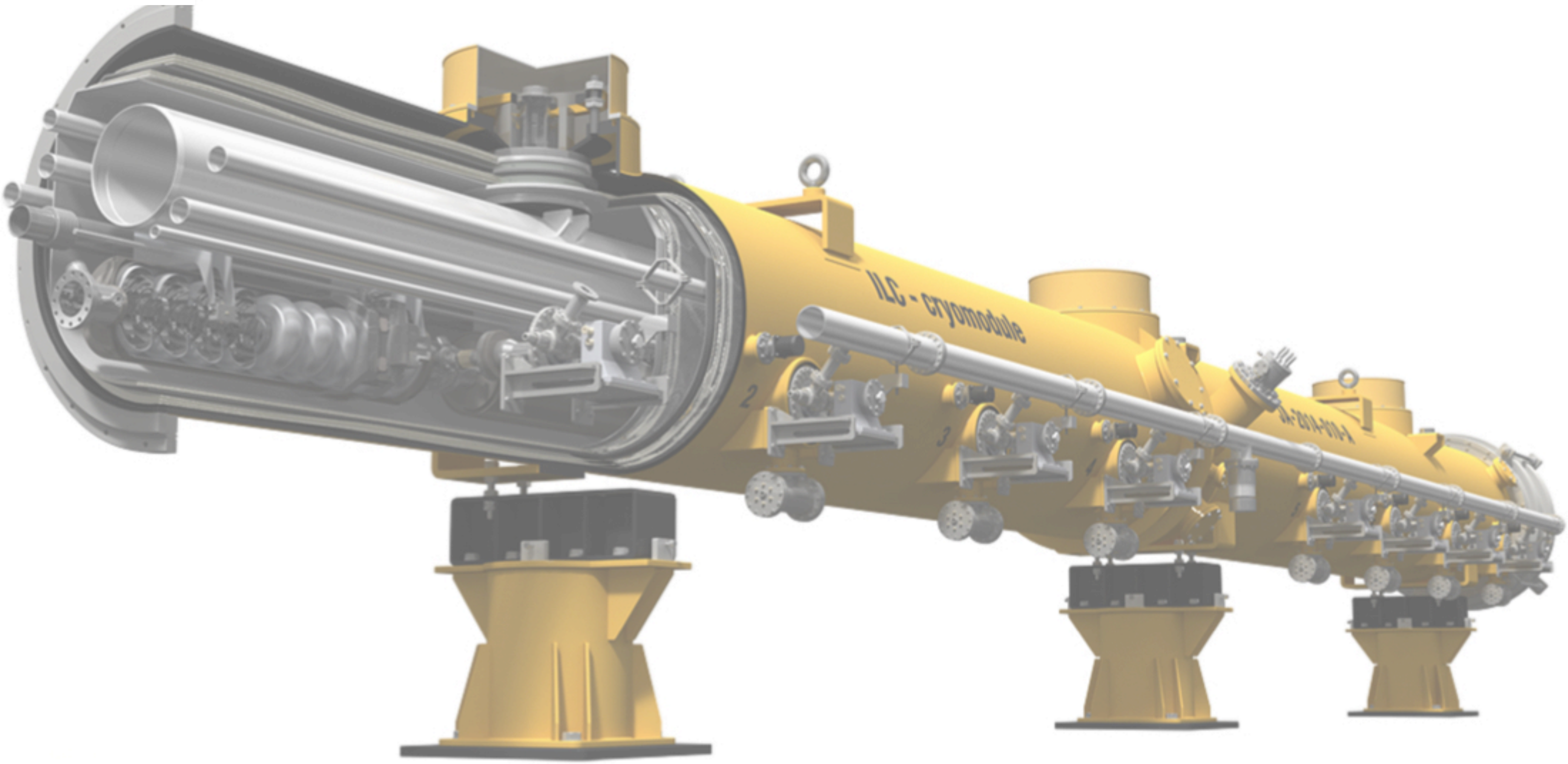
ILC



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for the LCC Physics WG

Ryo Yonamine

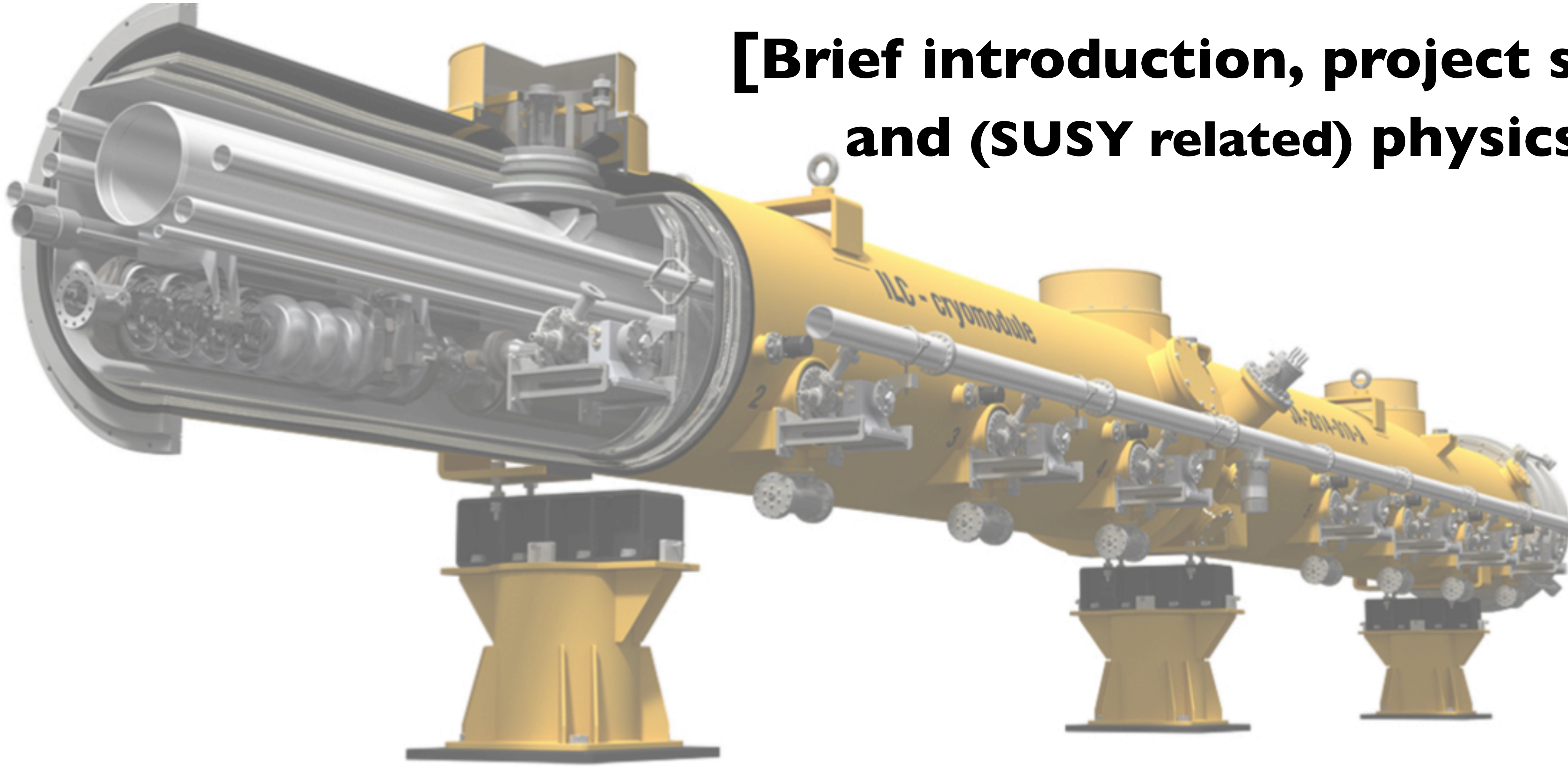
Tohoku University

27th International Conference on Supersymmetry and Unification of Fundamental Interaction

SUSY2019@Texas A&M University, 20-24 May 2019

ILC

[Brief introduction, project status and (SUSY related) physics]



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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)

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Outline

- **Introduction to ILC**
  - Overview
  - Beam polarization
  - Running scenario(Real-time evolution of integrated luminosity)
- **Recent situation in Japan**
  - Some slides from M. Yamauchi @ Linear Collider Community Meeting 8-9 April 2019).
- **(SUSY related) physics cases at ILC**
  - Pick up some SUSY-related topics that have been (or being) studied. (Not fully covered)
- **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 (Firm ground, Many local supports!)

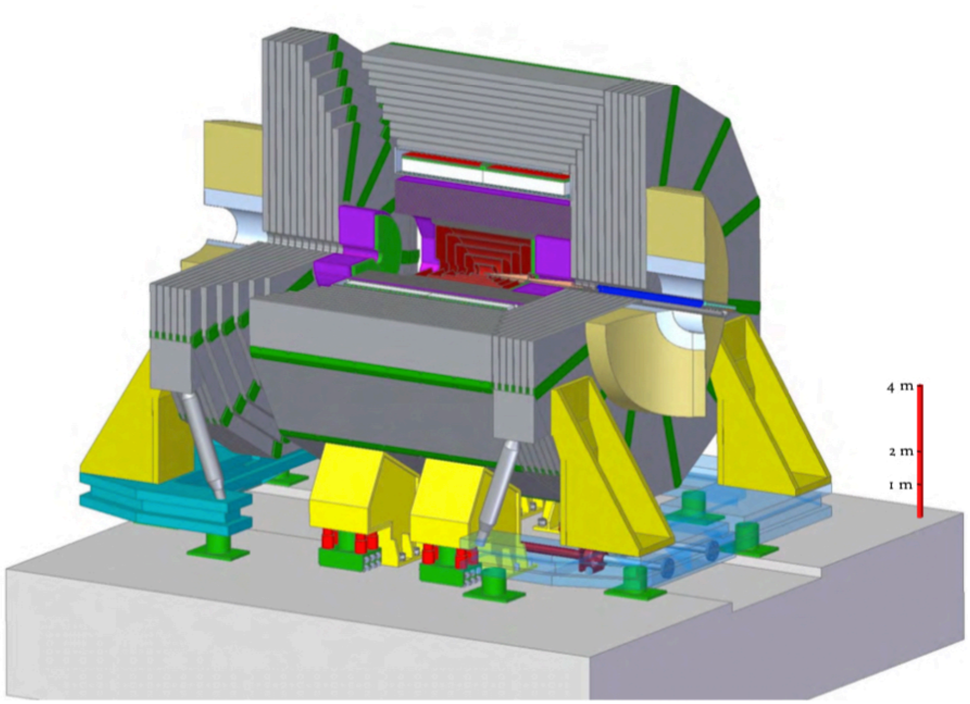
- **As merits from e+ e- collider**
  - Provides controllable initial particle energy
  - Low QCD background (compared to hadron colliders)
  - Can naturally reduce the number of EFT parameters (EW interaction)

- **As merit from linear collider**
  - Provides controllable **beam polarization**
  - Energy extendability (e.g. 350GeV, 500GeV, 1TeV)

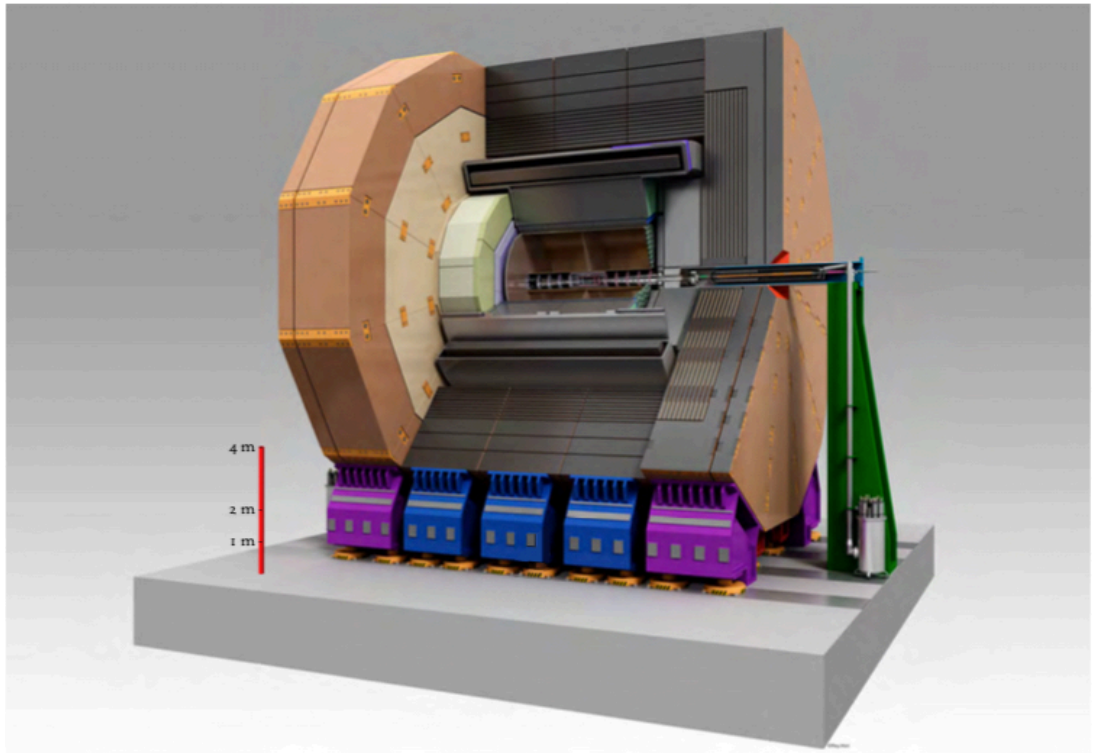
Detectors at ILC

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

- Swap into the IP on a timescale of a few hours to 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.
- To achieve ideal jet energy resolution (3% jet mass resolution above100GeV), detectors are optimized for Particle Flow Approach.

