University of Zurich[UZH]

Electroweak and Flavor Physics @ FCC-ee

Gino Isidori
[*University of Zürich*]

- General considerations
- Highlights of FCC-ee in tau & b physics
- Highlights of FCC-ee in EWPO
- Conclusions

General considerations [On the importance of indirect NP searches]

The present status of particle physics can be summarized as follows:

- The Higgs boson is SM-like and is "light" ($m_h \sim 125$ GeV)
  → SM consistent up to very high energies
  (*although it is more fine tuned, the more we push high its UV cut-off*)

- No unambiguous sing of NP up to ~ 1 TeV
  → Mass gap above the SM spectrum

General considerations [On the importance of indirect NP searches]

The present status of particle physics can be summarized as follows:

- The Higgs boson is SM-like and is "light" ($m_h \sim 125$ GeV)
  → SM consistent up to very high energies
  (*although it is more fine tuned, the more we push high its UV cut-off*)

- No unambiguous sing of NP up to ~ 1 TeV
  → Mass gap above the SM spectrum

This is perfectly consistent with the (pre-LHC) indications coming from indirect NP searches (EWPO + Flavor → light Higgs + mass gap SM spectrum).

N.B.: All "recent" discoveries at the HE 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*):

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

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

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*):

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

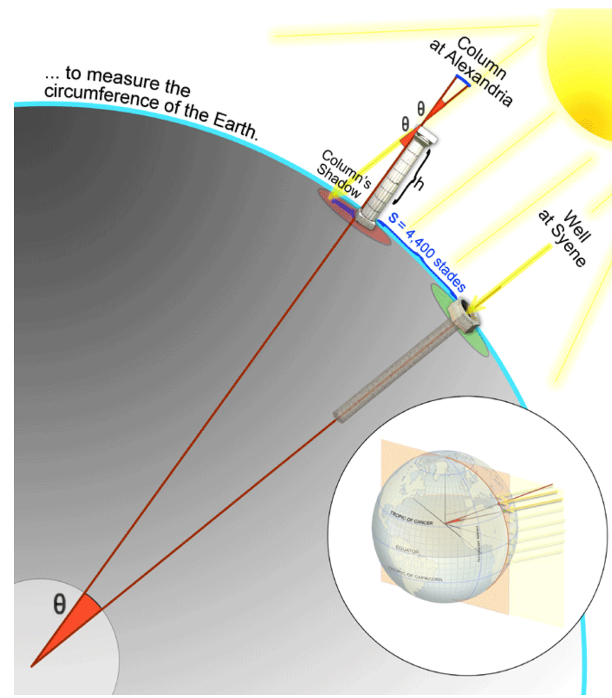
"No New Physics up to the Planck scale"

can we agree on that?

▸ *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*):

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



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

The present status of particle physics can be summarized as follows:

- The Higgs boson is SM-like and is "light" ($m_h \sim 125$ GeV)
  → SM consistent up to very high energies
  (*although it is more fine tuned, the more we push high its UV cut-off*)

- No unambiguous sing of NP up to ~ 1 TeV
  → Mass gap above the SM spectrum

This is perfectly consistent with the (pre-LHC) indications coming from indirect NP searches (EWPO + Flavor → light Higgs + mass gap SM spectrum).

N.B.: All "recent" discoveries at the HE frontier [c, b, t, H] were anticipated by indirect indications from flavor, CPV, and EWPO.

⬇

Hard to expect a discovery at HE without indirect clues at low energies...

⬇

Indirect NP searches must be a key ingredient of our future strategy!

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] $\rightarrow$ $18 \times \Lambda_{NP}$, $0.003 \times c_{NP}$ | $10^5 \times N_Z$ [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]

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

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

Unprecedented jump in precision!

Λ_{NP} | c_{NP} | $b\underline{b}$, $\tau\underline{\tau}$ [Belle] $\rightarrow$ $5.6 \times \Lambda_{NP}$ | $0.03 \times c_{NP}$ | $10^3 \times$ $b\underline{b}$, $\tau\underline{\tau}$ [FCC-ee]

For $b\underline{b}$ & $\tau\underline{\tau}$ 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

▸ *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]

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

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

Unprecedented jump in precision!

