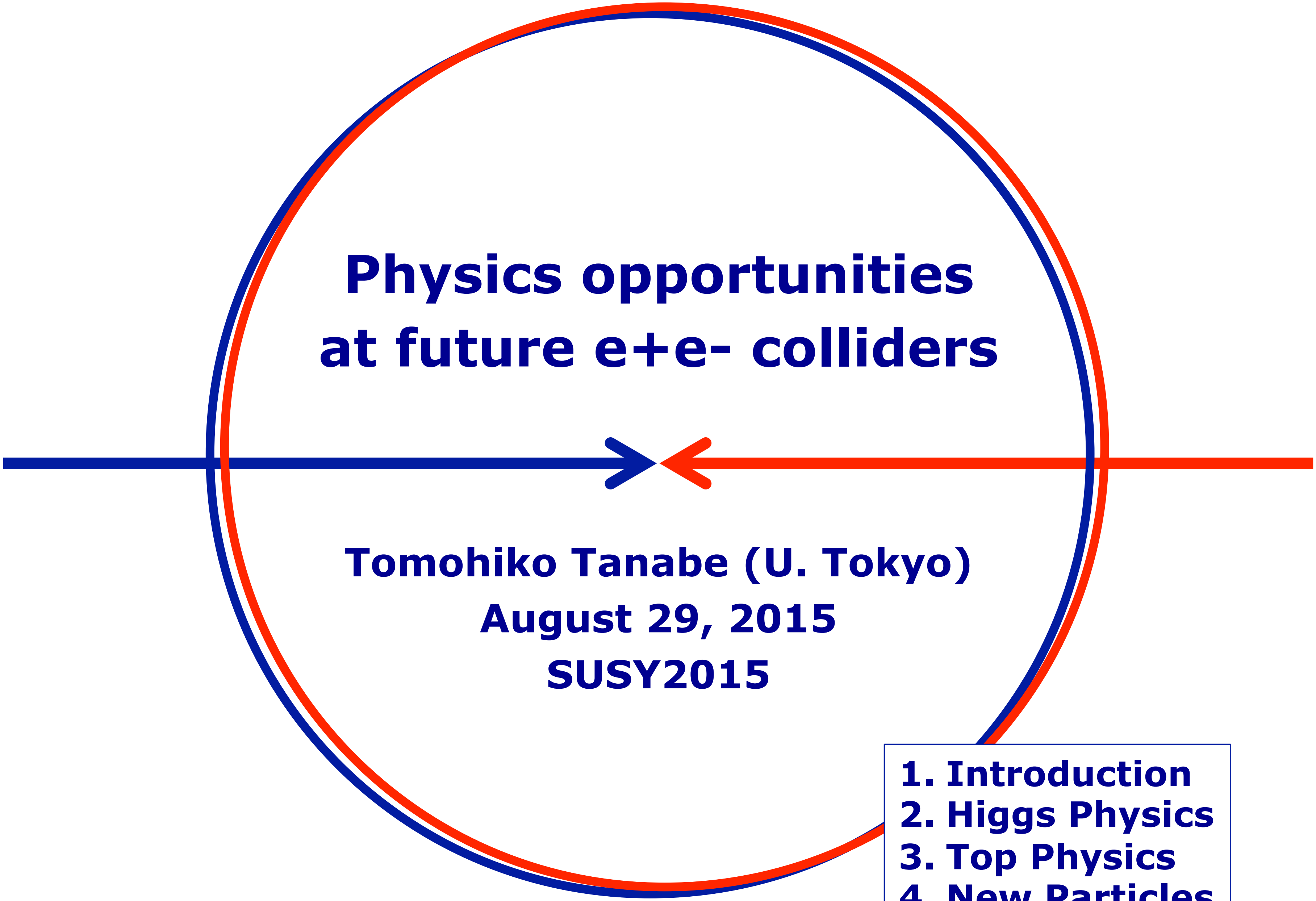
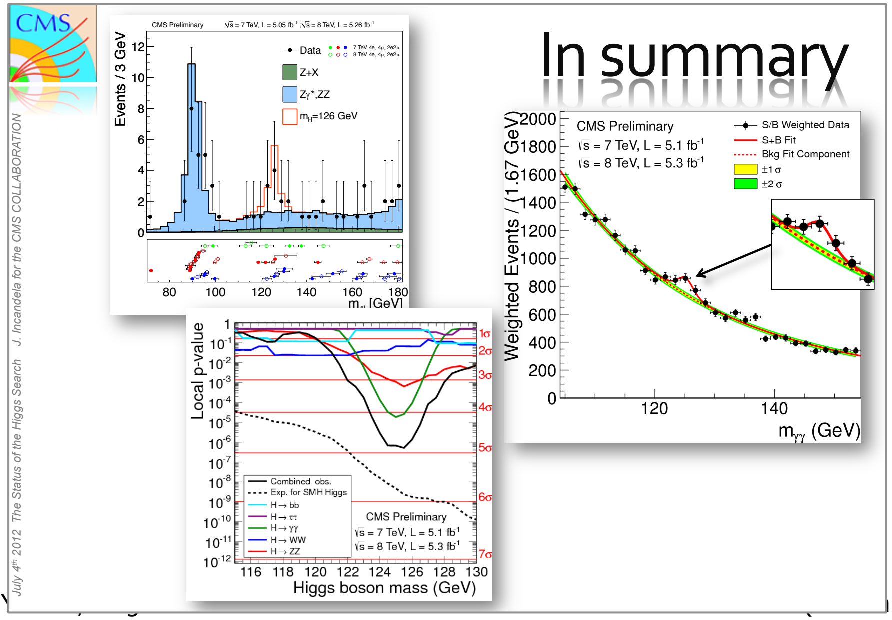


Physics opportunities at future e+e- colliders

Tomohiko Tanabe (U. Tokyo)
August 29, 2015
SUSY2015

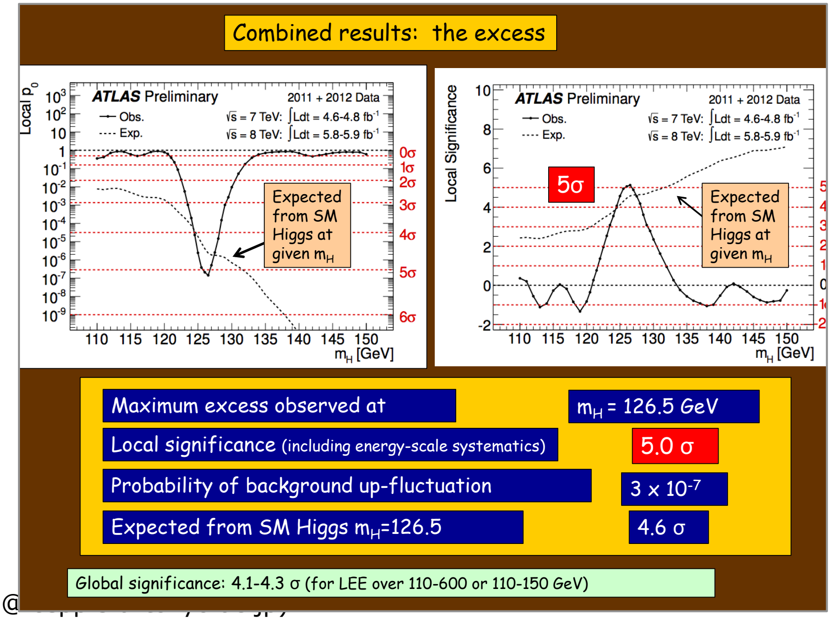
1. Introduction
2. Higgs Physics
3. Top Physics
4. New Particles

July 4, 2012



In summary

July 4th 2012 The Status of the Higgs Search J. Incandela for the CMS COLLABORATION



Combined results: the excess

Expected from SM Higgs at given m_H

Maximum excess observed at	m_H = 126.5 GeV
Local significance (including energy-scale systematics)	5.0 σ
Probability of background up-fluctuation	3×10^{-7}
Expected from SM Higgs m_H=126.5	4.6 σ

Global significance: 4.1-4.3 σ (for LEE over 110-600 or 110-150 GeV)

Electroweak Symmetry Breaking

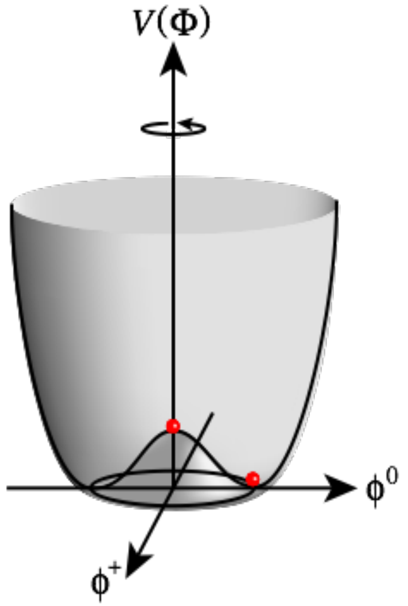
- With the discovery of H(125), we now understand how EWSB occurs: via the expectation value of the Higgs field. **However, we do yet know the physics behind the EWSB.**

- In order to explain the shape of the Higgs potential (if there is an explanation), we need to go **beyond the Standard Model.**

- Such BSM models predict the existence of **new particles/forces**. They also affect the properties of the **Higgs, top,** and **W/Z**, which can be probed via **precision measurements.**

- They could be connected to the **observed BSM phenomena**:
  - baryon asymmetry of the universe
  - neutrino oscillations
  - dark matter
  - dark energy
  - …

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$



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And today…

many proposals for a next generation electron-positron collider with which we can study the Higgs boson in great detail:

CEPC

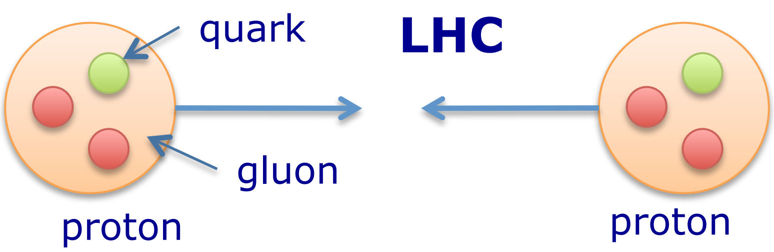
FCC
hh ee he

ilc

clic

At proton-proton colliders:

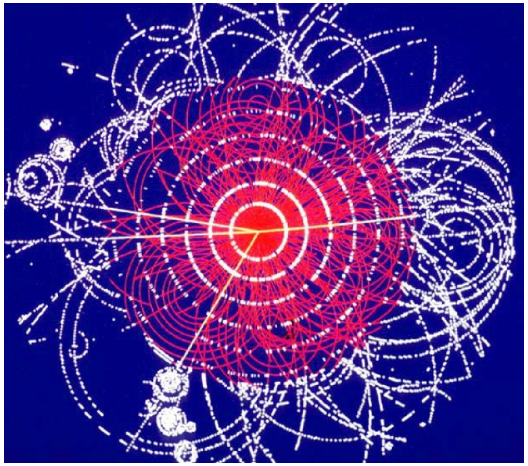
- Proton = quarks + gluons
- Ease of reaching high energy
- Longitudinal CM momentum not known



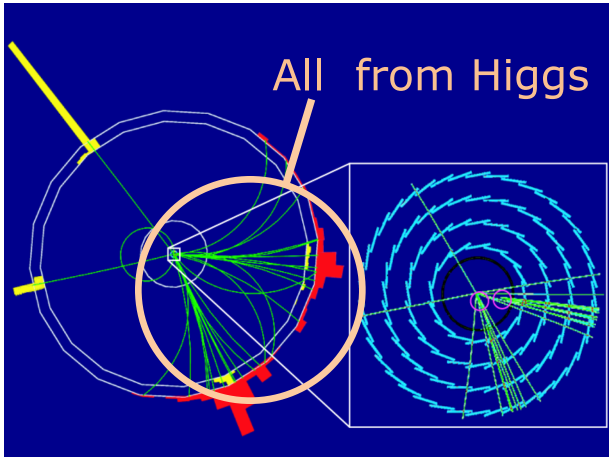
At electron-positron colliders:

- Clean reaction of elementary particles
- Precision probes / coverage without holes
- CM energy & momentum known

LHC



e.g. ILC



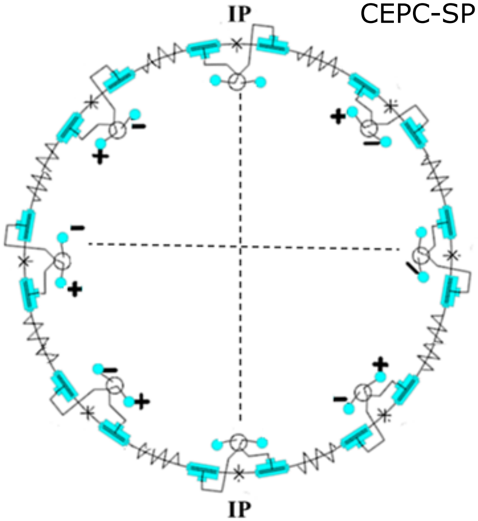
Circular Colliders

CEPC

Pre-CDR Mar. 2015

Circular Electron-Positron Collider

- Site: **China**
- CM energy: **90-240 GeV**
- Single main ring + booster ring
- Circumference: **50 km**
- # of IPs: **2**
- Precursor to 70 TeV pp collider (**SPPC**)

