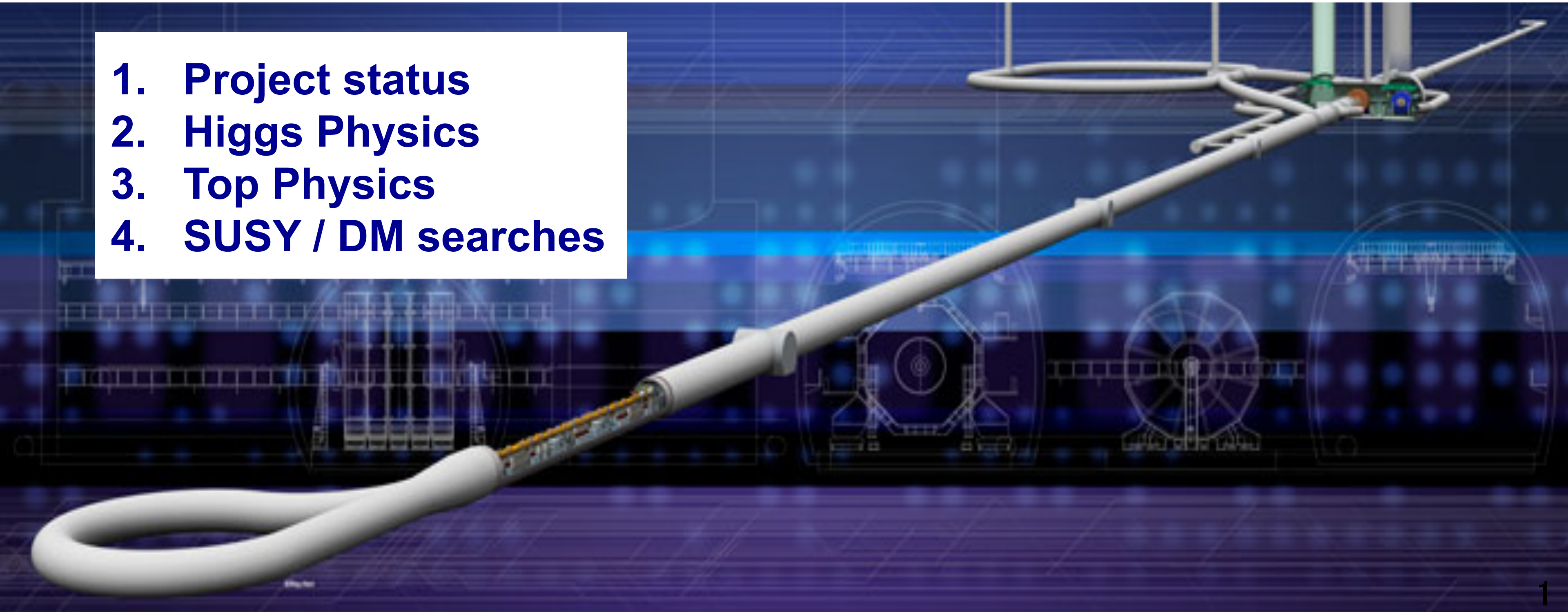
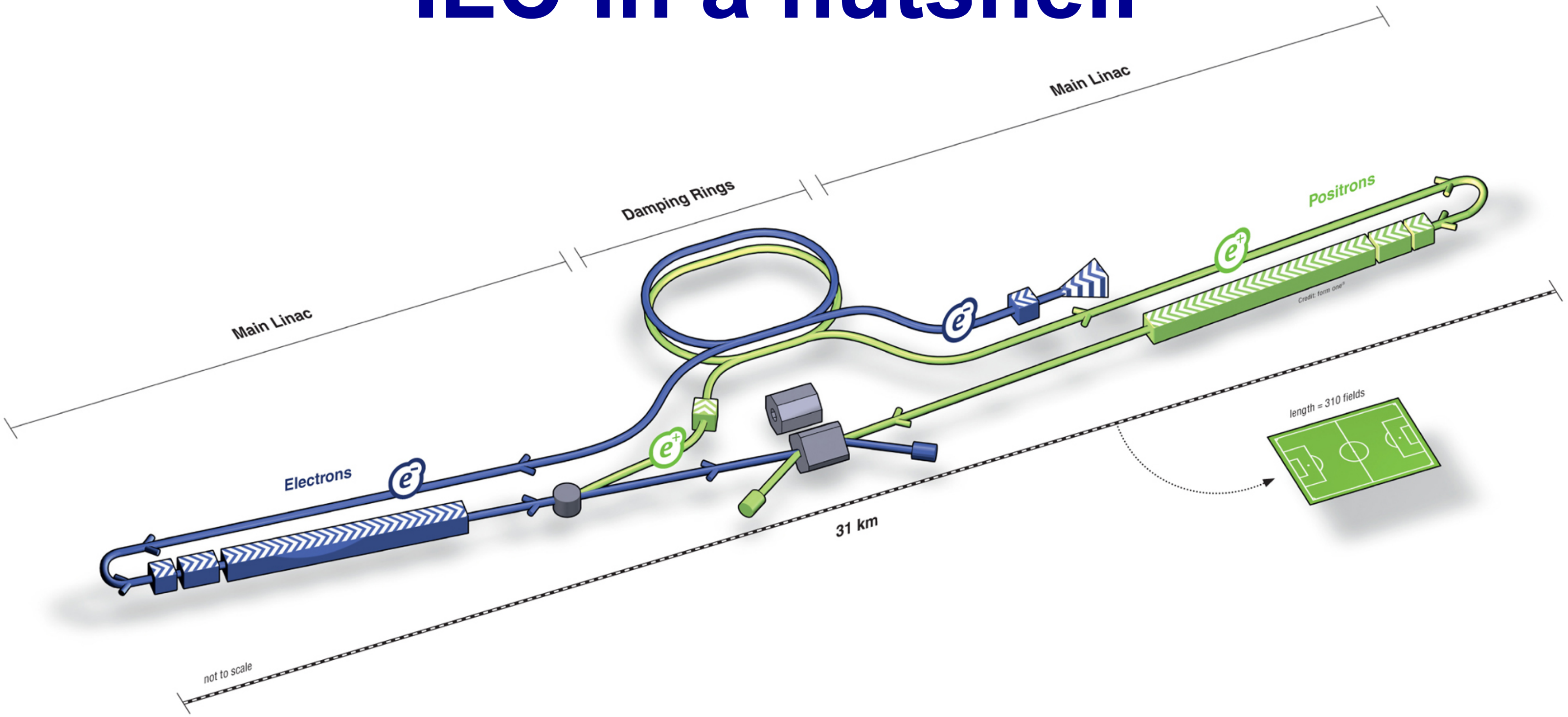
Overview of ILC Physics Case

Tomohiko Tanabe (U. Tokyo)
August 19, 2014
IPA 2014, Queen Mary University of London



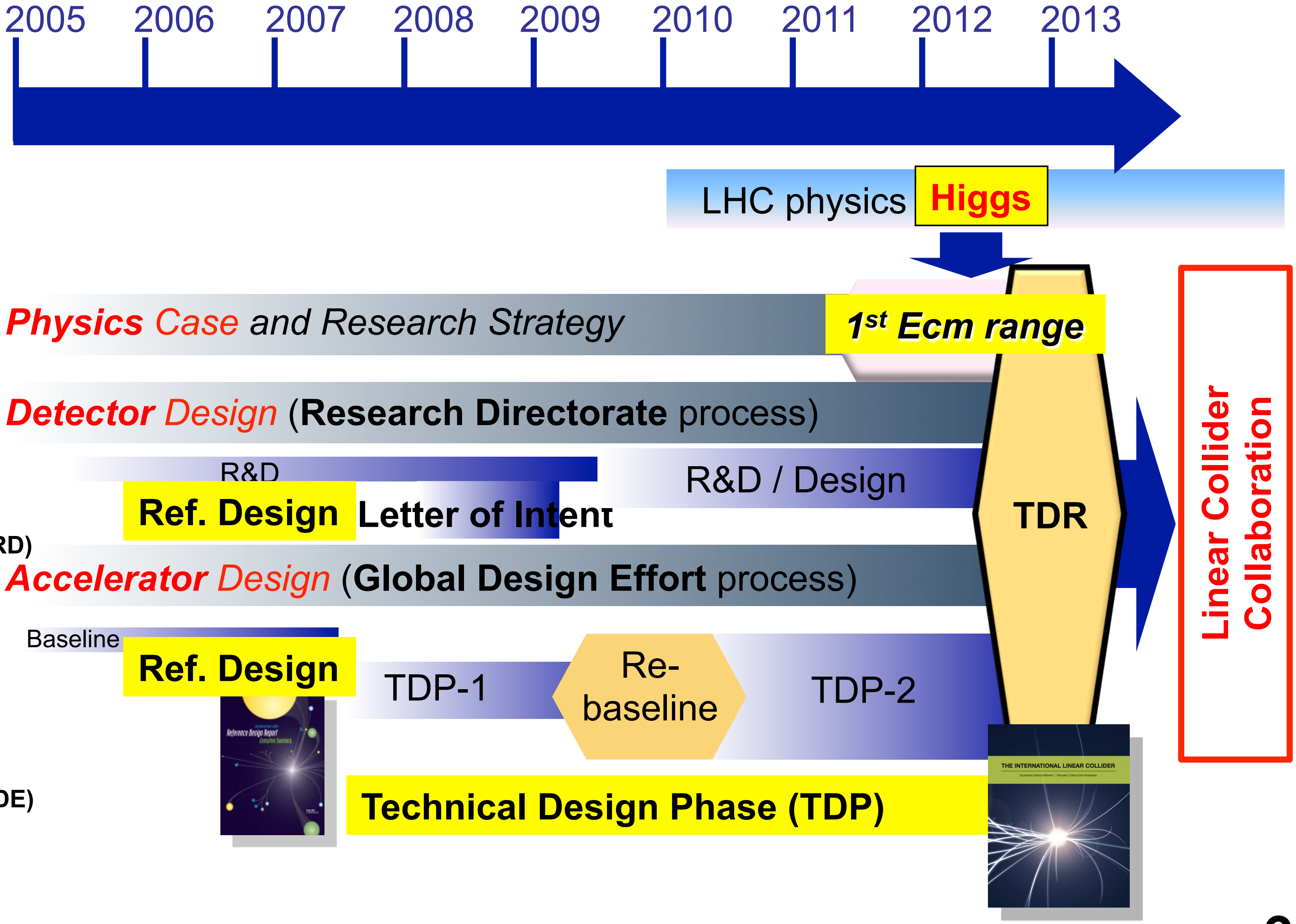
1. Project status
2. Higgs Physics
3. Top Physics
4. SUSY / DM searches

ILC in a nutshell



Stands for: **International Linear Collider**
Collides: electrons and positrons
CM energy: 250-500 GeV baseline, ~1 TeV upgrade option
ILC
Beam pol.: P(e-,e+) = (±80%, ±30%)
Length: 31 km @ 500 GeV → extend for higher energy
Organization: Multinational Laboratory is proposed
Site: Strong interest from Japan
Project phase: Engineering Design / Waiting for Green Light
Timeline: If decision in ~2016, first beam in ~2028

ILC Timeline (2005-2012)



LHC physics **Higgs**

***Physics Case** and Research Strategy*

1st Ecm range

Detector Design (**Research Directorate** process)

R&D

Ref. Design

Letter of Intent

R&D / Design

TDR

Accelerator Design (**Global Design Effort** process)

Baseline

Ref. Design

TDP-1

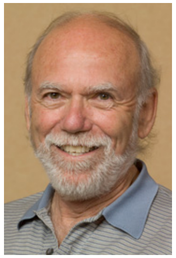
Re-baseline

TDP-2

Technical Design Phase (TDP)

Linear Collider Collaboration

S. Yamada (RD)

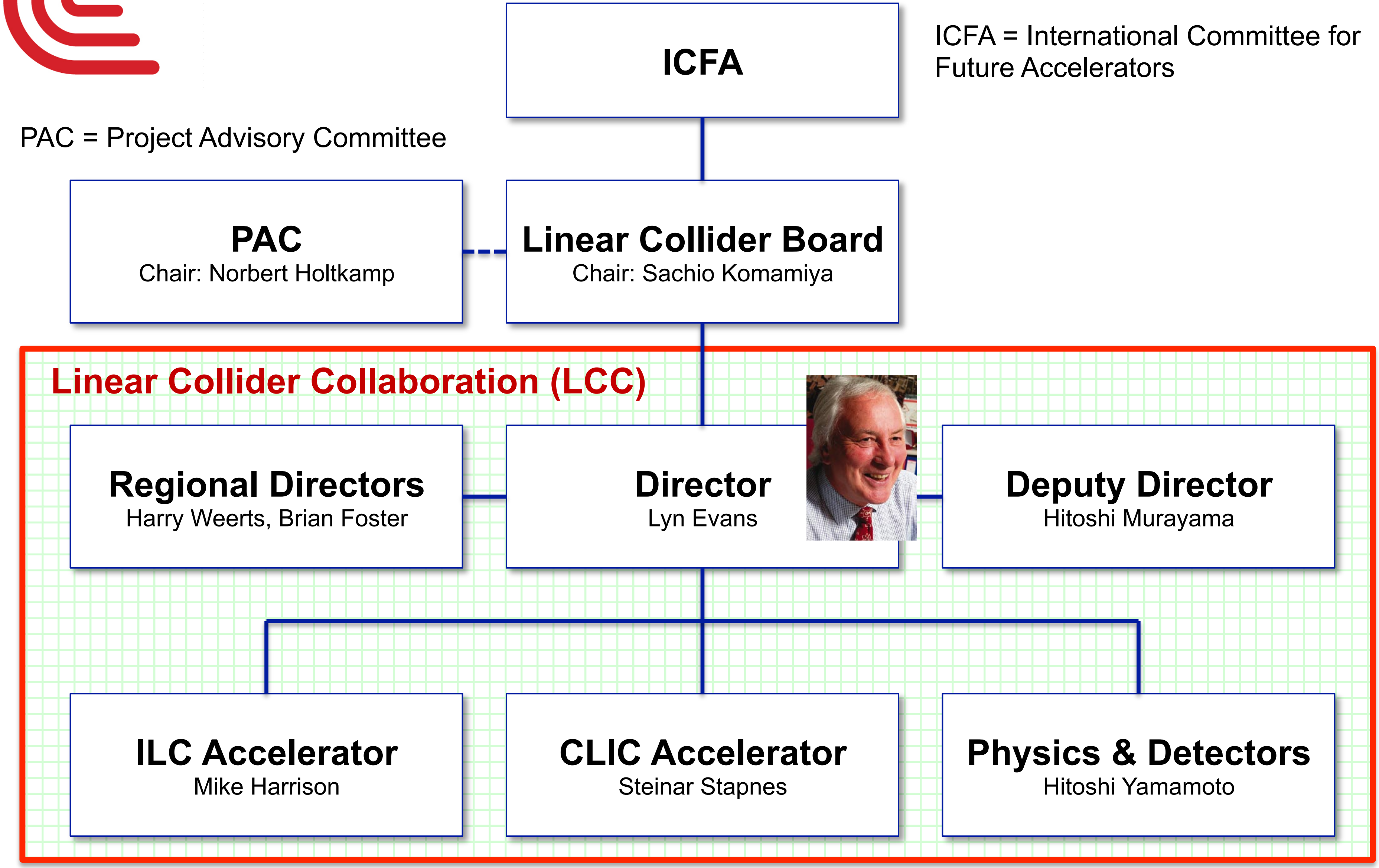


B. Barish (GDE)

Linear Collider Collaboration (LCC)

ICFA = International Committee for Future Accelerators

PAC = Project Advisory Committee



ICFA

PAC
Chair: Norbert Holtkamp

Linear Collider Board
Chair: Sachio Komamiya

Linear Collider Collaboration (LCC)

Regional Directors
Harry Weerts, Brian Foster

Director
Lyn Evans

Deputy Director
Hitoshi Murayama

ILC Accelerator
Mike Harrison

CLIC Accelerator
Steinar Stapnes

Physics & Detectors
Hitoshi Yamamoto

Recent Developments (2013~)

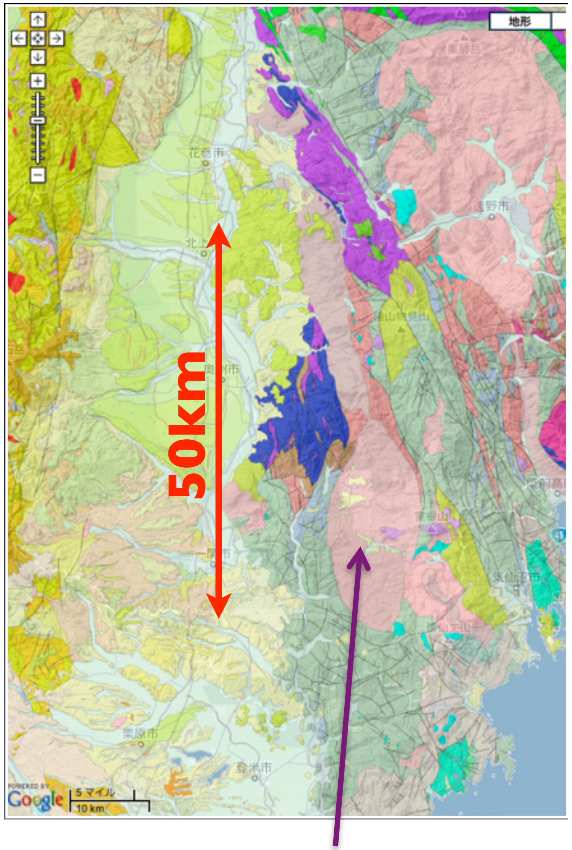
- With the completion of the Technical Design Report (Dec 2012), the project is in the **Engineering Design** Phase. The site-specific design will be based on the **proposed candidate site in Japan** (Aug 2013).

- ILC is featured in various **future strategy documents** around the world:
  - European Strategy (May 2013), AsiaHEP/ACFA (July 2013), USA P5 (May 2014)

- In Japan, the ILC project has been / is being reviewed by
  - Scientists (Science Council of Japan, Oct 2013)
  - Government (**MEXT**, expected completion by Mar 2016)

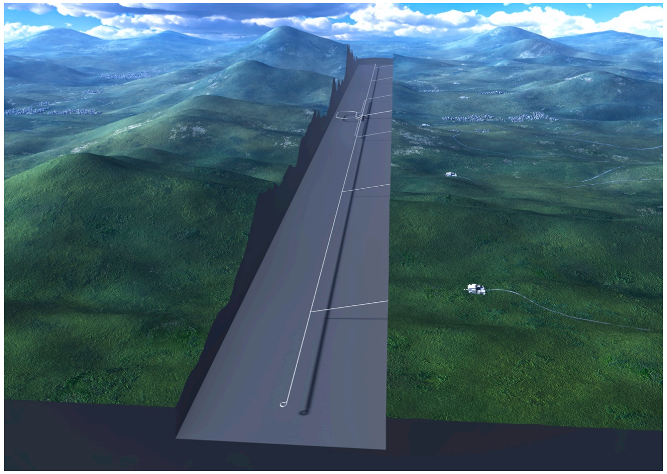
- Ongoing **high-level talks between governments** in preparation for international partnership (cost/personnel sharing)

Proposed Candidate Site



Stable granite rock capable of hosting 50+ km tunnel

Aerial view of the region

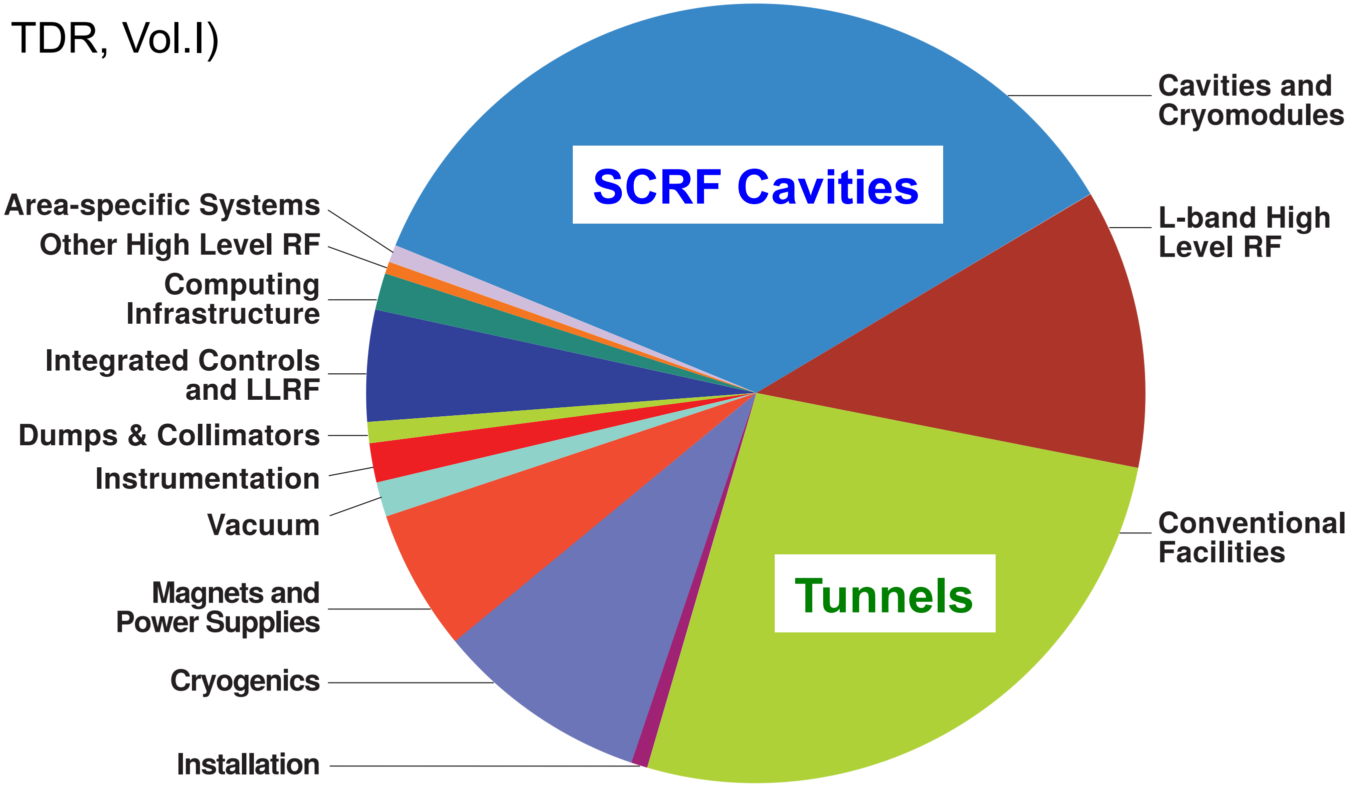


- Candidate site proposed by LCC (Aug. 2013)
    - Official decision pending government approval
- Ongoing site-specific engineering design

Construction Cost

cost-constrained design of ILC: minimized cost maintaining physics capabilities

(ILC TDR, Vol.I)



Estimated 7.8 billion US$ (2012)

for a baseline 500 GeV ILC, averaged over three regions
to be refined by engineering design

LCC proposes host country to pay for about half the construction cost
→ an international project

Power Consumption

Breakdown of estimated AC power (ILC TDR, Vol.3II; Unit in MW)

Accelerator section	RF Power	RF Racks	NC magnets & Power supplies	Cryo	Conventional		Total
					Normal load	Emergency load	
e^- source	1.28	0.09	0.73	0.80	1.02	0.16	4.08
e^+ source	1.39	0.09	4.94	0.59	2.19	0.35	9.56
Damping Ring	8.67		2.97	1.45	1.84	0.14	15.08
RTML	4.76	0.32	1.26	part of ML cryo	0.12	0.14	6.59
Main Linac	58.1	4.9	0.914	32	8.10	5.18	109.16
BDS			10.43	0.41	0.24	0.28	11.36
Dumps					1		1.00
IR			1.16	2.65	0.09	0.17	4.07
Total	74.2	5.4	22.4	37.9	14.6	6.4	161

161 MW for a 500 GeV ILC (baseline)

Modest power consumption (cf. circular colliders)

Scalability (short-term)

Luminosity can be enhanced by increasing the number of bunches and the collision rate.

