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Flavor Physics @ FCC-ee

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- General considerations
- Recent developments in Flavor Physics
- Highlights of FCC-ee in tau & b physics
- Conclusions

General considerations [On the importance of indirect NP searches]

- Despite all its phenomenological successes, the SM has some deep unsolved problems → we regard it as an *Effective Field Theory* (*EFT*), i.e. the low-energy limit of a more fundamental theory with new degrees of freedom

- No direct signlas of New Physics so far observed at the LHC (high-energy frontier), but some signals seem to emerge at low energies (→ *B anomalies*...)

- All "recent" discoveries at the high-energy frontier [c, b, t, H] were anticipated by indirect indications from flavor, CPV, 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*):

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

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

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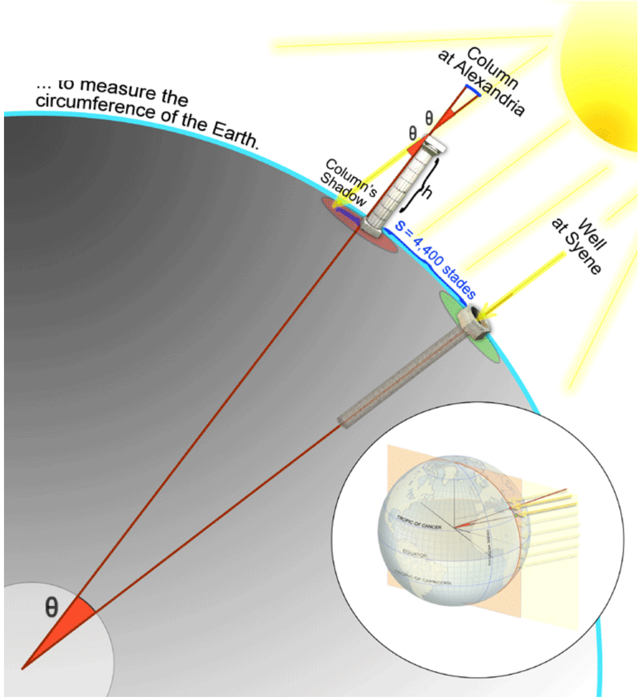

It's all a matter of precision...

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} c_{NP}	N_Z [LEP]	➡ $18 \times \Lambda_{NP}$ $0.003 \times c_{NP}$	$10^5 \times N_Z$ [FCC-ee]

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

Unprecedented jump in precision!

▸ *General considerations* [On the importance of indirect NP searches]

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Λ_{NP}, c_{NP} | $b\bar{b}$, $\tau\bar{\tau}$ [Belle] ➞ $5.6 \times \Lambda_{NP}$, $0.03 \times c_{NP}$ | $10^3 \times$ $b\bar{b}$, $\tau\bar{\tau}$ [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

Recent developments in Flavor Physics

Since 2013 LHCb & B-factory experiments reported a series of "anomalies" (= *deviations from SM predictions*) in semi-leptonic B-meson decays.

Data seem to indicate a different (*non-universal*) behavior of different lepton species in specific b (3rd gen.) → c,s (2nd) processes:

- $b \to c$ charged currents: τ vs. light leptons (μ, e) [R_K, R_{K*},...]
- $b \to s$ neutral currents: μ vs. e [R_D, R_{D*}]

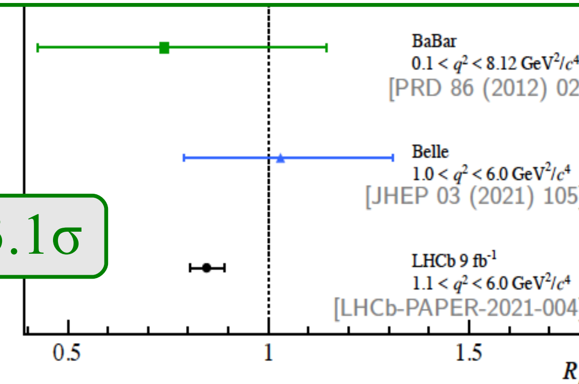
IF taken together... this is probably the largest "coherent" set of deviations from the SM we have ever seen...

