Potential and challenges of Lepton Universality studies at FCC-ee

R. Aleksan
14/9/2022

1) Motivation
2) Decay modes to be used
3) Expectation statistical sensitivities @FCC-ee
4) Theoretical and experimental limitations
5) Conclusions

This talk is not aimed at giving answers but to trigger discussions and hopefully new line of work

Actual evidences of lepton universality violation

$B \to D^{(*)}\tau\nu_\tau$ vs $B \to D^{(*)}\ell\nu_\ell$ $(\ell = e, \mu)$

~20% excess of τ compared to SM*

$$R_D^{\tau/\ell} = \frac{Br(B\to D\tau\nu_\tau)_{exp}/Br(B\to D\tau\nu_\tau)_{SM}}{Br(B\to D\ell\nu_\ell)_{exp}/Br(B\to D\ell\nu_\ell)_{SM}} = 1.37 \pm 0.18$$

$$R_{D^*}^{\tau/\ell} = \frac{Br(B\to D^*\tau\nu_\tau)_{exp}/Br(B\to D^*\tau\nu_\tau)_{SM}}{Br(B\to D^*\ell\nu_\ell)_{exp}/Br(B\to D^*\ell\nu_\ell)_{SM}} = 1.23 \pm 0.062 \pm 0.087$$

* Caveat : hadronic matrix uncertainties because phase spaces are very different

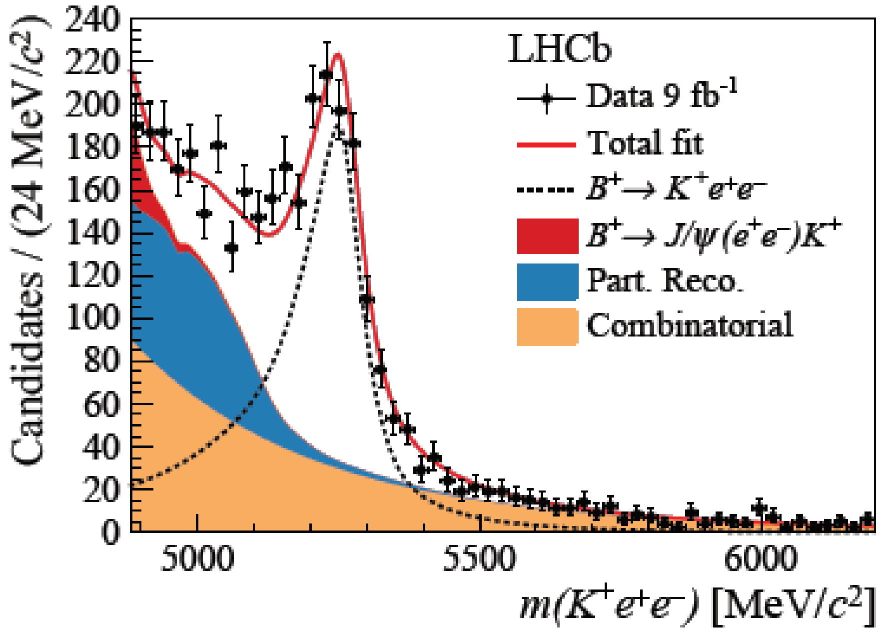
$B \to K^{(*)}\mu\mu$ vs $B \to K^{(*)}ee$

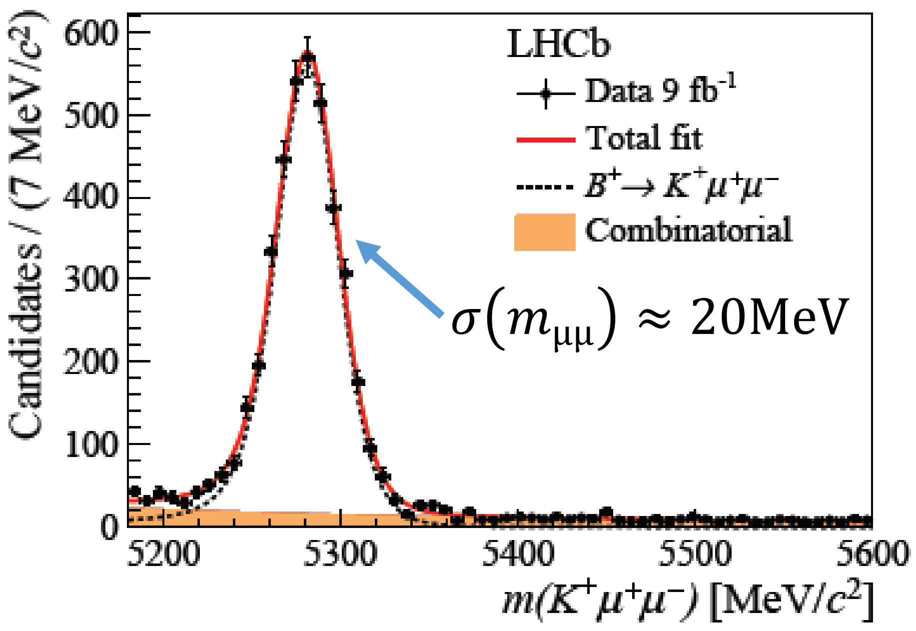
~20% deficit of μ compared to SM*

$$R_K^{\mu/\ell} = \frac{Br(B\to K\mu^+\mu^-)_{exp}/Br(B\to K\mu^+\mu^-)_{SM}}{Br(B\to Ke^+e^-)_{exp}/Br(B\to Ke^+e^-)_{SM}} = 0.846^{+0.042}_{-0.039}(stat.)^{+0.013}_{-0.012}(syst.)$$

$$R_{K^*}^{\mu/\ell} = \frac{Br(B\to K^*\mu^+\mu^-)_{exp}/Br(B\to K^*\mu^+\mu^-)_{SM}}{Br(B\to K^*e^+e^-)_{exp}/Br(B\to K^*e^+e^-)_{SM}} = 0.70^{+0.18}_{-0.13}(stat.)^{+0.03}_{-0.04}(syst.)$$

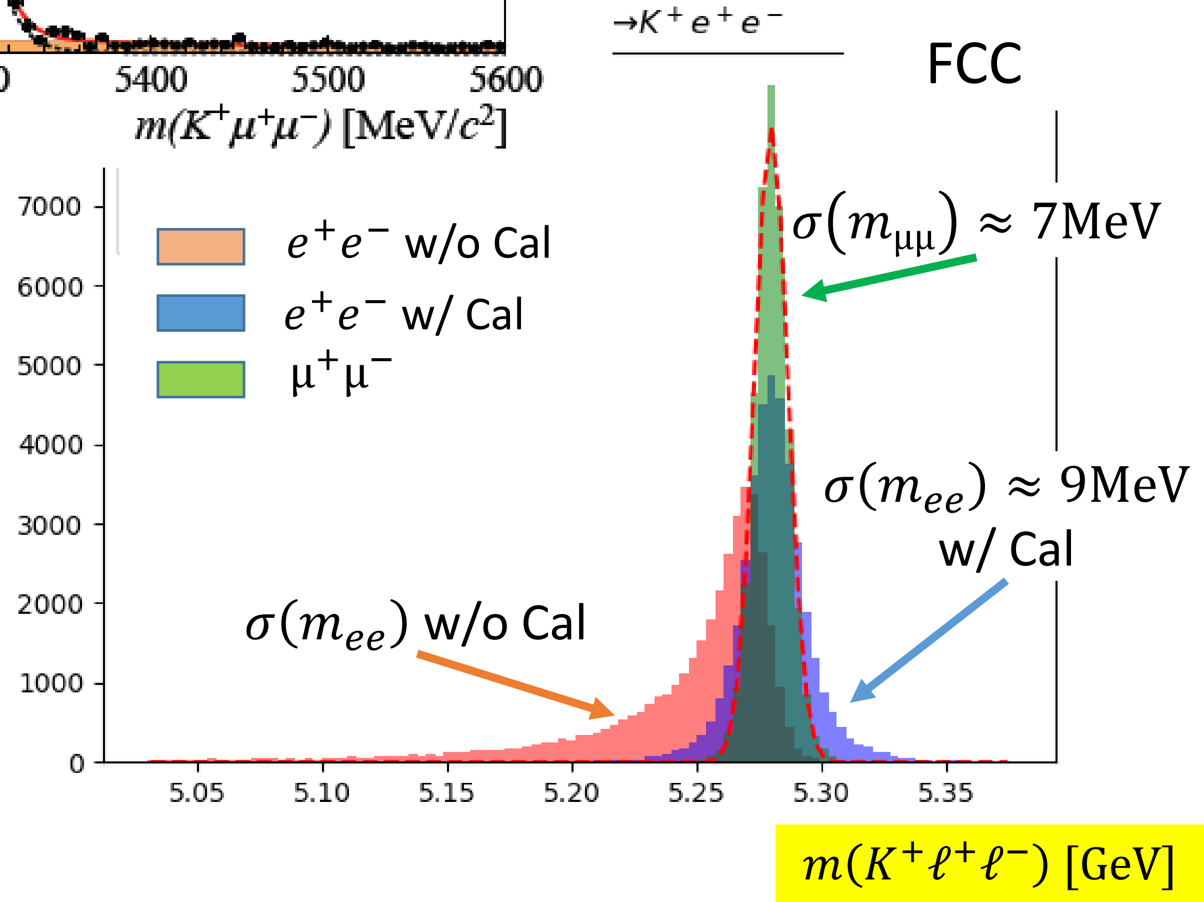
* Caveat : - experimentally difficult measurement for electrons (requires excellent detector resolutions),
- Do we understand correctly the J/ψ(1S, 2S …) interferences





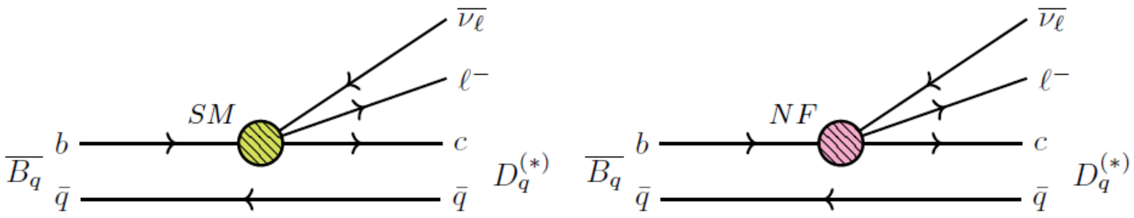
$$B^+ \to K^+\ell^+\ell^-$$

	FCC
$\int \mathcal{L}dt$	$150\ ab^{-1}$
$B^+ \to K^+\mu^+\mu^-$	$\sim 1.5 \cdot 10^5$
$B^0 \to K^{*0}\mu^+\mu^-$	$\sim 2.5 \cdot 10^5$

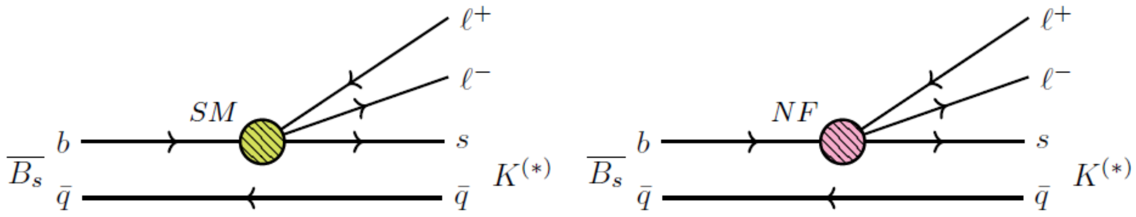


Could these effects be NF ?

