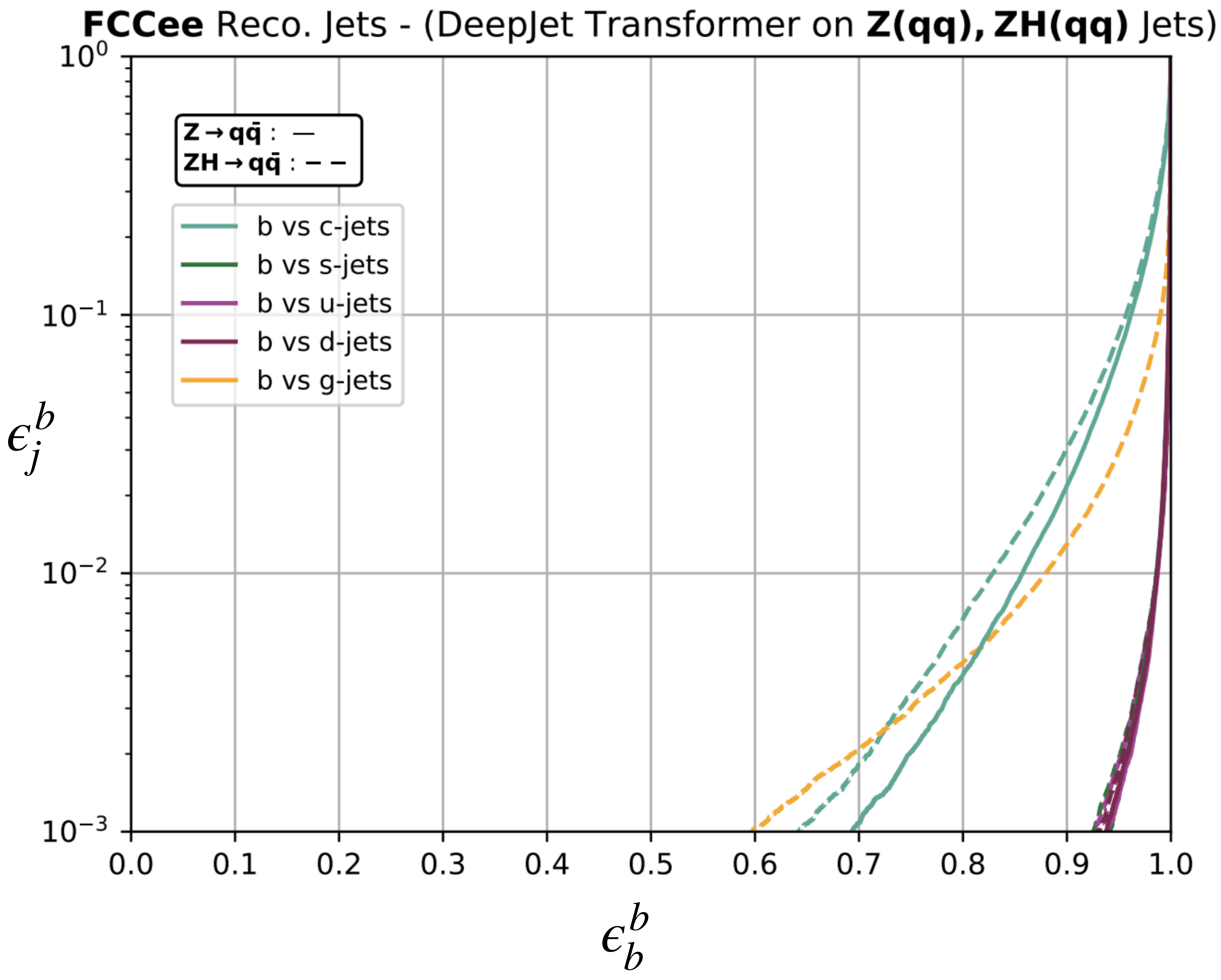

- Realistically $\delta_\epsilon \simeq 0.01$, consider WW run
- Minimize $\Delta R_b/R_b$ with $\epsilon_j^b = \epsilon_c^b(\epsilon_b^b)$ (conservative)

