Flavour physics at future colliders

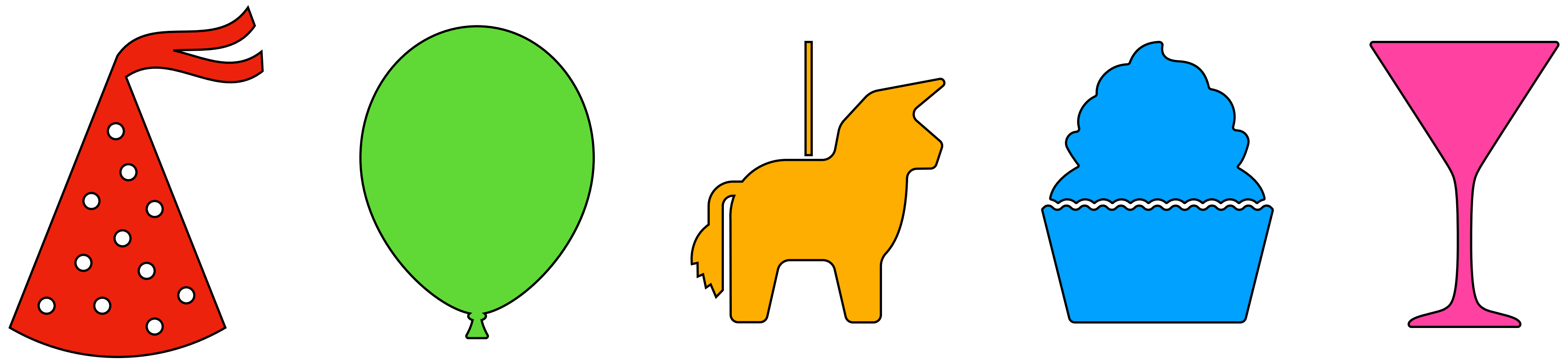
Sophie Renner, Workshop on Future Accelerators, Corfu 2023

University of Glasgow

UK Research and Innovation

Particle physics after the LHC...

Option 1: something new

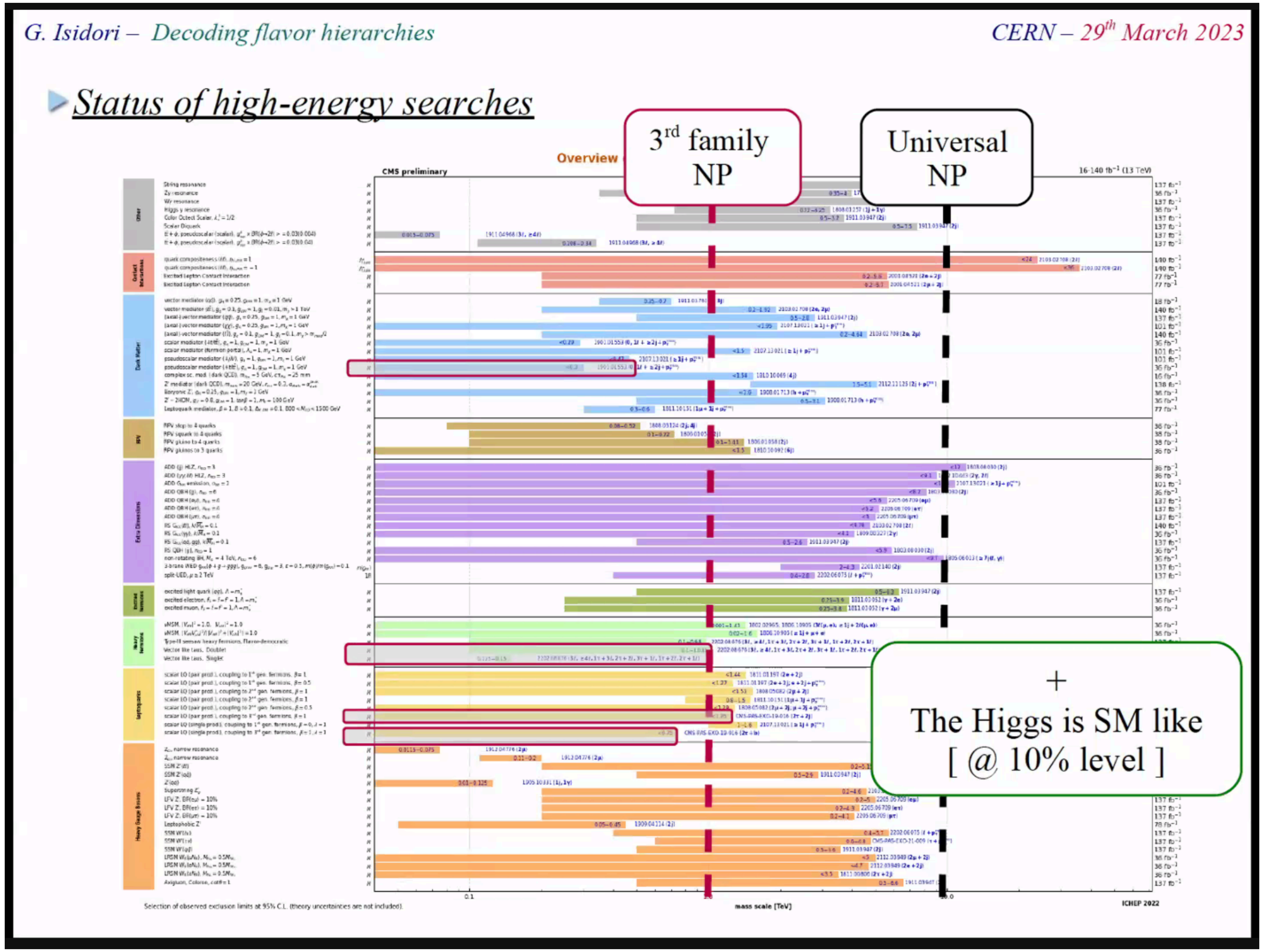


⇨ Understand the new thing

Option 2: SM still reigns

Is there still space for TeV-ish new physics? - where to look?

Best case scenario: flavourful physics



G. Isidori – Decoding flavor hierarchies

CERN – 29th March 2023

Status of high-energy searches

+
The Higgs is SM like
[@ 10% level]

If BSM physics couples differently to different flavours, bounds change

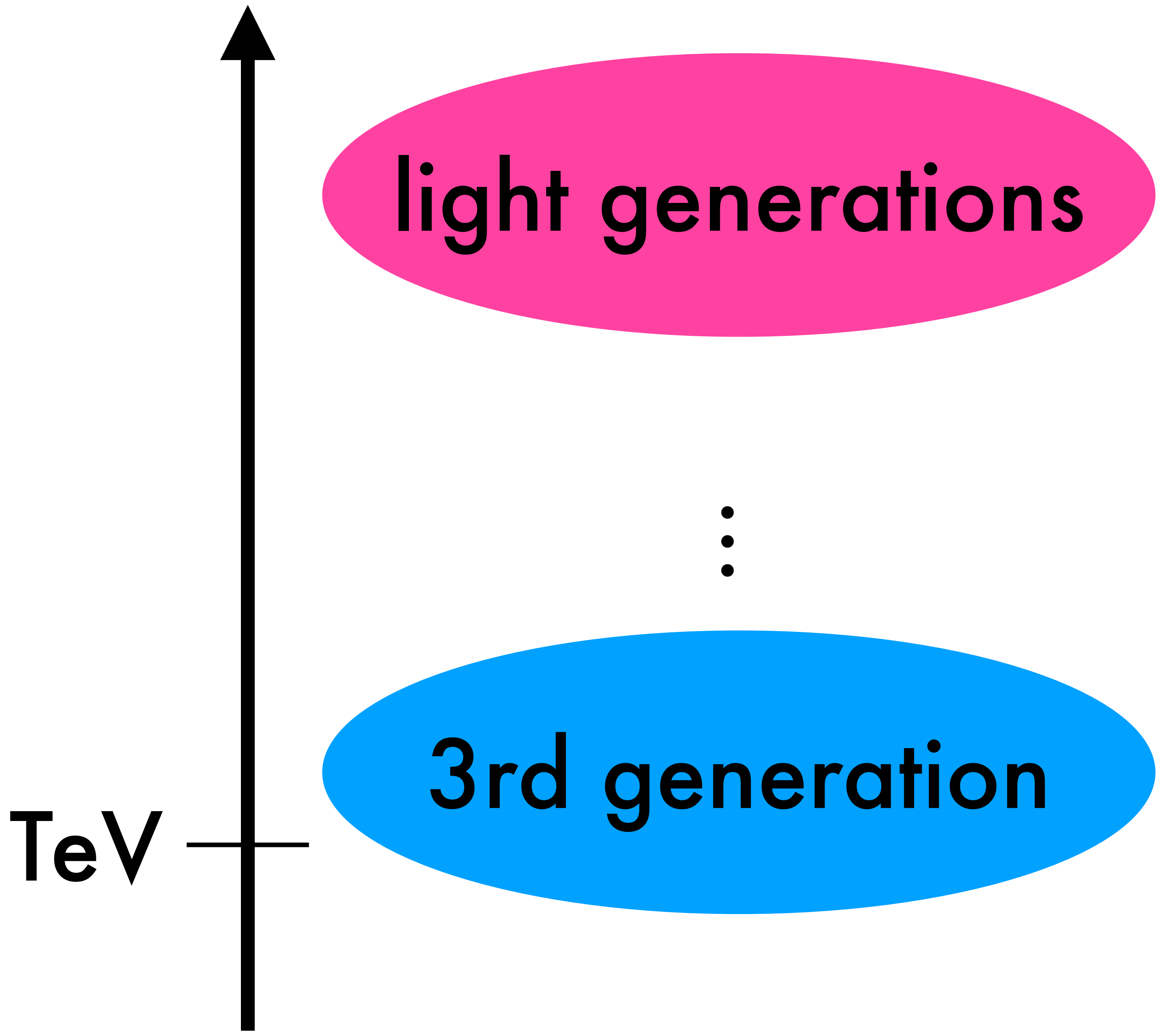
In particular, lowest bounds if NP couples only to 3rd family

At LHC: PDF suppression
Low energy: 3rd generations less precisely measured

Slide from Gino Isidori, CERN Theory Colloquium, 29/3/2023

Is the third generation special?

Not just a convenient way to lower the scales…



Hierarchy problem

Light top partners/stops

Connection to SM flavour structure, e.g. flavour-dependent gauge interactions

Origin of Yukawas
Davighi, Tooby-Smith 2201.07245
Fernandez Navarro, King 2209.00276
Davighi, Isidori, Pesut 2212.06163 , …

Hierarchy problem
Allwicher, Isidori, Thomsen, 2011.01946
Fuentes-Martin, Isidori, Lizana, Selimovic, Stefanek, 2203.01952
Davighi, Isidori 2303.01520, …

B anomalies

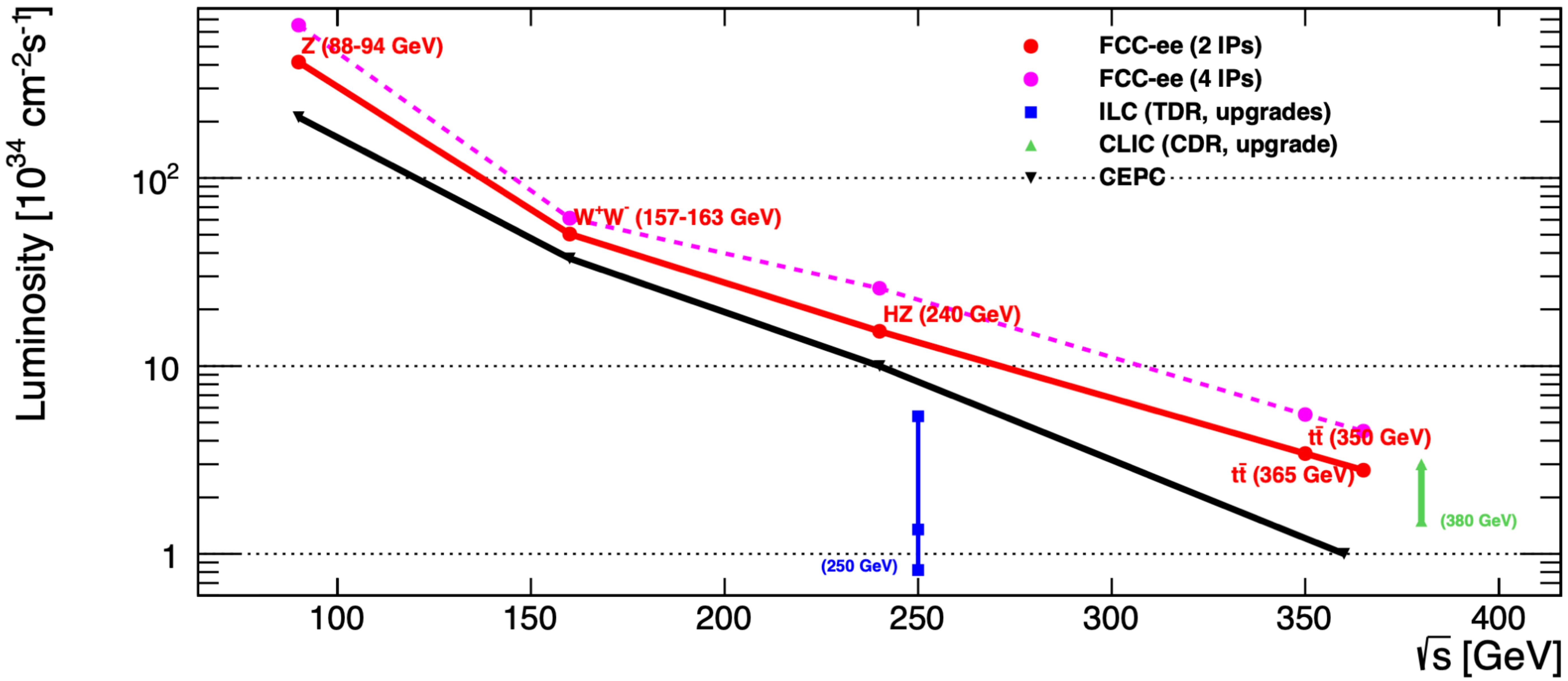
What this means for a future collider

Points to some aims for a new collider:

- ★ Testing the Yukawa sector Higgs couplings to fermions, CKM tests
- ★ Searching for new flavour changing interactions involving 3rd generation fermions
- ★ Searching for new flavour-conserving interactions involving 3rd generation fermions

Examples of how FCC-ee addresses each of these and what it might mean for BSM

FCC-ee is a flavour factory



FCC Snowmass report, 2203.06520

Numbers for decays of 5×10^{12} Z^0s:

