FCC-ee Phenomenology

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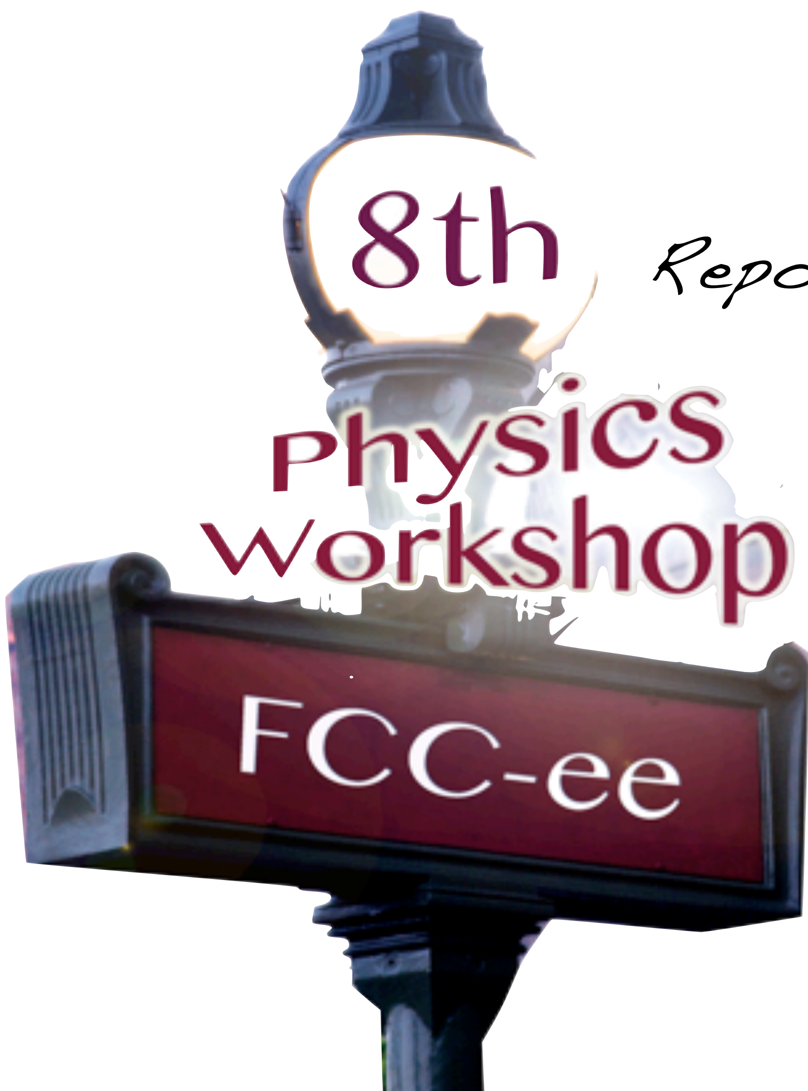


Report of the phenomenology session of the
Eigth FCC-ee Physics Workshop
Paris, October 27-29, 2014

Open issues for Higgs @ TLEP

- Access to light quark couplings via rare decays, e.g. $h \to J/\Psi + \gamma$ or $h \to \Phi + \gamma$? See Y. Soreq's talk
- Access to electron coupling? See D. d'Enterria's talk
- s-channel production: $\gamma\gamma \to h \to bb$ See P. Rebello Teles' talk
- Complementarity with EW precision data and Anomalous gauge couplings?
- Probing CP-odd couplings? See A. Falkowski's and T. You's talks
- Probing invisible Higgs decay, e.g. for Dark Matter Higgs portals?
- Estimating the sensitivity on flavor-violating Higgs decay, e.g. $h \to \tau + \mu$?

Higgs couplings to light quarks

See Y. Soreq's talk

BOUNDS ON LIGHT QUARK YUKAWA

from inclusive Higgs decays

Indirect bounds on light-quark Yukawas from current Higgs data (naive χ^2)

diagonal:

$$y_u/y_b^{\rm SM} < 1.0(1.3) \qquad y_d/y_b^{\rm SM} < 0.9(1.4)$$

$$y_s/y_b^{\rm SM} < 0.7(1.4) \qquad y_c/y_b^{\rm SM} < 0.7(1.4)$$

only the corresponding Yukawa is varied

all Higgs couplings are allowed to vary

@ 95% CL

off-diagonal: $y_{qq'}/y_b^{\rm SM} < 0.6(1) \qquad q, q' \in u, d, s, c, b \qquad q \neq q'$

FCNC not robust bound $y_{bs}/y_b^{\rm SM} < 8 \times 10^{-2}$

Harnik, Kopp, Zupan 1209.1397
Blankenburg, Ellis, Isidori 1202.5704

Can even be larger than the SM bottom Yukawa!

Leads to interesting Higgs phenomenology

Delaunay, Golling, Perez, YS 1310.7029

Yotam Soreq - "An Exclusive Window onto Higgs Yukawa Couplings" FCC ee/TLEP8

Important measurements

1. to understand flavor origins
2. to know if the Higgs vev is the only mass generator

Higgs couplings to light quarks

See Y. Soreq's talk

Exclusive decays

$h \to MV$

vector meson

γ W Z → work in progress

Bodwin, Petriello, Stoynev, Velasco 1306.5770

$h \to J/\psi\,\gamma \longrightarrow y_c$

$$h \to \begin{matrix} \phi\gamma \\ \rho\gamma \\ \omega\gamma \end{matrix} \quad \begin{matrix} \longrightarrow y_s \\ \longrightarrow y_d\,,\ y_u \end{matrix}$$

