Physics Summary

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Introduction to Terascale

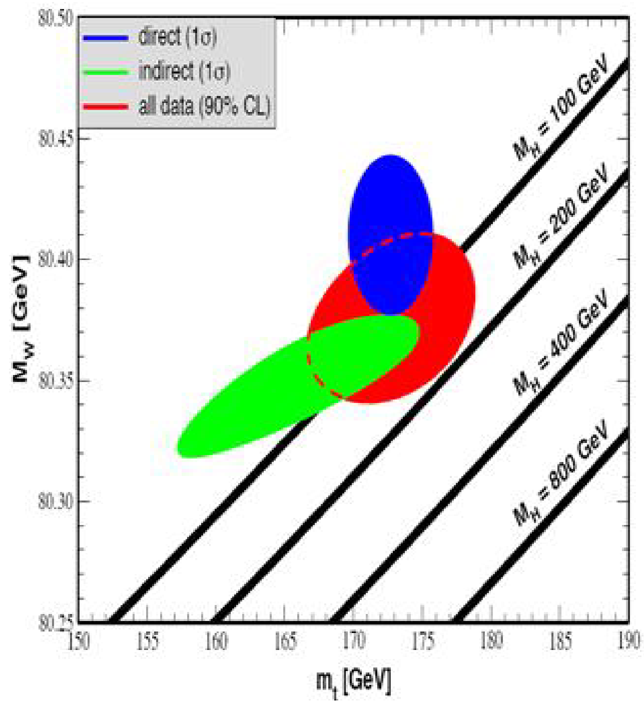
Physics Talks at TILC08

Summary

March 6, 2008 @ TILC08

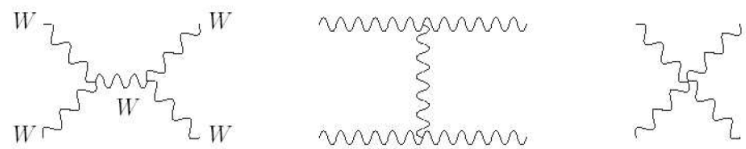
Introduction to Terascale

114.4 GeV · M_H · 166 GeV (95% CL)



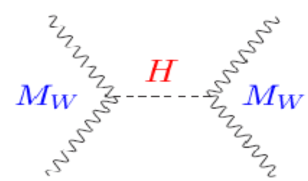
Fermi Scale = 246 GeV: EW Unification Scale

Tree-level Unitarity for W_L W_L ! $W_L W_L$



Probability » $(E/TeV)^2$

+



M_H < 1 TeV !

CDM Particle Mass

$$\Omega_X \sim 0.2 \quad \text{for} \quad \langle \sigma v \rangle = \frac{\pi \alpha^2}{8 m_X^2} = 0.1\,\text{pb} \quad \text{or} \quad m_X = 100\,\text{GeV}$$

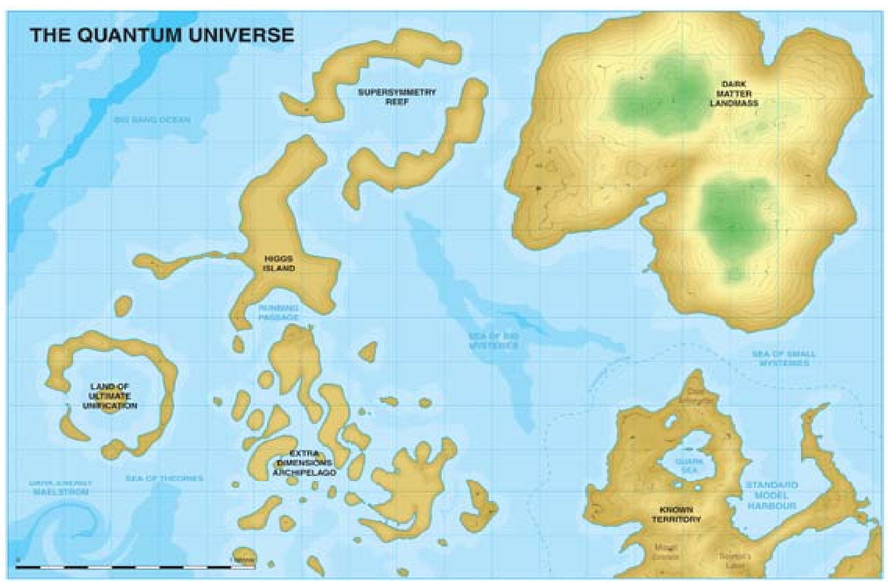
Electroweak Baryogenesis

Central Problems

Electroweak symmetry breaking
Unification of forces
Microscopic spacetime structure
Connection with cosmology

SUSY or Extra-D or Strong Dynamics or ⋯

Impact across all microscopic scales © cosmology



Genuine Path to the Ultimate Destination

Measure masses and mixings of new states,
decay widths and branching ratios,
production cross sections ....

⇩

Determine spin and parity,
gauge quantum #'s and couplings.

⇩

Reconstruct the Terascale Lagrangian as model independently as possible with great precision.

⇩

Shed light on the physics at the fundamental (GUT or Planck or TeV) scale.

Targets of ILC

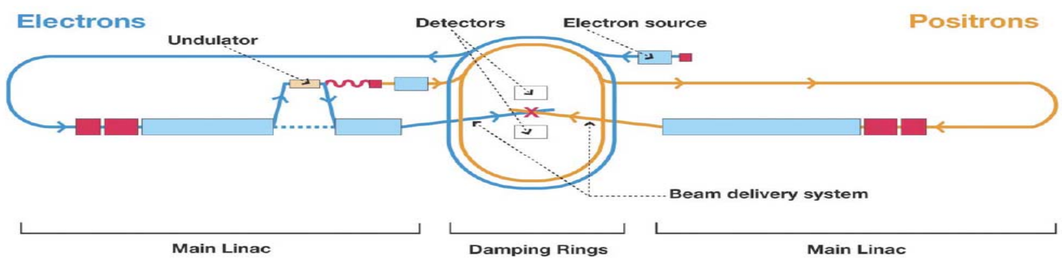
Model-independent and high-resolution picture at Terascale

⇩

Unification of matter and interactions

⇧

ILC = International e^+e^- linear collider



Characteristics

0.5 to 1 TeV to CLIC w/ 3 TeV
300 fb^{-1}/y) 1 ab^{-1} in total
90/60% e^-/e^+ polarization

Satellite modes

GigaZ: 10^9 Z bosons
e^-e^- w/ same E / reduced L
$\gamma e/\gamma\gamma$ via Compton backscattering

Precious Physics Talks at TILC08

16 talks (including 3 plenary talks)

Many important detailed studies

Physics Overview

H. Murayama: ILC, Future Particle Physics and Cosmology

T. Rizzo: The LHC and the Road Ahead

Y. Okada: Overview of Physics RDR and the Next Step

[not covered in my talk]

