Physics at ILC

Keisuke Fujii

What is High Energy Physics?

A field of science that amis at finding the ultimate building blocks of nature and at understanding their interactions.

A Major Tool = Particle Accelerator

Immediately after the creation of the universe (Big Bang)
= Ultra high temperature
= World consisting of fundamental particles interacting each other at high energy

Reproduce this situation in a laboratory with the particle accelerator

Language that describes the world of elementary particles

- Grammar of Nature's language = quantum field theory

  fundamental particles ⇔ quantum fields: ϕ
  ⇒ independent of the nature of objects in question

- Story told by Nature = Lagrangian: $\mathcal{L}(\partial_\mu \phi, \phi)$

  ⇒ information specific to the system (what kind of particles exist and how they interact) all lies in the Lagrangian

Least Action Principle

Action : $S = \int dx^4 \, \mathcal{L}\left(\partial_\mu \phi, \phi\right)$

$\delta S = 0$ ⟶ Euler-Lagrange Equation: $\dfrac{\partial \mathcal{L}}{\partial \phi} = \partial_\mu \left(\dfrac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)} \right)$

Equation of Motion is given by least action principle

Once the Lagrangian is given it is in principle possible to track time evolution of the objects

High Energy Physics (HEP)
= Quest for the fundamental Lagrangian

What is the central theme of the story told by Nature?

What decides the Lagrangian?

Symmetry and conservation laws

Some continuous transformation $x \to x'$ $\phi(x) \to \phi'(x')$
leaves
the action

$$S = \int d^4x\, \mathcal{L}(\partial_\mu \phi, \phi) \longleftrightarrow$$

∃conserved quantity
(Noether's theorem)

invariant

e.g.) Space time translation, rotation ⇒ energy momentum conservation, angular momentum conservation

The first deep result that suggests the central theme of the story told by Nature being symmetry.

Conjecture

Conversely, requirement of symmetry to the action strongly restricts the possible form of the Lagrangian. ⇒ Sufficient number of symmetries might uniquely determine the Lagrangian.

- External space (space time) symmetries
  Poincare symmetry (space time translation x Lorentz symmetry)
  ⇒ determination of free field Lagrangian
- Internal space symmetry (gauge symmetry)
  ⇒ determination of the full Lagrangian including interactions

What is the central theme of the story told by Nature?

What decides the Lagrangian?

Historical Trend

Small number of fundamental particles: beautiful symmetries among them + deep connection between symmetries and forces ← Empirical facts

Reverse the logic

↓

Central theme = Symmetry

Symmetry decides the Lagrangian !(?)

Dream: ultimate unification

Unique building block ⇒ Unification of all matter, all forces, and space-time which is uniquely determined by symmetry

Diversity observed in the present universe is because its original simplicity (symmetry) has been hidden as the universe cooled down.

Unification of particles } Unification of forces ←Gauge Principle→ (Gauge) symmetry ←Symmetry breaking→ Diversity

High Energy Physics (HEP)

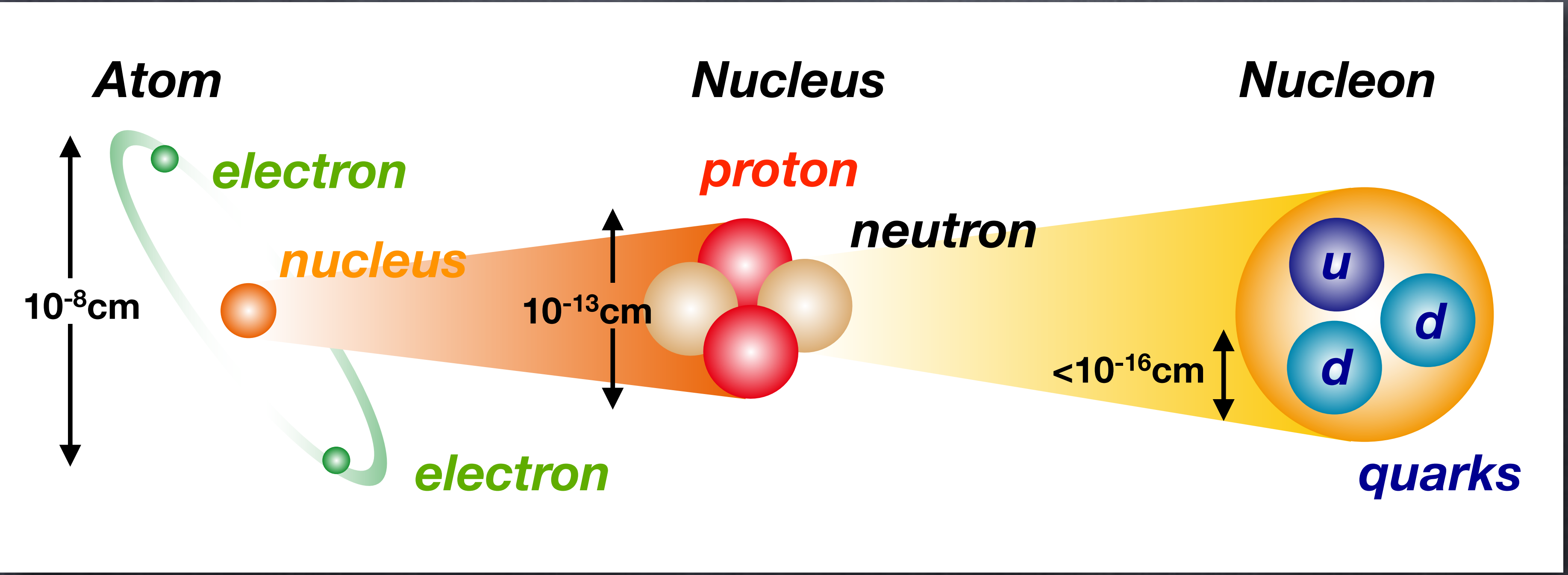
Reproduce the high energy world that happened immediately after the big bang and uncover the original simplicity of Nature.

Known
Fundamental Particles
and Interactions

What kind of particles are there and
how do they interact each other?

How is this related to symmetry?

Dividing things into smaller and smaller pieces



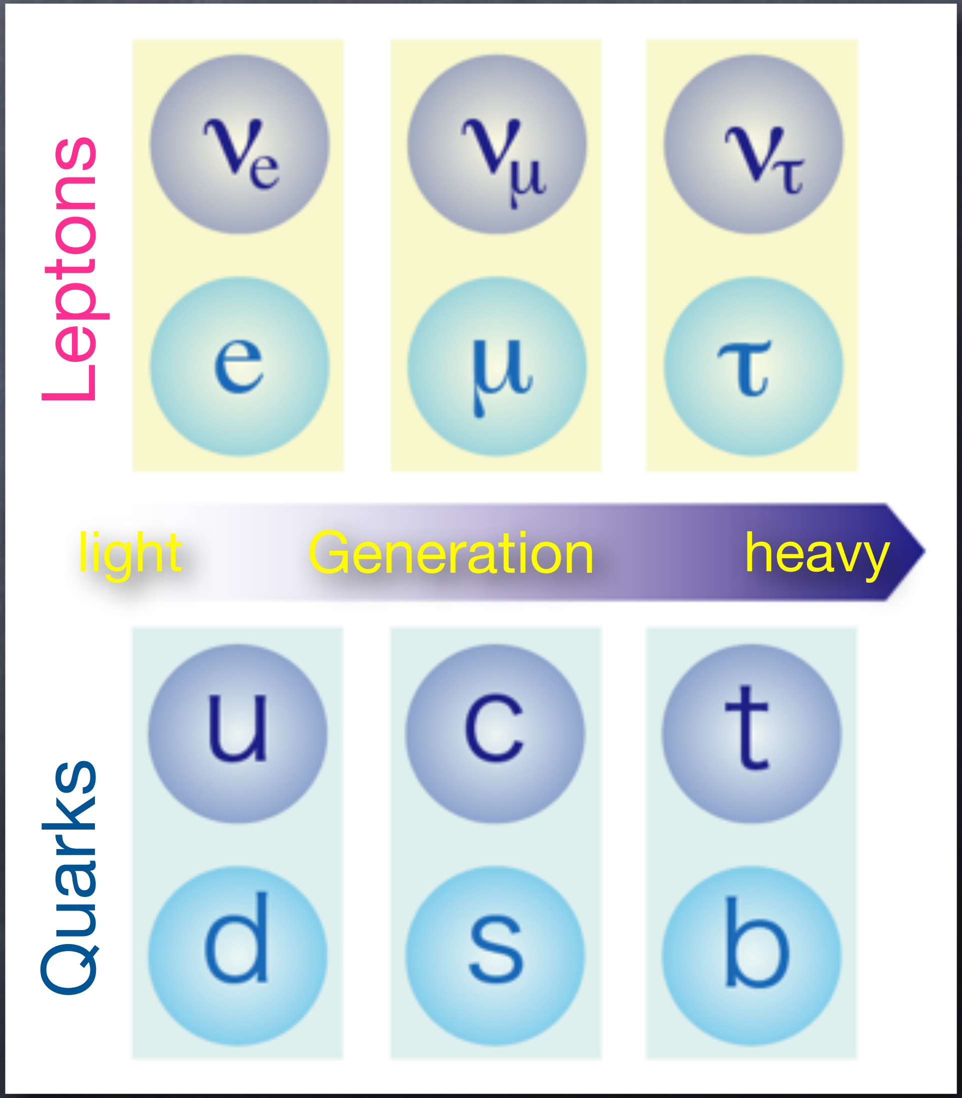
we will end up with the lepton family containing electron and the quark family including up quark and down quark.

So far no structure has been seen for leptons and quarks and hence they are considered fundamental.

Quarks and Leptons

Fundamental particles that comprise matter (matter particles)

- There are 3 generations of quarks and leptons that have the same properties except for the masses. So far no substructures have been seen.
- In each generation, both quarks and leptons seem to form pairs. There seems to be quark-lepton correspondence. These mysterious structure (symmetry) must have some deep reason.
- Each quark comes in three colors (Red, Green, and Blue: which have of course nothing to do with real colors.)
- Both quarks and leptons have spin one half: J = 1/2



Symmetry and Classification of Particles

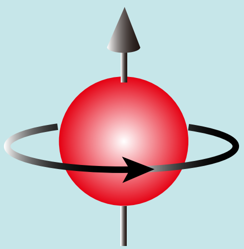
- Classification indices due to external symmetry: (M,J)
- Classification indices due to internal symmetries: (Y, I, I_3, Qc, G)
- For example, a left-handed electron has
  (Y, I, I_3, Qc, G)
  = (-1/2, 1/2, -1/2, 0, 1)
  and a right-handed one has
  (Y, I, I_3, Qc, G)
  = (-1, 0, 0, 0, 1)

  left-handed electron and right-handed electron are different particles!

Unification of particles = making a set of particles into a multiplet that transforms under a symmetry operation

Mass: M
Spin: J

Fundamental particles have a spin quantum number which takes discreet value: **J=0, 1/2, 1, …**



Weak hyper charge: Y
Weak isospin: I, I_3

Electric charge: $Q = I_3 + Y$

Color charge: Q_C

Electric-charge-like quantities that decide the forces on a fundamental particle which also take discreet values

Generation number: G

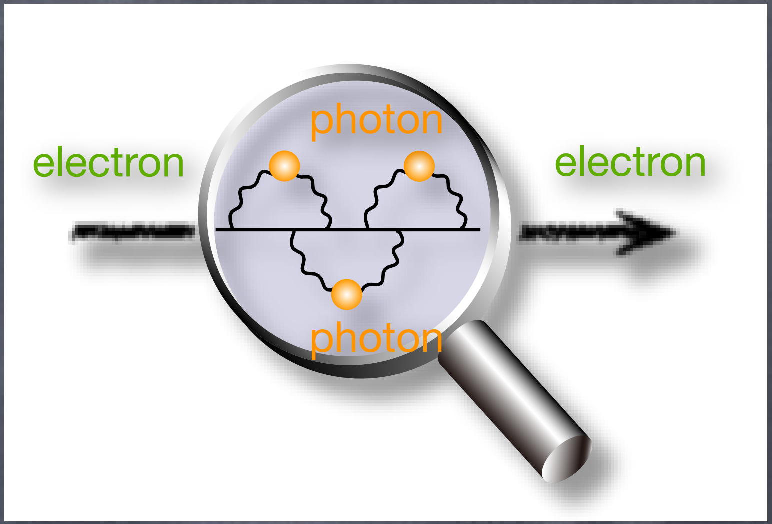
distinguishes 3 generations of quarks and leptons (So far no corresponding symmetry is know)

What is force or interaction?

Force carrying particles (lessons from QFT)

Looking at an electron in detail, we find it juggling photons!

When another electron nearby the first takes a juggled photon away, the momenta of the two electrons change by the amount carried by the exchanged photon.



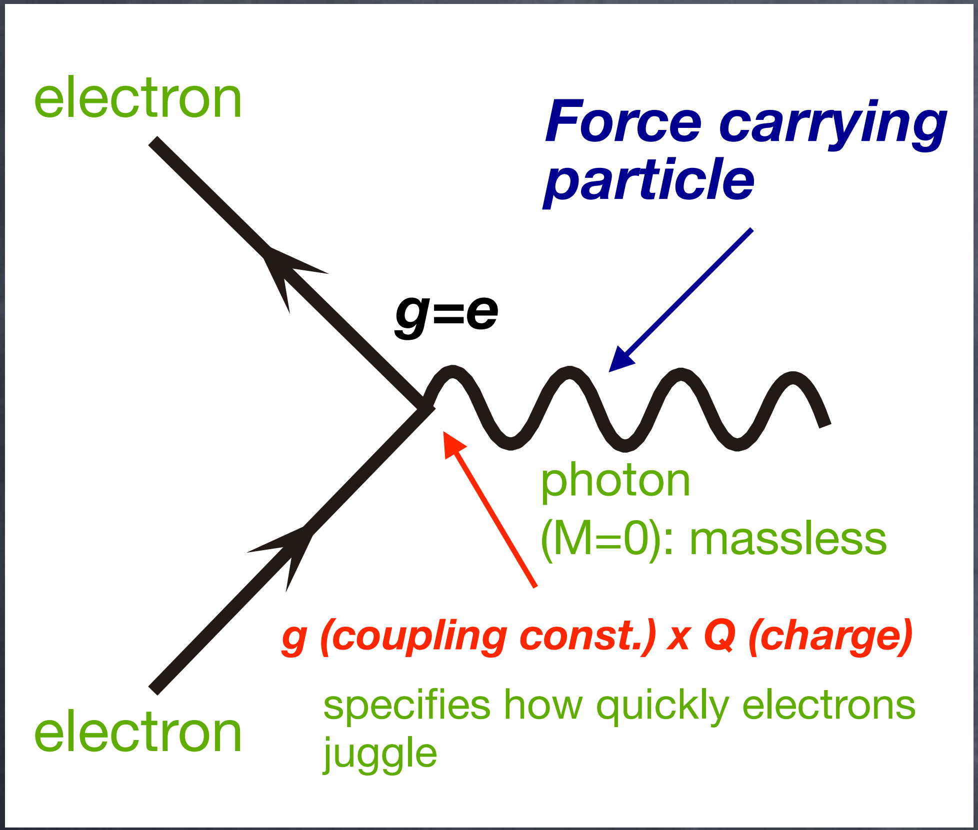
Newton's Eq. of Motion

Momentum change --- $$\frac{\Delta p}{\Delta t} = F$$ --- Force

Accelerator
= High Resolution Magnifying Glass

Interaction (force)
= Exchange of a force carrying particle

Vertices that govern fundamental forces



g: large ⇒ interaction: strong

Apparent strength of a force and the mass (M) of the corresponding force carrying particle:

- M: small ⇒ force particles fly long distance
- M=0 ⇒ force particles fly infinite distance (long-distance force)
- M: large ⇒ force particles fall short (short-distance force)

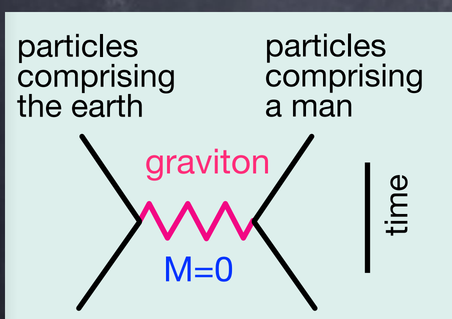
The true strength of a force is determined by "g" but its apparent strength also depends on the mass of the force carrying particle!