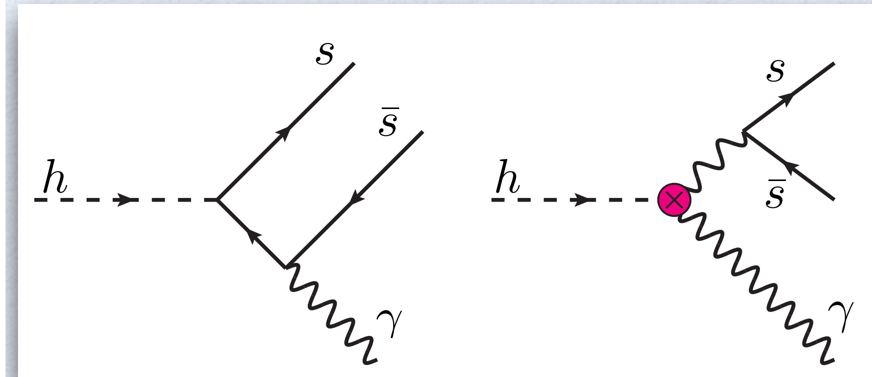
Small branching ratio, BUT reduced QCD background!

off-diagonal: $h \to \bar{B}_s^*\gamma\,,\ \bar{B}_d^*\gamma\,,\ D^*\gamma\ \ K^*\gamma$

from exclusive Higgs decays

main sensitivity to Yukawa due to interference!

direct indirect



Future experimental prospects

e^+e^- colliders:

- Very clean machine.
- σ~200 fb for $\sqrt{s}$= 240 GeV. 1308.6176
- For integrated luminosity of 10 pb^{-1}: 2×10^6 Higgses are expected. 1310.8361
- About 40 events in the $h\to\rho\gamma$ channel - can be used to put **direct** upper bound on the first generation Yukawa couplings at the order of the SM bottom Yukawa.

Huu and Hdd couplings: upper limit of O(2) SM value!

Higgs coupling to electrons

See D. d'Enterria's talk

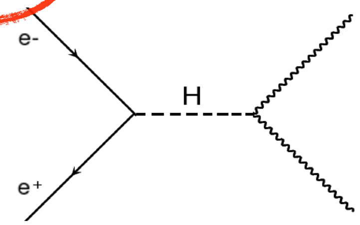
Resonant s-channel $e^+e^- \to H$ production

- Resonant Higgs production considered so far only for muon collider: $\sigma(\mu\mu \to H) \sim 70$ pb. Tiny g_{Hee} Yukawa coupling $\Rightarrow$ Tiny $\sigma(ee \to H)$

$$\frac{g_{H\mu\mu}}{g_{Hee}} \propto \frac{m_\mu^2}{m_e^2} = 4.28 \times 10^4$$

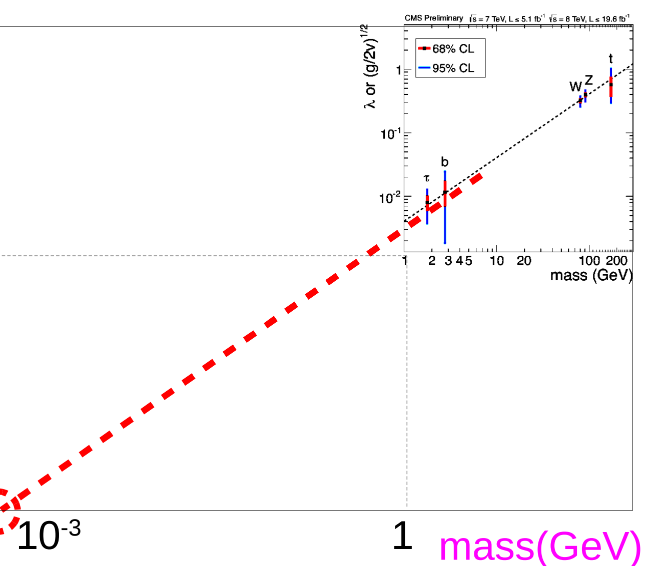
BR($H \to e^+e^-$) ~ $5.3 \cdot 10^{-9}$ (decay unobservable)

$$\sigma(e^+ e^- \to H) = \frac{4\pi \Gamma_H^2 Br(H \to e^+ e^-)}{(\hat{s} - M_H^2)^2 + \Gamma_H^2 M_H^2} = 1.64 \text{ fb } (m_H = 125 \text{ GeV}, \Gamma_H = 4.2 \text{ MeV})$$



$\sigma_{beam\text{-}spread+ISR}(e^+e^- \to H) = 0.17 \times \sigma(e^+e^- \to H)$

- Huge luminosities available at FCC-ee:

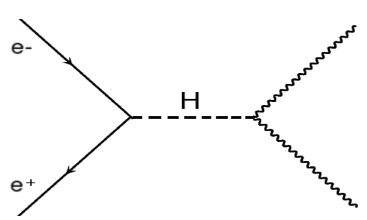


In theory, FCC-ee (L_{int}~10 ab^{-1}/yr) running at H-pole mass would produce O(16.000) H's

IFF we can handle: (i) beam-energy spread, (ii) ISR, and (iii) huge backgrounds...