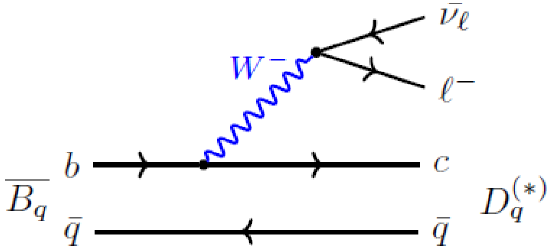
$B \to D^{(*)} \ell \nu_\ell$

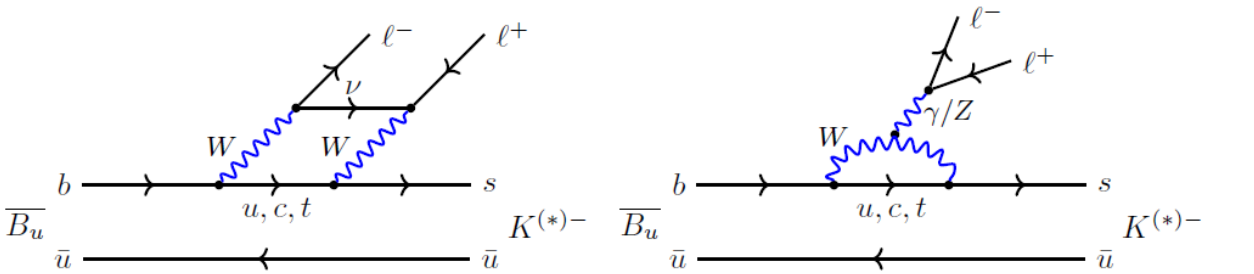


$B \to K^{(*)} \ell \ell$

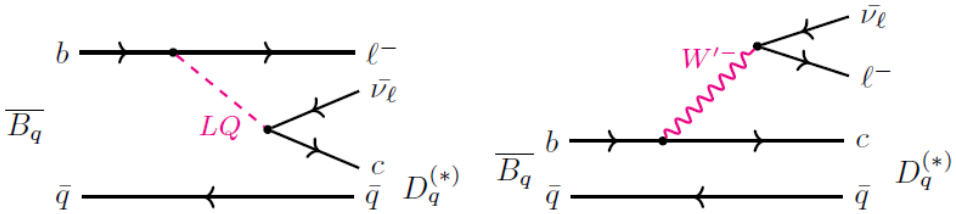


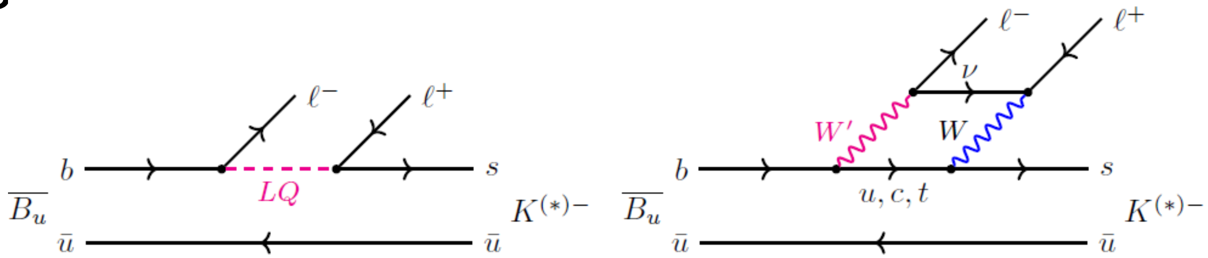
Dominant Diagrams in SM





Examples of Diagrams with NF





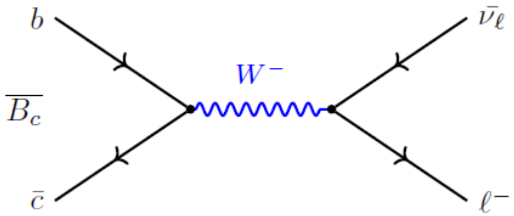
$B_c \to \ell \nu_\ell$

(same diagram as $B \to D^{(*)} \ell \nu_\ell$)

$B_s \to \ell^+ \ell^-$

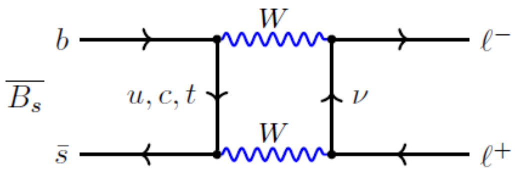
(same diagram as $B \to K^{(*)} \ell \ell$)

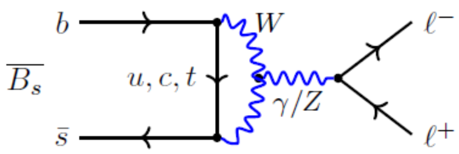
Dominant Diagrams in SM



$$\Gamma(P \to \ell \nu_\ell) = \frac{G_F^2}{8\pi} \times |V_{qq'}|^2 f_P^2 m_\ell^2 m_P \left(1 - \frac{m_\ell^2}{m_P^2}\right)^2 (1 + \Delta_\ell)$$

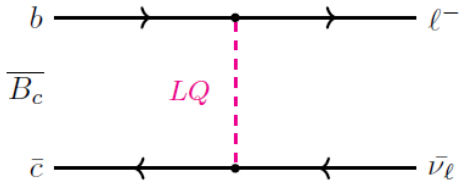
$$\frac{\Gamma(P \to \ell_1 \nu_\ell)}{\Gamma(P \to \ell_2 \nu_\ell)} = \frac{m_{\ell_1}^2}{m_{\ell_2}^2} \times \left(\frac{m_P^2 - m_{\ell_1}^2}{m_P^2 - m_{\ell_2}^2}\right)^2 (1 + \Delta_{\ell_1/\ell_2})$$

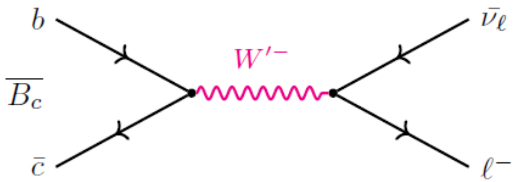


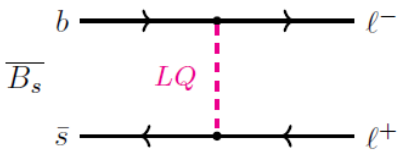


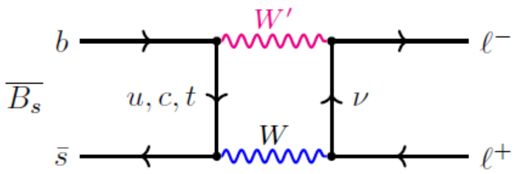
$$\Gamma(P \to \ell^+ \ell^-) \simeq \frac{G_F^2 \alpha^2}{16\pi^3} |V_{tq} V_{tq'}|^2 m_P m_\ell^2 \sqrt{1 - 4z} |C_{10}|^2 f_P^2 \times \zeta$$

Examples of Diagrams with NF









Note : only τ and μ modes might be accessible because of helicity suppression

Experimental situation in HF sector for leptonic decays

Decay	Br_{exp}	Br_{th}
$B^+ \to e^+\nu_e$	-	$(8.75 \pm 0.69) \cdot 10^{-12}$
$B^+ \to \mu^+\nu_\mu$	$(6.5 \pm 3.5) \cdot 10^{-7}$	$(3.74 \pm 0.30) \cdot 10^{-7}$
$B^+ \to \tau^+\nu_\tau$	$(1.09 \pm 0.24) \cdot 10^{-4}$	$(8.32 \pm 0.66) \cdot 10^{-5}$
$B_c \to e^+\nu_e$	-	$(2.10 \pm 0.29) \cdot 10^{-9}$
$B_c \to \mu^+\nu_\mu$	-	$(8.96 \pm 1.26) \cdot 10^{-5}$
$B_c \to \tau^+\nu_\tau$	-	$(2.15 \pm 0.30) \cdot 10^{-2}$
$D^+ \to e^+\nu_e$	-	$(9.46 \pm 0.89) \cdot 10^{-9}$
$D^+ \to \mu^+\nu_\mu$	$(3.74 \pm 0.17) \cdot 10^{-4}$	$(4.02 \pm 0.38) \cdot 10^{-4}$
$D^+ \to \tau^+\nu_\tau$	$(1.20 \pm 0.27) \cdot 10^{-3}$	$(1.07 \pm 0.10) \cdot 10^{-3}$
$D_s \to e^+\nu_e$	-	$(1.26 \pm 0.10) \cdot 10^{-7}$
$D_s \to \mu^+\nu_\mu$	$(5.49 \pm 0.16) \cdot 10^{-3}$	$(5.36 \pm 0.43) \cdot 10^{-3}$
$D_s \to \tau^+\nu_\tau$	$(5.48 \pm 0.23) \cdot 10^{-2}$	$(5.23 \pm 0.42) \cdot 10^{-2}$

Decay	Br_{exp}	$Br_{\text{Born SM}}$	significance
$D^0 \to \mu\mu$	–	$(3.6 \pm 0.6) \cdot 10^{-15}$	–
$D^0 \to ee$	–	$(8.5 \pm 1.4) \cdot 10^{-20}$	–
$B^0 \to \tau\tau$	–	$(2.22 \pm 0.32) \cdot 10^{-8}$	–
$B^0 \to \mu\mu$	$(1.1 \pm 1.3) \cdot 10^{-10}$	$(1.06 \pm 0.15) \cdot 10^{-10}$	0.03σ
$B^0 \to ee$	–	$(2.5 \pm 0.4) \cdot 10^{-15}$	–
$B_s \to \tau\tau$	–	$(7.73 \pm 1.09) \cdot 10^{-7}$	–
$B_s \to \mu\mu$	$(3.0 \pm 0.4) \cdot 10^{-9}$	$(3.65 \pm 0.51) \cdot 10^{-9}$	1.03σ
$B_s \to ee$	–	$(8.5 \pm 1.2) \cdot 10^{-14}$	–