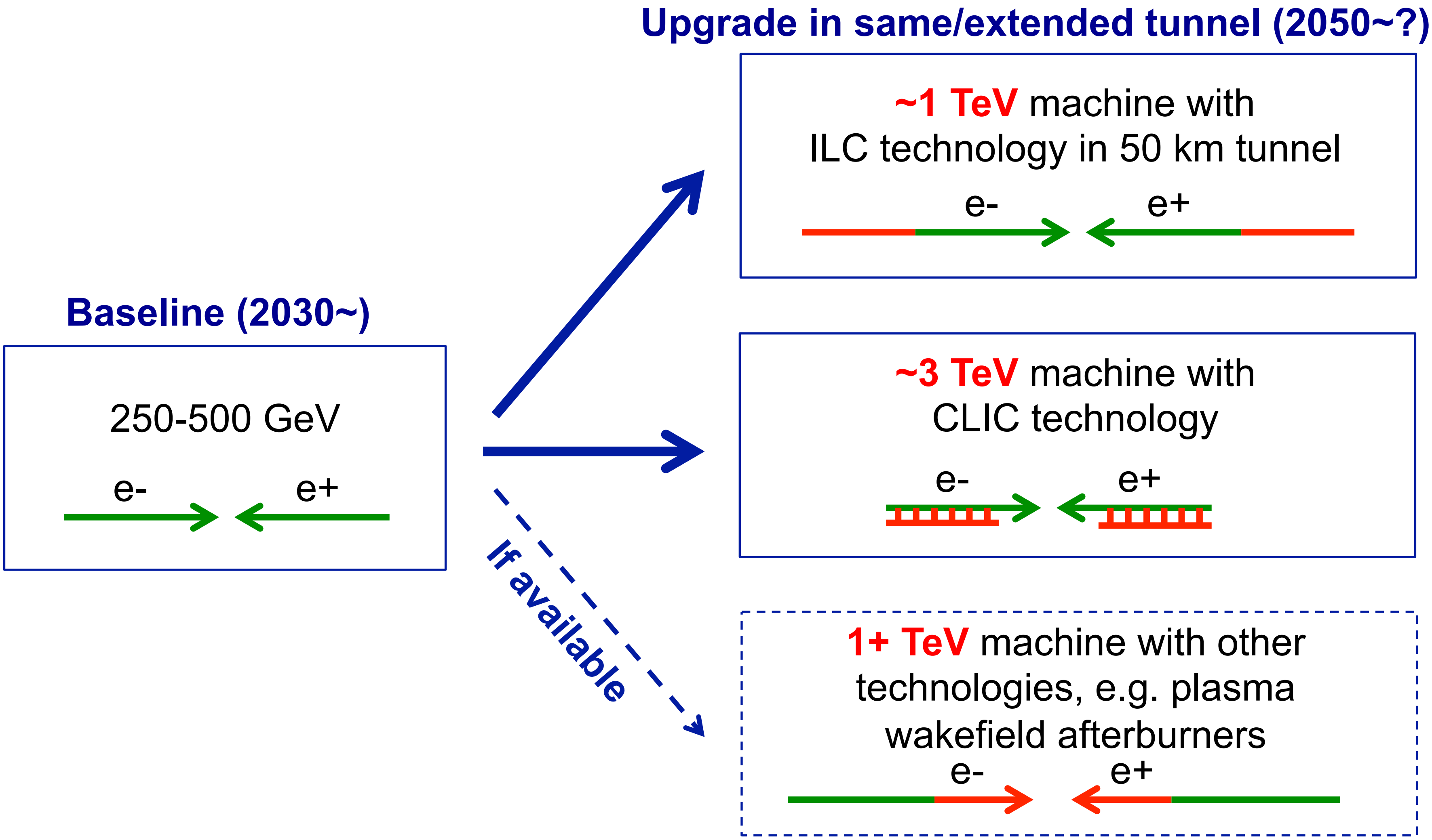
🟩 ILC TDR 🟪 Higgs Whitepaper for Snowmass (arXiv:1310.0763)

		Baseline			**Luminosity Upgrade**		
CM Energy	GeV	**250**	**500**	**1000**	**250**	**250**	**500**
Luminosity	10^{34} cm^{-2} s^{-1}	0.75	1.8	4.9	1.5	3.0	3.6
Collision rate	Hz	5	5	4	5	**10**	5
Number of bunches	Hz	1312	1312	2450	**2625**	**2625**	**2625**
Avg. total beam power	MW	5.9	10.5	27.2	11.8	21.0	21.0
AC power	MW	122	163	300	161	204	204
Relative cost		69%	100%	166%	74%	106%	106%

in a tunnel for 500 GeV ILC ↗

Luminosity upgrade available at a relatively small footprint;
→ the way to go if additional funds become available

Scalability (long-term)



Baseline (2030~)

250-500 GeV

Upgrade in same/extended tunnel (2050~?)

~1 TeV machine with ILC technology in 50 km tunnel

~3 TeV machine with CLIC technology

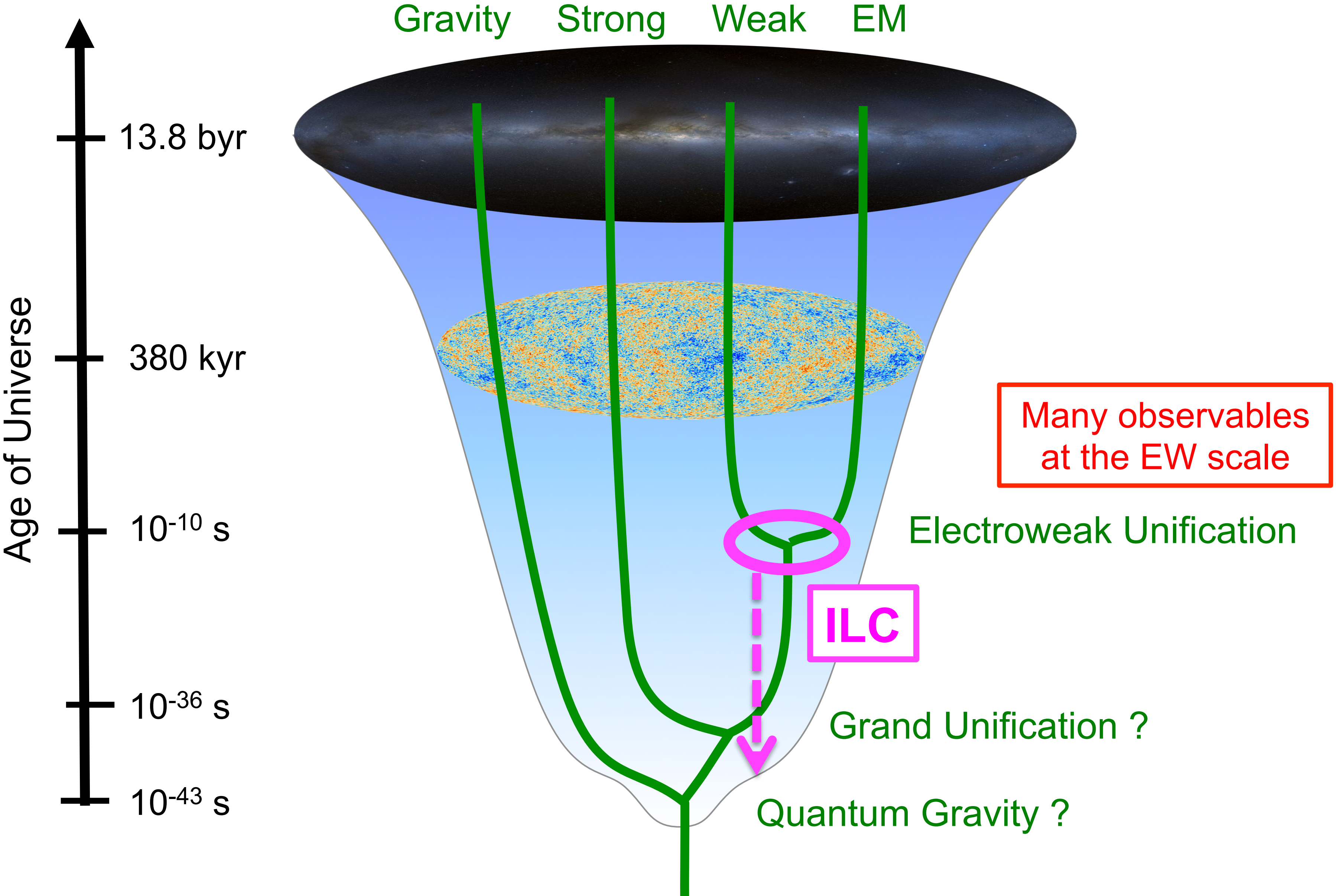
1+ TeV machine with other technologies, e.g. plasma wakefield afterburners

Choice determined by physics & availability of technology

Linear acceleration provides a clear path toward the future

Physics at ILC

Towards a fundamental theory



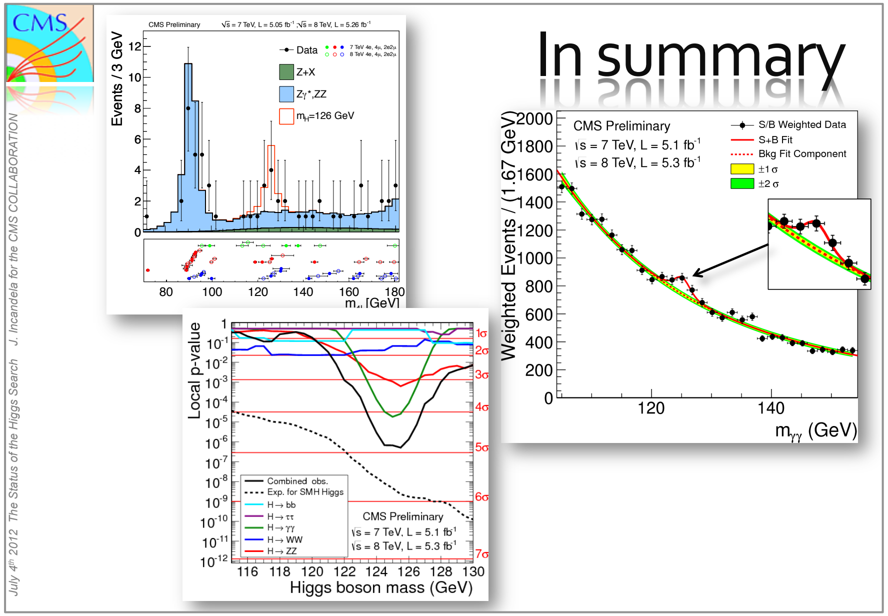
Many observables at the EW scale

Electroweak Unification

Grand Unification ?

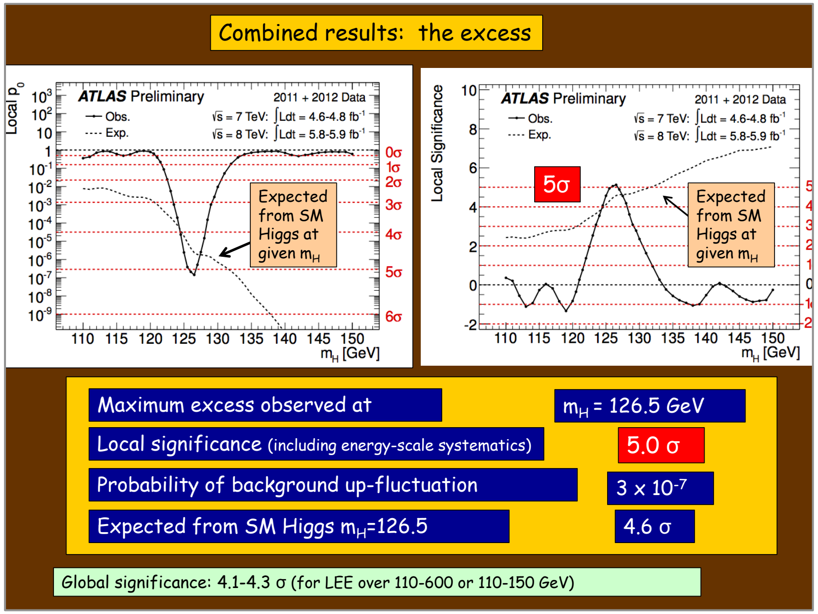
Quantum Gravity ?

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

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 the Higgs boson, we now understand how electroweak symmetry breaking (EWSB) occurs: via the expectation value of the Higgs field. **However, we do yet know the physics behind the EWSB.**
- Many **new physics** models which attempt to explain EWSB predict the existence of new forces/particles and modifications to the (SM) properties of **Higgs boson**, **top quark**, and **W/Z bosons**.
- It is **important to test these predictions** since they could be connected to the well-established observed phenomena which must require **new physics**, e.g.
  - baryon asymmetry
  - neutrino mixing
  - dark matter
  - …

Physics behind EWSB at TeV scale

There are two possible scenarios for the physics behind EWSB around the TeV scale:

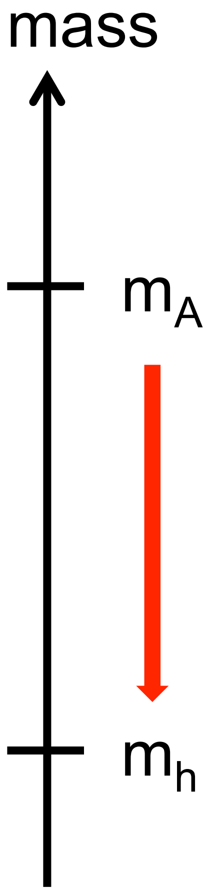
1. **Supersymmetry (SUSY):** SUSY breaking triggers EWSB.

2. **Composite Higgs:** a QCD-like theory is behind EWSB.

The **Higgs boson** and the **top quark** are crucial probes to distinguish these possibilities.

Higgs Physics at ILC

Deviation in Higgs Couplings



Many new physics models predict deviations in the properties of SM particles. **The size of the deviation depends on the scale of new physics.**

<u>Example 1:</u> MSSM (tanβ=5, radiative corrections ≈ 1)

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

heavy Higgs mass

<u>Example 2:</u> Minimal Composite Higgs Model

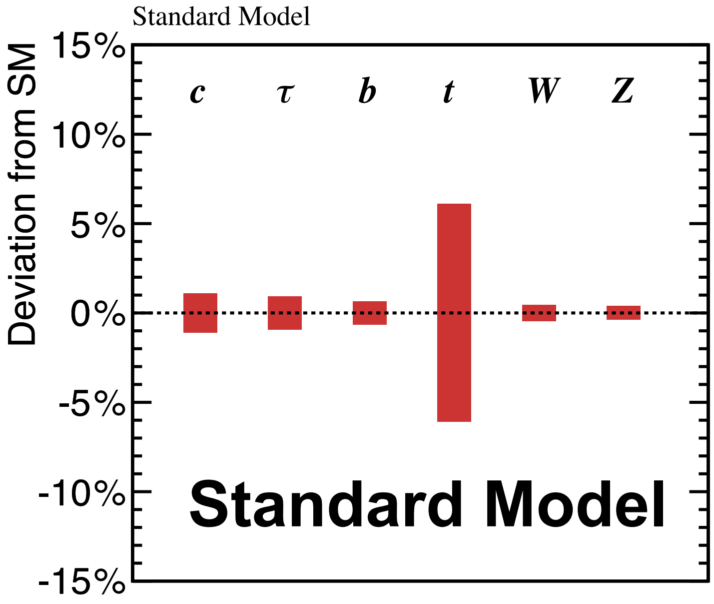
$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 8.3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$

composite scale

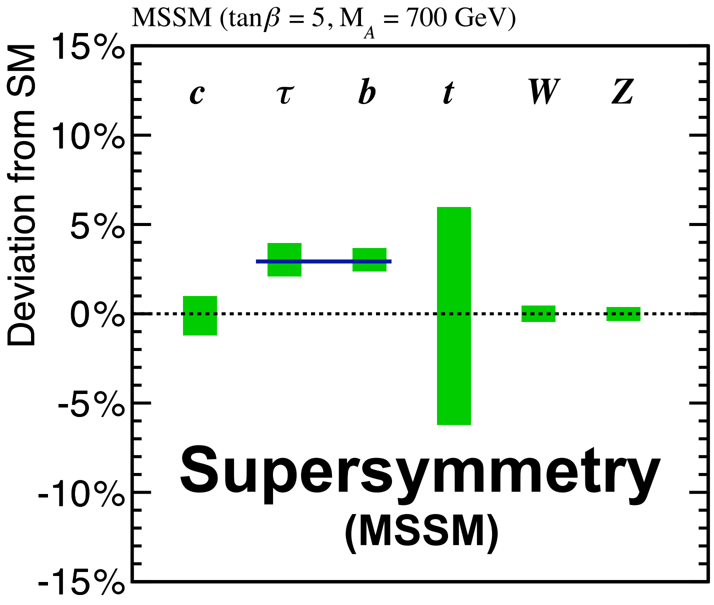
New physics at 1 TeV gives only a few percent deviation.
e+e- collider is needed to probe these scales via Higgs couplings.

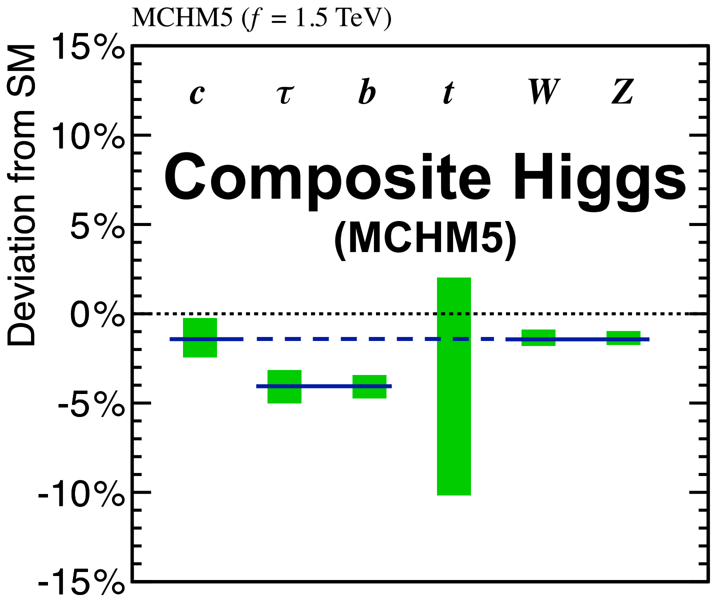
Impact of BSM on Higgs Sector

Deviations in Higgs couplings is a signature of many BSM theories. **The pattern of the deviations is often specific to certain models.** The precision Higgs coupling measurements at the ILC at the 1%-level enable us to discriminate the different models.

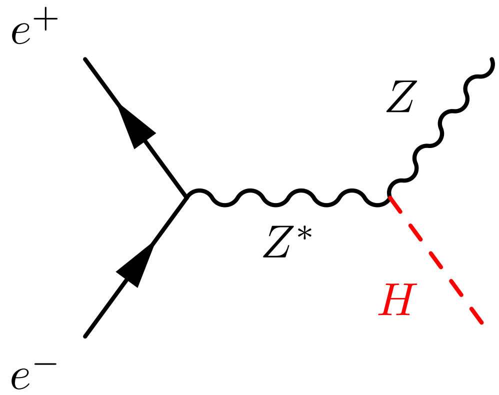


Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV

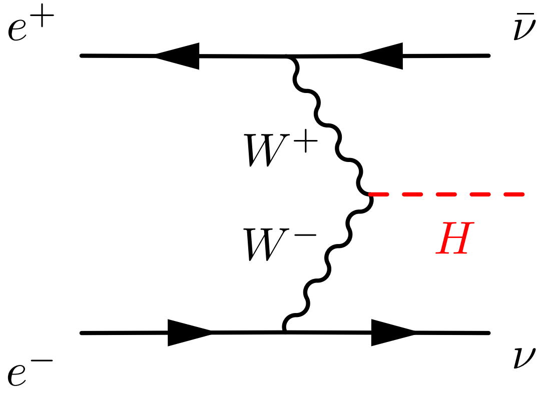




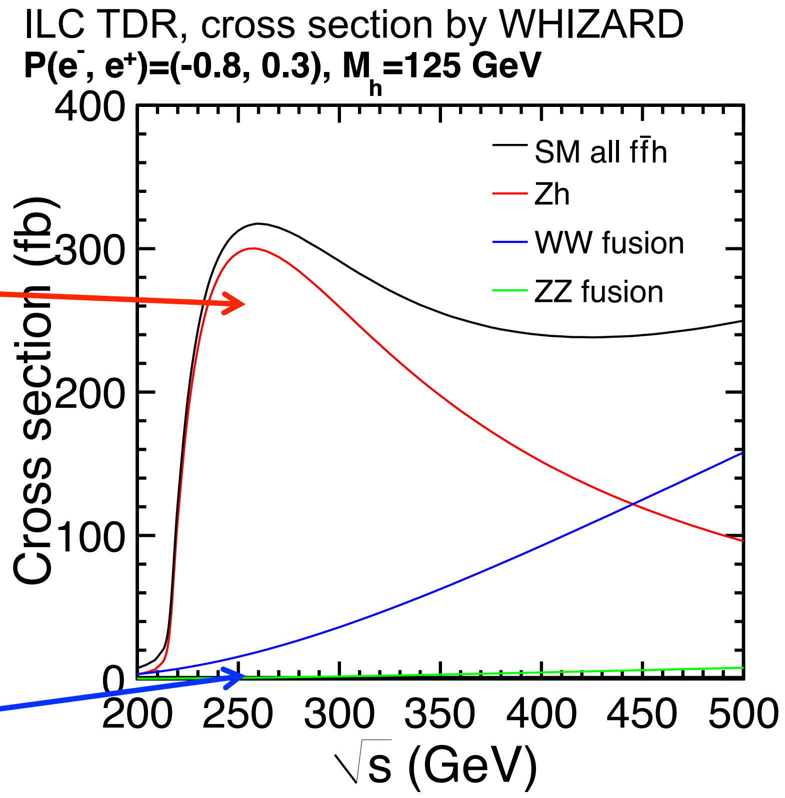
Higgs Production at ILC



Higgs-strahlung
peaks around 250 GeV



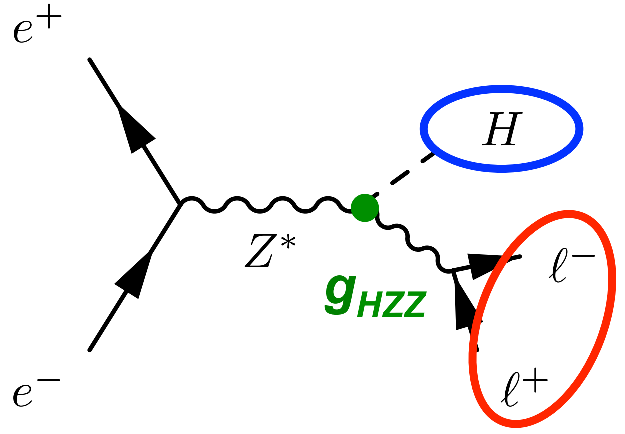
WW fusion
dominates at high energies


ILC TDR, cross section by WHIZARD
P(e⁻, e⁺)=(-0.8, 0.3), M_h=125 GeV

	250 GeV	500 GeV
$\sigma(e^+e^- \rightarrow ZH)$	303 fb	100 fb
$\sigma(e^+e^- \rightarrow \nu\nu H)$	16 fb	150 fb
Int. Luminosity	250 fb^{-1}	500 fb^{-1}
# ZH events	76,000	50,000
# vvH events	4,000	75,000