Spin Determination

M. Buckley: Discriminating Spin through Quantum Interference

S.Y. Choi: Spin Analysis of Supersymmetric Particles

(SM) Higgs Couplings

S. Kanemura: Physics Potential of Higgs Pair Production at a γ γ Collider

K. Tsumura: Impact of dim-6 Higgs-fermion and Higgs Genuine Operators on Processes at the Future Colliders

Y. Matsumoto: Precise Measurement of the Higgs-boson Electroweak Couplings at Linear Collider and Its Physics Impacts

Y. Takubo: Analysis of 4-jet Mode in ZHH

D. Jeans: Measurement of g(HHH) – Generator Level

and First Quicksim Studies

S. Uozumi: Report on ttH Analysis

Littlest Higgs Model

M. Asano: Determination of Dark Matter Properties in the Littlest Higgs Model with T-parity

T. Kusano: Simulation Study of $e^+ e^- \rightarrow Z_H + A_H$ in Littlest Higgs Model

Extended Higgs Sector

D. Zhuridov: Testing Extended Higgs Models by Resonance Effects at the ILC

Hidden Sector

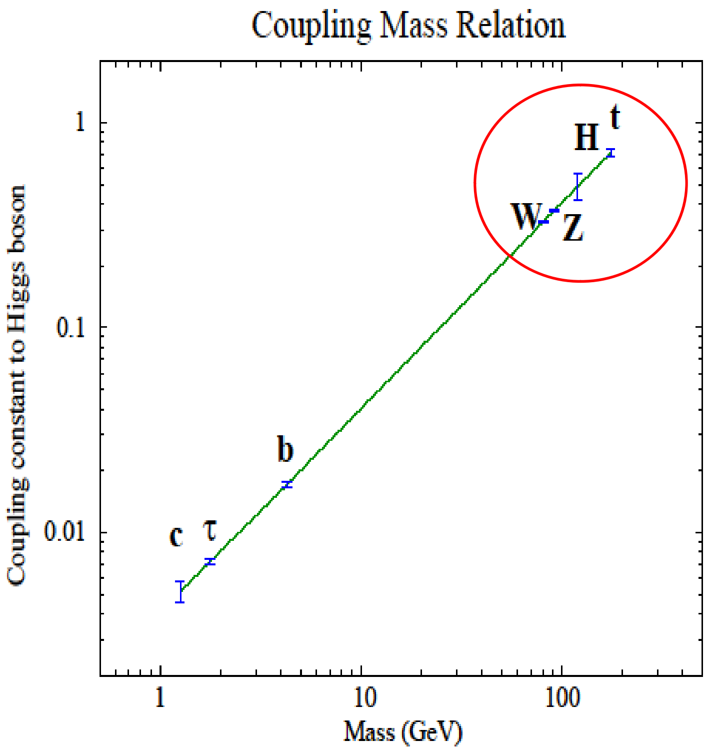
H. Itoh: Hidden Sector Particle Production at the ILC

Benchmark Studies

L. Lastovicka: Benchmark Studies with the LCFI Vertex Package

Disclaimer: I can't possibly cover all of the talks.
So, my prior apologies to those omitted!

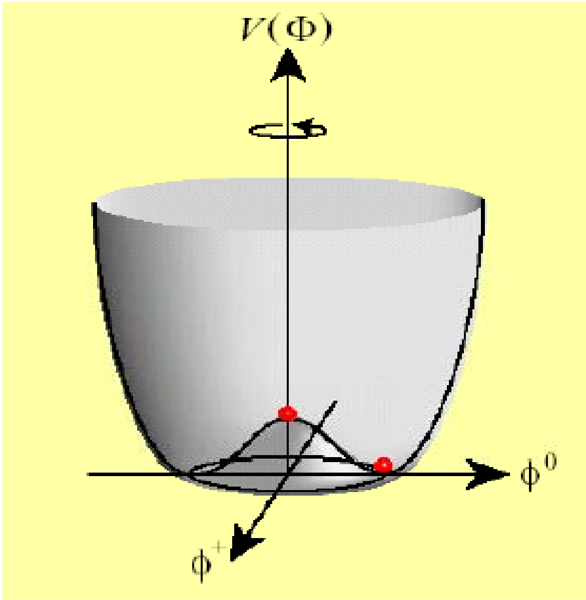
SM Higgs or Not



Linear or not?

HVV
Htt
HHH
…

EWSB ⇔ Mexican Hat

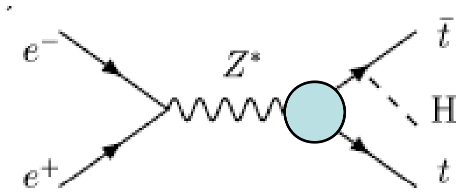


$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

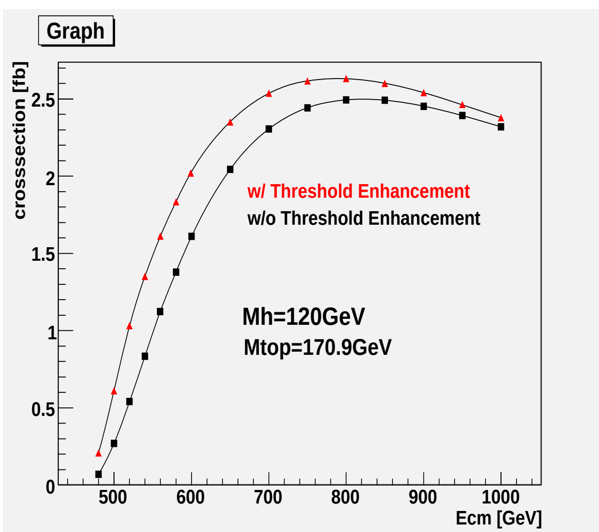
M_H ⇔ Self couplings: λ

Htt Couplings

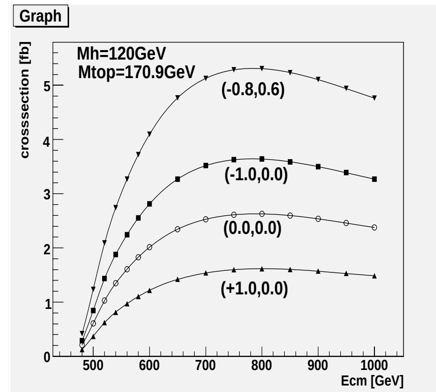
[S. Uozumi]



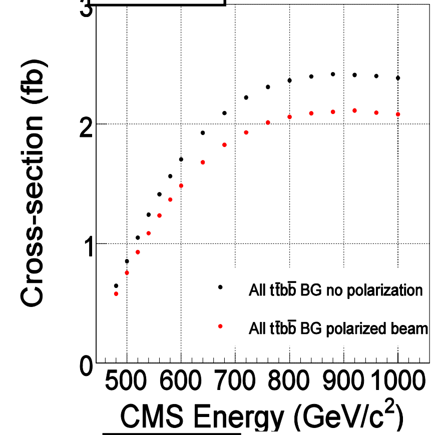
Signal generator with tt-system threshold enhancement done!