No deviation observed … but precisions are still poor

Many other modes can be used for probing lepton universality

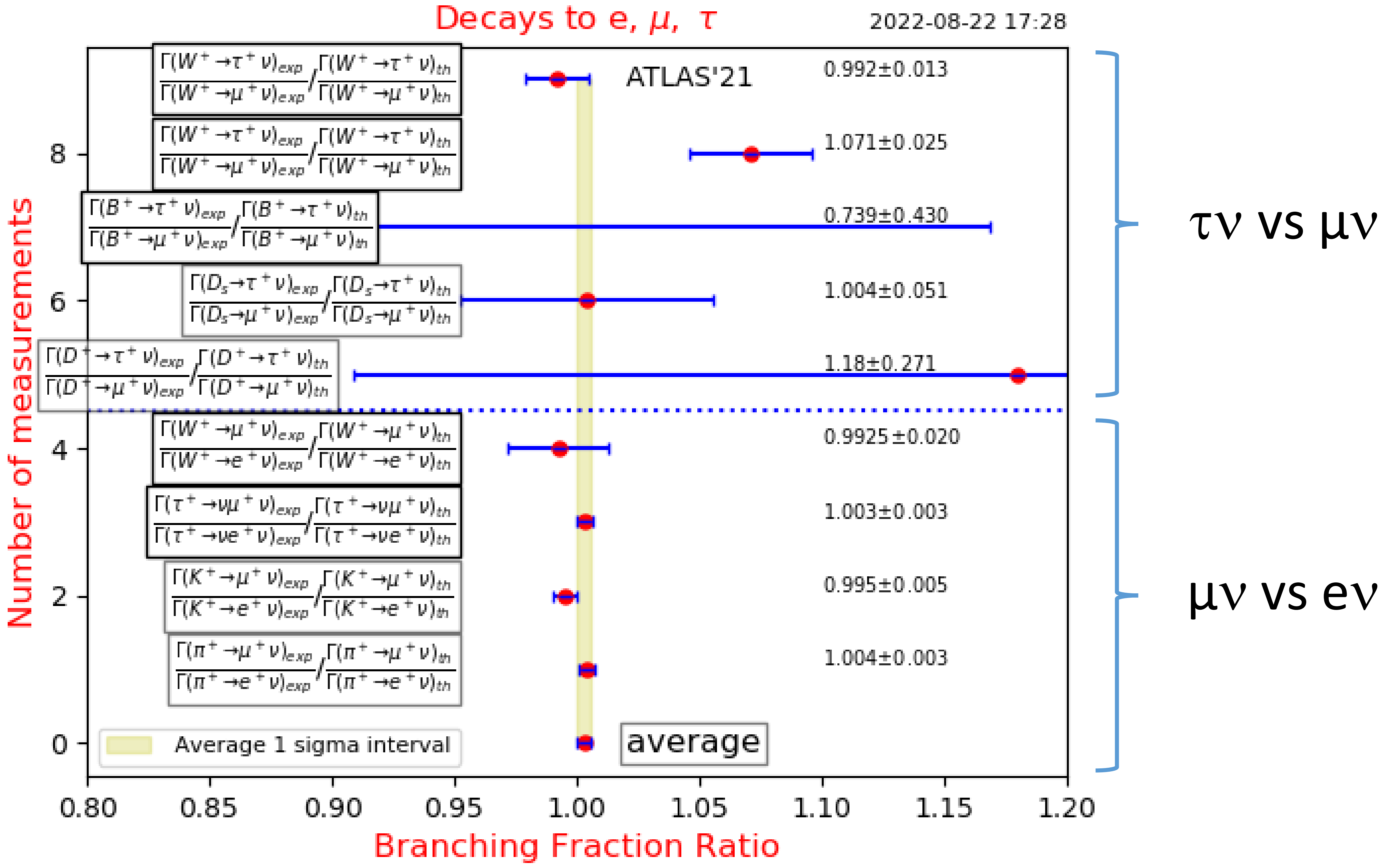
$$\Gamma(W \to \ell\nu_\ell) = \frac{G_F\sqrt{2}}{24\pi m_W} \times \kappa(m_W^2, m_\ell^2, m_{\nu_\ell}^2) \times G \times (1 + \Delta_r)$$

$$\Gamma(L \to \nu_L \ell \nu_\ell) = \frac{G_F m_\ell^5}{192\pi^3} \times [\zeta_0(\frac{m_\ell^2}{m_L^2}) + (\frac{\alpha}{\pi})\,\zeta_1(\frac{m_\ell^2}{m_L^2}) + (\frac{\alpha}{\pi})^2 \ldots]$$

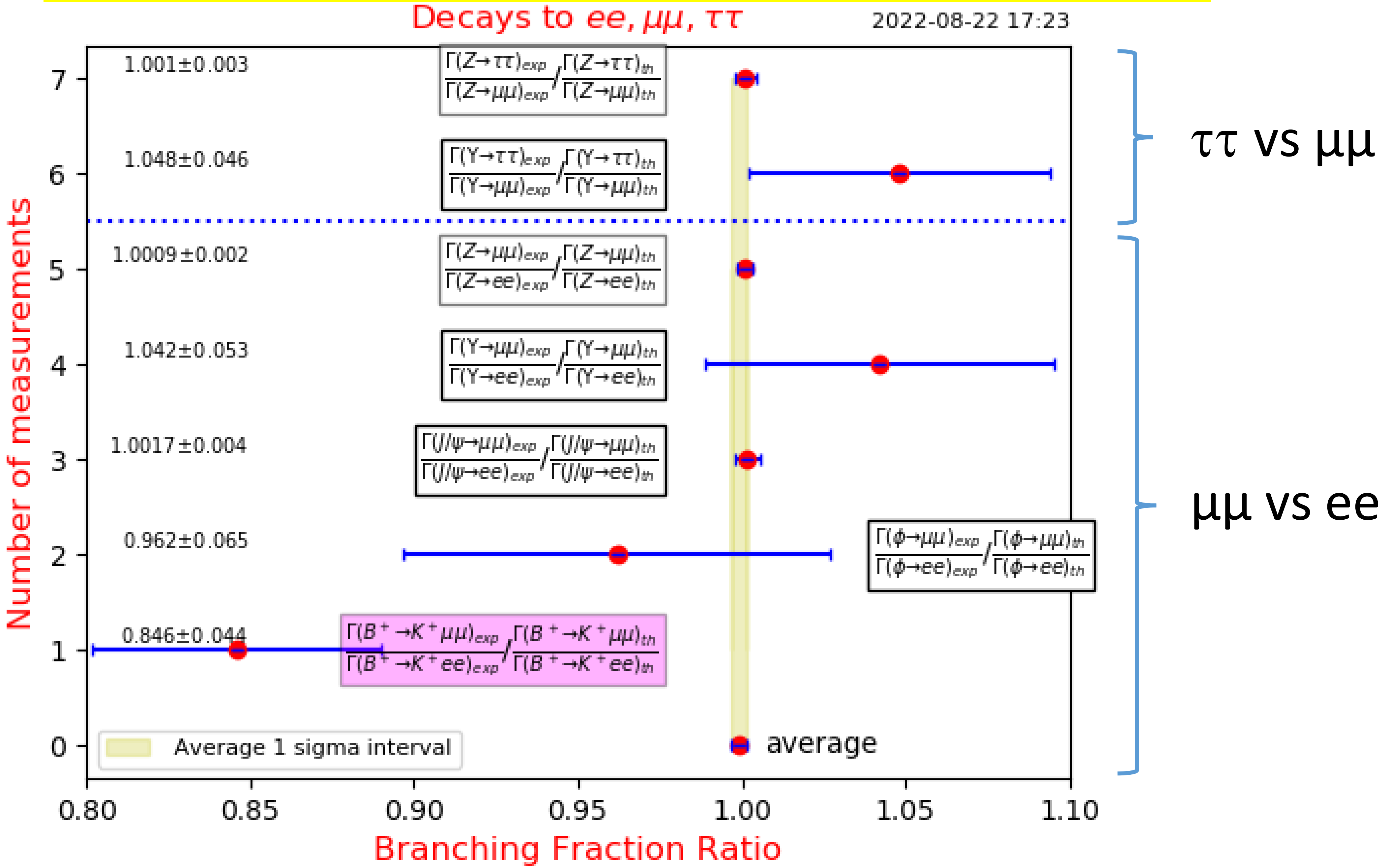
$$\Gamma(Z \to \ell^+\ell^-) = \frac{G_F m_Z^3}{6\pi\sqrt{2}} \sqrt{1 - 4z} \times [g_a^2(1 - 4z) + g_v^2(1 + 2z)] \times (1 + \Delta_r)$$

$$\Gamma(V \to \ell^+\ell^-) = \frac{4\pi}{3\alpha_{\mathrm{em}}} \frac{f_V^2}{m_V} \times q_q^2 \left(1 - \frac{4m_\ell^2}{m_V^2}\right)$$

Experimental situation in other leptonic decays

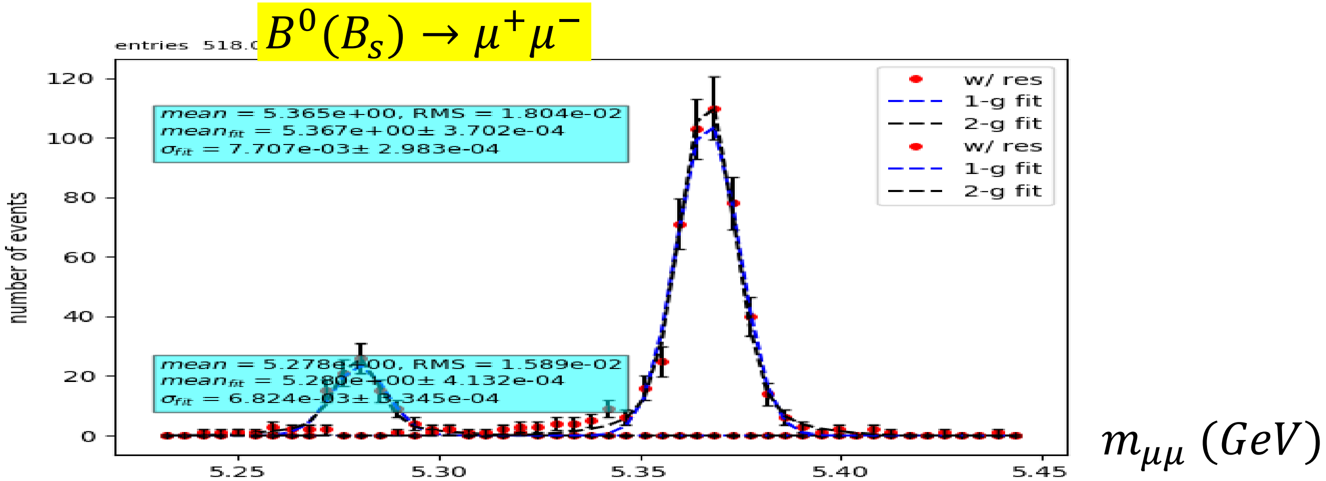


Experimental situation in other leptonic decays (cont'd)

