DETECTOR REQUIREMENTS FOR τ PHYSICS @ FCC

gratefully acknowledging the contributions of the FCC Infrastructure
and Operation WG and sub-WGs, all FCC study teams
and the collaborating partners.

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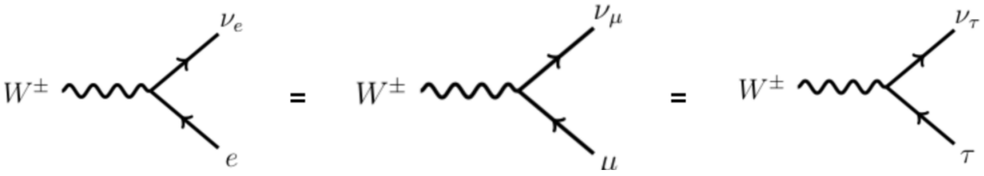
Based on:

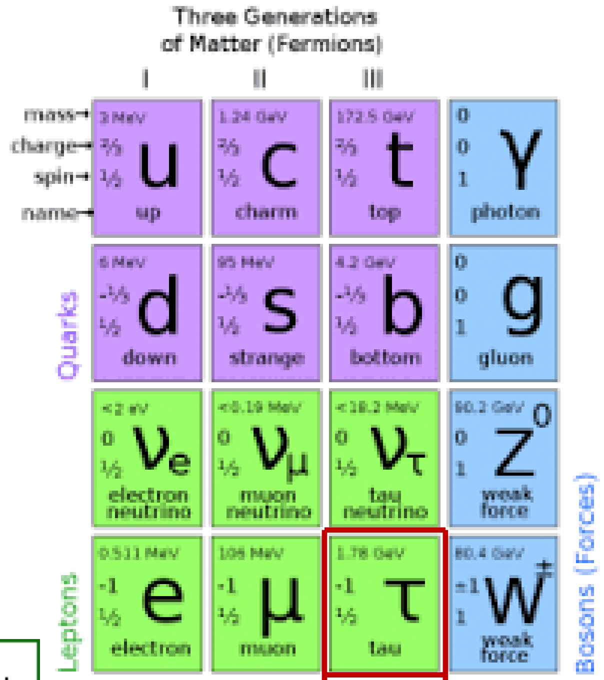
- **A. Lusiani, "Detector requirements from Tau Physics", FCC Week 2023**
- **A. Lusiani, "Tau Lifetime measurement at FCC-ee(Z)", 6th FCC Physics Workshop Kraków,**
- **A. Lusiani, "LFV and LFU in tau decays", CEPC Workshop**

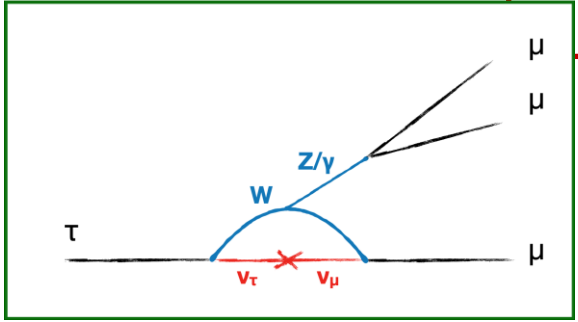
Why τ are interesting?

- Heaviest known lepton in SM!
- Test of lepton universality
- Only lepton that can decay hadronically
- Test of lepton universality:



- Probing Lepton Flavour Violation
- τ lifetime measurements.





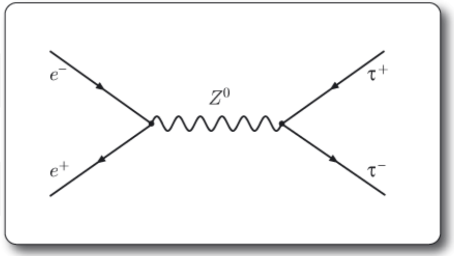
FCC – a τ factory!