Lenz & Monteil, 2207.11055

Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	310	310	75	65	1.5	600	170

$O(10^{11})$ B mesons

About 15 times larger than Belle II dataset

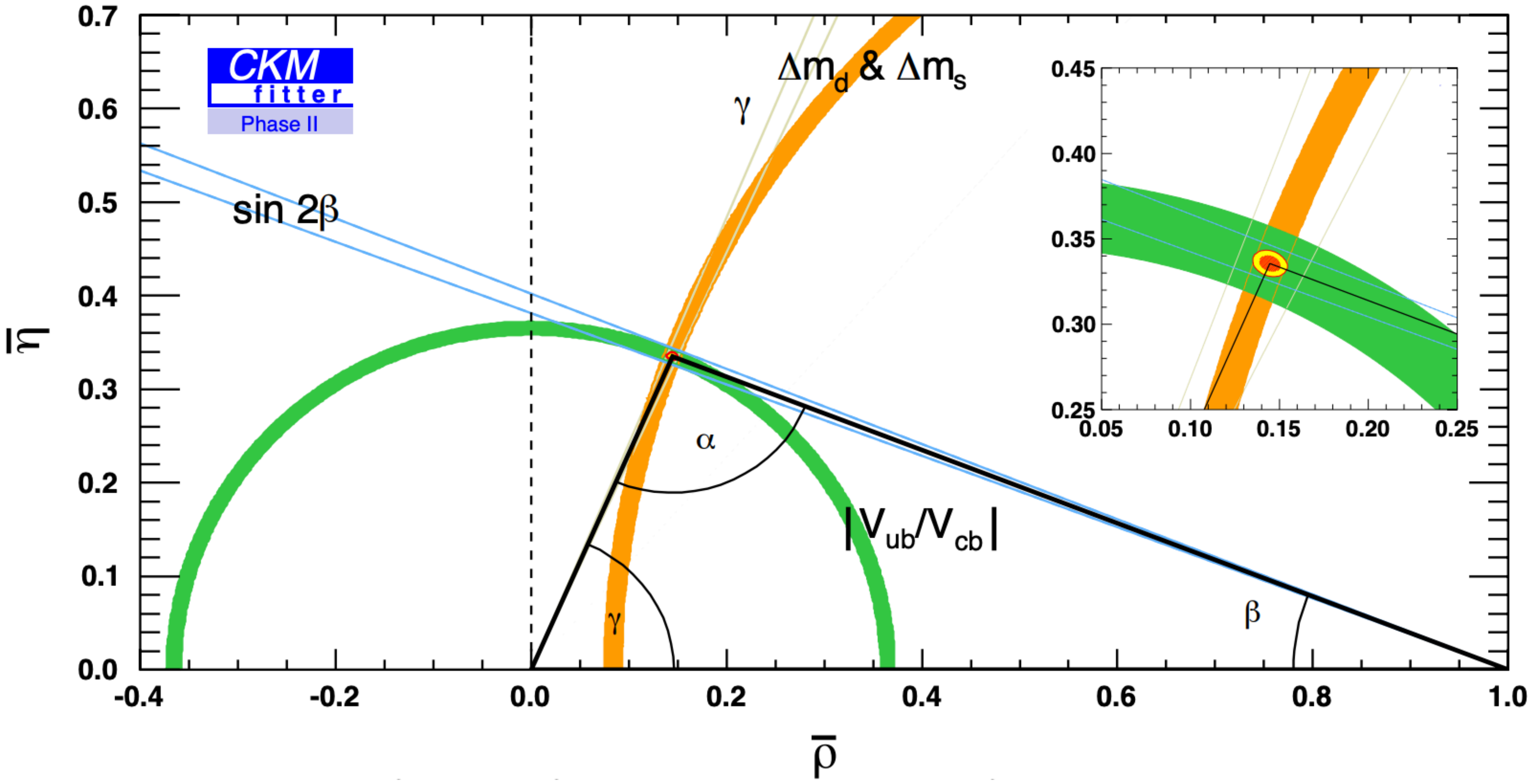
Combines the advantages of B factories and LHCb: highly boosted particles in a clean environment

(I will focus on FCC-ee, but similar numbers are projected for CEPC)

Status of flavour physics at start of FCC-ee

HL-LHC and Belle II will have completed their runs

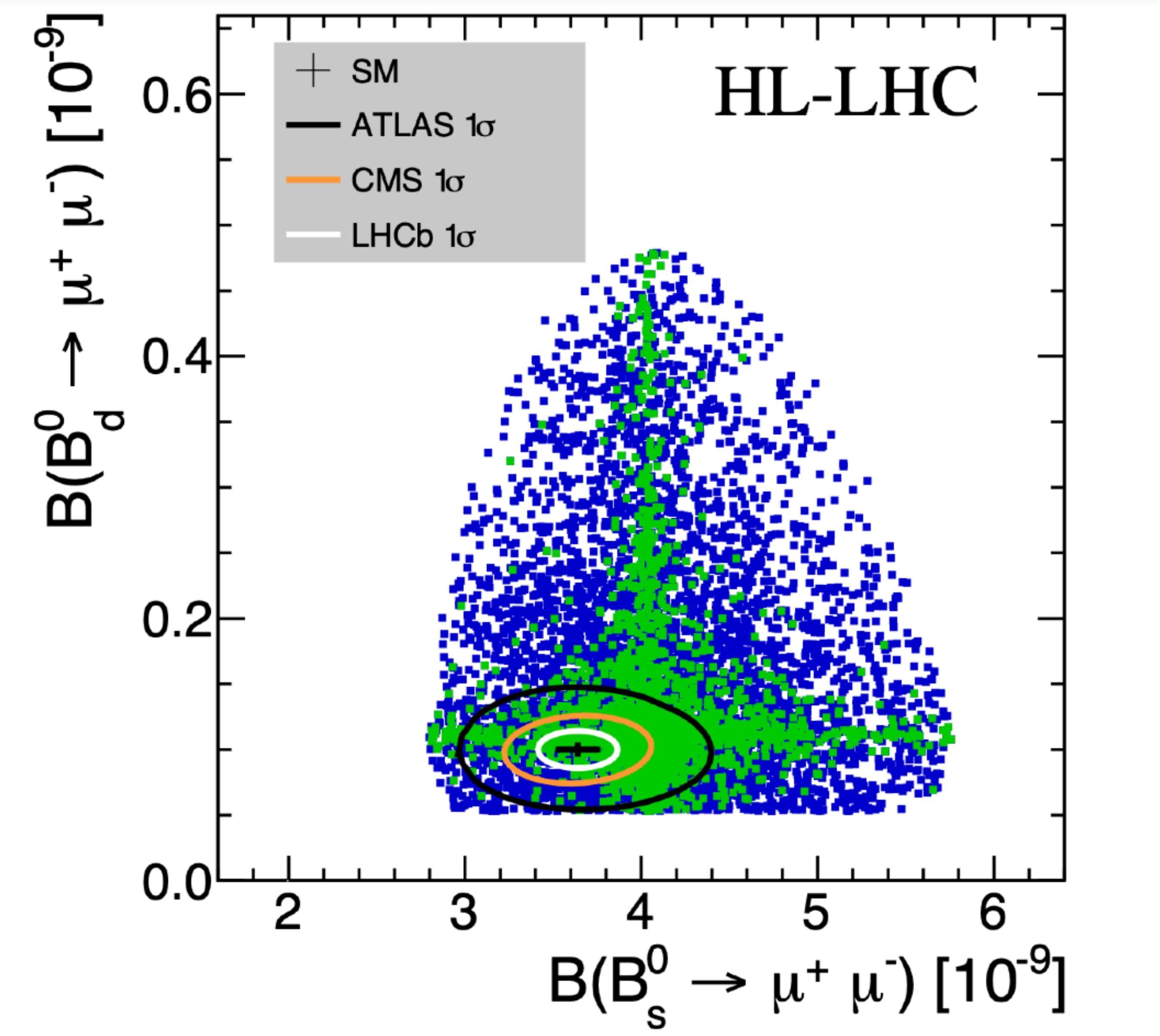
Possible unitarity triangle after LHCb HL-LHC



Bediaga et al, 1808.08865

FCNC highlights

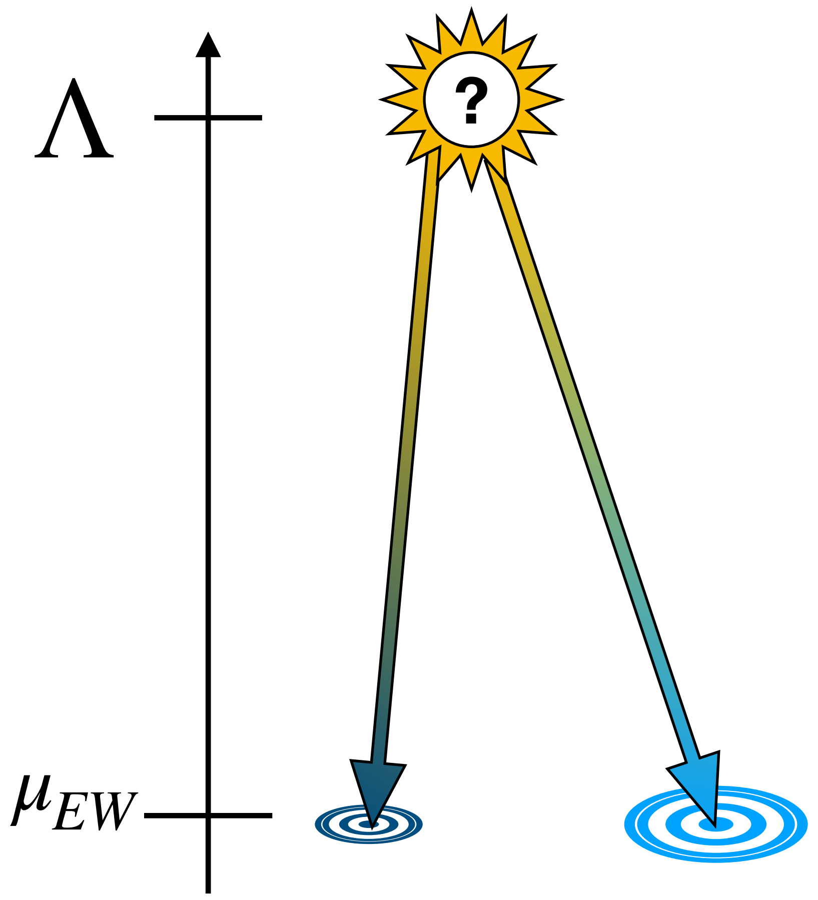
Belle II will measure $B \to K^{(*)}\bar{\nu}\nu$ to 10%



$B_{s,d} \to \mu^+\mu^-$
at LHC

The Standard Model Effective Field Theory

Approximate the effects of all possible heavy particles by writing down all possible new interactions between SM particles



$$\boxed{\mathscr{L}_{\text{SMEFT}} = \frac{1}{\Lambda^2}\sum_i \underline{C_i}\,\underline{O_i} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)}$$

Operators are suppressed by BSM scale

$$\Lambda$$

Different classes of operators built from SM fields...

$$X^3 \quad H^6 \quad H^4D^2 \quad \psi\bar{\psi}H^2D \quad \psi\bar{\psi}H^3 \quad \psi\bar{\psi}XH \quad X^2H^2 \quad \bar{\psi}^2\psi^2$$

$X = B_{\mu\nu}, G^A_{\mu\nu}, W^I_{\mu\nu}$

$\psi = Q, u, d, L, e$

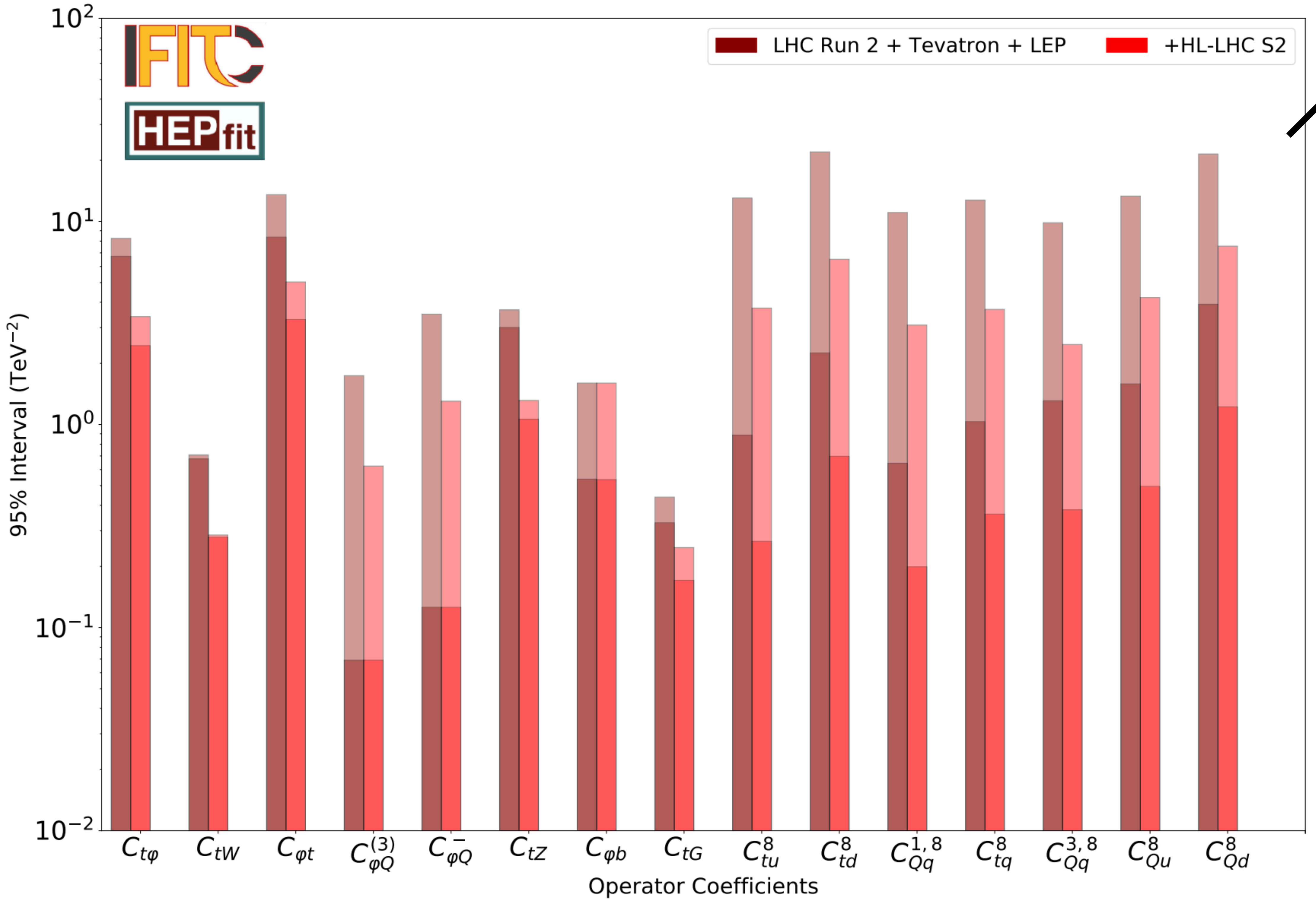
Parameters of the theory are contained in the Wilson coefficients

The search for new physics can be translated into searches in Wilson coefficient space

SMEFT in 2040

Projected fit to top-containing operators

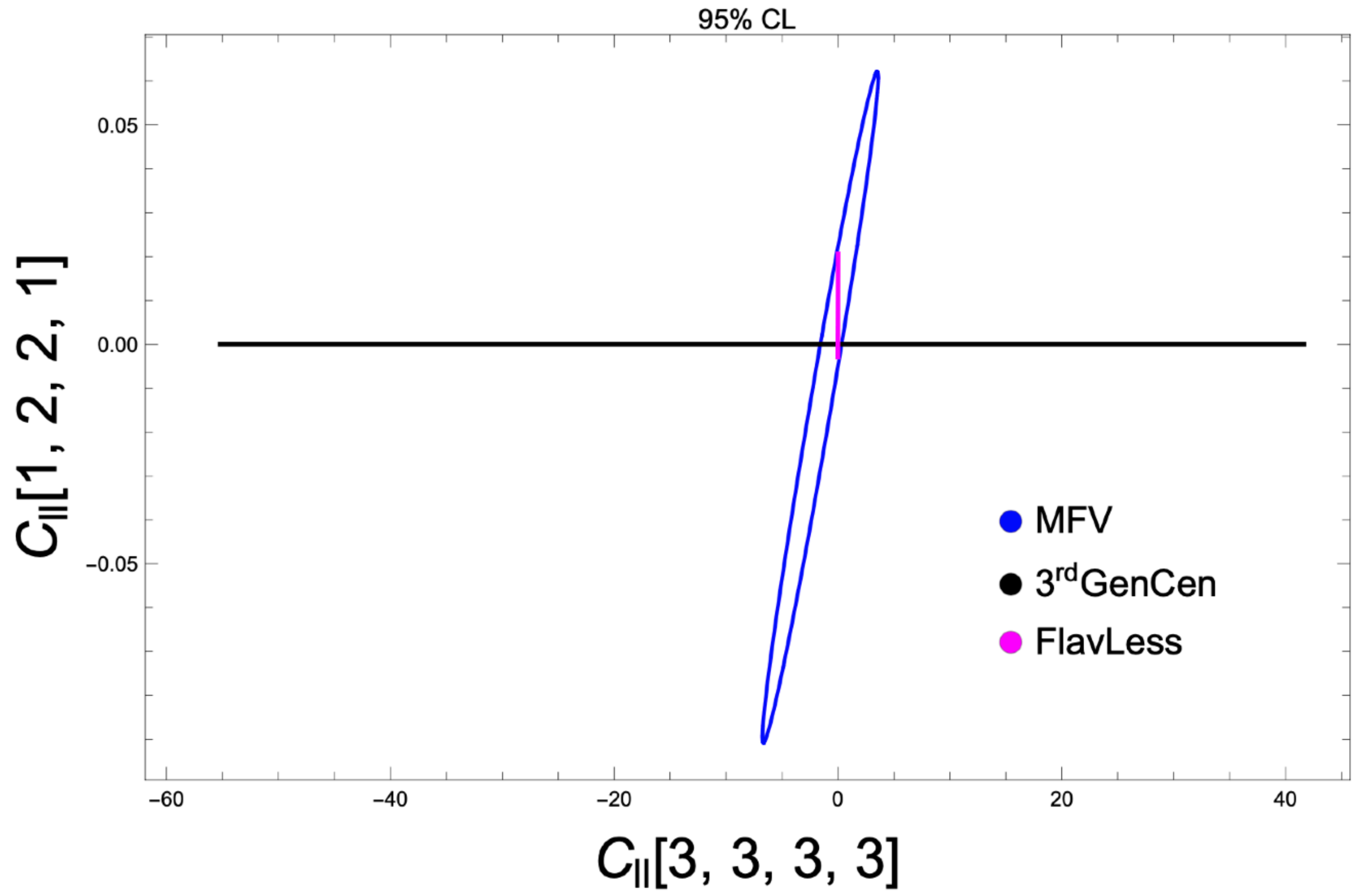
De Blas et al, 2206.08326



Lighter shade: single-parameter fit
Darker shade: marginalised fit

Some operators are only constrained to below 1 TeV, even after HL-LHC

Other types of flavoured operators have not been systematically studied (even using current data)



