FCC-ee

status and goals of phenomenological studies

(aka summary of the summaries)

A. Blondel, J. Ellis, C. Grojean and P. Janot

10th FCC-ee physics workshop
February 4, 2016

The physics questions are at the root of the science drivers for politics...

The Science Drivers

- P5 distilled the 11 groups of physics questions formulated at Snowmass into 5 compelling lines of inquiry that show great promise for discovery over the next 10 to 20 years.

- **The Science Drivers**:
  - **Use the Higgs boson as a new tool for discovery.**
  - **Pursue the physics associated with neutrino mass.**
  - **Identify the new physics of dark matter.**
  - **Understand cosmic acceleration: dark energy and inflation.**
  - **Explore the unknown: new particles, interactions, & physical principles.**

- *Recommendation 2:* ***Pursue a program to address the 5 science drivers.***

- The **drivers** are deliberately **not prioritized** because they are **intertwined**, probably more deeply than currently understood.
- A selected set of different experimental approaches that reinforce each other is required. **Projects are prioritized**.
- The vision for addressing each of the drivers using a selected set of experiments is given in the report, along with their approximate timescales and how they fit together.

- Explored at Energy Frontier with colliders

FCC Week 2015 - Lankford: US HEP community perspective 5

A. Lankford @ Washington '15

The handles that FCC-ee can play with to achieve its physics goals: **luminosity, beam polarization, energy**

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, Γ_Z
requires 'single bunches'
a priori doable up to W energies -- workarounds exist above (e.g. γZ events)
large ring with small emittance offers *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 *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- → H(125.2) (requires monochromatization A. Faus) (under study)
-- e+e- at ~70 GeV (Z-γ interference)
-- e+e- at top threshold + <~20 GeV for top couplings (E_max up to 180 -185 GeV)
-- no obvious case for going to 500 GeV

A. Blondet @ Washington

Phenomenology @ FCC-ee

1. Discovery via EW/Higgs physics
- potential of Higgs precision measurements
- EW precision measurements

2. EWSB and flavor probes of BSM
- sensitivity to new physics of precision EW/H observables
- direct searches
- rare phenomena: rare Higgs/Z decays, flavor violating decays

3. Probes of high-mass frontier
- search for sterile neutrinos
- fit of deformations of SM by higher-dimensional operators

4. DM @ FCC-ee

FCC-ee/eh/hh complementarity/interplay?

The FCC-ee phenomenology reference

Cornell University Library

We gratefully acknowledge support from the Simons Foundation and The Alliance of Science Organisations in Germany, coordinated by TIB, MPG and HGF

arXiv.org > hep-ex > arXiv:1308.6176

Search or Article-id (Help | Advanced search) All papers Go!

High Energy Physics – Experiment

First Look at the Physics Case of TLEP

M. Bicer, H. Duran Yildiz, I. Yildiz, G. Coignet, M. Delmastro, T. Alexopoulos, C. Grojean, S. Antusch, T. Sen, H.-J. He, K. Potamianos, S. Haug, A. Moreno, A. Heister, V. Sanz, G. Gomez-Ceballos, M. Klute, M. Zanetti, L.-T. Wang, M. Dam, C. Boehm, N. Glover, F. Krauss, A. Lenz, M. Syphers, C. Leonidopoulos, V. Ciulli, P. Lenzi, G. Sguazzoni, M. Antonelli, M. Boscolo, U. Dosselli, O. Frasciello, C. Milardi, G. Venanzoni, M. Zobov, J. van der Bij, M. de Gruttola, D.-W. Kim, M. Bachtis, A. Butterworth, C.Bernet, C. Botta, F. Carminati, A. David, D. d'Enterria, L. Deniau, G. Ganis, B. Goddard, G. Giudice, P. Janot, J. M. Jowett, C. Lourenco, L. Malgeri, E. Meschi, F. Moortgat, P. Musella, J. A. Osborne, L. Perrozzi, M. Pierini, L. Rinolfi, A. de Roeck, J. Rojo, G. Roy, A. Sciaba, A. Valassi, et al. (65 additional authors not shown)

(Submitted on 28 Aug 2013 (v1), last revised 11 Dec 2013 (this version, v3))

The discovery by the ATLAS and CMS experiments of a new boson with mass around 125 GeV and with measured properties compatible with those of a Standard-Model Higgs boson, coupled with the absence of discoveries of phenomena beyond the Standard Model at the TeV scale, has triggered interest in ideas for future Higgs factories. A new circular e+e- collider hosted in a 80 to 100 km tunnel, TLEP, is among the most attractive solutions proposed so far. It has a clean experimental environment, produces high luminosity for top-quark, Higgs boson, W and Z studies, accommodates multiple detectors, and can reach energies up to the t-tbar threshold and beyond. It will enable measurements of the Higgs boson properties and of Electroweak Symmetry-Breaking (EWSB) parameters with unequalled precision, offering exploration of physics beyond the Standard Model in the multi-TeV range. Moreover, being the natural precursor of the VHE-LHC, a 100 TeV hadron machine in the same tunnel, it builds up a long-term vision for particle physics. Altogether, the combination of TLEP and the VHE-LHC offers, for a great cost effectiveness, the best precision and the best search reach of all options presently on the market. This paper presents a first appraisal of the salient features of the TLEP physics potential, to serve as a baseline for a more extensive design study.

Comments: 43 pages, 18 figures, 11 tables, 85 references. Changes with respect to version V2: The comments from the JHEP referee are now included
Subjects: **High Energy Physics – Experiment (hep-ex)**; High Energy Physics – Phenomenology (hep-ph)
Journal reference: JHEP 01 (2014) 164
DOI: 10.1007/JHEP01(2014)164
Cite as: **arXiv:1308.6176 [hep-ex]**
(or **arXiv:1308.6176v3 [hep-ex]** for this version)

Submission history
From: Patrick Janot [view email]
[v1] Wed, 28 Aug 2013 14:55:58 GMT (2937kb,D)
[v2] Sun, 22 Sep 2013 14:13:43 GMT (1964kb,D)
[v3] Wed, 11 Dec 2013 17:16:06 GMT (1746kb,D)

Download:
- PDF
- Other formats

(license)

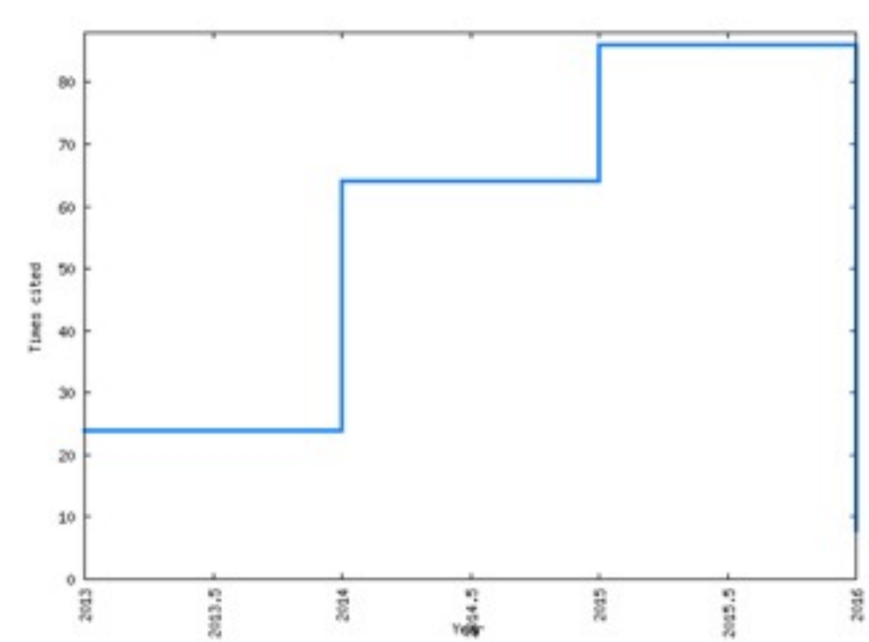
Current browse context:
hep-ex
< prev | next >
new | recent | 1308

Change to browse by:
hep-ph

References & Citations
- INSPIRE HEP (refers to | cited by)
- NASA ADS

Bookmark (what is this?)

Citation history:



Vivid activities

First FCC-ee mini-workshop on Precision Observables and Radiative Corrections

13-14 July 2015
CERN
Europe/Zurich timezone

Search

First FCC-ee workshop on Higgs physics

24-25 September 2015
CERN
Europe/Zurich timezone

Search

Workshop on high-precision alpha_s measurements: from LHC to FCC-ee

12-13 October 2015
CERN
Europe/Zurich timezone

Search

FCC-ee Mini-Workshop: "Physics Behind Precision"

2-3 February 2016
CERN
Europe/Zurich timezone

Search

1

Higgs measurements and BSM indirect searches

Higgs @ FCC-ee

K. Peters @ CERN '15

Overview of current FCC-ee Higgs results

- Higgs precision measurements

Discussion of new ideas / results

- 1st generation fermion couplings, rare decays etc.