→ Electron Yukawa coupling measurable?
→ Higgs width measurable (threshold scan)?
→ Separation of possible nearly-degen. H's?

what makes
this measurement challenging



$\sigma(e^+e^- \to H)_{B\text{-}W} \sim 1.64$ fb

$\sigma(e^+e^- \to H)_{visible} \sim 280$ ab (ISR + $E_{beam\text{-}spread} \sim \Gamma_H = 4.2$ MeV)

$L_{int} = 10\ ab^{-1}$, S=0.65: BR(Hee) < $4.63 \times BR_{SM}$ (3σ), $g_{hee} < 2.15 \times g_{Hee,SM}$ (3σ)

Are we ready to run @ 125GeV for x years to put a bound on the Hee coupling?

s-channel Higgs production $\gamma\gamma \to h \to bb$

See P. Rebello Teles' talk

$\gamma\gamma$ effective luminosities: $\mathcal{L}_{eff}(FCC,\gamma\gamma) \sim 20 \times \mathcal{L}_{eff}(pp\text{-}LHC,\gamma\gamma)$

- $\gamma\gamma$ collision offers the unique possibility to produce Higgs boson as s-channel resonance

- Signal:
  $\sqrt{s}$ = 161GeV: 0.053fb
  N(H → bb~)=**53** counts/ab^{-1}

  $\sqrt{s}$ = 240GeV: 0.208fb
  N(H → bb~)=**208** counts/ab^{-1}

- Backgrounds:
  Dominant $e^+e^- \to Z^*,\gamma^* \to$ bb~ (~2 pb without cuts) should be killed with e$^\pm$ tagging.

  Continuum $\gamma\gamma \to$ bb~(cc~,qq~)
  Effic(b-jet reco) = (70%)^2
  Prob(b-mistag.)=(5%)^2 (c)
  Prob(b-mistag.)=(1.5%)^2 (q)

- $\gamma\gamma \to H \to$ bb~ channel :
  - $e^+e^- \to$ bb~ removed by e$^\pm$ tagging (loss of 75% of signal);
  - Continuum $\gamma\gamma$ backgrounds removed with cuts in suitable kinematical variables ($\theta_{e\pm}$, p_{TJets} and M_{bb})
  - **Evidence/Observation $\gamma\gamma \to H \to$ bb~ with 1 ab^{-1} at FCC-ee(160, 240 GeV).**

Patrick's question:

There must also be some $(\gamma^* \to \rho)\,\gamma \to h$ and $\rho\rho \to h$ if I remember my vector-dominance model from LEP.
Can we exploit those to also constrain κ_u and κ_d ?

by-product:

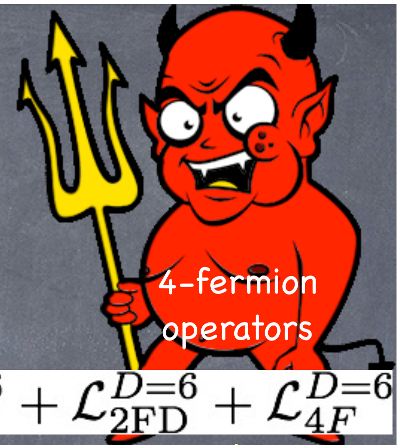
also studying $\gamma\gamma \to WW \to 4l$ to put bound on aQGC

Complementarity Higgs-EW-TGC data

See A. Falkowski's and T. You talks

(all hell breaks loose) **Dimension-6 Lagrangian**

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{v}\mathcal{L}^{D=5} + \frac{1}{v^2}\mathcal{L}^{D=6} + \dots$$



Higgs interactions with itself | Higgs interactions with gauge bosons | 2-fermion Yukawa interactions

$$\mathcal{L}^{D=6} = \mathcal{L}^{D=6}_{\rm H} + \mathcal{L}^{D=6}_{\rm V} + \mathcal{L}^{D=6}_{\rm HV} + \mathcal{L}^{D=6}_{\rm 2FV} + \mathcal{L}^{D=6}_{\rm 2FY} + \mathcal{L}^{D=6}_{\rm 2FD} + \mathcal{L}^{D=6}_{\rm 4F}$$

Self-interactions of gauge bosons | 2-fermion vertex corrections | 2-fermion dipole operators

e.g.

$O_H = \partial_\mu (H^\dagger H) \partial_\mu (H^\dagger H)$

$O'_{HL} = \bar{\ell}\sigma^i \bar{\sigma}_\mu l H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$

$O_{BE} = H^\dagger \bar{\sigma}_{\mu\nu} \ell e^c B_{\mu\nu}$

$O_u = H^\dagger H H q Y_u u^c$

$O_{3W} = \epsilon^{ijk} W^{i\,\nu}_{\mu} W^{j\,\rho}_{\nu} W^{k\,\mu}_{\rho}$

$O'_{e\mu} = (\bar{e}\sigma$

$O_S = B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$

To take away

- There are strong constraints on certain combinations of dimension-6 operators from the pole observables measured at LEP-1 and other colliders
- WW production process is extremely important, because it lifts flat directions of the pole observables
- Current model independent LEP-2 constrain are weak, due to an accidental flat directions
- Better probes of dimension-6 operators in WW production should be designed for future e+e- colliders