Bellafronte, Dawson, Giardino
2304.00029

Yukawas and CKM

Higgs couplings to fermions

Projected precision (%):

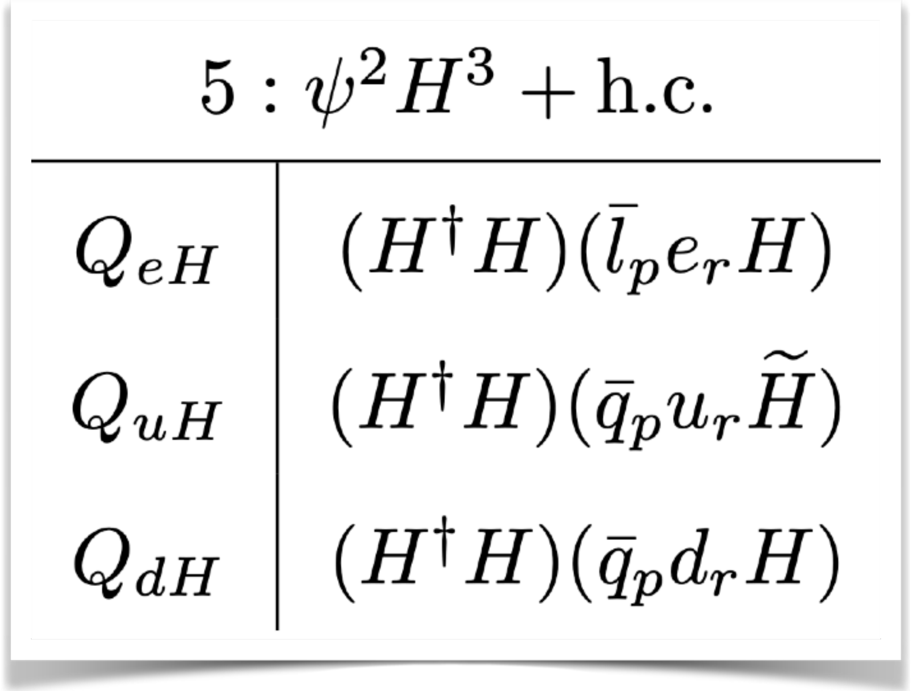
FCC Snowmass report, 2203.06520

Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-ee + HL-LHC	FCC-INT	FCC-INT + HL-LHC
Int. Lumi (ab^{-1})	3	5 + 0.2 + 1.5	–	30	–
Years	10	3 + 1 + 4	–	25	–
g_{Hbb} (%)	5.1	0.69	0.64	0.48	0.48
g_{Hcc} (%)	SM	1.3	1.3	0.96	0.96
$g_{\mathrm{H}\tau\tau}$ (%)	1.9	0.74	0.66	0.49	0.46
$g_{\mathrm{H}\mu\mu}$ (%)	4.4	8.9	3.9	0.43	0.43
g_{Htt} (%)	3.4	–	3.1	1.0	0.95

FCC-ee matters most (g_{Hbb}, g_{Hcc}, $g_{\mathrm{H}\tau\tau}$)

FCC-hh matters most ($g_{\mathrm{H}\mu\mu}$, g_{Htt})

In the SMEFT at dim 6, each of these decays is modified by a single operator:



$5:\psi^2H^3+\mathrm{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$$\frac{v^2}{2\sqrt{2}}(v+3h+\ldots)\,\bar{q}_L u_R$$

These operators can be generated at tree level in some models, e.g. 2HDM

$\Longrightarrow$ test of the Yukawa sector

V_{cb} at FCC-ee

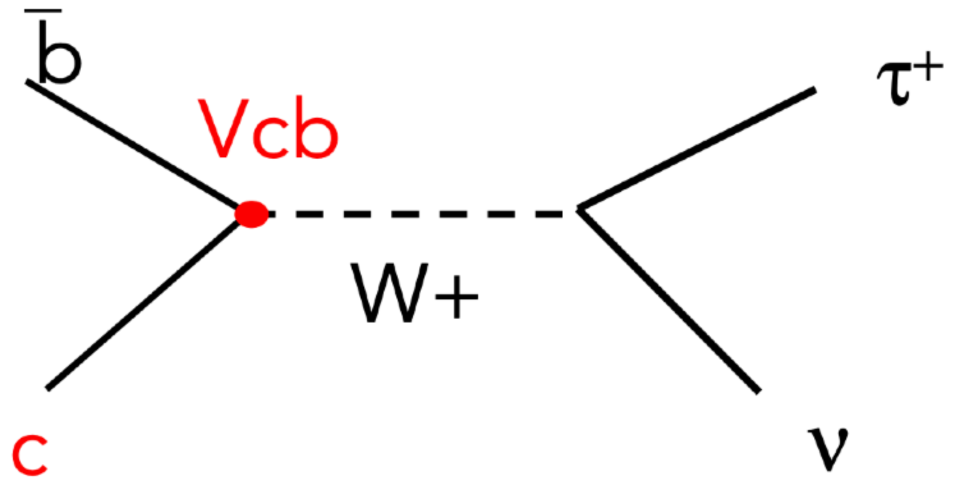
?

$$|V_{cb}|^{\text{incl.,2022}} = (42.16 \pm 0.51) \cdot 10^{-3}$$

$$|V_{cb}|^{\text{excl.,PDG}} = (39.5 \pm 0.9) \cdot 10^{-3}$$

Discrepancy between inclusive and exclusive determinations of V_{cb}

With $B_c \to \tau^+ \nu$ decays

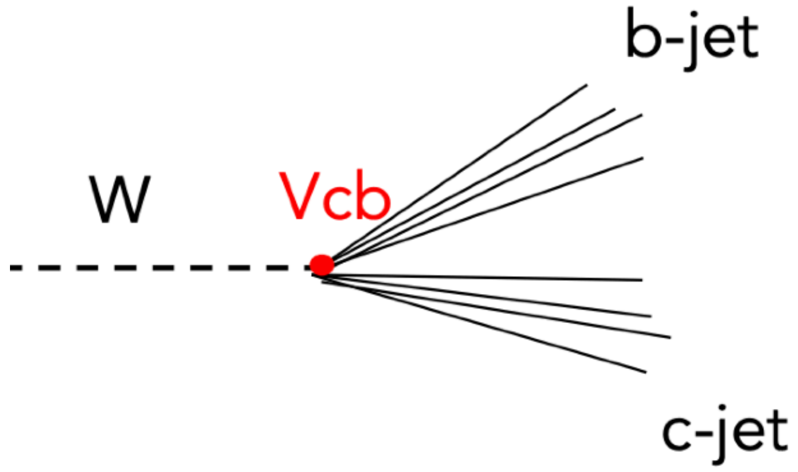


Amhis, Hartmann, Helsens, Hill, Sumensari 2105.13330
Zheng et al, 2007.08234 (CEPC study)

No form factors, just a decay constant

But need to know B_c fraction

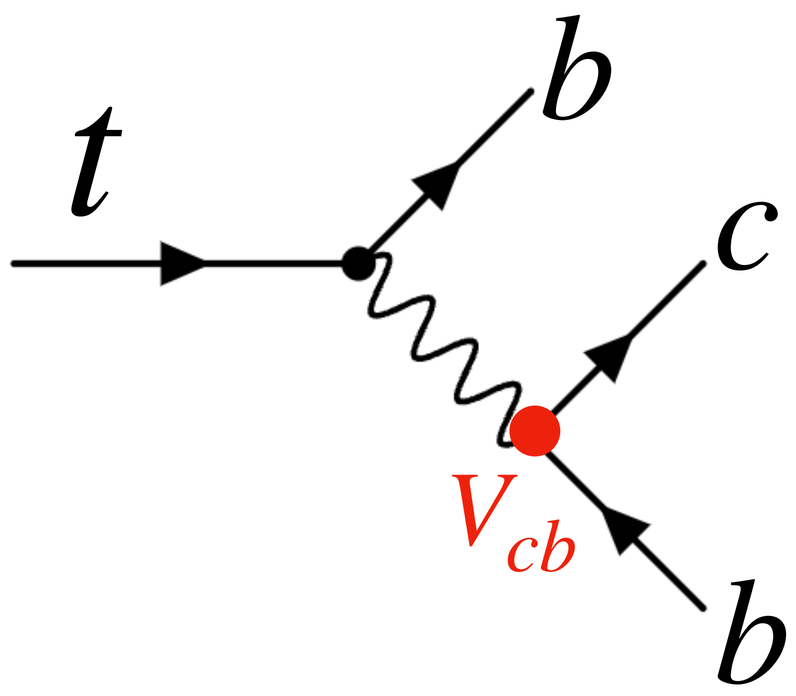
With W decays



Precision depends on tagging of b and c jets

Estimated achievable precision 0.4% Marie-Helene Schune, FCC-ee workshop 2020

With top decays



Harrison & Vladimirov, 1810.09424

Even more direct measurements of e.g. V_{ts}

Similar story for Vub

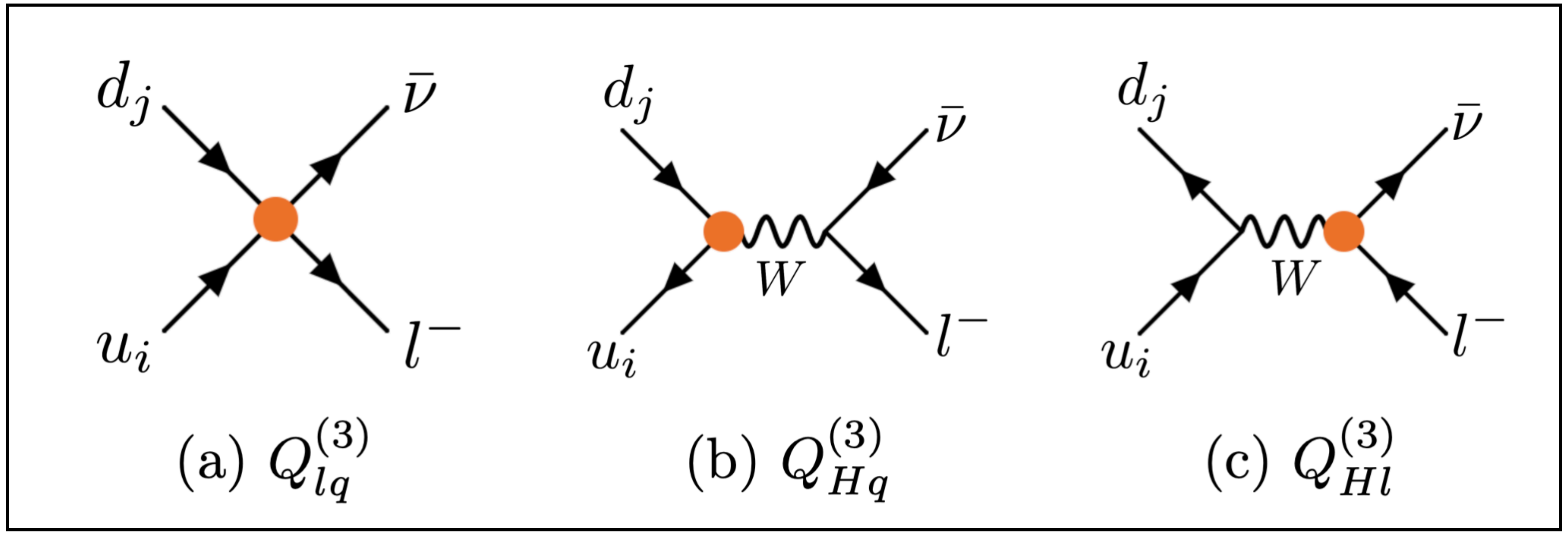
'CKM' in the SMEFT

In the absence of some symmetry forbidding it (e.g. R-parity), new physics can enter at tree level in observables from which the CKM is extracted

Possible SMEFT effects in CKM fits must be carefully propagated through Descotes-Genon et al., 1812.08163

Or do a bespoke CKM fit in which SMEFT effects cancel (only possible with flavour assumptions) Aoude, Hurth, SR, Shepherd, 2003.05432

e.g.



All three of these operators contribute to $b \to c\ell\bar{\nu}$

But only one contributes to $W \to \bar{b}c$

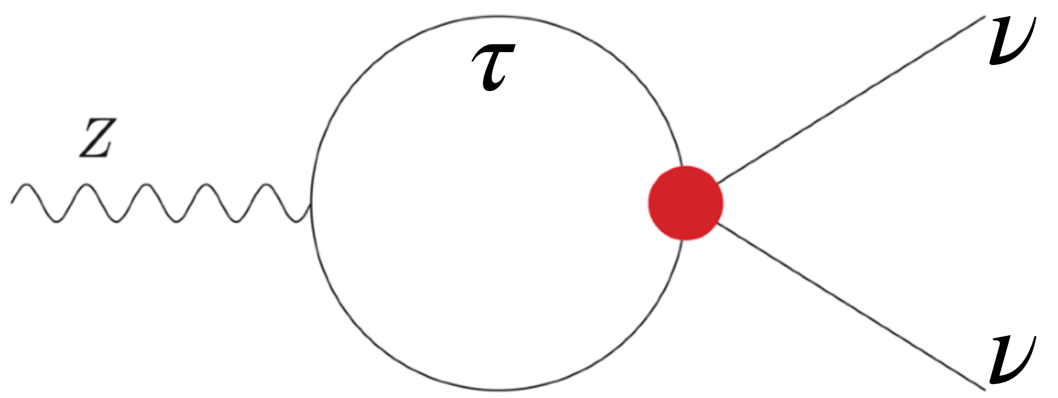
Easier to isolate new physics with more observables
Possibility of combined CKM + SMEFT fits?