Complementarity and synergy with other collider projects

- Complementarity between lepton and hadron colliders
- Synergies between different lepton collider studies

Which precision to aim for in Higgs measurements

- Which models can we constrain, which precision is needed
- Interplay with other EW precision measurements
- What precision is needed for the direct top-Yukawa coupling

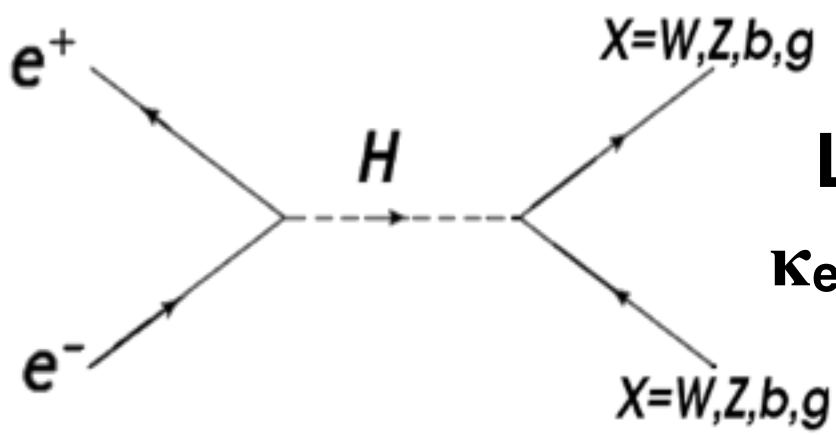
M. Klute @ CERN '15

➡ **FCC-ee offers fantastic opportunities to gain understanding of the Higgs boson and EWSB**

- Sub-precent level Higgs coupling measurements (absolute measurement, not ratios like at LHC)
- Access to first and second generation Higgs couplings (s-channel prod. & exclusive decays)
- Precision mass measurement and Higgs width (model-independent)
- Higgs CP studies
- BSM and exotic Higgs

Higgs @ FCC-ee

	Model-independent fit				Constrained fit		
Coupling	FCC-ee (240)	FCC-ee		ILC	FCC-ee		ILC
g_{HZZ}	0.16%	**0.15%**	(0.18%)	0.9%	0.05%	(0.06%)	0.31%
g_{HWW}	0.85%	**0.19%**	(0.23%)	0.5%	0.09%	(0.11%)	0.25%
g_{Hbb}	0.88%	**0.42%**	(0.52%)	2.4%	0.19%	(0.23%)	0.85%
g_{Hcc}	1.0%	**0.71%**	(0.87%)	3.8%	0.68%	(0.84%)	3.5%
g_{Hgg}	1.1%	**0.80%**	(0.98%)	4.4%	0.79%	(0.97%)	4.4%
$g_{\mathrm{H}\tau\tau}$	0.94%	**0.54%**	(0.66%)	2.9%	0.49%	(0.60%)	2.6%
$g_{\mathrm{H}\mu\mu}$	6.4%	**6.2%**	(7.6%)	45%	6.2%	(7.6%)	45%
$g_{\mathrm{H}\gamma\gamma}$	1.7%	**1.5%**	(1.8%)	14.5%	1.4%	(1.7%)	14.5%
$\mathrm{BR}_{\mathrm{exo}}$	0.48%	**0.45%**	(0.55%)	2.9%	0.16%	(0.20%)	0.9%



$L = 10\ \mathrm{ab}^{-1}$

$\kappa_e < 2.2$ at 3σ

$H \to J/\Psi\,\gamma$ → y_c

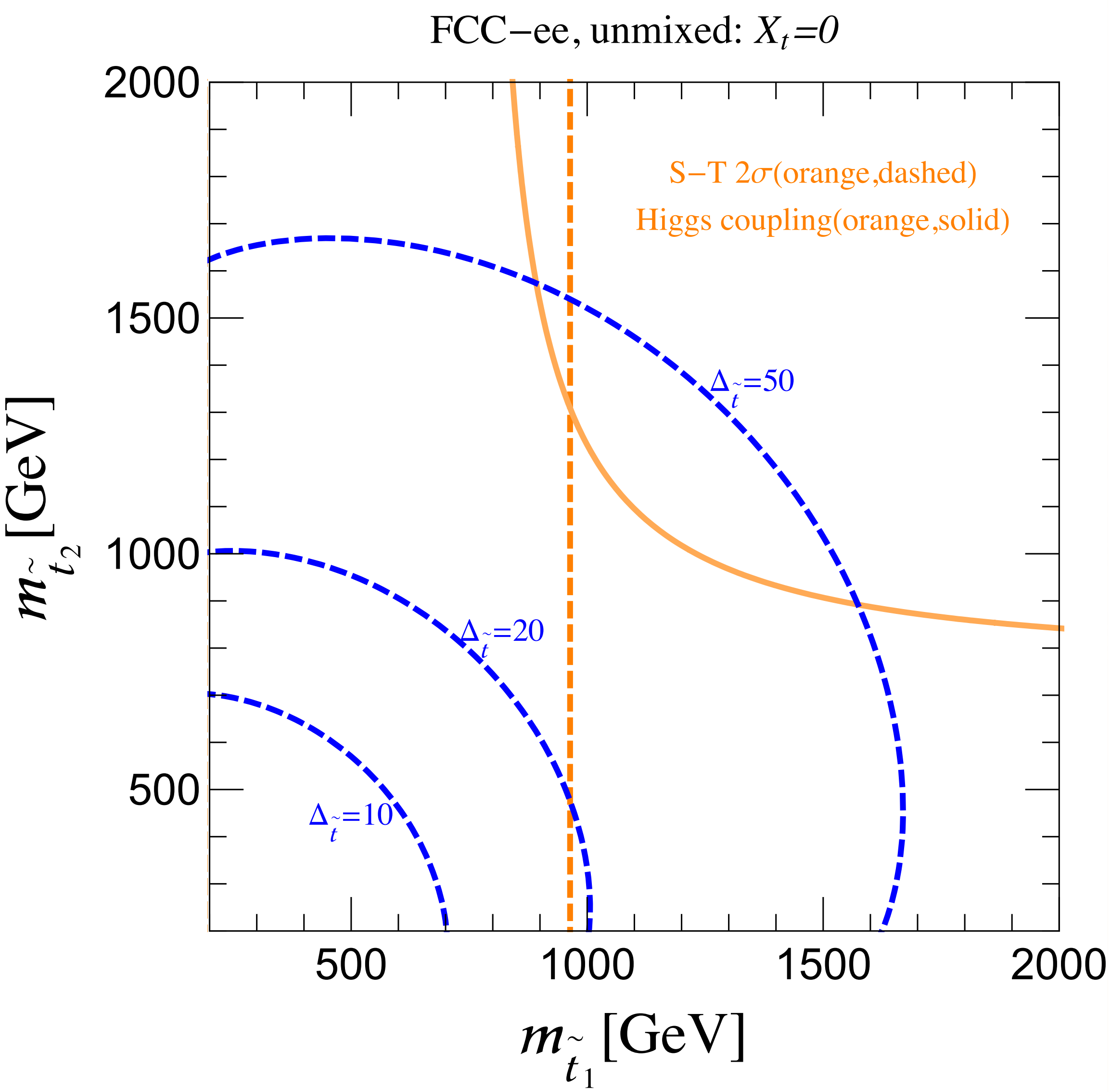
$H \to \phi\,\gamma$ → y_s

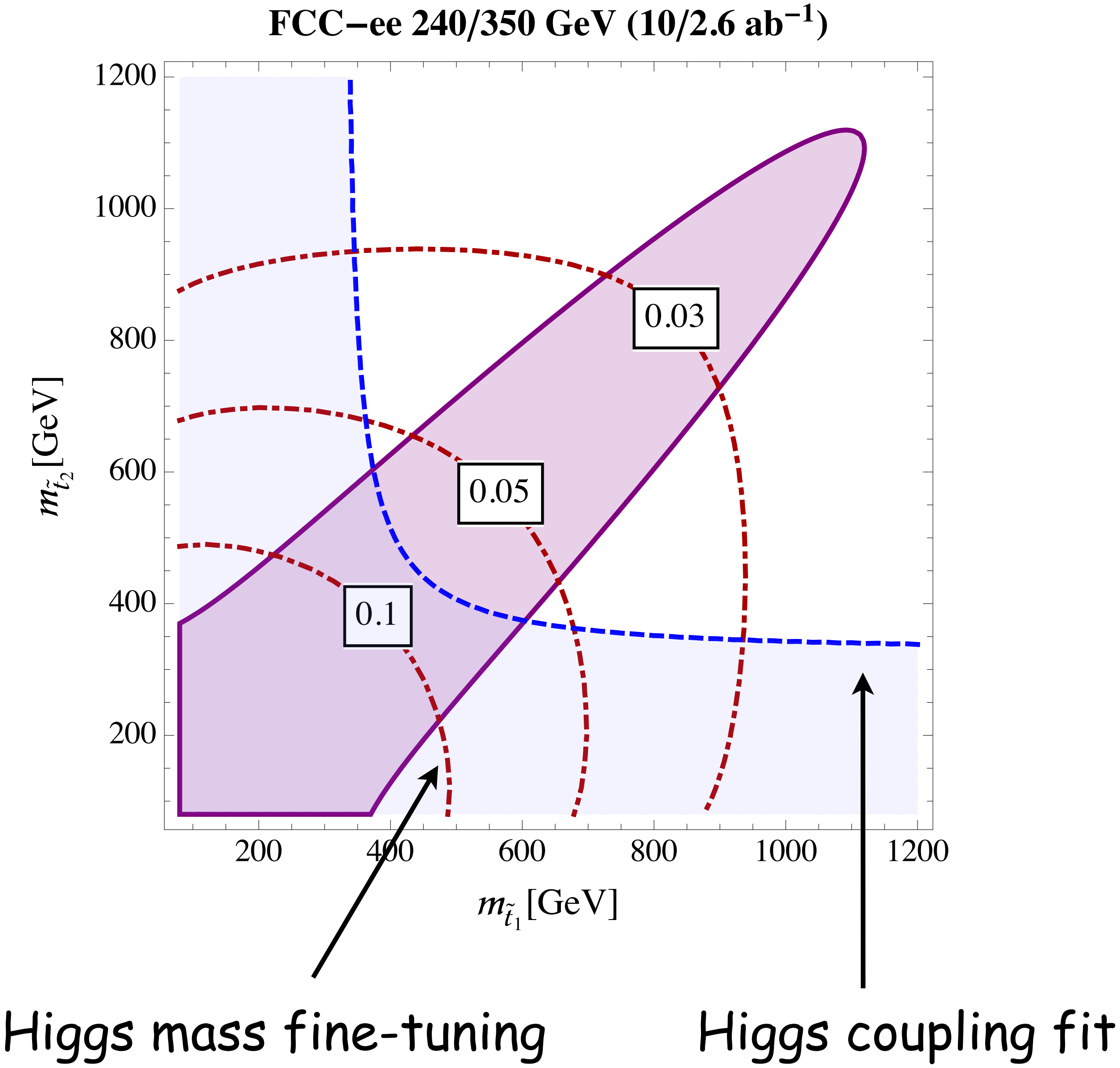
$H \to \rho\,\gamma$

$H \to \omega\,\gamma$ → y_u, y_d

Color naturalness & FCC-ee

Fan, Reece, Wang '14





Can exclude the 10% fine-tuned region and significantly constrain the 5% fine-tuned region

EW precision and Higgs data probe TeV-stops

Neutral naturalness & FCC-ee

D. Curtin @ Washington

Singlet Naturalness

Fermionic top partners *without* any SM charge *always* lead to tree-level Higgs coupling shifts. ⇛ Detectable at lepton colliders for partner masses ≲ 1-2 TeV!

