Sterile Neutrinos at Future Lepton Colliders

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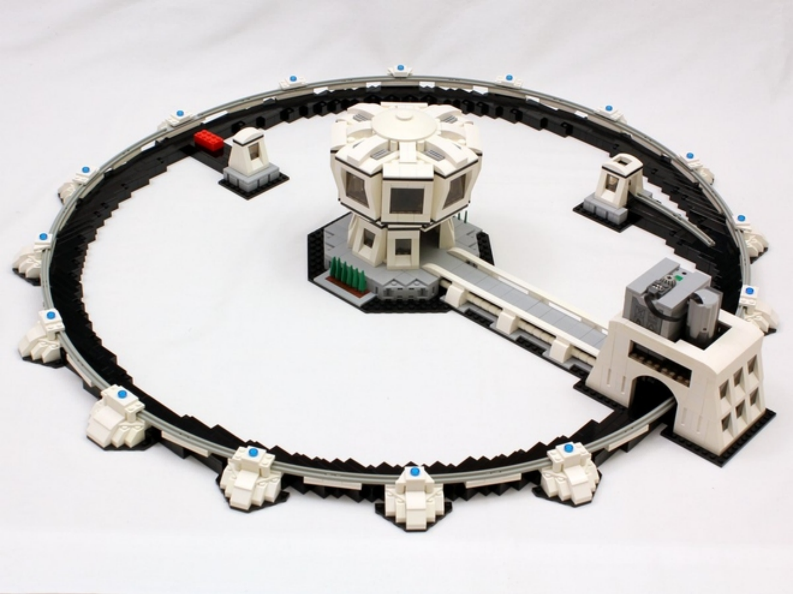
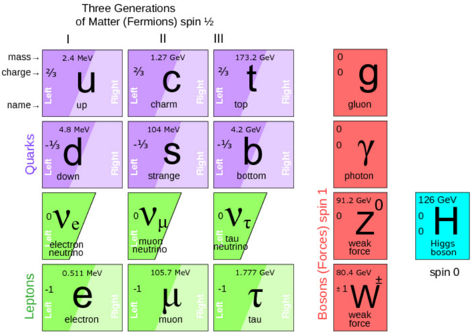
Lego Particle Accelerator



Motivation for Sterile Neutrinos

- Neutrino oscillations require *at least* two massive light/active SM neutrinos.
- This demands an extension of the SM.
- We consider the addition of right-handed fermion singlets – "sterile neutrinos" (N_i).
- Interesting scenario: Symmetry protected seesaw.



Courtesy Marco Drewes

Sterile Neutrinos

Incomplete author list:

Abada, Abazajian, Acero, Adhikari, Agarwalla, Aguilar-Arevalo, Aguilar-Saavedra, Akhmedov, Albright, Antusch, Aoki, Arguelles-Balantekin, Asaka, Atre, Basso, Biggio, Blanchet, Blondel, Blum, Bonivento, Bonnet, Borah, Boyanovsky, Boyarsky, Cely, Chen, Cheung, Das, delAguilar, DeRomeri, Dev, Dijkstra, Drewes, Egede, Fan, Ferro-Luzzi, Franceschini, Gariazzo, Gavela, Giunti, Goddard, Golutvin, Gorbunov, Gorbunov, Graverini, Hall, Hambye, Han, He, Hernandez, Hernandez, Hoang, Hung, Ibarra, Jacobsson, Kamat, Kanemura, Kartavtsev, King, Kopp, Laveder, Lello, Lindner, Ma, Merle, Michaels, Mohapatra, Molinaro, Monteil, Murakami, Murase, Nemevsek, Okada, Orloff, Panman, Pascoli, Petcov, Pinner, Pittau, Reece, Rodejohann, Schwetz-Mangold, Serra, Seto, Shaposhnikov, Smirnov, Sun, Tait, Tandean, Teixeira, Tenchini, Timiryasov, Tsai, van der Bij, Vicente, Wang, Weiland, Yanagida, Zhang, ...

... and others.

Appologies to those who are not on the list!