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

- Almost saturates naïve stat & theory limit
- LEP-II: $\Delta R_b/R_b \simeq O(0.01)$ 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 runs **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 $O(10^2)$ improvement compared to LEP-II

Room for improvement: s-tagging

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2. SMEFT interpretation
3. Conclusion

2. SMEFT interpretation

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

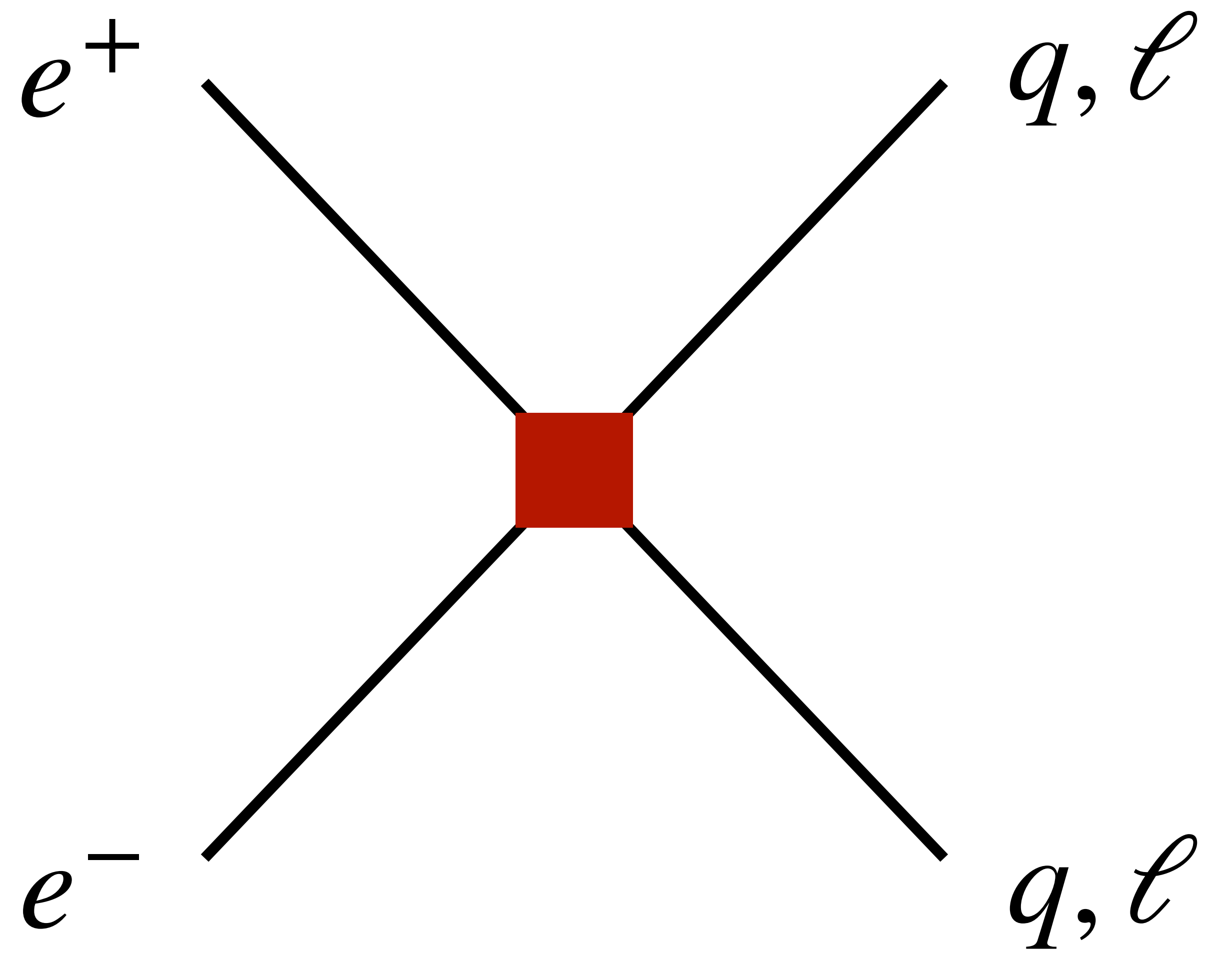
Consider ***flavor conserving, non-universal* 4F** interactions