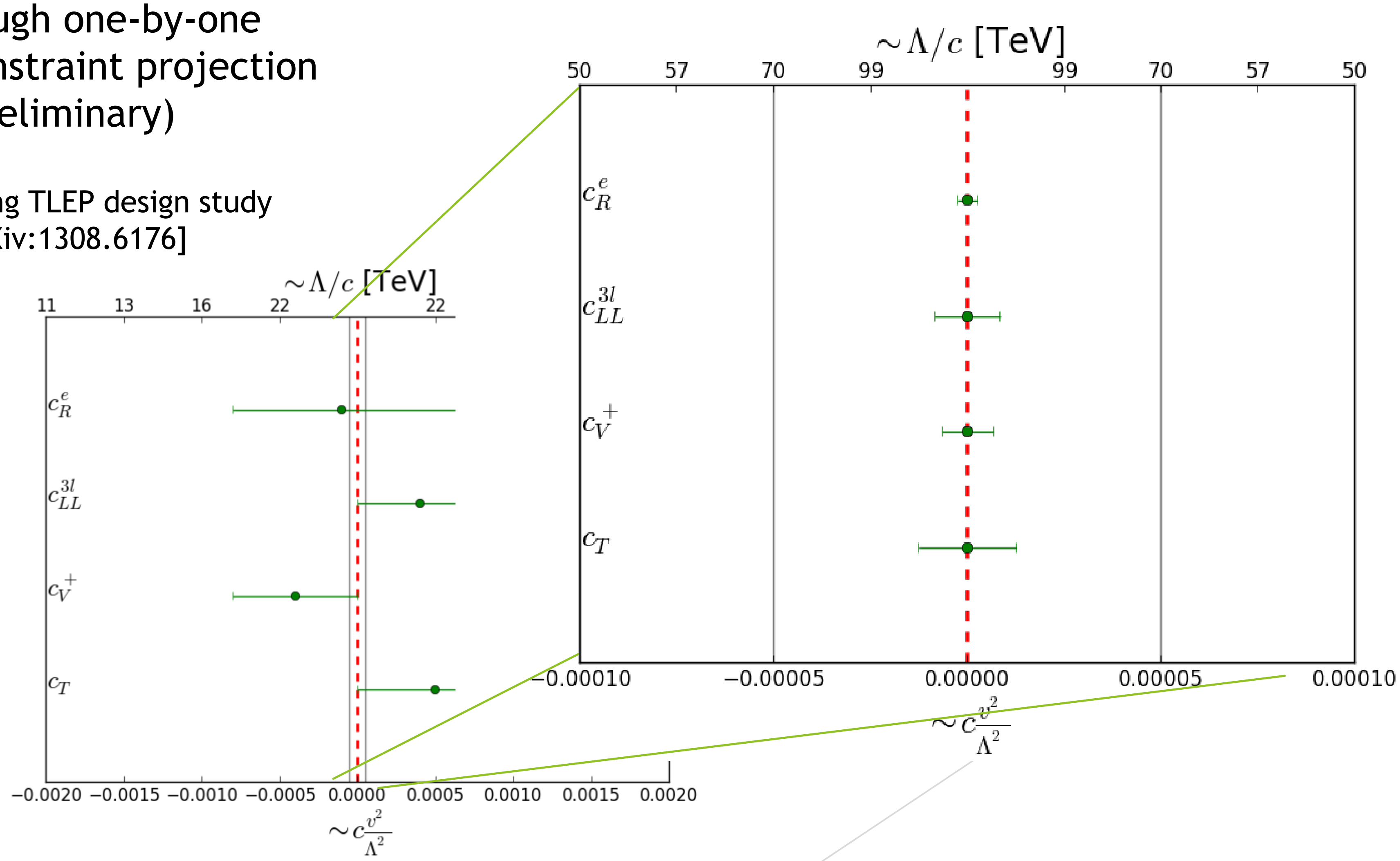
Complementarity Higgs-EW-TGC data

See A. Falkowski's and T. You talks

FCC-ee (TLEP)

Rough one-by-one constraint projection (Preliminary)

Using TLEP design study [arXiv:1308.6176]



See also recent preprint arXiv:1411.1054 by J.Fan, M. Reece and L-T. Wang

Physics with Large statistics

- 10^{12} Z (line-shape, mass & width, probe rare (FCNC) decays)
- 10^{8} W (mass)
- 3×10^{10} tau/muon pairs
- 2×10^{11} b/c quarks ⇒ >20'000 $B_s \to \tau^+\tau^-$
- TLEP@340/500: 10^{6} top pairs (pole mass, probe FCNC decays, top Yukawa)

What can we do with increased precision?

- indirect search for RH neutrinos for EW precision tests — See O. Fischer's talk
- direct search for RH neutrinos for Z decays — See N. Serra's talk

The precision challenges

See F. Piccinini's talk

- very high statistics at the Z peak poses some challenges for a model-independent extraction of the derived parameters
- a data/theory comparison at the level of measured cross sections could be more safe, even if
  - it requires more involved complete theoretical calculations for the processes $e^+e^- \to f\bar{f}$ within and in models beyond SM
  - it renders more involved the average over different experiments
- high precision predictions for Bhabha scattering will be required
- hadronic contributions to vacuum polarization will require input from high intensity low energy machines

- within or Beyond the SM, the high precision of FCCee will require higher order perturbative calculations

Indirect search for ν_R

See O. Fischer's talk

Presence of massive right-handed neutrinos (ν_R):

$$\mathscr{L}_{\text{Theory}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{\nu_R}$$

Leads to mixing of the neutral states (ν_L, ν_R):

$$\mathcal{U} = \begin{pmatrix} \begin{pmatrix} & N & \end{pmatrix} & \cdots \\ \vdots & \ddots \end{pmatrix} \quad \text{with} \quad \mathcal{U}^\dagger \mathcal{U} = 1$$

- $N \sim$ Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
- PMNS as submatrix in general **not** unitary