4 Forces in Nature

There are at least 4 known forces in Nature

Gravity

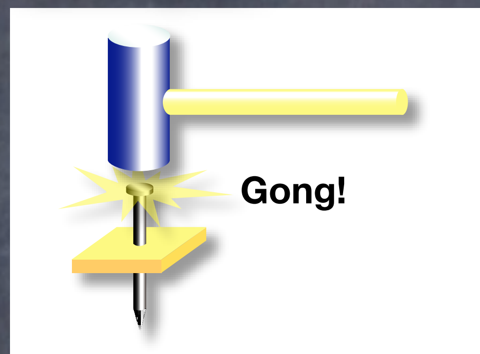
The well-known gravity that binds us to the earth

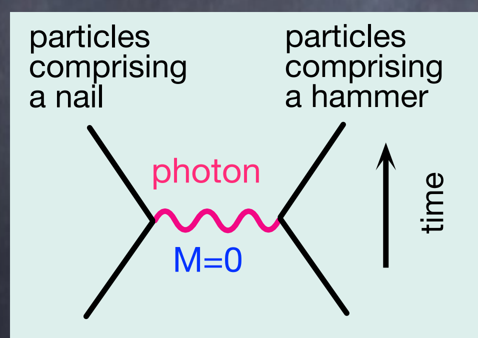


Gravity = Exchange of Gravitons

EM Force

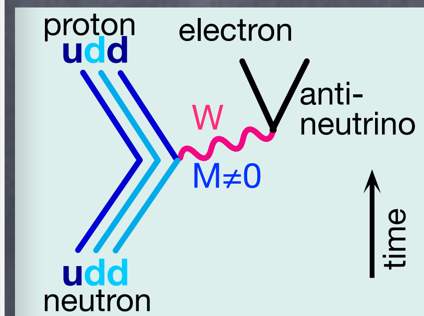
Not to mention electrostatic or magneto-static forces, all the forces, except for gravity, we experience everyday life are electromagnetic.





EM Force = Exchange of Photons

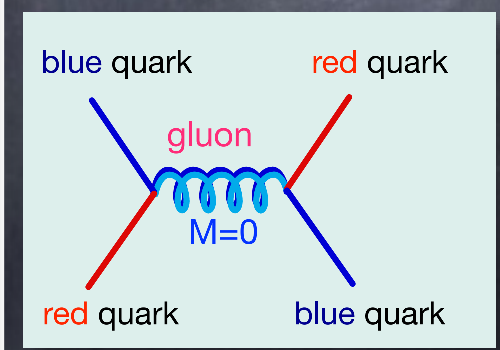
Weak Fore



The force that can transform particle spices as in beta decays of nuclei. Though it plays essentially no role in everyday life, it becomes very important in the microscopic world.

Weak Force = Exchange of W/Z bosons

Strong Force

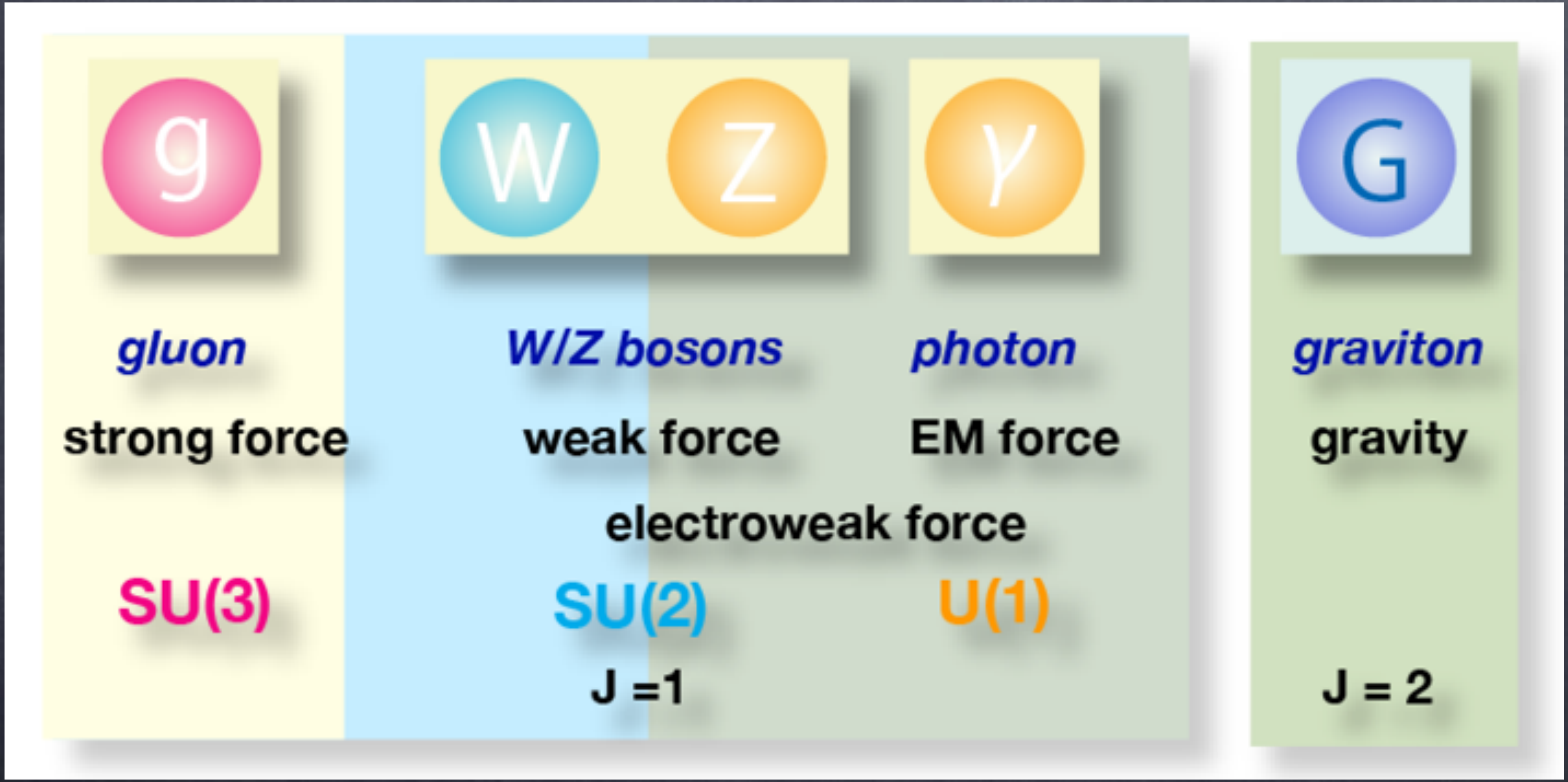


The force that binds quarks to make up protons and neutrons and then binds them together to form nuclei.

Strong Force = Exchange of Gluons

Force Carrying Particles

Interaction (force) = exchange of force carrying particle (gauge particle)



Symmetry dictates interactions ⇒ gauge principle

$SU(2)_L$ force acts only on left-handed particles!

Gauge Symmetry

What does unification of particles mean?

How does gauge principle dictates interactions?

Internal Symmetries and Unification of Particles

What does unification of particles mean?

What is internal space?

Space attached to each space time point, corresponding to the field component degrees of freedom

e.g.) Quarks have so called color degrees of freedom

$$q = \begin{pmatrix} q_R \\ q_G \\ q_B \end{pmatrix}$$: 3-vector consisting of 3 complex component fields

- a vector in color space
- its direction specifies quark color

$\boldsymbol{T} = (T_1, \cdots, T_8)$ ：８つの群の生成子

Rotation in color space (color SU(3) symmetry): $U(\boldsymbol{\theta}) = e^{i\boldsymbol{T}\cdot\boldsymbol{\theta}} \in SU(3)_C$

$$q = \begin{pmatrix} q_R \\ q_G \\ q_B \end{pmatrix} \longrightarrow q' = U(\boldsymbol{\theta}) \begin{pmatrix} q_R \\ q_G \\ q_B \end{pmatrix}$$

leaves the free quark Lagrangian: $\mathcal{L}_0 (\partial_\mu q, q) = \bar{q} (i\gamma^\mu \partial_\mu - m) q$

and hence the action invariant (physics remains the same)

- The 3 colors do not have absolute meanings (it is impossible to distinguish q' from q)
- Red, Green, Blue are 3 states of a single quark rather than 3 kinds of quarks.

Unification of particles = putting a set of particles in a single multiplet of a transformation group that leaves the action invariant!

Global Gauge Symmetry

Non-Abelian case
(Abelian case (U(1)) can be obtained by setting structure constants all zero)

Global gauge transformation

= space-time-independent rotation of a multiplet in an internal space consisting of n component fields

Rotation of internal space

Changed unit of θ for later convenience

$$\Psi = \begin{pmatrix} \Psi_1 \\ \Psi_2 \\ \vdots \\ \Psi_n \end{pmatrix} \cdots\cdots\rightarrow U(\boldsymbol{\theta}) = e^{-ig\boldsymbol{T}\cdot\boldsymbol{\theta}} \cdots\cdots\rightarrow \Psi' = U(\boldsymbol{\theta})\,\Psi$$

When this transformation leaves the Lagrangian:

$$\mathcal{L}_0\left(\partial_\mu \Psi', \Psi'\right) = \mathcal{L}_0\left(\partial_\mu \Psi, \Psi\right)$$

invariant, the system has a global gauge symmetry

Since the Lagrangian decides physics, this means that

Ψ and Ψ' are indistinguishable

However, such a global gauge symmetry is possible only for superhuman beings.

Local Gauge Symmetry

We want the world to be locally gauge symmetric!

Local gauge transformation: $U(\boldsymbol{\theta}(x)) = e^{-ig\boldsymbol{T}\cdot\boldsymbol{\theta}(x)}$

$\boldsymbol{T} = (T_1, \cdots, T_N)$ N generators of the group

$$\Psi(x) \longrightarrow \Psi'(x) = U(\boldsymbol{\theta}(x))\Psi(x)$$

changes the free field Lagrangian:

$$\mathcal{L}_0\left(\partial_\mu \Psi, \Psi\right) \neq \mathcal{L}_0\left(\partial_\mu \Psi', \Psi'\right)$$

since

$$\partial_\mu U(\boldsymbol{\theta}(x)) = U(\boldsymbol{\theta}(x))\partial_\mu + (\partial_\mu U(\boldsymbol{\theta}(x))) \neq U(\boldsymbol{\theta}(x))\partial_\mu$$

In order to make the Lagrangian invariant under space-time-dependent gauge transformation, we need covariant derivative (D_μ) which satisfies

$$D'_\mu U(\boldsymbol{\theta}(x)) = U(\boldsymbol{\theta}(x)) D_\mu$$

Covariant Derivative and Gauge Field

$$D_\mu = \partial_\mu + igW_\mu$$

Gauge fields : $a = 1, \cdots, N$

Multiplet of adjoint representation of the gauge field

Unification of forces = unification of force carrying particles

belonging to a vetor space spanned by the gauge group generators: Lie-Algebra valued

$$W_\mu = W_\mu^a T_a$$

$J = 1$

Generators of gauge group

$$\boldsymbol{T} = (T_1, \cdots, T_N)$$

If the gauge field transforms as

$$W_\mu \to W'_\mu = UW_\mu U^{-1} - \frac{i}{g} U \left(\partial_\mu U^{-1}\right)$$

we have

$$D'_\mu U(\boldsymbol{\theta}(x)) = U(\boldsymbol{\theta}(x)) D_\mu$$

and hence the new Lagrangian:

$$\begin{aligned} \mathcal{L}_0 \left(D_\mu \Psi, \Psi\right) &= \bar{\Psi} \left(i\gamma^\mu D_\mu - m\right) \Psi \\ &= \bar{\Psi} \left(i\gamma^\mu \partial_\mu - m\right) \Psi - g \left(\bar{\Psi}\gamma^\mu T_a \Psi\right) W_\mu^a \end{aligned}$$

universal coupling constant

is invariant under the local gauge transformation.

Emergence of the interaction term of matter and gauge fields

We need a kinetic term for the gauge fields, too!

This must be Lorentz scalar and locally gauge invariant, too!