What about SM singlet scalar top partners? No theory yet, but can probably write one down....

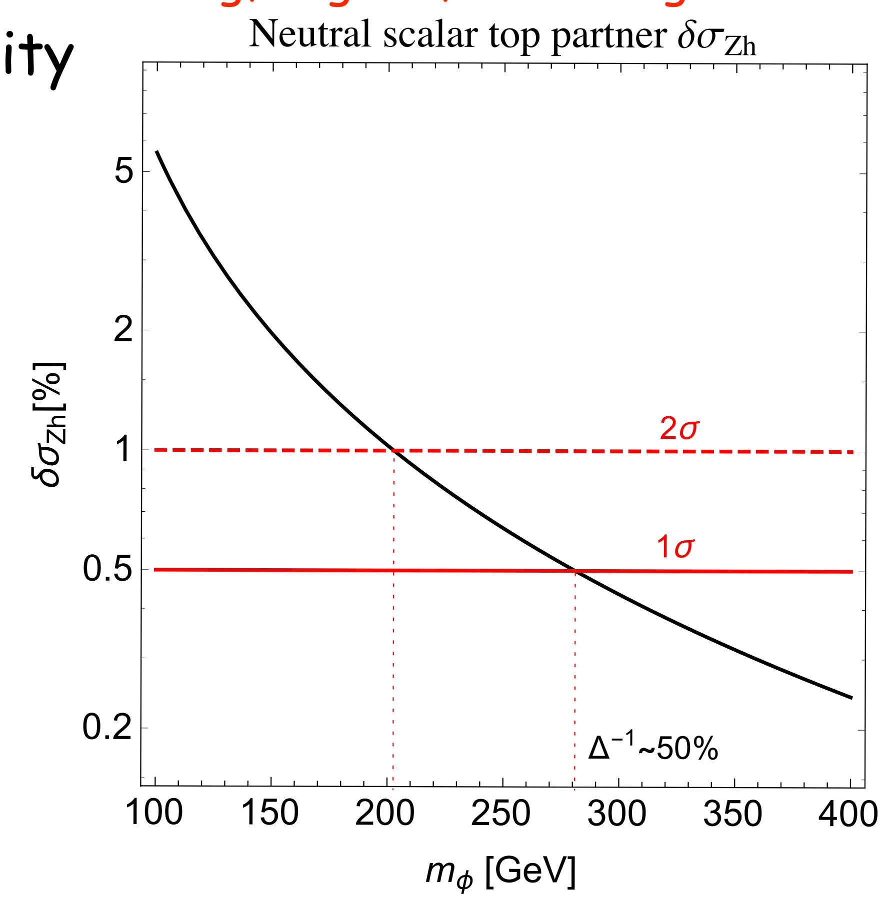
In that case, would have to rely on *Higgs Portal Observables* at future colliders:

- **h*→SS production** (100 TeV) ⟵ surprisingly low sensitivity
- **σ(Zh) shift** by partner loops (ILC/TLEP)
- **triple higgs coupling shift** by partner loops (100 TeV)

Sensitive to singlet scalar top partners at ~ 300 GeV

If there is a mirror QCD, h→invisible decays at lepton colliders *might* be sensitive to ~ 400 GeV

Craig, Englert, McCullough '13



BSM constraints from Zh precision

2 + 3

EW precision measuments and flavor probes
(In)direct probes of high-mass frontier

The Twin Frontiers of FCC-ee Physics

Precision Measurements

- Springboard for sensitivity to new physics
- Experimental issues:
  - Systematics
- Theoretical issues:
  - Higher-order QCD
  - Higher-order EW
  - Mixed QCD + EW

Heinemeyer, Freitas, Degrassi, Salvarezza, Soreq, Matsedonskyi, Riemann, Schwinn, De Curtis

Rare Decays

- Direct searches for new physics
- Many opportunities
- Z: 10^{13}
- b, c, τ: 10^{12}
- W: 10^{8}
- H: 10^{6}
- t: 10^{6}

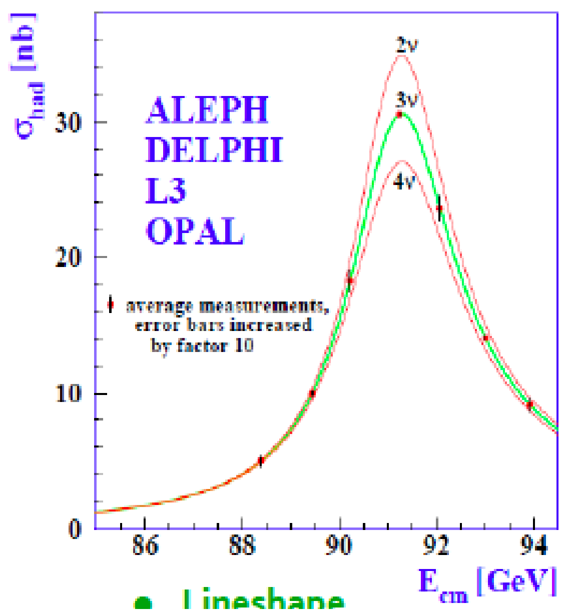
Soreq, Nemevsek, Azzi, Strumia, Fischer

SM parameters and quantum structure

d'Enterria Lomonosov '15

10^{12} Z

Z resonance: TeraZ

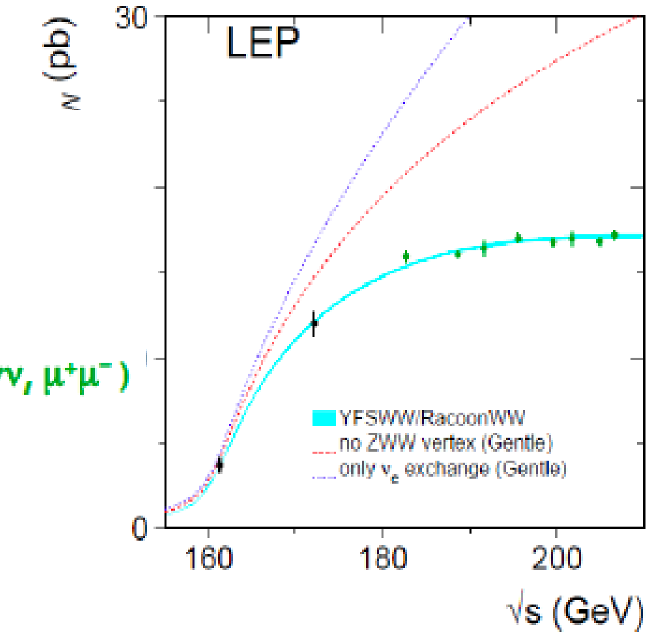


- Lineshape
  - Exquisite E_{beam} (unique!)
  - m_Z, Γ_Z to 10 keV
- Asymmetries
  - $\sin^2\theta_W$ to 2×10^{-6}
- Branching ratios, R_l, R_b
  - $\alpha_s(m_Z)$ to 0.0002
- Predict m_{top}, m_W in SM

