Overview of Quark Flavour Opportunities at FCC-ee

Joe Davighi, CERN TH

15th January, 8th FCC Physics Workshop, CERN

Outline of Talk

1. Some BSM motivation for precision flavour measurements
2. Why FCC-ee is best of both worlds when it comes to flavour
3. Survey of FCC-ee quark flavour studies that have been done
4. What else can/should be done?

w.i.p with Marzia Bordone and Claudia Cornella

Some BSM Motivation

BSM physics is needed to solve some big problems:

like the hierarchy problem and the flavour puzzle

At zeroth order:

- Electroweak measurements probe solutions to the hierarchy problem
- Flavour measurements probe solutions to the flavour puzzle

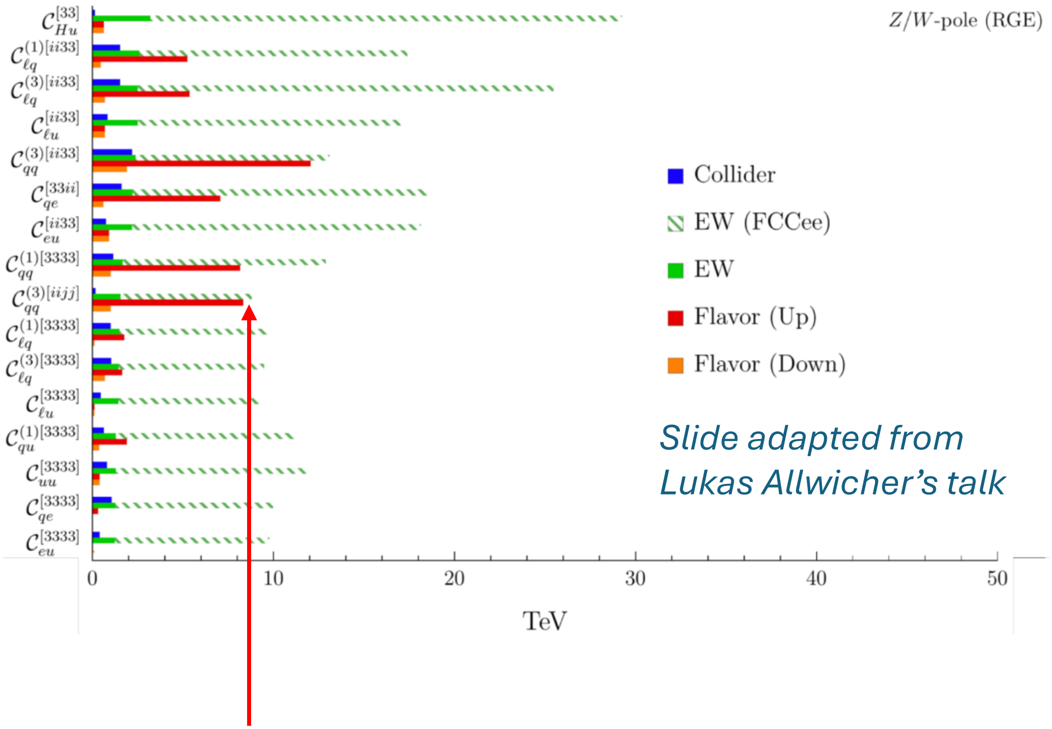
But this is too simple!

- EW **precision** probes almost generic BSM extensions b/c you **cannot turn off loops**!
- Flavour **precision** also probes generic BSM extensions b/c you **cannot turn off flavour violation**!

See talks by Matthew McCullough and Lukas Allwicher

Some BSM Motivation

$\mathcal{O}(10)$ TeV constraints for four-fermion operators (3$^{\text{rd}}$ ge. quarks)



Slide adapted from Lukas Allwicher's talk

Flavour reach – with $U(2)^5$ protection

These operators do not affect Z pole at tree, but you cannot switch off RGE

These operators are not flavour-violating, but you cannot switch off the CKM!

Some BSM Motivation

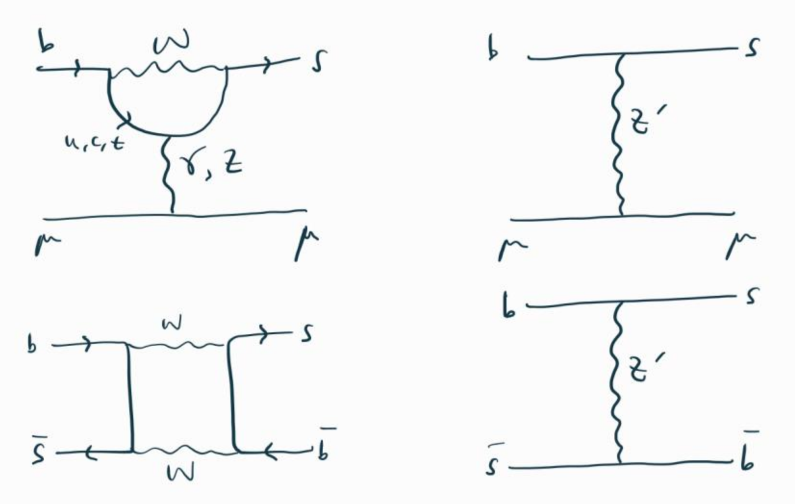
Q: Why is flavour so sensitive to BSM?

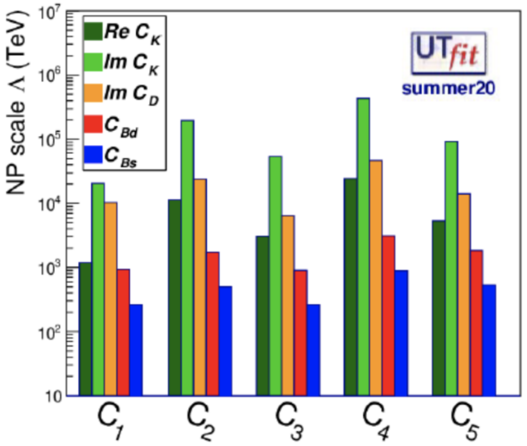
A: Because many flavour-changing processes are **rare** – due to accidents peculiar to the SM

c.f. proton decay probes GUT scale

c.f. m_W/m_Z due to custodial

Example: **FCNCs**





BSM particles won't necessarily respect these accidental features of the SM

E.g. a flavour non-universal Z': even if no direct flavour violation, get tree-level FCNCs suppressed only by CKM

Some BSM Motivation

To maximise sensitivity to BSM in these rare processes, **we need very precise measurements!**