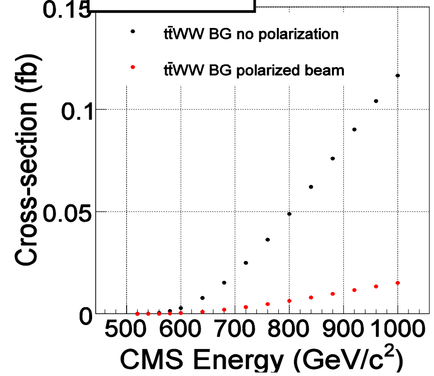
Signal



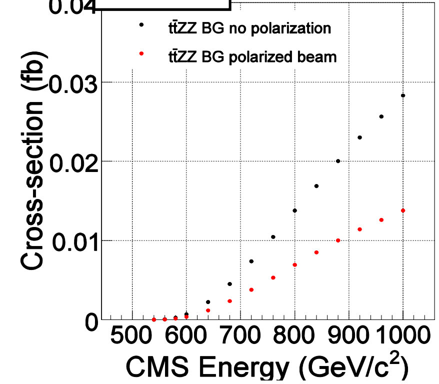
ttbb



ttWW



ttZZ

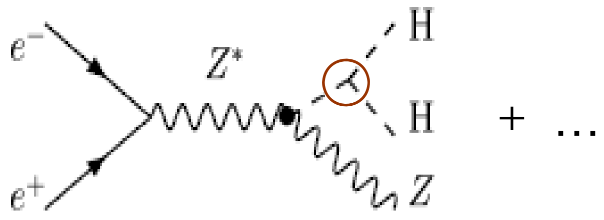


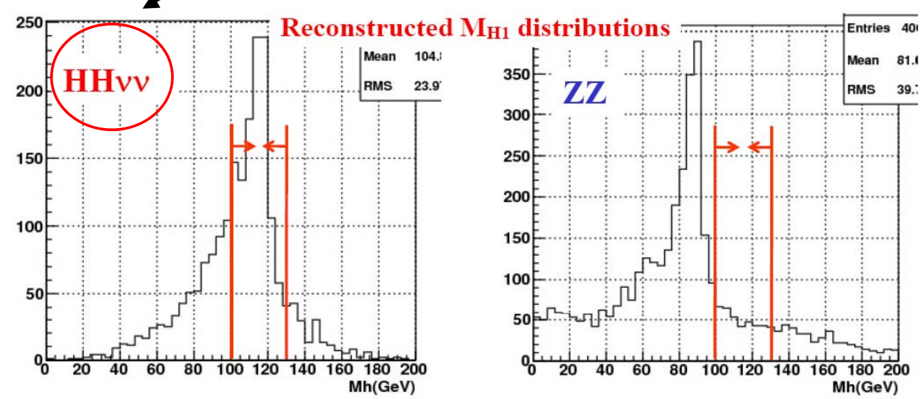
Polarization helps

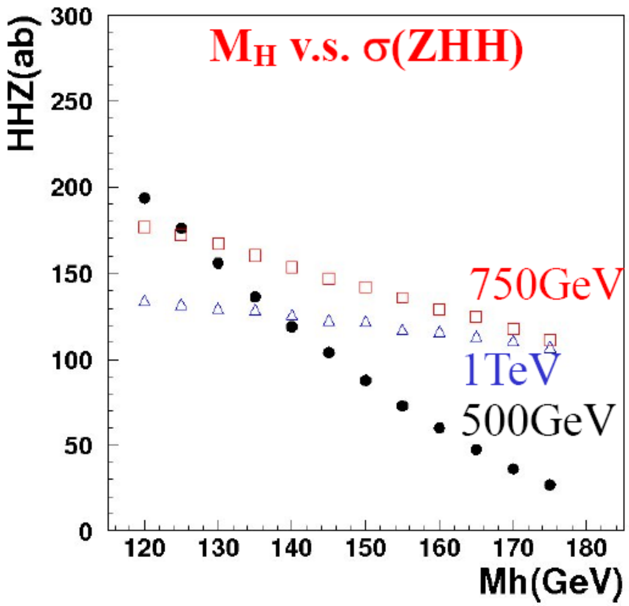
Dense 8-jet events ⇒ more works planned

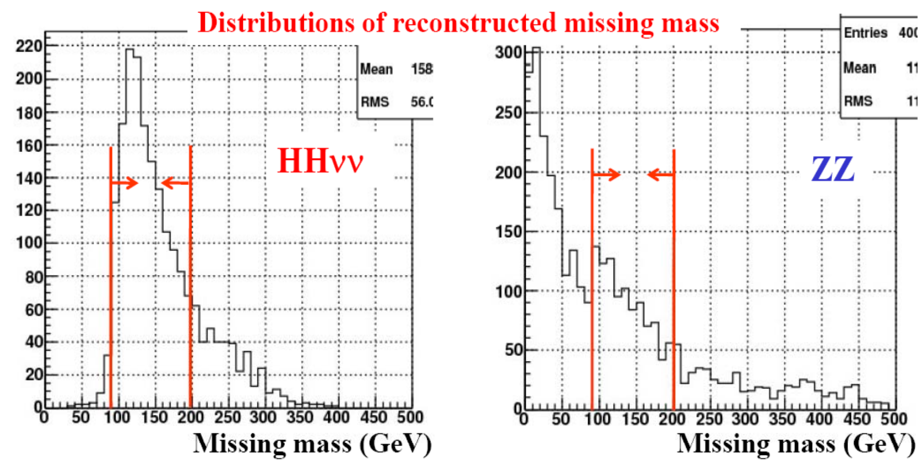
Trilinear HHH Self-Couplings

Mode easy to analyze





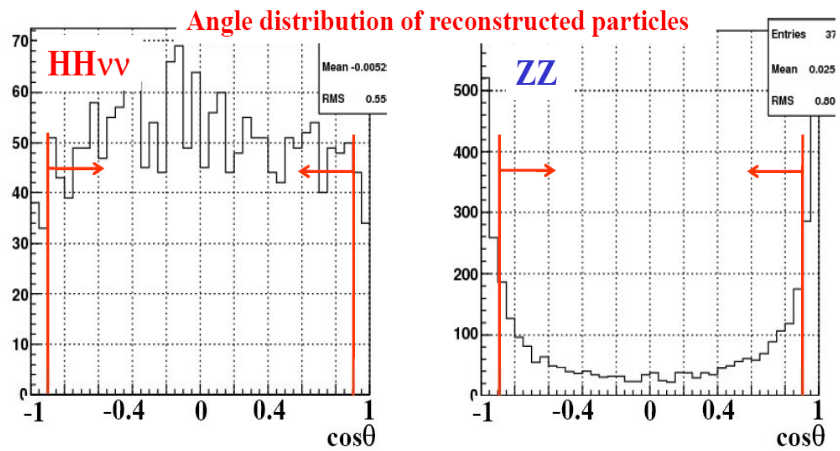




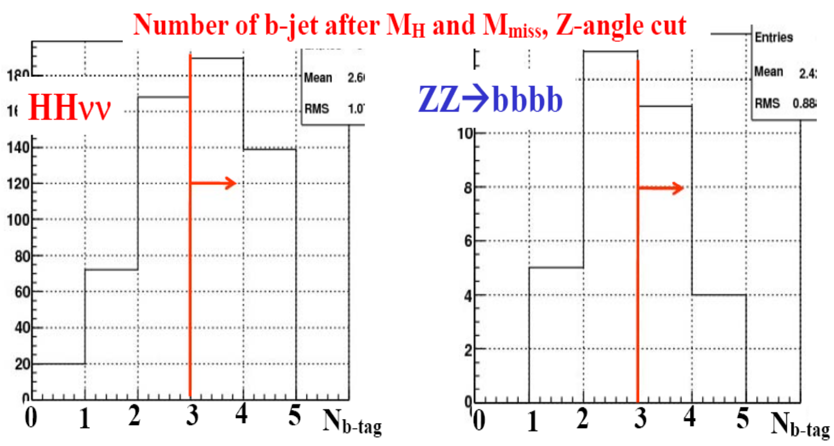
[Y.Takubo] with M_H = 120 GeV

Trilinear HHH Self-Couplings

Z-angle cut



b-tag cut



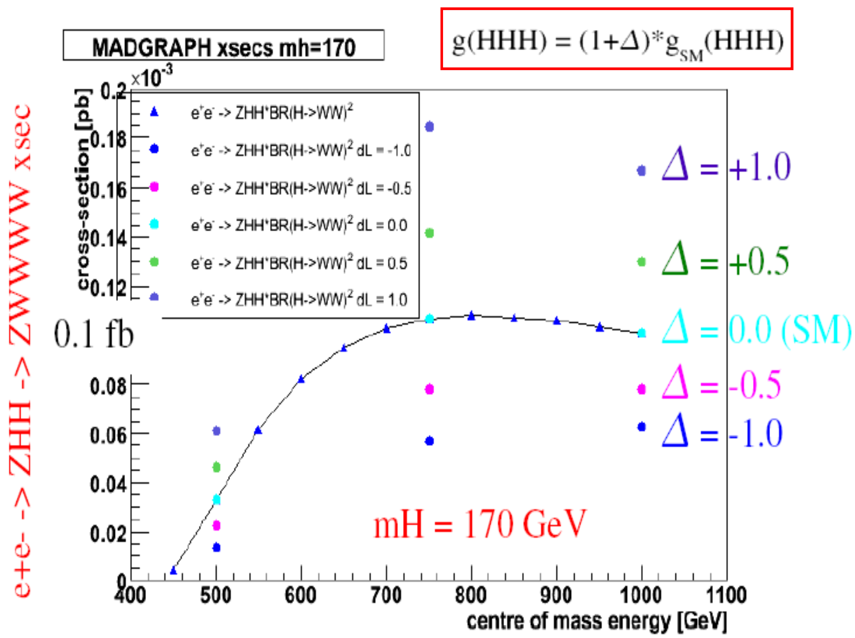
	HH νν	ZZ	ZZ→bbbb
• No cut	: 77 (1.00)	791,560 (1.00)	42,534 (1.00)
• 100GeV < $M_{H1,2}$ <130GeV	: 27 (0.35)	8,510 (1.1x10^{-2})	957 (2.2 x 10^{-2})
• 90GeV < M_{miss} < 200GeV	: 26 (0.34)	2,770 (3.5x10^{-3})	404 (9.5 x 10^{-3})
• $\lvert\cos\theta_{1,2}\rvert < 0.9$	: 22 (0.29)	594 (7.5x10^{-4})	141 (3.3 x 10^{-3})
• $N_{b\text{-tag}} \geqq 3$	12 (0.16)		64 (1.5 x 10^{-3})

1.4 σ significance: weak

↓

Modification and optimization in the selection criteria + combination with other modes required!