Recent developments in Flavor Physics

$b \to s\, l^+ l^-$ (neutral currents): μ vs. e

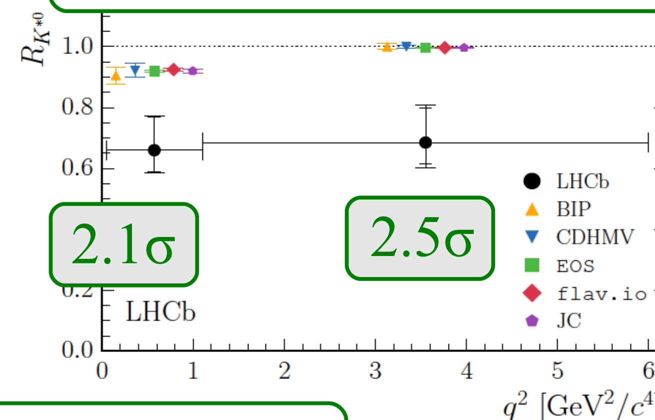
High significance: several observables pointing to the same coherent picture [3 new results in 2021]

$\Gamma(B^+ \to K^+ \mu\mu) / \Gamma(B^+ \to K^+ ee)$



3.1σ

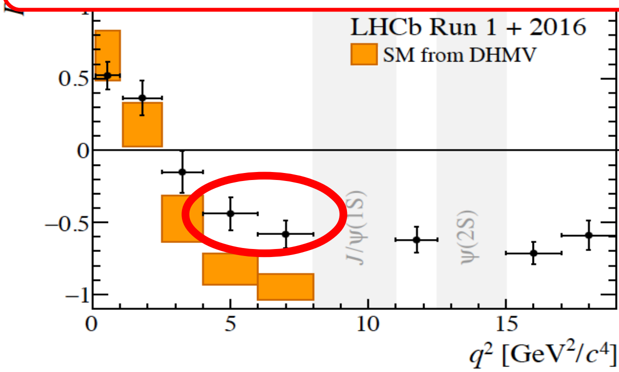
$\Gamma(B \to K^* \mu\mu) / \Gamma(B \to K^* ee)$

