Brief intro to Flavor Physics @ FCC-ee

Gino Isidori
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- General considerations
- The special role of the 3rd family
- Highlights of FCC-ee in tau & b physics
- Conclusions

General considerations [On the importance of indirect NP searches]

- We have good reasons to expect new degrees of freedom in the TeV-scale domain. However, no direct signals of New Physics has been observed so far at the high-energy frontier (*whose exploration is far from being complete...*)

↓

No clear indications on the precise location of the New Physics threshold

- We should not forget that in the last ~ 40 years all the discoveries at the high-energy frontier [c, b, t, H] were anticipated by indirect indications from indirect searches (flavor/CP and EWPO).

Hard to expect a discovery at High Energies without indirect clues at Low Energies...

General considerations [On the importance of indirect NP searches]

Hard to expect a discovery at HE without indirect clues at low energies (*general field-theory argument*):

$$A(\psi_i \to \psi_j + X) = A_0 \left[1 + \frac{c_{NP}\, m_W^2}{c_{SM}\, \Lambda^2} \right]$$

$$\mathscr{L}_{NP\text{-}EFT} = \mathscr{L}_{SM} + \Sigma_i \frac{c_{NP}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

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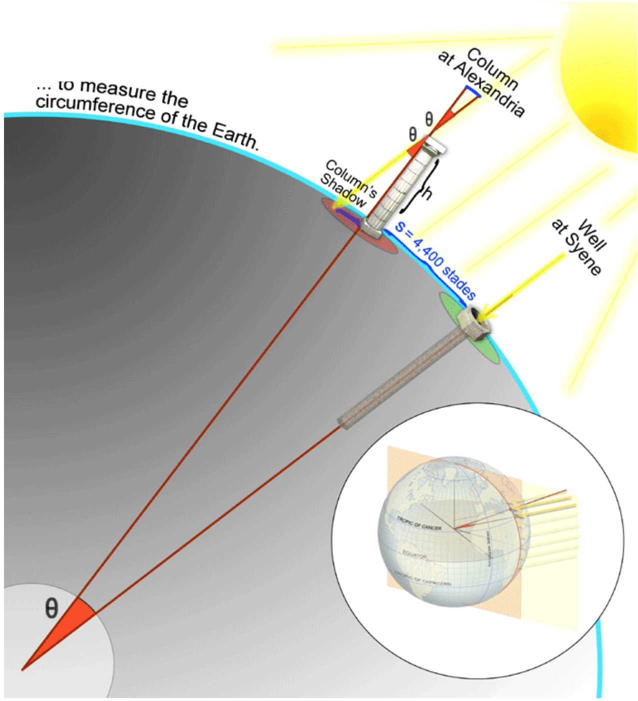

It's all a matter of precision...

General considerations [On the importance of indirect NP searches]

The FCC-ee offers a unique opportunity in this respect with the huge statistics @ the Z pole:

$$A(\psi_i \to \psi_j + X) = A_0 \left[\frac{c_{SM}}{M_W^2} + \frac{c_{NP}}{\Lambda^2} \right]$$

Λ_{NP}		$\sim 10 \times \Lambda_{NP}$	
c_{NP}	N_Z [LEP] →	$0.003 \times c_{NP}$	$10^5 \times N_Z$ [FCC-ee]

For th. clean observables (pure stat. error) determined by Z decays

Unprecedented jump in precision!

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Λ_{NP}, c_{NP}	N_Z [LEP]	→	$\sim 10 \times \Lambda_{NP}$, $0.003 \times c_{NP}$	$10^5 \times N_Z$ [FCC-ee]
Λ_{NP}, c_{NP}	$b\bar{b}$, $\tau\bar{\tau}$ [Belle]	→	$\sim 6 \times \Lambda_{NP}$, $0.03 \times c_{NP}$	$10^3 \times$ $b\bar{b}$, $\tau\bar{\tau}$ [FCC-ee]

For th. clean observables (pure stat. error) determined by Z decays

Unprecedented jump in precision!

For $b\bar{b}$ & $\tau\bar{\tau}$ pairs we have to take into account also Belle-II (~ 50 × Belle), & LHCb

But...
→ LHCb is poor on missing-energy modes (*virtually all tau decays..*)
→ At Belle-II there are no B_s, and b & τ have a very small boost

The special role of the 3rd family

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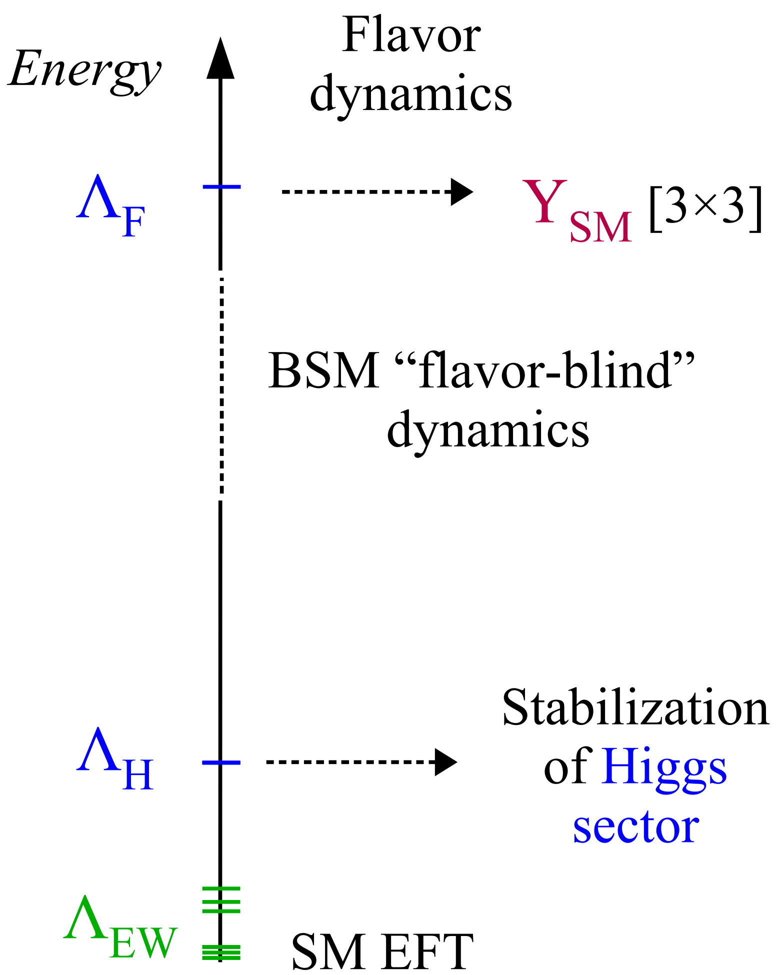
For a long time, the vast majority of model-building attempts to extend the SM was based on the *implicit* hypotheses of *flavor-universal* New Physics



- Concentrate on the Higgs hierarchy problem
- Postpone the flavor problem to higher scales

⬇

3 gen. = "identical copies" up to high energies

Less compelling after the LHC results:

No clear sign of NP from direct searches

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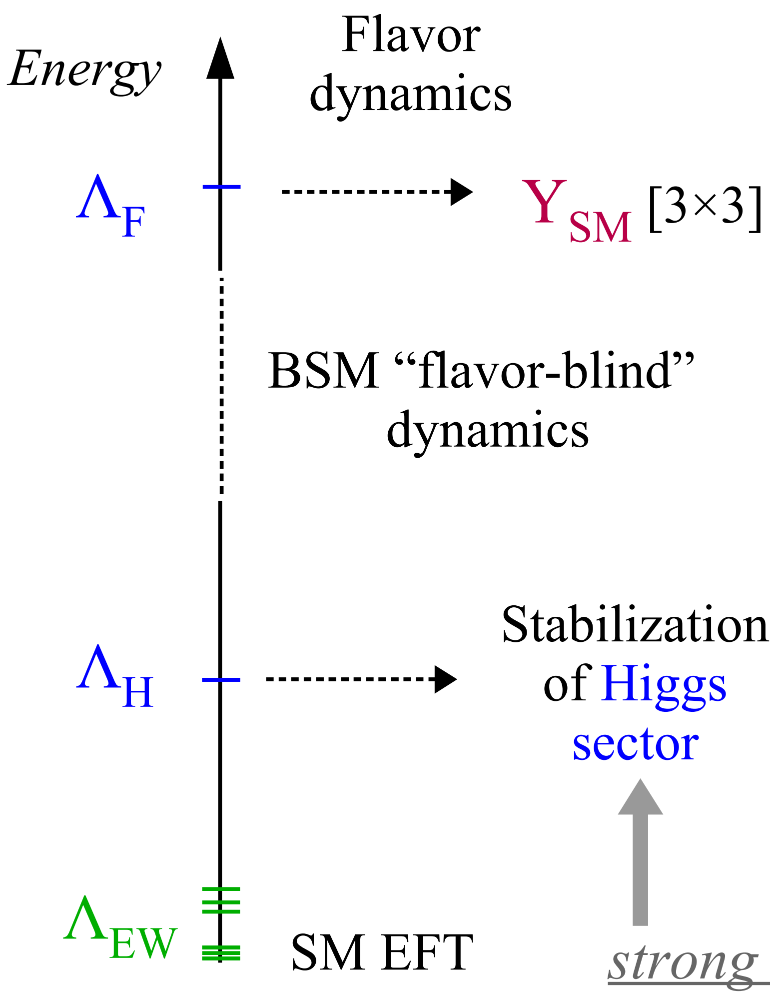