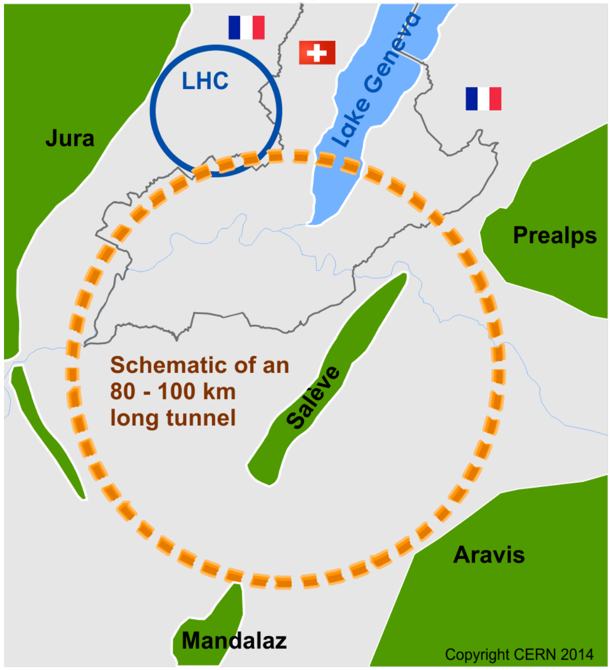


CEPC-SPPC PreCDR

FCC-ee

Future Circular Collider: e+e-

- Site: **CERN**
- CM energy: **90-350 GeV**
- Two main rings + booster ring
- Circumference: **100 km**
- # of IPs: **2-4**
- Possible precursor to
  100 TeV pp collider (**FCC-hh**)



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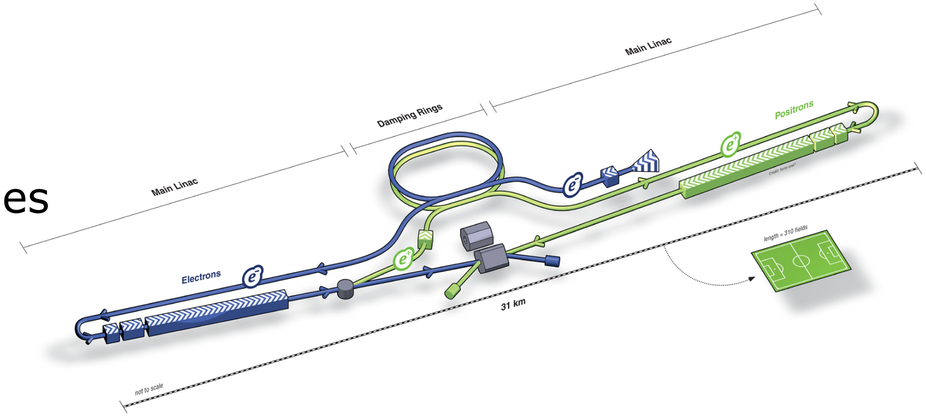
Linear Colliders

ILC

TDR 2012

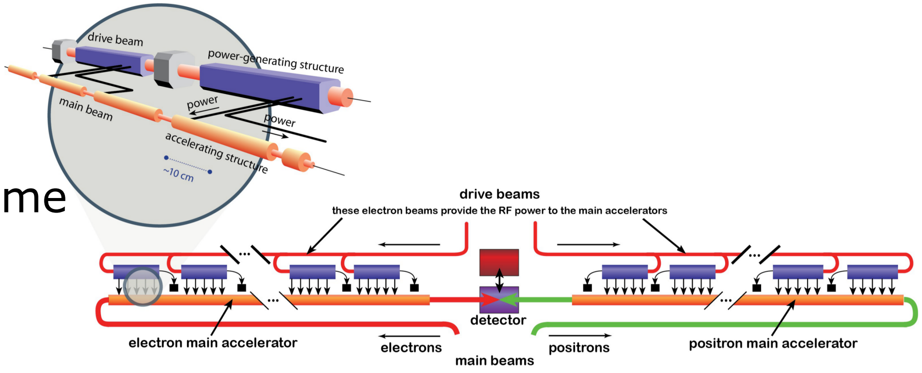
International Linear Collider
- Based on superconducting RF cavities
- Potential site: **Japan**
- CM energy: **250-500 GeV**
  (upgradable to 1 TeV)
- Length: **31 km** (for 500 GeV)



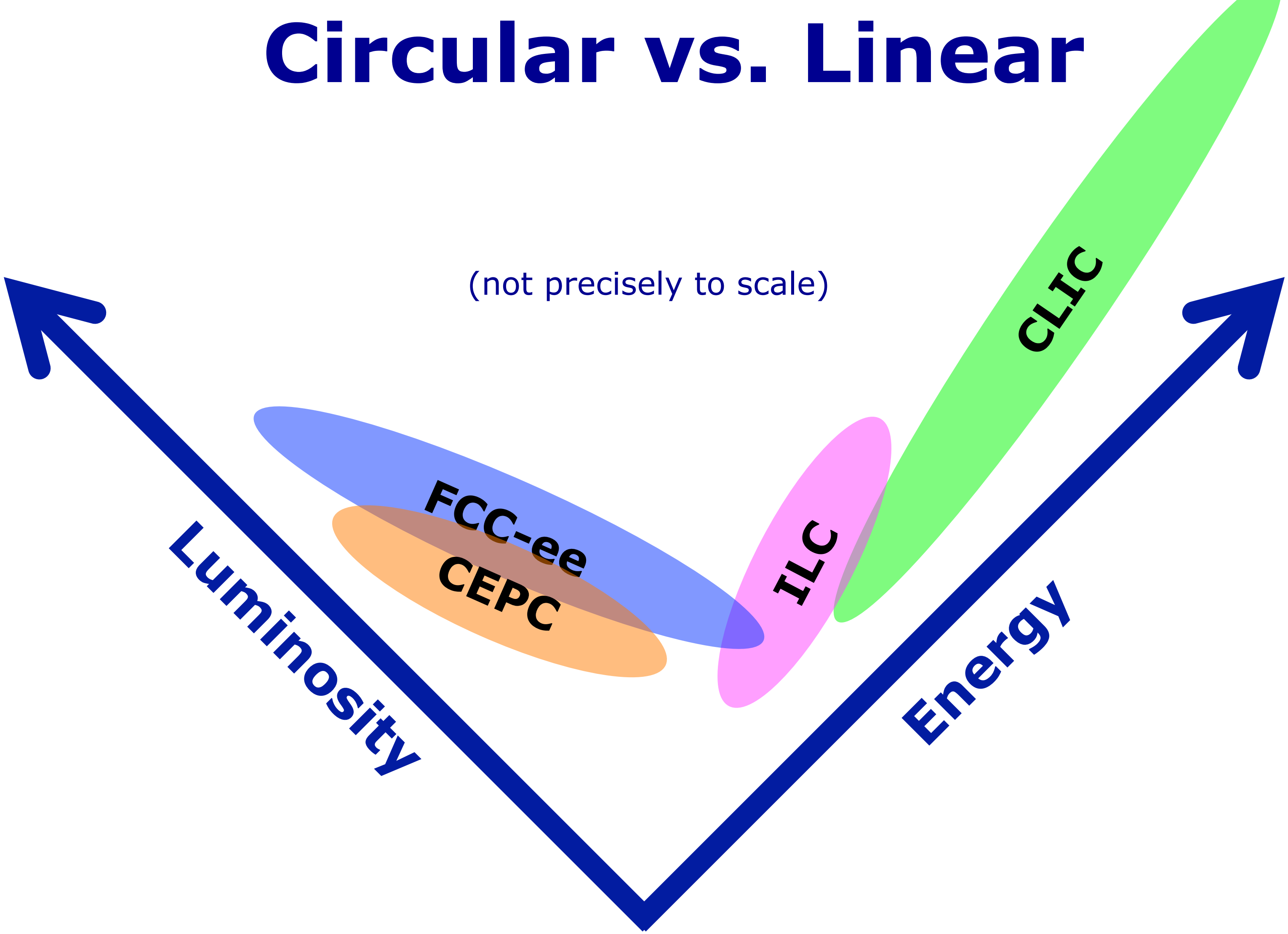
CLIC

CDR 2011

Compact Linear Collider
- Based on 2-beam acceleration scheme
- Site: **CERN**
- CM energy: **350 GeV → 3 TeV**
- Length: **50 km** (for 3 TeV)



Circular vs. Linear



They have different capabilities:

- Circular colliders → high luminosity
- Linear colliders → high energy

And therefore different approaches! (with some complementarity)

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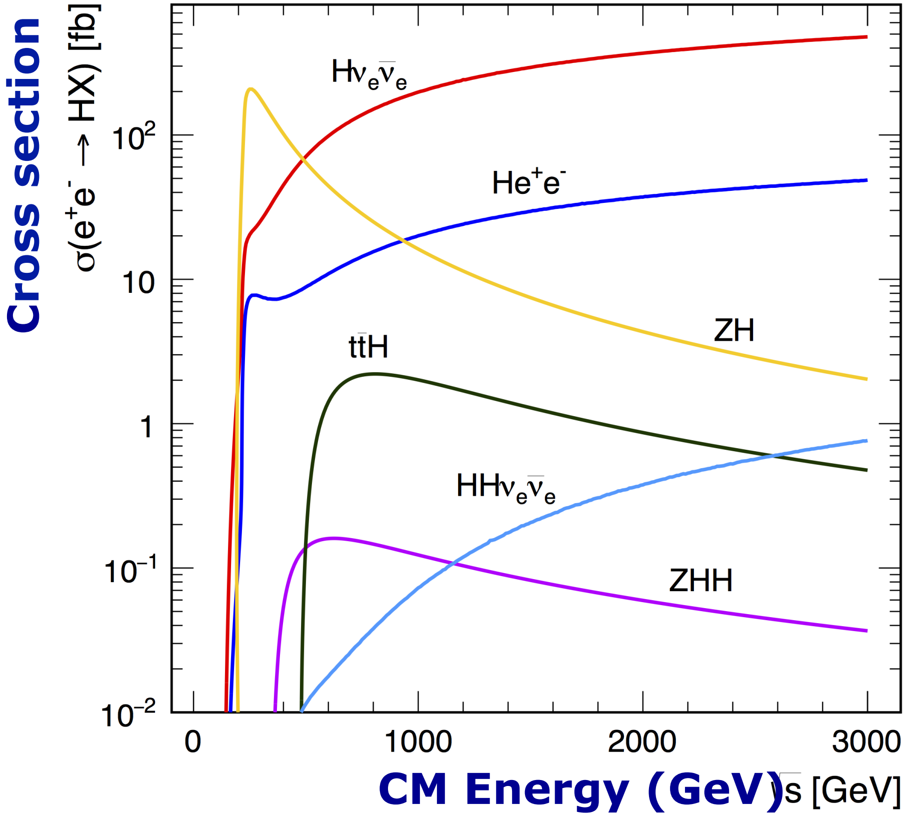
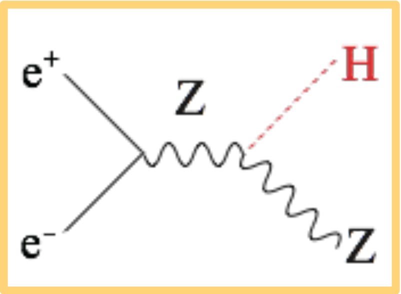
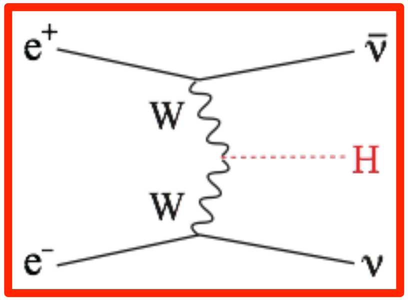
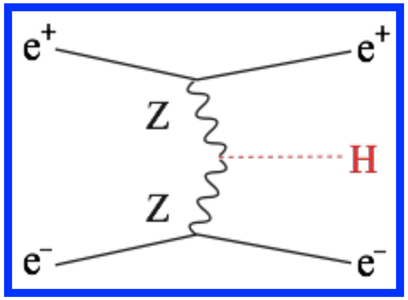
Higgs Physics at future e+e- colliders

Higgs Production









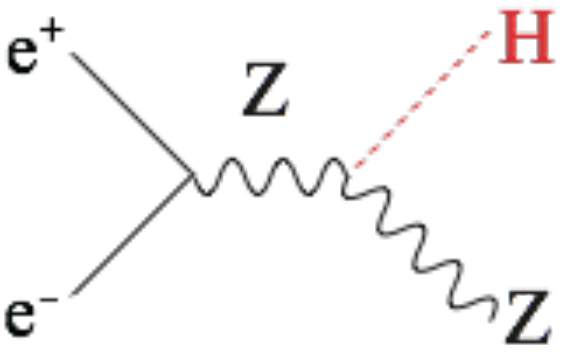
ZH associated prod.
Peaks around ~250 GeV

W fusion
Dominant at high energies

Z fusion

CEPC
FCC-ee
ILC
CLIC

Higgs recoiling against Z

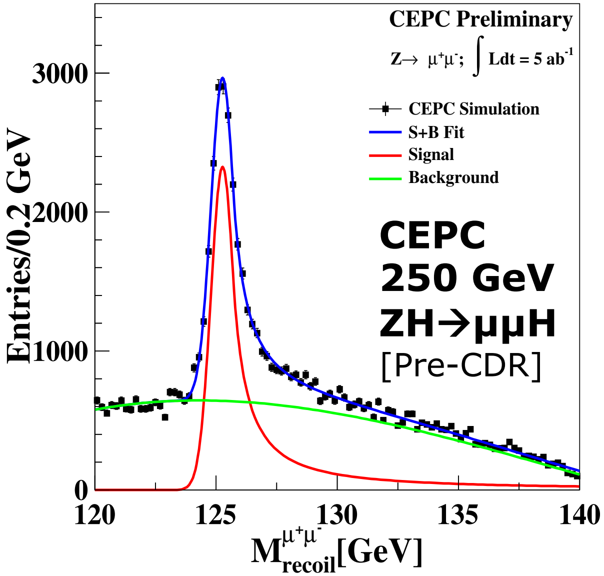


Reconstruct Z boson, subtract from well-known initial state 4-vector.

