New Physics Through Flavor Tagging at FCC-ee

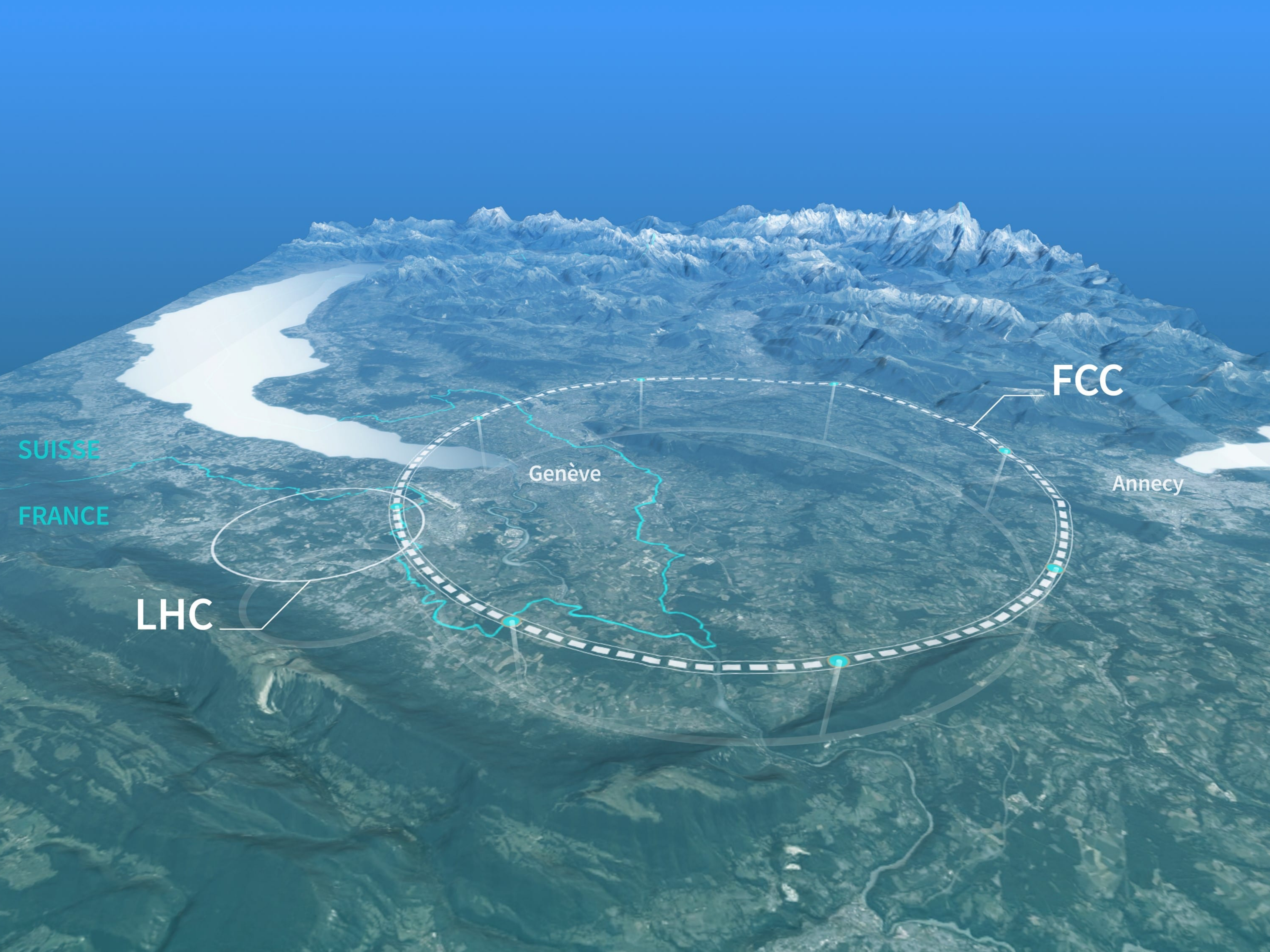
Based on: 2411.02485 with **Hector Tiblom** & **Alessandro Valenti**
and references there

Admir Greljo

University of Basel

FNSNF Swiss National Science Foundation
Eccellenza, Project-186866

06.11.2024, Open Questions and Future Directions in Flavour Physics, Mainz


FCC
SUISSE
FRANCE
Genève
Annecy
LHC

Motivation

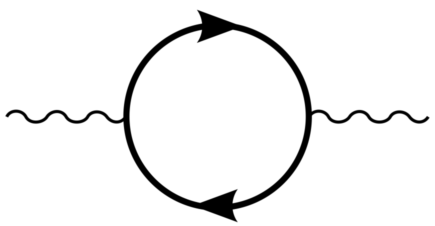
LEP

- Expedition to multi-TeV scale

$$m_W^2/m_*^2 \sim 10^{-3}$$

- Examination of the EW scale

Quantum corrections ~ 1-loop EW



FCC-ee

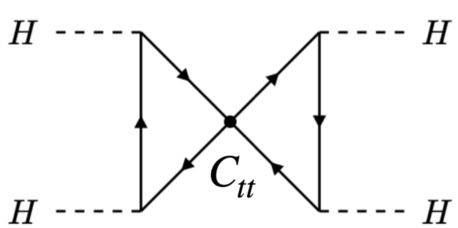
- Expedition to multi-10 TeV scale

$$m_W^2/m_*^2 \sim 10^{-5}$$

- Examination of multi-TeV scale

Access to broader BSM through quantum corrections

E.g. Right-handed top compositeness



Stefanek:2024kds

$$\mathrm{RG}: O_{4t} \to O_{Ht} \to O_{HD}$$

$$\frac{m_*}{g_*} \gtrsim 10\,\mathrm{TeV}$$

- Consolidation of the EW scale

~ 2-loop EW

Motivation

The baseline FCC-ee operation plan

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$		(s-channel H)
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340-350	365	m_H
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	115	230	28	8.5	0.95	1.55	(30)
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34	(7)
Physics Goal (ab^{-1})	150		10	5	0.2	1.5	(20)
Run time (year)	2	2	2	3	1	4	(3)
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k WW $\to$ H	$10^6 t\bar{t}$ +200k HZ +50k WW $\to$ H		(6000)

Blondel, Janot; 2106.13885

The Scope

- Physics focus: **New 4F contact interactions**!
- Three reference energies $> Z$:
  WW (163 GeV, 10 ab^{-1}), Zh (240 GeV, 5 ab^{-1}), $t\bar{t}$ (365 GeV, 1.5 ab^{-1})
- Processes: $e^+e^- \to b\bar{b}, c\bar{c}, s\bar{s}, jj, t\bar{t}, \tau^+\tau^-, \mu^+\mu^-, e^+e^-$
- Statistical precision $> Z$ is $10^{-4} - 10^{-3}$
- Theoretically clean observables: Sensitive to BSM & Experimentally accessible

Interference with the Z resonance

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{\mathcal{O}} C_{\mathcal{O}} \mathcal{O}_{4F}$$

$$\sigma_Z \sim \frac{s}{(s-M_z^2)^2 + M_z^2\Gamma_z^2}$$

$$\frac{\sigma_{\mathcal{O}}}{\sigma_Z} \sim C_{\mathcal{O}}(s-M_z^2)$$

$$s = (p_f + p_{\bar{f}})^2$$

- Two strategies:

1. Near the Z-pole ± 5 GeV: (Ge et al, 2410.17605)
   Larger statistics but smaller relative effect. Limited by theoretical uncertainty.

2. At $WW, Zh, t\bar{t}$ (our work)
   Smaller statistics but larger relative effect. Theory OK-ish.

Comparing our results with 2410.17605, method (2) stronger limits on $C_{\mathcal{O}}$

Even statistically!

Observables

$\sqrt{s'} > 0.85\sqrt{s}$

- (Inclusive, non-radiative) cross-section ratios

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

- Theoretically clean
  $\Delta R_b^Z / R_b^Z \sim 10^{-4}$ PDG EW review

- Experimentally, however, **flavor tagging** is crucial!

- Question:
  What are the FCC-ee projections on R_q ratios given the current state-of-the-art flavor taggers?

R_b measurement

Statistical model: Simplified scenario, R_b only

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

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

Total # of (hard) dijet events before flavor tagging

For simplicity, assume two quark flavors: j and b.
Run b-tagger on each jet.

ϵ_b^b (true positive) TP

ϵ_j^b (false positive) FP

R_b measurement

Statistical model: Simplified scenario, R_b only

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

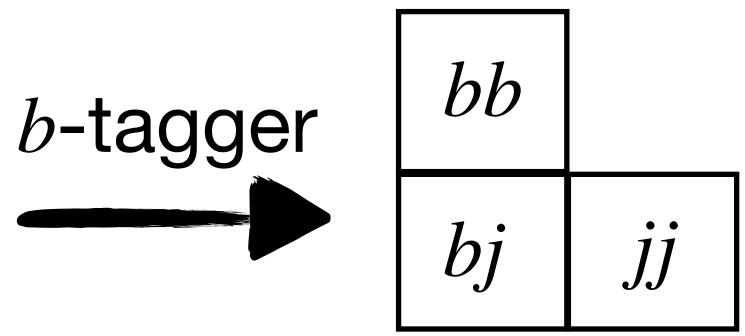
$$N_{\text{tot}} = \mathcal{L} \cdot \mathcal{A} \cdot \sigma(e^+e^- \to q\bar{q})$$

Total # of (hard) dijet events before flavor tagging

For simplicity, assume two quark flavors: j and b.
Run b-tagger on each jet.

ϵ_b^b (true positive) TP

ϵ_j^b (false positive) FP



$$R_j = 1 - R_b$$

$$N(n_b = 2) \equiv N_2 = N_{\text{tot}}[(\epsilon_b^b)^2 R_b + (\epsilon_j^b)^2 R_j]\,,$$

$$N(n_b = 1) \equiv N_1 = 2N_{\text{tot}}[\epsilon_b^b(1-\epsilon_b^b)R_b + \epsilon_j^b(1-\epsilon_j^b)R_j]$$

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

- - - - - - - - - - - - - - - - - - -

R_b measurement

Statistical model: Simplified scenario, R_b only

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

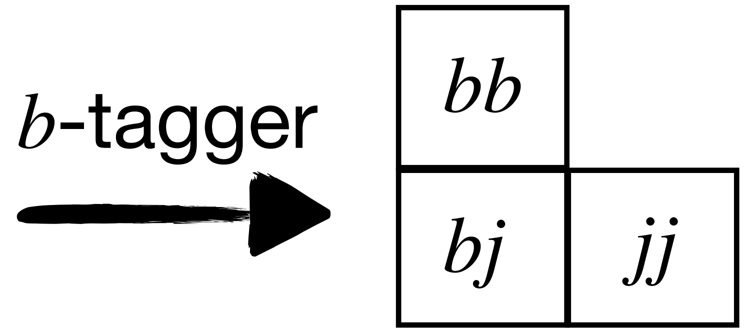
$$N_{\rm tot} = \mathcal{L} \cdot \mathcal{A} \cdot \sigma(e^+e^- \to q\bar{q})$$

Total # of (hard) dijet events before flavor tagging

For simplicity, assume two quark flavors: j and b.
Run b-tagger on each jet.