How to Test Sterile Neutrinos

- Sterile Neutrino Mass (M) $>$ Electroweak scale (Λ_{EW}):
  - Indirect effect on precision observables.
  - $\Rightarrow$ Presented at the 8th FCC-ee workshop in Paris.
- $M \sim \Lambda_{\mathrm{EW}}$:
  - Indirect effect on low energy precision observables and modified effect on EWPO.
  - N decays at the Z pole.
  - N decay to leptonic final states at and beyond the WW threshold.
  - Higgs boson branching ratios.
- This talk:
  (i) Two Sterile neutrinos with masses $\sim \Lambda_{\mathrm{EW}}/$ TeV scale.
  (ii) Present bounds from precision data and direct searches.
  (iii) Sensitivities of the FCC-ee (ILC and CEPC in the Backup).

Low Scale Seesaw Scenario

with two sterile neutrinos N_i and protective symmetry

$$\mathscr{L}_N = -\frac{1}{2}\overline{N_R^I} M_{IJ}^N (N_R^J)^c - y_\alpha \overline{N_R^I} \widetilde{\phi}^\dagger L^\alpha + \text{H.c.}$$

- The leptonic mixing matrix to leading order in the active-sterile mixing parameters:

$$\mathcal{U} = \begin{pmatrix} \mathcal{N}_{1e} & \mathcal{N}_{1\mu} & \mathcal{N}_{1\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{2e} & \mathcal{N}_{2\mu} & \mathcal{N}_{2\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{3e} & \mathcal{N}_{3\mu} & \mathcal{N}_{3\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau & \frac{1}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{\mathrm{i}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & -\frac{\mathrm{i}}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) & \frac{1}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) \end{pmatrix}.$$

- Active-sterile neutrino mixing parameters:

$$\theta_\alpha = \frac{y_\alpha}{\sqrt{2}}\frac{v_{\mathrm{EW}}}{M}, \qquad \alpha = e, \mu, \tau$$

Interactions between Heavy Neutrinos and the SM

- **Charged current** (CC):

$$j_\mu^\pm = \frac{g}{2}\,\theta_\alpha\,\bar{\ell}_\alpha\,\gamma_\mu\,(-\mathrm{i}N_1 + N_2)$$

- **Neutral current** (NC):

$$j_\mu^0 = \frac{g}{2\,c_W}\left[\theta^2\,\bar{N}_2\gamma_\mu\,N_2\ + (\bar{\nu}_i\,\gamma_\mu\,\xi_{\alpha 1}\,N_1 + \bar{\nu}_i\,\gamma_\mu\,\xi_{\alpha 2}\,N_2\ +\ \text{H.c})\right]$$

- Higgs boson **Yukawa** interaction:

$$\mathscr{L}_{\mathrm{Yukawa}} = \sum_{i=1}^{3} \xi_{\alpha 2}\,\frac{\sqrt{2}\,M}{v_{\mathrm{EW}}}\,\nu_i\phi^0\left(\overline{N}_1 + \overline{N}_2\right)$$

- With the mixing parameters:

$$\xi_{\alpha 1} = \sum_{\beta=e,\mu,\tau} (-\mathrm{i})\,\mathcal{N}^*_{\alpha\beta}\,\frac{\theta_\beta}{\sqrt{2}}\,, \qquad \text{and} \qquad \xi_{\alpha 2} = \sum_{\beta=e,\mu,\tau} \mathcal{N}^*_{i\beta}\,\frac{\theta_\beta}{\sqrt{2}}$$

Decays involving Heavy Neutrinos

$$\Gamma_{W\to N\ell} = \frac{|\theta_\alpha|^2}{2}\frac{G_F\, m_W^3}{6\sqrt{2}\pi}\Pi^W_{(1+1)} \qquad \Gamma_{N\to W\,\ell} = \frac{|\theta_\alpha|^2}{2}\frac{G_F\, M^3}{4\sqrt{2}\pi}\Pi^W_{(1+1)}$$

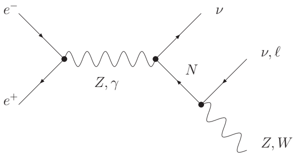
$$\Gamma_{Z\to\nu N} = |\xi_{ij}|^2\frac{G_F\, m_Z^3}{6\sqrt{2}\pi}\Pi^Z_{(1+1)} \qquad \Gamma_{N\to Z\,\nu} = |\xi_{ij}|^2\frac{G_F\, M^3}{4\sqrt{2}\pi}\Pi^Z_{(1+1)}$$

