“Unique Role” of Future e^+e^- Colliders

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The completion of the SM:

First time ever, we have a consistent relativistic, quantum mechanical theory: weakly coupled, unitary, renormalizable, vacuum-(quasi?)stable, valid up to an exponentially high scale, perhaps to the Planck scale M_{Pl}!

Further fundamental questions:

- Nature of EWSB: Higgs potential, self-coupling
- Vacuum stability: top quark mass/Yukawa coupling
- "Naturalness": TeV scale new physics
- Puzzle of flavor physics and neutrino mass

Future colliders will play key roles for the answers, and the e^+e^- & pp colliders would be complementary!

On the “Uniqueness of e^+e^- colliders”

A historical account:

温故知新

Review the past, foresee the future.

Discoveries:

- R value = $3 \, \Sigma \, Q_q^2$: quarks, color
- J/ψ: charm-quark (1974) 
- $\tau^+ \tau^-$: 3rd generation lepton (1974-77) 
- 3-jets: gluons (1979)
- CP violation in B-factories (2000’s) 

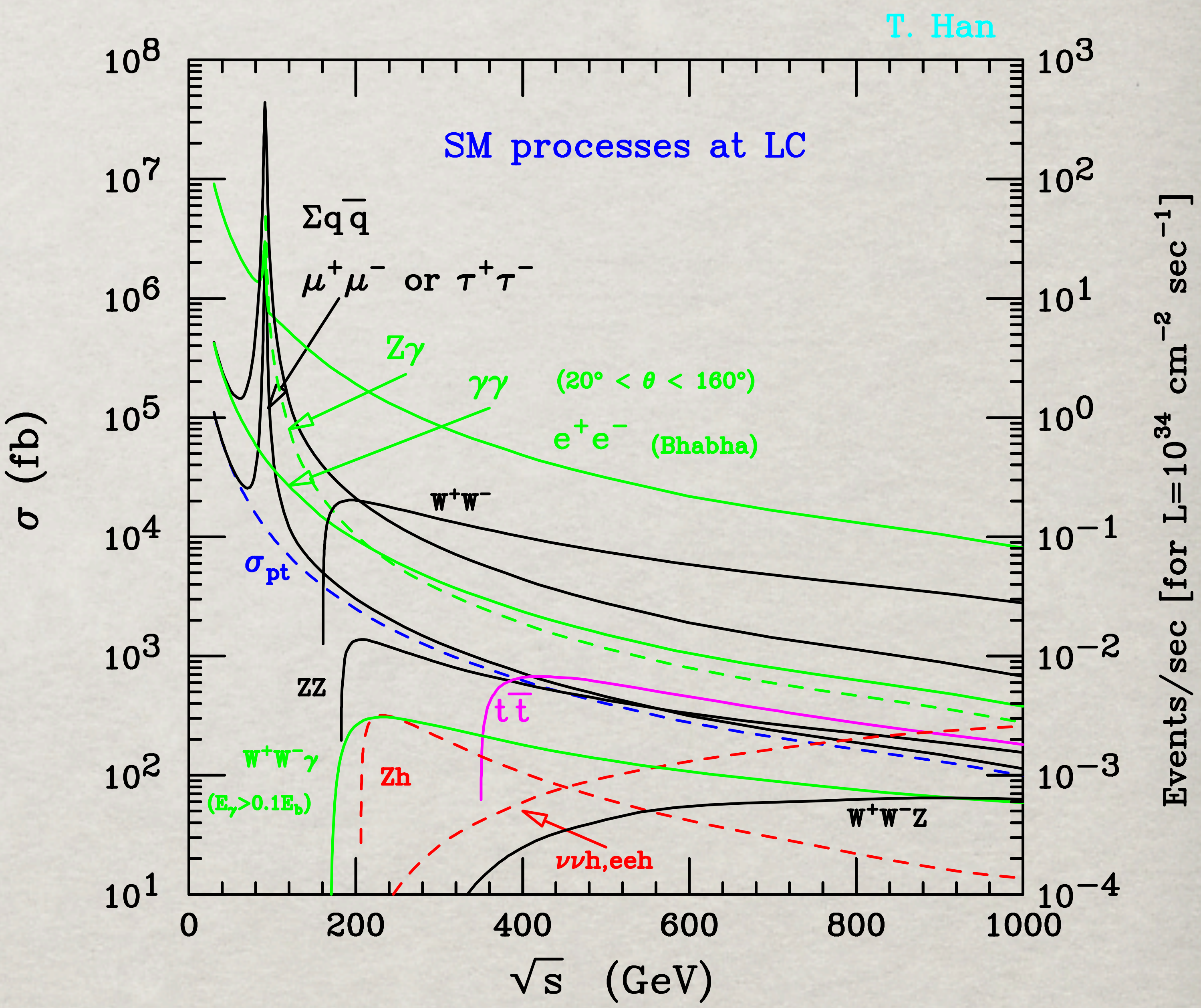
Best measurements:

- m_τ (BEPC)
- M_Z (LEP 1)
- $\boldsymbol{\alpha}(Mz)$, $\boldsymbol{\alpha}_s$, $\sin^2\boldsymbol{\theta}_W$, $n_{\boldsymbol{\nu}}$ (LEP 1, SLC)
- Rare B-decays (B-factories)

On the "Uniqueness of e^+e^- colliders"

Advantages:

- Well-measured CM energy (ILC ~ 0.2%)
- Well-measured luminosity (ILC ~ 0.1%)
- Low background R(WW@10^{34}) < 1Hz
- Beam polarization (ILC e^-e^+ 80% / 30%)
- ~ 4**π** coverage (ILC vertex: ~16 mrad)
- Resonances and thresholds

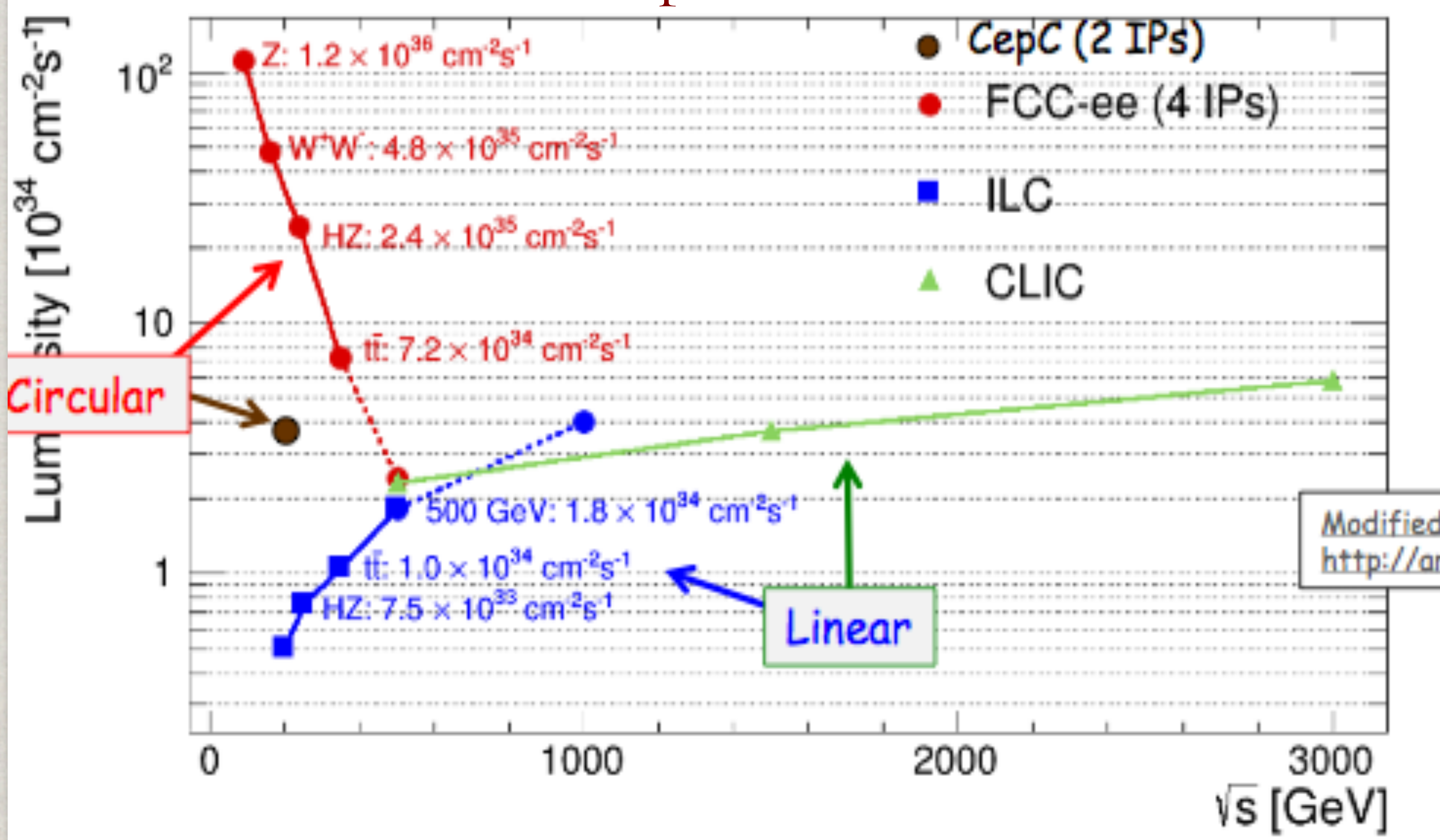


Disadvantages:

- Large synchrotron radiation for circular colliders
- Limited CM energy, challenging luminosity

e^+e^- colliders: Energy/Lumi projection

TLEP Report: 1308.6176



E_{cm}	running time	statistics (FCC-ee)
	b,c,τ	10^{11} b,c,τ
90 GeV	1-2 yrs	10^{12} Z (Tera Z)
160 GeV	1-2 yrs	10^8- 10^9 WW(Oku W)
240 GeV	4-5 yrs	$2\text{x}10^6$ ZH (Mega H)
350 GeV	4-5 yrs	10^6 tt (Mega top)

Open up 1-3 TeV threshold

ILC arXiv:1504.01726v2

CLIC arXiv:1307.5288v3

1. Higgs-Factory:

Need precision Higgs Physics:

Generically: $\Delta_i \equiv \frac{g_i}{g_{SM}} - 1 \sim \mathcal{O}(v^2/M^2)$

Tree-level corrections ≈ 6% @ M ≈ 1 TeV

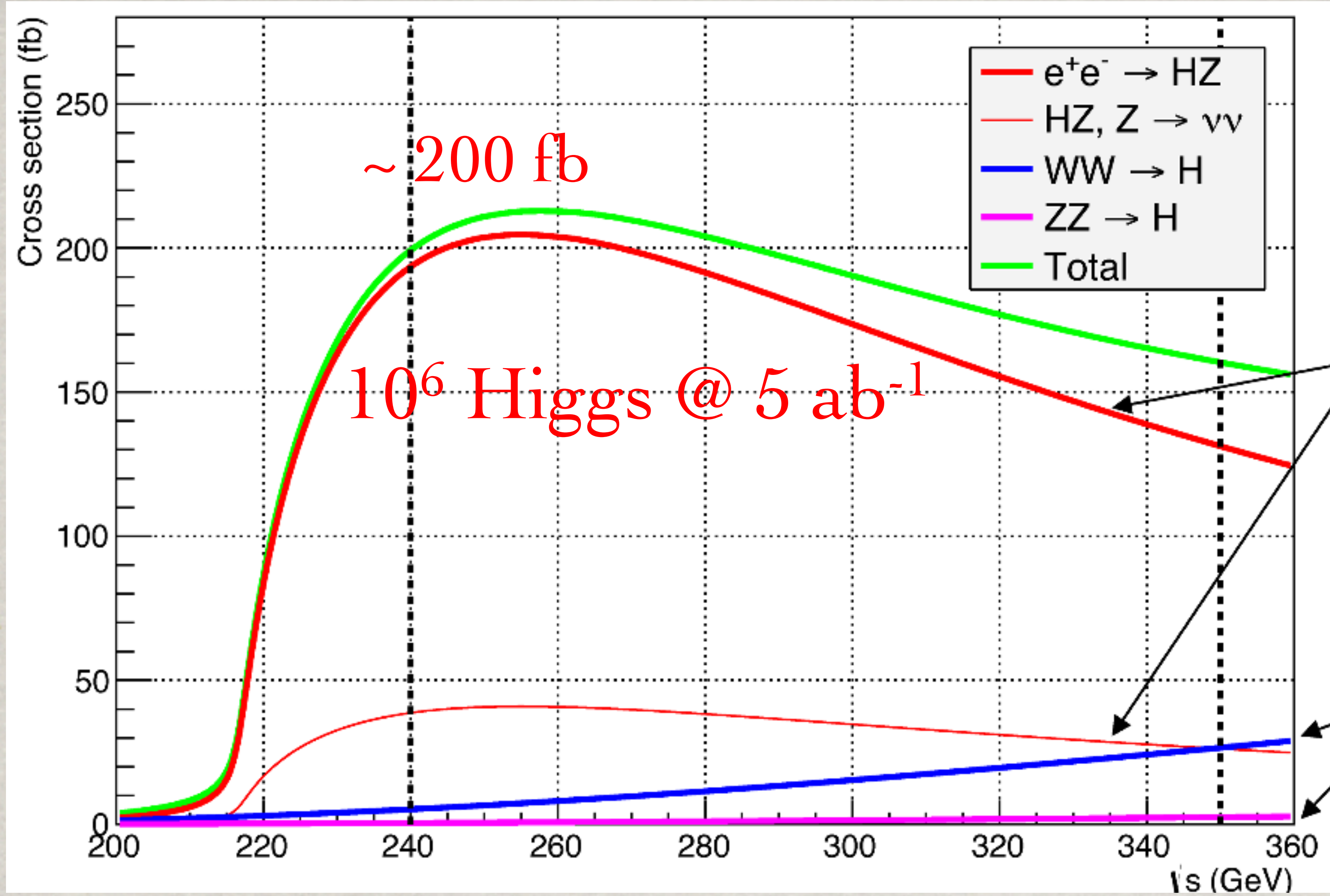
Important Model-dependent futures:

Gupta, Rzehak, Wells, arXiv:1205.3560.

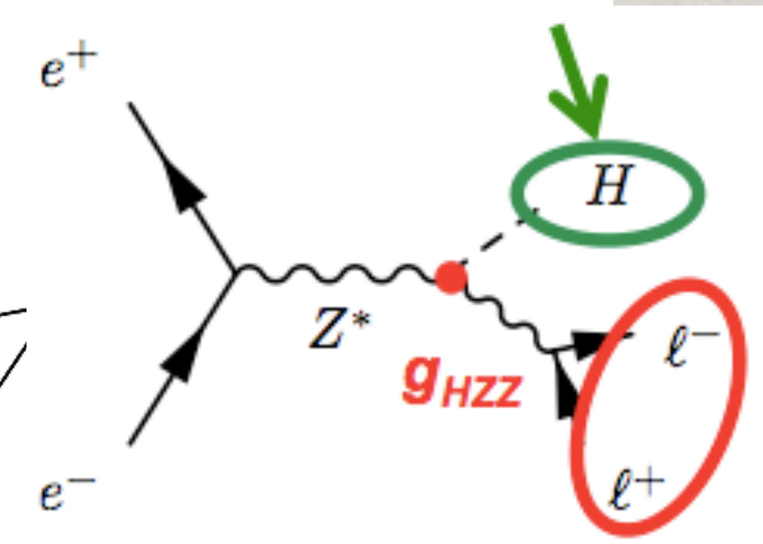
	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	10%[a], 100%[b]
LHC 14 TeV, 3 ab^{-1}	8%	10%	15%

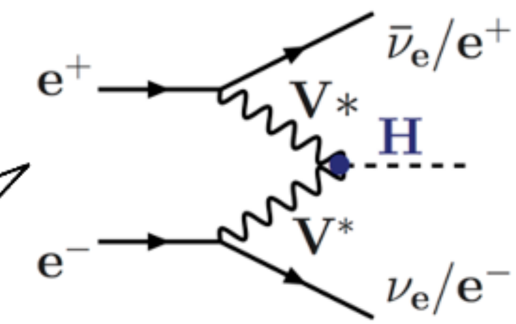
LHC measurements of ratios @ 10%-level:

$$\sigma_{AB} \propto \frac{\sigma(A \to h)\,\Gamma(h \to B)}{\Gamma_h} \propto \frac{g_A^2\, g_B^2}{\Gamma_h}\,, \qquad \frac{\Gamma(h \to A)}{\Gamma(h \to B)} = \frac{Br(h \to A)}{Br(h \to B)}$$