ϵ_b^b (true positive) TP

ϵ_j^b (false positive) FP



$$R_j = 1 - R_b$$

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

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

- Fit parameters:
  $N_{\rm tot}$, ϵ_b^b, R_b, ϵ_j^b

  $\epsilon_j^b \to \epsilon_j^b(1+x)$
- MC input systematics δ_ϵ

R_b measurement

Statistical model: Simplified scenario, R_b only

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

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

Total # of (hard) dijet events before flavor tagging

For simplicity, assume two quark flavors: j and b.
Run b-tagger on each jet.

ϵ_b^b (true positive) TP

ϵ_j^b (false positive) FP

b-tagger →

bb	
bj	jj

$$R_j = 1 - R_b$$

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

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

- Fit parameters: $N_{\rm tot}$, ϵ_b^b, R_b, ϵ_j^b

  $\epsilon_j^b \to \epsilon_j^b(1+x)$

- MC input systematics δ_ϵ

→

$$\left(\frac{\Delta R_b}{R_b}\right)^2 = \frac{1-\epsilon_b^b(2-\epsilon_b^b(2-R_b))}{N_{\rm tot}R_b(\epsilon_b^b)^2} + \frac{2(\epsilon_b^b - R_b(2-\epsilon_b^b)(2\epsilon_b^b-1))}{N_{\rm tot}R_b^2(\epsilon_b^b)^3}\epsilon_j^b + \frac{4(R_b-1)^2(\epsilon_j^b)^2}{R_b^2(\epsilon_b^b)^2}(\delta_\epsilon)^2 + \mathcal{O}\left((\epsilon_j^b)^2\right).$$

TP stat

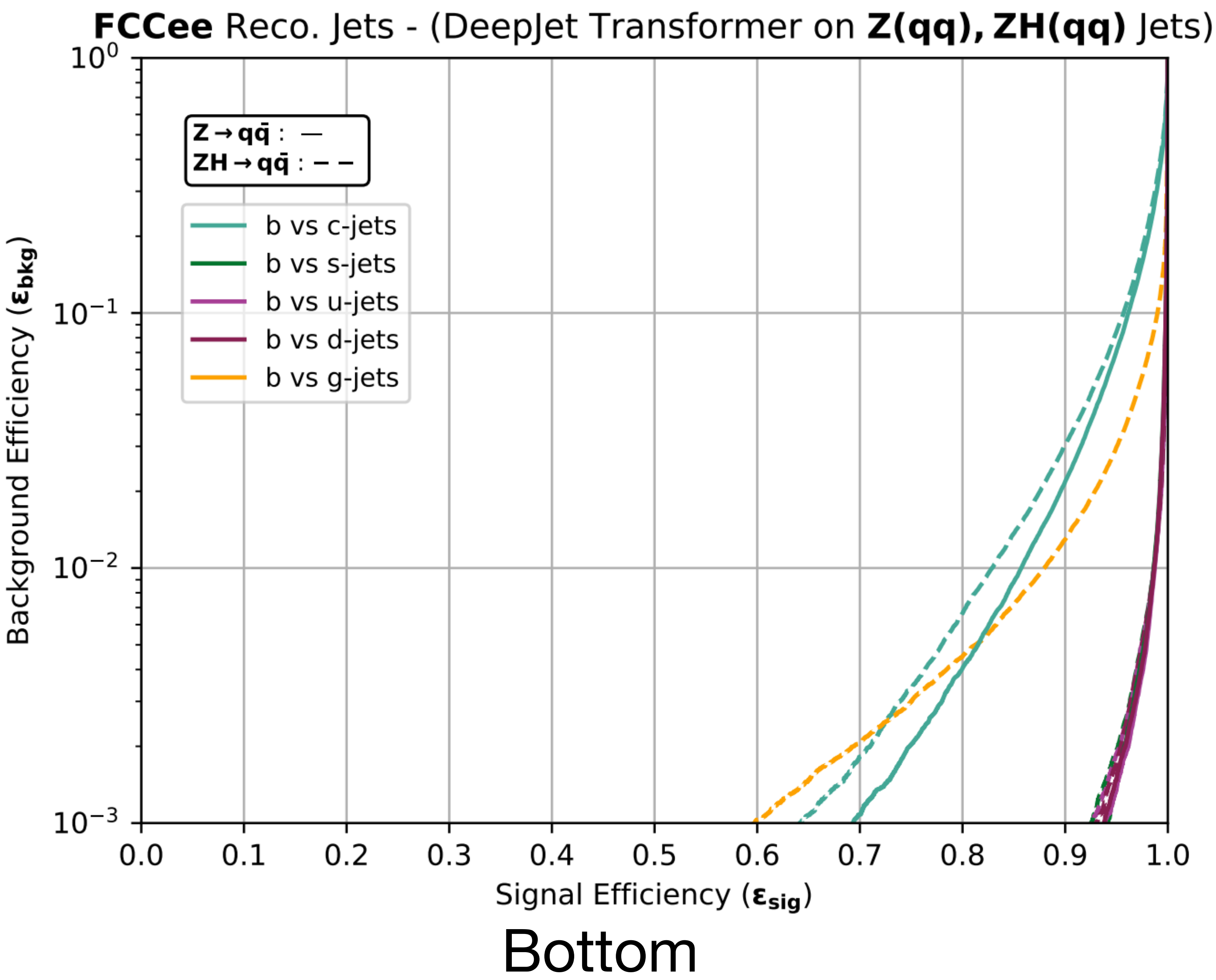
FP stat

FP syst

DeepJetTransformer

Blekman et all, 2406.08590

Jet Flavour Tagging ROC curves at FCC-ee: $FP(TP)$



- Conservatively take: $j = c$
- Optimal point $\epsilon_j^b \simeq 10^{-3}$, and $\epsilon_b^b \simeq 0.65$
- Realistic estimate

$$\delta_\epsilon \simeq 0.01$$

$$\Longrightarrow$$

$$\Delta R_b / R_b \approx 1/\sqrt{N_{\rm tot} R_b}$$

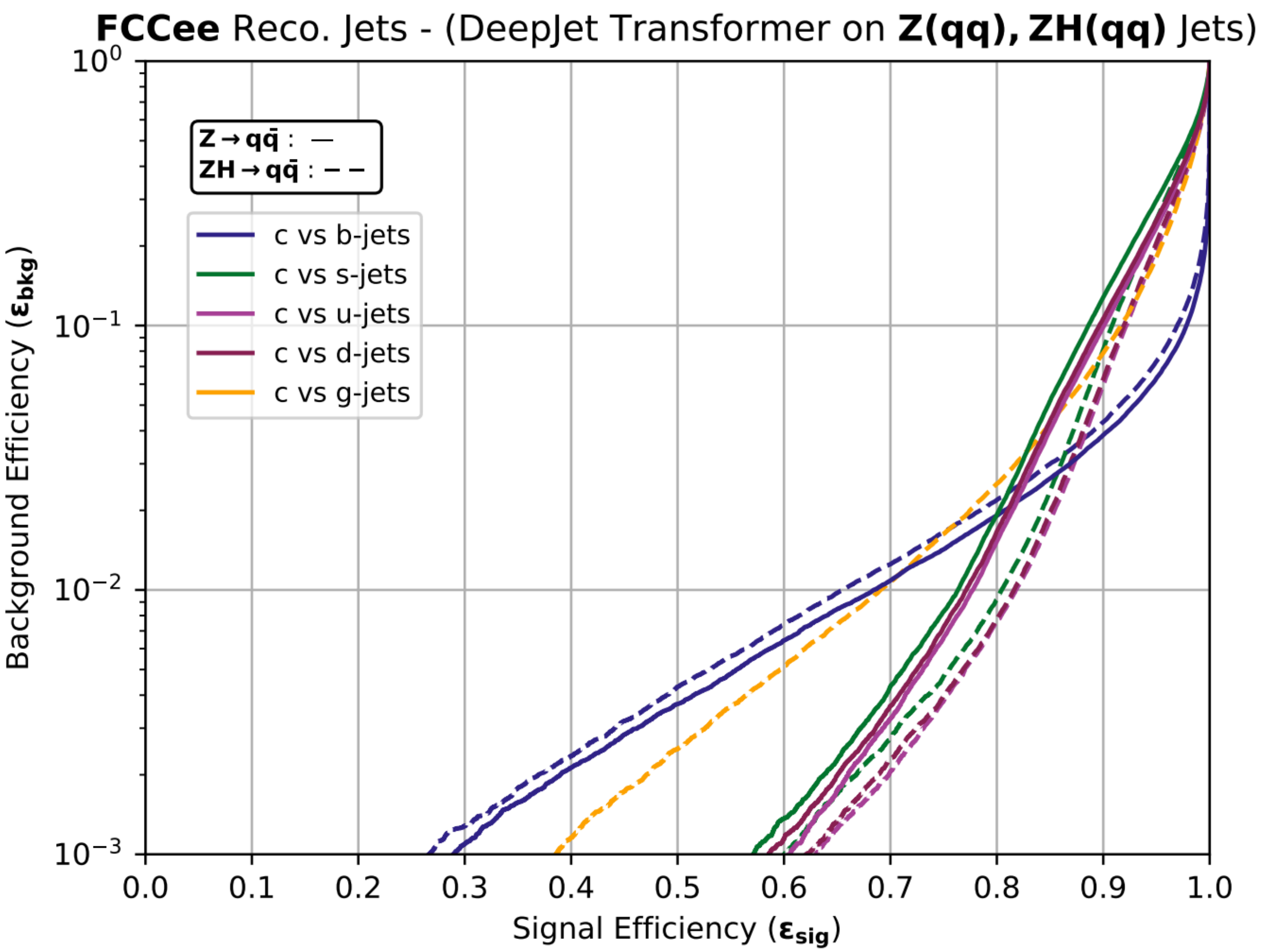
Almost reaches the naive statistical limit!

*Careful with additional backgrounds like collimated jets from VV; see the paper.