Anti-symmetric tensor made of gauge field:

commutator

$$W_{\mu\nu} = -\frac{i}{g}\left[D_\mu, D_\nu\right]$$
$$= \partial_\mu W_\nu - \partial_\nu W_\mu + ig\left[W_\mu, W_\nu\right]$$

Characteristic feature of non-Abelian group

2nd order in W_μ

$$[W_\mu, W_\nu] = [W_\mu^a T_a, W_\nu^b T_b]$$
$$= W_\mu^a W_\nu^b [T_a, T_b]$$
$$= W_\mu^a W_\nu^b i f_{ab}^c T_c$$

U(1): $f_{ab}^c = 0$

transforms covariantly under local gauge transformation

$$W_{\mu\nu} \rightarrow W'_{\mu\nu} = U W_{\mu\nu} U^{-1}$$

Therefore the Lagrangian:

$$\mathcal{L}_G = -\frac{1}{2}\, Tr\, W_{\mu\nu} W^{\mu\nu}$$

is locally gauge invariant!

containing 3rd and 4th order terms of W_μ

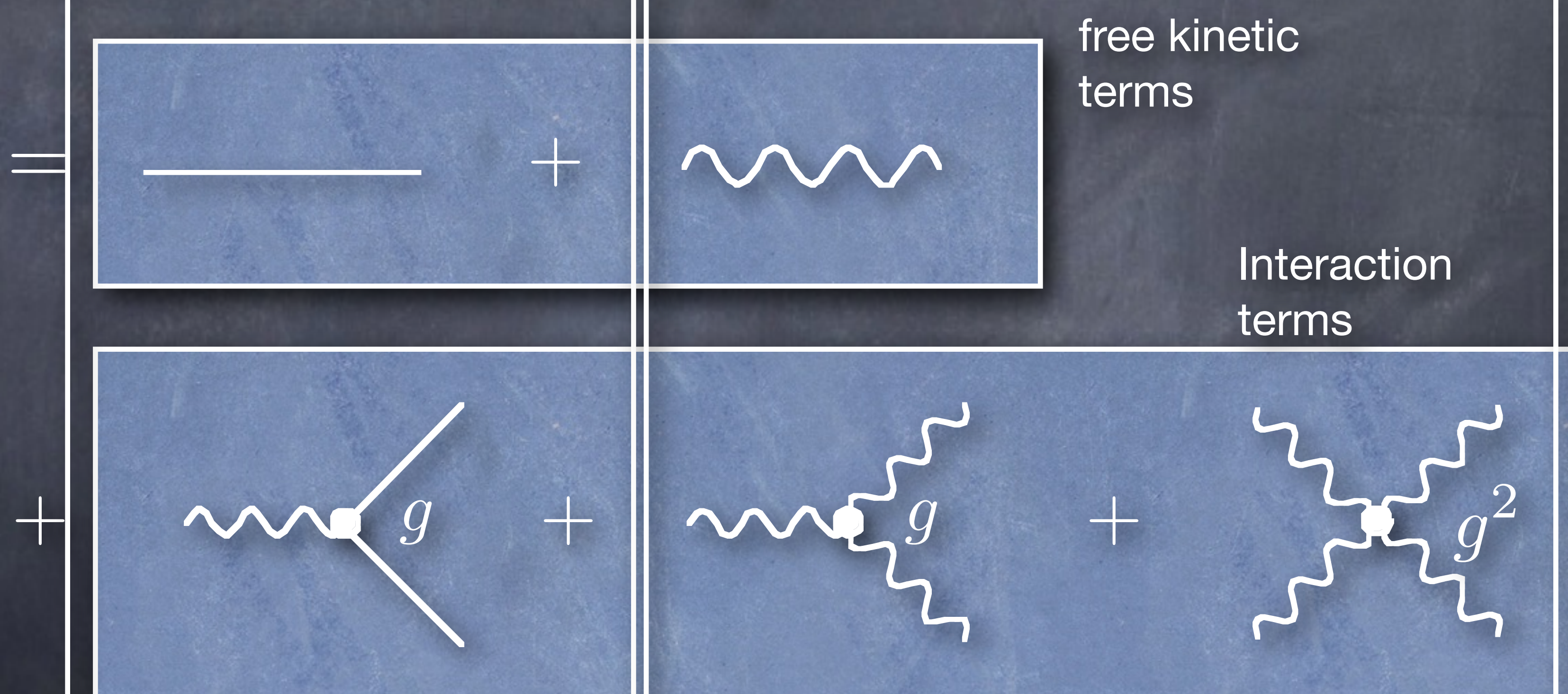
Emergence of the self-interaction term of the gauge field

Remark: Explicit mass term of gauge field is forbidden, since it breaks gauge symmetry!

Locally Gauge-invariant Lagrangian

Putting matter part and gauge part of the Lagrangians together, we get

$$\mathcal{L} = \bar{\Psi}\left(i\gamma^{\mu}D_{\mu} - m\right)\Psi - \frac{1}{2}Tr\,W_{\mu\nu}W^{\mu\nu}$$



Gauge interaction of matter fields

Self-interaction of gauge fields

Gauge Principle

- Requirement of local gauge invariance
  ⇒ Existence of force carrying field (gauge field) with properties:
    - vector (J=1)
    - massless (= no longitudinal component)
    - the number of states = the number of generators

  ⇒ Determination of matter gauge interactions
  - coupling constant = one for each symmetry (universal interaction)
  - Determination of self-interaction of gauge fields, if non-Abelian

Exact symmetry of Nature must be a gauge symmetry
⇒ Deep connection between symmetry and interaction

No constraint on matter particles other than Ψ must be a vector in a representation space of the gauge group: G, meaning that Ψ must belong to some multiplet of G!
There is no logic for the existence of matter fields → The choice of multiplet must be made empirically!

Intuitive Interpretation of Gauge Principle

For simplicity, consider complex 1-dimensional internal space (U(1) case: e.g. quantum electro dynamics)

phase transformation in wider sense ········▸ simple phase transformation

$$U(\boldsymbol{\theta}(x)) = e^{i\,\boldsymbol{T}\cdot\boldsymbol{\theta}(x)} \quad \cdots\cdots\cdots\blacktriangleright \quad U(\theta(x)) = e^{i\,\theta(x)}$$

Quantum mechanics

Particle-wave duality

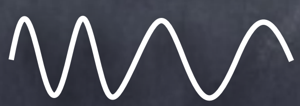
$$\phi(x) = e^{ipx}$$ plane wave (free particle)

$$p\,x = E\,t - \boldsymbol{p}\cdot\boldsymbol{x} \quad (\hbar = c = 1) \quad \cdots\cdots\cdots\blacktriangleright \quad |\boldsymbol{p}| = \frac{1}{\lambda}$$ (De Brogli)

local gauge transformation (space-time-dependent phase transformation)

$$U(\theta(x)) = e^{i\,\theta(x)}$$

$$\phi(x) \quad \cdots\cdots\cdots\cdots\cdots\blacktriangleright \quad e^{i\,\theta(x)}\phi(x) = e^{i\,[\theta(x) - px]}$$



Wave length modulated
⇒ momentum non-conservation

Acceleration in internal
space direction
= apparent force

Set reference point of phase at each space-time point

$$i\,D_\mu = i\,\partial_\mu - e\,A_\mu$$

gauge field as the reference point of phase

World from Gauge-Principle Point of View

Assign matter particles and force carrying particles into multiplets

- Gauge group $$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$
- Matter fields: quarks and leptons (3 generations)

  Left-handed: $SU(2)$ doublet Right-handed: $SU(2)$ singlet

  Quarks: $SU(3)$ triplet Leptons: $SU(3)$ singlet

$$Q = I_3 + Y$$

- Gauge fields = force carrying particles

  Strong force: gluons (8 states) $\longleftarrow$ $SU(3)$

  Weak force: W, Z bosons

  Electromagnetic force: photon

  $\Big\}\longleftarrow\Big\{$ $SU(2)$, $U(1)$

Problem of Mass Generation

The Standard Model (SM) gauge symmetry forbids masses of matter fermions and gauge bosons!

We know that quarks, leptons, and W/Z have mass: e.g. mW=80GeV, mZ=91GeV, mt=173GeV

How can we give masses to leptons, quarks, and W/Z bosons without breaking the symmetry of the SM Lagrangian?

Symmetry and Mass

- Mass of gauge field

  Mass term:

$$\mathcal{L}_M = M^2 \, Tr W_\mu W^\mu$$

  breaks gauge symmetry

  ⇒ Gauge symmetry forbids gauge field mass!

- Mass of matter field

  Mass term:

$$\mathcal{L}_m = -m \, \bar{\Psi}\Psi = -m \left(\bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L \right)$$

  breaks $SU(2)_L$!

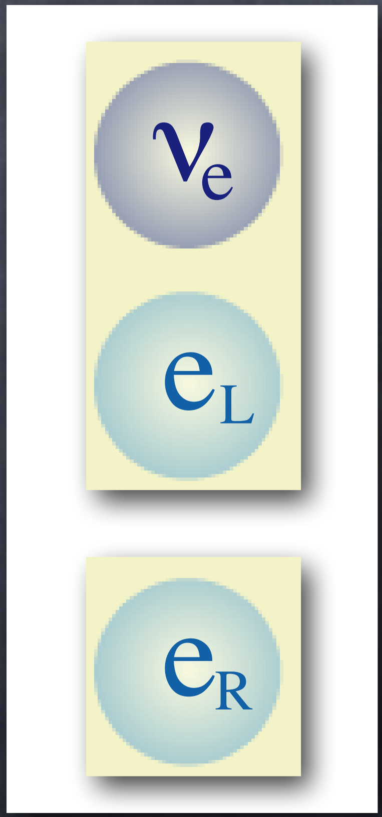
  ⇒ Chiral symmetry forbids matter field mass!

Both gauge and matter fields must be massless if they are to respect the standard model gauge symmetry
Completely inconsistent with reality!

We need something other than gauge principle!

Left-handed and right-handed electrons are different particles!

Left-handed and right-handed electrons have different weak isospins!



Left-handed electron belongs to a $SU(2)_L$ doublet (I=1/2)

In the symmetric world just after the big bang, it was impossible to tell left-handed electron from left-handed electron neutrino, since they are different states of the same particle

Right-handed electron belongs to a $SU(2)_L$ singlet (I=0)

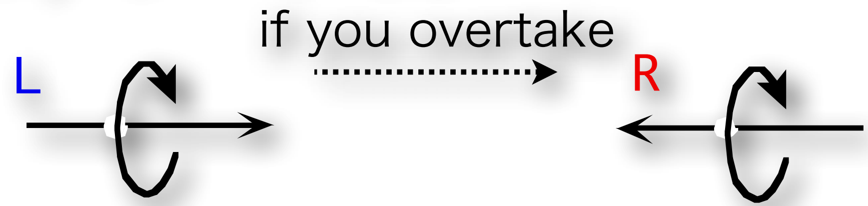
Left-handed and right-handed electrons are different particles with different interactions!

Left-handed and right-handed electrons are different particles!

e_L and e_R have different gauge charges

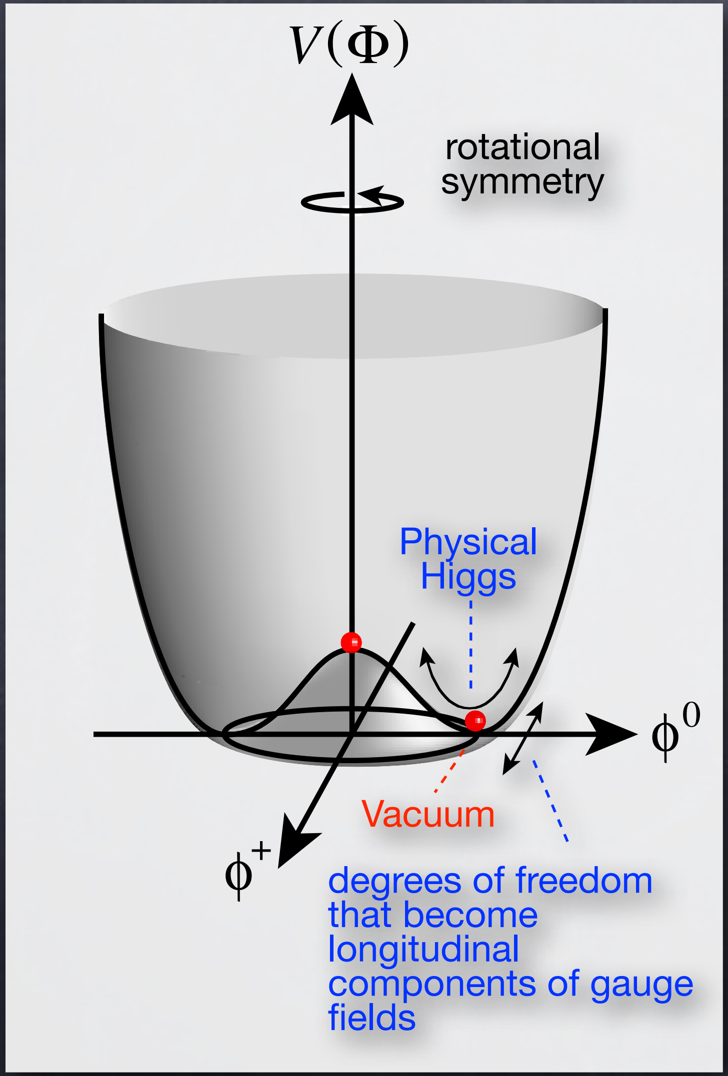
- The standard model gauge symmetry ($SU(2)_L \otimes U(1)_Y$), if unbroken, leads to conservation of weak isospin and weak hyper charge.
- e_L has (I3,Y)=(-1/2,-1/2), while e_R has (I3,Y)=(0,-1).
- On the other hand, if electron has mass, you can convert e_L to e_R by overtaking it.
- This violates the conservation of gauge charges.

$$m \neq 0 \rightarrow v < c$$



Spontaneous Symmetry Breaking

to break the symmetry of phenomena, while keeping the symmetry of Lagrangian



Higgs field ($SU(2)_L$ doublet) : $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Potential:

$$V(\phi) = \left(|\phi|^2 - \frac{v^2}{2} \right)^2$$

Lagrangian:

$$\mathcal{L}_S = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi)$$

is invariant

Vacuum:

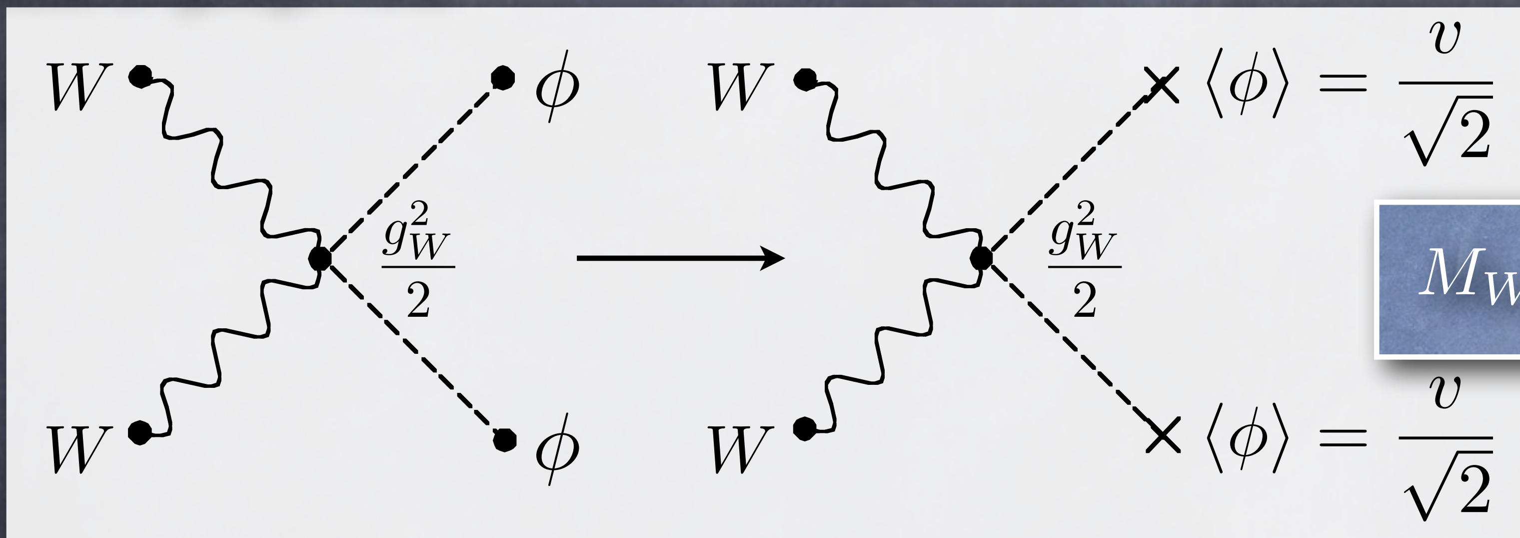
$$\langle \phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

is not invariant (asymmetric vacuum)

Mass Generation (Higgs Mechanism)