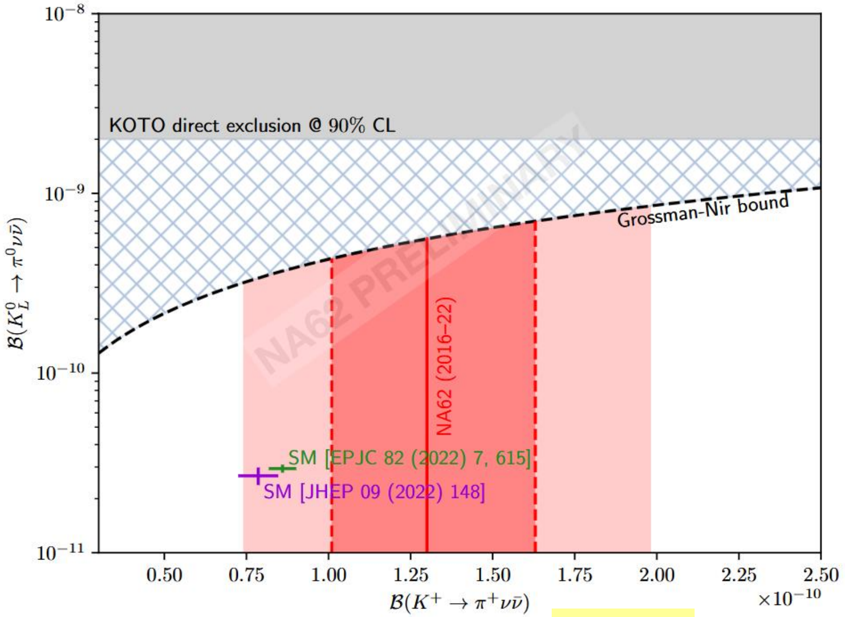
Flavour physics = an extremely rich experimental program…

- The flavour frontier is pushed back by many kinds of measurement at many specialised experiments [contrast to EW precision]

… and an ongoing journey

- Despite astonishing precision across many measurements, still many channels which cannot be probed by LHC + flavour factories

These should be **targets** for future colliders



$$\mathscr{B}^{16-22}_{\pi\nu\bar{\nu}} = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$

J Swallow for NA62, CERN Seminar, 9/24

1. Why is FCC-ee so good for flavour?

See Monteil, Wilkinson, 2106.01259

FCC-ee is a Next Generation Flavour Factory

The low-energy flavour prospects at FCC-ee come largely from the **tera-$\boldsymbol{Z}$** run:

Of the $O(10^{12})$ Z-bosons produced at tera-Z:

- 15% decay to $b\bar{b}$
- 12% decay to $c\bar{c}$
- 3% decay to $\tau^+\tau^-$

It's not just a numbers game: FCC-ee **combines advantages** of **B factories** and **LHC**

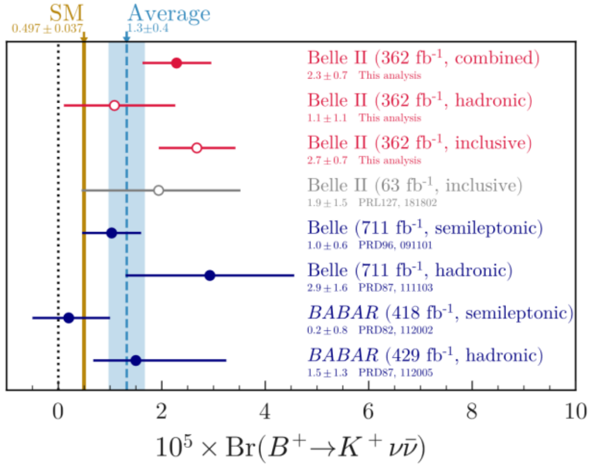
Flavour physics at e^+e^- vs pp colliders

e^+e^- (Belle II and FCC-ee)

1. **Low background**
2. No trigger losses
3. $\boldsymbol{4\pi}$ acceptance, missing energy can be measured
4. Initial energy knowledge

Showcase: allows much better measurements involving invisible neutrinos (hence also taus) than at e.g. LHCb

E.g. recent observation of $B^+ \to K^+\nu\bar{\nu}$

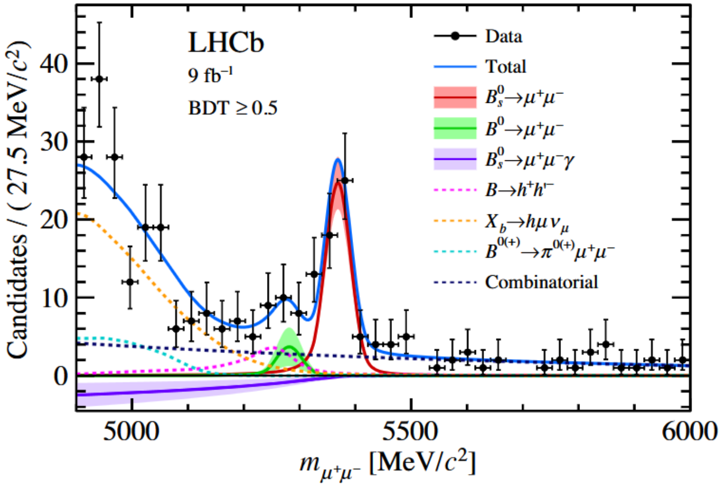


Belle II, 2311.14647

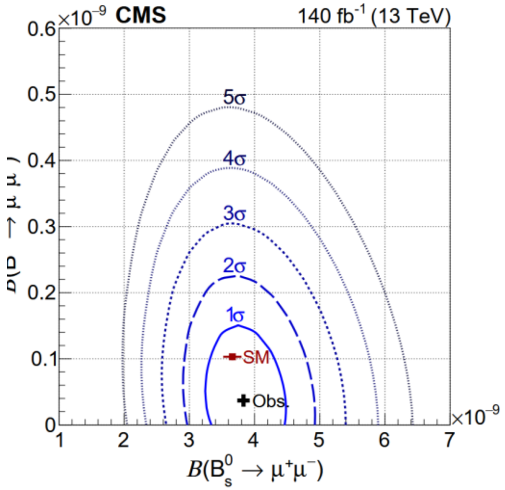
pp (HL-LHC and FCC-hh)

1. Huge **statistics**
2. Produce **full range** of hadrons
3. Many highly **boosted** B hadrons (mostly forward)

Showcase: enough stats to access ultra rare decays (especially involving muons e.g. $\boldsymbol{B_s \to \mu^+\mu^-}$) with high precision