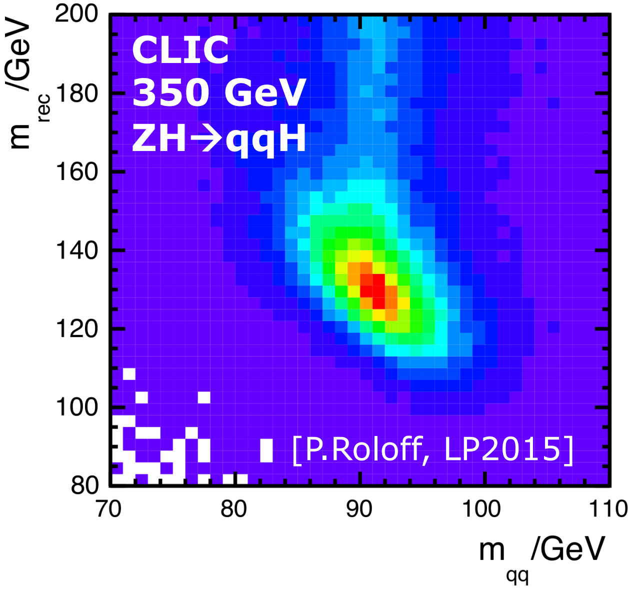
$$M_{\mathrm{recoil}}^2 = (\sqrt{s} - E_Z)^2 - |\vec{p}_Z|^2$$

Model-independent, absolute measurement of Higgs mass and σ(Zh):

Δm_h ~ 10 MeV
$\Delta\kappa_Z/\kappa_Z$ ~ 0.2%
for lumi ~ 5 ab-1
best for CEPC/FCC-ee



CEPC
250 GeV
ZH→μμH
[Pre-CDR]



CLIC
350 GeV
ZH→qqH
[P.Roloff, LP2015]

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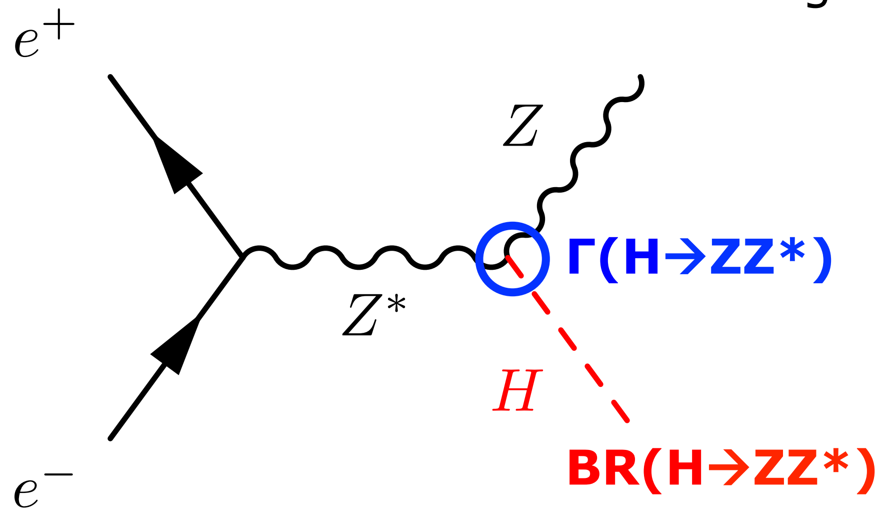
CEPC
FCC-ee
ILC
CLIC

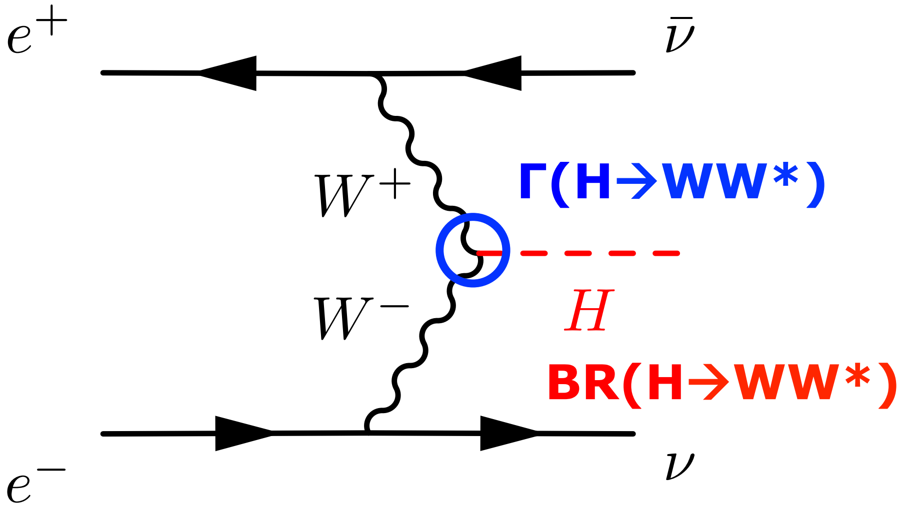
Higgs Total Width

In the SM, the Higgs total width is Γ_H ~ 4 MeV.
Too small to be measured directly even for e+e-.
Indirect measurement is possible.
Using the narrow-width approximation,

$$g_i^2 \propto \Gamma_i = \mathrm{BR}_i \times \Gamma_H$$

Partial Width & Branching Ratio measurements with Z/W:





Limited by low statistics due to small BR(H→ZZ*)~2%.

Require high CM energy for large statistics.

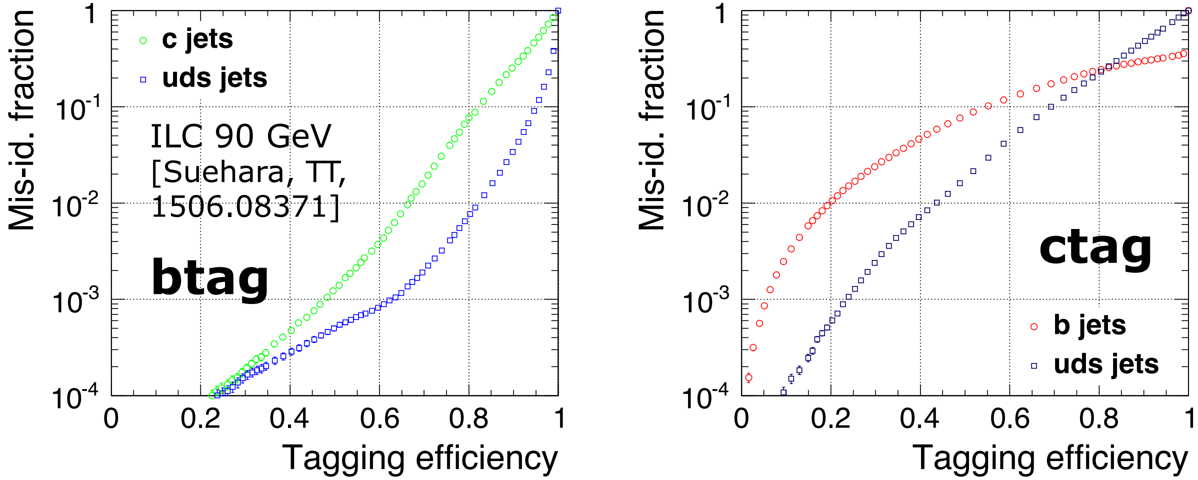
At ILC, Higgs width precision is ~2% [1506.06992]

CEPC
FCC-ee
ILC
CLIC

Higgs hadronic decays

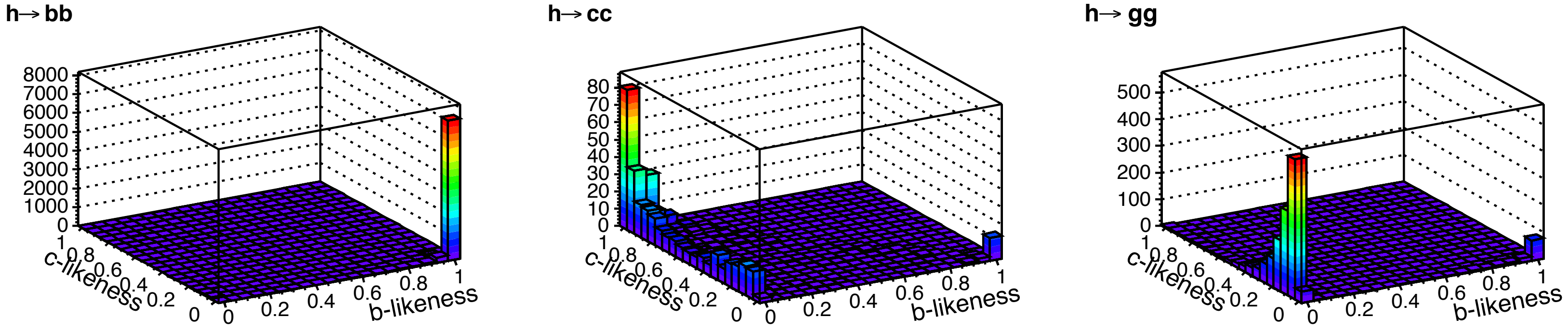
Detector foreseen to have excellent vertex detectors, with capability to identify bottom and charm jets.
→ measure Higgs hadronic BRs

b-tagging & c-tagging performance (per jet):



Template distributions for H→bb,cc,gg:

ILC 250 GeV [H.Ono]



$\Delta\kappa_b/\kappa_b < 1\%$, $\Delta\kappa_c/\kappa_c \sim O(1)\%$, $\Delta\kappa_g/\kappa_g \sim O(1)\%$

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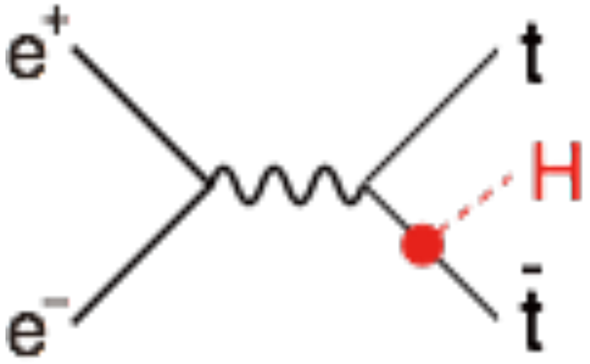
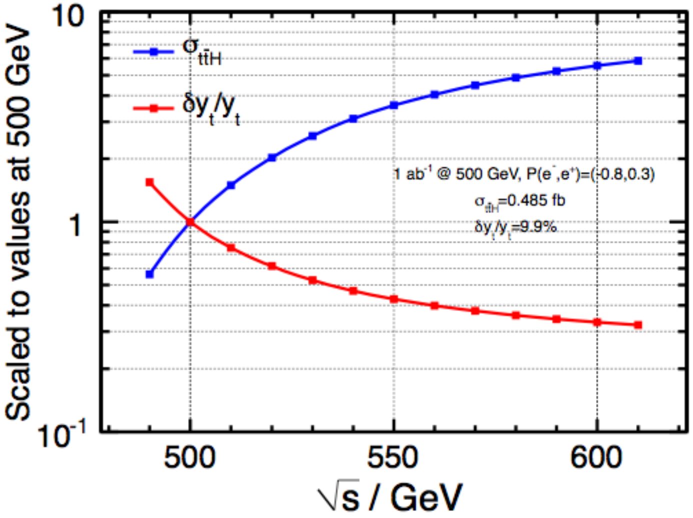
ILC
CLIC

Top Yukawa Coupling





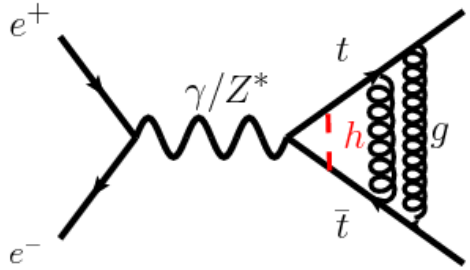
e+e- → ttH process: Bound-state effects significant @ 500 GeV

Final states analyzed: 8 jets, 6 jets+1 lepton, (4 jets+2 leptons not included in comb.)