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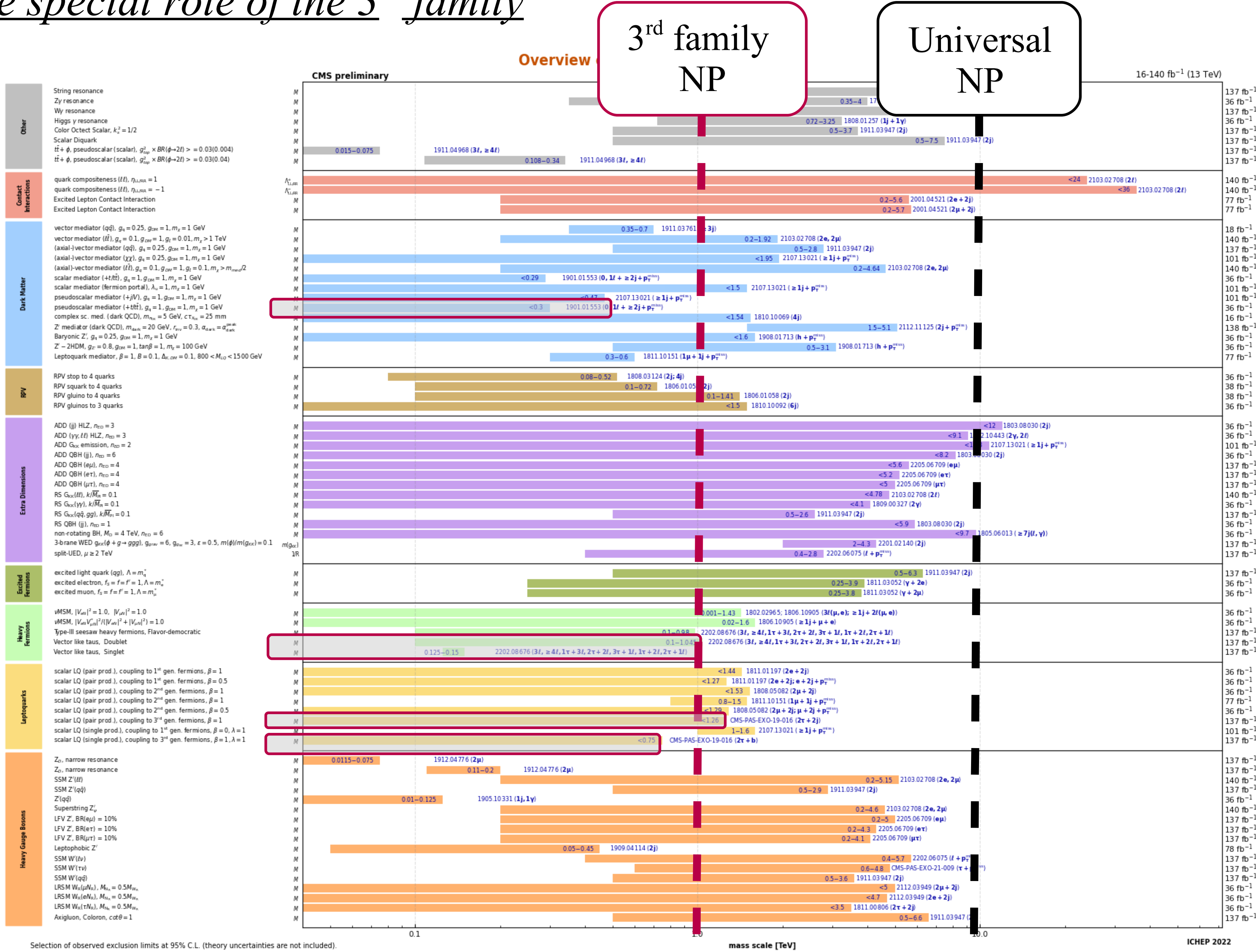
Less compelling after the LHC results:

No clear sign of NP from direct searches

strong bounds on NP coupled universally to all families

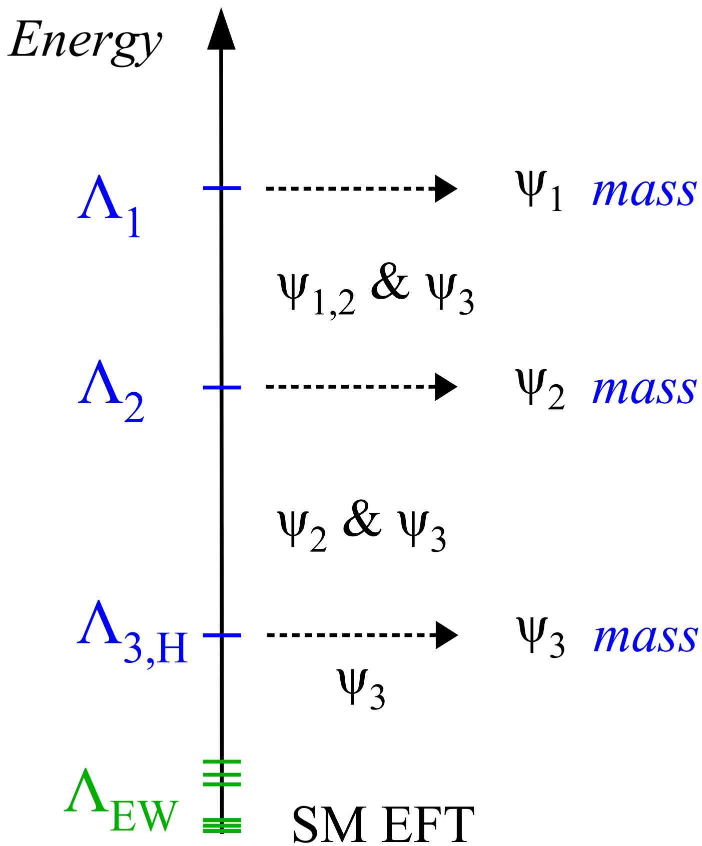
worsening of the Higgs hierarchy problem

The special role of the 3rd family



The special role of the 3rd family

Shift of paradigm to address both the Higgs hierarchy problem and the flavor puzzle: *multi-scale* UV completion with *flavor non-universal* interactions



Dvali & Shifman '00
Panico & Pomarol '16
⋮
Bordone *et al.* '17
Allwicher, GI, Thomsen '20
Barbieri '21
Davighi & G.I. '23

Main idea:

- Flavor non-universal interactions already at the TeV scale:
- 1st & 2nd gen. have small masses because they are coupled to NP at heavier scales

⬇

~~3 gen. = "identical copies" up to high energies~~

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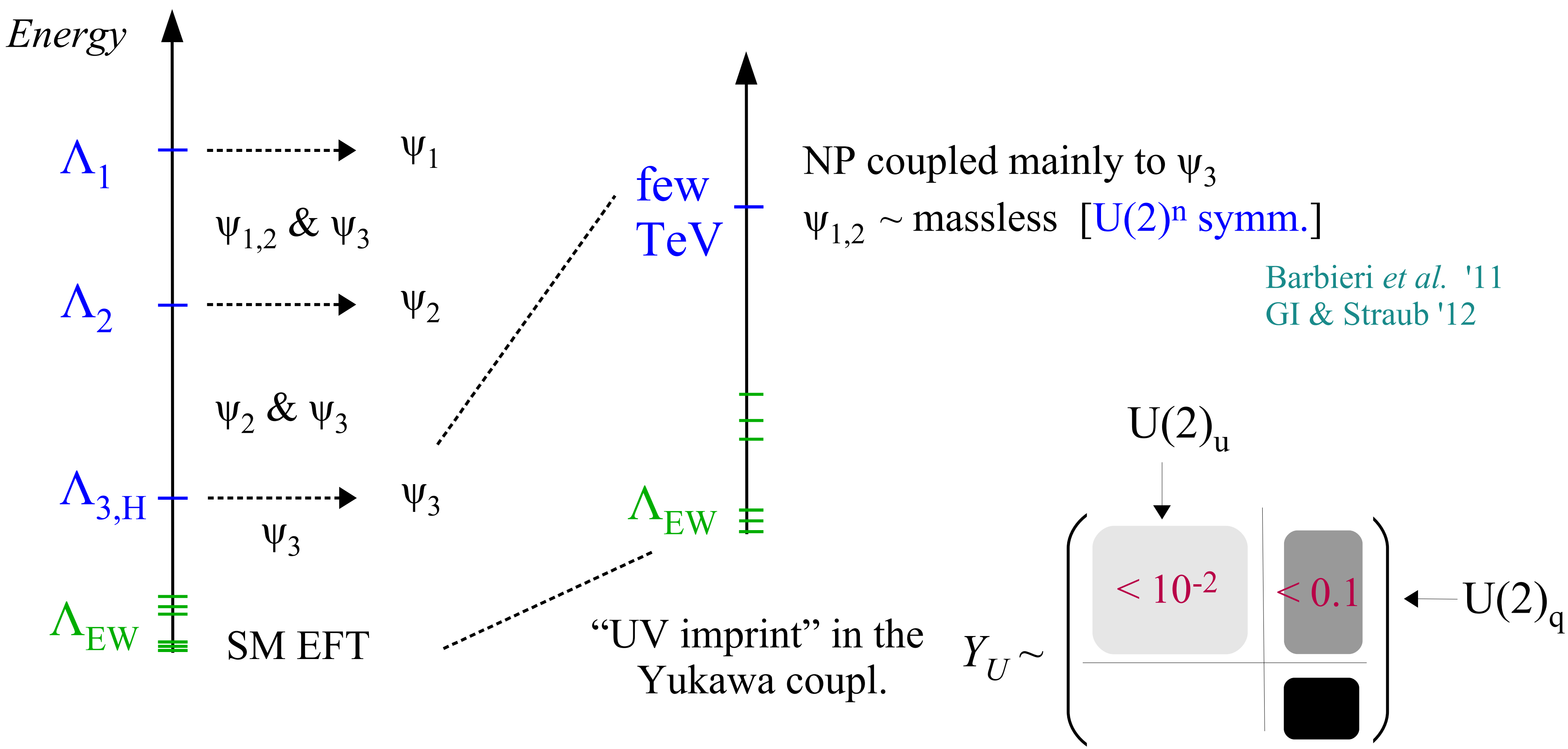