Flavour and EW precision

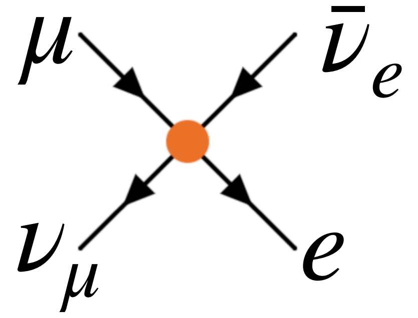
Flavour and EW precision

For Z pole measurements, flavour matters

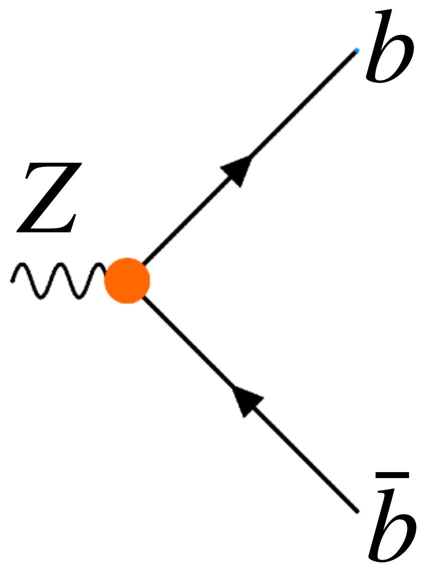
4-lepton operators

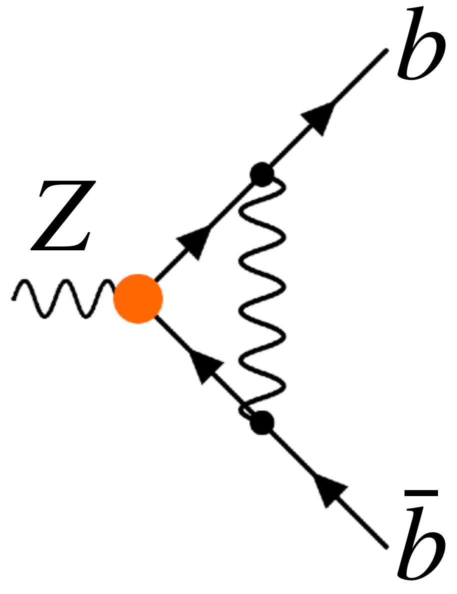


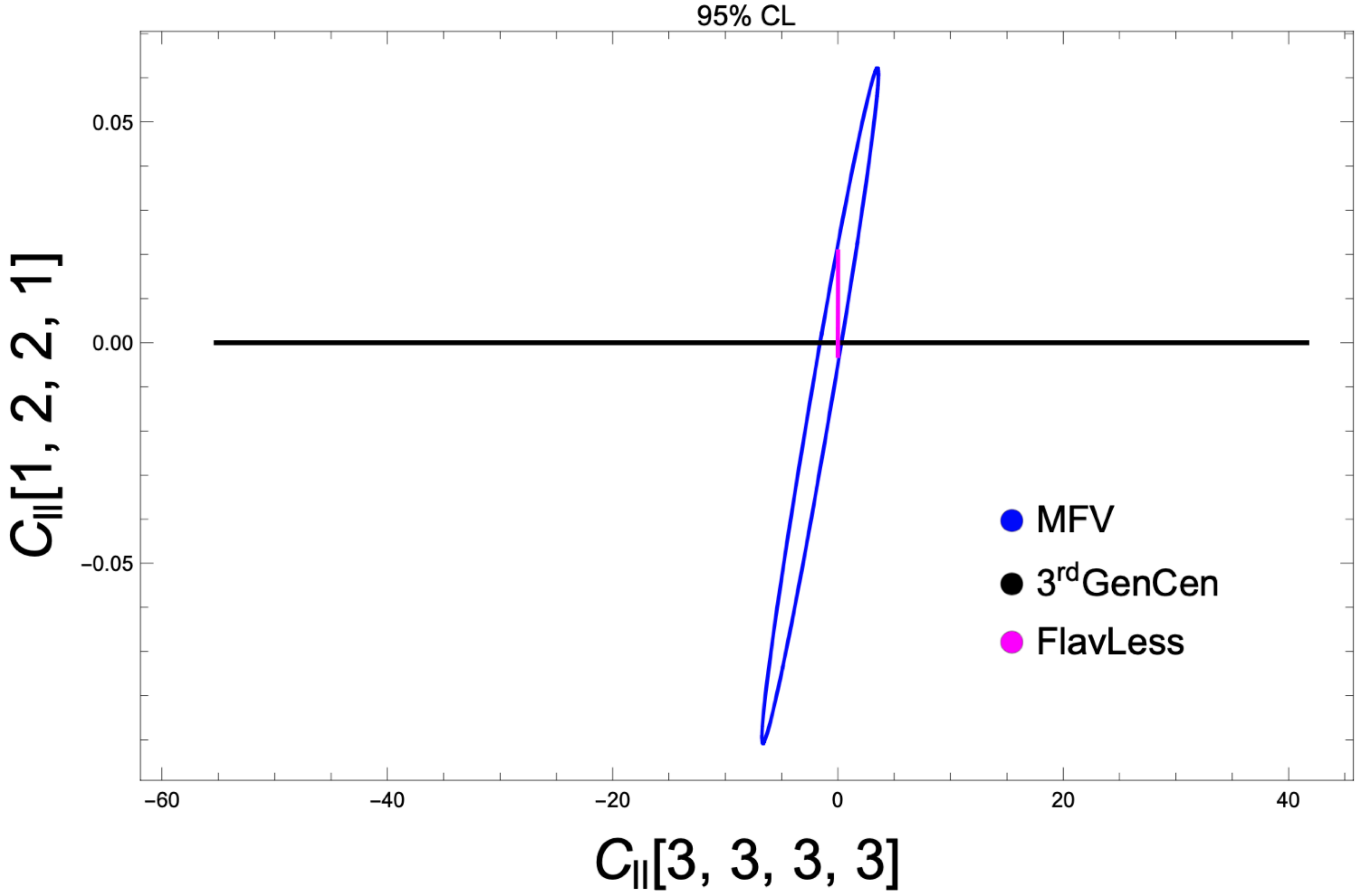
+ indirectly through definition of G_F



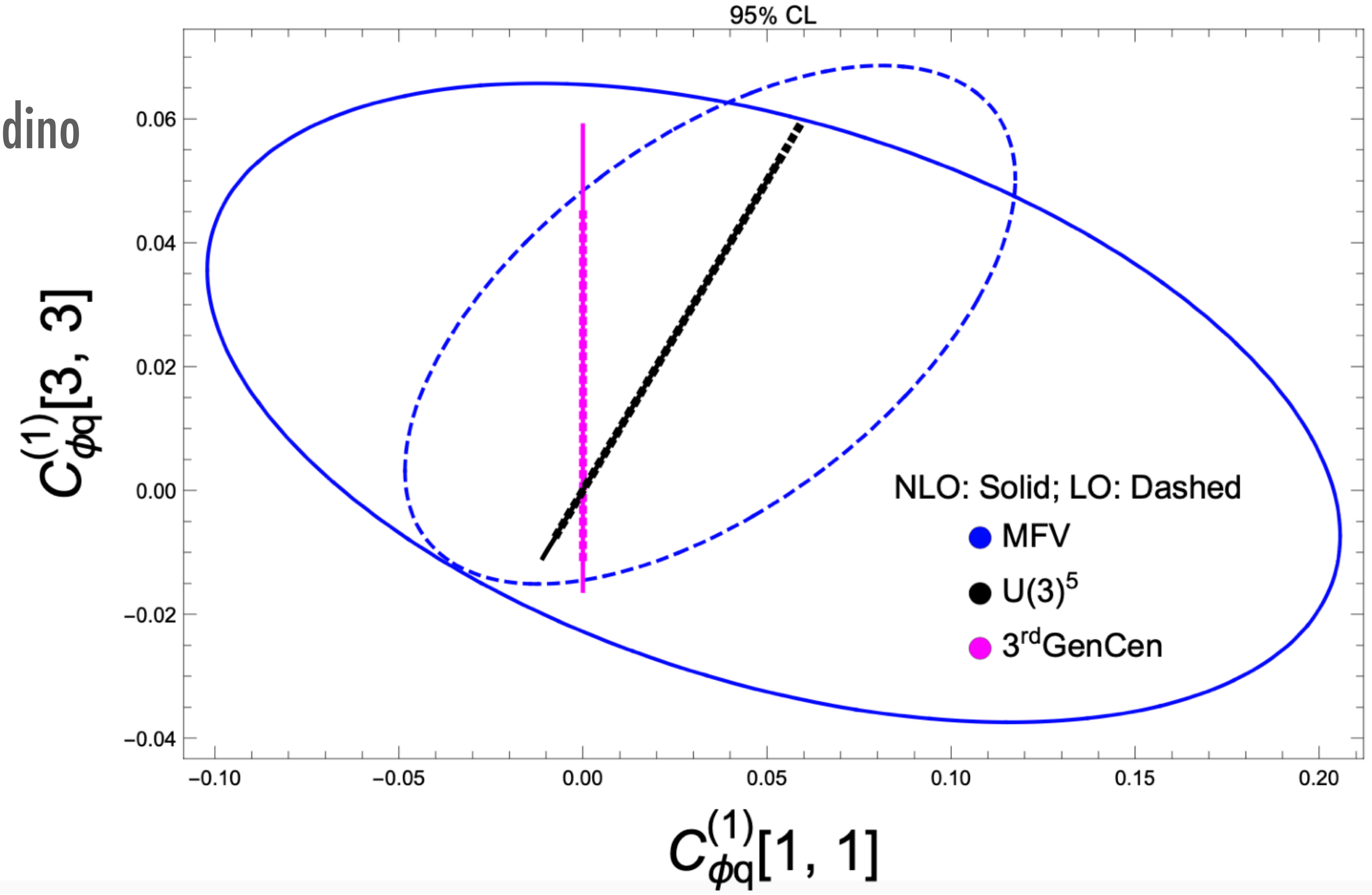
Z-quark operators





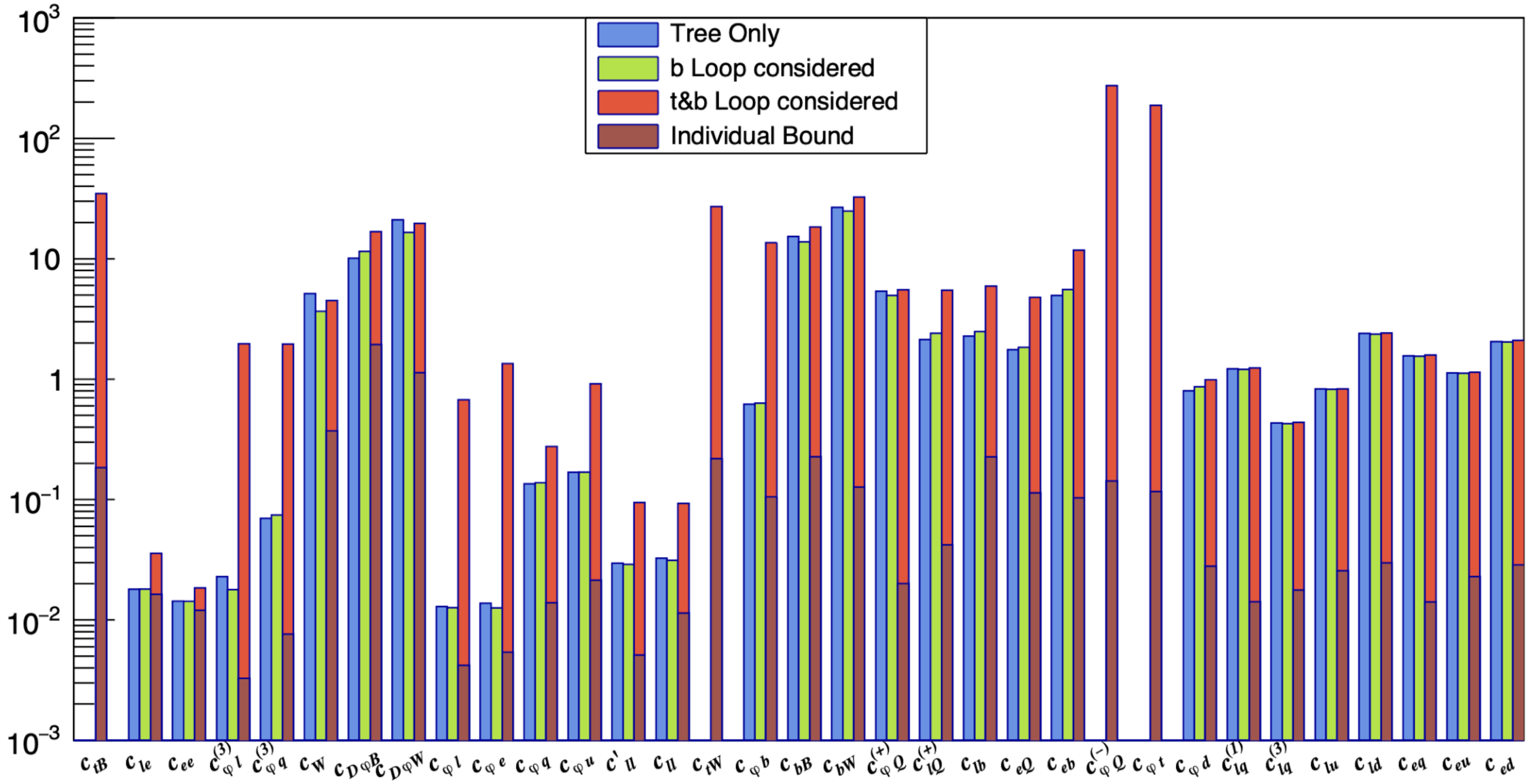


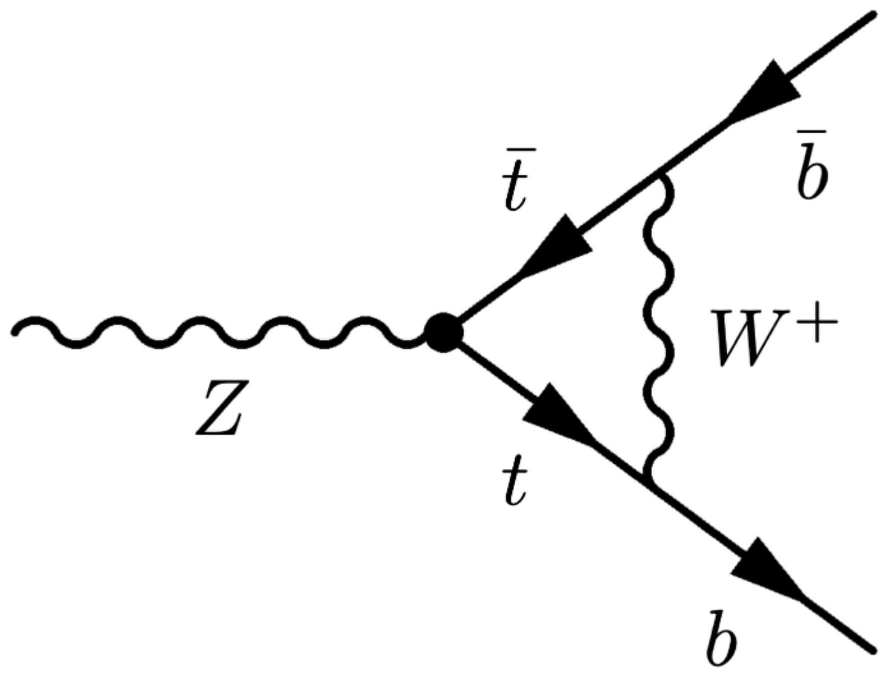
Bellafronte, Dawson, Giardino
2304.00029



Bounds from EW precision on flavour of BSM?