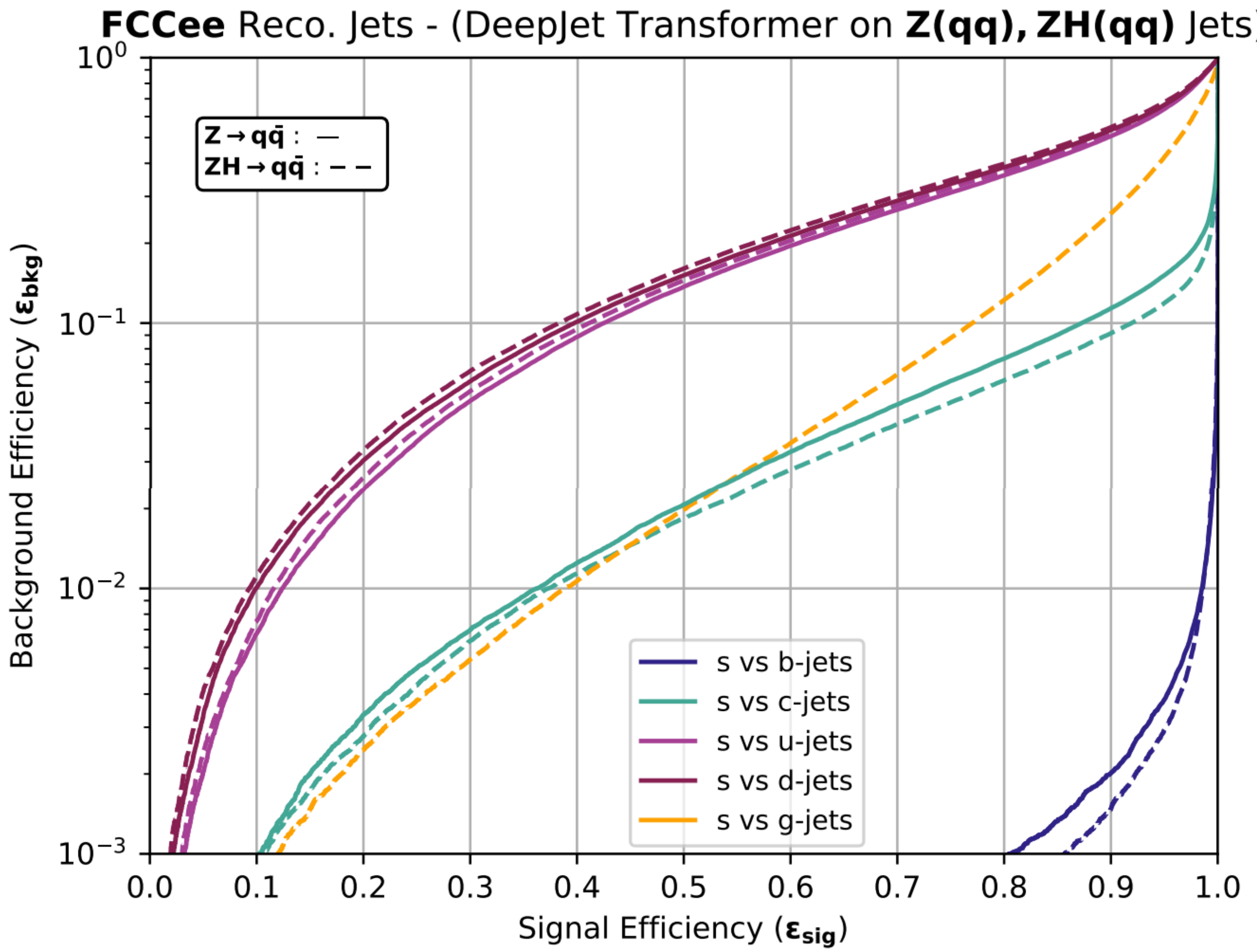
DeepJetTransformer

Blekman et all, 2406.08590

Jet Flavour Tagging ROC curves at FCC-ee: $FP(TP)$



Charm



Strange

- Question:
  What about simultaneous R_b, R_c, R_s determination?

R_b, R_c, R_s simultaneously

Generalisation

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

$i, j, z \in \{b, s, c, j\}$ $\quad \sum_z R_z = 1$

bb			
bc	cc		
bs	cs	ss	
bj	cj	sj	jj

Run orthogonal b-tagger, c-tagger and s-tagger on each jet.

$i \to z : \epsilon_i^z \qquad \sum_z \epsilon_i^z = 1$

- Fit parameters:

  $N_{\text{tot}}, R_b, R_s, R_c + \epsilon_b^b, \epsilon_s^s, \epsilon_c^c$

  +1% uncorr. systematics on FP

  closes the fit!

  → Optimize on the ROC curves

e.g. WW run small correlation

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

$$\frac{\Delta R_b}{R_b} = 1.7 \cdot 10^{-4}, \quad \frac{\Delta R_s}{R_s} = 3.7 \cdot 10^{-3}, \quad \frac{\Delta R_c}{R_c} = 1.4 \cdot 10^{-4}$$

:) :| :)

Summary: $> Z$ pole

Observable/FCC-ee Rel. Err. (10^{-4})	WW	Zh	$t\bar{t}$
R_b	1.7	3.6	9.6
R_s	37	58	100
R_c	1.4	2.7	6.9
R_t	-	-	12
$R_{\tau,\mu}$	1.6	3.5	9.7
R_e	5.0	5.2	6.4

Summary: Z pole

Observable	Curr. Rel. Err. (10^{-3})	FCC-ee Rel. Err. (10^{-3})
Γ_Z	2.3	0.1
$\sigma^0_{\rm had}$	37	5
R_b^Z	3.06	0.3
R_c^Z	17.4	1.5
$A_{\rm FB}^{0,b}$	15.5	1
$A_{\rm FB}^{0,c}$	47.5	3.08
A_b^Z	21.4	3
A_c^Z	40.4	8
R_e^Z	2.41	0.3
R_μ^Z	1.59	0.05
R_τ^Z	2.17	0.1
$A_{\rm FB}^{0,e}$	154	5
$A_{\rm FB}^{0,\mu}$	80.1	3
$A_{\rm FB}^{0,\tau}$	104.8	5
A_e^Z	14.3	0.11
A_μ^Z	102	0.15
A_τ^Z	102	0.3
N_ν	50	0.8

Summary: W pole and τ decays

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

SMEFT interpretation

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

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{\mathcal{O}} C_{\mathcal{O}} \mathcal{O}_{4F}$$

- Limits on $\Lambda_{\mathcal{O}} = C_{\mathcal{O}}^{-1/2}$
- Consider flavor-conserving non-universal $\Delta F = 0$

SMEFT interpretation

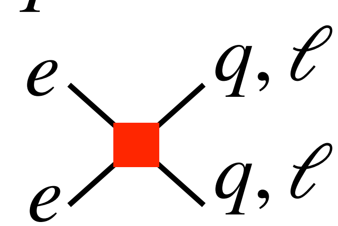
$2q2\ell$	$\mathcal{O}_{\ell q}^{(1)}$	$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{q}_s \gamma^\mu q_t)$
	$\mathcal{O}_{\ell q}^{(3)}$	$(\bar{\ell}_p \gamma_\mu \tau^I \ell_r)(\bar{q}_s \gamma^\mu \tau_I q_t)$
	$\mathcal{O}_{eu}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
	$\mathcal{O}_{ed}$	$(\bar{e}_p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

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{\mathcal{O}} C_{\mathcal{O}} \mathcal{O}_{4F}$$

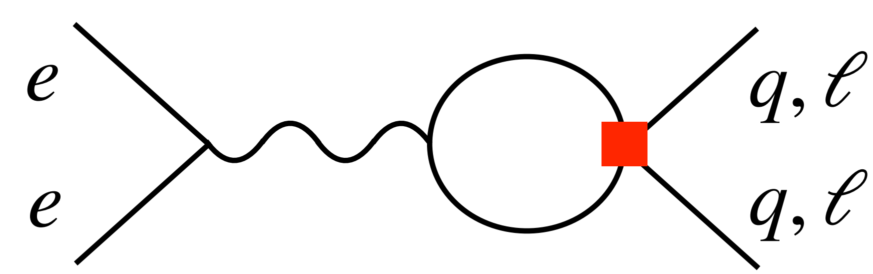
- Limits on $\Lambda_{\mathcal{O}} = C_{\mathcal{O}}^{-1/2}$
- Consider flavor-conserving non-universal $\Delta F = 0$

R ratios $> Z$

- Tree-level effect: $2q2\ell$ and 4ℓ with $pr = 11$



- SMEFT RG (gauge running): all vectorial operators



SMEFT interpretation

- Example: $[\mathcal{O}_{qe}]_{3311}$

Observable/FCC-ee Rel. Err. (10^{-4})	WW	Zh	$t\bar{t}$
R_b	1.7	3.6	9.6

But $\frac{\Delta R_b}{R_b} \sim \frac{s}{\Lambda^2}$

- Energy vs Precision!

Thus, the bound on

$$\Lambda_{qe,3311} = \{17.8, 17.4, 16.5\}\ \text{TeV}$$

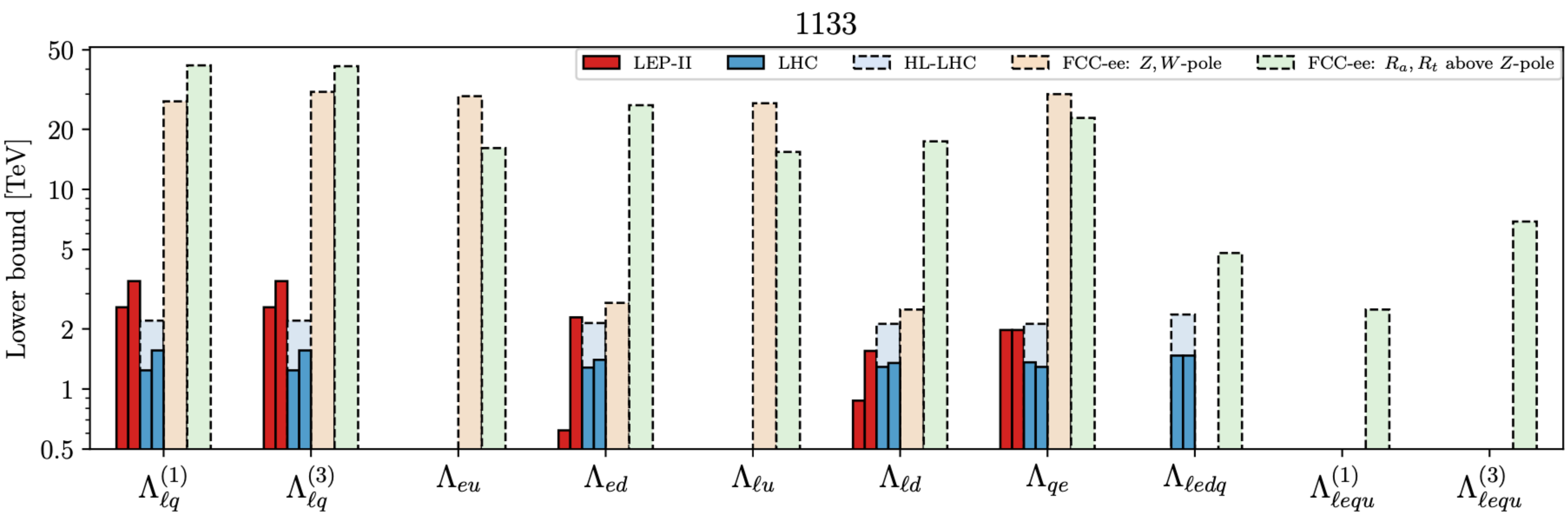
$WW, Zh,$ and $t\bar{t}$ runs

Similar sensitivity at different energies!

*in the rest of the talk, we combine the three runs.