Crucial tools: b-tagging, jet combination, lepton isolation

E_{CM}	Int. Lumi	Δy/y
500 GeV	**0.5 ab-1**	**18%**
500 GeV	**4 ab-1**	**6%**
1 TeV	**1.5 ab-1**	**2%**

FCC-ee
ILC
CLIC



Indirect measurement at ttbar threshold
Model-dependent, contribution from both anomalous coupling and new particles in the loop.
→ Top Yukawa Precision ~10%.

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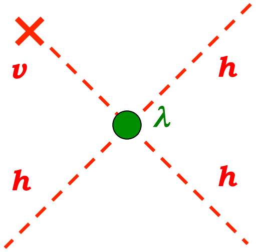
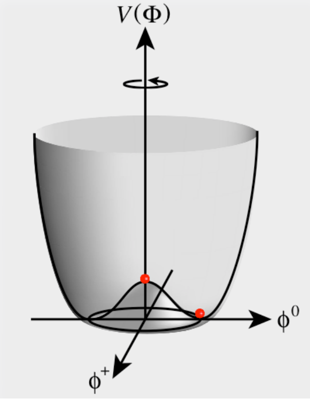
ILC
CLIC

Higgs Self-Coupling

- HHH coupling: direct probe of the Higgs potential
- Large (>20%) deviations predicted by models of electroweak baryogenesis



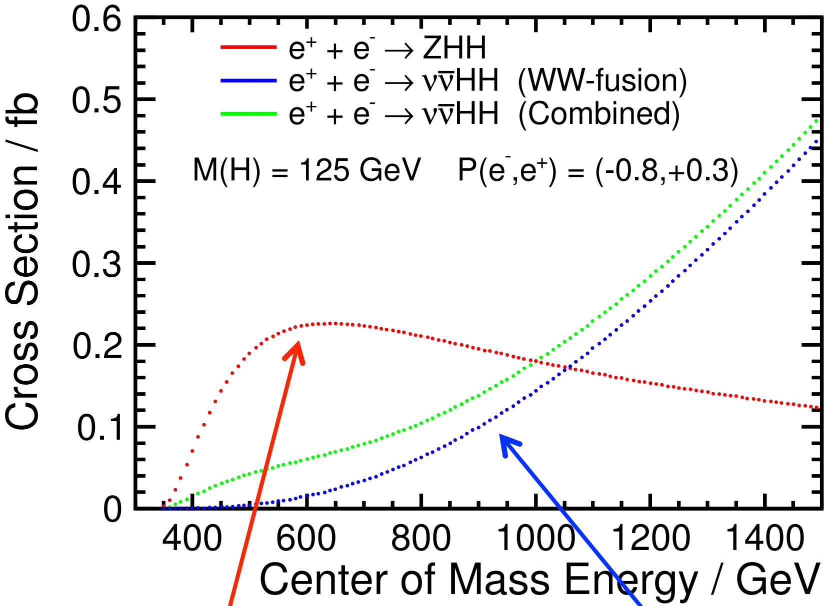


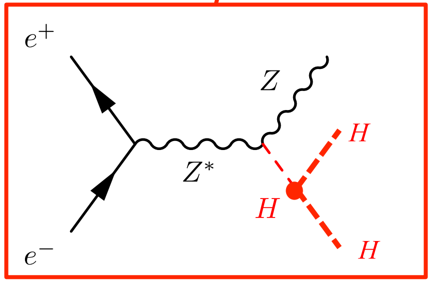
Challenging measurement due to:

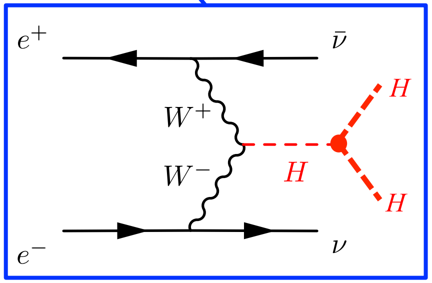
- Small cross section (~0.2 fb)
- Many jets in the final state
- **Effect of irreducible diagrams**

$\Delta\lambda/\lambda$ = 1.66 $d\sigma/\sigma$ @ 500 GeV
$\Delta\lambda/\lambda$ = 0.76 $d\sigma/\sigma$ @ 1 TeV

E_{CM}	Int. Lumi	$\Delta\lambda/\lambda$
500 GeV	**0.5 ab-1**	**77%**
500 GeV	**4 ab-1**	**27%**
1.4 TeV / 3 TeV	**1.5 ab-1 / 2 ab-1**	**10% combined**



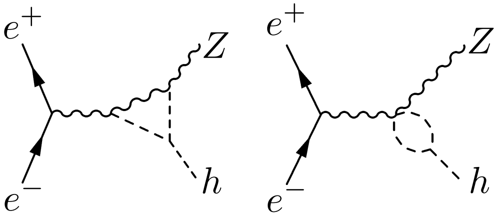




CEPC
FCC-ee

Indirect measurement

[McCullough, 1312.3322]

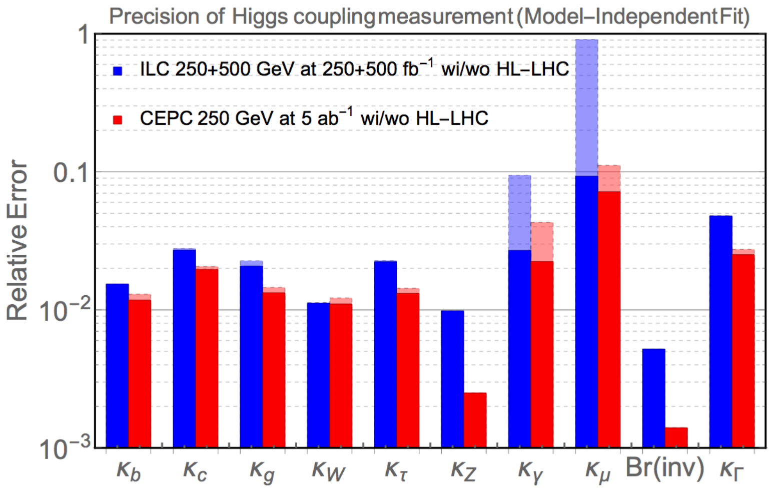


model-dependent loop corrections to ZH

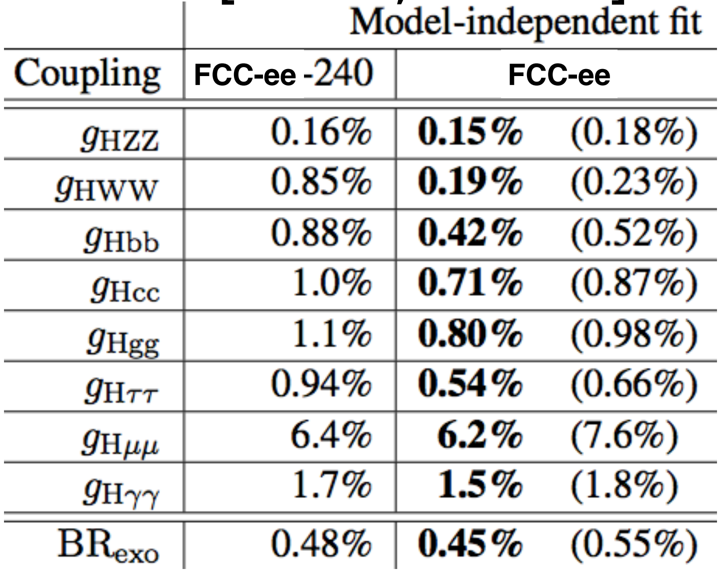
$\Delta\lambda/\lambda$ ~35%

$\sqrt{s}$=240 GeV, L=5 ab-1

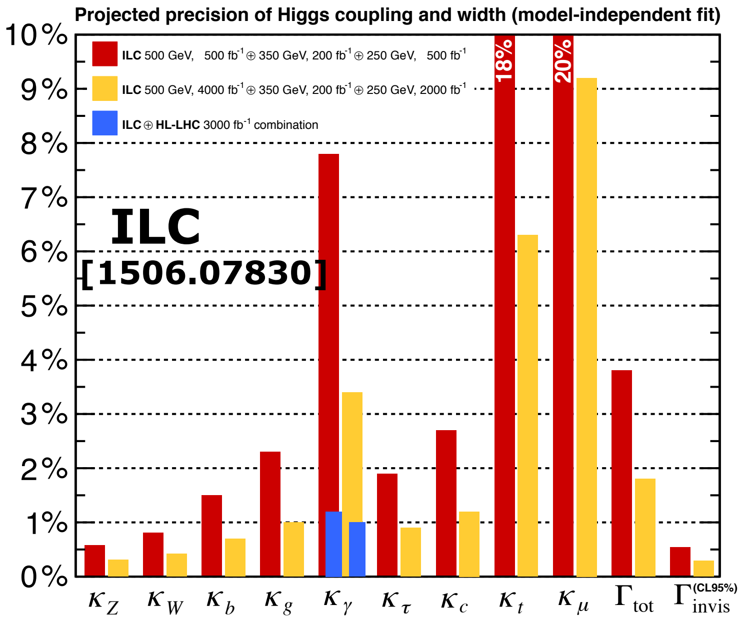
CEPC [Pre-CDR]



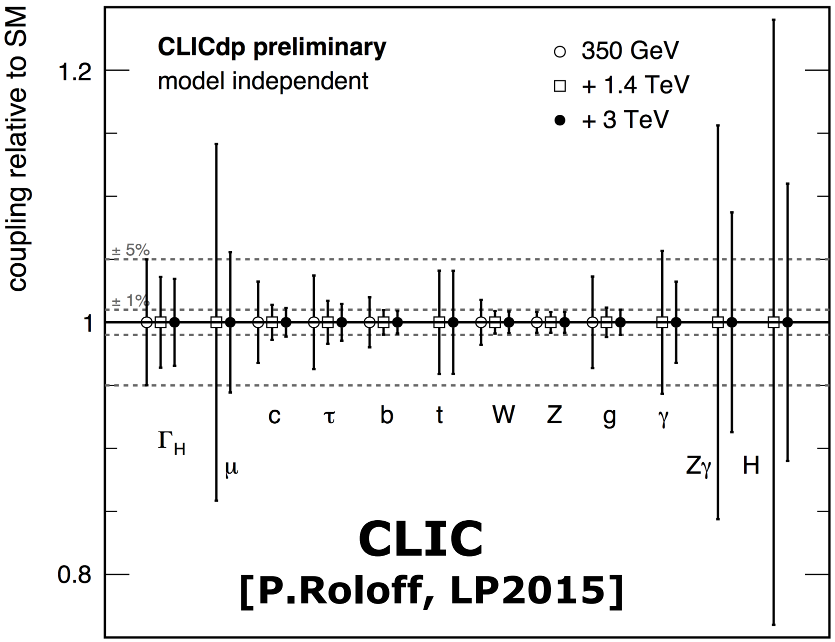
FCC-ee [M.Klute, EPS2015]



Coupling	Model-independent fit FCC-ee -240	FCC-ee	
g_{HZZ}	0.16%	**0.15%**	(0.18%)
g_{HWW}	0.85%	**0.19%**	(0.23%)
g_{Hbb}	0.88%	**0.42%**	(0.52%)
g_{Hcc}	1.0%	**0.71%**	(0.87%)
g_{Hgg}	1.1%	**0.80%**	(0.98%)
$g_{\mathrm{H}\tau\tau}$	0.94%	**0.54%**	(0.66%)
$g_{\mathrm{H}\mu\mu}$	6.4%	**6.2%**	(7.6%)
$g_{\mathrm{H}\gamma\gamma}$	1.7%	**1.5%**	(1.8%)
$\mathrm{BR}_{\mathrm{exo}}$	0.48%	**0.45%**	(0.55%)

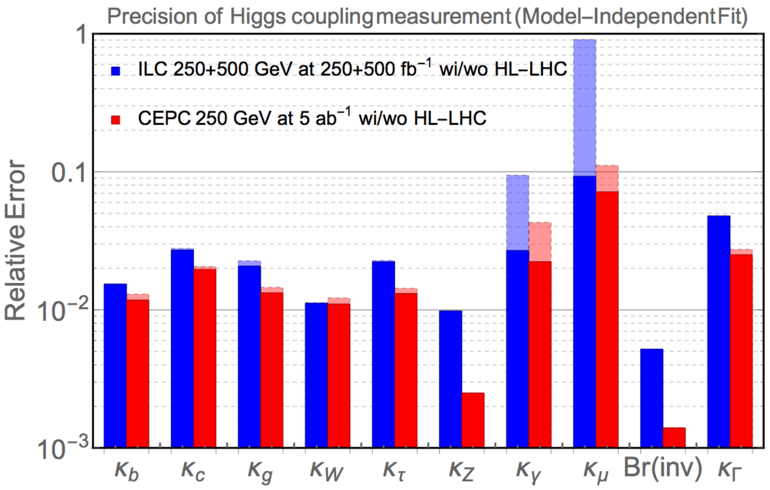


ILC
[1506.07830]