Liu, Wang, Zhang, Zhang, Gu 2205.05655





Individual bounds

	$c_{\varphi t}$	$c^{(-)}_{\varphi Q}$	c_{tW}	c_{tB}
Electroweak	0.233	0.286	0.438	0.36
LHC data	2.275	1.22	0.06	0.145

LEP outperforms LHC on some top operators

Flavoured decays involving τs

B decays into τs after Belle II and HL-LHCb

$$B \to K \tau^+ \tau^-$$

SM branching ratio: $(1.44 \pm 0.15) \times 10^{-7}$ HPQCD, 1306.0434

Current limits: 5 orders of magnitude above SM

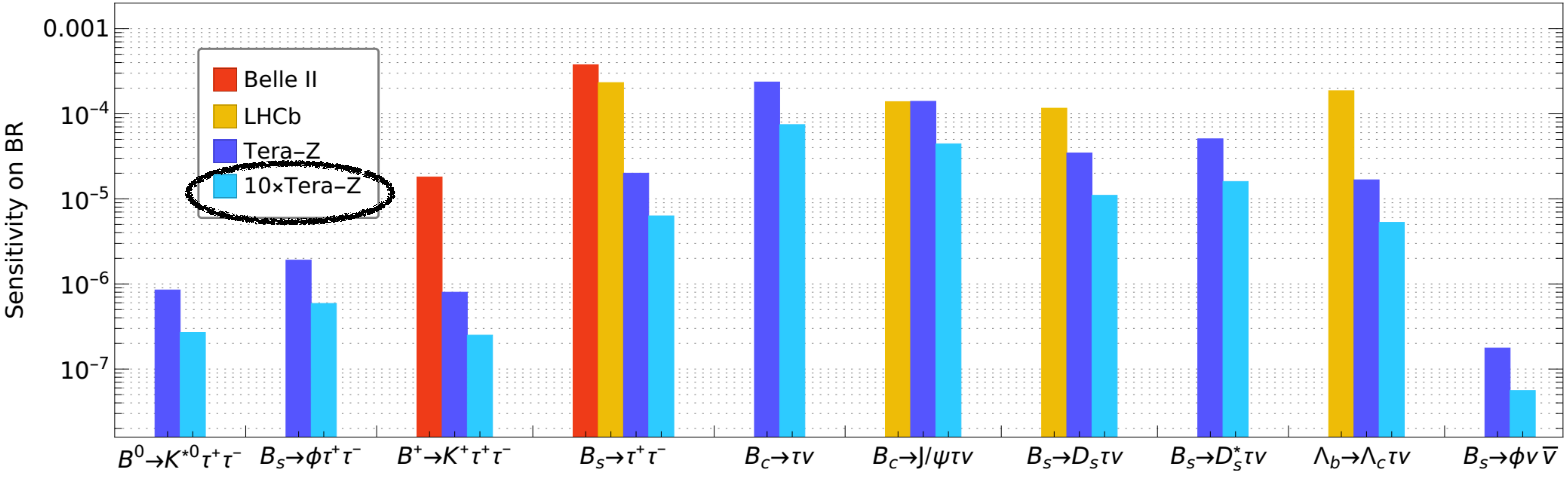
After Belle II: $BR \leq 10^{-4} - 10^{-5}$

$$B_s \to \tau^+ \tau^-$$

Bobeth, 1405.4907

$$\mathrm{Br}\left(B_s \to \tau^+\tau^-\right)_{\mathrm{SM}} = (7.73 \pm 0.49) \times 10^{-7}$$

$$\mathrm{Br}\left(B_s \to \tau^+\tau^-\right)_{\mathrm{EXP}} \leq 6.8 \times 10^{-3}$$ LHCb, 1703.02508

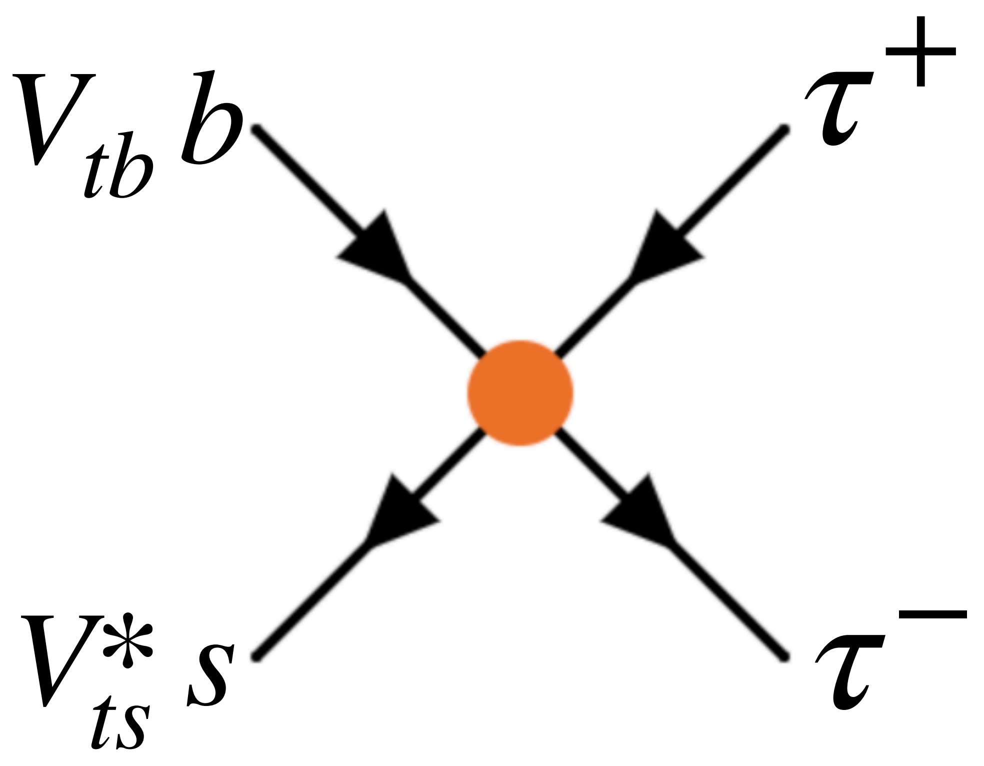


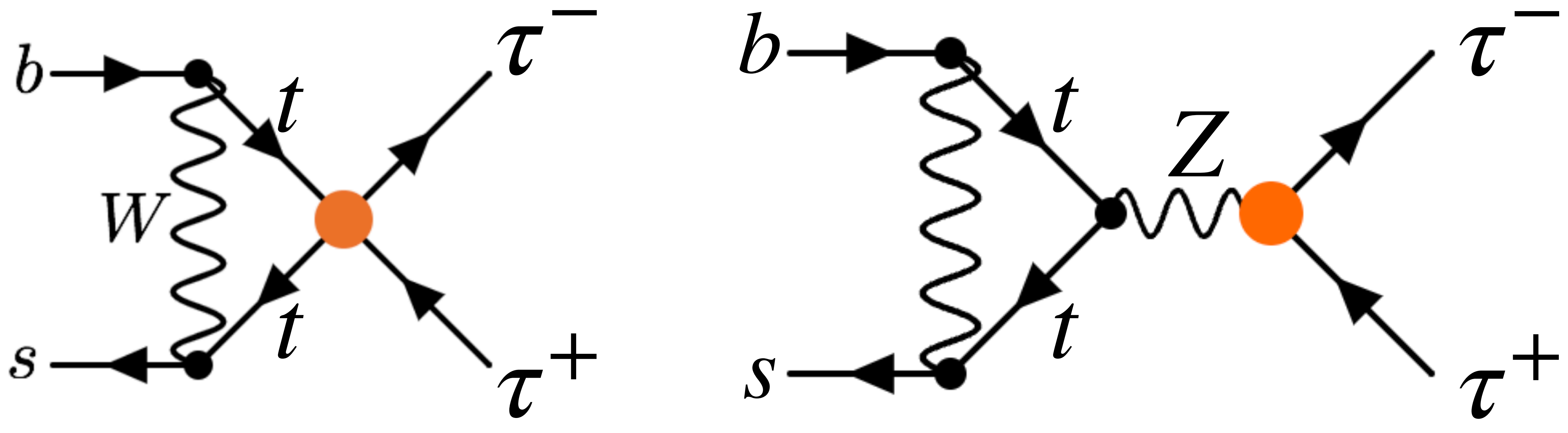
Ho, Jiang, Kwok, Li, Liu 2212.02433

$B \to K^{(*)}\tau^+\tau^-$ at FCC-ee

Can't be well studied at LHCb or Belle II

e.g.



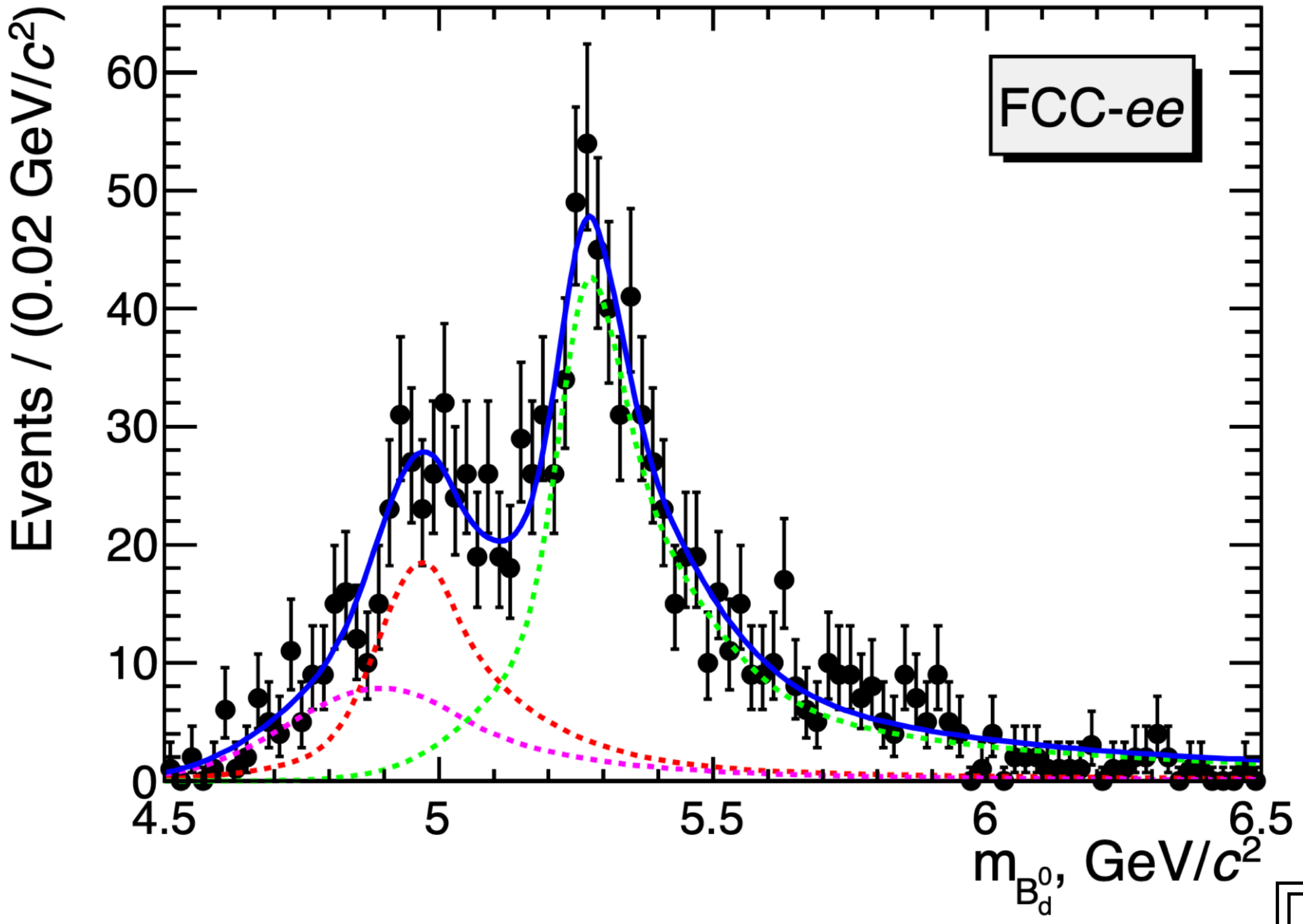


Likely that new physics that speaks only to the third generation should show up here

$\mathcal{O}(10^3)$ reconstructed $B \to K^*\tau^+\tau^-$events

Can measure τ polarization observables

Kamenik, Monteil, Semkiv, Silva, 1705.11106



$B \to K^{(*)}\tau^+\tau^-$ in the SMEFT

$$O_{lq}^{(1)\,ijkl} = (\bar{L}^i\gamma_\mu L^j)\left(\bar{Q}^k\gamma^\mu Q^l\right)$$

$$O_{lq}^{(3)\,ijkl} = (\bar{L}^i\gamma_\mu\tau^I L^j)\left(\bar{Q}^k\gamma^\mu\tau^I Q^l\right)$$

$$O_{qe}^{ijkl} = (\bar{e}^i\gamma_\mu e^j)\left(\bar{Q}^k\gamma^\mu Q^l\right)$$

$R_D^{(*)} \propto C_{lq}^{(3)}$

$B \to K^{(*)}\bar{\nu}\nu \propto C_{lq}^{(1)} - C_{lq}^{(3)}$

$B \to K^{(*)}\tau^+\tau^- \propto C_{lq}^{(1)} + C_{lq}^{(3)}$

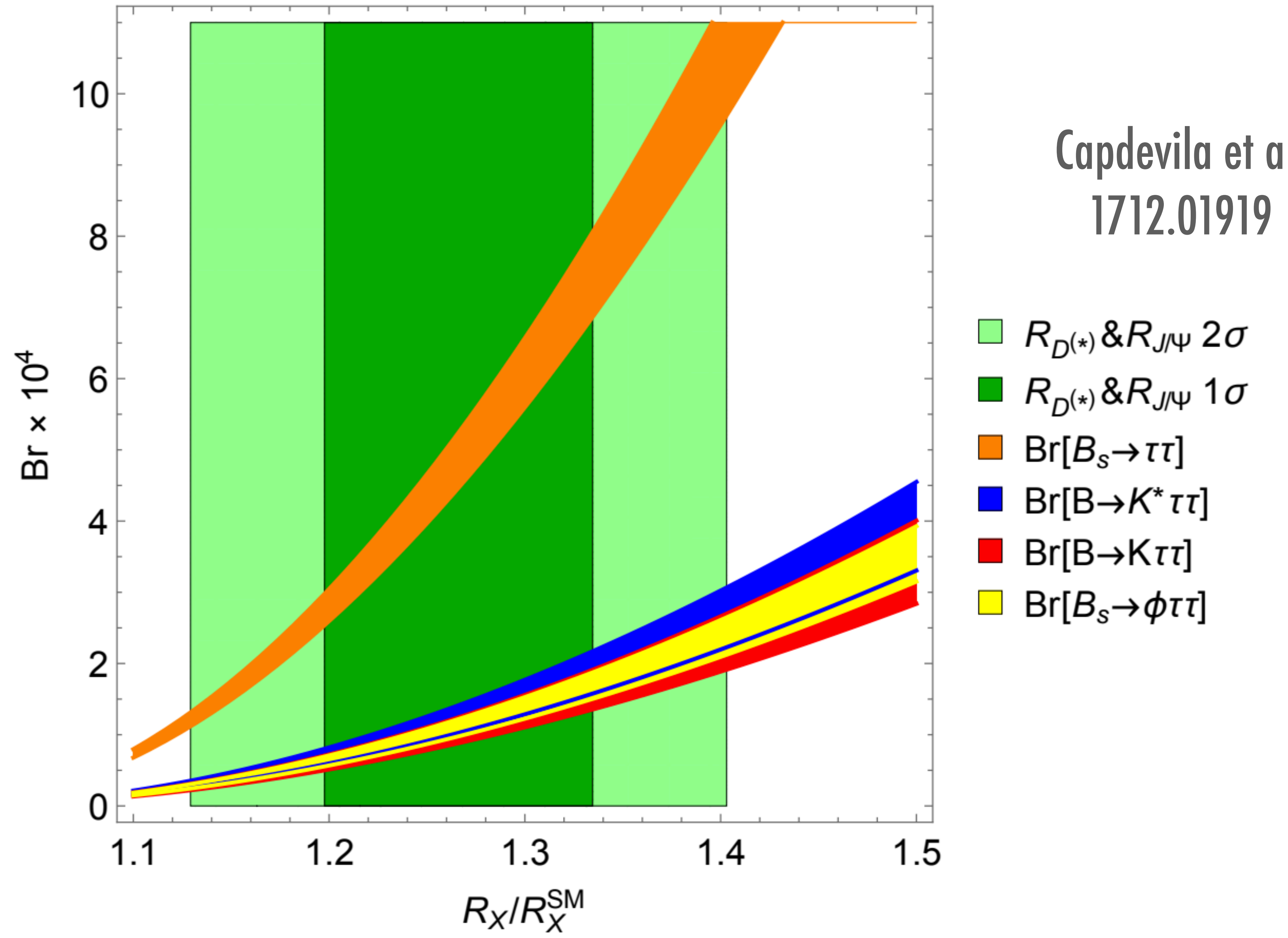
Can have large $R_D^{(*)}$ without disagreement with $B \to K^{(*)}\bar{\nu}\nu$ if

$$C_{lq}^{(1)} = C_{lq}^{(3)}$$

If the anomalies in $R_D^{(*)}$ persist, expect large deviations in $B \to K^{(*)}\tau^+\tau^-$ and $B_s \to \tau^+\tau^-$