LHCb, 2108.09284



CMS, 2212.10311

FCC-ee *vs.* Belle II

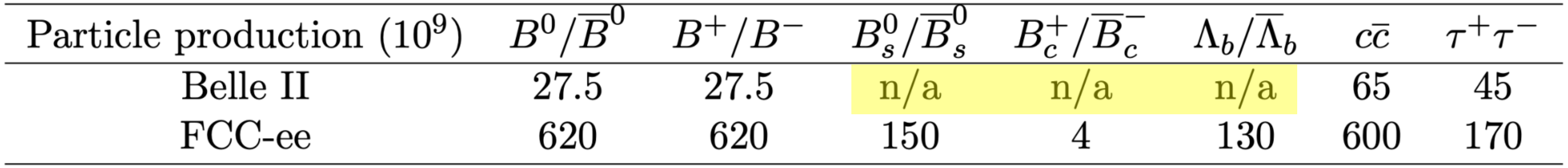
Key advantages of FCC-ee

- **Statistics**: tera-Z →15x (at least…) more $b\bar{b}$ pairs than Belle II

[opens possibility for ultra-rare decay measurements in a clean environment]

Replicates the main advantages of pp over current B factories

- Energy: $\sqrt{s} = m_Z \approx 91\ \mathrm{GeV}$ vs $m(\Upsilon(4S)) \approx 11\ \mathrm{GeV}$
  - FCC-ee can produce **full range** of hadron species inc. B_s, Λ_b etc
  - FCC-ee produces **boosted** mesons – aids reconstruction



Particle production (10^9)	$B^0/\overline{B}^0$	B^+/B^-	$B^0_s/\overline{B}^0_s$	$B^+_c/\overline{B}^-_c$	$\Lambda_b/\overline{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	n/a	65	45
FCC-ee	620	620	150	4	130	600	170

Belle II advantage: known initial B energy (although distribution well modelled at FCC-ee)

So, FCC-ee combines the USPs (for flavour) of B factories & LHC

New opportunities

Doing this not only allows comparable/better measurements at FCC-ee in the familiar channels suited to Belle II and LHC

➢ It also opens some completely new frontiers i.e. processes we have never measured before

Complementarity

Belle II and LHC each retain *some* advantage over FCC-ee (initial energy *vs* huge stats respectively), which means there will remain complementarity between all three

[Example: HL-LHC likely ends up with best precision on $B_s \to \mu^+\mu^-$]

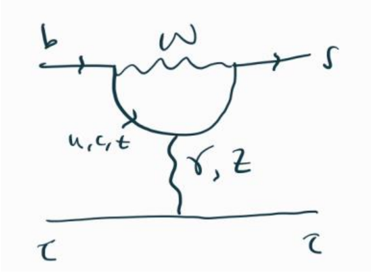
2. What FCC-ee flavour studies have been done?

Survey of studies

The following flagship channels have received dedicated studies, with detector simulation (IDEA baseline) and background modelling:

1. $B \to K^{*}\tau\tau$ new frontier!
2. $B_{c/u} \to \tau\nu$ new frontier!
3. $b \to s\bar{\nu}\nu$ pushing back the Belle II frontier: 10% to 1% precision

New frontiers at FCC-ee: $\boldsymbol{bs\tau\tau}$

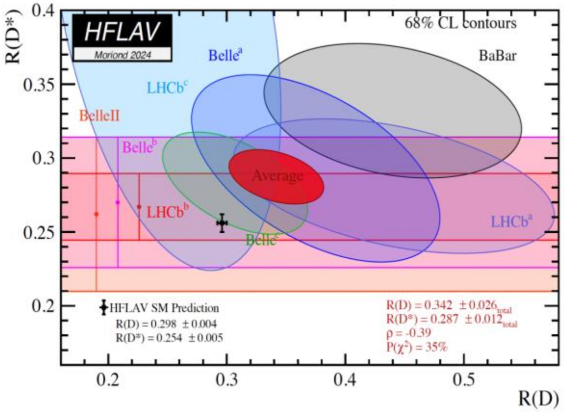


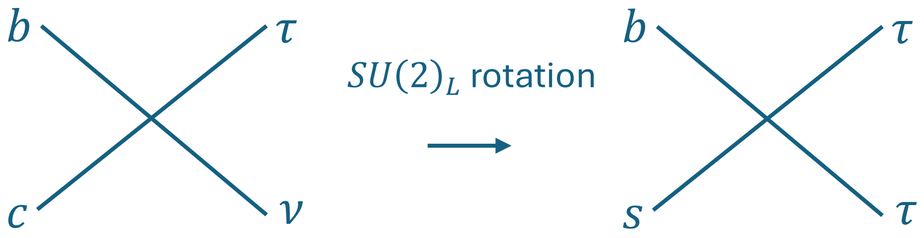
Current upper bound $BR(B \to K^*\tau^+\tau^-) \leq 3 \times 10^{-3}$ [BABAR] is **3 ÷ 4 orders of magnitude away from SM prediction**! Hopeless to observe with current experiments (modulo huge BSM contribution)

- LHC: problem is two neutrinos (contrast to $B \to K^*\mu^+\mu^-$ which is “routinely” measured in LHCb)
- B factories: not enough stats to approach SM rate

New physics in this channel is relatively unconstrained – could exceed SM by orders of magnitude

- Predicted to be large in many models e.g. addressing $R_{D^{(*)}}$ anomalies





$SU(2)_L$ rotation

See e.g. Buttazzo, Greljo, Isidori, Marzocca, 1706.07808 + ...

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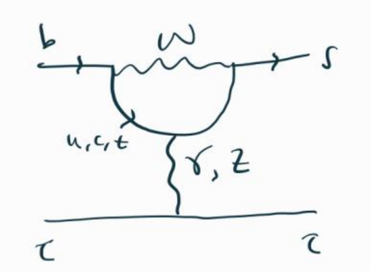

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- B factories: not enough stats to approach SM rate

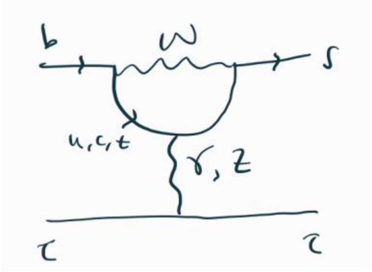
FCC-ee naïvely overcomes both hurdles

Proof of concept in $B \to K^*\tau^+\tau^-$ at FCC-ee early study Kamenik, Monteil, Semkiv, Vale Silva 1705.11106

1. **High boost** of the B (+ vertexing) allows reconstruction of 3-prong hadronic $\tau \to \pi\pi\pi\nu$ decay
2. Good **missing energy resolution** (neutrinos in each τ decay)
3. High **statistics** of tera-Z

Together is enough to make a measurement of $B \to K^*\tau^+\tau^-$ at SM rate a viable target!