For b$\underline{b}$ & τ$\underline{τ}$ 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

Highlights of FCC-ee in tau & b physics

In the last few years LHCb, B-factory experiments reported some "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 (3^{rd} gen.) → c,s (2^{nd}) processes:

- b → c charged currents: τ vs. light leptons (μ, e) [R_K, R_{K*},...]
- b → 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...

Highlights of FCC-ee in tau & b physics

In the last few years LHCb, B-factory experiments reported some "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 → c charged currents: τ vs. light leptons (μ, e) [R_K, R_{K^*},...]
- b → 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...

I made statements of this type back in 2015... Since then the evidence for the anomalies has significantly increased.

In winter 2019 we have seen a first small decrease of the significance of some the anomalies; however, the overall picture has not changed. Actually, I dare to say it has become even more consistent...

[2σ anomaly also in $B_s \to \mu\mu$ + smaller R_{D,D^*} → better consistency with high-pT ...]

Highlights of FCC-ee in tau & b physics

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

So far, the vast majority of BSM attempts

- Focus only on the Higgs hierarchy problem
- Ignore/postponed the flavor problem, implicitly assuming the 3 families are "identical" copies (but for Yukawa-type interactions)

Highlights of FCC-ee in tau & b physics

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

So far, the vast majority of BSM attempts

- ~~Focus only on the Higgs hierarchy problem~~
- ~~Ignore/postponed the flavor problem, implicitly assuming the 3 families are "identical" copies (but for Yukawa-type interactions)~~

These anomalies seems to suggest that

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

Highlights of FCC-ee in tau & b 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 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

Highlights of FCC-ee in tau & b physics

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

A. Pich '13

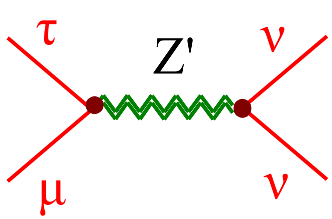
	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$
$\lvert g_\mu/g_e\rvert$	1.0018 (14)	1.0021 (16)	0.9978 (20)	1.0010 (25)	0.996 (10)
	$\Gamma_{\tau\to e}/\Gamma_{\mu\to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

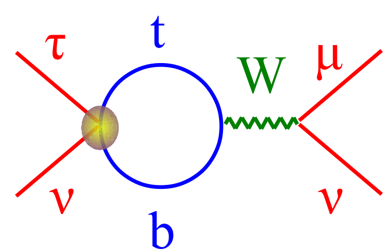
Highlights of FCC-ee in tau & b physics

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)	
	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$			
$\lvert g_\tau/g_e\rvert$	1.0030 (15)	1.031 (13)			