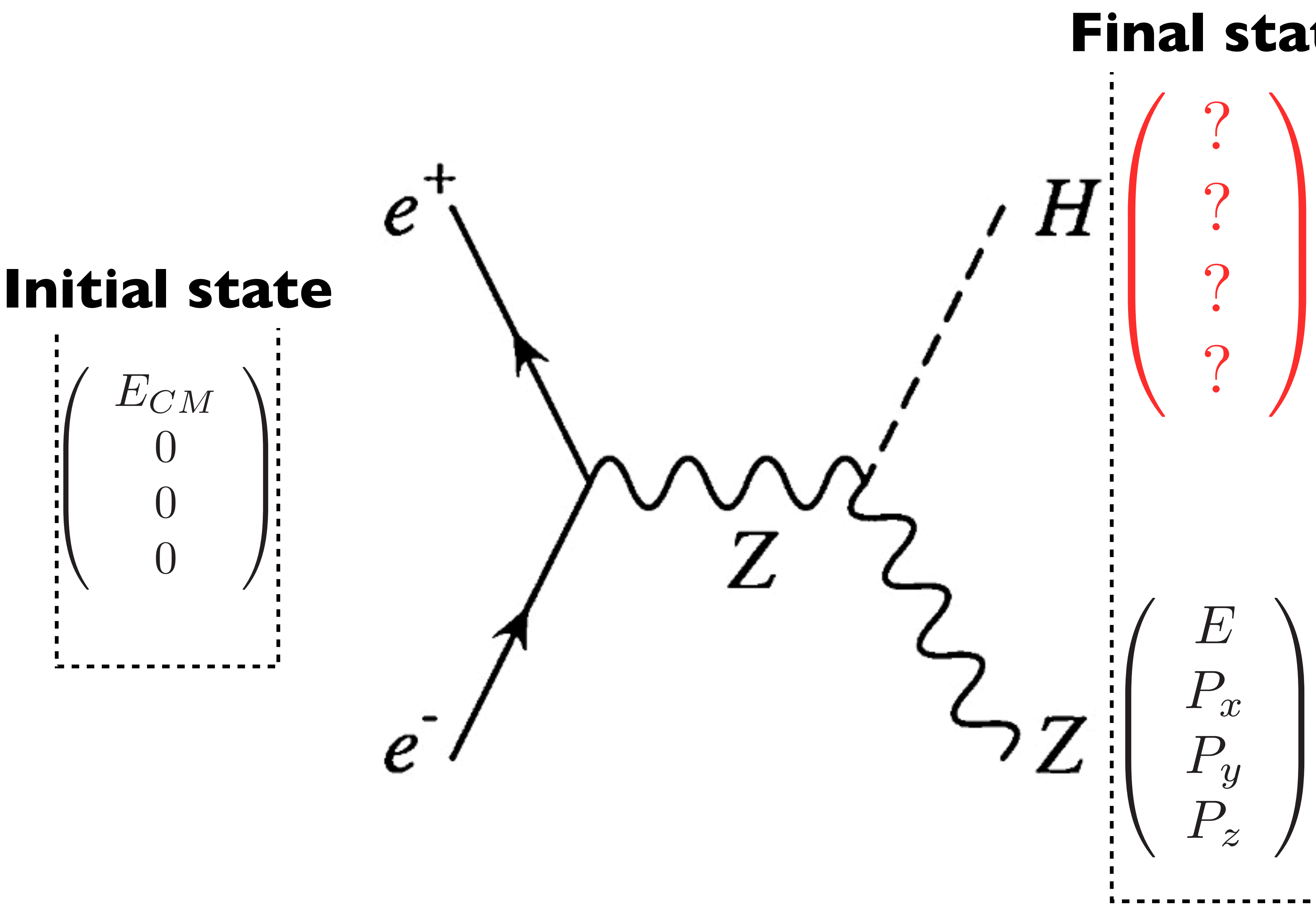


SiD: R~6m, B=5T, Silicon tracker



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

Notable Higgs reconstruction: “Higgs recoil mass technique”



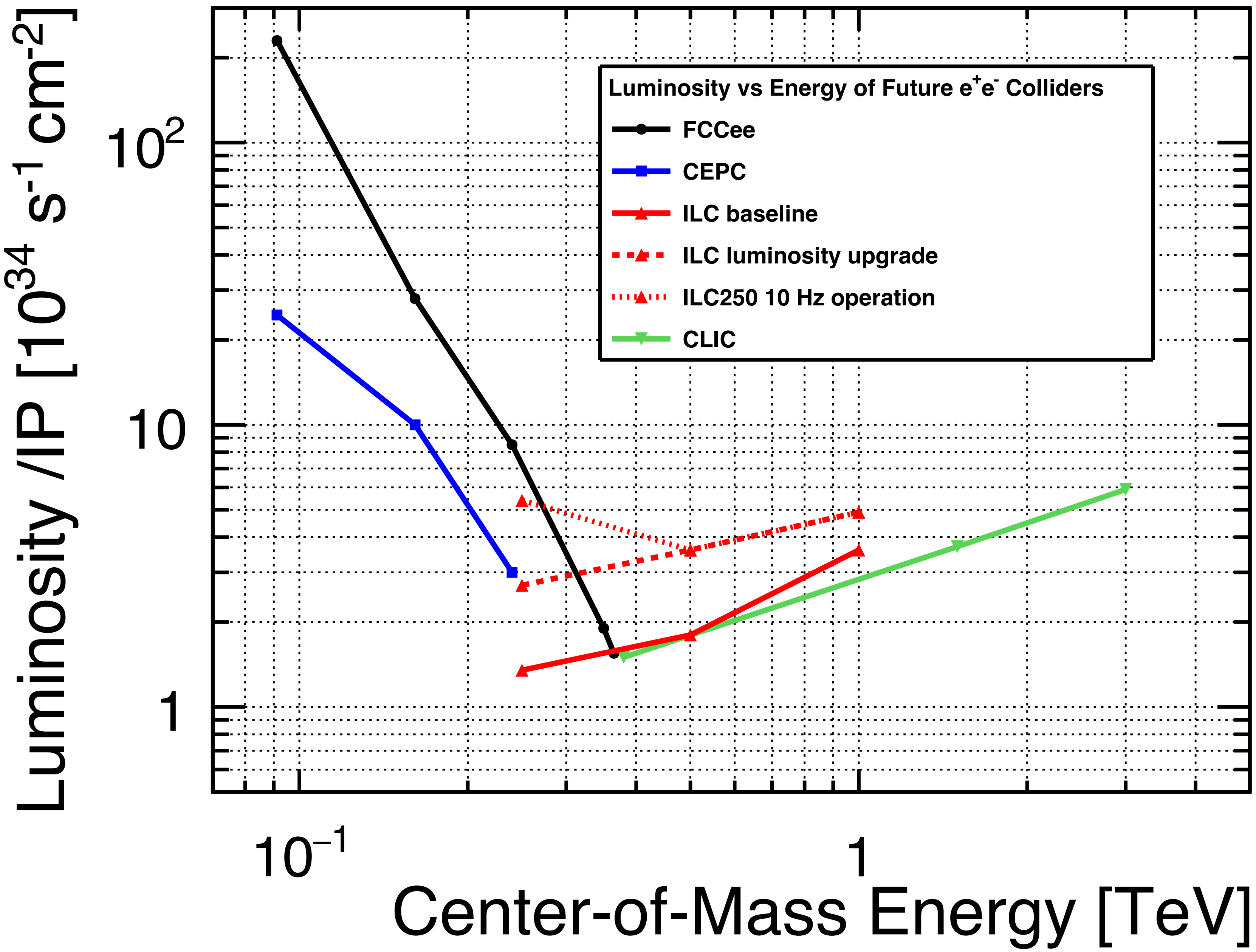
$$\begin{pmatrix} ? \\ ? \\ ? \\ ? \end{pmatrix} = \begin{pmatrix} E_{CM} \\ 0 \\ 0 \\ 0 \end{pmatrix} - \begin{pmatrix} E \\ P_x \\ P_y \\ P_z \end{pmatrix}$$

Higgs can be identified without looking at Higgs itself!
This allows us to measure the total cross section
<u>even if Higgs decays into unknown, undetectable particles.</u>
Also applicable for new scalar particle searches.

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 or 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 at 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, 2fb^{-1} of polarized data (Pe-/Pe+ = ±80%/±30%) (ILC) was turned out to be roughly equivalent to 5fb^{-1} of unpolarized data (FCCee/CEPC) (arXiv:1903.01629).

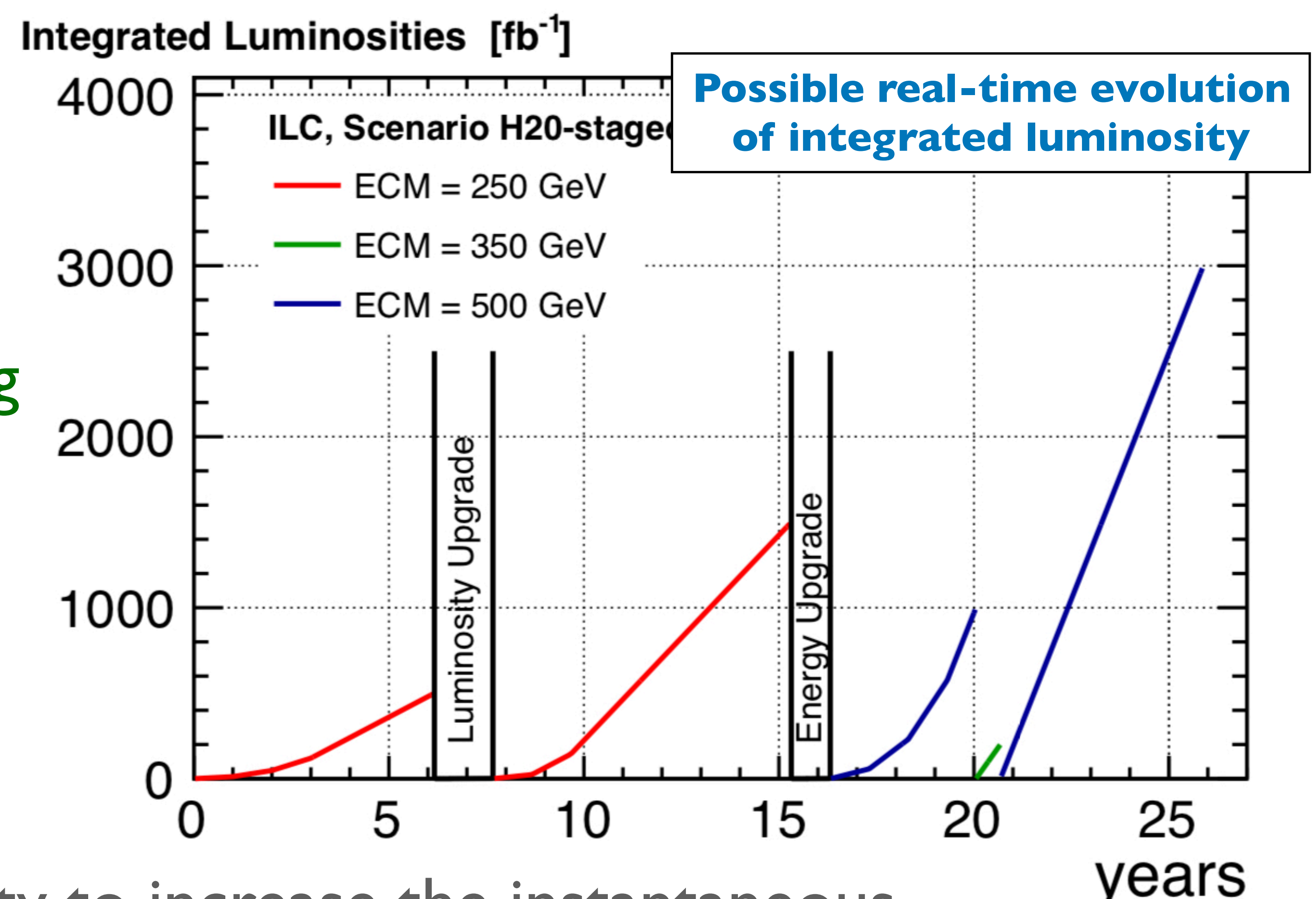
Beam polarization can compensate for 2 IPs at FCCee and CEPC.

ILC Running scenario

(https://arxiv.org/pdf/1710.07621.pdf)

- ❖ **Ecm = 250GeV**
  - 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 250GeV with data set at higher energies because some parameters in EFT have energy dependance.



- There is a cost-neutral possibility to increase the instantaneous luminosity by focussing the beam more strongly at the IP. This option can reduce 15 year-operation to 11.

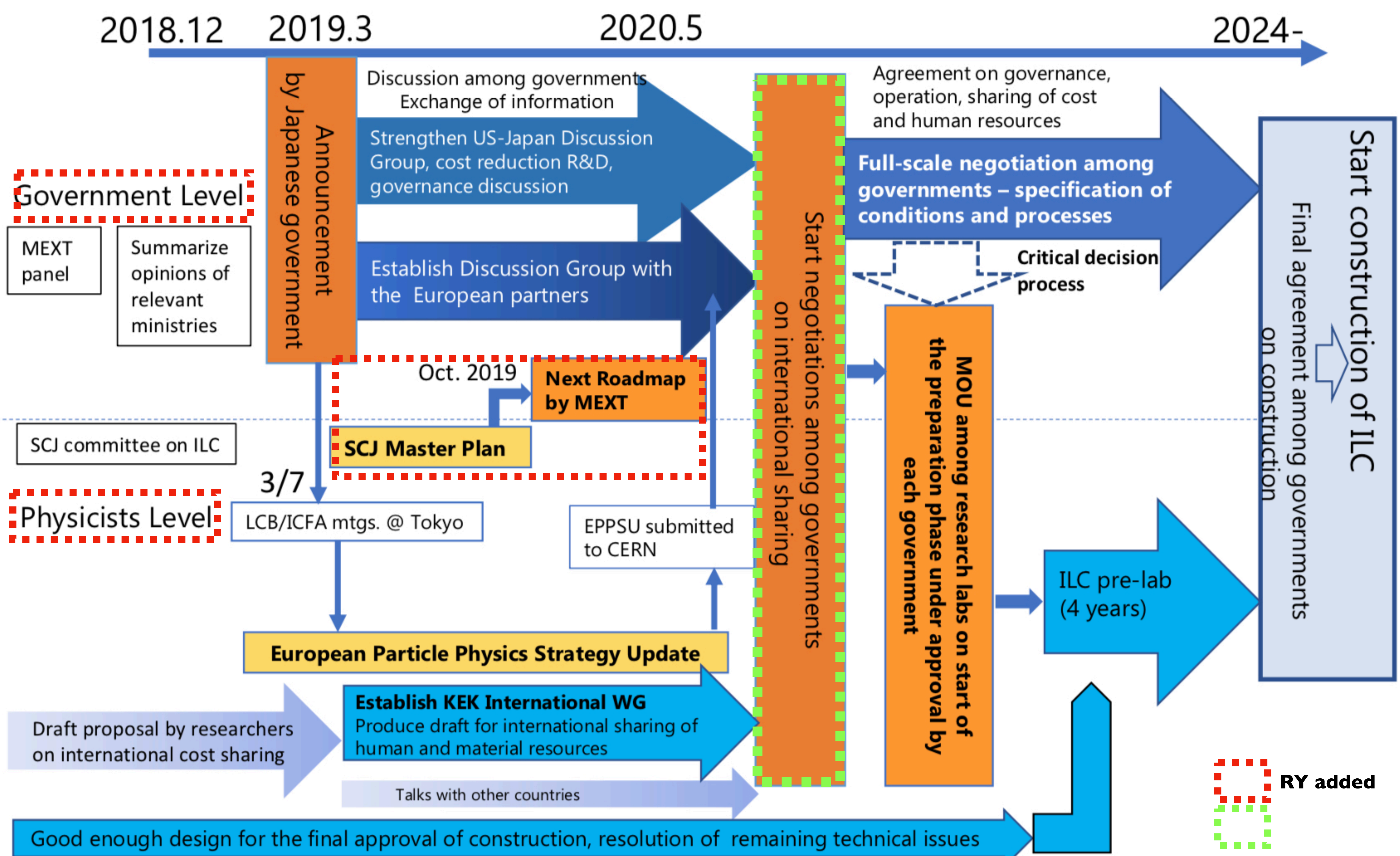
Situation in Japan

M. Yamauchi @ Lausanne

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.