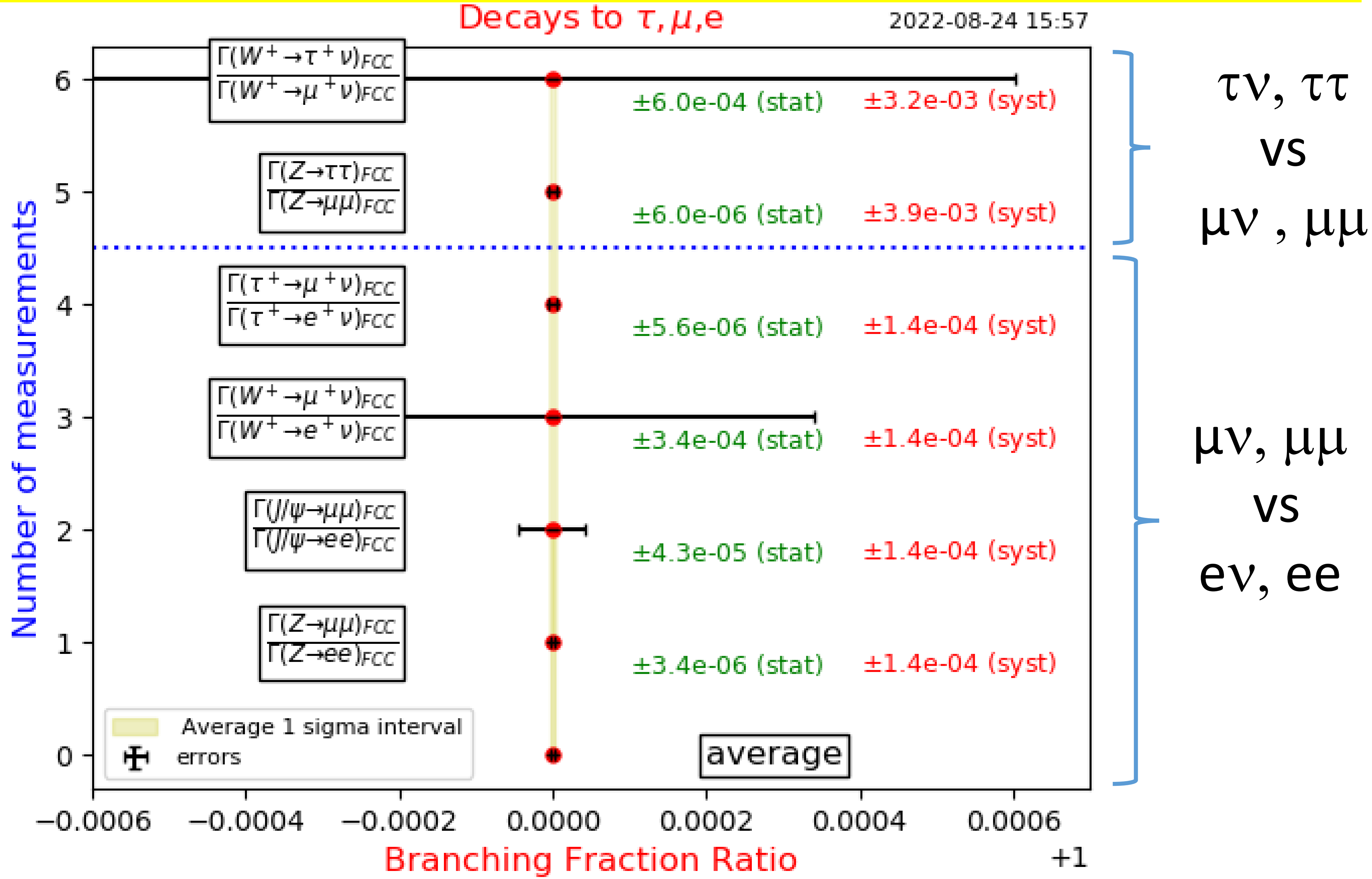


Large number of Z, W, τ , J/Ψ , B … are expected at FCCee

Particle type	E_{cm}	$\int \mathcal{L}dt\ (ab^{-1})$	# particles	$\sigma(m_{\mu\mu})$ MeV	$\sigma\left(m_{\mu\mu K^{*0}}\right)$ MeV
Z	91.2	150	$\sim 6 \cdot 10^{12}$	~ 140	n/a
$B^{\pm}, B^0\ (\bar{B}^0)$	91.2	150	$\sim 8 \cdot 10^{11}$	~7.5	~6.6
$B_s\ (\bar{B}_s)$	91.2	150	$\sim 2 \cdot 10^{11}$	~7.5	n/a
J/ψ	91.2	150	$\sim 2 \cdot 10^{10}$	~5.3	n/a
$\tau^{\pm}$	91.2	150	$\sim 4 \cdot 10^{11}$	n/a	n/a
$W^{\pm}$	161	10	$\sim 3 \cdot 10^{8}$	n/a	n/a



Anticipated statistical sensitivities for probing lepton universality at FCC

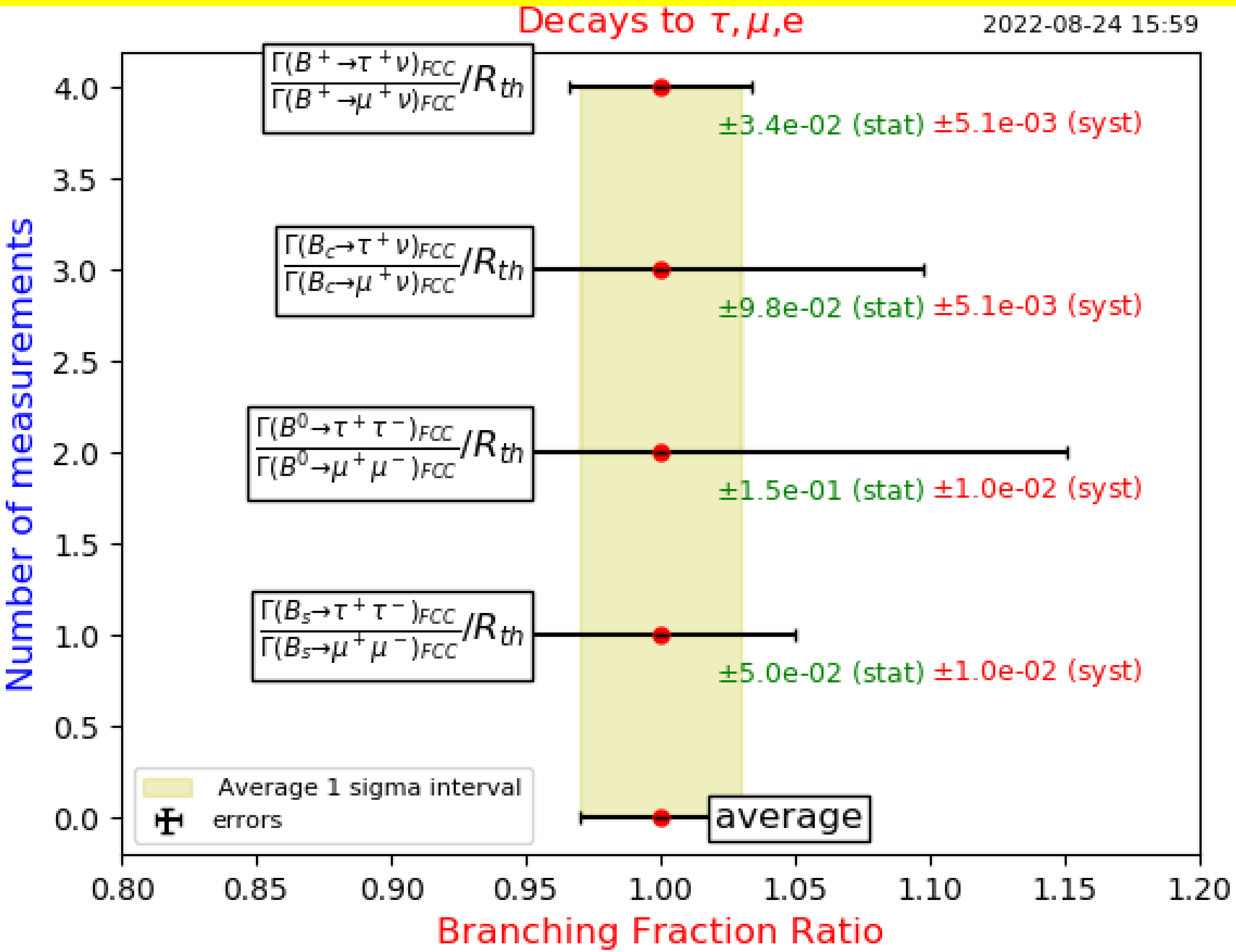


Statistical sensitivities are outstanding !

