Rare Z decays and neutrino flavour universality

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10^{12} Z's!

The FCC-ee would produce around 10^{12} Z's, and probe the SM in unprecedented ways! [1308.6176]

E.g. test flavour universality of $Z\nu\nu$ couplings which could be affected by $\tilde{Z}$ or $\tilde{\nu}$ mixing.

(Explicit model building not addressed here.)

As rare decays like

$$Z \to l\nu jj$$
$$Z \to ll'\nu\nu'$$
$$Z \to ll\nu\nu$$

- have sensitivity to individual $Z\nu\nu$ couplings,
- are accessible, with Br $\sim 10^{-8}$,
- feature large destructive interferences.

The same final states, with displaced vertex or boosted sub-system, are produced by sterile neutrinos. [1411.5230]

Phenomenological parametrization

Assume new physics only rescales $Z\nu\nu$ couplings

by real C_{ν_e}, C_{ν_μ}, C_{ν_τ} factors.

Check this hypothesis with many different processes:

- Neutrino *counting* at the Z pole: Γ_{inv}
  $e^+e^- \to \gamma\nu\nu$
- Charged lepton flavour universality: $Z \to ll$
- Neutrino scattering at low energy: $\nu_l e^- \to \nu_l e^-$
  $\nu_l N \to \nu_l + X$
  $\nu_l N \to l + X$
- Neutrino oscillations: $\nu_l \rightsquigarrow \nu_{l'}$
- Rare Z decays: $Z \to l\nu jj$
  $Z \to ll'\nu\nu'$
  $Z \to ll\nu\nu$

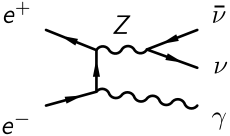
Existing constraints (I)

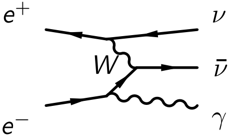
Neutrino *counting*

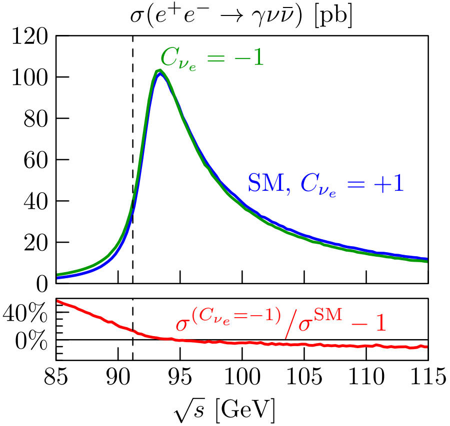
$\Gamma_{\rm inv} \cdot N_\nu = C_{\nu_e}^2 + C_{\nu_\mu}^2 + C_{\nu_\tau}^2 = 2.984 \pm 0.008$ [LEP '05]

$e^+e^- \to \gamma\nu\bar{\nu} \cdot N_\nu = C_{\nu_e}^2 + C_{\nu_\mu}^2 + C_{\nu_\tau}^2 \simeq 2.92 \pm 0.05$ [PDG]

$\cdot\ C_{\nu_e} > 0$







LO with MadGraph, $E_\gamma > 1$ GeV, $45^\circ < \theta_\gamma < 135^\circ$

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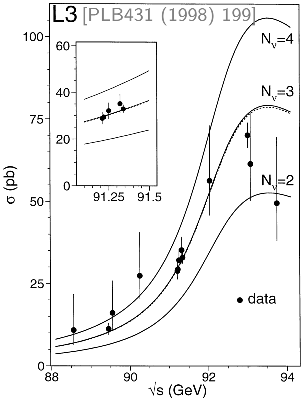
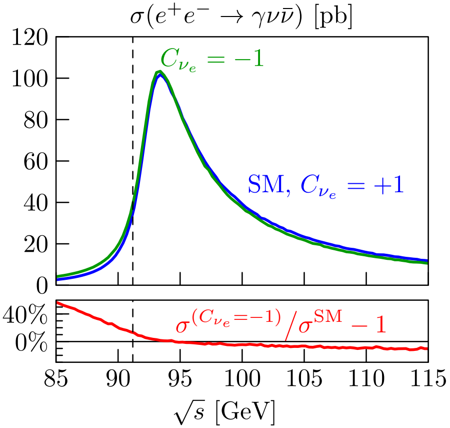




LO with MadGraph, $E_\gamma > 1$ GeV, $45^\circ < \theta_\gamma < 135^\circ$

Existing constraints (II)

Charged lepton flavour universality

estimate, without full gauge-invariant model:

$$\delta\Gamma(Z \to ll) \simeq g(C_{\nu_l} - 1)/16\pi^2 \lesssim 10^{-3} \quad \longrightarrow \quad 0.90 \lesssim C_{\nu_l} \lesssim 1.10$$