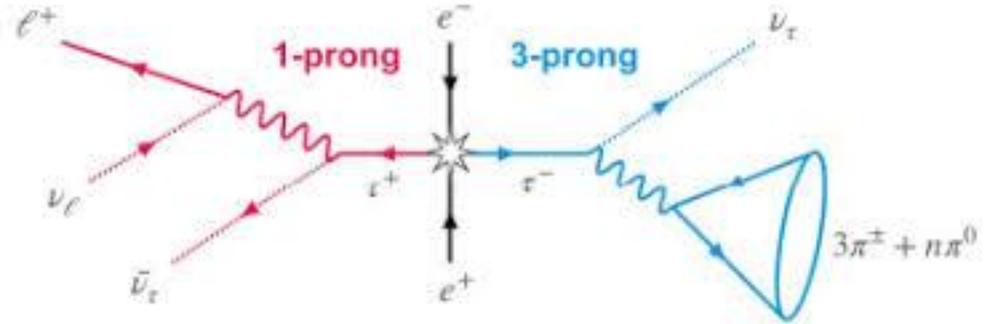
- FCC will accumulate $N_Z = 2\ 10^{12}\ Z$ decays!
- DELPHI measurement of τ_τ was done using $N_Z(DELPHI) = 5.7x\ 10^{6}\ Z$ decays.

hadrons	$(69.911 \pm 0.056)\%$
$(u\bar{u} + c\bar{c})/2$	$(11.6 \pm 0.6)\%$
$(d\bar{d} + s\bar{s} + b\bar{b})/3$	$(15.6 \pm 0.4)\%$
$c\bar{c}$	$(12.03 \pm 0.21)\%$
$b\bar{b}$	$(15.12 \pm 0.05)\%$

- There are 2 canonical signatures of τ pairs: 1-3 prong and 3-3 prong topologies.
- DELPHI used both of them, while Belle used 3-3 only.
- $\sigma^{stat}(\tau_\tau(DELPHI)) = 2.4\ fs$

Γ_1	e^+e^-		$(3.3632 \pm 0.0042)\%$
Γ_2	$\mu^+\mu^-$		$(3.3662 \pm 0.0066)\%$
Γ_3	$\tau^+\tau^-$		$(3.3696 \pm 0.0083)\%$
Γ_4	$\ell^+\ell^-$	[1]	$(3.3658 \pm 0.0023)\%$





Γ_2	particle$^-$ ≥ 0 neutrals $\geq 0K^0_L\ \nu_\tau$	$(84.58 \pm 0.06)\%$	
Γ_{62}	$h^-h^-h^+ \geq 0$ neutrals $\geq 0K^0_L\ \nu_\tau$	$(15.20 \pm 0.06)\%$	861

FCCee performance

assumed baseline FCC-ee detector performance	
track momentum	$\frac{\sigma_p}{p} = 0.02 \cdot 10^{-3} \cdot p_T(\mathrm{GeV}) \oplus 1 \cdot 10^{-3}$
track impact parameter	$\sigma_{d_0} = \frac{15\,\mu\mathrm{m}}{\sin^{3/2}\theta} \oplus 5\,\mu\mathrm{m}$
electromagnetic energy	$\frac{\sigma_{E_\gamma}}{E_\gamma} = \frac{15\%}{E_\gamma} \oplus 1\%$
electromagnetic energy xy position	$\sigma_{\gamma,xy} = \frac{6\,\mathrm{mm}}{E(\mathrm{GeV})} \oplus 2\,\mathrm{mm}$

Lifetime of τ lepton

$N_{1-3} = 15427$ $N_{3-3} = 2101$

- Let's calculate the statistical uncertainty from DELPHI under 3-3 prong hypothesis:

$$\sigma(\tau_\tau, 3\text{–}3) = 2.4\,\text{fs} \cdot \sqrt{\frac{N_{1-3} + 2 \cdot N_{3-3}}{2 \cdot N_{3-3}}} \simeq 5.19\,\text{fs}$$

$$\sigma(\tau_\tau, 3\text{–}3)\,[\text{ppm}] = \sigma(\tau_\tau, 3-3)/\tau_\tau \cdot 1{\cdot}10^6\,\text{ppm} \simeq 18000\,\text{ppm}\ ,$$

- The impact parameter resolution: $< d_0 > = 70\mu m$, while the resolution: $\sigma < d_0 > = 42\mu m$