This raises very challenging obstacles for the systematics errors

- Theoretical errors
  - Calculation of ratios of BR
  - Calculation of the effect of the radiative corrections (ISR and FSR)
- Experimental systematics
  - For τ versus μ , need to improve the errors on the τ Branching fractions in particular the 3 prongs (will be the case at FCC but strong constraints on detector)
  - More difficult is to estimate the acceptance effects for the muons versus the electrons

Anticipated statistical sensivities for probing lepton universality at FCC



τν, ττ
vs
μν , μμ

Statistical sensitivities are at the several % level

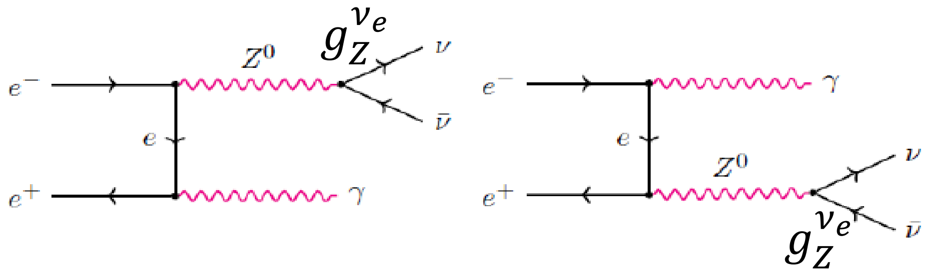
- Theoretical errors are less of a problem but should assess them
- Experimental systematics
  - For τ versus μ , need to improve the errors on the τ Branching fractions in particular the 3 prongs (will be the case at FCC)
  - Detector systematics should be manageable at the sub % level

Precision measurement of the Z boson to electron neutrino coupling at the future circular colliders*

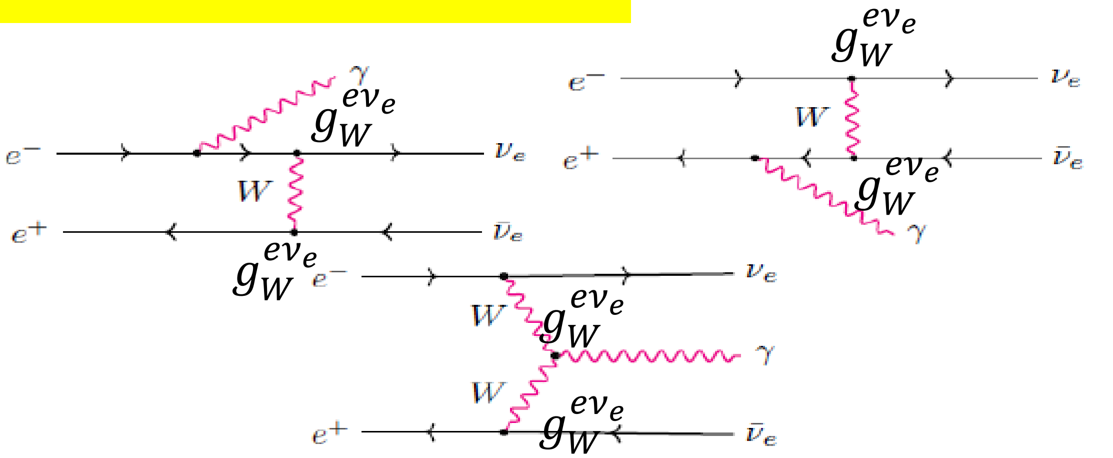
R.A. and S. Jadach

https://arxiv.org/abs/1908.06338
https://doi.org/10.1016/j.physletb.2019.135034

Idea is to look for interference with diagrams with measured couplings via the γ energy sprectrum



present $\delta(g_Z^{\nu_e}) = \pm 18\%$



Diagrams with Well known couplings $g_W^{e\nu_e} = 1$

- The method proposed would lead to a considerable improvement on the presicion on $g_Z^{\nu_e}$ at FCC

⇨ $\delta(g_Z^{\nu_e}) = \pm 1.2\%$ **with a excellent Xtal-type calorimètre** ($\frac{\delta E_\gamma}{E_\gamma} = \frac{0.03}{\sqrt{E_\gamma}} \oplus 0.005$)

Conclusions

FCC enables to probe lepton universality in a very large numbers of modes

- Potential sensitivities are outstanding
  - However it requires both important theoretical and experimental challenges in order to match the statistical uncertainties
- Should we observe a significant deviation, the multiplicity of mode would help understanding the origin of the underlying new physics

Additionnal slides

Detector response

➢ Modelisation of the detector response :

- Detailed description of tracks, accounting for multiple scattering

$$\text{Acceptance} :|\cos\theta| < 0.95$$

$$\text{Track p}_\text{T}\text{ resolution} : \frac{\sigma(p_T)}{p_T^2} = 2. \times 10^{-5} \oplus \frac{1.2 \times 10^{-3}}{p_T \sin\theta}$$

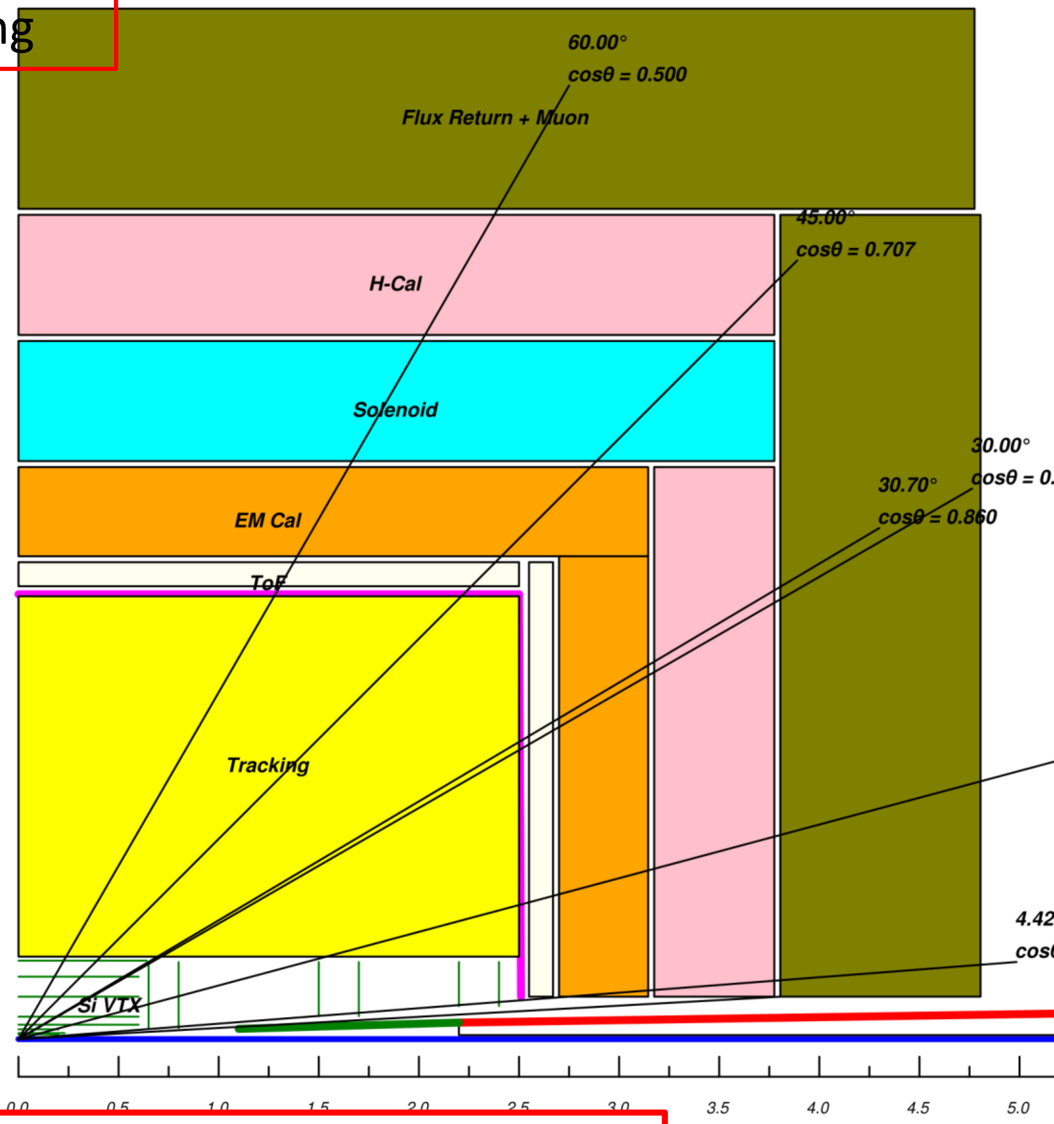
$$\text{Track } \phi, \theta \text{ resolution} : \sigma(\phi, \theta)\ \mu\text{rad} = 18 \oplus \frac{1.5 \times 10^{3}}{p_T \sqrt[3]{\sin\theta}}$$

$$\text{Vertex resolution} : \sigma(\text{d}_\text{Im})\ \mu\text{m} = 1.8 \oplus \frac{5.4 \times 10^{1}}{p_T \sqrt{\sin\theta}}$$

$$\text{Vertex resolution} : < \sigma(\text{d}_\text{Im}) > \text{bachelor K in } D_s K$$

$$< \sigma(\text{d}_\text{Im}) > \simeq 10\ \mu\text{m}$$

$$\text{Calorimeter resolution} : \frac{\sigma(E)}{E} = \frac{3 \times 10^{-2}}{\sqrt{E}} \oplus 5 \times 10^{-3}$$



➢ For vertexing Full MC events + response of the IDEA detector with DELPHES

- Genuine vertex fitting

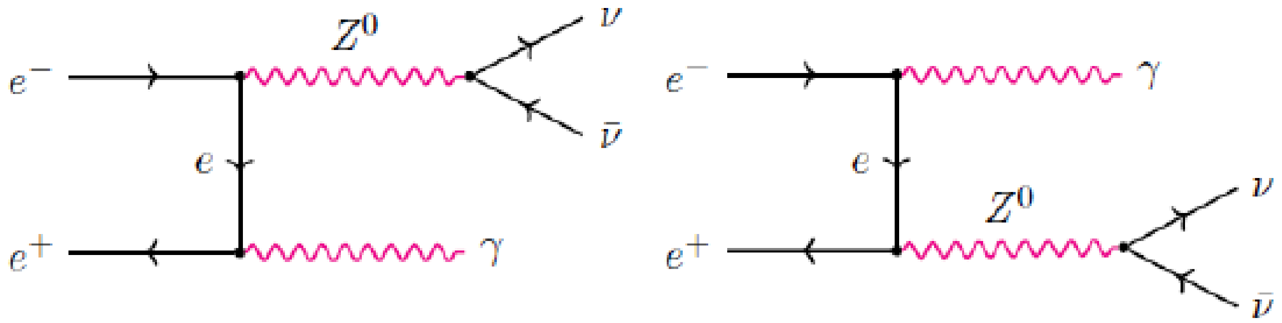
Precision measurement of the Z boson to electron neutrino coupling at the future circular colliders*

« …making the neutrino flavor visible in Z decays »

R.A. and S. Jadach

https://arxiv.org/abs/1908.06338

https://doi.org/10.1016/j.physletb.2019.135034



Neutrino counting measured at LEP with/without radiative γ :

Beam-beam effect correction

G. Voutsinas et al. , arXiv:1908.01704

Improved bhabha Xsection

P.Janot S.Jadach , arXiv:1912.02067

$$N_\nu = 2.9963 \pm 0.0074$$

$$\sigma(e^+e^- \to Z \to \text{invisible}) = (g_Z^{\nu_e} \mathcal{A}_Z^{\nu_e})^2 + (g_Z^{\nu_\mu} \mathcal{A}_Z^{\nu_\mu})^2 + (g_Z^{\nu_\tau} \mathcal{A}_Z^{\nu_\tau})^2 + (g_Z^{X} \mathcal{A}_Z^{X})^2$$

However NO distinction between neutrino flavor

$g_Z^{\nu_e}$ poorly measured

PDG
$$g_Z^{\nu_e} = 1.06 \pm 0.18$$
$$g_Z^{\nu_\mu} = 1.004 \pm 0.034$$

From ν_μ e and ν_e e scattering

$g_Z^{\nu_\tau}$ = ?