"Model-independent" effect linked to present anomalies

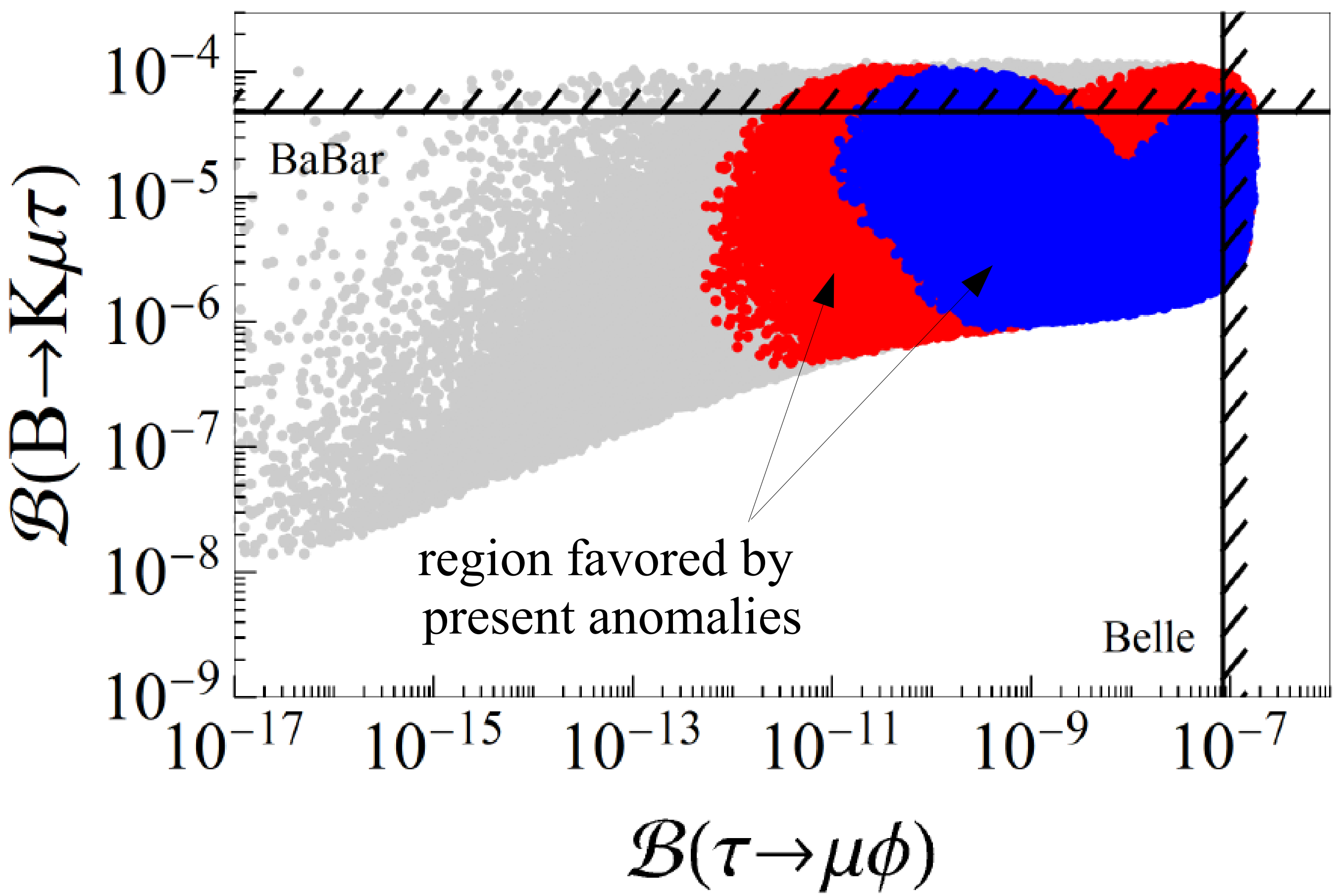
- NP expectation from current anomalies in the range $(0.5 - 2.0) \times 10^{-3}$
- SM theory precision $\sim 10^{-5}$
- Belle-II can (at most) reach an error $\sim 0.3 \times 10^{-3}$
- FCC-ee could go below 10^{-4} !

Unique opportunity !

