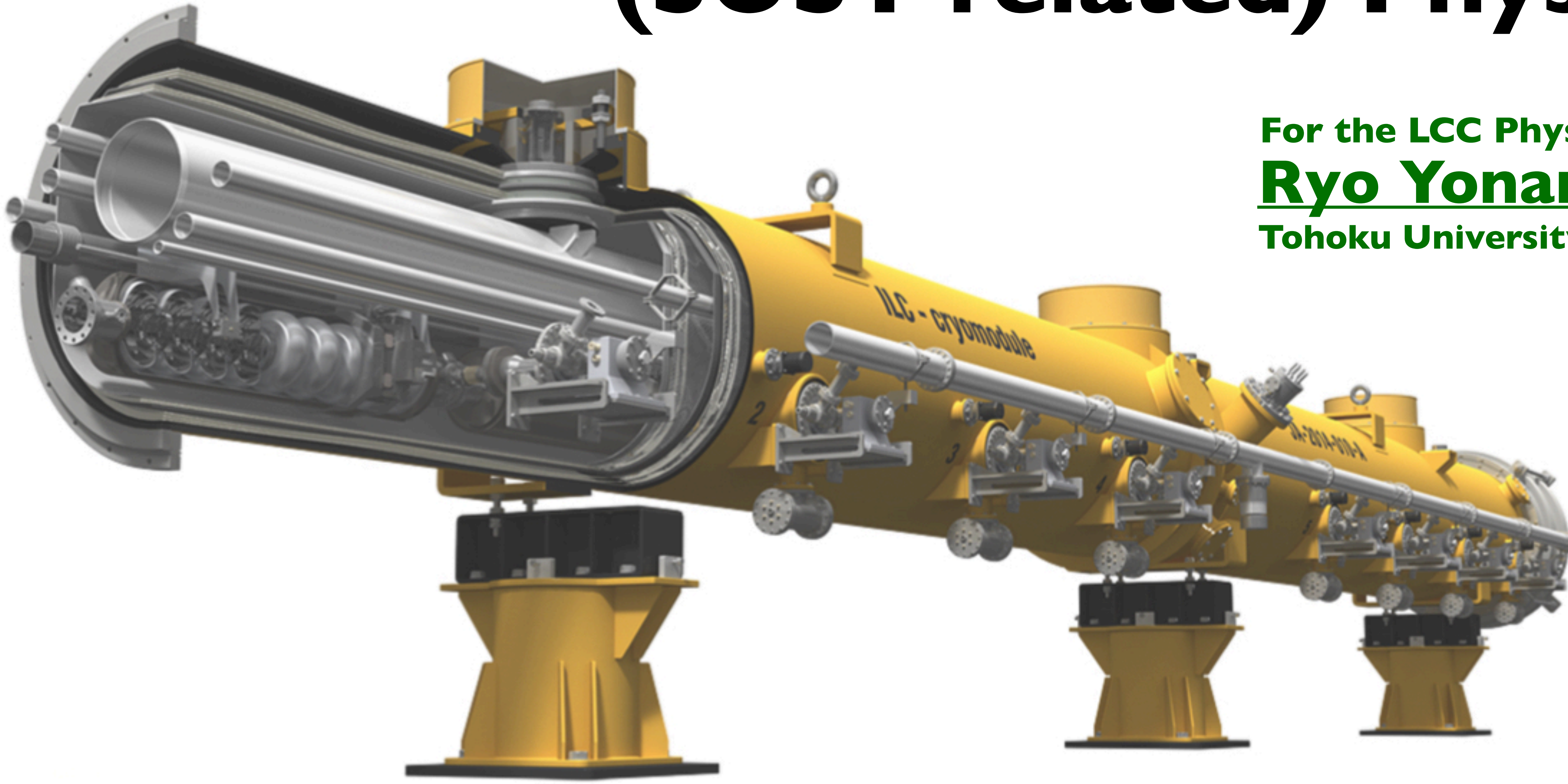
Overview of ILC status & (SUSY related) Physics

For the LCC Physics WG
Ryo Yonamine
Tohoku University



©Rey.Hori/KEK

This presentation is mainly based on

- "**The International Linear Collider A Global Project**" (arXiv:1903.01629)
- "**The Potential of the ILC for Discovering New Particles**" (arXiv:1702.05333) including their references and updates,
- "**ILC implementation status and plans**" (https://indico.cern.ch/event/789524/contributions/3340272/attachments/1827177/2990796/Lausanne_Apr._2019.pdf)

Outline

- Introduction to ILC
- Recent situation in Japan
- (SUSY related) physics cases at ILC
- Summary

What is ILC?

❖ e+ e- linear collider with Superconducting RF cavities

- The design is the result of ~20 years effort by a broad, global community.
- The successful construction and operation of the European XFEL at DESY, which uses the same SRF technology as ILC, provides confidence in realization.
- A most promising candidate site : **Kitakami**, Japan (Stable ground, Many local supporters!)

Find more about Kitakami :

http://www.kitakami-kanko.jp/english/index.php

https://www.iwate-ilc.jp/eng/ktimes/

❖ As merits from e+ e- collider

- Provides controllable initial particle energy
- Low QCD background (compared to hadron colliders)
- Can naturally reduce the number of EFT parameters (EW interaction)

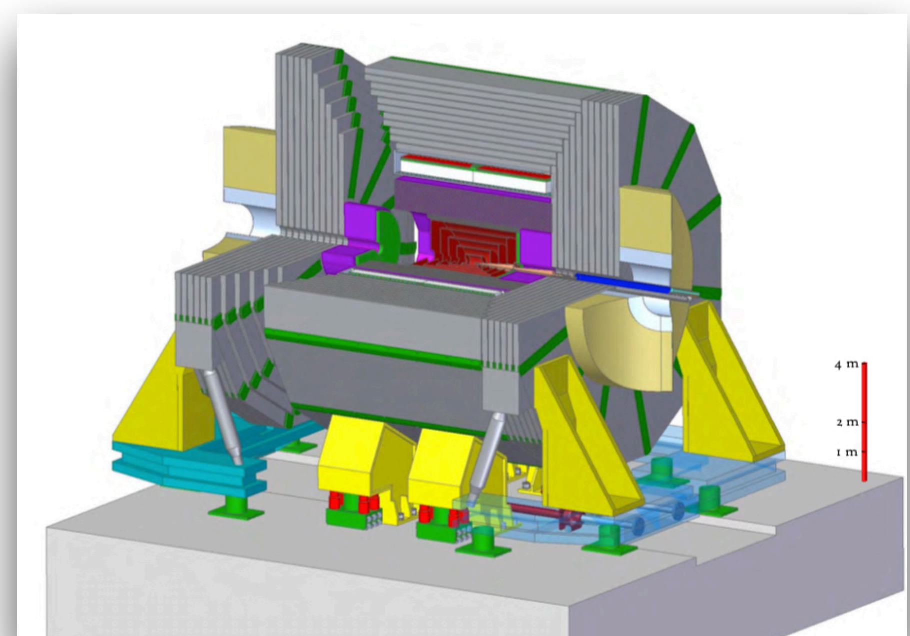
❖ As merit from linear collider

- Provides controllable **beam polarization**
- Energy extendability (e.g. 350 GeV, 500 GeV, 1 TeV)

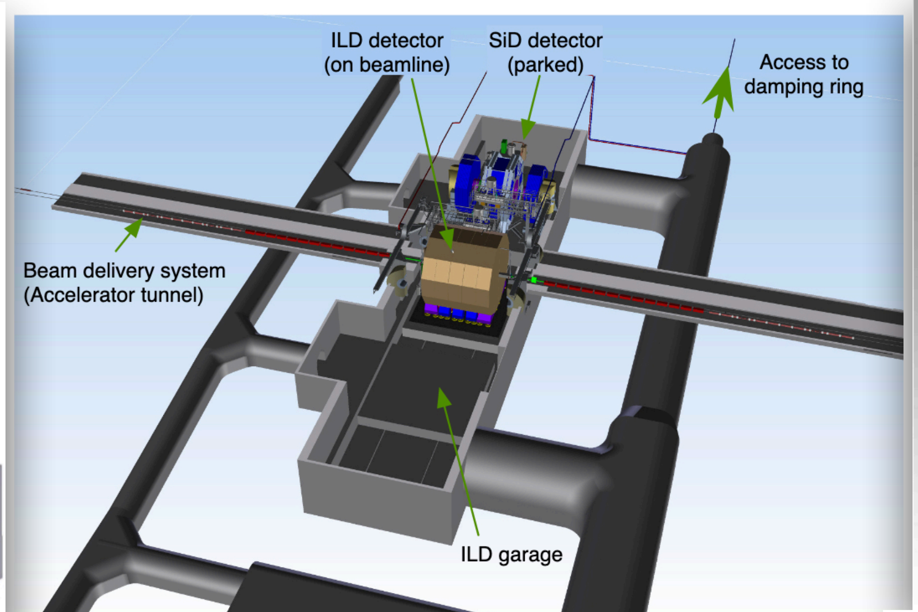
Detectors at ILC

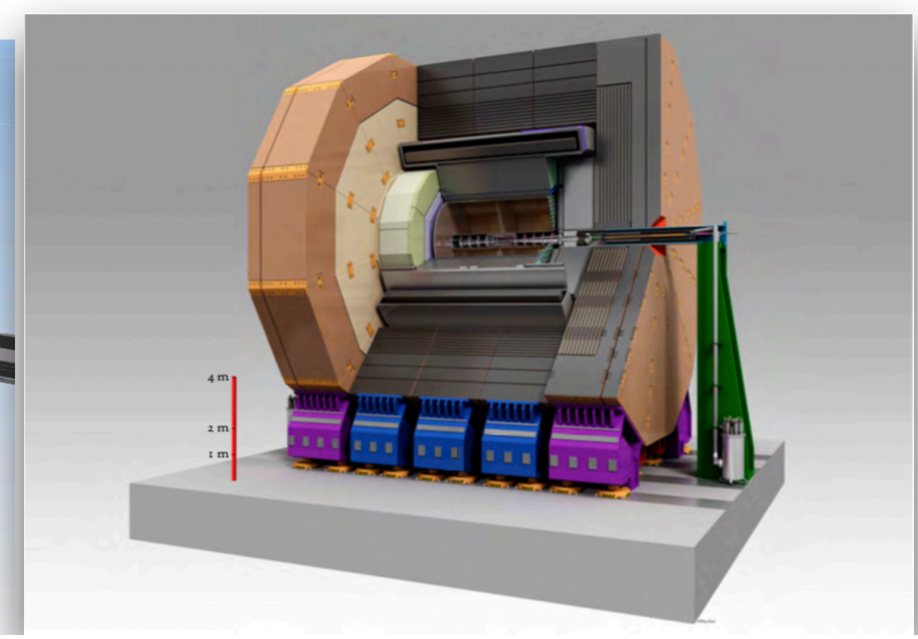
❖ **Two detector concepts proposed for ILC : SiD and ILD**

- Replace detectors on the IP within a day ("push-pull" scheme.),
- Low radiation levels at ILC allow the consideration of a wide range of materials and technologies for the tracking and calorimeter systems, and the innermost vertex detector can be very close to IP,
- Good hermetisity (to ensure reconstruct missing objects),
- To achieve ideal jet energy resolution (3% jet energy resolution above100 GeV), detectors are optimized for Particle Flow Approach.



SiD: R~6m, B=5T, Silicon tracker

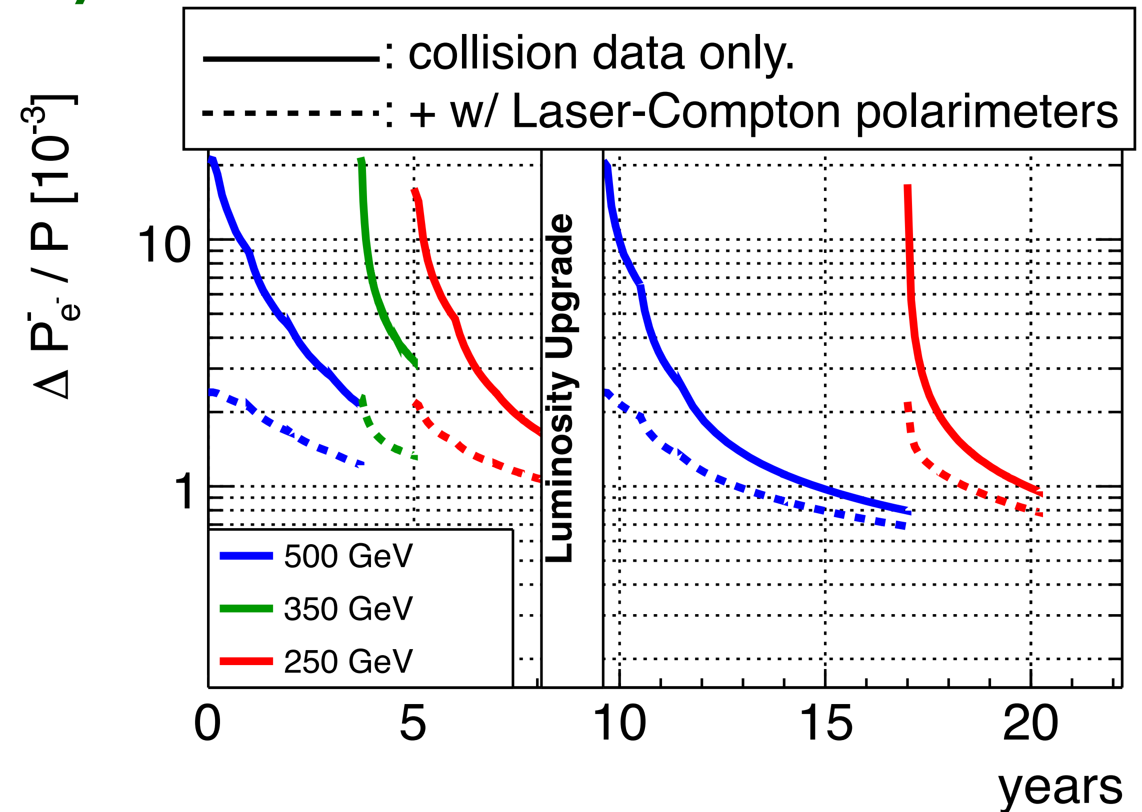




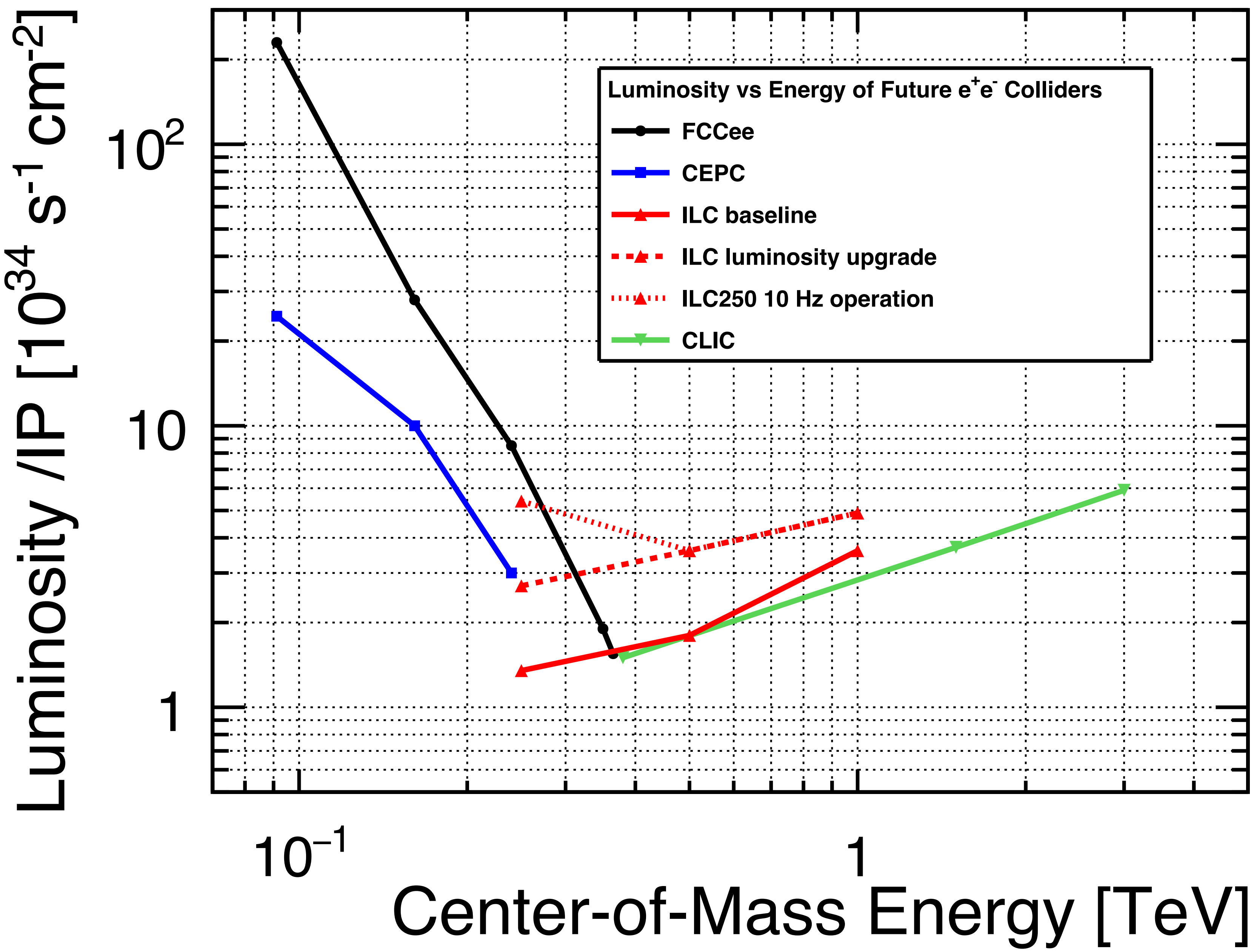
ILD : R~8m, B=3.5T, TPC

Beam polarization

- **One of the attractive features at linear colliders**
  - In circular colliders, very challenging to achieve high beam polarization, especially for longitudinal polarization.
  - A linear electron-positron collider naturally preserves longitudinal beam polarization.
  - Two polarizations for each beam provides 4 distinct datasets.
- **4 distinct datasets allow us to:**
  - Measure helicity-dependent electroweak couplings,
  - Suppress backgrounds and enhance signals (less running time/cost for same physics),
  - Cancel large parts of the experimental systematic uncertainties.
- **Polarimetry**
  - Laser-Compton polarimeters upstream and downstream of IP.
  - In-situ measurement with known SM processes (WW, W, γ, Z) (see more detail : arXiv:1703.00214)



Luminosity



ILC luminosity upgrade : Doubling the number of bunches per pulse from 1312 to 2625. The cost increase is expected to be less than 10%.

ILC 250 10 Hz operation : The collision rate may be doubled from 5 Hz to 10 Hz increasing with additional cryogenic capacity for 500GeV machine.

↓

Feasible to be comparable to FCCee/CEPC in terms of luminosity/per IP.

It should be noted that FCCee and CEPC : 2 IPs are expected (×2).

On the other hand, beam polarization increases effective luminosity for many processes. For example, $2ab^{-1}$ of polarized data (Pe-/Pe+ = ±80%/±30%) were shown to be almost equivalent to $5ab^{-1}$ of unpolarized data for Higgs coupling measurements (arXiv:1903.01629).

Beam polarization can compensate for 2 IPs at FCCee and CEPC.