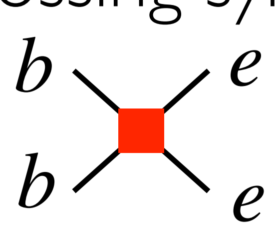
SMEFT interpretation

$2q2\ell$ **tree-level:** 3rd quark family — electrons



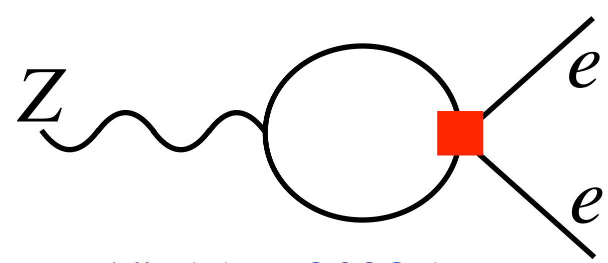
High-pT Drell-Yan

- Crossing symmetry



Greljo:2017vvb

Z-pole observables

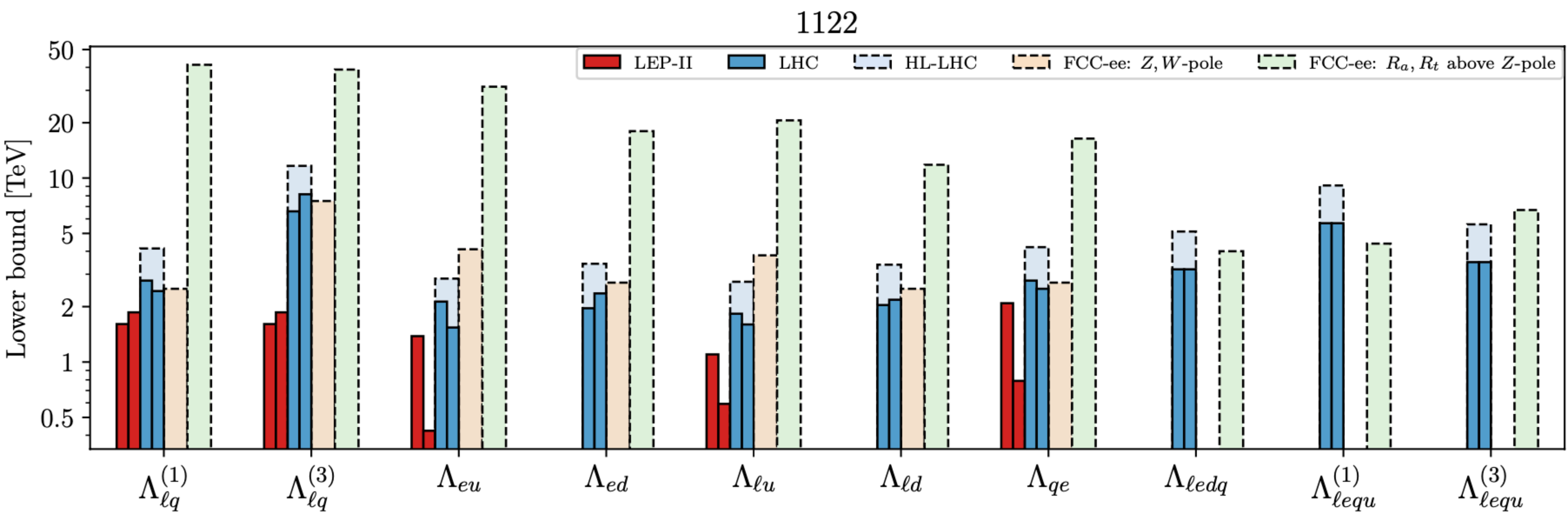


y_t^2 contribution for 3rd family
Otherwise, gauge running

Allwicher:2023shc

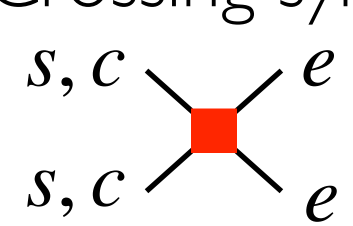
SMEFT interpretation

$2q2\ell$ tree-level: 2nd quark family — electrons



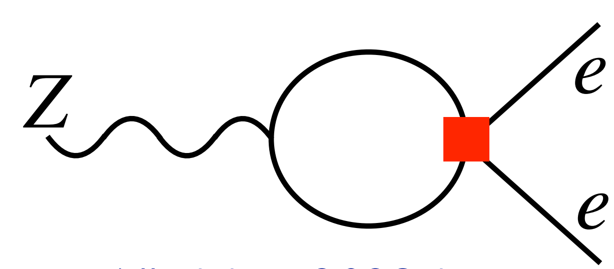
High-pT Drell-Yan

- Crossing symmetry



Greljo:2017vvb

Z-pole observables

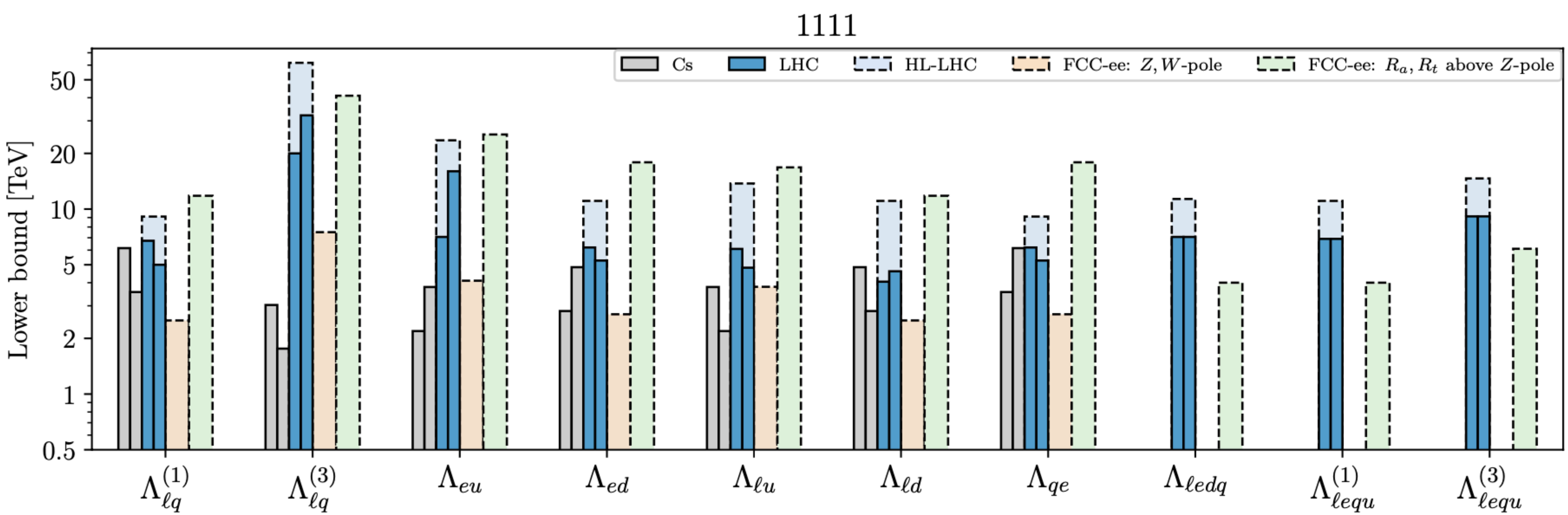


Gauge running

Allwicher:2023shc

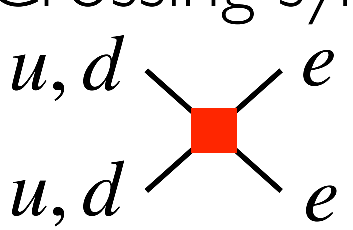
SMEFT interpretation

$2q2\ell$ tree-level: 1st quark family — electrons



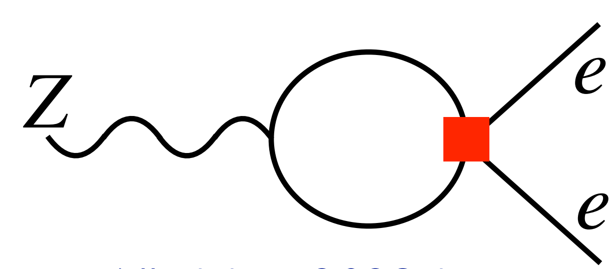
High-pT Drell-Yan

- Crossing symmetry



Greljo:2017vvb

Z-pole observables

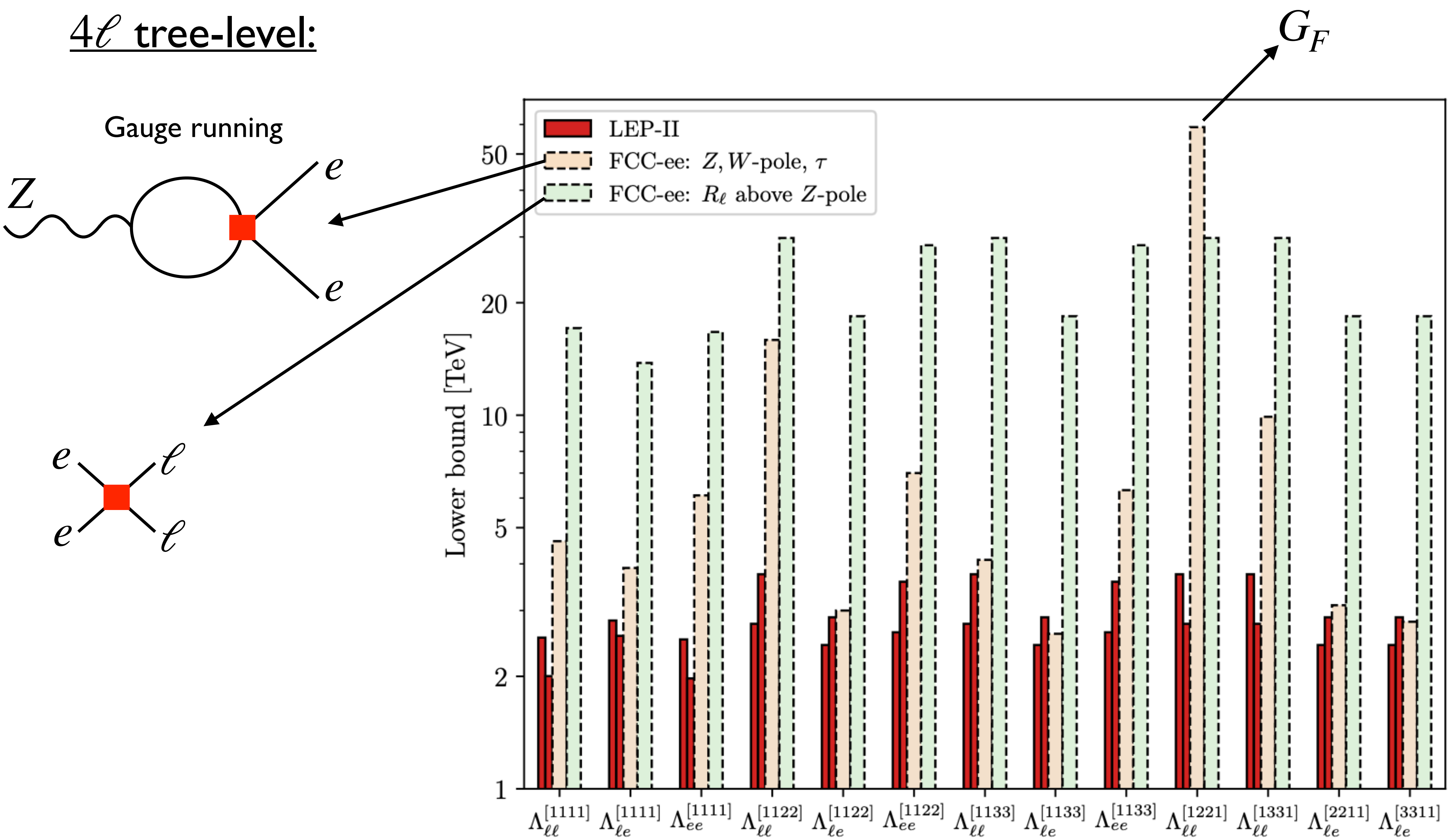


Gauge running

Allwicher:2023shc

SMEFT interpretation

4ℓ tree-level:



SMEFT interpretation

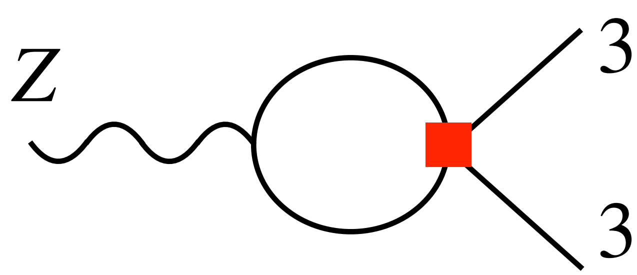
Oblique corrections:

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

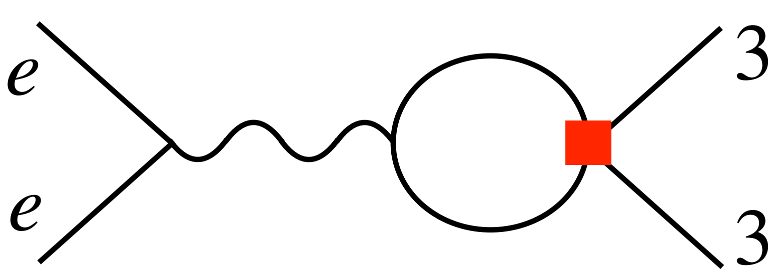
	$\hat{W} \times 10^5$	$\hat{Y} \times 10^5$
Current (LHC)	$[-19, 5]$	$[-31, 14]$
HL-LHC	$[-4.5, 6.9]$	$[-6.4, 8.0]$
FCC-ee pole observables	$[-1.7, 1.7]$	$[-12, 12]$
FCC-ee above the pole	$[-0.62, 0.62]$	$[-2.3, 2.3]$

SMEFT interpretation

Third-family dominance:



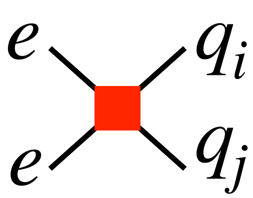
VS



$\Lambda^{[3333]}$ [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

TABLE VII: The 95% CL bounds at and above the Z-pole (at one-loop) on operators with flavor indices $prst = 3333$.