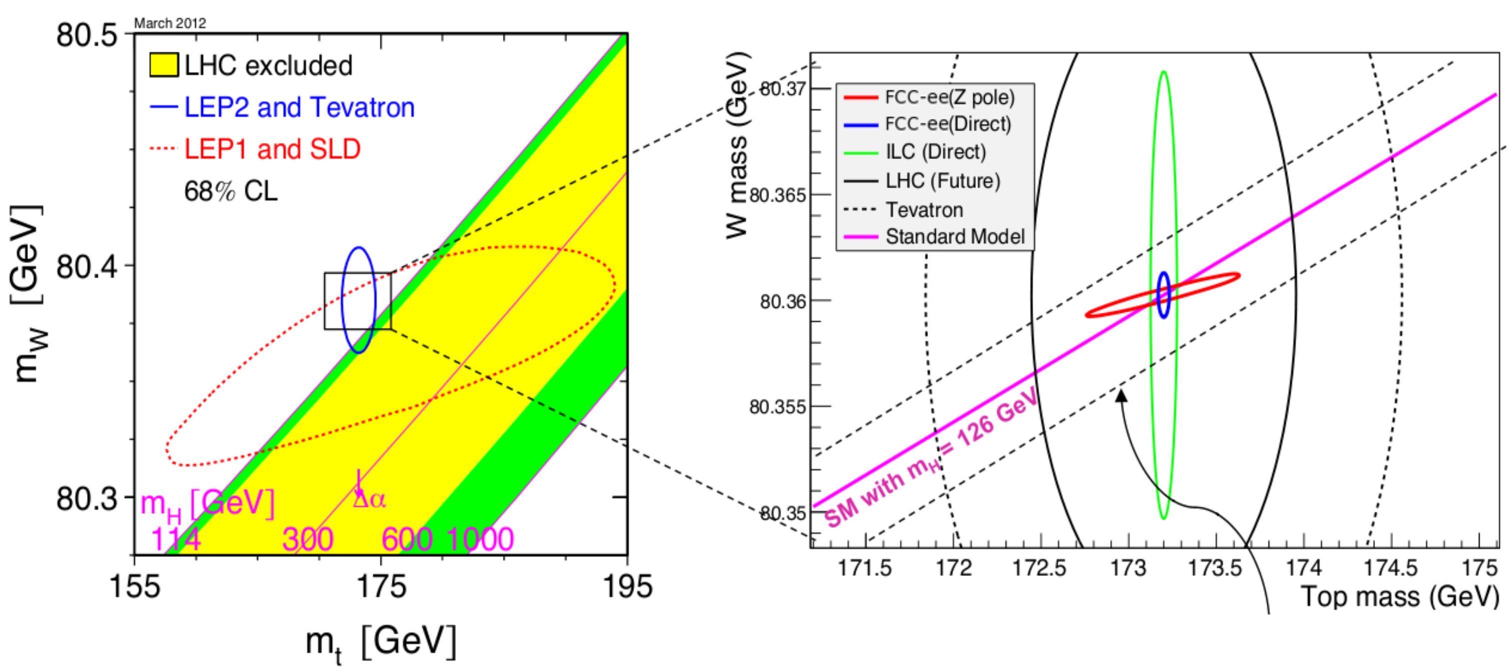
10^8 W

- Threshold scan
  - m_W to 500 keV
- Branching ratios R_l, R_{had}
  - $\alpha_s(m_W)$ to 0.0002
- Radiative returns $e^+e^-\to\gamma Z$ ($Z\to\nu\nu$, $\mu^+\mu^-$)
  - N_ν to 0.0004

WW threshold scan: OkuW



best test of QM beyond QED (and indirect probe of new physics up to ~40TeV)

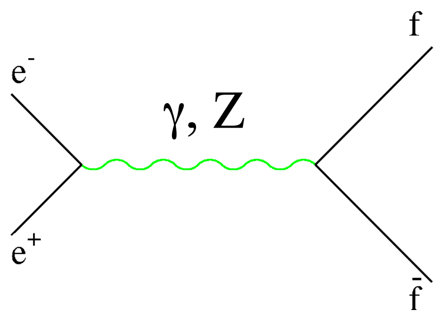


Accessing SM input parameters

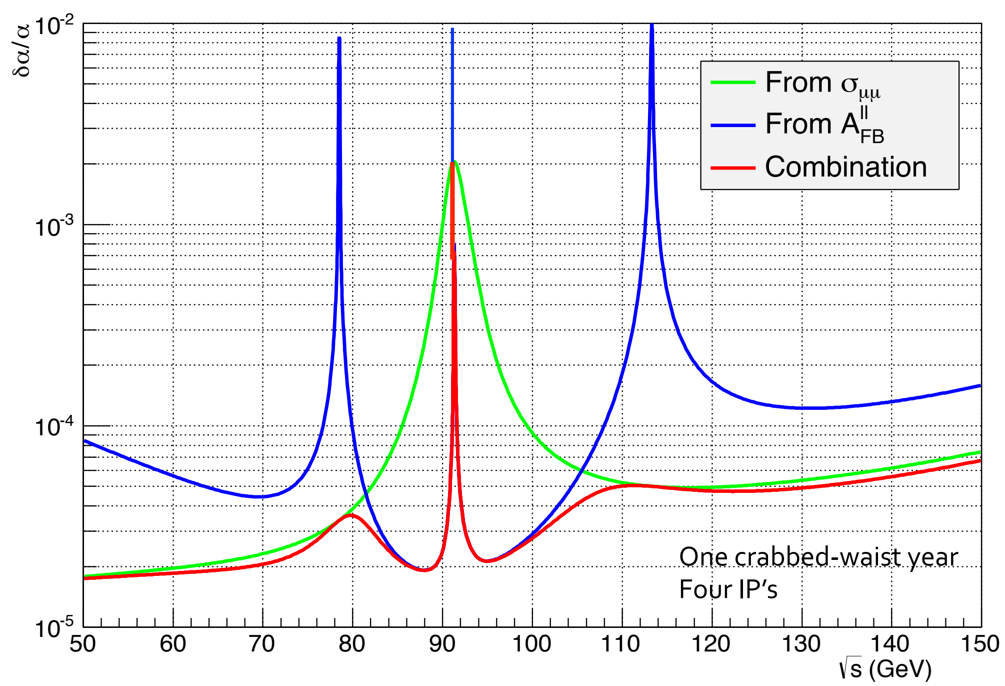
$\alpha_{QED}(m_Z)$

Janot '15

measure $\sigma(e^+e^- \to \mu^+\mu^-)$ and $A_{FB}^{\mu\mu}$ at (a) judicious $\sqrt{s}$



The γ exchange term is proportional to $\alpha^2_{QED}(\sqrt{s})$
The Z exchange term is proportional to G^2_F, hence independent of α_{QED}
The γZ interference is proportional to $\alpha_{QED}(\sqrt{s}) \times G_F$



By running six months at each of 88 and 95 GeV points:
➤ Could potentially reach a precision of : $\delta\alpha/\alpha = 2 \times 10^{-5}$

$\alpha_{QCD}(m_Z)$

Dam @ EPS'15

$$R_l = \Gamma_{had}/\Gamma_l$$

LEP measurements with
(1) new N^{3}LO results
(2) improved m_{top}
(3) m_{Higgs}

$\delta(\alpha_s(m_Z))_{LEP} = \pm 0.0038$ (exp.) ± 0.0002 (others)