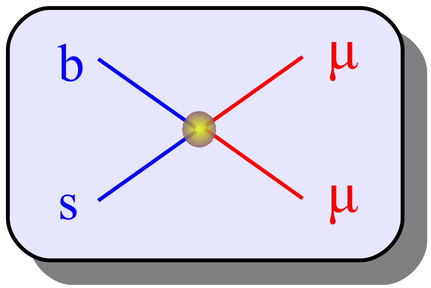


2.1σ

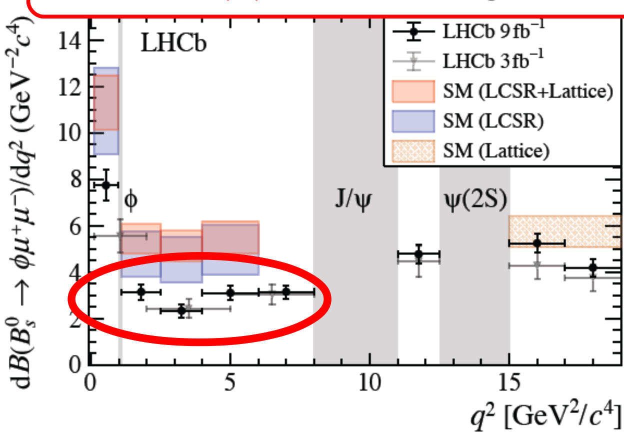
2.5σ

$B \to K^* \mu\mu$ angular distribution





$B \to H\, \mu\mu$ branching ratios



$BR(B_s \to \mu\mu)$

$BR_{exp} = (2.85 \pm 0.32) \times 10^{-9}$ ATLAS+CMS+LHCb '21

$BR_{SM} = (3.66 \pm 0.14) \times 10^{-9}$

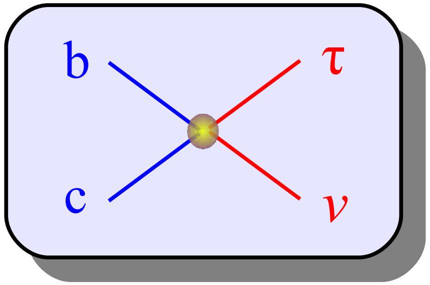
2.3σ

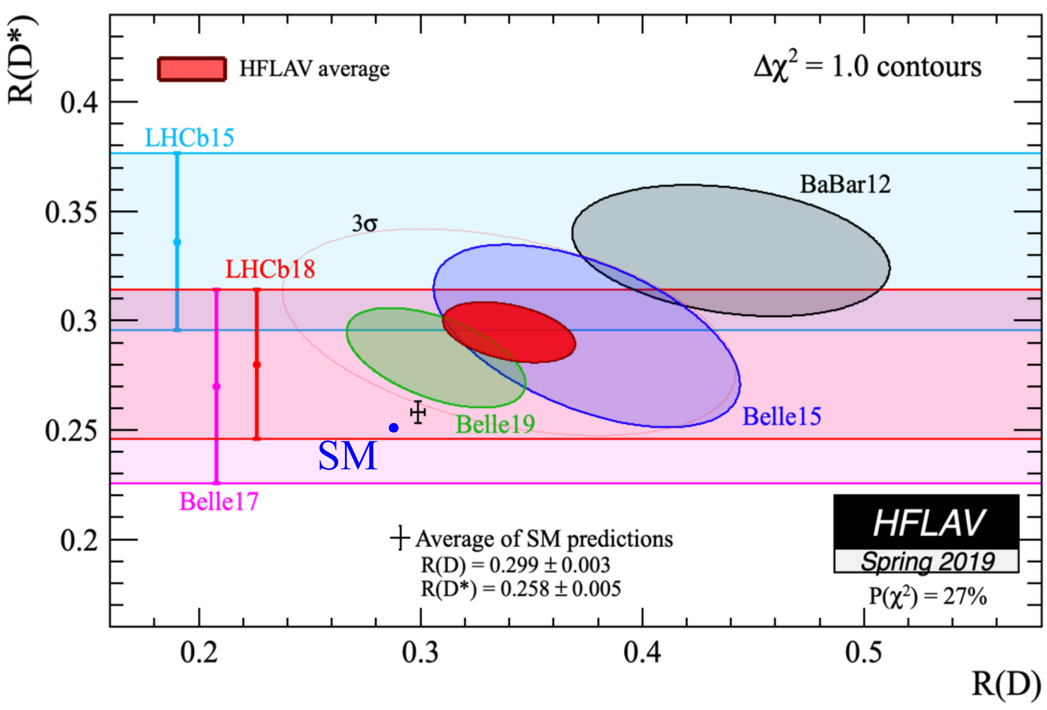
Recent developments in Flavor Physics

- $b \to s\, l^+ l^-$ (neutral currents): μ vs. e

High significance: several observables pointing to the same coherent picture [3 new results in 2021]

- $b \to c\, l\nu$ (charged currents): τ vs. light leptons (μ, e)





$$R(X) = \frac{\Gamma(B \to X\, \tau\nu)}{\Gamma(B \to X\, l\nu)}$$

X = D or D*

- Clean SM predictions (*uncertainties cancel in the ratios*)
- Smaller significance and slower progress
- Consistent results by 3 different exp. → 3.1σ excess over SM

Recent developments in Flavor Physics

These anomalies challenge the assumption of Lepton Flavor Universality, that we gave for granted for many years (*without many good theoretical reasons…*)

↓

Renewed interest in testing LFU with higher precision,
in processes involving 3rd generation fermions,
and search for LFV effects in the $\tau \to \mu$ sector

We should not ignore the flavor problem

[*fermion mass hierarchies are telling us something about BSM physics*]

A different behavior of the 3 families (*with special role for the 3rd gen.*) can be the key to solve also gauge hierarchy problem

Higlights of FCC-ee in tau & b physics

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)	
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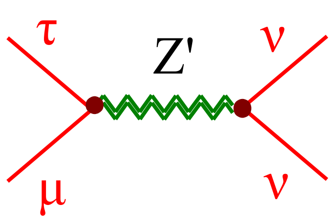
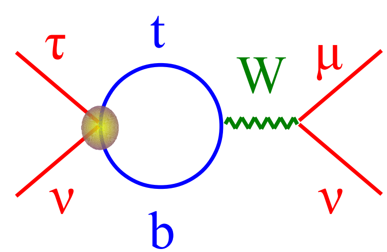




"Model-independent" effect linked to present anomalies

- NP expectation from current anomalies in the range $(0.2 - 4.0) \times 10^{-3}$
- SM theory precision $\sim 10^{-5}$
- Belle-II can (at most) reach an error $\sim 0.3 \times 10^{-3}$
- FCC-ee could go below 10^{-4} !