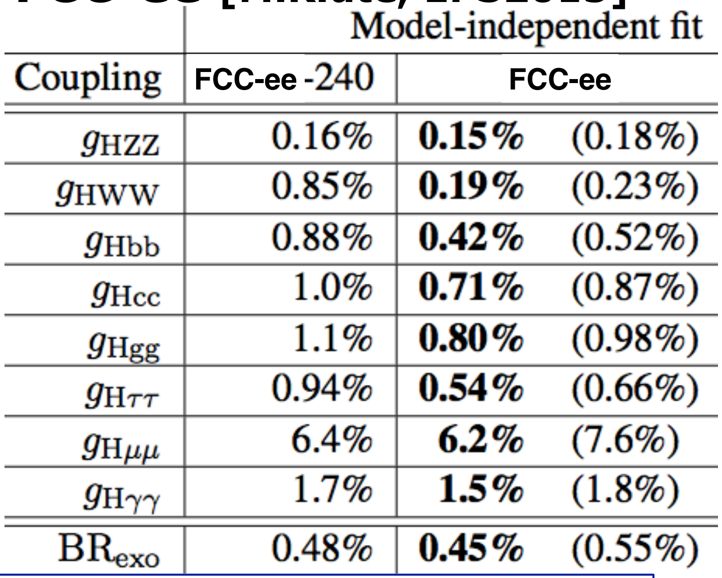


CLIC
[P.Roloff, LP2015]

CEPC [Pre-CDR]



FCC-ee [M.Klute, EPS2015]

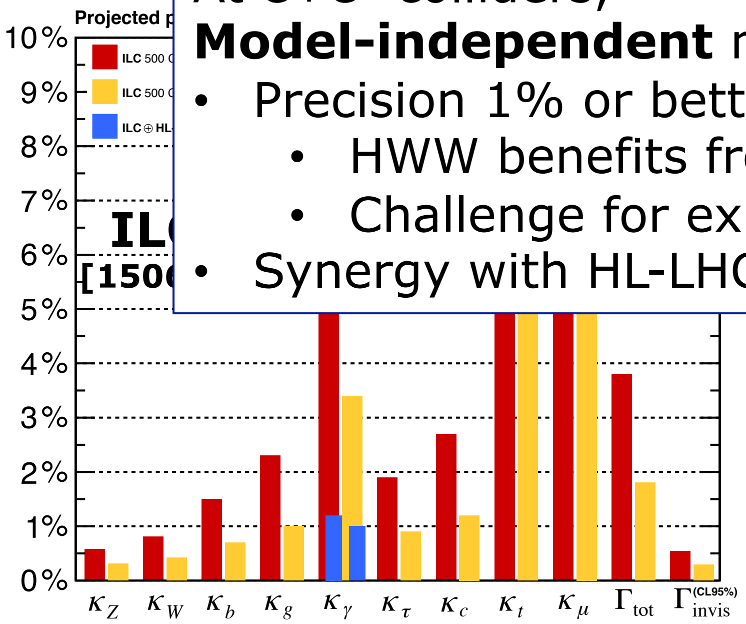


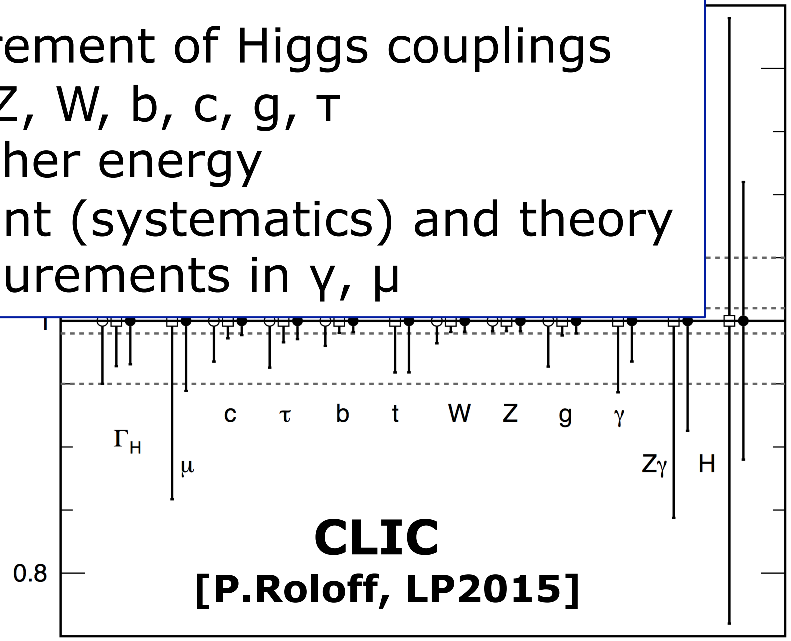
	Model-independent fit		
Coupling	FCC-ee -240	FCC-ee	
g_{HZZ}	0.16%	**0.15 %**	(0.18%)
g_{HWW}	0.85%	**0.19 %**	(0.23%)
g_{Hbb}	0.88%	**0.42 %**	(0.52%)
g_{Hcc}	1.0%	**0.71 %**	(0.87%)
g_{Hgg}	1.1%	**0.80 %**	(0.98%)
$g_{\mathrm{H\tau\tau}}$	0.94%	**0.54 %**	(0.66%)
$g_{\mathrm{H\mu\mu}}$	6.4%	**6.2 %**	(7.6%)
$g_{\mathrm{H\gamma\gamma}}$	1.7%	**1.5 %**	(1.8%)
$\mathrm{BR_{exo}}$	0.48%	**0.45 %**	(0.55%)

At e+e- colliders,

Model-independent measurement of Higgs couplings

- Precision 1% or better for Z, W, b, c, g, τ
  - HWW benefits from higher energy
  - Challenge for experiment (systematics) and theory
- Synergy with HL-LHC measurements in γ, μ





CLIC

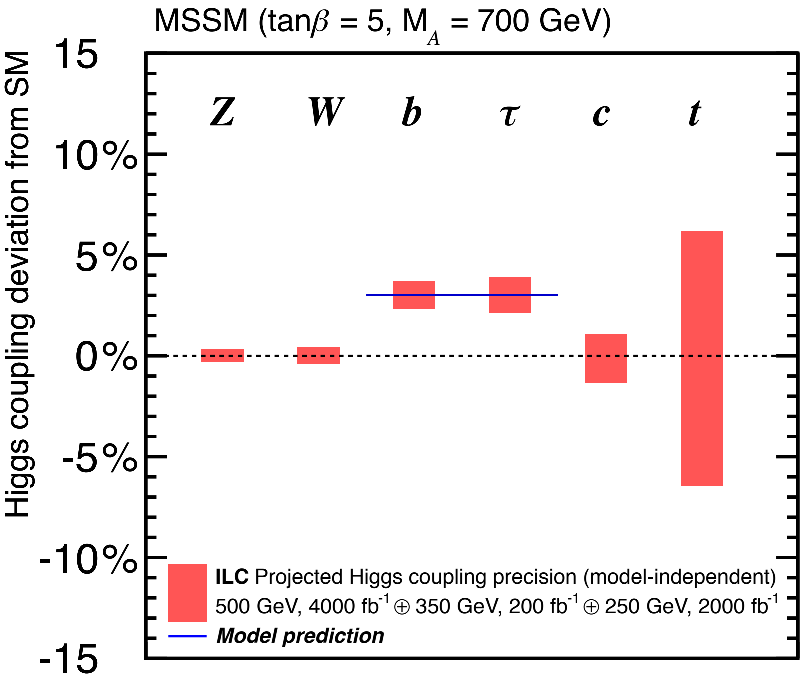
[P.Roloff, LP2015]

CEPC
FCC-ee
ILC
CLIC

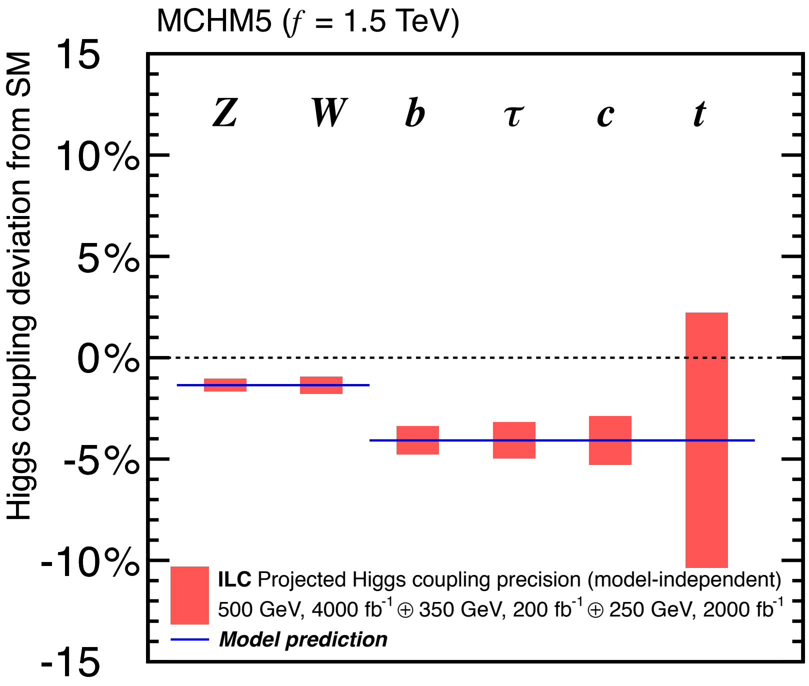
Fingerprinting

Higgs boson: elementary or composite?

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)

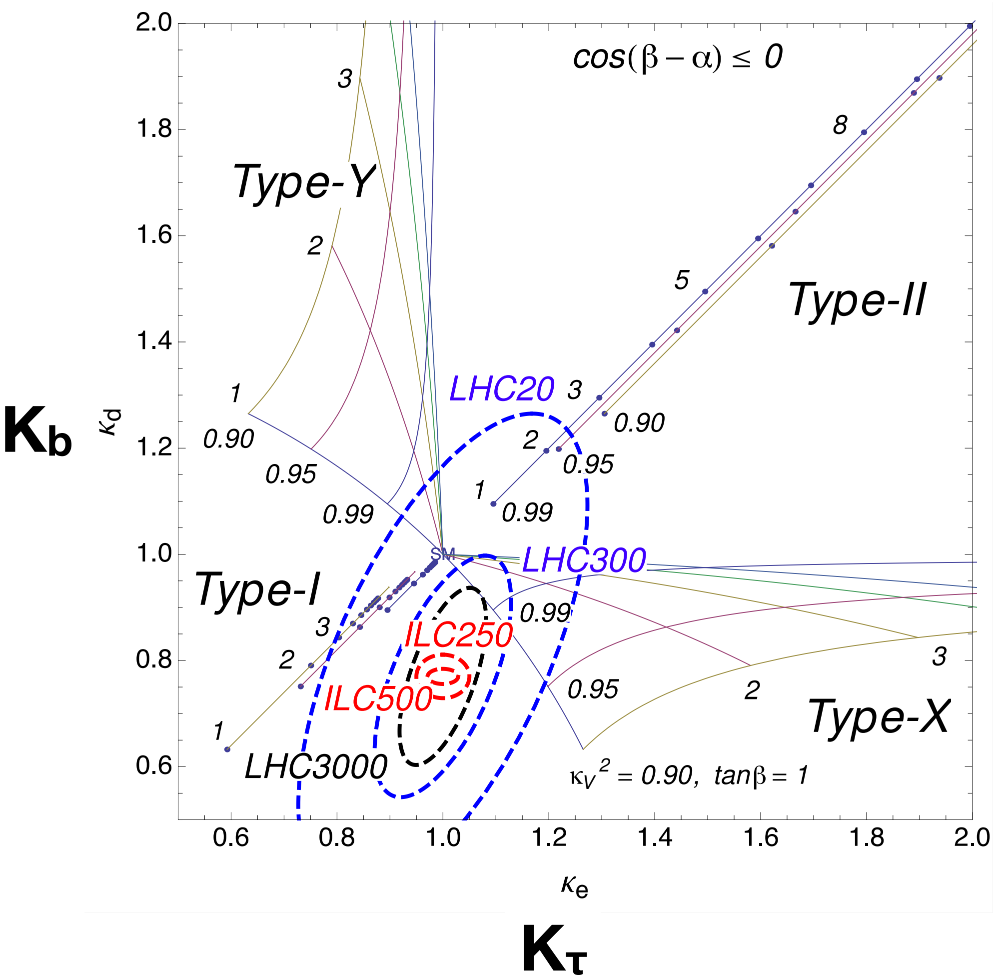


→ Distinguish models which have specific deviation patterns

CEPC
FCC-ee
ILC
CLIC

Fingerprinting

Two-Higgs Doublet Models

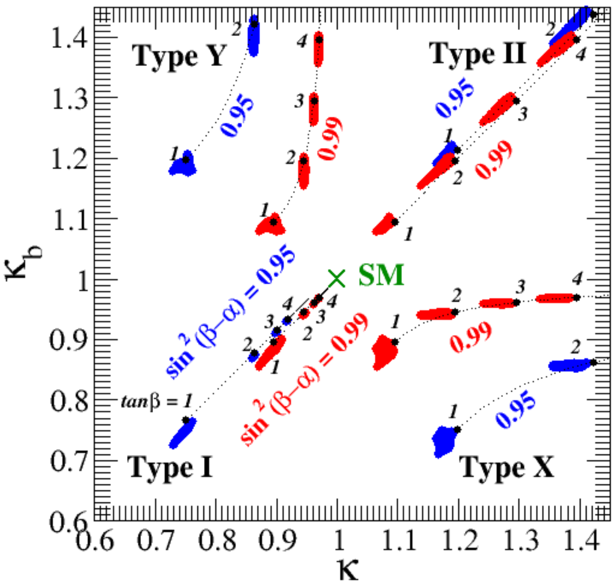


[Kanemura, Tsumura, Yagyu, Yokoya, 1406.3294]

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	+	−	−	−	−	+
Type II (SUSY)	+	−	−	+	+	+
Type X (Lepton-specific)	+	−	−	−	+	+
Type Y (Flipped)	+	−	−	+	−	+

4 Possible Z_2 Charge Assignments that forbids tree-level Higgs-induced FCNC

Discrimination of Higgs multiplet structure with precise coupling measurements.