Flavor violation $\Delta F = 1$



$$R_{ij} = \frac{\sigma(e^+e^- \to q_i\bar{q}_j) + \sigma(e^+e^- \to q_j\bar{q}_i)}{\sum_{k,l=u,d,s,c,b}\sigma(e^+e^- \to q_k\bar{q}_l)}$$

$$N_{ij} = N_{\rm tot}\sum_{k,l}\frac{1+\delta_{kl}}{1+\delta_{ij}}R_{kl}\epsilon^i_k\epsilon^j_l$$

$$R_{ij} < \frac{\sigma_b}{N_{\rm tot}\epsilon^i_i\epsilon^j_j}\cdot\Phi^{-1}(1-\alpha)$$

- 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	$2.70 \cdot 10^{-4}$

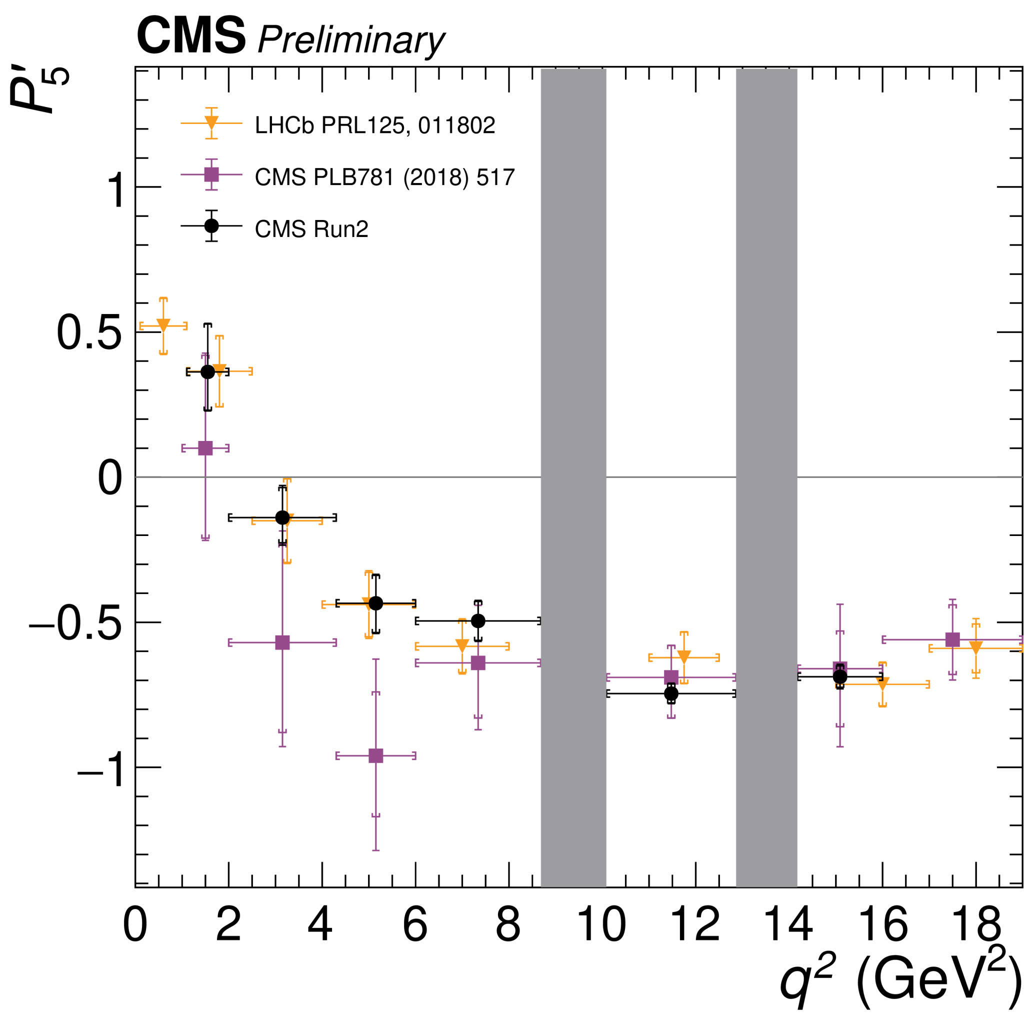
- SMEFT contributes at order Λ^{-4} to R_{ij}
- Indirect limits $q_i \to q_j e^+ e^-$ already provide too strong of a target.

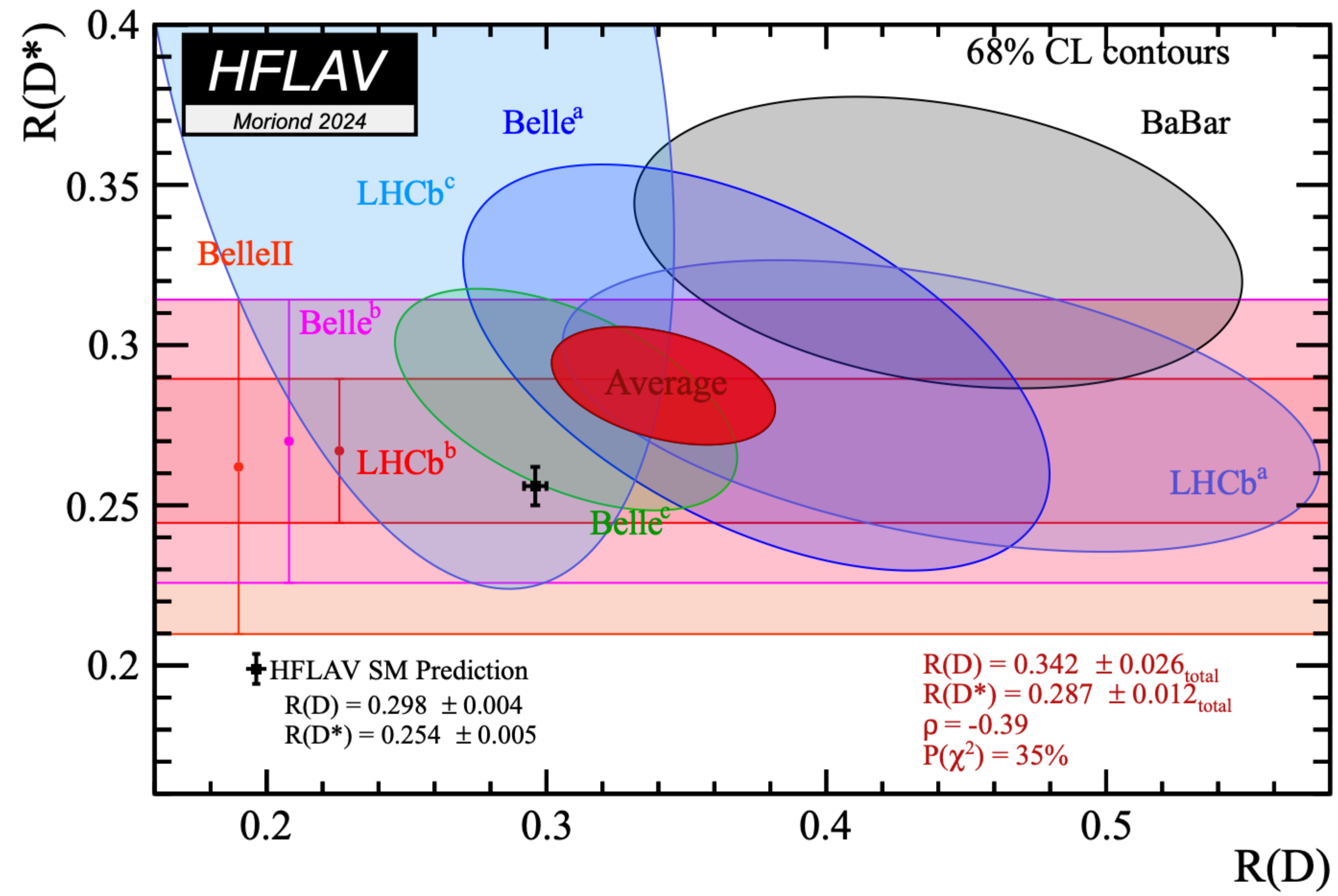
Models

Infamous B*-anomalies*

$$b \to s\ell^+\ell^-$$

$$b \to c\tau\nu$$





while $R_X \sim 1$

Let's take NP models that explain one (or both) and see what FCC-ee has to say!

