FUTURE CIRCULAR COLLIDERS

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http://espace2013.cern.ch/fcc/Pages/Science.aspx

4/30/2015  Alain Blondel  FCC Future Circular Colliders
1997-2013 Higgs boson mass cornered (LEP H, M$_Z$ etc +Tevatron m$_t$, M$_W$)
Higgs Boson discovered (LHC)
Englert and Higgs get Nobel Prize

(c) Sfyrla
4/30/2015

Alain Blondel  FCC Future Circular Colliders
Asymptotic safety of gravity and the Higgs boson mass

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12 January 2010

Abstract

There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson $m_H$ can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction $\lambda$ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\text{min}} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds $m_H$ in the interval $m_{\text{min}} < m_H < m_{\text{max}} \simeq 174$ GeV, now sensitive to $A_\lambda$ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

Key words:
Asymptotic safety, gravity, Higgs field, Standard Model
PACS: 04.60.-m 11.10.Hi 14.80.Bn

Detecting the Higgs scalar with mass around 126 GeV at the LHC could give a strong hint for the absence of new physics influencing the running of the SM couplings between the Fermi and Planck/unification scales.
Is it the end?

-- Dark matter
-- Baryon Asymmetry in Universe
-- Neutrino masses
-- and... why are the charges of e and p identical to 21 significant digits?

are experimental proofs that there is more to understand.

We must continue our quest
There MUST be new physics at TeV scale

mutually exclusive?

There is one way to find out: go look!
Design Study of Future Circular Colliders

FCC
Future Circular Collider Study - SCOPE CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

• **pp-collider (FCC-hh)** → defining infrastructure
  ~16 T ⇒ 100 TeV pp in 100 km
  ~20 T ⇒ 100 TeV pp in 80 km

• **$e^+e^-$ collider (FCC-ee)** as potential intermediate step ECM=90-400 GeV

• **p-e (FCC-he)** option

• **80-100 km infrastructure in Geneva area**
Future Circular Collider Study Mandate (FCC-GOV-PM-001)

Future Circular Collider Study - FCC

Mandate

Scope

The main emphasis of the conceptual design study shall be the long-term goal of a hadron collider with a centre-of-mass energy of the order of 100 TeV (currently referred to as VHE-LHC) in a new tunnel of 80-100 km circumference for the purposes of studying physics at the highest energies. The hadron collider and its detectors shall determine the basic requirements for the tunnel, surface and technical infrastructures. The corresponding hadron injector chain shall be included in the study, taking into account the existing CERN accelerator infrastructure and long-term accelerator operation plans. The performance and cost of the hadron collider shall be compared to a high-energy LHC based on the same high-field magnet technology and housed in the LHC tunnel.

The conceptual design study shall also include a lepton collider and its detectors (currently referred to as TLEP), as a potential intermediate step towards realization of the hadron facility. The design of the lepton collider complex shall be based on the hadron collider infrastructure and any substantial incompatibilities with respect to the hadron collider infrastructure requirements shall be analysed and quantified. Potential synergies with linear collider detector designs should be considered.
possible long-term strategy

FCC-ee (80-100 km, $e^+e^-$, 90-400 GeV)
Interm. step
FCC-hh
($pp, \text{ up to } 100 \text{ TeV c.m.}$)
Ultimate goal

$\geq 60$ years of $e^+e^-$, $pp$, $ep/A$ physics at highest energies

& $e^\pm$ (120 GeV)–$p$ (7, 16 & 50 TeV) collisions FCC-eh)
### Study time line towards CDR

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<thead>
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#### Key Events:
- **FCC Week 2015:**
  - Study plan, scope definition
  - Explore options “weak interaction”

- **FCC Week 2015:**
  - Work towards baseline

- **FCC Week 2016**
  - Conceptual study of baseline “strong interact.”
  - Progress review

- **FCC Week 17 & Review**
  - Cost model, LHC results
  - Study re-scoping?

- **FCC Week 2018**
  - Elaboration, consolidation
  - Contents of CDR

- **Report**
  - CDR ready
93km “optimised” racetrack

PRELIMINARY

Alignment

Choose alignment option
93km quasi-circular
Tunnel depth at centre: 236mAG
Gradient Parameters
Azimuth (°): -15
Slope angle x: x°: 3
Slope angle y: y°: 0

Alignment centre
X: 2493922 Y: 1108695
LHC Intersection IP 1 IP 2
Angle
Depth: 542m 542m

Alignment Location

Geology Intersected by Shafts
Shaft Depth (m) Geology (m)

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<th>Shaft</th>
<th>Actual</th>
<th>Min</th>
<th>Mean</th>
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Total

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Distance along ring clockwise from CERN (km)

Surface
Lake
Mollisol
Molasse
Calcaire
Alignment
Shaft

J. Osborne & C. Cook
Tunnel location: topography [1/3]

- Minimize ground coverage
  - Hydrostatic pressure for TBM tunnelling
  - Shaft depth/cost
FCC-ee (=TLEP)  
Electroweak Factory:  
TeraZ, OkuW, MegaHiggs and Megatops

Acknowledgments to all my FCC-ee colleagues for material and ideas (and hard work) in particular: J. Wenninger, F. Zimmermann, P. Lebrun, E. Jensen, R. Thomas, B. Harer, R. Martin, N. Bacchetta, P. Janot, B. Holzer, H. Burkhardt (CERN) M. Koratzinos (UNIGE), U. Wienands (SLAC) E. Gianfelice (FNAL), M. Boscolo (LNF) A. Bogomyagkov, I. Koop, E. Levichev, D. Shatilov, I. Telnov (BINP Novosibirsk) K. Ohmi, K. Oide (KEK) ... ...
Original motivation (end 2011): now that $m_H$ and $m_{\text{top}}$ are known, explore EW region with a high precision, affordable, high luminosity machine

→ Discovery of New Physics in rare phenomena or precision measurements

ILC studies → need increase over LEP 2 (average) luminosity by a factor 1000
How can one do that without exploding the power bill?

Answer is in the B-factory design: a low vertical emittance ring with higher intrinsic luminosity, and small $\beta^*$ (1mm vs 5cm at LEP)
Electrons and positrons have a much higher chance of interacting
→ much shorter lifetime (few minutes)
→ top up continuously with booster ==> increase operation efficiency
Increase SR beam power to 50MW/beam

1000
at ZH threshold in LEP/LHC tunnel
X 4 in FCC tunnel
X 4 interaction points
EXCITING!
SuperKEKB – TLEP demonstrator!

beam commissioning will start in early 2015

- $\beta_y^* = 300 \, \mu\text{m}$ (TLEP: 1 mm)
- lifetime 5 min (TLEP: \sim 15 min)
- $\varepsilon_y / \varepsilon_x = 0.25\%$ (\sim TLEP)
- off momentum acceptance
- $e^+$ production rate
LEP2 in 2000 (12th year!): fastest possible turnaround but average luminosity ~ 0.2 peak luminosity

B factory in 2006 with toping up average luminosity ≈ peak luminosity
<table>
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<th>Parameter</th>
<th>LEP2</th>
<th><strong>FCC-ee</strong></th>
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<tr>
<td></td>
<td>Z</td>
<td>Z (c.w.)</td>
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<tr>
<td>$E_{\text{beam}}$ [GeV]</td>
<td>104</td>
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<tr>
<td>Beam-beam par. $\xi_y/IP$</td>
<td>0.06</td>
<td>0.03</td>
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<tr>
<td>Current [mA]</td>
<td>3.0</td>
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<tr>
<td>$P_{\text{SR, tot}}$ [MW]</td>
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<td>100</td>
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<td>No. bunches</td>
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<td>16700</td>
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<td>$N_b$ [$10^{11}$]</td>
<td>4.2</td>
<td>1.8</td>
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<td>$\varepsilon_x$ [nm]</td>
<td>22</td>
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<td>$\varepsilon_y$ [pm]</td>
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<td>60</td>
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<tr>
<td>$\beta_x^*$ [m]</td>
<td>1.2</td>
<td>0.5</td>
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<td>$\beta_y^*$ [mm]</td>
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<td>$\sigma_y^*$ [nm]</td>
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<td>250</td>
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<tr>
<td>$\sigma_{z,SR}$ [mm]</td>
<td>11.5</td>
<td>1.64</td>
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<tr>
<td>$\sigma_{z, tot}$ [mm] (w beamstr.)</td>
<td>11.5</td>
<td>2.56</td>
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<tr>
<td>Hourglass factor $F_{hg}$</td>
<td>0.99</td>
<td>0.64</td>
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<tr>
<td>$L/IP$ [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>0.01</td>
<td>28</td>
</tr>
<tr>
<td>$\tau_{\text{beam}}$ [min]</td>
<td>434</td>
<td>298</td>
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</table>
Overlapp in Higgs/top region, but differences and complementarities between linear and circular machines.
TLEP: PARAMETERS & STATISTICS