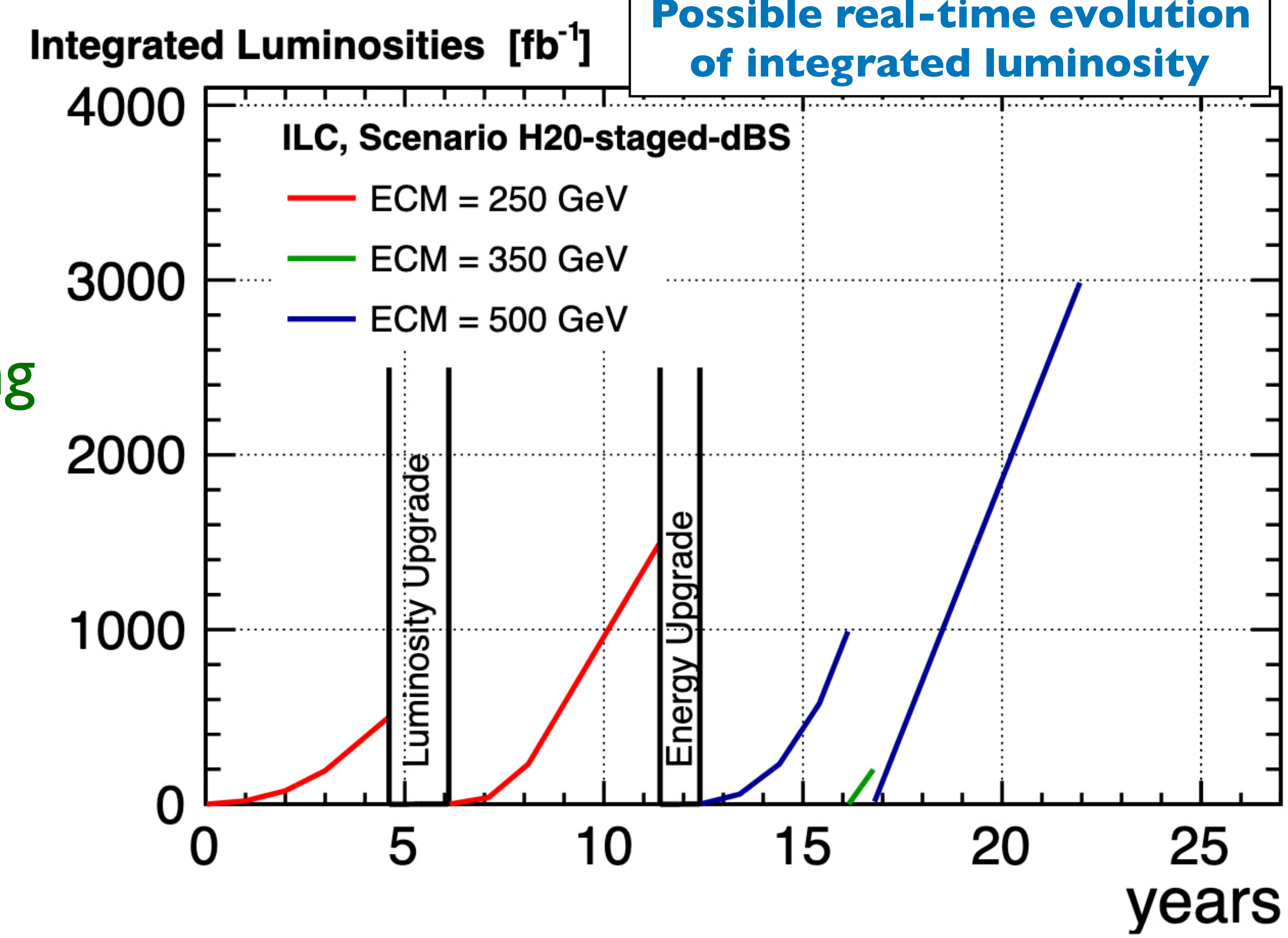
ILC Running scenario

(arXiv:1710.07621, arXiv:1903.01629)

- **Ecm = 250 GeV**
  - Maximum of ZH production cross section.
  - 15 years running (L=2ab^{-1}) together with **HL-LHC results** and **EFT framework** will give powerful and model-independent constraints on the Higgs properties! (see more details in the reference.)

- **Energy upgrade**
  - Higgs self coupling, Top EW couplings
  - New particle searches
  - Great advantage in combining a data set taken at 250 GeV with data set at higher energies because some parameters in EFT have energy dependance.

Possible real-time evolution of integrated luminosity



Situation in Japan

Based on the slides at the Lausanne meeting from M. Yamauchi KEK DG

https://indico.cern.ch/event/789524/contributions/3340272/attachments/1827177/2990796/Lausanne_Apr._2019.pdf

Progress status

❖ **2019.3 : Japanese MEXT released its statement**

Ministry of Education, Culture, Sports, Science and Technology

- MEXT will continue to discuss the ILC project with other governments having an interest in the project.
- International discussions at the government level
- Funding plan discussion among governments

https://www.sankei.com/life/news/190307/lif1903070025-n1.html

⟶ **Now MEXT is strongly involved in the ILC project.**

❖ **2019.3 : KEK submitted a proposal of ILC to SCJ master plan.**

- SCJ master plan: Science Council of Japan (SCJ) calls for proposals of large-scale research projects every three years, and recommends "priority programs" to MEXT.
- MEXT Minister suggested the ILC to be evaluated in this process to provide an evidence of getting support by the broader academic community in Japan.

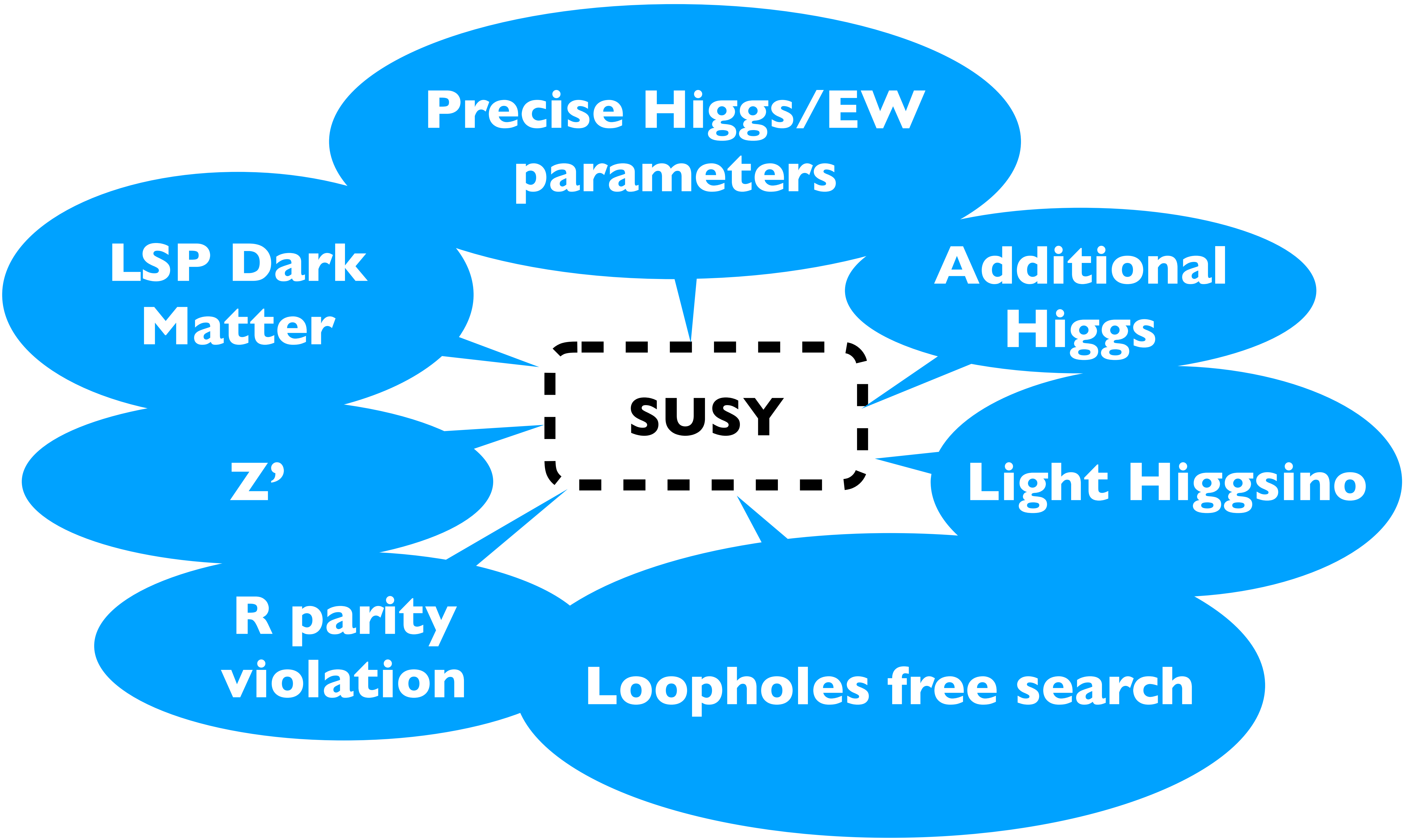
❖ **2019.9 : SCJ will recommend "priority programs" to MEXT**

- Results of the evaluation will be publicized officially 2020.2.

❖ **2020.5? : MEXT will show a new roadmap for next 3 years.**

(SUSY related) Physics

What can ILC do on top of LHC?

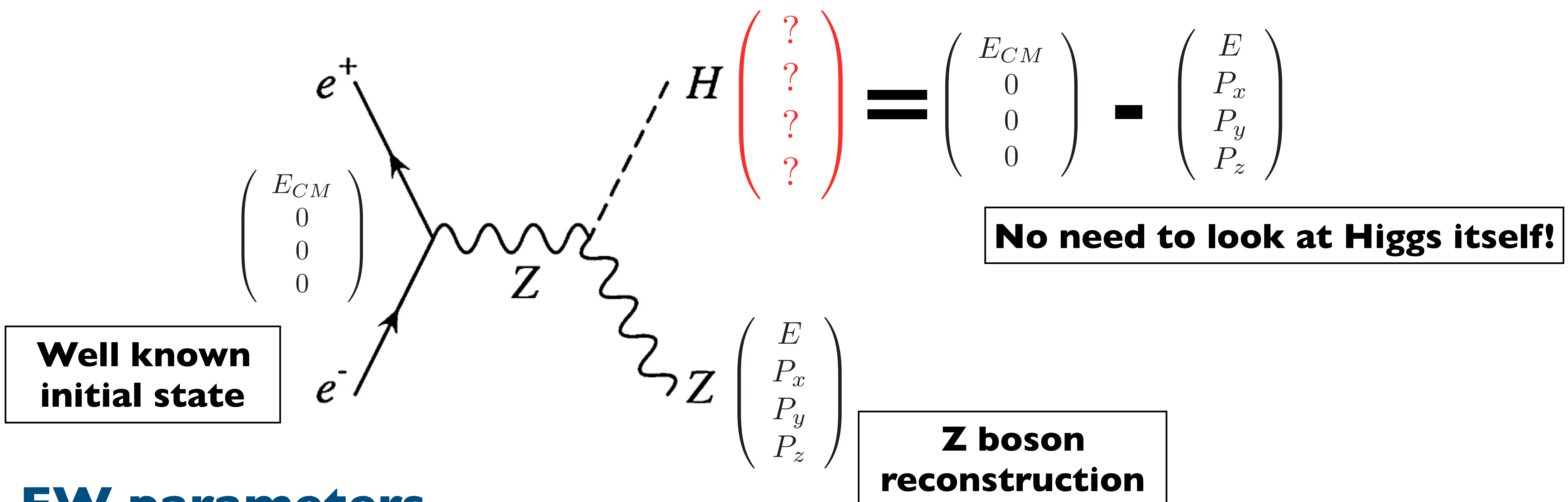


ILC will add many probes for SUSY!

Higgs/EW precision measurements

- **Higgs parameters**
  - Total decay width —> can discover decays to unknown particles.
  - Higgs mass —>**ΔM_H~14 MeV** together with ΔM_t~0.3 GeV (HL-LHC) can probe New Physics up to **10^{12} GeV** considering the vacuum stability.
  - "Higgs recoil mass technique"

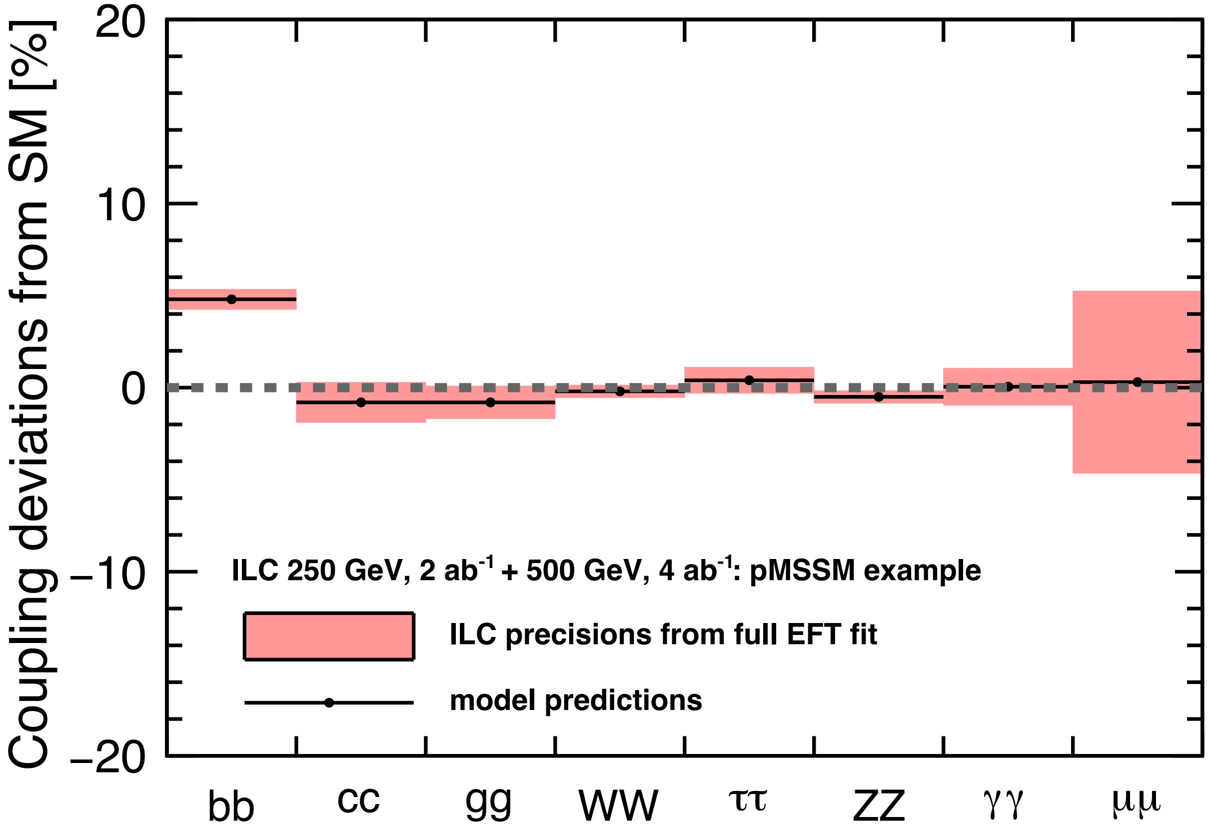
  —> **Model-independent** Higgs (or new scalars) coupling measurement.

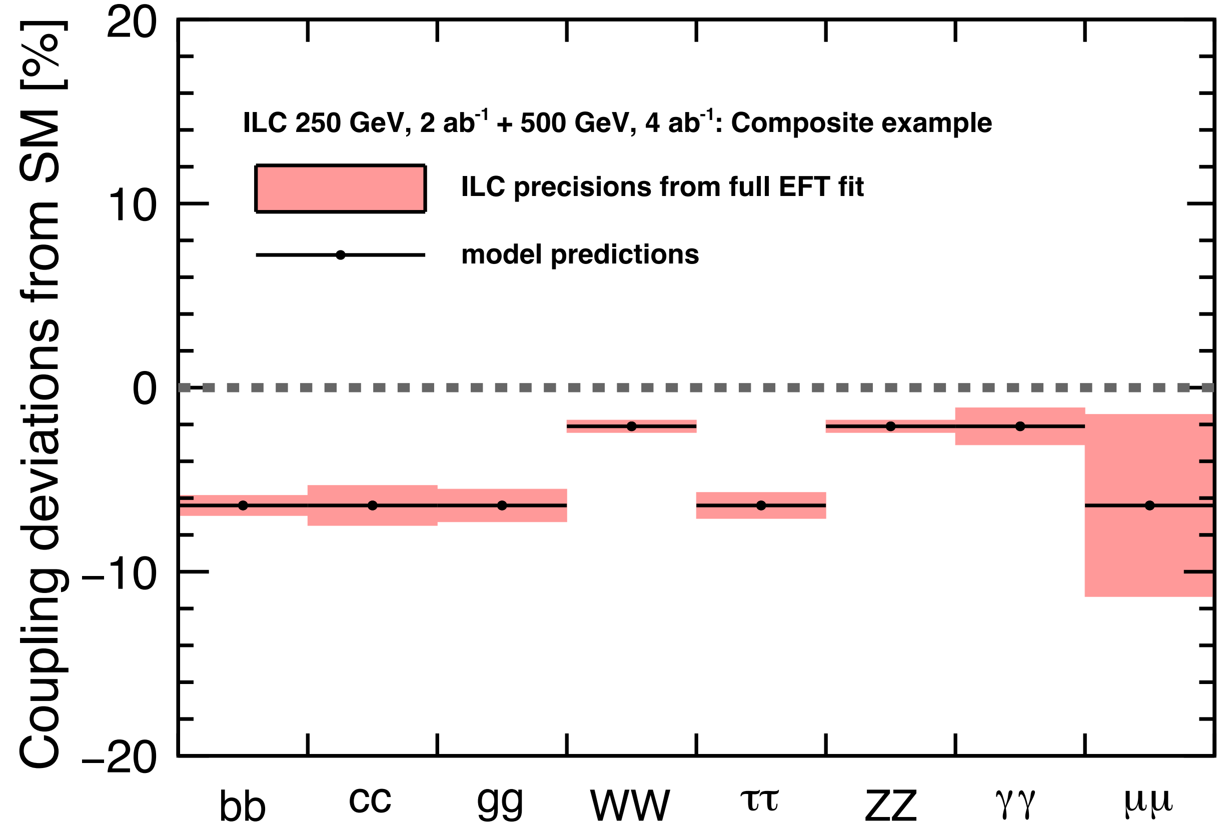


- **EW parameters**
  - M_W, $\sin\theta_{eff}$ —> Assuming the center values remain as they are, ILC measurements would result in 3~4σ discrepancy, which indicate SUSY at TeV scale.