Model I: Scalar LQ for $b \to s\ell^+\ell^-$

$U(2)_\ell$ flavor doublet: $\alpha = 1, 2$

$S^\alpha \sim (\overline{\mathbf{3}}, \mathbf{3}, 1/3) = (S_e, S_\mu)^T$

Quark doublet:

$q^i = (V^*_{ji} u^j_L, d^i_L)^T$

$$\mathcal{L} \supset -M^2 S^\dagger_\alpha S^\alpha - (\lambda_i \, \bar{q}^c_i \ell_\alpha S^\alpha + \text{h.c.})$$

Model I: Scalar LQ for $b \to s\ell^+\ell^-$

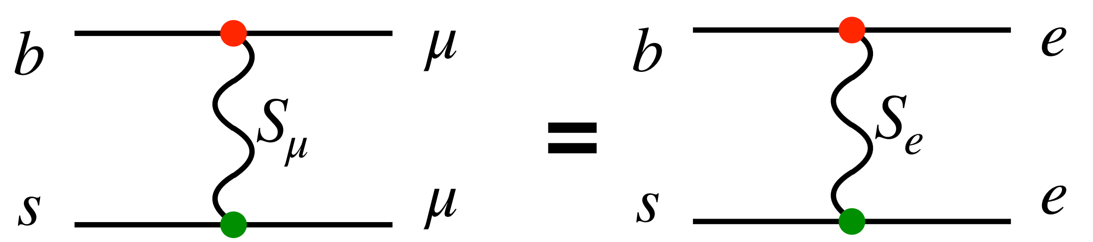
$U(2)_\ell$ flavor doublet: $\alpha = 1, 2$

$S^\alpha \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3) = (S_e, S_\mu)^T$

Quark doublet:

$q^i = (V^*_{ji} u^j_L, d^i_L)^T$

$$\mathcal{L} \supset -M^2 S^\dagger_\alpha S^\alpha - (\lambda_i\, \bar{q}^c_i \ell_\alpha S^\alpha + \text{h.c.})$$



$\Delta C_9^{\rm univ} = -\Delta C_{10}^{\rm univ}$

$\sim r_s r_b$ where $r_i = \dfrac{\lambda_i}{M}$

LFU LQ: Corrects P_5' while $R_X = 1$

Model I: Scalar LQ for $b \to s\ell^+\ell^-$

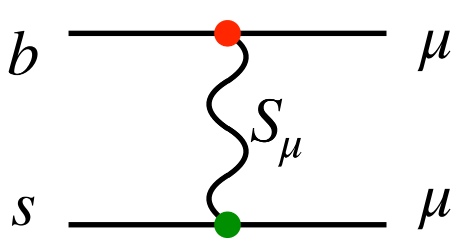
$U(2)_\ell$ flavor doublet: $\alpha = 1, 2$

$S^\alpha \sim (\overline{\mathbf{3}}, \mathbf{3}, 1/3) = (S_e, S_\mu)^T$

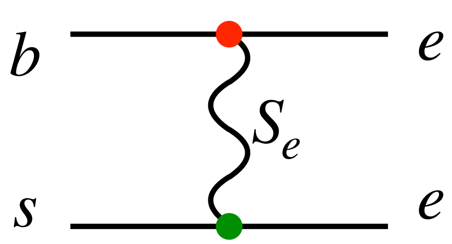
Quark doublet:

$q^i = (V^*_{ji} u^j_L, d^i_L)^T$

$$\mathcal{L} \supset -M^2 S^\dagger_\alpha S^\alpha - (\lambda_i \, \bar{q}^c_i \ell_\alpha S^\alpha + \text{h.c.})$$



=



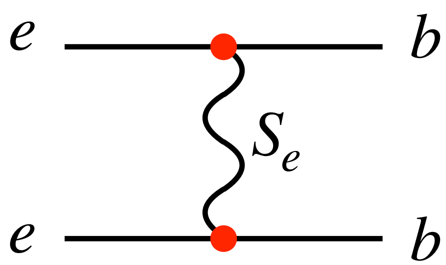
$\Delta C_9^{\text{univ}} = -\Delta C_{10}^{\text{univ}}$

$\sim r_s r_b$

where $r_i = \dfrac{\lambda_i}{M}$

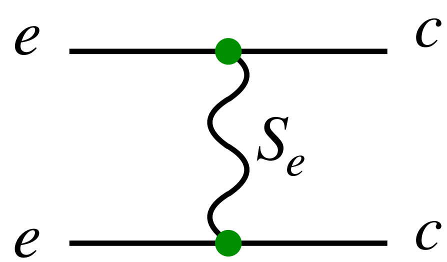
LFU LQ: Corrects P_5' while $R_X = 1$

FV implies FC!



$\sim r_b^2$

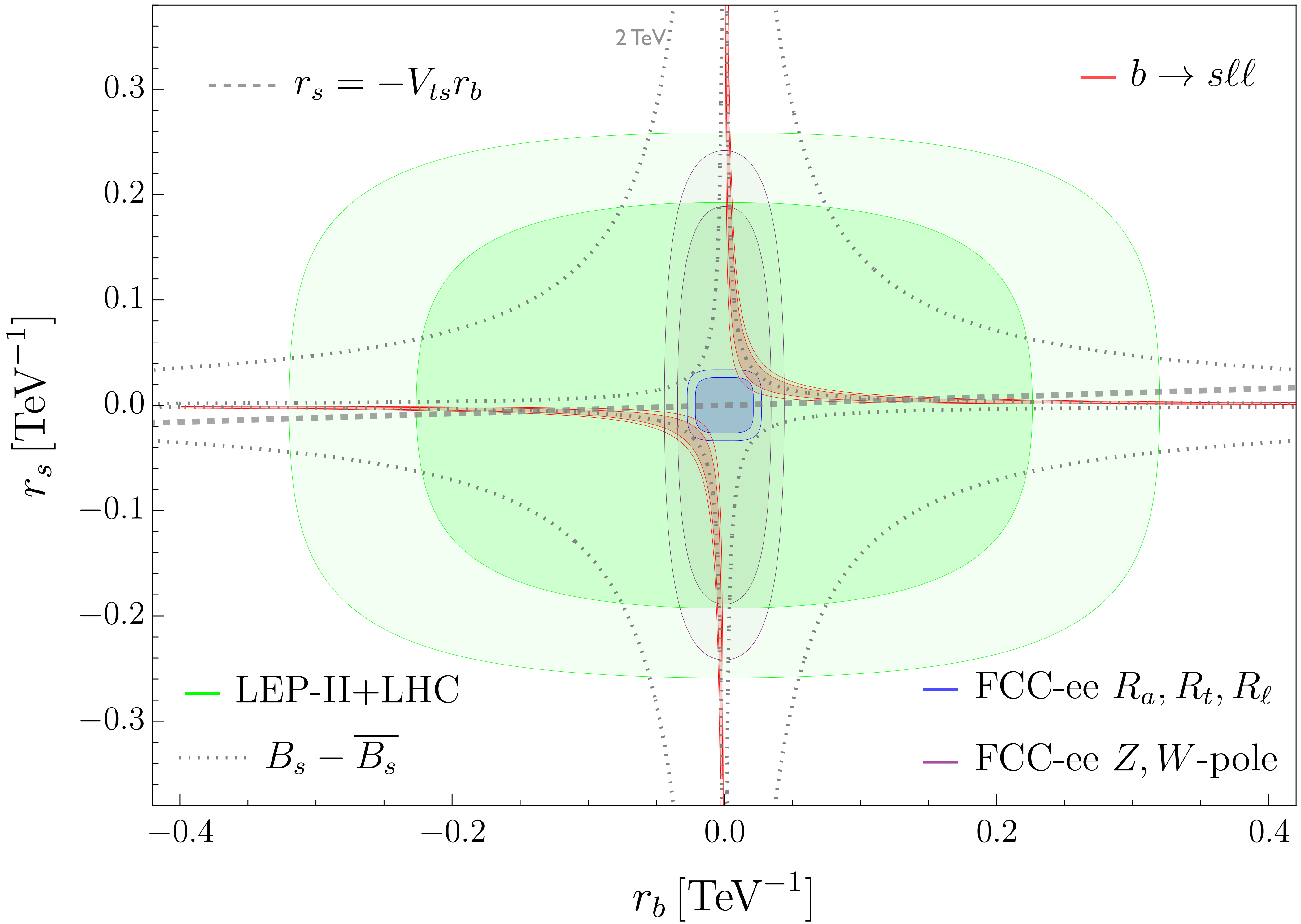
R_b **at FCC-ee**



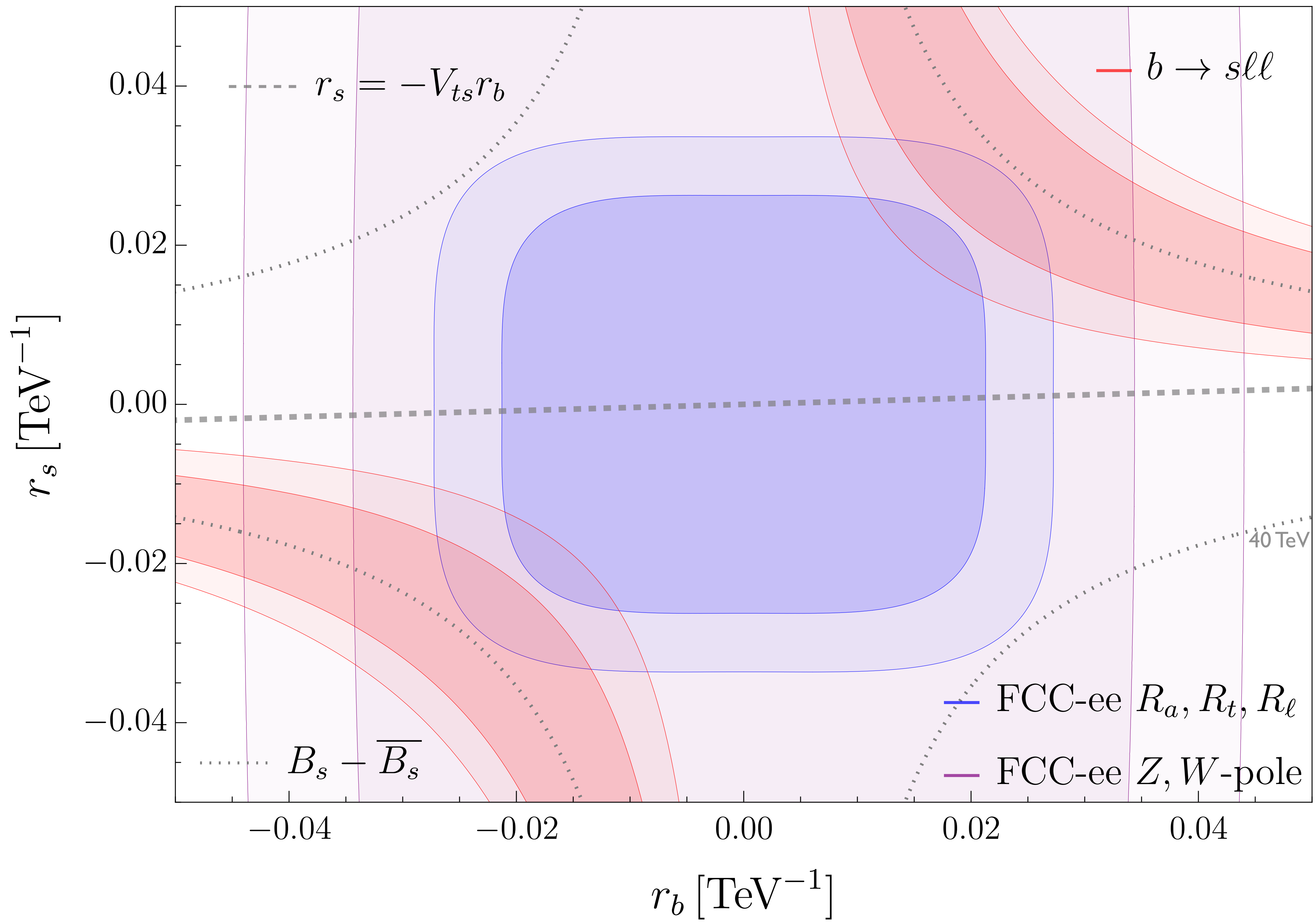
$\sim r_s^2$

R_c **at FCC-ee**

Model I: **Scalar LQ for $b \to s\ell^+\ell^-$**



Model I: Scalar LQ for $b \to s\ell^+\ell^-$



Model II: Z' for $b \to s\ell^+\ell^-$

Massive vector: $Z'_\mu \sim (\mathbf{1}, \mathbf{1}, 0)$

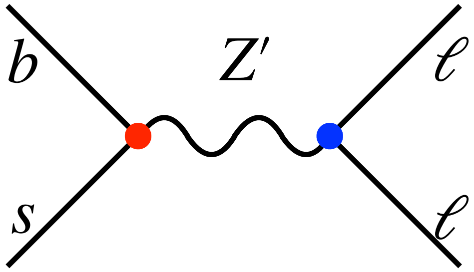
$$\mathcal{L} \supset g_{ij}\bar{q}_i\gamma_\mu q_j Z'^\mu + g_\ell(\bar{\ell}_\alpha\gamma_\mu\ell_\alpha + \bar{e}_\alpha\gamma_\mu e_\alpha)Z'^\mu$$