Consistent with DELPHI tracking+beamspot resolution

- Assuming the resolution in FCC $\sigma < d_0 > \ll 42\mu m$ we can scale down the stat. error:

$$\sigma(\tau_\tau, 3\text{–}3, \text{FCC})[\text{ppm}] = \sigma(\tau_\tau, 3\text{–}3)\,[\text{ppm}] \cdot \frac{\tau_\tau}{\sigma(\tau_\tau, 3\text{–}3, 1\,\text{ev})} \cdot \sqrt{\frac{N_Z(\text{DELPHI 2004})}{N_Z(\text{FCC})}}$$
$$\simeq 15.0\,[\text{ppm}]\ ,$$

Lifetime of τ lepton – systematics…

- Luminosity correlated systematics:
  - Background subtraction
  - Reconstruction bias
  - Vertex alignment.
- Luminosity unrelated systematics:
  - Detector length scale
  - Average τ energy
  - Radiative energy loss
  - τ mass

Calibration of simulation with data events
Prompt decays
Data events

In LEP 100ppm. No data can tell us about the overall size of the detector. Use interferometry to achieve 1 μm over a meter
doi: 10.23919/MIPRO55190.2022.9803636
Overall possible to reduce this to 5ppm @ FCCee.

$$\tau_\tau = \frac{\lambda_\tau}{\beta\gamma} = \frac{\lambda_\tau m_\tau}{\sqrt{E_\tau^2 - m_\tau^2}} = \frac{\lambda_\tau m_\tau}{\sqrt{(E_{\rm beam} - E_{\rm rad})^2 - m_\tau^2}}\ .$$

- The beam energy @ FCCee we will know with 1ppm precision.
- E_{rad} is estimated with MC simulation. @LEP 350 ppm. FCC assuming x30 improvement to reach 11.5 ppm
- m_τ is measured by external experiments. Currently 68 ppm. Belle II will reach 50 ppm. Tau-charm factory: 9 ppm.

Lifetime of τ lepton – systematics…

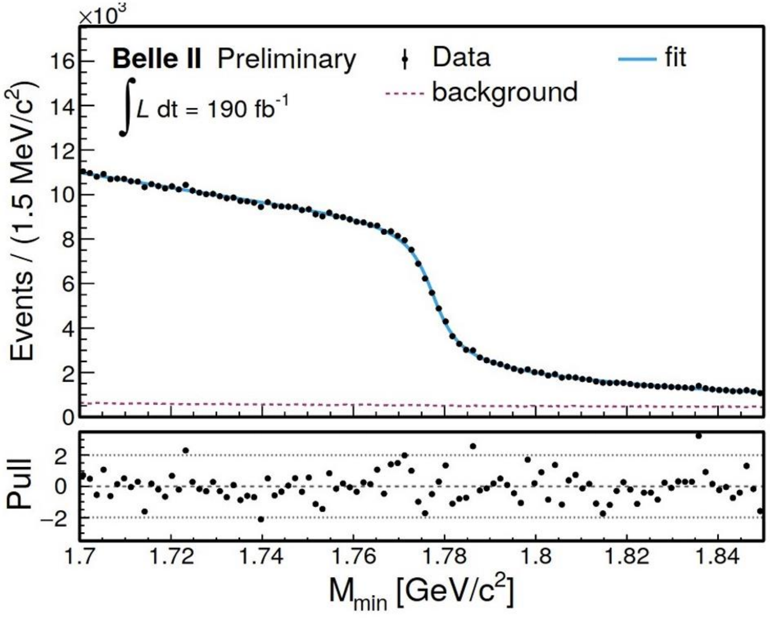
	DELPHI 2004 [fs]	DELPHI 2004 [ppm]	FCC-ee(Z) 210 ab^{-1} [ppm]
statistical uncertainty	5.2	18000	15.0
luminosity-dependent systematics	1.3	4500	3.9
- background	0.2		
- reconstruction bias	0.8		
- vertex detector alignment	1.0		
luminosity-independent systematics			
- detector length scale	-	100	5.0
- average tau energy	-	-	1.0
- radiative energy loss	0.1	350	11.5
- tau mass	-	68	9.0
total systematics			15.9
total uncertainty			21.5