MEXT: Ministry of Education, Culture, Sports, Science and Technology

KEK High Energy Accelerator Research Organization

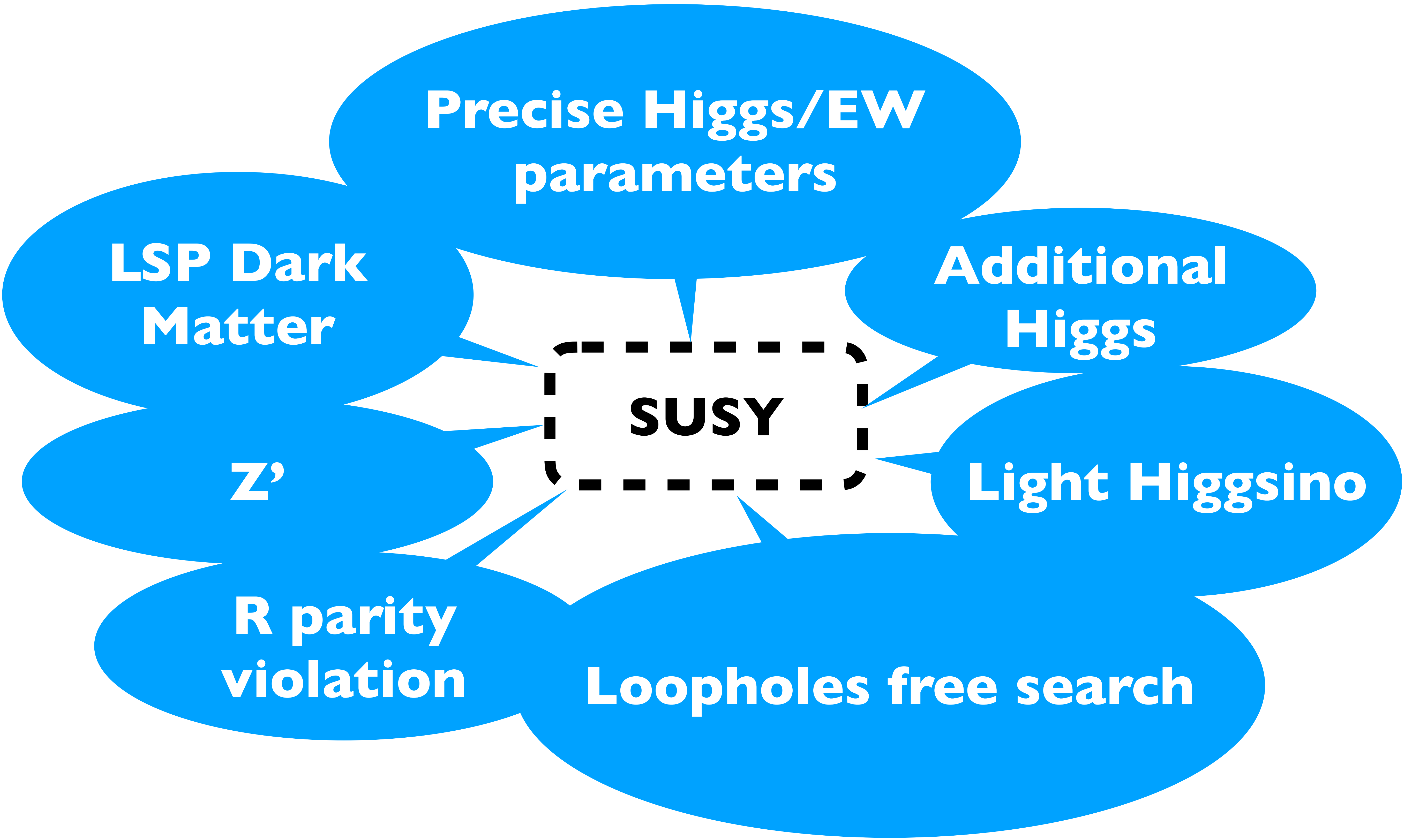
SCJ Master Plan

- 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 (KEK) submitted a proposal of ILC with a recommendation letter from Barry Barish.
- Results of this evaluation will be publicized officially in February 2020.

RY added

(SUSY related) Physics

What can ILC do on top of LHC?

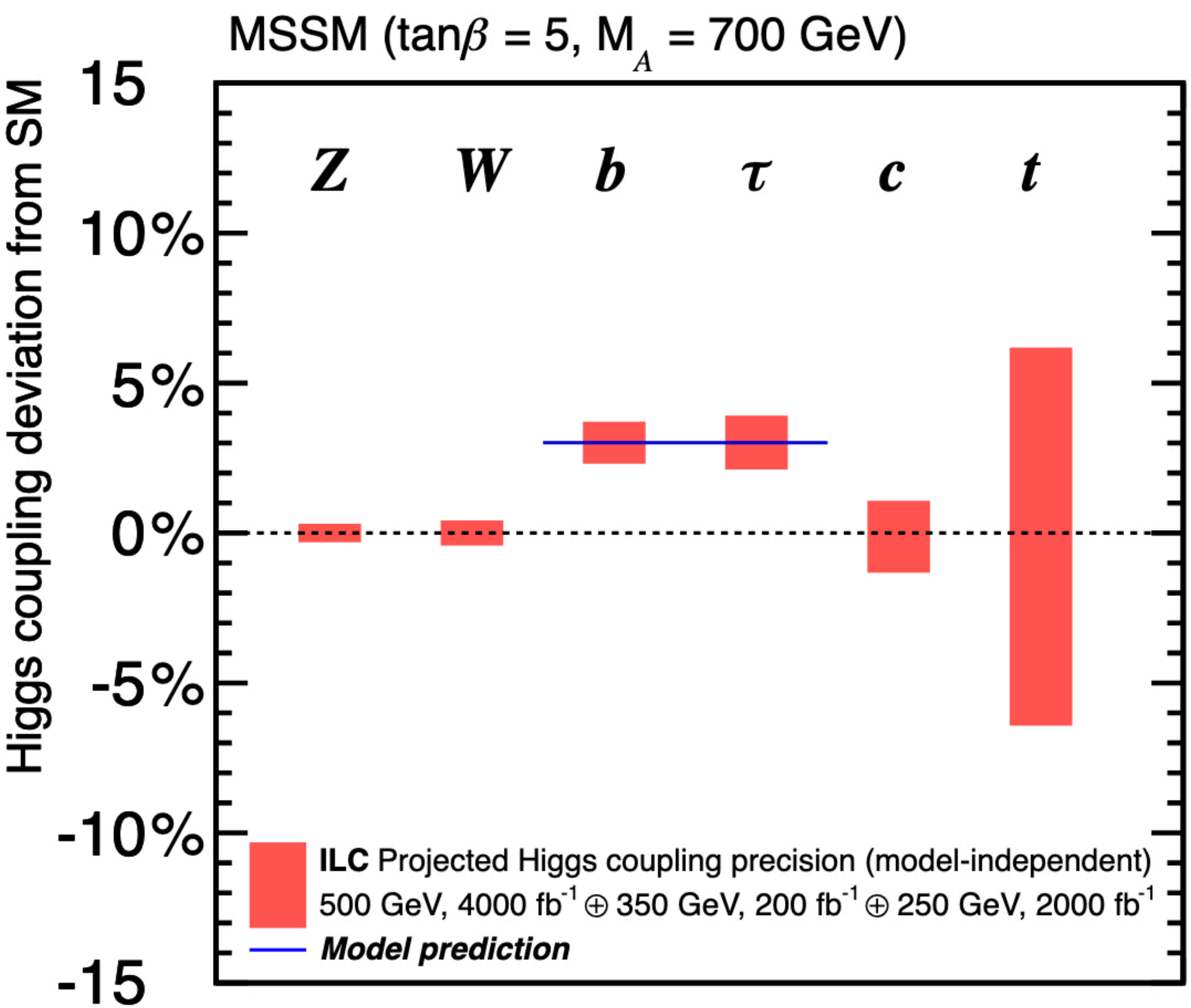


ILC will add many probes for SUSY!

Precise SM parameter measurements

- **Higgs parameters**
  - Total decay width —> can discover decay to unknown particles.
  - Higgs mass —>ΔM_H~14MeV together with ΔM_t~0.3GeV (HL-LHC) can probe New Physics up to 10^{12}GeV considering the vacuum stability.
  - Higgs self coupling —> Could deviate by ~20% level if a new scaler boson exists.
  - The CP nature of the Higgs boson using the spin correlations of τ lepton pairs produced in their decays.
  - Masses of additional Higgs bosons —>Can be probed far beyond the kinematic limit and beyond the reach of the LHC by its very precise and model-independent determinations of the Higgs couplings to fermions and gauge bosons.
- **EW parameters**
  - M_W, $\sin\theta_{eff}$ —> Assuming the centre 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



Percent-level precision is the key!

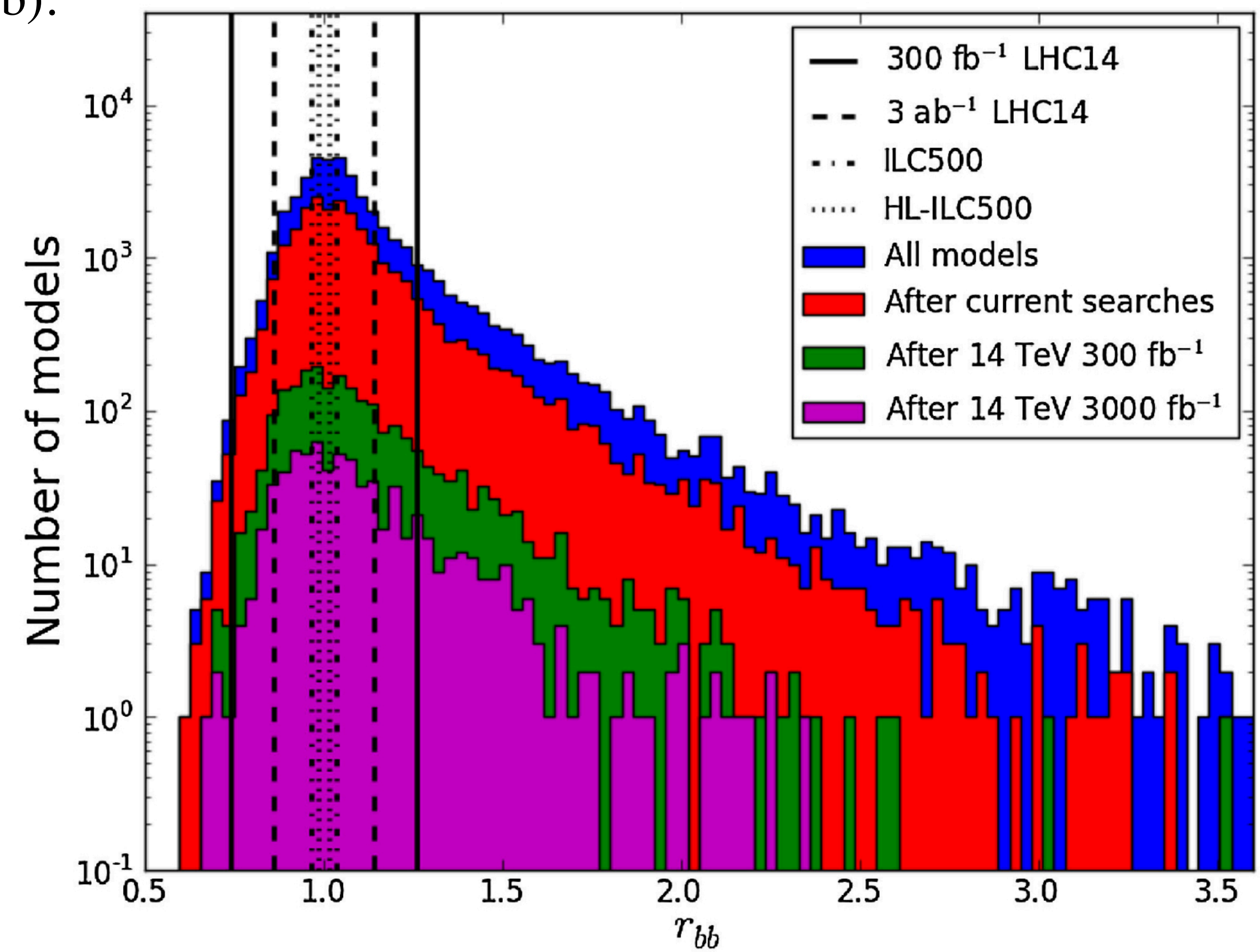
For couplings to Z and W, EFT framework tells that $\Delta M_h \sim 14$MeV leads to 0.1% level of precision.

https://arxiv.org/pdf/1506.05992.pdf

Phenomenological MSSM

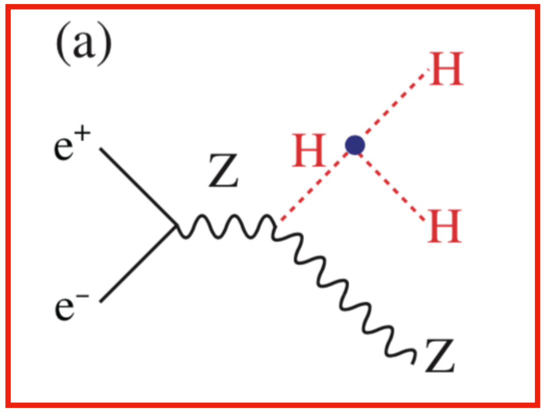
PHYSICAL REVIEW D90,095017 (2014)
M. Cahill-Rowley, J. Hewett, A. Ismail, and T. Rizzo

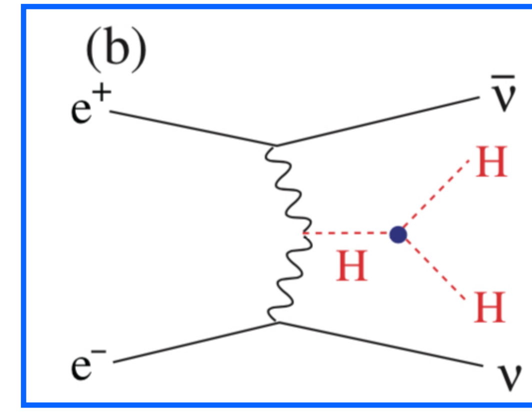
The most general version of the R-parity conserving MSSM with a minimal set of experimentally motivated guiding principles gives many possible models depending on Γ(H->bb).