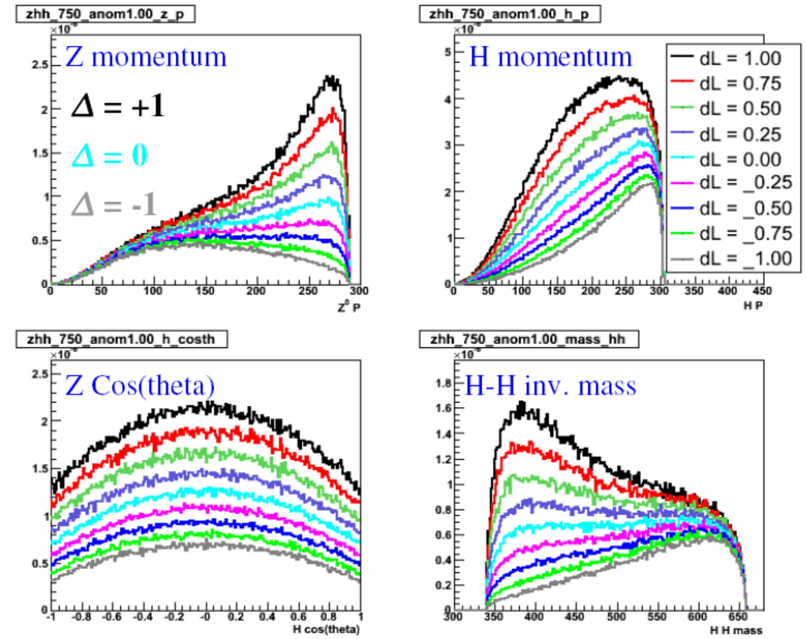
[D. Jeans] with M_H = 170 GeV: generator-level and 1st quick sim. studies



750 GeV

e+e- -> ZHH -> ZWWWW -> 10f

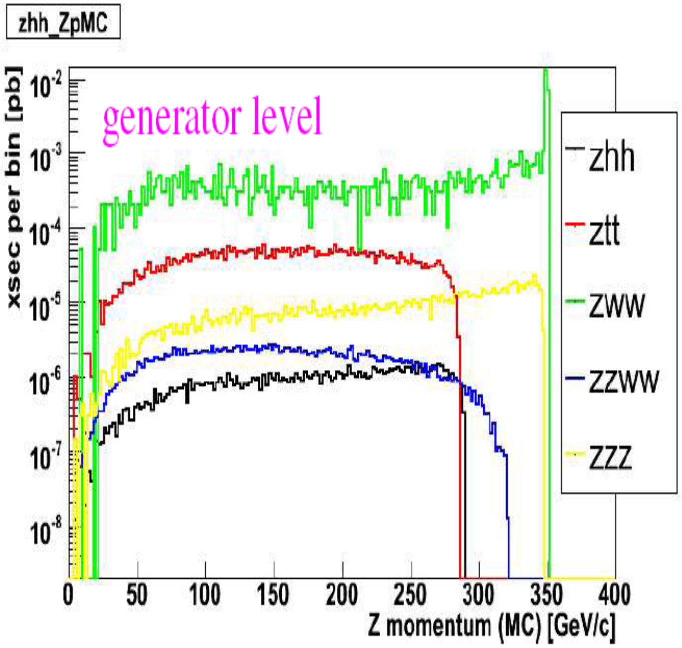
Many different final states
<u>from</u> 4 leptons + neutrinos
<u>to</u> 10 quarks

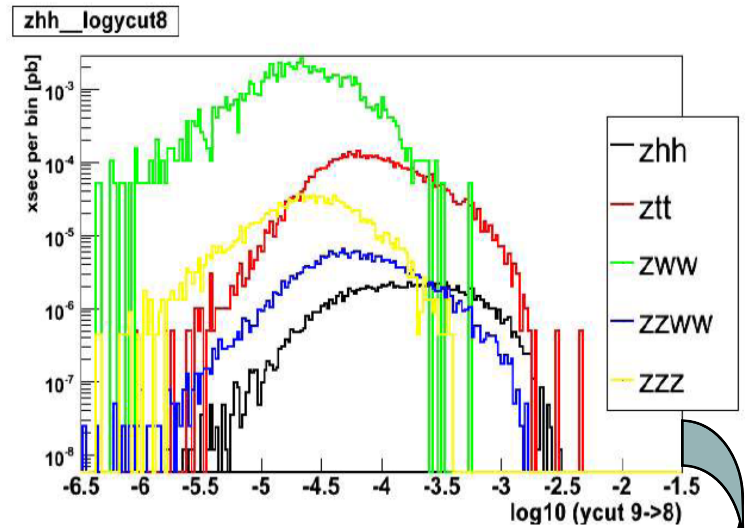


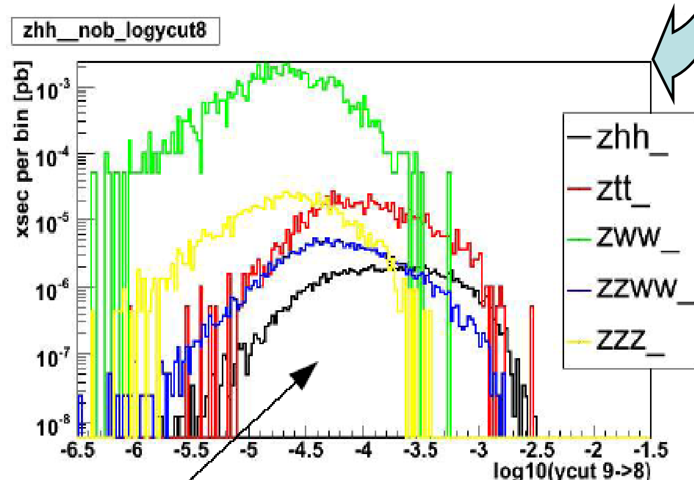
Sensitive kinematic distributions

How to implement?

Several huge backgrounds ⇒ develop clever selection methods







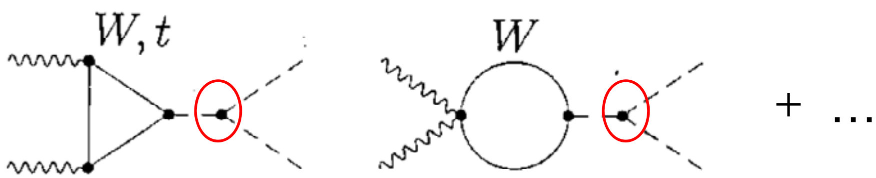
Any other powerful strategies?
More studies required