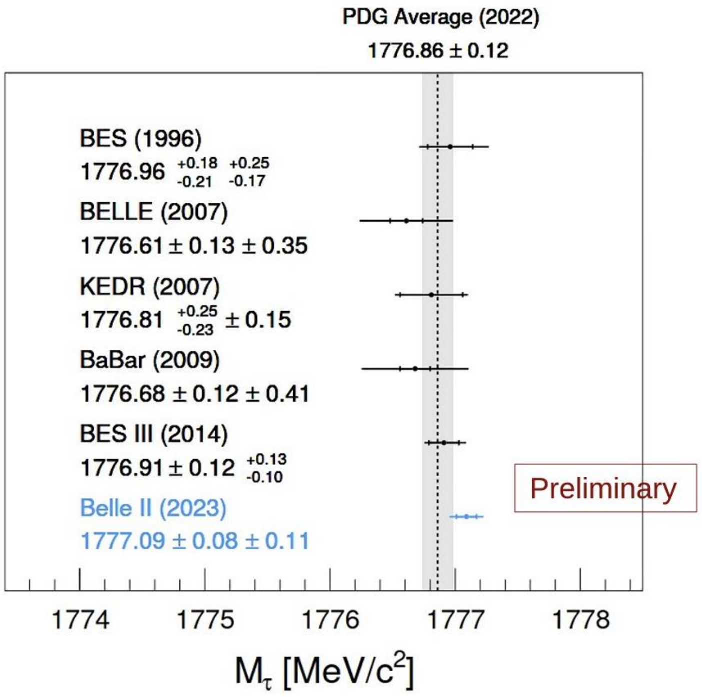
Detector
Accelerator
Theory
External Experiment

NEW for Moriond!

World's most precise measurement

- World's most precise measurement of $\mathbf{m_\tau = 1777.09 \pm 0.08_{stat} \pm 0.11_{sys}}$ **MeV/c^2**





Proof of high precision capability of Belle II!

arXiv:2305.19116 [hep-ex], May 30, 2023

NEW for Moriond!

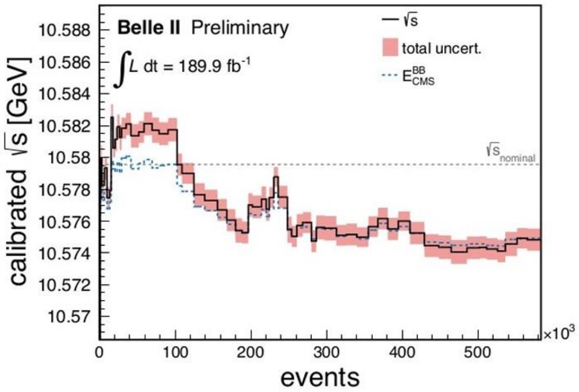
τ mass: precision challenge

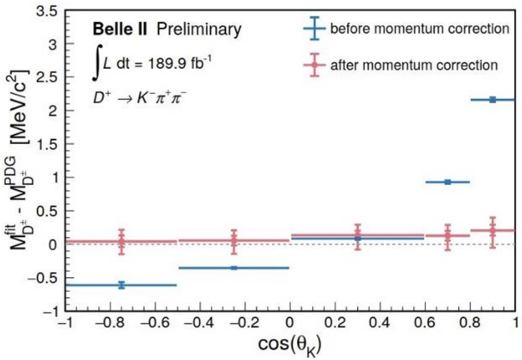
- Excellent control of systematic uncertainties thanks to precise understanding of beam energies and tracking: $M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \leq M_\tau$

Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam energy correction	0.07
Boost vector	≤ 0.01
Reconstruction of charged particles:	
Charged particle momentum correction	0.06
Detector misalignment	0.03
Fitting procedure:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	≤ 0.01
Imperfections of the simulation:	
Detector material budget	0.03
Modeling of ISR and FSR	0.02
Momentum resolution	≤ 0.01
Neutral particle reconstruction efficiency	≤ 0.01
Tracking efficiency correction	≤ 0.01
Trigger efficiency	≤ 0.01
Background processes	≤ 0.01
Total	0.11

Beam energy calibration with B-meson hadronic decays method and Υ(4S) lineshape measurement to get √s

Momentum scale factor cures the bias due to imperfect B-eld: extract corrections dependent on $\cos\theta_{track}$ by comparing D^0 Kπ mass peak w.r.t PDG mass.