(e^+e^- -> ZH, e^+e^- \rightarrow W^+W^-, e^+e^- \rightarrow Z, [e^+e^- \rightarrow t\bar{t}] )

<table>
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<tr>
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<th>TLEP-4 IP, per IP</th>
<th>statistics</th>
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<tr>
<td>circumference</td>
<td>80 km</td>
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<tr>
<td>max beam energy</td>
<td>175 GeV</td>
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<td>no. of IPs</td>
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<tr>
<td>Luminosity/IP at 350 GeV c.m.</td>
<td>1.3x10^{34} cm^{-2}s^{-1}</td>
<td>10^6 ( \bar{t}t ) pairs</td>
</tr>
<tr>
<td>Luminosity/IP at 240 GeV c.m.</td>
<td>6.0x10^{34} cm^{-2}s^{-1}</td>
<td>2 \times 10^6 ZH evts</td>
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<tr>
<td>Luminosity/IP at 160 GeV c.m.</td>
<td>1.6x10^{35} cm^{-2}s^{-1}</td>
<td>10^8 WW pairs</td>
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<td>Luminosity/IP at 90 GeV c.m.</td>
<td>2. ( 10^{35/36} ) cm^{-2}s^{-1}</td>
<td>10^{12/13} Z decays</td>
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at the Z pole repeat the LEP physics programme in a few minutes...
First look at the physics case of TLEP

The TLEP Design Study Working Group

M. Bicer, a H. Duran Yildiz, b I. Yildiz, e G. Coignet, d M. Delmastro, d T. Alexopoulos, e C. Grojean, f S. Antusch, g T. Sen, h H.-J. He, i K. Potamianos, j S. Haug, b A. Moreno, i A. Heister, m V. Sanz, n G. Gomez-Ceballos, o M. Klute, n M. Zanetti, o L.-T. Wang, r M. Dam, q C. Boehm, t N. Glover, f F. Krauss, f A. Lenz, m M. Syphers, q C. Leonidopoulos, f V. Ciulli, t P. Lenzi, q G. Sguazzoni, k M. Antonelli, o M. Boscolo, i U. Dosselli, i O. Frasciello, c M. Milardi, q G. Venanzoni, k M. Zobov, t J. van der Bij, t M. de Gruttola, t D.-W. Kim, q M. Bachtis, a A. Butterworth, c Bernet, e C. Botta, h F. Carminati, d A. David, d L. Deniau, d D. d’Enterria, g G. Gaisler, b Goddard, i G. Giudice, c P. Janot, t J. M. Jowett, c C. Lourenco, z L. Malgeri, z E. Meschi, z F. Moortgat, c P. Musella, c J. A. Osborne, z L. Perrozzi, z M. Pierini, z L. Rinolfi, z A. de Roeck, z J. Rojo, t G. Roy, t A. Sciabà, z A. Valassi, c S. Waaijers, t J. Wenninger, t H. Woehri, z F. Zimmermann, a, x A. Blondel, a, x M. Koratzinos, a, x P. Mermod, a, x Y. Onel, a, x R. Talman, a, c E. Castaneda Miranda, a, x E. Bulyak, a, e D. Porsuk, a, d Kovalskyi, a, q S. Padhi, a, q P. Faccioli, a, h J. R. Ellis, a, t M. Campanelli, a, j Y. Bai, a, k M. Chamizo, a, d R.B. Appleby, a, m H. Owen, a, m H. Maury Cuna, a, a C. Gracia, a, m G. A. Munoz-Hernandez, a, o L. Trentadue, a, p E. Torrente-Lujan, a, q S. Wang, a, t D. Bertsche, a, t A. Gramolin, a, q V. Telnov, a, q M. Kado, a, m P. Petroff, a, u P. Azzi, a, c O. Nicrosini, a, m F. Piccinini, a, w G. Montagna, a, z F. Kapusta, a, q S. Laplace, a, q W. da Silva, a, y N. Gizani, a, z N. Craig, a, b T. Han, a, b C. Luci, a, b B. Mele, a, b L. Silvestrini, a, b M. Ciuchini, b, d R. Cakir, b, c R. Aleksan, b, f F. Couderc, b, f S. Ganjour, b, f E. Lançon, b, f E. Locci, b, f P. Schwemling, b, f M. Spiro, b, f C. Tanguy, b, f J. Zinn-Justin, k, f S. Moretti, a, q M. Kikuchi, b, h H. Koiso, b, h K. Ohmi, b, h K. Oide, b, h G. Pauletti, b, h R. Ruiz de Austri, b, j M. Gouzevitch, b, k and S. Chattopadhyay
First look at the physics case of TLEP, arXiv:1308.6176v3 scoped the precision measurements:
-- Model independent Higgs couplings and invisible width
-- Z mass (0.1 MeV), W mass (0.5 MeV) top mass (~10 MeV), $\sin^2 W_{\text{eff}}, R_b, N_\nu$ etc...
  ➔ powerful exploration of new physics with EW couplings up to very high masses
  ➔ importance of luminosity and $E_{\text{beam}}$ calibration by beam depolarization up to W pair
So far: simulations with CMS detector (Higgs) -- or «just» paper studies.

Snapshot of novelties appeared in recent workshops
Higher luminosity prospects at W, Z with **crab-waist**
  ➔ sensitivity to right handed (sterile) neutrinos
  ➔ s-channel e+e- $\rightarrow$ H(125.2) production almost possible ( ➔ monochromators?)
  ➔ rare Higgs Z W and top decays, FCNCs etc...
  ➔ discovery potential for very small couplings
  ➔ precision event generators (Jadach et al)

[http://cern.ch/FCC-ee](http://cern.ch/FCC-ee)
"higgstrahlung" process close to threshold
Production xsection has a maximum at near threshold \( \sim 200 \text{ fb} \)

\[ 10^{34}/\text{cm}^2/\text{s} \rightarrow 20'000 \text{ HZ events per year.} \] (~ ILC, muon collider)

FCC-ee \( \rightarrow 400'000 \text{ HZ events a year.} \)

Z – tagging by missing mass

For a Higgs of 125GeV, a centre of mass energy of 240GeV is sufficient

\( \rightarrow \text{kinematical constraint near threshold for high precision in mass, width, selection purity} \)
Z tagging by missing mass

- Total rate $\propto g_{HZZ}^2$
- $ZZZ$ final state $\propto g_{HZZ}^4 / \Gamma_H$
- Measure total width $\Gamma_H$
- Empty recoil = invisible width
- ‘Funny recoil’ = exotic Higgs decay
- Easy control below threshold
**Higgs factory**

- **2 $10^6$ ZH events in 5 years**
- **«A tagged Higgs beam»**.

### Table:

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<th>$g$</th>
<th>4 IPs</th>
<th>TLEP</th>
<th>(2 IPs)</th>
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<td>$g_{ZZ}$</td>
<td>$0.05%$</td>
<td>$(0.06%)$</td>
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</tr>
<tr>
<td>$g_{WW}$</td>
<td>$0.09%$</td>
<td>$(0.11%)$</td>
<td></td>
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<tr>
<td>$g_{bb}$</td>
<td>$0.19%$</td>
<td>$(0.23%)$</td>
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<tr>
<td>$g_{cc}$</td>
<td>$0.68%$</td>
<td>$(0.84%)$</td>
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<td>$g_{gg}$</td>
<td>$0.79%$</td>
<td>$(0.97%)$</td>
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<tr>
<td>$g_{tt}$</td>
<td>$0.49%$</td>
<td>$(0.60%)$</td>
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<td>$g_{\mu\mu}$</td>
<td>$6.2%$</td>
<td>$(7.6%)$</td>
<td></td>
</tr>
<tr>
<td>$g_{\gamma\gamma}$</td>
<td>$1.4%$</td>
<td>$(1.7%)$</td>
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<tr>
<td>$\text{BR}_{exo}$</td>
<td>$0.16%$</td>
<td>$(0.20%)$</td>
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</table>

- **Total width**: $<1\%$
- **HHH** (best at FCC-hh) $28\%$ from HZ thresh
- **Htt** (best at FCC-hh) $13\%$ from tt thresh

### Diagram:

- **sensitive to new physics in loops**
- **incl. invisible = (dark matter?)**

**A big challenge, but unique:**

Higgs s-channel production at $\sqrt{s} = m_H$

- **$10^4$ events per year.**
- Very difficult because huge background and beam energy spread $\sim 10 \times \Gamma_H$
- Limits or signal? monochromators?

