International Linear Collider

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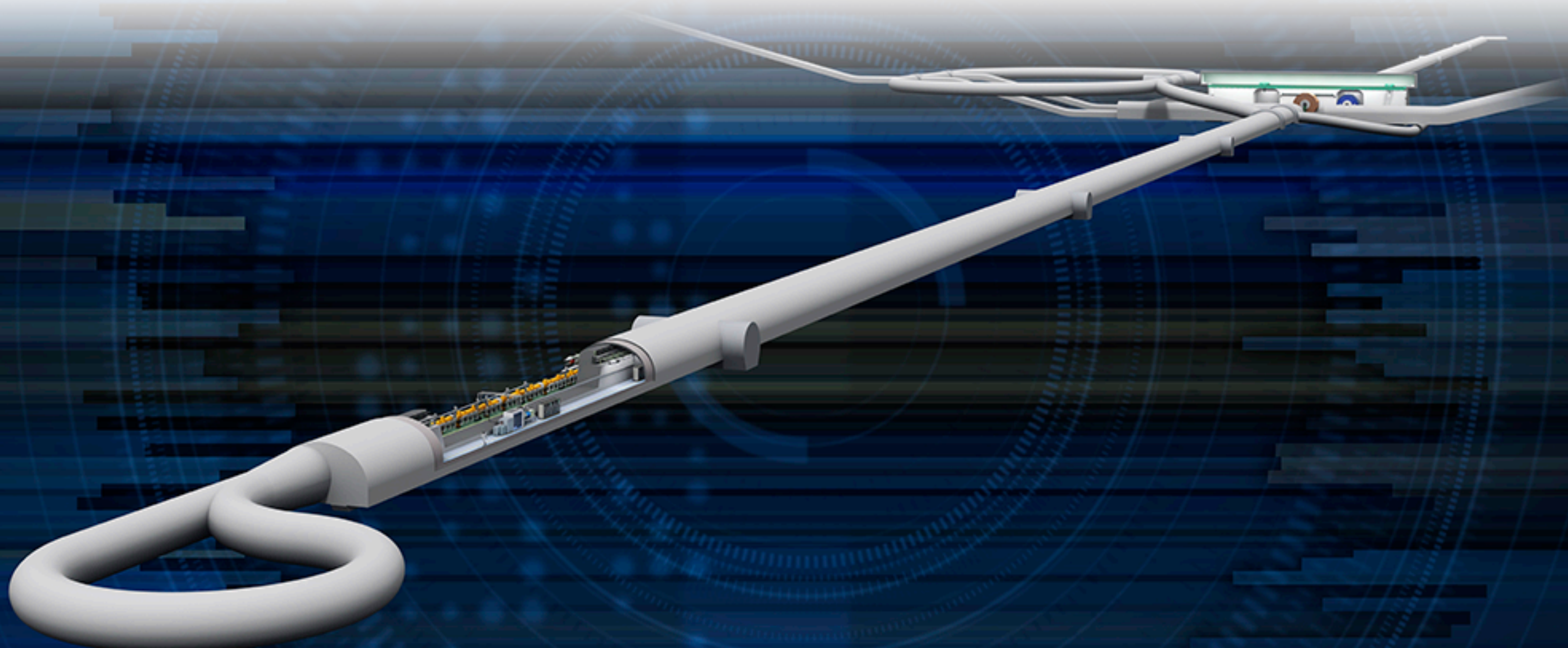
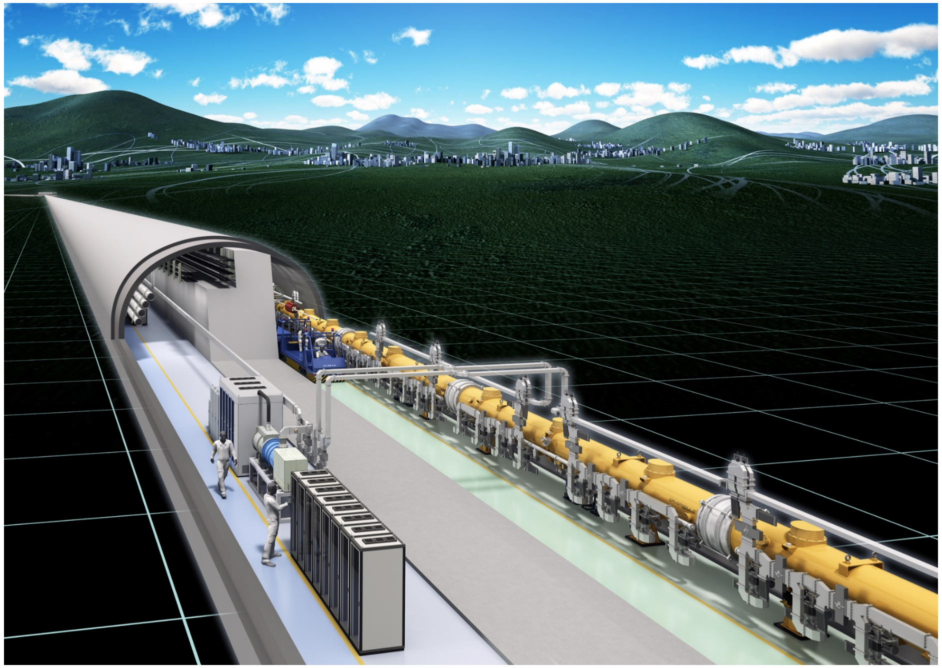
July 15, 2016

PASCOS 2016, XIIth Rencontres du Vietnam, ICISE, Quy Nhon, Vietnam

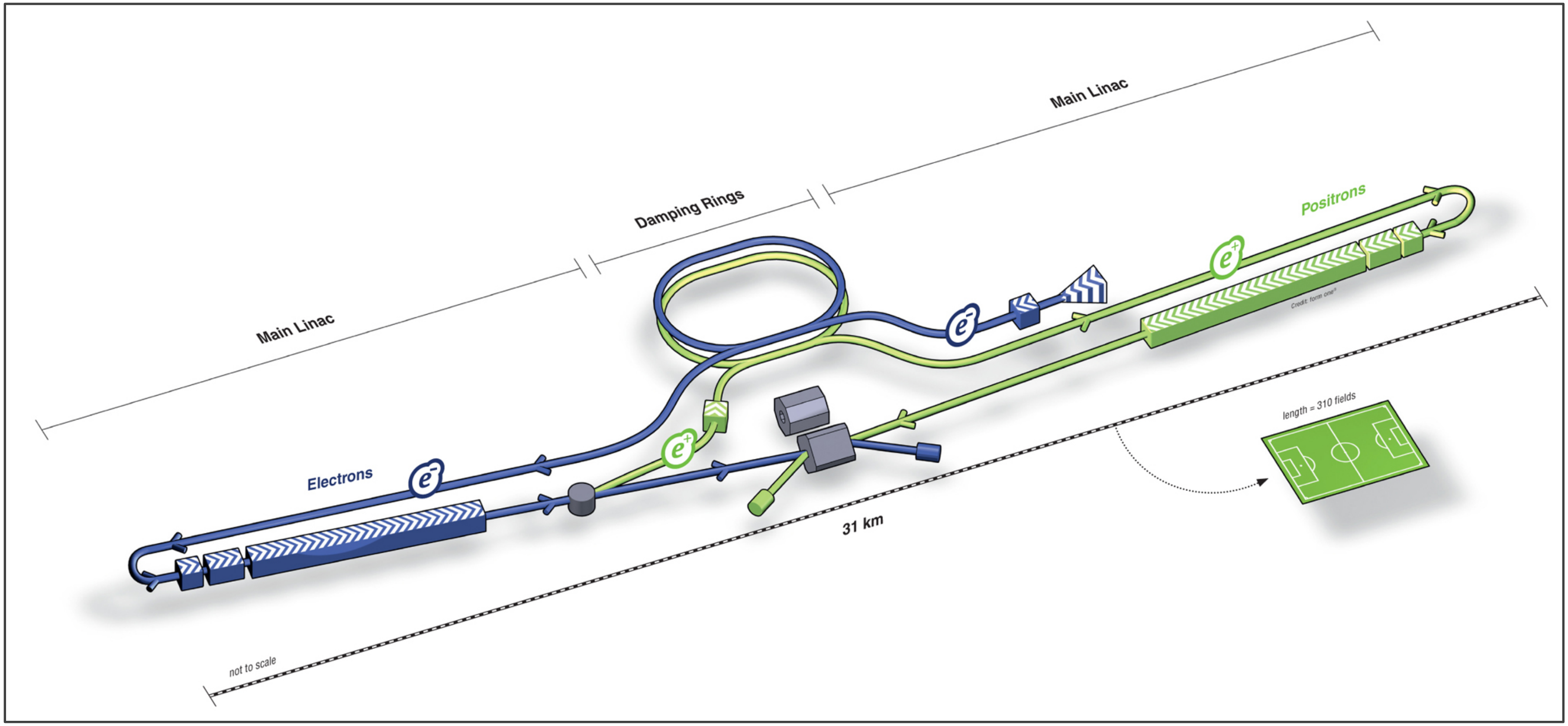


Outline

- **ILC Project Status**
  - Overview
  - News on political situation
  - Accelerator Technology
- **Physics Highlights**
  - Higgs
  - Top
  - Dark Matter
  - SUSY



ILC in a nutshell

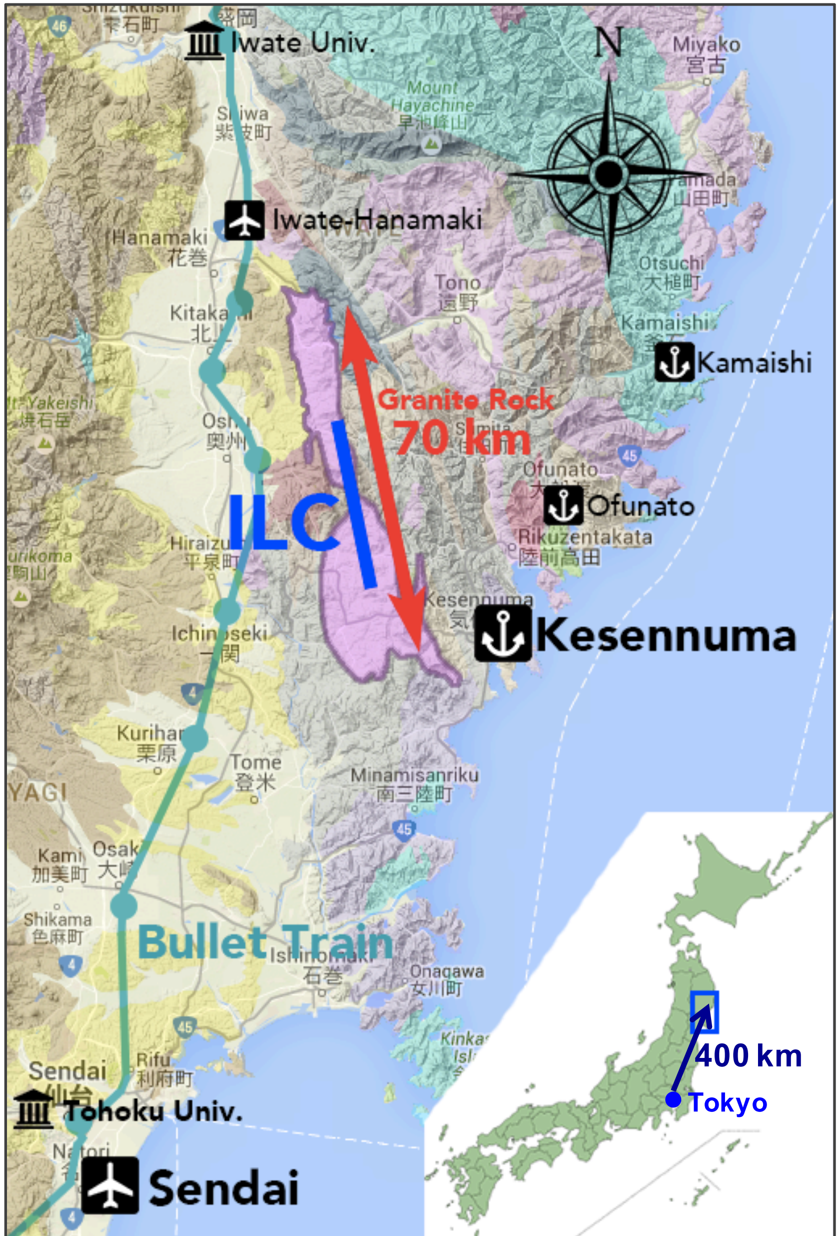


- **e+e- collisions at √s= 200…500 GeV (34 km tunnnel)**
  - ➢ Upgradable to 1 TeV (50 km)
  - ➢ Beam energy tunable
- **Luminosity at 500 GeV: 1.8 x 10^{34} c^{-2} s^{-1}**
  - ➢ Upgrade to 3.6 x 10^{34} cm^{-2} s^{-1}
- **Beam polarization: P(e^-) ≥80%, P(e^+) = 30%**
  - ➢ P(e^+) upgradable to 60%

TDR (2012)

Candidate Site

Selected by an international panel of scientists



North-eastern Japan: Kitakami Mountains

Access via train (Tokyo→Ichinoseki): 2.5h

Earthquake-proof, stable granite bedrock
Can accommodate up to 70 km tunnel
(c.f. 34 km for 500 GeV ILC)

Engineering design in progress

View of the Kitakami mountains

Oshu City

Ichinoseki Station

Morioka

Tohoku tourism ad seen on Tokyo Metro

Posters and "Toy ILC" by school children of Oshu City welcoming international workshop on ILC

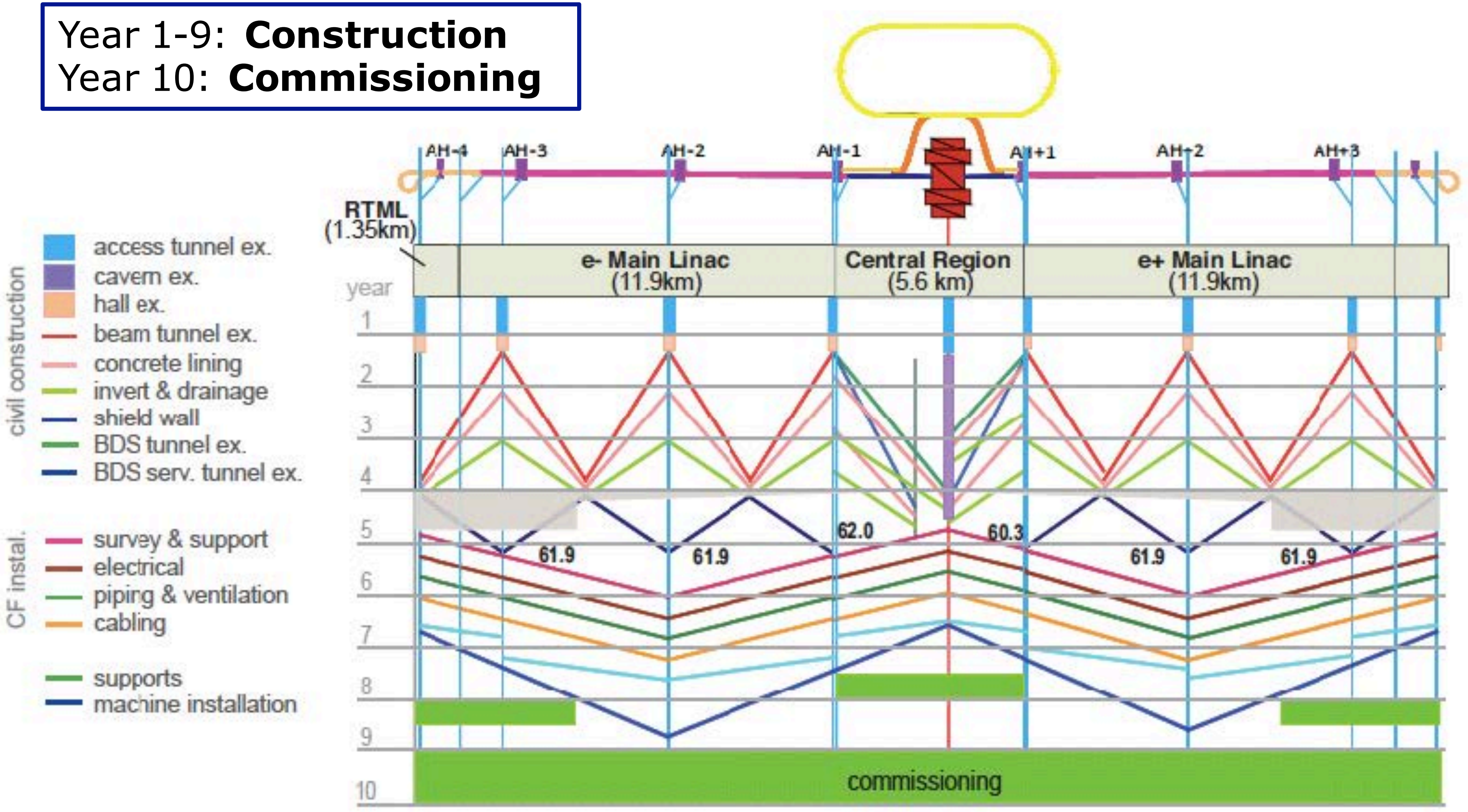
Summary of ILC Project in Japan
[most recent news]

- Strong support from: **Politicians**, **Industry**, and **Local Governments**
- **Review by MEXT** (Japanese ministry on education/S&T/etc.) is ongoing, following the recommendation of the Science Council of Japan
  - **Interim report by MEXT's ILC Advisory Panel (June 2015):** discussions with other countries at the government level are indispensable; LHC results (~2017) should be monitored closely and taken into account
  - Ongoing effort to increase understanding at higher level of Japanese government
- **US-Japan inter-governmental discussion** is in progress: Collaboration framework in science and technology, including ILC, is being established
  - **New (May 2016)**: **MEXT-DOE Joint Discussion Group on ILC**
  - Discussions will be expanded to European and Asian countries