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

- Tree-level: $2\ell 2q + 4\ell$ operators involving e^+e^- $(pr = 11)$



$2\ell 2q$	$\mathcal{O}_{\ell q}^{(1)}$	$(\bar\ell_p\gamma_\mu\ell_r)(\bar q_s\gamma^\mu q_t)$
	$\mathcal{O}_{\ell q}^{(3)}$	$(\bar\ell_p\gamma_\mu\tau^I\ell_r)(\bar q_s\gamma^\mu\tau_I q_t)$
	$\mathcal{O}_{eu}$	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$
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	$\mathcal{O}_{qe}$	$(\bar e_p\gamma_\mu e_r)(\bar q_s\gamma^\mu q_t)$
	$\mathcal{O}_{\ell edq}$	$(\bar\ell_p^j e_r)(\bar d_s q_t^j)$
	$\mathcal{O}_{\ell equ}^{(1)}$	$(\bar\ell_p^j e_r)\epsilon_{jk}(\bar q_s^k u_t)$
	$\mathcal{O}_{\ell equ}^{(3)}$	$(\bar\ell_p^j\sigma_{\mu\nu}e_r)\epsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$
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

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

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

- Tree-level: $2\ell 2q + 4\ell$ operators involving e^+e^- ($pr = 11$)
- Global 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)

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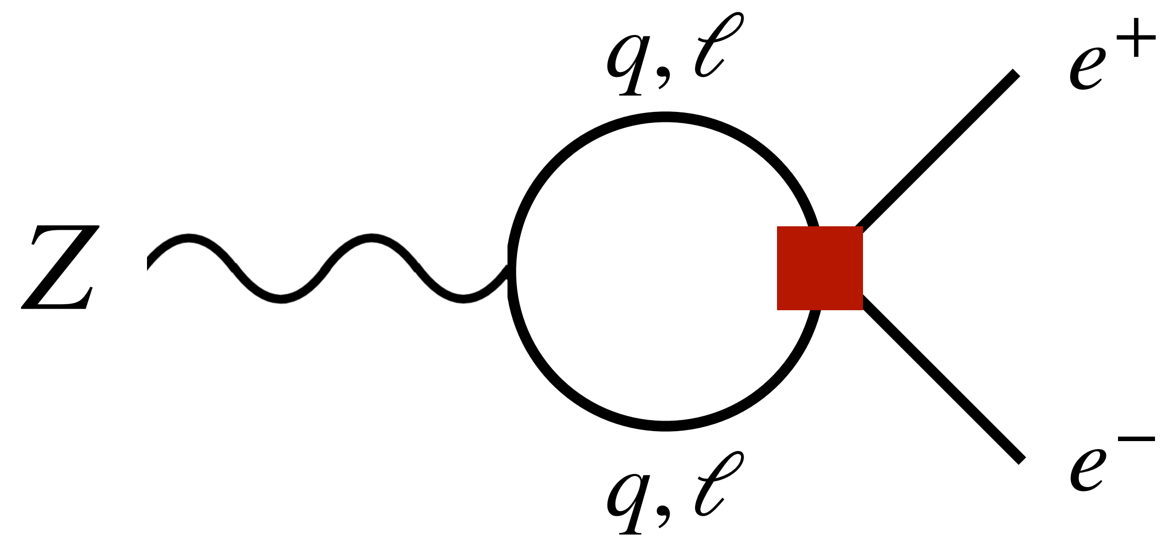
2. SMEFT interpretation