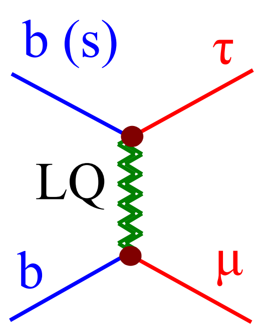
Highlights of FCC-ee in tau & b physics

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



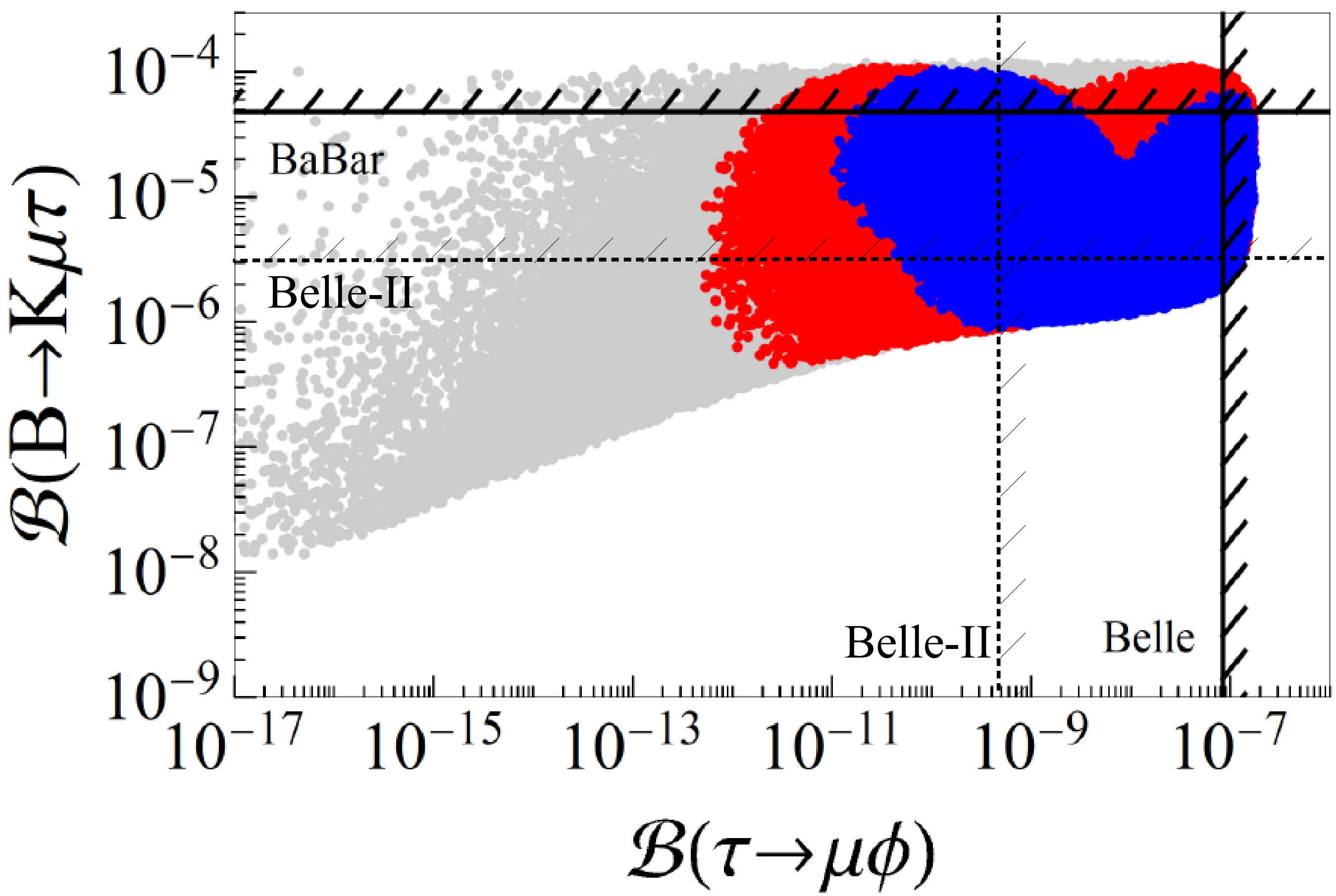
Angelescu, Becirevic, Faroughi, Sumensari. '18