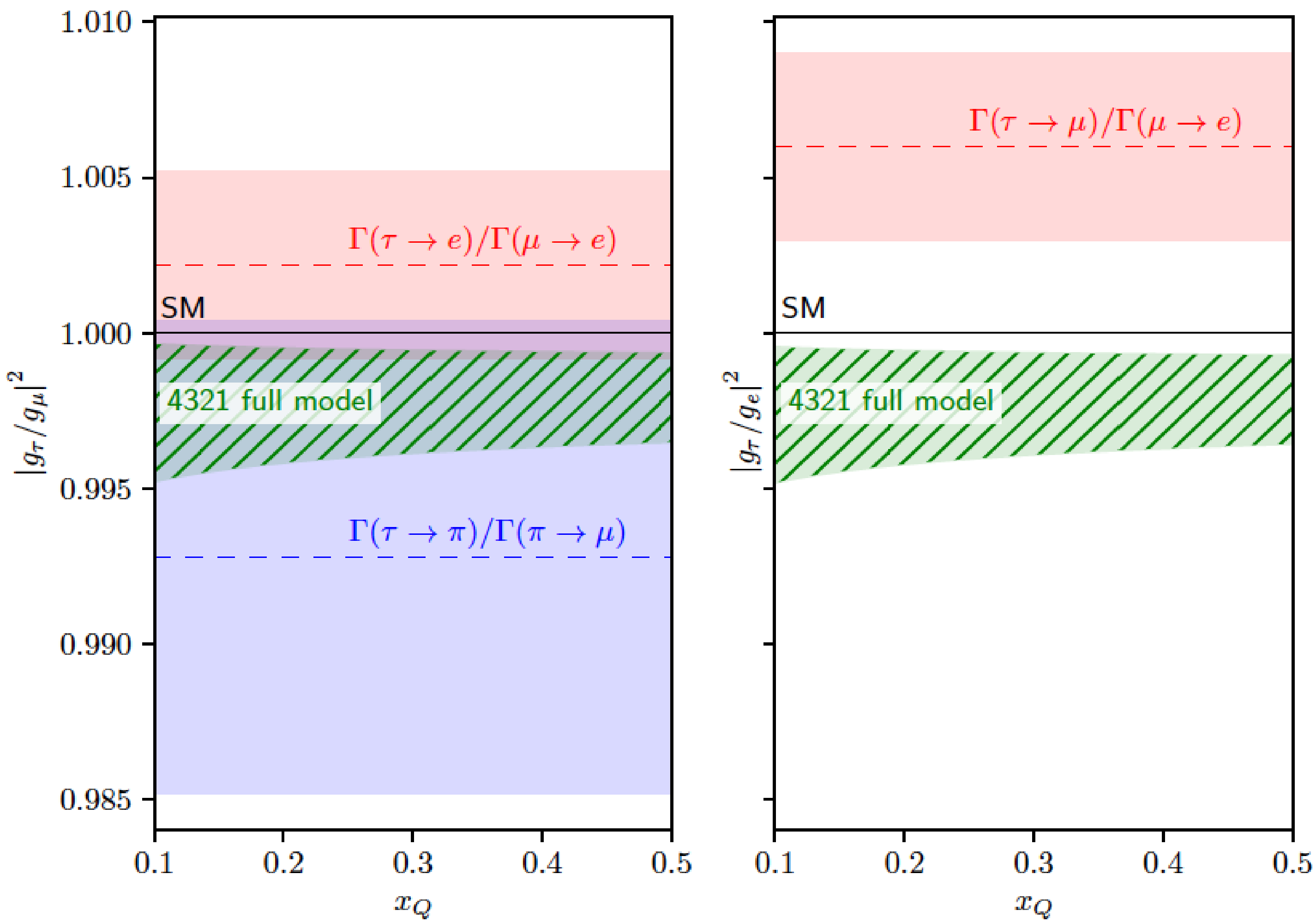
Unique opportunity !

Higlights of FCC-ee in tau & b physics

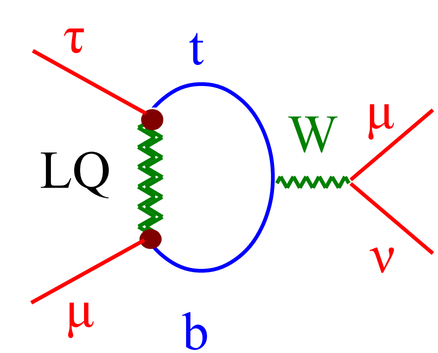
E.g.: (I) LFU tests in tau decays

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

Allwicher, GI, Selimovic - arXiv:2109....