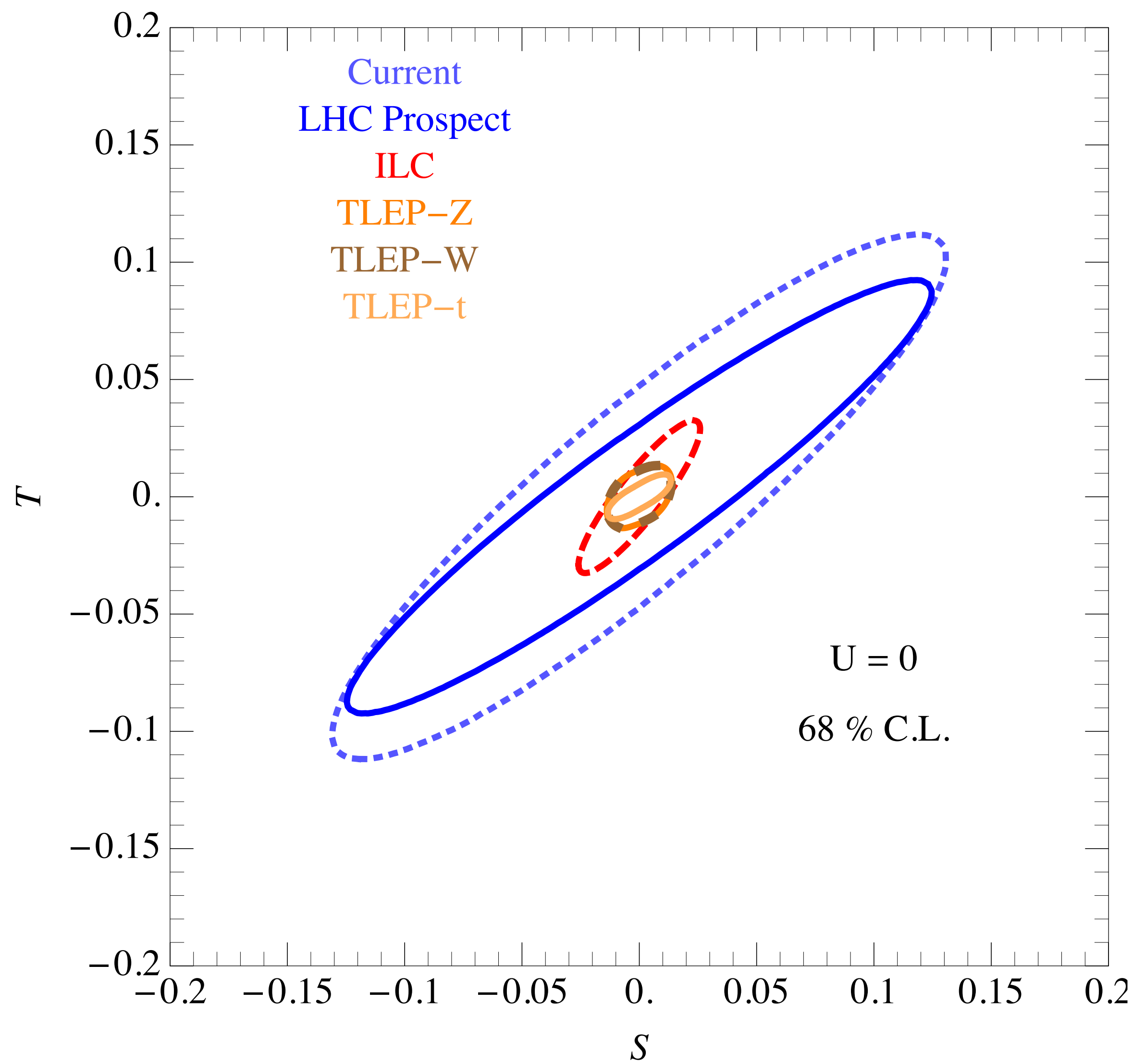
stat. limited

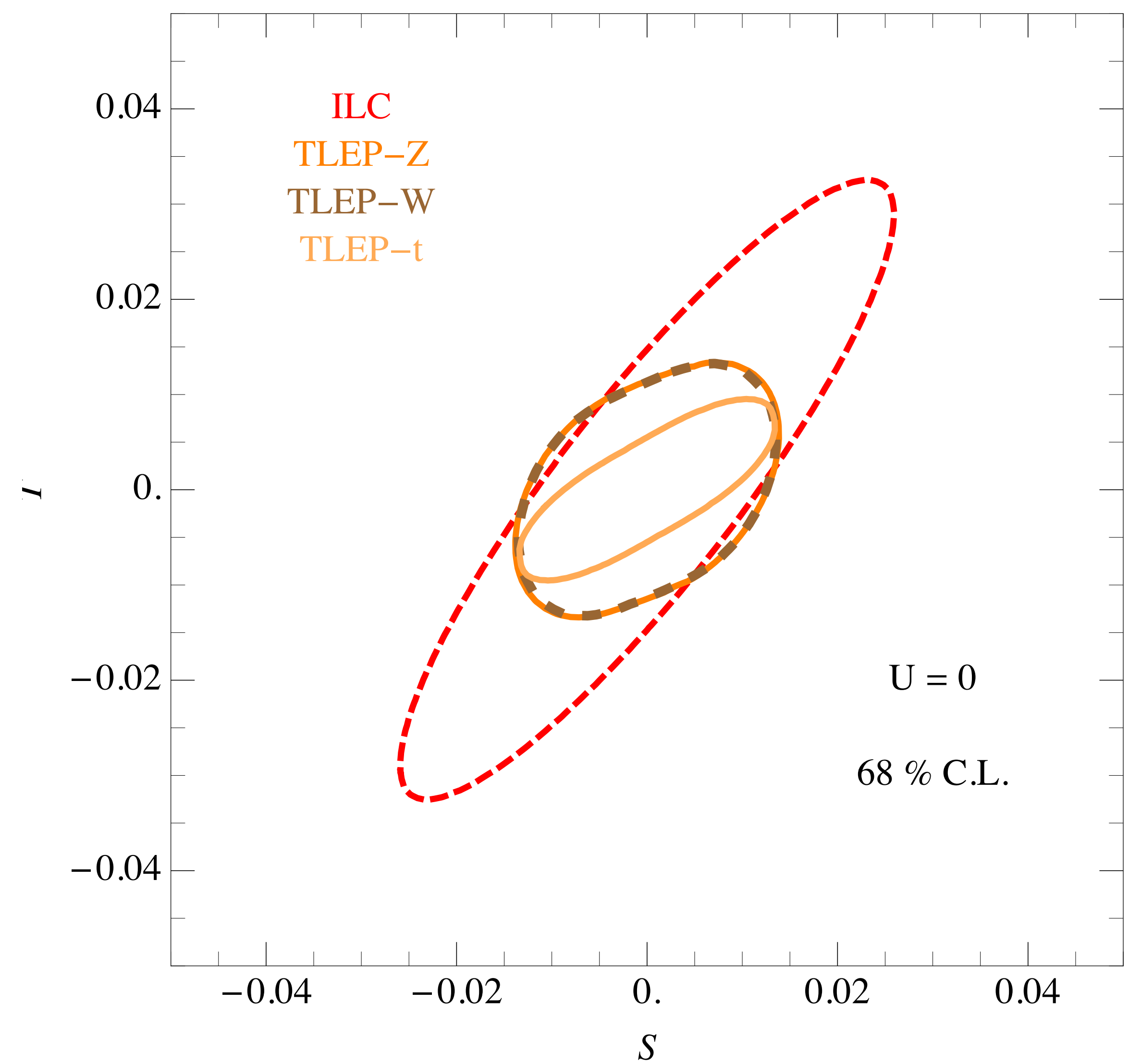
TLEP statistics

$\delta(\alpha_s(m_Z))_{FCC\text{-}ee} = \pm 0.00015$

Improving EW fit

LEP: 10^6 Z's ➠ TLEP: 10^{12} Z's





Fan, Reece, Wang '14

Landmarks for precision studies

oblique parameters not most suited for EW constraints at that level of sensitivity

A. Blondel @ Washington

-- 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 ($\Delta\alpha$_QED(m_Z)) *Was, Gluza, Heynemeyer, Kuhn, Frietas, Jadach, Ward..*

M. Reece @ HKUST '16

A Wish List

Of course, we want the best measurements possible of many quantities. But here are reasonable goals to probe loops of ~TeV particles. **CEPC will deliver what's in bold.**

- **Measure m_W to better than 5 MeV (now 15 MeV) and $\sin^2\theta_W$ to better than 2×10^{-5} (now 16×10^{-5})**
- **Measure m_Z to 500 keV precision (now 2 MeV)**
- Measure m_t to 100 MeV precision (now ~0.8 GeV*)
- Have precise enough theory to make use of these results: *at least 3-loop* calculations.

importance of tt threshold ->

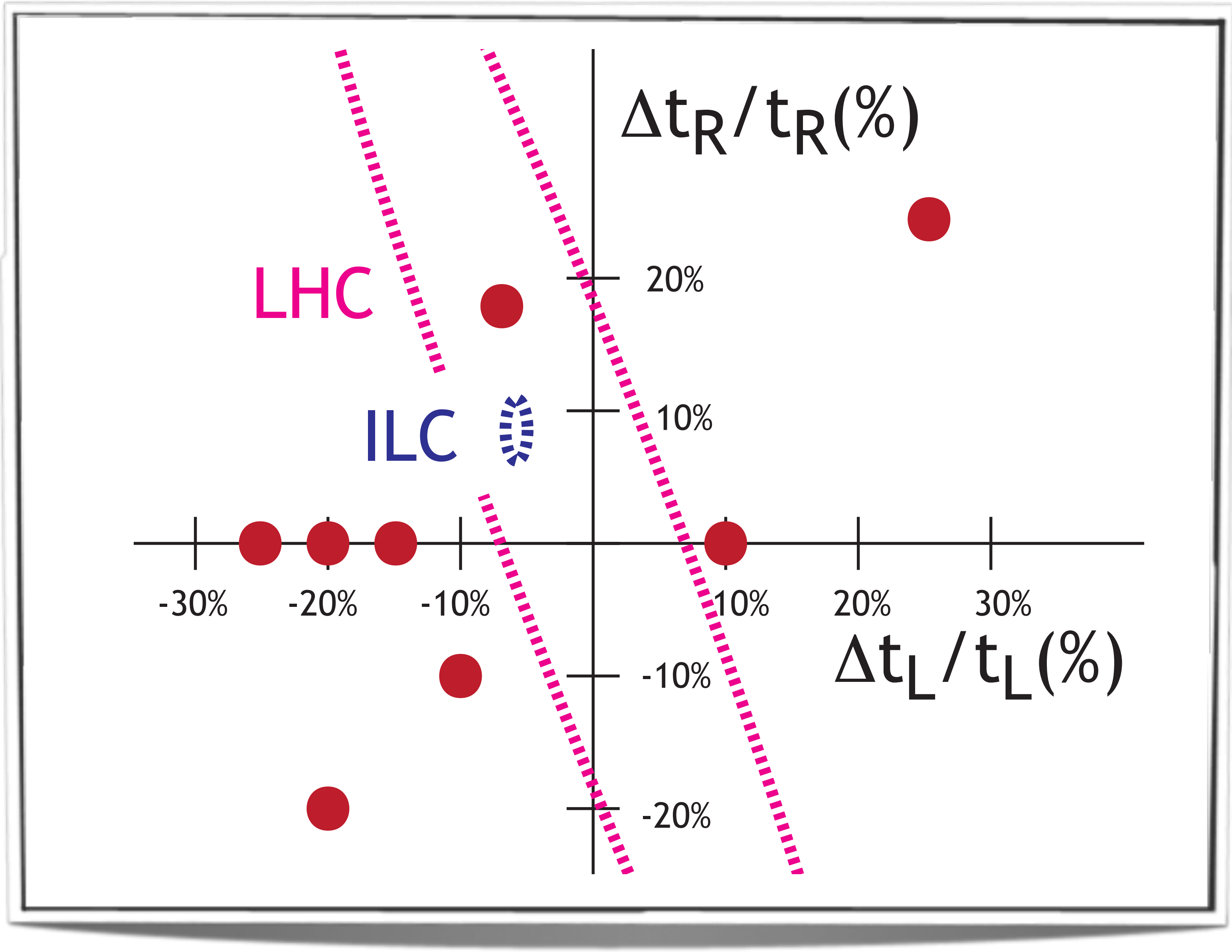
Top EW couplings

important to access the EW top couplings

chiral gauge symmetries are the only one to be spontaneously broken?

probe various scenarios of physics beyond the SM

adapted from Richard '14
see also Agashe et al '13



FCC sensitivity down to 0.5%

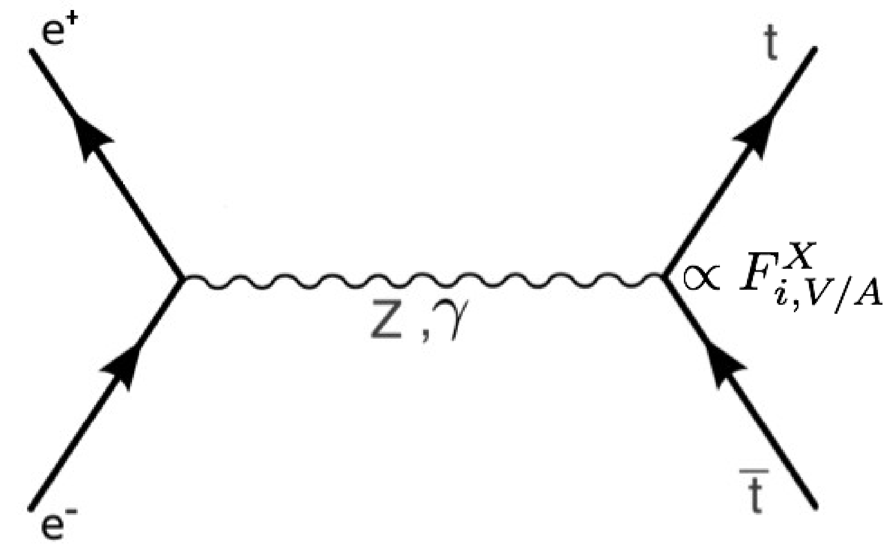
⇛ probe New Physics resonances up to 15-20 TeV, way above direct LHC access