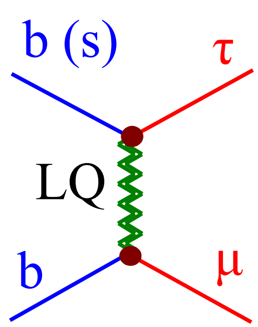
Highlights of FCC-ee in tau & b physics

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



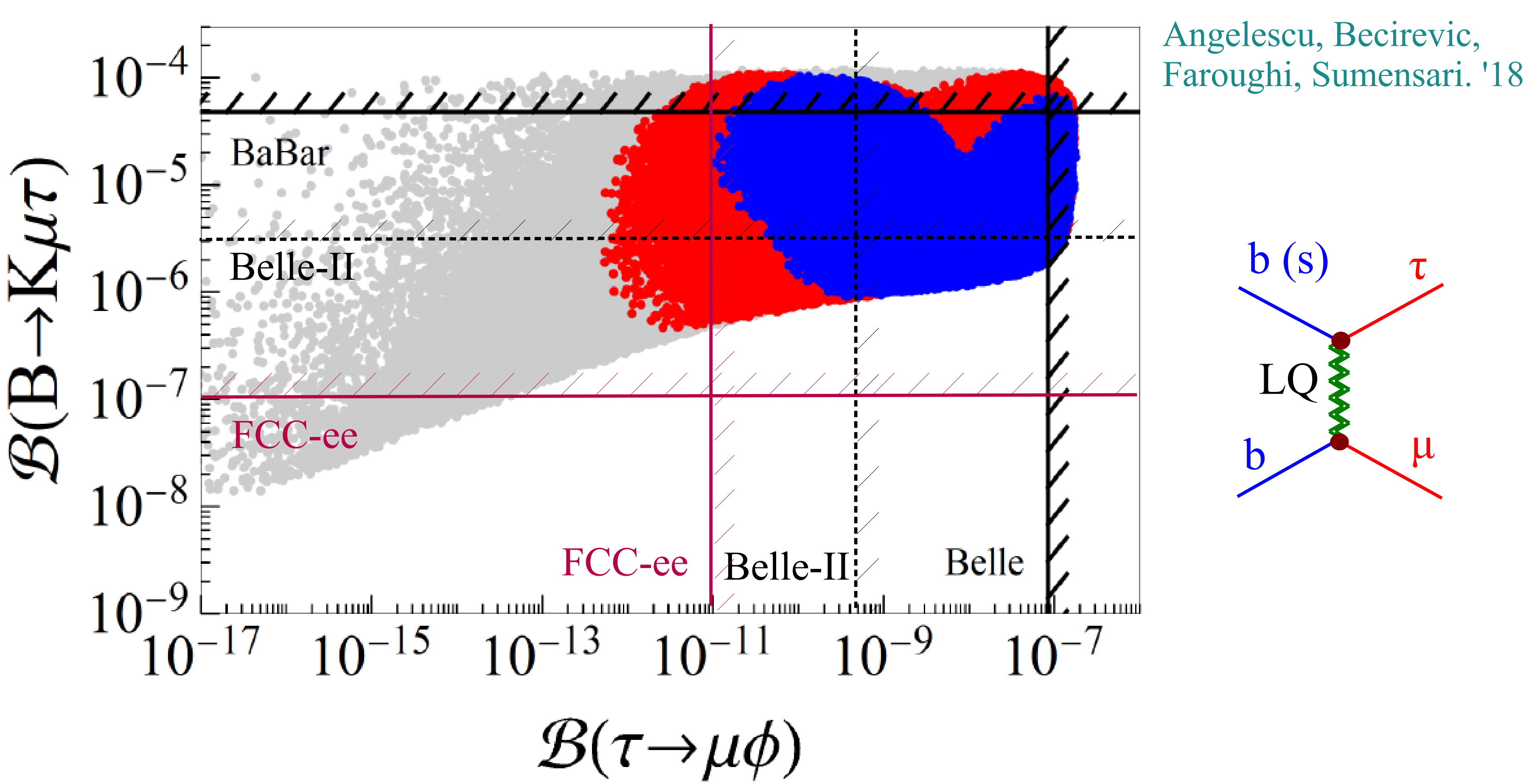
Angelescu, Becirevic, Faroughi, Sumensari. '18



Highlights of FCC-ee in tau & b physics

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 $\tau \rightarrow \mu$ sector



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 of present anomalies, with potential huge NP effects*]

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:

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

[*Golden modes of present anomalies, with potential huge NP effects*]

- BR_{exp} $(B \to K\tau\underline{\tau})$: $< 2\times10^{-3}$ [Babar]
- Belle $(B \to K^*\tau\underline{\tau})$: 1 event @ SM rate
- FCC-ee $(B \to K^*\tau\underline{\tau})$: 10^3 events @ SM rate !

[FCC-ee CDR]

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:

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

[*Golden modes of present anomalies, with potential huge NP effects*]

- BR_{exp} $(B \to K\tau\underline{\tau})$: $< 2\times10^{-3}$ [Babar]
- Belle $(B \to K^*\tau\underline{\tau})$: 1 event @ SM rate
- FCC-ee $(B \to K^*\tau\underline{\tau})$: 10^3 events @ SM rate !