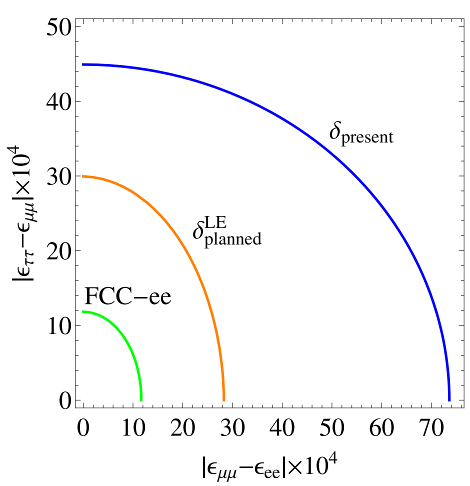
$$(NN^\dagger)_{\alpha\beta} = \mathbb{1}_{\alpha\beta} + \varepsilon_{\alpha\beta}$$

current bounds

-0.0021	$\leq \varepsilon_{ee} \leq$	-0.0002	$\lvert\varepsilon_{e\mu}\rvert$	$<$	1.0×10^{-5}
-0.0004	$\leq \varepsilon_{\mu\mu} \leq$	0	$\lvert\varepsilon_{e\tau}\rvert$	$<$	2.1×10^{-3}
-0.0053	$\leq \varepsilon_{\tau\tau} \leq$	0	$\lvert\varepsilon_{\mu\tau}\rvert$	$<$	8.0×10^{-4}

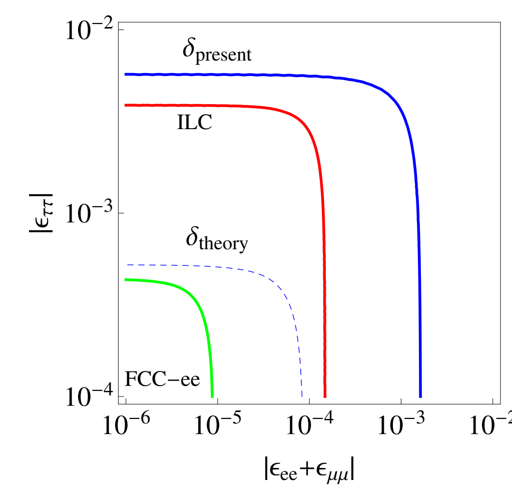
future prospects

Sensitivity to Non-Unitarity from Lepton Universality Tests



- Assumption: SM is true ($\varepsilon \equiv 0$ & $O^{exp} = O^{SM}$).
- Blue line: experimental constrains (present).
- Orange line: experimental sensitivity (planned). *MOLLER, TRIUMF, PSI, NA62, Tau/Charm factories*
- Green line: W decays at the FCC-ee.

Sensitivity to Non-Unitarity from EWPOs

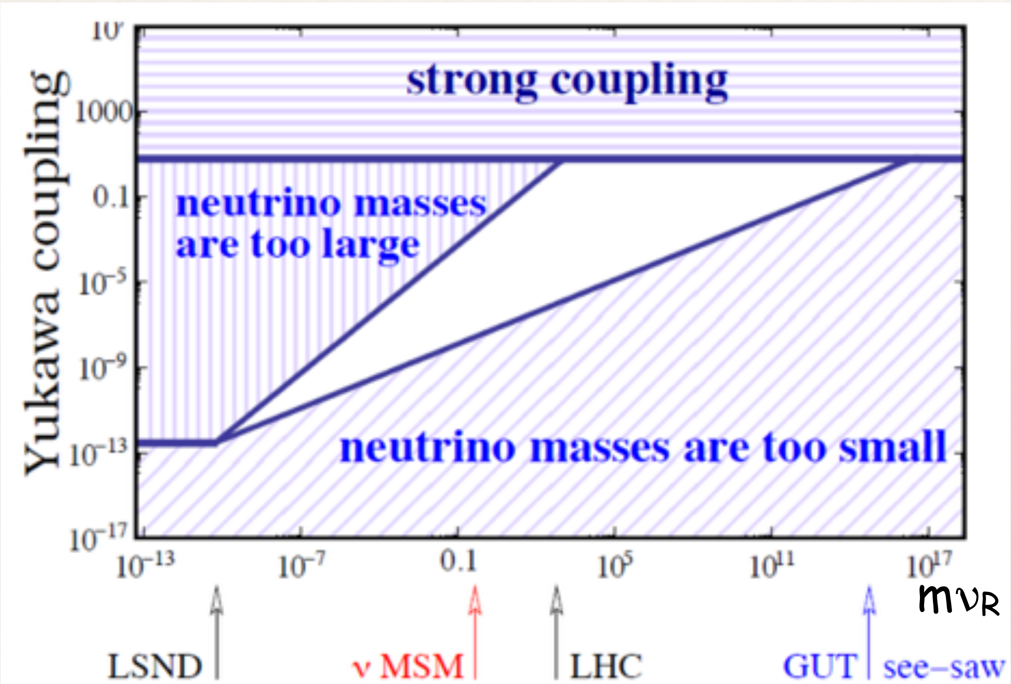


- Non-unitarity of the EWPO only.
- Blue lines: theoretical and experimental constrains (present).
- Red/Green line: ILC/FCC-ee sensitivity, see Backup VI.
- $\varepsilon_{\alpha\beta} = -y^*_\alpha y_\beta v^2_{EW}/(2\, m^2_{\nu_R}) \Rightarrow$ Test m_{ν_R} up to $\sim$ 60 TeV.