Can one do better at FCC-ee? → Test lepton universality in neutrino sector

In the following we assume $N_{inv} \equiv 3\,\nu$ since it will be measured at FCC with negligible error

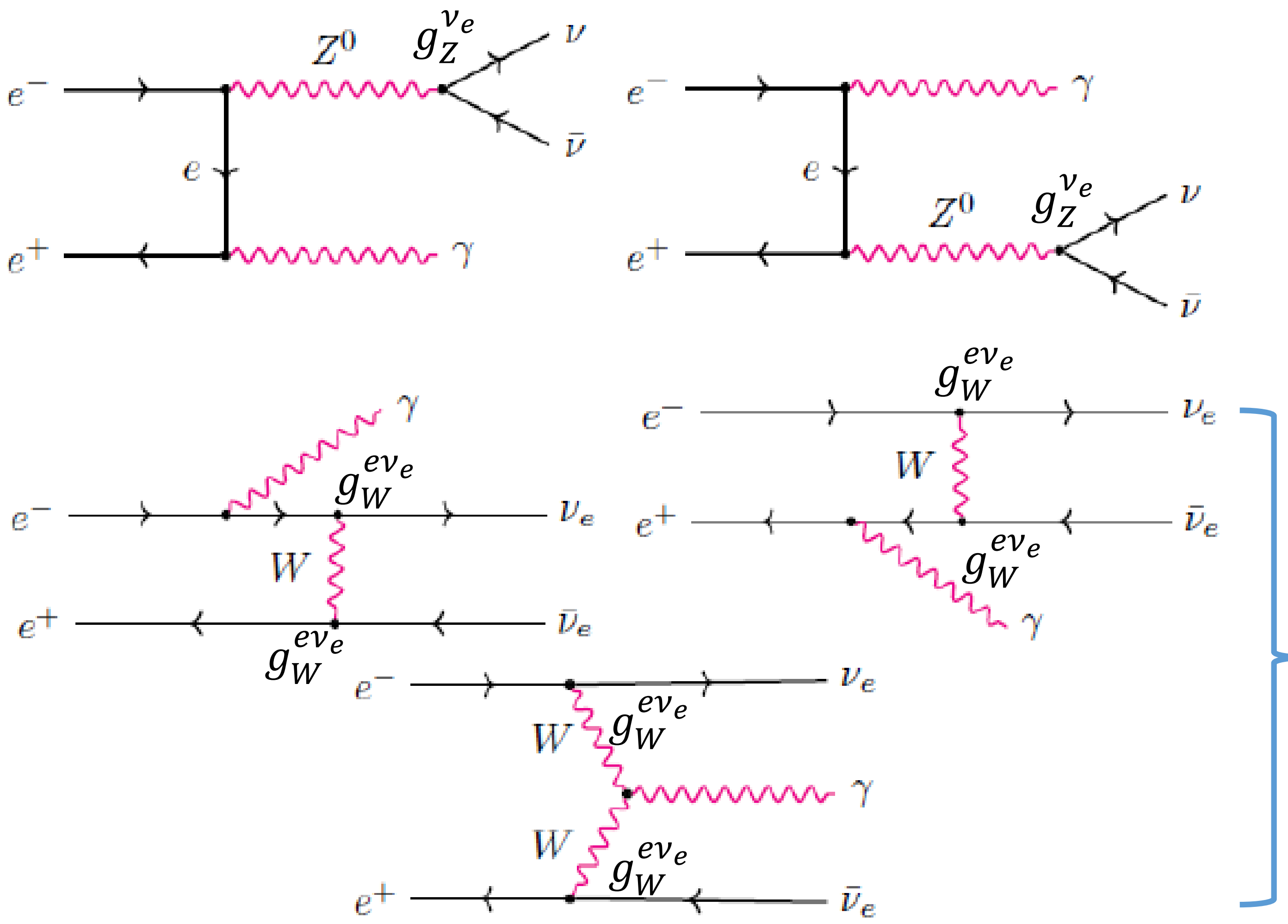
$$N_\nu \equiv (g_Z^{\nu_e})^2 + (g_Z^{\nu_\mu})^2 + (g_Z^{\nu_\tau})^2$$

We introduce the parameter η such as $g_Z^{\nu_e} = \sqrt{1+\eta}\,,\; g_Z^{\nu_\mu} = 1\,,\; g_Z^{\nu_\tau} = \sqrt{1-\eta}$

This preserves $N_{invisible} \equiv 3\,\nu$ in Z width

In Standard Model $\eta = 0$ (lepton universality)

Idea is to look for interference with diagrams with well known couplings

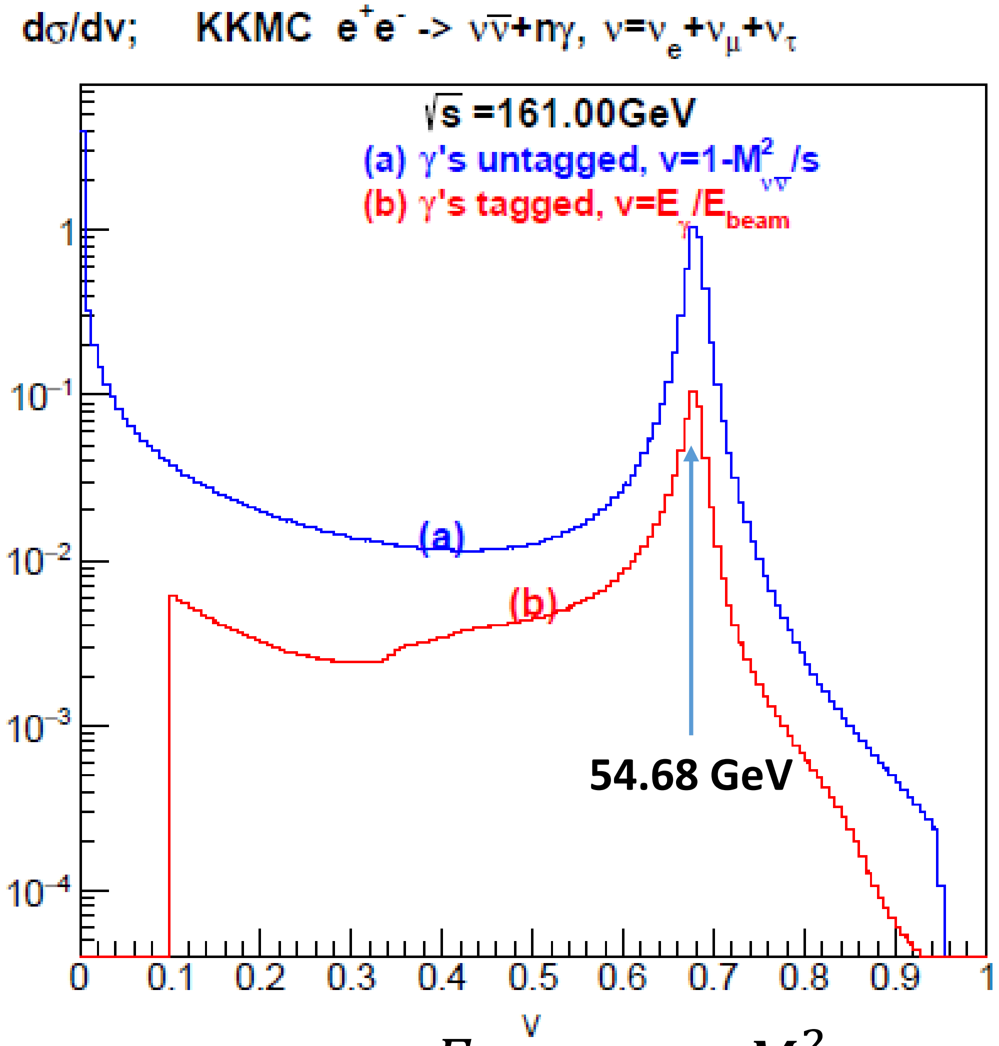


Diagrams with Well known couplings

$$g_W^{e\nu_e} = 1$$

Only ν_e interfere ⇨ interference effect measures $g_Z^{\nu_e}$ but HUGE statistics needed **⇨FCCee**

We concentrate on $\sqrt{S} = 161\ GeV$ with L=10 ab^{-1} (i.e. with 2 detectors)
MC used KKMC (see Staszek Jadach et al.)