Pattern of Higgs boson couplings could tell us existence of SUSY

(arXiv:1708.08912)





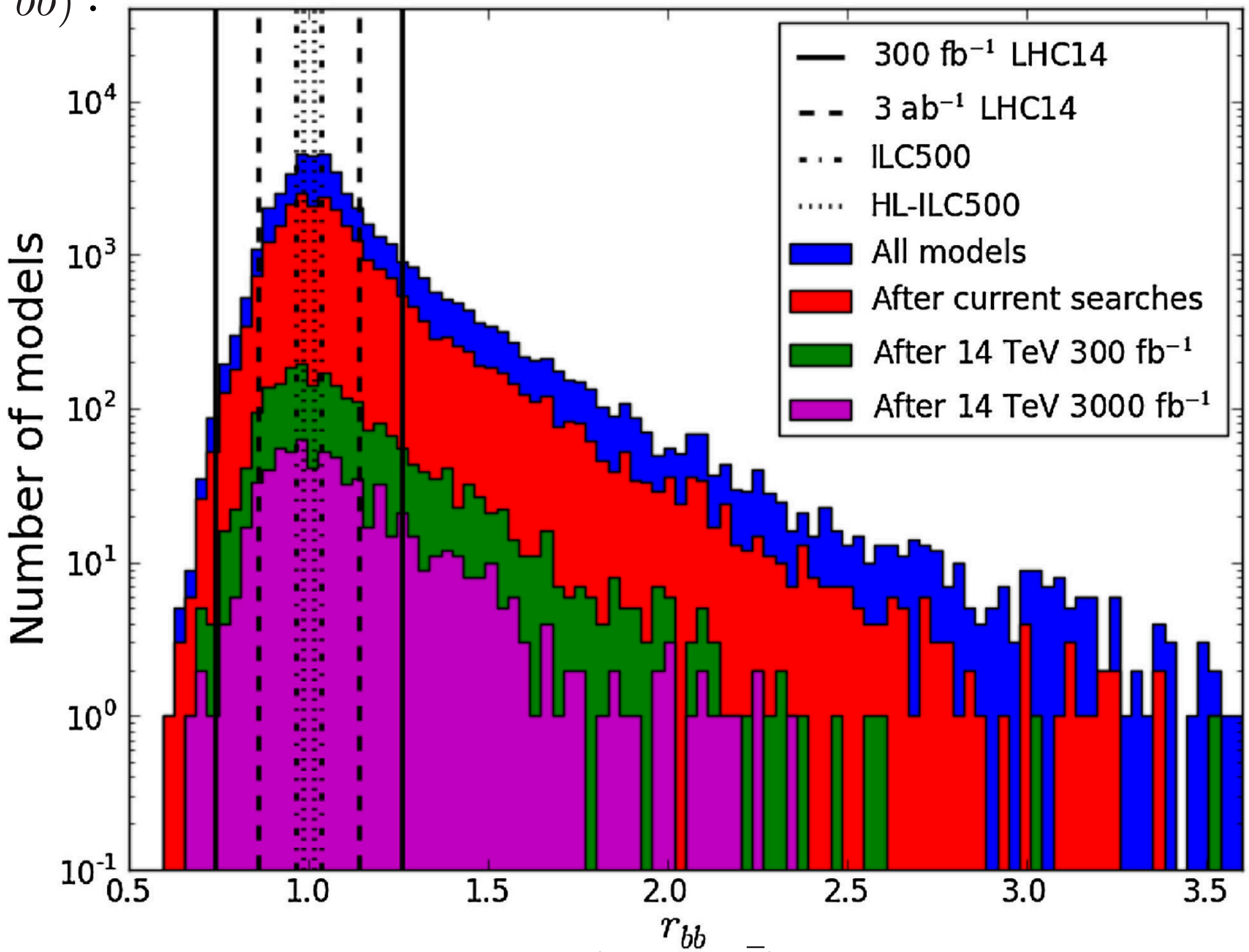
Percent-level precision is the key!

ILC precision for Higgs mass (~14MeV) leads to 0.1% level of higgs coupling precisions to Z and W!

Phenomenological MSSM

PHYSICAL REVIEW D90,095017 (2014) M. Cahill-Rowley, J. Hewett, A. Ismail, and T. Rizzo

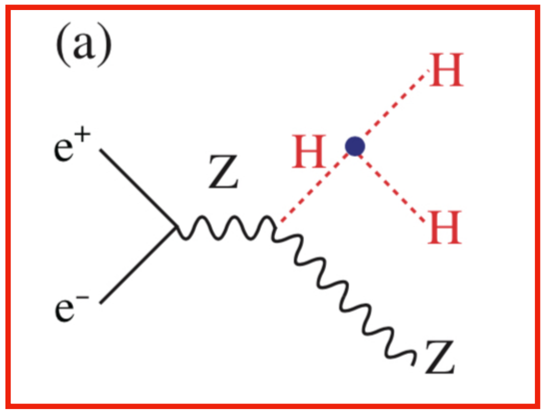
The most general version of the R-parity conserving MSSM with a minimal set of experimentally motivated guiding principles gives many possible models depending on $\Gamma(H \to b\bar{b})$.



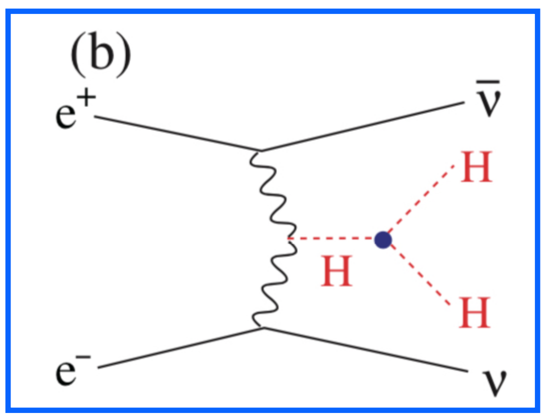
$\Gamma(H \to b\bar{b})$

Higgs self coupling λ

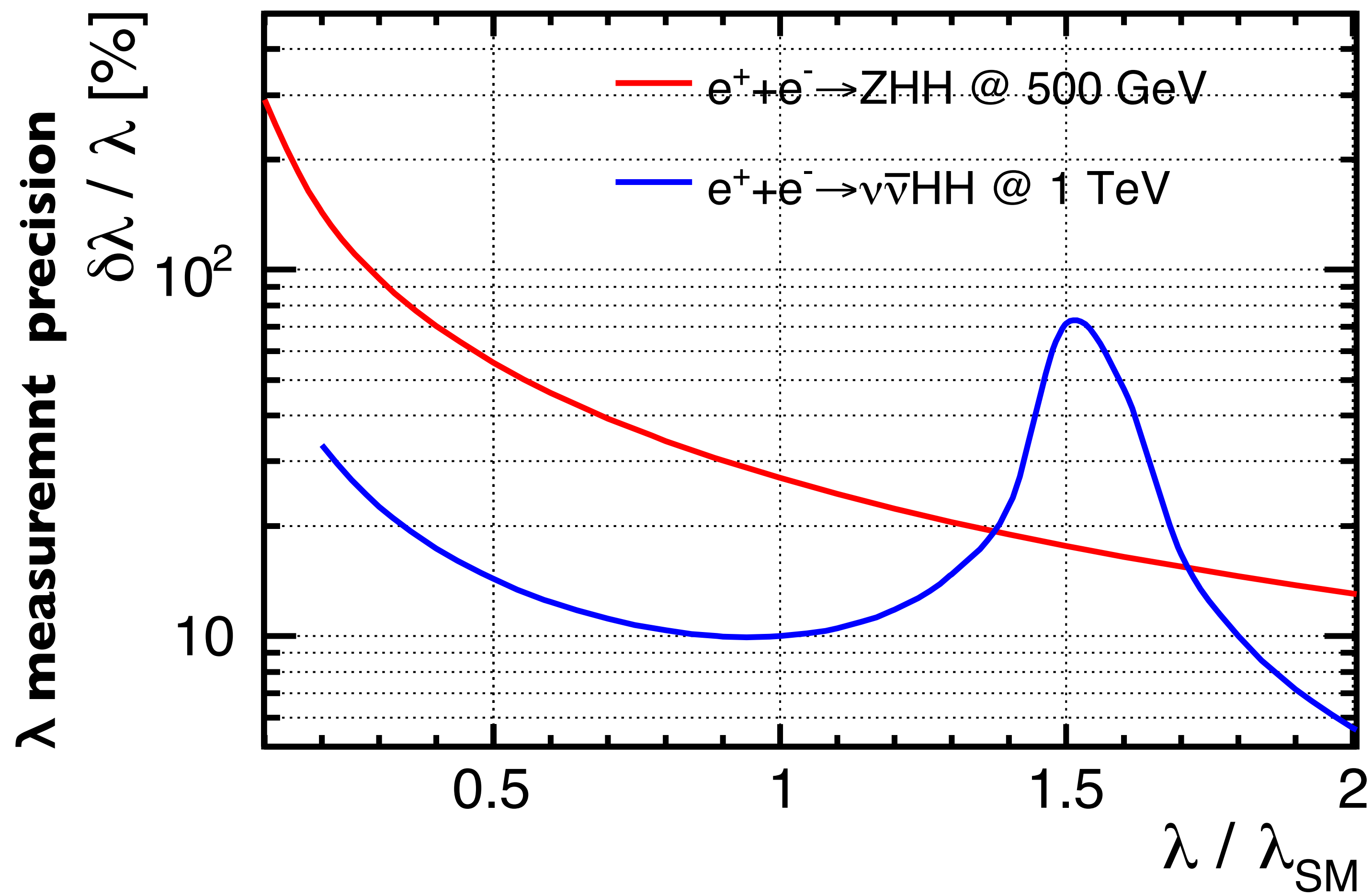
- Could deviate by ~20 % level if a new scaler boson exists.



Dominant at 500 GeV



Comparable to ZHH at 1 TeV



λ normalized by its SM value

Two channels are complementary :

$$\frac{\lambda}{\lambda_{SM}} < 1 \longrightarrow \nu\bar{\nu}HH$$ (1TeV) **is better**

$$\frac{\lambda}{\lambda_{SM}} > 1 \longrightarrow ZHH$$ (500GeV) **is better**

(especially λ/λSM ~ 1.5)

$$\delta\lambda/\lambda \sim 10\%$$

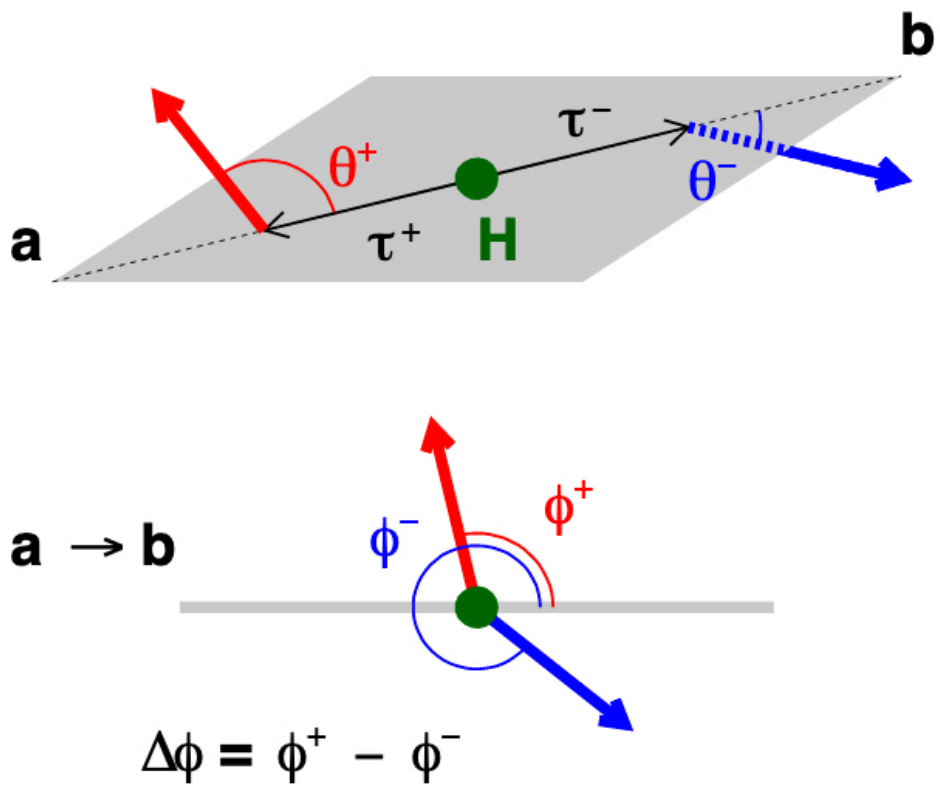
is feasible ! ($\lambda \sim \lambda_{SM}$, 1TeV)

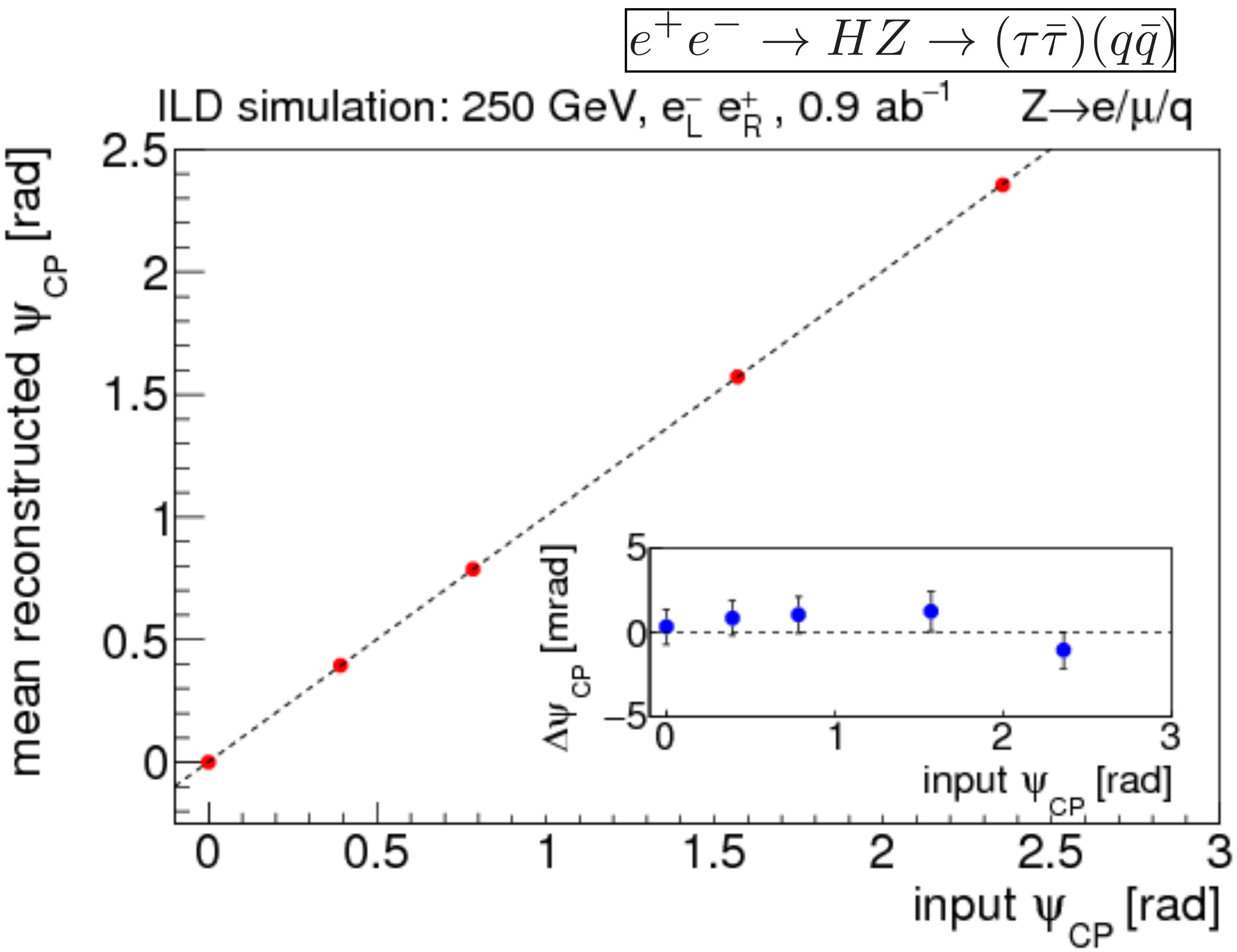
Higgs CP properties

(arXive:1903.01629, arXive:1804.01241)

$$\mathcal{L}_{H\tau\tau} = g\bar{\tau}(\cos\psi_{CP} + i\gamma_5 \sin\psi_{CP})\tau H$$

- The CP phase angle Ψ_{CP} can be determined using the transverse spin correlation ($\Delta\Phi$) between the two τs.



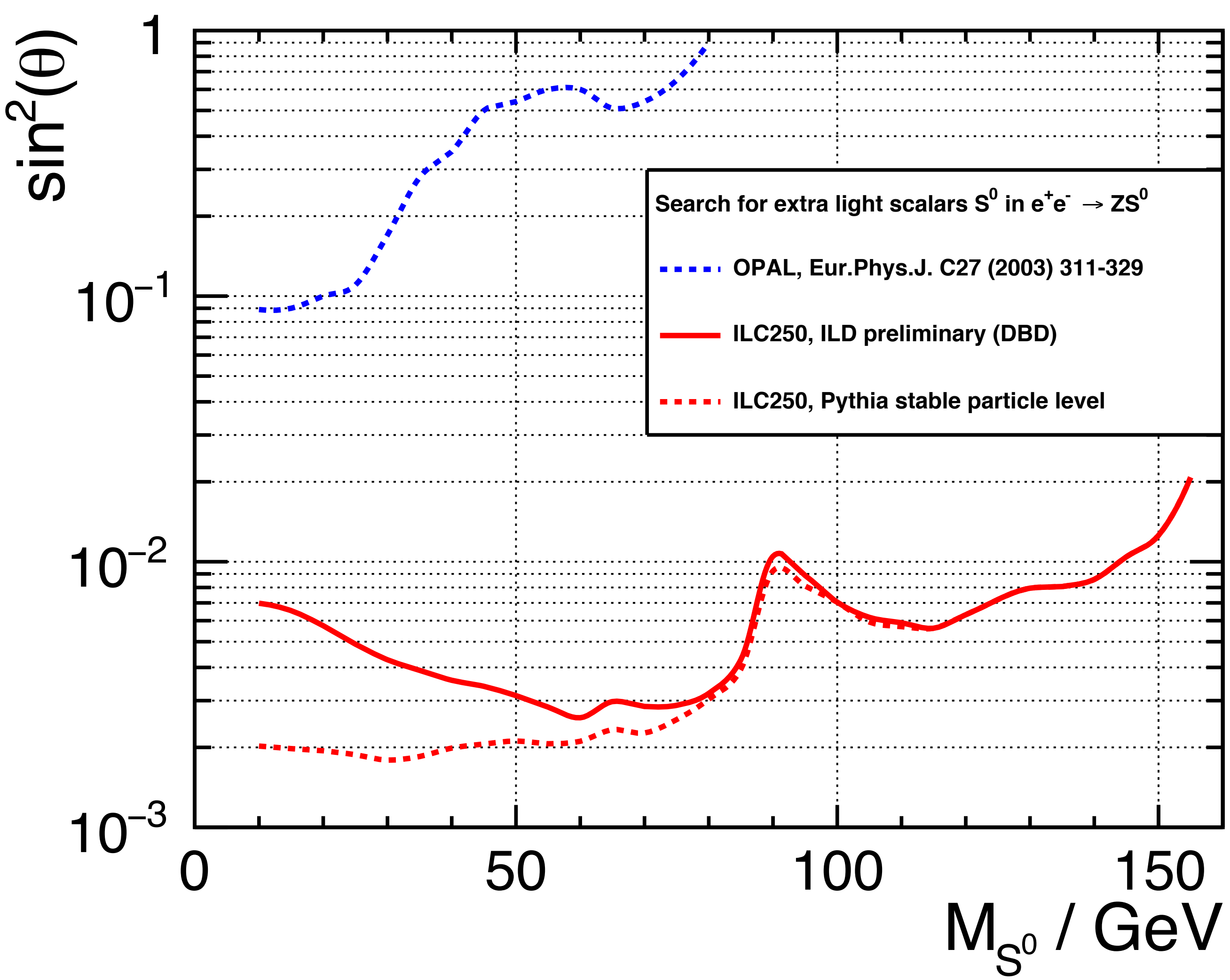


Possible to measure CP-phase better than 4°.