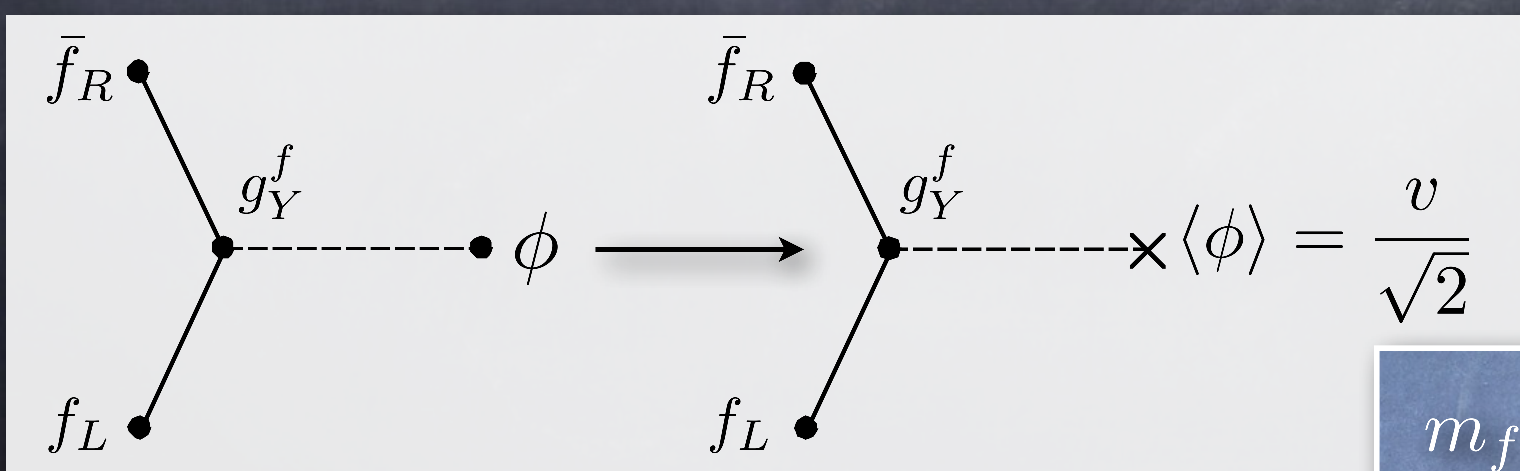
Generate mass through interaction with the Higgs field condensed in the vacuum

Mass of gauge field



$$M_W = \frac{g_W v}{2}$$

Mass of matter field (through Yukawa interaction)



$$m_f = g_Y^f v$$

Intuitive Interpretation of the Origin of mass

What is mass?

mass = resistance against acceleration

Newton's eq. of motion

F (force) = m (mass) x a (acc.)

↓

$$m\ (\text{mass}) = \frac{F\ (\text{force})}{a\ (\text{acc.})}$$

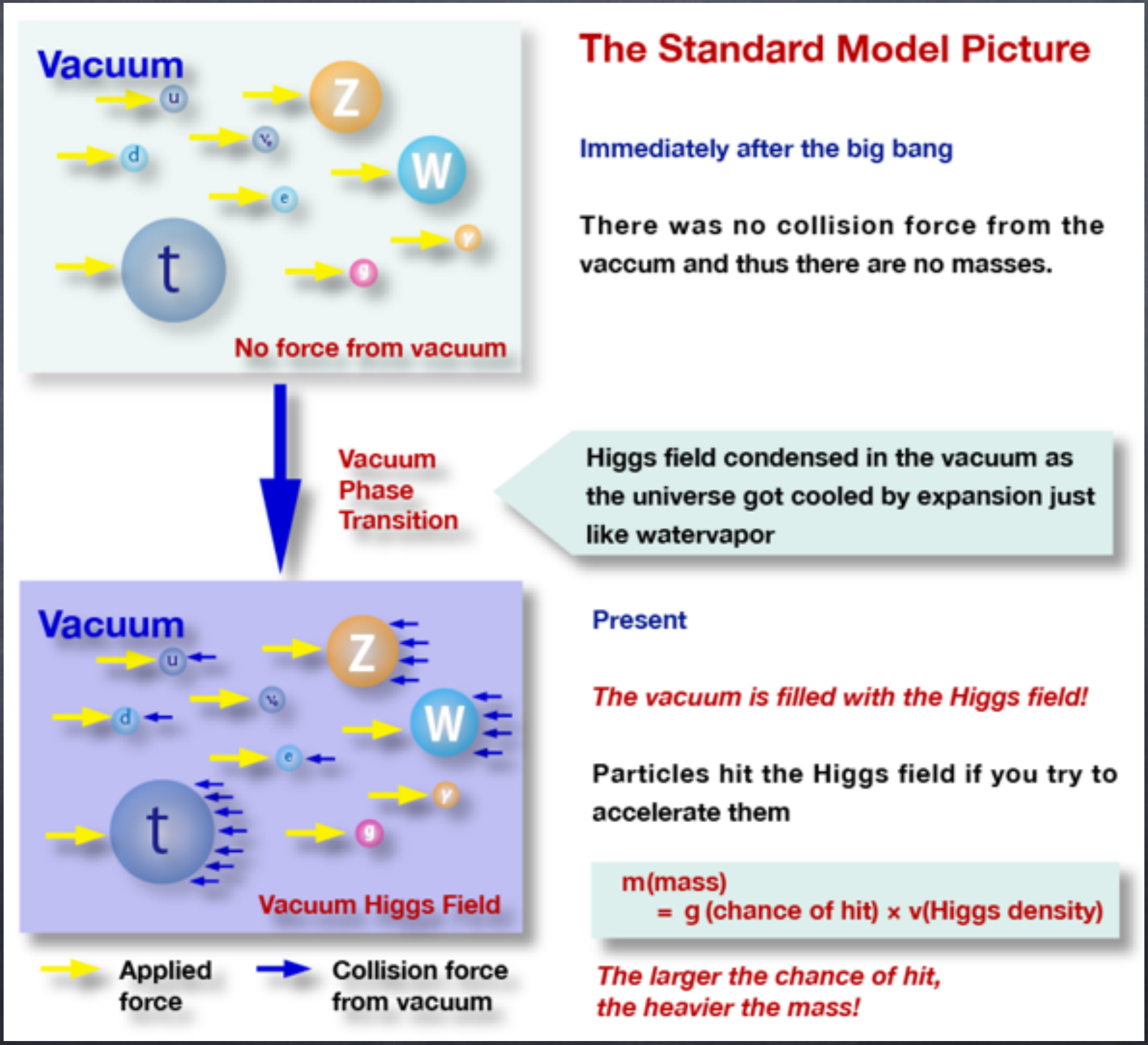
With the same strength of force applied, a lighter particle gets larger acceleration.

Origin of Mass

SM's answer = one Higgs doublet

Is this true?

One of the most important and urgent questions of HEP!

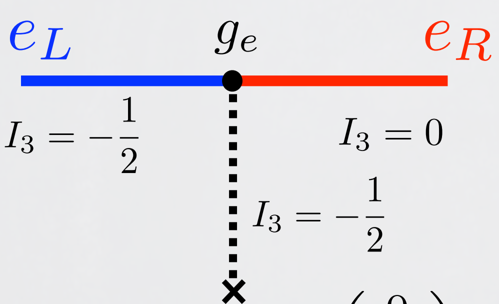


Interaction with Vacuum

The vacuum Higgs field supplies gauge charge!

Conversion of eL to eR violates conservation of weak isospin and weak hyper charge

⇒ The difference is supplied from the vacuum Higgs field!



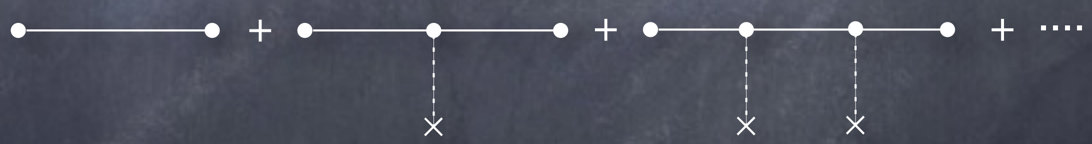
$$\langle \phi \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

The vacuum has non-zero isospin (vacuum violates symmetry)

Spontaneous Symmetry Breaking

with the vacuum Higgs field mixes eL and eR

⇒ Generation of mass (mass is proportional to the coupling to the Higgs field)



$$= \frac{1}{\not p} \sum_{n=0}^{\infty} \left(\frac{g_f v}{\sqrt{2}} \frac{1}{\not p} \right)^n = \frac{1}{\not p} \frac{1}{1 - \left(\frac{g_f v}{\sqrt{2}} \frac{1}{\not p} \right)} = \frac{1}{\not p - \left(\frac{g_f v}{\sqrt{2}} \right)}$$

$$m_f = \frac{g_f v}{\sqrt{2}}$$

Flavor mixing takes place also through the interaction with the vacuum Higgs field

⇒ Both mass and mixing will vanish in the v=0 limit

Standard Medel

Summary of our current understanding of Nature

Nature comprises small number of matter particles and force carrying particles that connect them!

- Matter fermions = Quarks and Leptons (3 gen.)
- Force carrying bosons = gauge bosons
- Mass generating boson = Higgs boson

Discovered in July 2012

New forces introduced in SM:

- Higgs force: makes Higgs condense
- Yukawa force: connect left- and right-handed mater fermions

Need thorough tests

Problems with Standard Model

Standard Model = Summary of our current understanding of Nature

Theoretically unsatisfactory

Why SU(3)xSU(2)xU(1) ?

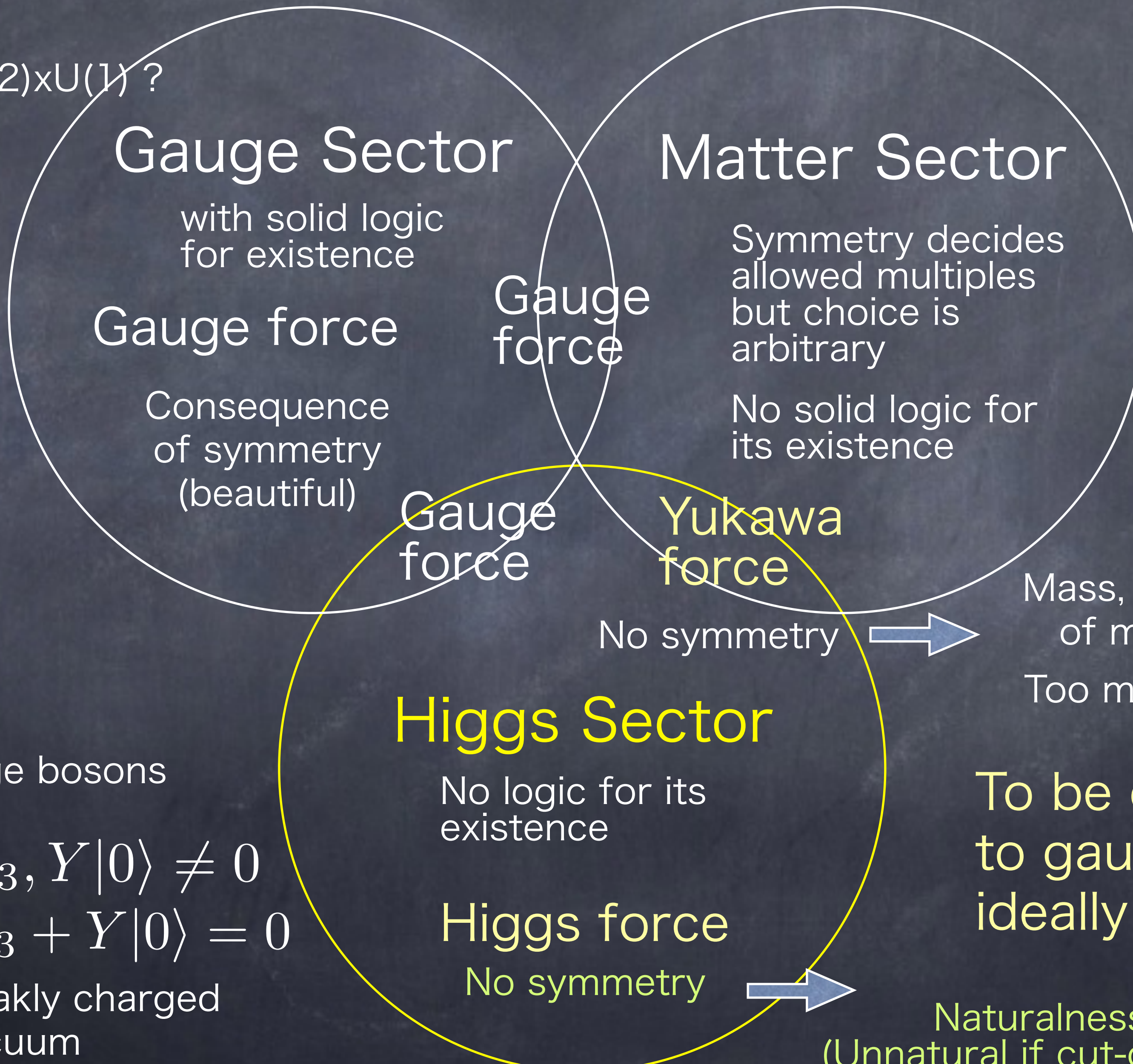
GUT ?

What about gravity ?

Couplings should unify (prejudice?)

Charge quantization

Cancellation of quantum anomalies



Mass, mixing, and CPV of matter particles

Too many parameters!

To be elevated to gauge force ideally!

Naturalness Problem (Unnatural if cut-off scale is high)

Mass of gauge bosons

SSB $\langle 0|I_3, Y|0\rangle \neq 0$

$\langle 0|I_3 + Y|0\rangle = 0$

Electro-weakly charged vacuum

Problem with Naturalness

SM is unnatural if the cutoff is high!

$$\delta M_H^2 \approx \int_{M_W}^{M_X} d\mu \left(\cdots + \cdots + \cdots + \ldots \right)$$

$$\approx C \cdot \frac{\alpha}{\pi} \cdot \left(M_X^2 - M_W^2 \right)$$

The cutoff scale at which SM breaks down

Quantum Correction

In unobservable short time, the Higgs boson turns into different particles or juggles other particles

kinetic energy = mass

The upper limit to this kinetic energy is determined by the cutoff scale at which the theory breaks down (virtual particles in the loop may have energy up to this cutoff scale!)

In order to keep the Higgs mass parameter in the weak scale and make the electroweak symmetry breaking happen in the weak scale, we need to fine tune the bare Higgs mass parameter to many many digits!

→ Such a fine tuning is very unnatural and needs explanation!

Solutions to Naturalness Problem

Two logical possibilities

- Cutoff is high

  Reason of divergence

  Gauge bosons: gauge symmetry
  Matter fermions: Chiral symmetry
  Higgs boson: No guardian

  Introduce new symmetry that protects the Higgs mass

  Supersymmetry: symmetry between bosons and fermions
  ⇒ Import chiral symmetry to scalar field

  Warped extra-dimension (Randall-Sandrum)

  Fine-tuning is somehow miraculously realized.