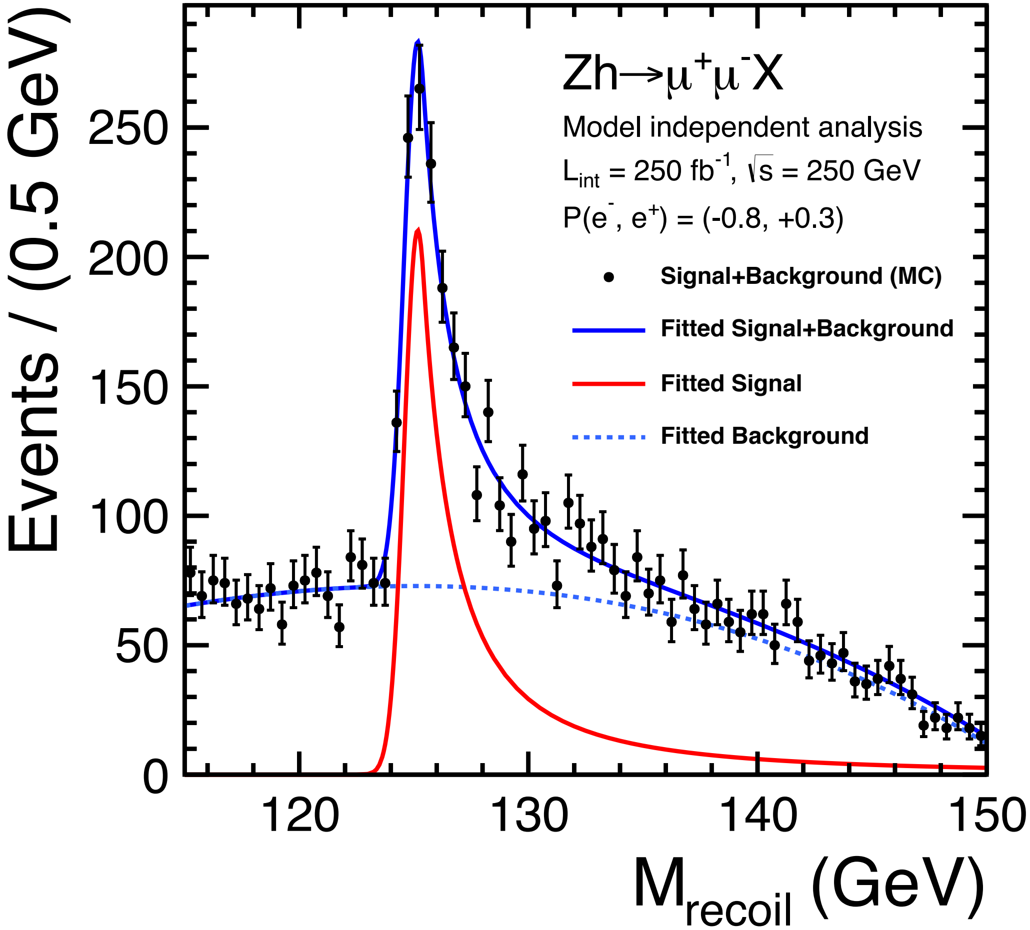
Expected number
of Higgs events

Higgs Recoil Mass



Reconstruct Z boson leptonic decay.
Reconstruct Higgs mass without looking at the Higgs decay

$$m^2_{\text{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$



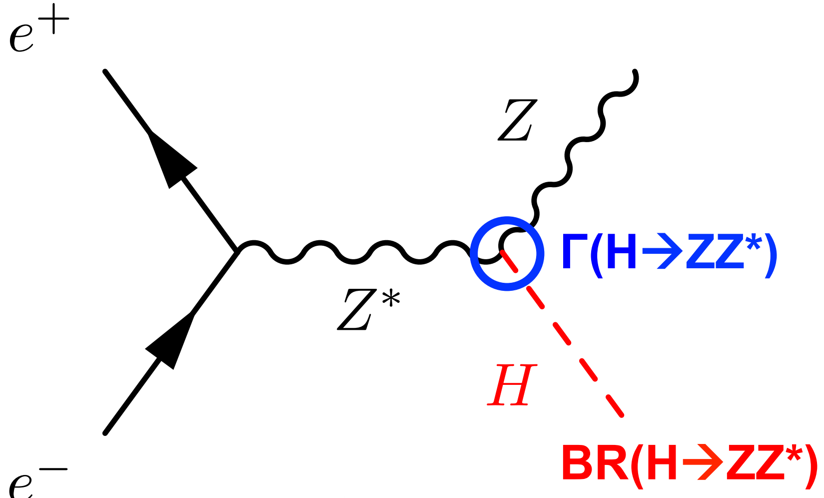
Model-independent, absolute measurement of the Higgs mass and σ(Zh):
$\Delta m_h \leq$ 15 MeV, $\sigma_{Zh} \leq$ 1.2% ($\sqrt{s}$=250 GeV, L=1150 fb-1)

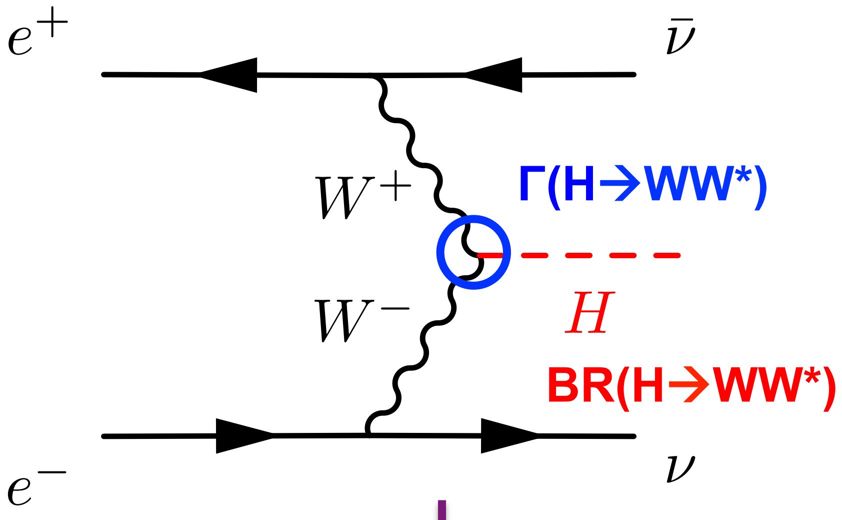
Higgs Coupling Determination

Total decay width needed to fix the absolute couplings

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

Partial Width & Branching Ratio measurements with Z/W:





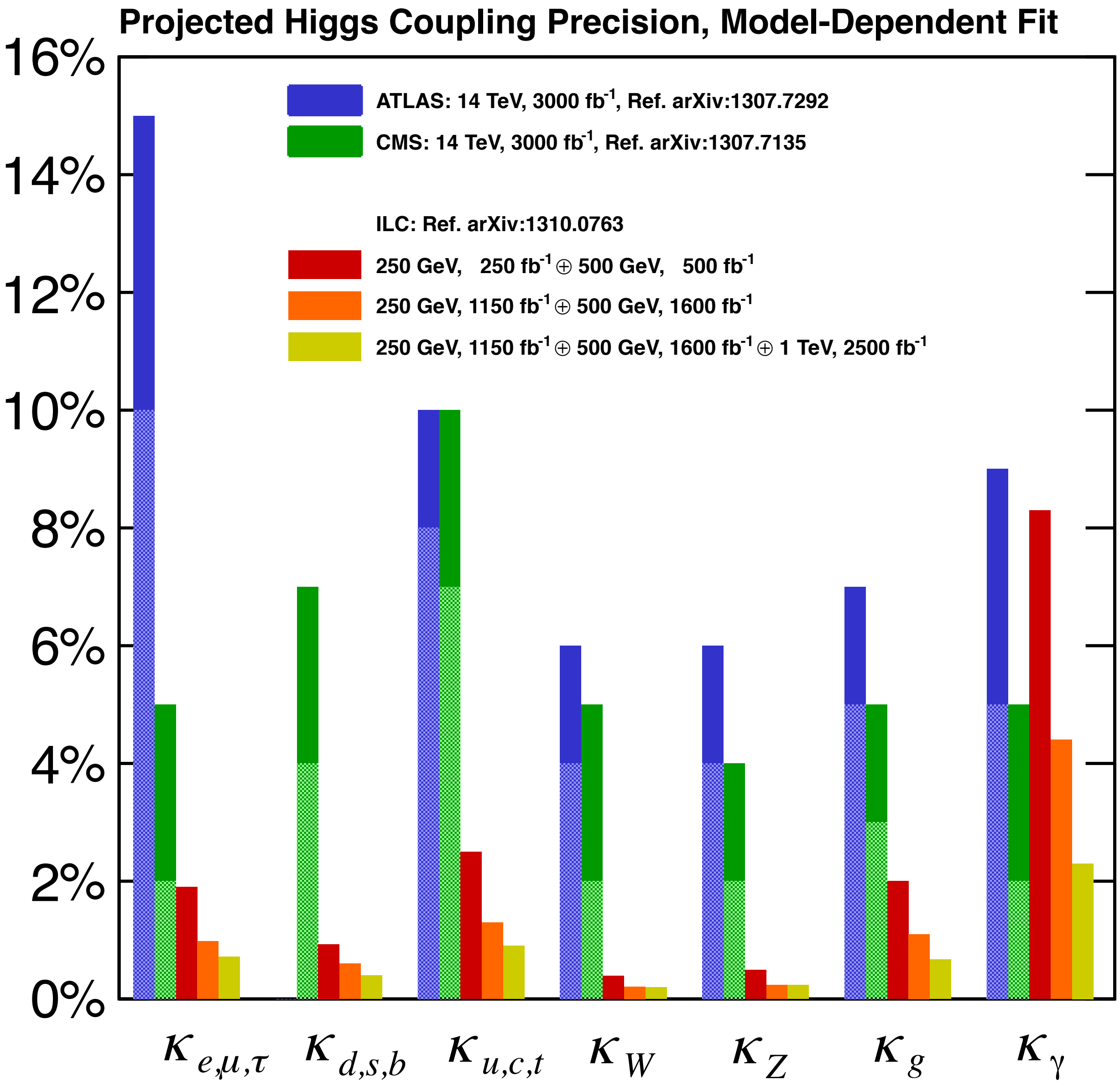
ZHH at 250 GeV alone requires very high statistics since BR(H→ZZ*) ~ 2%.

Very small cross section at 250 GeV. Clean reaction at 500 GeV

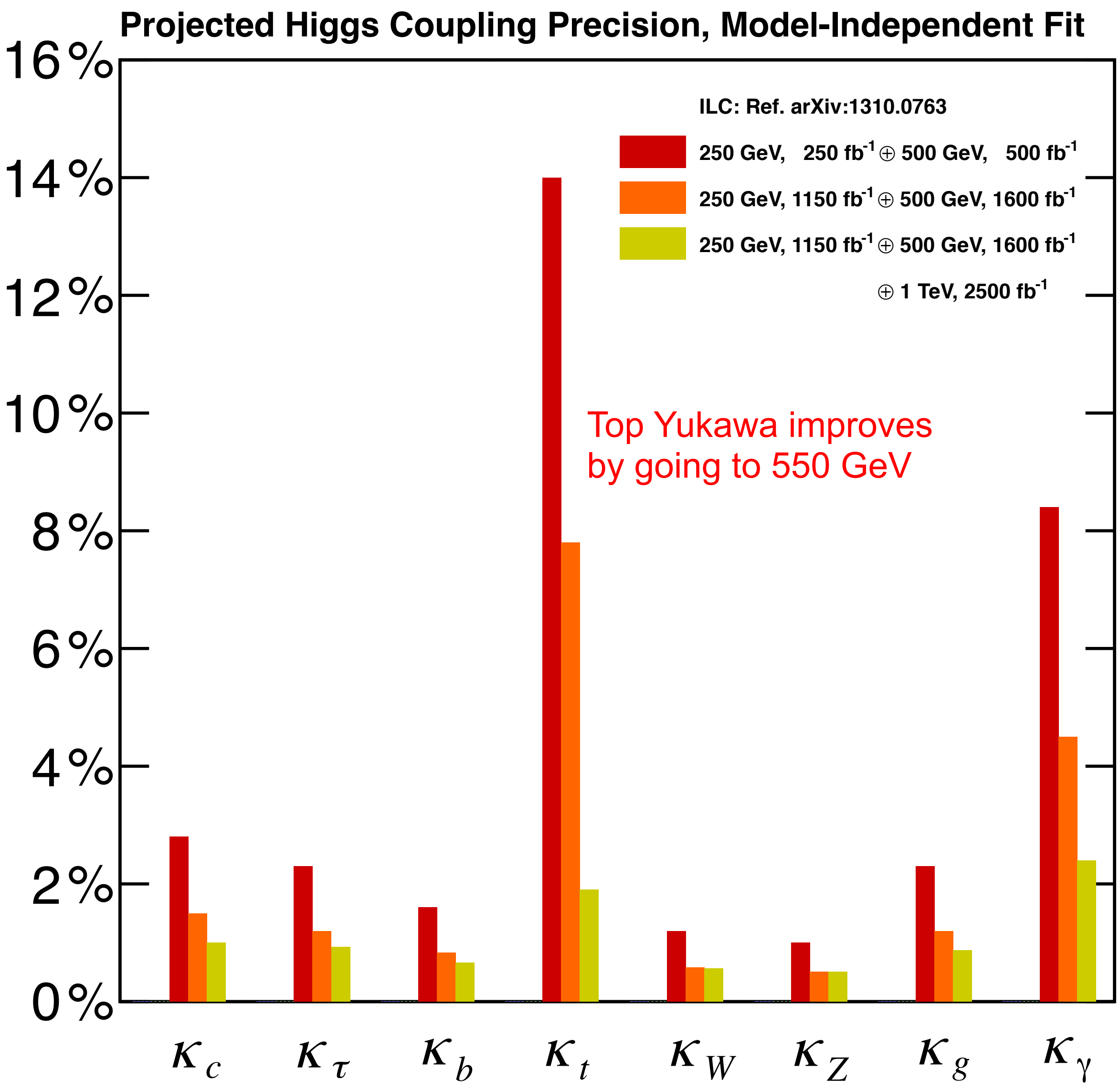
Combination of 250 GeV & 500 GeV data essential for the precise determination of Higgs couplings

Higgs Couplings (1/2)

[With assumptions; not model-independent.]



Higgs Couplings (2/2)



Top Yukawa improves
by going to 550 GeV

Better hγγ with
LHC/ILC
synergy

Excellent
b-tagging
c-tagging
at ILC

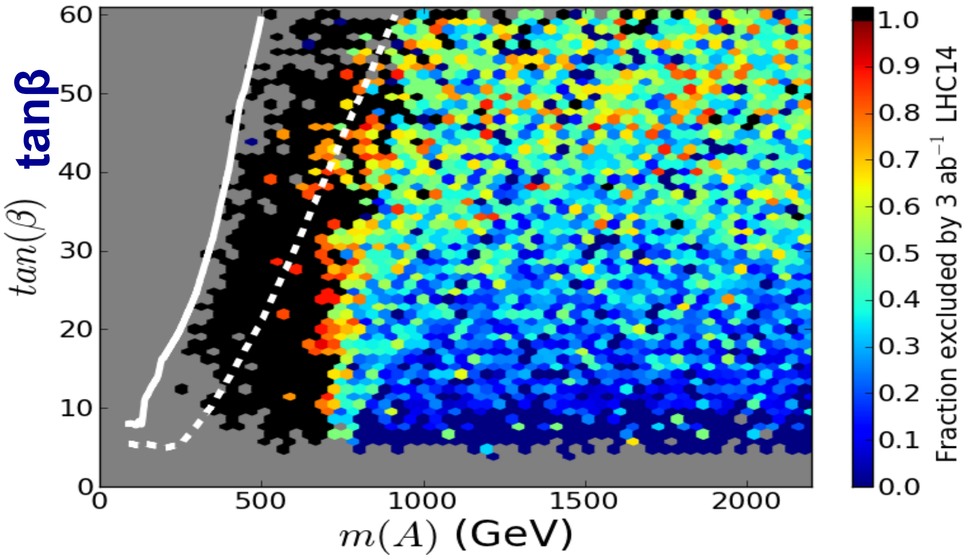
Model-independent coupling determination unique to ILC

MSSM Heavy Higgs Bosons

Exclusions of pMSSM points via Higgs couplings (combining hγγ, hττ, hbb)

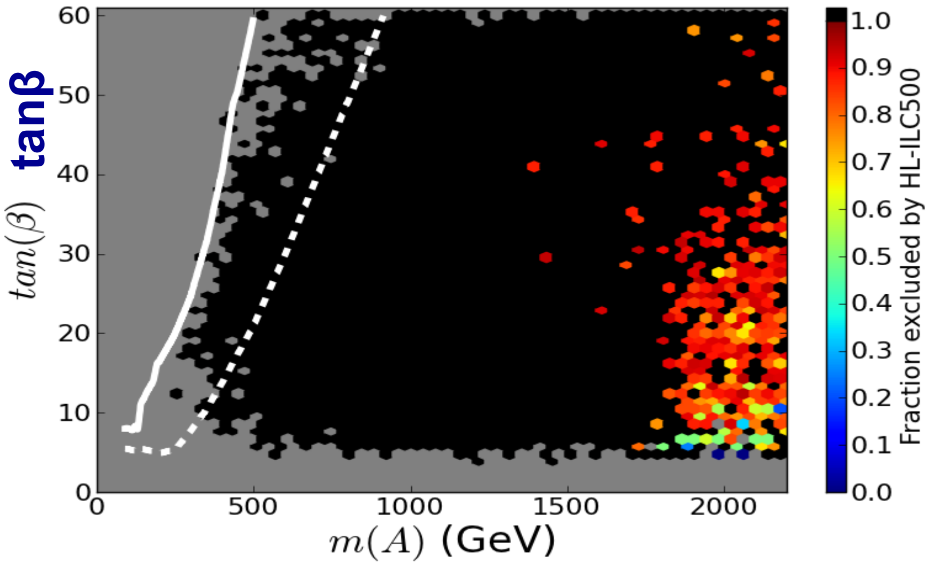
Cahill-Rowley, Hewett, Ismail, Rizzo, arXiv:1407.7021 [hep-ph]

HL-LHC 3000 fb-1



Heavy Higgs mass

ILC (1150 fb^{-1}@250 GeV & 1600 fb^{-1}@500 GeV)

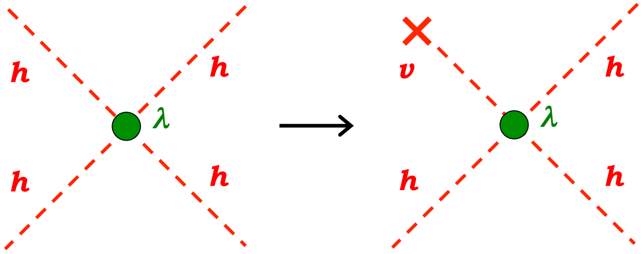


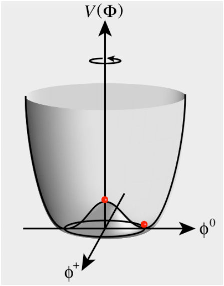
Heavy Higgs mass

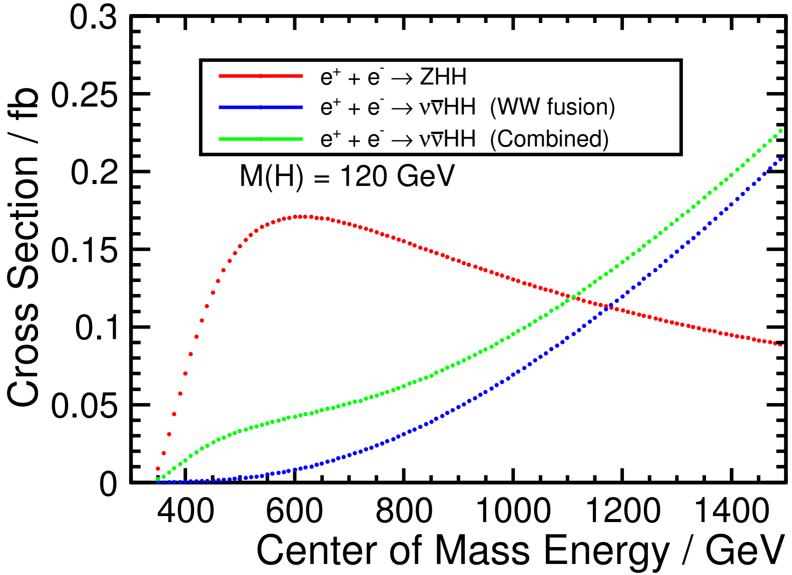
Precision Higgs coupling measurements sensitive probe for heavy Higgs bosons
mA ~ 2 TeV reach for any tanβ at the ILC

Higgs Self-Coupling

Existence of hhh coupling =
Direct evidence of vacuum condensation

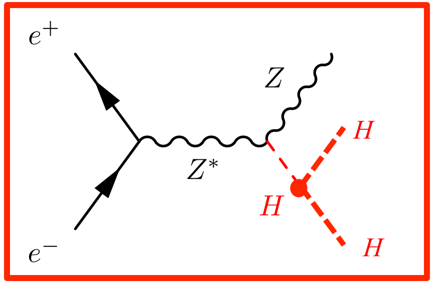


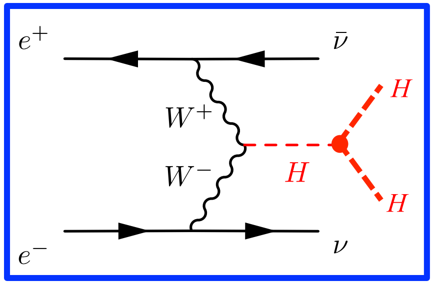




Challenging measurement because of:

- Small cross section (Zhh 0.2 fb at 500 GeV)
- Many jets in the final state
- Presence of interference diagrams





arXiv:1310.0763	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000
$\int \mathcal{L}dt$ (fb^{-1})	500	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$
$\sigma(ZHH)$	42.7%		42.7%	23.7%
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%
λ	83%	46%	21%	13%