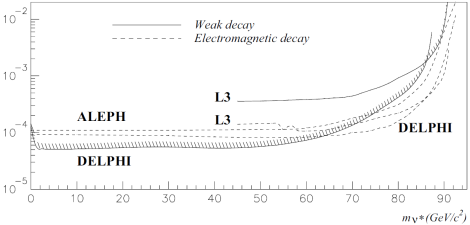
$$\Gamma_{Z\to N\,N} = |\xi_{55}|^2\frac{G_F\, m_Z^3}{6\sqrt{2}\pi}\Pi^Z_{(2)} \qquad \Gamma_{N\to h\,\nu} = |\xi_{ij}|^2\frac{M}{16\,\pi}\left(1-\frac{m_h^2}{M^2}\right)^2$$

$$\Gamma_{h\to\nu N} = \frac{m_h\,\theta^2\,M^2}{8\,\pi\,v_{\mathrm{EW}}^2}\left(1-\frac{M^2}{m_h^2}\right)^2$$

Π^W, Π^Z : Phase space factors.

Sterile Neutrino searches @ the Z pole I





DELPHI collaboration, Abreu **et al.** (1997)

- Search for $Z \to \nu\, N$ in Z–pole data at LEP.
- Null results $\Rightarrow$ Upper limit on active-sterile neutrino mixing.

Sterile Neutrino searches @ the Z pole II

- Exclusion contour at 95% confidence level:

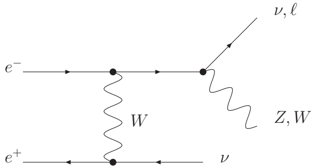
$$\theta^2 = \sum_{\alpha=e,\mu,\tau} |\theta_\alpha|^2 \leq \frac{1.1 \times 10^{-5}}{\Pi^Z_{(1+1)}}$$

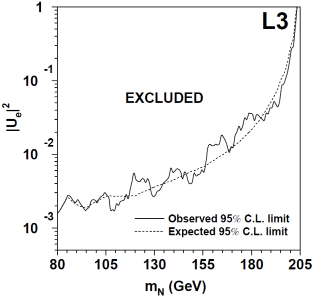
- Search for displaced vertices at the FCC-ee (TLEP) by Blondel, Graverini, Serra, Shaposhnikov (2014).
- In general: the sensitivity scales with the luminosity.

⇒ Limit on Yukawa couplings:

$$\theta_\alpha = \frac{y_\alpha}{\sqrt{2}} \frac{v_{\mathrm{EW}}}{M}, \qquad \Rightarrow \sum_{\alpha=e,\mu,\tau} |y_\alpha|^2 \leq \frac{M}{v_{\mathrm{EW}}} \frac{1.5 \times 10^{-5}}{\Pi^Z_{(1+1)}}$$

Searches in 4ℓ Final States for $\sqrt{s} \geq 2\, m_W$





L3 collaboration, Achard **et al.** (2001)

- N decay also contributes to 4ℓ final states.
- We use the experimental uncertainty from the Aleph measurement of the WW production cross section.

$$\frac{n_{WW}^{Aleph}}{n_{WW}^{\mathrm{SM}}} = 0.995 \pm 0.011_{stat} \pm 0.007_{syst}$$

OPAL collaboration, Abbiendi **et al.** (2007)

Present Indirect Constraints from Precision Data

The following sets of precision observables are used:

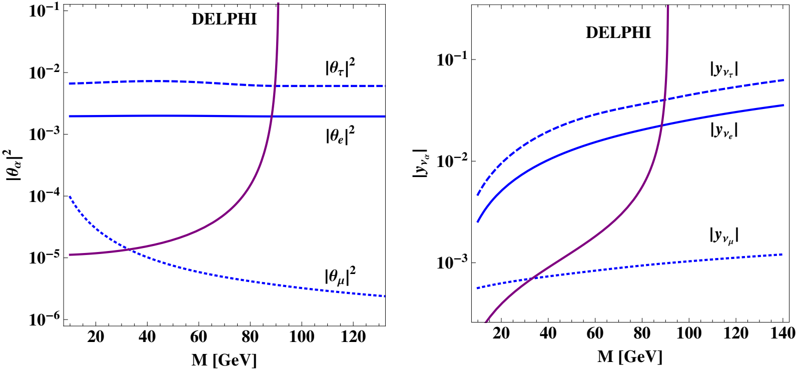
- Electroweak Precision Observables (mainly LEP).
- Non-universality observables at low Energy (decays of μ, τ, π, K).
- Rare charged lepton flavour violating decays.
- CKM unitarity tests.
- Low energy measurements of the weak mixing angle.