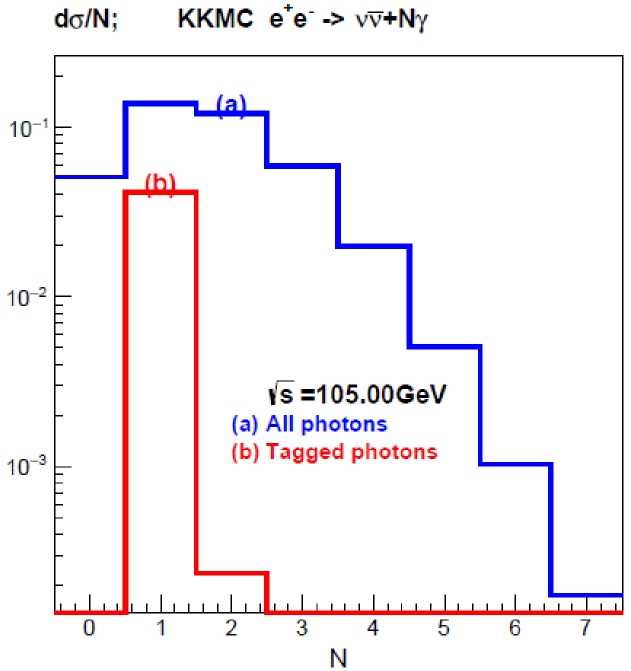


$$\mathcal{V} = \frac{E_\gamma}{E_{beam}} \approx 1 - \frac{M^2_{\nu\bar{\nu}}}{s}$$

Cuts for **(b)** curve

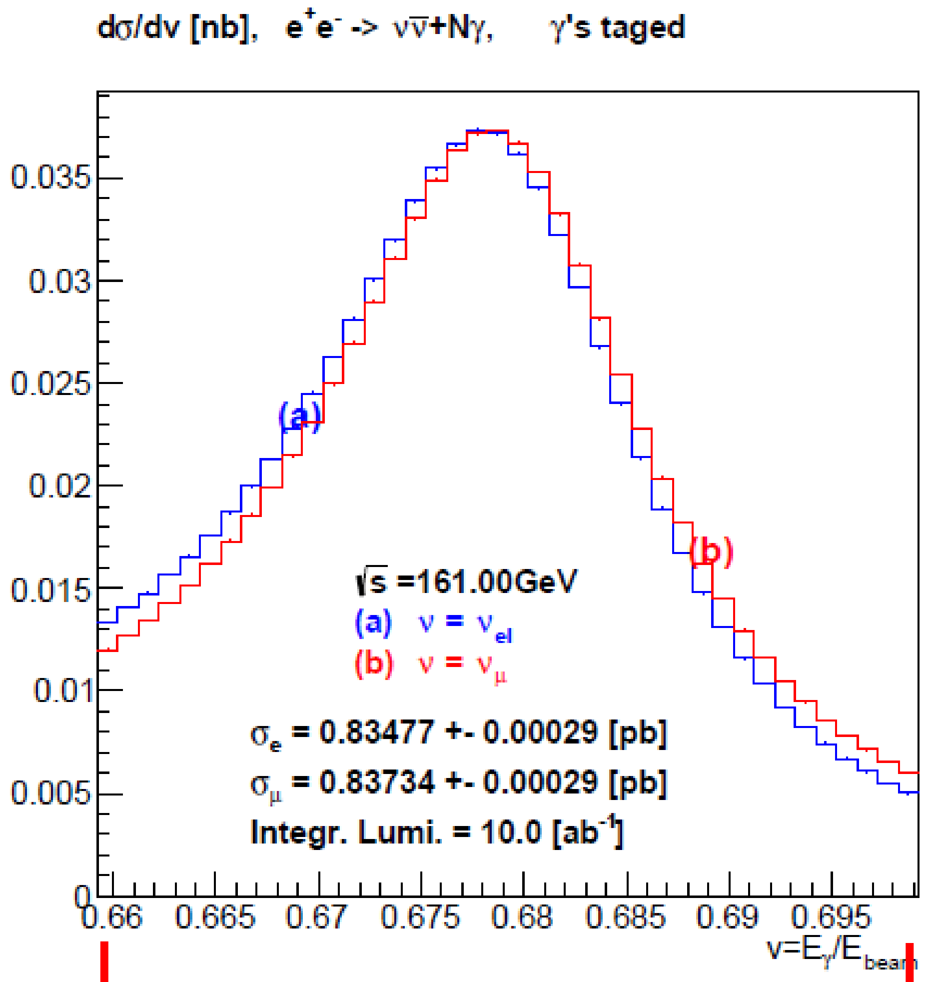
$$\sum E_\gamma > 0.1 E_{beam}$$
$$\theta_\gamma > 15°$$
$$E_{T\gamma} > 0.02\ E_{beam}$$

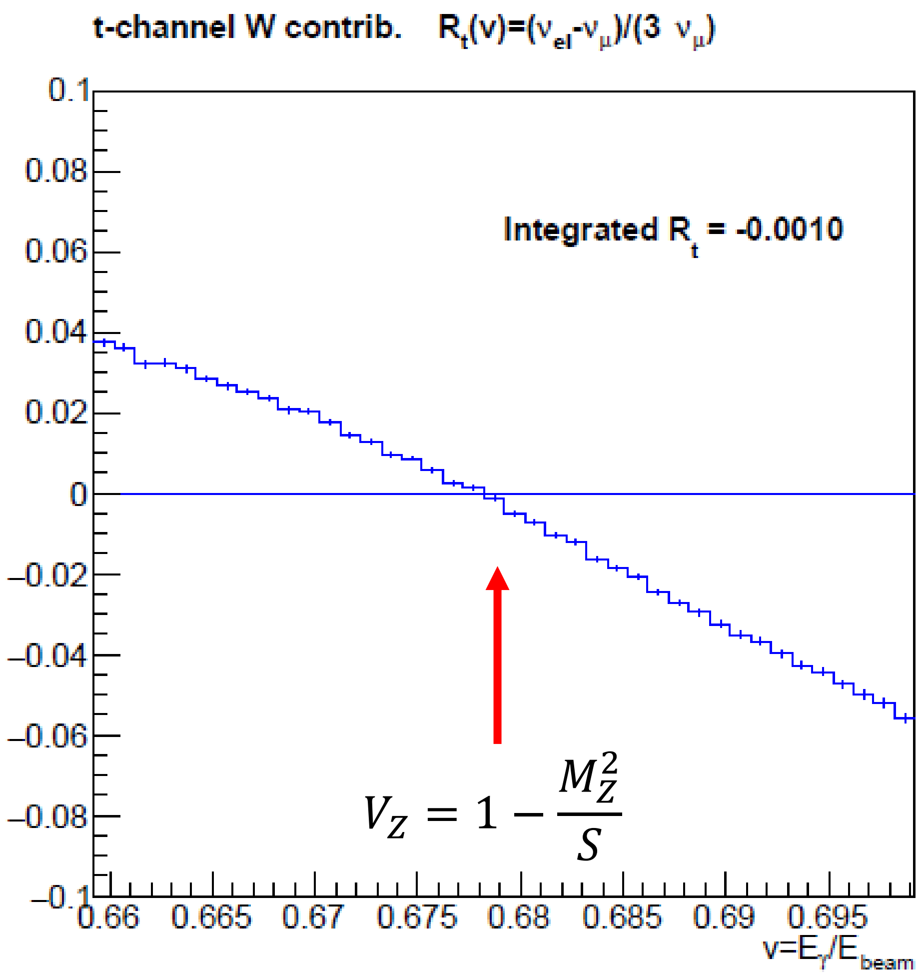
Essentially 1 γ after cuts



Zoom on Z Radiative Return (ZRR)