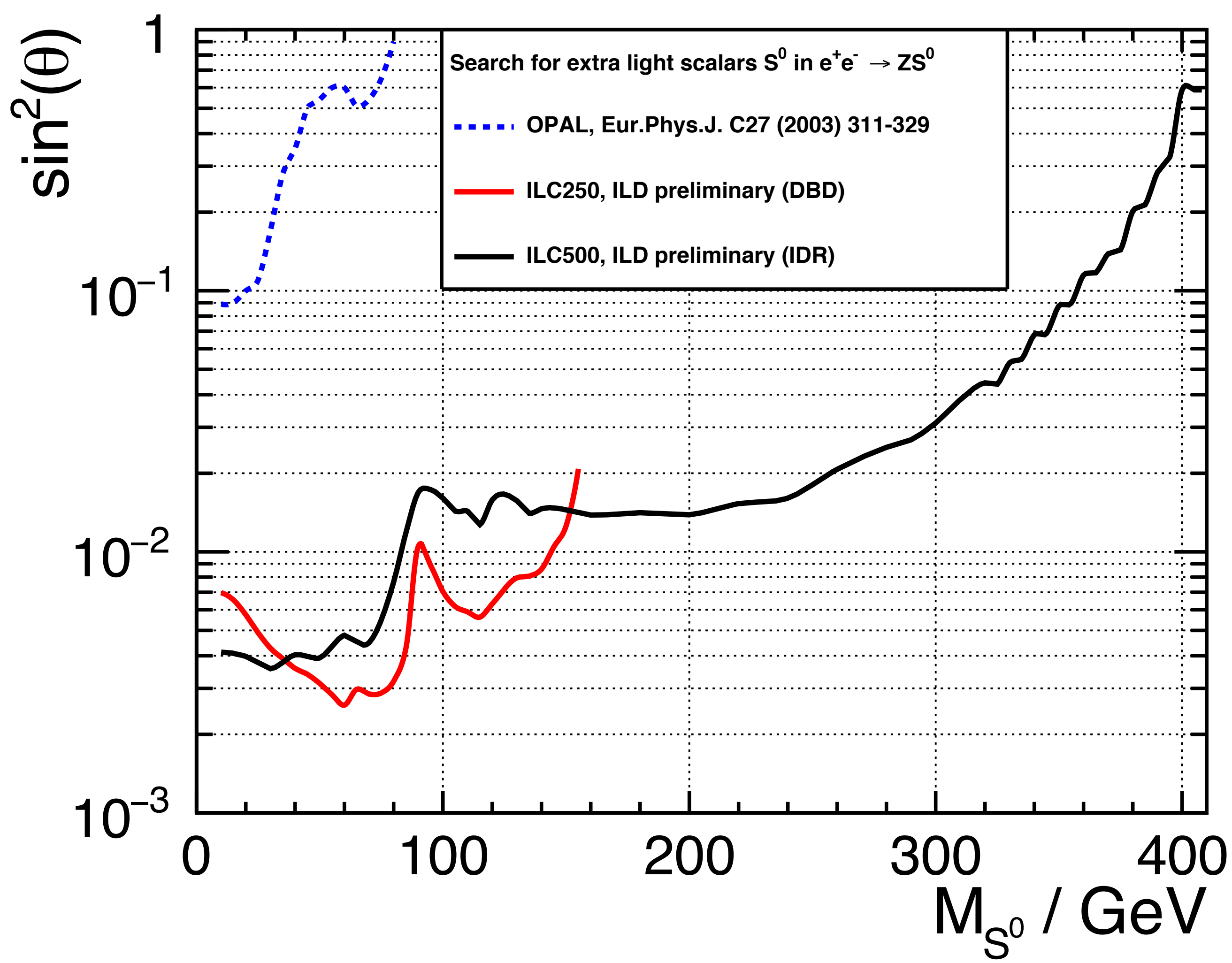
Additional Higgs bosons

- Very precise and model-independent measurements of 125-GeV particle can probe far beyond the kinematic limit and beyond the reach of the LHC.
- ILC offers unique opportunities to directly produce additional lighter Higgs bosons (or any weakly interacting light scalar / pseudo-scalar particles).

θ : **Mixing angle of new scalar to H_{SM}**



1-2 orders of magnitude improvement over LEP recoil results

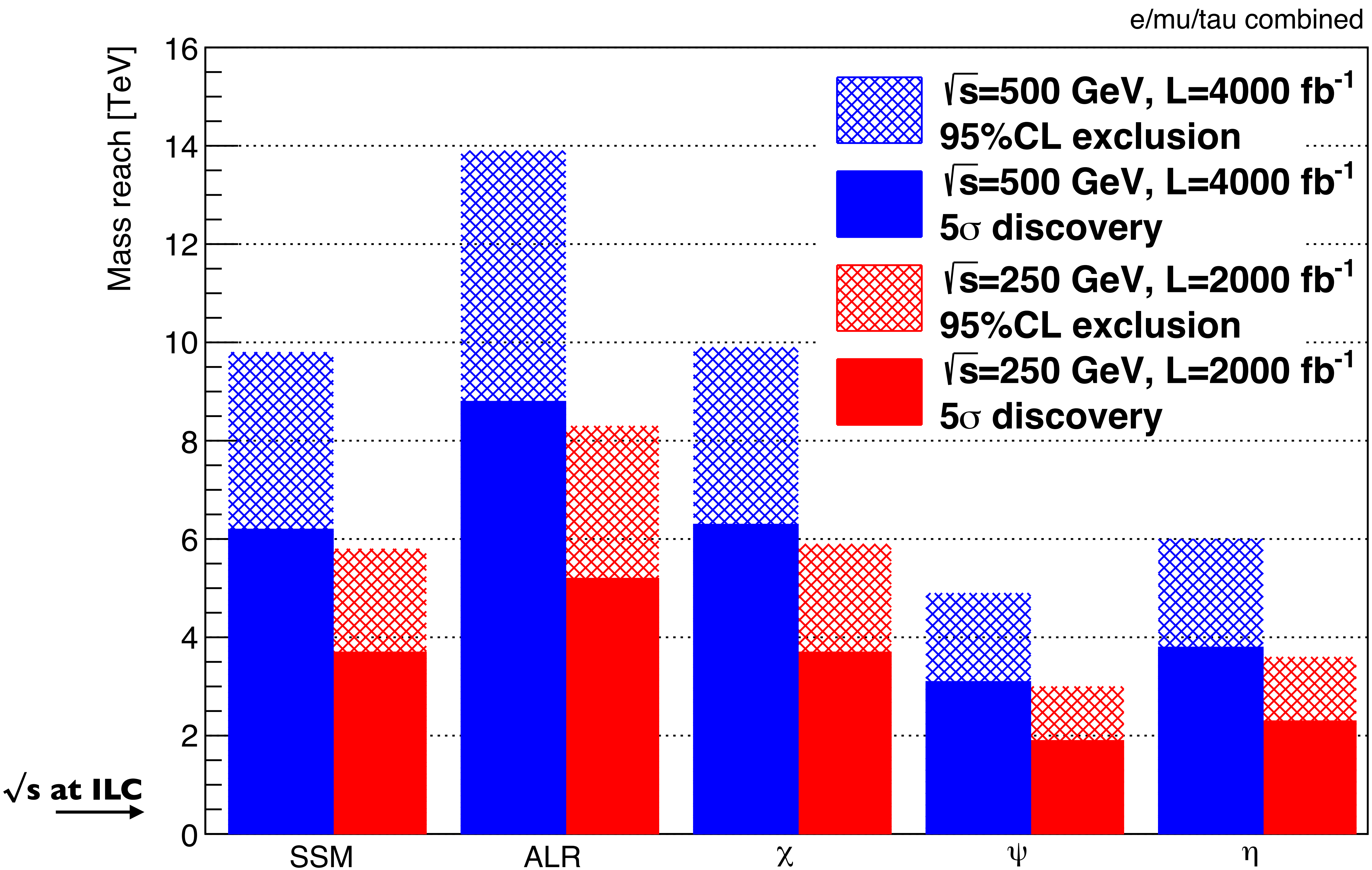


500 GeV ILC covers larger mass region (<~300 GeV).

A new gauge symmetry U'(1)

- **SUSY U'(1) extension**
  - Solves the μ problem by replacing μ by a dynamical variable linked to the U'(1) breaking, and the allowed MSSM parameter range would be extended.
  - U'(1) has many possible implications for supersymmetry breaking and mediation, and for communication with a hidden sector.
  - U'(1) occurs frequently in Superstring constructions.
  - It is natural to expect $M_{Z'}$ in TeV range if there is supersymmetry at TeV scale, then both the electroweak and Z' scales are usually set by the scale of soft supersymmetry.
  - $e^+e^- \to f\bar{f}$ can be used as the probe because s-channel resonance could affect the cross sections.

Z' discovery reach



Study by Kyushu group and KEK group

500 GeV results were extrapolated from 250 GeV full simulation results.

Generic WIMP search

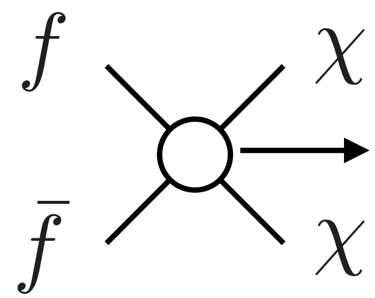
(http://bib-pubdb1.desy.de/record/417605/files/Moritz_Habermehl_PhD.pdf)

❖ General approach with effective operators

- Setup and cross-section formulas from Chae and Perelstein (JHEP05(2013)138).
- WIMP pair production in association with an ISR photon.

Observables : E_γ, θ_γ

$$\mathscr{L}^{\mathrm{eff}} = \frac{1}{\Lambda^2}(\bar{f}\Gamma f)(\chi\Gamma\chi) \qquad \Gamma = \begin{cases} 1 \\ \gamma^\mu \\ \gamma^5\gamma^\mu \end{cases}$$

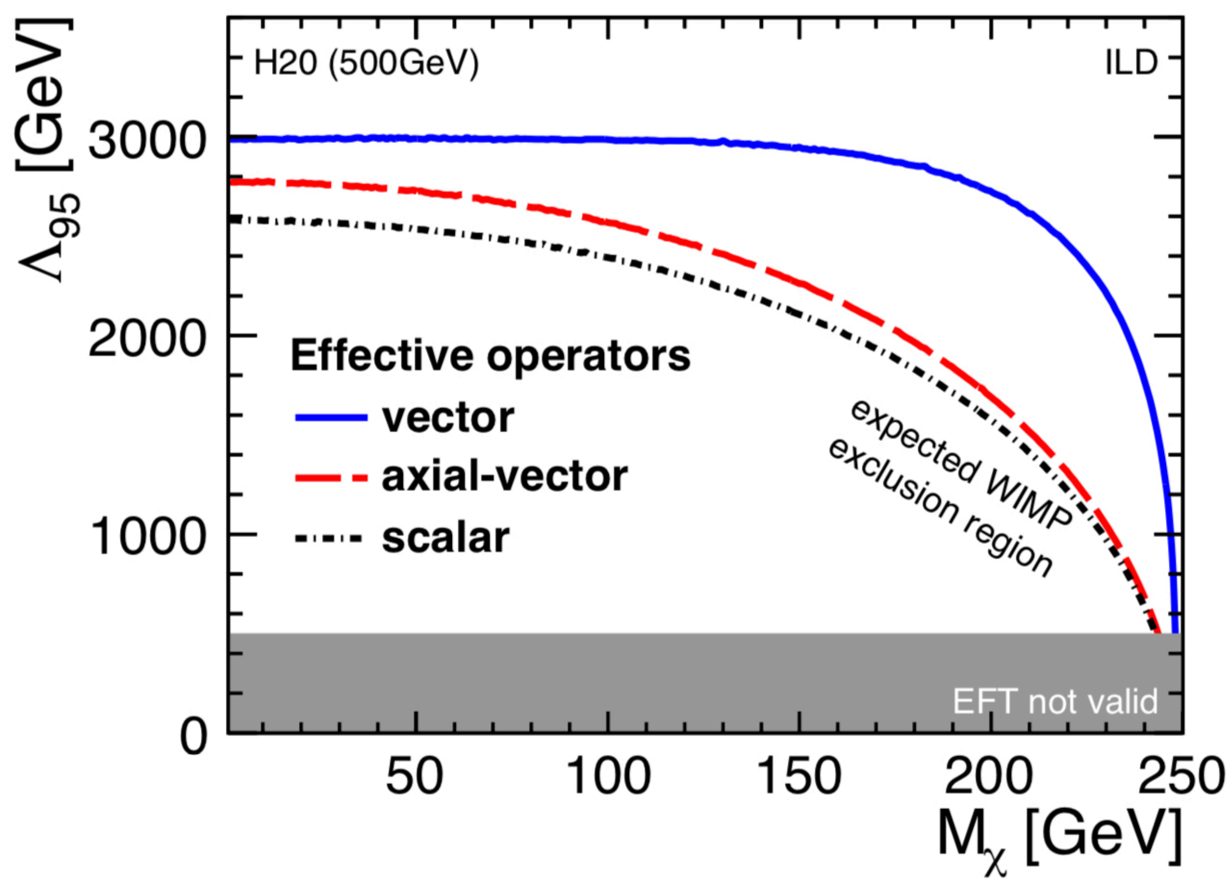


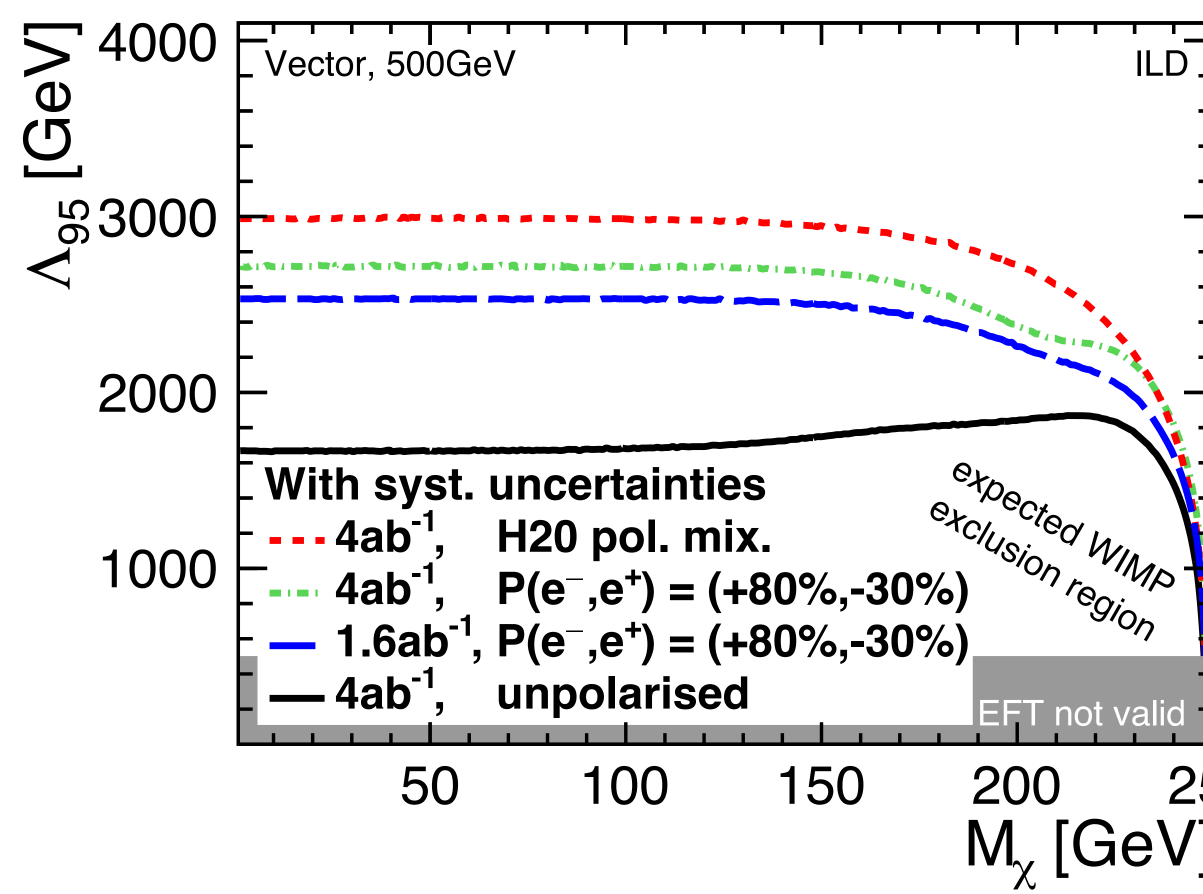
$$\frac{1}{\Lambda^2} = \frac{g_f g_\chi}{M_{\mathrm{med}}^2}$$

Models are parameterized by Λ (energy scale of new physics).

- Detailed detector simulation study for Ecm=500GeV has been done.

2σ expected exclusion limits

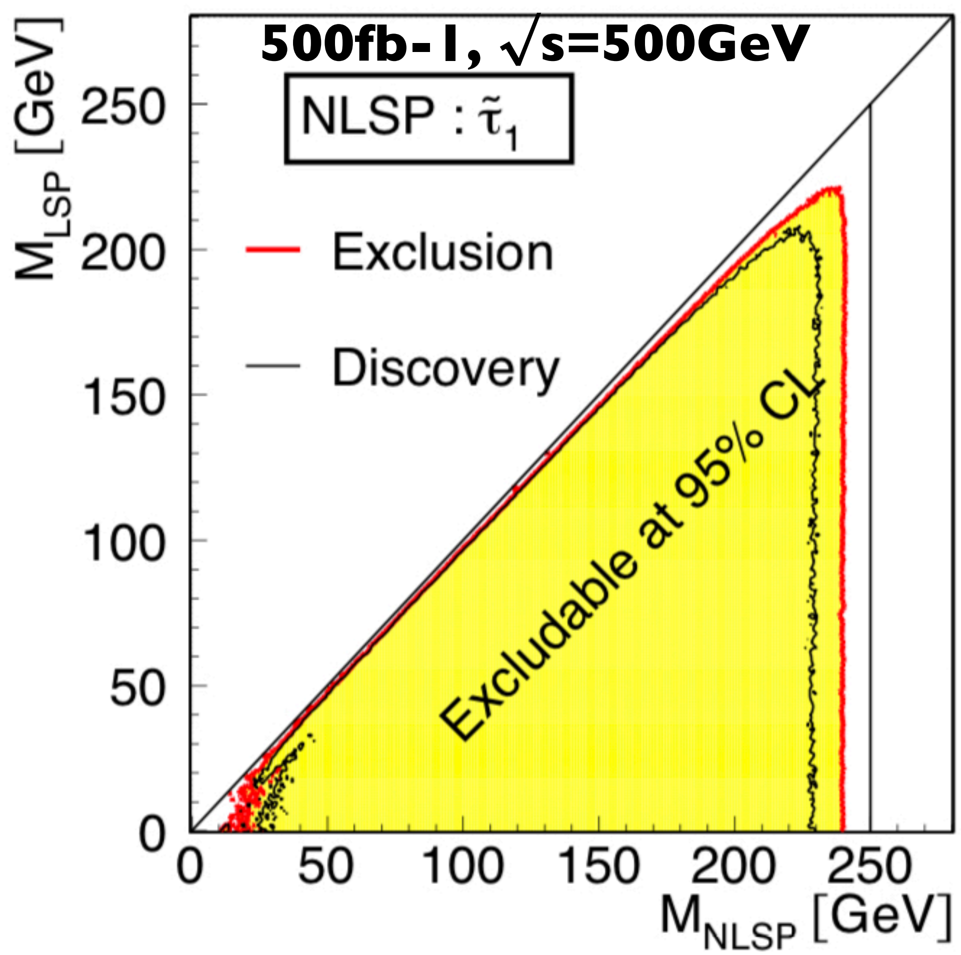




Loophole free searches

❖ **Draw attention to NLSP —> LSP + SM particles**

- Assuming R-parity conservation, NLSP must decay to LSP and SM partner of the NLSP.
- NLSP pair production allows us to study entire space of models (if kinematically reachable and R-parity conserving).
- This analysis was already carried out at LEP.
- A few difficult cases (R-parity violation, Mixed NLSP, etc.) are discussed in arXiv:1308.1461 (In conclusion, none of them will represent a loophole).