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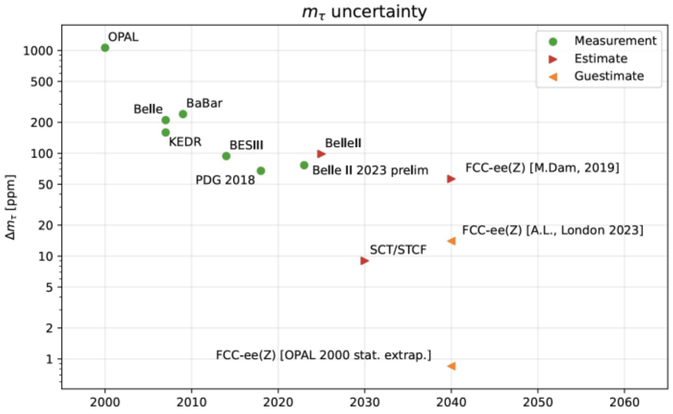
τ mass measurement



- BelleII statistical uncertainty is 45ppm with $190\ fb^{-1}$ corresponding to 175M τ pairs.
- FCC-ee statistical uncertainty with $8\ 10^{12}$ Z, $2.7 \cdot 10^{11}$ τ pairs would be 1.1ppm!!!
  - Neglecting surely better FCC-ee efficiency

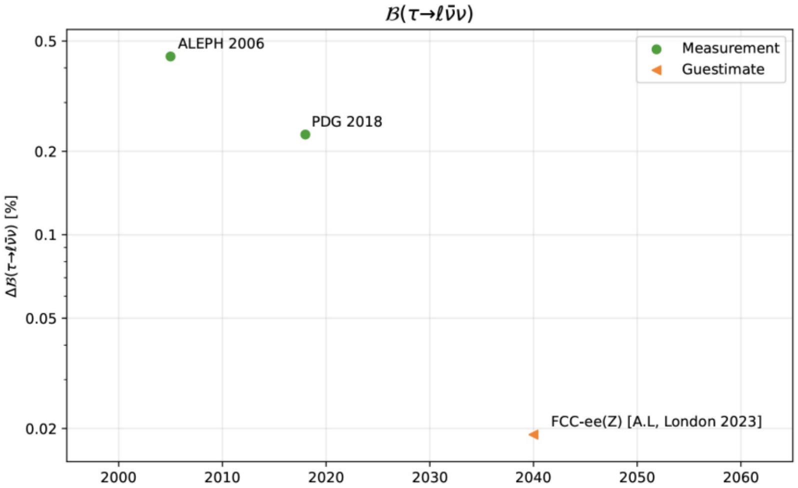
- Belle II dominant systematics expected very reduced at FCC-ee.
  - Beam energy (1ppm @ FCC-ee)
  - Track momentum scale (2ppm calibration may be possible at FCC-ee with J/ψ)
- Alignment systematics can be expected to scale with statistics.
- Limiting systematics from empirical fit function 0.05MeV or 28ppm.
- May expect to reduce this limiting systematic uncertainty to ½ of 14ppm @ FCC-ee
- Guestimate FCC-ee tau mass precision at 14ppm

- Baseline performance is adequate, no gain expected from improvements!!