Ongoing analysis improvements towards O(10)% measurement

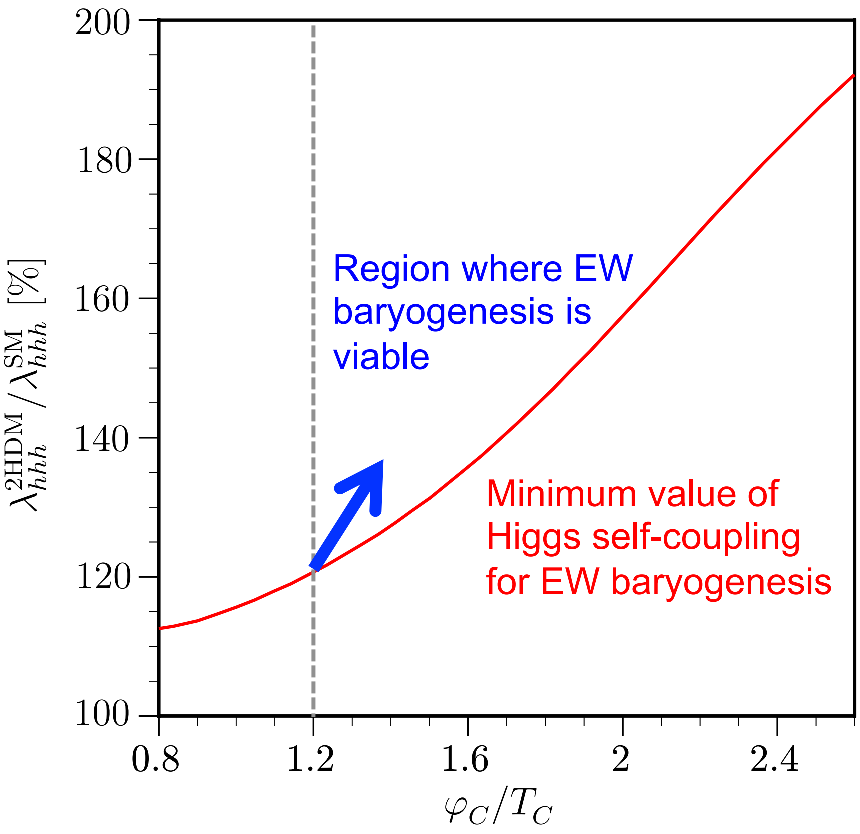
Baryon Asymmetry of Universe

There are different models of baryogenesis at different energy scales. Some examples:

- EW scale: EW baryogenesis → can be probed at the ILC
- Middle scale: Affleck-Dine baryogenesis
- GUT scale: Leptogenesis

A generic feature of new physics models with electroweak baryogenesis typically predict large deviations in Higgs coupling measurements which can be tested at the ILC

Example of EW baryogenesis in a 2HDM model (Senaha, Kanemura):



Region where EW baryogenesis is viable

Minimum value of Higgs self-coupling for EW baryogenesis

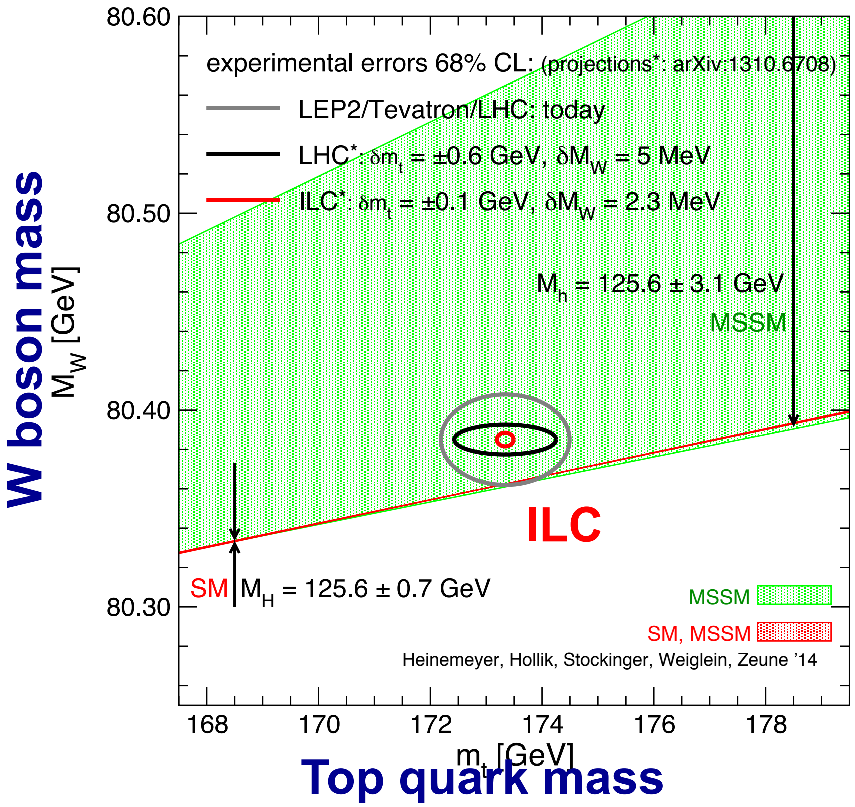
Ratio of Higgs self-coupling 2HDM / SM

φ_C Higgs field vev at critical temperature T_C

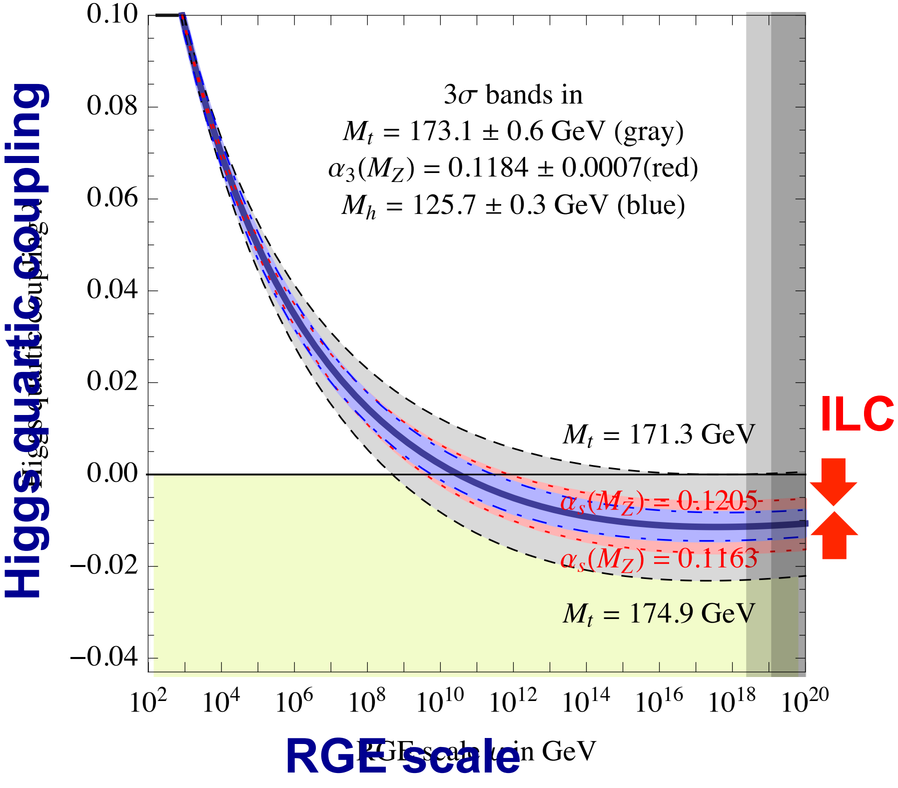
Top Physics at ILC

Top quark mass

- The top quark mass is a fundamental parameter for both SM and BSM.
- With L=100 fb^{-1} at the ILC around the pair production threshold (~350 GeV), the **top mass in the MSbar scheme** can be measured to **100 MeV**. (At least factor 5 improvement over HL-LHC.) The measurement is limited by the theoretical uncertainty associated with the slow convergence in the perturbation theory.



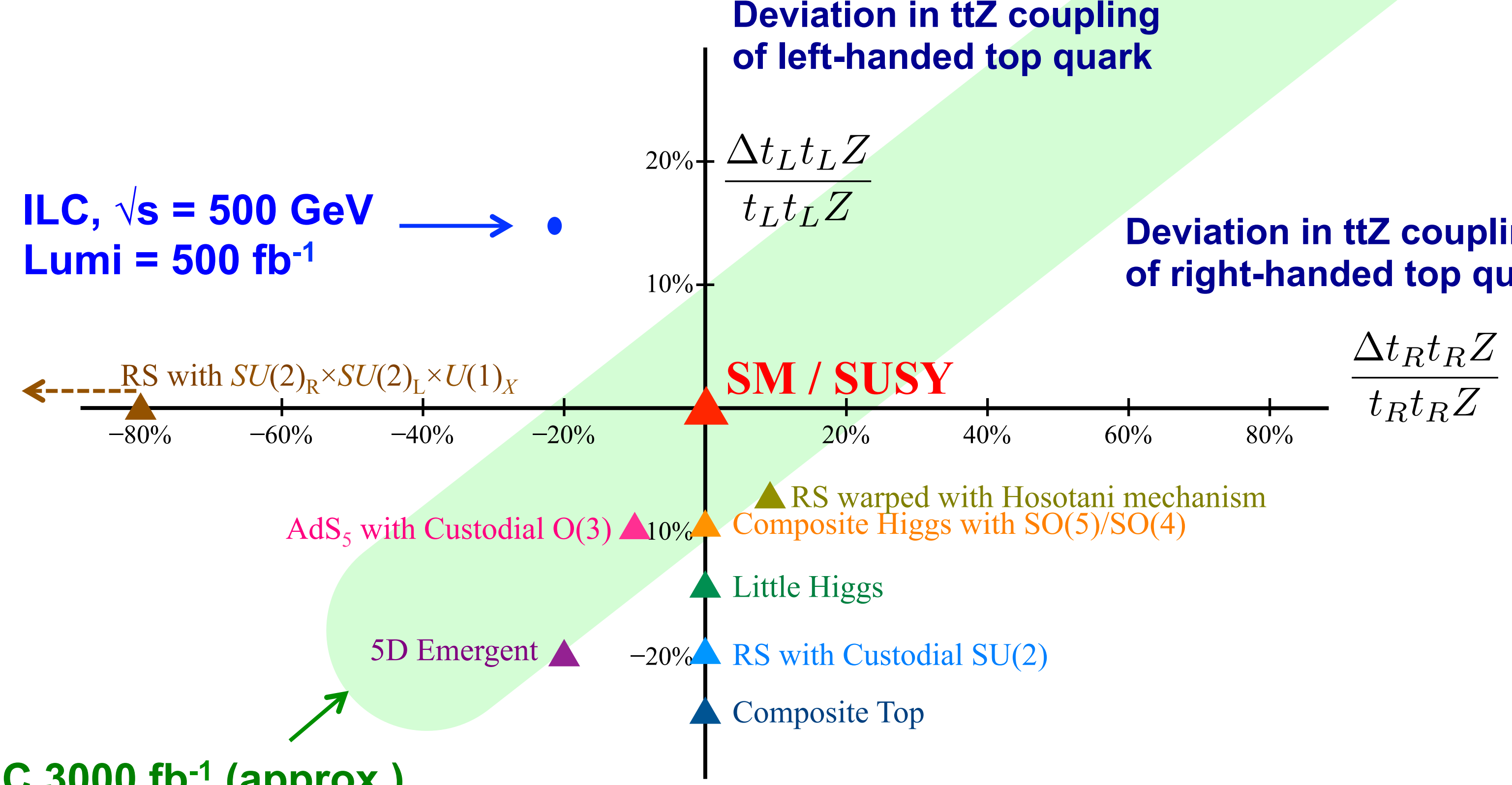
Heinemeyer et al.



Degrassi et al., JHEP 1208 (2012) 098

Impact of BSM on Top Sector

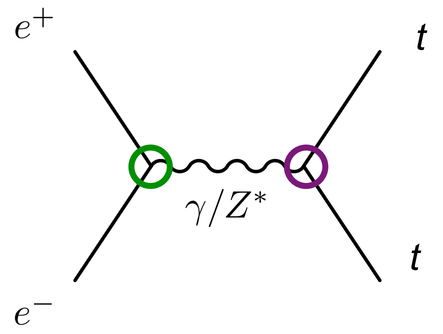
Composite Higgs theories have an impact on the top sector. Composite Higgs models can be tested at the ILC through precise measurements of the top couplings. Beam polarization (both e- and e+) is essential to distinguish the ttZ and ttγ couplings.



HL-LHC 3000 fb^{-1} (approx.)
Based on Baur, Juste, Orr, Rainwater, PRD71, 054013 (2005)

Deviations for different models for new physics scale at ~1 TeV.
Based on F. Richard, arXiv:1403.2893

Top Coupling Measurements



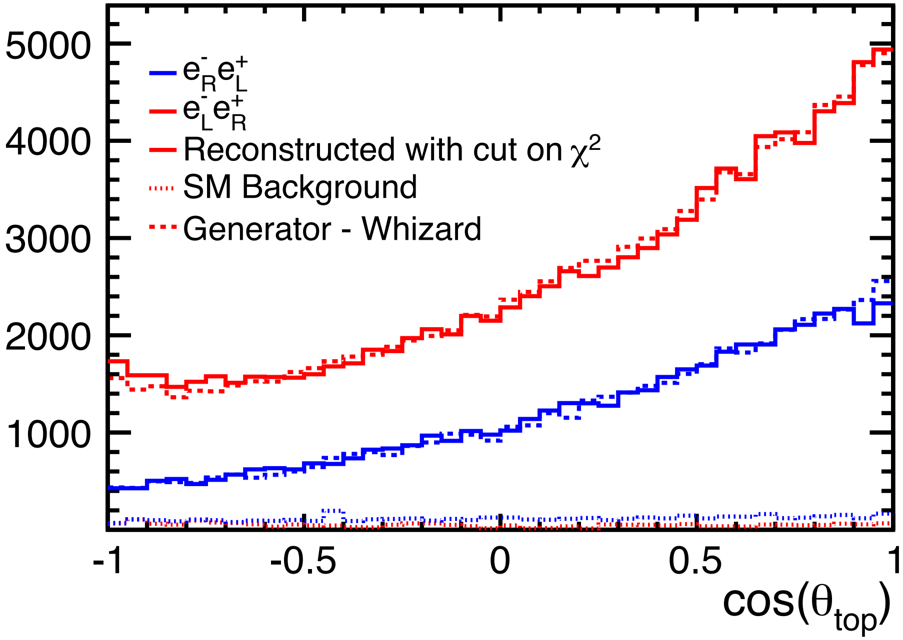
Measure cross section σ and asymmetries A_{FB}, A_{hel} to measure the top form factors $F^{tt\gamma}_{1L}$, $F^{tt\gamma}_{1R}$, F^{ttZ}_{1L}, F^{ttZ}_{1R}

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

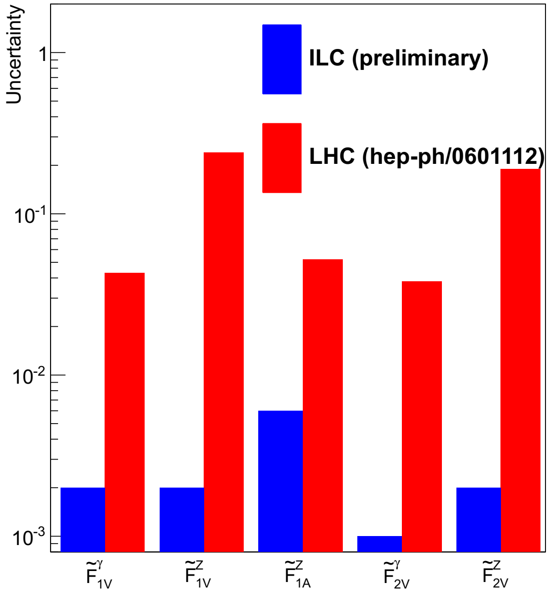
At 500 GeV: large asymmetries & high statistics

Polarization needed to extract all observables

Reconstructed top angle



Expected precision



Amjad et al. arXiv:1307.8102

Searches for direct production of SUSY / DM at the ILC

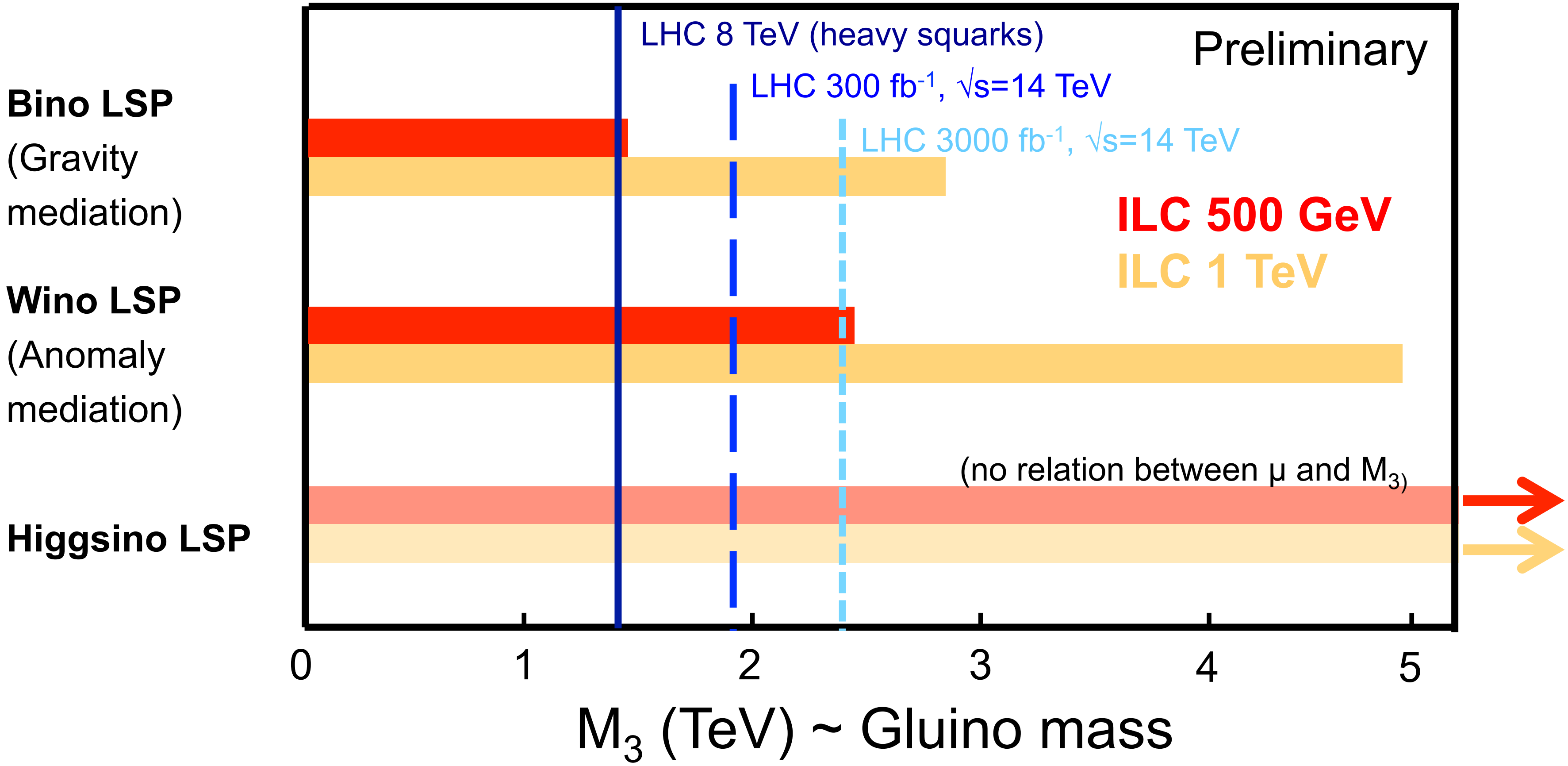
Sensitivity to SUSY

[this comparison is for illustration only; specific channels should be looked at for actual comparisons]

Examples of model-independent SUSY searches

- LHC: Gluino search
- ILC: Chargino/Neutralino search

Compare using gaugino mass relations

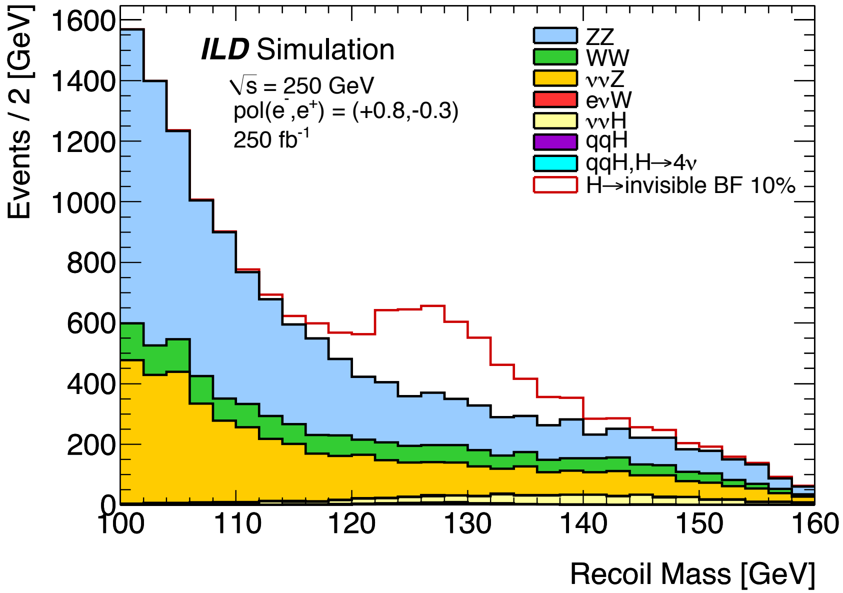


[Assumptions: MSUGRA/GMSB relation $M_1 : M_2 : M_3 = 1 : 2 : 6$; AMSB relation $M_1 : M_2 : M_3 = 3.3 : 1 : 10.5$]

WIMP Dark Matter @ ILC

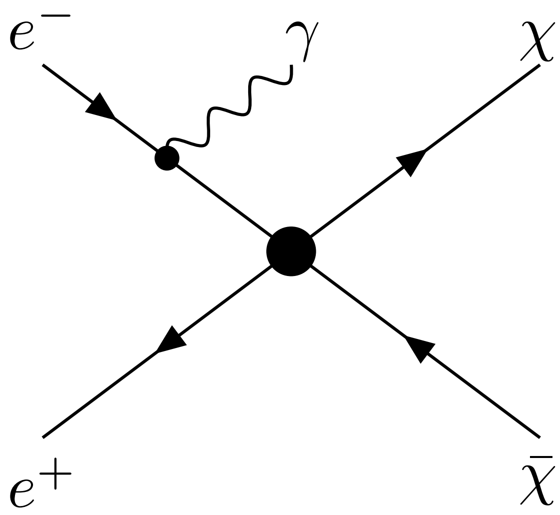
WIMP searches at colliders are complementary to direct/indirect searches.
Examples at the ILC:

Higgs Invisible Decay



BR(H→invis.) < 0.4%
at 250 GeV, 1150 fb^{-1}

Monophoton Search



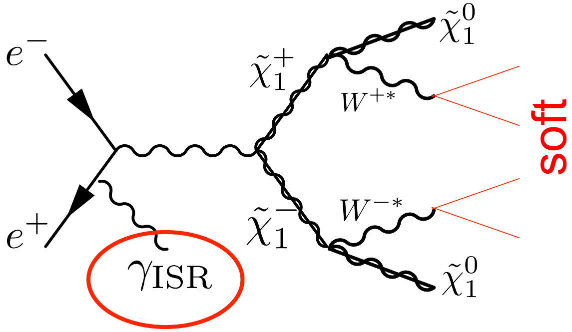
→ DM mass sensitivity
nearly half the CM energy

SUSY-specific signatures (decays to DM)

- light Higgsino, light stau, etc.