_Aleksan, D’Enterria, Wojcik_
Figure 1.4. Measurement precision on $\kappa_b$, $\kappa_T$, and $\kappa_t$, measured both directly via $t\bar{t}H$ and through global fits at different facilities.
Figure 1-3. Measurement precision on $\kappa_W$, $\kappa_Z$, $\kappa_\gamma$, and $\kappa_g$ at different facilities.
Performance Comparison

\[ \sigma_{HZ} \propto g_{HZZ}^2, \text{ and } \sigma_{H_{WW\to H}} \times \text{BR}(H \rightarrow XX) \propto g_{HZZ, HWW}^2 g_{HXX}^2 / \Gamma_H \]

- Same conclusion when \( \Gamma_H \) is a free parameter in the fit

TLEP: sub-percent precision, BSM Physics sensitivity beyond several TeV

---

**Expected precision on the total width**

<table>
<thead>
<tr>
<th>( \mu^+\mu^- )</th>
<th>ILC350</th>
<th>ILC1000</th>
<th>TLEP240</th>
<th>TLEP350</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td>5%</td>
<td>3%</td>
<td>2%</td>
<td>1%</td>
</tr>
</tbody>
</table>

±1%
very accurate precision on threshold cross-section sensitive to loop corrections

\[ \sigma_{Zh} = \left[ \begin{array}{c} \text{e} \\ \text{e} \end{array} \right] \left[ \begin{array}{c} \text{Z} \\ \text{h} \end{array} \right]^2 + 2 \text{Re} \left[ \begin{array}{c} \text{Z} \\ \text{h} \end{array} \right] \cdot \left( \begin{array}{c} \text{e}^+ \\ \text{e}^- \end{array} \right) \] 

\[ \delta^{240}_{\sigma} = 100 \left( 2\delta_Z + 0.014\delta_h \right) \% \]

arxiv:1312.3322

- Very large datasets at high energy allow extreme precision \( g_{Zh} \) measurements
- Indirect and model-dependent probe of Higgs self-coupling
- Note, the time axis is missing from the plot
First generation couplings

- **s-channel Higgs production**
  - Unique opportunity for measurement close to SM sensitivity
  - Highly challenging; $\sigma(\text{ee} \rightarrow H) = 1.6 \text{fb}$; 7 Higgs decay channels studied

> **Work in progress**
  - How large are loop induced corrections? How large are BSM effects?
  - Do we need an energy scan to find the Higgs?
  - How much luminosity will be available for this measurement? By how much is the luminosity reduced by monochromators?

**Preliminary Results**

\[ L = 10 \text{ ab}^{-1} \]

\[ \kappa_e < 2.2 \text{ at } 3\sigma \]
Exclusive Higgs boson decays

- First and second generation couplings accessible
  - Study of $\rho \gamma$ channel most promising; expect $\sim 50$ evts.
  - Sensitivity to $u/d$ quark Yukawa coupling
  - Sensitivity due to interference

$$\frac{\text{BR}_{h \rightarrow \rho \gamma}}{\text{BR}_{h \rightarrow b\bar{b}}} = \kappa_\gamma \left[ (1.9 \pm 0.15) \kappa_\gamma - 0.24 \kappa_u - 0.12 \kappa_d \right] \times 10^{-5}$$

- Also interesting to FCC-hh program
- Alternative $H \rightarrow \text{MV}$ decays should be studied ($V=\gamma, W, \text{and } Z$)

$H \rightarrow J/\Psi \gamma \quad y_c$
$H \rightarrow \phi \gamma \quad y_s$
$H \rightarrow \rho \gamma \quad y_u, y_d$
$H \rightarrow \omega \gamma$
### CP Measurements

- CP violation can be studied by searching for CP-odd contributions; CP-even already established
- Higgs to Tau decays of interest

\[ \mathcal{L}_{hf} \propto h \bar{f}(\cos \Delta + i \gamma_5 \sin \Delta)f \]

<table>
<thead>
<tr>
<th>Colliders</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>FCCee (1 ab(^{-1}))</th>
<th>FCCee (5 ab(^{-1}))</th>
<th>FCCee (10 ab(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy(1(\sigma))</td>
<td>25°</td>
<td>8.0°</td>
<td>5.5°</td>
<td>2.5°</td>
<td>1.7°</td>
</tr>
</tbody>
</table>
Rare and Exotics Higgs Bosons

- 2,000,000 ZH events allow for detailed studies of rare and exotic decays
  - requires hadronic and invisible Z decays
  - set requirements for FCC-ee detector
- Coupling measurements have sensitivity to BSM decays
- Dedicated studies using specific final states improve sensitivity
- Example: Higgs to invisible, flavor violating Higgs, and many more
- Potential at the LHC (and HL-LHC) currently not fully explored
- Modes with of limited LHC sensitivity are of particular importance to FCC-ee program
  - currently under study
- FCC-ee might allow precision measurement of exotic Higgs decays
HIGGS AT FCC-pp

Proton-proton Higgs datasets

LHC Run I

x300-600

HL LHC

x10-400

FCC pp

<table>
<thead>
<tr>
<th>Process</th>
<th>8 TeV</th>
<th>14 TeV</th>
<th>100 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>gF</td>
<td>0.38</td>
<td>1</td>
<td>14.7</td>
</tr>
<tr>
<td>VBF</td>
<td>0.38</td>
<td>1</td>
<td>18.6</td>
</tr>
<tr>
<td>WH</td>
<td>0.43</td>
<td>1</td>
<td>9.7</td>
</tr>
<tr>
<td>ZH</td>
<td>0.47</td>
<td>1</td>
<td>12.5</td>
</tr>
<tr>
<td>ttH</td>
<td>0.21</td>
<td>1</td>
<td>61</td>
</tr>
<tr>
<td>bbH</td>
<td>0.34</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>gF to HH</td>
<td>0.24</td>
<td>1</td>
<td>42</td>
</tr>
</tbody>
</table>

\[ \sqrt{s} \text{ (TeV)} \]

\[ \int L dt \text{ (fb}\^{-1}) \]

\[ \sigma \cdot BR(pp \to HH \to bb\gamma\gamma) \text{ (fb)} \]

\[ S/\sqrt{B} \]

\[ \lambda \text{ (stat)} \]

arXiv:1310.8361
... but also new measurements not possible at the LHC/HL-LHC

\[ ttH / ttZ \]

\[ \rightarrow \text{Theoretical uncertainties cancel mostly} \]

- PDF (CTEQ 6.6) ± 0.5%
- Missing higher orders ± 1.2%

\[ \rightarrow \text{One cannot conclude that one can measure the cross section ratio with} \]
\[ \sim 2\% (\delta \lambda_{\text{top}} \approx 1\%) \text{ precision. More detailed studies are ongoing.} \]
Table from D. Curtin FCC workshop, Washington, 23-27 March 2015)

Both lepton and 100 TeV pp colliders are vital for this effort!

<table>
<thead>
<tr>
<th>Observables at Current + Future Colliders</th>
<th>100 TeV</th>
<th>ILC/TLEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>producing extra higgs states (incl. superpartners)</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Exotic Higgs Decays</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Electroweak Precision Observables</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Higgs coupling measurements</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Higgs portal direct production of new states</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Higgs self coupling measurements</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Zh cross section measurements</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

Higgs invisible decays

Right handed Neutrinos

e tc.. etc..
because of Luminosity FCC-ee (in combination with HL-LHC and/or FCC-hh) is a very powerful Higgs Factory, but....