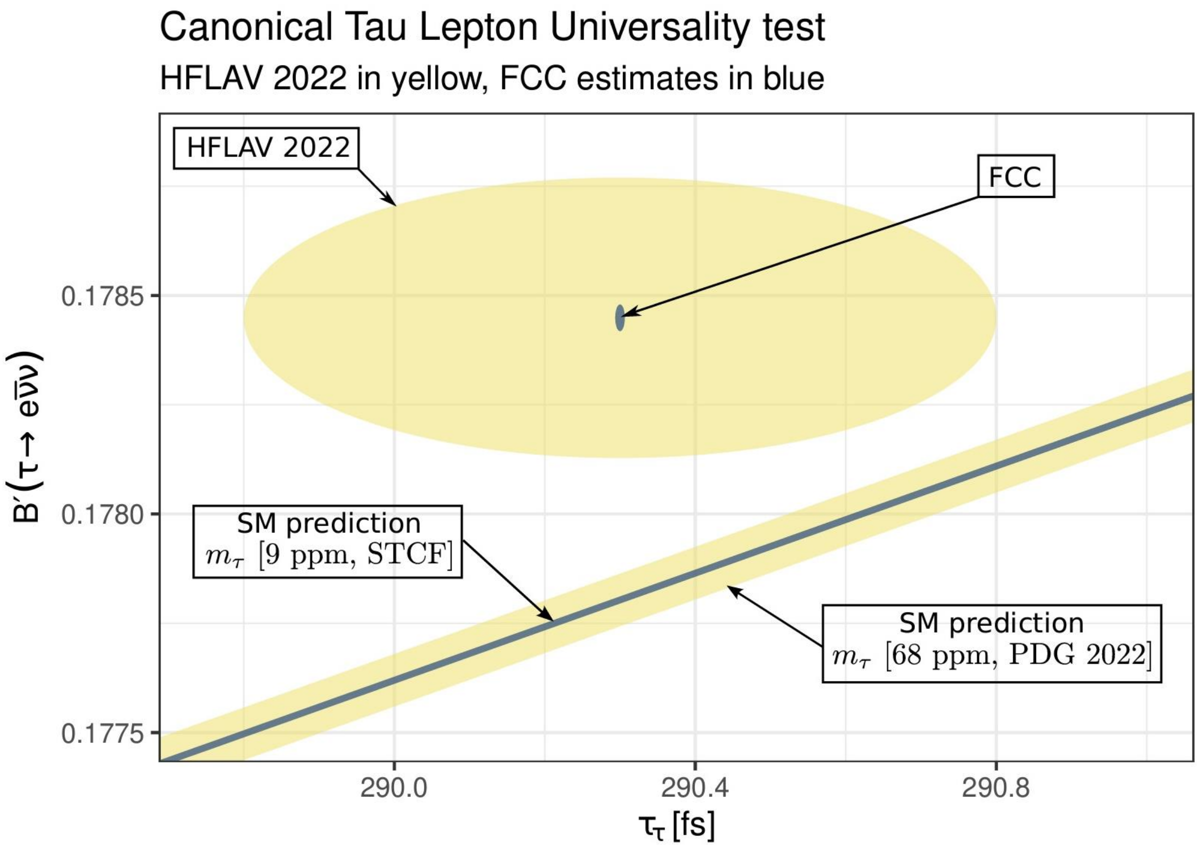
$\tau \to l\nu\nu$ leptonic branching fraction

- ALEPH 2006 measurement precision: 4400ppm=[4000(stat.)+1900(syst.)]ppm (average of the two similar electron and muon decays branching fractions)
  - Complex simultaneous measurement of 12 τ branching fractions
  - Many systematic uncertainties, nonreliable extrapolations to FCC-ee statistics
  - Several systematics related to photon and $\pi^0 \to \gamma\gamma$ reconstruction

  - FCC-ee extrapolated statistical precision: 4.5ppm
  - Systematic: 190ppm



Lepton universality

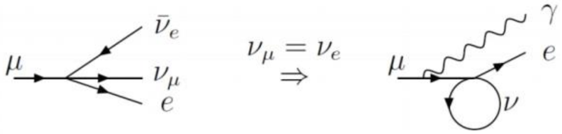


LFV in τ decays

Lepton Flavour Violation(LFV):

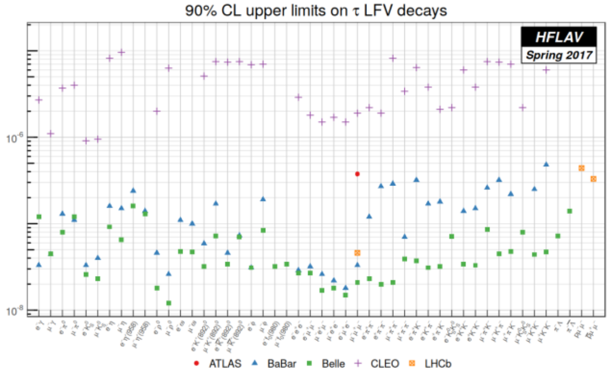
After μ^- was discovered it was natural to think of it as an excited e^-.

- Expected: $B(\mu \to e\gamma) \approx 10^{-4}$
- Unless another ν, in intermediate vector boson loop, cancels.