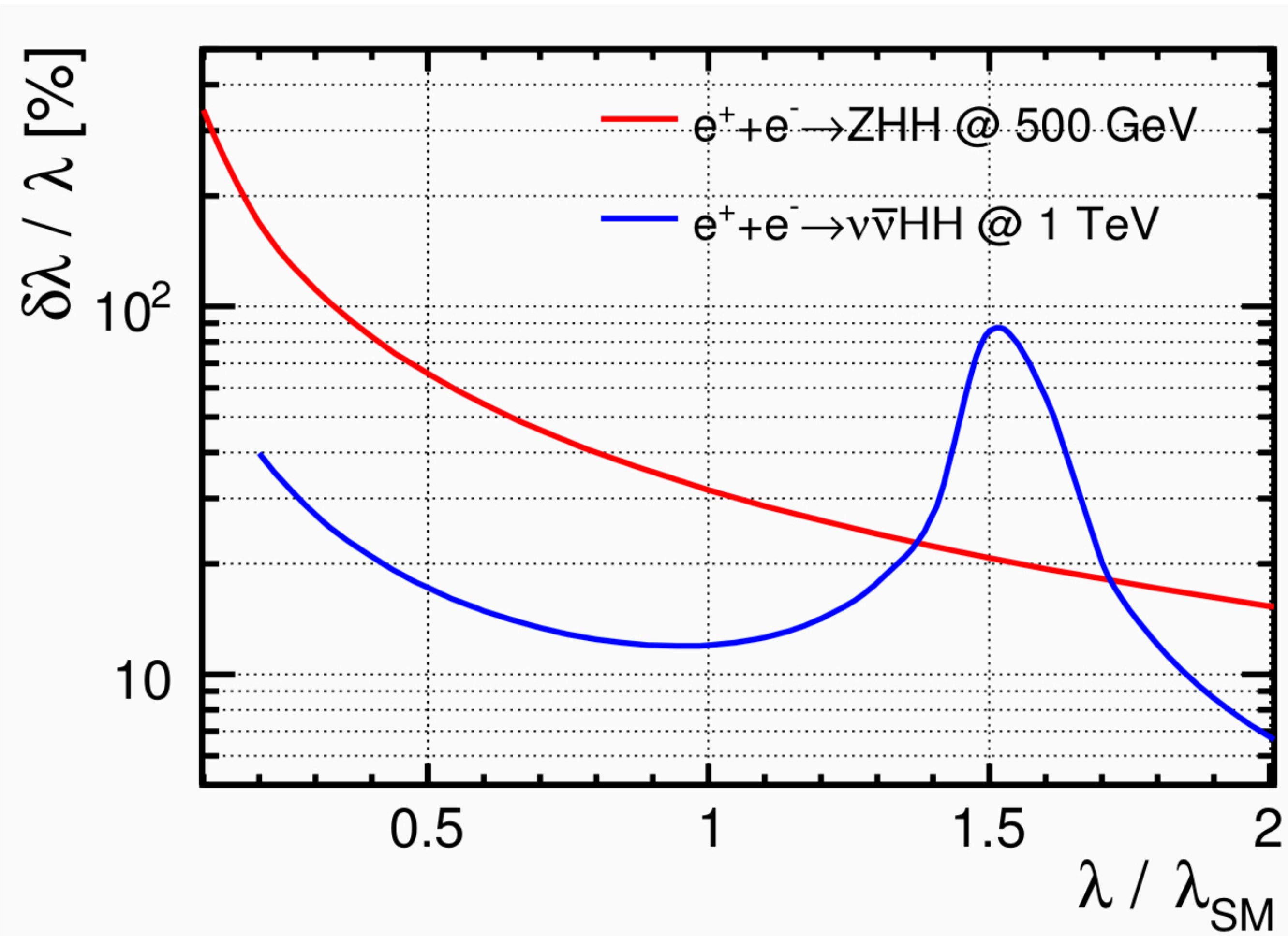


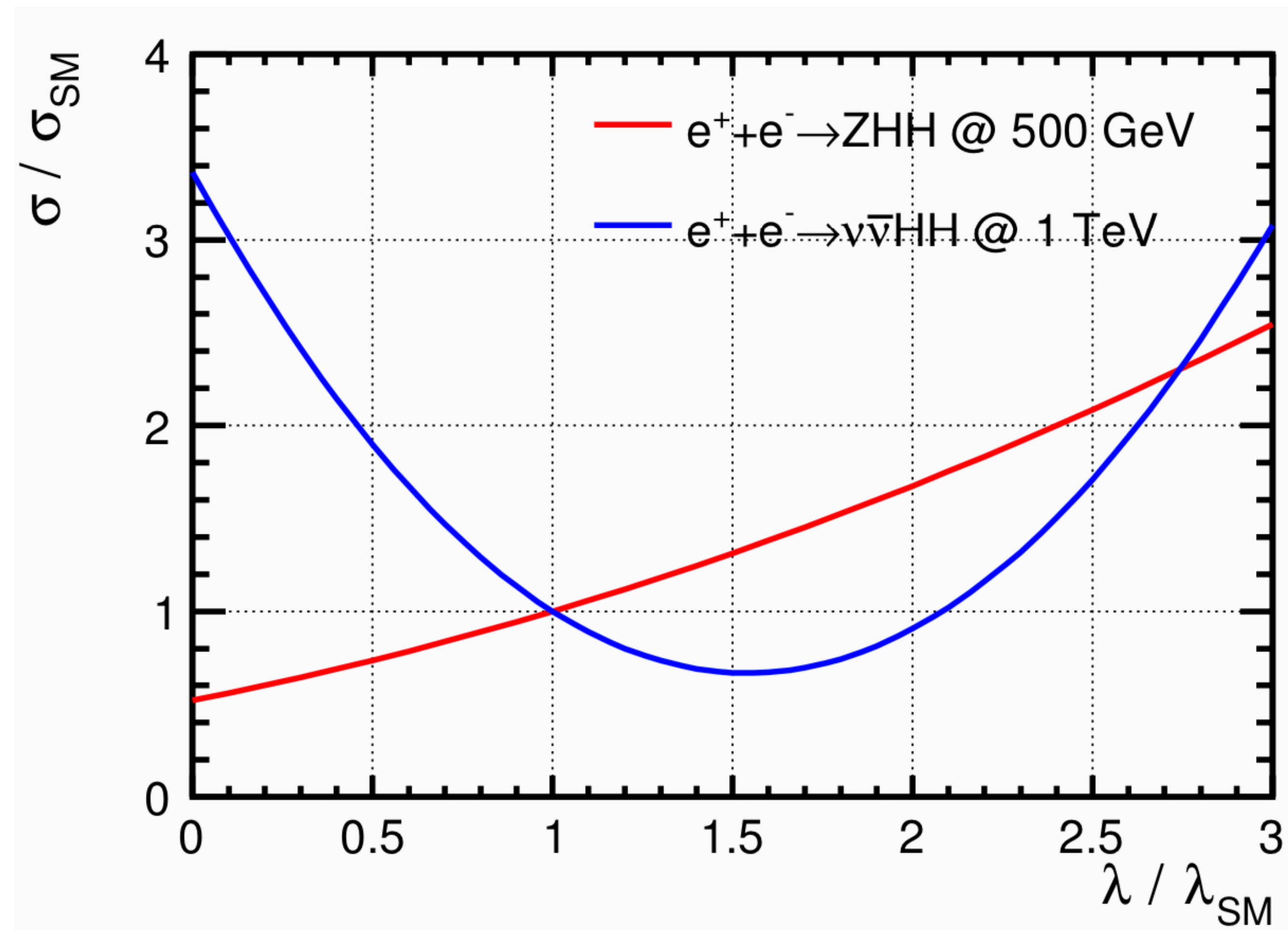
Ratio of partial width for h —> bb

Higgs self coupling









Two channels are complementary :

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

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

(especially λ/λSM ~ 1.5)

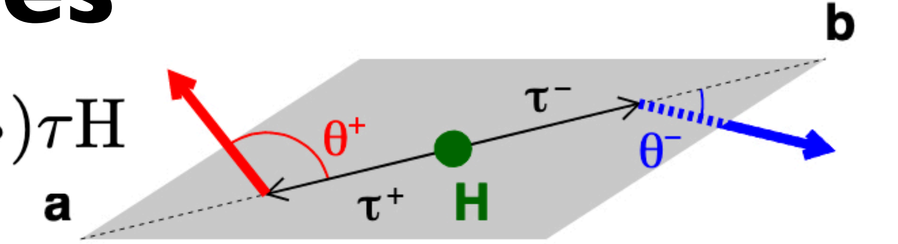
$\delta\lambda/\lambda \sim 10\%$

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

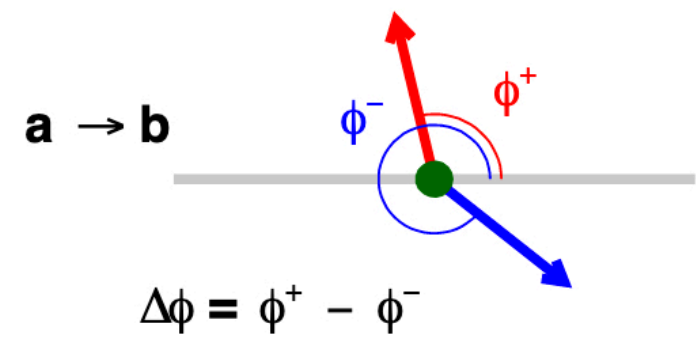
https://arxiv.org/pdf/1903.01629.pdf
https://arxiv.org/pdf/1804.01241.pdf