- Cutoff is low

  No severe naturalness problem from the beginning

  Composite Higgs (strongly interacting Higgs sector)

  Large extra-dimension

  …

Our Goal

Fundamental Lagrangian

The central theme of the story told by Nature

- What decides the Lagrangian?   Symmetry

Internal symmetry → Unification of matter → Unification of matter and force

Internal symmetry → Unification of forces → Unification of matter and force

particles in the same multiplet are different states of the same particle

Supersymmetry

SUSY will be needed for this unification

Unification of matter and force → Unificatoin of gravity with other forces → Unification of matter, force, and space-time

Ultimate Theory

Gauge Principle

External symmetry
Local Pincare symmetry → Unification of gravity with space-time → Unificatoin of gravity with other forces

symmetry → conservation laws → stability → removal of divergence

Symmetry of physical law and symmetry of phenomena

Symmetry of action does not necessarily mean symmetry of phenomena!

- Symmetry of physical law → symmetry of set of solutions
  - does not mean symmetry of a particular solution
  - vacuum may break symmetry (spontaneous symmetry breaking)
  - vacuum may decide apparent symmetry
- Response of vacuum against external field tells you everything (Quantum Field Theory)

↓

Gauge Principle alone is not enough

↓

Study of Vacuum!

Standard Model = Summary of our current understanding of Nature

Theoretically unsatisfactory

Why SU(3)xSU(2)xU(1) ?

GUT ?

What about gravity ?

Couplings should unify (prejudice?)

Charge quantization

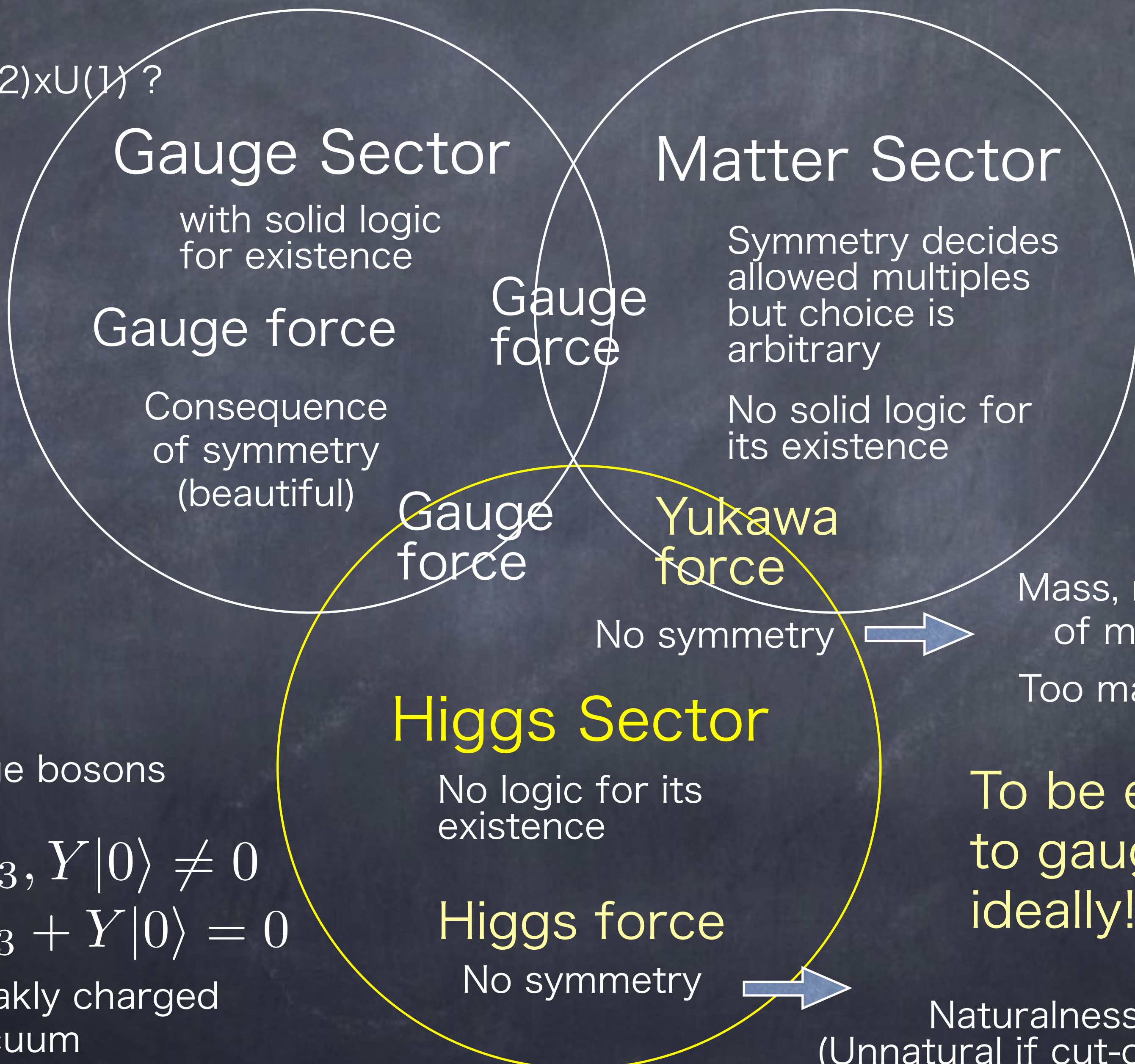
Cancellation of quantum anomalies

Mass of gauge bosons

SSB $\langle 0|I_3, Y|0\rangle \neq 0$

$$\langle 0|I_3 + Y|0\rangle = 0$$

Electro-weakly charged vacuum



Mass, mixing, and CPV of matter particles

Too many parameters!

To be elevated to gauge force ideally!

Naturalness Problem (Unnatural if cut-off scale is high)

World Map Now

Land of civilization

Unknown territory (Frontier)

$$\mathcal{L}_{world} = \mathcal{L}_{gauge} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa} + \mathcal{L}_{BSM}$$

Gauge Sector

Gauge force

Yukawa Sector

Yukawa force

$m_f, \theta_{mix}, \delta_{CP}$

Maybe solutions lie high up beyond TeV scale

Dark Matter

Naturalness problem

B/ν

Link?

Higgs Sector

M_W, M_Z

New dimension / symmetry

Fermionic or Bosonic?

What is condensed in vacuum?

What force make it condense? Higgs force?

Solution must be there at TeV scale!

LHC, ILC

Solutions are likely to be at TeV scale

LHC, ILC, LFV Exp.

ILC Physics

Primary Goal

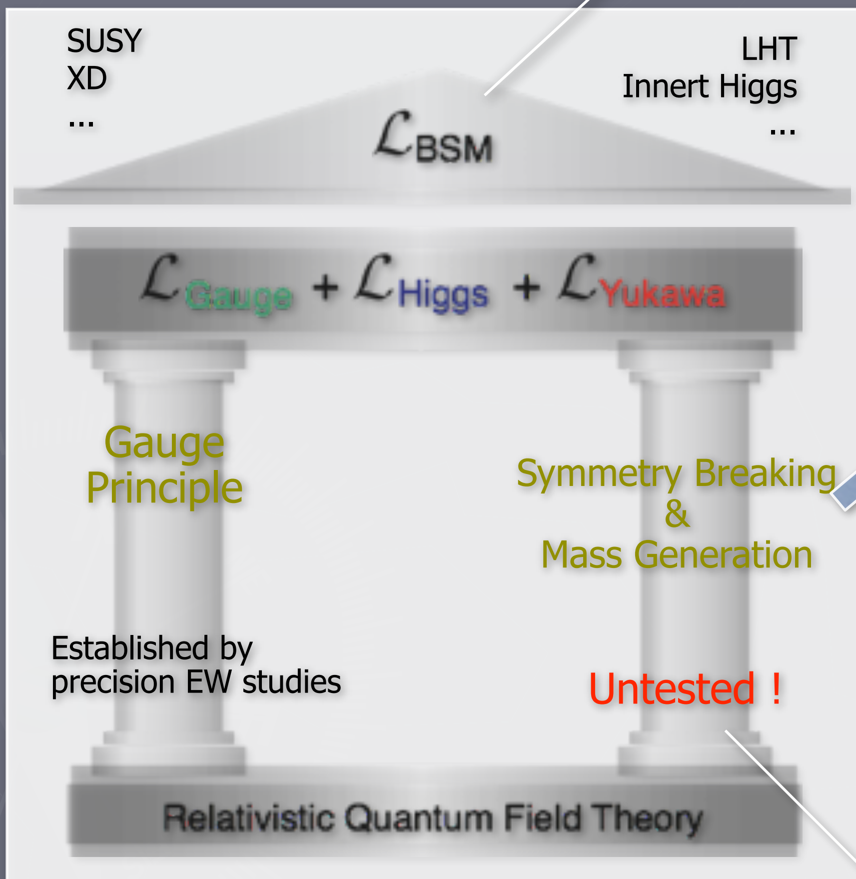
Test of the 2nd Pillar of the SM

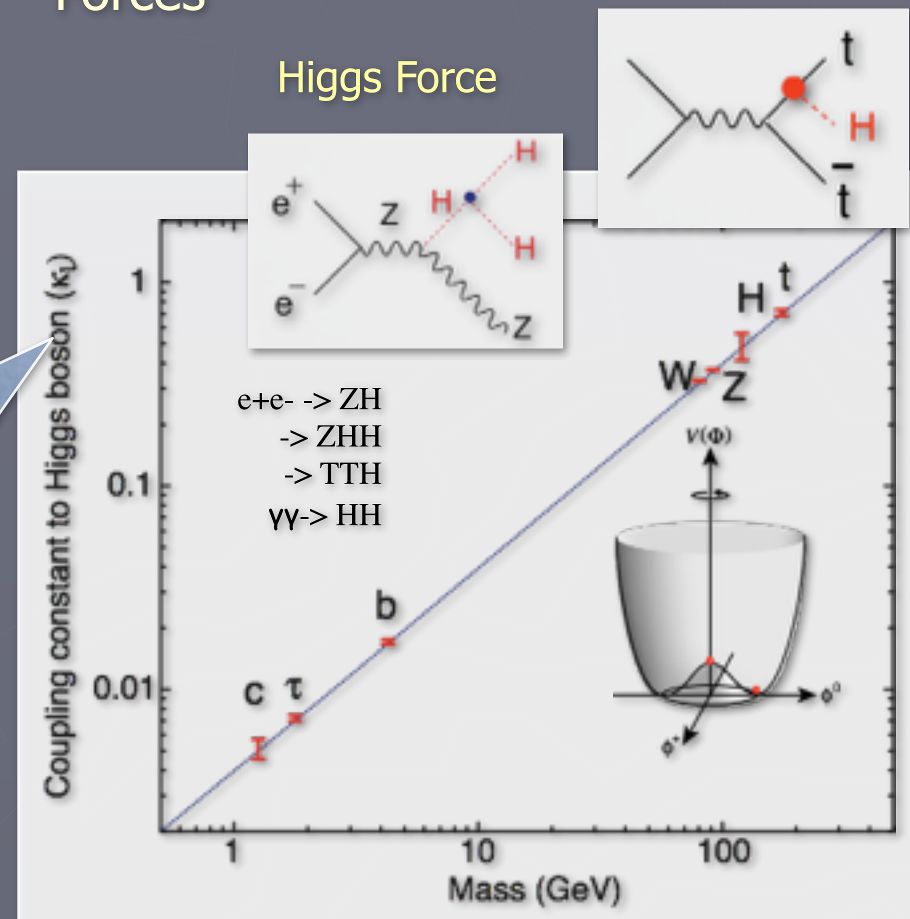
Two Main Pillars of the Standard Model

Dark matter particle is probably at TeV scale

New Fundamental Forces

Yukawa Force





We don't know how firm it is!

First verify the 2nd pillar, then put the BSM roof!

Beyond the Standard Model

In search of new symmetries and/or new dimensions

- In the case of high cut-off scale
  - Supersymmetry (fermionic extra dimensions)
    - Strongly motivated and well studied
    - Yet the most likely scenario, I believe
    - Allows extrapolation to GUT scale over the grand desert
  - Warped extra dimension (bosonic extra dim.)
  - SM survives up to Planck scale? (land scape? vacuum stability?)
  - ???
- In the case of relatively low cut-off scale
  - Large extra dimension (bosonic extra dim.)
  - New symmetries (new strong interactions?)
    - Little Higgs
    - Technicolor
    - ???

It is very likely that there is something totally new at TeV scale and hopefully LHC will find some. ILC, too, is an energy frontier machine and capable of finding uncolored new particles that are difficult to find at LHC.

Once produced, ILC can provide tremendous amount of information!

Priority / Strategy

How to decide priority?

Private view before July 4, 2012

- Forget about money
- Concentrate on something fundamental
- Start from the unknown parts of the standard model
- For BSM, look for new symmetry according to gauge principle
- Put higher priority to questions which are likely to have solutions in the energy region technically reachable in foreseeable future.
- If LHC indicates that the fundamental scale might be in the TeV scale energy region, we can be more optimistic about directly probing the fundamental scale, but no indication so far.

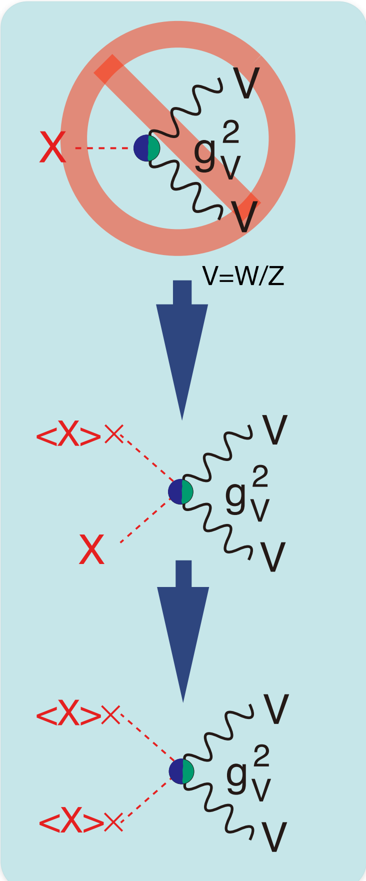
The world has changed since July 4th, 2012

The discovery of the ~125 GeV boson at LHC could be called a quantum jump.

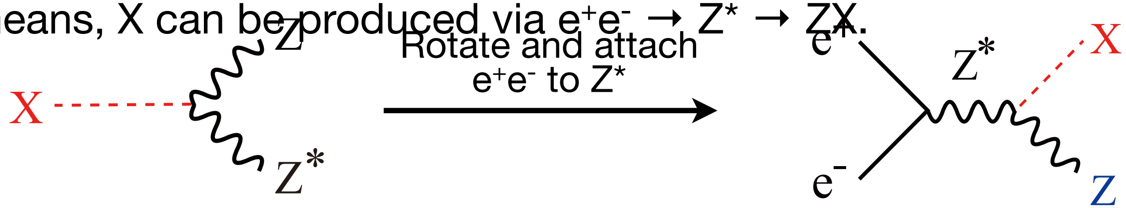
Since the July 4th, the world has changed!

The discovery of the ~125 GeV boson at LHC could be called a quantum jump.