- 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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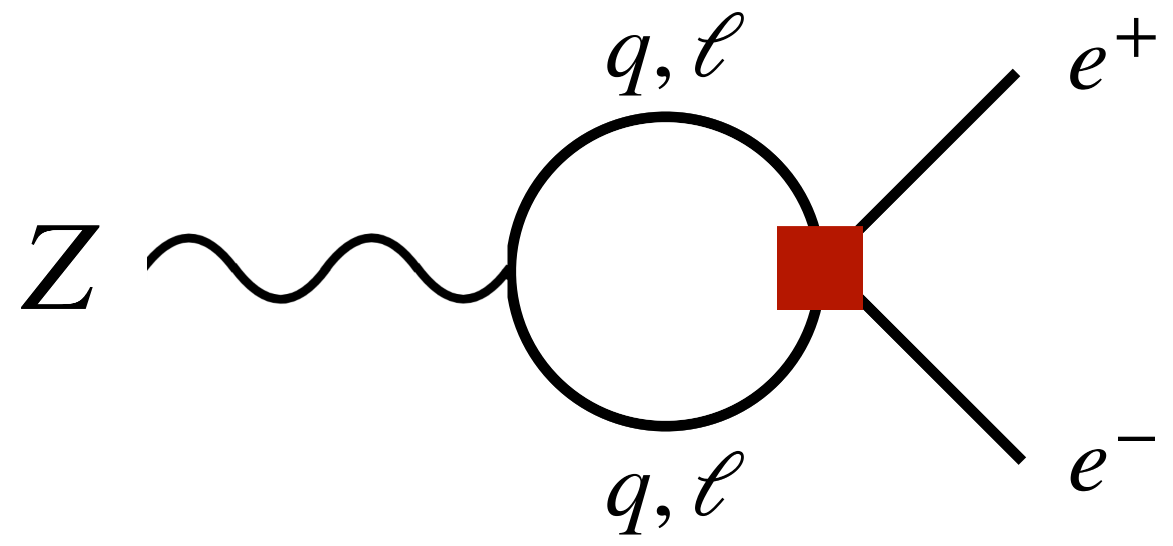
- **FCC-ee Z-pole**: **1-loop RGE** →