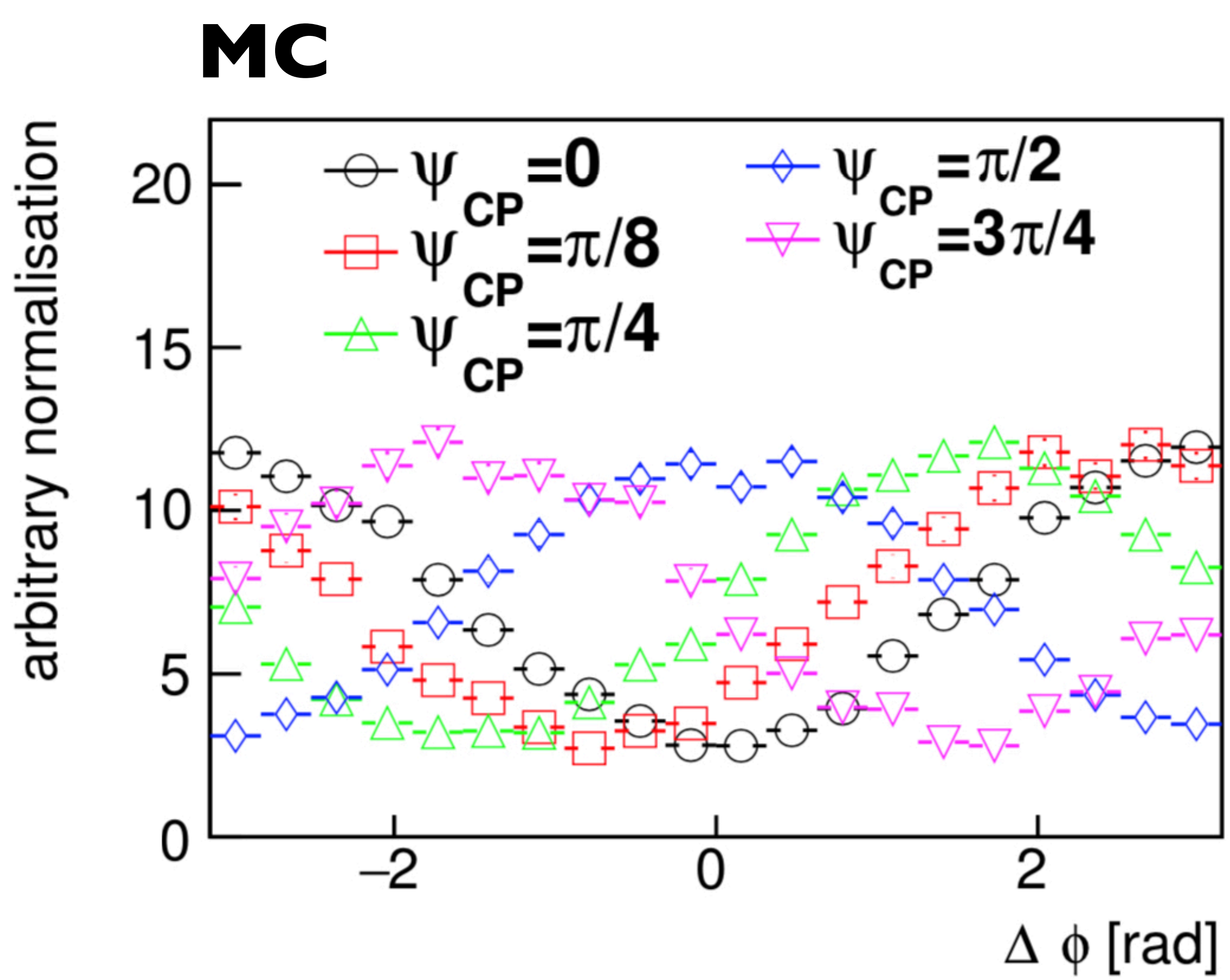
Higgs CP properties

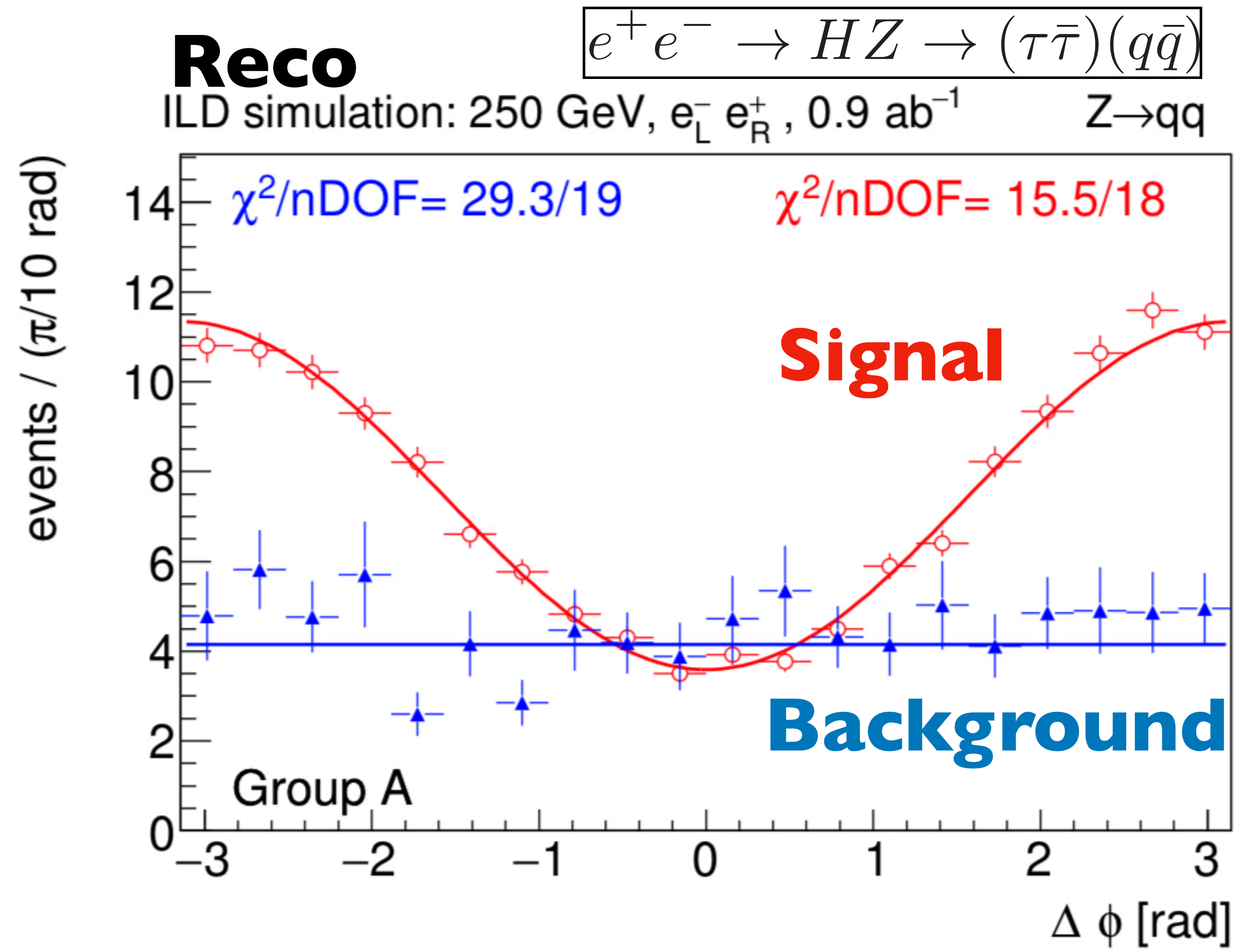
$$\mathcal{L}_{H\tau\tau} = g\bar{\tau}(\cos\psi_{CP} + i\gamma_5 \sin\psi_{CP})\tau H$$



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





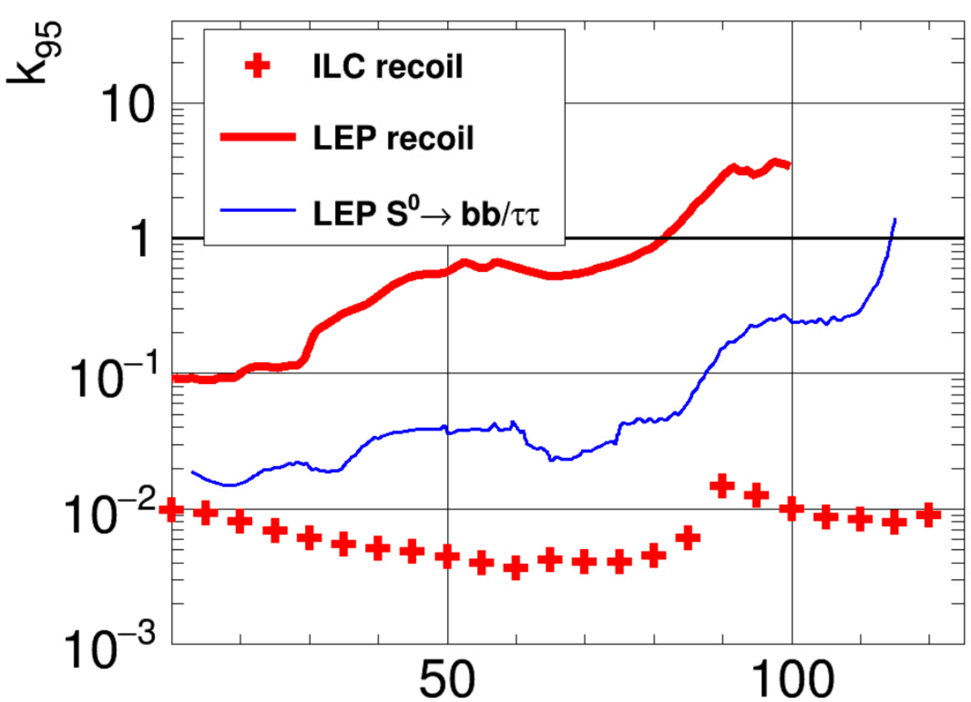


Possible to measure CP-phase better than 4°.

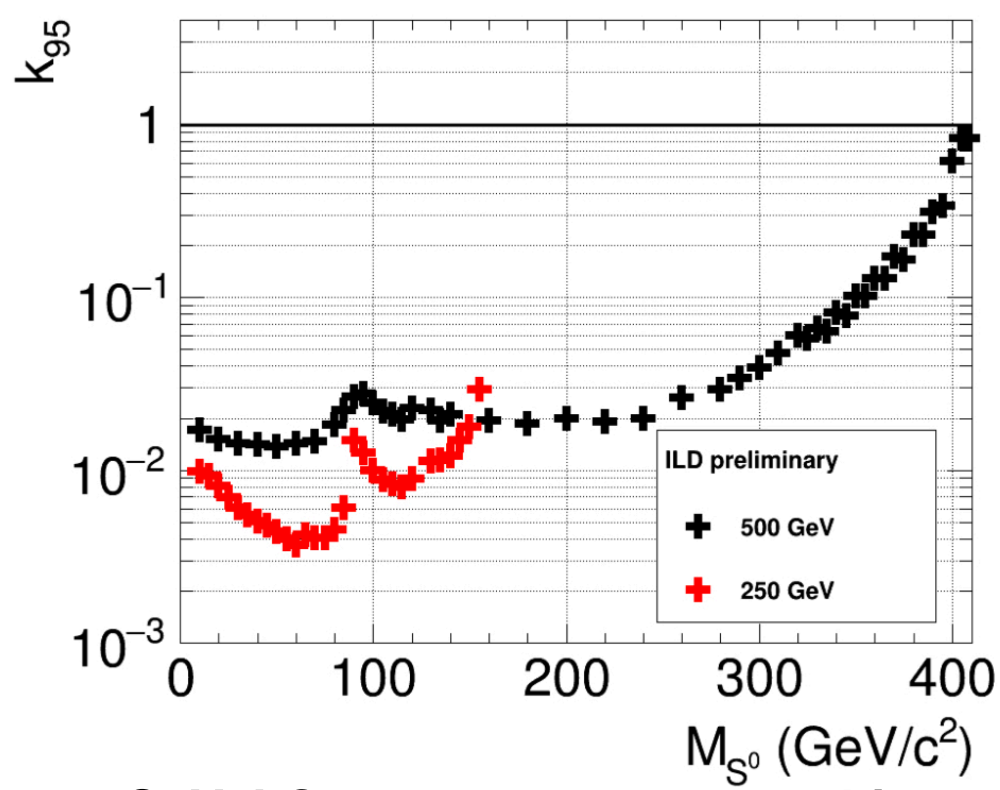
Additional Higgs bosons

- Model-independent ("Recoil mass technique").
- Possibility to discover via studying the properties of the 125-GeV particle.
- ILC offers unique opportunities to directly produce additional lighter Higgs bosons (or any weakly interacting light scalar / pseudo-scalar particles).
- The OPAL collaboration has searched for light scalars (less than 100 GeV) in a model-independent way at LEP, but with limited luminosity(~2.5fb^{-1}).

k: $\sigma_S/\sigma_H(M_H=M_s)$, k_{95} is the point giving 2σ significance($S/\sqrt{(S+B)}$).



1-2 orders of magnitude improvement over LEP recoil results



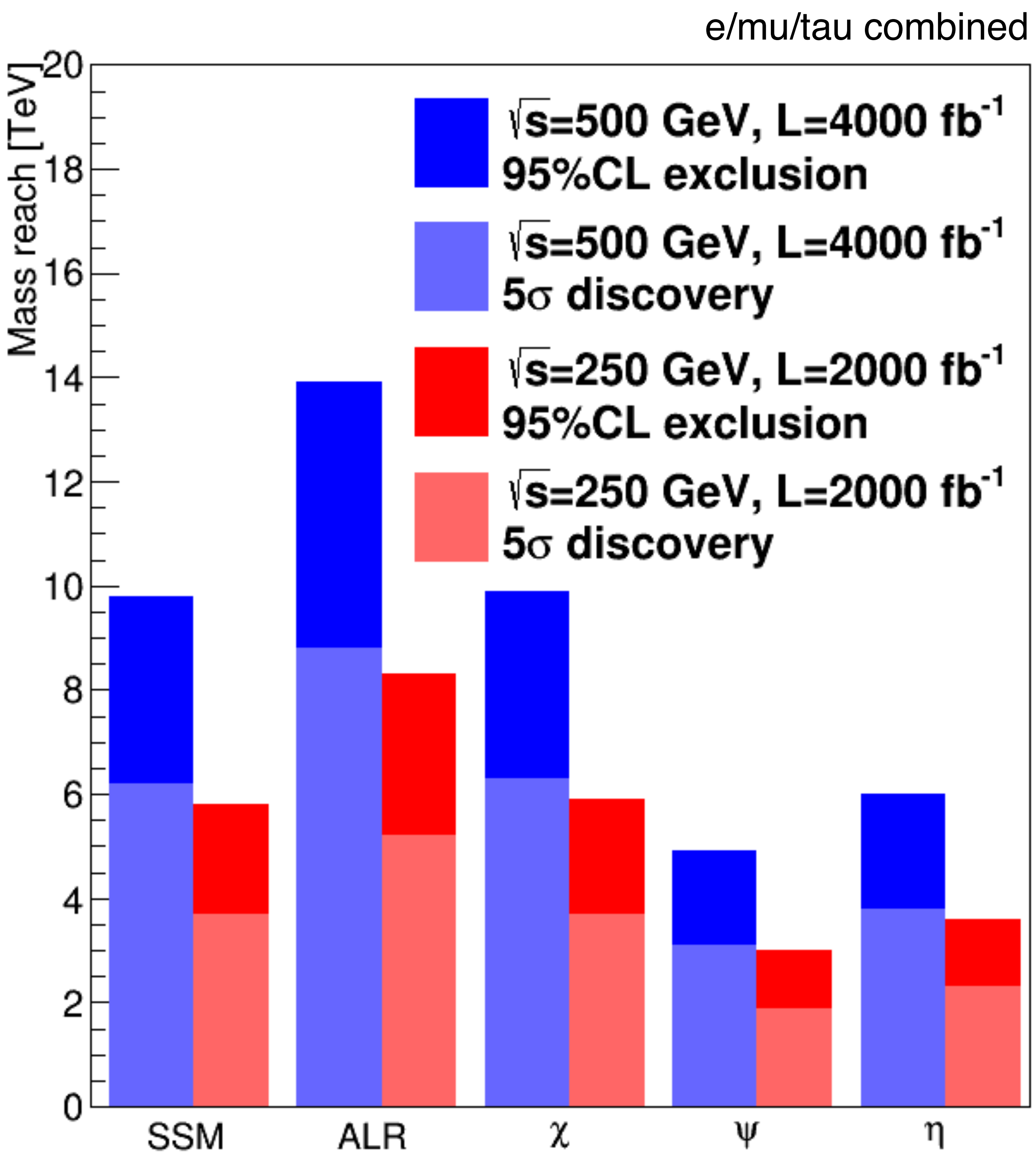
500GeV ILC covers a larger searching region.

Especially when M<300GeV, k_{95} is in the order of 10^{-2}, which could set strong model-independent constraints for the extra scalars.

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- —> f fbar can be used as the probe because s-channel resonance could affect the cross sections.