Effective organizing principle for the flavor structure of the SMEFT

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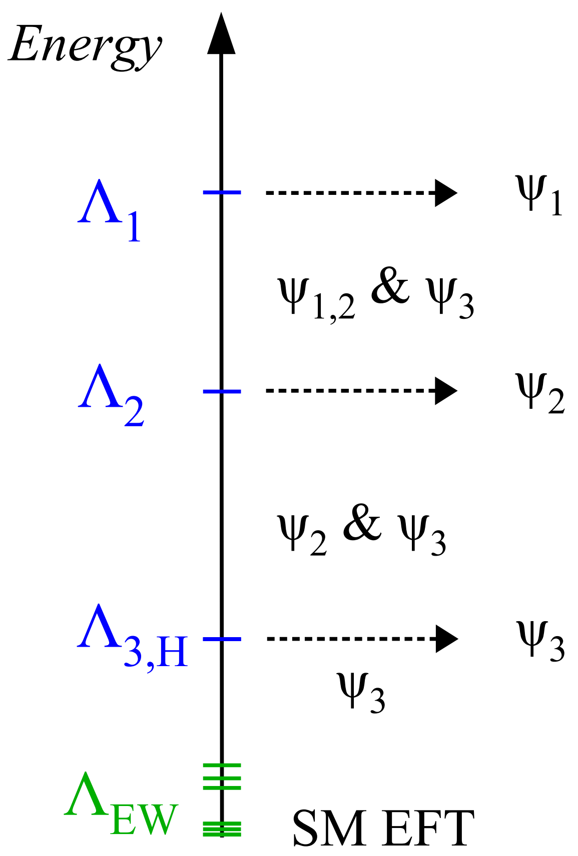


A renewed phenomenological interest in this type of approach has been triggered by the B-physics anomalies (*hinting to violations of lepton flavor universality, mainly in 3rd gen.*)

But the construction has an intrinsic, more general, interest:

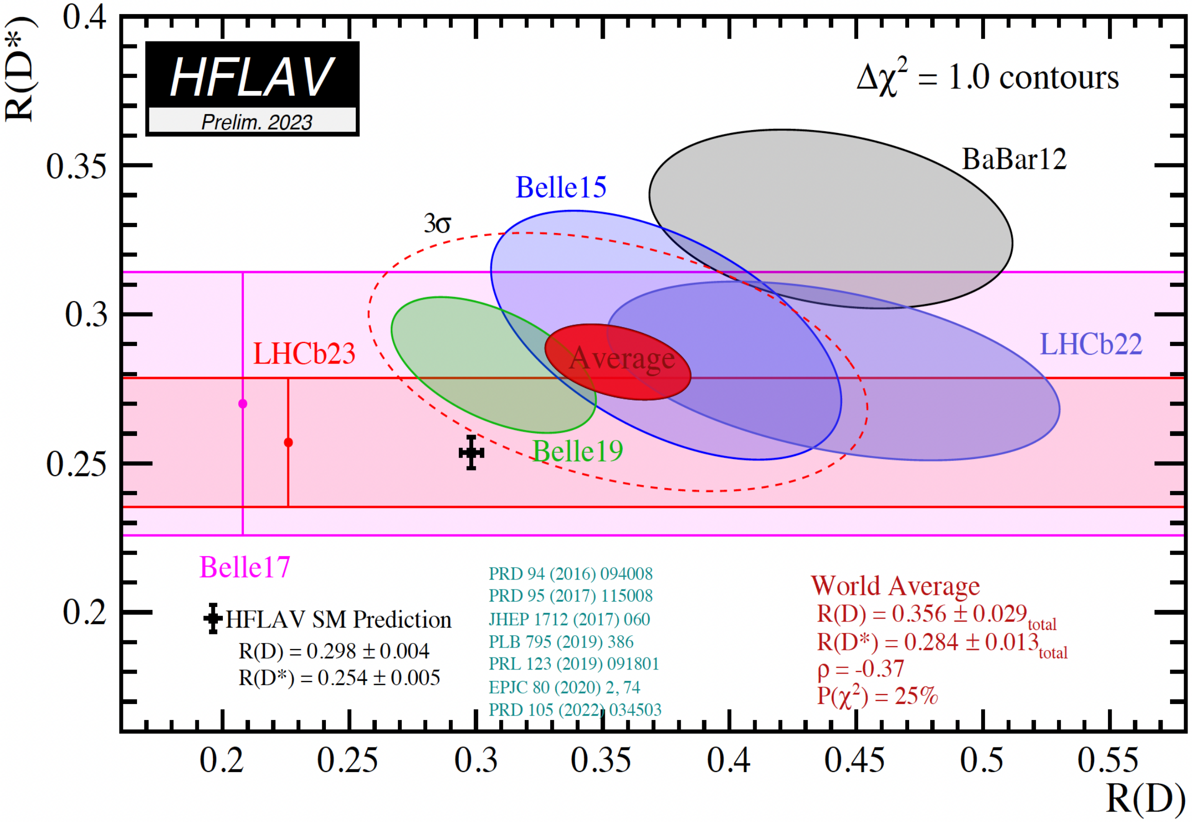
- Explain the origin of the flavor hierarchies
- Allow TeV-scale NP coupled (mainly) to 3rd gen. → Higgs sector stabilization

Allwicher, GI, Thomsen '20
Davighi & G.I. '23

→ talk by Joe Davighi

▸ The special role of the 3rd family

Renewed phenomenological triggered by the B-physics anomalies:



N.B.:

1) The drop in significance of the neutral-current anomalies does not imply a major shift in the preferred parameter space

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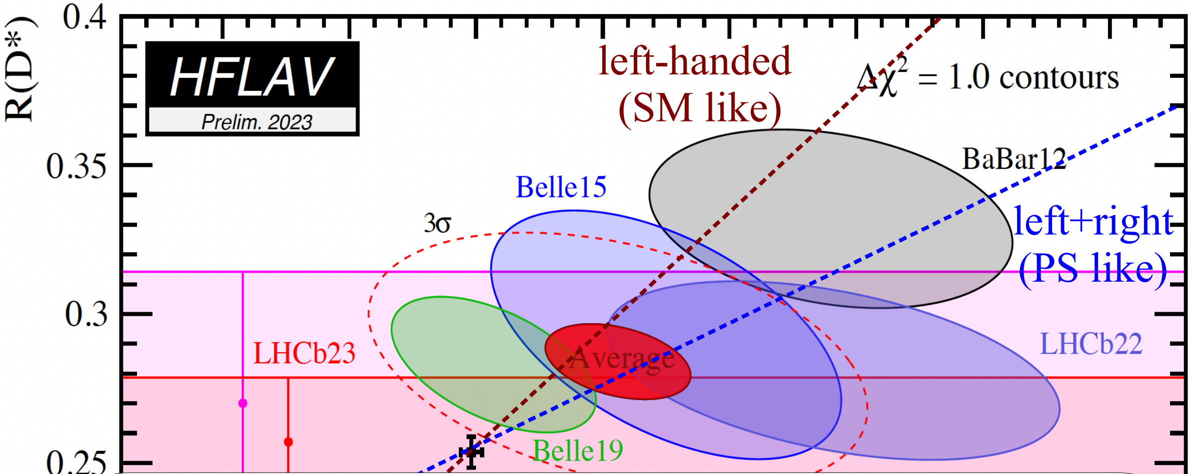

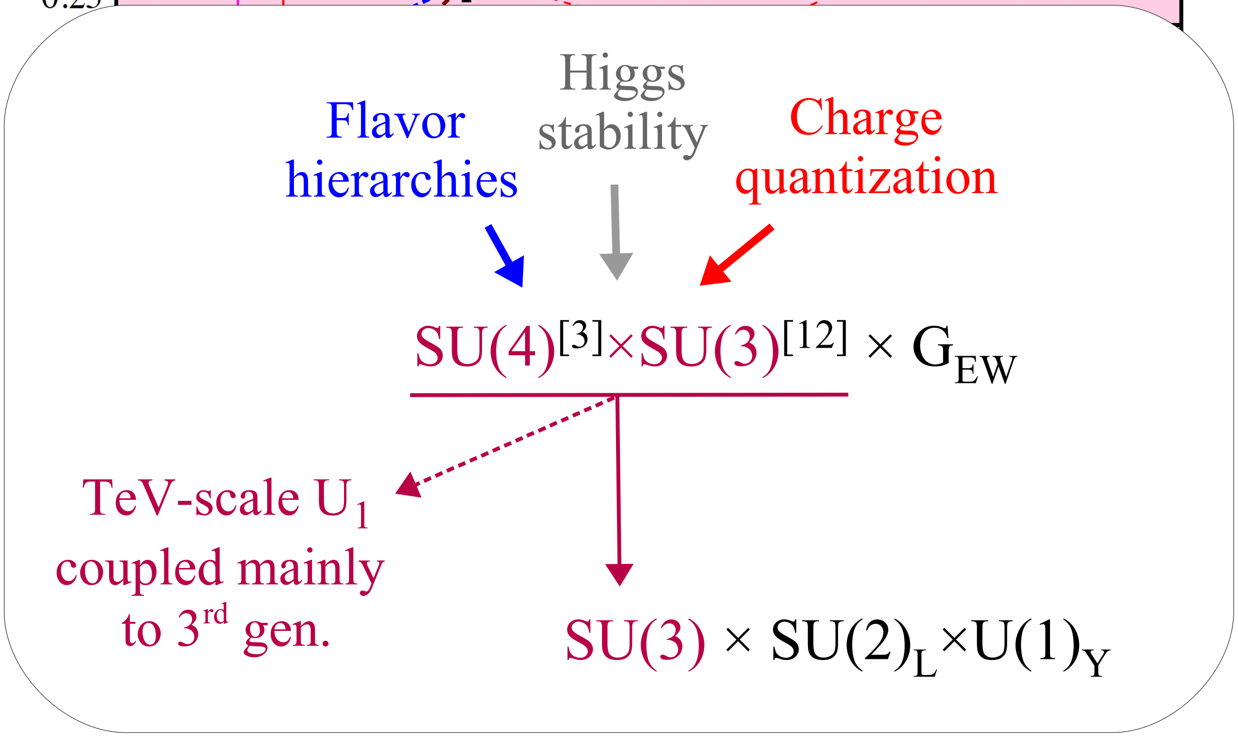

N.B.:

1) The drop in significance of the neutral-current anomalies does not imply a major shift in the preferred parameter space

2) Beside the (*low*) significance in present data, this set-up has an interesting "UV motivation" → useful benchmark for FCC-ee studies

Highlights of FCC-ee in tau & b physics

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E.g.: (I) LFU tests in tau decays

A. Pich '13

	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$
$\lvert g_\mu/g_e\rvert$	1.0018 (14)	1.0021 (16)	0.9978 (20)	1.0010 (25)	0.996 (10)
	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$	
$\lvert g_\tau/g_\mu\rvert$	1.0011 (15)	0.9962 (27)	0.9858 (70)	1.034 (13)	
	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$			
$\lvert g_\tau/g_e\rvert$	1.0030 (15)	1.031 (13)			

- NP expectation from motivated NP ($\to$ *flavor deconstruction*) up to current bounds (i.e. ~ 2×10^{-3})
- SM theory precision ~ 10^{-5}
- Belle-II can (at most) reach an error ~ 0.3×10^{-3}
- FCC-ee could go below 10^{-4} !