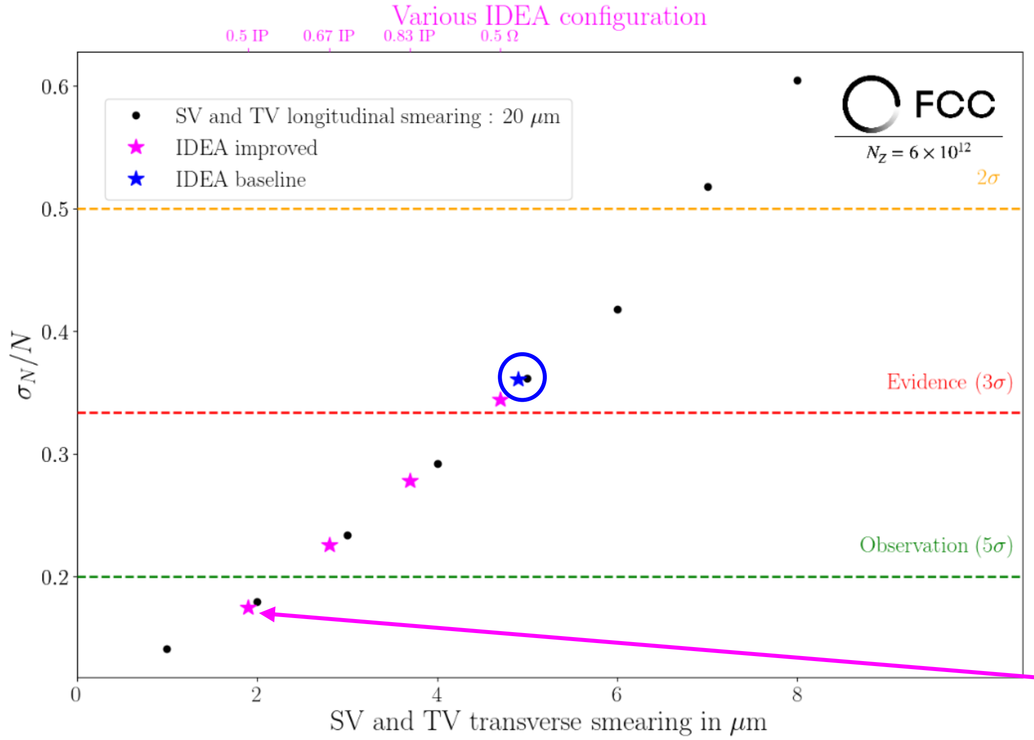
New frontiers at FCC-ee: $\boldsymbol{bs\tau\tau}$

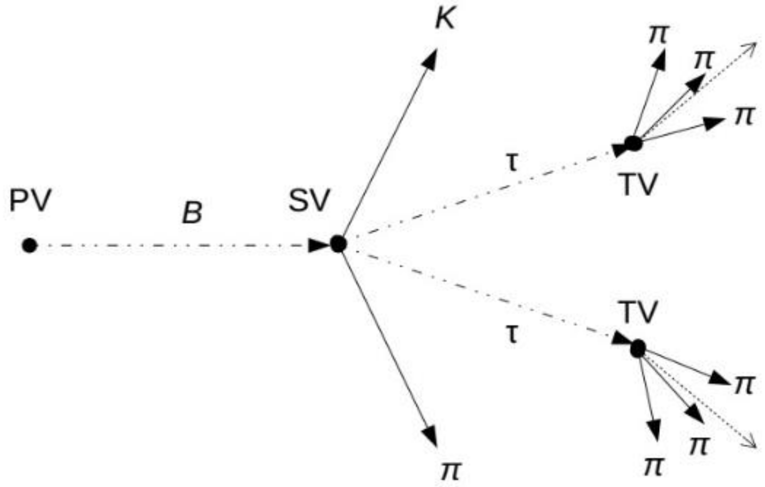


Updated study – see slides of Tristan Miralles from FCC Physics Workshop 2024, Annecy

Still uses **only fully hadronic $\boldsymbol{\tau}$** decay; $K^* \to K\pi$; detector simulation using **IDEA** baseline design

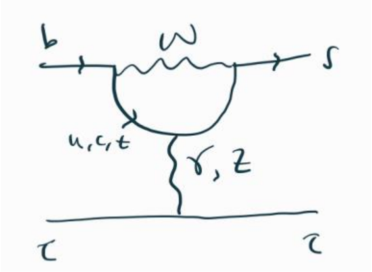
Vertex resolutions is a key parameter affecting BR sensitivity [$\epsilon_{\text{vertex}} = 0.8$ in this study]



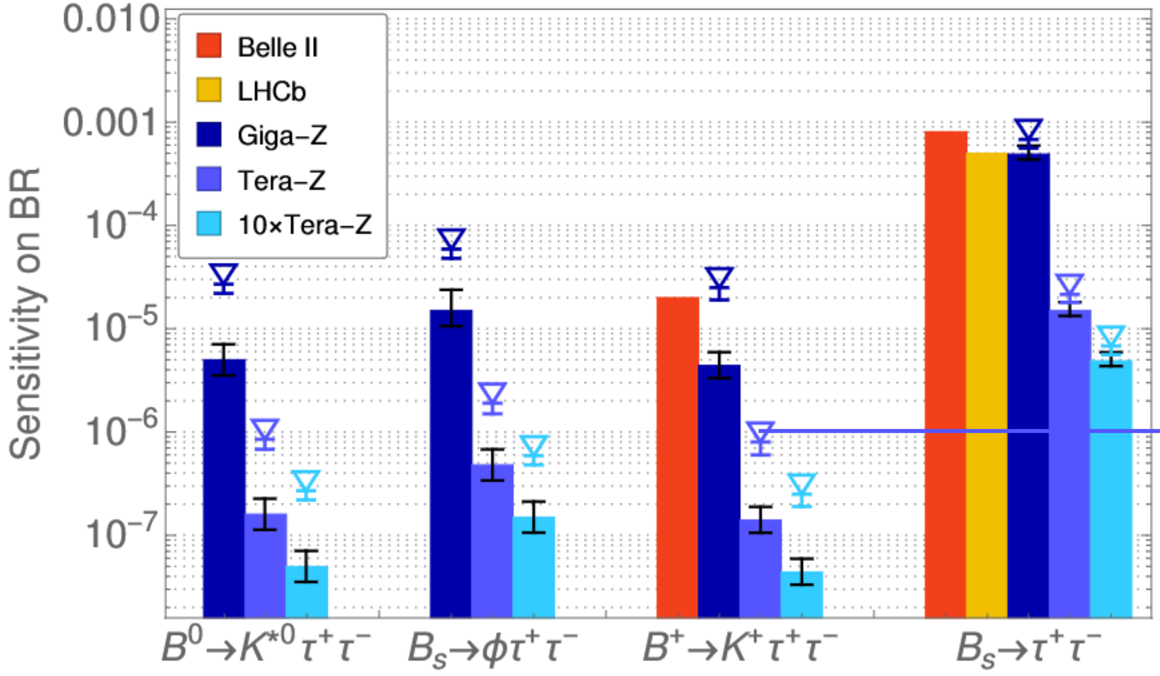


Identifies detector requirements needed to achieve observation at 5σ (SM rate)