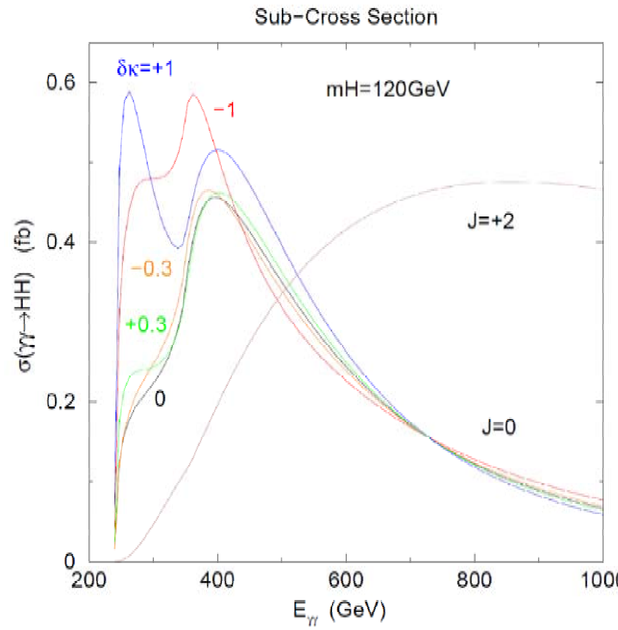
[T. Lastovicka] ⇒ LC FI vertex package

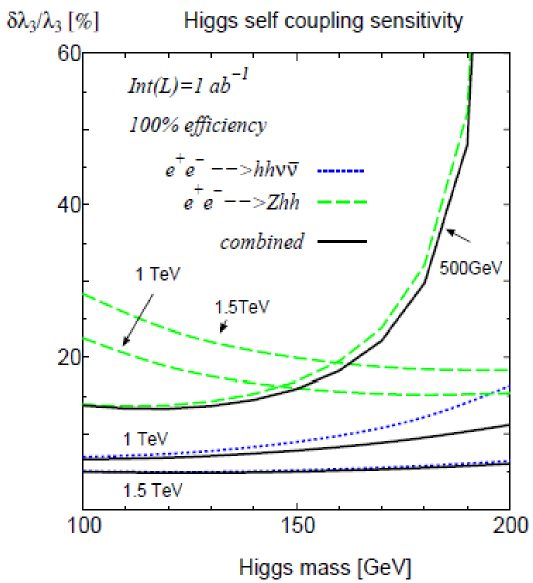
b-jets ≤ 1

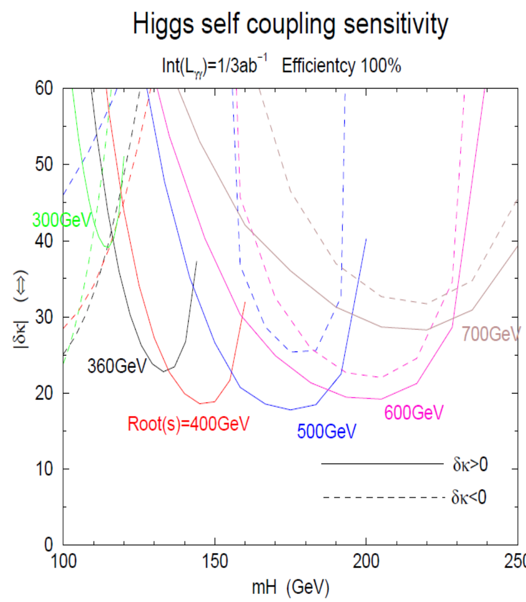
Higgs Self-couplings at PLC

[S. Kanemura]









$$\lambda_{e_1} = \lambda_{e_2} = 0.45$$
$$\lambda_{\gamma_1} = \lambda_{\gamma_2} = -1$$

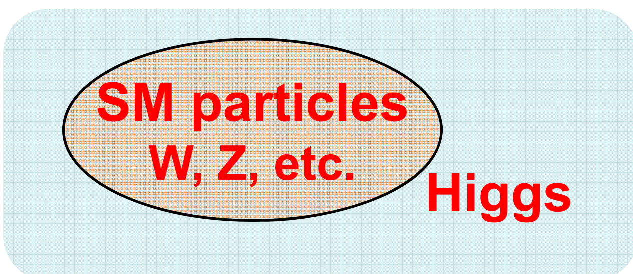
Polarization: crucial

$M_H < 150$ GeV $\Rightarrow e^+e^-$
$M_H > 150$ GeV $\Rightarrow \gamma\gamma$

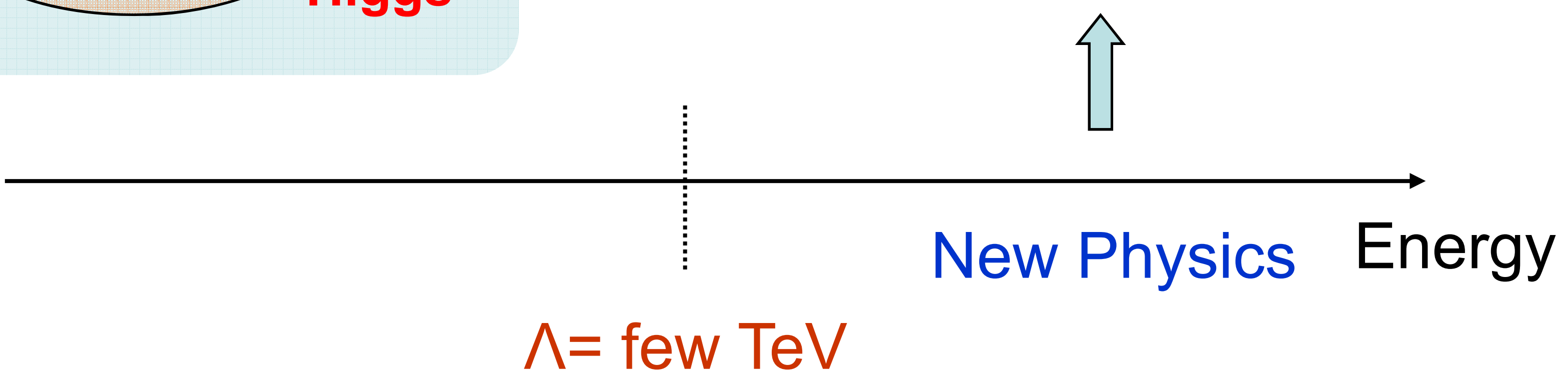
Consider more realistic Photon spectrums

Dim-6 Effective Operators as New physics

Worst: The SM Higgs is discovered, but no other new particles
⇔ New physics effects described with higher-dim. Operators
⇔ Modify all the Higgs couplings to SM particles



$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{n>4} \frac{C_i}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$



A few less-constrained dim-6 operators

[K. Tsumura]

$$\mathcal{O}_{t1} = \left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)\left(\bar{q}_L t_R \tilde{\Phi} + \text{h.c.}\right)$$

⇩

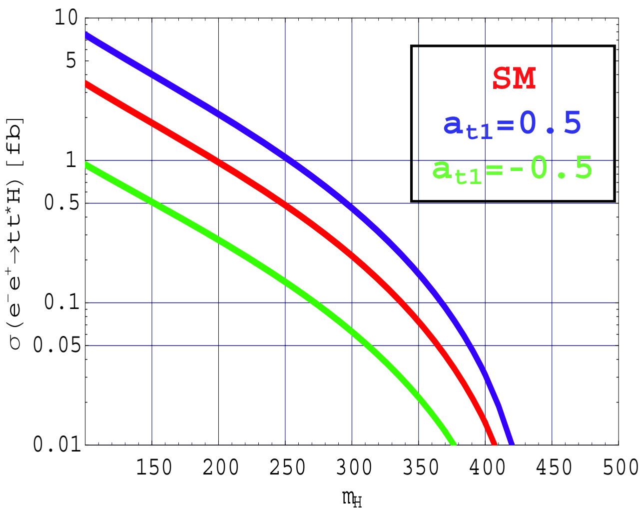
$$y_t^{SM} \to y_t^{SM} - a_{t1}, \left(a_i = \frac{v^2}{\Lambda^2} C_i\right)$$

$$\mathcal{O}_{H1} = \frac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$$

⇩

$$g[HVV] \to (1 + a_{H1})^{-1/2}\, g[HVV]$$

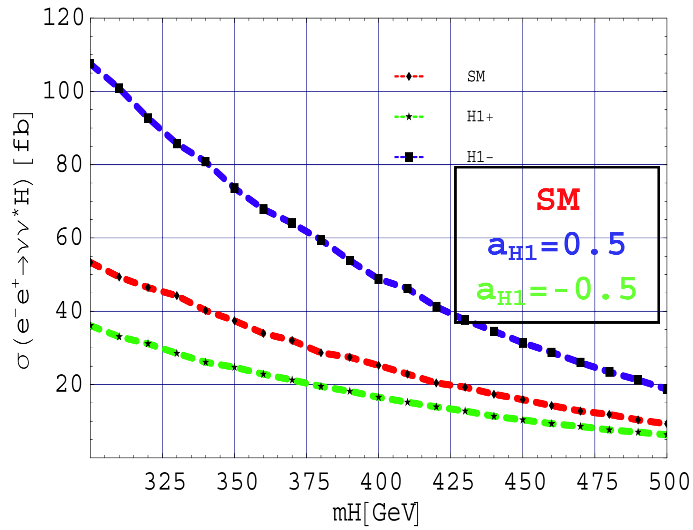
$e^+e^- \to ttH$



M_H [GeV]

$\sqrt{s} = 800\text{GeV}$

$e^+e^- \to \nu\nu H$

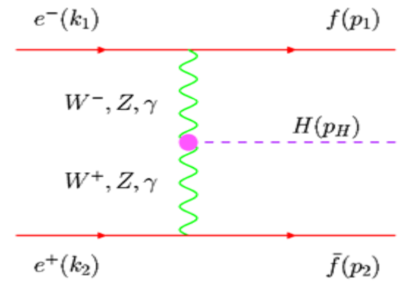


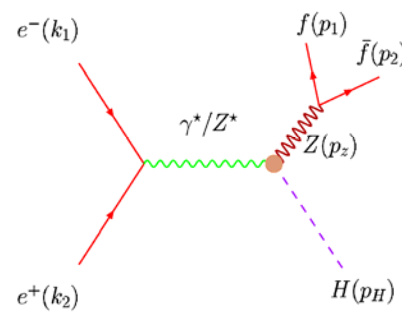
[+ a few others]