FCC-ee is MUCH more than a Higgs Factory!
TERA-Z, Oku-W, Megatops

Precision tests of the closure of the Standard Model
Precision tests of EWSB

**Z pole symmetries, lineshape**

**WW threshold scan**

**tt threshold scan**

**TLEP**: Repeat the LEP1 physics programme every 15 mn

- Transverse polarization up to the WW threshold
- Exquisite beam energy determination (10 keV)
- Longitudinal polarization at the Z pole
  - Measure $\sin^2 \theta_W$ to $2 \times 10^{-6}$ from $A_{\text{LR}}$

- Statistics, statistics: $10^{10}$ tau pairs, $10^{11}$ bb pairs, QCD and QED studies etc...
Beam polarization and E-calibration @ FCC-ee

Precise meast of $E_{\text{beam}}$ by resonant depolarization
$\sim 100 \text{ keV each time the meast is made}$

At LEP transverse polarization was achieved routinely at Z peak.
instrumental in $10^{-3}$ measurement of the Z width in 1993
led to prediction of top quark mass (179+- 20 GeV) in March 1994

Polarization in collisions was observed (40% at BBTS = 0.04)

At LEP beam energy spread destroyed polarization above 60 GeV
$\sigma_E \propto E^2/\sqrt{\rho}$ ➔ At FCC-ee transverse polarization up to at least 80 GeV
to go to much higher energies requires spin rotators and siberian snake

FCC-ee: use ‘single’ bunches to measure the beam energy continuously
no interpolation errors due to tides, ground motion or trains etc...
but saw-tooothing must be well understood! require Wigglers to speed up pol. time

<< 100 keV beam energy calibration around Z peak and W pair threshold.
$\Delta m_Z \sim 0.1 \text{ MeV}, \Delta \Gamma_Z \sim 0.1 \text{ MeV}, \Delta m_W \sim 0.5 \text{ MeV}$
Example (from Erler & Freytas PDG 2014)

\[ \Delta \rho = \varepsilon_1 = \alpha(M_Z) \cdot T \]
\[ \varepsilon_3 = 4 \sin^2 \theta_W \cdot \alpha(M_Z) \cdot S \]

\[ \Delta \rho \text{ today} = 0.00040 \pm 0.00024 \]

-- is consistent with 0 at 1.7\( \sigma \)
-- is sensitive to non-conventional Higgs bosons (e.g. in SU(2) triplet with ‘funny v.e.v.s) 
-- is sensitive to Isospin violation such as \( m_t \neq m_b \) or \textit{ibid for stop-sbottom}
-- does not decouple!

\[ \rho_0 = 1 + \frac{3 G_F}{8 \sqrt{2} \pi^2} \sum_i \frac{C_i}{3} \Delta m_i^2, \]

(10.63)

where the sum includes fourth-family quark or lepton doublets, \( (t') \) or \( (\tilde{E}^0) \), right-handed (mirror) doublets, non-degenerate vector-like fermion doublets (with an extra factor of \( 2 \)), and scalar doublets such as \( (\tilde{t}) \) in Supersymmetry (in the absence of \( L-R \) mixing).

Present measurement implies

\[ \sum_i \frac{C_i}{3} \Delta m_i^2 \leq (52 \text{ GeV})^2. \]

Similarly:

\[ S = \frac{C}{3 \pi} \sum_i \left( t_{3L}(i) - t_{3R}(i) \right)^2, \]

Most e.g. SUSY models have these symmetries embedded from the start

4/30/2015 Alain Blondel Fu
best-of ee-FCC/TLEP #2: Precision EW measts

Asset: -- high luminosity ($10^{12}$ Z decays + $10^8$ W pairs + $10^6$ top pairs )
-- exquisite energy calibration up and above WW threshold

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Present precision</th>
<th>Measured from</th>
<th>Statistical uncertainty</th>
<th>Systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z$ (keV)</td>
<td>91187500 ± 2100</td>
<td>Z Line shape scan</td>
<td>5 (6) keV</td>
<td>≤ 100 keV</td>
</tr>
<tr>
<td>$\Gamma_Z$ (keV)</td>
<td>2495200 ± 2300</td>
<td>Z Line shape scan</td>
<td>8 (10) keV</td>
<td>≤ 100 keV</td>
</tr>
<tr>
<td>$R_{\ell}$</td>
<td>20.767 ± 0.025</td>
<td>Z Peak</td>
<td>0.00010 (12)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>$N_\nu$</td>
<td>2.984 ± 0.008</td>
<td>Z Peak</td>
<td>0.000008 (10)</td>
<td>&lt; 0.004</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>2.92 ± 0.05</td>
<td>$Z\gamma$, 161 GeV</td>
<td>0.0010 (12)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21629 ± 0.00066</td>
<td>Z Peak</td>
<td>0.000003 (4)</td>
<td>&lt; 0.000060</td>
</tr>
<tr>
<td>$A_{LR}$</td>
<td>0.1514 ± 0.0022</td>
<td>Z peak, polarized</td>
<td>0.000015 (18)</td>
<td>&lt; 0.000015</td>
</tr>
<tr>
<td>$m_W$ (MeV)</td>
<td>80385 ± 15</td>
<td>WW threshold scan</td>
<td>0.3 (0.4) MeV</td>
<td>≤ 0.5 MeV</td>
</tr>
<tr>
<td>$m_{top}$ (MeV)</td>
<td>173200 ± 900</td>
<td>tt threshold scan</td>
<td>10 (12) MeV</td>
<td>&lt; 10 MeV</td>
</tr>
</tbody>
</table>

Also -- $\Delta \sin^2 \theta_W \approx 10^{-6}$
-- $\Delta \alpha_s = 0.0001$ from W and Z hadronic widths
-- orders of magnitude on FCNCs and rare decays etc.

Design study to establish possibility of corresponding precision theoretical calculations.

4/30/2015
Alain Blondel  FCC Future Circular Colliders
Asset: -- high luminosity (10^{12} Z decays + 10^8 W pairs + 10^6 top pairs) -- exquisite energy calibration up and above WW threshold

\[ \Delta \sin^2 \theta_W \approx 10^{-6} \]

\[ \Delta \alpha_{\text{S}} \approx 0.0001 \] from W and Z hadronic widths

systematic uncertainties on FCNCs and rare decays etc. etc.

Design study to establish possibility of corresponding precision theoretical calculations.

4/30/2015 Alain Blondel  FCC Future Circular Colliders
## A Sample of Essential Quantities:

<table>
<thead>
<tr>
<th>$X$</th>
<th>Physics</th>
<th>Present precision</th>
<th>TLEP stat Syst Precision</th>
<th>TLEP key</th>
<th>Challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_Z$ MeV/c²</td>
<td>Input</td>
<td>91187.5 ± 2.1 (Z) Line shape scan</td>
<td>0.005 MeV &lt;±0.1 MeV</td>
<td>E_cal</td>
<td>QED corrections</td>
</tr>
<tr>
<td>$\Gamma_Z$ MeV/c²</td>
<td>$\Delta \rho_4 (T)$ (\text{no } \Delta \alpha)</td>
<td>2495.2 ± 2.3 (Z) Line shape scan</td>
<td>0.008 MeV &lt;±0.1 MeV</td>
<td>E_cal</td>
<td>QED corrections</td>
</tr>
<tr>
<td>$R_\ell$</td>
<td>$\alpha_s, \delta_b$</td>
<td>20.767 ± 0.025 (Z) Peak</td>
<td>0.0001 ± 0.002 - 0.0002</td>
<td>Statistics</td>
<td>QED corrections</td>
</tr>
<tr>
<td>$N_\nu$</td>
<td>Unitarity of PMNS, sterile $\nu$'s</td>
<td>2.984 ±0.008 (Z) Peak (Z+\gamma(161 \text{ GeV}))</td>
<td>0.000008 ±0.004 0.0004-0.001</td>
<td>-lumi meast Statistics</td>
<td>QED corrections to Bhabha scat.</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$\delta_b$</td>
<td>0.21629 ±0.00066 (Z) Peak</td>
<td>0.000003 ±0.000020 - 60</td>
<td>Statistics, small IP</td>
<td>Hemisphere correlations</td>
</tr>
<tr>
<td>$A_{LR}$</td>
<td>$\Delta \rho, \varepsilon_3, \Delta \alpha (T, S)$</td>
<td>0.1514 ±0.0022 (Z) peak, polarized</td>
<td>±0.000015</td>
<td>4 bunch scheme</td>
<td>Design experiment</td>
</tr>
<tr>
<td>$M_W$ MeV/c²</td>
<td>$\Delta \rho, \varepsilon_3, \varepsilon_2, \Delta \alpha (T, S, U)$</td>
<td>80385 ± 15 (161 \text{ GeV}) (\text{Threshold})</td>
<td>0.3 MeV &lt;1 MeV</td>
<td>E_cal &amp; Statistics</td>
<td>QED corrections</td>
</tr>
<tr>
<td>$m_{\text{top}}$ MeV/c²</td>
<td>Input</td>
<td>173200 ± 900 (\text{Threshold scan})</td>
<td>10 MeV</td>
<td>E_cal &amp; Statistics</td>
<td>Theory limit at 100 MeV?</td>
</tr>
</tbody>
</table>
Input from Physics to the accelerator design