Construction Schedule

after groundbreaking

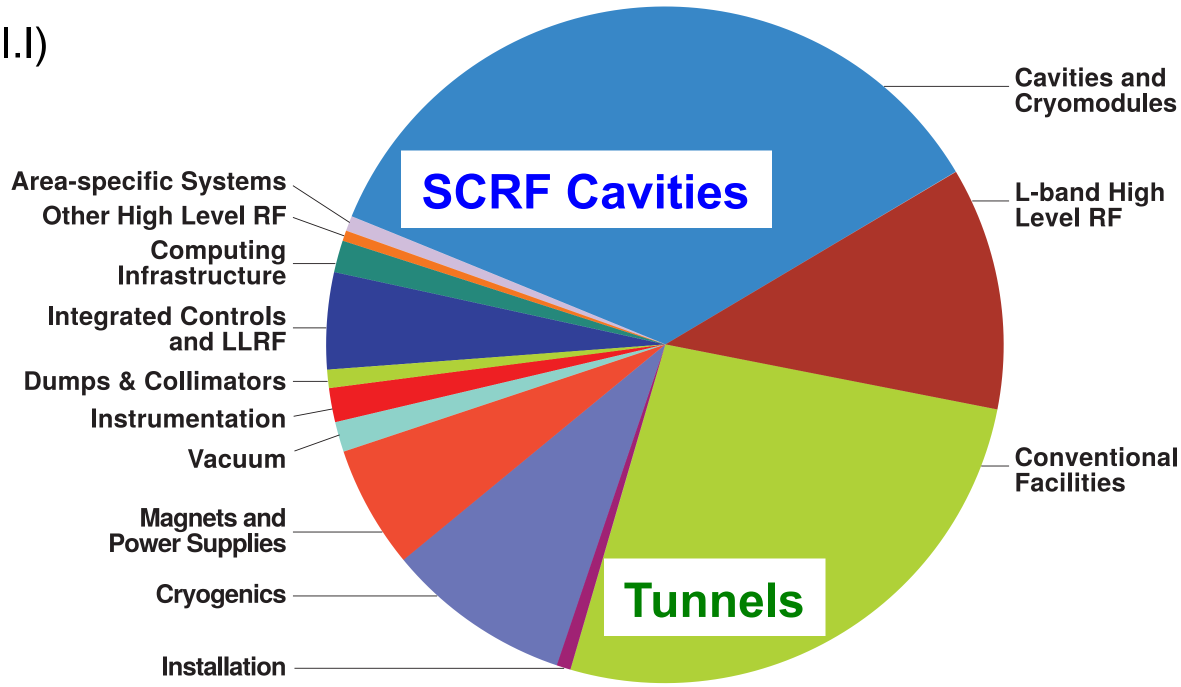
Year 1-9: **Construction**
Year 10: **Commissioning**



Construction Cost

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

(ILC TDR, Vol.I)



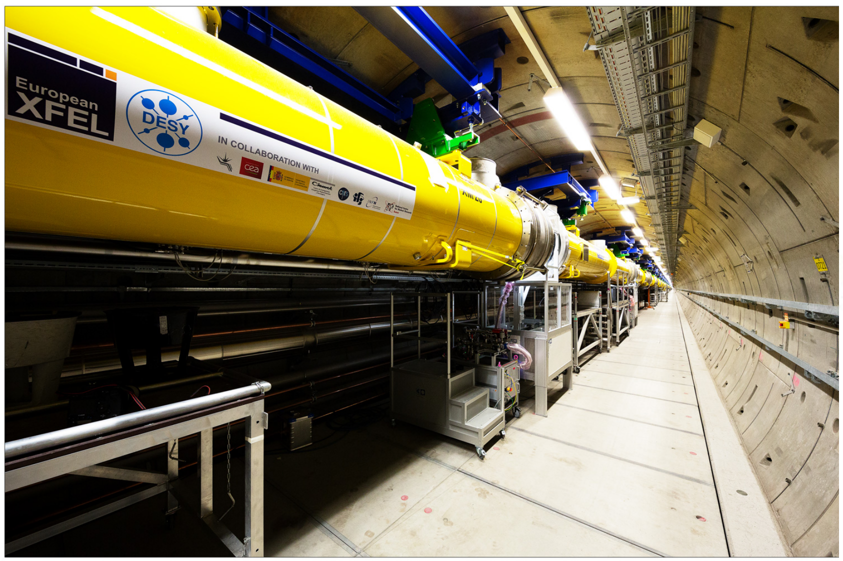
- **Estimated 7.8 billion US$ (2012)**
  - For baseline 500 GeV ILC, averaged over three regions (not including HR / contingencies)
  - Currently being refined by engineering design
- **"Guideline:" host country to pay half the construction cost**

Superconducting RF Cavities

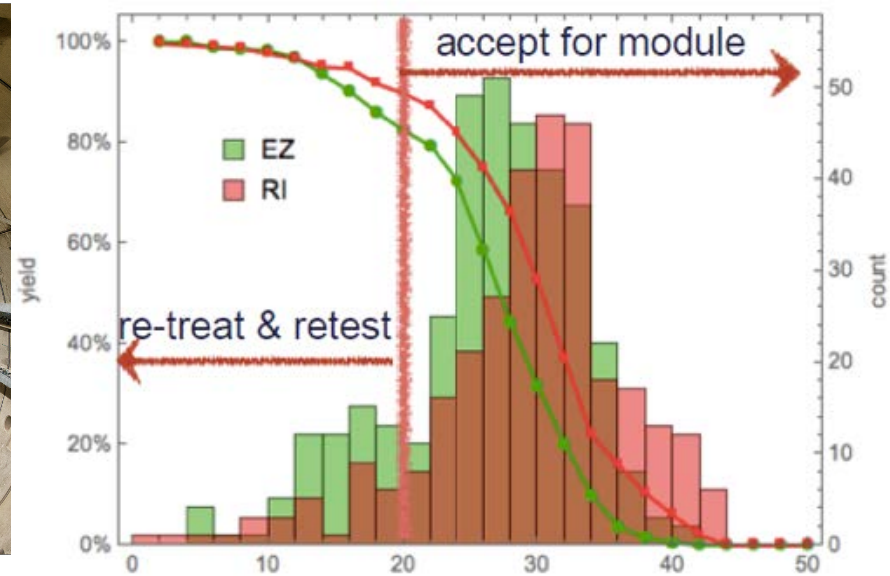
Key technology for ILC
Requires high gradient:
31.5 MV/m (±20%)

~16,000 cavities needed for ILC

European XFEL (DESY) in commissioning
"10% prototype of one ILC linac"



XFEL cavities "as received"

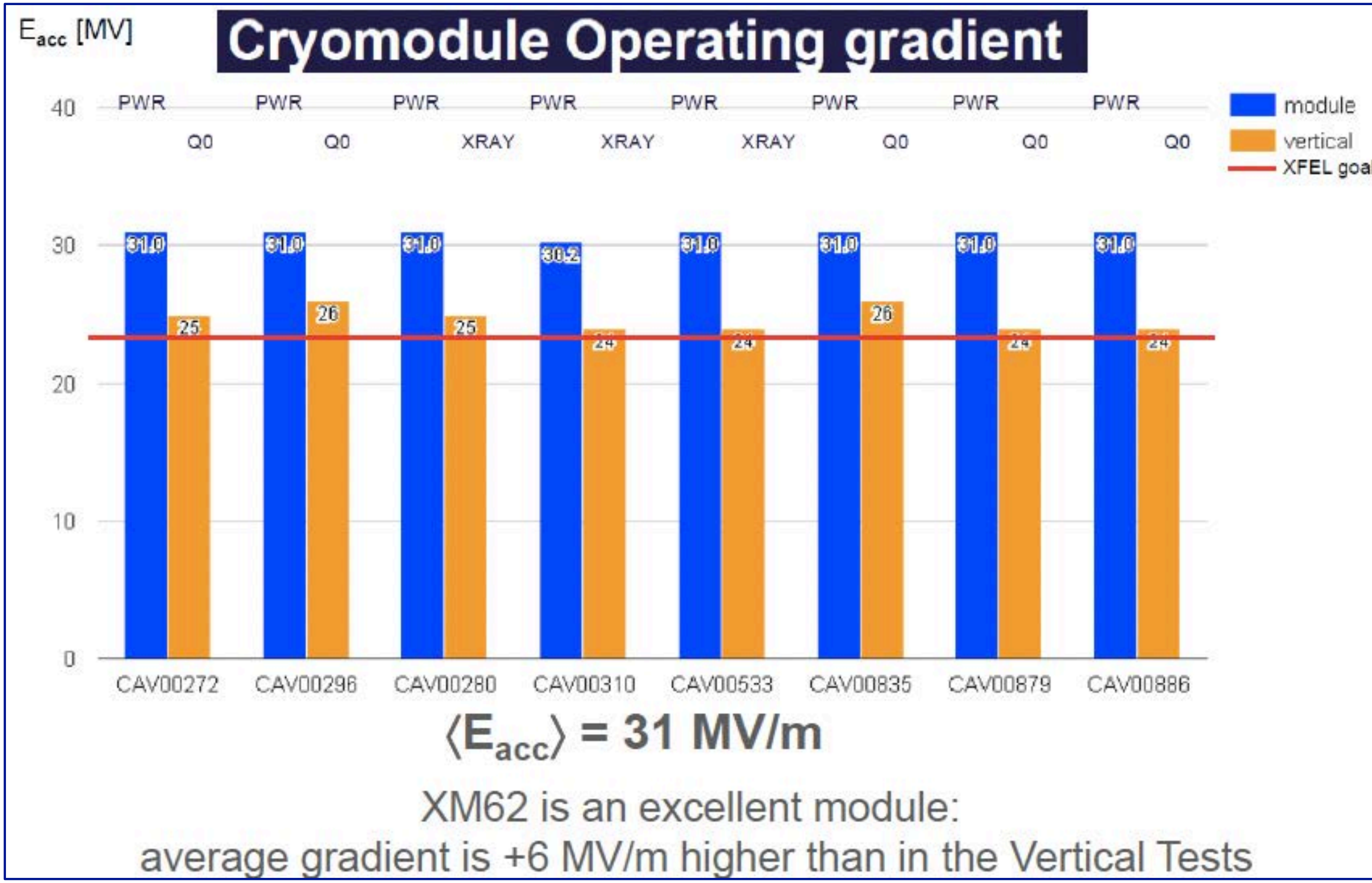


Average usable gradient after rinsing: **30 MV/m**

<u>Successful demonstration of mass production of ILC cryomodules</u>

LCLS-II (SLAC) is also under construction.

ILC-grade cryomodules in XFEL

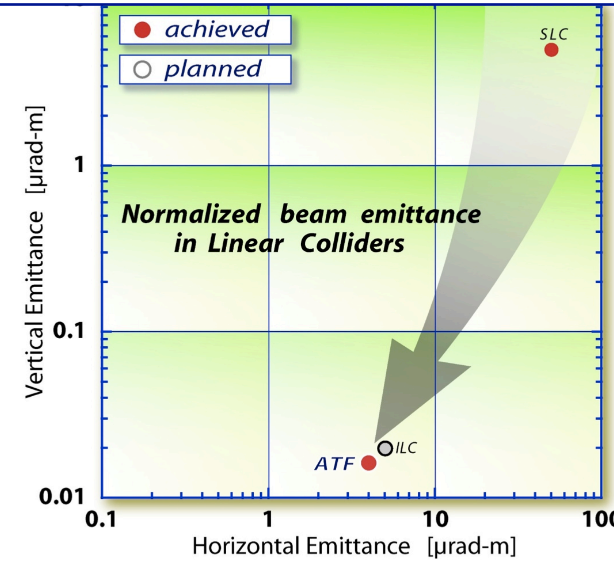


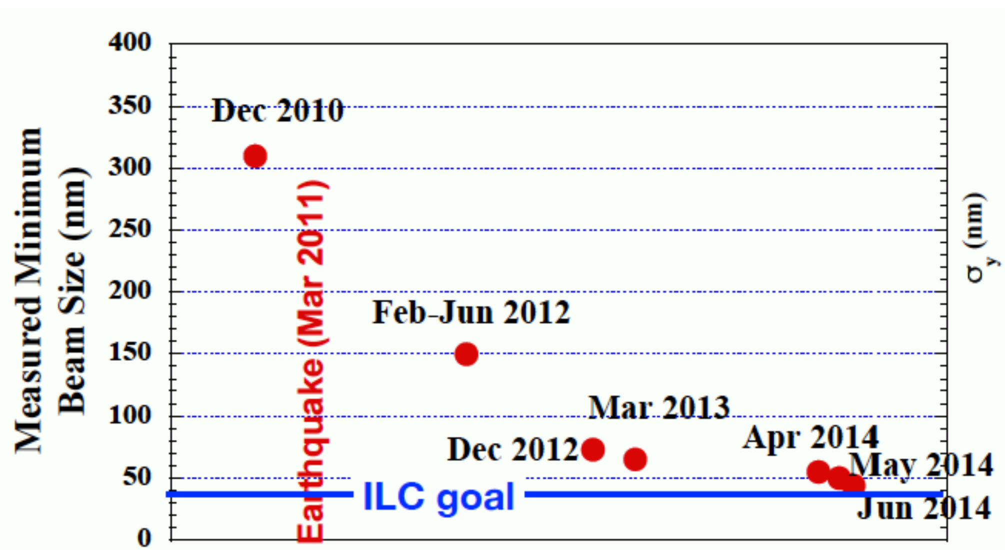
31MV/m only limited by test stand

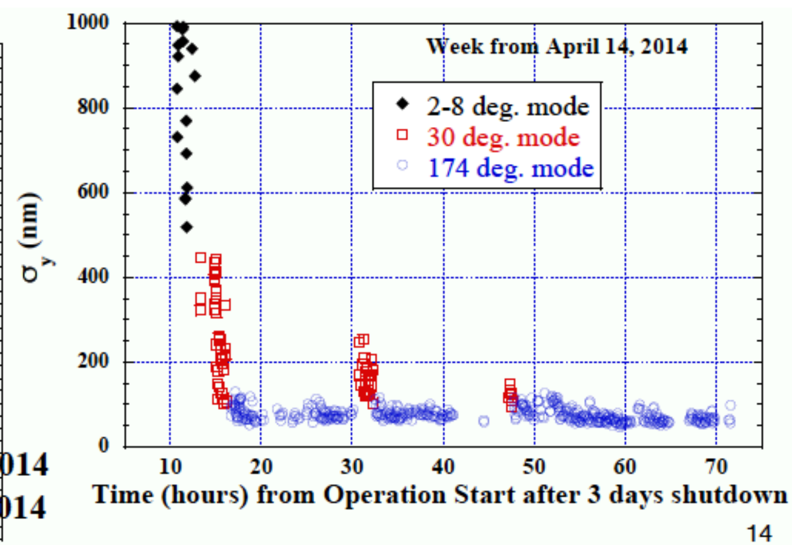
Final Focus @ ILC

ATF2 Test Facility at KEK

Target beam emittance achieved

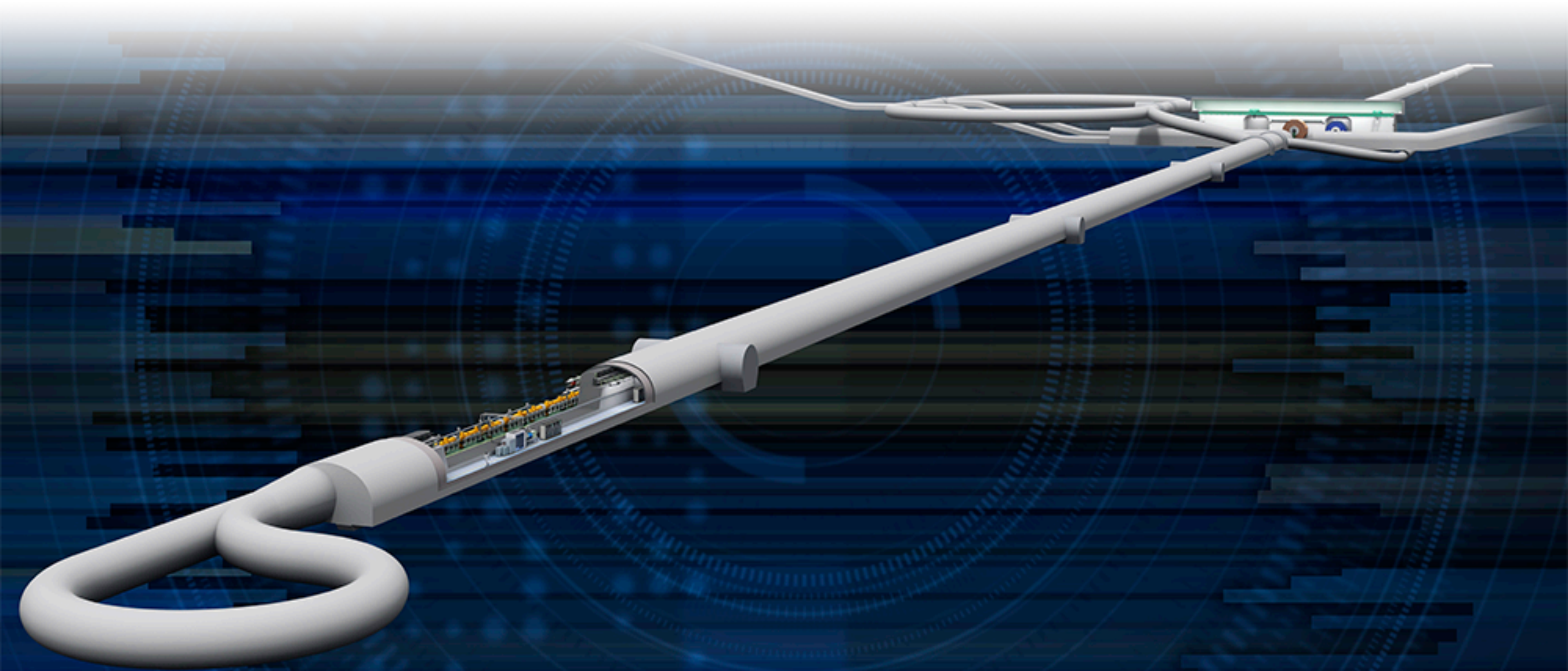






Target beam size achieved routinely (5nm@ILC → 37nm@ATF2)

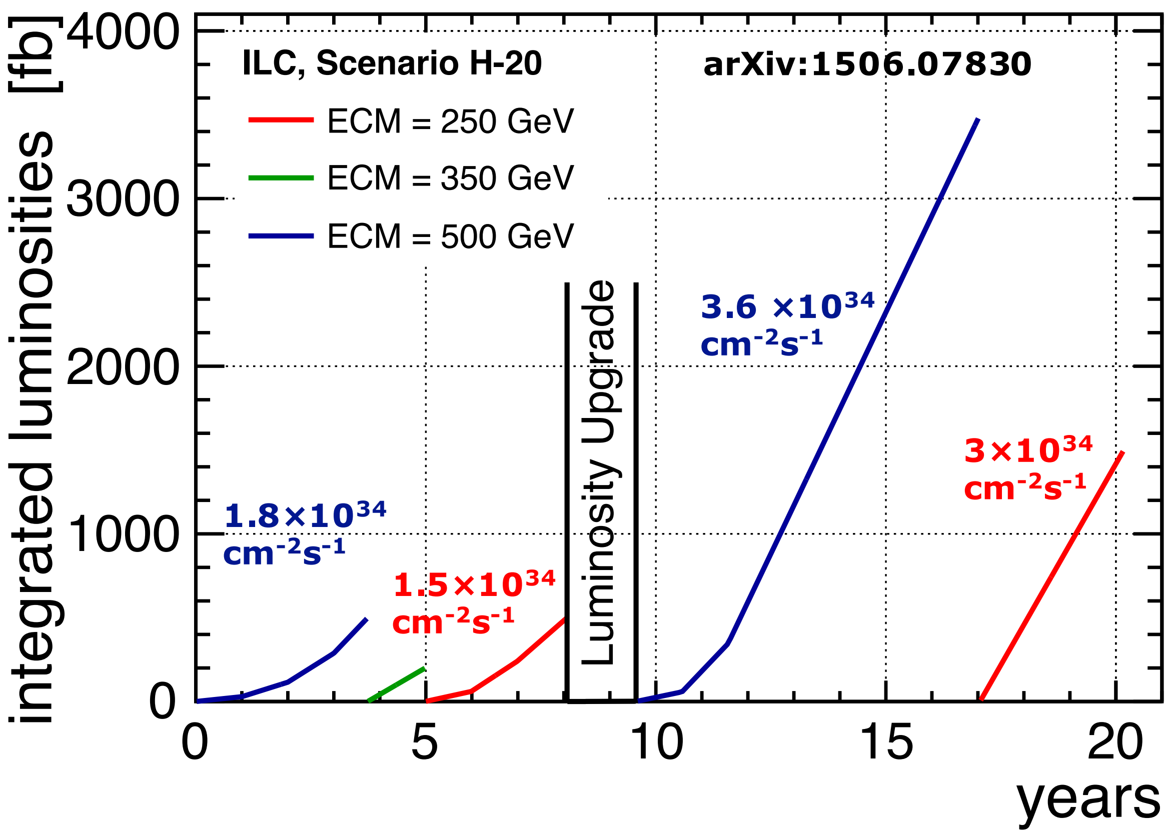
ILC Physics Highlights



A 20 Year Running Scenario for the ILC

- **500 GeV:** General purpose Higgs & top physics,
  Higgs self-coupling, top Yukawa, BSM
- **350 GeV:** Top threshold scan
- **250 GeV:** Dedicated Higgs measurements (mass, CP, …)