If not, these observables combined will constrain the relevant operators to O(10 TeV)

Ho, Jiang, Kwok, Li, Liu 2212.02433

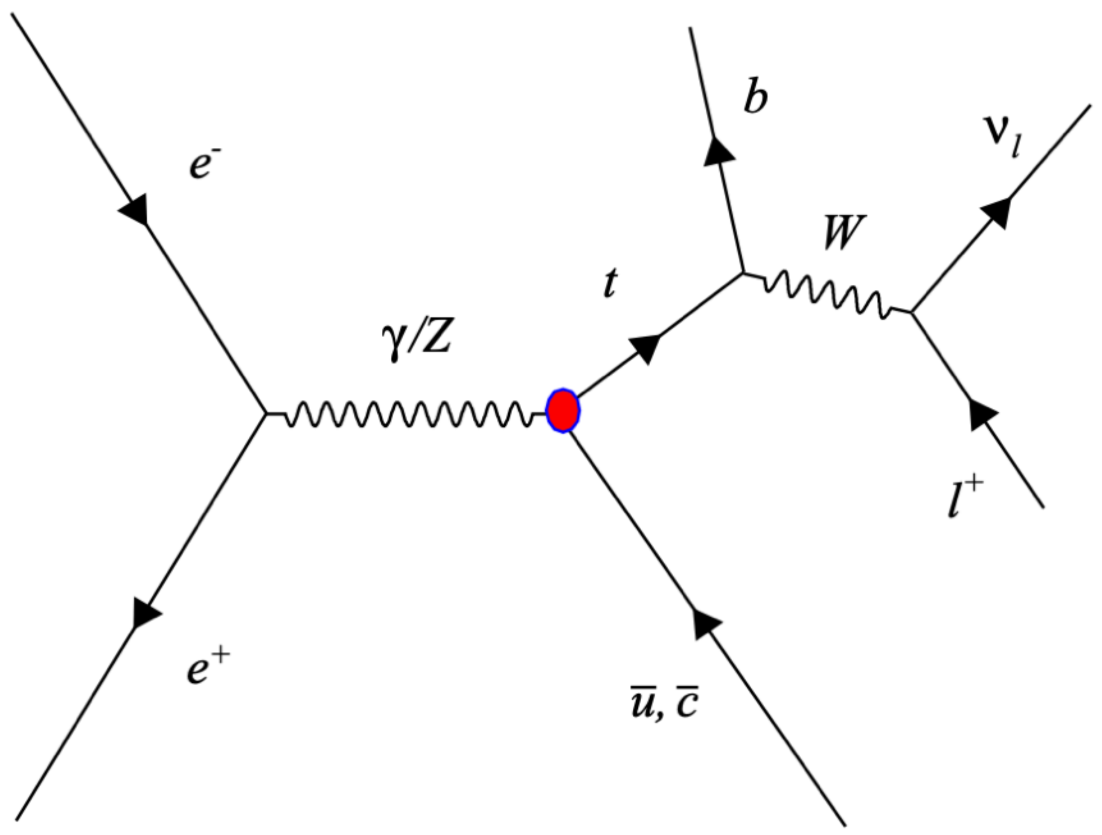


Capdevila et al, 1712.01919

Top

Top FCNCs

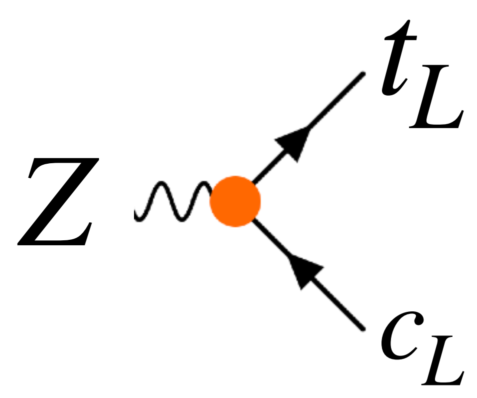
Khanpour et al, 1408.2090

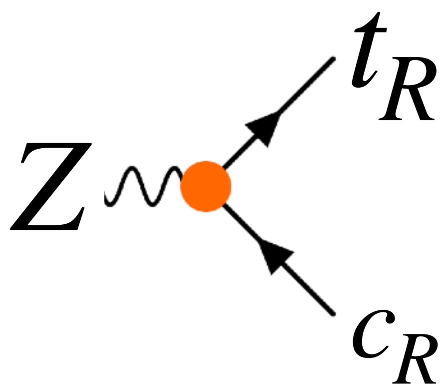


Effective operators contributing to t-q-Z coupling

$$O_{\phi q}^{(1,3)}$$

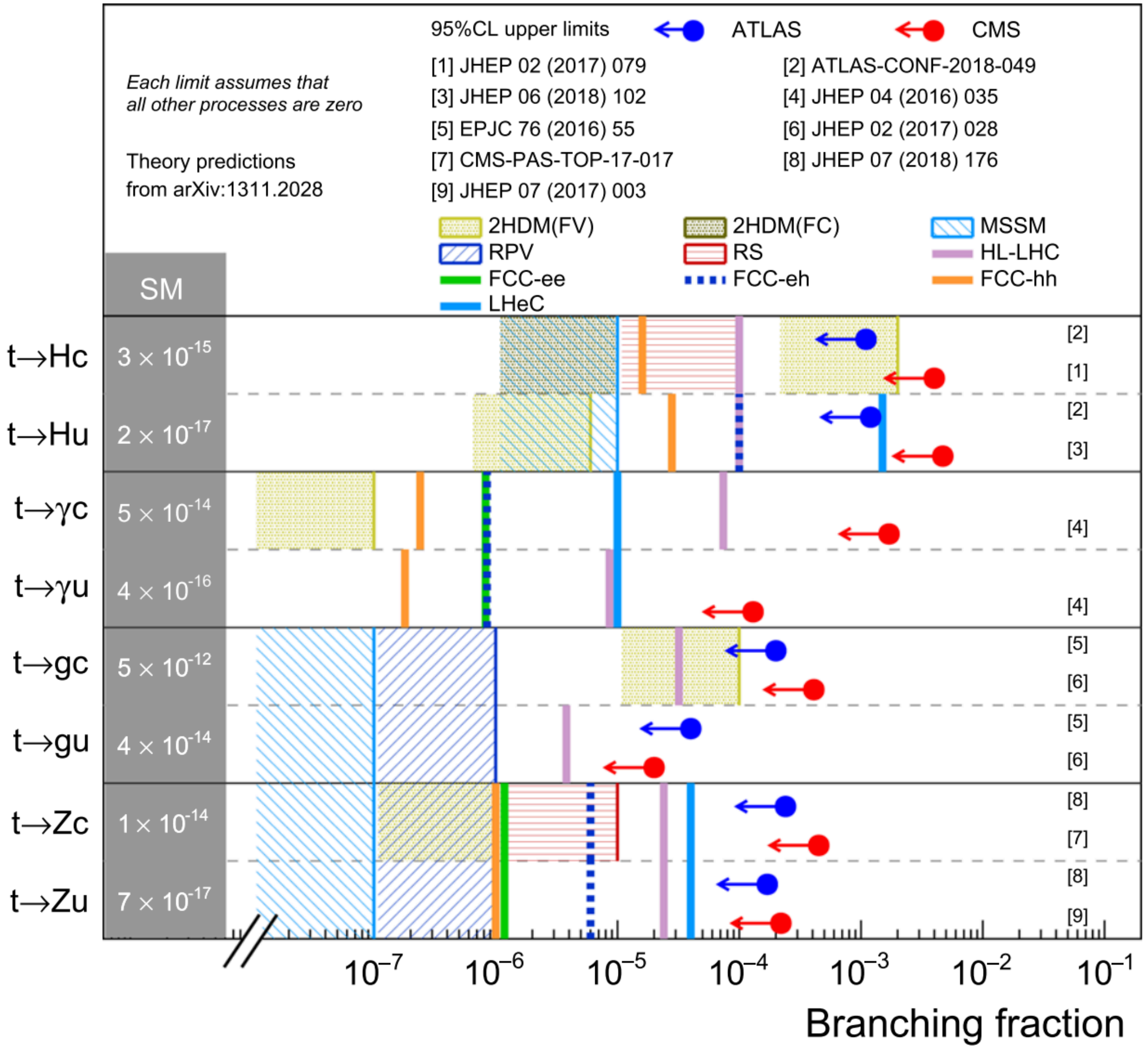
$$O_{\phi u}$$





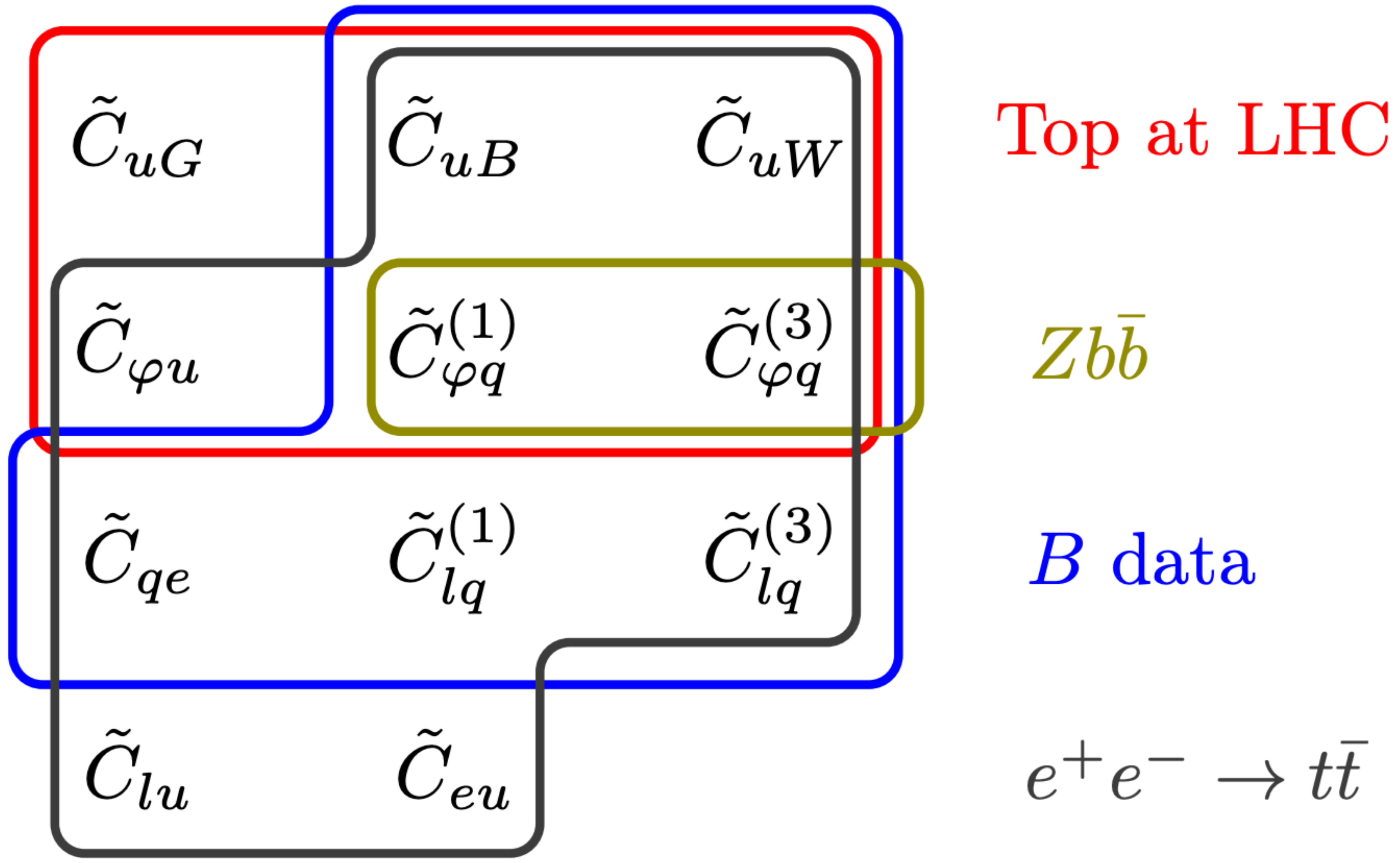
Also gives Z-b-s coupling

Future Circular Collider Conceptual Design Report Volume 1

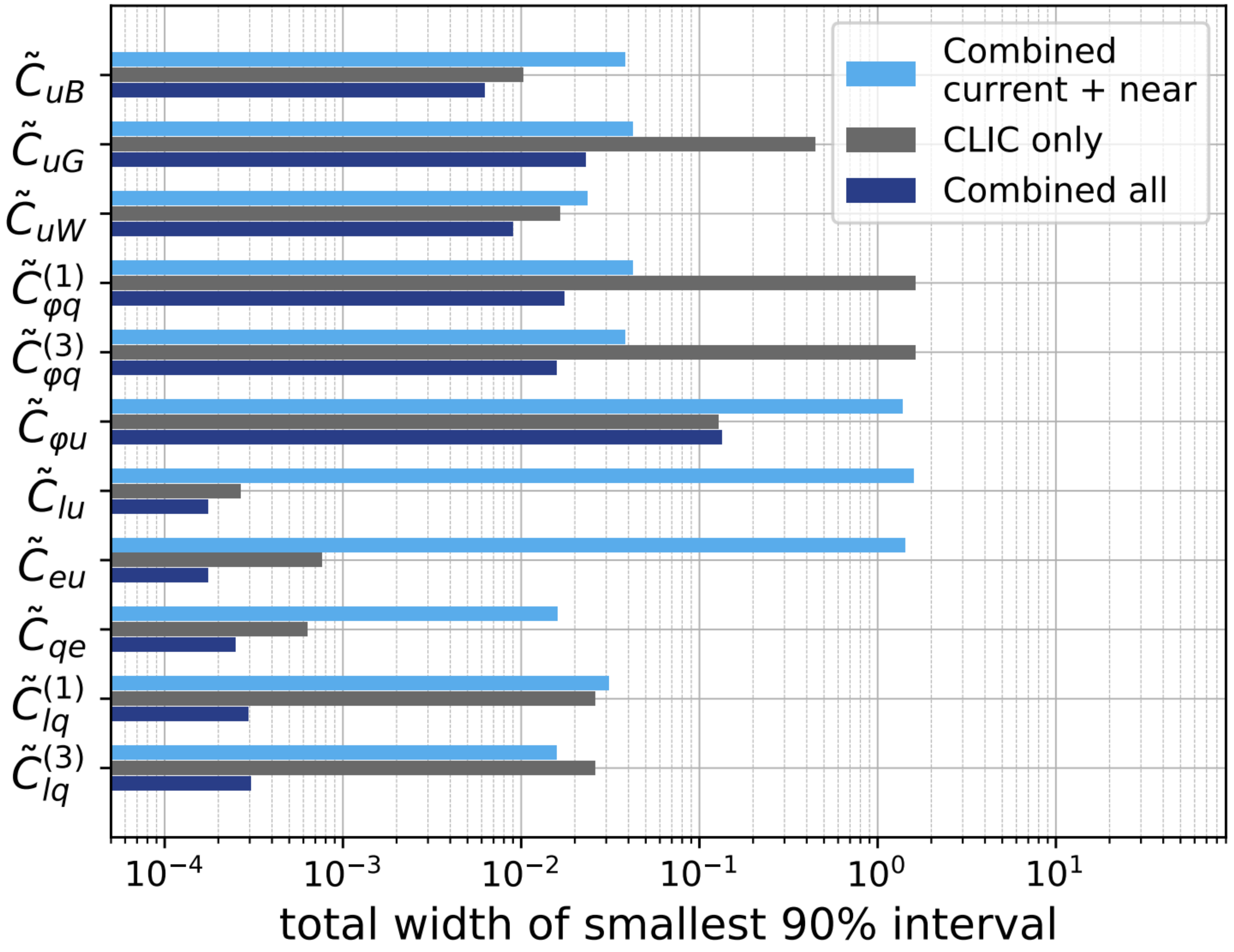


Top pairs at e^+e^- vs B observables

Top pair production probes some of the same operators as B decays



Bißmann, Grunwald, Hiller, Kröninger, 2012.10456



Observable	$\sqrt{s}$	Polarization (e^-, e^+)	Ref. experiment	SM Ref.
$\sigma_{t\bar{t}}$, A_{FB}	380 GeV	$(\pm 80\,\%, 0)$	[27]	[40]
$\sigma_{t\bar{t}}$, A_{FB}	1.4 TeV	$(\pm 80\,\%, 0)$	[27]	[40]
$\sigma_{t\bar{t}}$, A_{FB}	3 TeV	$(\pm 80\,\%, 0)$	[27]	[40]