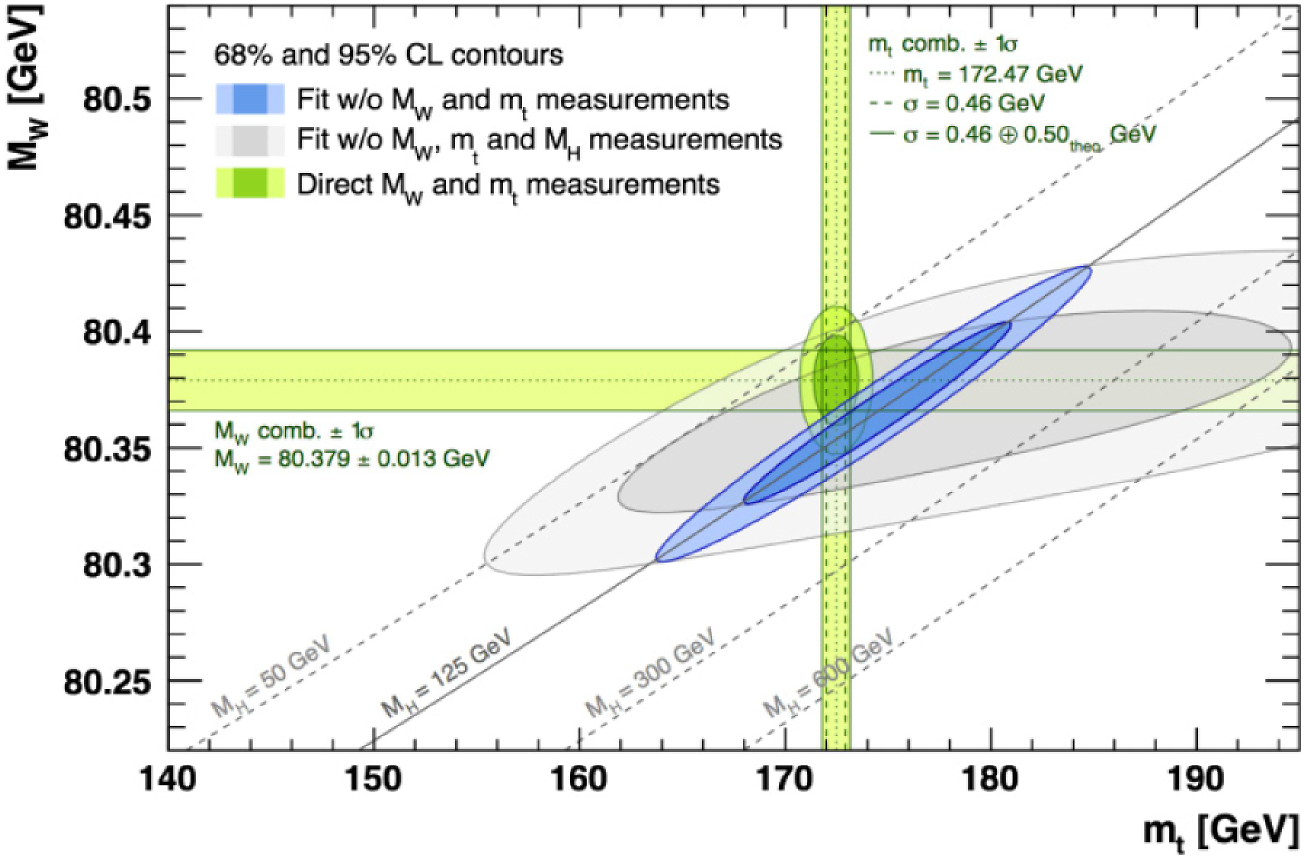
III.b All FCNC inclusive modes

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

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

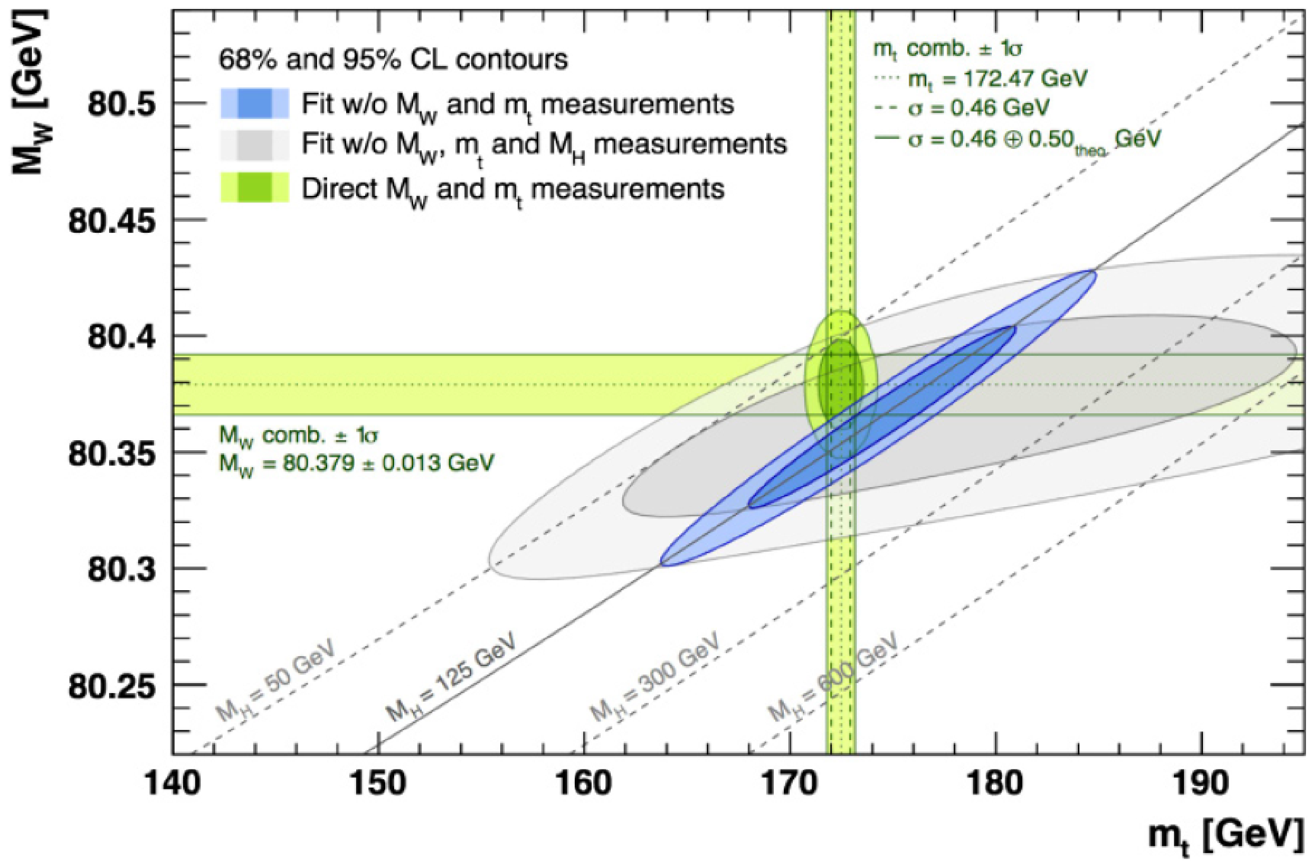
Highlights of FCC-ee in EW physics

Present status of the global EW fit:



Highlights of FCC-ee in EW physics

Present status of the global EW fit:

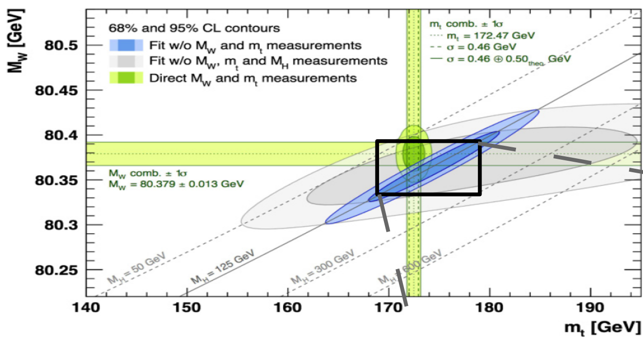


$$A_{EWPO} = A_0 \left[\frac{c_{SM}}{M_W^{\,2}} + \frac{c_{NP}}{\Lambda^2} \right]$$

Qualitative statement:

Present indirect bounds from EPWO constraint NP scales in the (0.1 – few) TeV range (*depending on couplings*) → direct bounds from LHC often (*not always*) more stringent