LQ model



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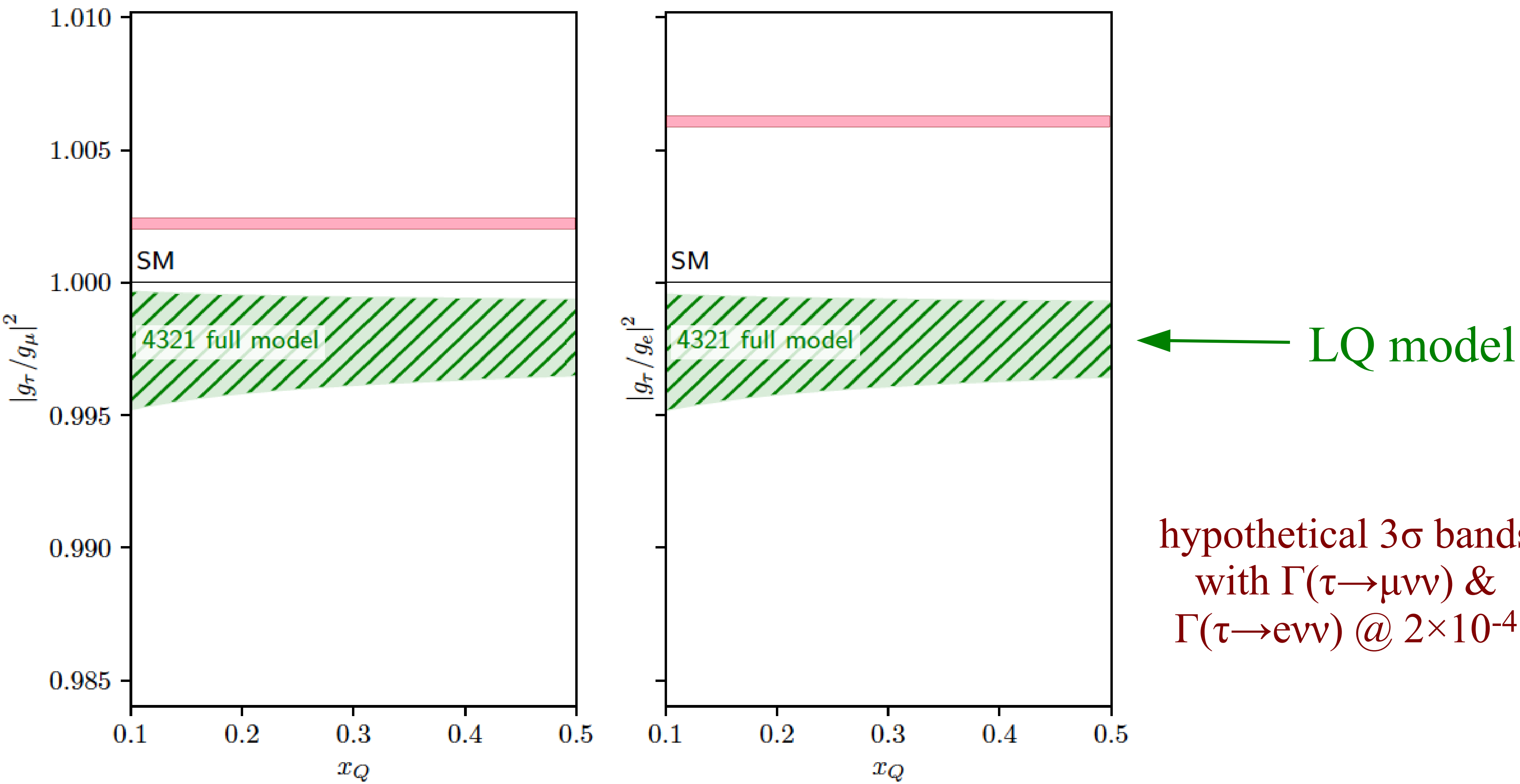