Integrated Luminosities [fb]



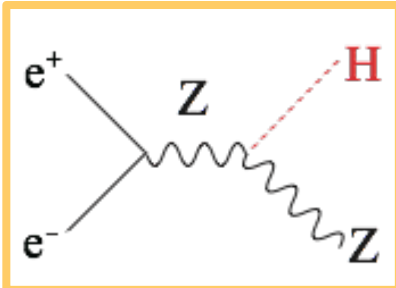
Total integrated luminosities:

$\sqrt{s}$	$\int \mathcal{L}\, dt$
250 GeV	2000 fb^{-1}
350 GeV	200 fb^{-1}
500 GeV	4000 fb^{-1}

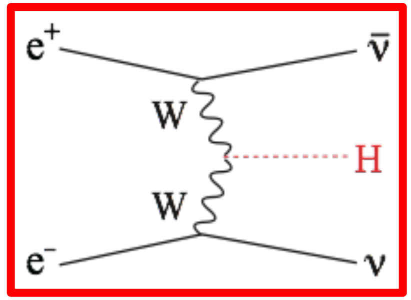
Refer to this as full ILC500 program

Actual profile will depend on new physics, funding, and other projects

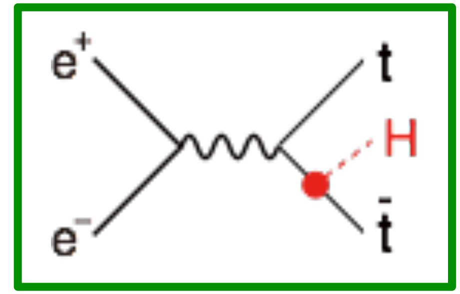
Higgs Production



ZH: √s ≥250 GeV

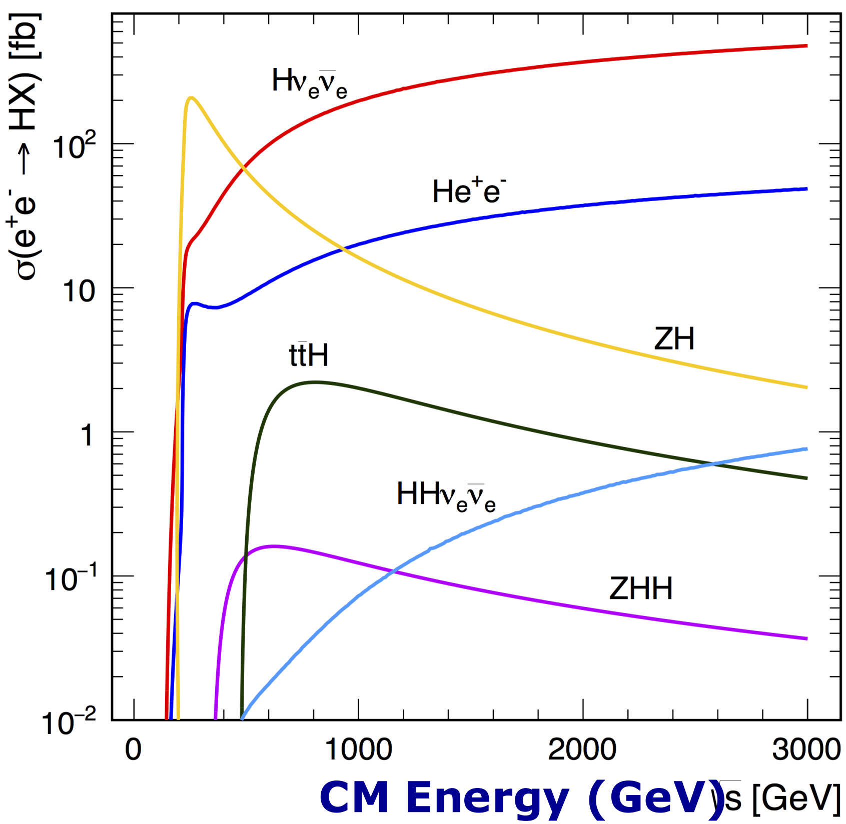


vvH: √s ≥350 GeV

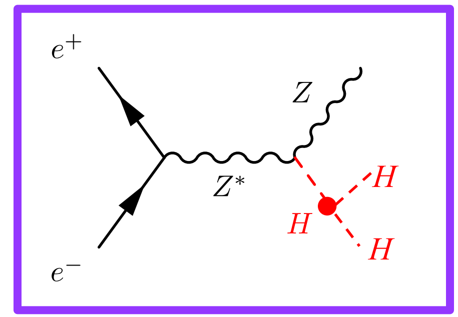


ttH: √s ≥500 GeV

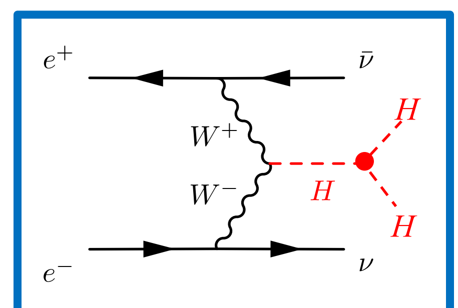
Cross section



CM Energy (GeV)



ZHH: √s ≥500 GeV



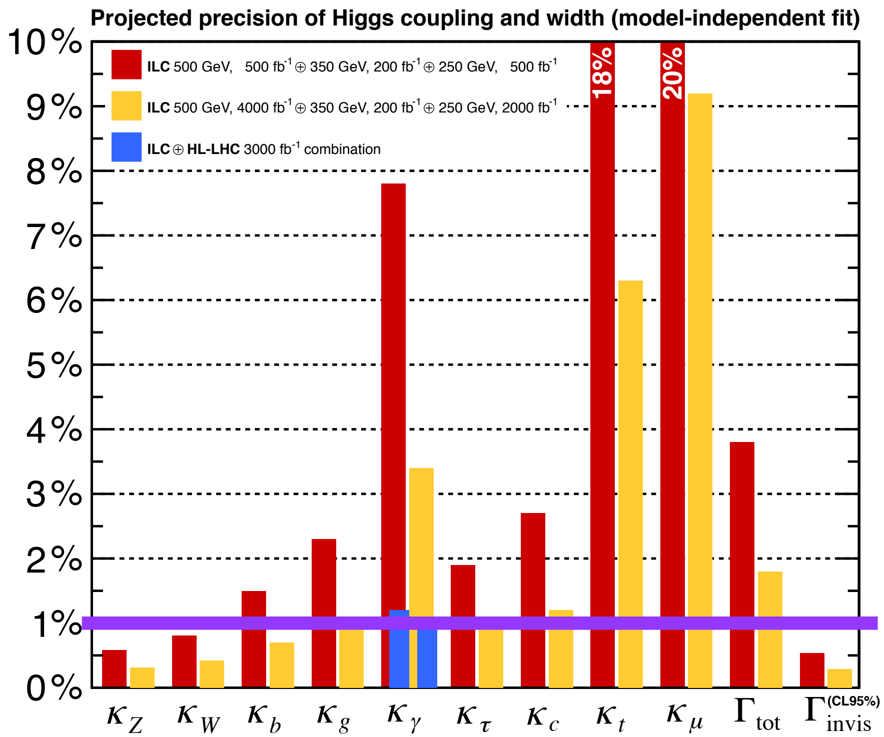
vvH: √s ≥1 TeV

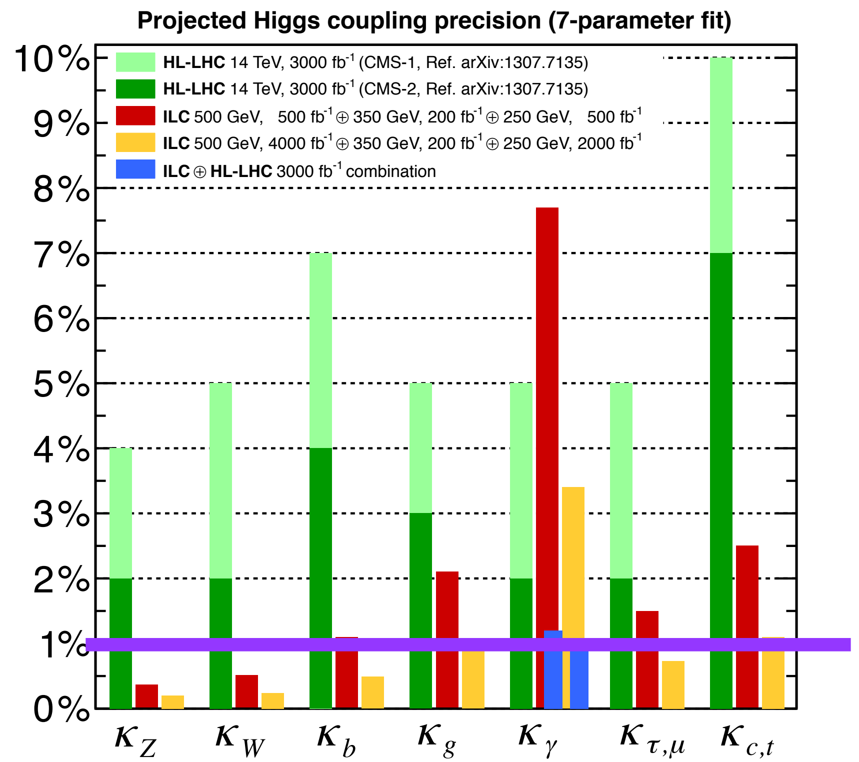
Higgs Couplings

Model-Independent:
Only possible at e+e-

Model-Dependent:
Compare with LHC

Including systematic uncertainties [arXiv:1506.05992]

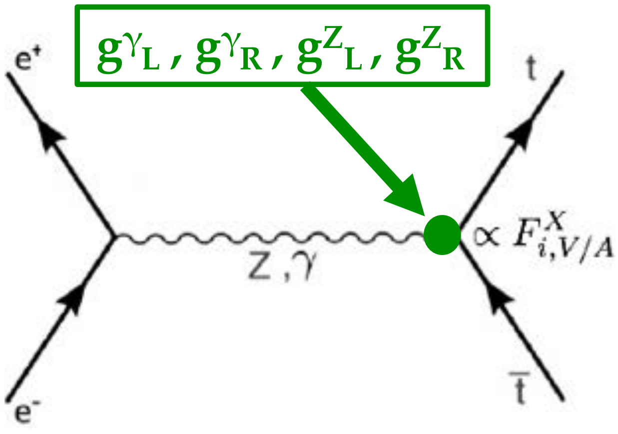


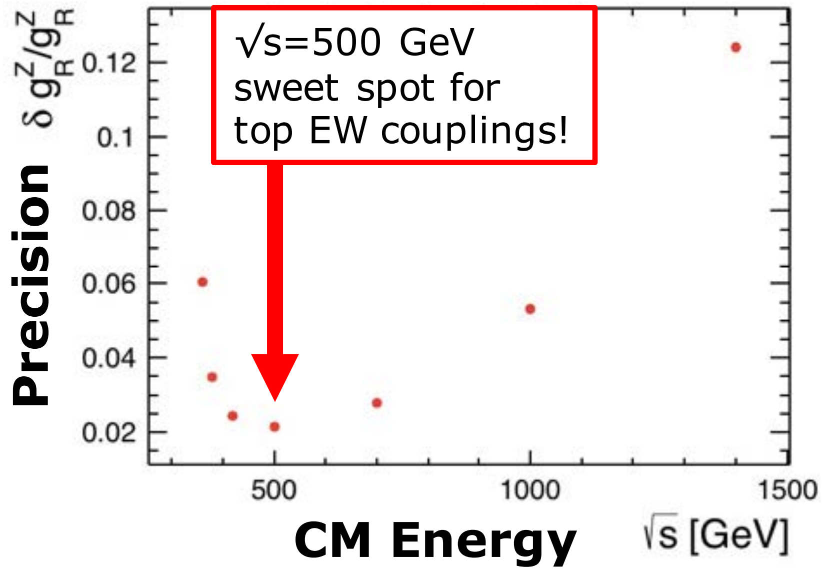


Sub-percent precision on most Higgs couplings with full ILC500 program

Top Electroweak Couplings

Probing the top quark in e+e- collisions for the first time





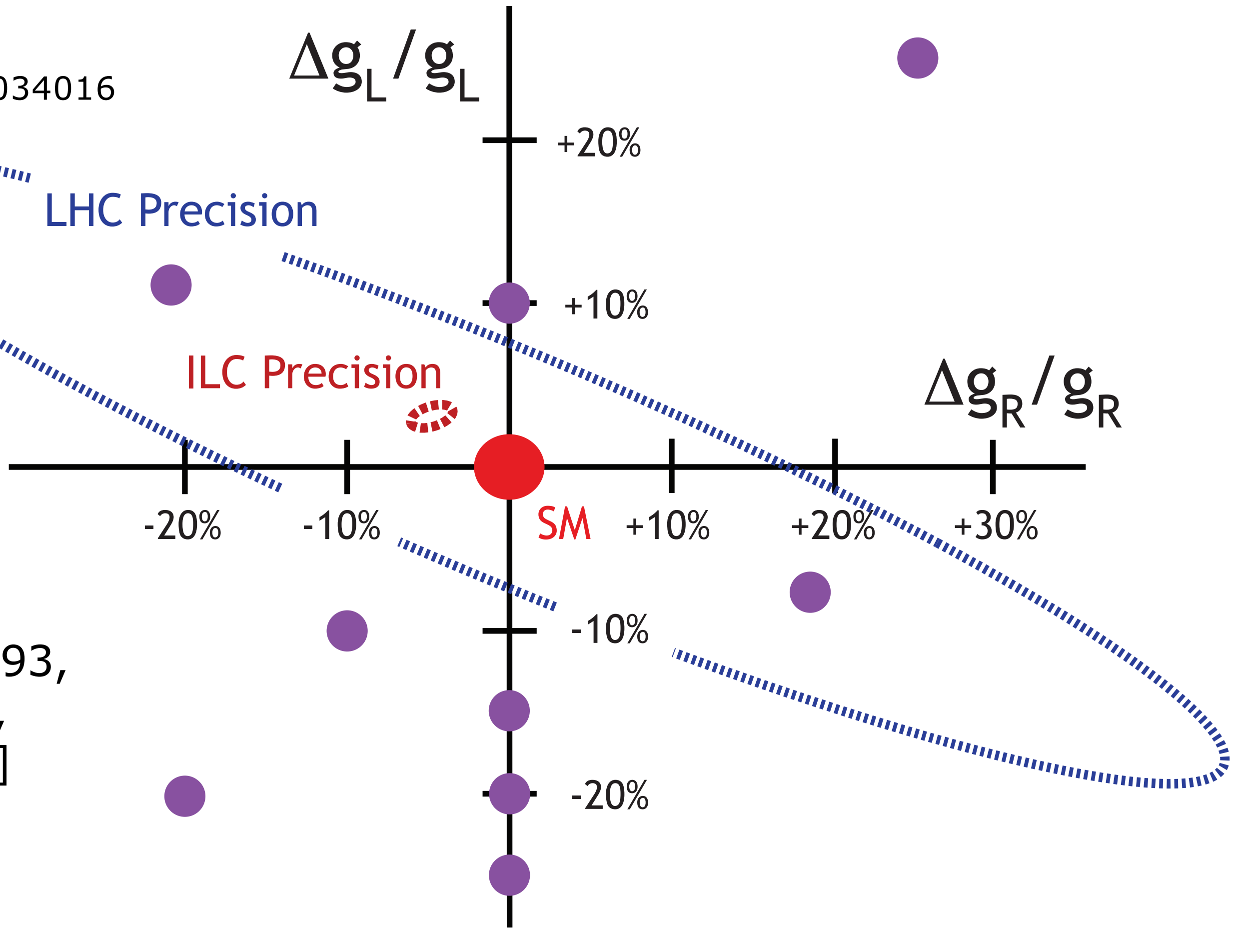
P(e-) = ±0.8 P(e+) = ∓0.3

Beam polarization essential to disentangle ttγ and ttZ couplings

Top Couplings and BSM

ILC has sensitivity to a variety of models with
Compositeness / Extra dimensions:

LHC14, 3000fb^{-1}
From PRD63 (2006) 034016

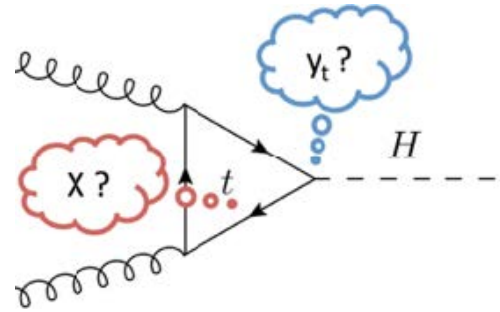


[arXiv:1403.2893,
1505.06020,
1506.05992]

ILC precision allows model discrimination.
(Complementary to resonance searches at LHC)

Top Yukawa Coupling

Indirect: loop couplings (LHC), ttbar threshold scan (e+e-)
→ Cannot disentangle quantum effects and top Yukawa



Direct: production possible at √s=500 GeV

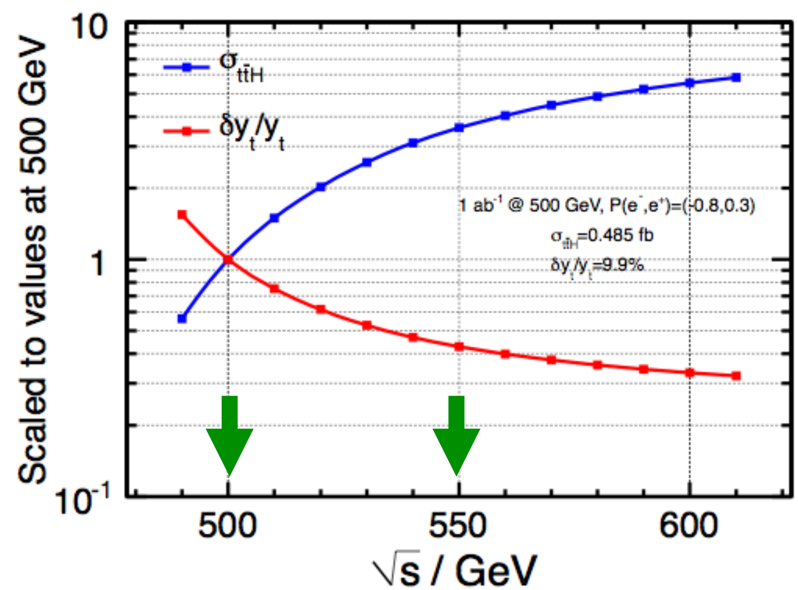
Expected precsion at ILC

$\Delta y_t/y_t$ = 6.3%

with full ILC500 program

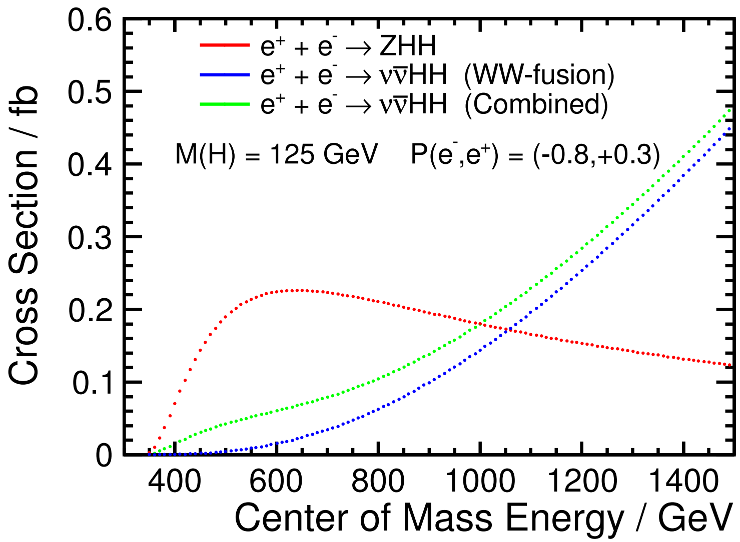
There is a large safety margin in the tunnel (~1.5 km of reserve space on each side).