FCC-ee sensitive to m_{ν_R}~60TeV but not ν_R of traditional seesaw Actually, for **traditional seesaw**: $\varepsilon \sim 10^{-5} \times (10\text{keV}/m_{\nu_R}) \Rightarrow$ no visible effects

Direct search for (light) ν_R

See N. Serra's talk



$m\nu_R$ [GeV]

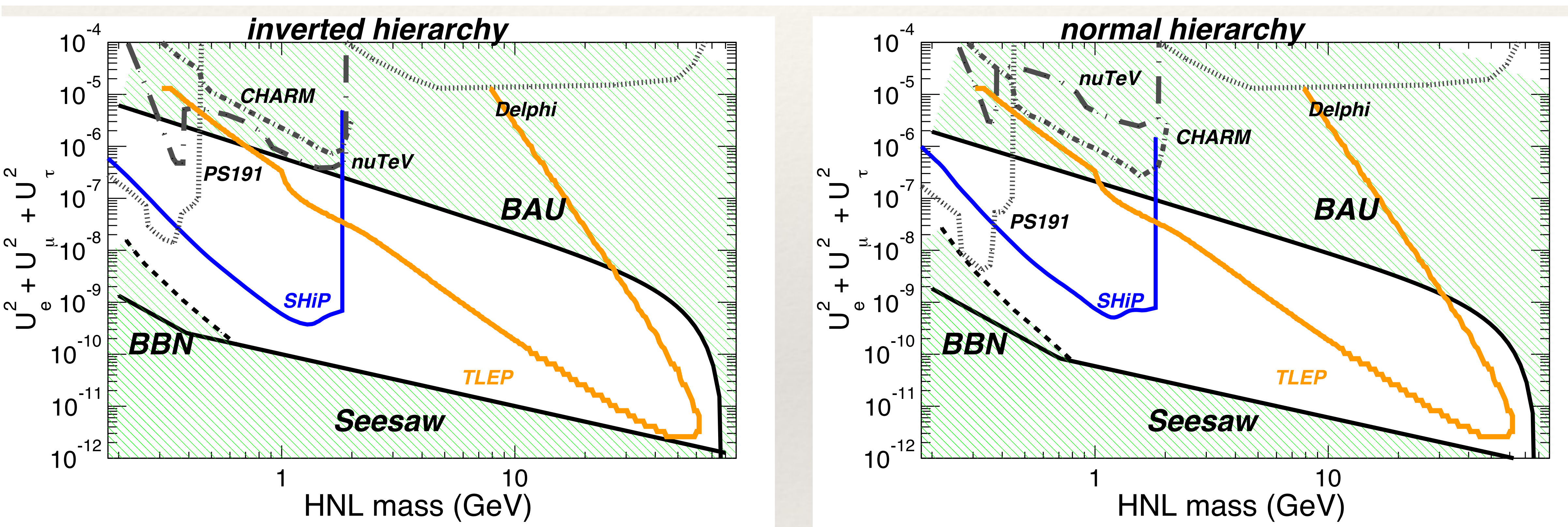
- Assuming $m_\nu = 0.1\text{eV}$
- if $Y \sim 1$ implies $M \sim 10^{14}\text{GeV}$
- if $M_N \sim 1\text{GeV}$ implies $Y_\nu \sim 10^{-7}$