- X(125) → γγ means X is a neutral boson and J ≠ 1 (Landau-Yang theorem). Recent LHC results prefer $J^P=0^+$.
- X(125) → ZZ*, WW* ⇒ ∃ XVV couplings: (V=W/Z: gauge bosons)

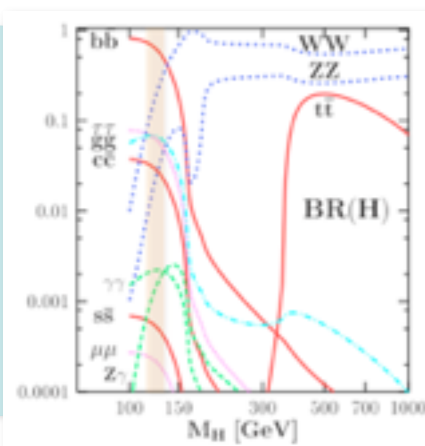


- There is no gauge coupling like XVV, only XXVV or XXV
  ⇒ XVV probably from XXVV with one X replaced by <X> ≠ 0, namely <X>XVV
  ⇒ There must be <X><X>VV, a mass term for V.
  ⇒ X is at least part of the origin of the masses of V=W/Z.
  ⇒ This is a great step forward but we need to know whether <X> saturates the SM vev = 246GeV.
- X → ZZ* means, X can be produced via e^+e^- → Z* → ZX.



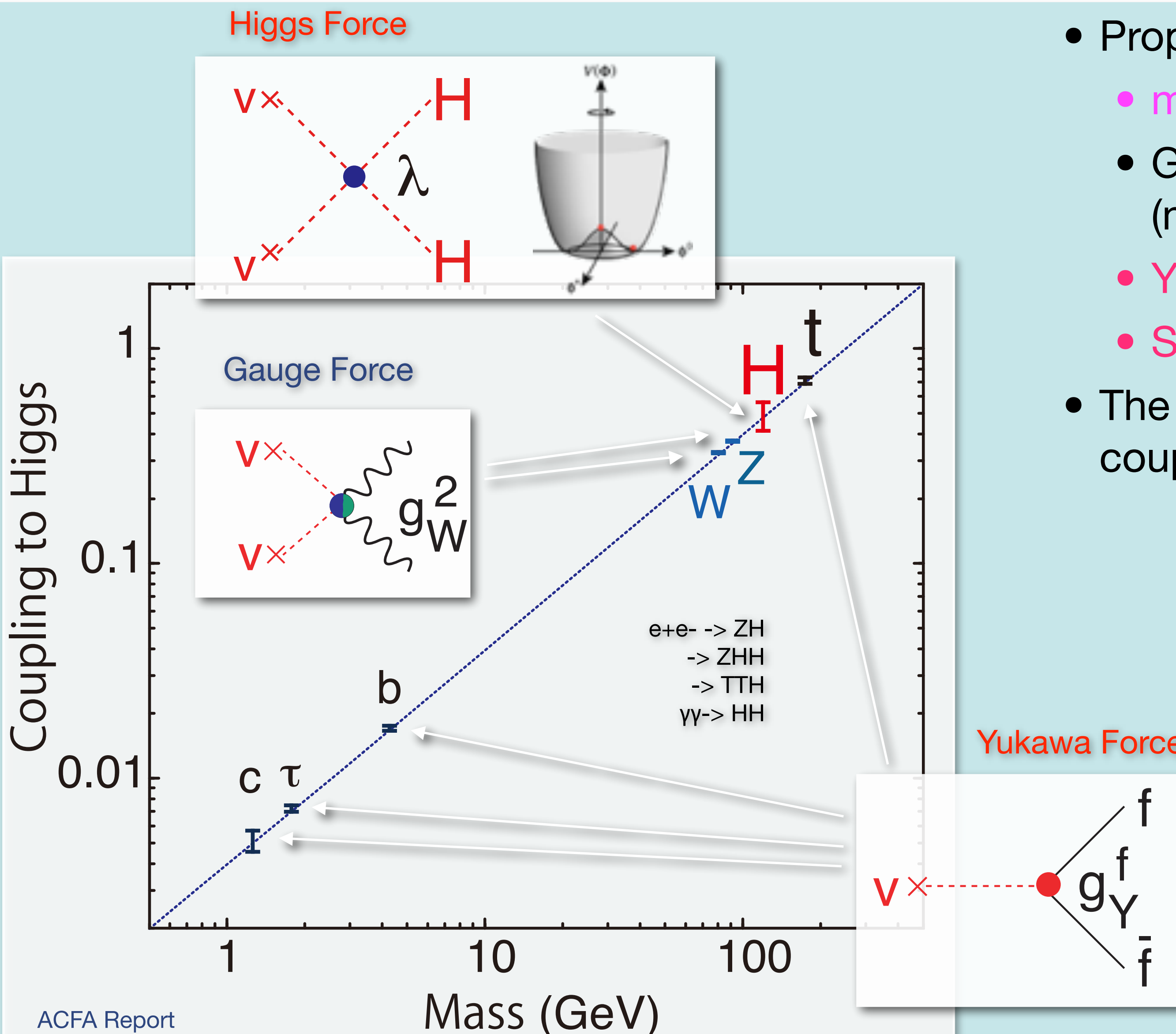
- By the same token,
  X → WW* means, X can be produced via W fusion: e^+e^- → $\nu\nu X$.

- So we now know that the major Higgs production mechanisms in e^+e^- collisions are indeed available at the ILC ⇒ No lose theorem for the ILC.
- ~125GeV is the best place for the ILC, where variety of decay modes are accessible.
- We need to check this ~125GeV boson in detail to see if it has indeed all the required properties of the something in the vacuum.



What Properties to Measure?

The Key is the Mass-Coupling Relation



- Properties to measure are
  - mass, width, J^{PC}
  - Gauge quantum numbers (multiplet structure)
  - Yukawa couplings
  - Self-coupling
- The key is to measure the mass-coupling relation

If the 125GeV boson is the one to give masses to all the SM particles, coupling should be proportional to mass.

Any deviation from the straight line signals BSM!

Or we need to test this relation until it breaks!

The Higgs is a window to BSM physics!

Our Mission = Bottom-up Model-Independent Reconstruction of the EWSB Sector

through Precision Higgs Measurements

- Multiplet structure :
  - Additional singlet?
  - Additional doublet?
  - Additional triplet?
- Underlying dynamics :
  - Weakly interacting or strongly interacting?
    = elementary or composite ?
- Relations to other questions of HEP :
  - DM
  - EW baryogenesis
  - neutrino mass
  - inflation?

There are many possibilities!

Different models predict different deviation patterns --> Fingerprinting!

Model	μ	τ	b	c	t	g_V
Singlet mixing	↓	↓	↓	↓	↓	↓
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

Mixing with singlet

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \frac{g_{hff}}{g_{h_{SM}ff}} = \cos\theta \simeq 1 - \frac{\delta^2}{2}$$

Composite Higgs

$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\%(1\ \mathrm{TeV}/f)^2$$

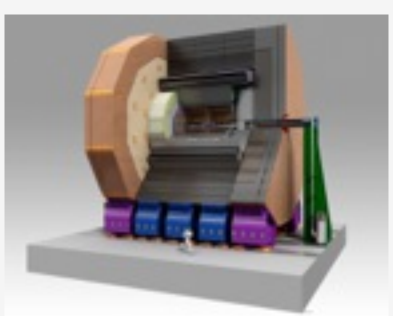
$$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \mathrm{TeV}/f)^2 & \text{(MCHM4)} \\ 1 - 9\%(1\ \mathrm{TeV}/f)^2 & \text{(MCHM5)} \end{cases}$$

SUSY

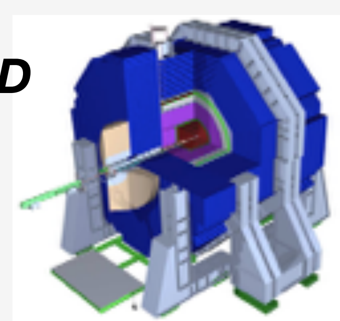
$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

Expected deviations are small --> Precision!

ILD



SiD

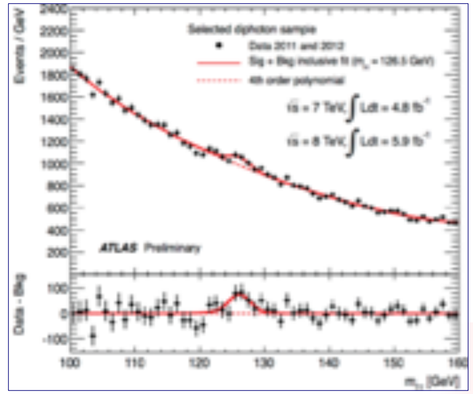


For the precision we need a 500GeV LC and high precision detectors

International Linear Collider (ILC) – From Design to Reality

1980 ~
- Basice Study started

2004
- SC Technology selected



Higgs discovered

LHC

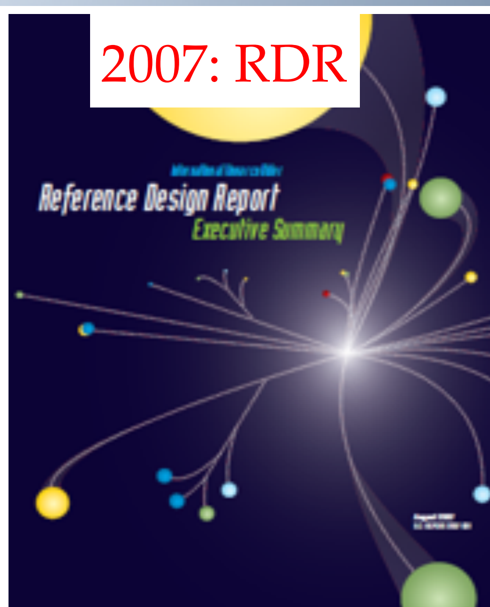
2005 2006 2007 2008 2009 2010 2011 2012 2013

ILC - GLOBAL DESIGN EFFORT (GDE)

LCC

Ref. Design Report (RDR)

2007: RDR



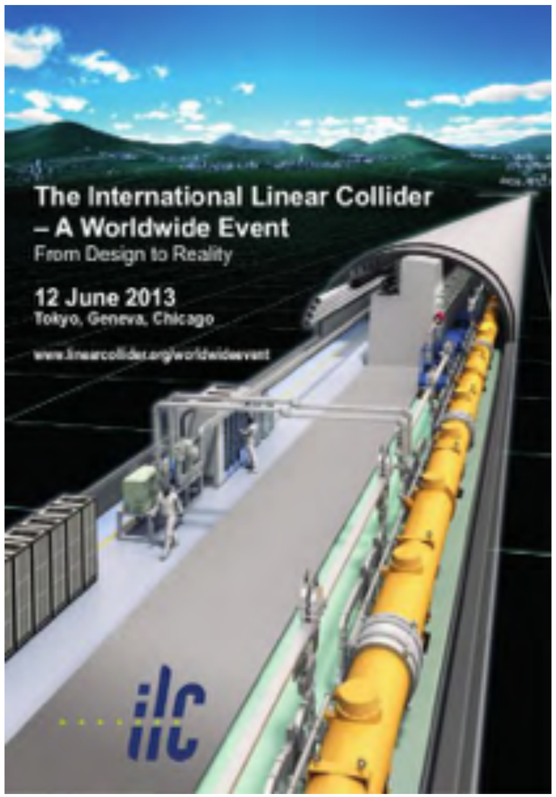
2013: TDR

COMPLETED

Linear Collider Collaboration

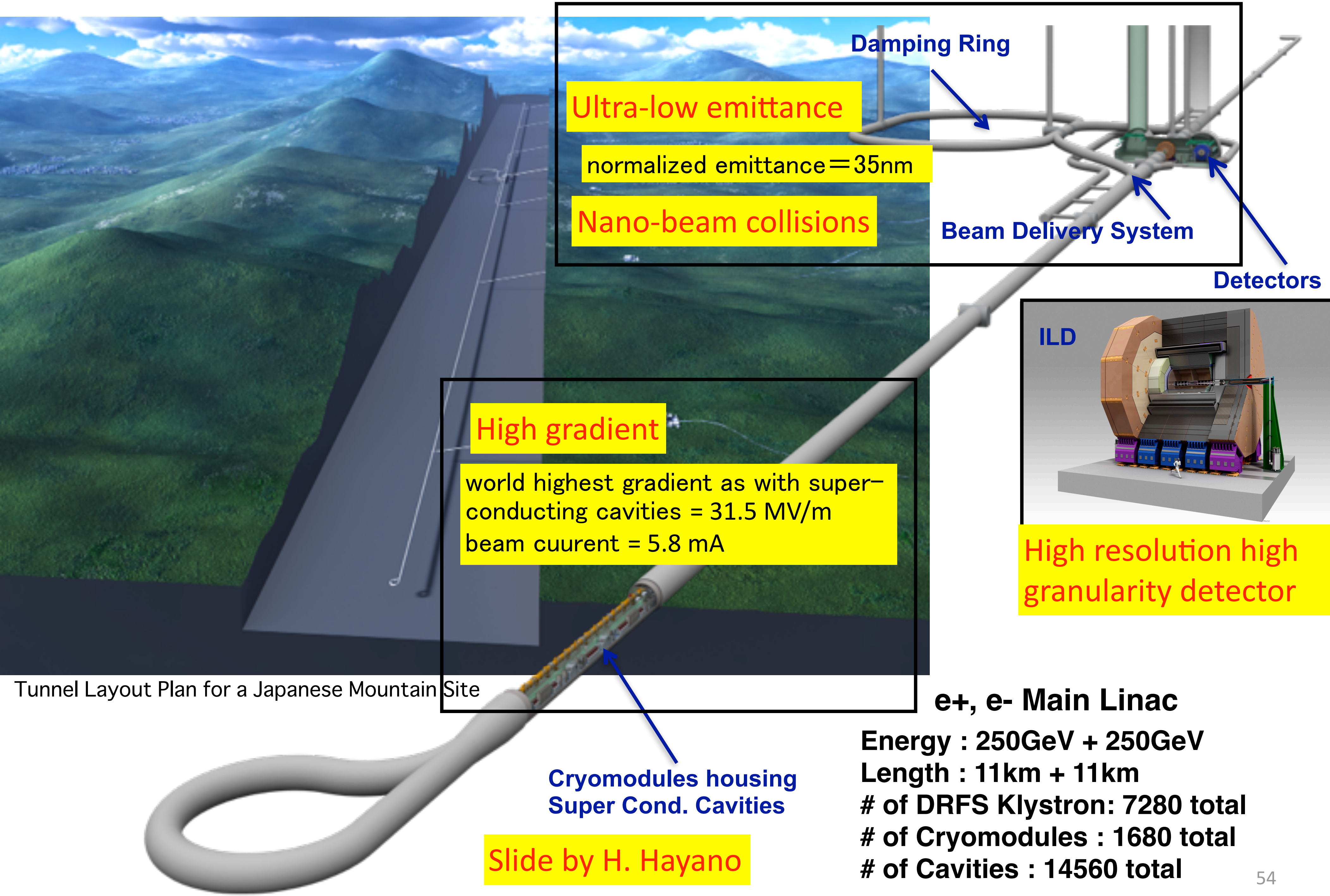
Official Completion of ILC TDR
"From Design to Reality"
June 12, 2013:

TDR handed to LCC Director Lyn Evans



ILC TDR published in a Worldwide Event:
Tokyo → Geneva → Chicago

Bird's Eye View of the ILC Accelerator



Slide by H. Hayano

e+, e- Main Linac

Energy : 250GeV + 250GeV
Length : 11km + 11km
# of DRFS Klystron: 7280 total
# of Cryomodules : 1680 total
# of Cavities : 14560 total