Note that the EWPO predictions change wrt. MUV:

$$R_{inv} = [R_{inv}]_{\rm SM} \, (1 - \frac{2}{3} \sum_{\alpha} |\theta_\alpha|^2 \left(1 - c_R \Pi^Z_{(1+1)}\right) - 0.09(|\theta_e|^2 + |\theta_\mu|^2)$$

$c_R \neq -1$ for sterile neutrinos decaying within the detector.

Bounds on Mixing Parameters and Higgs Branching Ratios



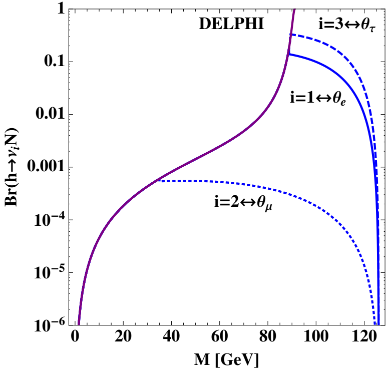
Antusch, Fischer (2015) *to appear*

- Reminder: Delphi constraints 95% confidence level.
- Large branchings of Higgs to sterile neutrinos are possible.
- Investigated also by Dev, Franceschini, Mohapatra (2012) and Cely, Ibarra, Molinaro, Petcov (2013).

Higgs Boson Branching Ratio into Neutrinos

- From "indirect" tests and Delphi.
- $\mathcal{O}(1)$ branching ratio possible.

$\Rightarrow$ Possible effect on Higgs decay rates into Standard Model particles.



Constraints from Higgs Branching Ratios

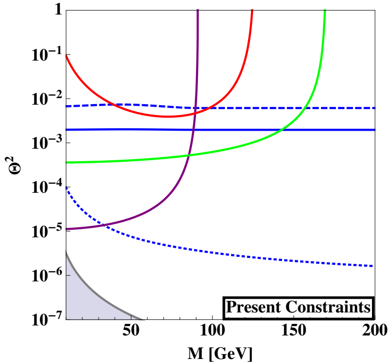
- Focus on the currently best measured branching ratios $h \to ZZ, WW, \gamma\gamma$.
- Include N decays as misidentified vector boson events.
- Branching ratios become modified by heavy neutrinos:

$$Br_{h\to XX} = r\, Br_{h\to XX,\,\mathrm{SM}} + c_X\, Br_{h\to \nu N}$$

$$r = \frac{\Gamma_{h,\,\mathrm{SM}}}{\Gamma_{h,\,\mathrm{SM}} + \Gamma_{h\to\nu N}}, \qquad c_X = \begin{cases} \frac{1}{2}, & X = Z, W \\ 0, & X = \gamma,\, f \end{cases}$$

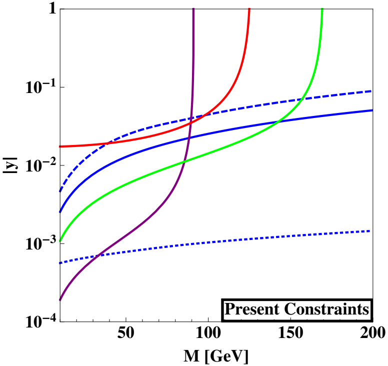
- CMS+Atlas: $Br_{h\to\gamma\gamma} = 1.15(27)$

Combination of Present Bounds



Direct searches

- Delphi (N decays) @2σ: $|y|=\sqrt{\sum_\alpha |y_\alpha|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- LHC (Higgs decays*) @1σ: $|y|=\sqrt{\sum_\alpha |y_\alpha|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- Opal ($e^+e^- \to$ 4 leptons) @1σ: $|y|=|y_e|$, $\Theta^2=|\theta_e|^2$



Other (global fit)

- $|y|=|y_e|$, $\Theta^2=|\theta_e|^2$
- $|y|=|y_\mu|$, $\Theta^2=|\theta_\mu|^2$
- $|y|=|y_\tau|$, $\Theta^2=|\theta_\tau|^2$

Antusch, Fischer (2015) *to appear*

* Currently dominated by $h \to \gamma\gamma$.