remember $Y_{top} \sim 1.$ and $Y_e \sim 10^{-6}$

Traditional seesaw

$m\nu_L = Y^2 v^2 / m\nu_R$

ν_R are produced in the 10^{12} TLEP Z decays and can be searched for



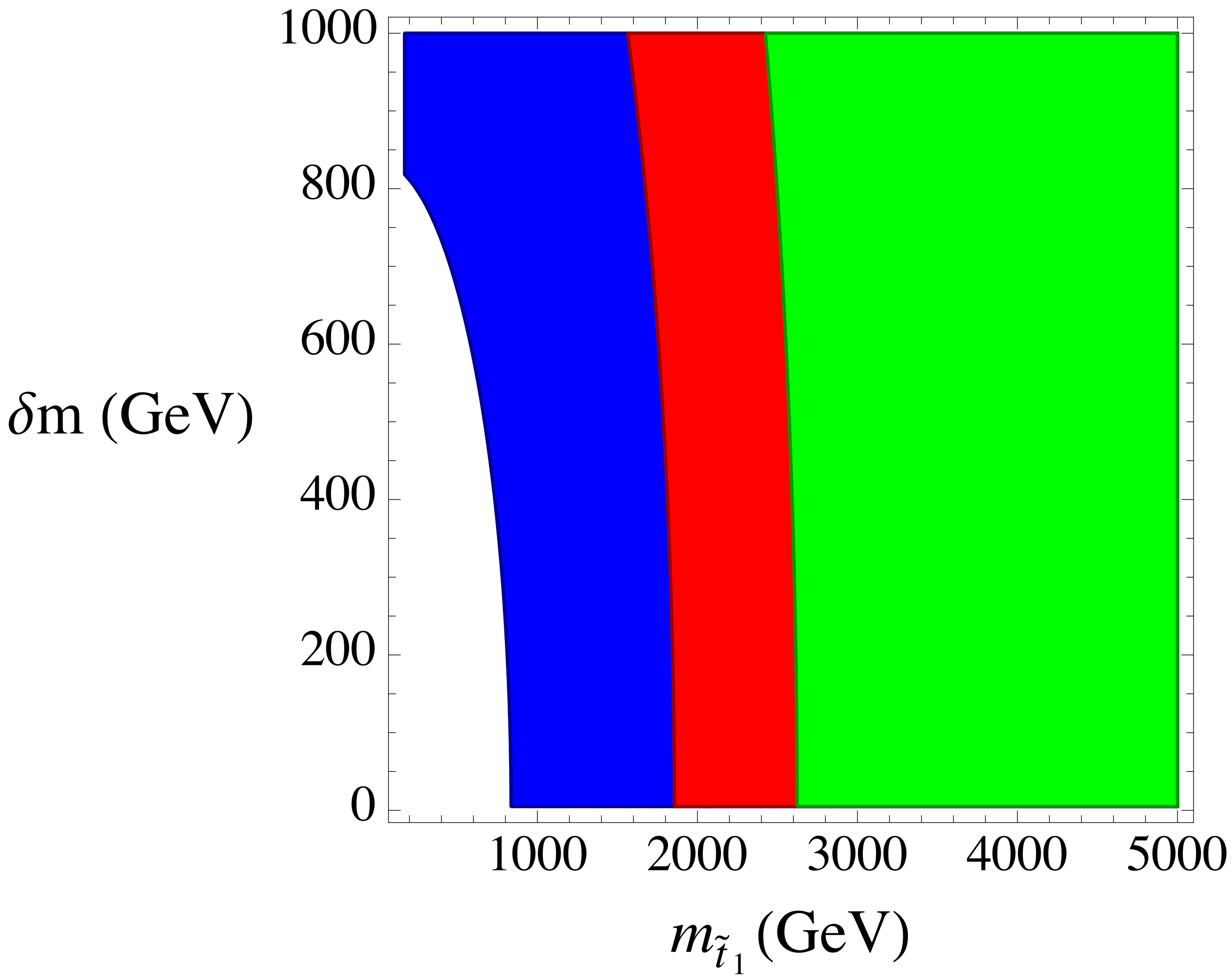
W mass and New Physics

See S. Heinemeyer's talk

In the SM, W mass is "predicted" in terms of Z mass, G_F, α_{em}...

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1+\Delta r)$$

Any deviation (if the TH uncertainty can be kept under control) tests NP



Probing MSSM stops

$\delta m_W < 5\,\mathrm{MeV} \Rightarrow m_{\tilde{t}_1} > 850\,\mathrm{GeV}$

$\delta m_W < 1\,\mathrm{MeV} \Rightarrow m_{\tilde{t}_1} > 1.9\,\mathrm{TeV}$

$\delta m_W < 0.5\,\mathrm{MeV} \Rightarrow m_{\tilde{t}_1} > 2.6\,\mathrm{TeV}$

TLEP (physics case) '13

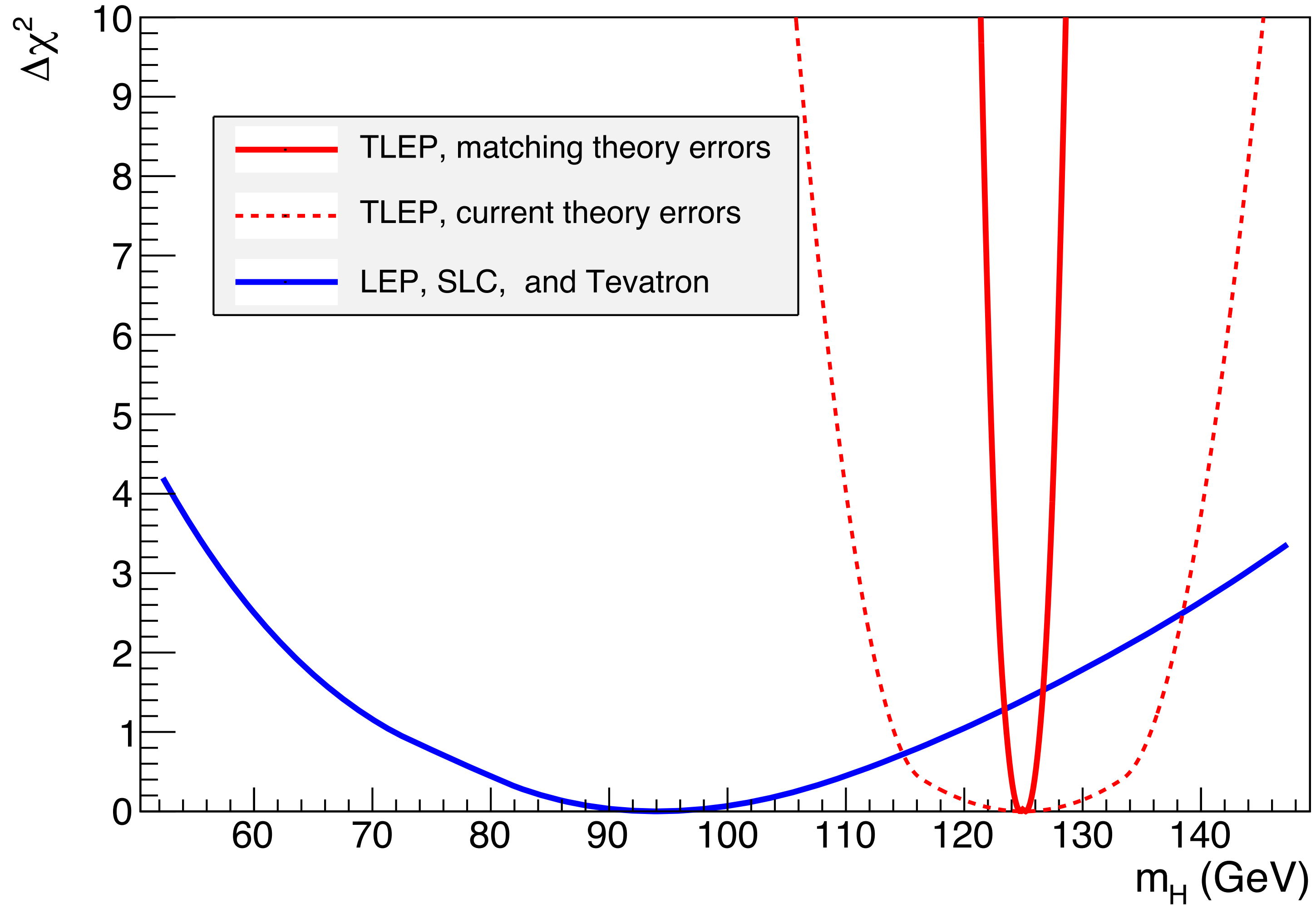
Uncertainties on input parameters

See S. Heinemeyer's talk

The measurements of today give the input parameters of tomorrow

e.g. a precise Higgs mass measurement needed for the Higgs couplings measurements

Δm_H = 200 MeV shifts prediction for BR($H \to VV$) by 2%



TLEP (physics case) '13

Where is New Physics after LHC run 1?