Taus

Tests of lepton flavour universality in tau decays

$\mu - e$ universality

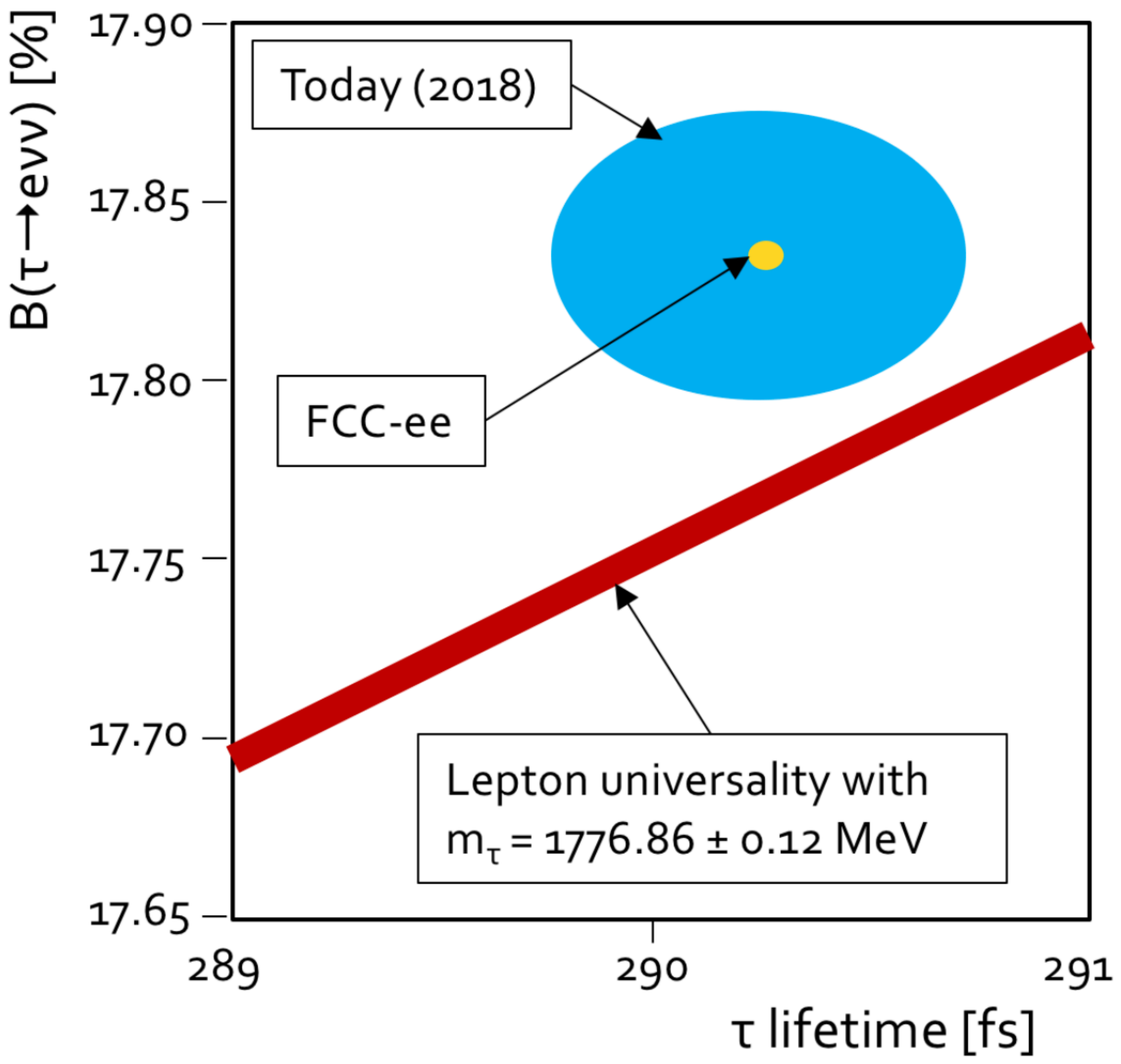
$$\left(\frac{g_\mu}{g_\mathrm{e}}\right)^2 = \frac{\mathcal{B}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{B}(\tau \to \mathrm{e}\bar{\nu}\nu)} \cdot \frac{f_{\tau\mathrm{e}}}{f_{\tau\mu}}$$

$\tau - \mu$ universality

$$\left(\frac{g_\tau}{g_\ell}\right)^2 = \frac{\mathcal{B}(\tau \to \ell\bar{\nu}\nu)}{\mathcal{B}(\mu \to \ell\bar{\nu}\nu)} \cdot \frac{\tau_\mu m_\mu^5}{\tau_\tau m_\tau^5} \cdot \frac{f_{\mu\mathrm{e}}}{f_{\tau\ell}} \cdot \frac{R_\gamma^\mu R_\mathrm{W}^\mu}{R_\gamma^\tau R_\mathrm{W}^\tau}$$

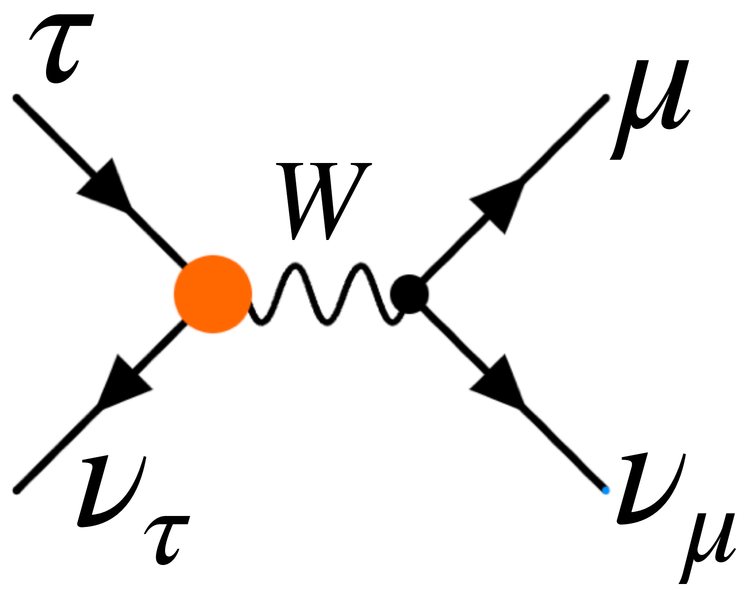
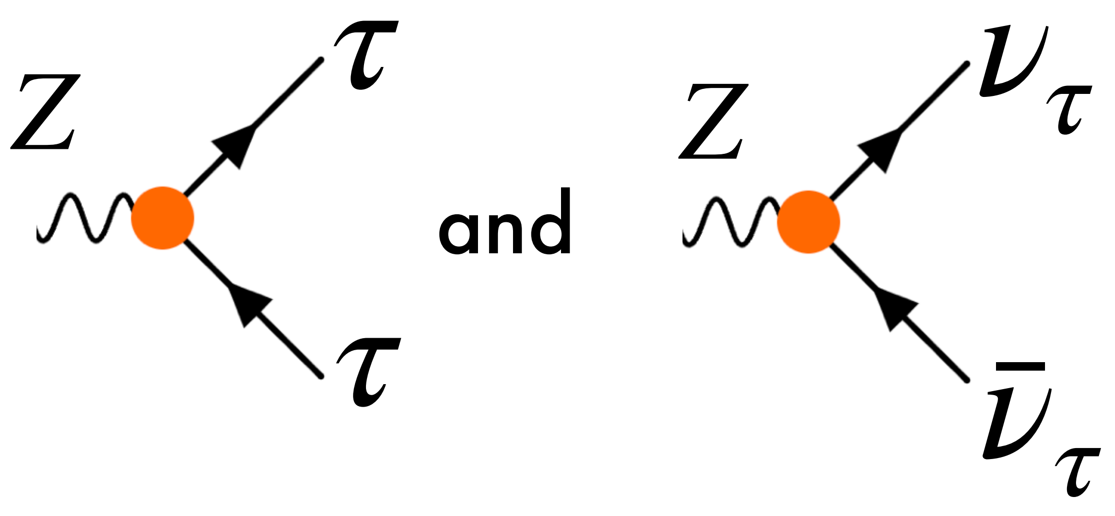
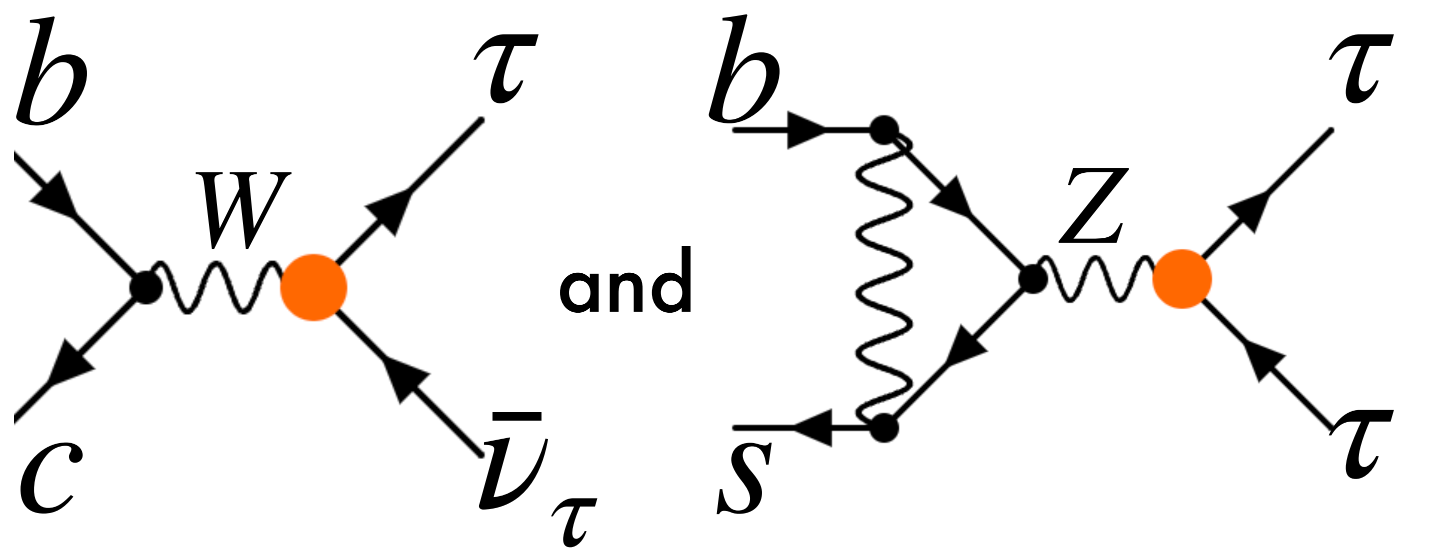
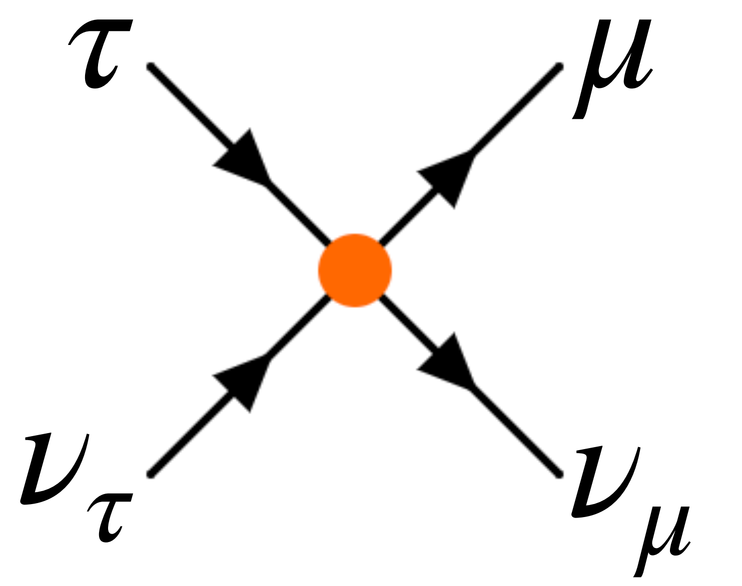
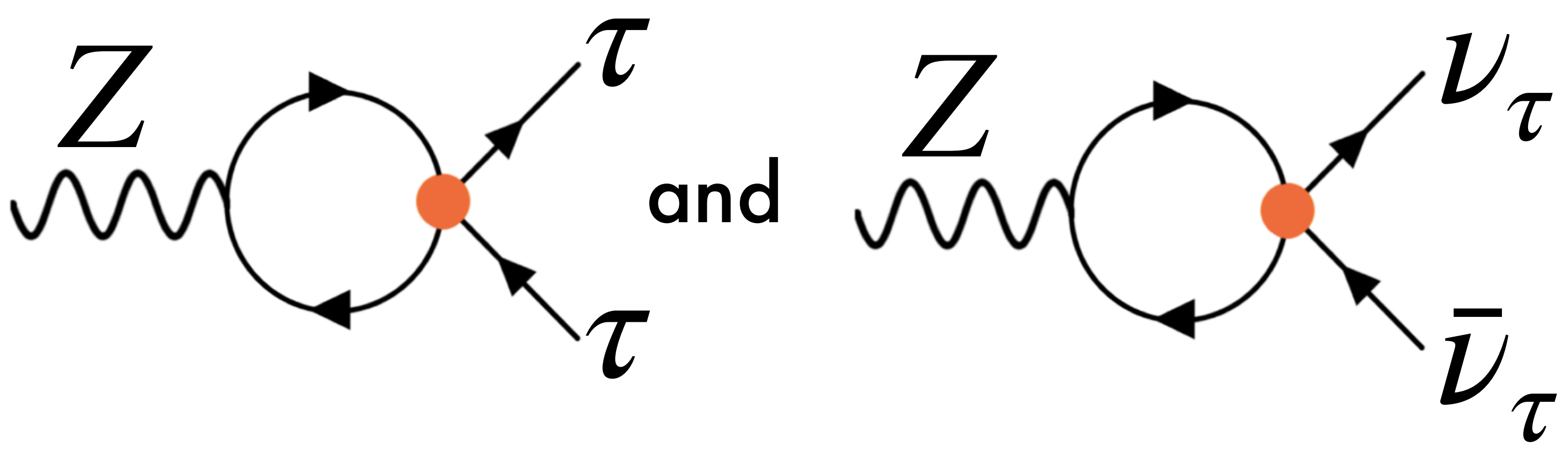
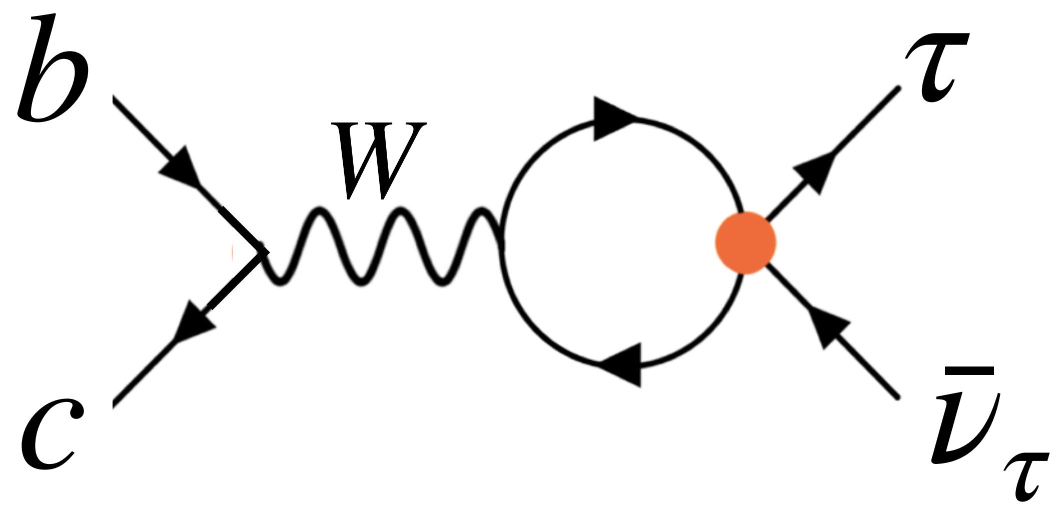
Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.
m_τ (MeV)	1776.86 ± 0.12	0.004	0.1
$\mathcal{B}(\tau \to \mathrm{e}\bar{\nu}\nu)$ (%)	17.82 ± 0.05	0.0001	0.003
$\mathcal{B}(\tau \to \mu\bar{\nu}\nu)$ (%)	17.39 ± 0.05	0.0001	0.003
τ_τ (fs)	290.3 ± 0.5	0.001	0.04