0. Nobody complains that the luminosity is too high (the more you get, the more you want)

1. Do we need polarized beams?

-1- transverse polarization:
  continuous beam Energy calibration with resonant depolarization
  central to the precision measurements of $m_Z$, $m_W$, $\Gamma_Z$
  requires ‘single bunches’
  a priori doable up to $W$ energies -- workarounds exist above (e.g. $\gamma Z$ events)
  large ring with small emittance offers \emph{a priori} excellent prospects
  need wigglers; simulations ongoing (E. Gianfelice, M. Koratzinos)

-2- longitudinal polarization requires spin rotators and is very difficult at high energies
  -- We recently found that it is not necessary to extract top couplings (Janot, Azzi)
  -- improves Z peak measurements \textit{if loss in luminosity is not too strong}
  but brings no information that is not otherwise accessible

2. What energies are necessary?

  -- in addition to Z, W, H and top listed the following are being considered
    -- $e^+e^- \rightarrow H(125.2)$ (requires monochromatization A. Faus) (under study)
    -- $e^+e^-$ at ~70 GeV (Z-$\gamma$ interference)
    -- $e^+e^-$ at top threshold + $<\sim 20$ GeV for top couplings ($E_{\text{max}}$ up to 180 -185 GeV)
    -- no obvious case for going to 500 GeV
Determination of top-quark EW couplings via measurement of top-quark polarization. In semileptonic decays, fit to lepton momentum vs scattering angle.

Typically best sensitivity just above production threshold.

Momenta up to: 175 GeV

Patrizia Azzi:
Top physics at FCC-ee

Patrick Janot
arXiv:1503.01325v2
Next plans for FCC-ee

-- quality of FCC-ee experiments is intimately related to accelerator performance
  -- available energy points
  -- Luminosities
  -- beam polarization and energy calibration
  -- knowledge of other beam parameters (e.g. energy spread vs Z width)

-- we can (mostly out of LEP experience) project fairly well the experimental precisions
  -- sometimes they are vertiginously small
  \[ \Delta \sin^2 \theta_W^{\text{eff}} = 5 \times 10^{-6}, \Delta m_Z = 0.1 \text{ MeV} \Delta \Gamma_Z = 0.1 \text{ MeV} \Delta m_W = 0.5 \text{ MeV} \Delta \sigma_{ZH}/\sigma_{ZH} \sim 10^{-3} \text{ etc...} \]
  careful revisiting will be necessary.

-- full use of precision measurements requires a considerable improvement
  in the theory calculations
  -- for the measurements themselves (e.g. Full two loops exponentiated for the QED ISR)
  -- for the interpretation; full three loop calculations for EWRCs
    and on inputs (\(\Delta \alpha_{\text{QED}}(m_Z)\) Was, Gluza, Heynemeyer, Kuhn, Frietas, Jadach, Ward...)
Rare decays

-- FCNC:  $Z \rightarrow e + \tau$  $Z \rightarrow \mu + \tau$

-- Heavy neutrinos (they must be somewhere!)

    neutrino counting and search for explicit $Z \rightarrow \nu-N$
    (with $N \rightarrow \nu X$ or $eX'$ and possibly displayed vertices)

-- other final states with single or double photons and jets

-- flavour physics...

-- and many others ($Z \rightarrow \gamma\gamma$ etc)

-- How far can one go with $10^{12}$ or $10^{13}$ $Z$ decays?
But Where Is Everybody?
At higher masses -- or at smaller couplings?
neutrinos have mass...
and this very probably implies new degrees of freedom

⇒ Right-Handed, Almost «Sterile» (very small couplings) Neutrinos completely unknown masses (meV to ZeV), nearly impossible to find.

.... but could perhaps explain all: DM, BAU, $\nu$-masses
### Electroweak eigenstates

<table>
<thead>
<tr>
<th>Left-handed states</th>
<th>Right-handed states</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(e)_L$</td>
<td>$(e)_R$</td>
</tr>
<tr>
<td>$(\nu_e)_L$</td>
<td>$(\nu_e)_R$</td>
</tr>
<tr>
<td>$(\nu_\mu)_L$</td>
<td>$(\nu_\mu)_R$</td>
</tr>
<tr>
<td>$(\nu_\tau)_L$</td>
<td>$(\nu_\tau)_R$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Charge $Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q = -1$</td>
</tr>
<tr>
<td>$Q = 0$</td>
</tr>
</tbody>
</table>

- $I = 1/2$
- $I = 0$

Right handed neutrinos are singlets:
- no weak interaction
- no EM interaction
- no strong interaction

They can’t produce them, can’t detect them.

---

4/30/2015  Alain Blondel Future Circular Collider
See-saw in a general way:

\[
\mathcal{L} = \frac{1}{2} (\bar{\nu}_L, \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}
\]

\[
\begin{align*}
M &= \frac{1}{2} \left[ (0 + M_R) + \sqrt{(0 - M_R)^2 + 4 m_D^2} \right] \\
M &= \frac{1}{2} \left[ (0 + M_R) - \sqrt{(0 - M_R)^2 + 4 m_D^2} \right]
\end{align*}
\]

\[
\tan 2\theta = \frac{2 m_D}{M_R - 0} \lesssim 1
\]

\[
m_\nu = \frac{1}{2} \left[ (0 + M_R) - \sqrt{(0 - M_R)^2 + 4 m_D^2} \right] \simeq -\frac{m_D^2}{M_R}
\]

- **Dirac only, (like e- vs e+):**
  - \( \nu_L \) \( \bar{\nu}_R \)
  - \( \nu_R \) \( \bar{\nu}_L \)
  - 4 states of equal masses
  - Some have \( I=1/2 \) (active)
  - Some have \( I=0 \) (sterile)

- **Majorana only**
  - \( \nu_L \) \( \nu_R \)
  - \( \nu_L \) \( \nu_R \)
  - 2 states of equal masses
  - All have \( I=1/2 \) (active)

- **Dirac + Majorana**
  - \( \nu_L \) \( N_R \)
  - \( \bar{\nu}_R \) \( \bar{N}_L \)
  - 4 states, 2 mass levels
  - \( m_1 \) have \( I=1/2 \) (~active)
  - \( m_2 \) have \( I=0 \) (~sterile)
There even exists a scenario that explains everything: the νMSM

\[
\begin{align*}
\nu_1 & \\
\nu_2 & \\
\nu_3 & 
\end{align*}
\]

\[
\begin{align*}
N_2, N_3 & \\
N_1 &
\end{align*}
\]

Shaposhnikov et al

can generate Baryon Asymmetry of Universe
if \( m_{N_2,N_3} > 140 \text{ MeV} \)

constrained:
mass: 1-50 keV
mixing: 10\(^{-7}\) to 10\(^{-13}\)
decay time:
\( \tau_{N_1} > \tau_{\text{Universe}} \)

\[
N_1 \rightarrow \nu \gamma
\]

\text{may have been seen:}
\text{arxiv:1402:2301}
\text{arxiv:1402:4119}

(or not)
**Manifestations of right handed neutrinos**

One family see-saw:

\[ \theta \approx \left( \frac{m_D}{M} \right) \]

\[ m_N \approx \left( \frac{m_D}{M} \right) \]

\[ |U|^2 \approx \theta^2 \approx \frac{m_v}{m_N} \]

\[ \nu = \nu L \cos\theta - N^c_R \sin\theta \]

\[ N = N_R \cos\theta + \nu^c_L \sin\theta \]

What is produced in W, Z decays is:

\[ \nu_L = \nu \cos\theta + N \sin\theta \]