Model II: Z' for $b \to s\ell^+\ell^-$

Massive vector: $Z'_\mu \sim (\mathbf{1}, \mathbf{1}, 0)$

$$\mathcal{L} \supset g_{ij} \bar{q}_i \gamma_\mu q_j Z'^\mu + g_\ell (\bar{\ell}_\alpha \gamma_\mu \ell_\alpha + \bar{e}_\alpha \gamma_\mu e_\alpha) Z'^\mu$$

$\Longrightarrow C_9^{\text{univ}} \sim r_\ell r_{sb}$



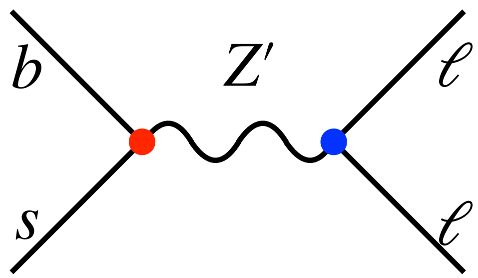
$r_x = \frac{g_x}{M}$

Model II: Z' for $b \to s\ell^+\ell^-$

Massive vector: $Z'_\mu \sim (\mathbf{1}, \mathbf{1}, 0)$

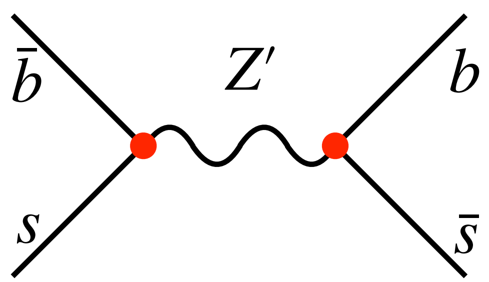
$$\mathcal{L} \supset g_{ij}\bar{q}_i\gamma_\mu q_j Z'^\mu + g_\ell(\bar{\ell}_\alpha\gamma_\mu\ell_\alpha + \bar{e}_\alpha\gamma_\mu e_\alpha)Z'^\mu$$

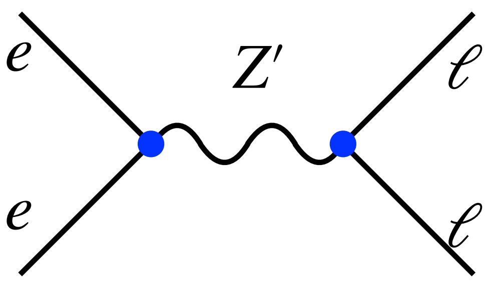
$$\Longrightarrow C_9^{\text{univ}} \sim r_\ell r_{sb}$$



$$r_x = \frac{g_x}{M}$$

However, also:





Meson mixing

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

LEP-II, R_ℓ at FCC-ee

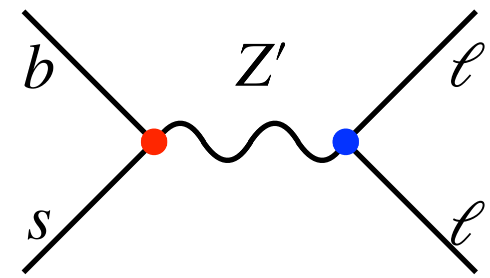
$$\sim r_\ell^2$$

Model II: Z' for $b \to s\ell^+\ell^-$

Massive vector: $Z'_\mu \sim (\mathbf{1}, \mathbf{1}, 0)$

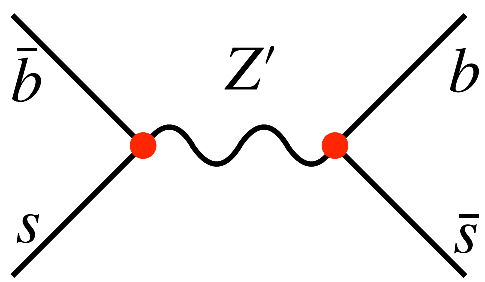
$$\mathcal{L} \supset g_{ij}\bar{q}_i\gamma_\mu q_j Z'^\mu + g_\ell(\bar{\ell}_\alpha\gamma_\mu\ell_\alpha + \bar{e}_\alpha\gamma_\mu e_\alpha)Z'^\mu$$

$\Longrightarrow C_9^{\text{univ}} \sim r_\ell r_{sb}$



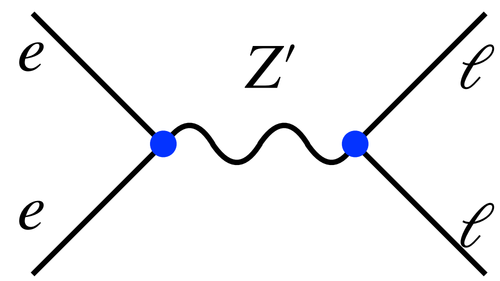
$$r_x = \frac{g_x}{M}$$

However, also:



Meson mixing

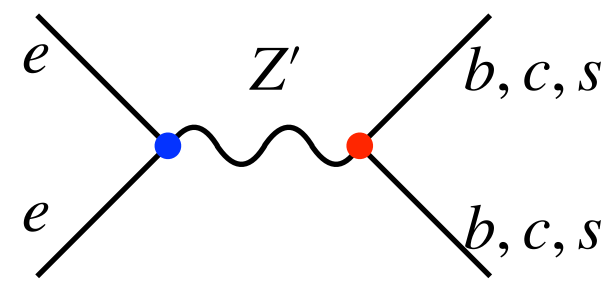
$\sim r_{sb}^2$



LEP-II, R_ℓ at FCC-ee

$\sim r_\ell^2$

In addition:

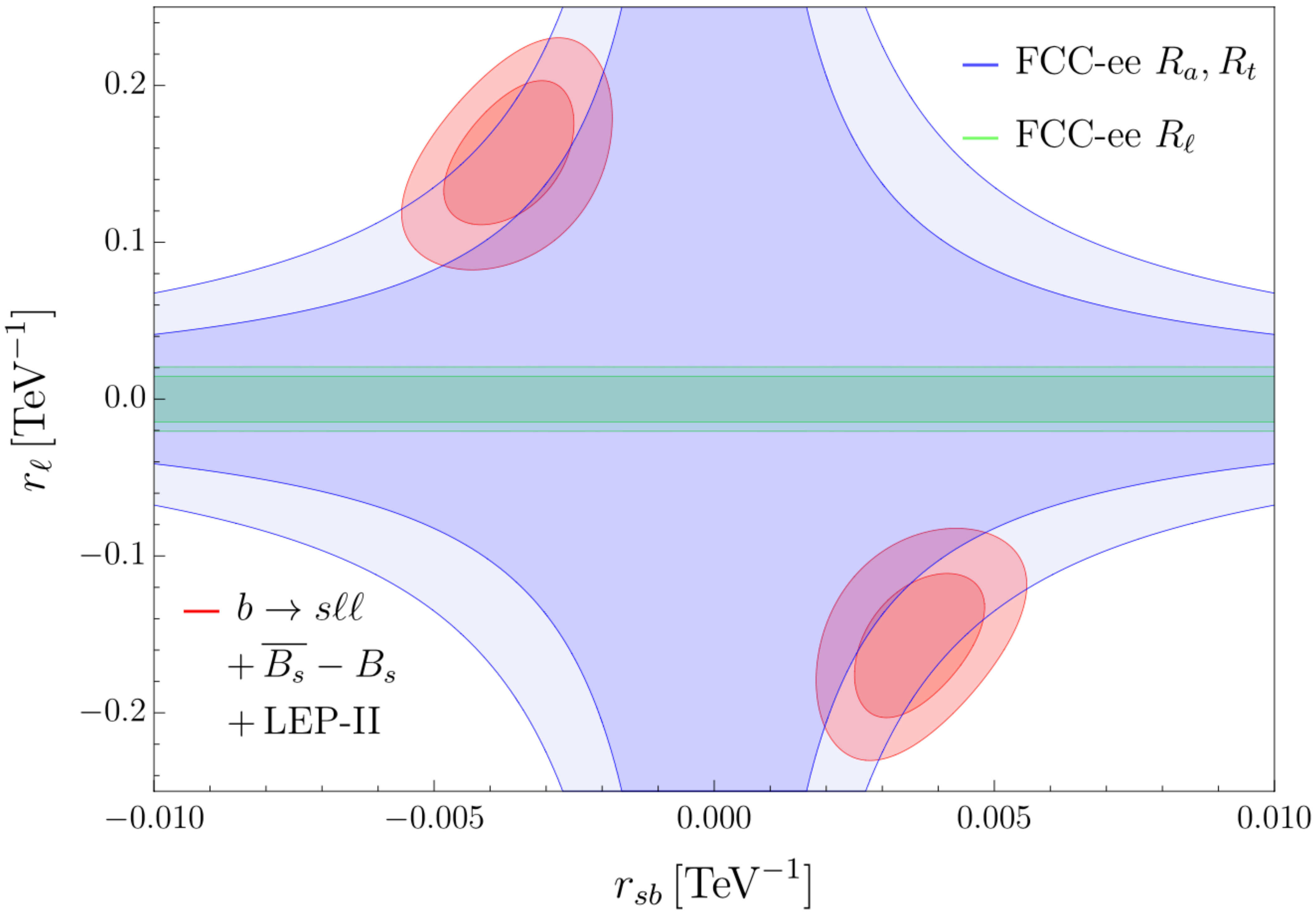


$R_{b,c,s}$ **at FCC-ee**

Fairly generic UV completions satisfy:

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

Model II: Z' for $b \to s\ell^+\ell^-$



Model III:

Vector LQ for $b \to c\tau\nu$ and $b \to s\ell^+\ell^-$

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

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} \beta_{i\alpha}\, \bar{q}_L^i \gamma^\mu l_L^\alpha\, U_\mu + \text{h.c.}$$

Model III:

Vector LQ for $b \to c\tau\nu$ and $b \to s\ell^+\ell^-$

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

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} \beta_{i\alpha}\, \bar{q}_L^i \gamma^\mu l_L^\alpha\, U_\mu + \text{h.c.}$$

↓ Matching

$$\mathcal{L}_{\text{SMEFT}} \supset -\frac{g_U^2}{4M_U^2} \beta_{i\alpha}\beta_{j\beta}^* \left[Q_{lq}^{(1)} + Q_{lq}^{(3)} \right]^{\beta\alpha ij}$$

Model III:

Vector LQ for $b \to c\tau\nu$ and $b \to s\ell^+\ell^-$

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

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} \beta_{i\alpha}\, \bar{q}_L^i \gamma^\mu l_L^\alpha\, U_\mu + \text{h.c.}$$

Matching

$$\mathcal{L}_{\text{SMEFT}} \supset -\frac{g_U^2}{4M_U^2} \beta_{i\alpha}\beta_{j\beta}^* \left[Q_{lq}^{(1)} + Q_{lq}^{(3)}\right]^{\beta\alpha i j}$$