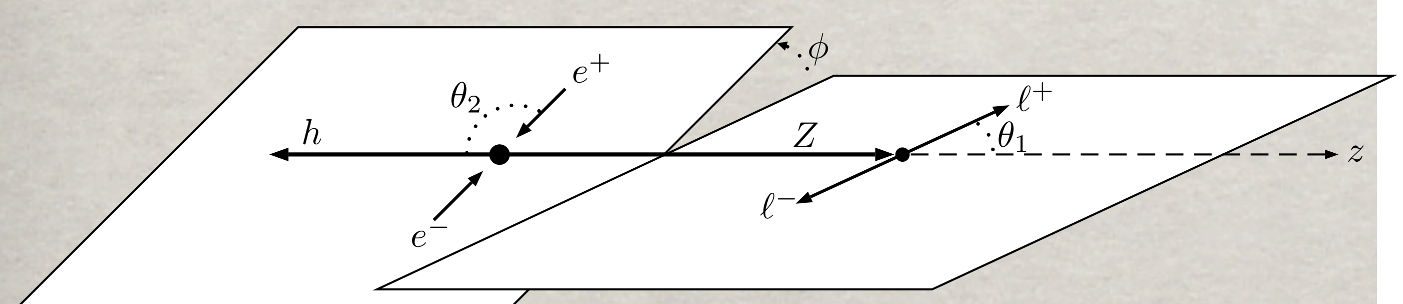
TLEP Report: 1308.6176

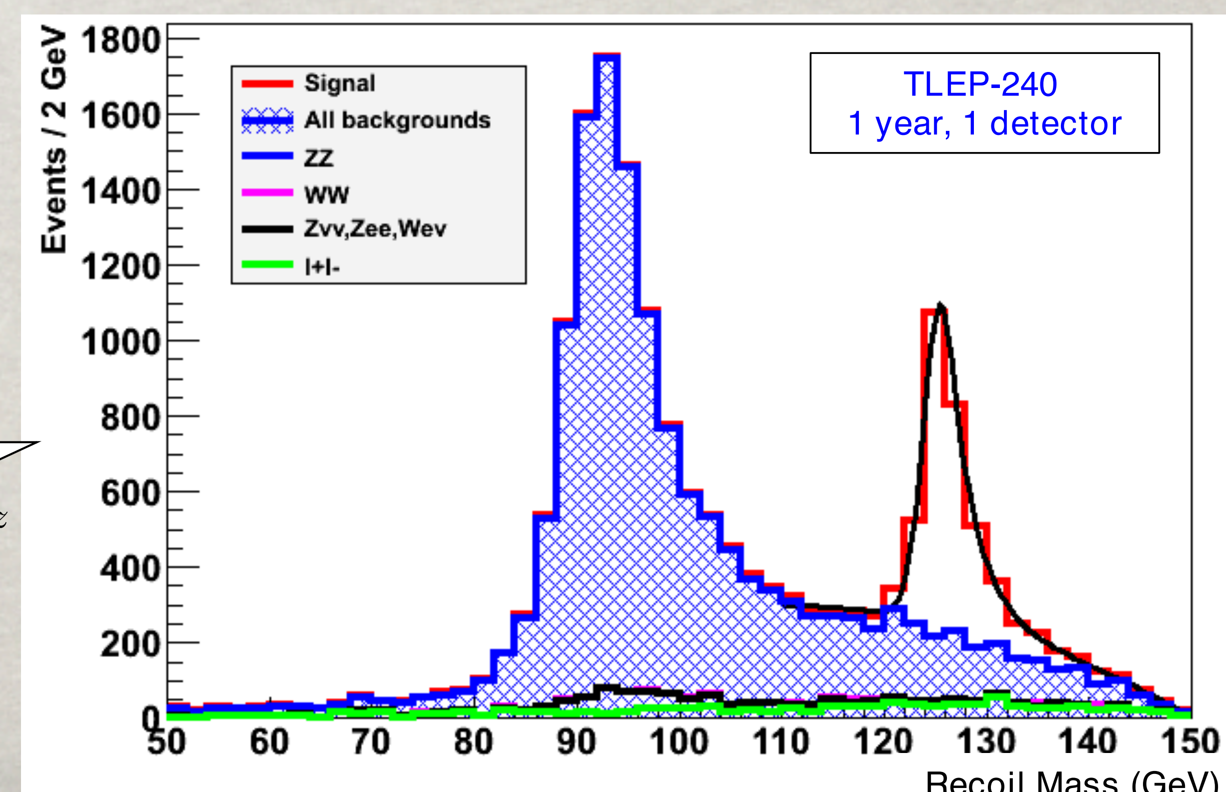




"Recoil mass"

$$m_h^2 = (p_{e^-} + p_{e^+} - q_{\mu^-} - q_{\mu^+})^2$$





Higgs factories under consideration:

- ILC (Japan): 250 GeV, 2 ab^{-1}, 80% / 30% polarization.
- FCC_{ee} (CERN): 250 GeV, 20 ab^{-1} .
- CEPC (China): 240 GeV, 5 ab^{-1} .

- ILC: Model-independent measurement:

$\Gamma_H = \Gamma_X/BR_X \sim 6\%$, $\Delta m_H \sim 30$ MeV

(HL-LHC: assume SM, $\Gamma_H \sim$ 5-8%, $\Delta m_H \sim 50$ MeV)

ILC Report: 1308.6176

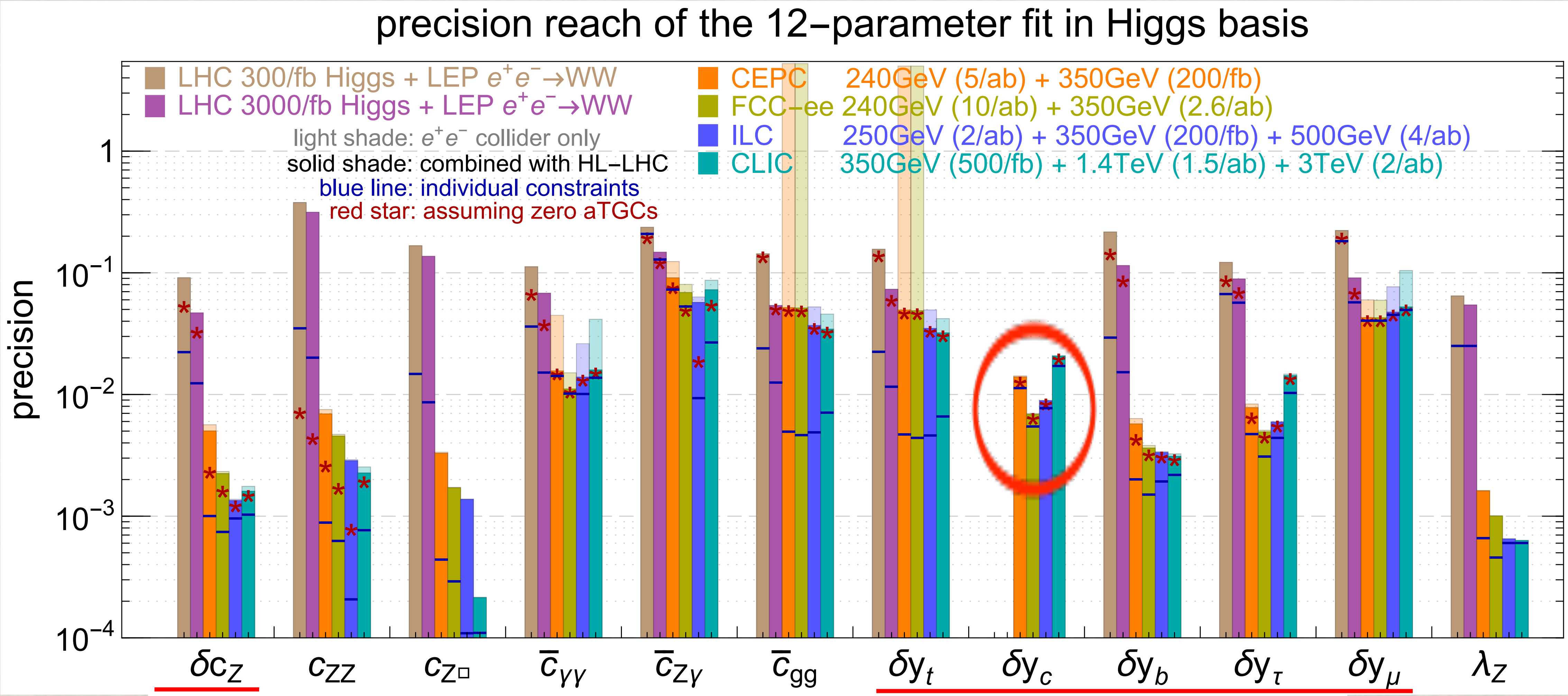
- FCCee/CEPC **10^6** Higgs:

$\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV, $BR_{inv} < 1\%$.