hypothetical 3σ bands with Γ(τ→μνν) & Γ(τ→eνν) @ 2×10^{-4}

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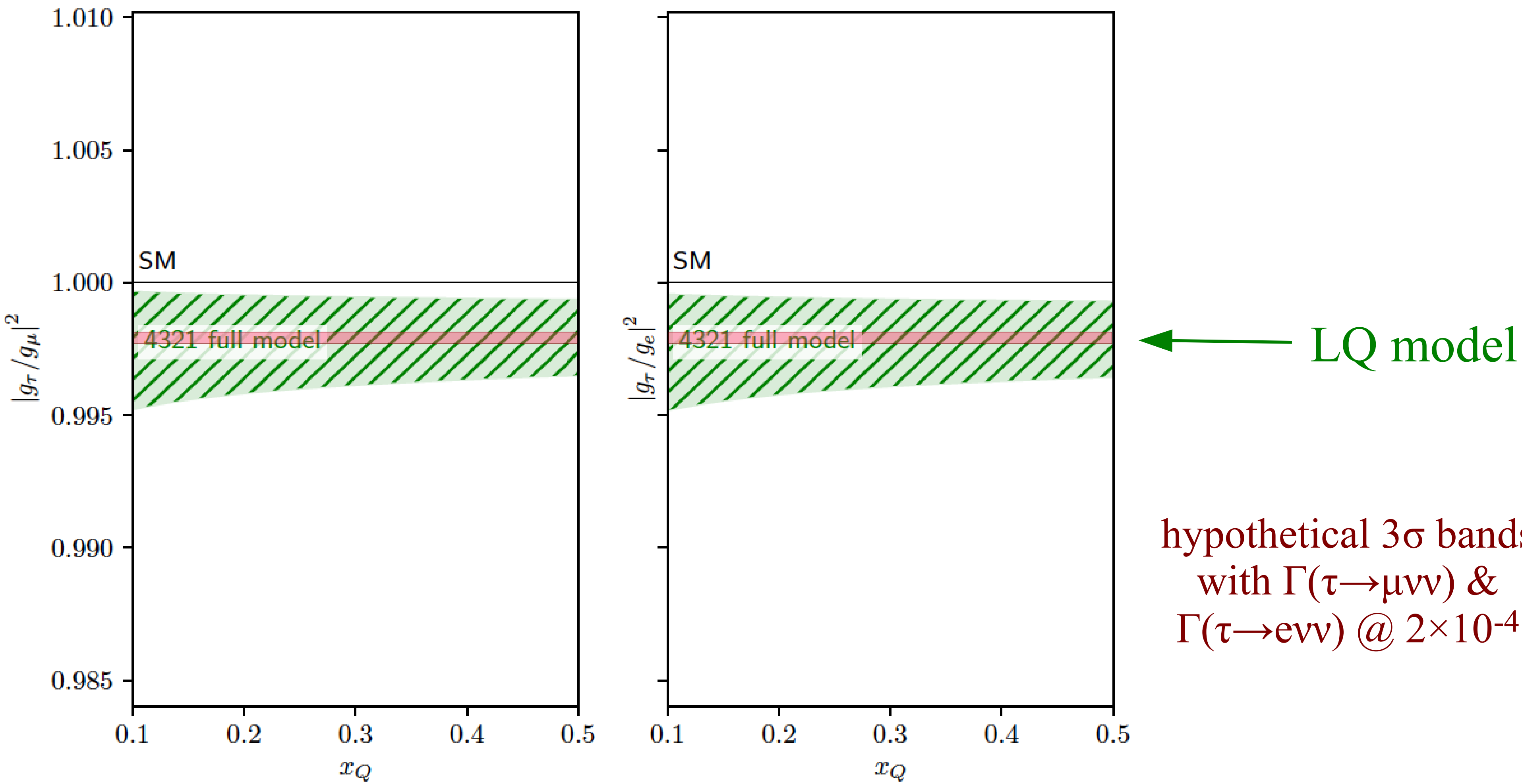