Unique opportunity !

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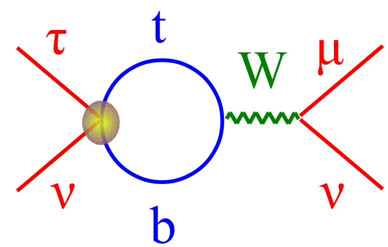

"Model-independent" O(10^{-3}) correction linked to the CC anomalies

Feruglio, Paradisi, Pattori '16

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LFU violations in tau decays expected in motivated LQ models addressing the B anomalies

Allwicher, GI, Selimovic, '21
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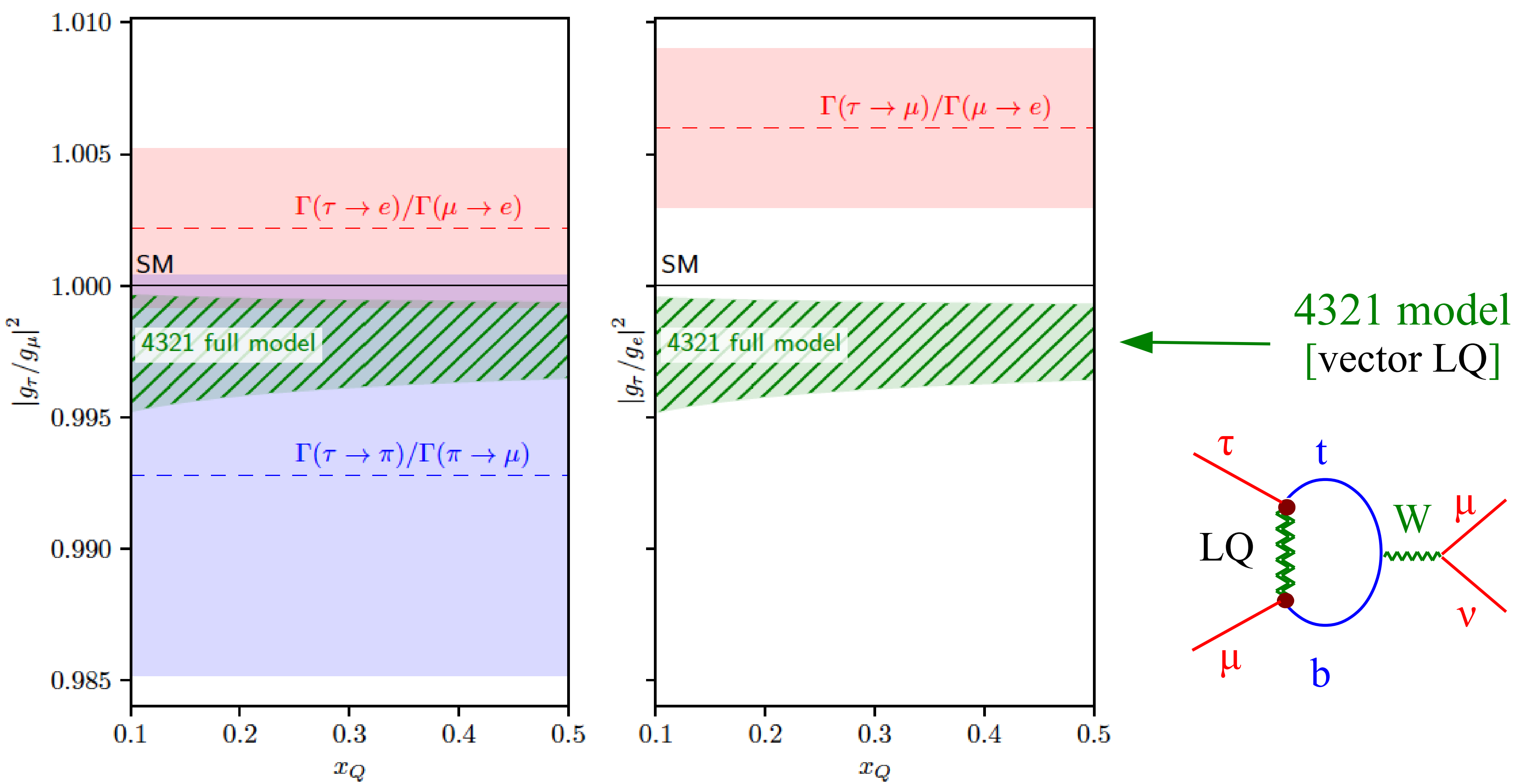

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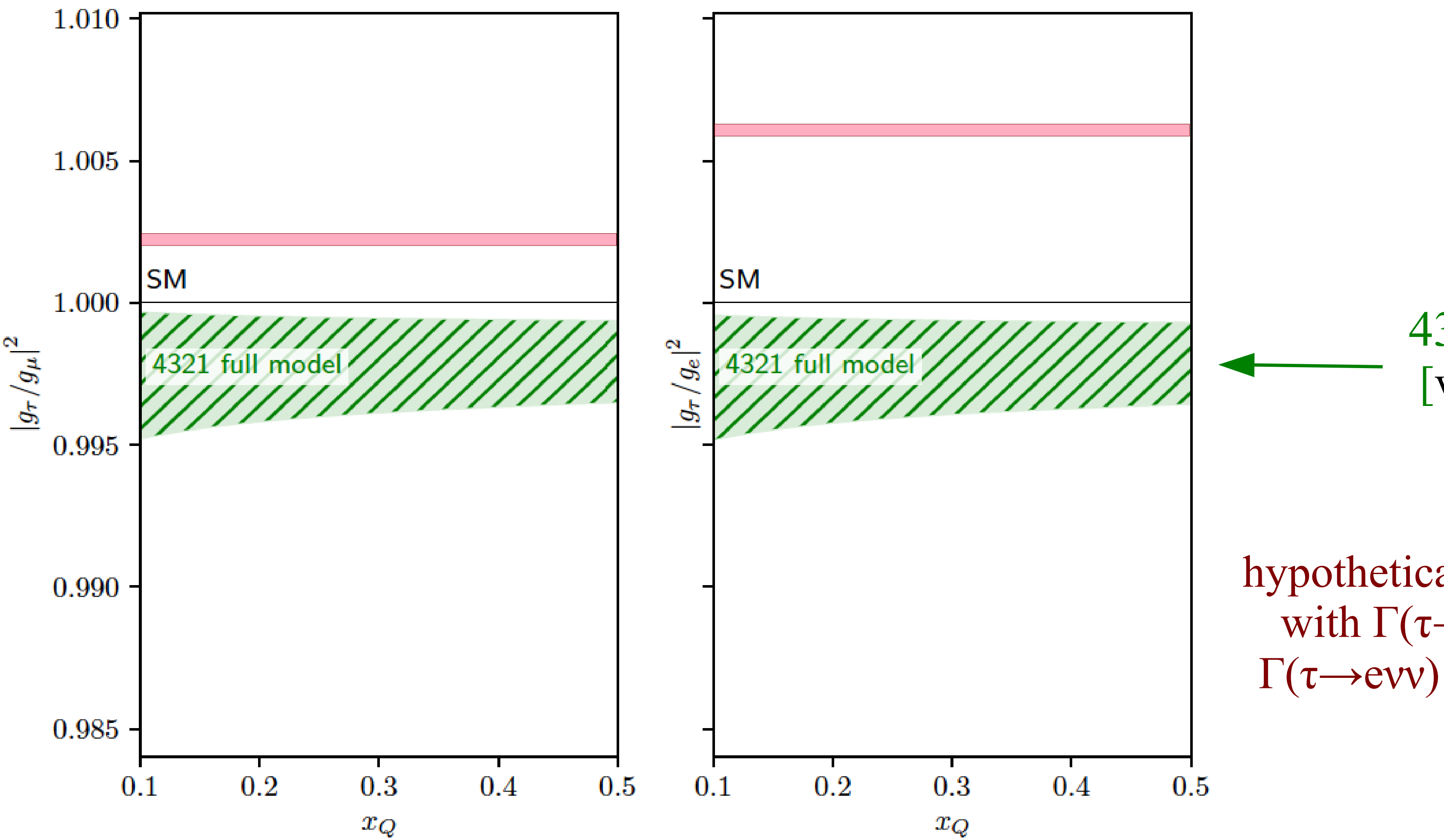

4321 model [vector LQ]