TLEP Report: 1308.6176

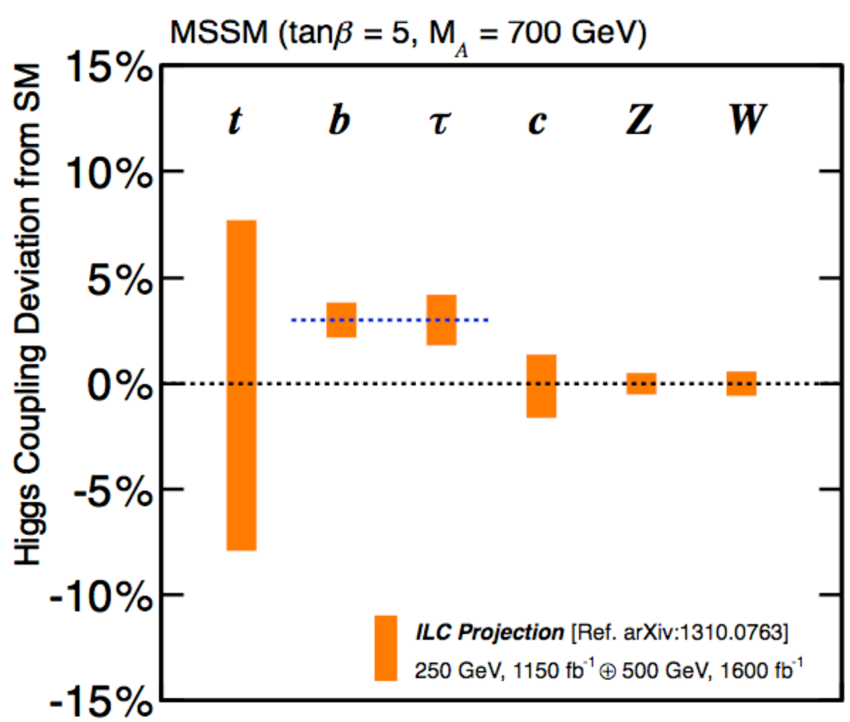
CEPC/SppC Preliminary Conceptual Design Reports:
http://cepc.ihep.ac.cn/preCDR/volume.html

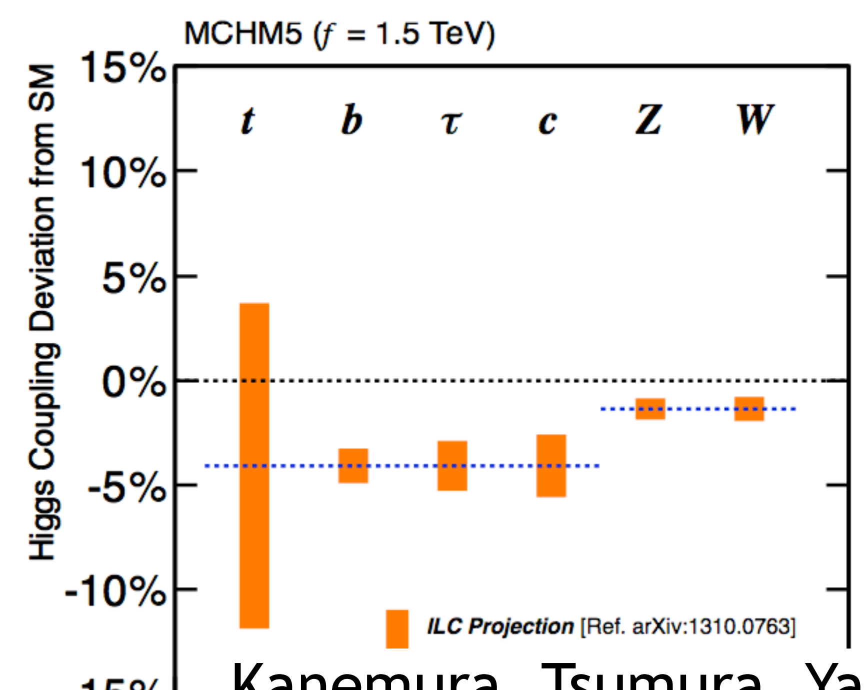
Couplings to sub-percent accuracy: Grojean et al. 1704.02333



SUSY

Composite Higgs





Kanemura, Tsumura, Yagyu, Yokoya

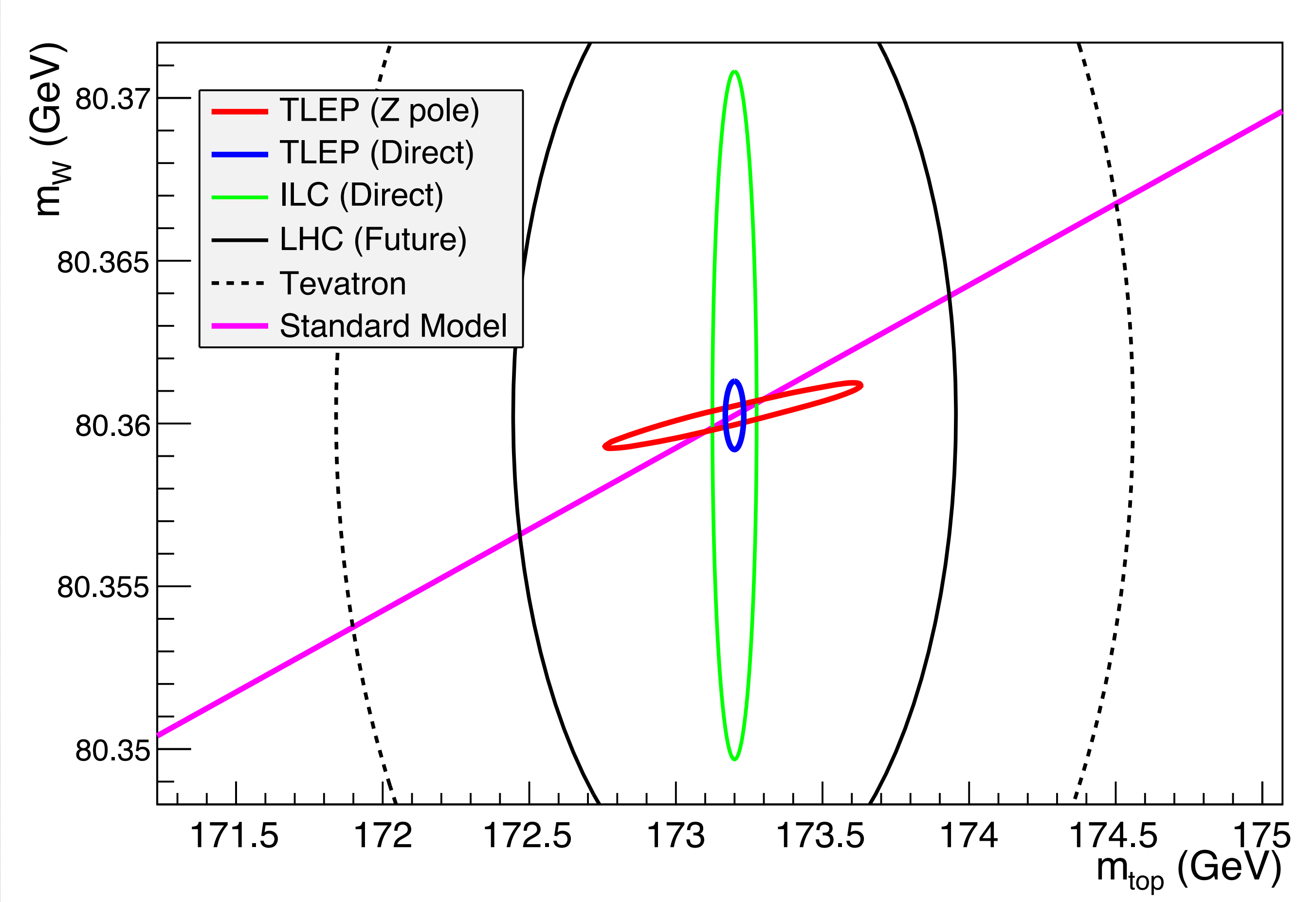
2. Z-Factory: Tera (10^{12}) Z Physics

TLEP Report: 1308.6176; EW WG Report: 1310.6708

- Clean environment, $\Delta E_{cm} < 1$ MeV, 10^5 x LEP-I
- Z-ploe: ΔM_Z, $\Delta\Gamma_Z < 0.1$ MeV, $\Delta\sin^2\theta_w < 3\text{x}10^{-6}$
  (theory systematic error dominant!)