Difference between $\nu_{\mu(\tau)}$ and ν_e





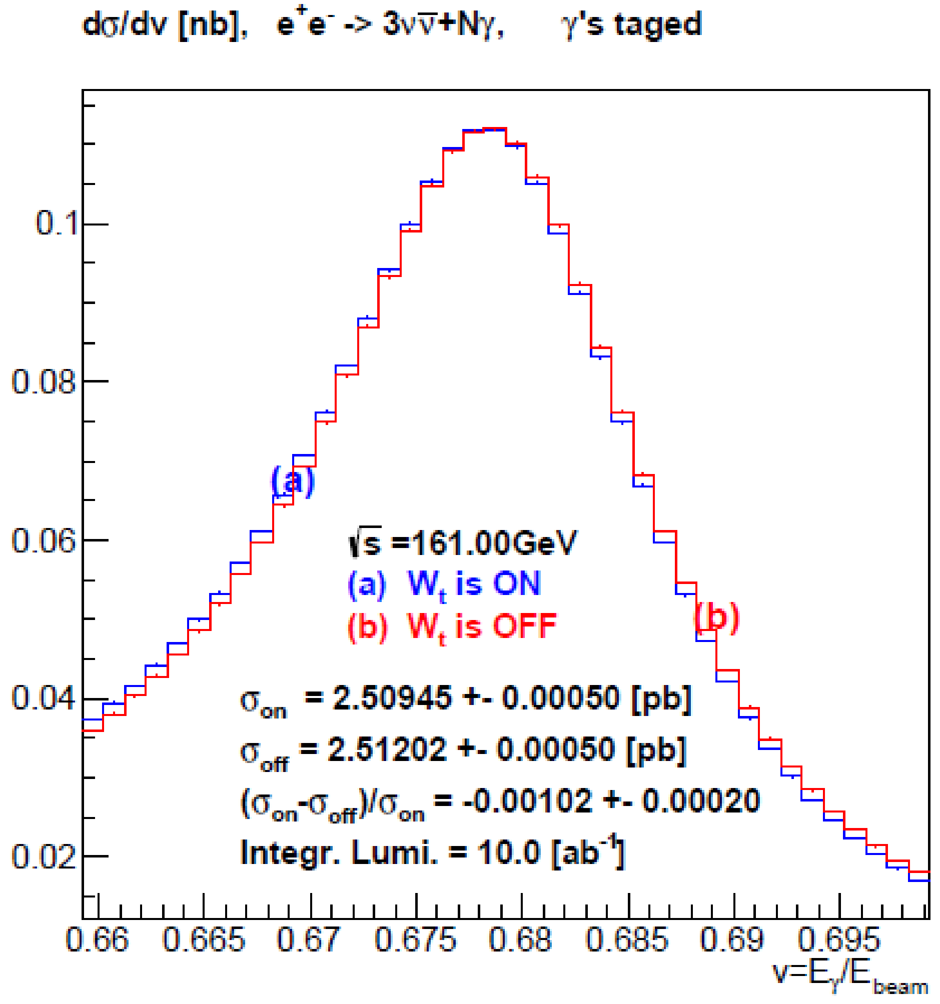
$$V_Z = 1 - \frac{M_Z^2}{S}$$

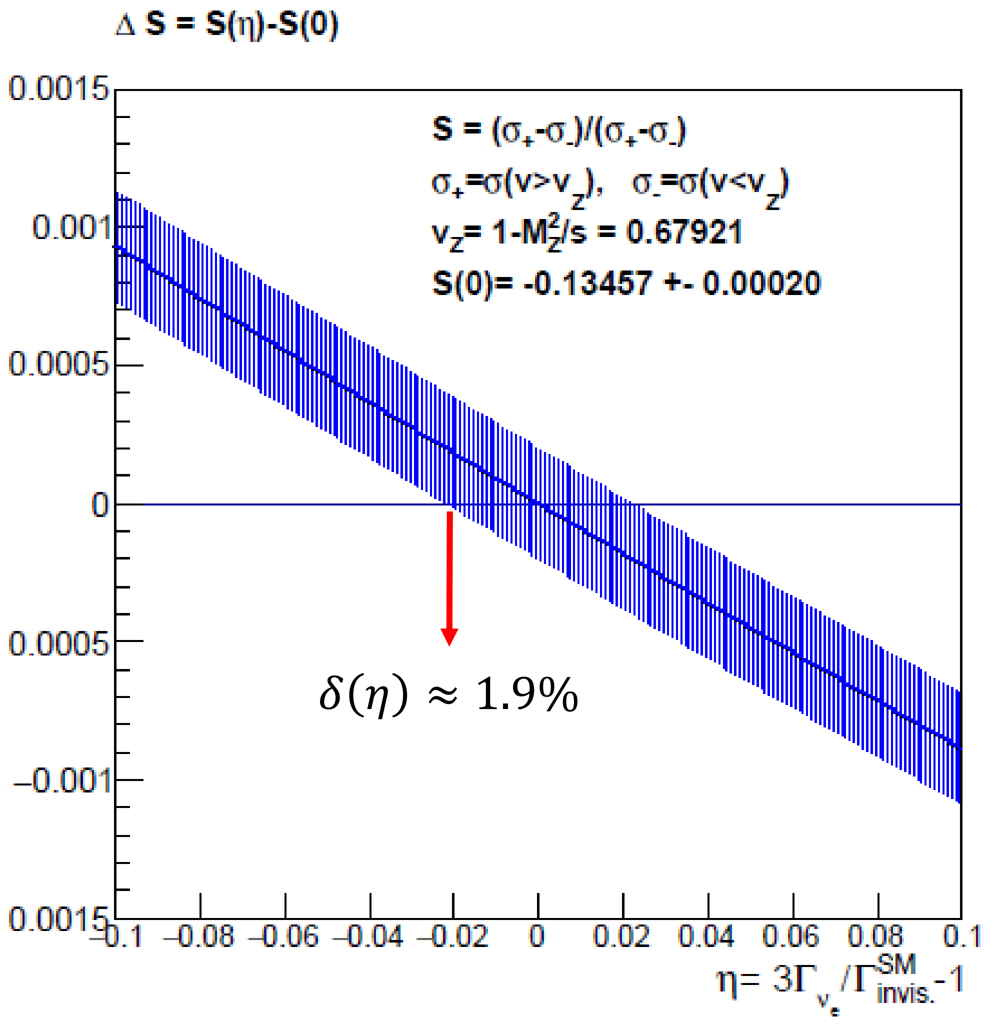
$E_\gamma = 53.13\ GeV$ ⟷ $E_\gamma = 56.35\ GeV$

Interference effects may look small but
Huge statistics is available ~25 x 10^6 events

For simplicity let's define the Asymmetry $S = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$

with $\sigma_+ = \sigma(v>v_z)$, $\sigma_- = \sigma(v<v_z)$

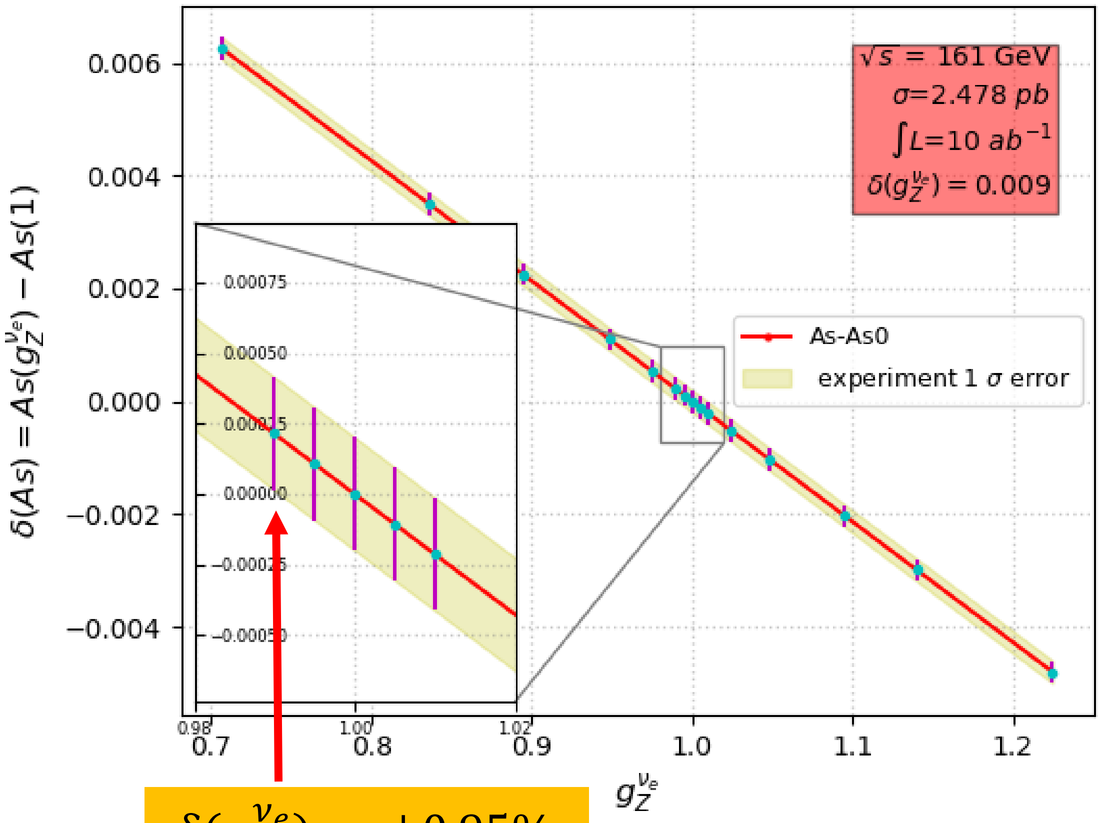




MC can be checked with μμγ events, although
not exactly same diagrams involved

Error on $g_Z^{\nu_e}$

Without detector resolution dilution effects

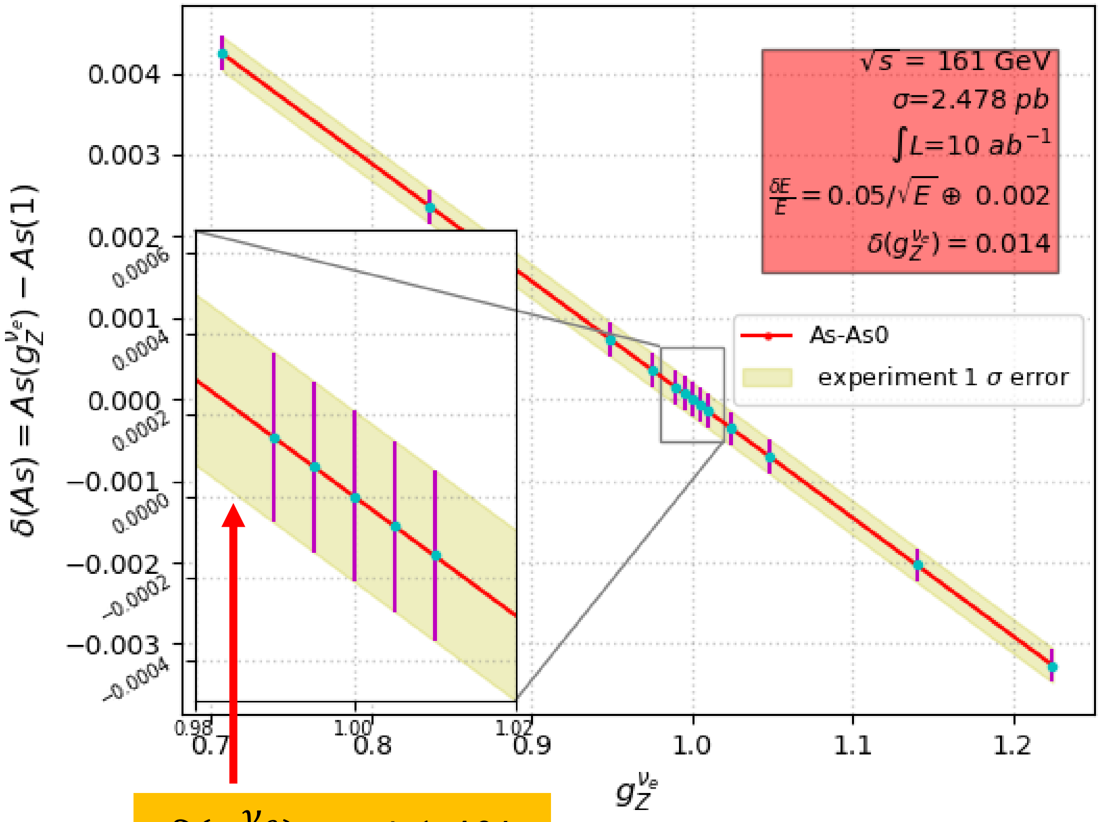


$\delta(g_Z^{\nu_e}) = \pm 0.95\%$

With detector resolution dilution effects

$$\frac{\delta E_\gamma}{E_\gamma} = \frac{\mathbf{0.05}}{\sqrt{E_\gamma}} \oplus 0.005$$

Can be calibrated with μμγ events



$\delta(g_Z^{\nu_e}) = \pm 1.4\%$

If stochastic term =**3%** (Excel. Xtal detector) ⇨	$\delta(g_Z^{\nu_e}) = \pm 1.2\%$
If stochastic term =**7%** (sampling detector) ⇨	$\delta(g_Z^{\nu_e}) = \pm 1.8\%$
If stochastic term =**10%** (sampling detector) ⇨	$\delta(g_Z^{\nu_e}) = \pm 2.4\%$

Xtal-type calorimeter is highly desired

Caveat : Study of the optimal range of E_γ is to be done to optimize the sensitivity. However general conclusion for calorimeter is likely to be the same

Summary

- The method proposed would lead to a considerable improvement on the presicion on $g_Z^{\nu_e}$

  ⇨ $\boldsymbol{\delta(g_Z^{\nu_e}) = \pm 1.2\%}$ **with a excellent Xtal-type calorimètre** $\left(\frac{\delta E_\gamma}{E_\gamma} = \frac{\mathbf{0.03}}{\sqrt{E_\gamma}} \oplus 0.005\right)$

- Assuming 3 ν and no new physics coupled to Z, one would derive

  ⇨ $\boldsymbol{\delta(g_Z^{\nu_\tau}) = \pm 4.6\%}$ (limited by resolution on $g_Z^{\nu_\mu}$)

- $\sqrt{S} = 161\ GeV$ may not be optimal (but we will run there anyway), e.g. 6 months at $\sqrt{S} = 105\ GeV \equiv 13\ ab^{-1}$ would potentially allow for ~ twice smaller errors. Optimization of C.o.M. energy to be done.