Neutrino scattering at low energy

$$\nu_\mu e^- \to \nu_\mu e^- \to |C_{\nu_\mu}| = 1.004 \pm 0.033$$ [CHARM II '94]

$$\nu_e e^- \to \nu_e e^- \to C_{\nu_e} = 0.92 \pm 0.28$$ [LAMPF '93]

$$\frac{\nu_\mu N \to \nu_\mu X}{\nu_e N \to \nu_e X} \to |C_{\nu_e}/C_{\nu_\mu}| = 1.05^{+0.15}_{-0.18}$$ [CHARM '86]

$$\ldots$$ [LSND '01] [NuTeV '01]

$$\text{global fits} \to \begin{cases} 0.94 < C_{\nu_e} < 1.07 \\ 0.99 < |C_{\nu_\mu}| < 1.01 \end{cases} \quad (90\%\text{CL})$$ [Davidson et al '03] [Forero et al '11]

Neutrino oscillations

help constraining the flavour off-diagonal couplings

(not considered here)

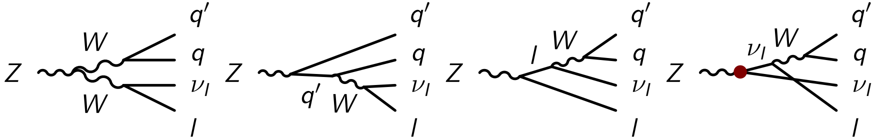
Rare Z decays (I)

Accessible rates

$$\Gamma^{\rm SM}(Z \to l\nu_l qq') \simeq 6.4 \times 10^{-8}\ \text{GeV}$$
$$\Gamma^{\rm SM}(Z \to ll'\nu_l\nu_{l'}) \simeq 1.4 \times 10^{-8}\ \text{GeV}$$
$$\Gamma^{\rm SM}(Z \to ll\nu_l\nu_l) \simeq 2.3 \times 10^{-8}\ \text{GeV}$$

No sum over l,l',q,q' flavours, or over conjugate processes.

Large destructive interferences



e.g. $\Gamma(Z \to e^- \bar{\nu}_e\, u\bar{d}) = (8.2 - 10\,C_{\nu_l} + 8.7\,C_{\nu_l}^2) \times 10^{-8}\,\text{GeV}$

Note the NWA for one W doesn't work.

- sign flip $\to$ 4-fold increase in rate!
- $\left.\dfrac{1}{\Gamma}\dfrac{\mathrm{d}\Gamma}{\mathrm{d}C}\right|_{C=1} \simeq 1.1$!

$\Longrightarrow$ resolve C_{ν_μ} and C_{ν_τ} signs

$\Longrightarrow$ bring the precision on C_{ν_e} and C_{ν_τ} to the percent level

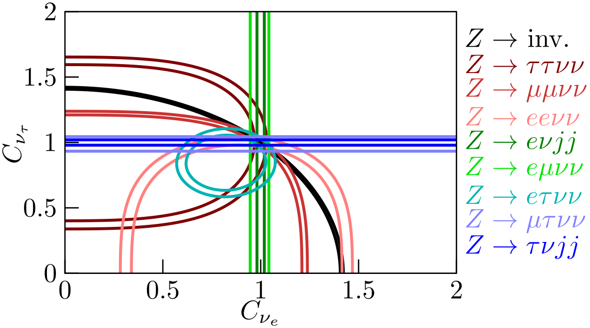
Rare Z decays (II)

$$\frac{\Gamma(Z \to l\,\nu_l q q')}{10^{-8}\ \text{GeV}} \simeq \begin{cases} 8.2 - 10C_{\nu_l} + 8.7C_{\nu_l}^2 & \text{for } l = e, \mu \\ 8.1 - 9.9C_{\nu_l} + 8.0C_{\nu_l}^2 & \text{for } l = \tau \end{cases}$$

$$\frac{\Gamma(Z \to l\,l'\nu_l\nu_{l'})}{10^{-8}\ \text{GeV}} \simeq \begin{cases} 2.8 - 2.3(C_{\nu_l} + C_{\nu_{l'}}) - 0.085C_{\nu_l}C_{\nu_{l'}} + 1.5(C_{\nu_l}^2 + C_{\nu_{l'}}^2) & \text{for } l = e, \quad l' = \mu \\ 2.7 - 2.4C_{\nu_l} - 2.3C_{\nu_{l'}} - 0.080C_{\nu_l}C_{\nu_{l'}} + 1.5C_{\nu_l}^2 + 1.4C_{\nu_{l'}}^2 & \text{for } l = e, \mu, \quad l' = \tau \end{cases}$$