3. W^+W^- threshold scan: (10^8 W's)

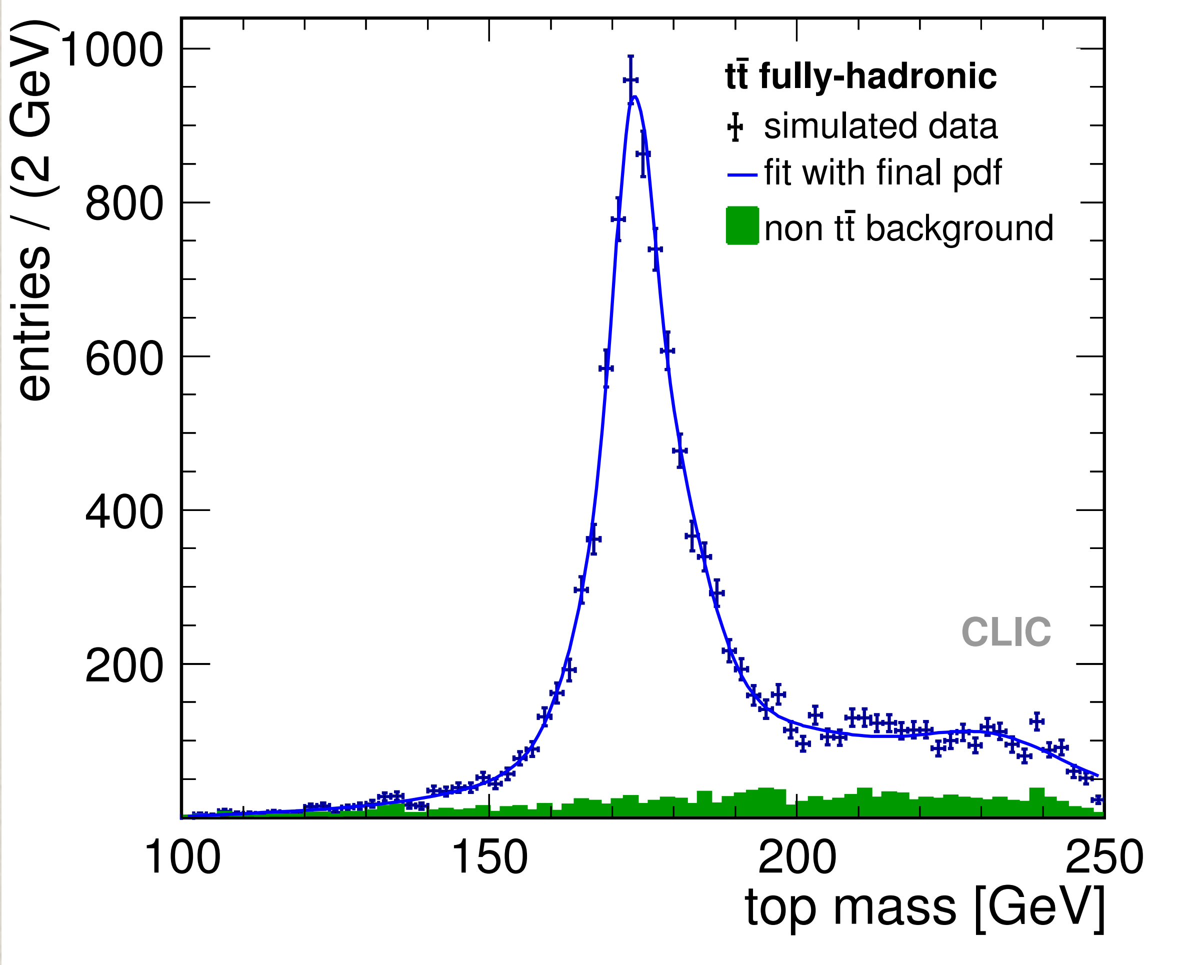
$\Delta M_W \sim O(1\text{ MeV})$, $\Delta m_t \sim O(10\text{ MeV})$, $\Delta m_H \sim O(10\text{ MeV})$.