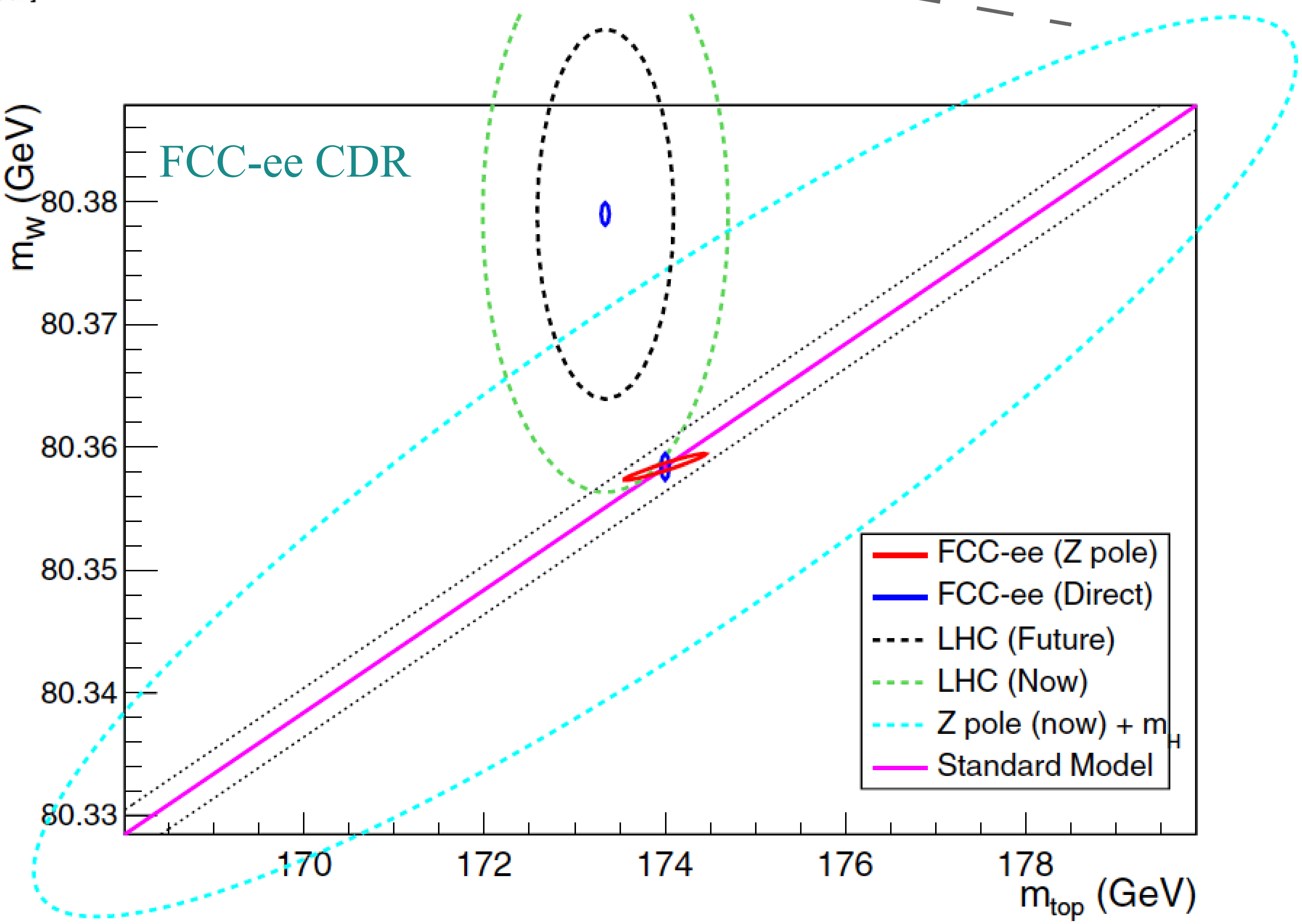
▶ *Highlights of FCC-ee in EW physics*



How the situation could change with FCC-ee, assuming all th. errors are kept under control ($\sigma_{TH} < \sigma_{EXP}$)

$\sigma(m_t^{SM})$: 10 → 1 GeV

<u>Qualitative statement:</u>
Increase of factor 3 to 5 in sensitivity to NP scales



Concluding remarks

- The fact we have not seen NP at the LHC is disappointing, but is not such a big surprise... it is the natural expectation of the (un-successful) indirect NP searches performed in the '90 – '00 (EWPO + Flavor)

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

Concluding remarks

- The fact we have not seen NP at the LHC is disappointing, but is not such a big surprise... it is the natural expectation of the (un-successful) indirect NP searches performed in the '90 – '00 (EWPO + Flavor)
- A new generation of indirect NP searches with EWPO + Flavor must be a key ingredient of our future strategy → FCC-ee offers a unique opportunity in this respect
- Outstanding improved performances on EPWO @ the Z-pole with no competition (*and same is true for Higgs physics...*)

Concluding remarks

- The fact we have not seen NP at the LHC is disappointing, but is not such a big surprise... it is the natural expectation of the (un-successful) indirect NP searches performed in the '90 – '00 (EWPO + Flavor)

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

- Outstanding improved performances on EPWO @ the Z-pole with no competition (*and same is true for Higgs physics...*)

- 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 "current anomalies"