Higgsino decays to DM with small mass differences

Study of Higgsino pair production, with ISR tag

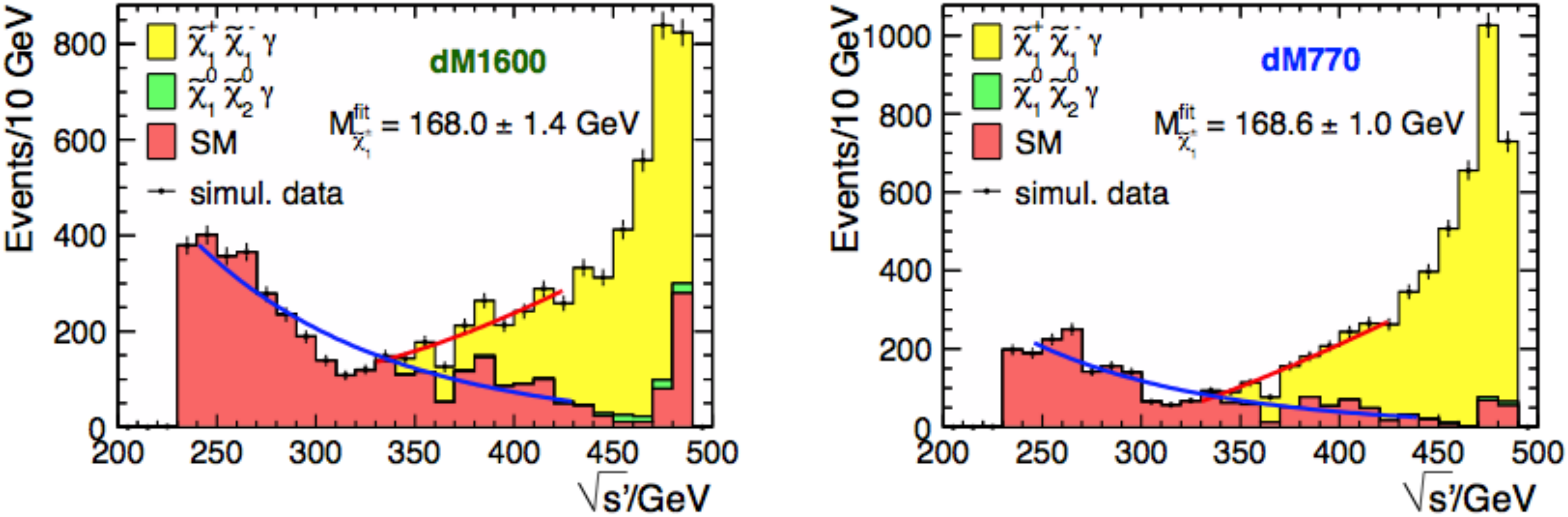


Benchmark models with
m(NLSP) – M(LSP) = 1.6 GeV and 0.8 GeV

$$\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-) = 78.7\ (77.0)\ \mathrm{fb}$$

$$\Delta M = 1.60\ (0.77)\ \mathrm{GeV}$$

Berggren, Bruemmer, List, Moortgat-Pick, Robens, Rolbiecki, Sert,
EPJ C73 (2013) 2660 [arXiv:1307.3566]



√s=500 GeV, Lumi=500 fb-1, P(e-,e+)=(-0.8,+0.3)
LSP mass resolution ~1%

Slepton decays to DM with small mass differences

Study of stau pair production at the ILC

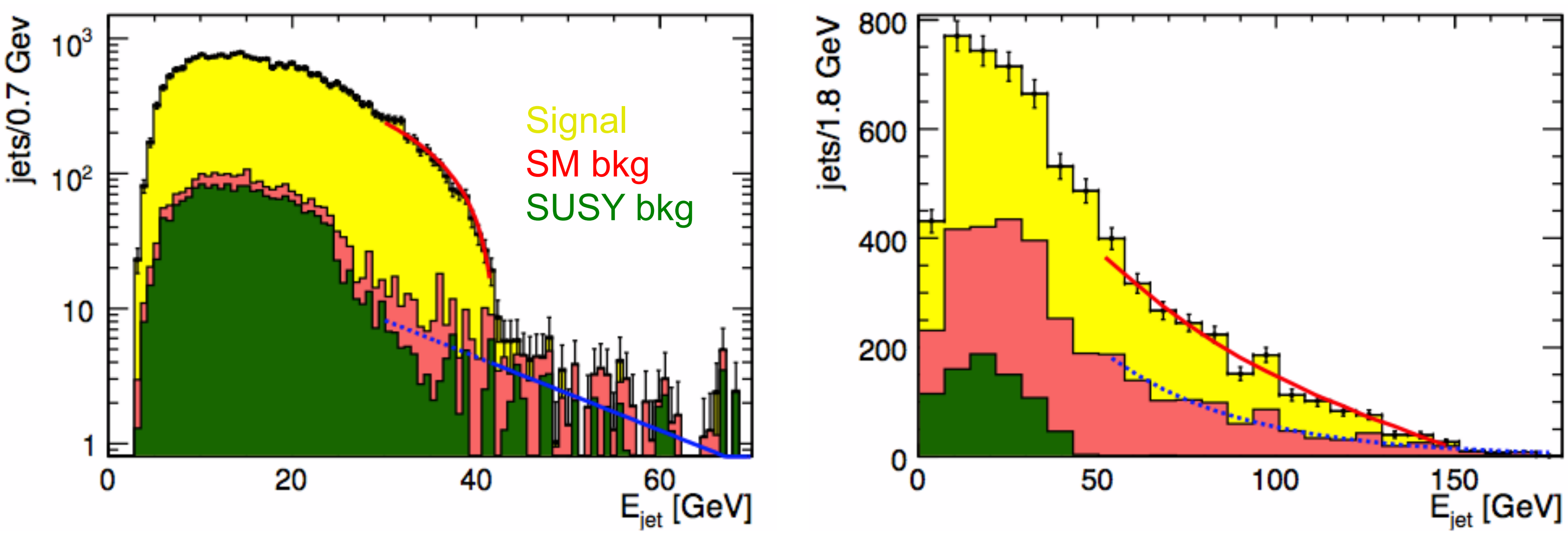
Observation of lighter and heavier stau states with decay to DM + hadronic tau

Benchmark point: m(LSP) = 98 GeV, m(stau1) = 108 GeV, m(stau2) = 195 GeV

$$\sigma(e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-) = 158 \text{ fb}$$

$$\sigma(e^+e^- \to \tilde{\tau}_2^+\tilde{\tau}_2^-) = 18 \text{ fb}$$

Bechtle, Berggren, List, Schade, Stempel, arXiv:0908.0876, PRD82, 055016 (2010)



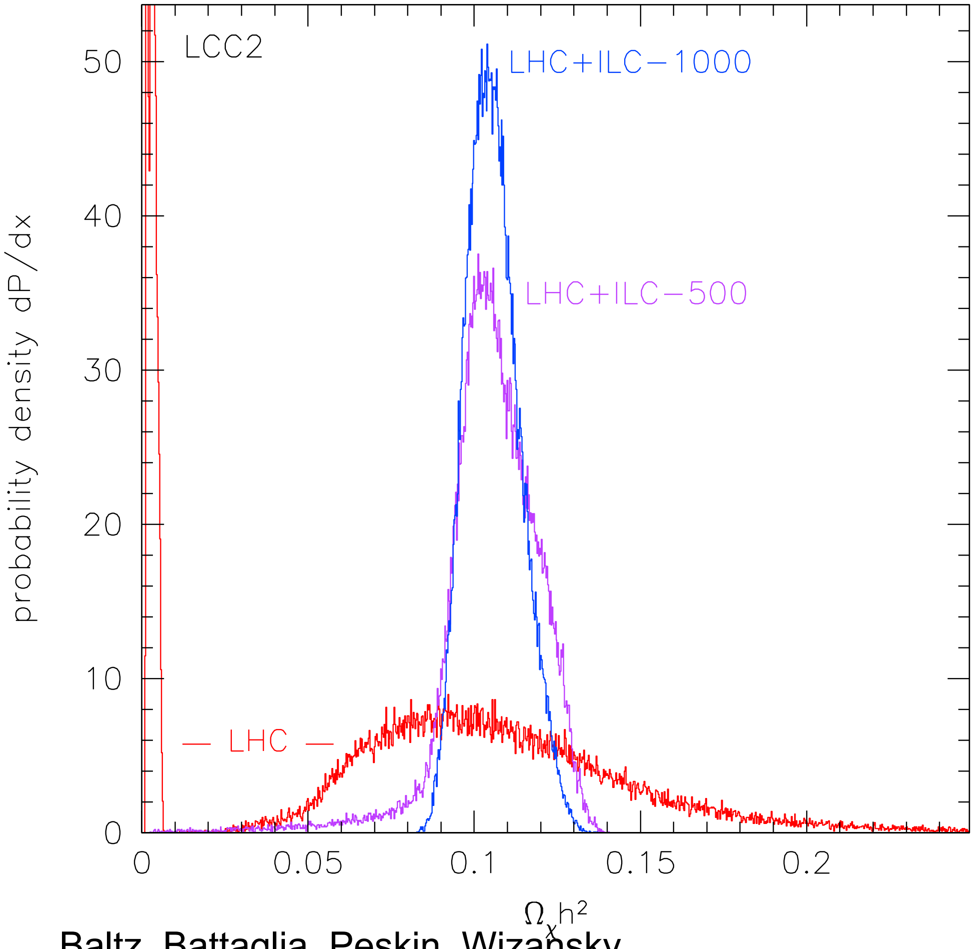
√s=500 GeV, Lumi=500 fb-1, P(e-,e+)=(+0.8,-0.3)

Stau1 mass ~0.1%, Stau2 mass ~3% → LSP mass ~1.7%

DM Relic Abundance

WMAP/Planck (68% CL)

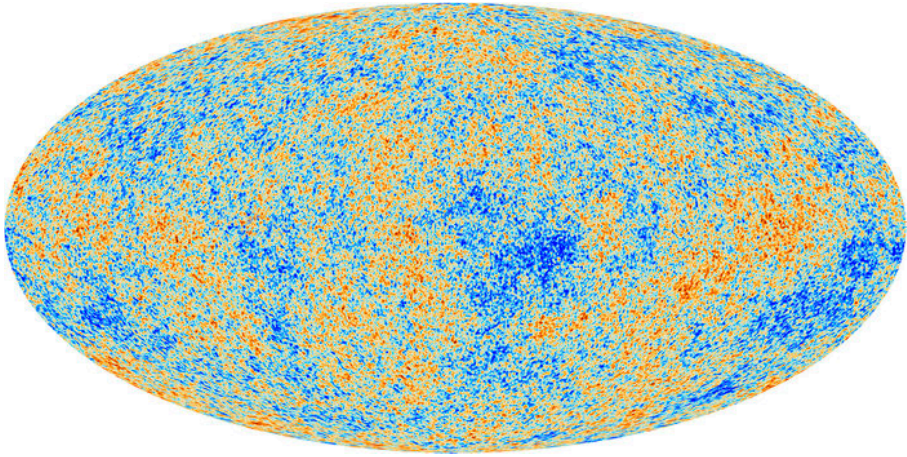
$$\Omega_c h^2 = 0.1196 \pm 0.0027$$



Baltz, Battaglia, Peskin, Wizansky
PRD74 (2006) 103521, arXiv:hep-ph/0602187

**This particular benchmark point is excluded. Update is in progress.*

ESA/Planck



Once a DM candidate is discovered, crucial to check the consistency with the measured DM relic abundance.

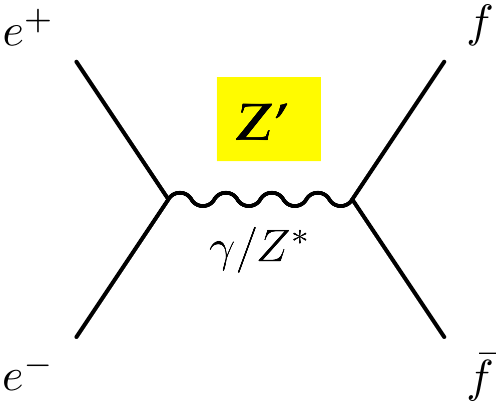
→ ILC precise measurements of mass and cross sections

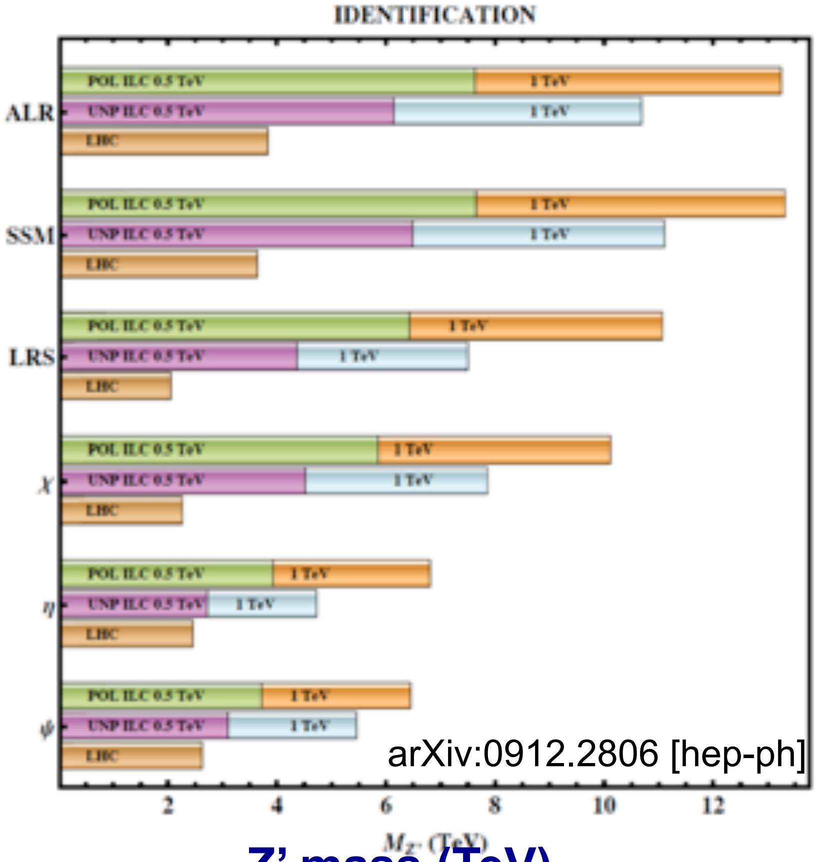
Z' : Heavy Neutral Gauge Bosons

New gauge forces imply existence of heavy gauge bosons (Z')

Complementary approaches LHC/ILC

- LHC: Direct searches for Z' (mass determination)
- ILC: Indirect searches via interference effects (coupling measurements and model discrimination) – beam polarizations improve reach and discrimination power

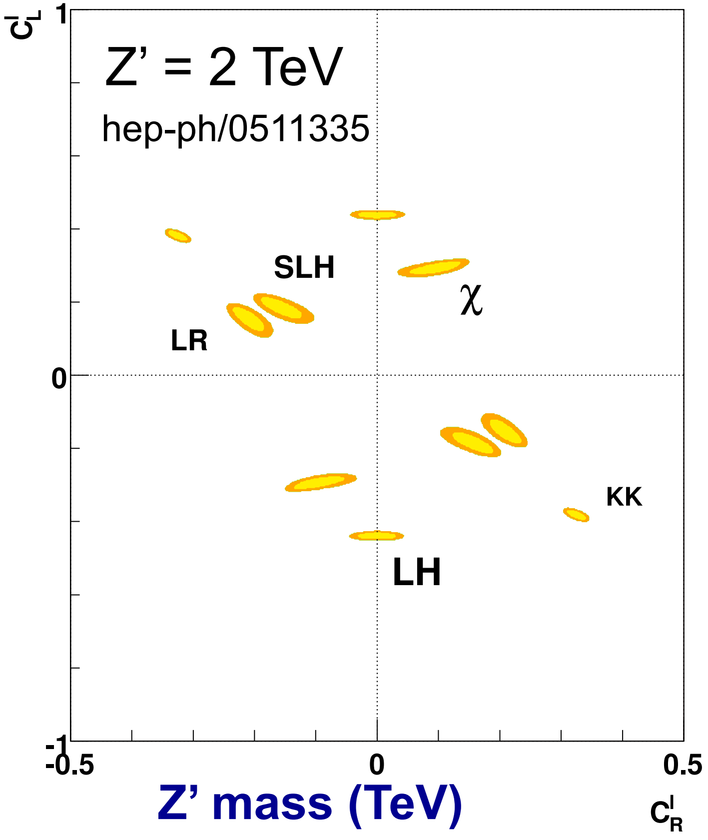




Models with Z' boson

arXiv:0912.2806 [hep-ph]

Z' mass (TeV)



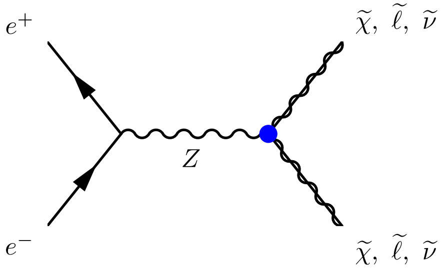
Z' = 2 TeV

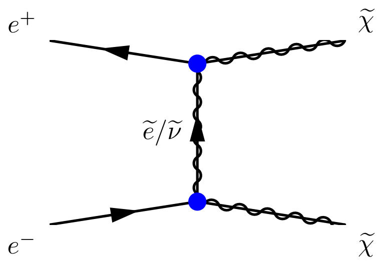
hep-ph/0511335

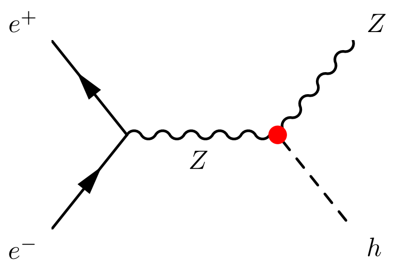
Z' mass (TeV)

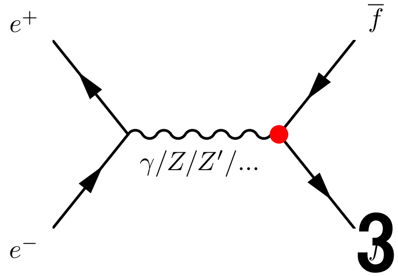
Summary

- ILC is a proposed **energy frontier** machine in e+e- collisions. The technology is ready. We have a country interested in hosting it. The extendability of linear colliders provide a **clear path for the future**.
- ILC will address **fundamental questions** in particles physics associated with **new physics at the TeV scale**.
  - What is the physics behind the **electroweak symmetry breaking**?
    - Supersymmetry, composite Higgs, …
    - Precise measurements of Higgs / top and direct searches
  - What is the nature of **dark matter**?
    - Searches complementary to direct/indirect/LHC
      - Higgs invisible width, monophotons, SUSY-specific
    - Cross section measurements → relic abundance







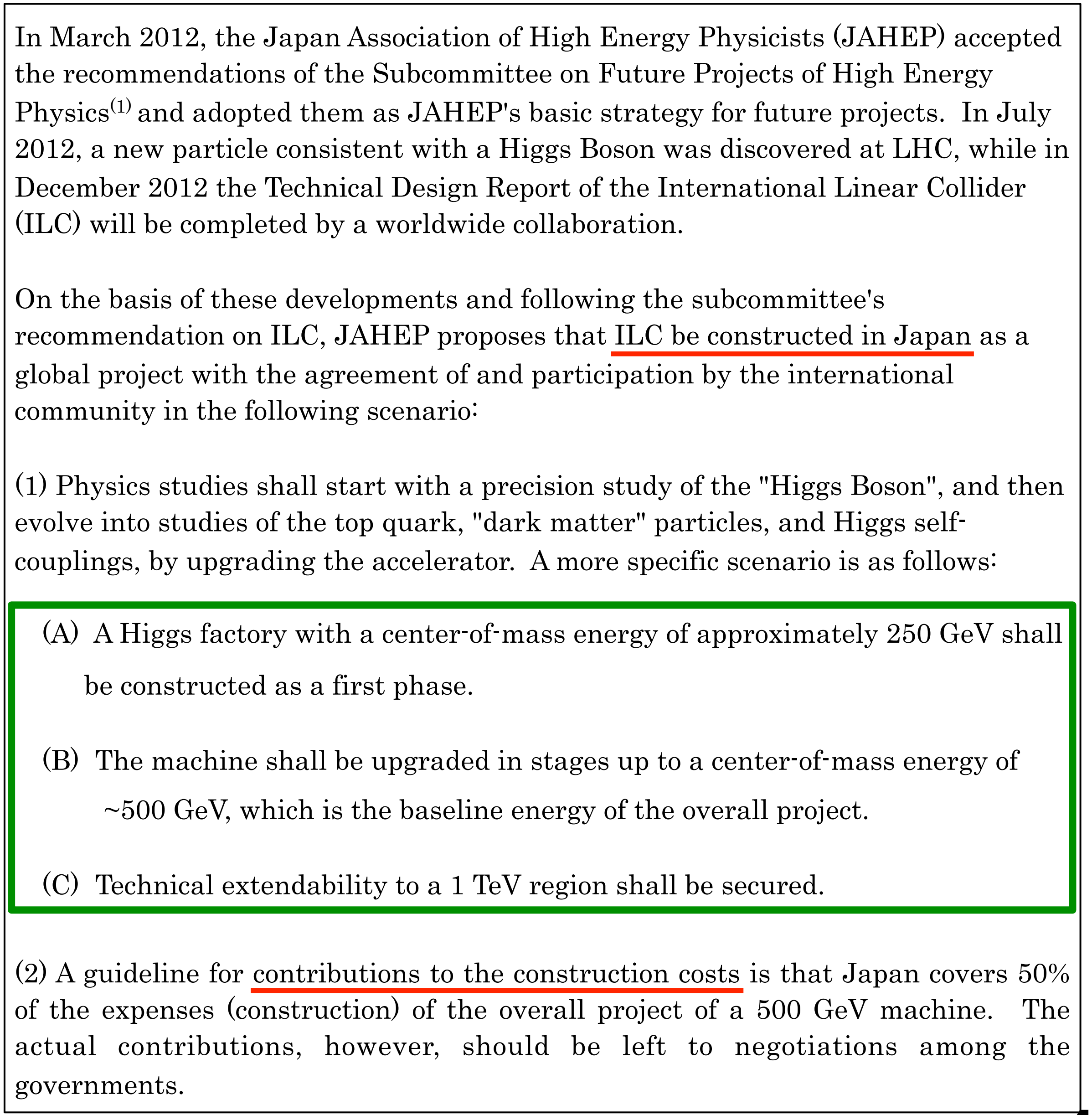


Additional Slides

Proposal for a Staged ILC in Japan

The Higgs discovery prompted a staged construction of the ILC.

Statement of Japanese HEP community (JAHEP), Oct 2012



In March 2012, the Japan Association of High Energy Physicists (JAHEP) accepted the recommendations of the Subcommittee on Future Projects of High Energy Physics(1) and adopted them as JAHEP's basic strategy for future projects. In July 2012, a new particle consistent with a Higgs Boson was discovered at LHC, while in December 2012 the Technical Design Report of the International Linear Collider (ILC) will be completed by a worldwide collaboration.

On the basis of these developments and following the subcommittee's recommendation on ILC, JAHEP proposes that ILC be constructed in Japan as a global project with the agreement of and participation by the international community in the following scenario:

(1) Physics studies shall start with a precision study of the "Higgs Boson", and then evolve into studies of the top quark, "dark matter" particles, and Higgs self-couplings, by upgrading the accelerator. A more specific scenario is as follows:

(A) A Higgs factory with a center-of-mass energy of approximately 250 GeV shall be constructed as a first phase.

(B) The machine shall be upgraded in stages up to a center-of-mass energy of ~500 GeV, which is the baseline energy of the overall project.

(C) Technical extendability to a 1 TeV region shall be secured.

(2) A guideline for contributions to the construction costs is that Japan covers 50% of the expenses (construction) of the overall project of a 500 GeV machine. The actual contributions, however, should be left to negotiations among the governments.