See A. Weiler's talk

BSM physics

heavy	stealthy
$\tilde{m} \gtrsim 1\ \mathrm{TeV}$	$\tilde{m} \sim m_h$

Precise measurements at TLEP can close the stealthy loopholes

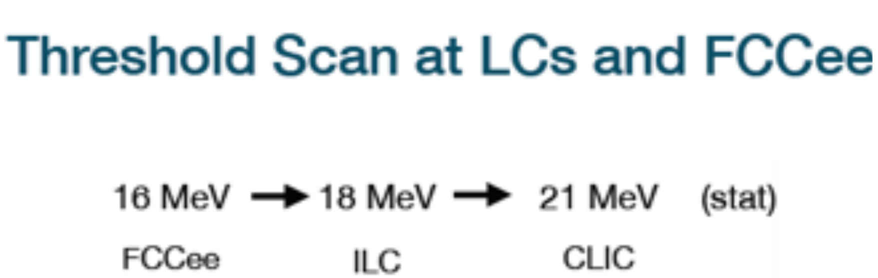
Sometimes we can learn about new physics by precisely studying the background

- WW xs example
- stop contribution to tt xs: for $m_{stop}=m_{top}$, $\sigma_{stop}/\sigma_{top}$~17% @7TeV ⇛ tt xs NNLO needed
- rare processes: $t \to cZ$ in composite Higgs models: $\mathrm{BR}(t \to cZ) \sim 10^{-5} \left(\frac{700}{M_*}\right)^4$

The top physics program @ TLEP

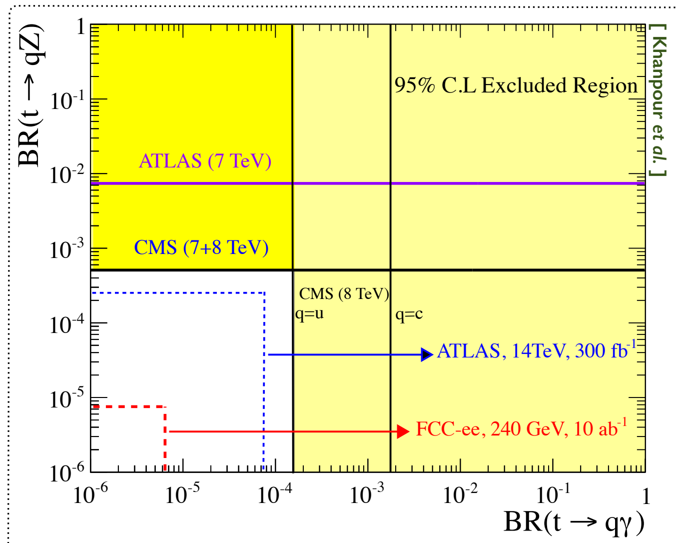
See P. Azzi's talk

- **top mass measurement at threshold @350GeV**: « the measurement »
  - need to compare with current ILC expectation. *some work being done (see later)*
  - need to have specific FCC-ee complete analysis (i.e. with detector simulation)
  - as a byproduct of these analyses would come the precise determination of other precision variables: width, Yt, etc
- **top rare decays and anomalous couplings (240 or 350)**: the real fast way to find BSM physics.
  - need to explicitly evaluate the potential. *some work being done here (see later)*
  - in particular use of single top final states profiting of higher luminosity run at 240 GeV
- **the case for 500 GeV run:**
  - direct extraction of Ytt from ttH signal
  - any other BSM signal to look for?



✦ FCNC production of a top and a light quark

✤ At a center-of-mass energy of 240 GeV

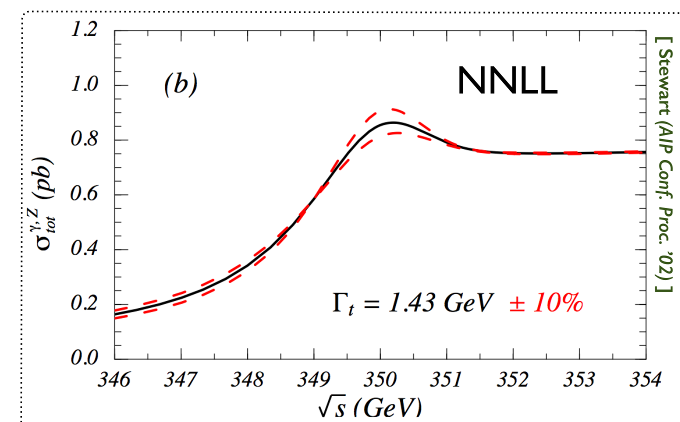


very preliminary results (IPM group) cross checks in progress: also hadronic channel being studied (Rome)

✦ Inclusive approach via $t\bar{t}$ production cross section

✤ At a center-of-mass energy of 350 GeV

✤ Five-year scan of the top-antitop threshold



[TLEP Design Working Group (JHEP'14)]

	m_{top}	Γ_{top}	λ_{top}
TLEP	**10 MeV**	**11 MeV**	**13%**
ILC	31 MeV	34 MeV	40%

✤ Indirect constraints from the top width

★ Constraining the magnitude of the rare decay modes