At √s=550 GeV, the precision could be **$\Delta y_t/y_t$ = 2.5%**

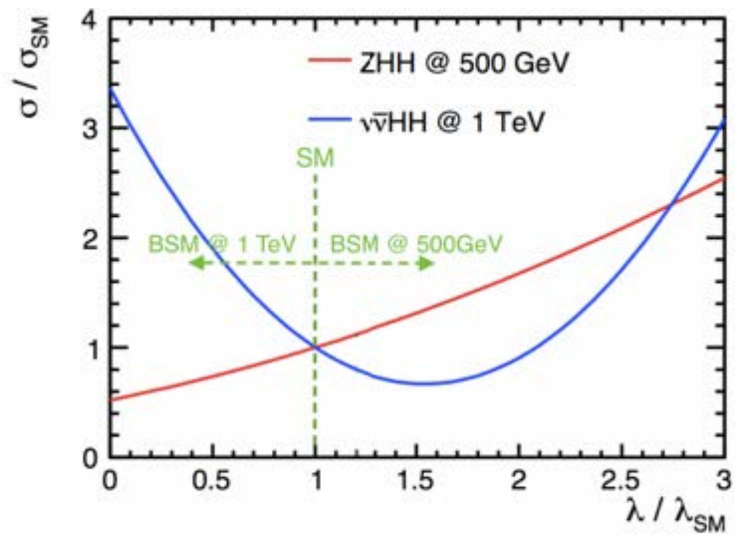


Double Higgs Production & Higgs Self-Coupling

Cross section: ZHH & vvH



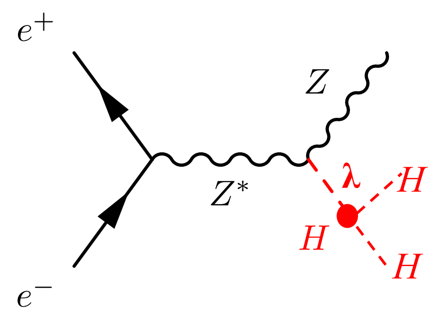
Cross section vs. anomalous λ



Two complementary processes:

ZHH

$\sqrt{s}$ ~500 GeV



Expected precision

$\Delta\sigma/\sigma$ = 16%

$\Delta\lambda/\lambda$ = 27%

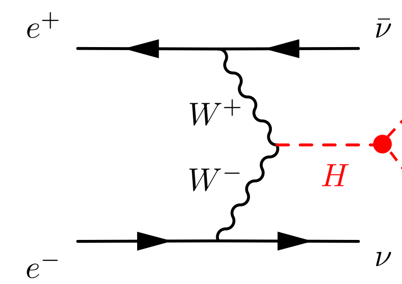
BSM sensitivity:

$\lambda > \lambda_{SM}$

UNIQUE FEATURE OF ILC

vvH (VBF)

$\sqrt{s}$ ~1 TeV



Expected precision:

$\Delta\sigma/\sigma$ = 13%

$\Delta\lambda/\lambda$ = 10%

BSM sensitivity:

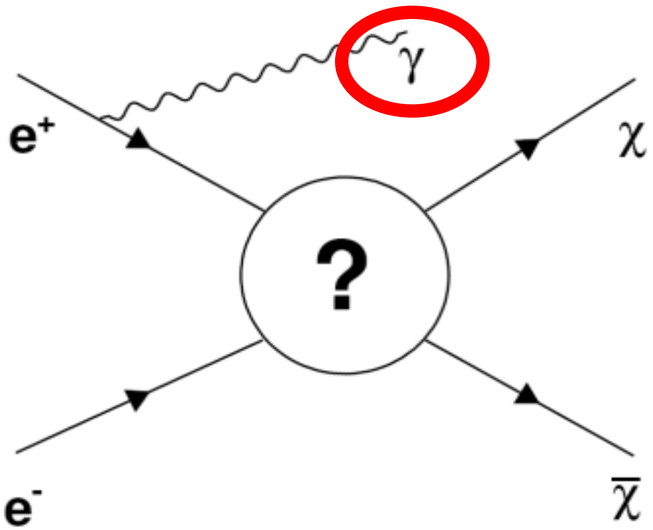
$\lambda < \lambda_{SM}$

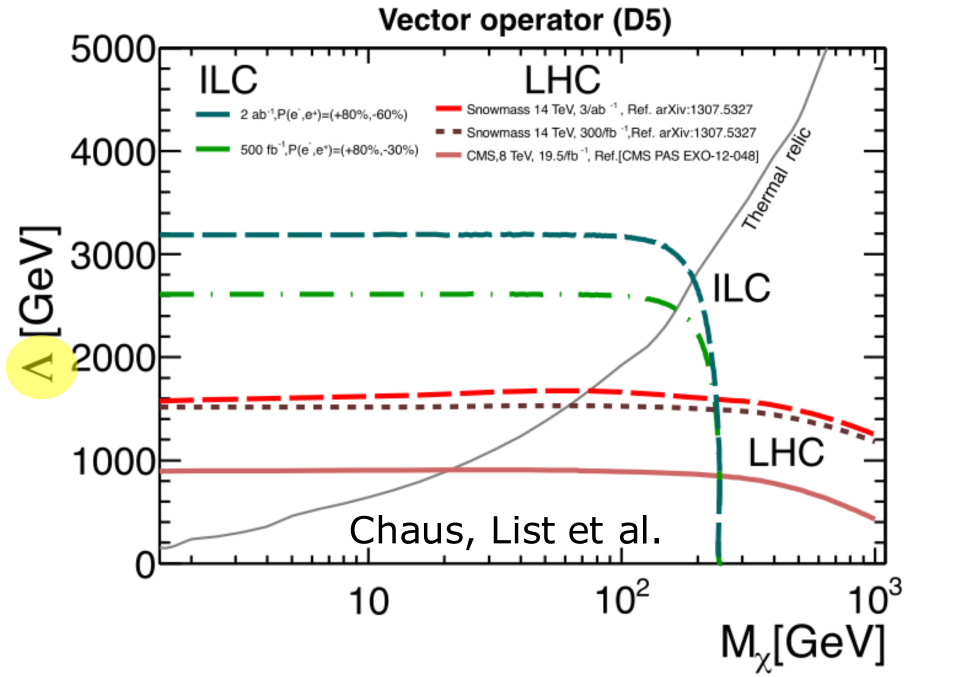
(Same tendency as LHC)

Electroweak baryogenesis requires λ/λ_{SM} > 1.2, can be higher ~2.0

WIMP Dark Matter at ILC

Monophoton Search





$$\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^2}\mathcal{O}_i \qquad \mathcal{O}_V = (\overline{\chi}\gamma_\mu\chi)(\overline{\ell}\gamma^\mu\ell)$$

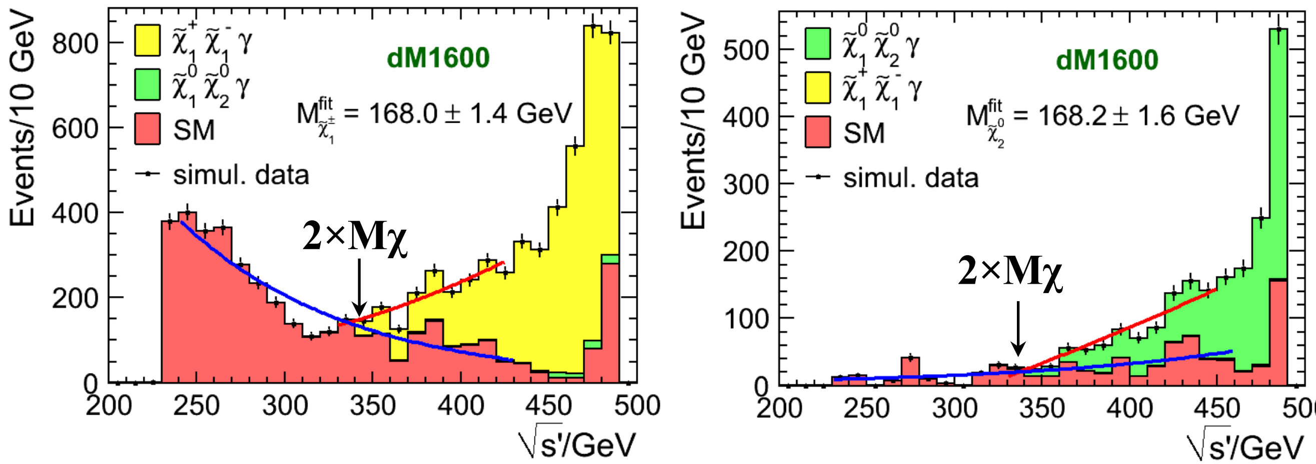
<u>ILC DM search complementary</u> with LHC & Direct Detection:

- Sensitivity to **lepton couplings** (vs. quark couplings)
- Sensitivity to **large mediator scale** (vs. large DM mass)

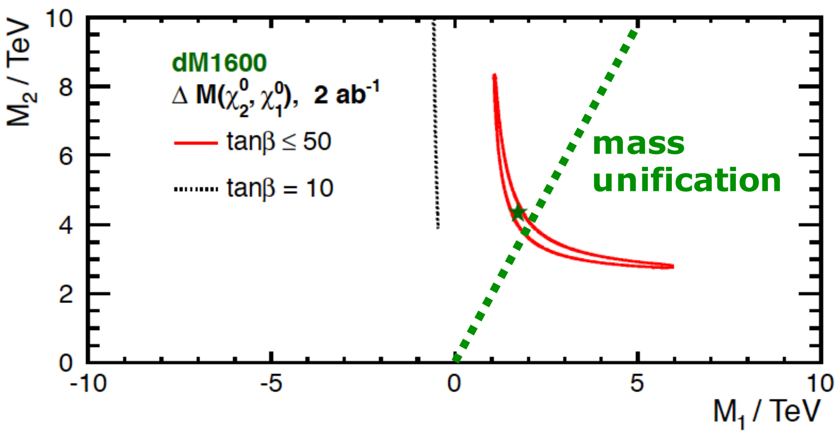
Natural SUSY at ILC

- Prediction: 4 light Higgsinos (χ^0_1 χ^0_2 χ^+_1 χ^-_1) with O(100) GeV mass
- Naturally compressed spectra, challenging for LHC
- ILC reach: up to $M=\sqrt{s}/2$, no loopholes

[arXiv:1307.3566]



Gaugino mass extraction via mixing



Sensitive to multi-TeV parameters

- If gluino observed at LHC, test of **gaugino mass unification**
- If gluino not seen at LHC, prediction of gluino mass → next pp collider

X(750) @ ILC

NEW

arXiv:1607.03829

"Implications of the 750 GeV gamma-gamma Resonance as a **Case Study** for the International Linear Collider"

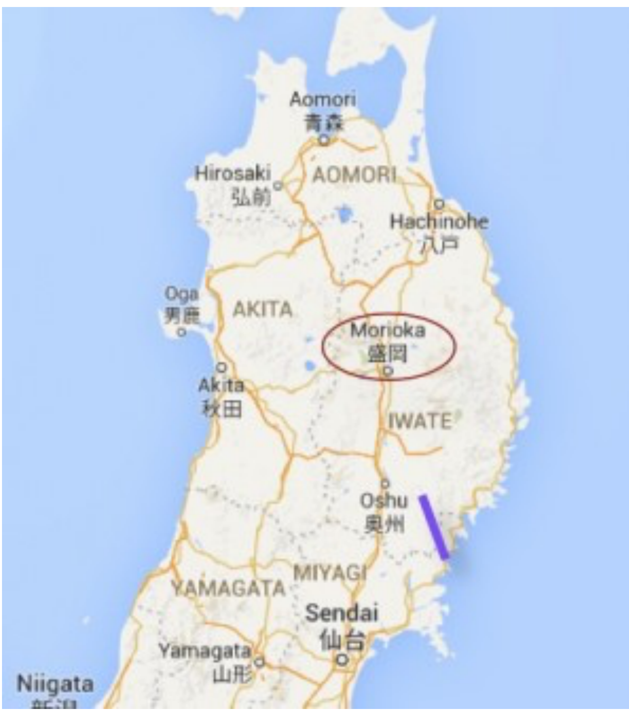
Sect.		hWW hZZ	$hb\bar{b}$ $h\tau\tau$	$h\gamma\gamma$ hgg	$ht\bar{t}$	$h \to$ invis.	$h\tau\mu$	$t\bar{t}Z$	$ee \to$ $ee, \mu\mu$	$ee \to$ $\gamma+$ invis.
3.1	Vectorlike fermions		X	X	X			X	X	
3.2	Higgs singlet		X	X	X			X		
3.2	2 Higgs doublet	X	X	X	X					
3.2	NMSSM	X	X	X	X	X				X
3.2	Flavored Higgs	X	X	X			X			
3.3	Bound state								X	
3.4	Pion of new forces		X	X	X	X		X	X	X
3.5	RS radion	X	X	X	X			X		
3.6	RS graviton	X	X		X			X		

Table 2: Anomalies in precision measurements expected to be visible at the ILC for the models of the Φ discussed in Section 3 of this report.

ILC500 has sensitivity to a wide range of new models compatible with X(750)
Direct production possible with ILC 1 TeV and/or photon-photon collider