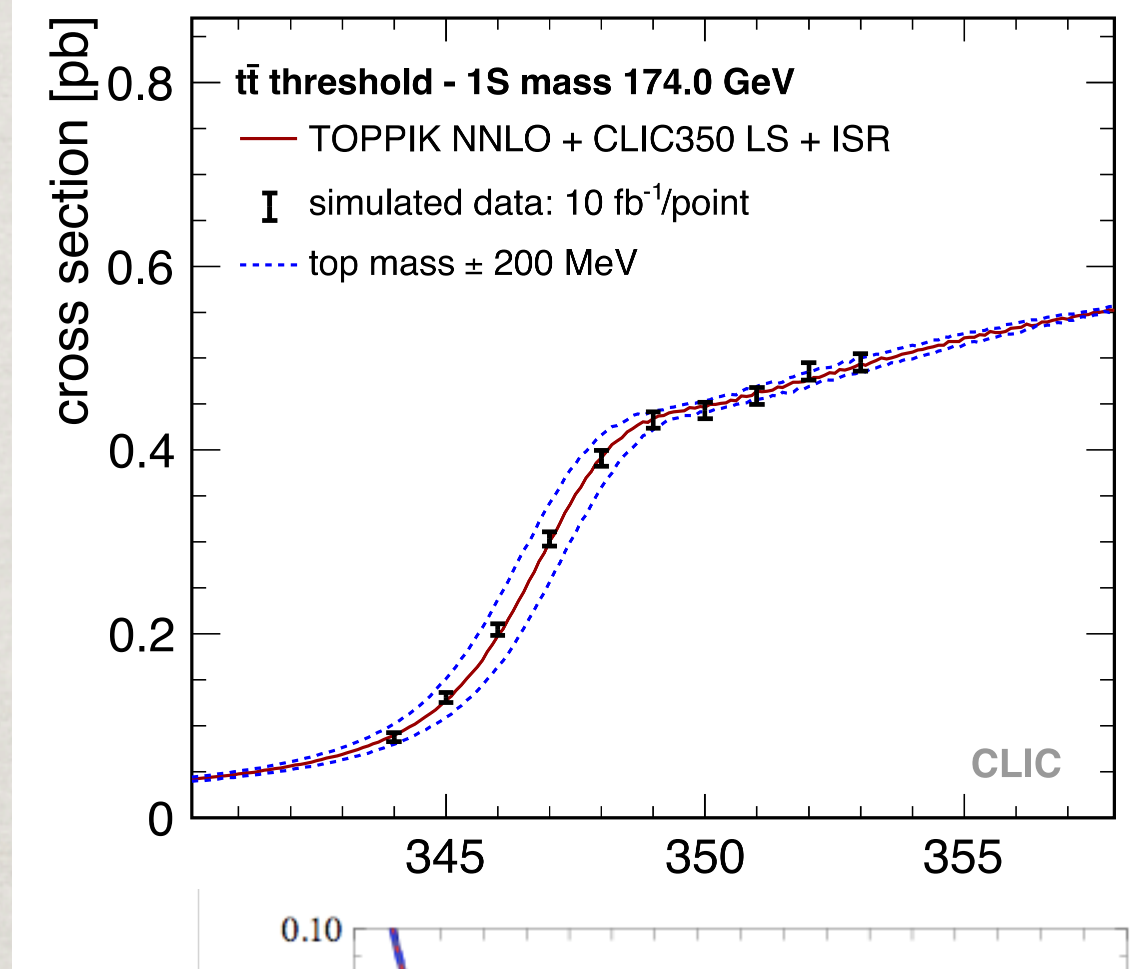


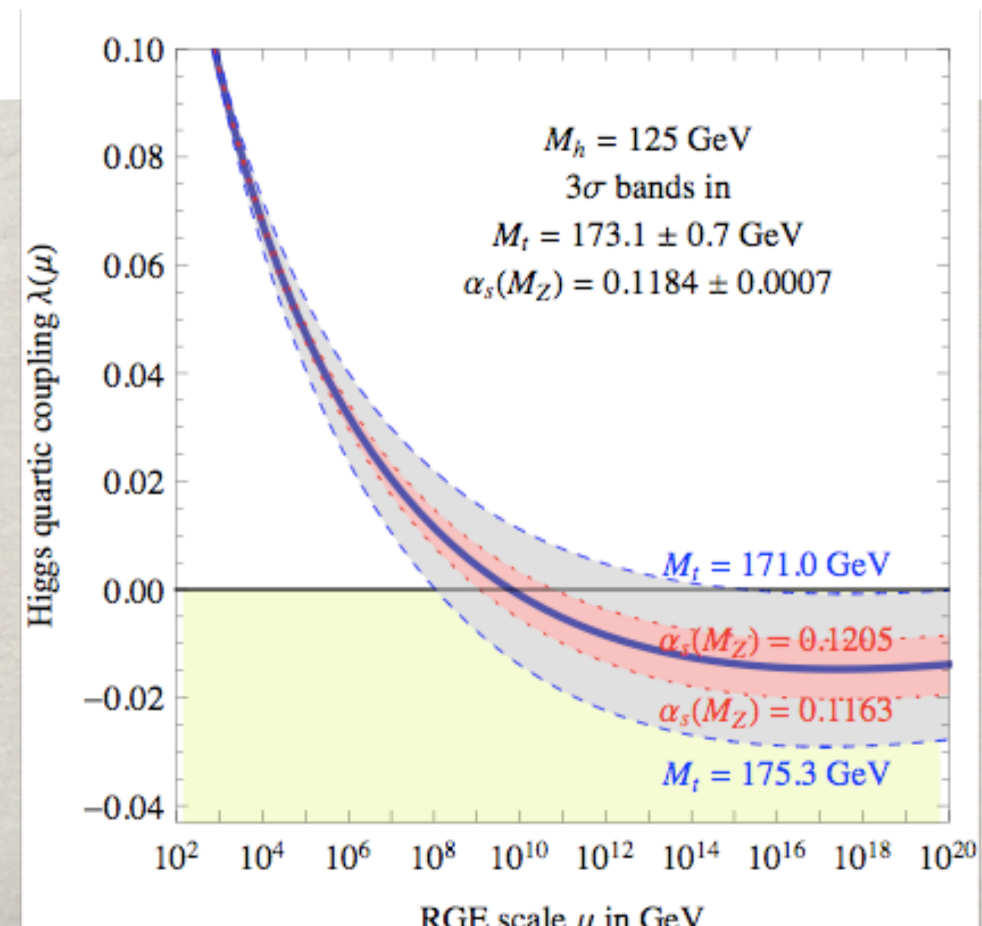
(definitive test for the SM vacuum stability)

4. Top-quark Threshold

ILC: 1604.08122; CLIC: 1307.5288v3







Combining threshold scan and top-reconstruction:

$\Delta m_t(\overline{MS}) < 50$ MeV, $\Delta \boldsymbol{\alpha}_s < 1\%$

→ Sufficient to decide on the SM vacuum stability!

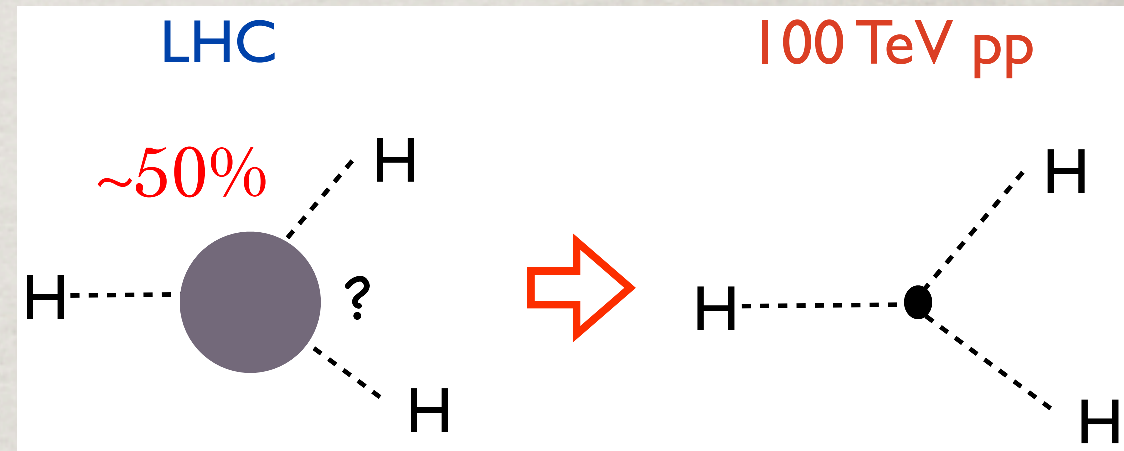
5. Toward Energy Frontier

ILC: 0.5 – 1 TeV,   CLIC: 1.4 – 3 TeV

a. Higgs Self-couplings:

$$\mathcal{L} = -\frac{1}{2} m_H^2 H^2 - \frac{g_{HHH}}{3!} H^3 - \frac{g_{HHHH}}{4!} H^4$$

$$g_{HHH} = 6 \quad v = \frac{3m_H^2}{v}, \qquad g_{HHHH} = 6 \quad = \frac{3m_H^2}{v^2}.$$



Triple coupling sensitivity:

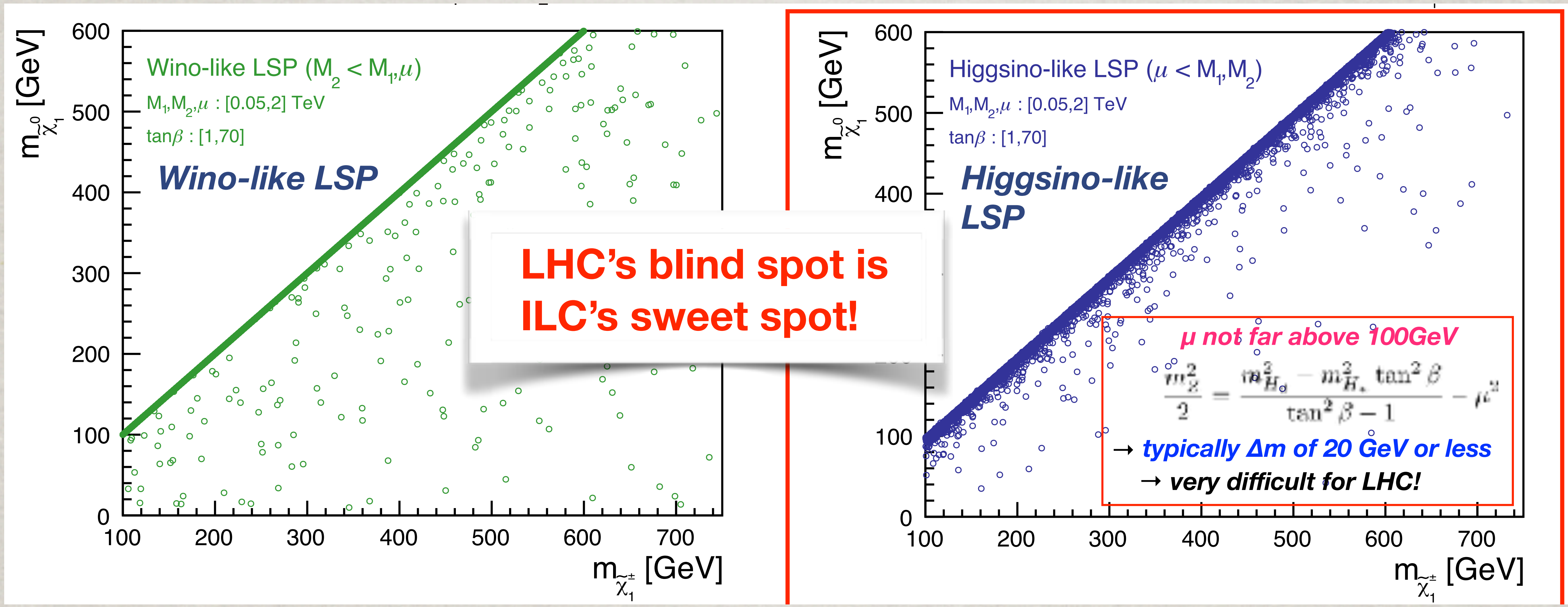
ILC arXiv:1506.07870   CLIC Report: 1307.5288v3