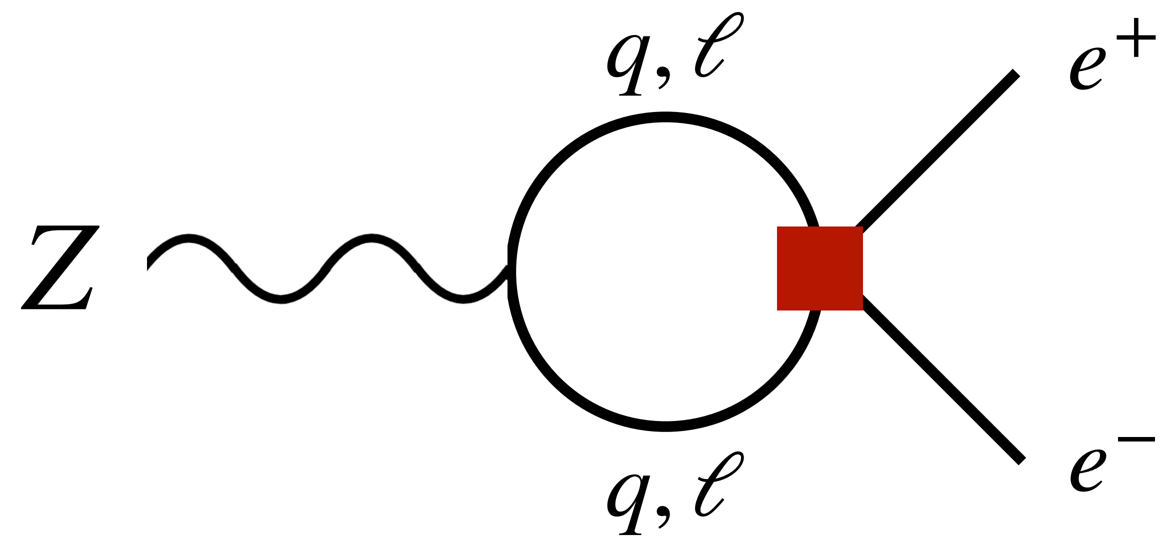


(y_t^2 for top, gauge others)

2. SMEFT interpretation

$2\ell 2q \quad 1111$

- 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