New frontiers at FCC-ee: $\boldsymbol{bs\tau\tau}$



Not just $B \to K^*\tau\tau$, but other $bs\tau\tau$ channels have been studied in Li, Liu, 2012.00665



More conservative projection includes **finite tracker resolution**

New frontiers at FCC-ee: $\boldsymbol{bc\tau\nu}$ in $B_c^+ \to \tau^+\nu$

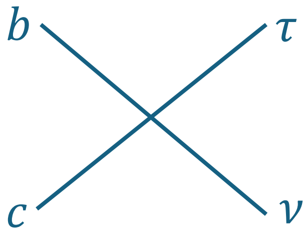
Note these are tree-level decays in SM – not "rare"

$BR(B_c^+ \to \tau^+\nu) = 2 \times 10^{-2}$ in SM; $BR(B^+ \to \tau^+\nu) = 0.9 \times 10^{-4}$

Nonetheless $B_c^+ \to \tau^+\nu$ measurement is practically impossible at current experiments:*

- LHC: tau vertex plus an extra neutrino, no initial knowledge of the B momentum, no 2nd vertex, and huge background…
- Belle II: operates below B_c threshold [$B \to \tau\nu$ measured at B factories with 20% precision]

New physics in this channel directly correlated to anomalies in $R_{D^{(*)}}$



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Again, the combination of boosted B_c mesons, high statistics (albeit significantly fewer than B and B_s mesons), and clean hermitic environment, make $\boldsymbol{B_c^+ \to \tau^+\nu}$ an opportunity unique to FCC-ee

FCC-ee studies:

- $B_c^+ \to \tau^+\nu$ Amhis, Hartmann, Helsens, Hill, Sumensari, 2105.13330
- $B_{u,c}^+ \to \tau^+\nu$ Zuo, Fedele, Helsens, Hill, Iguro, Klute, 2305.02998

See also **CEPC study**:

- $B_c^+ \to \tau^+\nu$ Zheng, Cao, Yu, Wang, Prell et al, 2007.08234

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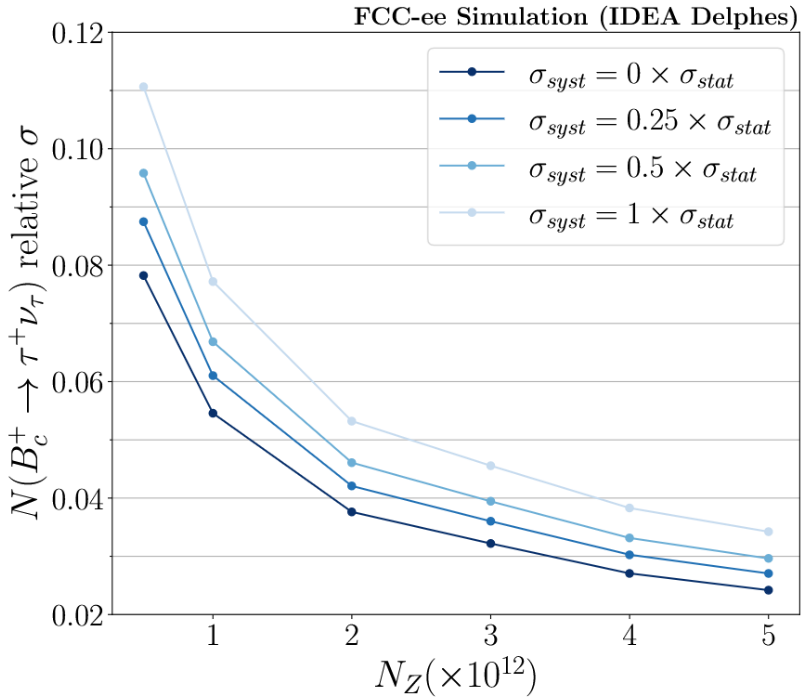
New frontiers at FCC-ee: $\boldsymbol{bc\tau\nu}$ in $B_c^+ \to \tau^+\nu$

Amhis, Hartmann, Helsens, Hill, Sumensari, 2105.13330; Zuo, Fedele, Helsens, Hill, Iguro, Klute, 2305.02998

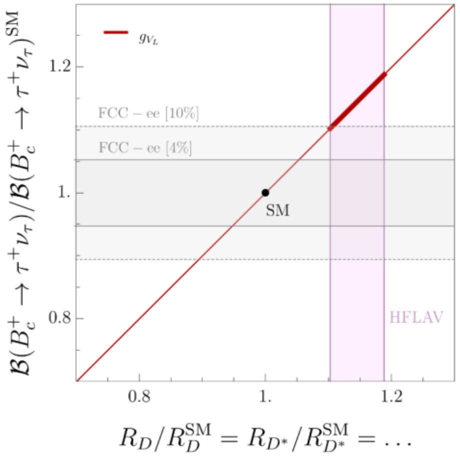
- Hadronic 3-prong tau decay (as for $B \to K^*\tau^+\tau^-$). Reconstruction of tau vertex (thus τ^+ flight distance) helps bkg rejection (done by training BDTs)

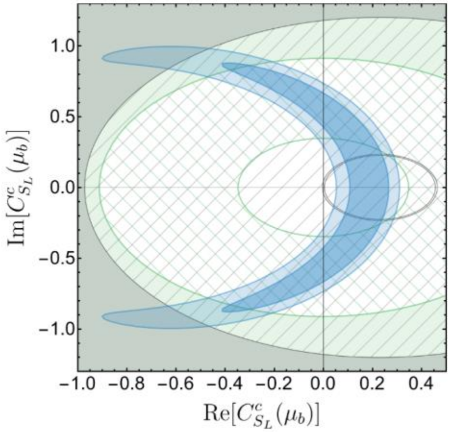


2105.13330: relative precision ~3% on $B_c^+ \to \tau^+\nu$

2305.02998: ~ 1 ÷ 2% precision on $B_c^+ \to \tau^+\nu$ and $B^+ \to \tau^+\nu$

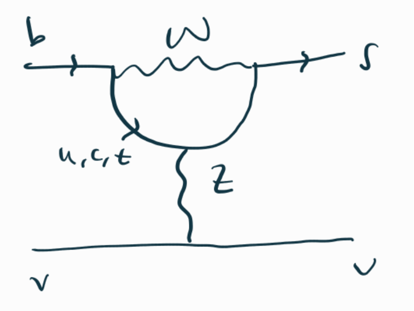
The corresponding sensitivity to NP requires a reliable estimate of the theory precision to estimate; but it is comparable to the current uncertainties in fits to $R_{D^{(*)}}$ tensions