One of the experimentally most challenging case :
NLSP = $\tilde{\tau}_1$

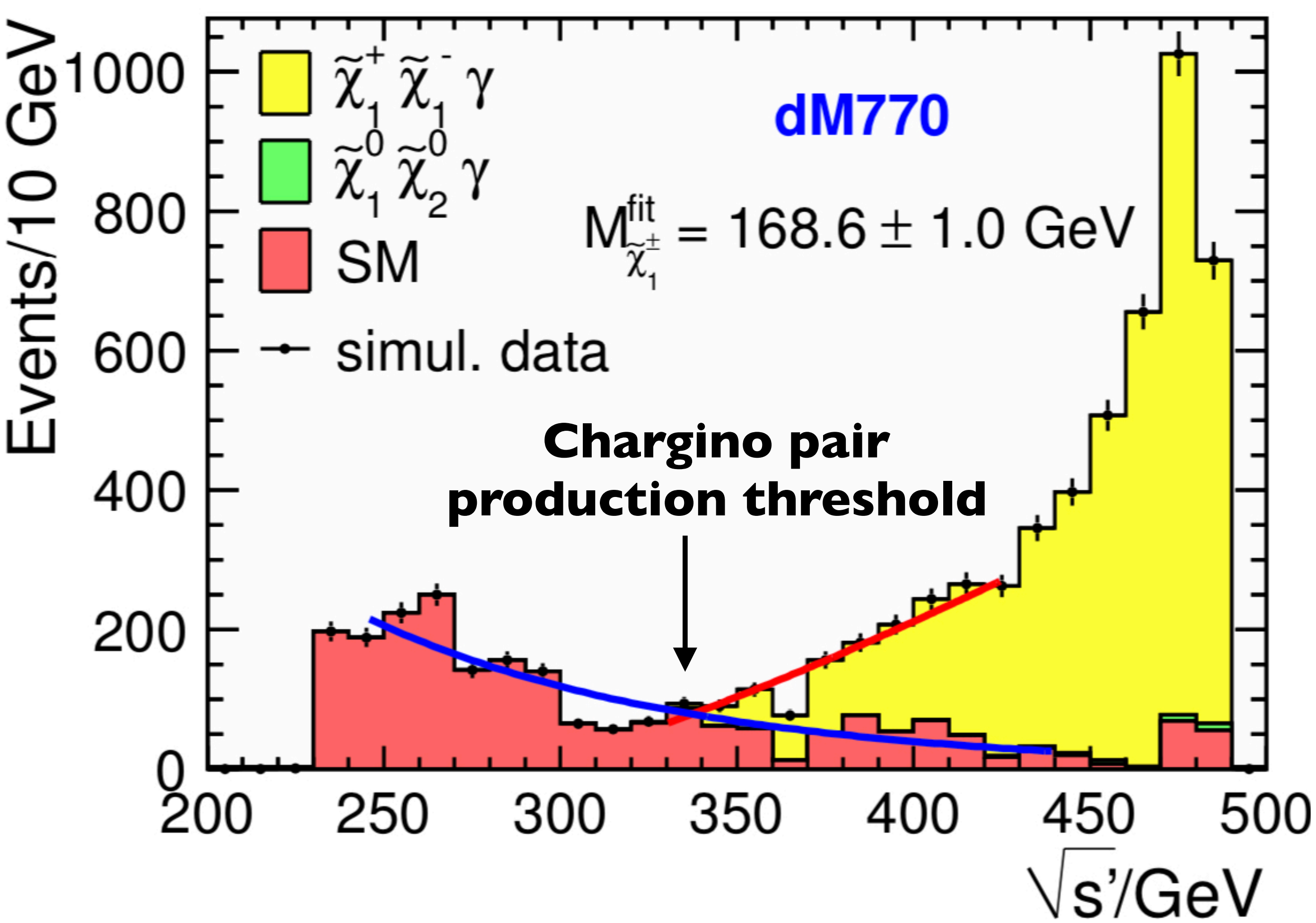
- Need to reject two τ background events.

Even in this most difficult case, most of the kinematically allowed area can be model-independently tested!

Light Higgsinos

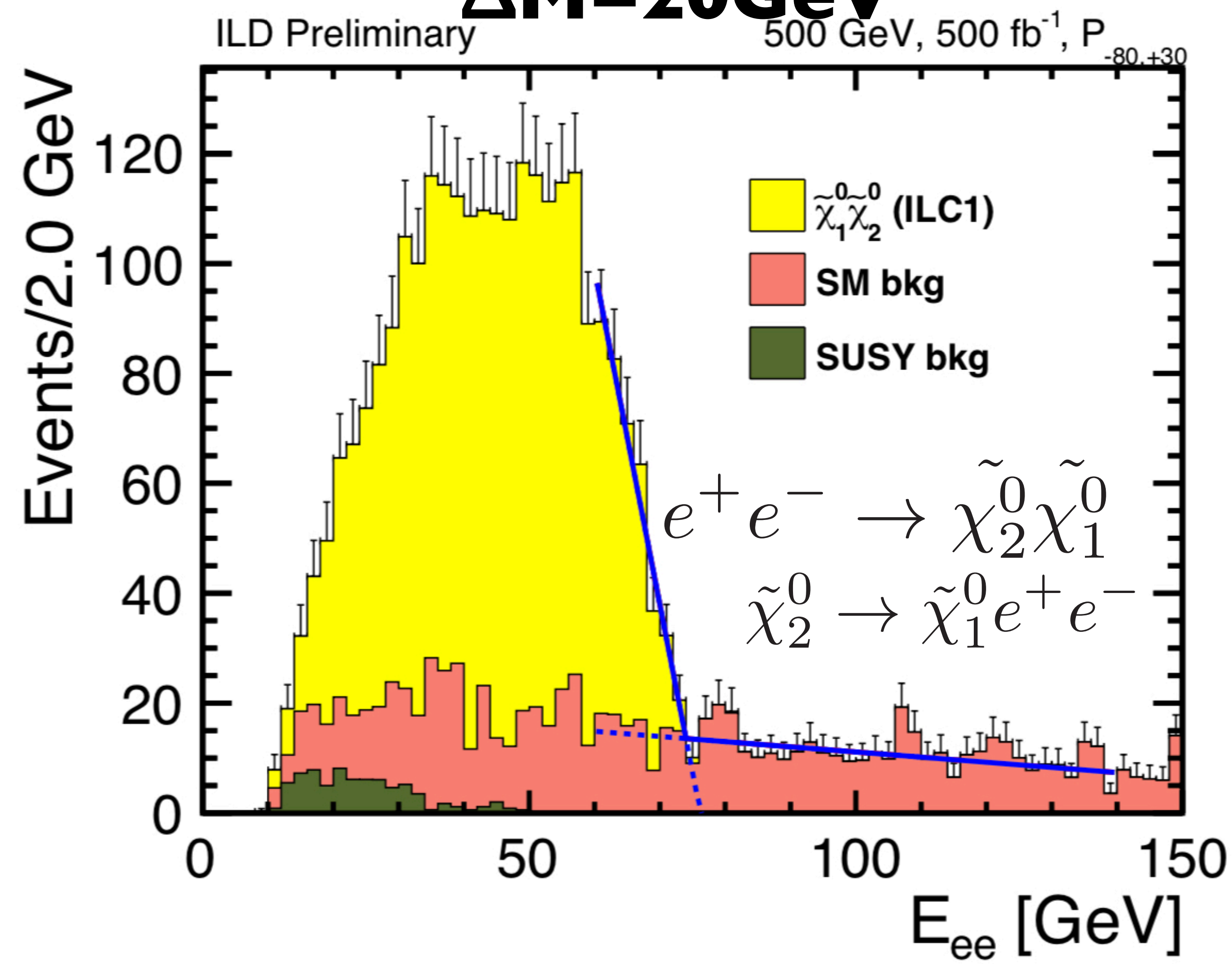
- **Naturalness-motivated SUSY requires Higgsino masses not to be far above Higgs mass even if the other SUSY particles are much heavier.**
  - Mass differences within the higgsino sector are small (typically below 20GeV)
  - ILC can detect soft visible particles from such decays!

ΔM=770MeV



Reduced centre-of-mass energy of the system recoiling against the ISR photon

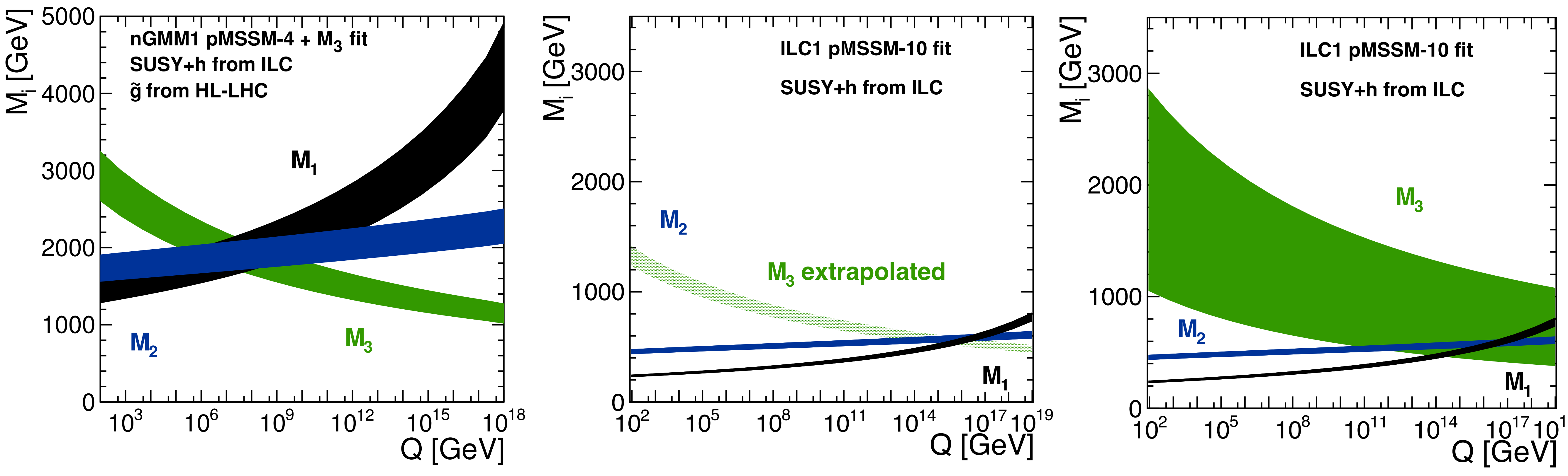
ΔM=20GeV



Di-electron energy

Once SUSY particle has been found...

- **ILC flexibly can react to the target of the new discoveries.**
  - e.g Higgs factory —> Higgsino factory, DM factory
- **LSP Dark Matter properties**
  - mass, couplings to SM particles, associated mediator particle
- **Physics at GUT scale!**
  - Natural SUSY + SUSY mass spectra measurements open possibility to study physics at GUT scale!



Summary

- **ILC is the most advanced future e+e- collider**
  - The technologies for ILC is well advanced (e.g. XFEL success).
  - Even at 250 GeV, it is feasible to be comparable to FCCee and CEPC in luminosity-wise thanks to the beam polarization.
  - ILC is being discussed now at governmental level as well as physicist level.

- **ILC is powerful tool for searching/characterizing SUSY.**
  - well-defined initial state and low QCD backgrounds,
  - Beam polarization plays an important role for many analyses.
  - Has naturally energy extendability.

- **Some examples of SUSY related analyses are presented.**
  - Precise measurements of Higgs couplings and EW parameters
  - A new heavy gauge boson search
  - Model independent Dark Matter search
  - Loophole free search
  - Light higgsino search

LCWS2019

28 Oct. - 1st Nov. 2019
in Sendai/Japan.

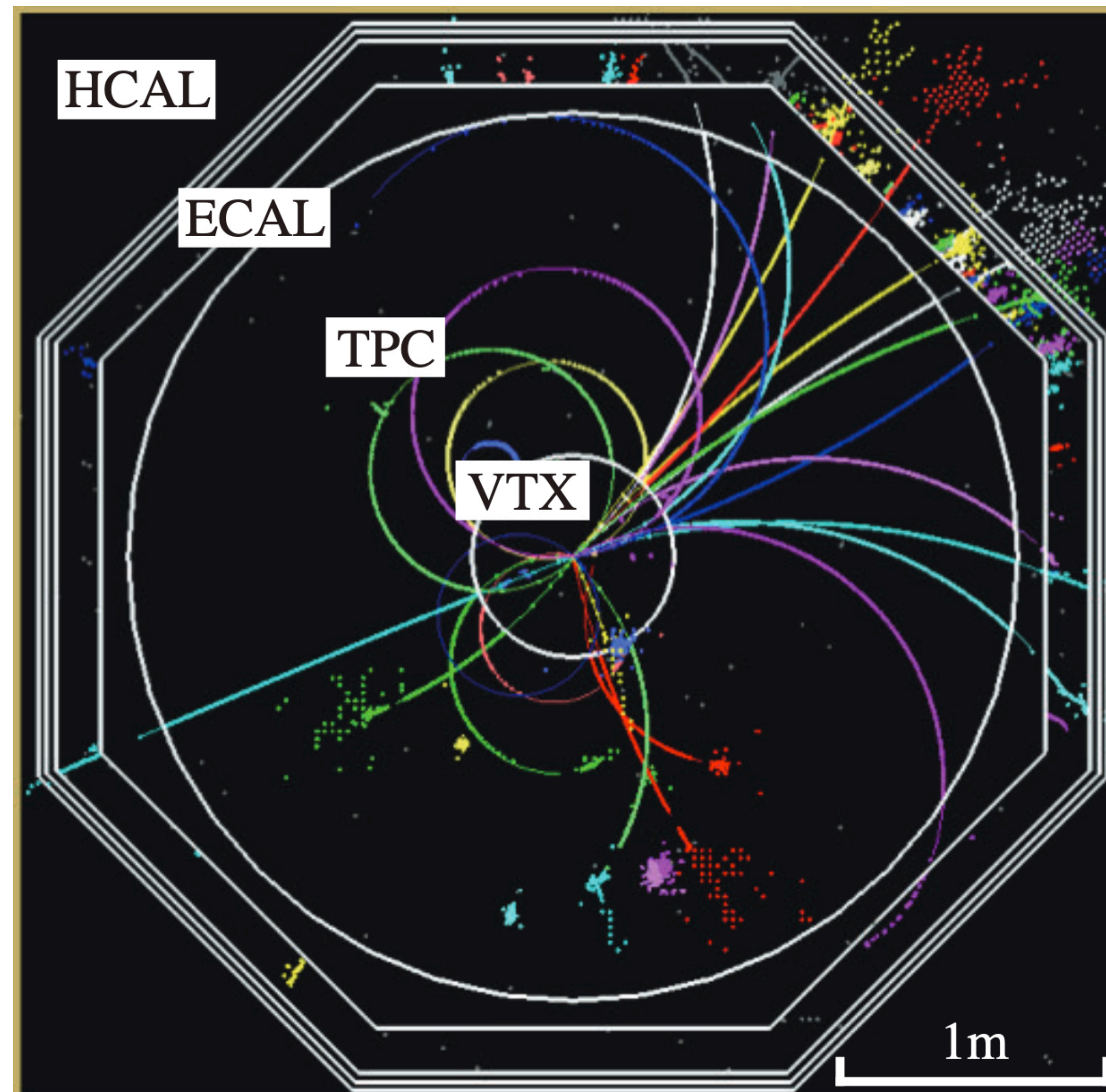
Why not come to join us?

Find more about Sendai:
http://www.sendaimiyagidc.jp/en/

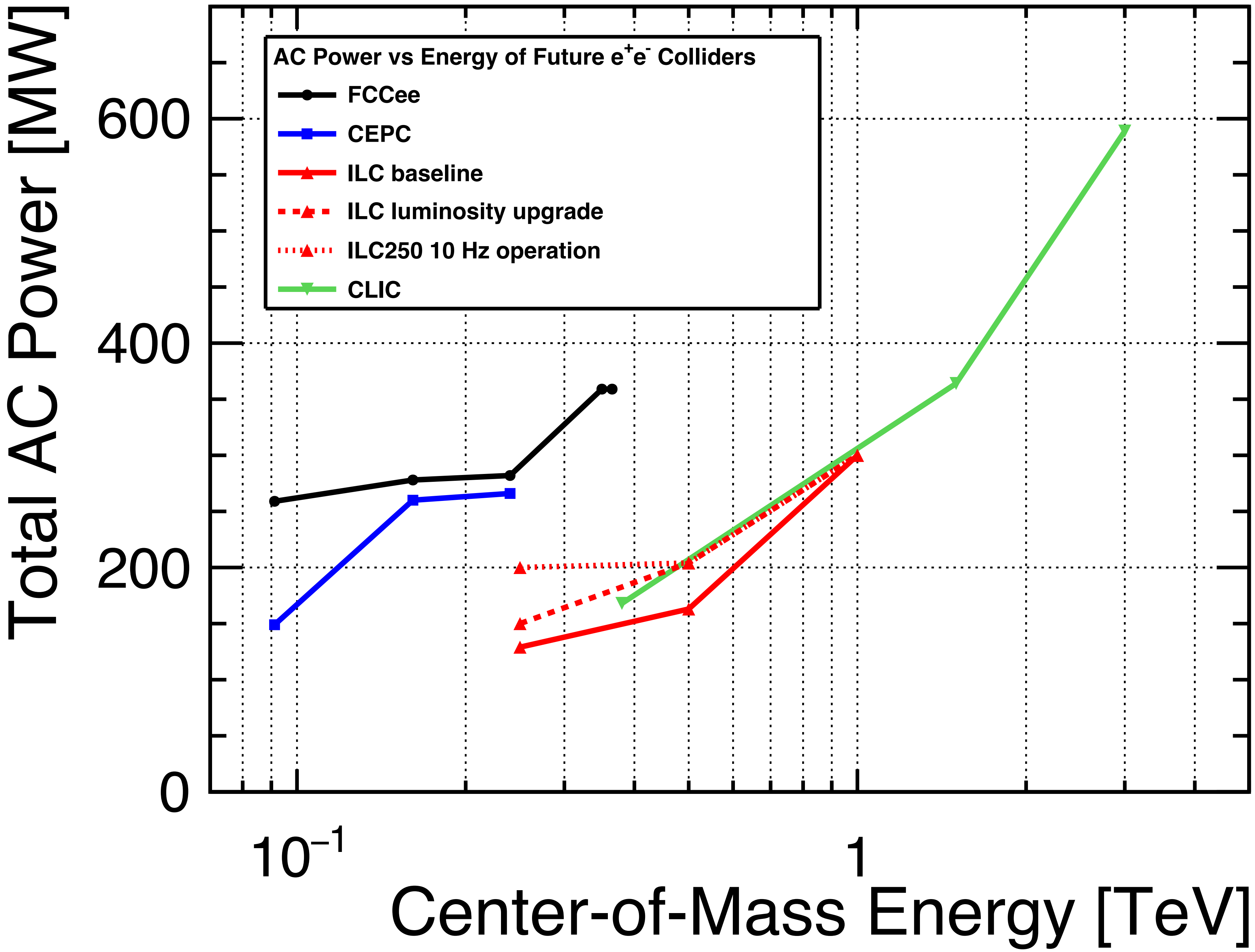
Backup

Particle Flow Approach (PFA)

- Requires individual particle reconstruction including jets in calorimeters so that each particle can be reconstructed with a best performance sub-detector (e.g. tracker, calorimeter).
- For instance, electron creates signals both in tracker and ECal but typically tracker gives better performance (depends on its energy) and in such a case tracker information is used in PFA.



- For photons, however, we have to rely on ECal. In this case, cluster hits made by charged particles must be removed to measure pure cluster hits by photons.
- **Track-cluster matching** is essential in PFA and this leads us to basic detector design : **low material budget for tracker** (to reconstruct low energy tracks), **high granularity for calorimeters** (to distinguish cluster hits depending on their origins).



AC Power vs Energy of Future e+e- Colliders
FCCee
CEPC
ILC baseline
ILC luminosity upgrade
ILC250 10 Hz operation
CLIC
Total AC Power [MW]
0
200
400
600
10^-1
1
Center-of-Mass Energy [TeV]

	fraction with $\text{sgn}(P(e^-), P(e^+))$ =			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	[%]	[%]	[%]	[%]
250 GeV (2015)	67.5	22.5	5	5
250 GeV (update)	**45**	**45**	5	5
350 GeV	67.5	22.5	5	5
500 GeV	40	40	10	10

TABLE V: Relative sharing between beam helicity configurations proposed for the various center-of-mass energies. The update of the luminosity sharing for 250 GeV originates from the importance of the left-right asymmetry of the Higgsstrahlung cross section in the EFT-based Higgs coupling fit.