With radiative corrections
[Kikuchi, 1412.0375]

Top Physics
at future e+e- colliders

Vacuum Stability and Top Mass

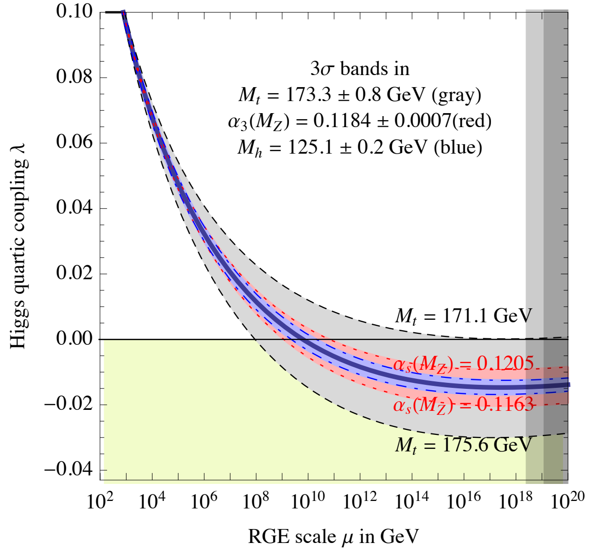
With the observed Higgs boson mass, the SM can be extrapolated to very high energies, possibly up to the Planck scale.

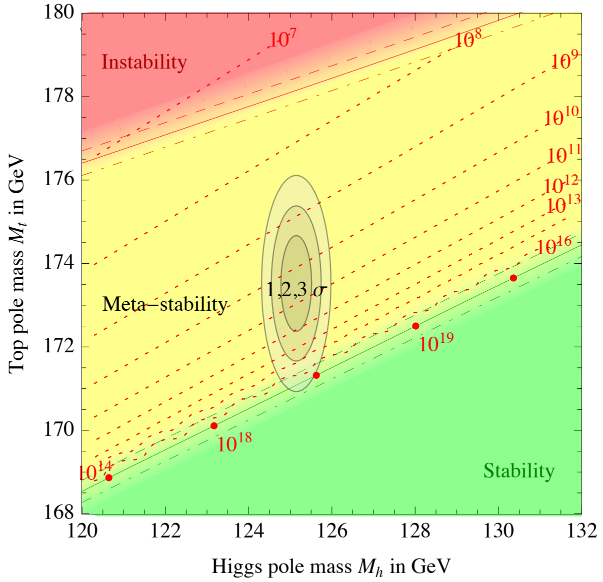
The SM vacuum appears to be at a point of meta-stability.

Does the Higgs quartic coupling really become negative below the Planck scale, or become exactly zero at the Planck scale?

To answer this question, need precise measurement of the top quark mass.

[Buttazzo et al. 1307.3536]





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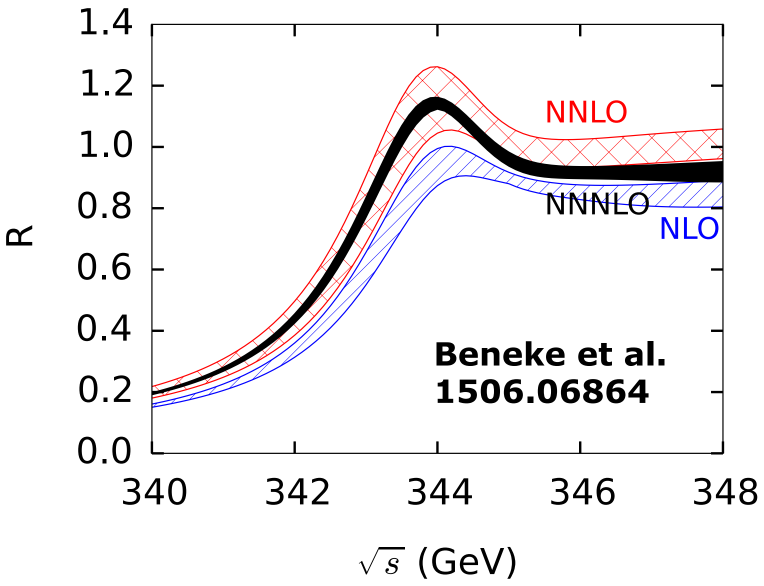
m_t : threshold scan

Hadron colliders measure the “Monte-Carlo” mass.
Uncertainty associated with the conversion into theoretically well-defined top mass (e.g. $\overline{MS}$).
→ Future prospects: **500 MeV** [Snowmass Top WG, 1311.2028]

At e+e- colliders, can measure the 1S or the potential-subtracted top mass. They can be converted into the $\overline{MS}$ mass at high accuracy. From recent 4-loop calculation of uncertainty [Marquard et al. 1502.01030], **7 MeV (from 1S), 23 MeV (from PS)**

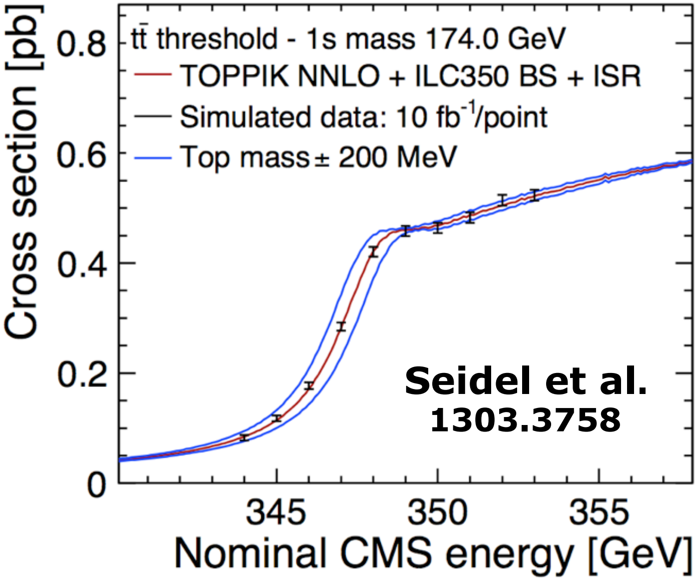
Additional uncertainty coming from the calculation of the line shape of the ttbar cross section;

Recent NNNLO calculation [Beneke et al, 1506.06864] shows **50 MeV** theory uncertainty is feasible.



FCC-ee
ILC
CLIC

m_t : threshold scan



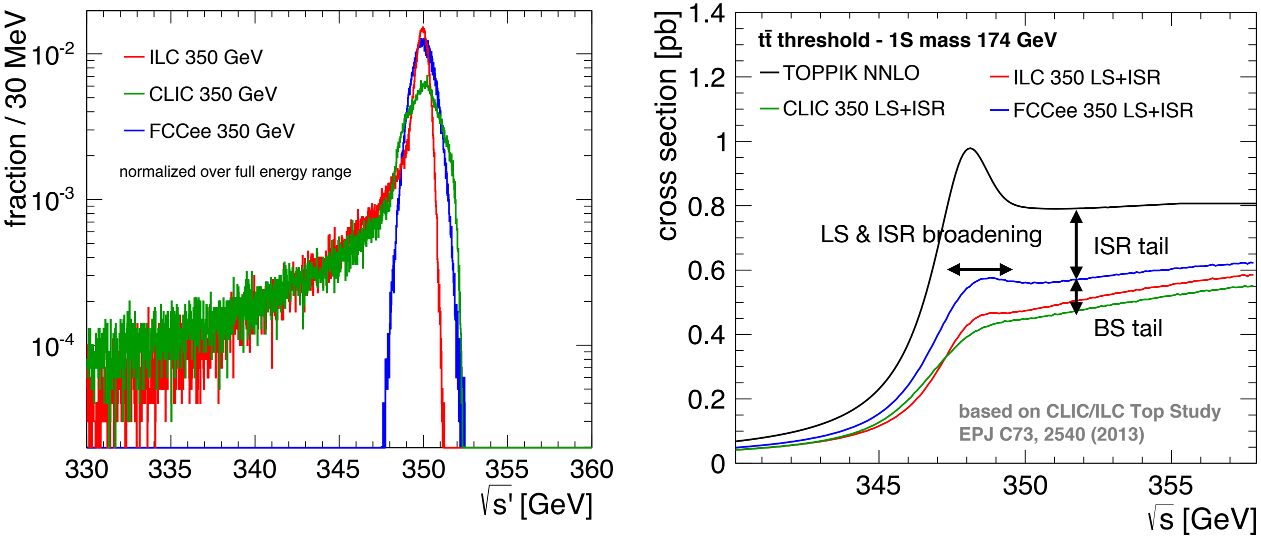
Measure 10 points (10 fb-1 each) around 350 GeV.

Statistical uncertainty:

FCC-ee:	16 MeV
ILC:	18 MeV
CLIC:	21 MeV

→ **Prospect for 50 MeV accuracy of top mass ($\overline{MS}$)**

Effect of beam spectrum not negligible at all e+e- colliders.
[F. Simon, FCC-ee Workshop, 2014]

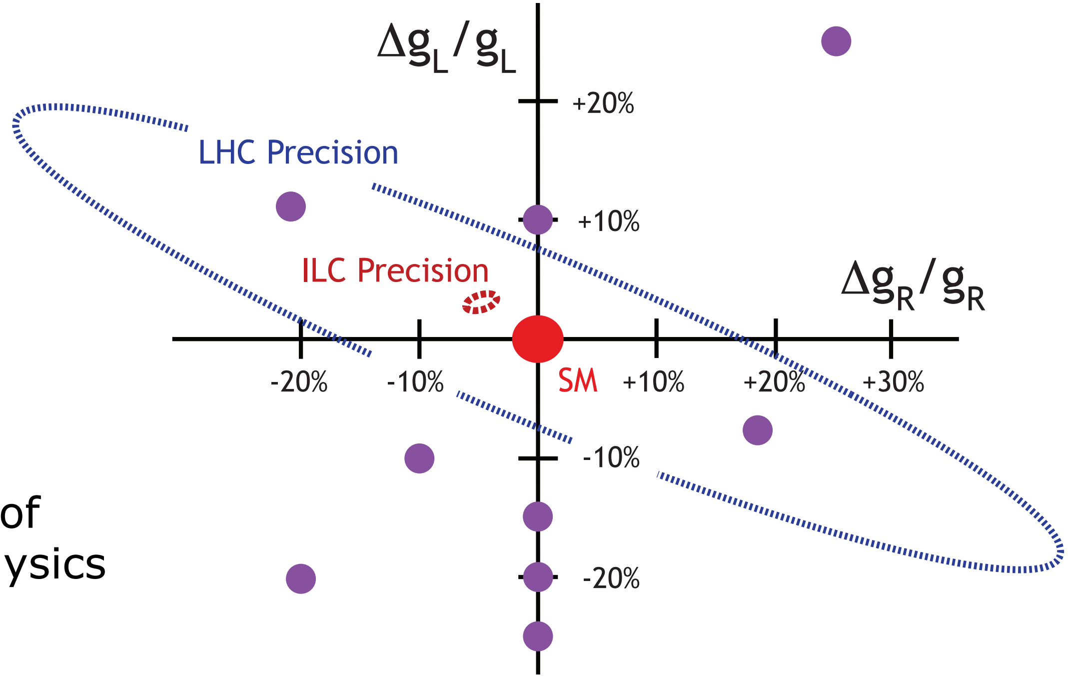


FCC-ee
ILC
CLIC

Top Electroweak Couplings

Top electroweak couplings are currently not well constrained.
In composite Higgs models, the **top quark** is often **partially composite**.
This results in **form factors in ttZ couplings**, which can be measured at e+e- colliders.