Europe & Asia

European Strategy, adopted by CERN Council on May 30, 2013

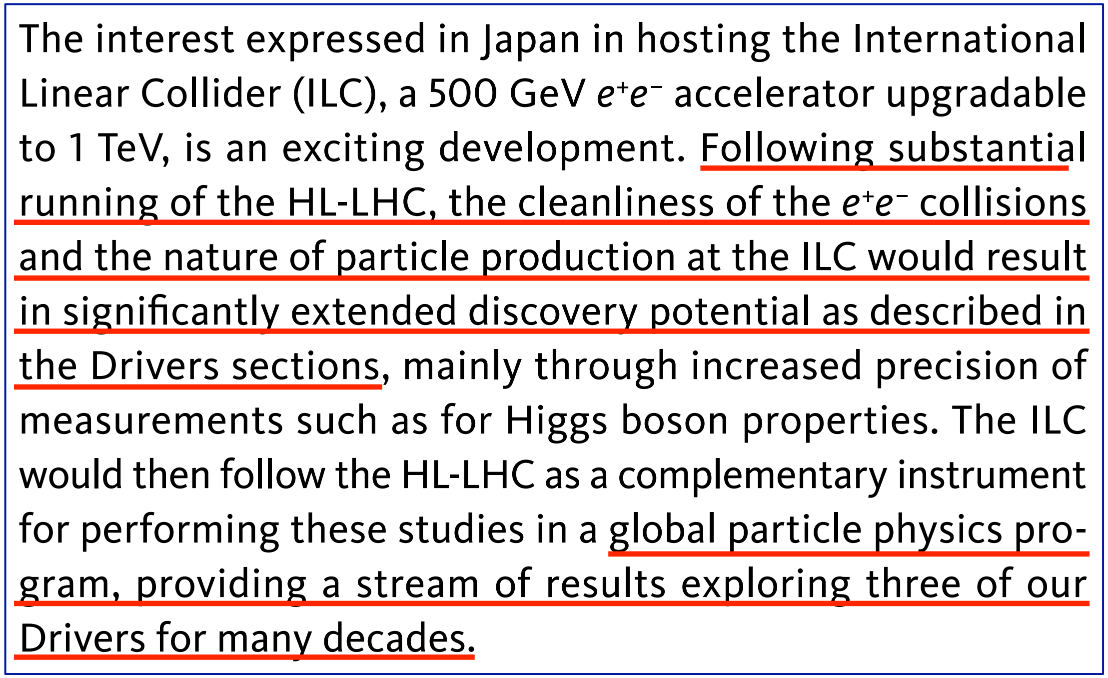
> e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. *Europe looks forward to a proposal from Japan to discuss a possible participation*.

Asia ACFA-HEP, 3rd ACFA-HEP Meeting on July 17, 2013 in Chiba, Japan

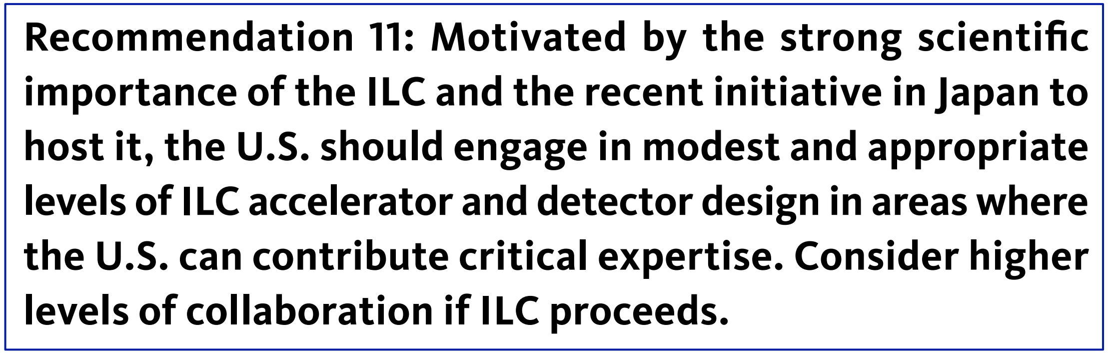
> AsiaHEP/ACFA welcomes the proposal by the Japanese HEP community for the ILC to be hosted in Japan. AsiaHEP/ACFA looks forward to a proposal from the Japanese Government to initiate the ILC project.

USA

Particle Physics Project Prioritization Panel (P5) Report, May 2014



The interest expressed in Japan in hosting the International Linear Collider (ILC), a 500 GeV e^+e^- accelerator upgradable to 1 TeV, is an exciting development. Following substantial running of the HL-LHC, the cleanliness of the e^+e^- collisions and the nature of particle production at the ILC would result in significantly extended discovery potential as described in the Drivers sections, mainly through increased precision of measurements such as for Higgs boson properties. The ILC would then follow the HL-LHC as a complementary instrument for performing these studies in a global particle physics program, providing a stream of results exploring three of our Drivers for many decades.



Recommendation 11: Motivated by the strong scientific importance of the ILC and the recent initiative in Japan to host it, the U.S. should engage in modest and appropriate levels of ILC accelerator and detector design in areas where the U.S. can contribute critical expertise. Consider higher levels of collaboration if ILC proceeds.

Drivers:
Higgs*
Neutrino Mass
Dark Matter*
Dark Energy/Inflation
New Particles/Interactions*

*where the ILC can contribute

Strong emphasis on global cooperation!

Accelerator R&D

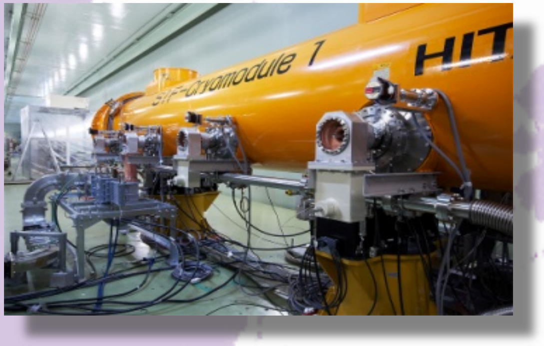
TTF/FLASH (DESY) ~1 GeV
ILC-like beam ILC RF unit
(* lower gradient)

DESY

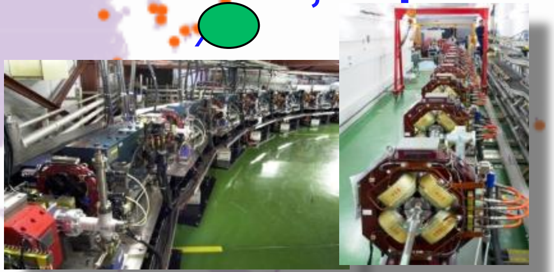
INFN Frascati

DA^{f}NE (INFN Frascati)
kicker development
electron cloud

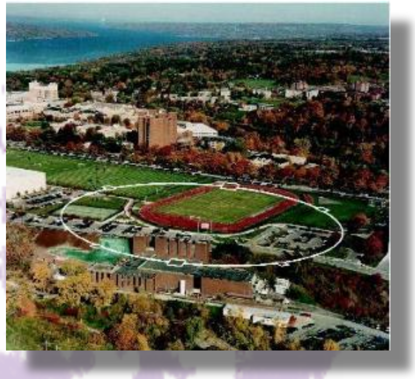
STF (KEK) operation/construction
ILC RF unit test



KEK, Japan



ATF & ATF2 (KEK)
ultra-low emittance
Final Focus optics
KEKB electron-cloud



CesrTA (Cornell)
electron cloud
low emittance

FNAL **Cornell**

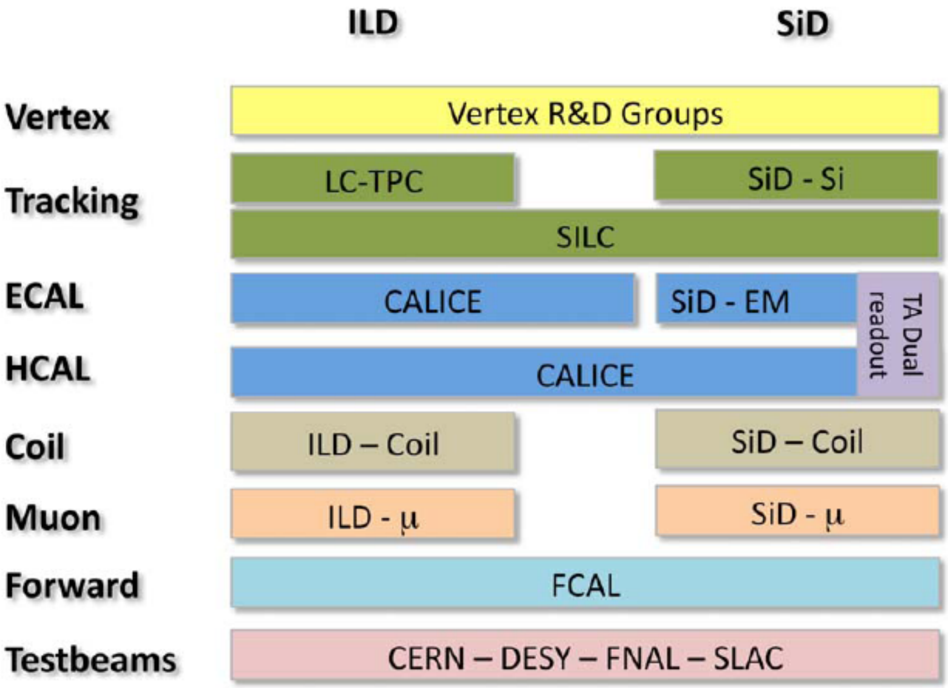
NML facility ILC RF unit test
Under construction

Detector R&D

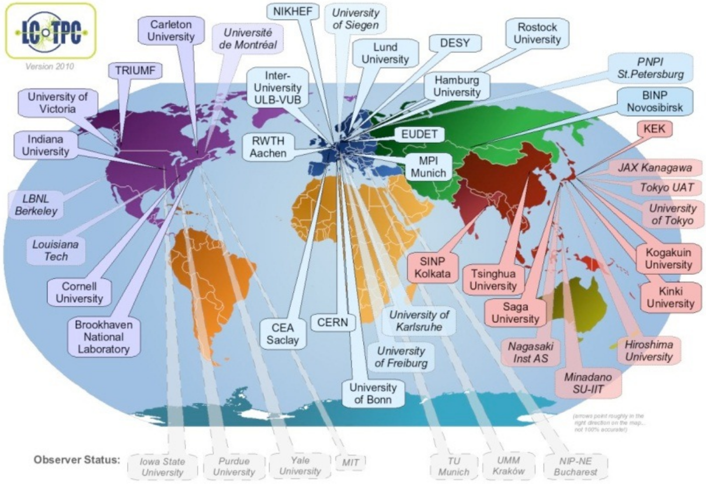
International Collaboration

Detector collaborations encompass concept groups to avoid duplicate effort.

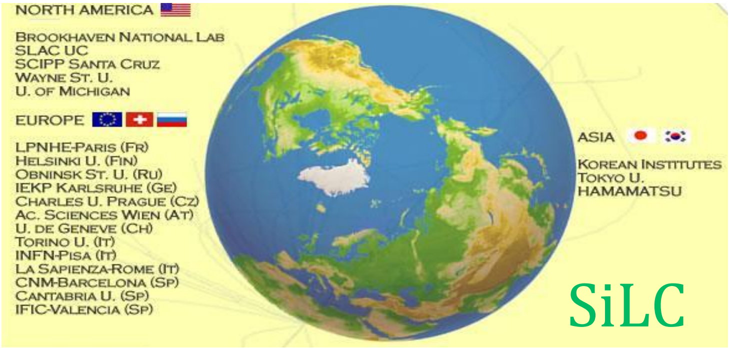
- TPC : ***LC-TPC***
- Calorimeter : ***CALICE***
- Silicon tracker : SiLC
- Forward detector : FCAL



	ILD	SiD
Vertex	Vertex R&D Groups	
Tracking	LC-TPC	SiD - Si
	SILC	
ECAL	CALICE	SiD - EM TA Dual readout
HCAL	CALICE	TA Dual readout
Coil	ILD – Coil	SiD – Coil
Muon	ILD - μ	SiD - μ
Forward	FCAL	
Testbeams	CERN – DESY – FNAL – SLAC	



CALICE
Calorimeter for ILC



NORTH AMERICA

BROOKHAVEN NATIONAL LAB
SLAC UC
SCIPP SANTA CRUZ
WAYNE ST. U.
U. OF MICHIGAN

EUROPE

LPNHE-PARIS (FR)
HELSINKI U. (FIN)
OBNINSK ST. U. (RU)
IEKP KARLSRUHE (GE)
CHARLES U. PRAGUE (CZ)
AC. SCIENCES WIEN (AT)
U. DE GENEVE (CH)
TORINO U. (IT)
INFN-PISA (IT)
LA SAPIENZA-ROME (IT)
CNM-BARCELONA (SP)
CANTABRIA U. (SP)
IFIC-VALENCIA (SP)

ASIA

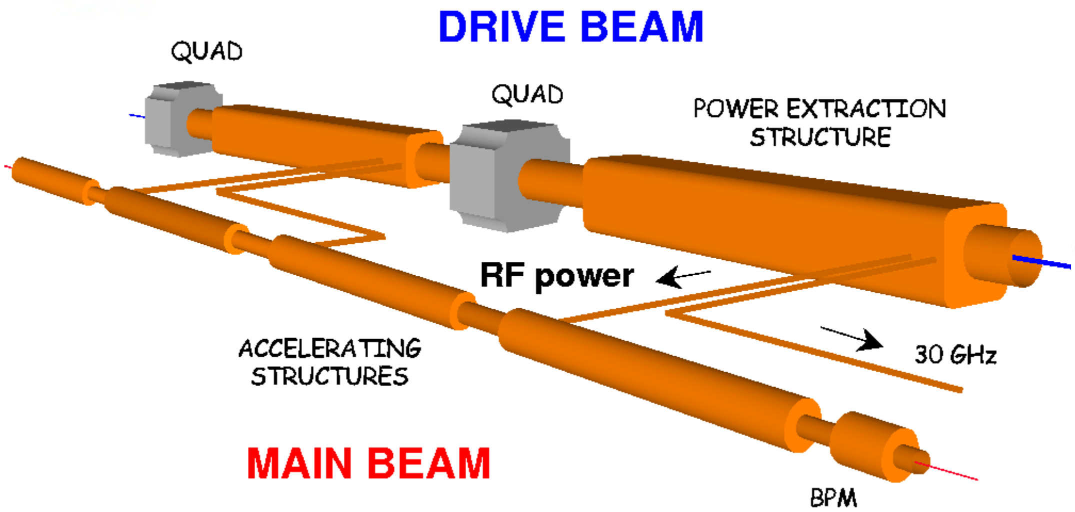
KOREAN INSTITUTES
TOKYO U.
HAMAMATSU

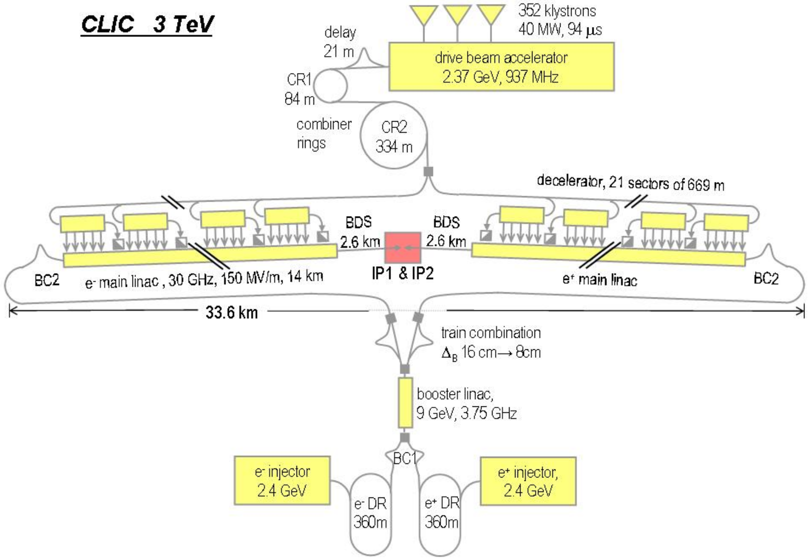
SiLC

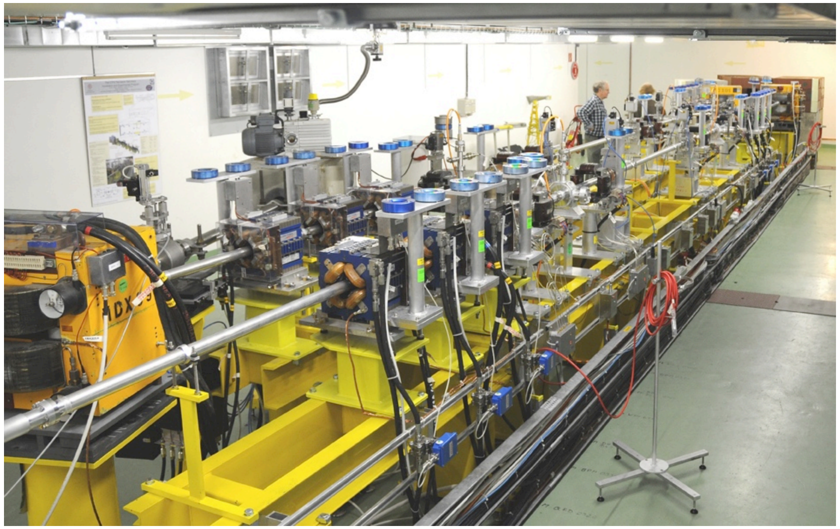
FCAL
Collaboration
High precision design

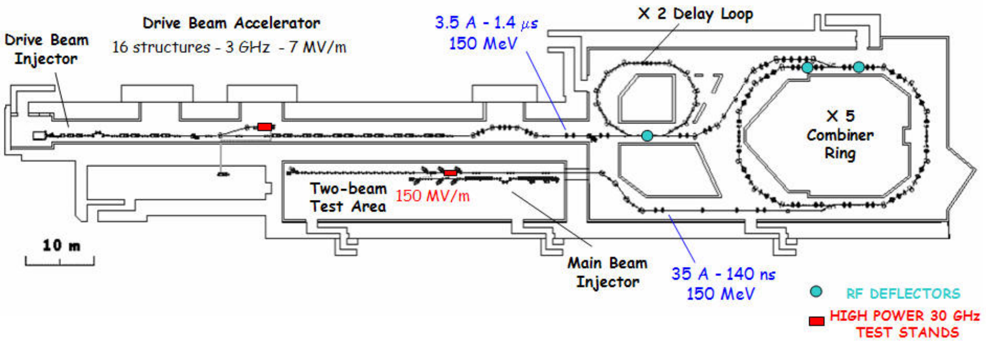
			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
Centre-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_{b}		1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_{b}	ns	554	554	554	554	366	366	366
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_{a}	$\mathrm{MV\,m^{-1}}$	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_{z}	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_{-}	%	80	80	80	80	80	80	80
Positron polarisation	P_{+}	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_{\mathrm{x}}$	μm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β^*_{x}	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β^*_{y}	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ^*_{x}	nm	729.0	683.5	474	729	474	481	335
IP RMS veritcal beam size	σ^*_{y}	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	L	$\times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^{3}$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0

CLIC: Compact Linear Collider









CDR published in 2012

→ Most mature technology for multi-TeV lepton collider

European XFEL

European XFEL:
Pulsed X-ray source based on TESLA-type superconducting RF cavities (same as ILC)

800 SRF cavities @ 23.6 MV/m in 3.4 km tunnel

European XFEL

The European X-Ray Free-Electron Laser Facility

Niobium cavities, cryostats, magnets…

29

ASEPS2013, Chiba, 16.07.2013

Massimo Altarelli, European XFEL GmbH, Hamburg

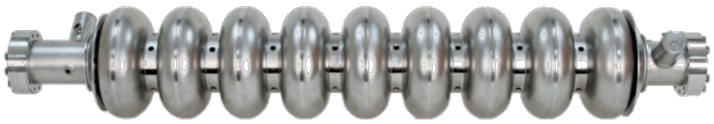
M. Altarelli, ASEPS13

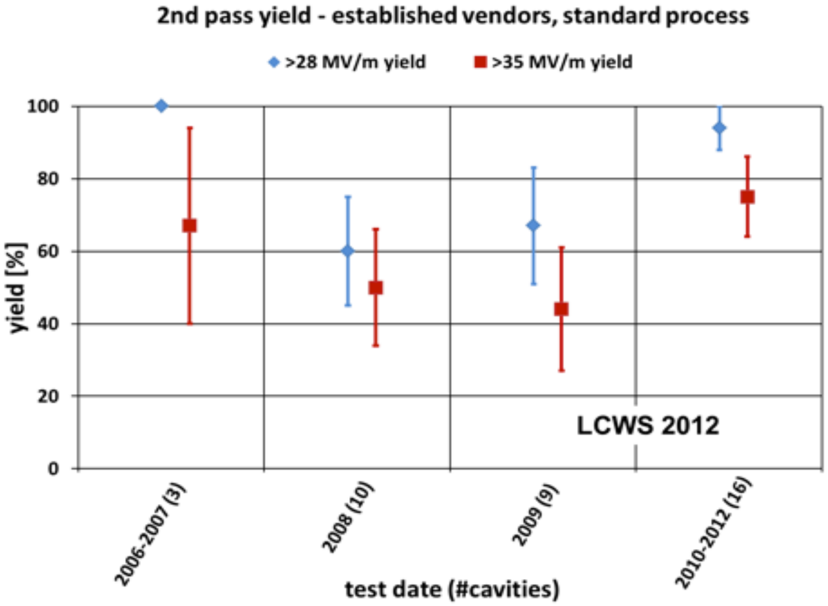
ILC will benefit from this experience.
(~16,000 SRF cavities @ 31.5 MV/m for ILC)

Key Technologies of ILC

Superconducting RF Cavities

Average of three regions

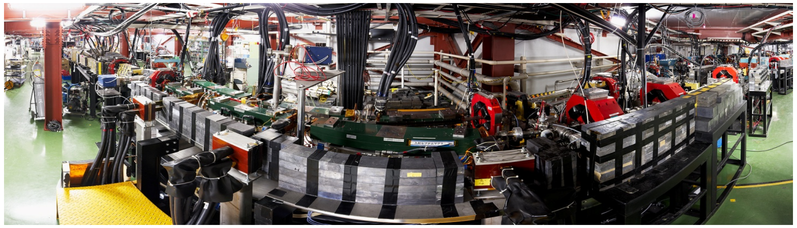


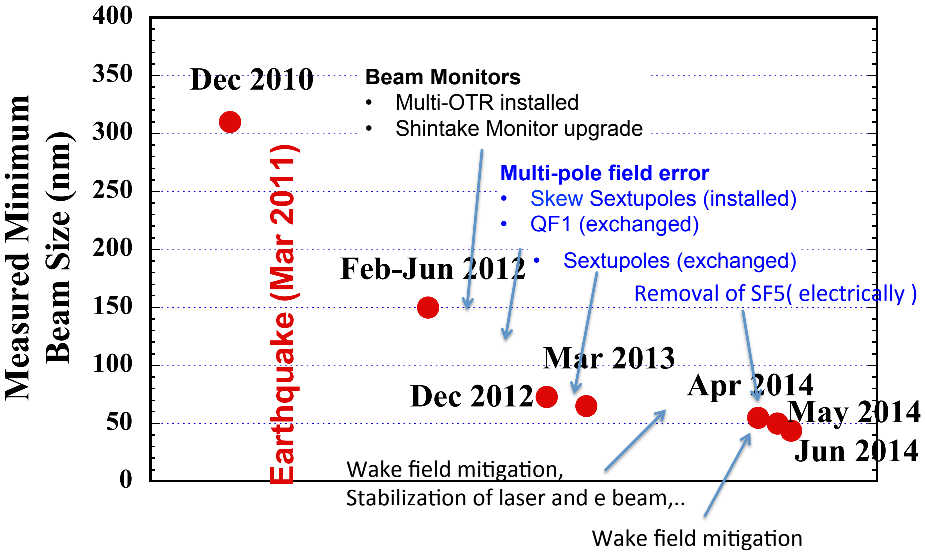


Yield: 94% at >28 MV/m
Average: 37.1 MV/m
(Target: 31.5 MV/m)