Top EW couplings

Important properties of tt production above threshold

M. Peskin @LCWS'15

- events are fully reconstructable,
  all final parton angles can be measured
- production is from γ-Z interference,
  asymmetries are of order 1
- decay is by weak interactions,
  asymmetries are of order 1



$$\Gamma^{ttX}_{\mu}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu\left(F^X_{1V}(k^2) + \gamma_5 F^X_{1A}(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\mu\left(iF^X_{2V}(k^2) + \gamma_5 F^X_{2A}(k^2)\right)\right\}$$

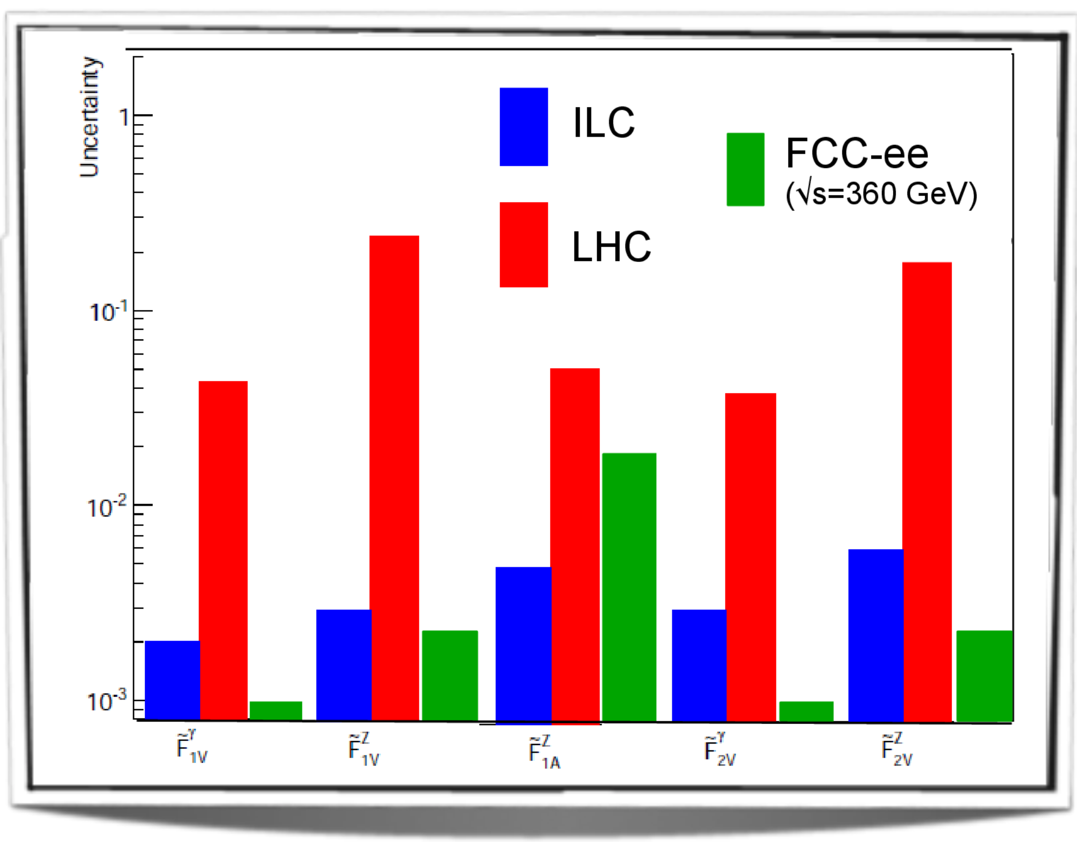
7 (gauge invariant) form factors, 5 CP-even & 2 CP-odd

Khiem et al '15,
arXiv:1503.04247

. syst. error included

. show feasibility of kinematic reconstruction of the di-lepton final state: $e^+e^- \to tt \to 6f$

. extract all ten form factors simultaneously using ME method



Janot '15,
arXiv:1503.01325

. stast. error only

. no beam polarization

. use final-state polarization instead

. cross-over region (365GeV) well under control?

Z = atomic clock of HEP

(1) probing rare Z decays:

$$\mathrm{Br}(Z^0 \to J/\psi\,\gamma) \overset{\text{SM}}{\approx} 8 \times 10^{-8}$$
$$\mathrm{Br}(Z^0 \to \Upsilon(nS)\,\gamma) \overset{\text{SM}}{\approx} 1.0 \times 10^{-7}$$

(2) probing flavor-violating decays:

S. Monteil @ Washington '15

- In the minimal SM (with massive neutrinos and PMNS mass mixing matrix), the LFV leptonic *Z* decays are beyond experimental reach

$$\mathcal{B}(Z \to e^{\pm}\mu^{\mp}) \sim \mathcal{B}(Z \to e^{\pm}\tau^{\mp}) \sim 10^{-54} \text{ and } \mathcal{B}(Z \to \mu^{\pm}\tau^{\mp}) \sim 4.10^{-60}$$

- Many NP models do foresee LFV *Z* decays: SUSY, Little Higgs etc...

- The current experimental bounds:

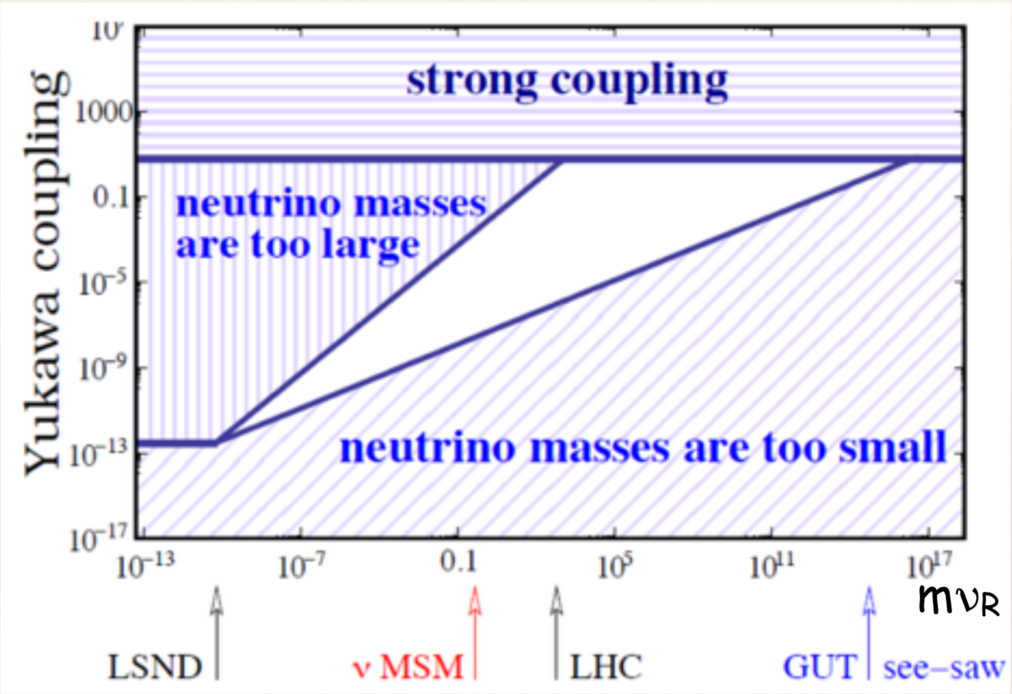
$$\mathcal{B}(Z \to e^{\pm}\mu^{\mp}) < 7.5\ 10^{-7},$$
$$\mathcal{B}(Z \to e^{\pm}\tau^{\mp}) < 9.8\ 10^{-6},$$
$$\mathcal{B}(Z \to \mu^{\pm}\tau^{\mp}) < 1.2\ 10^{-5}.$$

- We could potentially go more than 5 orders of magnitude beyond.

Direct search for (light) ν_R

N. Serra @ Paris '14

A. Blondel @ Washington '15



$m\nu_R$ [GeV]