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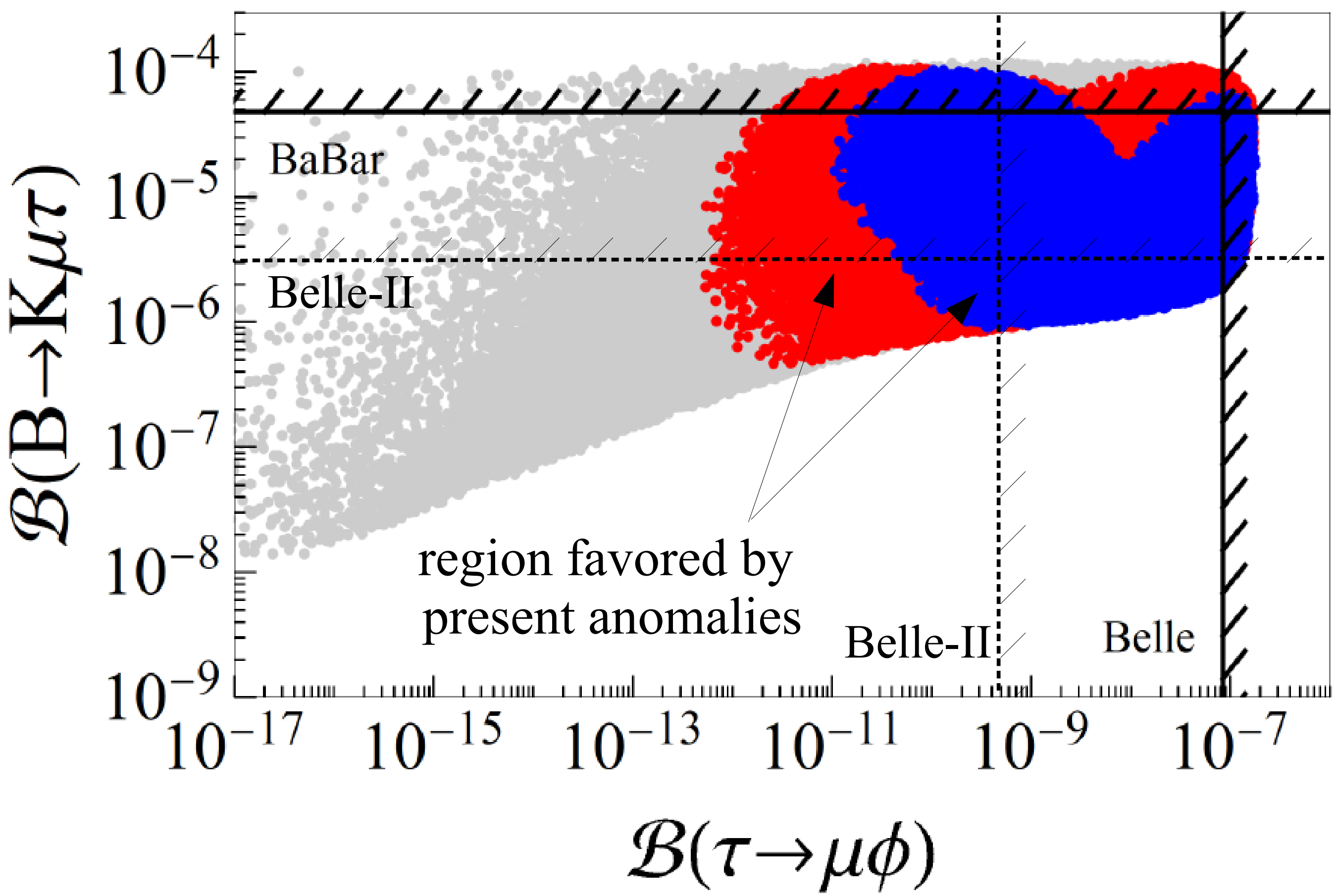
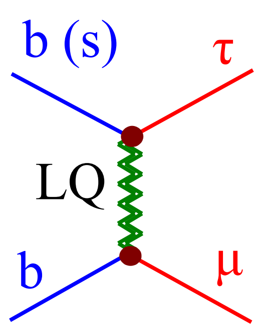
E.g.: (II) LFV in tau & B decays

One of the most striking expectation of virtually all models addressing the anomalies are large LFV effects in the $\tau \to \mu$ sector