Nanometer-sized beams

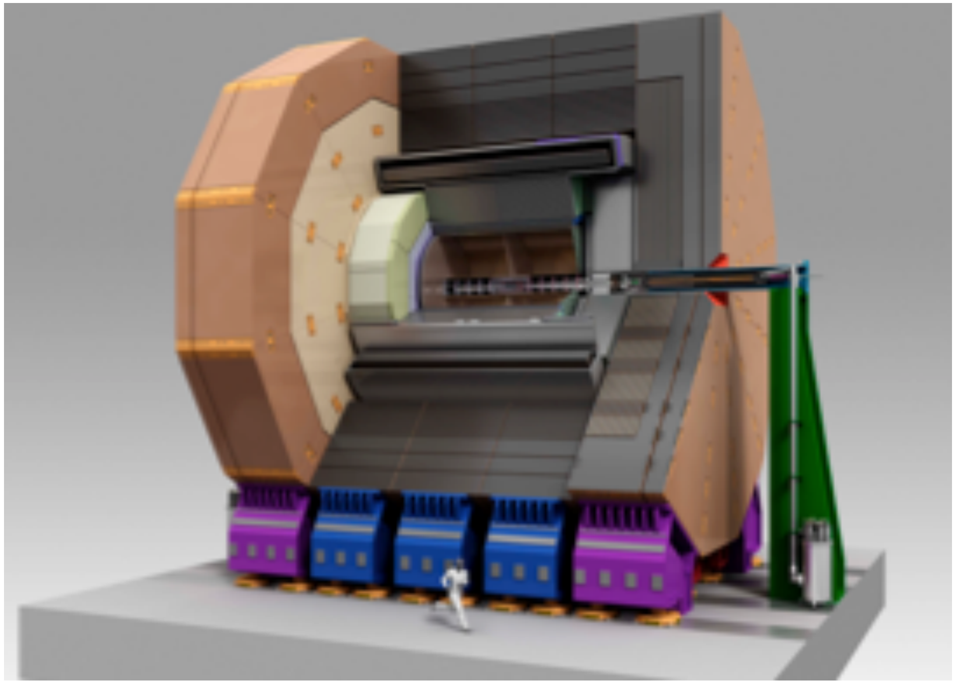
ATF2 at KEK

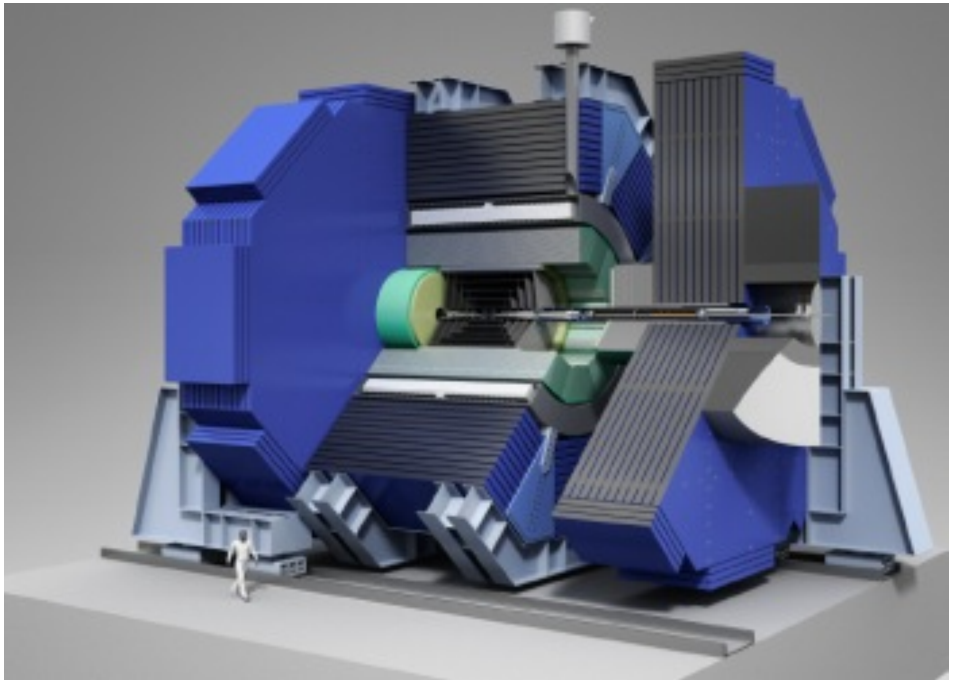




Achieved: 44 ± 3 nm @ 1.3 GeV (June 2014)
(Target beam size: 37 nm,
Equivalent to 5 nm @ 250 GeV)

ILC Detector Concepts



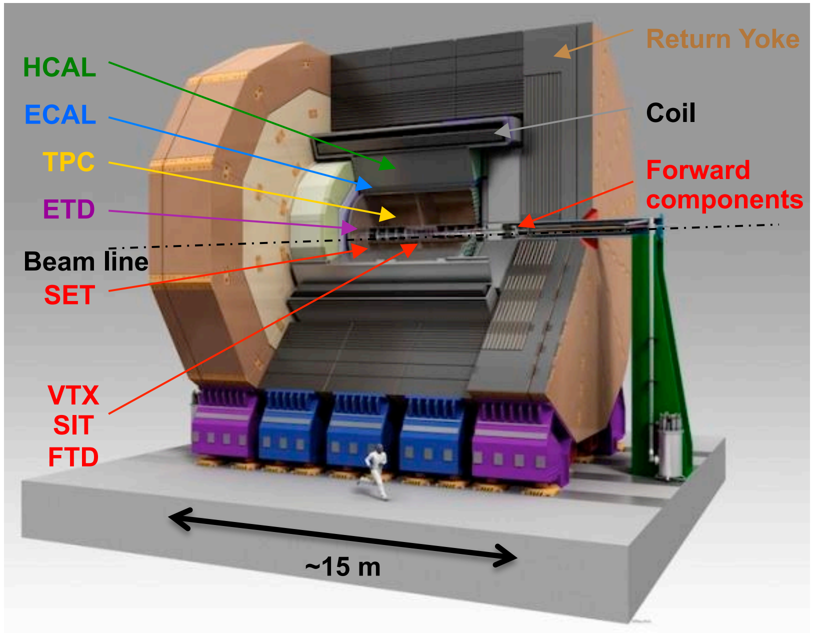


	ILD (International Large Detector)	SiD (Silicon Detector)
Height x Length	16 m x 14 m	14 m x 11 m
Weight	14,000 t	10,100 t
Magnetic field	3.5 T	5 T
ECAL inner radius	1.8 m	1.3 m
Tracker	TPC	Silicon strip

Both optimized for particle flow performance ~BR^2

ILC Detector R&D

- **Vertex Detector:** low mass pixel sensors
- **Time Projection Chamber:** high resolution & low mass
- **Calorimeters:** high granularity sensors, 5x5mm^2 (ECAL), 3x3cm^2 (HCAL); absorbers for compact showers
- **Solenoid:** outside ECAL + HCAL



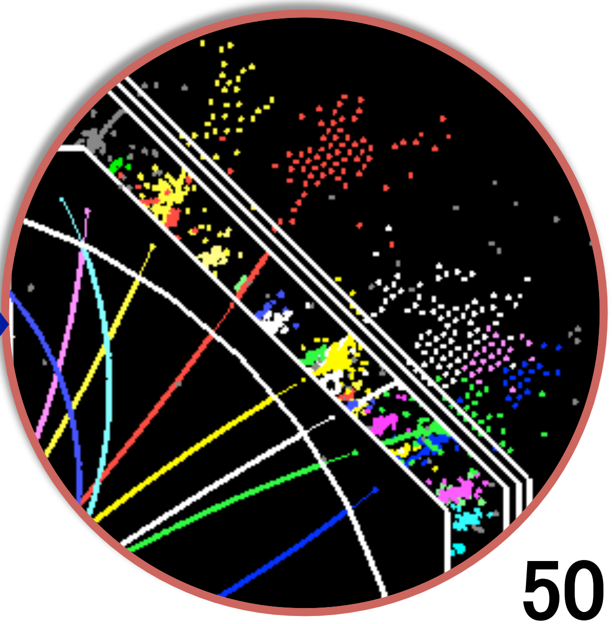
Sensor Size	ILC	ATLAS	Ratio
Vertex	5×5 mm^2	400×50 mm^2	x800
Tracker	1×6 mm^2	13 mm^2	x2.2
ECAL	5×5 mm^2 (Si)	39×39 mm^2	x61

Optimized for Particle Flow Algorithm

Identify calorimeter hits for each particle

- use *best* energy measurement for *each* particle
- offers unprecedented **jet energy resolution**

Charged Tracks → Tracker
Photons → ECAL
Neutral Hadrons → HCAL



Detector Requirements

Vertex resolution for b/c tagging

- Higgs BRs: Separation of $H \to bb, cc, gg$
- Top Yukawa: $ttH \to bWbWbb$
- Higgs self-coupling: $ZHH \to qqbbbb$

$$\sigma_{r\phi} = a\ \mu\mathrm{m} \oplus \frac{b}{p(\mathrm{GeV}) \sin^{3/2}\theta} \mu\mathrm{m}$$

	a (μm)	*b* (μm GeV)
LEP	25	70
SLC	8	33
LHC	12	70
RHIC-II	13	19
ILC	**< 5**	**< 10**

2.5x **7x LHC**

Momentum resolution for precise recoil mass

- Higgs mass, production cross section, invisible Higgs decay: $e^+e^- \to ZH \to \mu\mu H$

$$\sigma_{1/p_T} \approx 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$$

10x LHC

Jet energy resolution to separate W, Z, H

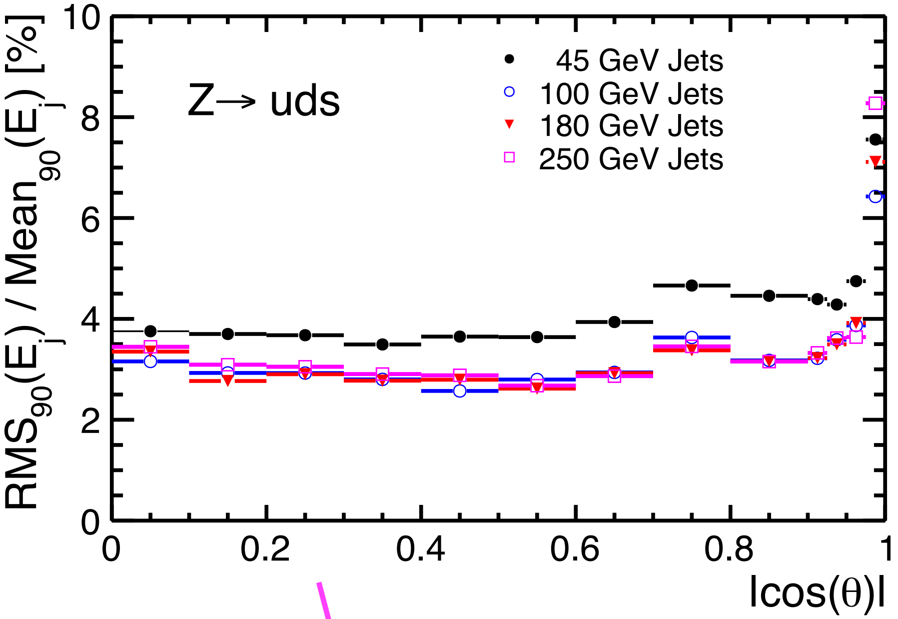
- Higgs self-coupling: ***Z/H*** separation
- SUSY: Separation of
  - $e^+ e^- \to \chi_1^+ \chi_1^- \to \chi_1^0 \chi_1^0 W^+ W^-$
  - $e^+ e^- \to \chi_2^0 \chi_2^0 \to \chi_1^0 \chi_1^0 Z^0 Z^0$
- Strong EWSB: $e^+ e^- \to \nu\nu W^+ W^-, \nu\nu Z^0 Z^0$

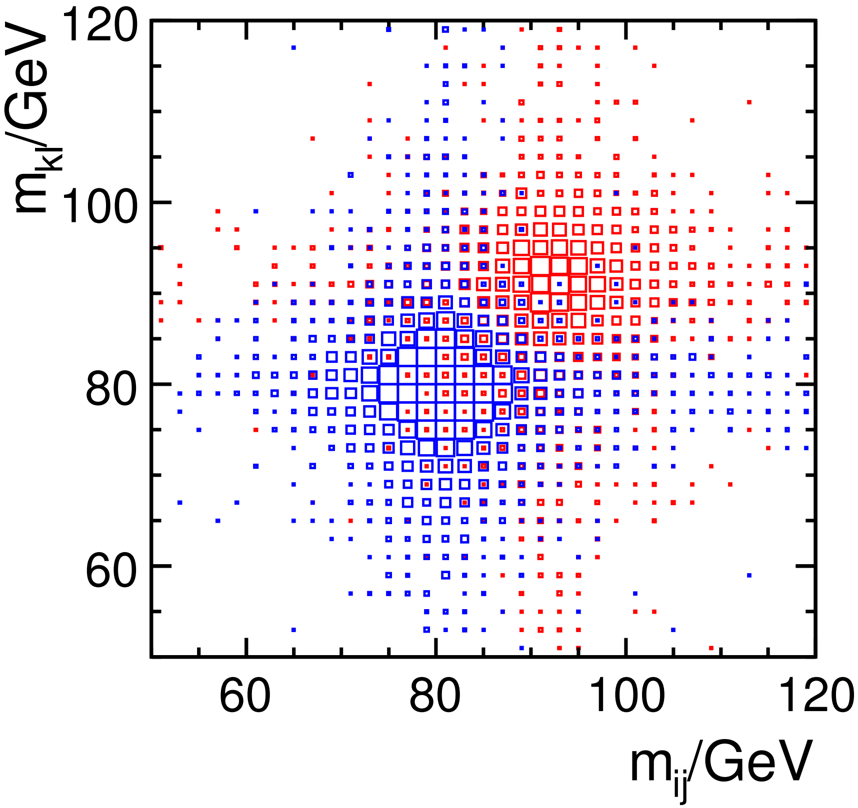
$$\frac{\sigma_{E_j}}{E_j} = \begin{cases} 0.3/\sqrt{E(\mathrm{GeV})} & \text{for } E \lesssim 100\ \mathrm{GeV} \\ 0.03 & \text{for } E \gtrsim 100\ \mathrm{GeV} \end{cases}$$

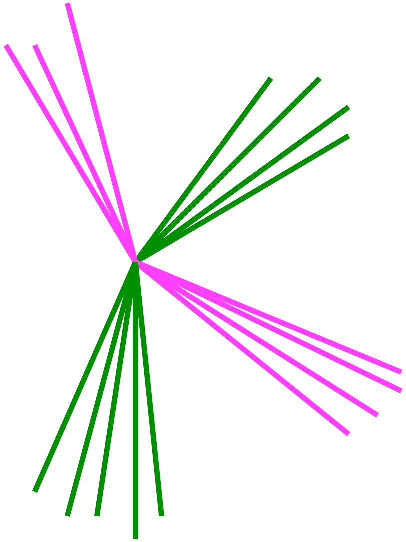
~2x LHC

Jet Energy Resolution

Full simulation ILD detector model for TDR

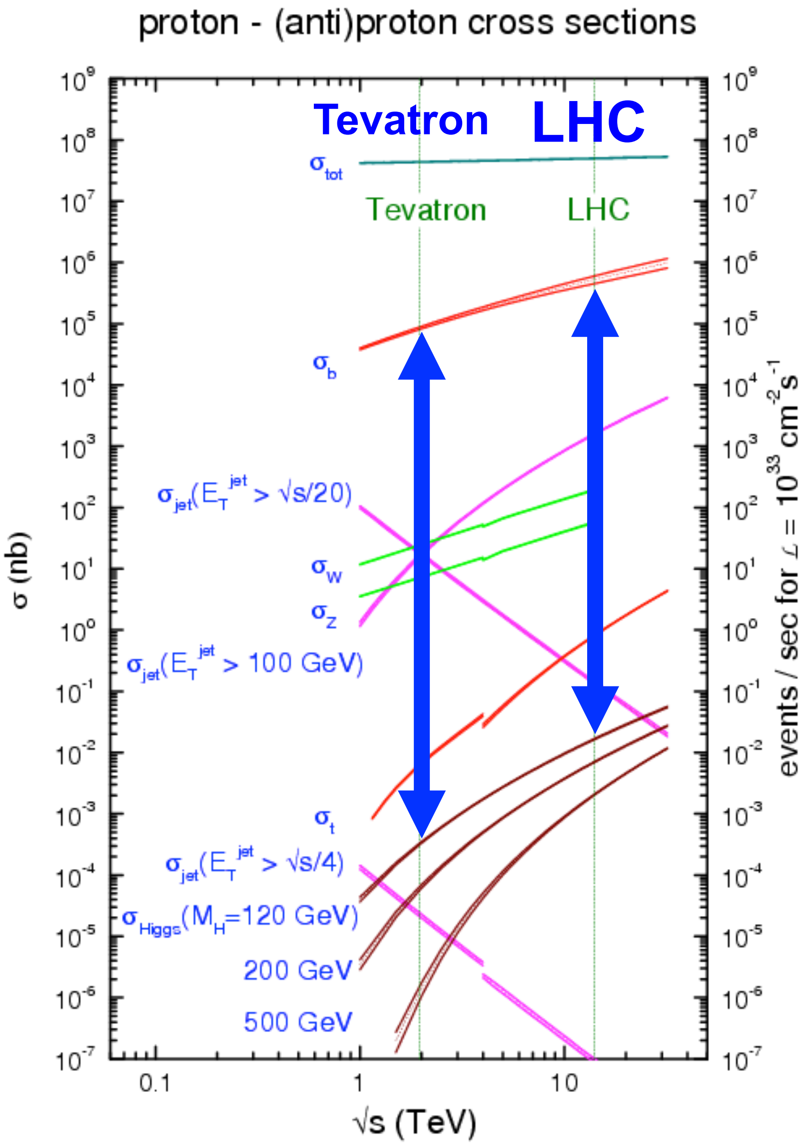






3-4% jet energy resolution
→ Good W/Z separation

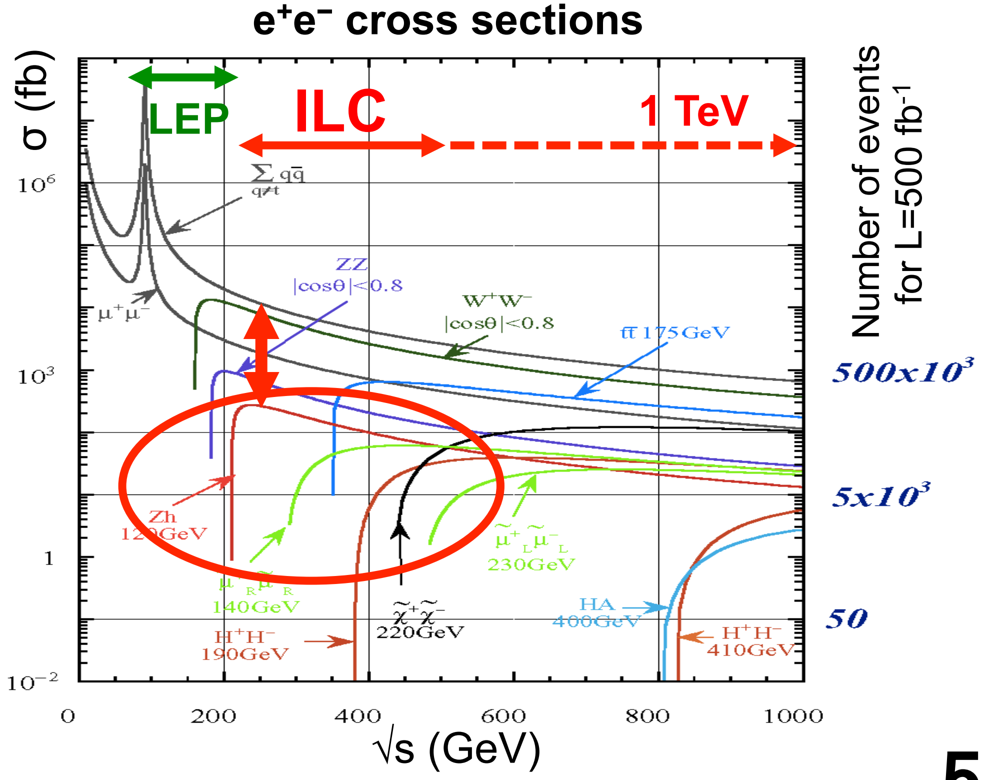
Cross Sections



Typically,

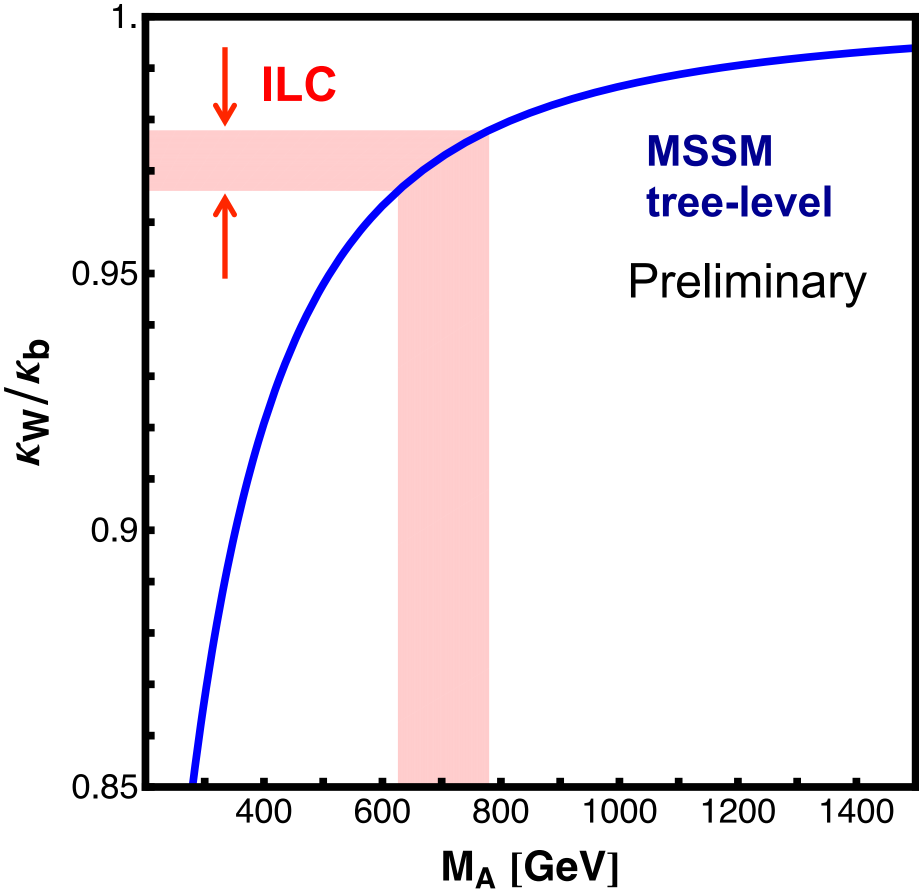
$$N_{\rm sig}^{pp} > N_{\rm sig}^{e^+e^-}$$

$$N_{\rm bkg}^{pp} \gg N_{\rm bkg}^{e^+e^-}$$



Heavy Higgs Predictions

If deviations in Higgs couplings consistent with an extended Higgs sector are found, the heavy Higgs mass can be predicted from the size of the deviation. Here we give an example based on the MSSM.



The effect of the multiple Higgs fields manifests as deviations in Higgs couplings of the lightest (SM-like) Higgs boson.