Z' discovery reach



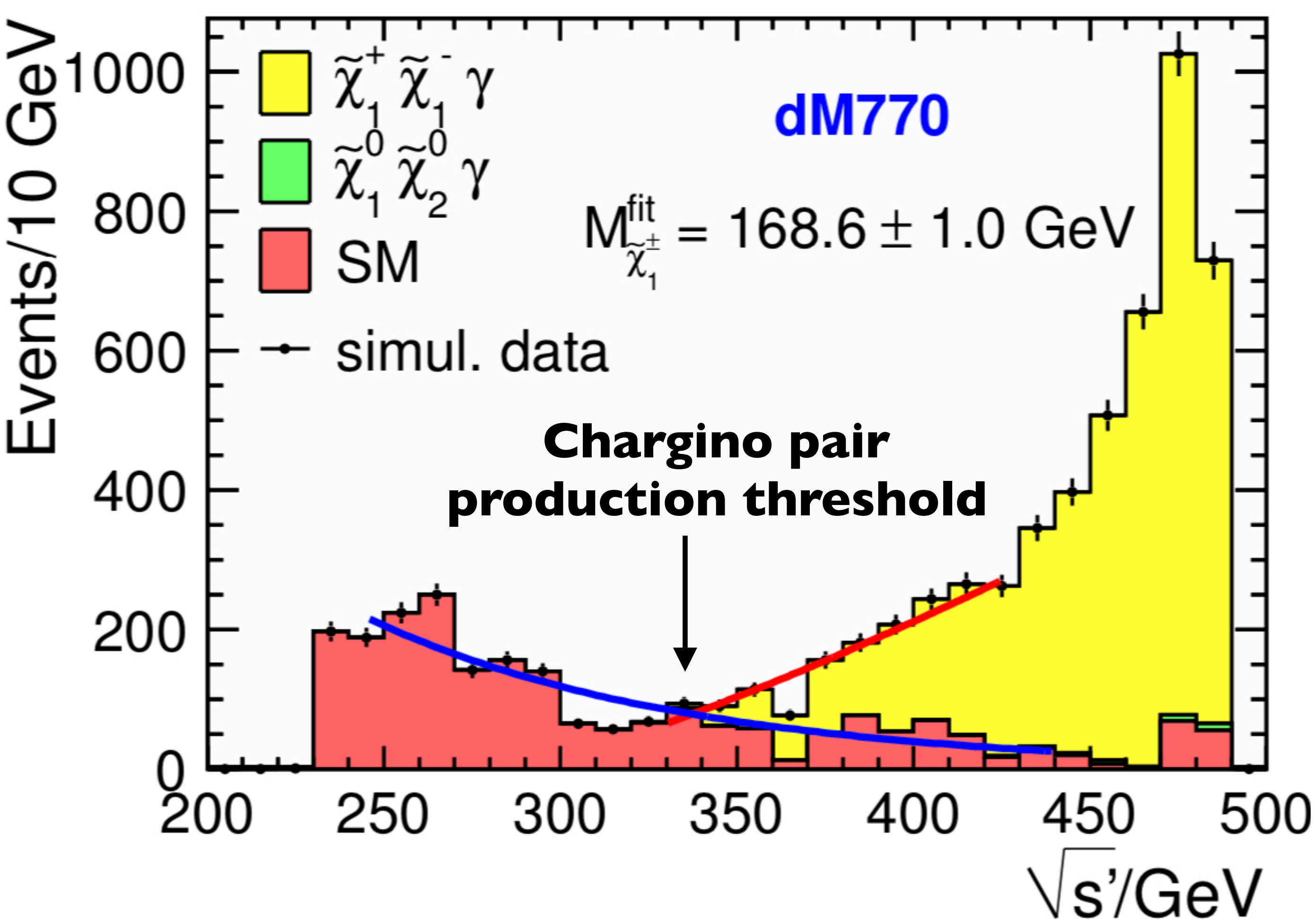
Study by Kyushu group and KEK group

500 GeV results extrapolated from 250 GeV full simulation.

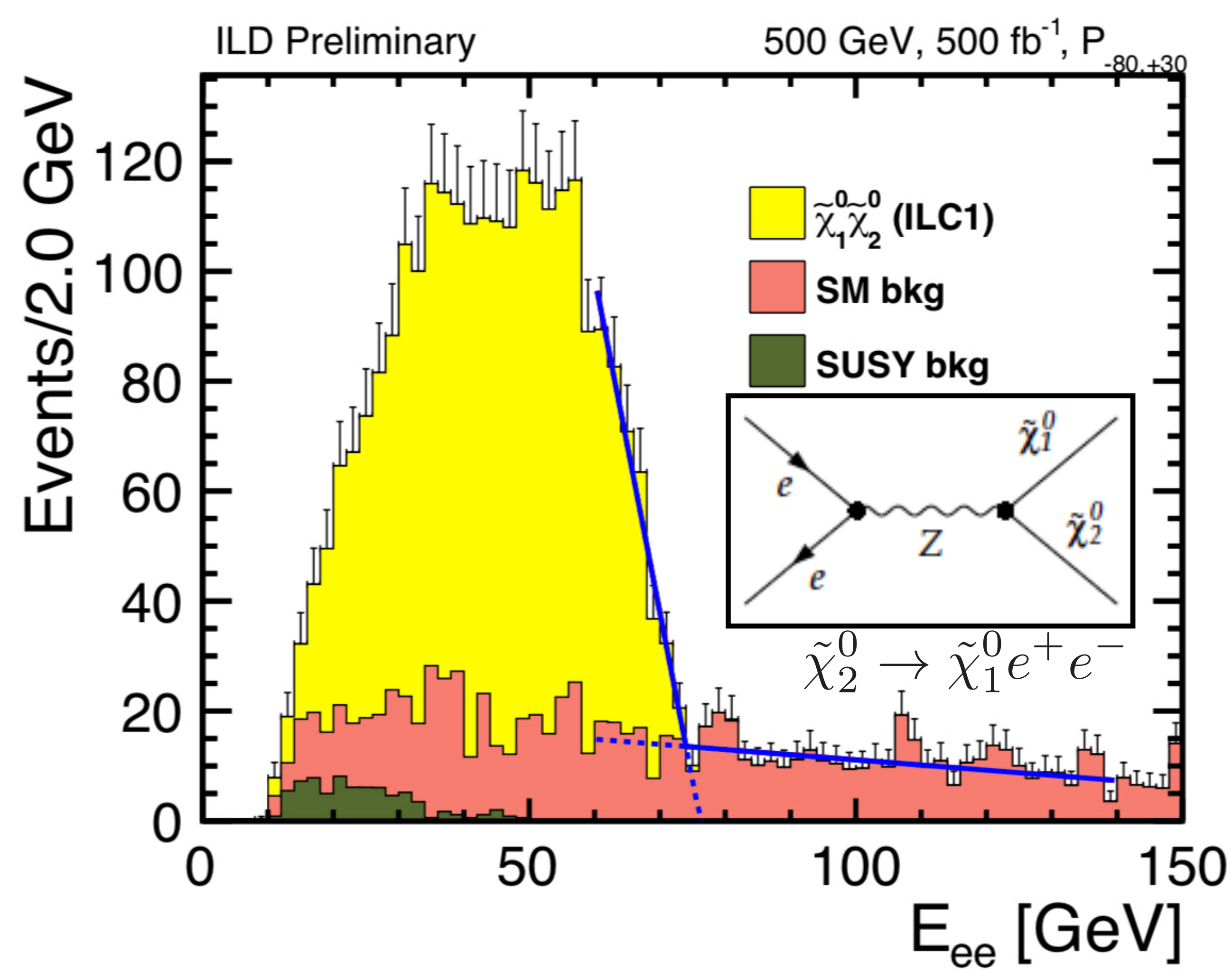
http://nuclear.korea.ac.kr/indico/getFile.py/access?contribId=8&sessionId=37&resId=0&materialId=slides&confId=395

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!



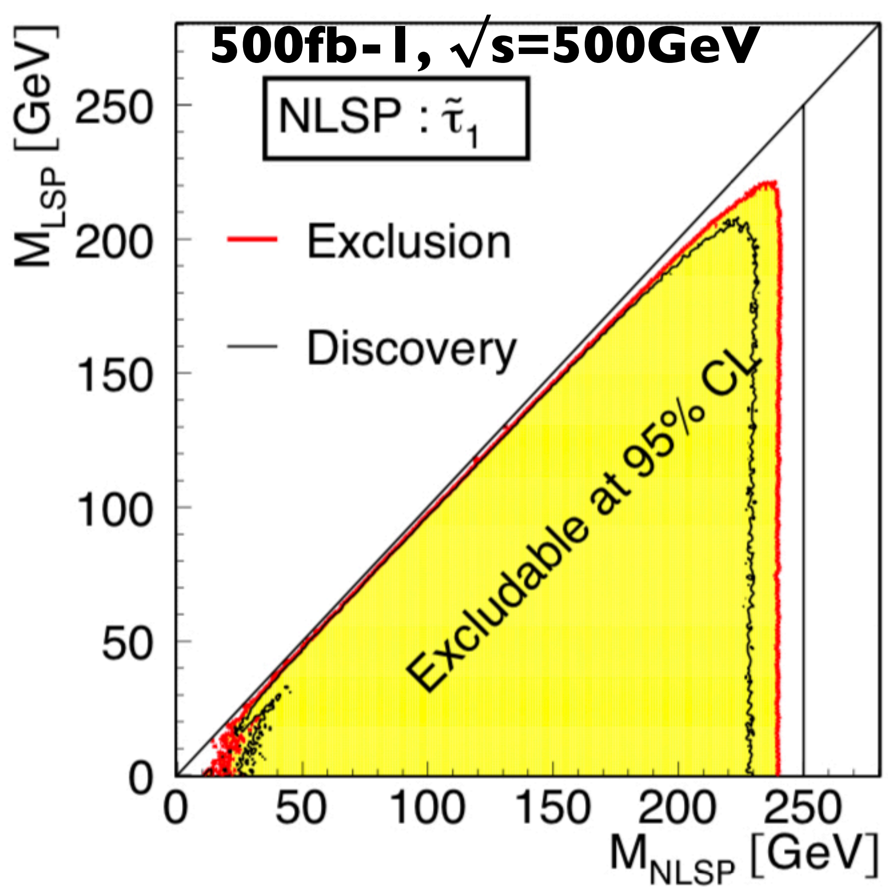
$$M_{\tilde{\chi}^{\pm}_1} - M_{\tilde{\chi}^0_1} = 770 \text{ MeV}$$



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

Loophole free searches

- **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!

Generic WIMP search

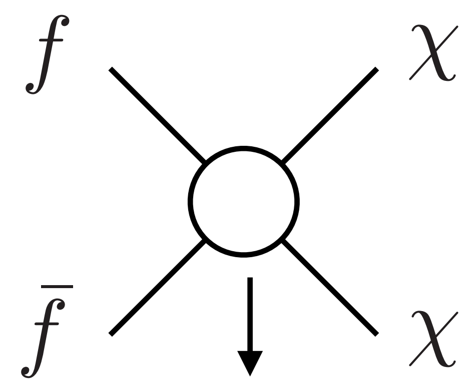
http://bib-pubdb1.desy.de/record/417605/files/Moritz_Habermehl_PhD.pdf

❖ 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.