6-dim Higgs-gauge operators

[Y. Matsumoto]

$\mathcal{O}$	WW	ZZ	$Z\gamma$	$\gamma\gamma$	$WW\gamma$	WWZ	HWW	HZZ	$HZ\gamma$	$H\gamma\gamma$	Hgg
$\mathcal{O}_{\phi,1} = \left[(D_\mu\Phi)^\dagger\Phi\right]\left[\Phi^\dagger(D^\mu\Phi)\right]$		√					√	√			
$\mathcal{O}_{BW} = \Phi^\dagger\hat{B}^{\mu\nu}\hat{W}_{\mu\nu}\Phi$		√	√	√	√	√	√	√	√	√	
$\mathcal{O}_W = (D^\mu\Phi)^\dagger\hat{W}_{\mu\nu}(D^\nu\Phi)$					√	√	√	√	√		
$\mathcal{O}_B = (D^\mu\Phi)^\dagger\hat{B}_{\mu\nu}(D^\nu\Phi)$					√	√		√	√		
$\mathcal{O}_{WW} = \Phi^\dagger\hat{W}^{\mu\nu}\hat{W}_{\mu\nu}\Phi$	–	–	–	–	–	–	√	√	√	√	
$\mathcal{O}_{BB} = \Phi^\dagger\hat{B}^{\mu\nu}\hat{B}_{\mu\nu}\Phi$		–	–	–				√	√	√	
$\mathcal{O}_{\phi,4} = (\Phi^\dagger\Phi)(D_\mu\Phi)^\dagger(D^\mu\Phi)$	–	–					√	√			
$\mathcal{O}_{\phi,2} = \frac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$							√	√			
$\mathcal{O}_{gg} = \Phi^\dagger\hat{G}^{\mu\nu}\hat{G}_{\mu\nu}\Phi$											√





Beam polarization + optimal observable methods

Sensitivities depend strongly on the Higgs mass?

Spin Determination

Spin measurements are crucial in distinguishing SUSY from any bosonic (space-time) extensions.

Unless the spin of every particle is known, the Lagrangian cannot be written.

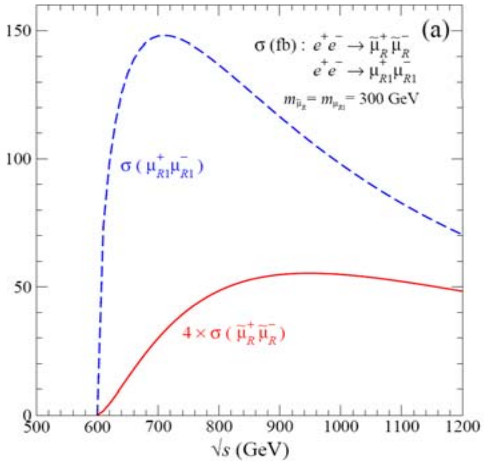
ILC

Threshold scans in production
Polar-angle distributions in production
Decay polar-angle distributions
Decay azimuthal angle distributions
...

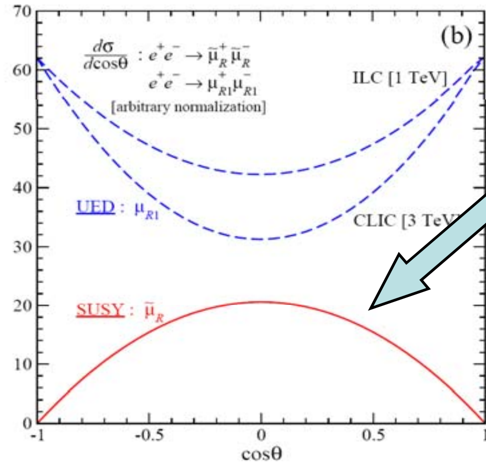
SUSY or Not

[S.Y. Choi]

Threshold Excitation



Production Angle



$\sin^2\Theta$: unique for J=0
β^3: not unique for J=0

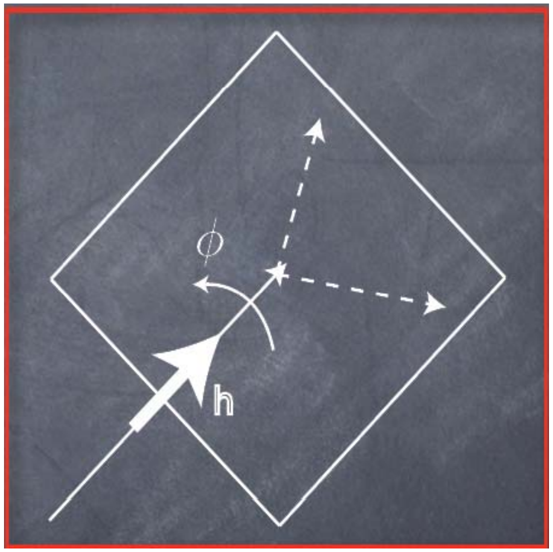
		thr excitation	thr ang distrib
SUSY	$\tilde\chi^+\tilde\chi^-$	β	flat
UED	$W_1^+W_1^-$	β	flat
GENERAL	*Dirac pair*	β	flat
SUSY	$\tilde\chi^0\tilde\chi^0$ [*Majorana*]	β^3	$1+\kappa\cos^2\theta$
UED	Z_1Z_1 [*Dirac*]	β	flat
GENERAL	*Majorana pair*	β^3	$1+\kappa\cos^2\theta$

Decays required for spin-1/2 charginos and neutralinos

Confusion

Azimuthal-angle Distributions

[M. Buckley]



purely kinematic

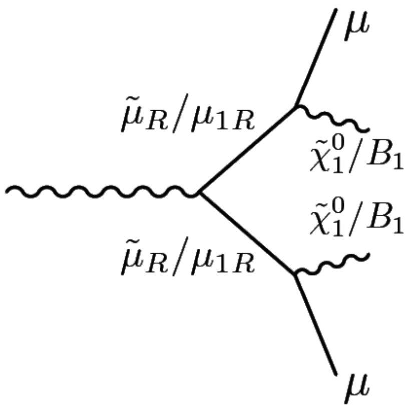
$$\mathcal{M}_{decay}(h,\phi) = e^{ih\phi}\mathcal{M}_{decay}(h,\phi=0)$$

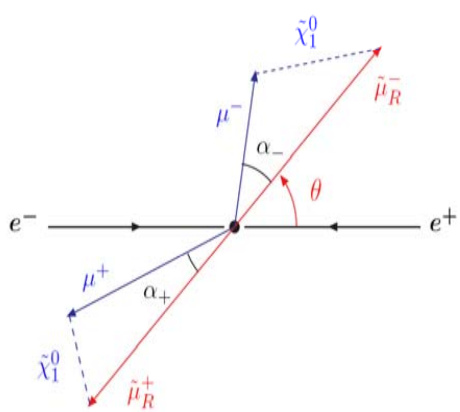
$$\sigma \propto \left|\sum_h \mathcal{M}_{prod.}(h) e^{ih\phi}\mathcal{M}_{decay}(h,\phi=0)\right|^2$$

Quantum Interference

$$\sigma = A_0 + A_1\cos(\phi) + \cdots + A_n\cos(n\phi), \;\; n = 2\times\text{spin}$$

Azimuthal-angle Distributions

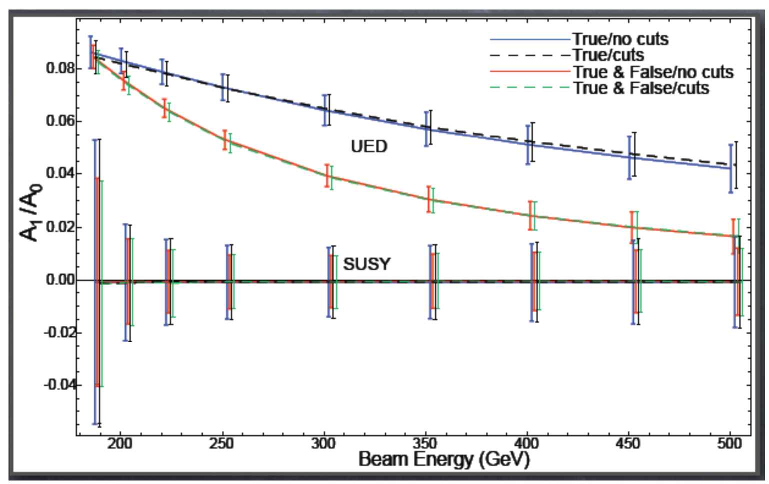




Two-fold ambiguity:
true and false axes

Non-trivial TF correlations: tractable?!