- Mixing with active neutrinos leads to various observable consequences
  - If very light (eV), possible effect on neutrino oscillations
  - If in keV region (dark matter), monochromatic photons from galaxies with \( E = m_N/2 \)

-- Possibly measurable effects at High Energy
  - If \( N \) is heavy it will decay in the detector (not invisible)
    - PMNS matrix unitarity violation and deficit in Z «invisible» width
    - Higgs and Z visible exotic decays \( H \rightarrow \nu_i \bar{N}_i \) and \( Z \rightarrow \nu_i \bar{N}_i \), \( W \rightarrow l_i \bar{N}_i \)
    - Also in charm and b decays via \( W^* \rightarrow l_i \bar{N}_i \)
    - Violation of unitarity and lepton universality in \( Z, W \) or \( \tau \) decays
      -- etc... etc...
  - Couplings are small \( (m_v/m_N) \) (but who knows?) and generally out of reach of hadron colliders (but this deserves to be revisited for detached vertices @LHC, HL-LHC, FCC-hh)

See recent work arXiv:1411.5230  arXiv:1412.6322v1
At the end of LEP:

\[ N_\nu = 2.984 \pm 0.008 \]

This is determined from the Z line shape scan and dominated by the measurement of the hadronic cross-section at the Z peak maximum.

The dominant systematic error is the theoretical uncertainty on the Bhabha cross-section (0.06%) which represents an error of \( \pm 0.0046 \) on \( N_\nu \).

Improving on \( N_\nu \) by more than a factor 2 would require a large effort to improve on the Bhabha cross-section calculation!
Neutrino counting at TLEP

given the very high luminosity, the following measurement can be performed

\[
N_\nu = \frac{\gamma Z\,(\text{inv})}{\gamma Z \to ee, \mu\mu} \frac{\Gamma_\gamma}{\Gamma_{e,\mu}} \quad (SM)
\]

The common \( \gamma \) tag allows cancellation of systematics due to photon selection, luminosity etc. The others are extremely well known due to the availability of \( O(10^{12}) \) \( Z \) decays.

The full sensitivity to the number of neutrinos is restored, and the theory uncertainty on \( \frac{\Gamma_\gamma}{\Gamma_{e}} \quad (SM) \) is very very small.

A good measurement can be made from the data accumulated at the WW threshold where \( \sigma (\gamma Z(\text{inv}) ) \sim 4 \) pb for \( |\cos \theta_\gamma| < 0.95 \)

161 GeV (10^7 s) running at 1.6x10^{35}/cm^2/s x 4 exp \( \Rightarrow \) 3x10^7 \( \gamma Z(\text{inv}) \) evts, \( \Delta N_\nu = 0.0011 \)
adding 5 yrs data at 240 and 350 GeV ............................................................................................................. \( \Delta N_\nu = 0.0008 \)

A better point may be 105 GeV (20pb and higher luminosity) may allow \( \Delta N_\nu = 0.0004 \)?

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RHASnu’s production in Z decays

Production:

$$BR\ (Z^{0} \rightarrow \nu_{m} \bar{\nu}) = BR\ (Z^{0} \rightarrow \nu \bar{\nu}) \ |U|^2 \left( 1 - \frac{m_{\nu_{m}}^2}{m_{Z^{0}}^2} \right)^2 \left( 1 + \frac{1}{2} \frac{m_{\nu_{m}}^2}{m_{Z^{0}}^2} \right)$$

multiply by 2 for anti neutrino and add contributions of 3 neutrino species (with different $|U|^2$)

Decay

(a)

$N \times \nu_{i} \rightarrow W^{-} \rightarrow l_{i}^{-} \nu_{i}$

(b)

$N \times \nu_{i} \rightarrow Z \rightarrow l_{j}^{-} \bar{l}_{j}^{+}, \nu_{j} \bar{\nu}_{j}$

FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton $l_{i}$ denotes $e, \mu$, or $\tau$.

Decay length:

$$L \approx \frac{3}{|U|^2 \left( m_{\nu_{m}}(\text{GeV}/c^2) \right)^6} \text{ cm}$$

NB CC decay always leads to $\geq 2$ charged tracks

Backgrounds: four fermion:  $e^+e^- \rightarrow W^+ W^-$  $e^+e^- \rightarrow Z^*(\nu \bar{\nu}) + (Z/\gamma)^*$
Order-of-magnitude extrapolation of existing limits
Interesting region
$|U|^2 \sim 10^{-9}$ to $10^{-12} @ 50$ GeV

Decay length

heavy neutrino mass $\sim M$

a large part of the interesting region will lead to detached vertices

... $\Rightarrow$ very strong reduction of background!

Exact reach domain will depend on detector size and details of displaced vertex efficiency & background

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$N_z = 10^{12}$  $1 \text{mm} < L < 1 \text{m}$

region of interest

FCC-ee sensitivity

A.B, Elena Graverini, Nicola Serra, Misha Shaposhnikov
$N_Z = 10^{13}$  \(100 \mu m < L < 5 m\)

- **Region of interest**
- **FCC-ee sensitivity**
$N_Z = 10^{13}$ 100$\mu$m $< L < 5$ m

region of interest

FCC-ee sensitivity

see recent work arXiv:1411.5230
FCC-ee is a wonderful first step towards the Ultimate goal of a 100 TeV hadron collider and this is one of the reasons it is attractive.

But...

FCC-ee is MUCH more than a launching pad!
The combination of the FCC machines offers outstanding discovery potential by exploration of new domains of
-- precision
and
-- direct search,
both at high energy and at very small couplings

join us! http://cern.ch/fcc-ee
http://espace2013.cern.ch/fcc/Pages/Science.aspx
CONCLUSIONS

Kick-off Meeting of the Future Circular Colliders Design Study
12 - 15 February 2014, University of Geneva / Switzerland

330 registered participants
Experimental Studies: Conveners

- Coordinators A. Blondel, P. Janot
  - Study the properties of the Higgs and other particles with unprecedented precision
  - Develop the necessary tools
  - Understand the experimental conditions
  - Set constraints on the possible detector designs to match statistical precision

EW Physics (Z pole)
  R. Tenchini
  F. Piccinini

Diboson physics, $m_W$
  R. Tenchini

H(126) Properties
  M. Klute
  K. Peters

Top Quark Physics
  P. Azzi

QCD and $\gamma\gamma$ Physics
  D. d’Enterria
  P. Skands

Flavour Physics
  S. Monteil
  J. Kamenik

New Physics
  M. Pierini
  C. Rogan

Detector Designs
  A. Cattai
  G. Rolandi

Physics Software
  C. Bernet
  B. Hegner

Online & Trigger
  C. Leonidopoulos

Exp’tal Environment
  N. Bacchetta

Synergy with FCC-hh, LHC, Linear Colliders

Synergy with FCC-hh and Linear Colliders

Synergy with Linear Collider detectors and others
Phenomenological Studies: Conveners

- Coordinators: J. Ellis, C. Grojean
  - Set up a long-term programme to match theory predictions to experimental precisions
  - Understand how new physics would show up in precision measurements, and in searches for rare decays (Z, W, t, H, b, c, \(\tau\), ...) and rare processes
  - Set up the framework for global fits and understand the complementarity with other colliders (LHC, FCC-hh, in particular)
some REFERENCES for right handed neutrino searches

Arxiv:1208.3654

Higgs Decays in the Low Scale Type I See-Saw Model
C. Garcia Cely, A. Ibarra, E. Molinaro and S.T. Petcov

FLAVOUR (267104)-ERC-23 TUM-HEP 850/12 SISSA 25/2012/EP CFTP/12-013

arxiv:1208.3654

The Role of Sterile Neutrinos in Cosmology and Astrophysics
Alexey Boyarsky, Oleg Ruchayskiy and Mikhail Shaposhnikov


Search for Neutral Heavy Leptons Produced in Z Decays

DEPHI Collaboration

arxiv:1308.6176


talks by Maurizio Pierini (BSM), Manqi Ruan (Higgs) Roberto Tenchini (Top & Precision) tomorrow, posters tonight at Future accelerator session
Arc lattice (circular machine)

LATTICE V12B-S

B = bending magnet, Q = quadrupole, S = sextupole

Circumference: 100 km
Arc length: 2 × 3.4 km
Straight section: 1.5 km

B. Harer, B. Holzer
Tunnel transverse width of both FCC-ee designs ~3-4 m.

Additional length is required to bend beams back, plus room for RF.