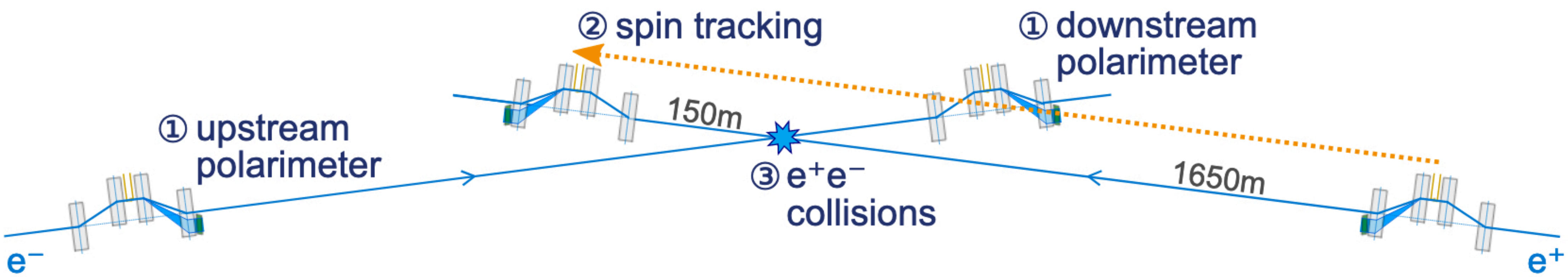
https://indico.desy.de/indico/event/15730/session/0/contribution/81/material/slides/0.pdf

Systematic Polarization Uncertainty

contribution	uncertainty $[10^{-3}]$
Beam and polarization alignment at polarimeters and IP ($\Delta\vartheta_{\text{bunch}} = 50\,\mu\text{rad}$, $\Delta\vartheta_{\text{pol}} = 25\,\text{mrad}$)	0.72
Variation in beam parameters (10 % in the emittances)	0.03
Bunch rotation to compensate the beam crossing angle	< 0.01
Longitudinal precession in detector magnets	0.01
Emission of synchrotron radiation	0.005
Misalignments (10 μ) without collision effects	0.43
Total (quadratic sum)	0.85
Collision effects in absence of misalignments	< 2.2

[Ref.:] Thesis Moritz Beckmann (http://bib-pubdb1.desy.de/record/155874)

ILC Polarimetry Concept



1. Measurement of the time-resolved beam polarization before and after the $e^- e^+$ IP
   - Via laser-Compton polarimeter

Ref.: Jenny List, Annika Vauth, and Benedikt Vormwald:
A Quartz Cherenkov Detector for Compton-Polarimetry at Future $e^+ e^-$ Colliders (https://bib-pubdb1.desy.de/record/221054)
A Calibration System for Compton Polarimetry at $e^+ e^-$ Colliders(https://bib-pubdb1.desy.de/record/289025)

2. Extrapolating the beam polarization to the $e^- e^+$ IP
   - Via Spin Tracking

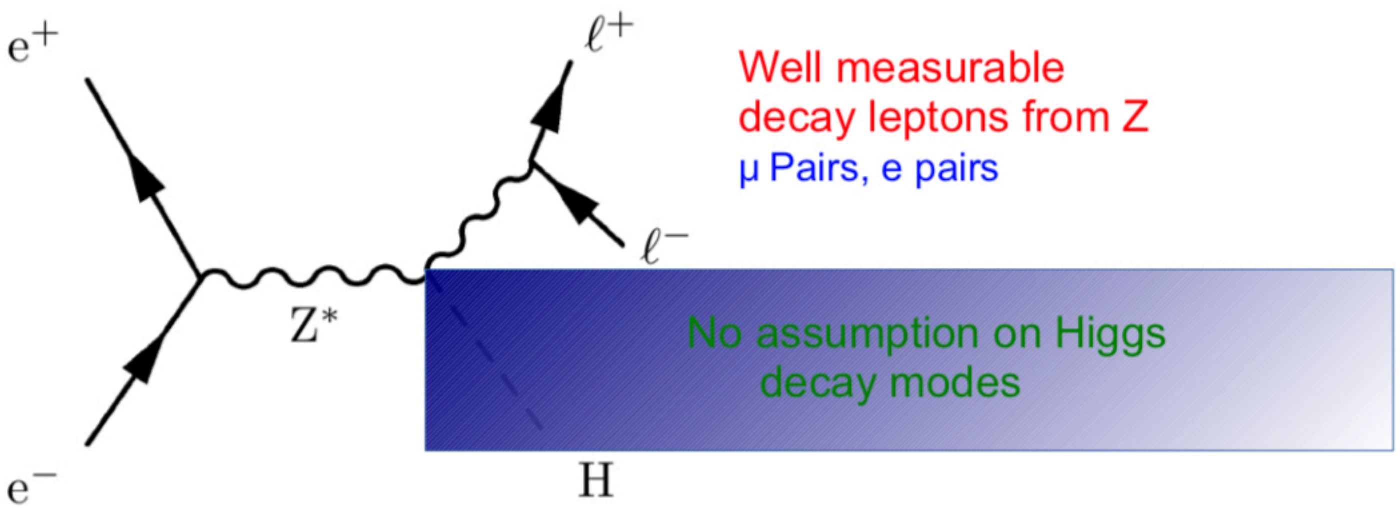
Ref.: Moritz Beckmann, Jenny List, Annika Vauth, and Benedikt Vormwald:
Spin transport and polarimetry in the beam delivery system of the international linear collider
(http://iopscience.iop.org/article/10.1088/1748-0221/9/07/P07003/pdf)

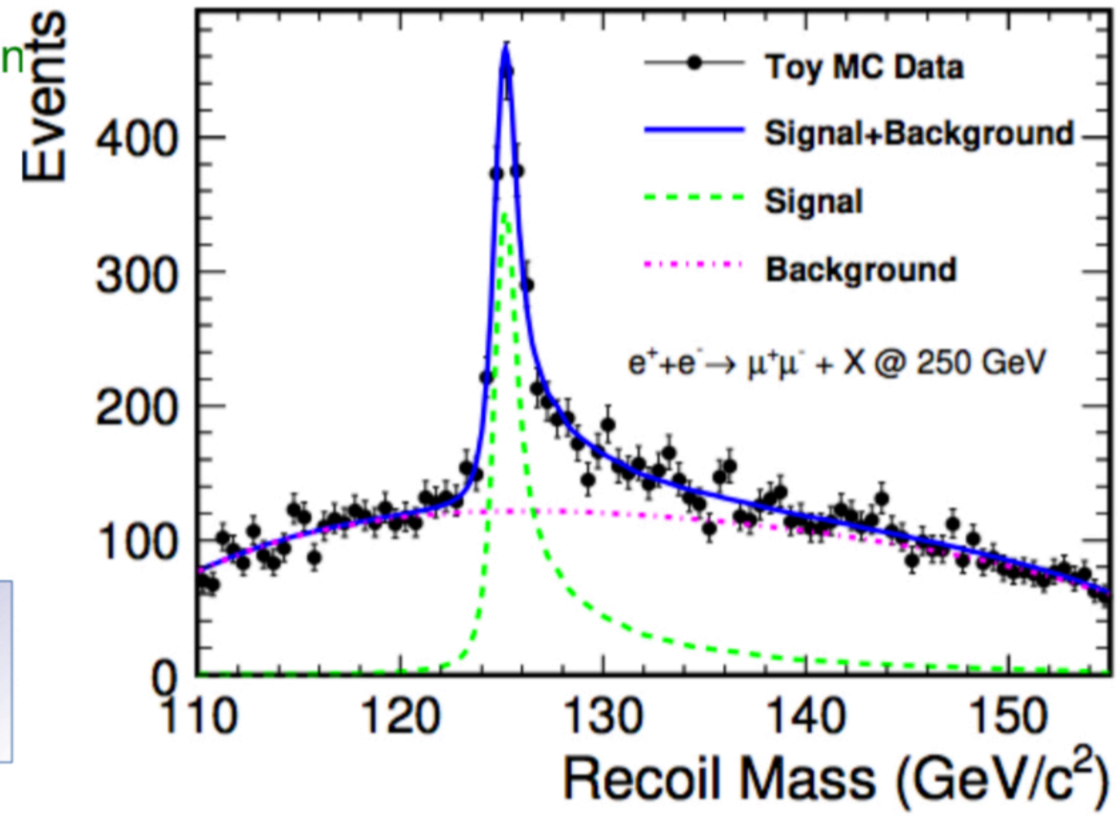
3. Determination of the luminosity-weighed averaged polarization from collision data
   - Calculating the polarization from known standard model processes

$\Rightarrow$ Discussed in the following

Higgs-strahlung at lepton colliders

- Powerful channel for unbiased tagging of Higgs Even
- Absolute normalisation of Higgs couplings
- Sensitivity to invisible Higgs decays





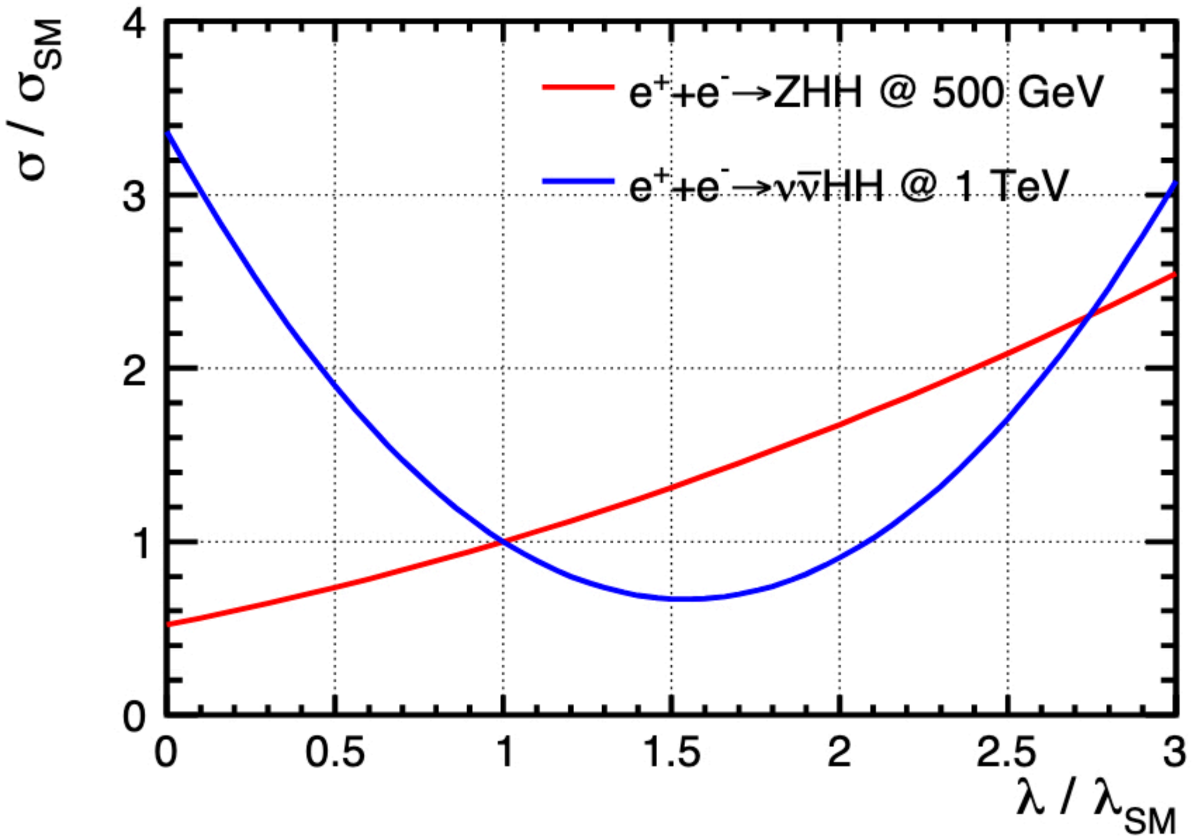
Higgs Recoil Mass: $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$

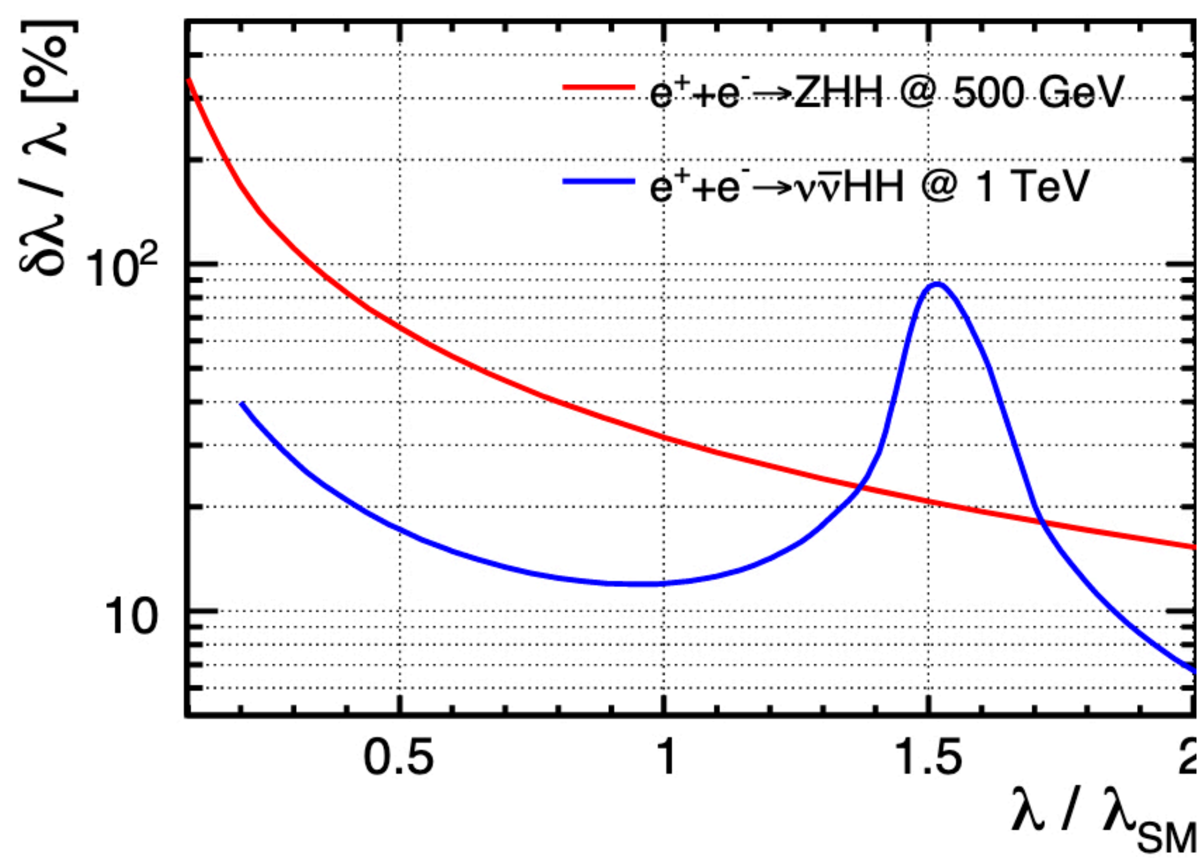
- Clean and sharp peak in Z recoil spectrum
- Illustrates precision that can be expected from e+e- colliders

https://agenda.linearcollider.org/event/6662/contributions/32620/attachments/26815/40942/SelfCoupling_LCWS15.pdf

J. Tian @ LCWS2015

what's the expectation if $\lambda \neq \lambda_{SM}$? @ LCs



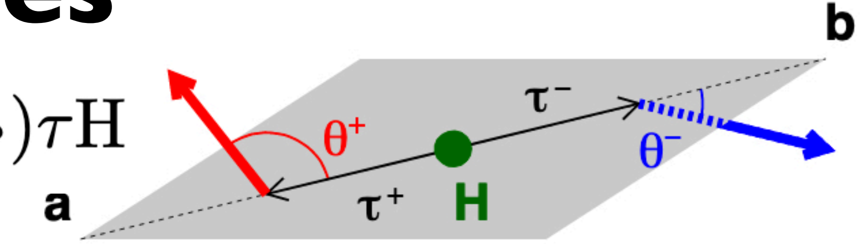


- for ZHH, interference is constructive, enhanced λ will increase the total σ, and improve sensitive factor as well, e.g. if $\lambda = 2\lambda_{SM}$, σ increase by 60%, F decease by half, $\delta\lambda/\lambda$ ~15%, —> we may finish the λ story at 500 GeV ILC
- for ννHH, interference is destructive, enhanced λ will decrease σ, minimum when λ~$1.5\lambda_{SM}$, $\delta\lambda/\lambda$ degrade significantly if $\lambda/\lambda_{SM} \in (1.3, 1.7)$
- but if $\lambda < \lambda_{SM}$, more difficult to use ZHH, have to rely on more on ννHH
- two channels are complementary in terms of λ measurement in BSM

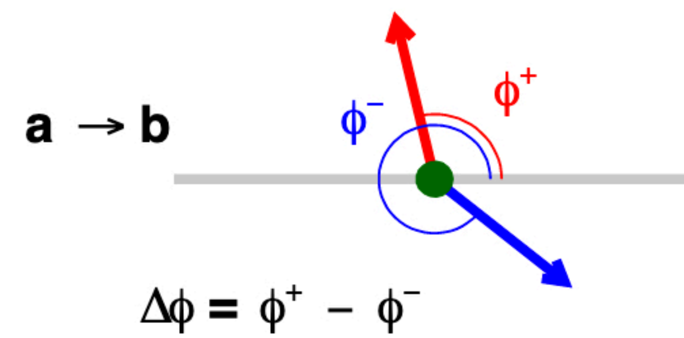
https://arxiv.org/pdf/1903.01629.pdf
https://arxiv.org/pdf/1804.01241.pdf