J=1/2 J=0



Clear distinction

Littlest Higgs Model with T-parity

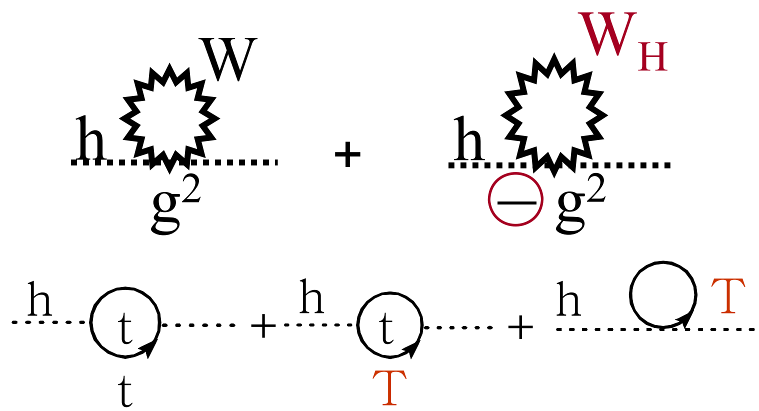
Gauge-Higgs sector

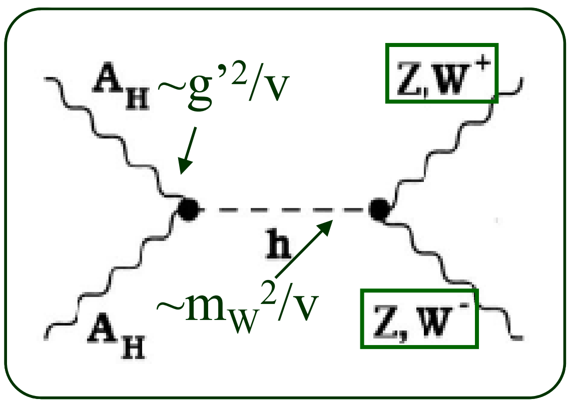
T-even	A, $W^{\pm}$, Z, h; t, …
T-odd	A_H, $W_H^{\pm}$, Z_H, Φ; T, …

LTP

mass ~f

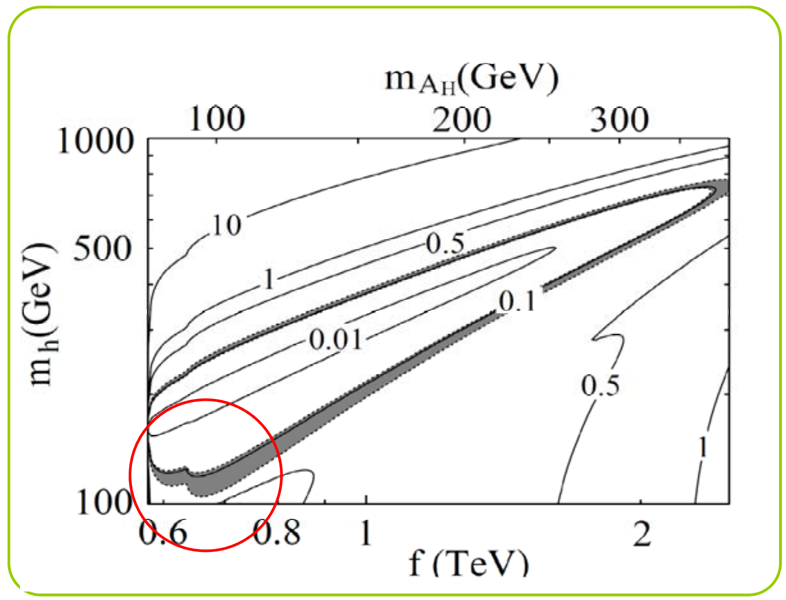
QD cancellation at 1-loop



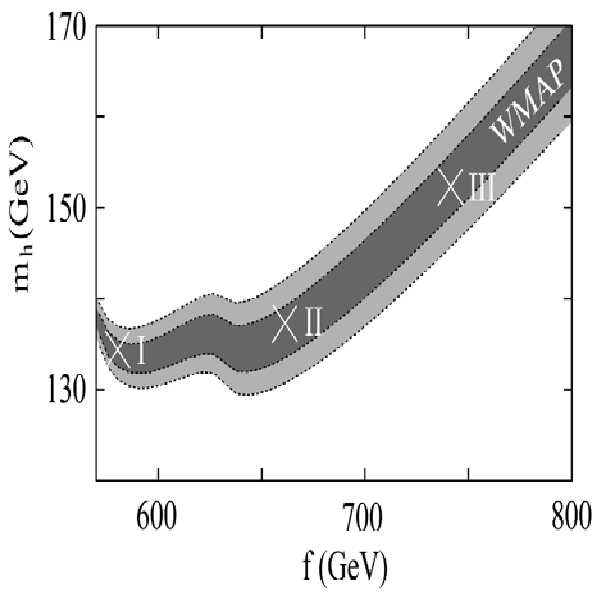


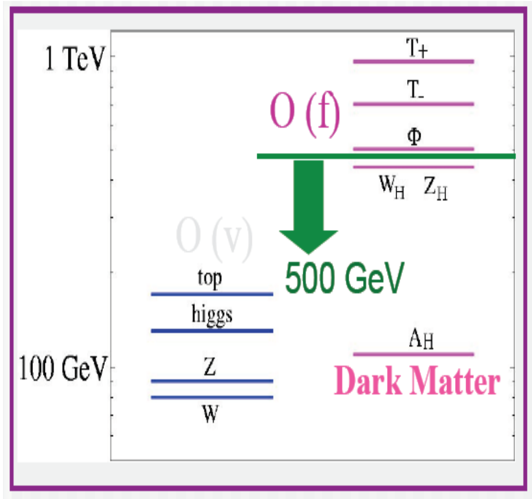
σ_{ann}

WMAP



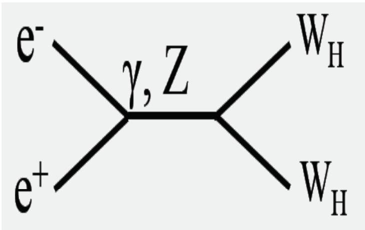
ILC/Cosmology Connection in LHM





Accessible at ILC

[T. Asano]



only on f

[+] $W_H \to A_H + W$

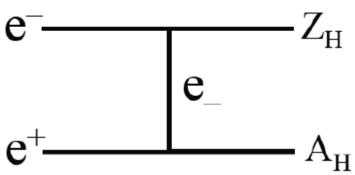
$E_{W,H}$ spectrum

Precise $m[h,V_H,A_H] \Rightarrow f$

↓

A_H relic density at 2% level (?)