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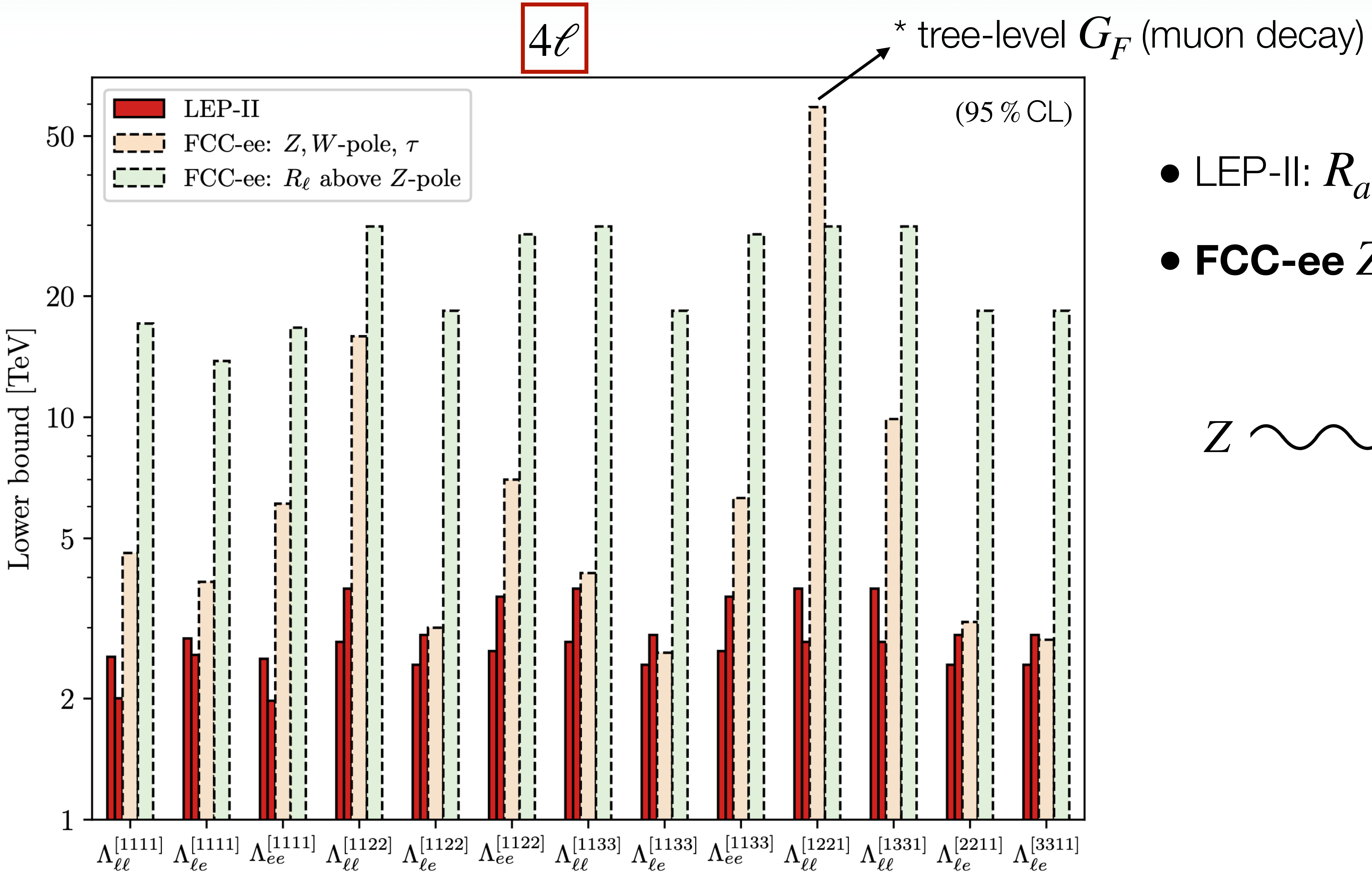
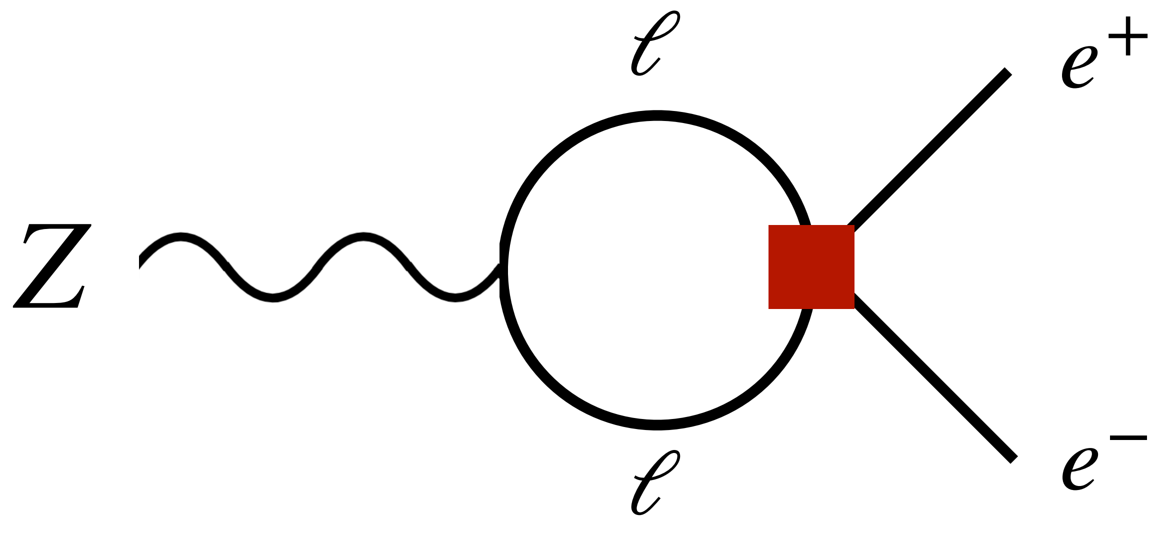