Linear Collider Workshop 2016

- December 5-9, 2016
- Morioka, Japan

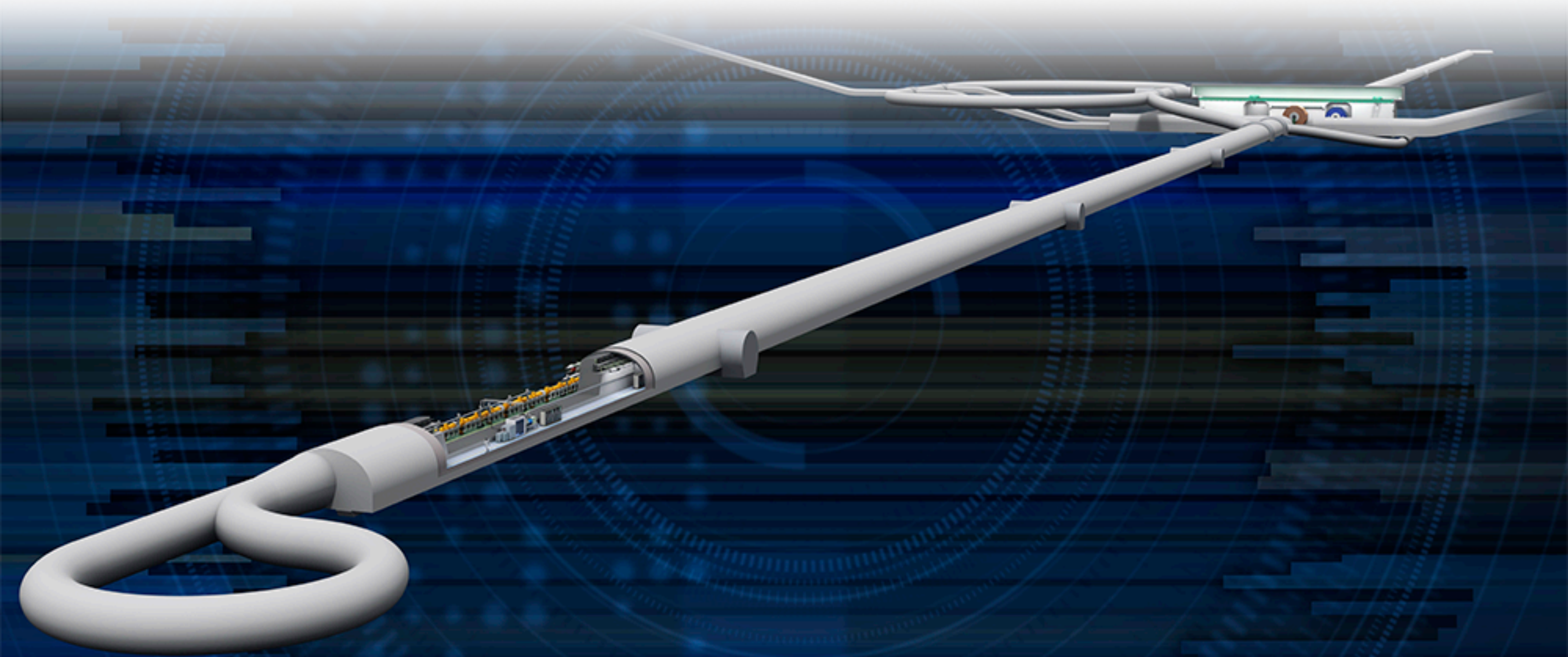


Summary

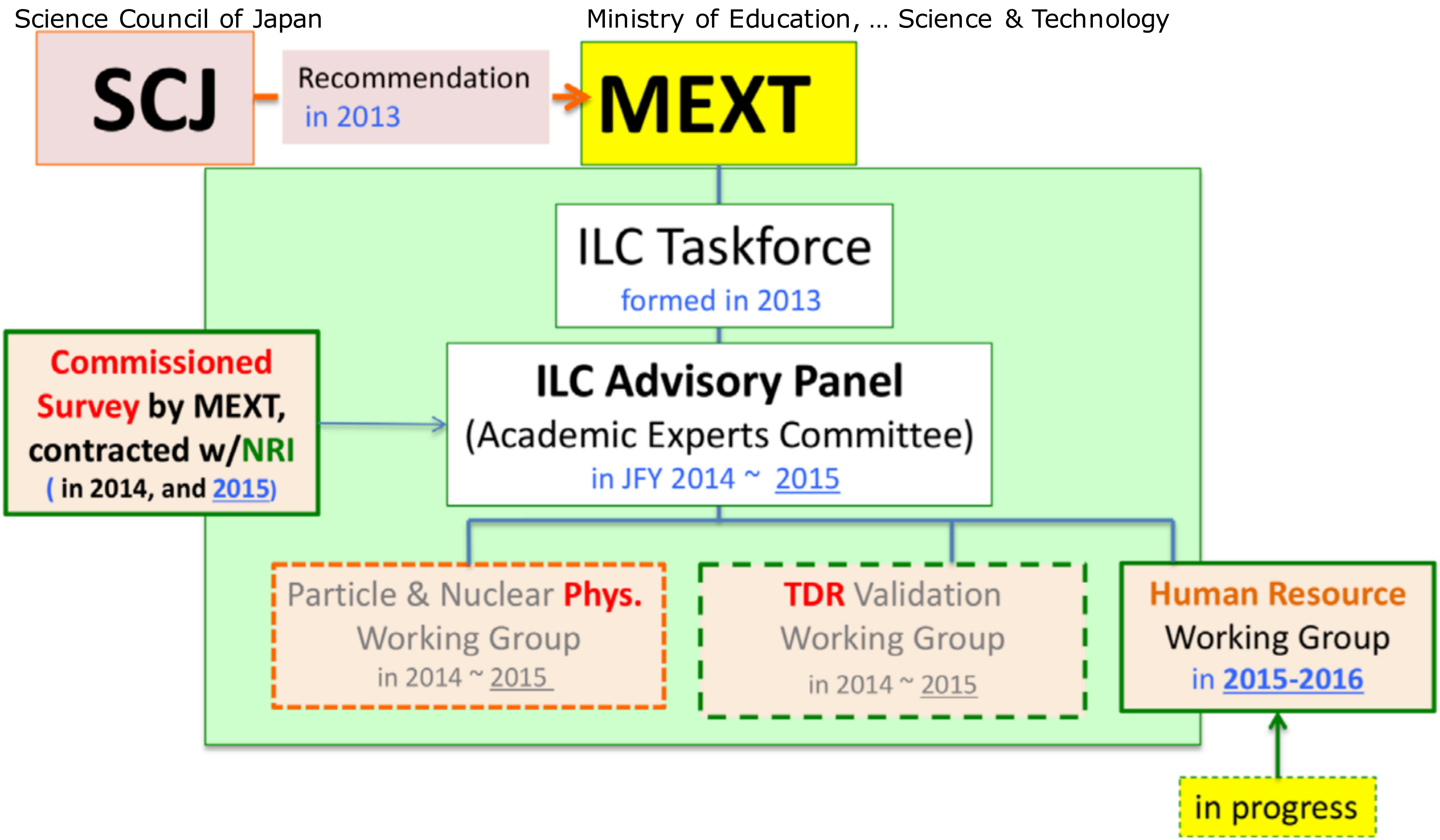
- **ILC physics case is already very strong**
  - Energy range guarantees the measurements of Higgs couplings, top couplings, top Yukawa coupling, Higgs self-coupling, and many more.
  - Unique opportunities for direct discoveries, e.g. Dark Matter, Natural SUSY
- **ILC machine has unique capabilities**
  - Beam polarizations
  - Upgradable in luminosity and energy (→**investment for the future**)
- **ILC technology is mature**
  - R&D complete; industrialization with XFEL construction
- **The project is currently under political consideration.**
  - Japan is very serious about the ILC.
  - International discussions have begun.

There is still a lot to do. Everyone is welcome to join!

Additional Slides



Review by Japanese Government



Why linear?

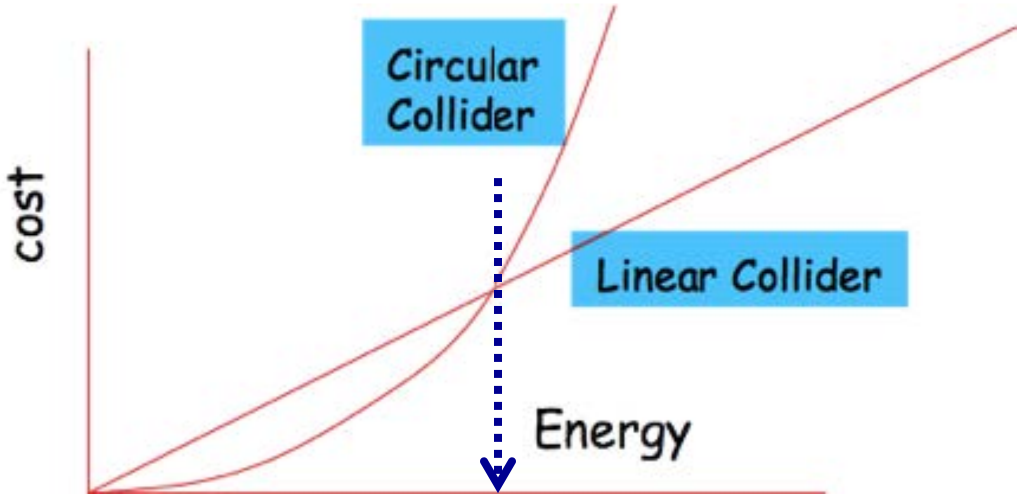
Synchrotron radiation:

$\Delta E \sim (E^4/m^4R)$ per turn (2 GeV at LEP2)

Cost in the high-energy limit

\$\$\$ ~ (construction) + (operation)

- **Circular:** \$\$\$ $\sim a\,\mathbf{R} + b\,\Delta\mathbf{E} \sim a\,\mathbf{R} + b'\,(\mathbf{E}^4/\mathbf{m}^4\mathbf{R})$
  optimization: $R \sim E^2$ → **\$\$\$ ~ E^2**
- **Linear:** \$\$\$ $\sim c\,\mathbf{L} + d\,\mathbf{E}$, with $\mathbf{L} \propto \mathbf{E}$ → **\$\$\$ ~ E**



Linear collider is the future!

ILC Luminosity Upgrades

- **E_{CM} = 250 GeV**
  - x4 luminosity → $3x10^{34}$ $cm^{-2}s^{-1}$
  - x2 Nbunch, x2 rep rate; 122 → 200 MW wall plug

    (LHC 2012: 187 MW)
- **E_{CM} = 500 GeV**
  - x2 luminosity → $3.6x10^{34}$ $cm^{-2}s^{-1}$
  - x2 Nbunch; 163 → 204 MW wall plug
- **E_{CM} = 1 TeV**
  - x1.4 luminosity → $5x10^{34}$ $cm^{-2}s^{-1}$
  - Aggressive beam parameters;
    Same wall plug power (300 MW)

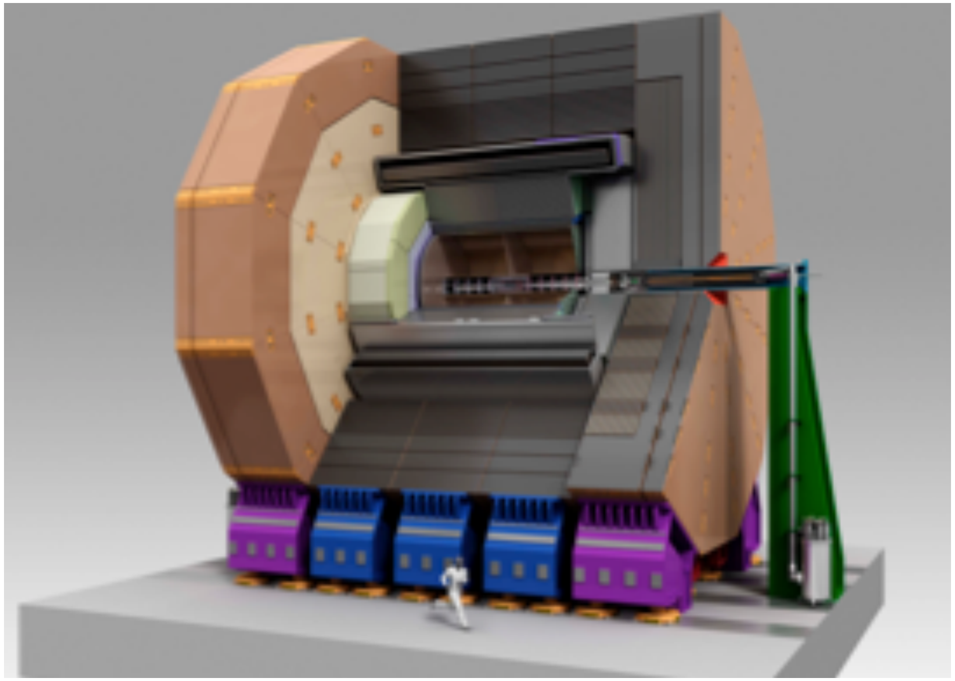
Reference: arXiv:1310.0763 (ILC Higgs White Paper)

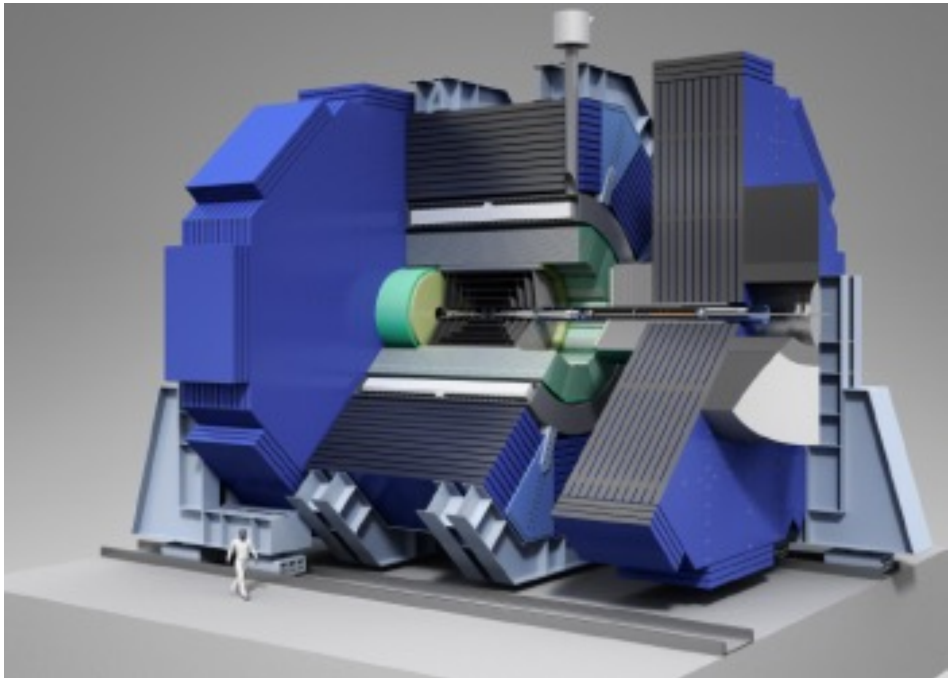
Power Consumption and Cost

- **Power consumption**
  - ILC design driven by **<u>self-imposed</u>** limits on the total site power
    - 200 MW for 500 GeV
    - 300 MW for 1 TeV
- **Cost awareness**
  - Critical review of design in order to reduce costs (from RDR to TDR)
  - Power reduction in favor of stronger focusing of beams

- Luminosity ~ Power Consumption ~ Operating Cost

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

Detector Requirements

Vertex resolution for b/c tagging

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

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

	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: $e^+e^- \rightarrow ZH \rightarrow \mu\mu H$

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

10x LHC

Jet energy resolution to separate W, Z, H

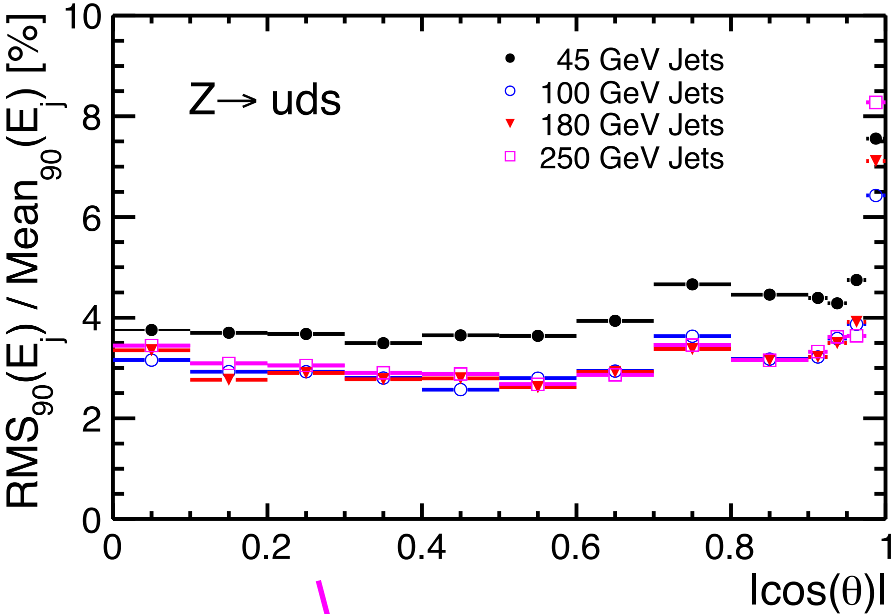
- Higgs self-coupling: ***Z/H*** separation
- SUSY: Separation of
  - $e^+e^- \rightarrow \chi_1^+\chi_1^- \rightarrow \chi_1^0\chi_1^0 W^+W^-$
  - $e^+e^- \rightarrow \chi_2^0\chi_2^0 \rightarrow \chi_1^0\chi_1^0 Z^0 Z^0$
- Strong EWSB: $e^+e^- \rightarrow \nu\nu W^+W^-, \nu\nu Z^0 Z^0$

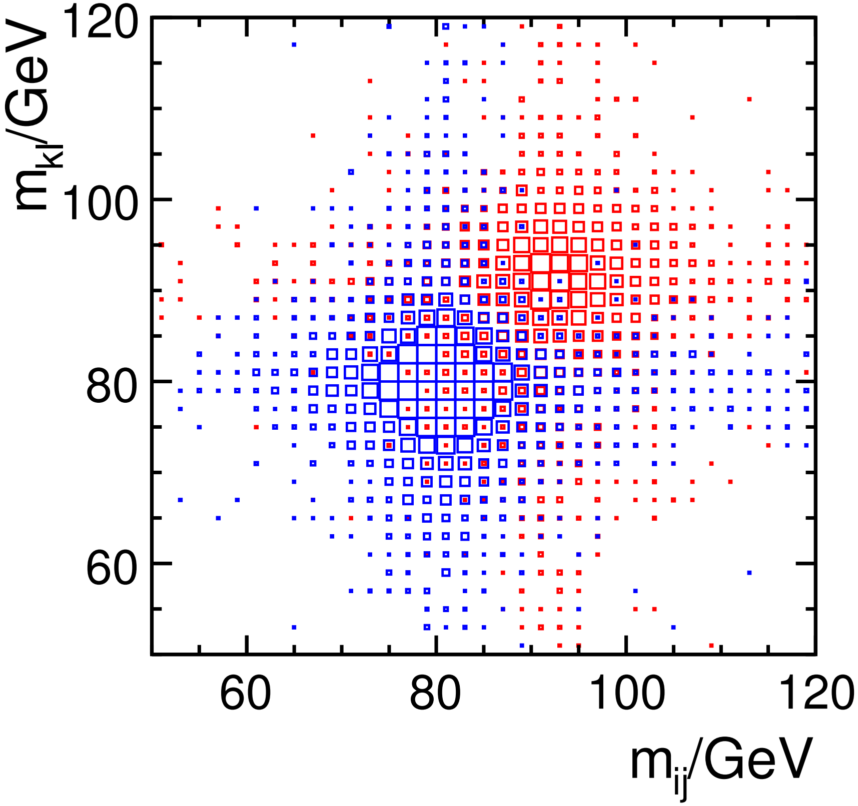
$$\frac{\sigma_{E_j}}{E_j} = \begin{cases} 0.3/\sqrt{E(\text{GeV})} & \text{for } E \lesssim 100 \text{ GeV} \\ 0.03 & \text{for } E \gtrsim 100 \text{ GeV} \end{cases}$$