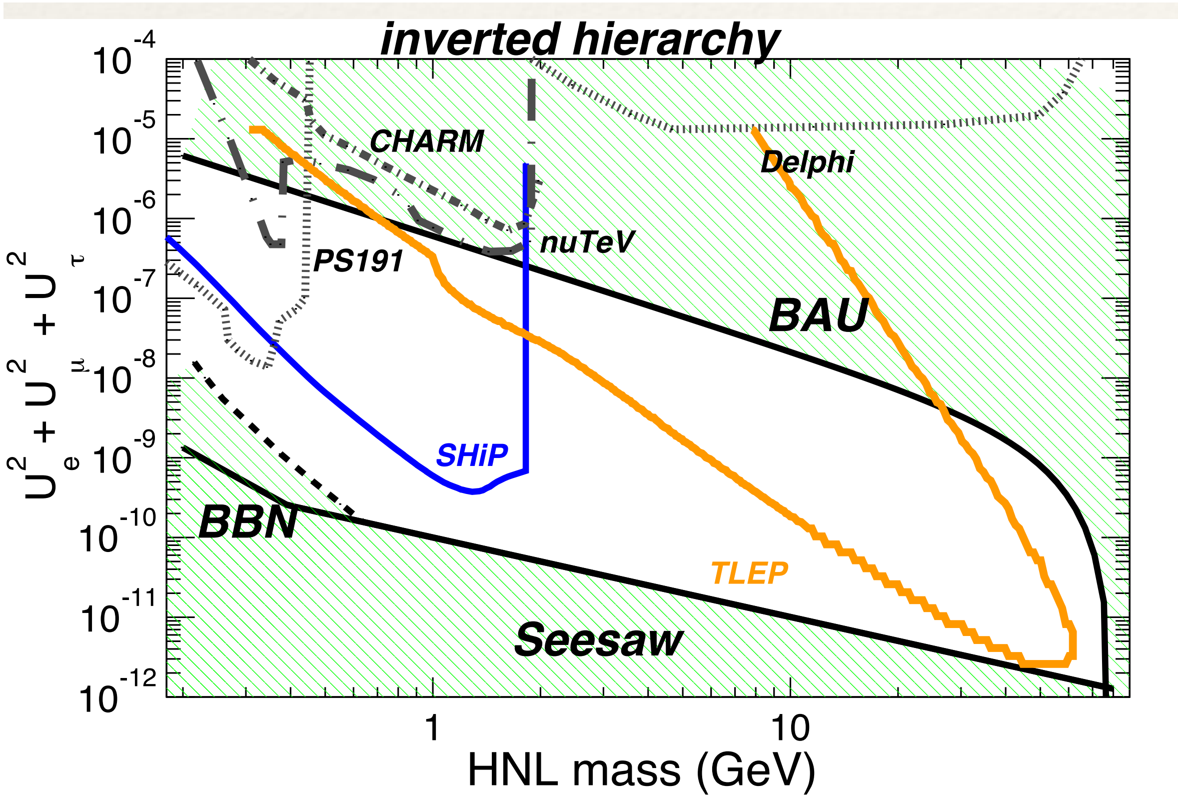
- Assuming $m_\nu = 0.1\text{eV}$
- if $Y \sim 1$ implies $M \sim 10^{14}\text{GeV}$
- if $M_N \sim 1\text{GeV}$ implies $Y_\nu \sim 10^{-7}$

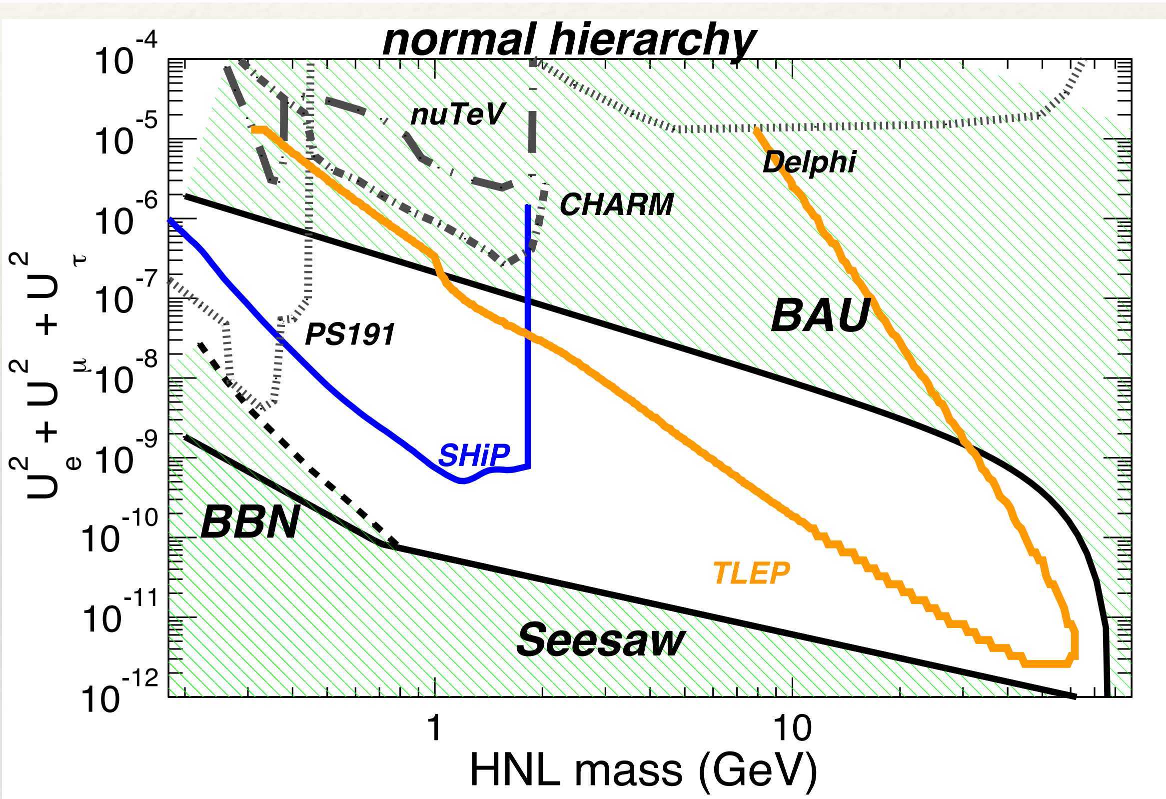
remember $Y_{top} \sim 1.$ and $Y_e \sim 10^{-6}$

Traditional seesaw

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

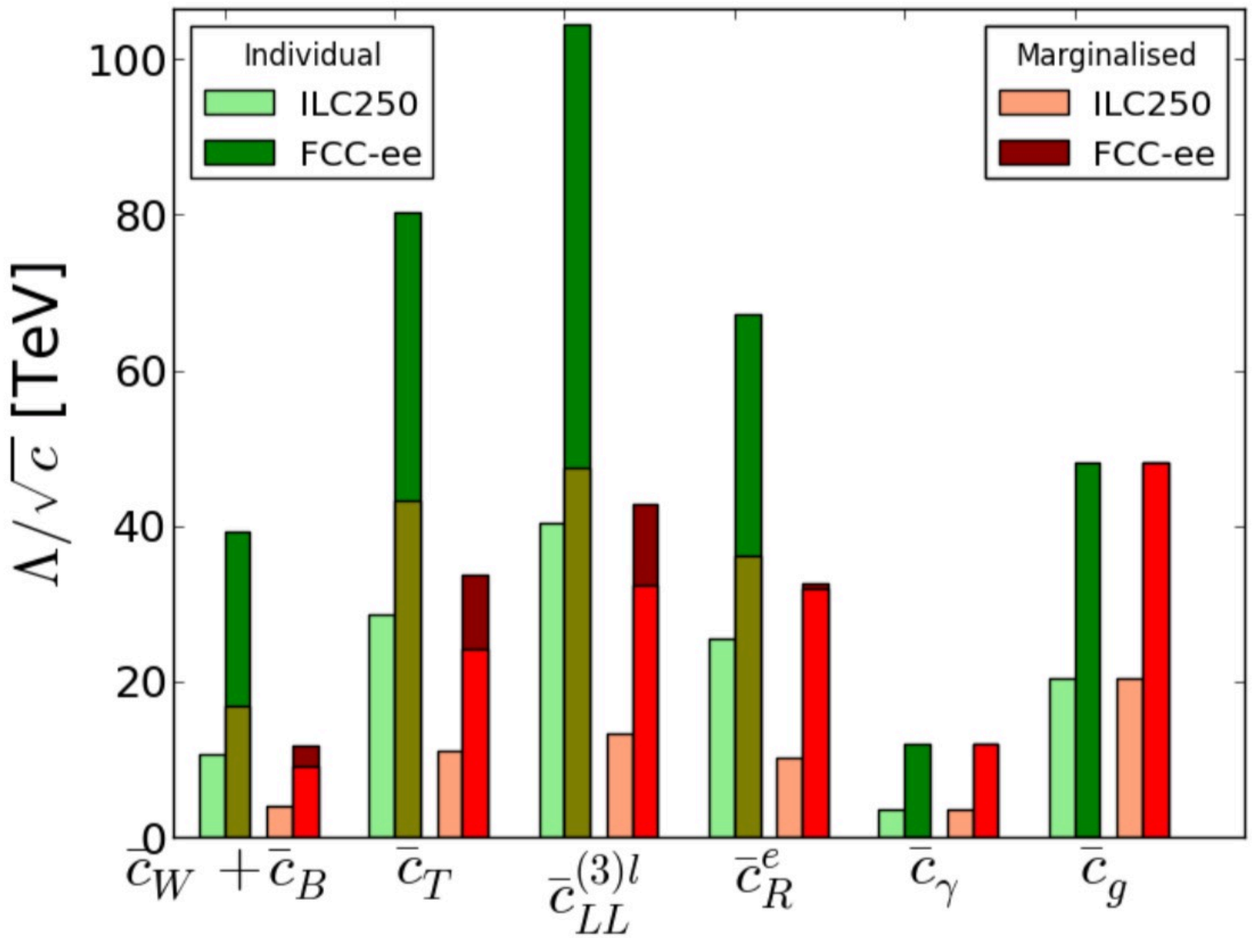
ν_R are produced in the 10^{12} TLEP Z decays and can be searched for