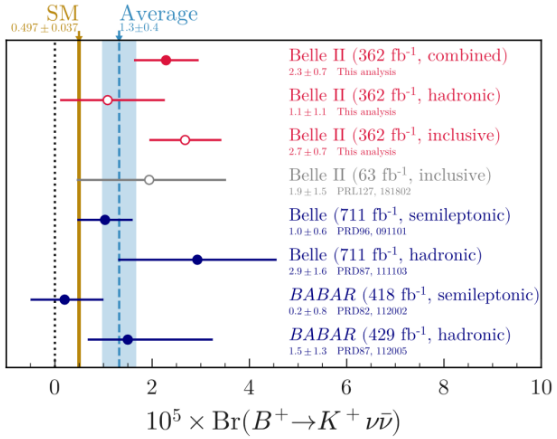


For a Scalar LQ model

Pushing back the frontier: $\boldsymbol{bs\nu\bar{\nu}}$



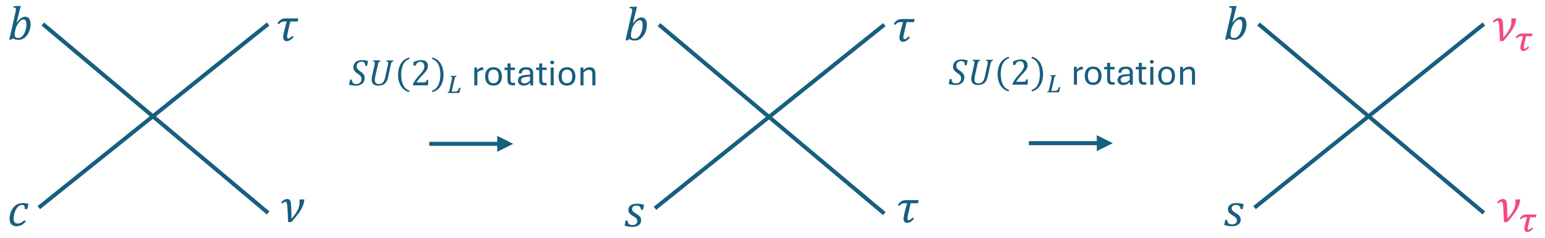
- LHC: missing energy prevents meaningful measurements
- Belle II: currently a big opportunity
  - $B \to K^* \nu\bar{\nu}$ observation not out yet (still only an upper limit)
  - Belle II only observed $B^+ \to K^+ \nu\bar{\nu}$ already because of a statistical over-fluctuation
  - If SM rate, best case scenario ($\int L = 50\ \mathrm{ab}^{-1}$) at Belle II is **$\boldsymbol{O(10\%)}$ precision**



Belle II, [2311.14647]

Theoretically $bs\nu\bar{\nu}$ rare FCNC decays are cleaner than $bsll$; **very sensitive to BSM**

Again, predicted to be large in BSM models addressing $R_{D^{(*)}}$ anomalies



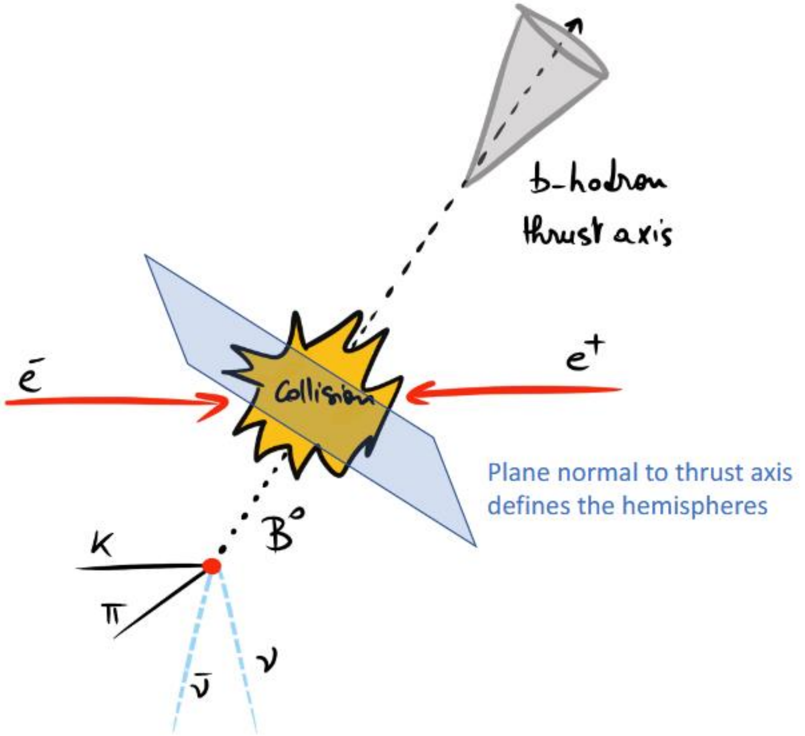
Pushing back the frontier: $bs\nu\bar{\nu}$ at 1%

FCC-ee study: Amhis, Kenzie, Reboud, Wiederhold, 2309.11353

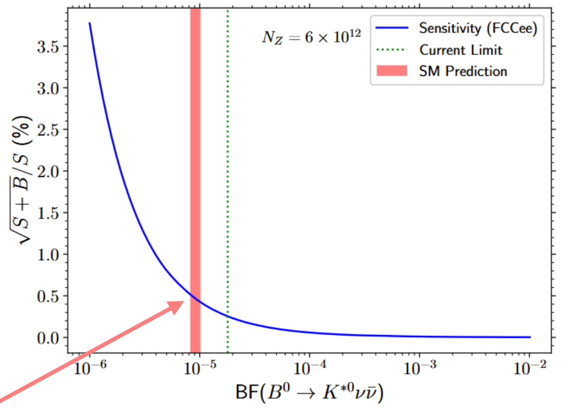
Like in Belle II, events characterized by large missing energy on signal side

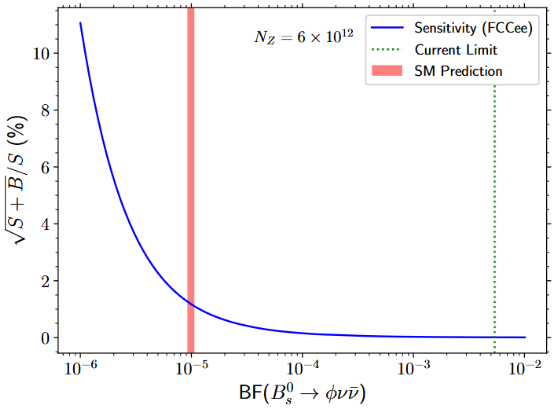
Upshot: go from 10% precision (Belle II) to 1% precision (FCC-ee)