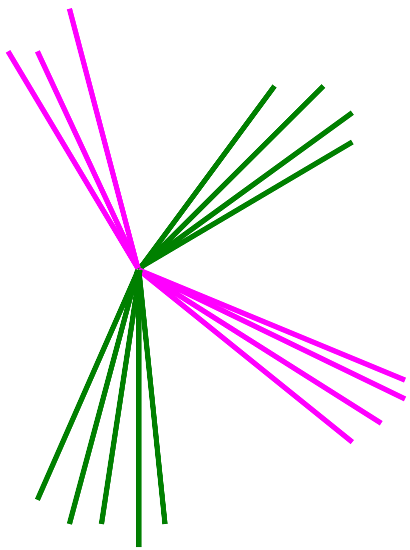
~2x LHC

Jet Energy Resolution

Full simulation ILD detector model for TDR

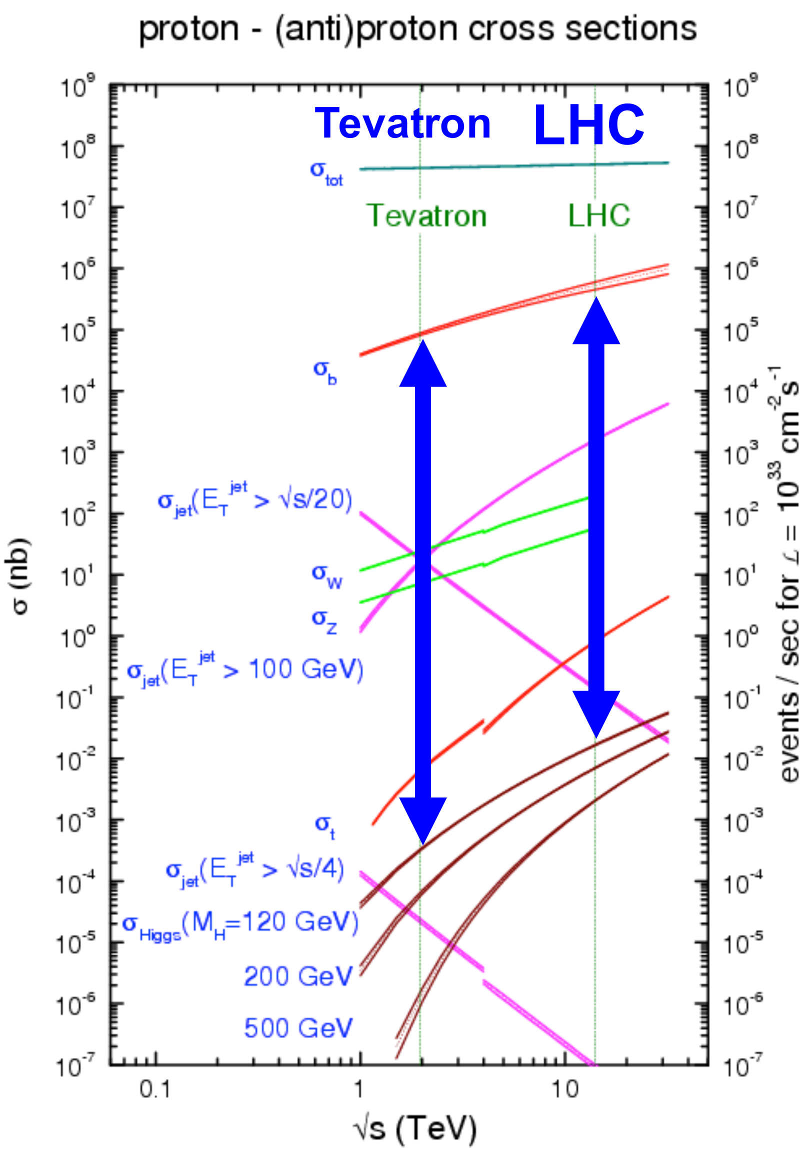






3-4% jet energy resolution
→ Good W/Z separation

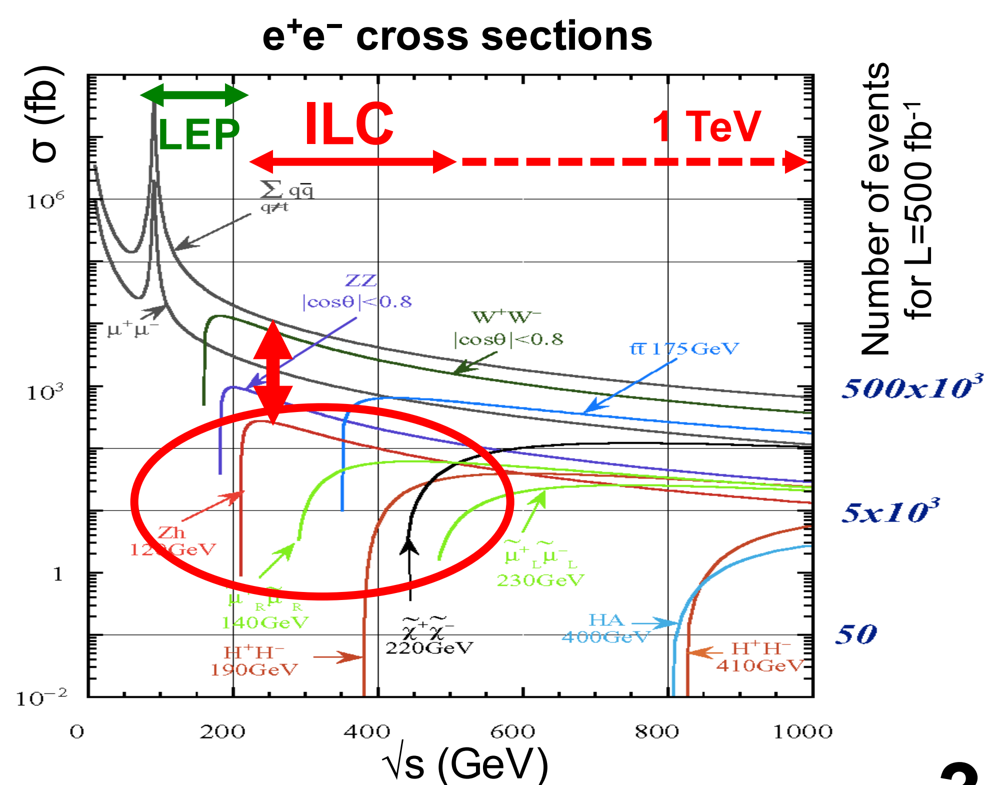
Cross Sections



Typically,

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

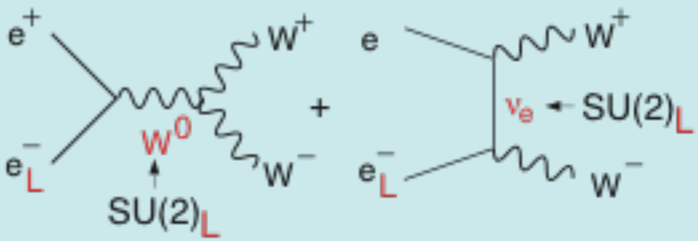
$$N_{\rm bkg}^{pp} \gg N_{\rm bkg}^{e^+e^-}$$



Power of Beam Polarization

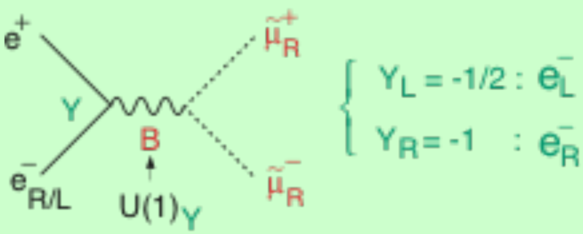
Bkg. Suppression

W^+W^- **(Largest SM bkg in SUSY searches)**



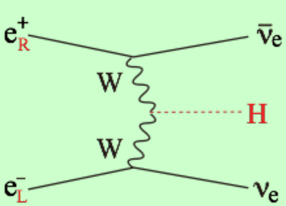
In the symmetry limit, $\sigma_{WW} \to 0$ for e^-_R !

Slepton pair



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

WW-fusion Higgs prod.

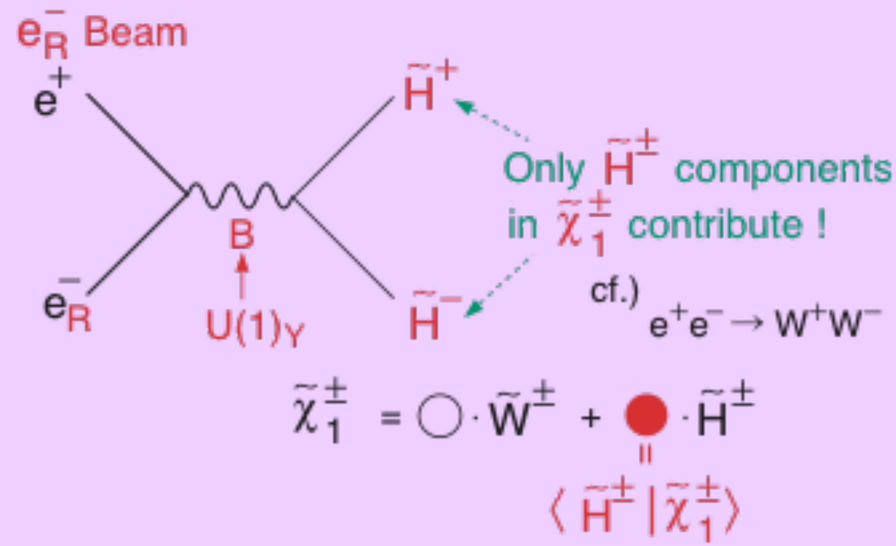


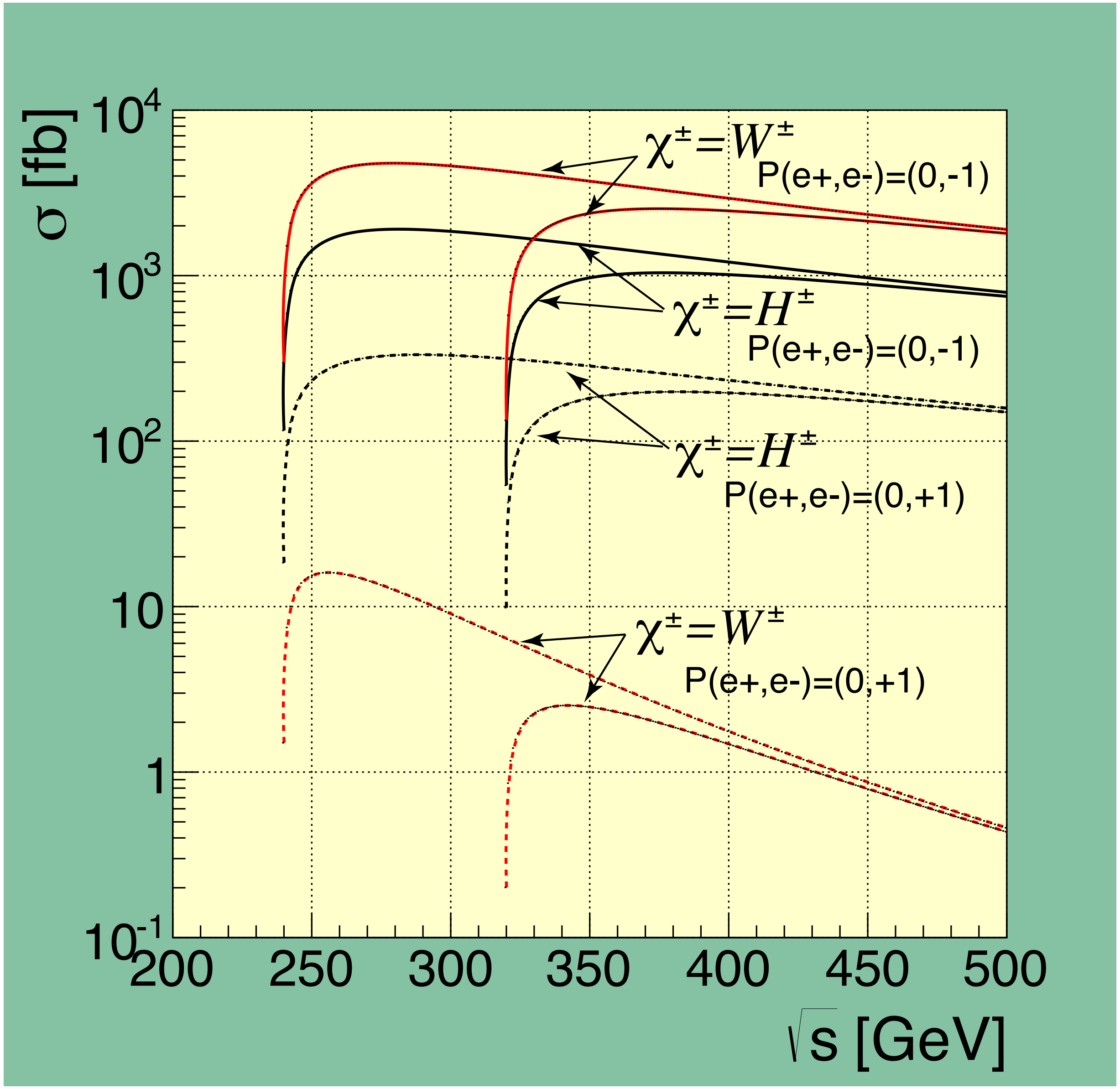
Pol(e^-)	-0.8
Pol (e^+)	+0.3
$(\sigma/\sigma_0)_{\nu\nu H}$	1.8x1.3=**2.34**

Signal Enhancement

Decomposition

Chargino pair

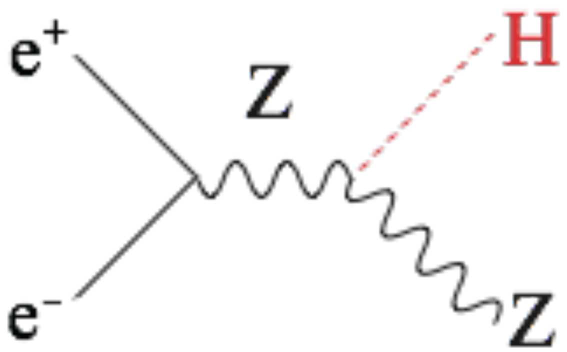


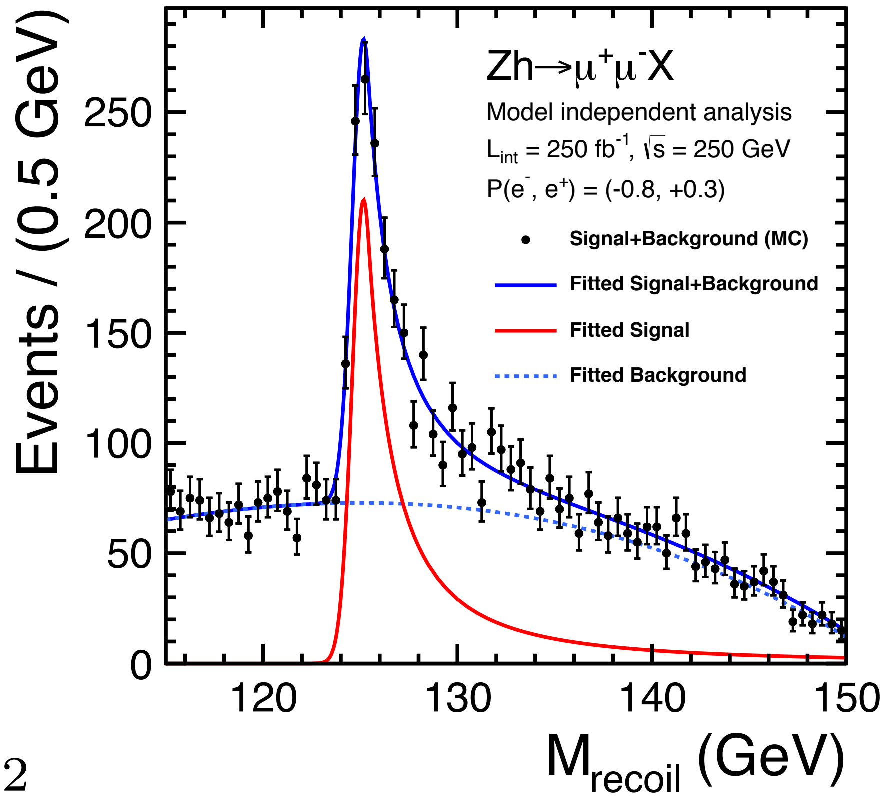


σ [fb]
$\chi^{\pm}=W^{\pm}$
P(e+,e-)=(0,-1)
$\chi^{\pm}=H^{\pm}$
P(e+,e-)=(0,-1)
$\chi^{\pm}=H^{\pm}$
P(e+,e-)=(0,+1)
$\chi^{\pm}=W^{\pm}$
P(e+,e-)=(0,+1)
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
200
250
300
350
400
450
500
$\sqrt{s}$ [GeV]

K. Fujii

Higgs recoiling against Z





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

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

Clean Higgs peak with Z→ll (Z→qq is also usable.)

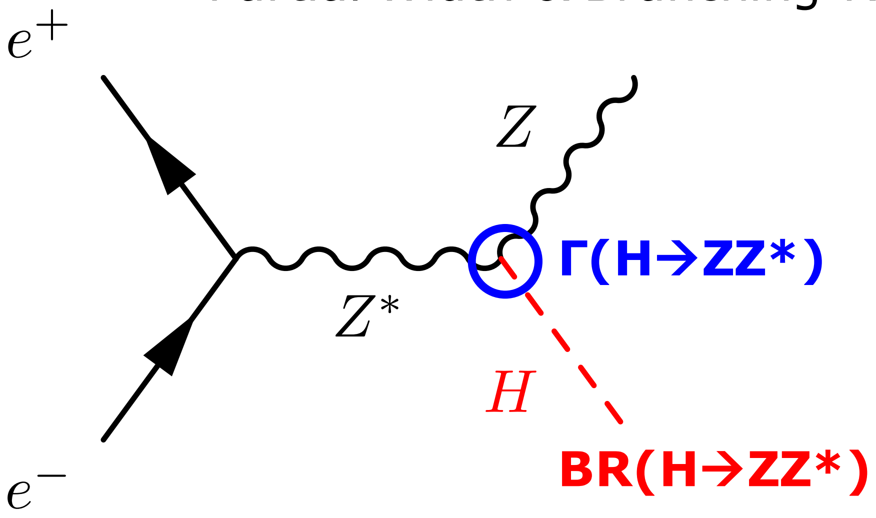
Model-independent, absolute measurement of Higgs mass and Zh cross section.

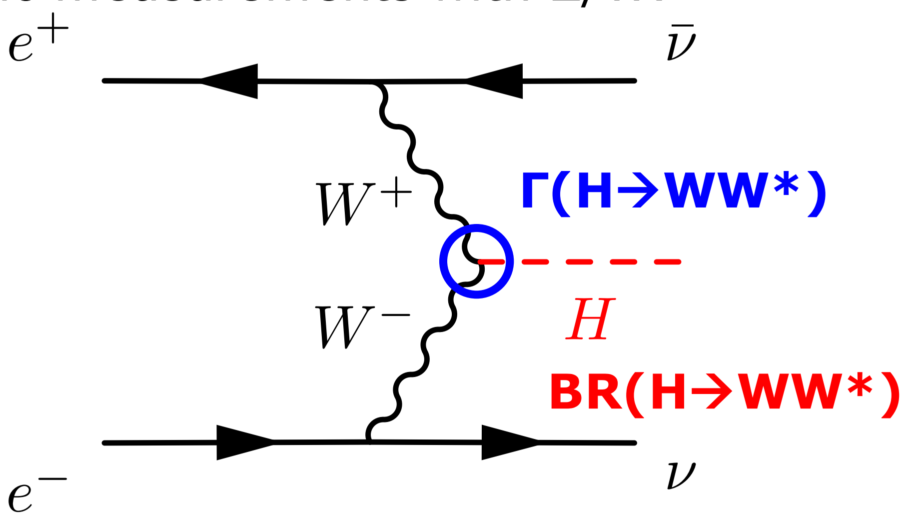
Higgs Total Width

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%.