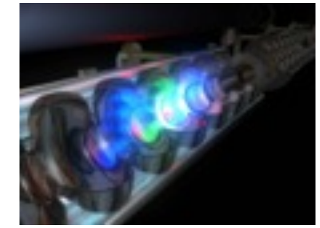
Major Technical Challenges

- **High gradient acceleration with super-conducting RF cavities**
  - Average acceleration gradient: 35 MV/m
    5-times more powerful than super-conducting cavities used fro CERN/KEP and KEKB
- **Nano-beam generation/control**
  - Ultra-low emittance beam: 1mm divergence over 1000km
  - Beam position control to 2nm (10 times more accurate)
- **High precision high granularity detector**

  (>5 times better resolutions than LHC detectors)

ILC Accelerator

Advantage of Superconducting RF



- Ultra-high ($Q_0 = 10^{10}$):
  - small surface resistance → almost zero power (heat) in cavity walls
  - use relatively low-power microwave source to 'charge up' cavity
- Long beam pulses (~1 ms)
  → intra-pulse feedback
- Larger aperture / smaller beam loss
  → better beam quality w/ larger aperture - lower wake-fields
- Work necessary on engineering for:
  - Cryomodule (thermal insultation)
  - Cryogenics
  - Gradient to be further improved

Luminosity:

RF efficiency — RF power / beam current

$$L \propto \frac{\eta P_{RF}}{E_{CM}} \sqrt{\frac{\delta_{BS}}{\varepsilon_y}}$$

Vertical emittance (tiny beams)

- Luminosity proportional to RF efficiency ILC
  - for given total power (electricity bill !),
  - ~160MW @ 500GeV
- Capable of efficiently accelerating high beam currents
- Low impedance aids preservation of high beam quality (low emittance)

→ Ideal for Linear Collider

ILC Accelerator R&D at KEK

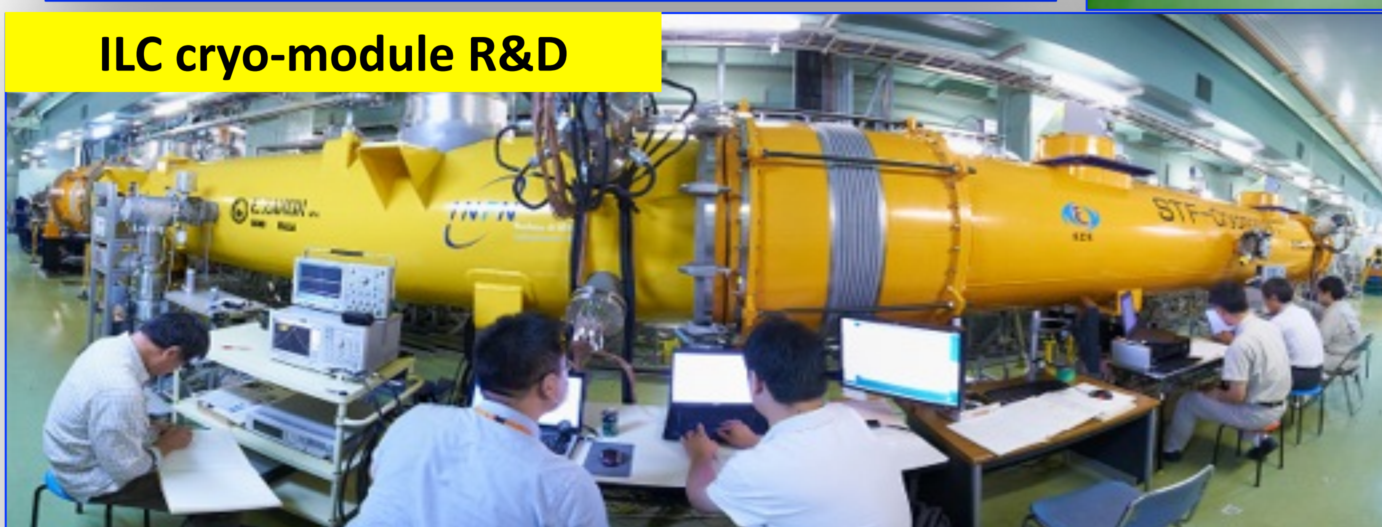
Achieved >90% yield for ILC spec cavities

ILC super conducting RF cavity R&D

ATF2: International effort hosted by KEK from teams from UK, France, US, Korea, China, Japan; beam spot size: ***goal=37nm*** (corresponding to 6nm of ILC), ***44nm achieved!***

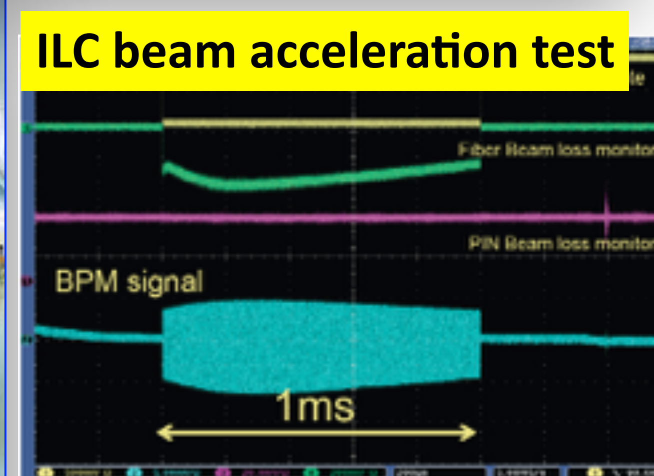
ILC final focus test beam line

ILC cryo-module R&D



S1–Global: international collaboration for cryo–module assembly, connection and high power test by Germany, US, UK, Italy, Japan, hosted by KEK

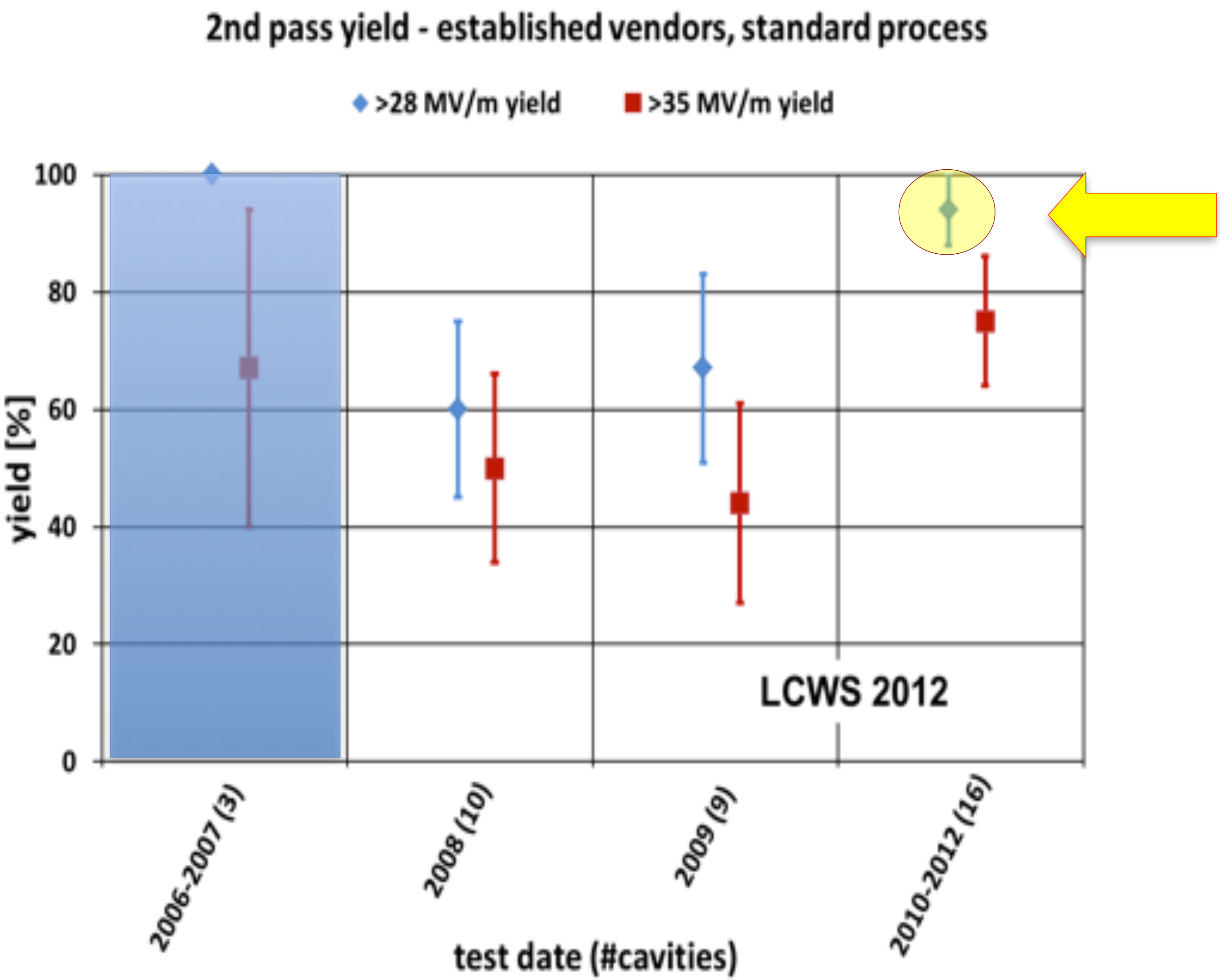
ILC beam acceleration test



Achieved stable operation with the same duration (1 ms) and current (6.6 mA) as ILC

High gradient acceleration with super-conducting RF cavities

Progress in SCRF Cavity Gradient



Production yield:
94 % at > 35+/-20%

Average gradient:
37.1 MV/m

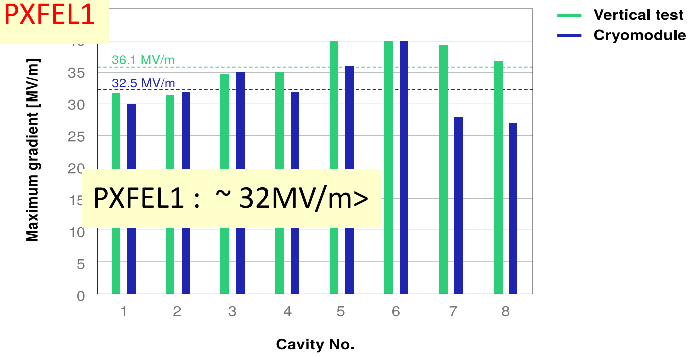
reached (2012)

Cryomodule System Test

DESY: FLASH

- 1.25 GeV linac (TESLA-Like tech.)
- ILC-like bunch trains:
- 600 ms, 9 mA beam (2009);
  800 ms 4.5 mA (2012)
- RF-cryomodule string with beam → PXFEL1 operational at FLASH

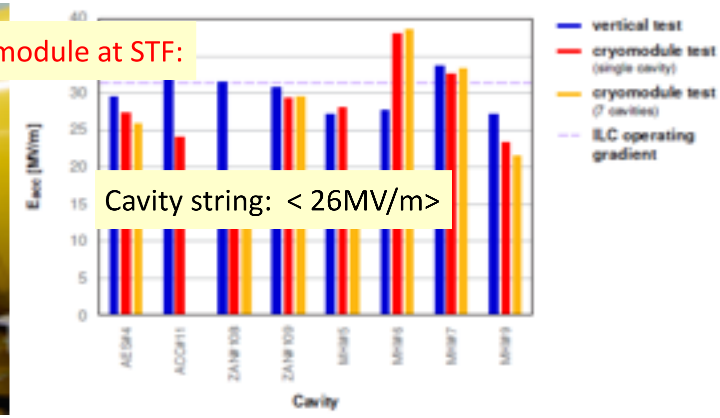
← Demonstrated



KEK: STF/STF2

- S1-Global: completed (2010)
- Quantum Beam Accelerator (Inverse Llaser Compton): 6.7 mA, **1 ms**
- CM1 test with beam (2014 ~2015)
- STF-COI: Facility to demonstrate CM assembly/test in near future

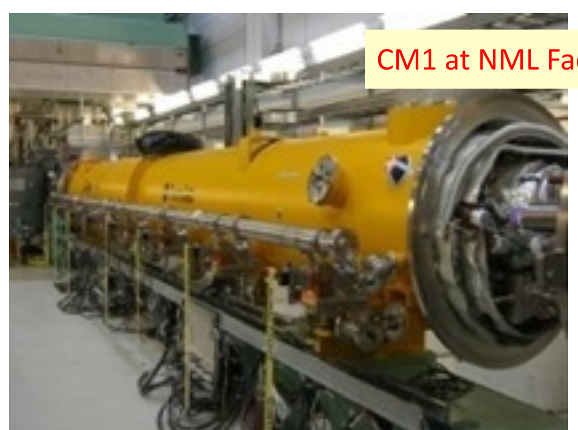
← Demonstrated

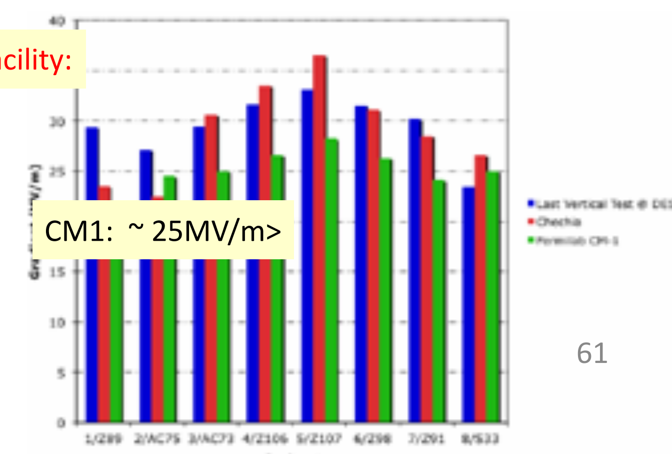


FNAL: ASTA

(Advanced Superconducting Test Accelerator)

- CM1 test complete
- CM2 operation (2013)
- CM2 with beam (soon)