Improvements in Precision at Future Lepton Colliders - I

- Systematical uncertainty for the EWPO from 1308.6176.
- Summary table for all the future colliders in the backup.

Improvements in Precision at Future Lepton Colliders - II

- Higgs measurements (per year of data taking for one detector):

Branching ratio	ILC [%]	CEPC [%]	FCC-ee [%]
$\delta Br_{h\to WW}$	6.4	1.3	0.9
$\delta Br_{h\to ZZ}$	19	5.1	3.1
$\delta Br_{h\to\gamma\gamma}$	35	8	3.0
Reference	1310.6708	1411.5606	1308.6176

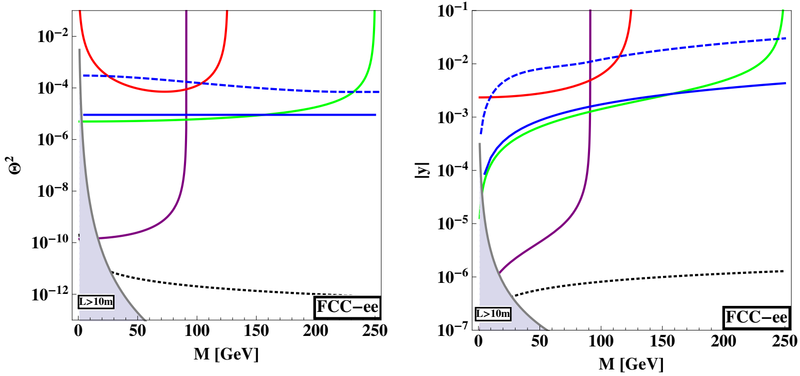
- Analysis uses 10 years of data taking with two detectors.

- Expected W boson yield:

	Opal	ILC	CEPC	FCC-ee
$\#W$'s prod.	10^4	10^7	10^8	2×10^8
$\delta_{\rm stat.}$	0.011	3×10^{-4}	10^{-4}	7×10^{-4}
$\delta_{\rm syst.}$	0.007	n.a.	n.a.	n.a.

- At the moment it seems $\delta_{\rm syst.} \sim \delta_{theo.} \sim 10^{-3}$ is realistic. (Not considered in the following.)

Prospects of Sensitivity at the FCC-ee



Direct searches

- Z pole search @2σ: $|y|=\sqrt{\sum_\alpha |y_\alpha|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- Higgs → WW @1σ: $|y|=\sqrt{\sum_\alpha |y_\alpha|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- $e^+e^- \to$ 4 leptons* @1σ: $|y|=|y_e|$, $\Theta^2=|\theta_e|^2$

Other

- Precision constraints: $|y|=\sqrt{|y_e|^2+|y_\mu|^2}$, $\Theta^2=|\theta_e|^2+|\theta_e|^2$
- Precision constraints: $|y|=|y_\tau|$, $\Theta^2=|\theta_\tau|^2$
- Unprotected type−I seesaw

Antusch, Fischer (2015) *to appear*

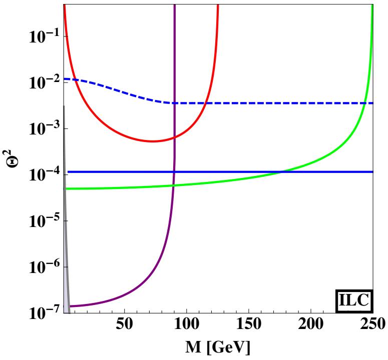
∗ Preliminary estimate using statistical uncertainty only.