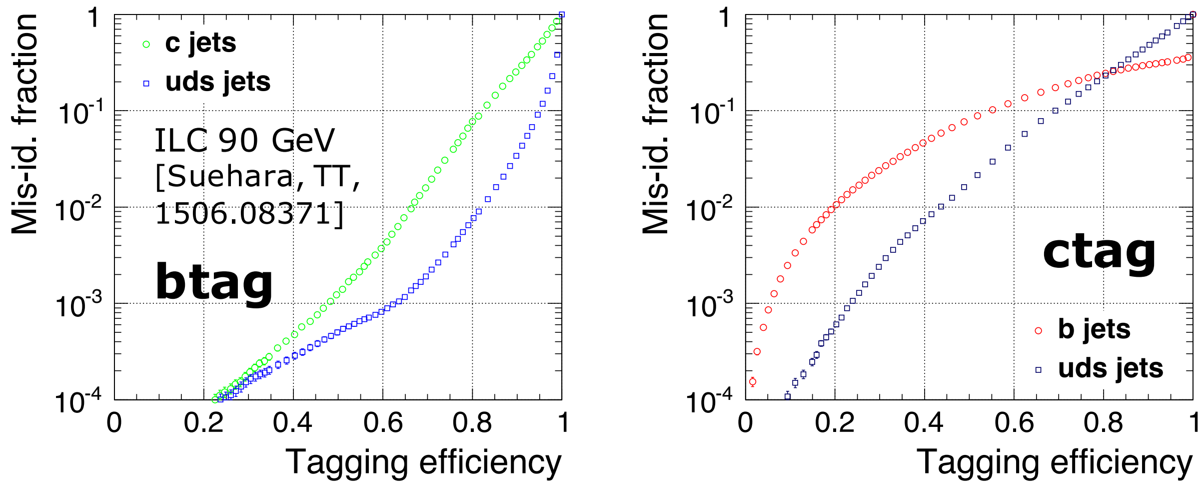
Require high CM energy for large statistics.

At ILC, Higgs width precision is ~2% [1506.05992]

Higgs hadronic decays

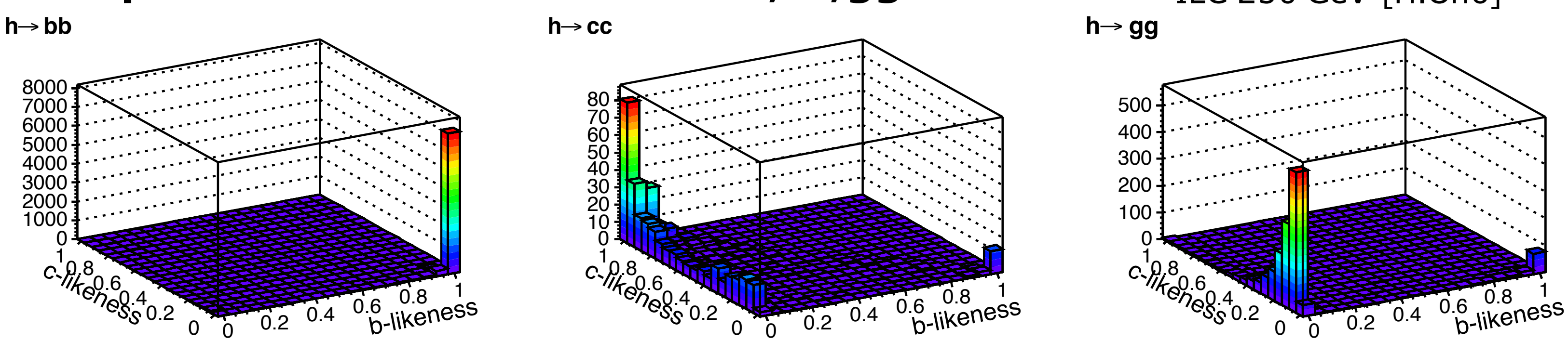
Detector foreseen to have excellent vertex detectors, with capability to identify bottom and charm jets.
→ measure Higgs hadronic BRs

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



Template distributions for H→bb,cc,gg:

ILC 250 GeV [H.Ono]

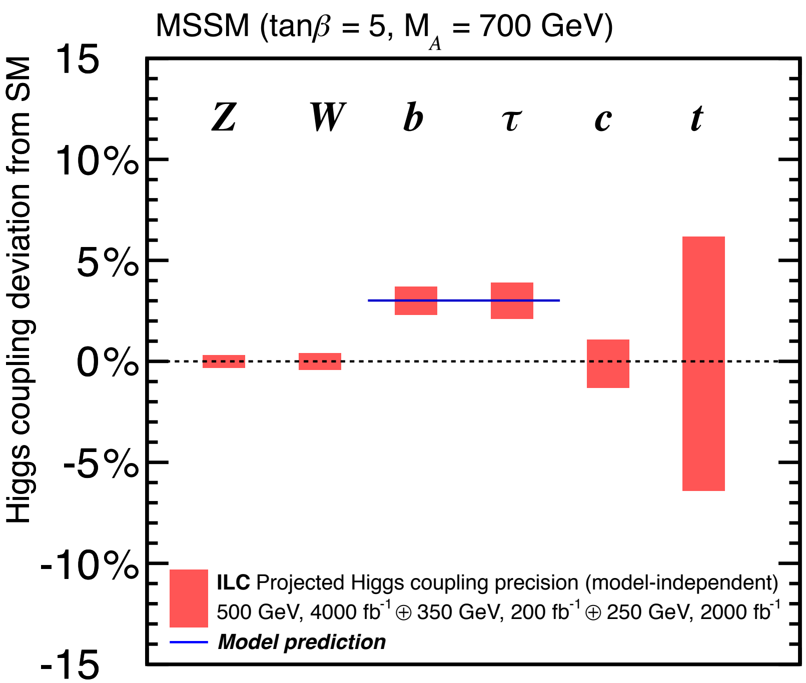


$\Delta\kappa_b/\kappa_b < 1\%$, $\Delta\kappa_c/\kappa_c \sim O(1)\%$, $\Delta\kappa_g/\kappa_g \sim O(1)\%$

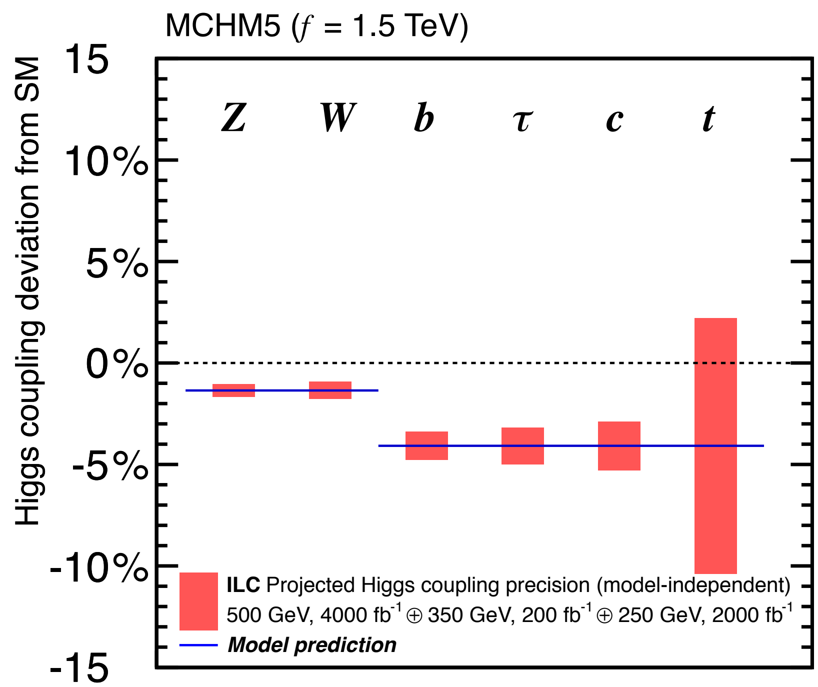
Fingerprinting

Higgs boson: elementary or composite?

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)

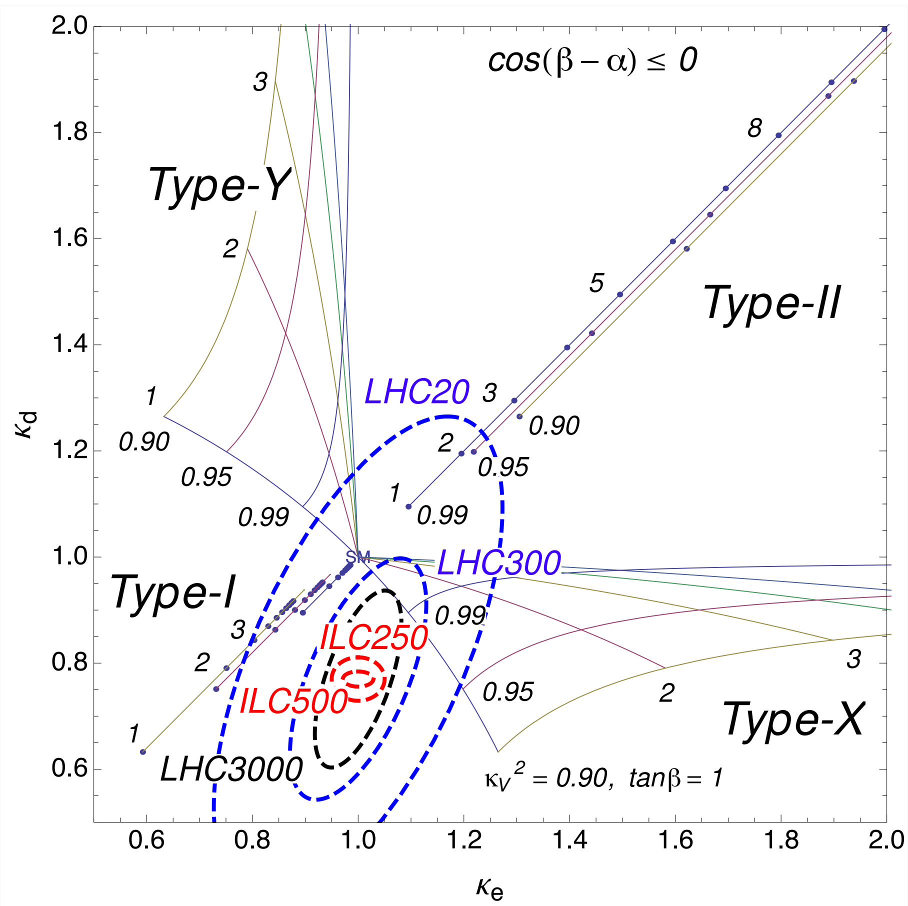


Power of precision: Model Discrimination

Fingerprinting

Two-Higgs Doublet Models

Kb



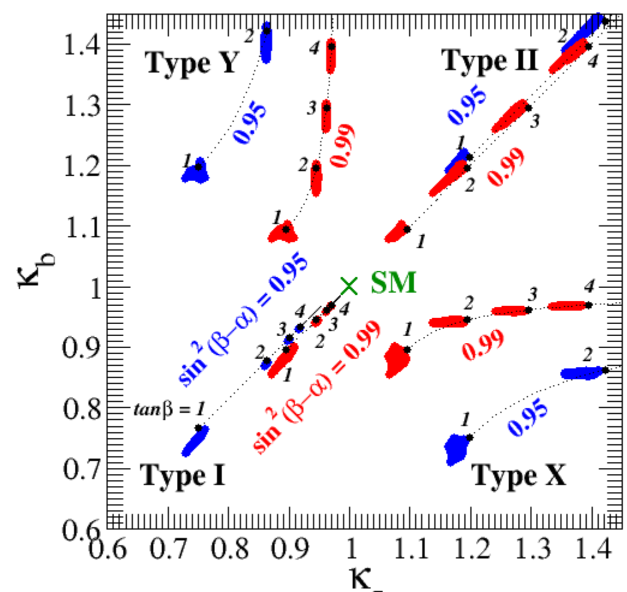
Kτ

[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)	+	−	−	+	−	+

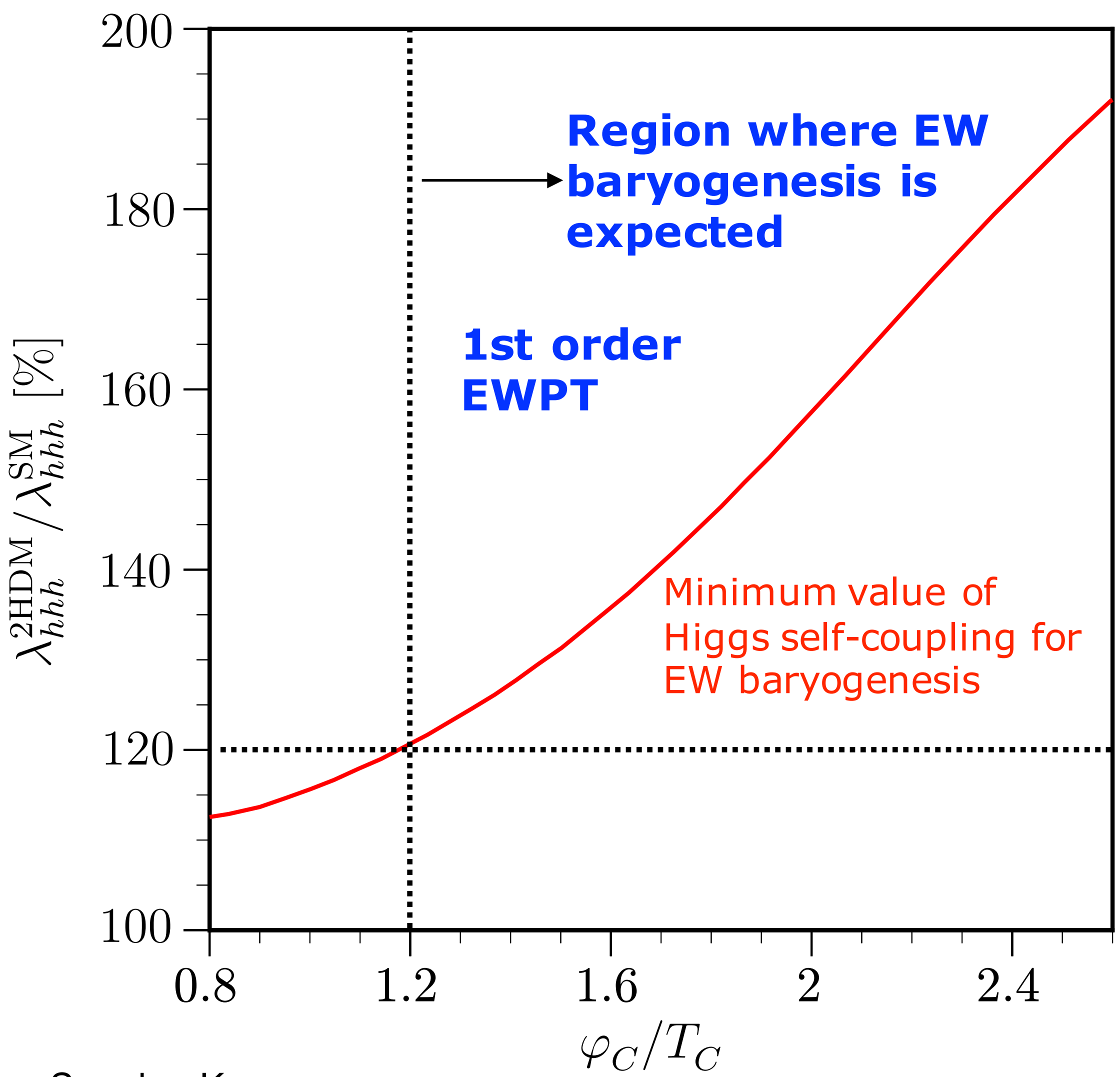
4 Possible Z₂ Charge Assignments that forbids tree-level Higgs-induced FCNC

Discrimination of Higgs multiplet structure with precise coupling measurements.



With radiative corrections [Kikuchi, 1412.0375]

Electroweak Baryogenesis



Senaha, Kanemura

Example:

Electroweak baryogenesis in a ***Two Higgs Doublet Model***

Large deviations in Higgs self-coupling

→ **1st order EW phase transition**

→ **Out of equilibrium**

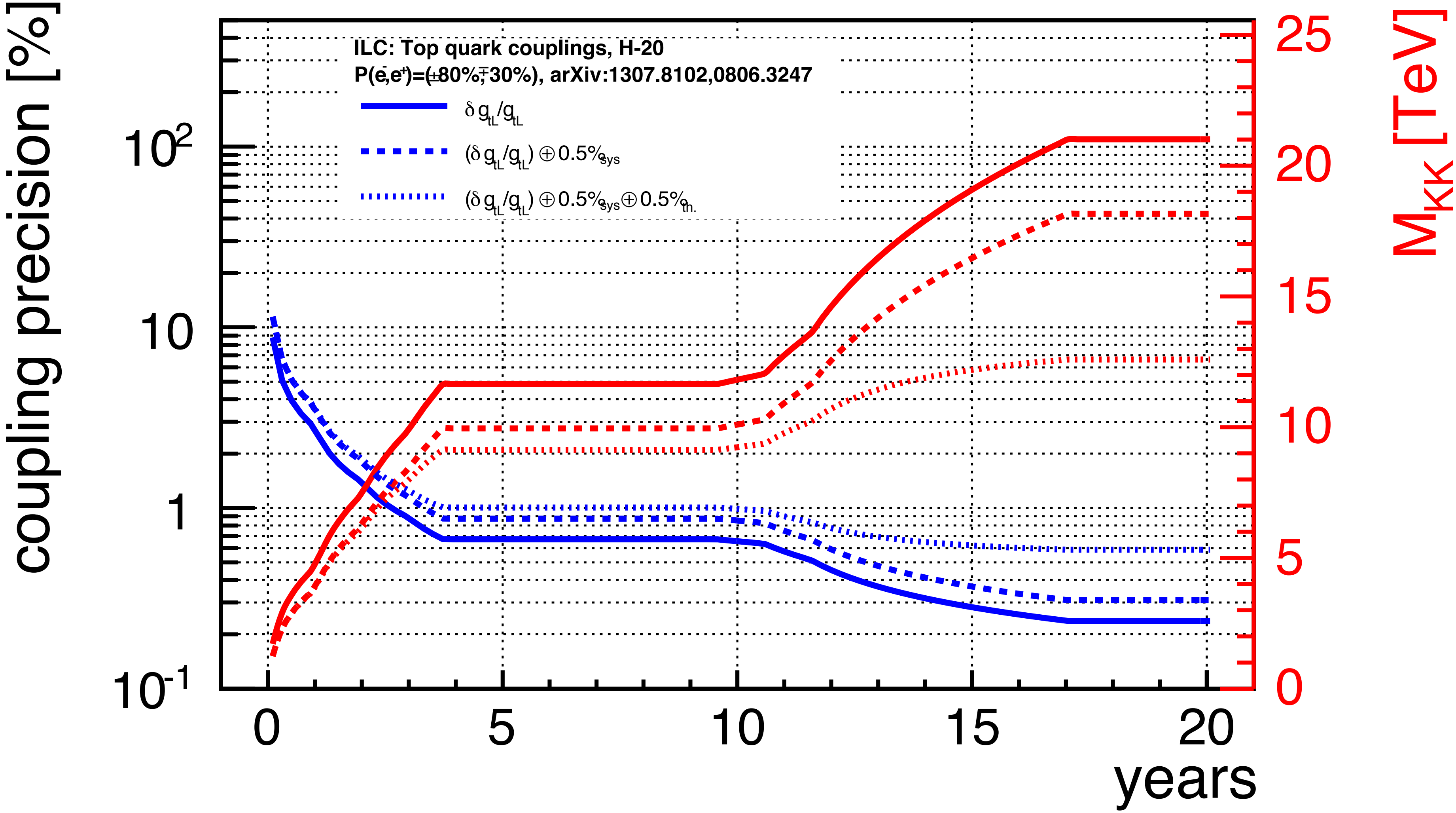
+ CPV in Higgs sector

→ **EW baryogenesis possible**

Test the idea of **baryogenesis at the electroweak scale**.