Recent developments:
[Amjad et al., 1307.8102] Cross section, A_FB, helicity angle, beam polarizations
[Khiem et al., 1503.04247] Matrix Element Analysis in leptonic decays
[Janot, 1503.01325] Lepton angle & energy, final-state polarizations



[1506.05992]
Discrimination of various new physics models.

Electroweak Observables

At circular colliders, the high luminosity at the Z-pole and WW threshold mean that the electroweak observables expected to improve significantly.

CEPC-SPPC Pre-CDR

Observable	LEP precision	CEPC precision	CEPC runs	$\int \mathcal{L}$ needed in CEPC
m_Z	2 MeV	0.5 MeV	Z lineshape	> 150 fb^{-1}
m_W	33 MeV	3 MeV	ZH (WW) thresholds	> 100 fb^{-1}
A^b_{FB}	1.7%	0.15%	Z pole	> 150 fb^{-1}
$\sin^2\theta_W^{\text{eff}}$	0.07%	0.01%	Z pole	> 150 fb^{-1}
R_b	0.3%	0.08%	Z pole	> 100 fb^{-1}
N_ν (direct)	1.7%	0.2%	ZH threshold	> 100 fb^{-1}
N_ν (indirect)	0.27%	0.1%	Z lineshape	> 150 fb^{-1}
R_μ	0.2%	0.05%	Z pole	> 100 fb^{-1}
R_τ	0.2%	0.05%	Z pole	> 100 fb^{-1}

Precise measurement of Higgs, top, W/Z become important in the absence of new particles.

M. Dam, EPS2015

Selected set of FCC-ee precision observables

Experimental uncertainties mostly of systematic origin

- So far, mostly conservatively estimated based on LEP experience
- Work ahead to establish more solid numbers

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 **± 2.1**	**0.005**	**< 0.1**	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 **± 2.3**	**0.008**	**< 0.1**	QED corr.
R_l	Peak	20.767 **± 0.025**	**0.0001**	**< 0.001**	Statistics
R_b	Peak	0.21629 **± 0.00066**	**0.000003**	**< 0.00006**	g -> bb
N_ν	Peak	2.984 **± 0.008**	**0.00004**	**0.004**	Lumi meast.
$A_{FB}^{\mu\mu}$	Peak	0.0171 **± 0.0010**	**0.000004**	**<0.00001**	E_{beam} meast.
$\alpha_s(m_Z)$	R_l	0.1190 **± 0.0025**	**0.000001**	**0.00015**	New Physics
m_W (MeV)	Threshold scan	80385 **± 15**	**0.3**	**< 1**	QED corr.
N_ν	Radiative return e^+e^- -> $\gamma Z(inv)$	2.92 **± 0.05** 2.984 **± 0.008**	**0.0008**	**< 0.001**	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 **± 0.27**	**0.00018**	**0.00015**	CKM Matrix
m_{top} (MeV)	Threshold scan	173200 **± 900**	**10**	**10**	QCD (~40 MeV)

Generally better by factor ≥ 25

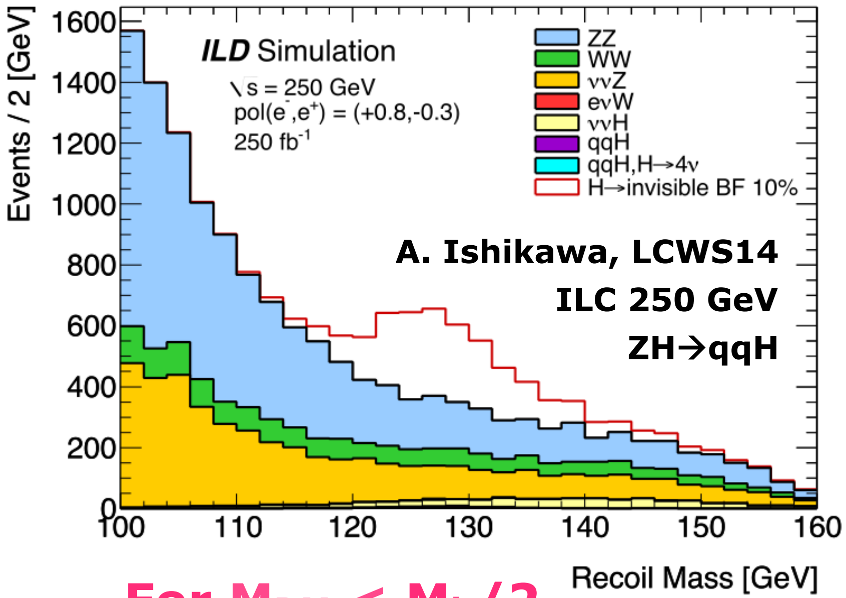
Search for New Particles at future e+e- colliders

CEPC
FCC-ee
ILC
CLIC

WIMP Dark Matter

WIMP searches at colliders are complementary to direct/indirect searches. Examples at e+e- colliders:

Higgs Invisible Decay



A. Ishikawa, LCWS14

ILC 250 GeV

ZH→qqH

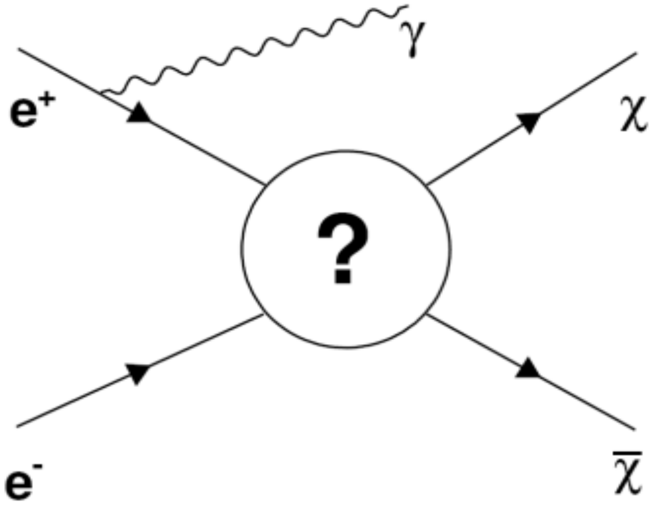
For $M_{DM} < M_h/2$,

BR(H→invis.) < 0.4%

at 250 GeV, 1150 fb^{-1}

Best with high luminosity (CEPC/FCC-ee)

Monophoton Search



M_{DM} reach ~ Ecm/2

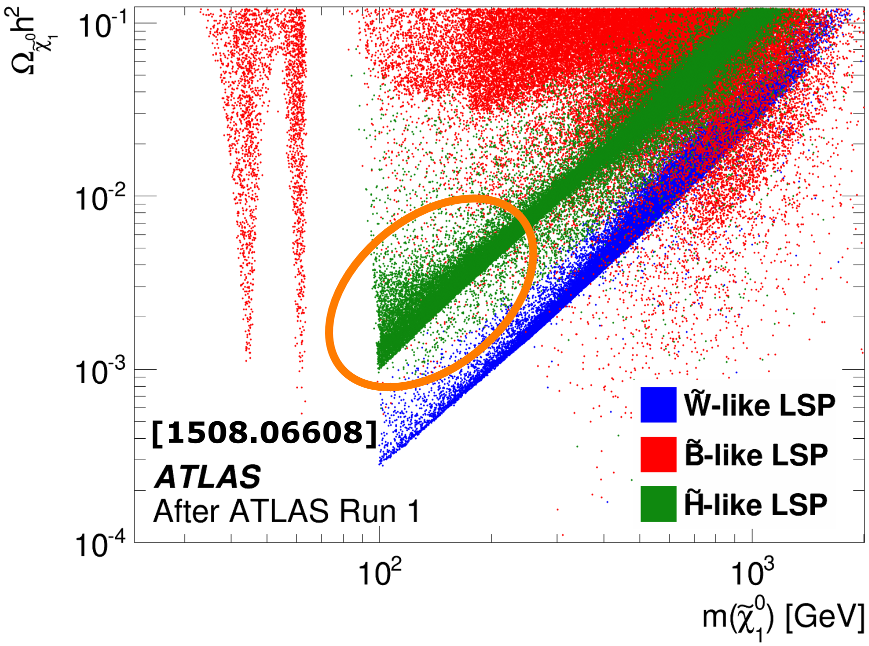
Best with high energy (ILC/CLIC)

In many models, DM has a charged partner e.g. Wino, Higgsino

SUSY-specific signatures (decays to DM)

- light Higgsino, light stau, etc.

Naturalness and Light Higgsino



[1508.06608]

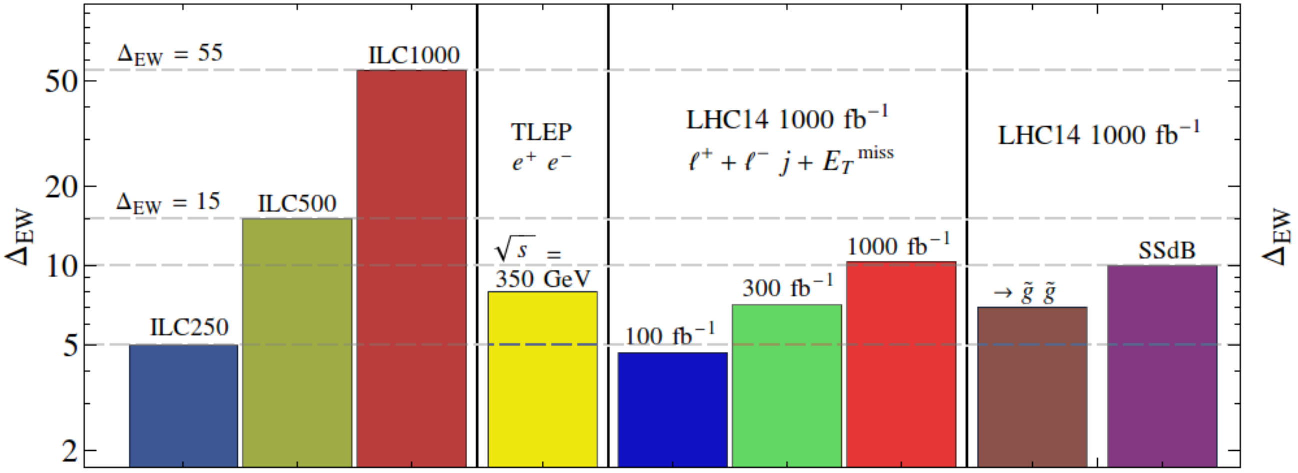
ATLAS

After ATLAS Run 1

Mass degeneracy
20 MeV < ΔM < 30 GeV
challenging for LHC,
e.g. **Higgsino-like LSP**

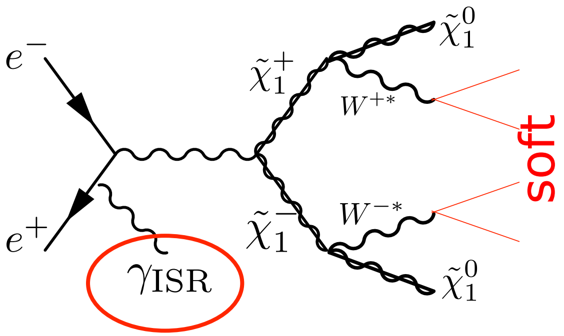
→ No problem for e+e- colliders

Light Higgsinos motivated by **EW naturalness**.
High-energy e+e- colliders have the best reach for EW naturalness measure:



[Bae et al. 1505.03541]

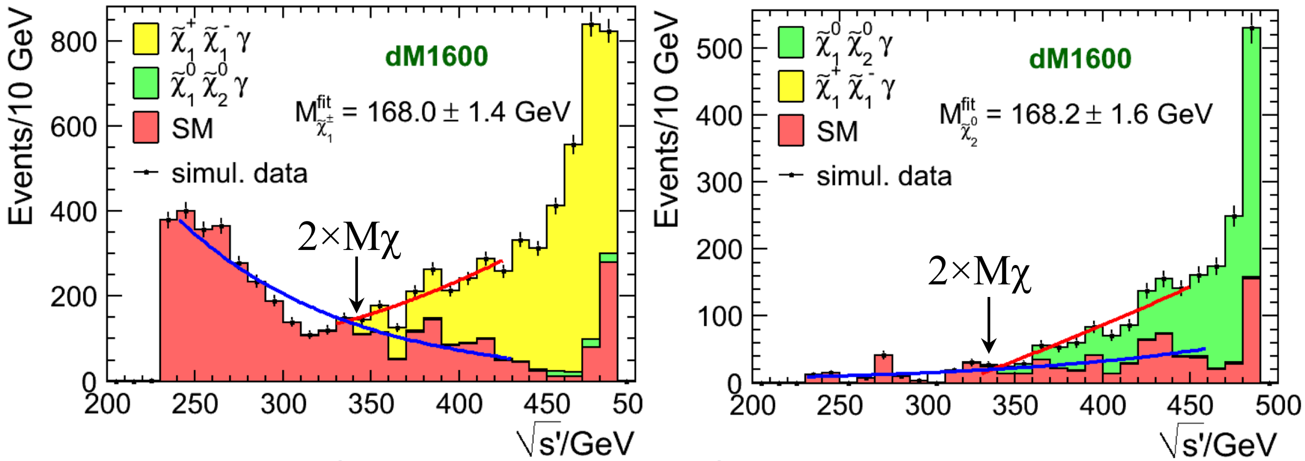
Higgsinos in Natural SUSY (ΔM~1 GeV)



[Berggren et al. 1307.3566]

M(cha,neu) ~ 170 GeV, ΔM ~ 1.6 and 0.8 GeV
Only very soft particles in the final states
→ Require a hard ISR to reduce large two-photon background.