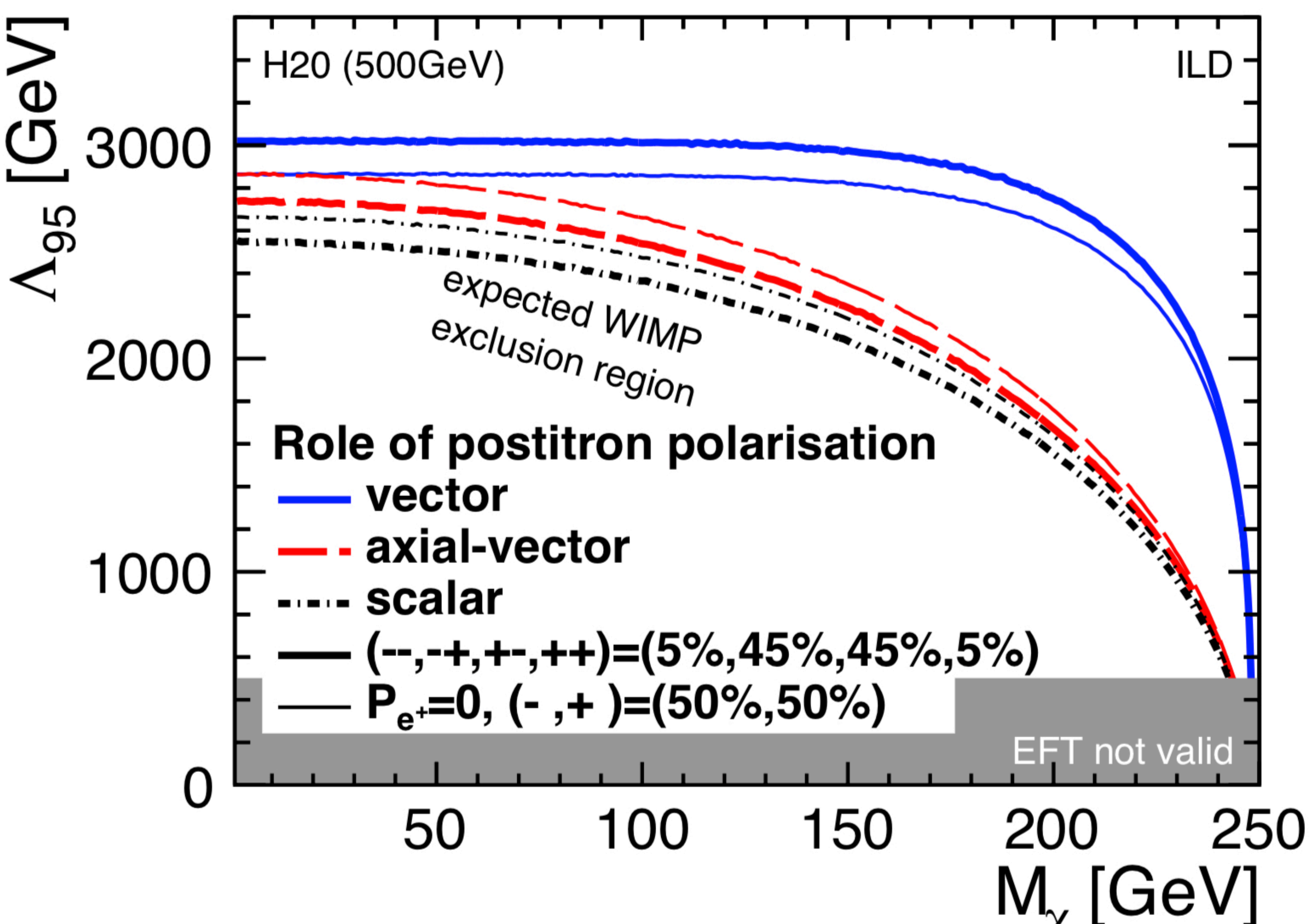
Observables : E_γ, θ_γ

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



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

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



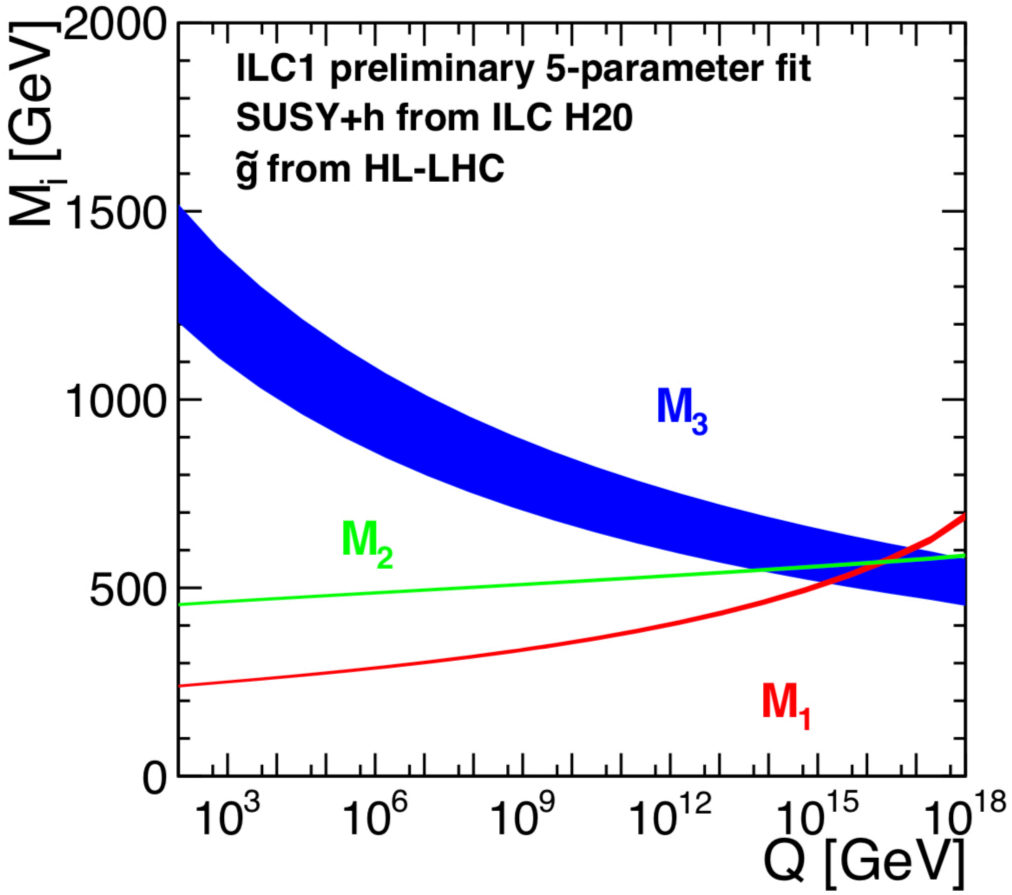
- Detailed detector simulation study for Ecm=500GeV has been done.
- Comprehensive study can be found in the reference.

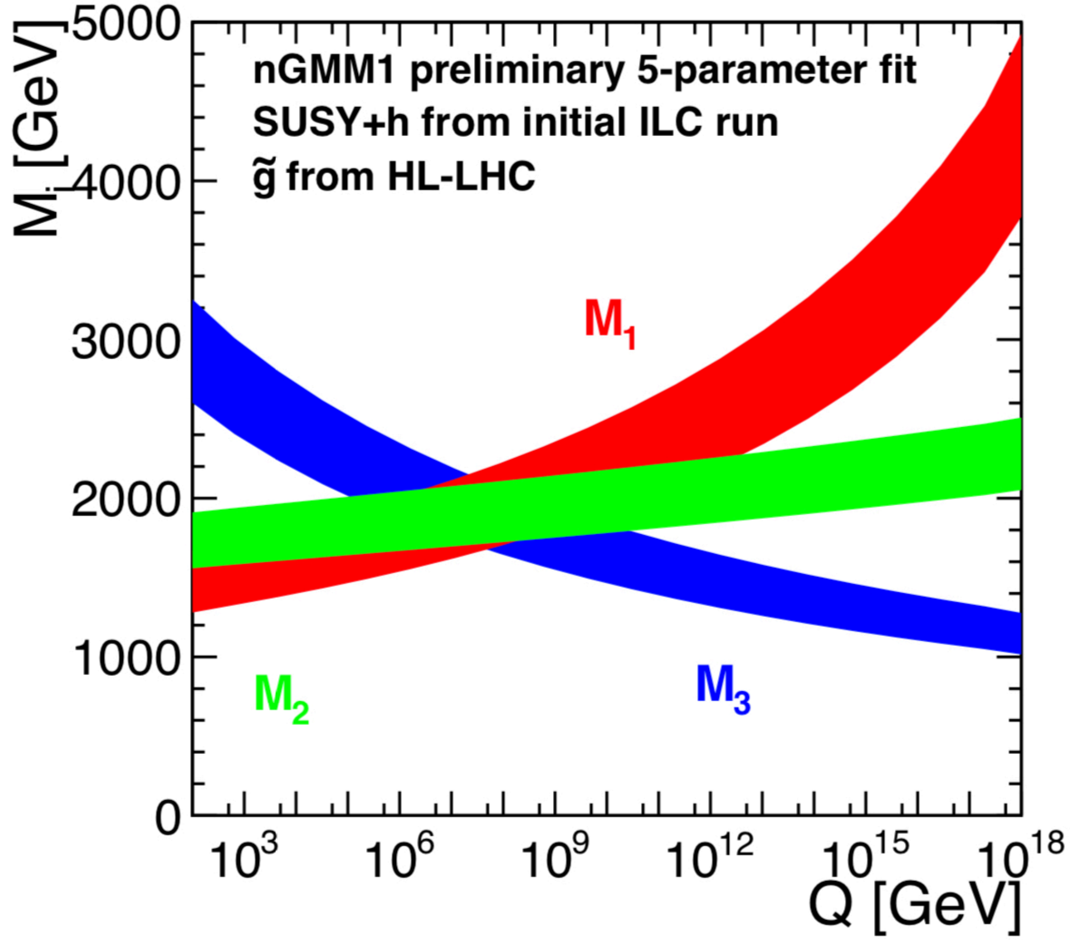
Once SUSY particle has been found…

- **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 250GeV, 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 SM parameters at ILC can probe SUSY models.
  - A new heavy gauge boson search
  - Light higgsino search
  - Loophole free search
  - Model independent Dark Matter search

LCWS2019

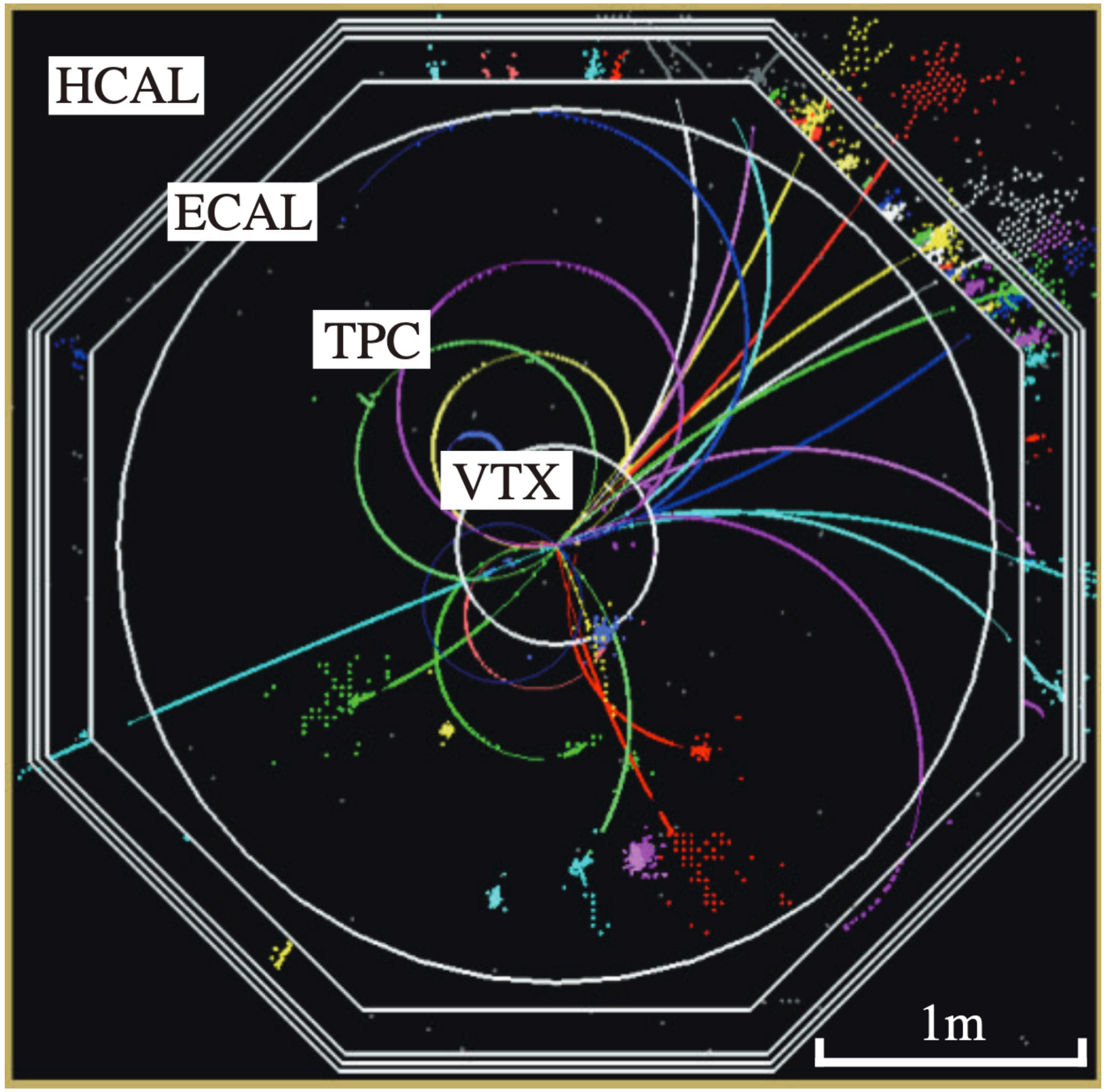
28 Oct. - 1st Nov. 2019 in Sendai/Japan.

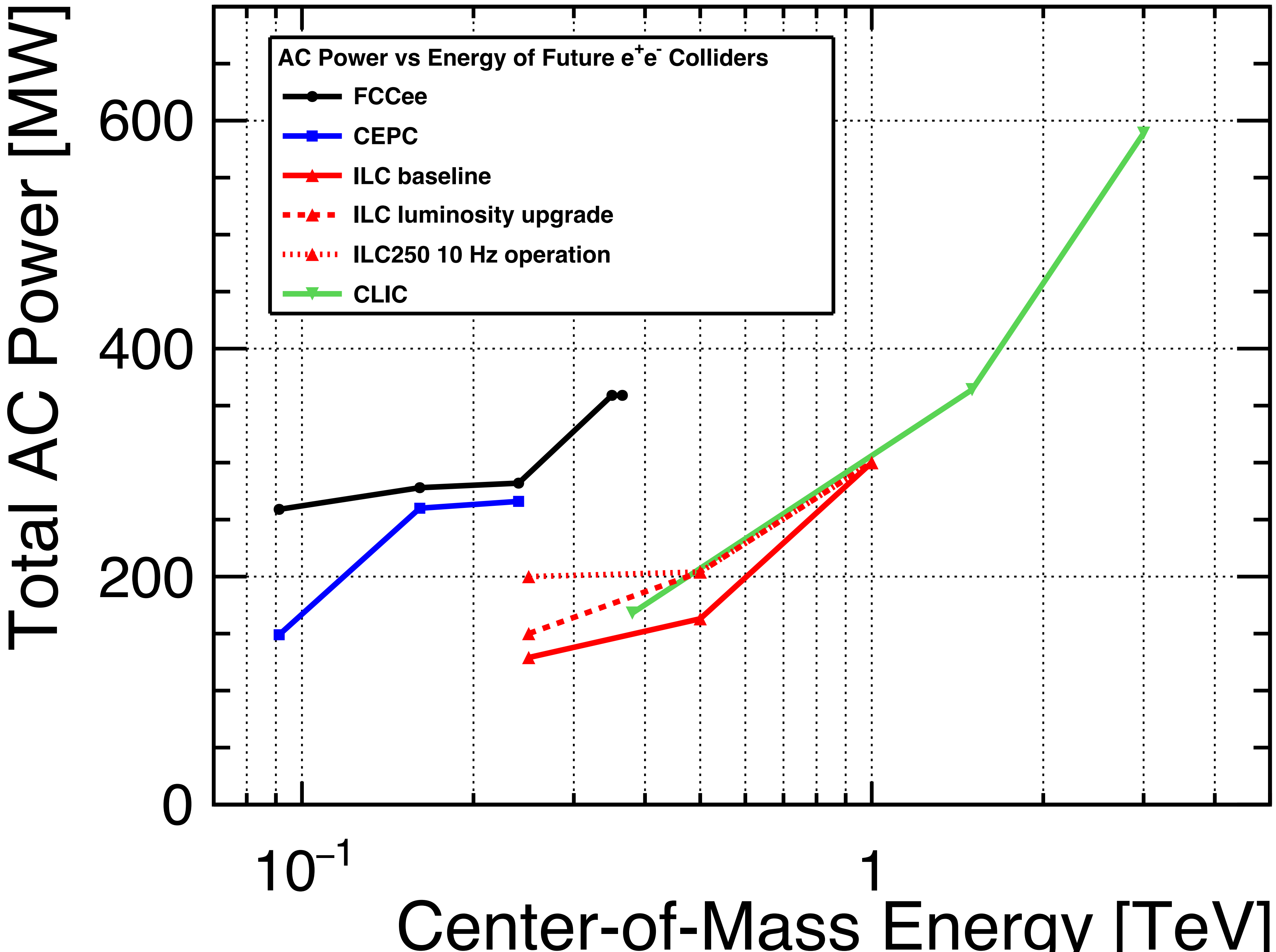
Why not come to join us?