Indirect BSM constraints: EFT fits

Ellis & You '15



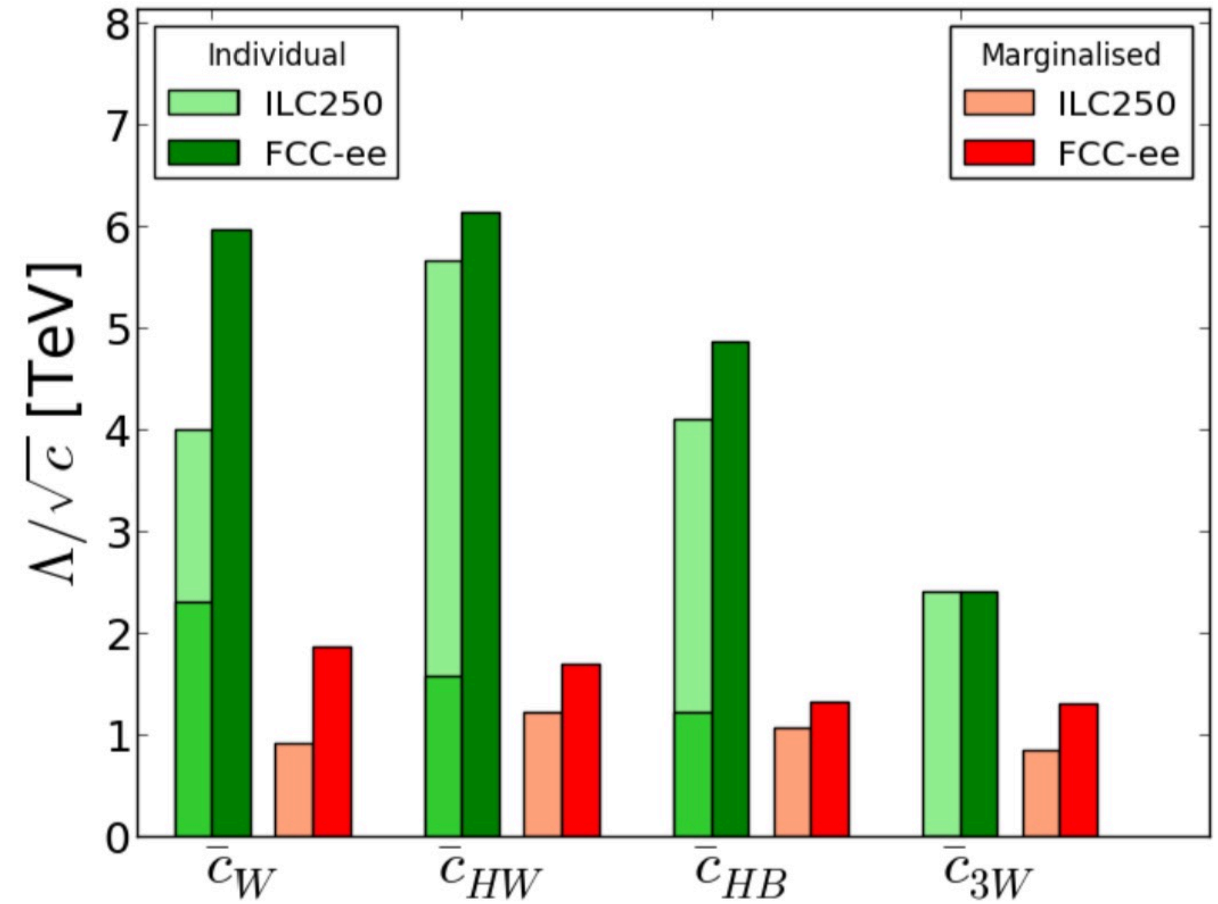


Figure 9: *Summary of the reaches for the dimension-6 operator coefficients with TeV scale sensitivity, when switched on individually (green) and when marginalised (red), from projected precision measurements at the ILC250 (lighter shades) and FCC-ee (darker shades). The left plot shows the operators that are most strongly constrained by EWPTs and Higgs physics, where the different shades of dark green and dark red represent the effects of EWPT theoretical uncertainties at FCC-ee. The right plot is constrained by Higgs physics and TGCs, and the different shades of light green demonstrate the improved sensitivity when TGCs are added at ILC250.*

4

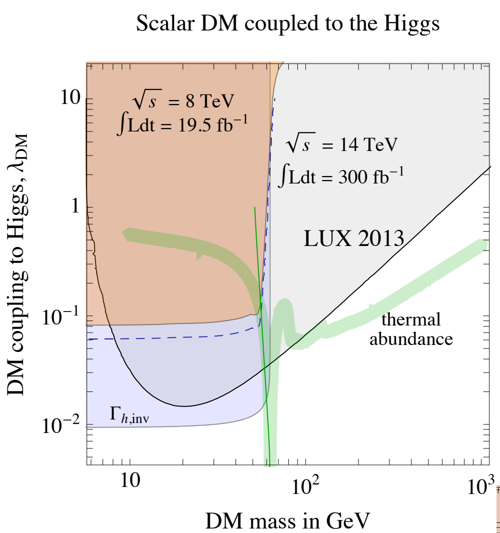
DM @ FCC-ee

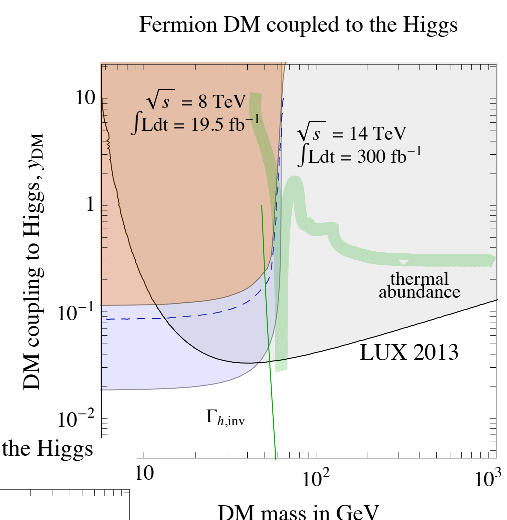
DM & FCC-ee

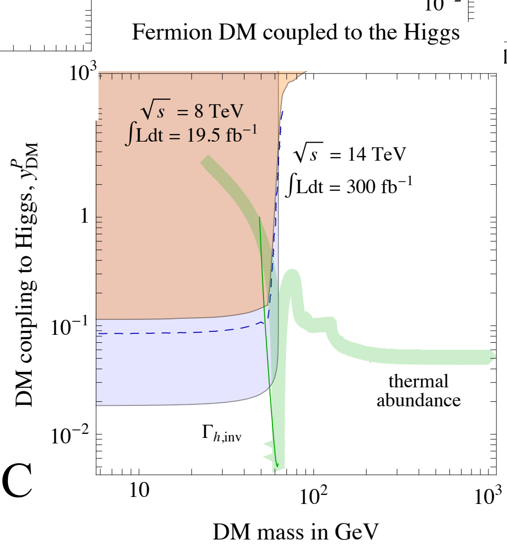
In traditional WIMP model, DM caries SM (weak) charges
Other models where FCC-ee can be particularly relevant:
SM neutral DM + light mediators (could be the Higgs itself!)

Higgs portal: $\mathcal{L} = -hJ_h\,, \quad J_h = \frac{1}{\sqrt{2}}\left[\sum_f y_f \bar{f} f + \bar{\psi}_{\rm DM}(y_{\rm DM} + i y^P_{\rm DM}\gamma_5)\psi_{\rm DM} + \frac{\lambda_{\rm DM} v}{2} s^2_{\rm DM}\right]$ $\quad y\,,\, y^P\,,\, \lambda$ arbitrary couplings

current LHC bounds



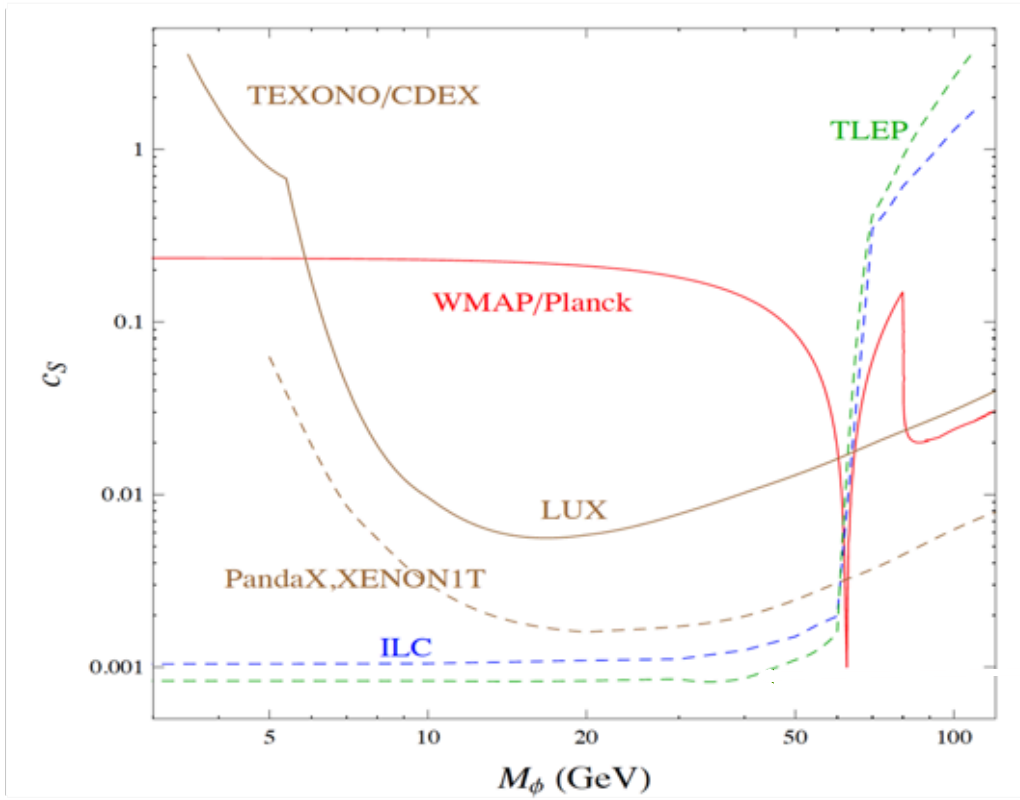




Γ_h invisible & direct DM do better than LHC

De Simone, Giudice, Strumia '14

future bounds



J. Shelton @ Higgs-FCCee '15

Γ_Z and Γ_h invisible are the most efficient way to explore SM-mediated DM at colliders

Conclusions

LHC-FCC interplay

If the LHC does not see any sign of NP, what should be the energy of the next machine?

FCC-hh -> exploration of the unknown/energy frontier
FCC-ee -> dedicated study of the EW+Higgs+top

Do we need to ttH, HH thresholds?

If the LHC sees a sign of NP, e.g @ 750GeV, does it make sense to go for low E machine?

importance of precision measurements

open new horizons beyond LHC!