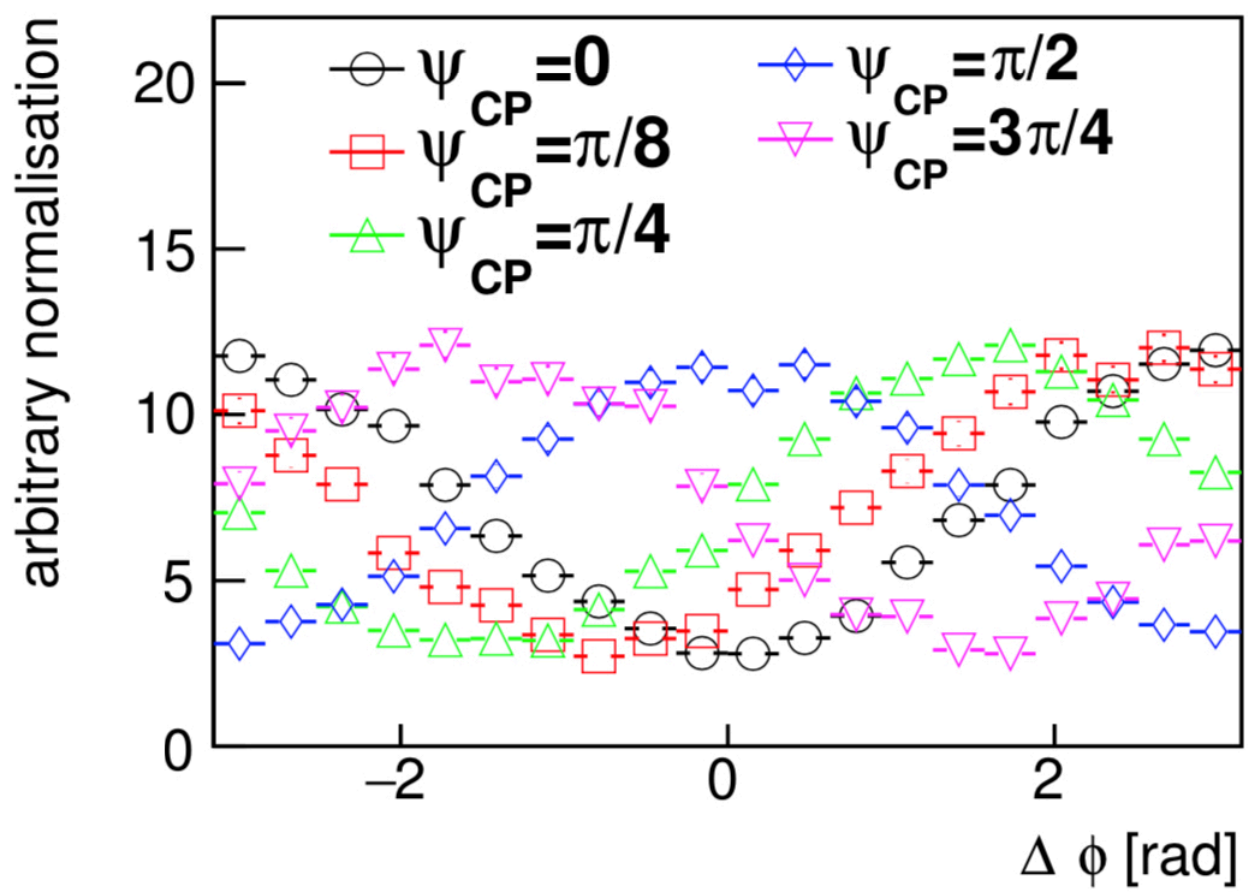
Higgs CP properties

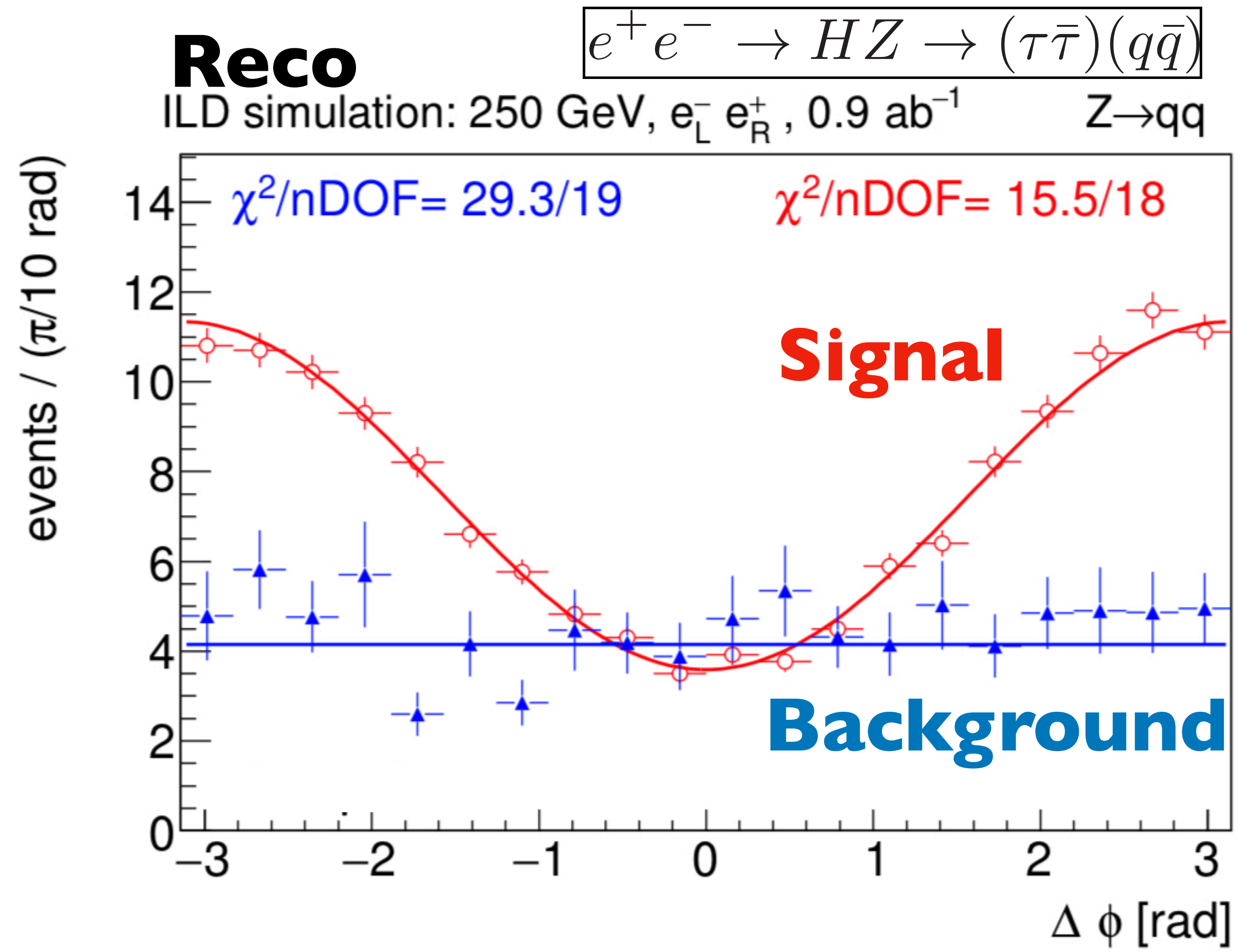
$$\mathcal{L}_{H\tau\tau} = g\overline{\tau}(\cos\psi_{CP} + i\gamma_5 \sin\psi_{CP})\tau H$$



- The CP phase angle Ψ_{CP} can be determined using the transverse spin correlation between the two τ, which gives different Δφ distributions for different values of ΨCP .







Possible to measure CP-phase better than 4°.

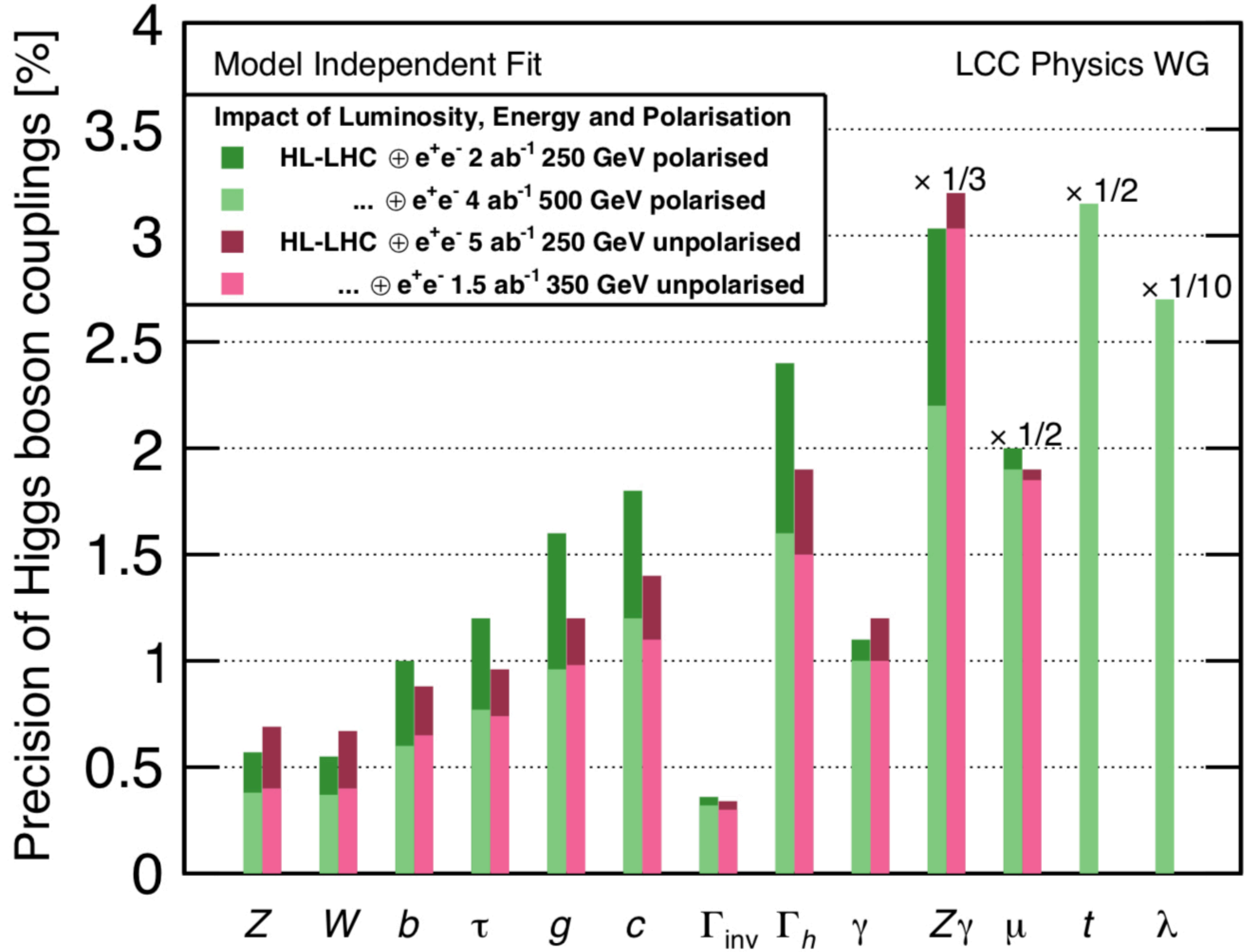
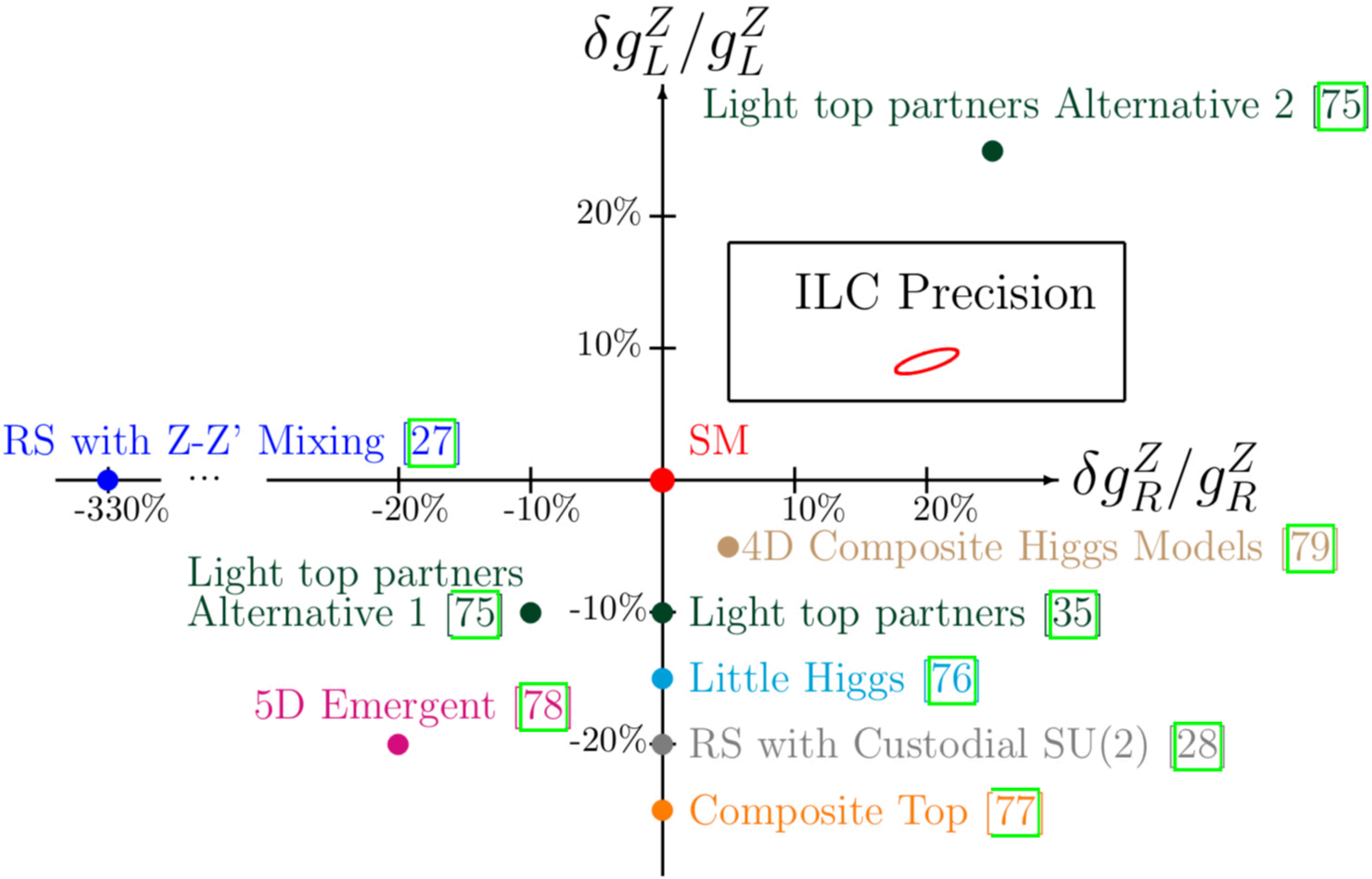


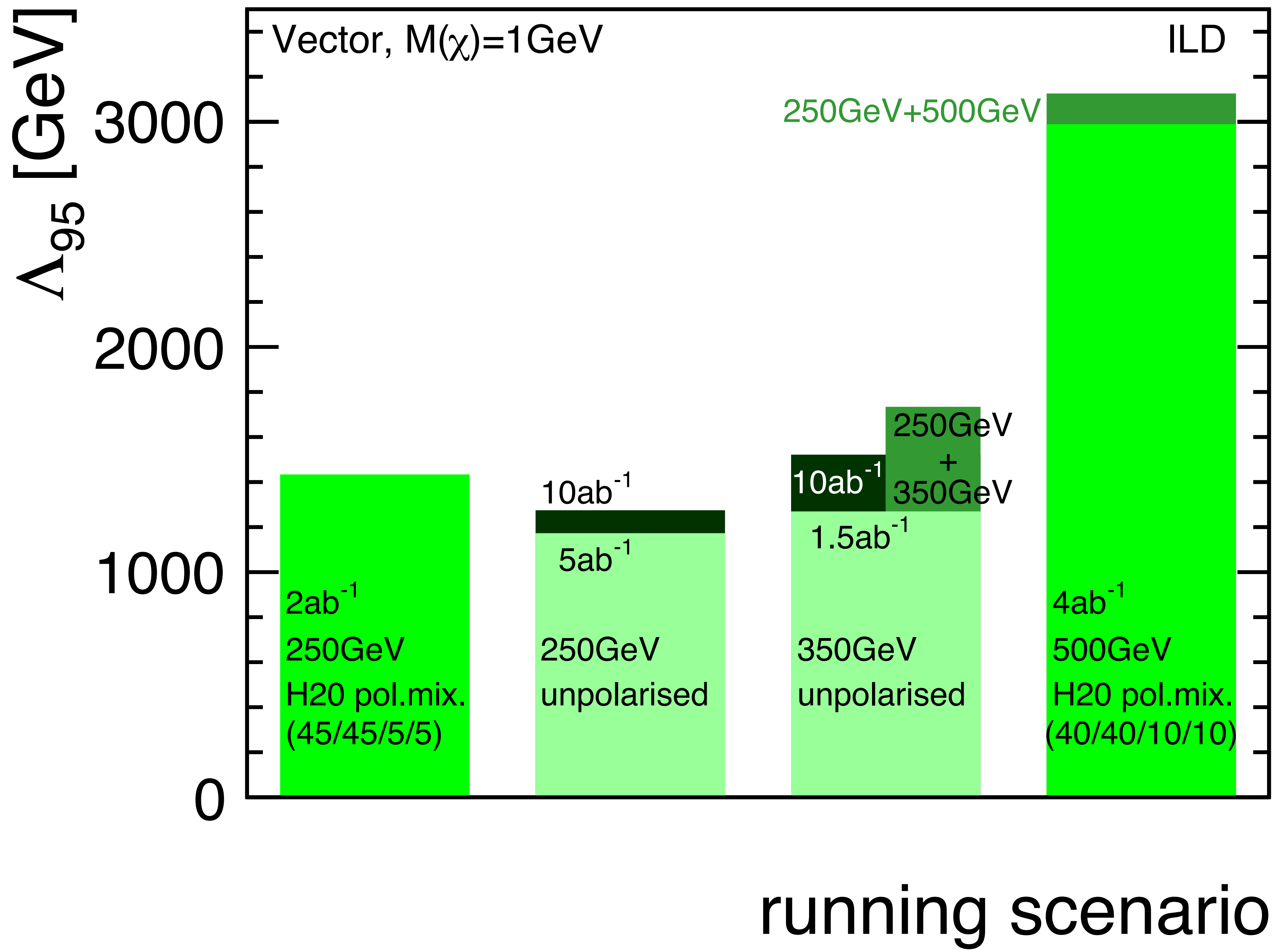
FIG. 76: Projected Higgs boson coupling uncertainties for selected scenarios from Table XVIII. In particular it shows that at $\sqrt{s} = 250\,\text{GeV}$, 2 ab^{-1} with polarised beams yield comparable results to a much larger data set of 5 ab^{-1} with unpolarised beams.



$\delta g_L^Z / g_L^Z$
Light top partners Alternative 2 [75]
20%
ILC Precision
10%
RS with Z-Z' Mixing [27]
SM
$\delta g_R^Z / g_R^Z$
-330%
-20%
-10%
10%
20%
4D Composite Higgs Models [79]
Light top partners
Alternative 1 [75]
-10%
Light top partners [35]
Little Higgs [76]
5D Emergent [78]
-20%
RS with Custodial SU(2) [28]
Composite Top [77]

Generic WIMP search

http://bib-pubdb1.desy.de/record/417605/files/Moritz_Habermehl_PhD.pdf



KEK High Energy Accelerator Research Organization

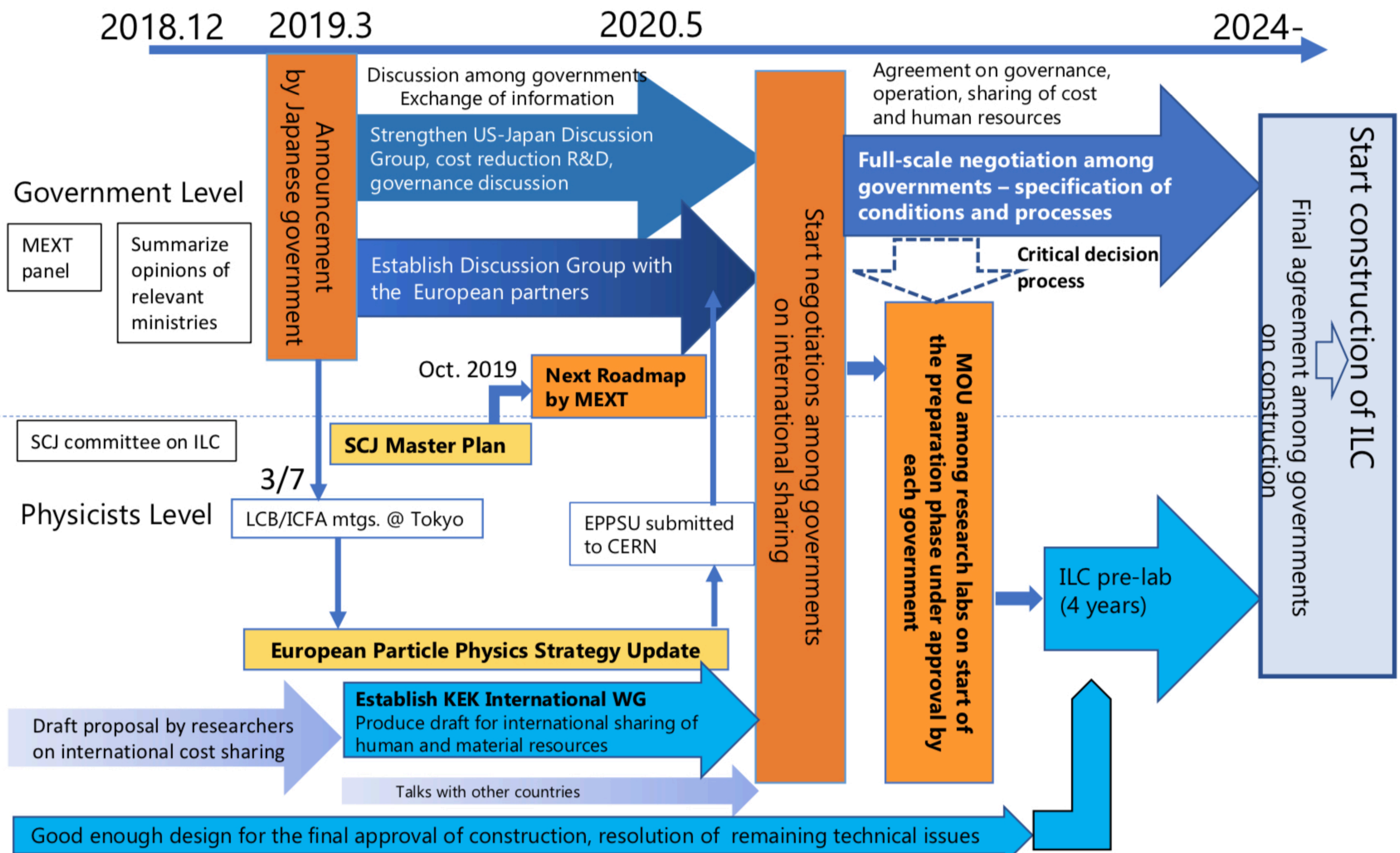
Actions to be done by KEK

- Organize the international working group with close consultation with MEXT.
- Promote activities to gain a better understanding of the broader academic community in Japan.
  - Propose the ILC project to the SCJ Master Plan
  - Organize a symposium
- Cooperate MEXT to establish the governmental level discussion groups with France and Germany. Also, we need to strengthen the discussion group with the US DOE.
- Conducts R&D program at ATF, STF and CFF facilities collaborating with the international teams.
- … and so on.