Decay mode	$\mathcal{B}/\lvert\lambda_t\rvert^2\,[10^{-3}]$	$\mathcal{B}\,[10^{-6}]$	
$B^0 \to K^0_S \nu\bar{\nu}$	1.33 ± 0.04	2.02 ± 0.12	
$B^0 \to K^{*0} \nu\bar{\nu}$	5.13 ± 0.51	7.93 ± 0.89	Prompt $K^* \to K\pi$
$B^0_s \to \phi \nu\bar{\nu}$	6.31 ± 0.67	9.74 ± 1.15	Prompt $\phi \to K^+K^-$
$\Lambda^0_b \to \Lambda \nu\bar{\nu}$	5.55 ± 0.56	8.57 ± 0.97	



Plane normal to thrust axis defines the hemispheres





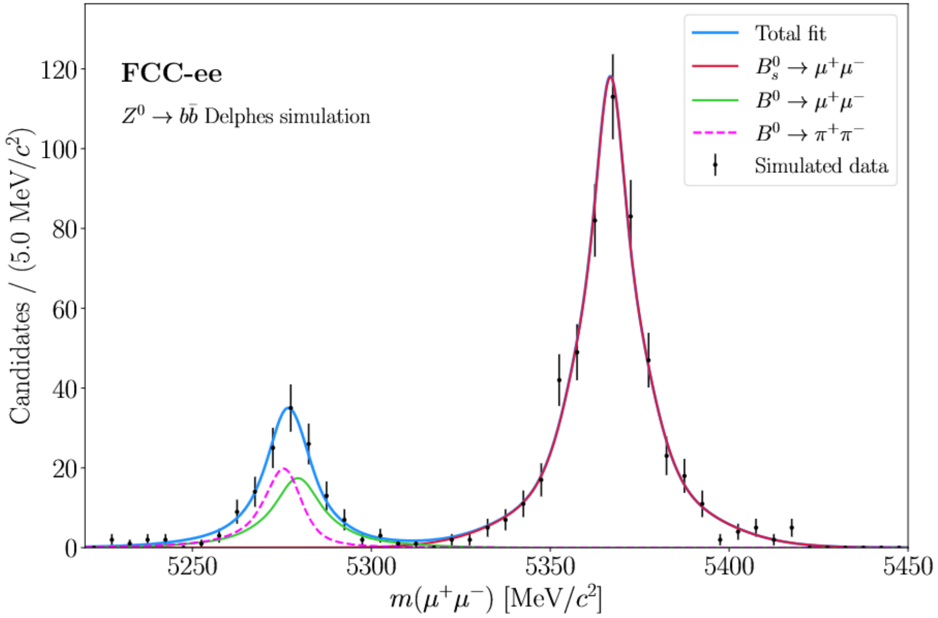
Sub-% precision at SM rate!

Complementarity to LHC: $\boldsymbol{B_{d/s} \to \mu^+\mu^-}$

This is a challenge at FCC-ee!

- Tera Z: 1.5×10^{11} B_s mesons; $BR(B_s \to \mu\mu) = 3 \times 10^{-9}$;
- expect around 500 $B_s \to \mu\mu$ events across whole distribution [n.b. $B_s \to \mu\mu$ could not be done at giga Z!]
- Precise measurement still realistic thanks to clean environment; complements LHC measurements

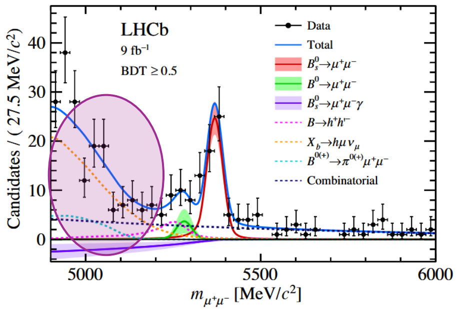
From Monteil, Wilkinson, 2106.01259; study by **Donal Hill**



FCC-ee benefits from excellent mass resolution and low backgrounds

Theoretically clean; the complementarity is especially interesting because of related anomalies in $bs\mu\mu$ transitions measured at LHCb

Reminder:



2021 LHCb

What more can be done?

- More serious studies of these flagship decays (e.g. improving background modelling)
- Detailed studies of new processes (I'm sure many are under way…)

Our goal:

with Marzia Bordone and Claudia Cornella (+ thanks already due to Stephane Monteil)

- Perform a crude extrapolation of the results from this handful of detailed studies to a much larger wishlist of processes, using conservative estimates of unknown efficiencies / background modelling
- In doing so, we plan to provide a somewhat global picture for FCC-ee flavour opportunities

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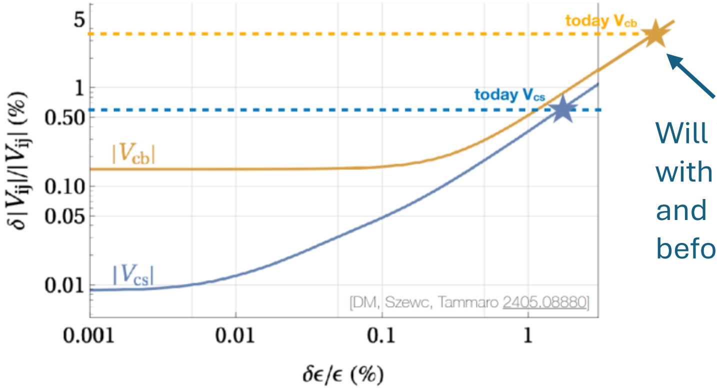
- Perform a crude extrapolation of the results from this handful of detailed studies to a much larger wishlist of processes, using conservative estimates of unknown efficiencies / background modelling
- In doing so, we plan to provide a somewhat global picture for FCC-ee flavour opportunities
- We also hope this will be helpful for understanding the **BSM reach** of **flavour @ FCC-ee**, and complementarity with EW precision*
  - This also requires some ‘guestimates’ of **SM theory** improvements
  - + **CKM elements** are a key input: big improvements at FCC-ee