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]
600
400
200
0
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.

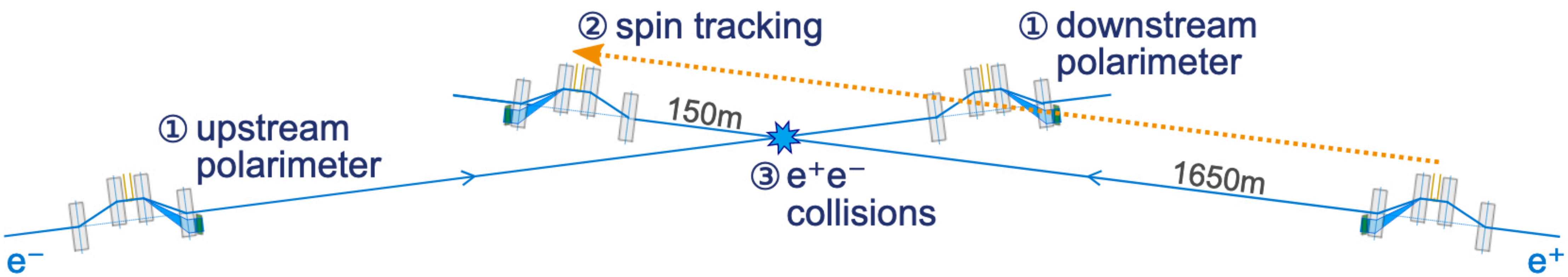
https://indico.desy.de/indico/event/15730/session/0/contribution/81/material/slides/0.pdf

Systematic Polarization Uncertainty

contribution	uncertainty $[10^{-3}]$
Beam and polarization alignment at polarimeters and IP ($\Delta\vartheta_{\text{bunch}} = 50\,\mu$rad, $\Delta\vartheta_{\text{pol}} = 25$ 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

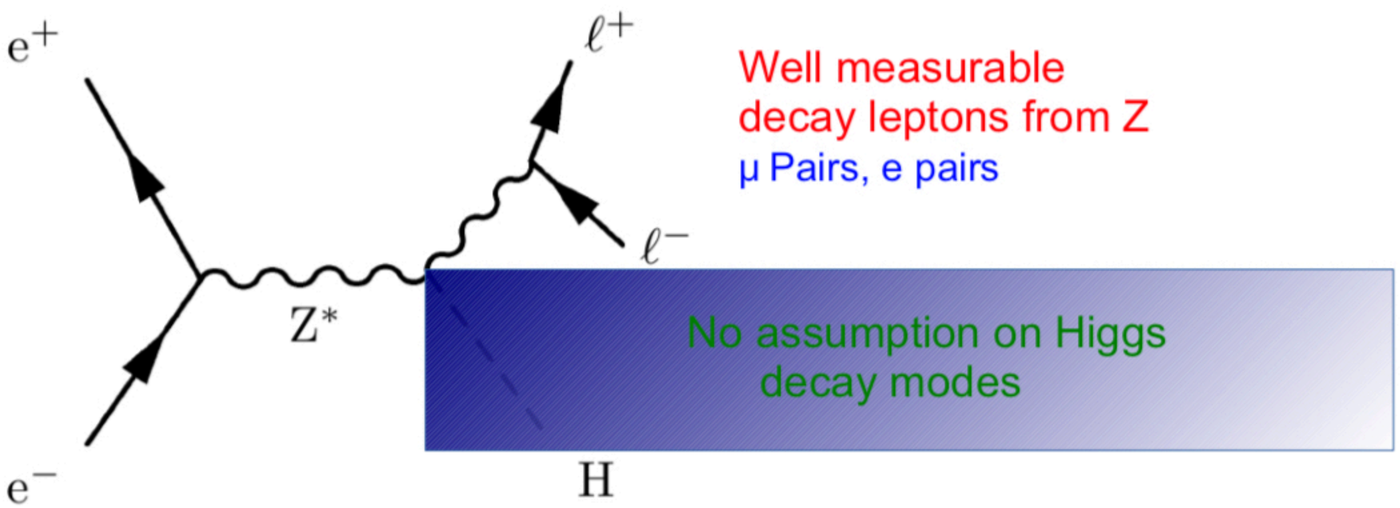
Ref.: Moritz Beckmann, Jenny List, Annika Vauth, and Benedikt Vormwald:
Spin transport and polarimetry in the beam delivery system of the international linear collider
(http://iopscience.iop.org/article/10.1088/1748-0221/9/07/P07003/pdf)

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

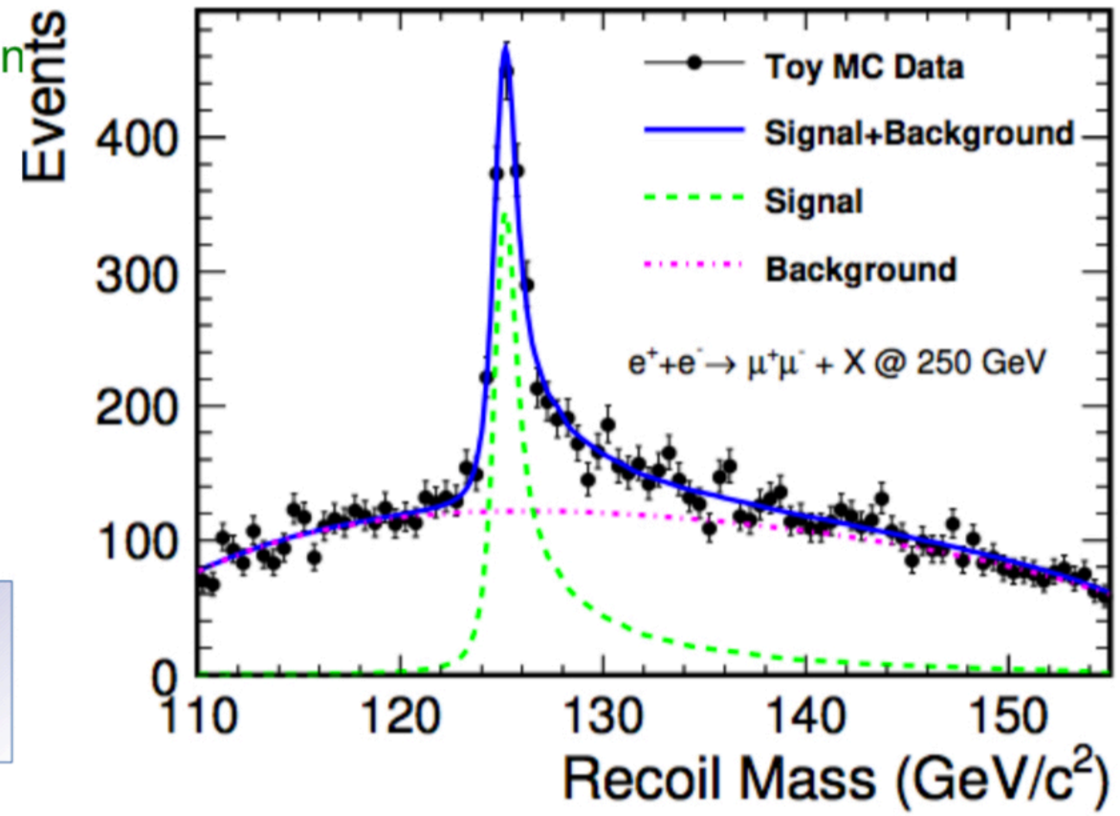
$\Rightarrow$ Discussed in the following

Higgs-strahlung at lepton colliders

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



Well measurable decay leptons from Z
μ Pairs, e pairs



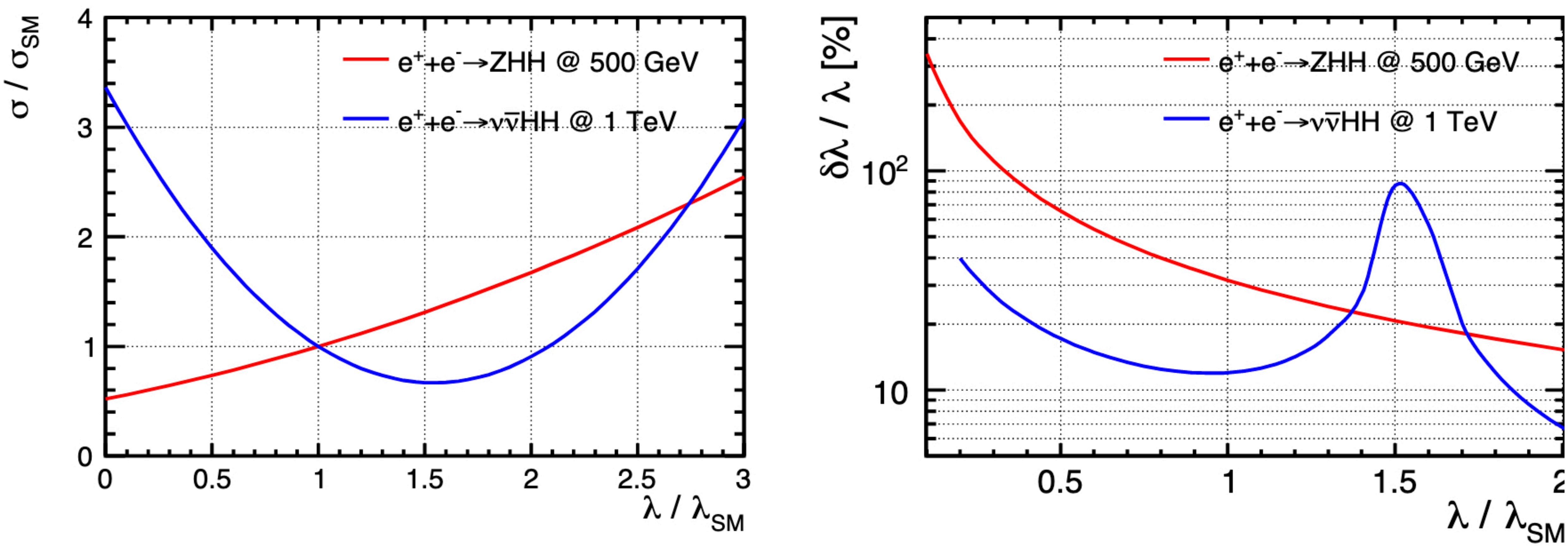
Higgs Recoil Mass: $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2 E_Z \sqrt{s}$

- 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

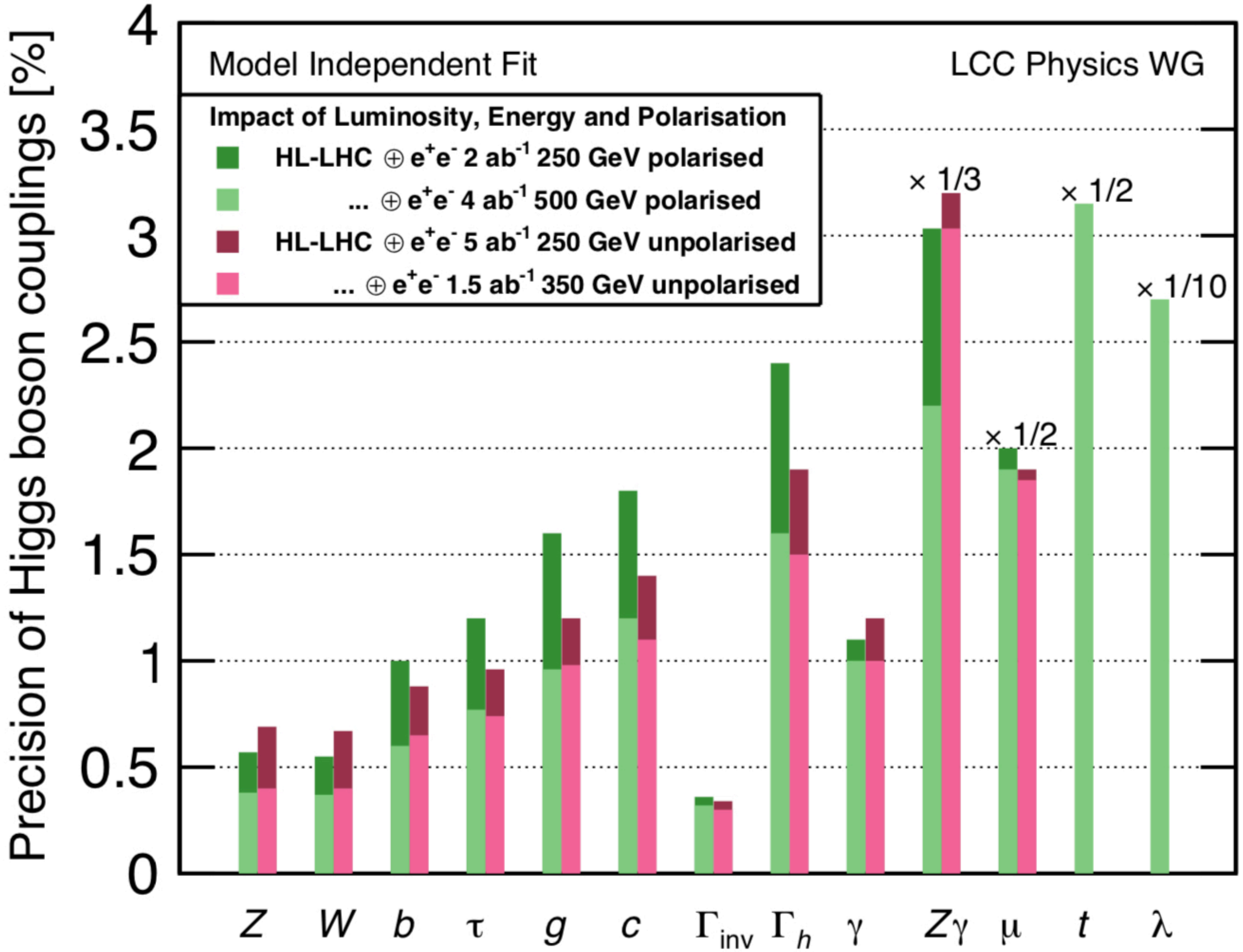


FIG. 76: Projected Higgs boson coupling uncertainties for selected scenarios from Table XVIII. In particular it shows that at $\sqrt{s} = 250\,\text{GeV}$, 2 ab^{-1} with polarised beams yield comparable results to a much larger data set of 5 ab^{-1} with unpolarised beams.