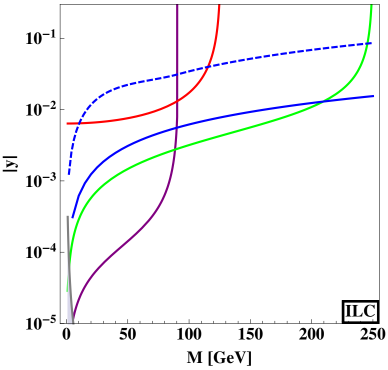
Summary and Conclusions

- Sterile neutrinos are well motivated extensions of the SM.
- Symmetry protected scenarios allow for electroweak scale sterile neutrino masses and $\mathcal{O}(1)$ active-sterile mixings.
- LHC starts to constrain Higgs branching ratios to sterile neutrinos.
- Searches in Z, W, h decay data @ FCC-ee are very sensitive probes of sterile neutrino extensions of the SM.
- There is **a lot** to do.
- Feedback is very welcome.

Thank you for your attention.

Backup I - ILC Summary Plot





Direct searches

- Z pole search @2σ: $|y|=\sqrt{\sum_\alpha |y_\alpha|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- Higgs $\to$ WW @1σ: $|y|=\sqrt{\sum_\alpha |y_\alpha|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
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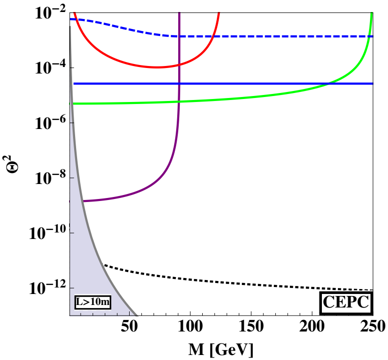
Other

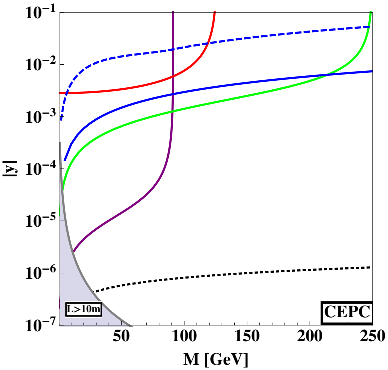
- Precision constraints: $|y|=\sqrt{|y_e|^2+|y_\mu|^2}$, $\Theta^2=|\theta_e|^2+|\theta_e|^2$
- Precision constraints: $|y|=|y_\tau|$, $\Theta^2=|\theta_\tau|^2$
- Unprotected type−I seesaw

Antusch, Fischer (2015) *to appear*

$*$ Preliminary estimate using statistical uncertainty only.

Backup II - CEPC Summary Plot





Direct searches

- Z pole search @2σ: $|y|=\sqrt{\sum_\alpha |y_\alpha|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- Higgs $\to$ WW @1σ: $|y|=\sqrt{\sum_\alpha |y_\alpha|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- $e^+e^- \to$ 4 leptons* @1σ: $|y|=|y_e|$, $\Theta^2=|\theta_e|^2$

Other

- Precision constraints: $|y|=\sqrt{|y_e|^2+|y_\mu|^2}$, $\Theta^2=|\theta_e|^2+|\theta_e|^2$
- Precision constraints: $|y|=|y_\tau|$, $\Theta^2=|\theta_\tau|^2$
- Unprotected type−I seesaw

Antusch, Fischer (2015) *to appear*

$*$ Preliminary estimate using statistical uncertainty only.

Backup III - Electroweak Precision Observables

Observable	ILC	FCC-ee	CEPC	CEPC*
R_ℓ	0.004	0.001	0.01	0.003*
R_{inv}	0.01	0.002	0.012	0.006*
R_b	0.0002	0.00002	0.00017	0.00007*
M_W [MeV]	2.5	0.5	0.5	0.5
$s_{eff}^{2,\ell}$	1.3×10^{-5}	1×10^{-6}	2.3×10^{-5}	$3.3 \times 10^{-6*}$
σ_h^0 [nb]	0.025	0.0025	n.a.	0.008*
Γ_ℓ [MeV]	0.042	0.0042	n.a.	0.014*
Reference	1310.6708	1308.6176	Ruan (2014)†	scaled*

† Private communication.

∗ Assumption: CEPC produces 10^{11} Z bosons, compared to the 10^{12} Z bosons @FCC-ee.

⇒ Uncertainties scaled: $\delta_{\mathrm{CEPC}} = \delta_{\mathrm{FCC-ee}} \times \sqrt{10}$.