Flavor structure $U(2)^5$

$\beta_{b\tau} = 1$, real $\beta_{s\tau} = \mathcal{O}(V_{cb})$

other couplings smaller

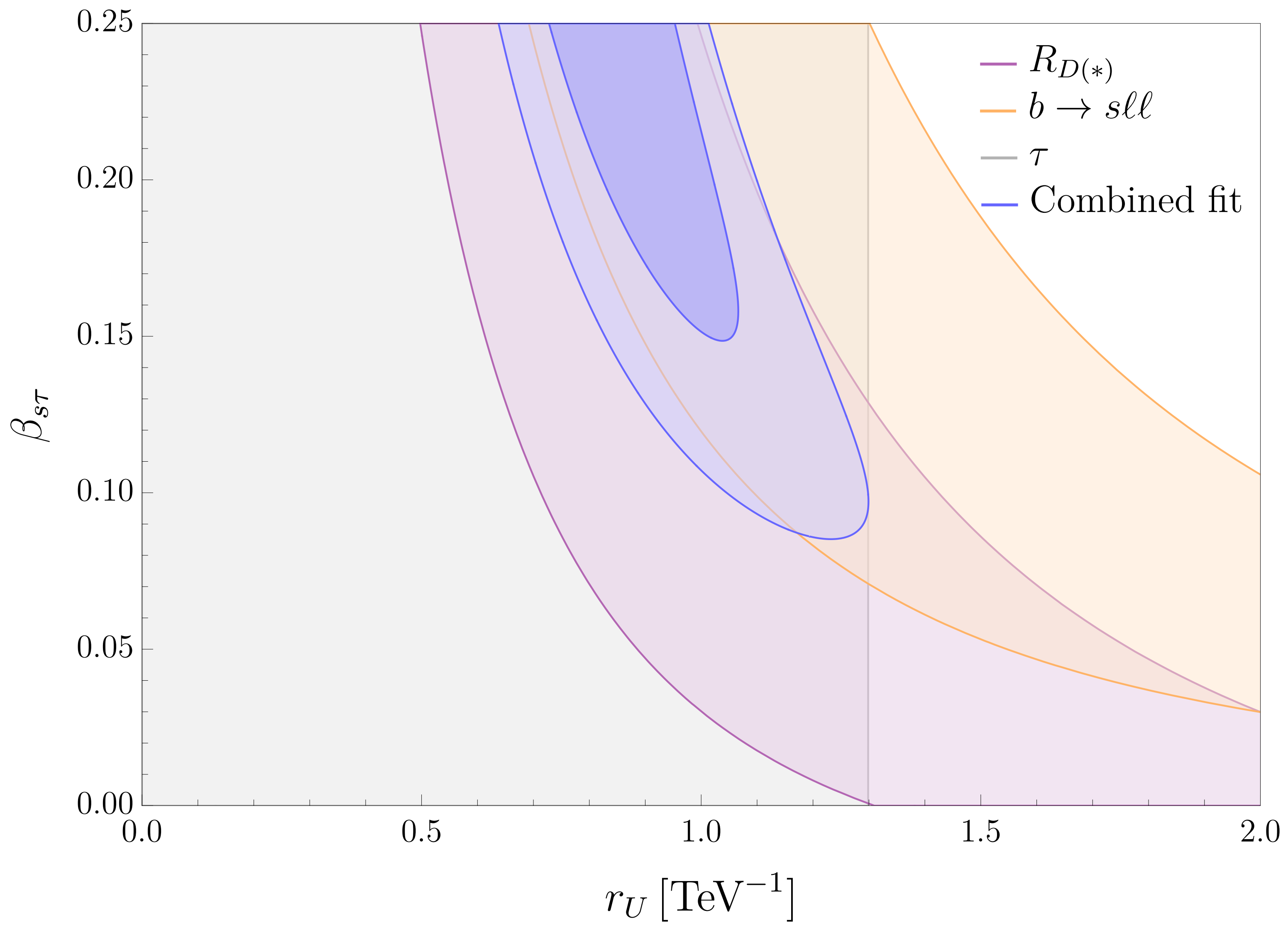
Parameters of interest: $r_U = g_U / M_U$ and $\beta_{s\tau}$

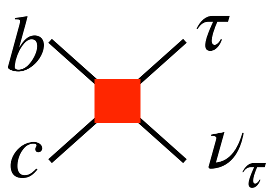
Model III:

Vector LQ for $b \to c\tau\nu$ and $b \to s\ell^+\ell^-$

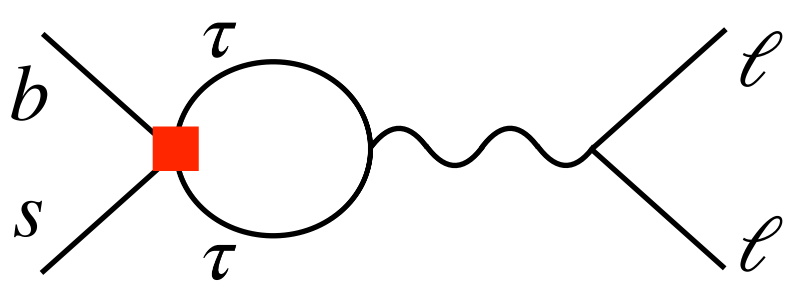
$U_\mu \sim (\mathbf{3}, \mathbf{1}, 2/3)$

Present constraints





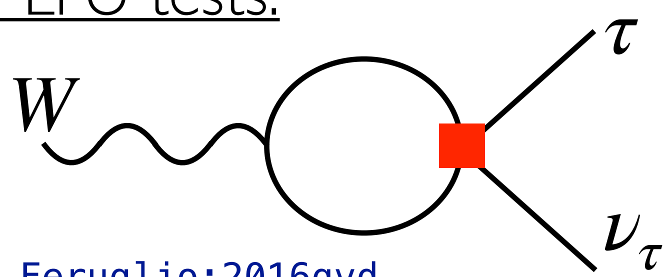
Cornella:2021sby
Crivellin:2018yvo



$R_{D^{(*)}}$ and P_5' compatible!

Profiled over $\Delta C_9^\mu = -\Delta C_{10}^\mu$

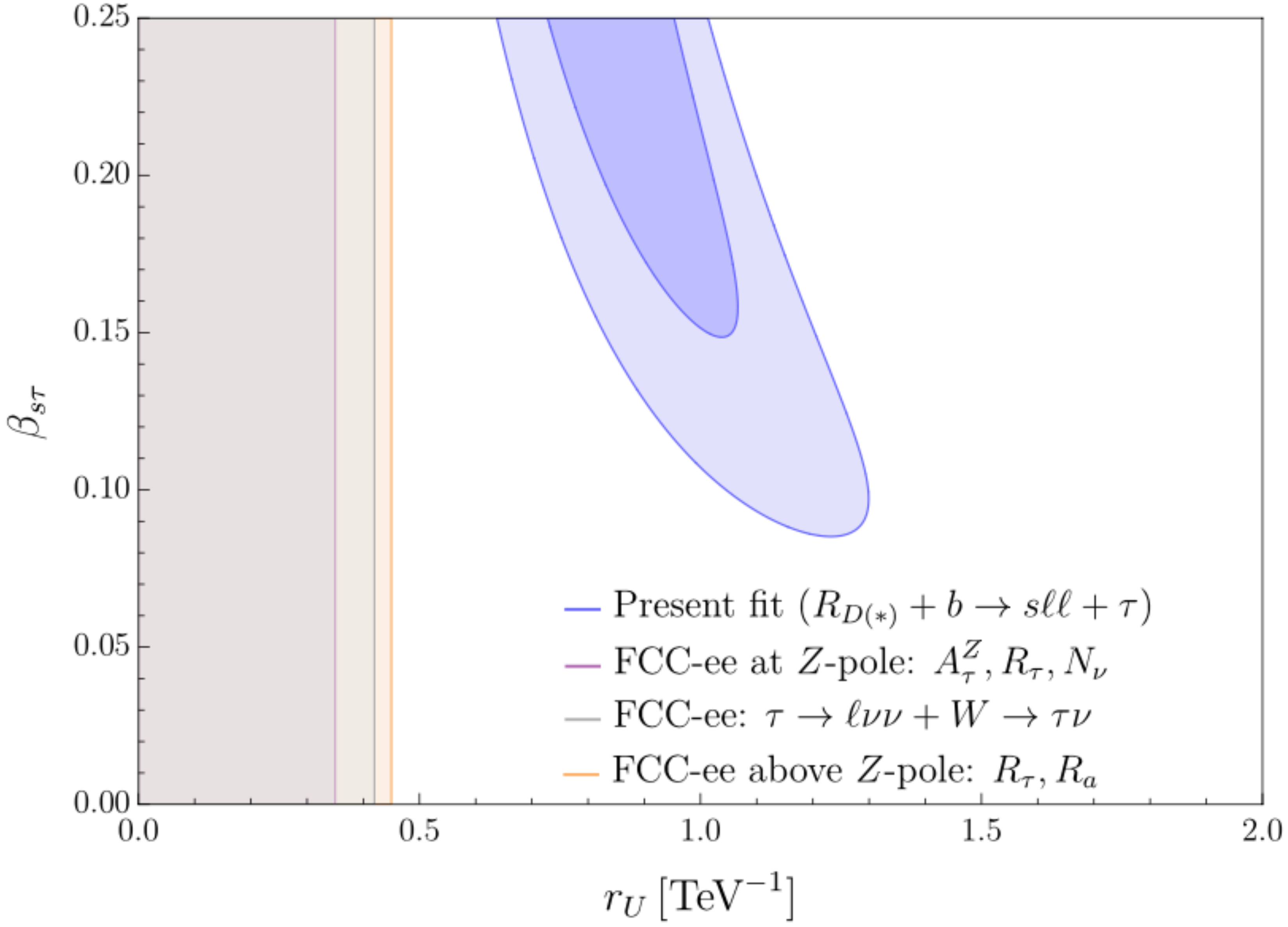
τ LFU tests:



Feruglio:2016gvd

Model III:
Vector LQ for $b \to c\tau\nu$ and $b \to s\ell^+\ell^-$

<u>FCC-ee constraints:</u> All RG effects, starting from the 3333 operator in the UV!



2σ projected bounds:

R_a and R_ℓ above the Z-pole

R_τ : $|r_U| < 0.47\,\text{TeV}^{-1}$

R_b : $|r_U| < 0.78\,\text{TeV}^{-1}$

Z-pole observables

$A_\tau, R_\tau, N_{\text{eff}}$: $|r_U| < 0.35\ \text{TeV}^{-1}$

R_τ, N_{eff} : $|r_U| \lesssim 0.5$

g^2 | y_t^2

τ and W decays at FCC-ee

$\tau \to \ell\nu\nu$: $|r_U| < 0.44\ \text{TeV}^{-1}$

$W \to \tau\nu$: $|r_U| \lesssim 0.64\ \text{TeV}^{-1}$

Conclusions

- Recent developments in flavor tagging at FCC-ee allow for optimal measurements of $R_b, R_c,$ but further improvements needed for R_s.
- R_x ratios at $WW, Zh, t\bar{t}$ can improve the bounds on the effective scales of new 4F non-universal $\Delta F = 0$ interactions by up to factor ~ 10.
- This is most important for heavy quark flavors and all lepton flavors.
- SMEFT RG implies subtle interplay and complementarity with the Z pole.
- FCC-ee has a great potential to rule out/discover NP models behind present B anomalies
  $\Longrightarrow \Delta F = 0$ interactions will compete against FCNC!