I.I.Rabi:

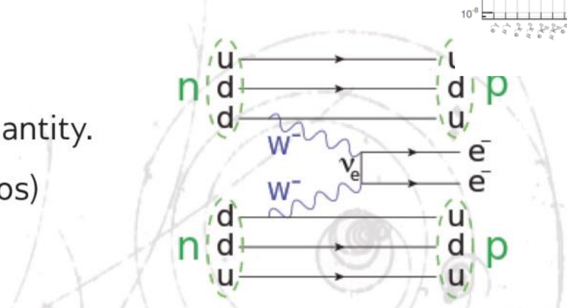
"Who ordered that?"



- Up to this day charged LFV is being searched for in various decay modes.
- LFV was already found in neutrino sector (oscillations).

Lepton Number Violation (LNV)

- Even with LFV, lepton number can be a conserved quantity.
- Many NP models predict it violation(Majorana neutrinos)
- Searched in so called Neutrinoless double β decays.



Credit to R. Bernstein

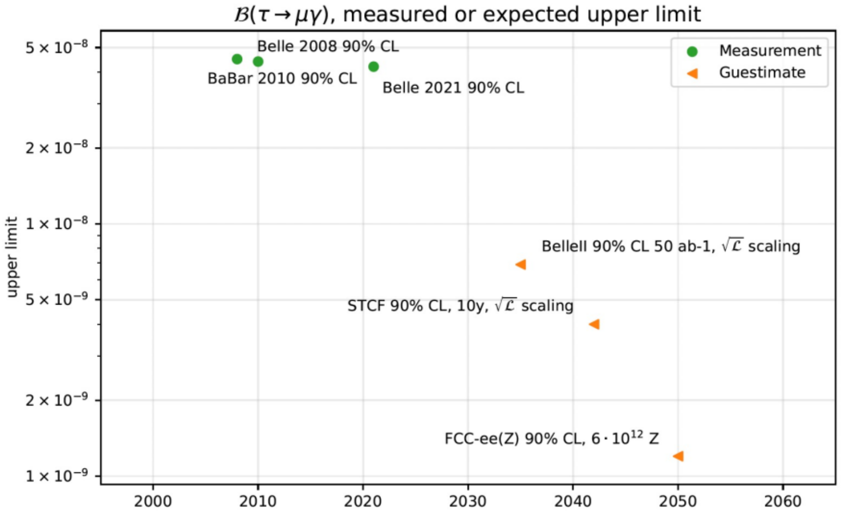
Search for $\tau \to \mu\gamma$ decay

- Detector resolutions better or equal to parameters in M.Dam simulation
- photon energy resolution:

$$\frac{\sigma E(\gamma)}{E(\gamma)} \leq \frac{15\%}{E(\gamma)} + 1\%$$

- Photon x,y position:

$$\frac{\sigma(x,y\,(\gamma))}{x,y\,(\gamma)} \leq \frac{6}{E(\gamma)} + 2\%$$



$$\mathcal{B}(\tau \to \mu\gamma) < 2.0{\cdot}10^{-9} \cdot \frac{qN\left[1 - \frac{1-90\%}{2}\right]}{2} \cdot \frac{\sqrt{3{\cdot}10^{12}}}{\sqrt{6{\cdot}10^{12}}} \simeq 1.2{\cdot}10^{-9} \quad \text{at } 90\%\ \text{CL},$$

Conclusions

- FCCee will provide huge samples of heavy flavour particles and very favorable experimental conditions to perform τ Physics measurements
- Detector improvements:

assumed baseline FCC-ee detector performance	
track momentum	$\frac{\sigma_p}{p} = 0.02 \cdot 10^{-3} \cdot p_T(\mathrm{GeV}) \oplus 1 \cdot 10^{-3}$
track impact parameter	$\sigma_{d_0} = \frac{15\,\mu\mathrm{m}}{\sin^{3/2}\theta} \oplus 5\,\mu\mathrm{m}$
electromagnetic energy	$\frac{\sigma_{E_\gamma}}{E_\gamma} = \frac{15\%}{E_\gamma} \oplus 1\%$
electromagnetic energy xy position	$\sigma_{\gamma,xy} = \frac{6\,\mathrm{mm}}{E(\mathrm{GeV})} \oplus 2\,\mathrm{mm}$

Sufficient to perform most interesting τ measurements!

1 Lorem Ipsum Dolor Sit amet

Thank you
for your attention.