	0.5 TeV	1 TeV(2 ab^{-1})	1.4 TeV	3 TeV
λ_{hhh}	26%	10%	21%	10%

Test the shape of the Higgs potential better than O(1) deviations, conclusive on the fate of EW-phase transition!

b. New particle discovery: e.g. electroweakinos

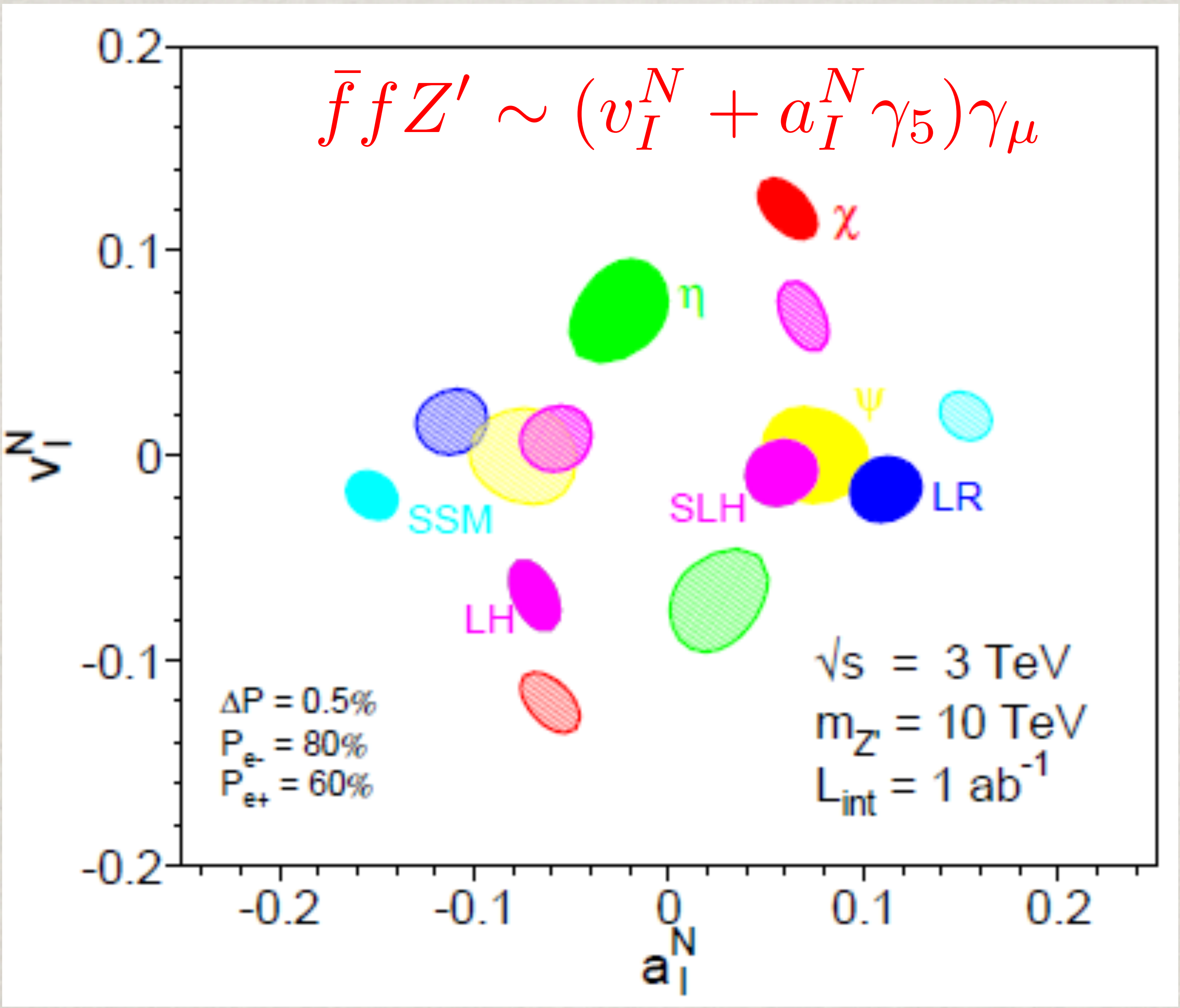
Keisuke Fujii



Discovery of an X: $M_x < E_{cm}/2$

Sensitive to $M_x^* >> E_{cm}$!

c. (virtual) Z' resolution: beam polarizations



EPJ-C: arXiv:1504.01726

Fig. 121 Top: Resolving power (95% CL) for $M_{Z'} = 1$, 1.5, and 2 TeV and $\sqrt{s} = 500$ GeV, $\mathscr{L}_{\text{int}} = 1\text{ab}^{-1}$, $|P_{e^-}|$ =80%, $|P_{e^+}|$ =60%, for leptonic couplings based on the leptonic observables σ, A_{LR}, A_{FB}. The couplings correspond to the E_6 χ, LR, LH, and KK models. From Ref. [905]. Bottom: Expected resolution at CLIC with $\sqrt{s} = 3$ TeV and $\mathscr{L} = 1$ ab^{-1} on the "normalised" leptonic couplings of a 10 TeV Z' in various models, assuming lepton universality. The mass of the Z' is assumed to be unknown. The couplings correspond to the E_6 χ, η, and ψ, the SSM, LR, LH and SLH models. The couplings can only

d. DM searches & mass determination:

$e^+e^- \rightarrow X\,X\,\gamma$

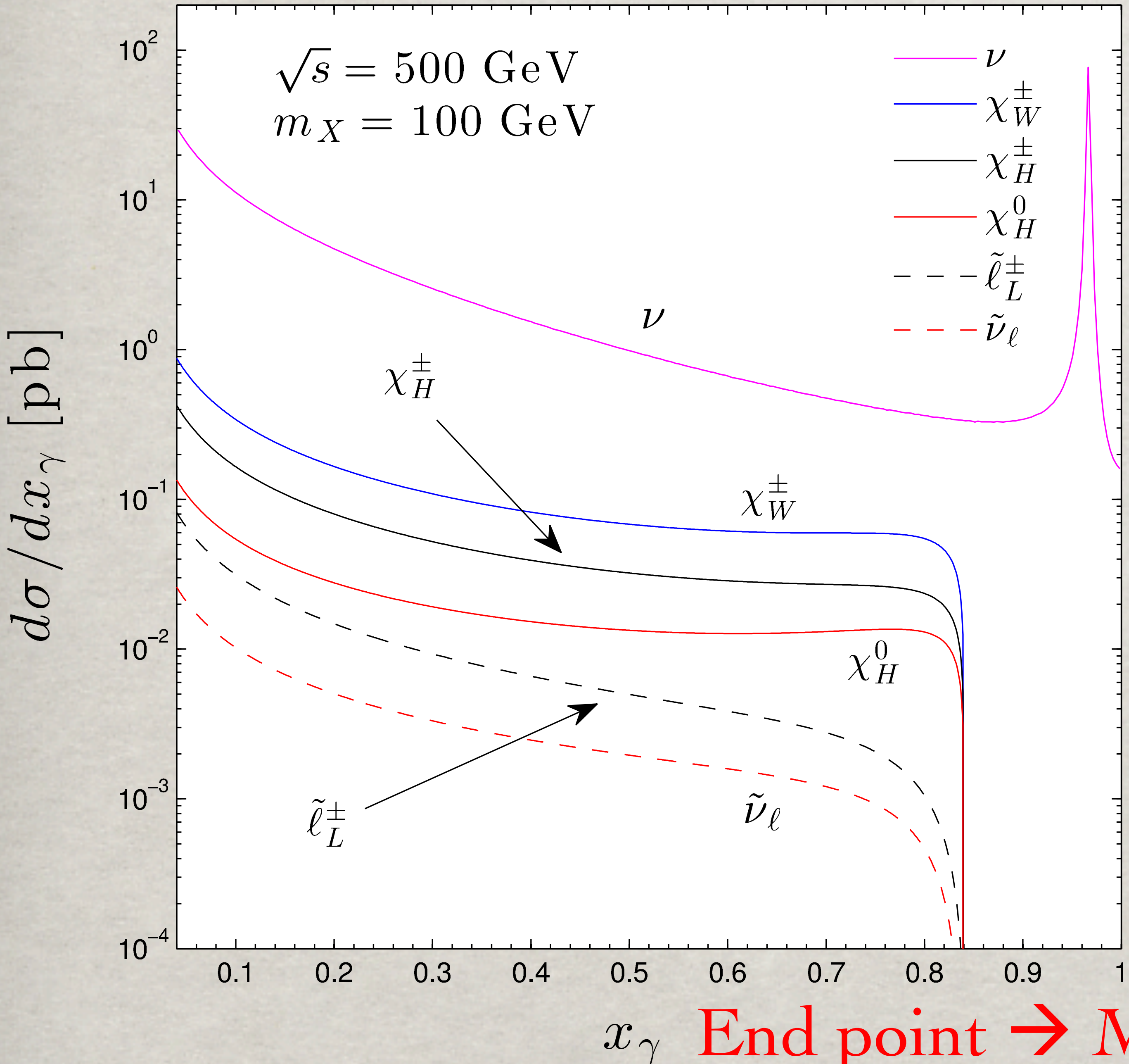
$E_\gamma = (s - M^2_{xx})/2\sqrt{s}$

$e^+e^- \rightarrow \tilde{\mu}_R^+\,\tilde{\mu}_R^-$

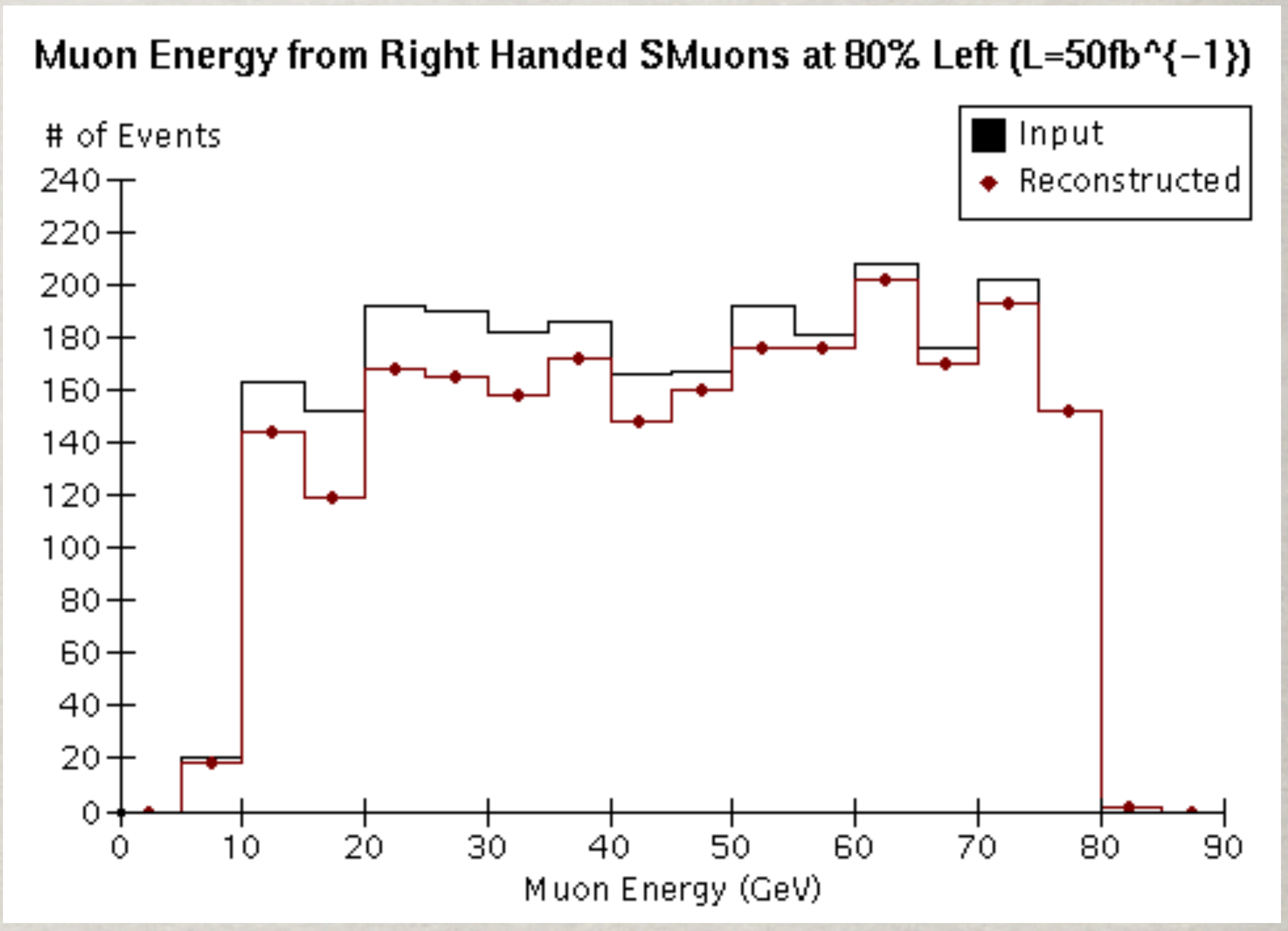
with two – body decays : $\tilde{\mu}_R^+ \rightarrow \mu^+\tilde{\chi}_0$

$$E_\mu^0 = \frac{M^2_{\tilde{\mu}_R} - m^2_\chi}{2M_{\tilde{\mu}_R}}$$

$$(1-\beta)\gamma E_\mu^0 \leq E_\mu^{lab} \leq (1+\beta)\gamma E_\mu^0$$



End point → M_X



End points → 2 Masses

TH et al. arXiv:1503.08538

hep-ex/0106056

Many other potential measurements:

EPJ-C:
arXiv:1504.01726

- SM Higgs: CP property studies
- Other heavy Higgs H^0A^0, H^+H^-, …
- SUSY parameter determination
- Test GUTs: m_0, $m_{1/2}$ A_0 → M_1, M_2, $\boldsymbol{\mu}$, $\tan\boldsymbol{\beta}$
- Contact interaction scale ~ 50 TeV

- For linear colliders, e^-e^-, $e\,\boldsymbol{\gamma}$, $\boldsymbol{\gamma}\,\boldsymbol{\gamma}$ options.

Conclusions

Higgs boson discovery has sharpened our questions in understanding Nature.

Future e^+e^- colliders have unique capabilities:

Higgs factory: $\kappa_v \sim 0.2\%$, $\Gamma_H \sim 1\%$, $Br_{inv.} \sim 1\%$, $\Delta m_H \sim 5$ MeV.
(model-independent; test invisible decay.)

Z factory: ΔM_Z, $\Delta\Gamma_Z < 0.1$ MeV, $\Delta \sin^2\theta_w < 10^{-6}$, $\Delta\boldsymbol{\alpha}_s < 0.6\%$.
(3-loop quantum effects; precision $\boldsymbol{\alpha}_s$)

WW thresholds: $\Delta M_W \sim 1$ MeV, fit $\Delta m_t \sim 10$ MeV.

Top thresholds: $\Delta m_t < 50$ MeV.
(conclusive on SM EW vacuum stability.)

LC: 1 TeV – 3 TeV: $M_x < 1.5$ TeV, $M_x^* > 70$ TeV;
(new particle discovery, chiral/CP properties.)

An exciting journey ahead!

Higgs factories under consideration:

- ILC: 250 GeV, 2 ab^{-1}, 80% / 30% polarization.
- CEPC: 240 GeV, 5 ab^{-1} .
- FCC_{ee}: 250 GeV, 20 ab^{-1} .

Z Factory : at M_Z, 20 ab^{-1} .

Higher Energy e^+e^- Colliders:

- ILC: 500 GeV, 4 ab^{-1}, 80% / 30% polarization.
- CLIC: 380 GeV, 0.5 ab^{-1}, 80% / 0 polariation.
- 1.5 TeV, 1.5 ab^{-1}; 3 TeV, 3 ab^{-1}.