https://indico.cern.ch/event/789524/contributions/3340272/attachments/1827177/2990796/Lausanne_Apr._2019.pdf

Processes and Approximate Timelines Toward Realization of ILC (Physicists' view)

Restricted

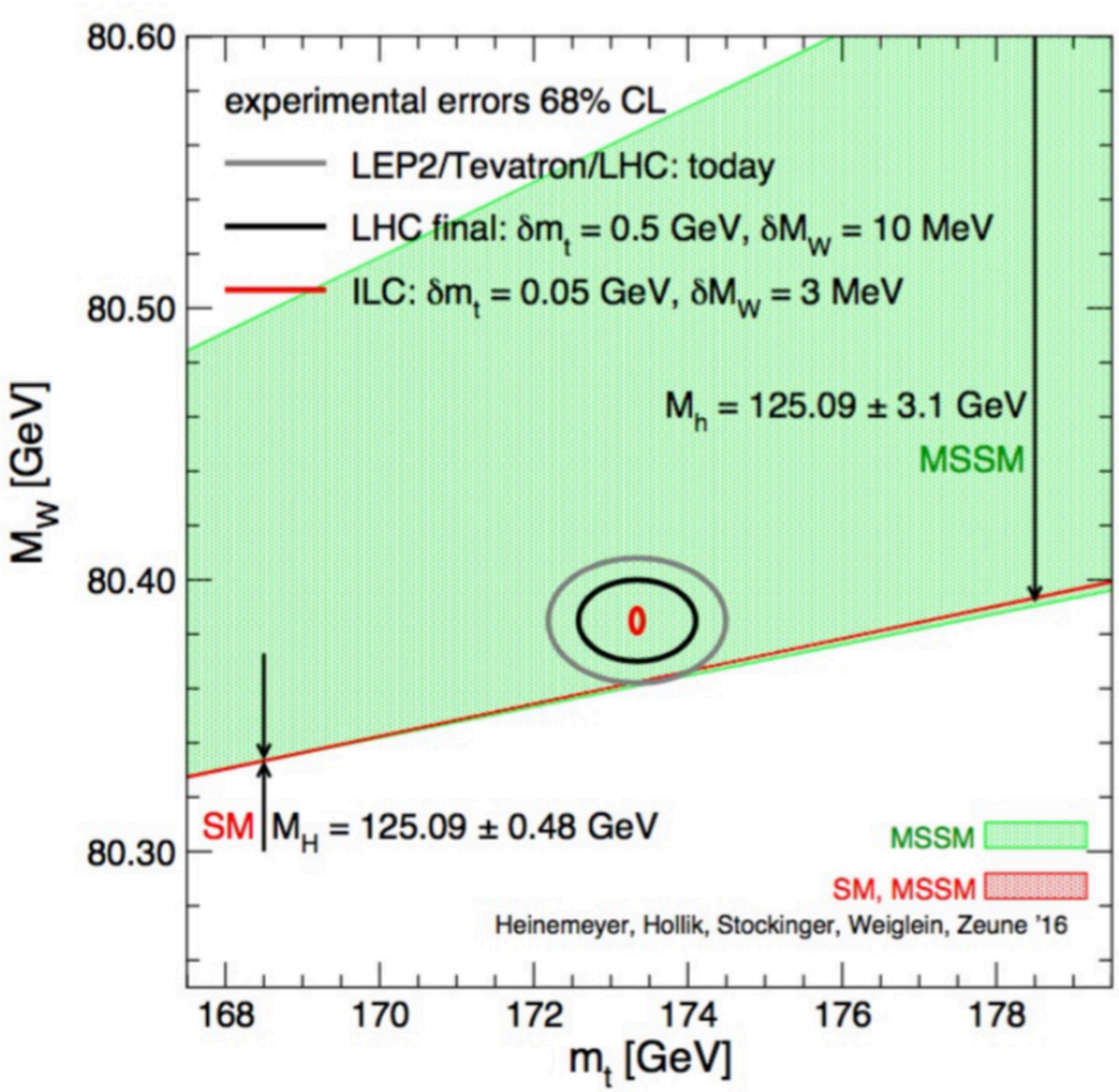


* ICFA: international organization of researchers consisting of directors of world's major accelerator labs and representatives of researchers
* ILC pre-lab: International research organization for the preparation of ILC based on agreements among world's major accelerator labs such as KEK, CERN, FNAL, DESY etc.

KEK
High Energy Accelerator Research Organization

SCJ Master Plan

- Science Council of Japan (SCJ) is an organization that represents the Japanese scientists. It has no policy-making or budgetary authority.
- SCJ calls for proposals of large-scale research projects every three years, and recommends "priority programs" to MEXT. In the latest one in 2017, 20 programs were selected from 200 proposals.
- MEXT Minister suggested the ILC to be evaluated in this process to provide an evidence of getting support by the broader academic community in Japan.
- Following this this suggestion, we submitted a proposal of ILC with a recommendation letter from Barry Barish.
- Results of this evaluation will be publicized officially in February 2020.



- Precise Top (and W) mass crucial to test compatibility of measured Higgs mass

- SM might not be sufficient to explain Higgs mass

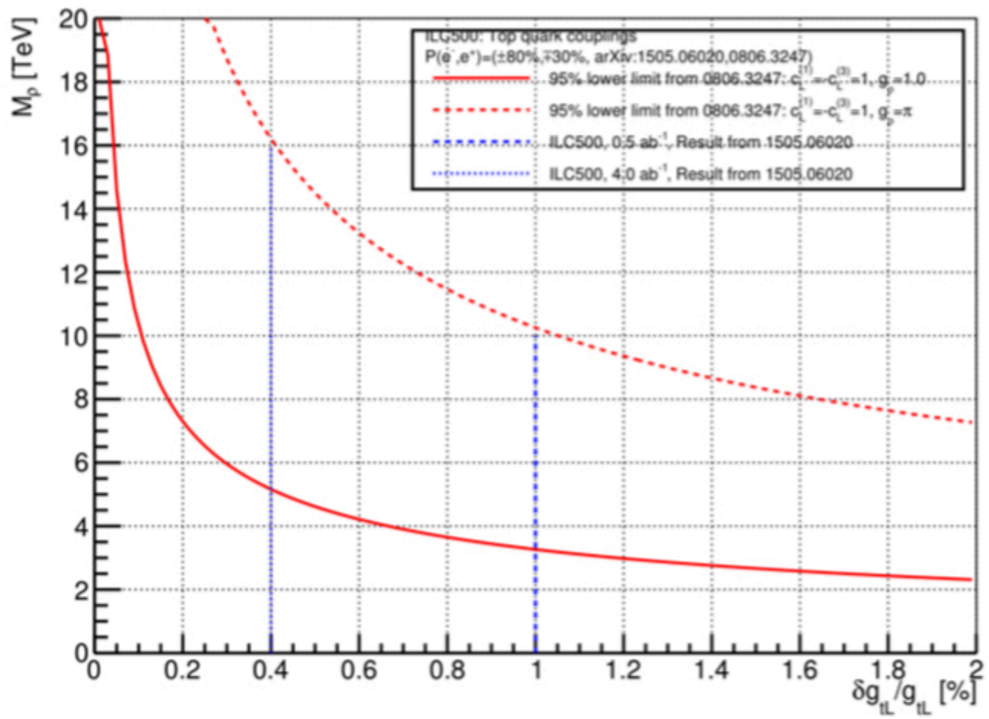
- LHC may not reach sufficient discriminative power

- A lepton collider will for sure

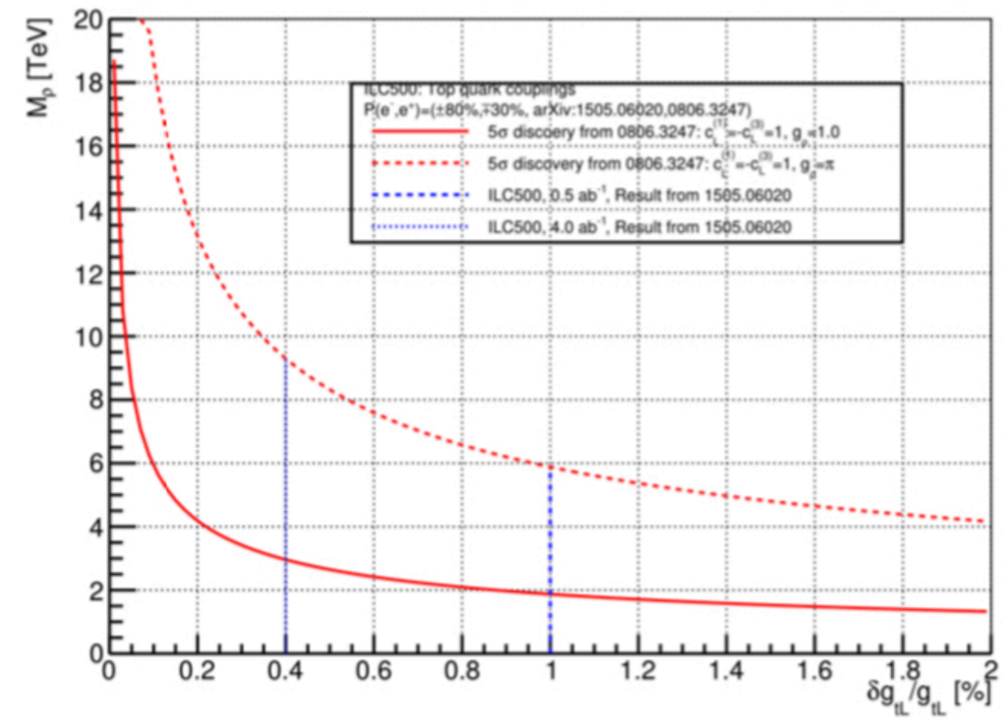
Electroweak top couplings and discovery reach

New physics reach for typical BSM scenarios with composite Higgs/Top and/or extra dimensions
Based on phenomenology described in Pomerol et al. arXiv:0806.3247

95% Exclusion Limit



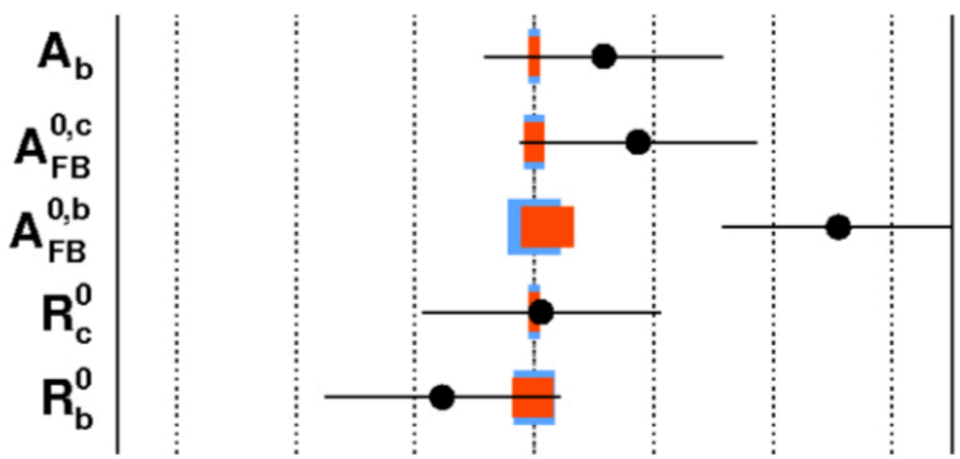
5σ discovery



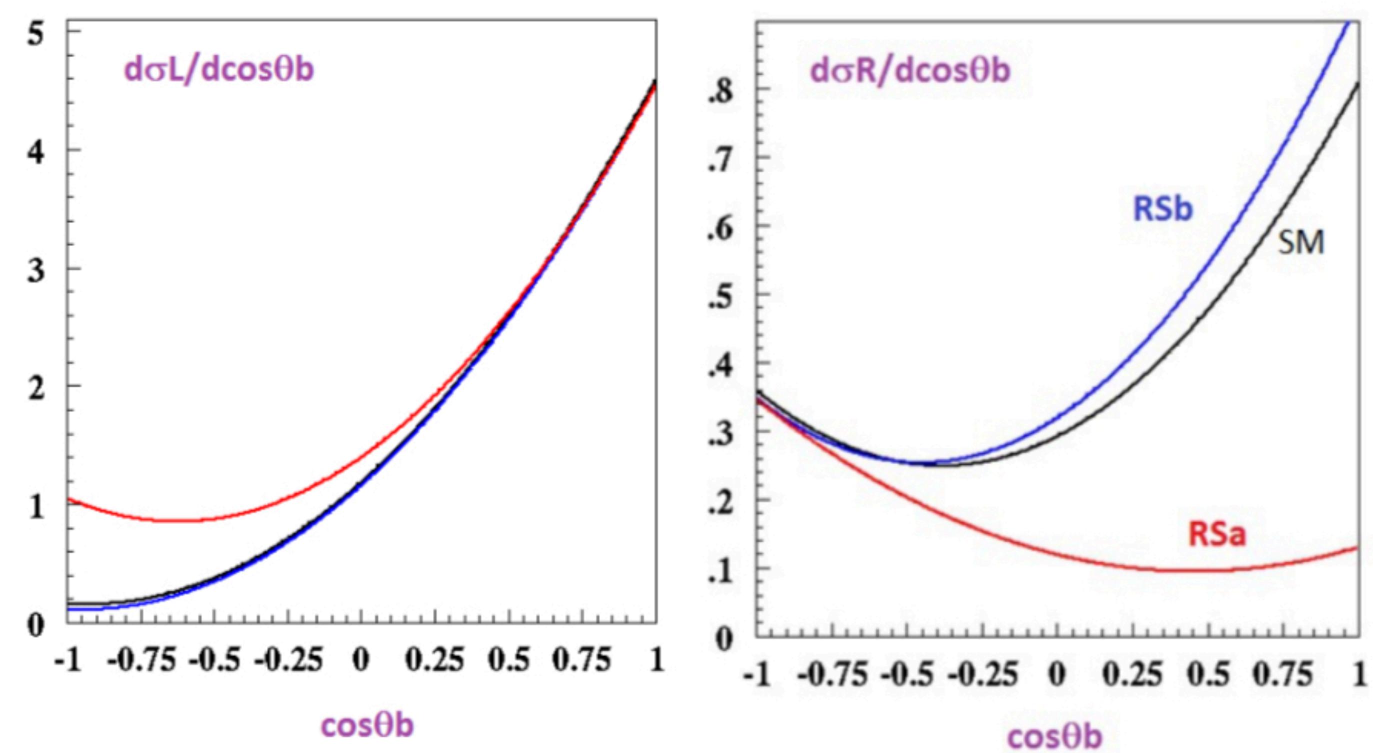
ILC@500 has discovery potential up to 10 TeV for typical BSM scenario
More cms e.g. at CLIC would of course help a great deal (also for disentangling effects)

New physics below tt threshold? - Example b quark couplings

~3σ in heavy quark observable A_{FB}^{b}



ee->bb@250 GeV

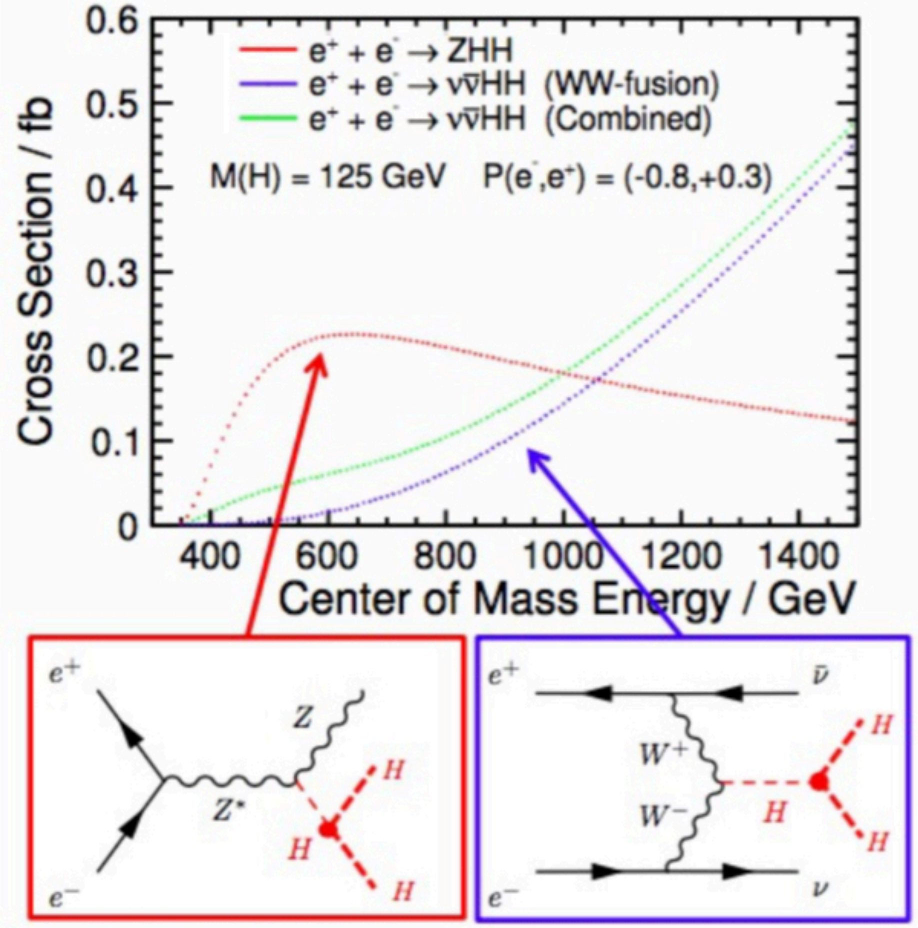


Randall Sundrum Models Djouadi/Richard '06

- Is tension due to underestimation of errors or due to new physics?
- High precision e+e- collider will give final word on anomaly
- In case it will persist polarised beams will allow for discrimination between effects on left and right handed couplings
- Randall Sundrum Models generate basically automatically a symmetry group of type $SU(2)_R$

Higgs self-coupling – Precisions at LC

Cross section vs CM energy (e+e-)



Diagrams with triple-Higgs coupling

Expected precision based on **full detector simulation** studies:

ILC	ILC
500 GeV, 4 ab-1	500 GeV, 4 ab-1 & 1 TeV, 8 ab-1
δλ = 27%	**δλ = 10%**

References:
J. Tian, LC-REP-2013-003
M. Kurata, LC-REP-2014-025
C. Duerig, Ph.D. thesis at DESY, 2016
HH→bbbb, bbWW* combination

CLIC	CLIC
1.4 TeV, 1.5 ab-1	1.4 TeV, 1.5 ab-1 & 3 TeV, 2 ab-1
δλ = 21%	**δλ = 10%**

References:
arXiv: 1307.5288
HH→bbbb only, upgrade in progress including bbWW*