Dam, 1811.09408



Lepton flavour universality tests

All the tests of LFUV can be tests of the same physics

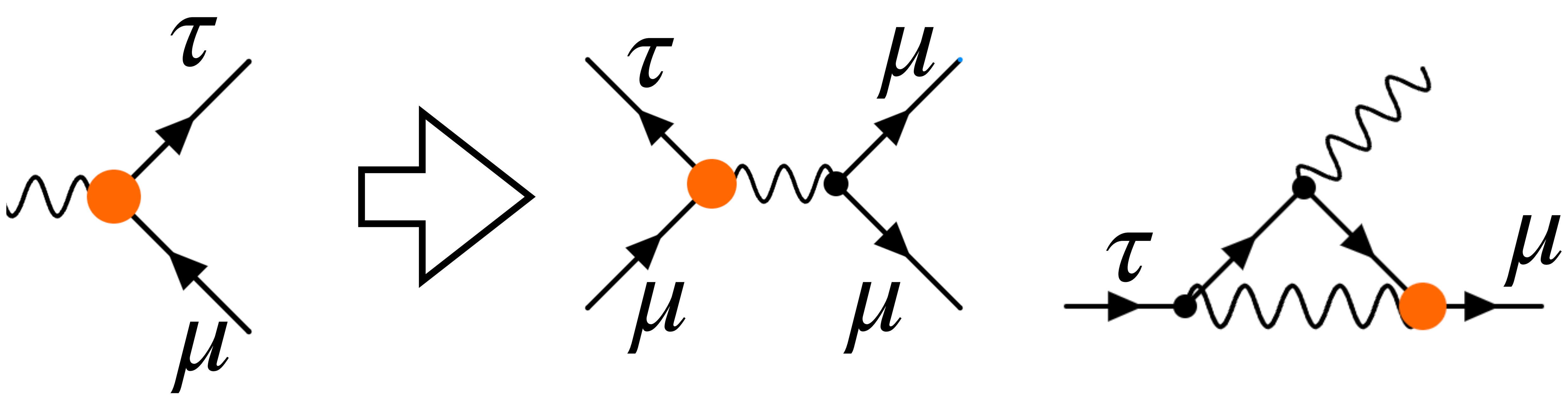
	Tau decays	Z decays	B decays
$O_{\phi l}^{(1,3)}$ $(\phi^\dagger D_\mu \tau^a \phi)(\bar{L}^3 \gamma^\mu L^3)$			
O_{ll} $(\bar{L}^2 \gamma_\mu L^2)(\bar{L}^3 \gamma^\mu L^3)$			

Lepton flavour violation at FCC-ee

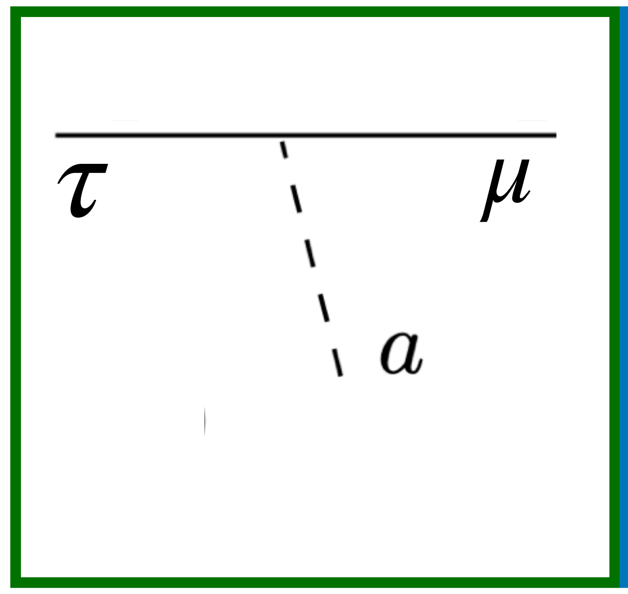
FCC Snowmass report, 2203.06520

Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	10^{-10}–10^{-8}
$Z \to \tau\mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}

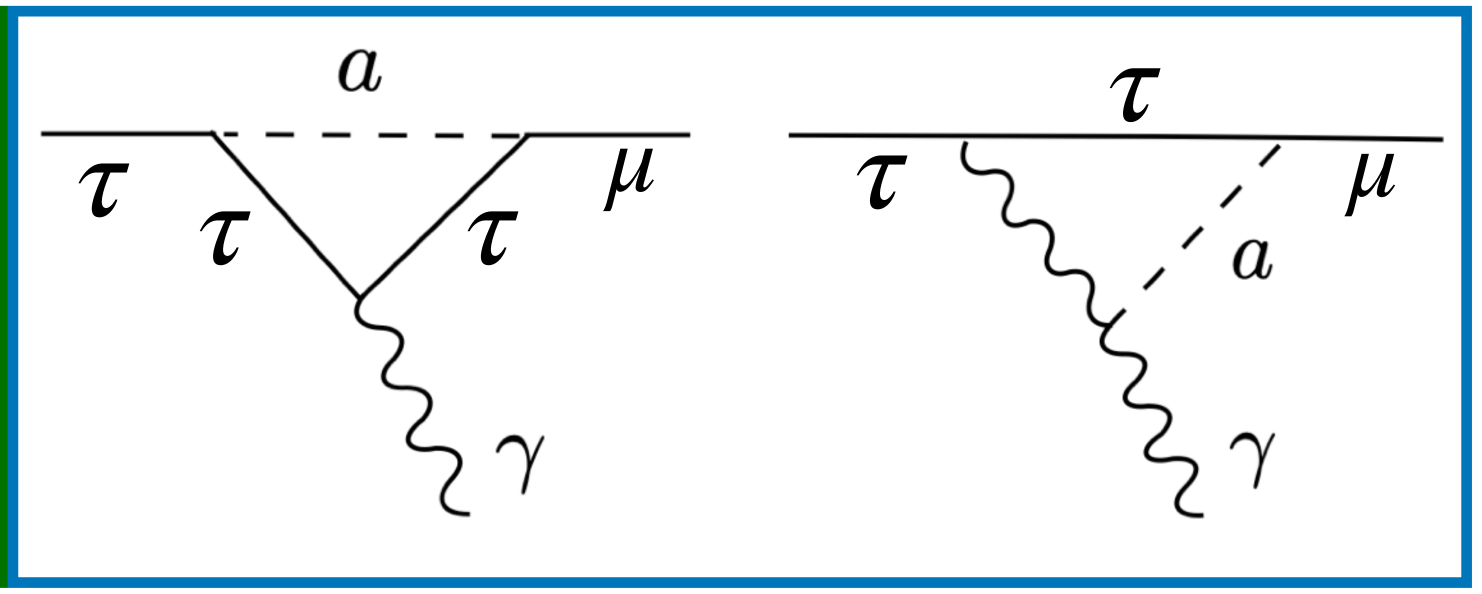
In SMEFT, if you have $Z \to \tau\mu$, then you generate $\tau \to 3\mu$ and $\tau \to \mu\gamma$



With light new physics, can get a resonant enhancement of $\tau \to 3\mu$

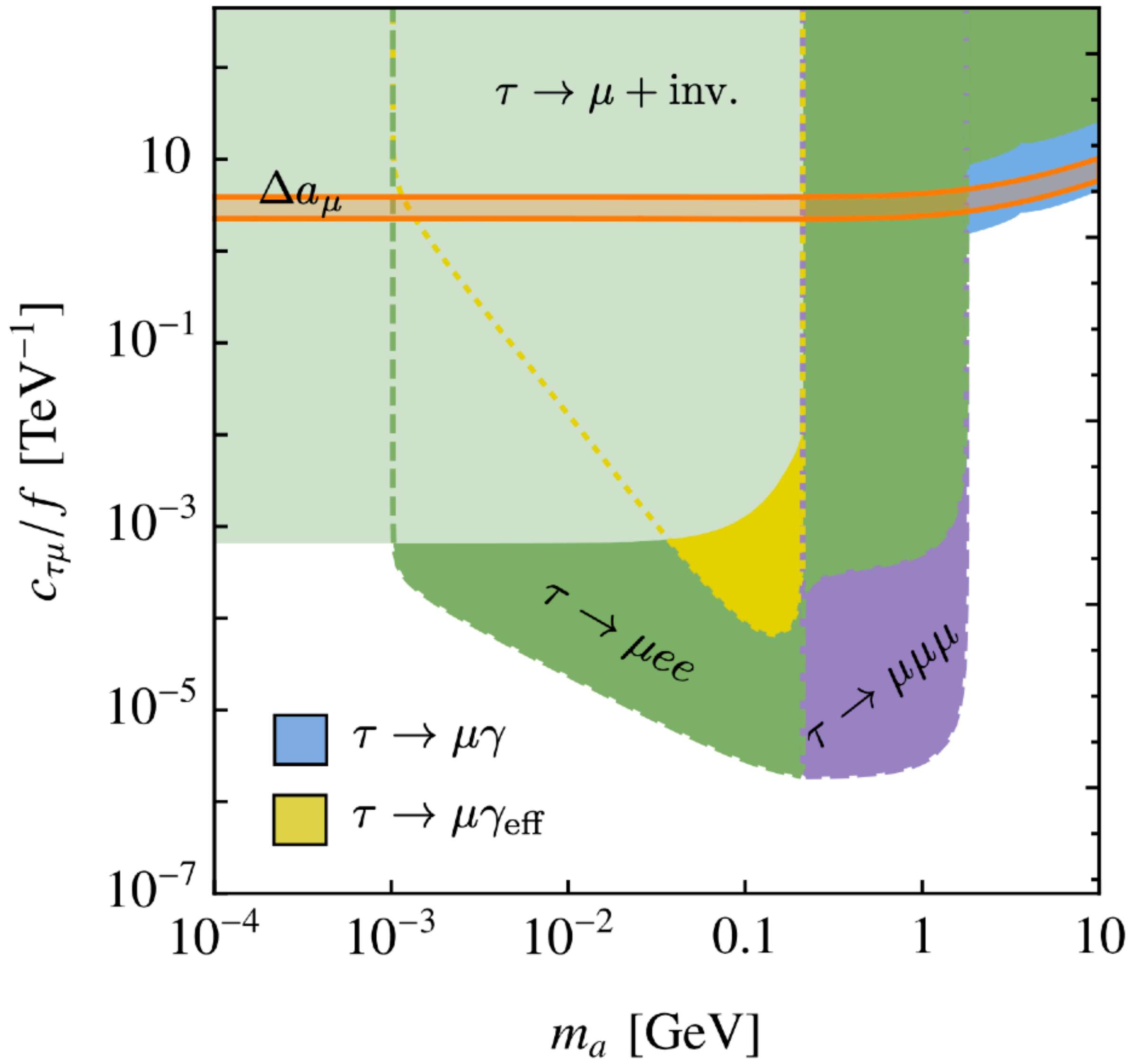


$\tau \to 3\mu$



$\tau \to \mu\gamma$

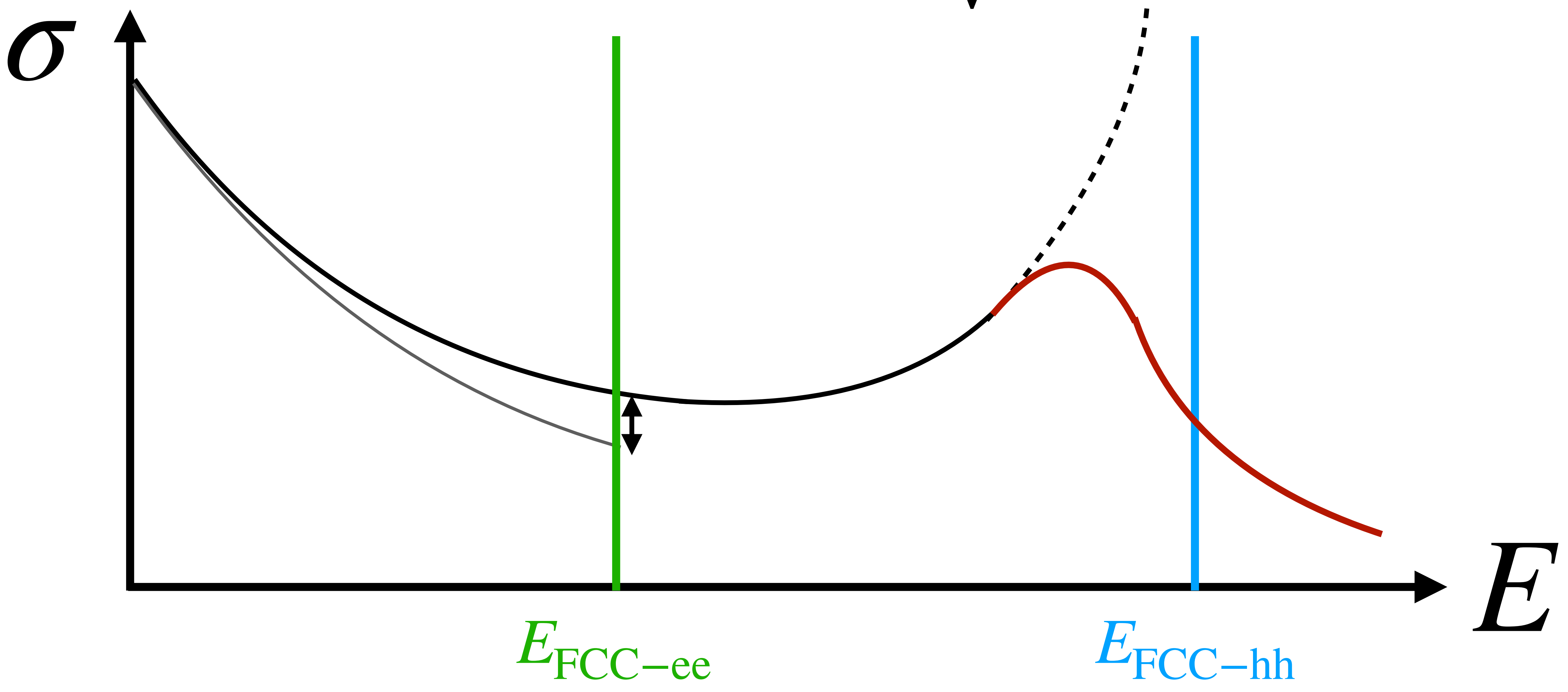
Bauer, Neubert, SR, Schnubel, Thamm 2110.10698



From FCC-ee to FCC-hh

A measured non-zero value of SMEFT Wilson coefficient(s) could provide a no-lose theorem for FCC-hh

Measure $\frac{C_i}{\Lambda^2} = x \implies$ at energies $E \lesssim \frac{4\pi}{\sqrt{x}}$, amplitude violates unitarity



If not, any new physics at FCC-hh will have to pass stringent indirect tests, à la S, T parameters of LEP: informs search strategies

Summary

After the LHC, questions will still remain about the third generation of fermions and about the Yukawa sector of the SM

FCC-ee provides multiple lines of attack to close in on these, including:

- *Flavour factory* via copious b, c mesons and τs produced at the Z pole
- Measurements of *Higgs couplings to fermions*
- *Precision Z pole and W pole* measurements
- *Top precision*

All of these play an important role, and their combination will help understand flavour in the SM and beyond