hypothetical 3σ bands with Γ(τ→μνν) & Γ(τ→eνν) @ 2×10^{-4}

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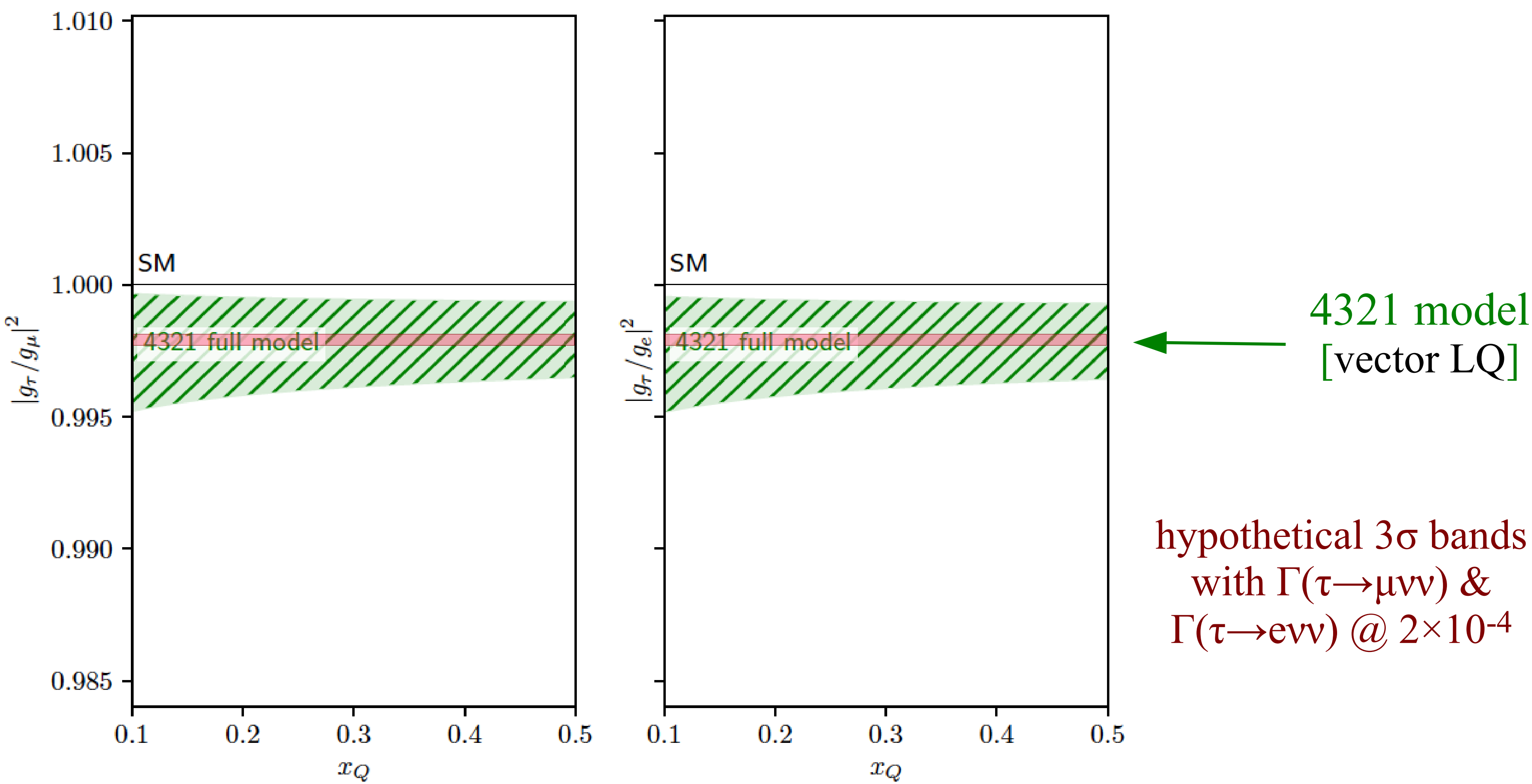

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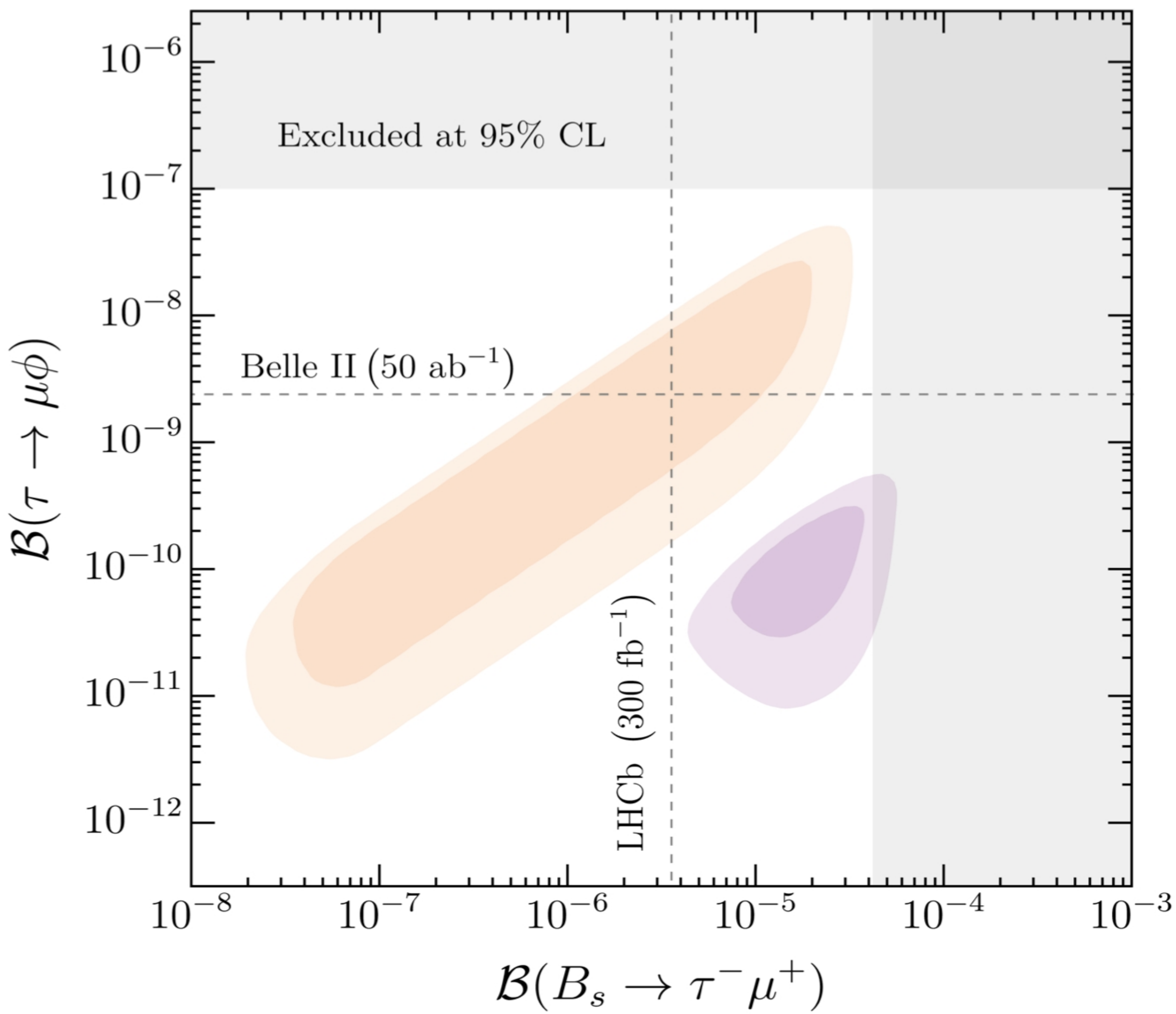
E.g.: (II) LFV in tau & B decays

Cornella *et al.* '21

Lepton Flavor Violation of the type $\tau \to \mu$ naturally large ($\sim |V_{cb}|$) in several NP models

...including the vector LQ [*] →



[*] upper bound on $\tau \to \mu$ mixing reduced by ~ ½ due to new R_K

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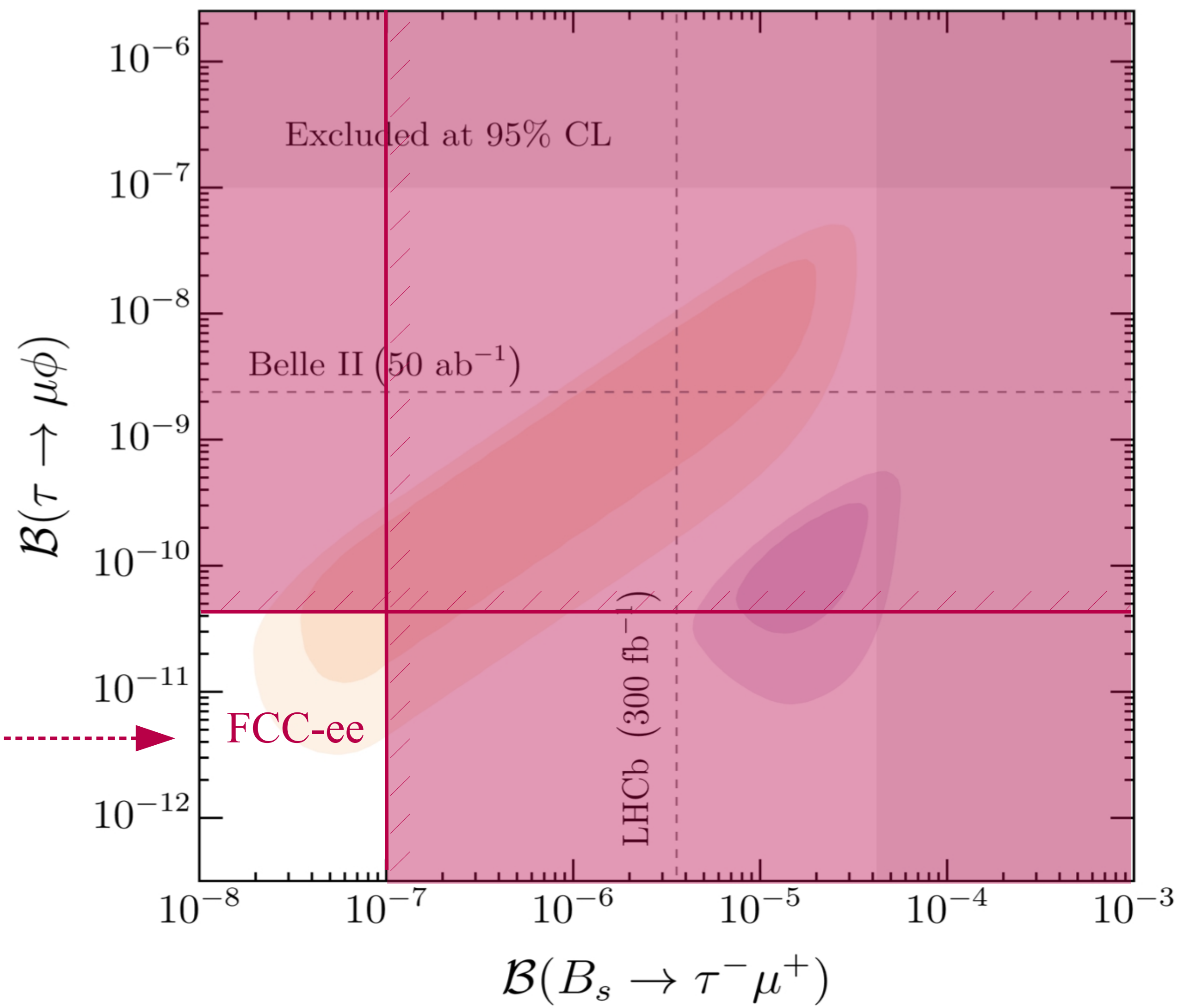
my naive estimate ⇢



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Highlights of FCC-ee in tau & b physics