- LEP-II: R_a ratios
- **FCC-ee Z-pole**: **1-loop RGE***



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3. Conclusion

- Current results in flavor tagging at FCC-ee basically allow saturation

  of the naïve stat limit on R_b, R_c (for R_s improvement needed)

- R_a ratios above the Z-pole at FCC-ee:

  probe flavor conserving, non-universal new phyisics via 4F ops. up to $\mathcal{O}(50)$ TeV!

- SMEFT RGE:

  interplay/complementarity between Z-pole EWPO (1-loop) and above the pole (TL)

Thank you for your attention!

BACKUP

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:

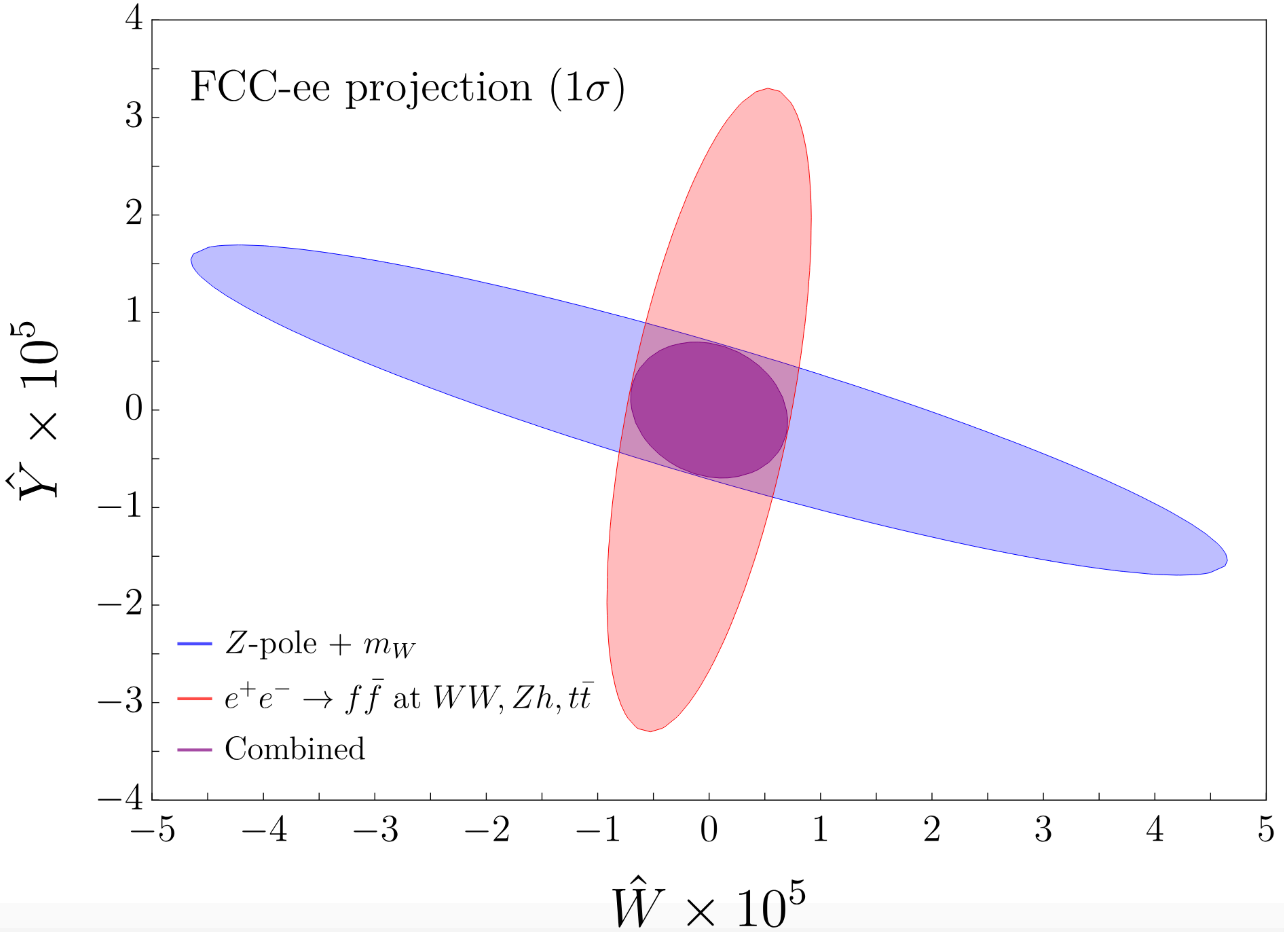
flavor conserving, non-universal 4F

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

$\sqrt{s} \supset m_z \pm 5$ 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:

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

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

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

<u>Bounds generally weaker/comparable with ones from hadronic decays</u>