$$\frac{\Gamma(Z \to l\,l\,\nu\bar{\nu})}{10^{-8}\ \text{GeV}} \simeq \begin{cases} 2.8 - 4.3C_{\nu_l} + 3.2C_{\nu_l}^2 - 1.3C_{\nu_l}^3 + \sum_{\alpha=e,\mu,\tau}\left(0.077C_{\nu_\alpha}^2 + 0.27C_{\nu_\alpha}^3 + 0.33C_{\nu_\alpha}^4\right) & \text{for } l = e, \mu \\ 2.7 - 4.0C_{\nu_l} + 3.0C_{\nu_l}^2 - 1.4C_{\nu_l}^3 + \sum_{\alpha=e,\mu,\tau}\left(0.076C_{\nu_\alpha}^2 + 0.26C_{\nu_\alpha}^3 + 0.31C_{\nu_\alpha}^4\right) & \text{for } l = \tau \end{cases}$$

- marginalizing over (90%CL) $0.99 < C_{\nu_\mu} < 1.01$, with sign resolved
- assuming (90%CL) $2.998 < N_\nu < 3.002$
- assuming (90%CL) $0.98 < \Gamma/\Gamma^{SM} < 1.02$
- showing only the branches containing the SM point



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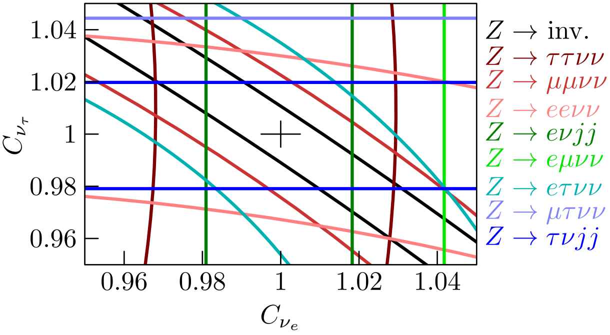
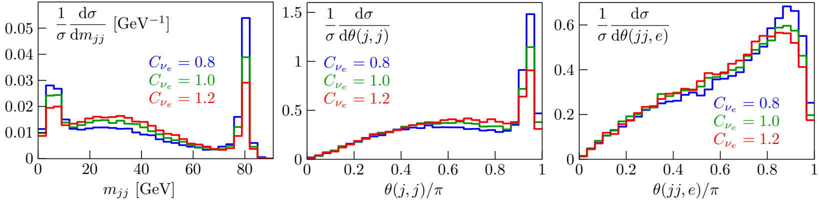


Rare Z decays (III)

Further gain in sensitivity from differential distributions
given 10^4 expected yield

e.g. $\Gamma(Z \to e^- \bar{\nu}_e \, u\bar{d})$:



with $m_{jj} \in [15, 75]$ GeV cut:

$$\left.\frac{1}{\Gamma}\frac{d\Gamma}{dC}\right|_{C=1} \simeq 1.1 \quad \text{inclusive} \quad \longrightarrow \quad 1.9$$

or, better, $\Gamma|_{m_{jj} \in [15,75]\ \text{GeV}} - \Gamma|_{m_{jj} \notin [15,75]\ \text{GeV}}$
or, ...

Rare Z decays and neutrino flavour universality

Huge samples
make rare Z decays accessible.

Four-body channels
give access to individual $Z\nu_l\nu_l$ couplings
with sensitivities $\gtrsim 1$ and large destructive interferences.

Unambiguous sign determination and percent-level precision
could be achieved for all three couplings.

Backup

Full $e^+e^- \to l\nu qq'$ process

- Z s-channel only

$$\sigma(e^+e^- \to Z \to u\bar{d}\mu^-\bar{\nu}_\mu)\ [\text{fb}] \simeq 0.72 - 1.15\,C_{\nu_\mu} + 1.04\,C^2_{\nu_\mu}$$

$$\longrightarrow \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}C}\bigg|_{C=1} \simeq 1.51$$

- γ s-channel and WW contamination

$$\sigma(e^+e^- \to u\bar{d}\mu^-\bar{\nu}_\mu)\ [\text{fb}] \simeq 0.75 - 1.15\,C_{\nu_\mu} + 1.04\,C^2_{\nu_\mu}$$

$$\longrightarrow \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}C}\bigg|_{C=1} \simeq 1.45$$

- t-channels contributions, for an electron in the final state

$$\sigma(e^+e^- \to u\bar{d}e^-\bar{\nu}_e)\ [\text{fb}] \simeq 1.70 - 1.15\,C_{\nu_e} + 1.04\,C^2_{\nu_e}$$

$$\longrightarrow \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}C}\bigg|_{C=1} \simeq 0.59$$

MadGraph LO, $E_{j,l} > 5$ GeV, $\Delta R_{jj,jl} > 0.2$, $|\eta_{j,l}| < 5$