Synchrotron rad. power per IP: CERN 140 kW, BINP 1400 kW.
  - Optimum between length and power loss to be identified!
  - 93 km racetrack IR straights of 1400 m may be too short for ee!
Beam-beam simulations

BBSS strong-strong simulation with beamstrahlung

FCC-ee at 120 GeV:
$L = 7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ per IP

FCC-ee in crab-waist mode at the Z pole (45.5 GeV):
$L = 1.5 \times 10^{36}$ cm$^{-2}$s$^{-1}$ per IP

Tracking confirms assumptions!
### Key Parameters FCC-hh

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [TeV]</td>
<td>100 c.m.</td>
<td>14 c.m.</td>
</tr>
<tr>
<td>Dipole field [T]</td>
<td>16</td>
<td>8.33</td>
</tr>
<tr>
<td># IP</td>
<td>2 main, +2</td>
<td>4</td>
</tr>
<tr>
<td>Luminosity/IP&lt;sub&gt;main&lt;/sub&gt; [cm&lt;sup&gt;-2&lt;/sup&gt;s&lt;sup&gt;-1&lt;/sup&gt;]</td>
<td>5 - 25 x 10&lt;sup&gt;34&lt;/sup&gt;</td>
<td>1 x 10&lt;sup&gt;34&lt;/sup&gt;</td>
</tr>
<tr>
<td>Stored energy/beam [GJ]</td>
<td>8.4</td>
<td>0.39</td>
</tr>
<tr>
<td>Synchrotron rad. [W/m/aperture]</td>
<td>28.4</td>
<td>0.17</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>25 (5)</td>
<td>25</td>
</tr>
</tbody>
</table>
• Stored beam energy: 8 GJ/beam (0.4 GJ LHC) = 16 GJ total
  ➔ equivalent to an Airbus A380 (560 t) at full speed (850 km/h)

- Collimation, beam loss control, radiation effects: very important
- Injection/dumping/beam transfer: very critical operations
- Magnet/machine protection: to be considered from early phase
$H^3 @ TLEP$

- At LHC (Requires $E_{CM} > 2 m_h$): 

- At ILC (Requires $E_{CM} > 2 m_h + m_Z$): 

- At TLEP 240 GeV: $M. McCullough '14$

\[
\sigma_{Zh} = \frac{1}{2} \left( \sum_{h} \right) + 2 \Re \frac{(e^+ e^- Z h)}{Z} \cdot \left( \delta_{240} = 100 \left( 2 \delta_Z + 0.014 \delta_h \right) \% \right)
\]

tiny effect but visible thanks to the extraordinary TLEP sensitivity on Zh (0.05%)
Table 1-16. Uncertainties on coupling scaling factors as determined in a completely model-independent fit for different $e^+e^-$ facilities. Precisions reported in a given column include in the fit all measurements at lower energies at the same facility, and note that the model independence requires the measurement of the recoil $HZ$ process at lower energies. $^3$ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to TLEP and CLIC numbers without accounting for the additional running period. ILC numbers include a 0.5% theory uncertainty. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.

<table>
<thead>
<tr>
<th>Facility</th>
<th>ILC</th>
<th>ILC (LumiUp)</th>
<th>TLEP (4 IP)</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>250</td>
<td>500</td>
<td>1000</td>
<td>250/500/1000</td>
</tr>
<tr>
<td>$\int \mathcal{L} dt$ (fb$^{-1}$)</td>
<td>250</td>
<td>+500</td>
<td>+1000</td>
<td>$1150+1600+2500$</td>
</tr>
<tr>
<td>$P(e^-, e^+)$</td>
<td>$(-0.8, +0.3)$</td>
<td>$(-0.8, +0.3)$</td>
<td>$(-0.8, +0.2)$</td>
<td>(same)</td>
</tr>
<tr>
<td>$\Gamma_H$</td>
<td>12%</td>
<td>5.0%</td>
<td>4.6%</td>
<td>2.5%</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>18%</td>
<td>8.4%</td>
<td>4.0%</td>
<td>2.4%</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>6.4%</td>
<td>2.3%</td>
<td>1.6%</td>
<td>0.9%</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>4.9%</td>
<td>1.2%</td>
<td>1.2%</td>
<td>0.6%</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>1.3%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$\kappa_\mu$</td>
<td>91%</td>
<td>91%</td>
<td>16%</td>
<td>10%</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>5.8%</td>
<td>2.4%</td>
<td>1.8%</td>
<td>1.0%</td>
</tr>
<tr>
<td>$\kappa_c$</td>
<td>6.8%</td>
<td>2.8%</td>
<td>1.8%</td>
<td>1.1%</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>5.3%</td>
<td>1.7%</td>
<td>1.3%</td>
<td>0.8%</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>-</td>
<td>14%</td>
<td>3.2%</td>
<td>2.0%</td>
</tr>
<tr>
<td>$BR_{inv}$</td>
<td>0.9%</td>
<td>&lt;0.9%</td>
<td>&lt;0.9%</td>
<td>0.4%</td>
</tr>
</tbody>
</table>

4/30/2015
Alain Blondel FCC Future Circular Colliders

10BS$ ILC
example of challenge: crab crossing to increase further luminosity? (Novosibirsk) emittance and polarization compensation, etc
Beam polarization and E-calibration @ TLEP

Precise measurement of $E_{\text{beam}}$ by resonant depolarization

$\sim 100 \text{ keV each time the measurement is made}$

At LEP transverse polarization was achieved routinely at Z peak.

instrumental in $10^{-3}$ measurement of the Z width in 1993

led to prediction of top quark mass (179+/- 20 GeV) in March 1994

Polarization in collisions was observed (40% at BBTS = 0.04)

At LEP beam energy spread destroyed polarization above 60 GeV

$\sigma_E \propto E^2/\sqrt{\rho} \Rightarrow \text{At TLEP transverse polarization up to at least 80 GeV}$

to go to higher energies requires spin rotators and siberian snake

TLEP: use ‘single’ bunches to measure the beam energy continuously

no interpolation errors due to tides, ground motion or trains etc...

$\ll 100 \text{ keV beam energy calibration around Z peak and W pair threshold.}$

$\Delta m_Z \sim 0.1 \text{ MeV, } \Delta \Gamma_Z \sim 0.1 \text{ MeV, } \Delta m_W \sim 0.5 \text{ MeV}$

4/30/2015
in 2010 Shaposhnikov and Wetterich predict $m_H=126$ GeV
if there is no intermediate energy scale between the Fermi and Planck scales...
Work/meeting structures established based on INDICO, see:
- **FCC Study: [https://indico.cern.ch/category/5153/](https://indico.cern.ch/category/5153/)**
- **http://cern.ch/FCC-ee** (more developed, for FCC-ee)

In particular:

- **FCC-hh Hadron Collider Physics and Experiments VIDYO meetings**
  - [https://indico.cern.ch/category/5258/](https://indico.cern.ch/category/5258/)
  - **Contacts:** michelangelo.mangano@cern.ch, fabiola.gianotti@cern.ch, austin.ball@cern.ch

- **FCC-ee Lepton Collider (TLEP) Physics and Experiments VIDYO meetings**
  - [https://indico.cern.ch/category/5259/](https://indico.cern.ch/category/5259/)
  - **Contacts:** alain.blondel@cern.ch, patrick.janot@cern.ch
- FCC-hh Hadron Collider VIDYO meetings
  - [https://indico.cern.ch/category/5263/](https://indico.cern.ch/category/5263/)
  - Contacts: daniel.schulte@cern.ch

- FCC-hadron injector meetings
  - [https://indico.cern.ch/category/5262/](https://indico.cern.ch/category/5262/)
  - Contacts: brennan.goddard@cern.ch

- FCC-ee (TLEP) Lepton Collider VIDYO meetings
  - [https://indico.cern.ch/category/5264/](https://indico.cern.ch/category/5264/)
  - Contacts: jorg.wenninger@cern.ch,

- FCC infrastructure meetings
  - [https://indico.cern.ch/category/5253/](https://indico.cern.ch/category/5253/)
  - Contacts: philippe.lebrun@cern.ch, peter.sollander@cern.ch
The Higgs Boson

**Discovered Higgs-like Boson:** Clear mass peak in $\gamma\gamma$ and $ZZ^*$ → 4l

Is this the SM one? From searches to measurements

CMS

HCP

observed: 6.9; expected: 7.8
1994-1999: top mass predicted (LEP, mostly Z mass & width) 
top quark discovered (Tevatron) 
t’Hooft and Veltman get Nobel Prize
We cannot explain:

Dark matter

Standard Model particles constitute only 5% of the energy in the Universe

Where is antimatter gone?