See David Marzocca’s talk

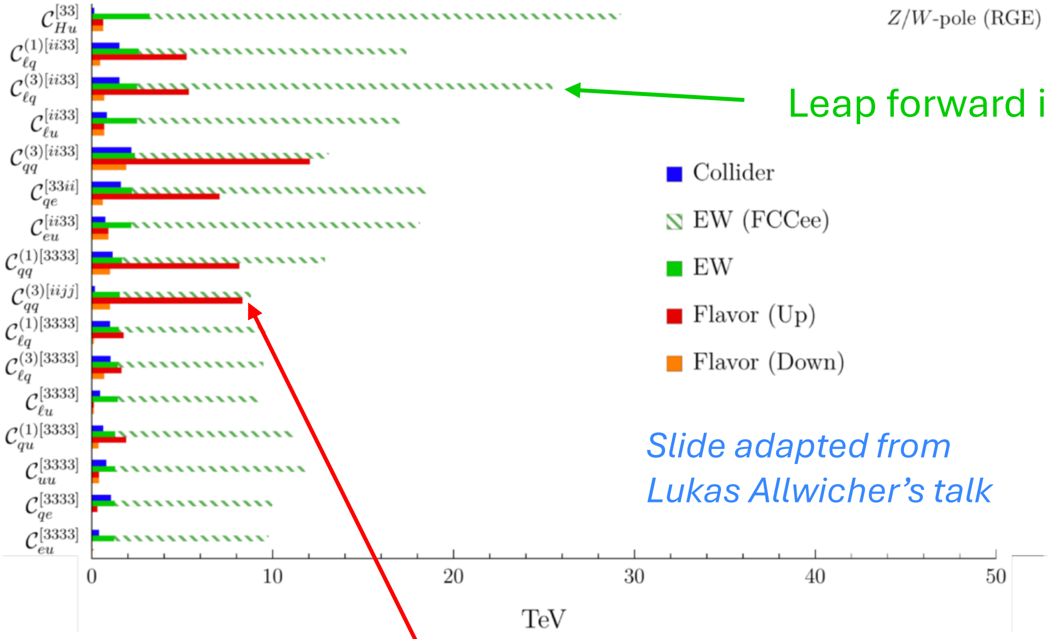


[DM, Szewc, Tammaro 2405.08880]

Will improve with HL-LHC and Belle II before FCC-ee

**See Lukas Allwicher’ talk for an example of such complementarity SMEFT implications of this*

$\mathcal{O}(10)$ TeV constraints for four-fermion operators (3^{rd} ge. quarks)



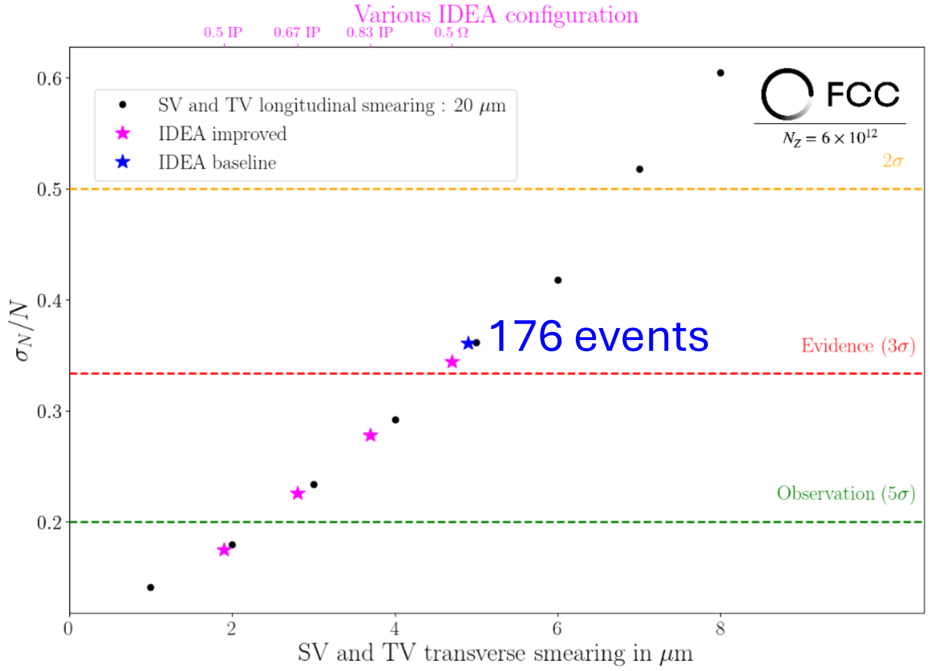
Leap forward in EW precision at FCC-ee

Slide adapted from
Lukas Allwicher's talk

We could begin to answer the Q:
where do the red/orange bars jump to with FCC-ee precision?

Wishlist

1. Extend the $bs\tau\tau$ and $bc\tau\nu$ to include **leptonic tau decays**



$$N = N_Z \cdot BR(Z \to b\bar{b}) \cdot 2f_B \cdot BR(B \to K^*\tau\tau) \cdot BR(\tau \to 3\pi\nu)^2 \cdot \epsilon_{\text{reco}} \cdot \epsilon_{\text{vertex}}$$

$(9\%)^2$

For two hadronic taus, requires reconstructing **8 tracks** [$\epsilon_{\text{reco}} \approx 0.38$]

3 vertices [$\epsilon_{\text{vertex}} = 0.8$ assumed]

*BUT for leptonic taus we **lose tertiary vertices** (significantly help reject background in τ_h case)

For each hadronic → leptonic τ, number of tracks ↓ by 2

Also a combinatoric efficiency in addition to each track…

Rough idea: reasonable to estimate that including say $\tau_h\tau_l$ channel could e.g. double number of signal events, and help us reach 5σ observation of $B \to K^*\tau\tau$

Wishlist

1. Extend the $bs\tau\tau$ and $bc\tau\nu$ to include leptonic tau decays
2. $B \to K^{(*)}\tau\tau \Longrightarrow B \to K^{(*)}\mu\mu$ estimate [preliminary: ~80k in central bin], and other $b \to s\mu\mu$? Muons constructed perfectly, but lose vertices
3. Rare decays with electrons e.g. $B \to K^{(*)}ee$;
    a) Can presumably make big gains w.r.t. LHCb, for processes that are too rare for Belle II. A new frontier?
4. To complement $B_c \to \tau\nu$ study: estimate $B \to D^*\tau\nu$?
    a) Likewise for $B \to \tau\nu$, estimate $B \to \pi\tau\nu$
5. The above $b \to c$ processes but with $\tau \to \mu$ (could provide competitive V_{cb} measurement)
6. B_s mixing – study at FCC-ee is so far limited to V_{cb} improvement

   Charles, Descotes-Genon, Ligeti, Monteil, Papucci, Trabelsi, Vale Silva, 2006.04824
7. LFUV R-ratios like in LHCb? Theoretically clean, this time without experimental electron challenges
8. LFUV R-ratios involving taus?
9. …

Conclusions

- Precision flavour program offers crucial and unique exploration of generic BSM, to high scales
- LHC experiments and B factories (+ kaon factories) are highly complementary: together they make astonishing measurements in a huge range of rare processes
- FCC-ee combines best of both, which also opens up totally new opportunities:
  1. $B \to K^* \tau\tau$
  2. $B_{c/u} \to \tau\nu$
  3. $b \to s\bar{\nu}\nu$ to % precision

- In progress: FCC-ee can surely also improve and/or provide complementary measurements besides these flagship processes (e.g. measurements involving muons). Need wider range of estimates, even if crude
  - ➢ Get a global picture for the flavour leap forward at FCC-ee, and implications for BSM

- An important question: dedicated flavour experiment at FCC-ee? Now that 4 experiments seems settled.

- I focussed on B physics. Excellent opportunities for charm (not much explored) and tau also.