Angelescu, Becirevic, Faroughi, Sumensari. '18



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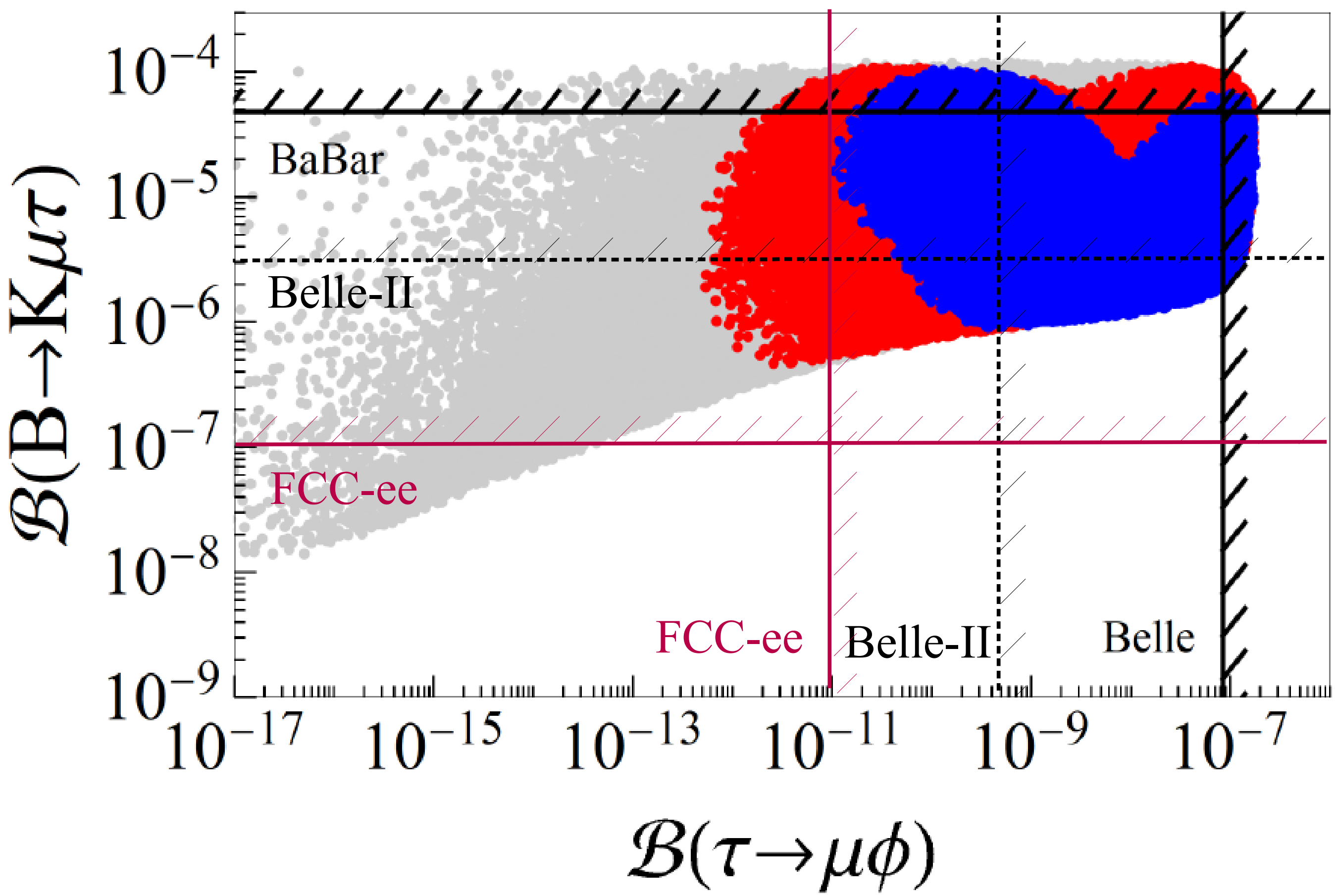

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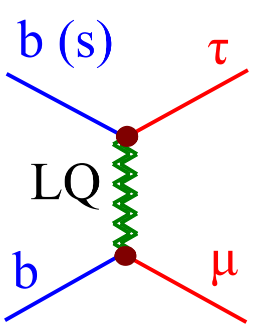

Higlights of FCC-ee in tau & b physics

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 of present anomalies, with 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
- FCC-ee ($B \to K^{*}\tau\tau$): 10^{3} events @ SM rate ! [FCC-ee CDR]

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- FCC-ee $(B \to K^*\tau\underline{\tau})$: 10^3 events @ SM rate !

III.b All FCNC inclusive modes

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

decay modes sensitive to a variety of NP models, where we have a very good theory control compared to exclusive modes

Concluding remarks

- A new generation of indirect NP searches with EWPO + Flavor must be a key element of our future strategy → FCC-ee offers a unique opportunity in this respect

- 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 and tau modes due its peculiar environment (*boosted b's & tau's + clean*)

- Interestingly enough, many of the the b and tau modes where FCC-ee has a strong advantage are those interesting in view of the current B-physics anomalies