[M. Kusano]



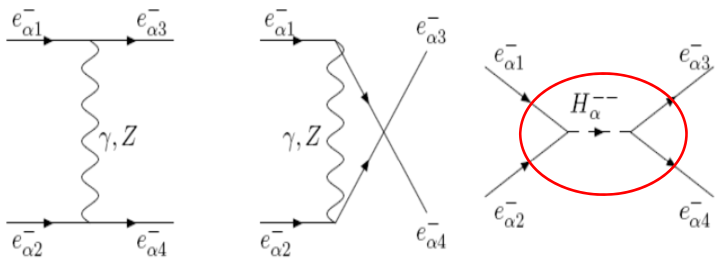
[+] $Z_H \to A_H + h$

Extended Higgs Sector

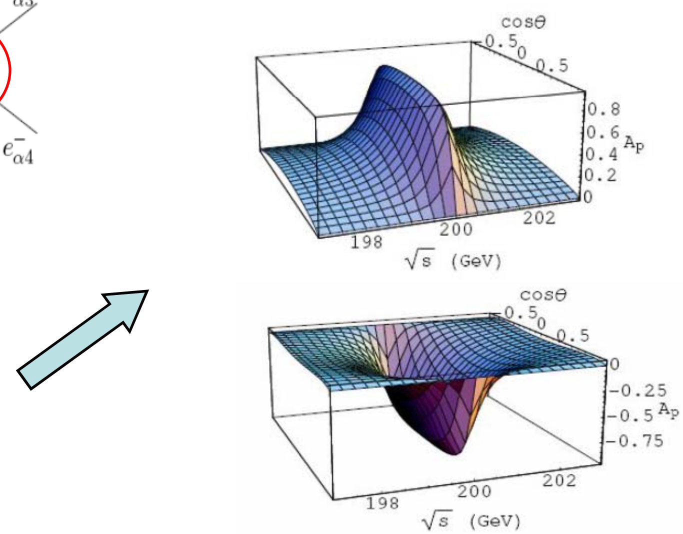
[D. Zhuridov]

Tiny neutrino mass ⇒ doubly charged singlets and triplets

Singlet	$\mathcal{L}_R = Y_{ij}\overline{\ell^c_{iR}}\ell_{jR}\Psi + \text{H.c.},$	$Y_{ij} \lesssim 1$	⇨	maybe
Triplet	$\mathcal{L}_L = g_{ij}\overline{L^c_{iL}}T^\dagger L_{jL} + \text{H.c.},$	$m_\nu \sim g_{ij} v_T \lesssim 0.1 \text{ eV}.$	⇨	hopeless



$$A_P = \frac{\frac{d\sigma_{LL}}{d\cos\theta} - \frac{d\sigma_{RR}}{d\cos\theta}}{\frac{d\sigma_{LL}}{d\cos\theta} + \frac{d\sigma_{RR}}{d\cos\theta}}$$



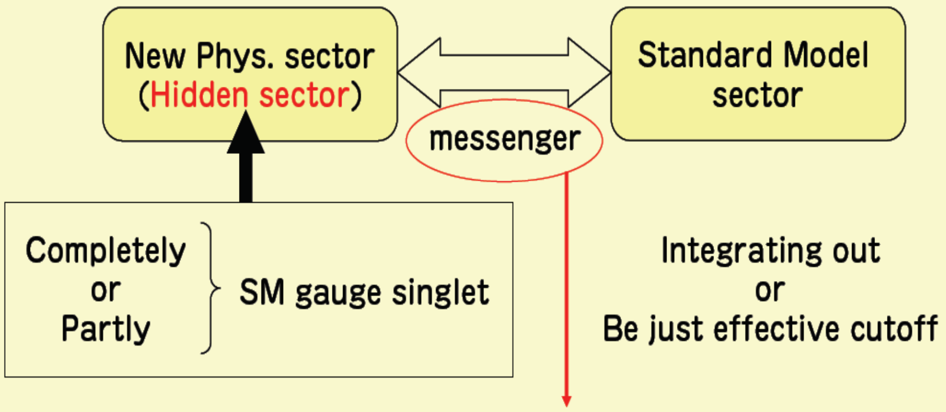
Triplet

Singlet

If Y ~ g

Hidden Sector

[H. Itoh]



Effective Lagrangian: $\mathcal{L} = \frac{c_n}{\Lambda^n}\mathcal{O}_{\rm NP}\mathcal{O}_{\rm SM}$

⇒ Simplest Realization

$$\mathcal{L} \sim \frac{c}{\Lambda^{d_{SM}-3}} X \mathcal{O}_{\rm SM}$$

X: SM singlet scalar

$\Lambda \sim 1\,\text{TeV}$

$m X H^\dagger H \qquad \frac{X}{\Lambda}(H^\dagger H)^2$ ⇒ HX mixing

$\frac{X}{\Lambda}\bar{\Psi}\gamma^\mu\partial_\mu\Psi \to \frac{X}{\Lambda} m_f \bar{\Psi}\Psi$ ⇒ linear?

$$\frac{X}{\Lambda}G^a_{\mu\nu}G^{a\mu\nu} \qquad \frac{X}{\Lambda}F_{\mu\nu}F^{\mu\nu} \qquad \frac{X}{\Lambda}Z_{\mu\nu}F^{\mu\nu}$$

$\sim$

$$\mathcal{L}_{\rm SM} \sim \frac{\alpha_s}{4\pi v} h G^a_{\mu\nu}G^{a\mu\nu}$$

$$\mathcal{L}_{\rm SM} \sim \frac{\alpha}{4\pi v} h F_{\mu\nu}F^{\mu\nu}$$

$$\mathcal{L}_{\rm SM} \sim \frac{eg}{16\pi^2 v} h Z_{\mu\nu}F^{\mu\nu}$$

$$\frac{X}{\Lambda}W^+_{\mu\nu}W^{-\mu\nu} \qquad \frac{X}{\Lambda}Z_{\mu\nu}Z^{\mu\nu}$$

⇔

$$\mathcal{L}_{\rm SM} \sim 2\frac{m_W^2}{v} h W^+_\mu W^{-\mu}$$

$$\mathcal{L}_{\rm SM} \sim \frac{m_Z^2}{v} h Z_\mu Z^\mu$$

X ⇔ H: Branching ratios and different structures

Summary

Every physics talk @ TILC08 adds value to the important role of ILC in probing Terascale physics.

⇩

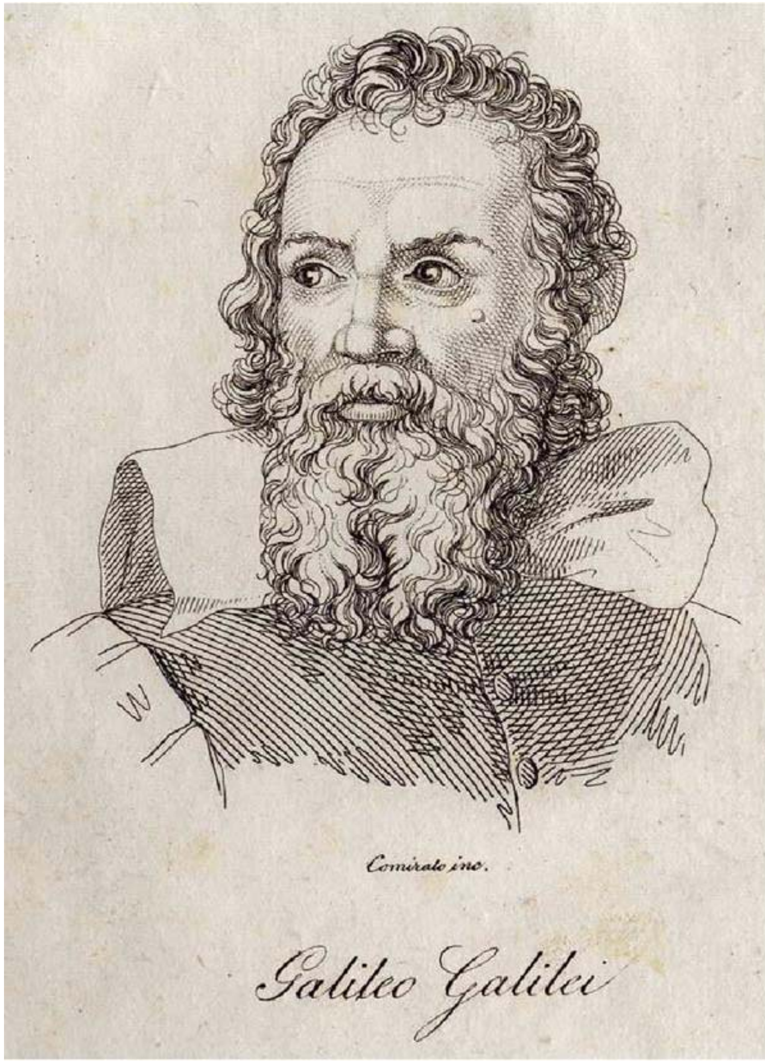
More comprehensive/precision analysis of both SUSY and other Terascale scenarios in progress

⇩

ILC is a powerful micro/telescope toward unification of interactions wherever it is realized.

Quite Probably

ILC



Galileo Galilei

Io stimo più il trovar un vero, benchè di cosa leggiera, ch'l disputar lungamente delle massime questioni senza conseguir verità nissuna.

I attach more value to finding a fact, even about the slightest thing, than to lengthy disputations about the Greatest Questions that fail to lead to any truth whatever.

[C. Quigg]