E.g.: (III) Rare B decays

The kinematical configuration with boosted b's and tau's (from Z decays) + "clean" environment, gives to the FCC-ee b-physics program a special advantage (compared to B-factories & LHC-b) to a series of very interesting rare B decays

III.a All decays into tau leptons:

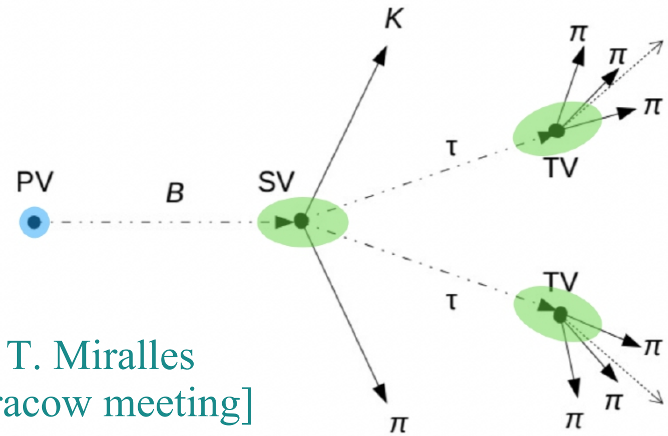
$B \to K^* (K)\, \tau^+\tau^-$: $BR_{SM} \sim 10^{-7}$

[*Golden modes related to present anomalies → potential huge NP effects*]

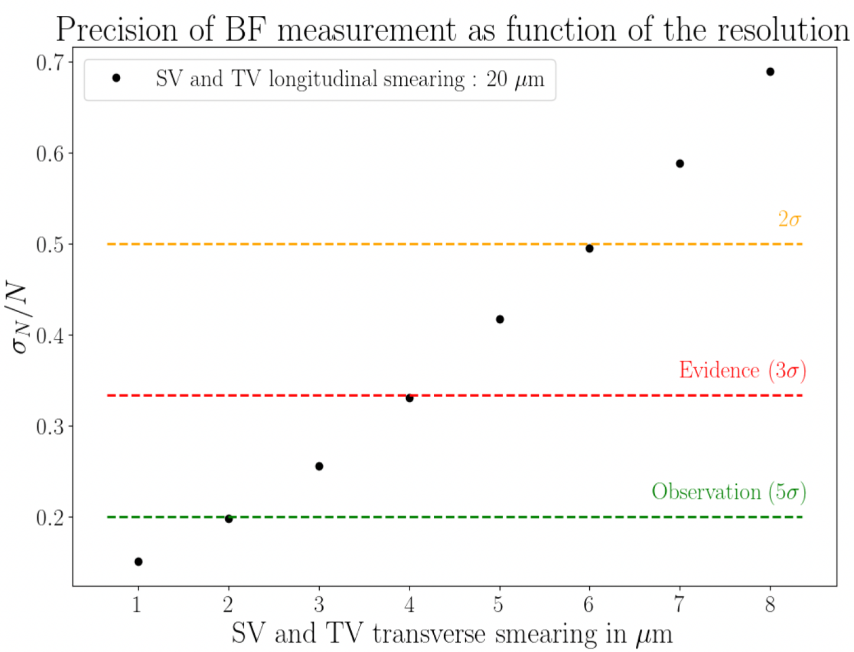
- BR_{exp} $(B \to K\tau^+\tau^-)$: $< 2\times10^{-3}$ [Babar]
- Belle-II $(B \to K^*\tau^+\tau^-)$: ~ 1 event @ SM rate (with small S/B)

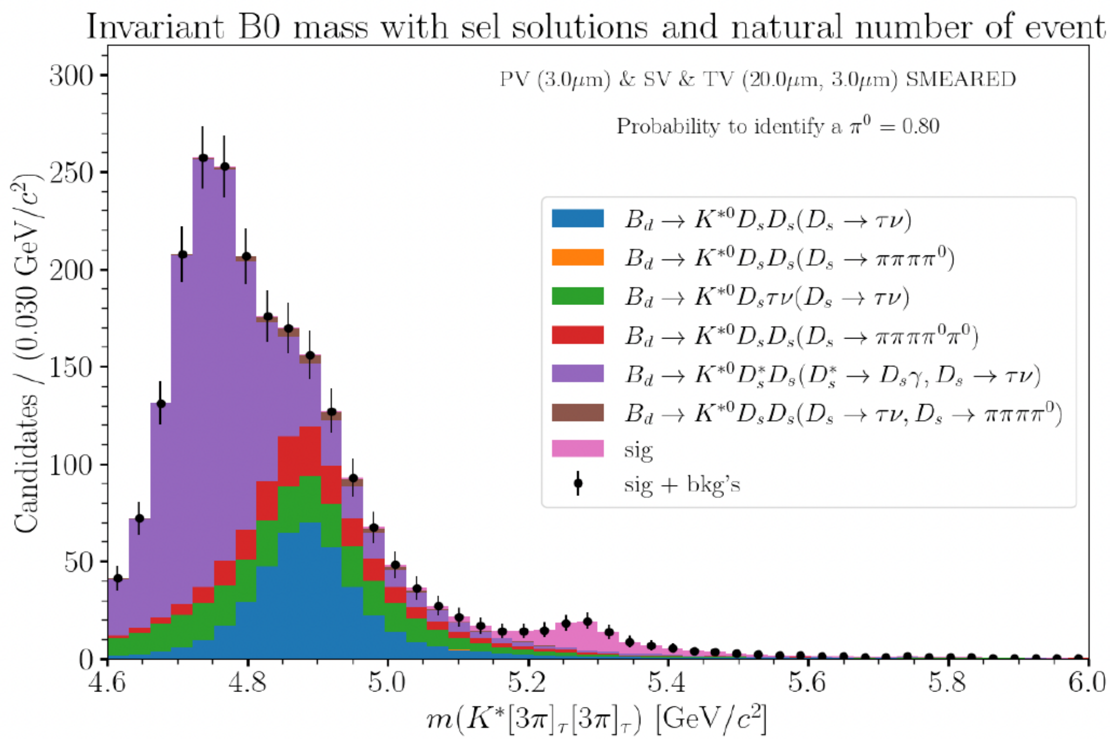
Highlights of FCC-ee in tau & b physics

Detailed study of $B \to K^{*}\tau^{+}\tau^{-}$ [highly non-trivial channel also @ FCC-ee]:



T. Miralles
[Cracow meeting]





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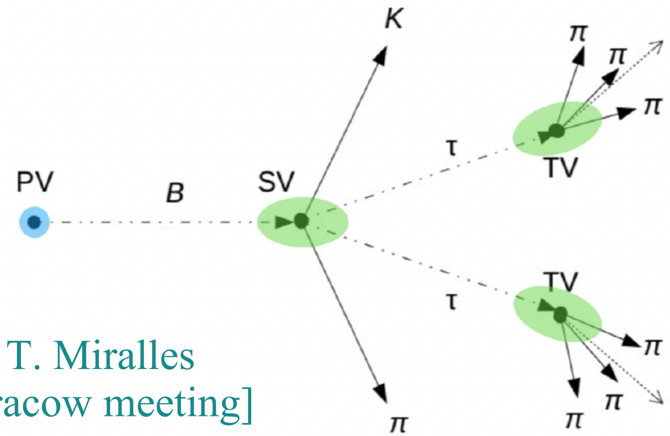

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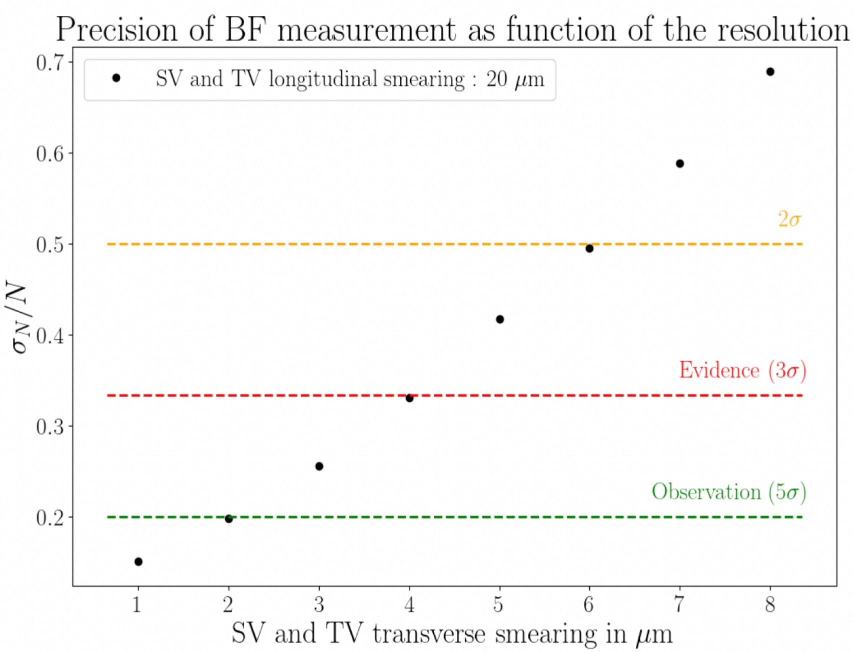
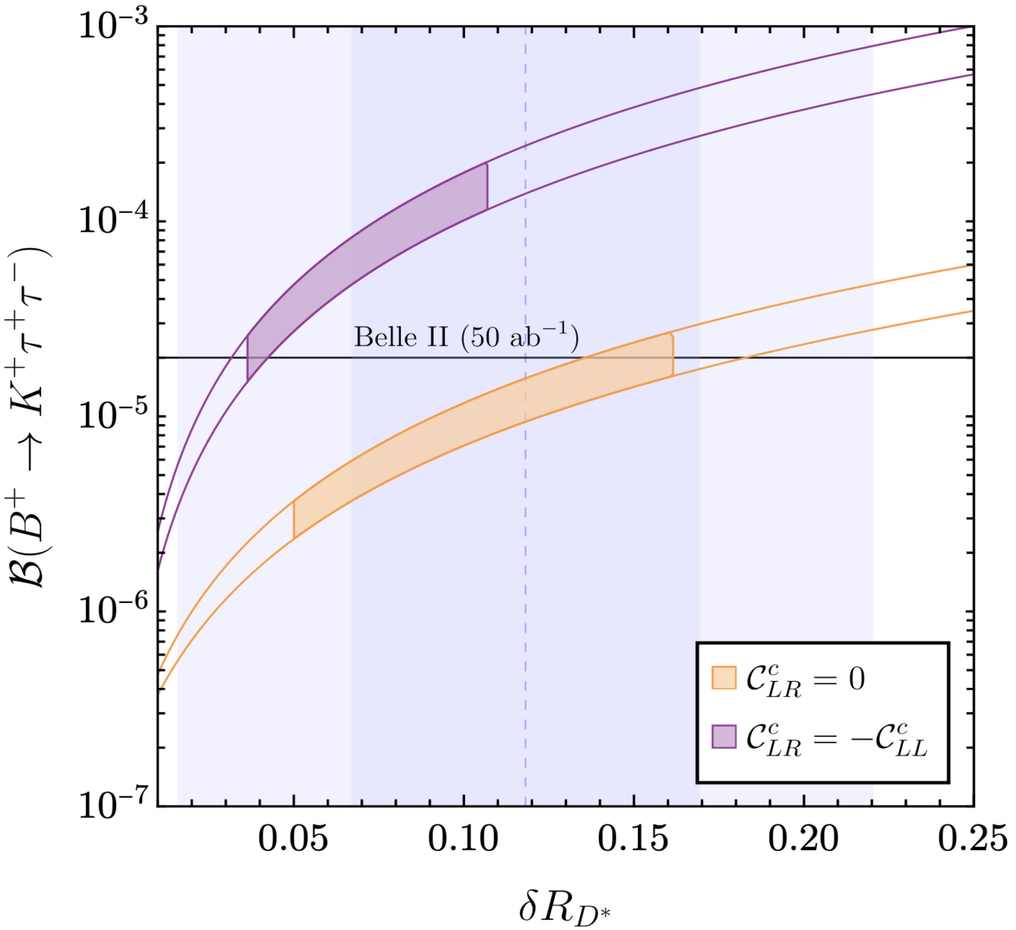