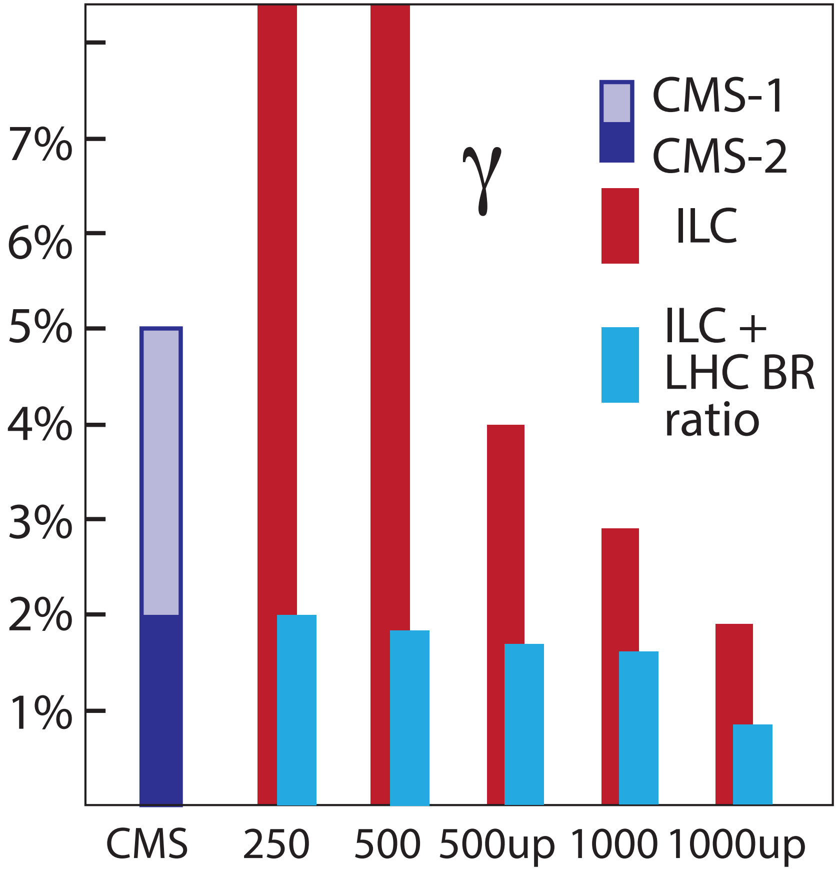
The size of the deviations depends on the mass of the heavy Higgs (MSSM)

The mass of the heavy Higgs can be predicted with precise Higgs measurements at the ILC

n.b. systematic uncertainties are suppressed by taking the ratio of the couplings.

Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV

Improving hγγ coupling precision



M. Peskin, arXiv:1312.4974

Beautiful example of LHC/ILC synergy

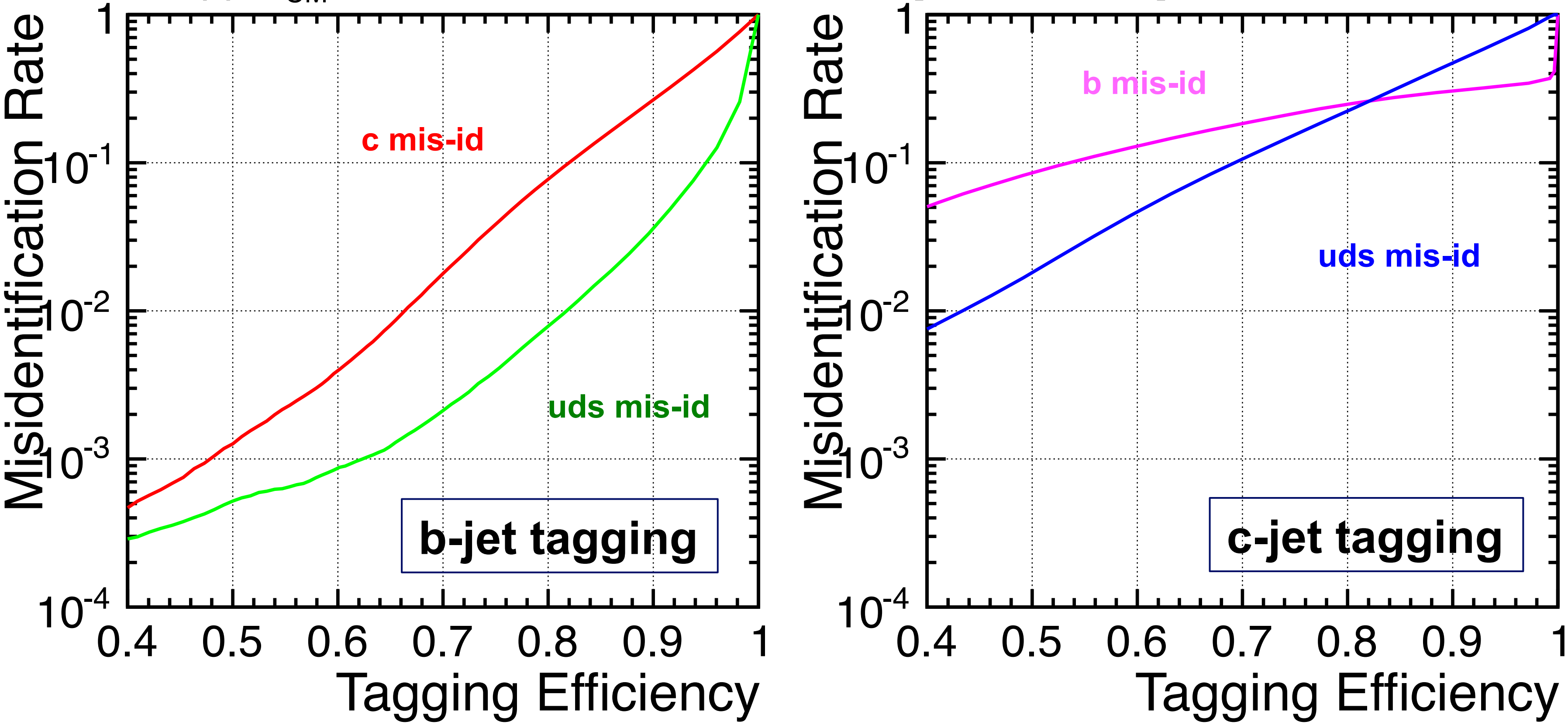
Combine:

1. HL-LHC g(hγγ)/g(hZZ)
2. ILC g(hZZ)

(both model-independent)

→ Precise model-independent measurement of g(hγγ) !

Higgs Hadronic Decays: Flavor Tagging

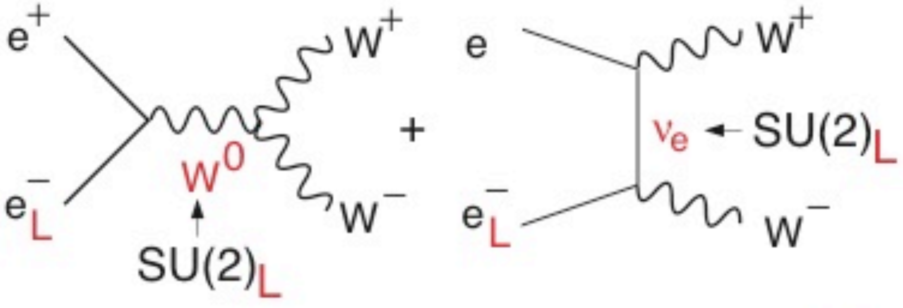

Z→qq, E_{CM}=91.2 GeV, ILD Full Simulation [Suehara, TT]

ILC detectors allow high performance b/c/g tagging
Precise measurement of BR(H→bb, cc, gg)

Power of Beam Polarization

[Fujii]

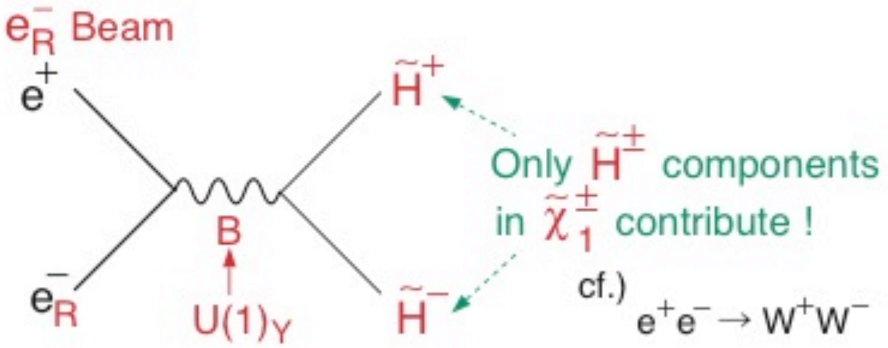
W^+W^- (Largest SM BG)



In the symmetry limit, $\sigma_{WW} \to 0$ for e^-_R !

BG Suppression

Chargino Pair

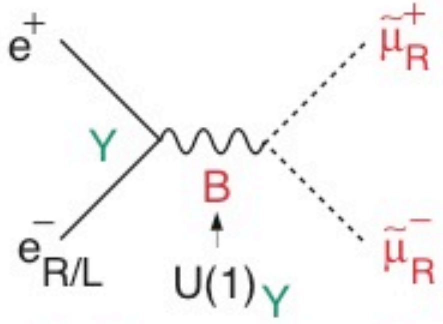


$$\tilde{\chi}^\pm_1 = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$$

$$\bullet = \langle \tilde{H}^\pm | \tilde{\chi}^\pm_1 \rangle$$

Decomposition

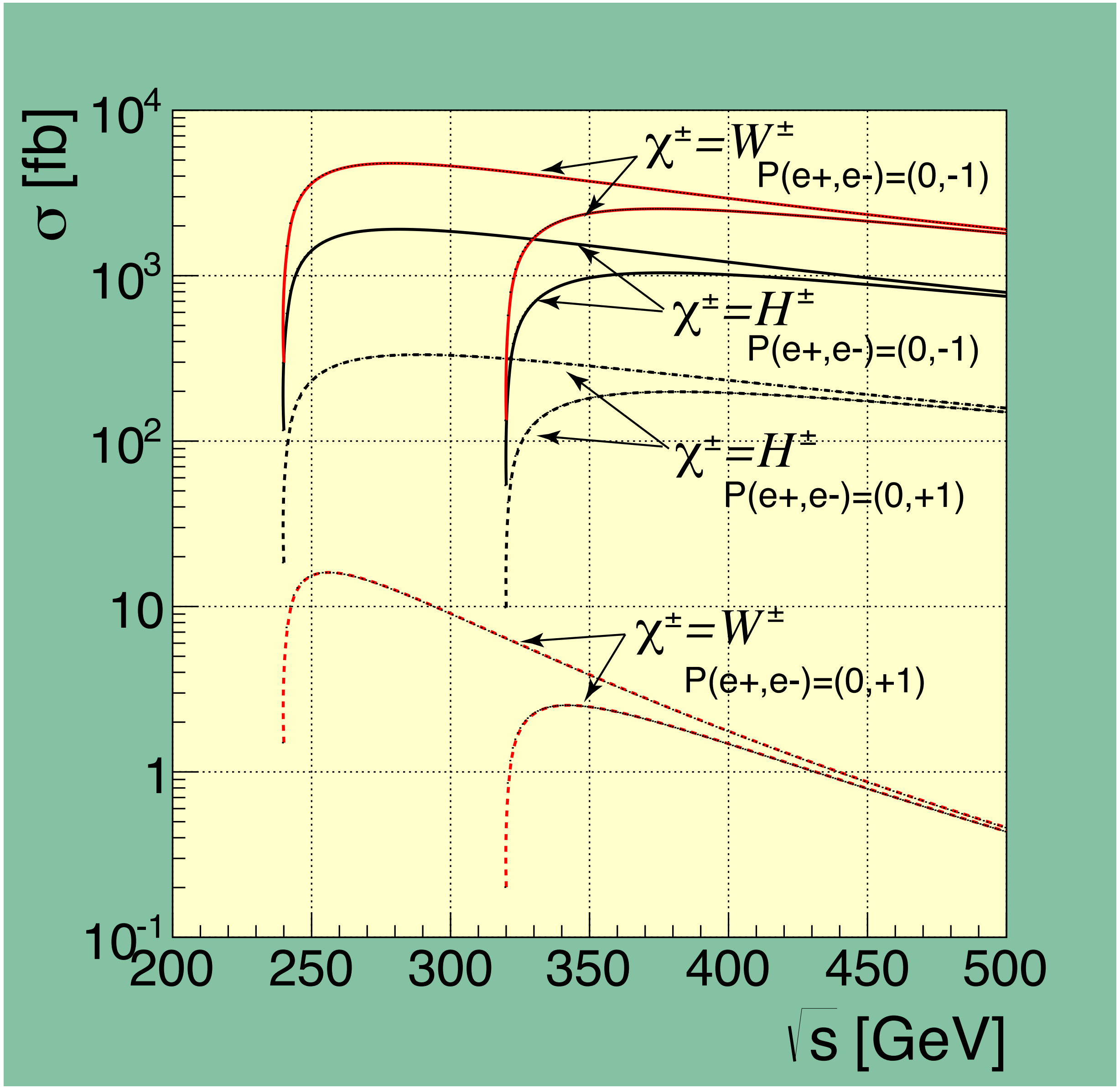
Slepton Pair



$$\begin{cases} Y_L = -1/2 : e^-_L \\ Y_R = -1 \quad : e^-_R \end{cases}$$

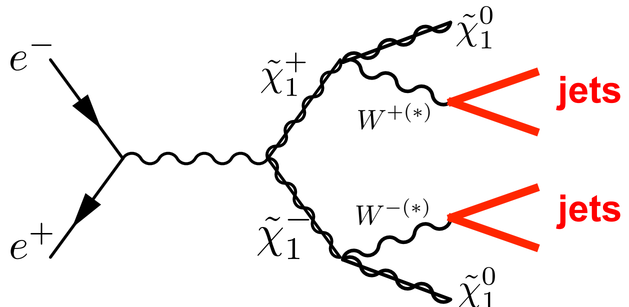
In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

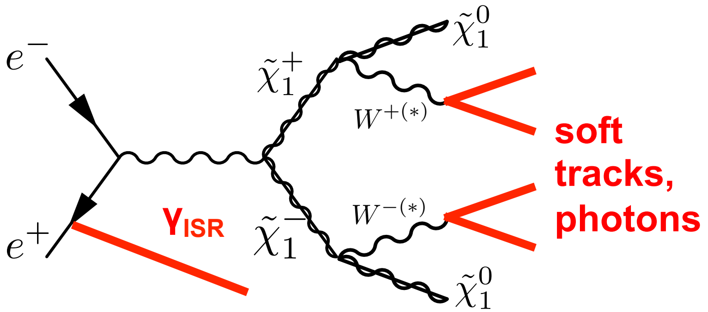
Signal Enhancement

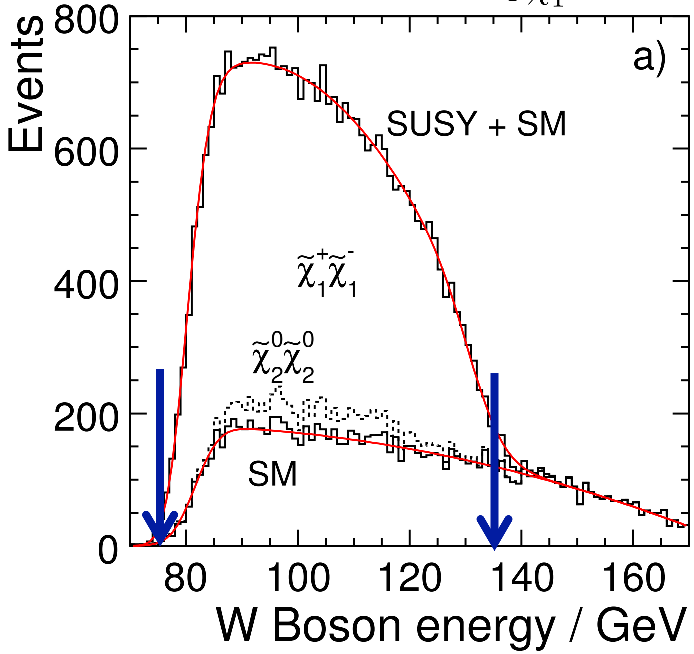

σ [fb]
10^4
10^3
10^2
10
1
10^{-1}
200
250
300
350
400
450
500
$\sqrt{s}$ [GeV]
$\chi^{\pm}=W^{\pm}$ P(e+,e-)=(0,-1)
$\chi^{\pm}=H^{\pm}$ P(e+,e-)=(0,-1)
$\chi^{\pm}=H^{\pm}$ P(e+,e-)=(0,+1)
$\chi^{\pm}=W^{\pm}$ P(e+,e-)=(0,+1)

Fujii

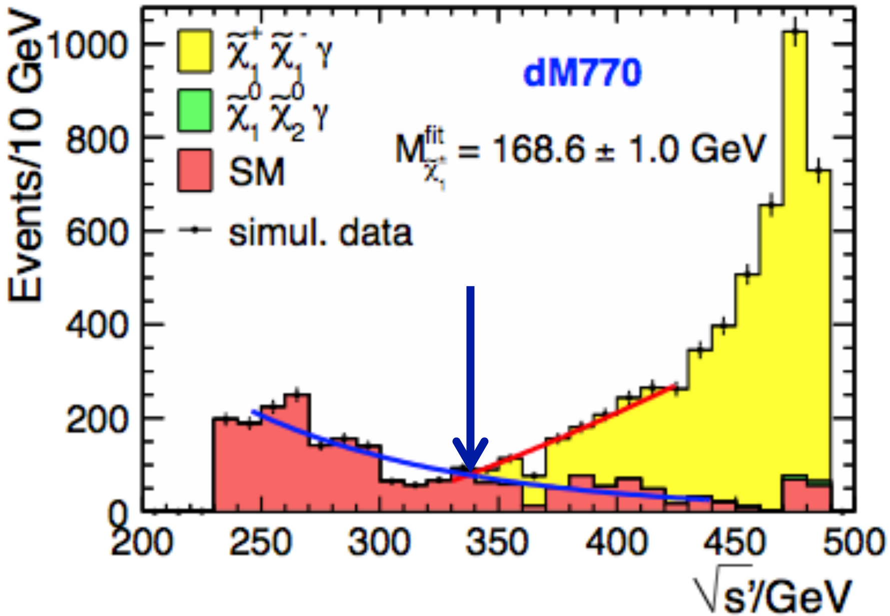
SUSY Precision Measurements







Suehara, List, arXiv:0906.5508



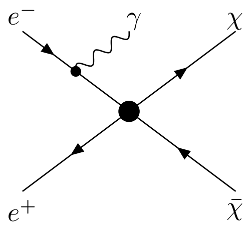
Berggren, Bruemmer, List, Moortgat-Pick, Robens, Rolbiecki, Sert, EPJ C73 (2013) 2660 [arXiv:1307.3566]

Mass determination via kinematic edges

Large mass differences between chargino/neutralino; decays to jets.
O(1)% mass precision

Small mass differences between chargino/neutralino; ISR photon tag.
O(1)% mass precision

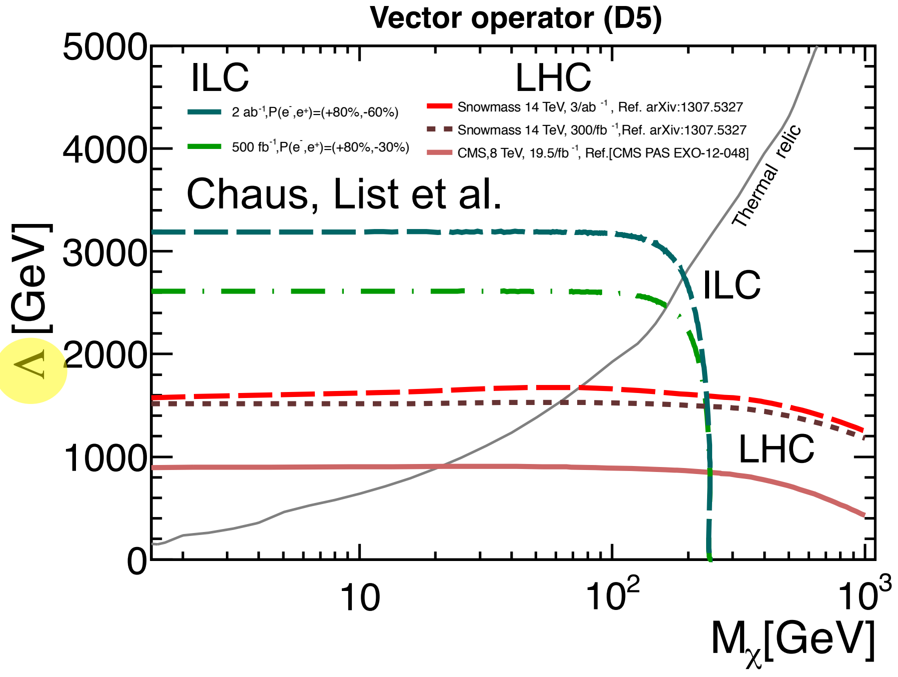
DM: Effective Operator Approach

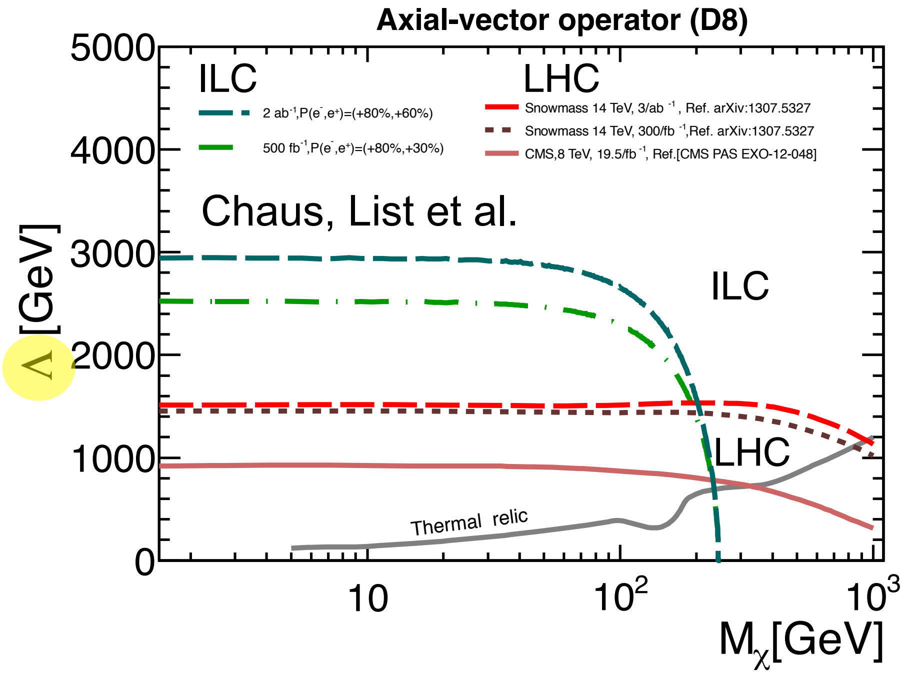


$$\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^2}\mathcal{O}_i$$

$$\mathcal{O}_V = (\overline{\chi}\gamma_\mu\chi)(\overline{\ell}\gamma^\mu\ell)$$

$$\mathcal{O}_A = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{\ell}\gamma^\mu\gamma^5\ell)$$


Vector operator (D5)


Axial-vector operator (D8)

LHC sensitivity: Mediator mass up to Λ~1.5 TeV

ILC sensitivity: Mediator mass up to Λ~3 TeV for DM mass up to ~√s/2