Separation of chargino and neutralino channels



Precision Expected for 500 GeV, 500 fb-1 P(e-,e+)=(-0.8,+0.3)

Production Cross section

$$\sigma(\gamma\tilde{\chi}_0^+\tilde{\chi}_0^-) \approx 80 \text{ fb}$$

$$\sigma(\gamma\tilde{\chi}_1^0\tilde{\chi}_2^0) \approx 50 \text{ fb}$$

$$\Delta M = 1.6 \text{ GeV}$$

$$\delta(\sigma \times BR) \simeq 3\%$$

$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 2.1(3.7)\,\text{GeV}$$

$$\delta\Delta M(\tilde{\chi}_1^\pm,\tilde{\chi}_1^0) \simeq 70\,\text{MeV}$$

$$\Delta M = 0.8 \text{ GeV}$$

$$\delta(\sigma \times BR) \simeq 1.5\%$$

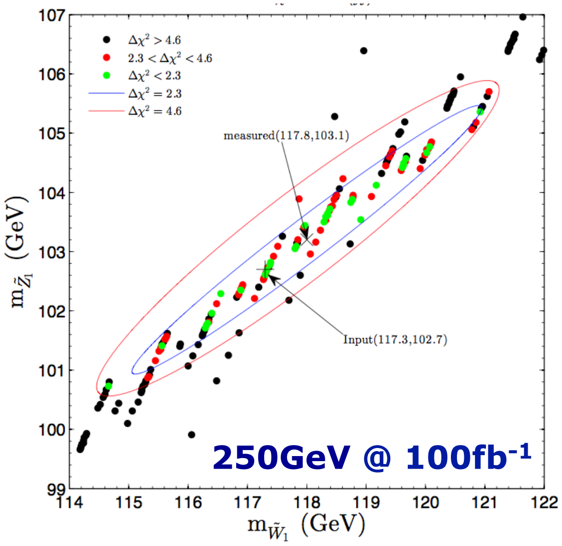
$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 1.5(1.6)\,\text{GeV}$$

$$\delta\Delta M(\tilde{\chi}_1^\pm,\tilde{\chi}_1^0) \simeq 20\,\text{MeV}$$

CEPC
FCC-ee
ILC
CLIC

Extracting M_1 and M_2

[Baer et al. 1404.7510]

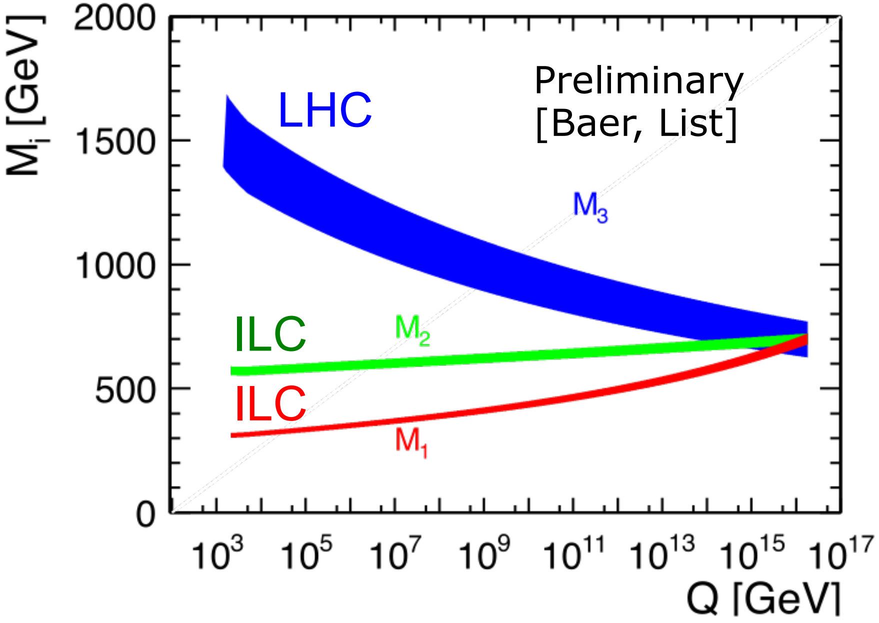


$$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$$

M(ch1+)~118 GeV, M(ch10)~103 GeV
→ **ΔM=15GeV**

In this benchmark, precision of M_1 and M_2 expected to be few % or better.

→ Test of gaugino mass relation



Assume:

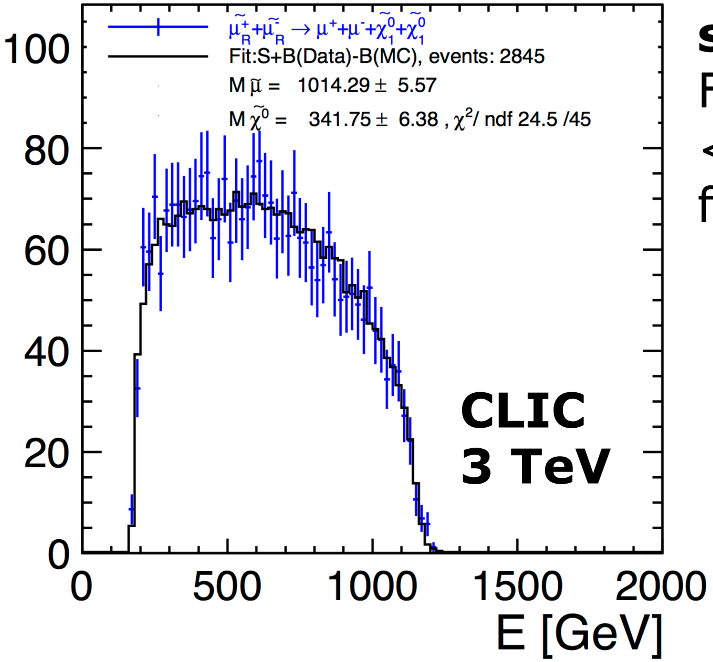
Gluino discovery @ LHC

EWK-ino @ e+e- collider

→ Test of gaugino mass relation by hadron/lepton collider synergy

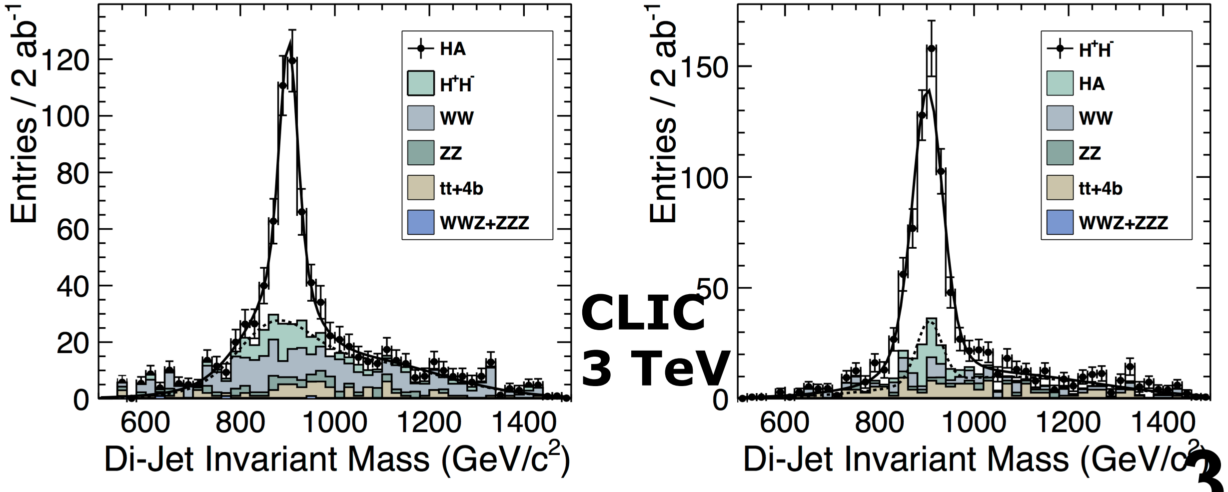
→ Possible discrimination of SUSY breaking models

Reconstruction of SUSY particles



smuon pair production
From endpoints,
<1% mass precision
for slepton mass ~1 TeV

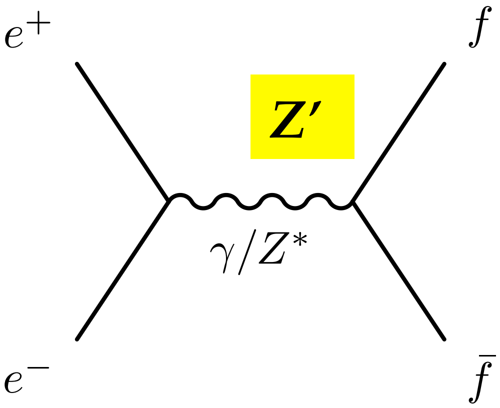
Heavy Higgs:
HA → bbbb & H^+H^- → tbbt
b-tagging required for separation
→ mass precision ~0.3%

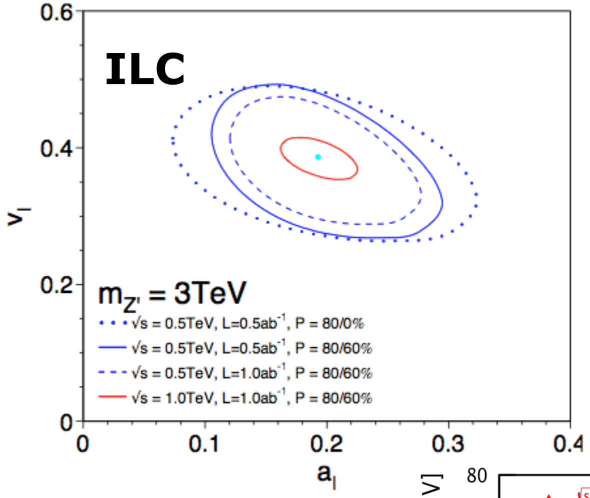


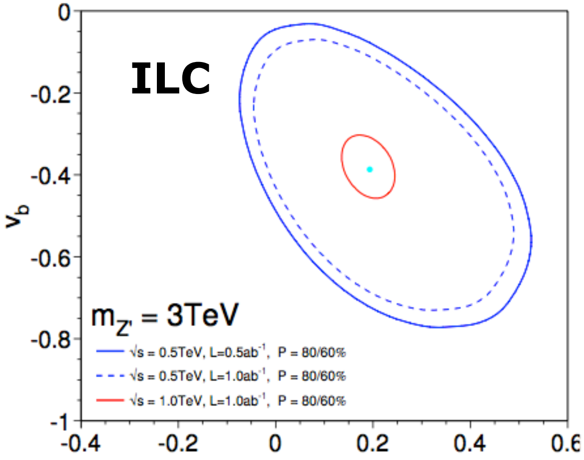
Z'

New gauge forces imply existence of heavy gauge bosons (Z'). Synergy of hadron/lepton colliders:

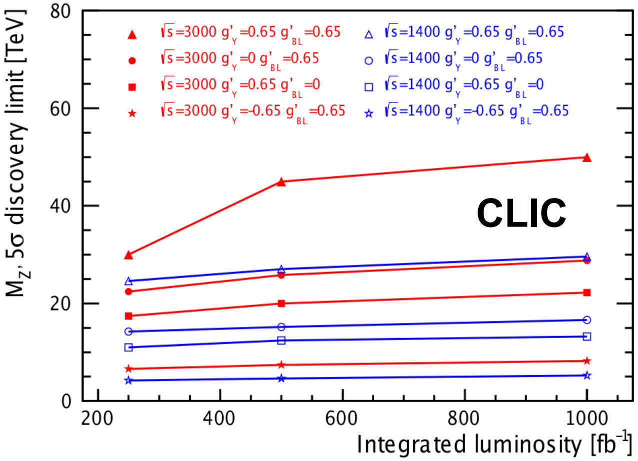
- **If LHC discovery** → determine mass of Z'
- **At e+e- collider** → access to couplings through precise measurements of interference effects







If no LHC discovery, **CLIC** can reach multiple **10s of TeV** in Z' mass.



Example: minimal anomaly free Z' model

Summary

Summary

- With the discovery of the Higgs boson, the question of why the electroweak symmetry is broken has become urgent. Any explanation requires BSM.
- Future e+e- colliders will tackle this with its powerful probes:
  - Precise Higgs, top, W/Z measurements
  - Direct search for new particles
- Any such collider will significantly advance our field. Because of the differences in their capabilities, it does not hurt to have multiple next-generation e+e- colliders.
- We seem to have good prospects ahead. We should seize these opportunities!