Aebischer, GI, Pesut, Stefanek, Wilsch, 23



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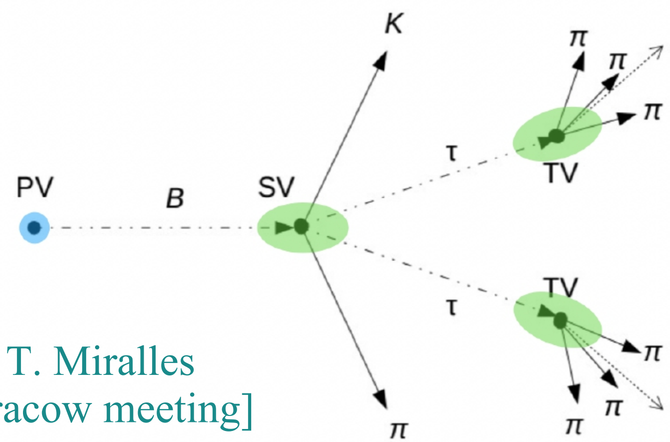

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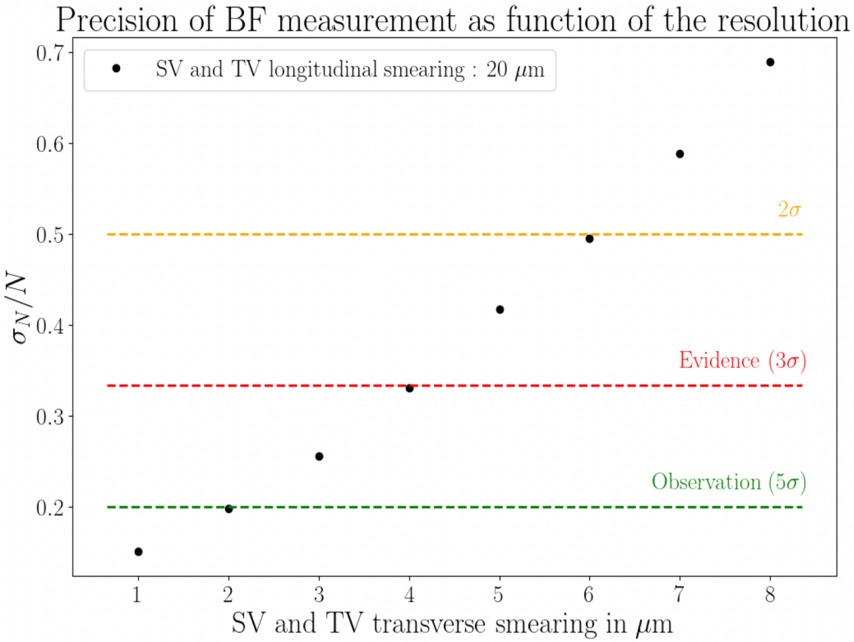

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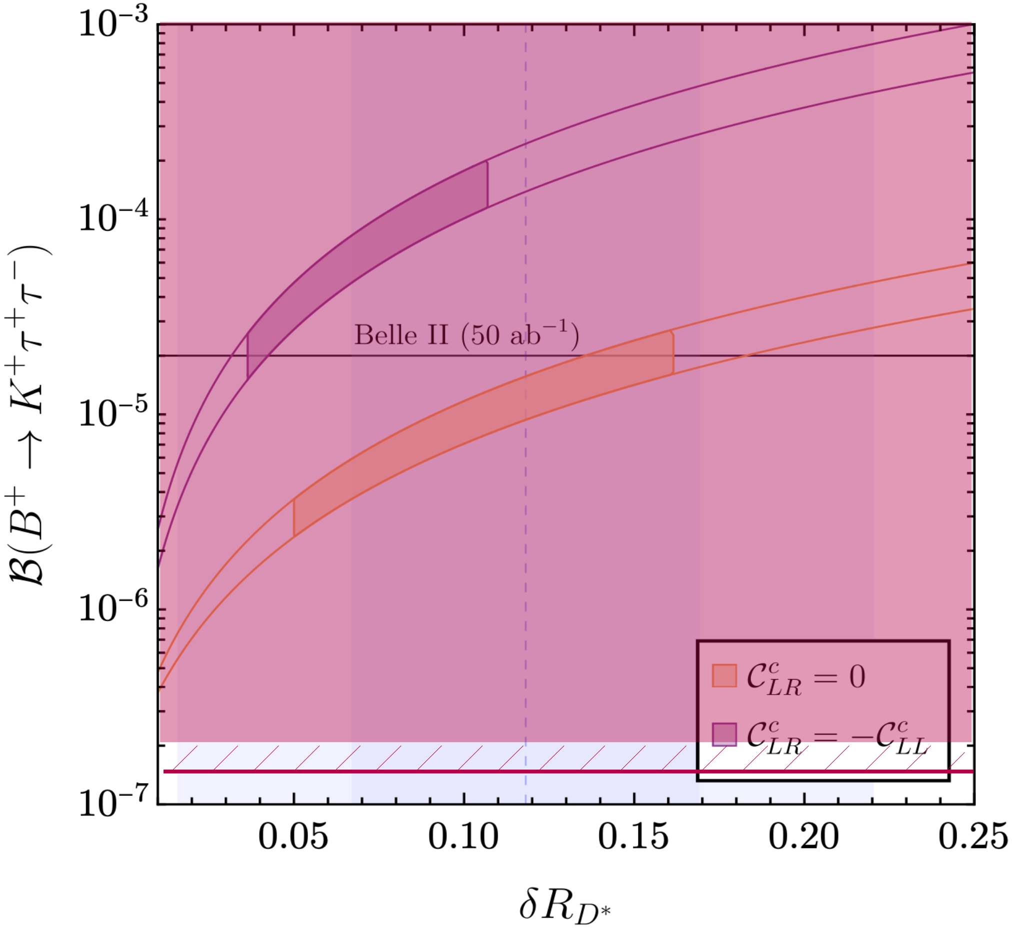

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III.b Charged-currents (w & w/o taus)

$B_{c,u} \to \tau\nu$

$B(B_{u(c)} \to \tau\nu)/B(B_{u(c)} \to \mu\nu)$

Very interesting LFU tests below 1 %,
provided th. control on QED corrections...

→ talk by Claudia Cornella

III.c FCNC inclusive modes:

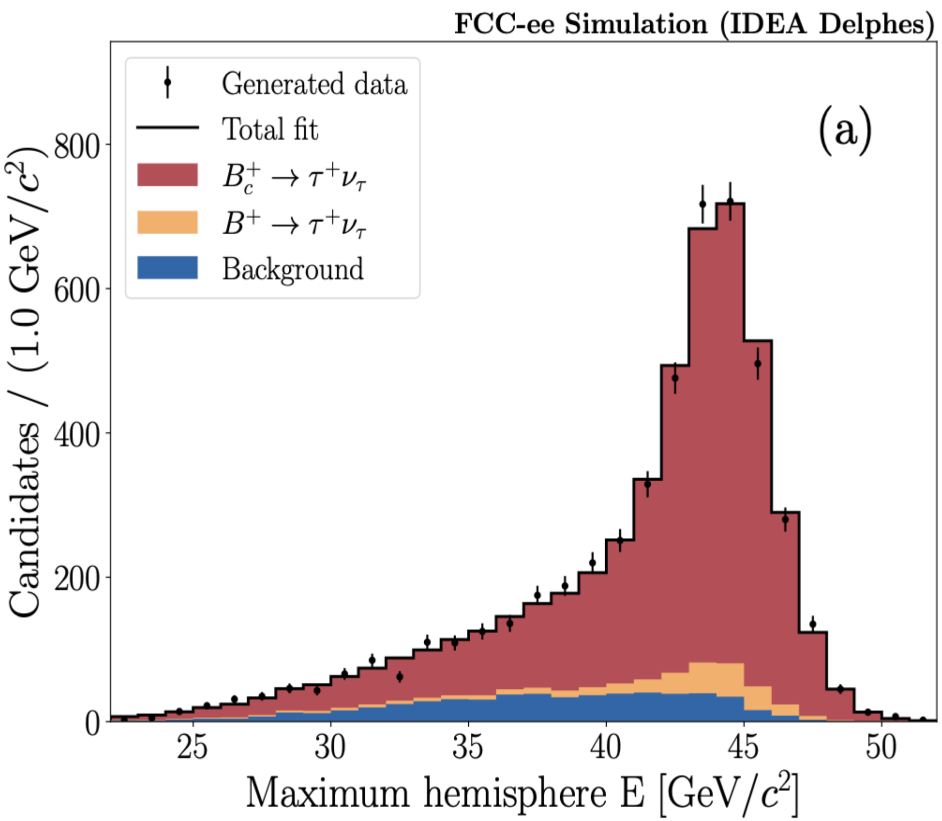
$B \to X\, l\bar{l}$ & $B \to X\, \nu\bar{\nu}$