What makes neutrino masses?

Not a unique solution in the SM --
Dirac masses (why so small?)
Majorana masses (why not Dirac?)
Both (the preferred scenarios, see-saw...)
⇒ heavy right handed neutrinos?
we cannot explain:

charge of proton = - charge of electron

\[ \left| q_p + q_e \right| / e < 1 \times 10^{-21} \]

we have no explanation for this, except ...
that it is necessary for the stability of
1. the universe
2. the Standard Model calculations
## PARAMETERS FOR CRAB WAIST OPERATION

<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>W</th>
<th>H</th>
<th>tt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>45</td>
<td>80</td>
<td>120</td>
<td>175</td>
</tr>
<tr>
<td>Perimeter [km]</td>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crossing angle [mrad]</td>
<td></td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particles per bunch [10^{11}]</td>
<td>1</td>
<td>4</td>
<td>4.7</td>
<td>4</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>29791</td>
<td>739</td>
<td>127</td>
<td>33</td>
</tr>
<tr>
<td>Energy spread [10^{-3}]</td>
<td>1.1</td>
<td>2.1</td>
<td>2.4</td>
<td>2.6</td>
</tr>
<tr>
<td>Emittance hor. [nm]</td>
<td>0.14</td>
<td>0.44</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>Emittance ver. [pm]</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4.3</td>
</tr>
<tr>
<td>$\beta_x^<em>/\beta_y^</em>$ [m]</td>
<td></td>
<td>0.5/0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity / IP [10^{34} cm^{-2} s^{-1}]</td>
<td>Nominal:</td>
<td>28</td>
<td>12</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>212</td>
<td>36</td>
<td>9</td>
<td>1.3</td>
</tr>
<tr>
<td>Energy loss / turn [GeV]</td>
<td>0.03</td>
<td>0.3</td>
<td>1.7</td>
<td>7.7</td>
</tr>
</tbody>
</table>

*Important scope for improvement in luminosity.*
Luminosity optimisation

Ideal situation is that beam lifetime is driven by particle-particle interactions
  -- dominated by radiative Bhabha scattering $e^+e^- \rightarrow e^+e^-\gamma$ (typically 150 mb)
    with $e^+/-$ out of energy acceptance (improved with larger acceptance)

At high luminosity considered in FCC-ee, Beamstrahlung (particle-opp. beam interaction) becomes important.
  -- requires very flat beams and +- 2% energy acceptance
  -- reduces beam lifetime
  -- increases energy spread and bunch length
This is the case in FCC-tt

At lower energy the beams are blowing eachother (beam-beam interaction)
  -- this can be fought with ‘crab waist’ crossing
This is the case at all lower energies operating points

Numbers in main parameter list include beamstrahlung treatment, but have not considered crab waist operation.
Luminosity

\[ efkN = \text{beam current} \propto \frac{1}{E^4} \]

\[ L = \frac{f k N^2}{4\pi \sigma_x \sigma_y} \]

\[ \xi_y \propto \frac{\beta_y^* N}{E \sigma_x \sigma_y} \leq \xi_{y,\text{max}}(E) \]

\[ L \propto \frac{P_{SR}}{E^3} \frac{\xi_y}{\beta_y^*} \]

\[ \sigma = \text{beam size} \]

\[ k = \text{no. bunches} \]

\[ f = \text{rev. frequency} \]

\[ N = \text{bunch population} \]

\[ P_{SR} = \text{synch. rad. power} \]

\[ \beta^* = \text{betatron fct at IP} \]

(beam envelope)
Crab Waist Scheme

\[ \phi = \frac{\sigma_z}{\sigma_x} \tan \left( \frac{\theta}{2} \right) \] – Piwinski angle

1) Large Piwinski angle: \( \phi \gg 1 \)
2) \( \beta_y \) approx. equals to overlapping area: \( \beta_y \sim \sigma_z / \phi \)
3) Crab Waist: minimum of \( \beta_y \) along the axis of the opposite beam

Advantages:

- Impact of hour-glass is small and does not depend on bunch lengthening
- Suppression of betatron coupling resonances allows to achieve \( \xi_y \sim 0.2 \)
- As a result, luminosity can be significantly increased especially at Z, otherwise \( \xi_y \sim 0.03 \)
The beam-beam parameter $\xi$ measures the strength of the field sensed by the particles due to the counter-rotating bunch.

Beam-beam parameter limits are empirically scaled from LEP data (also 4 IPs).

$$\xi_y \propto \frac{\beta_y^* N}{E \sigma_x \sigma_y} \leq \xi_{y\max}^\max(E)$$

$$\xi_{y\max}(E) \propto \frac{1}{\tau_s^{0.4}} \propto E^{1.2}$$

$L \propto \frac{P_{SR}}{E^{1.8}} \frac{1}{\beta_y^*}$

$\xi_y$ and $L$ may be raised significantly ($x$ 4) with Crab-Waist schemes!
Beam-beam simulations

FCC-ee in crab-waist mode at the Z pole (45.5 GeV):
$L \approx 1.5 \times 10^{36} \text{ cm}^{-2}\text{s}^{-1} \text{ per IP}$

BBSS strong-strong simulation with beamstrahlung

FCC-ee at 120 GeV:
$L \approx 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \text{ per IP}$

Tracking confirms assumptions!
Hard photon emission at the IPs, ‘Beamstrahlung’, can become a lifetime / performance limit for large bunch populations \((N)\), small hor. beam size \((\sigma_x)\) and short bunches \((\sigma_s)\).

\[
\tau_{bs} \propto \frac{\rho^{3/2}\sqrt{\eta}}{\sigma_s} \exp(A\eta\rho)
\]

\[
\frac{1}{\rho} \approx \frac{N r_e}{\gamma \sigma_x \sigma_s}
\]

\(\eta\) : ring energy acceptance

\(\rho\) : mean bending radius at the IP (in the field of the opposing bunch)

Lifetime expression by V. Telnov

To ensure an acceptable lifetime, \(\rho \times \eta\) must be sufficiently large.

- Flat beams: large \(\sigma_x\) and small \(\sigma_y\)!
- Bunch length!
- Large momentum acceptance of the lattice: 1.5 – 2% required.
  - LEP had < 1% acceptance, SuperKEKB \sim 1-1.5%.

Alain Blondel  FCC-ee  Epiphany Conference Krakow
Reasonable agreement between tracking and analytical estimates.

$E_{\text{beam}} = 175$ GeV (most critical case)

- Formula of A. Bogomyagkov
- Formula of V. Telnov

Calculations include dynamic $\beta^*$ function

M. Koratzinos, K. Ohmi, V. Telnov, A. Bogomyagkov, E. Levichev, D. Shatilov
Emittances

- FCC-ee is a very large machine, scaling of achievable emittances (mainly vertical) is not straightforward.
  - Coupling, spurious vertical dispersion.

- Low emittances tend to be more difficult to achieve in colliders as compared to light sources or damping rings – beam-beam!

- FCC-ee parameters:
  - $\varepsilon_y / \varepsilon_x \geq 0.001$
  - $\varepsilon_y \approx 2 \text{ pm}$
  with a ring ~50-100 larger than a typical light source.

- Very challenging target for a ring of that size!

- LEP2 achieved routinely 0.004
  beam corrections are much better now.

R. Bartolini, DIAMOND
Adding masses to the Standard model neutrino 'simply' by adding a Dirac mass term (Yukawa coupling)

\[ m_D \nu_L \nu_R \quad m_D \nu_L \nu_R \]

implies adding a right-handed neutrino (new particle)

No SM symmetry prevents adding then a term like

\[ m_M \nu_R^c \nu_R \quad (\bar{\nu})_R \nu_L \]

and this simply means that a neutrino turns into a antineutrino (the charge conjugate of a right handed antineutrino is a left handed neutrino!)

It is perfectly conceivable (‘natural’?) that both terms are present ➔ ‘see-saw’