BSM Reach with Top Couplings

Benchmark model with composite top [Pomarol, Serra, arXiv:0806.3247]



Vacuum Stability and Top Mass

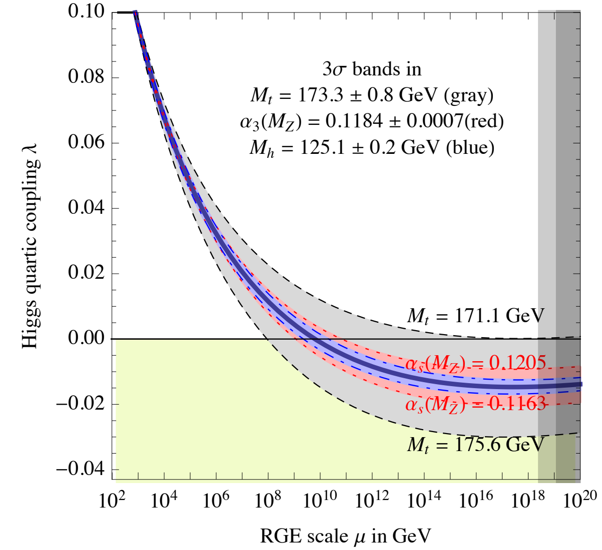
With the observed Higgs boson mass, the **SM** can be extrapolated to very high energies, possibly up to the Planck scale.

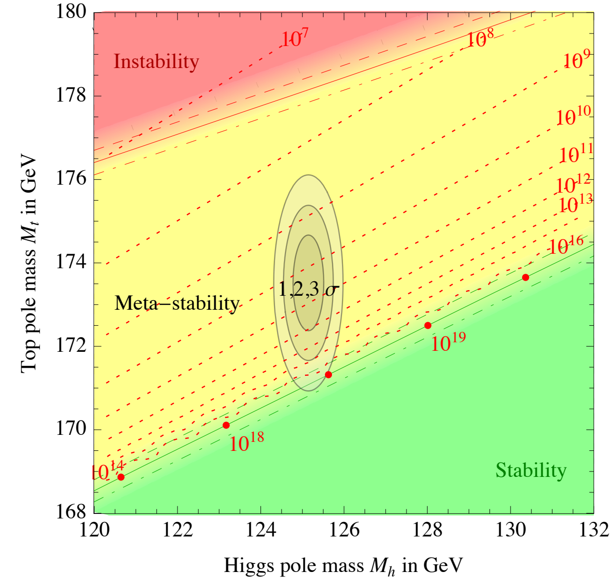
The SM vacuum appears to be at a point of **meta-stability**.

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]





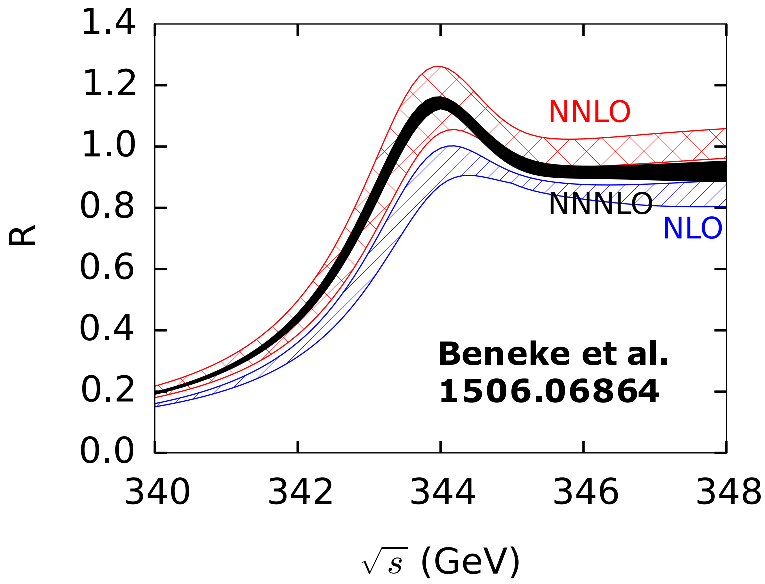
m_t : threshold scan

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]

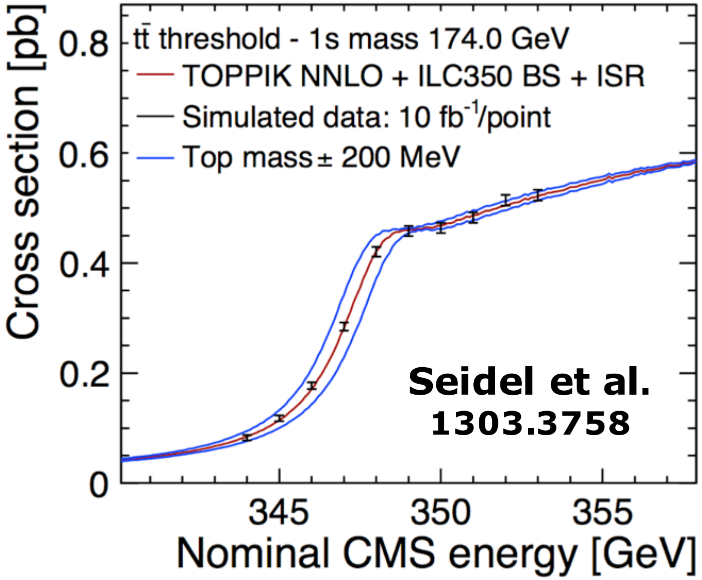
At e+e- colliders, can measure the 1S or the potential-subtracted top mass. They can be converted into the $\overline{MS}$ mass at high accuracy.
From recent 4-loop calculation of uncertainty [Marquard et al. 1502.01030], **7 MeV (from 1S), 23 MeV (from PS)**

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.



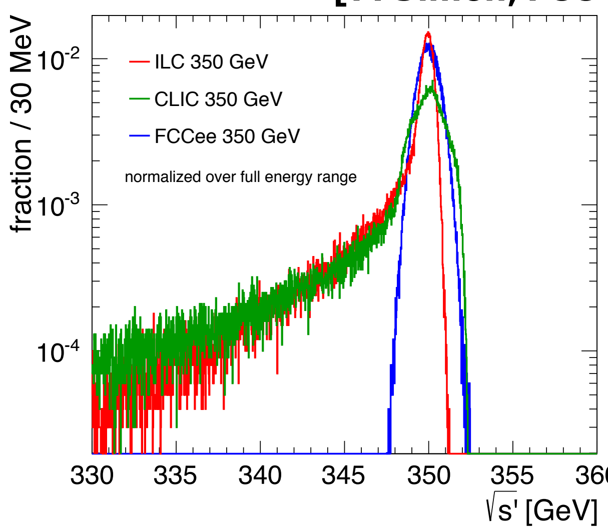
m_t : threshold scan

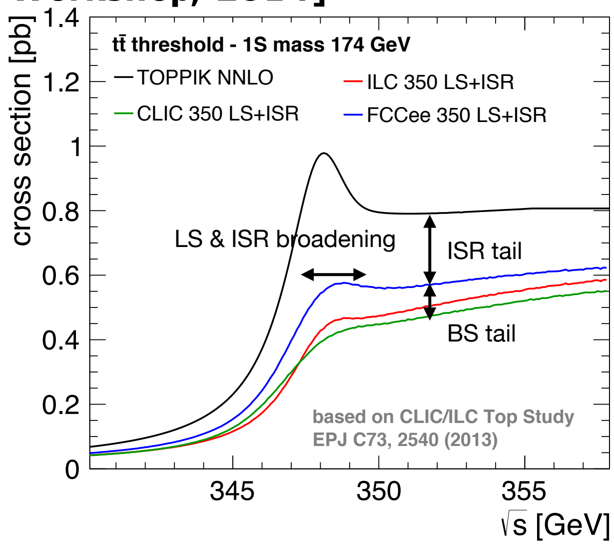


Measurement of 10 points (10 fb-1 each) around 350 GeV gives statistical uncertainty ~20 MeV
→ Theory uncertainty dominates

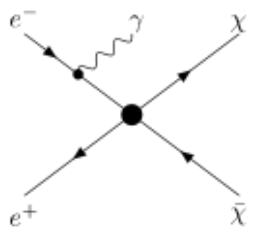
→ **Prospect for 50 MeV accuracy of top mass ($\overline{MS}$) measurement**

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





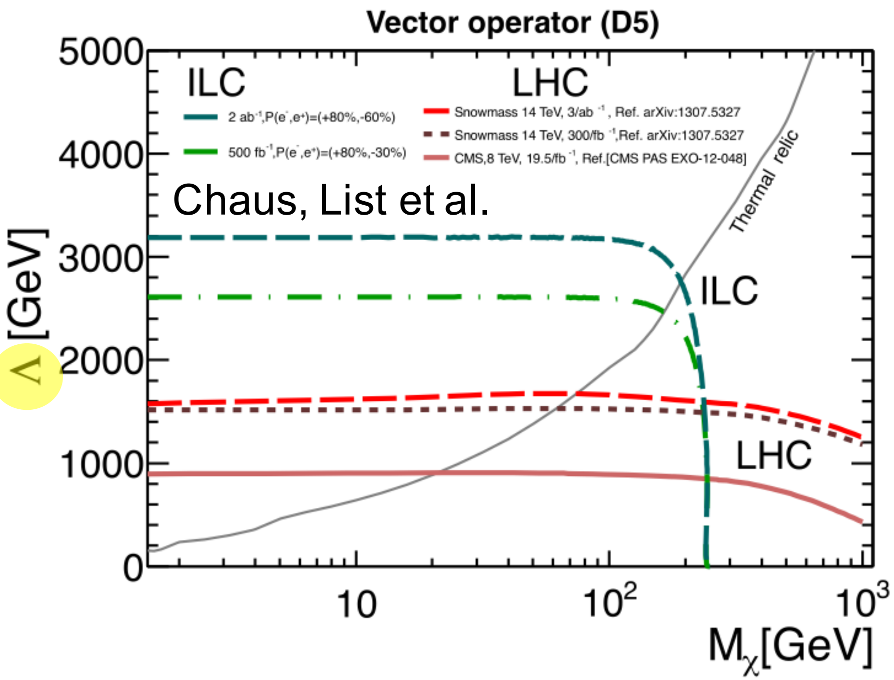
DM: Effective Operator Approach

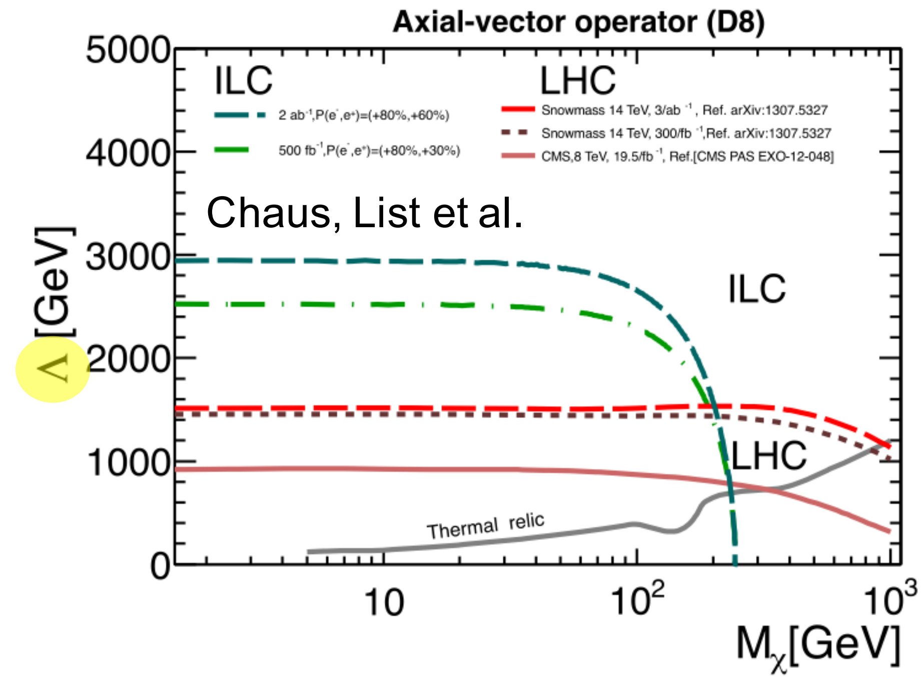


$$\mathcal{L}_{\mathrm{int}} = \frac{1}{\Lambda^2}\mathcal{O}_i$$

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

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





LHC: Mediator mass up to Λ~1.5 TeV for large DM mass

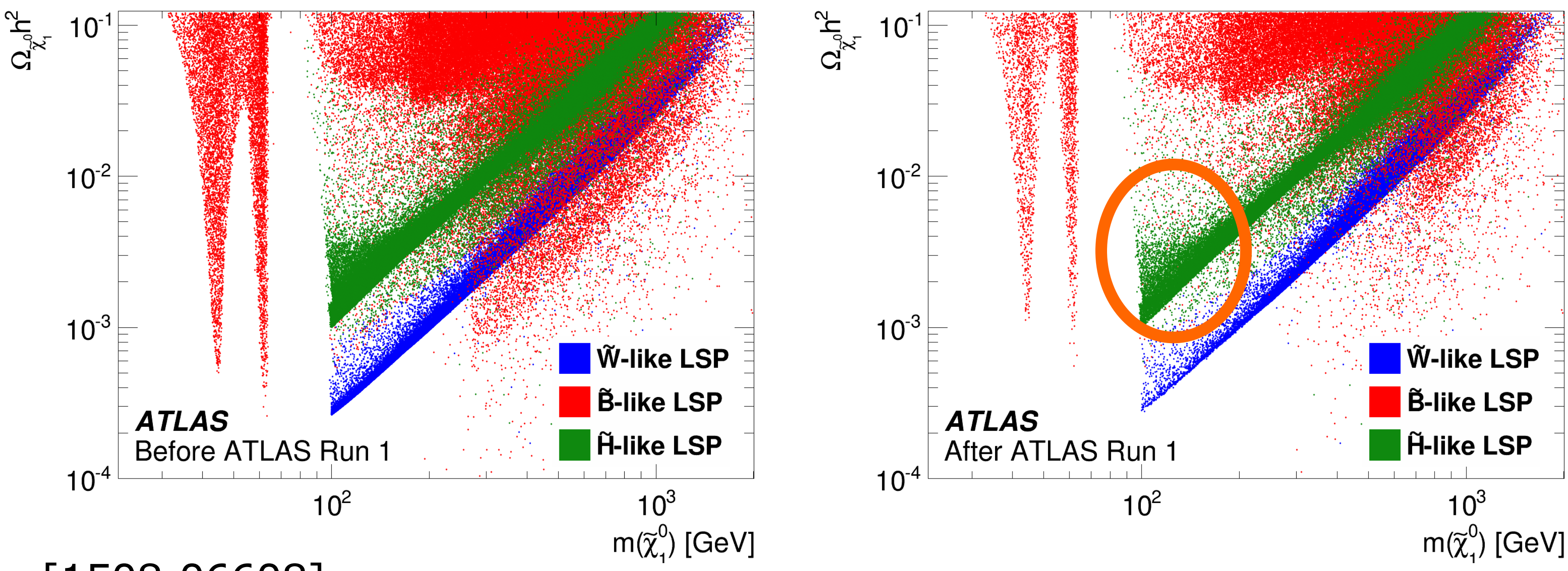
ILC: Mediator mass up to **Λ~3 TeV** for **DM mass up to ~√s/2**

Naturalness and Light Higgsino

Naturalness arguments [e.g. Baer et al, 1207.3343] imply existence of **light Higgsinos at O(100) GeV.**

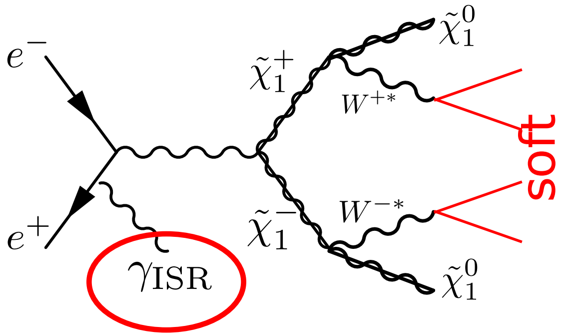
Higgsino LSP scenarios typically lead to **compressed spectra:**
→ small mass gaps between LSP and NLSPs

Small mass gaps (20 MeV < ΔM < 30 GeV) challenging for LHC
→ **No problem for ILC** (next page)



[1508.06608]

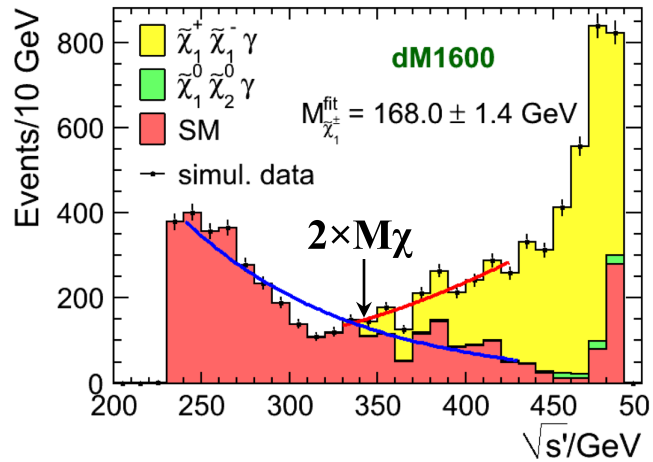
Higgsinos in Natural SUSY (ΔM~1 GeV)

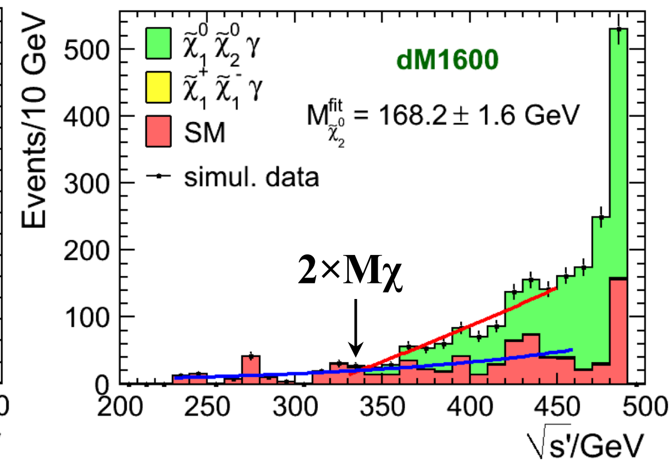


[Berggren et al. 1307.3566]

M(cha1,neu1) ~ 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 clearly possible:





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

Production Cross section

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

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

$\Delta M = 1.6$ GeV

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

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

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

$\Delta M = 0.8$ GeV

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

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

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

Z′

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

- **If LHC discovery** → determine mass of Z′
- **At ILC** → access to couplings through precise measurements of interference effects