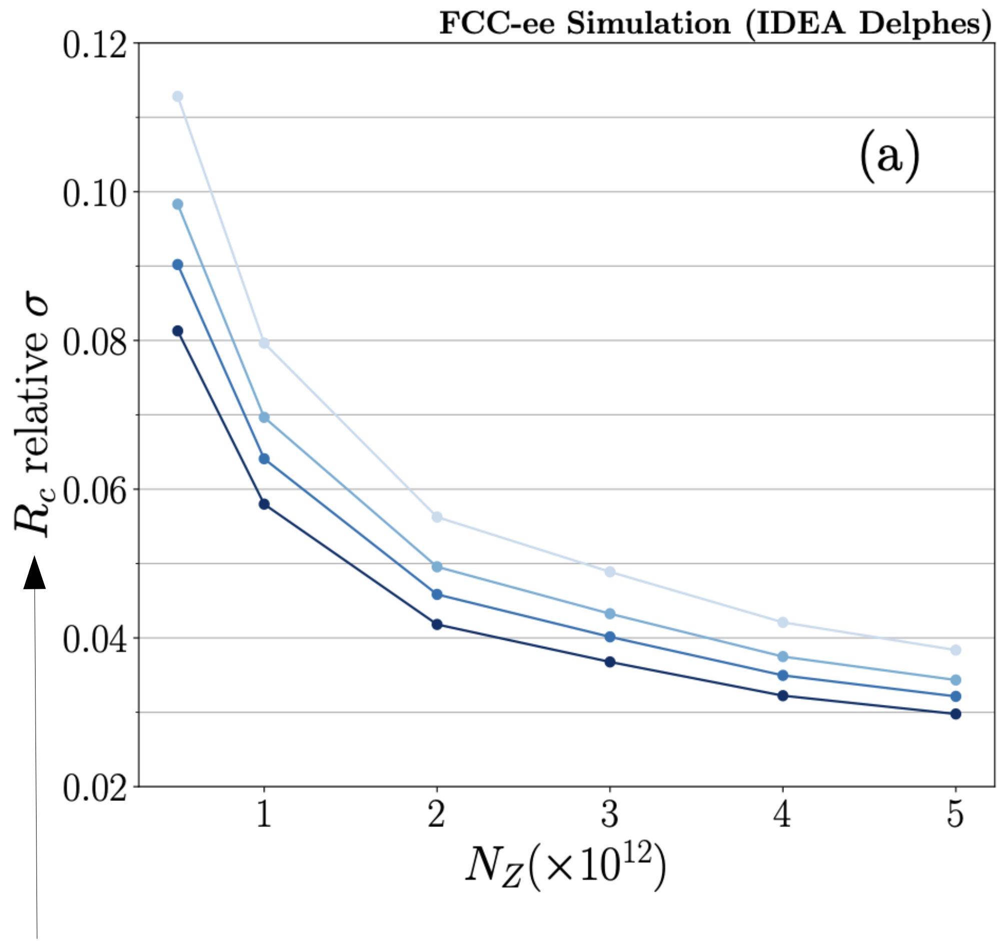
Decay modes sensitive to a variety of NP models, with good th. control compared to exclusive modes

Highlights of FCC-ee in tau & b physics

Detailed study of $B_c \to \tau\nu$

Amhis, Hartmann, Helsens, Hill, Sumensari, '23





$$R_c = \mathcal{B}(B_c^+ \to \tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$$

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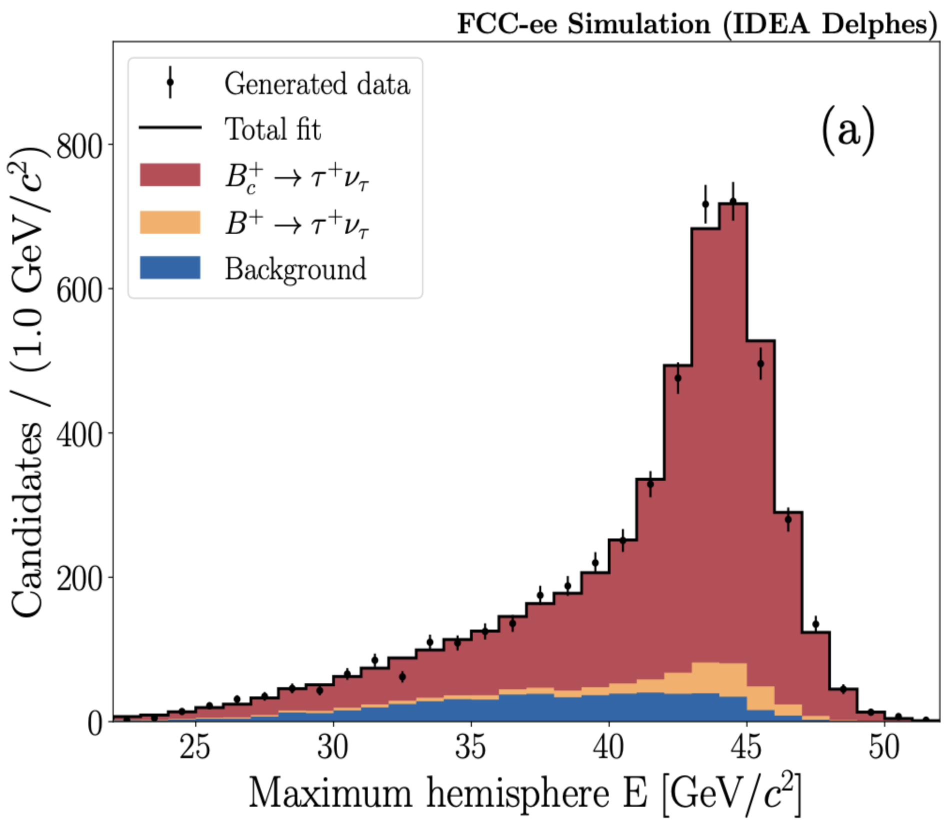

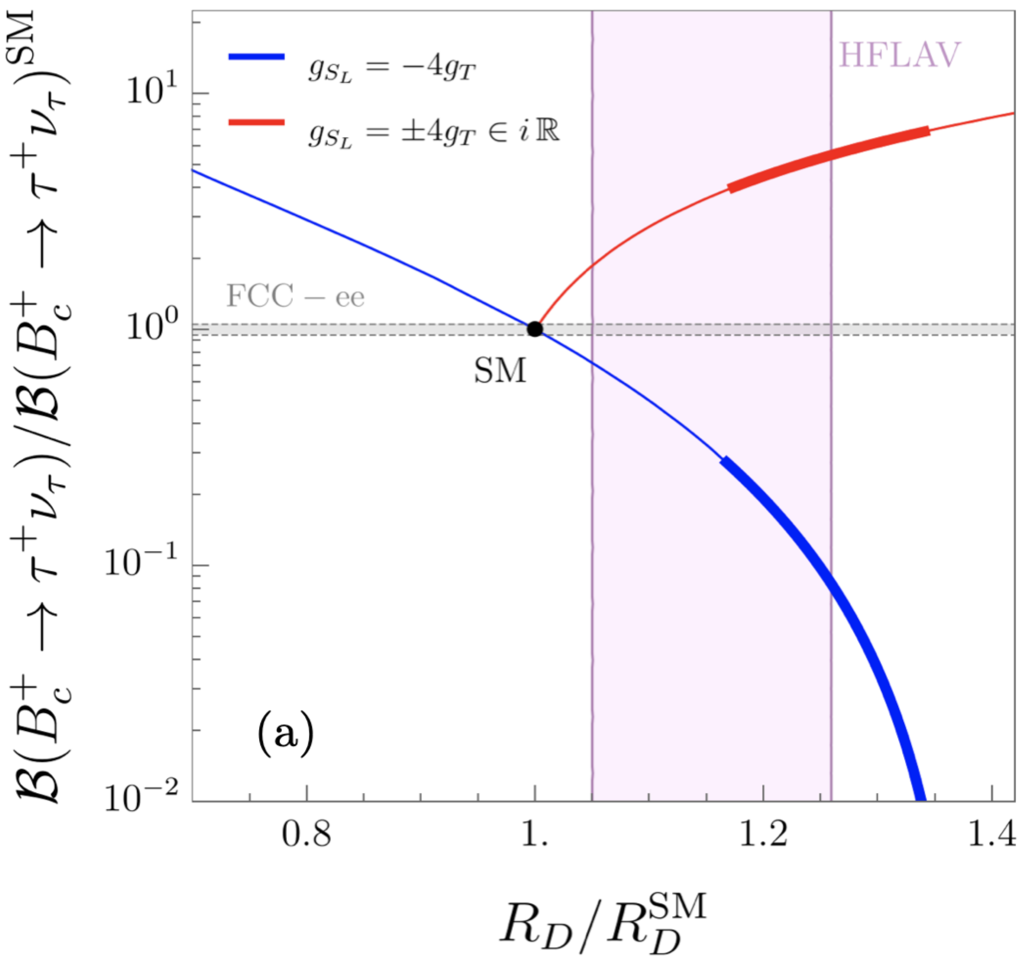

Concluding remarks

- In the absence of a clear indication for the next energy threshold, a new generation of indirect NP searches with EWPO + Flavor is a must → unique opportunity with FCC-ee
- In the Flavor sector there will be two other important players before FCC-ee (LHCb-II + Belle-II), but FCC-ee has key advantages in specific b & τ modes due its peculiar environment (*boosted b & τ + clean*)
- From a model-building perspective, these b and τ modes are very interesting probes of a wide class of motivated models (→ *flavor deconstruction*)
- More work is needed to fully exploit the discovery potential of FCCee in this area. Three main directions:
  - *feasibility studies;*
  - *SM precision calculations;*
  - *identification of NP benchmarks ↔ correlation studies*