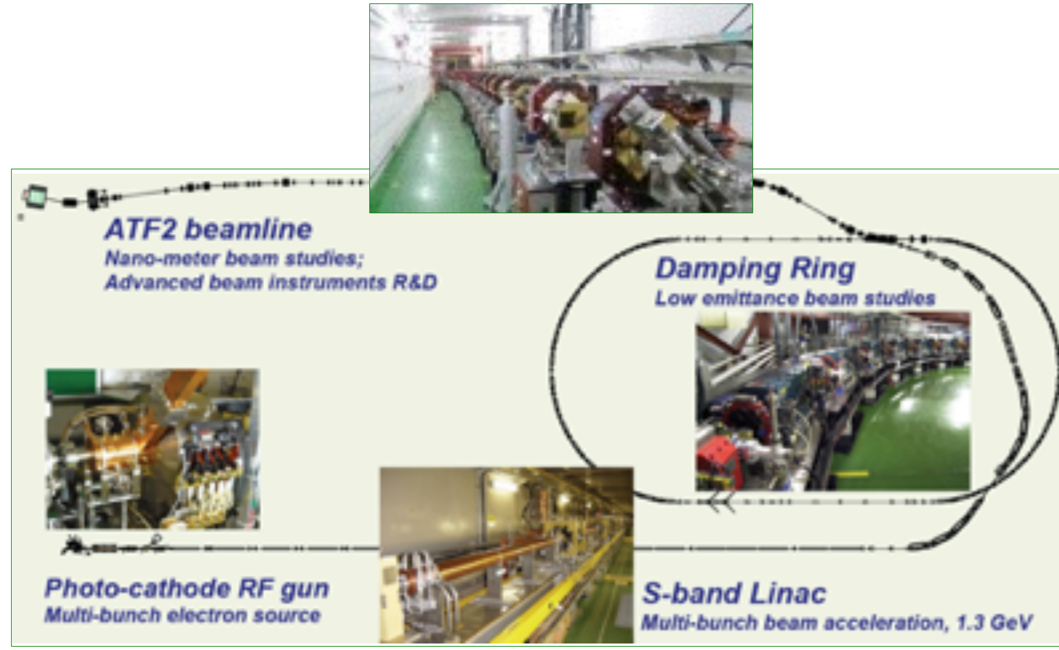


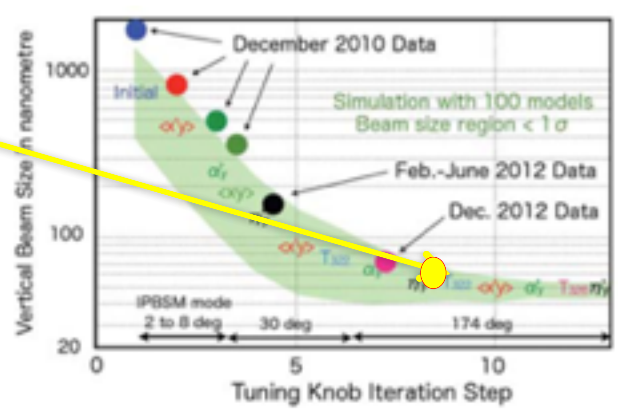
Nano-beam generation / control

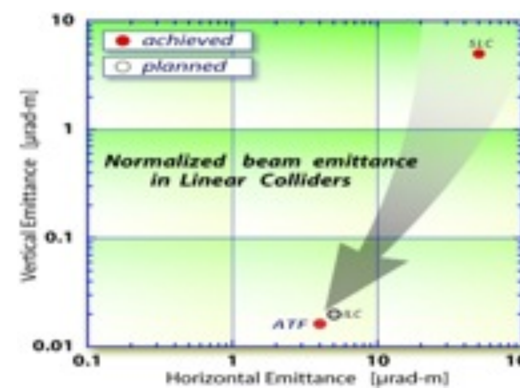
ATF2 Progress by 2013

Ultra-small beam

- Low emittance : KEK-ATF
  - 4 pm achieved
  - (ILC target value, in 2004).
- Small vertical beam size : KEK ATF2
  - Goal = 37 nm,
    - 160 nm (spring, 2012)
    - 65 nm (April, 2013) at low beam current

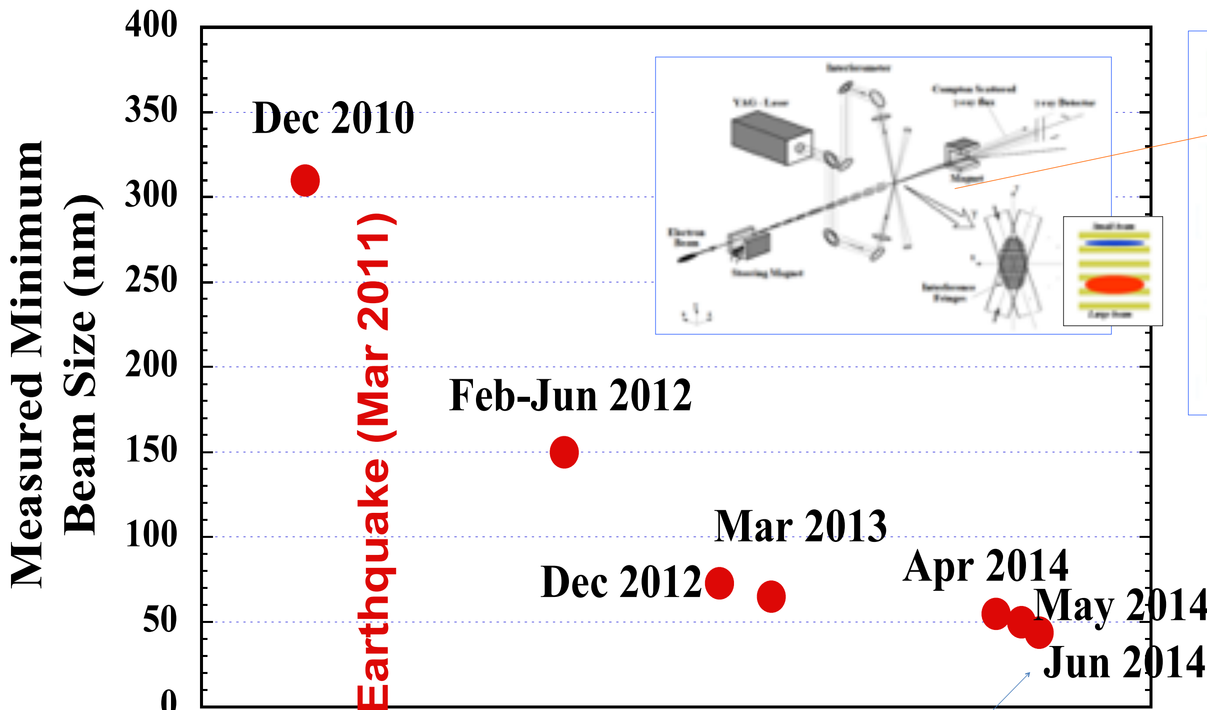


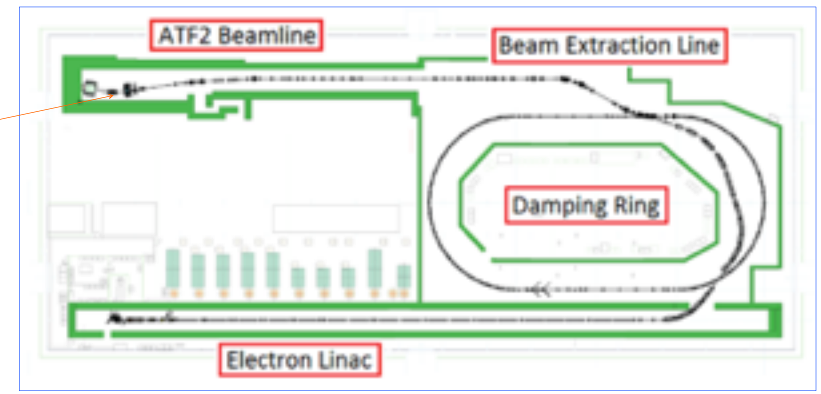


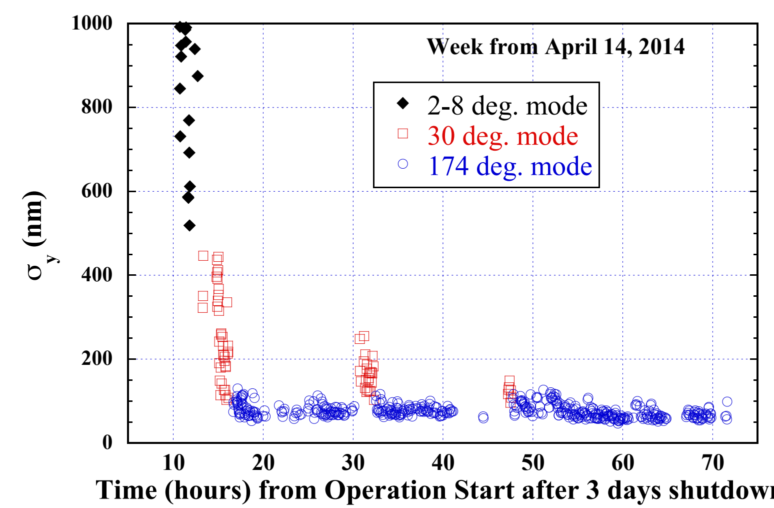


Progress in measured min. beam size at ATF2

Progress in 2014 (We are almost there!)







Beam Size 44 nm observed,
(Goal : 37 nm)

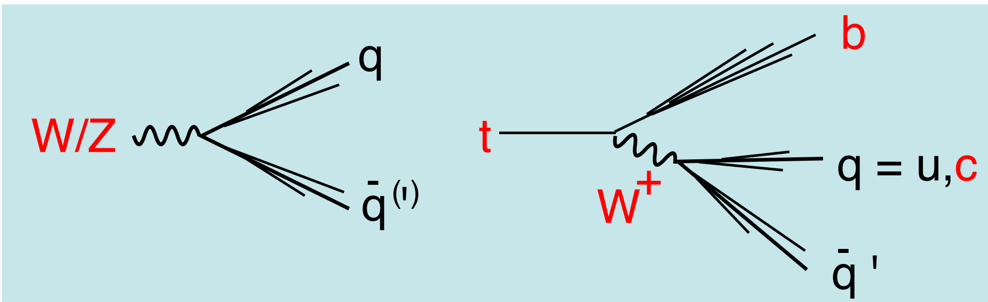
Reproducible in short time!

ILC Detector

ILC Experiments

View events as viewing Feynman diagrams

Reconstruct events in terms of (q, l, gb, hb)



Jet invariant mass → W/Z/t/h ID → p^μ

→ angular analysis → s^μ

Missing momentum → neutrinos

b/c ID with 2ndary/3tiary vertices

Thin and high resolution vertexing

Particle Flow Analysis

High resolution tracking

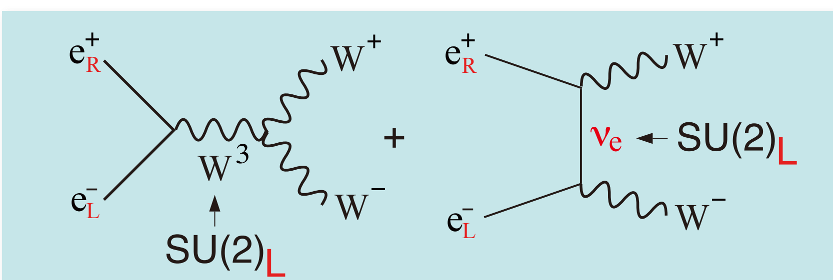
high granularity calorimetry

Hermeticity

down to O(10mrad) or better

both ECAL and HCAL inside the solenoid

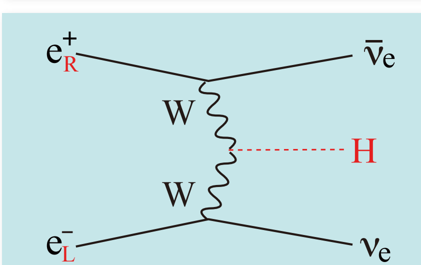
Select Feynman diagrams with polarized beams



To these processes, only left-handed electrons and right-handed positrons contribute !

If you have a wrong combination, cross section is zero.

Beam polarization plays an essential role !

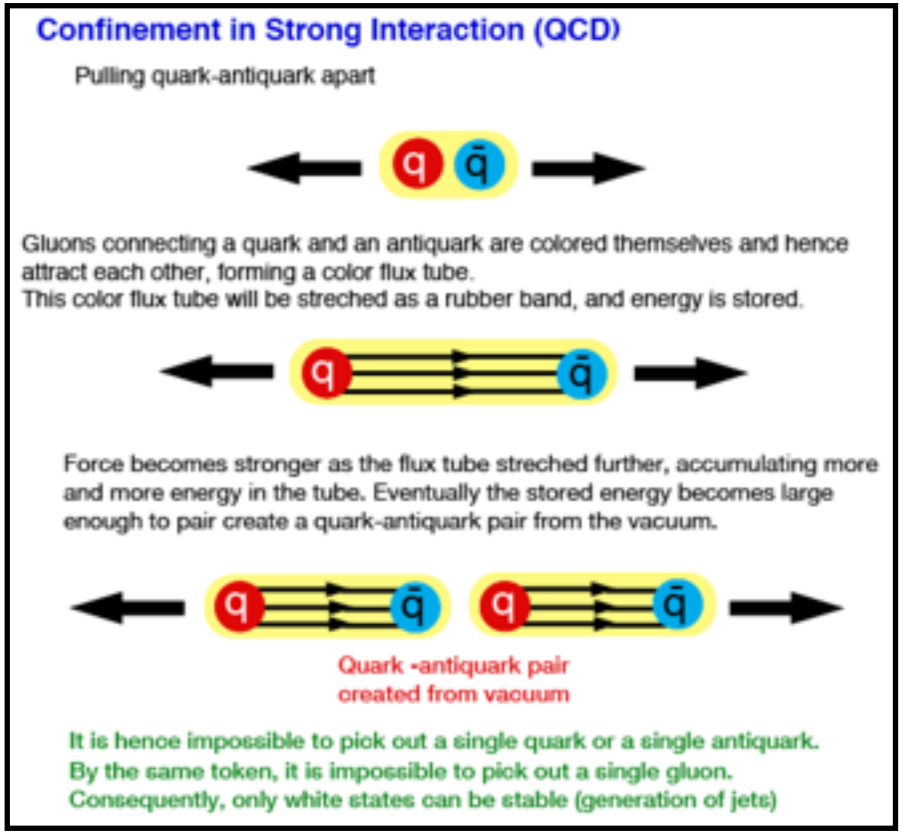


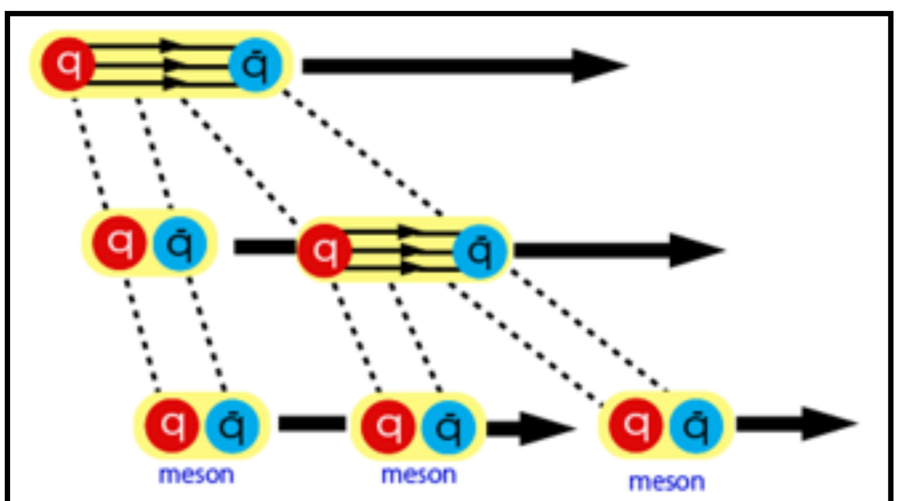
	ILC	CLIC	TLEP
Pol (e	-0.8	-0.8	0
Pol (e	+0.3	0	0
(σ/σ	1.8x1.3=2.34	1.8x1.0=1.8	1

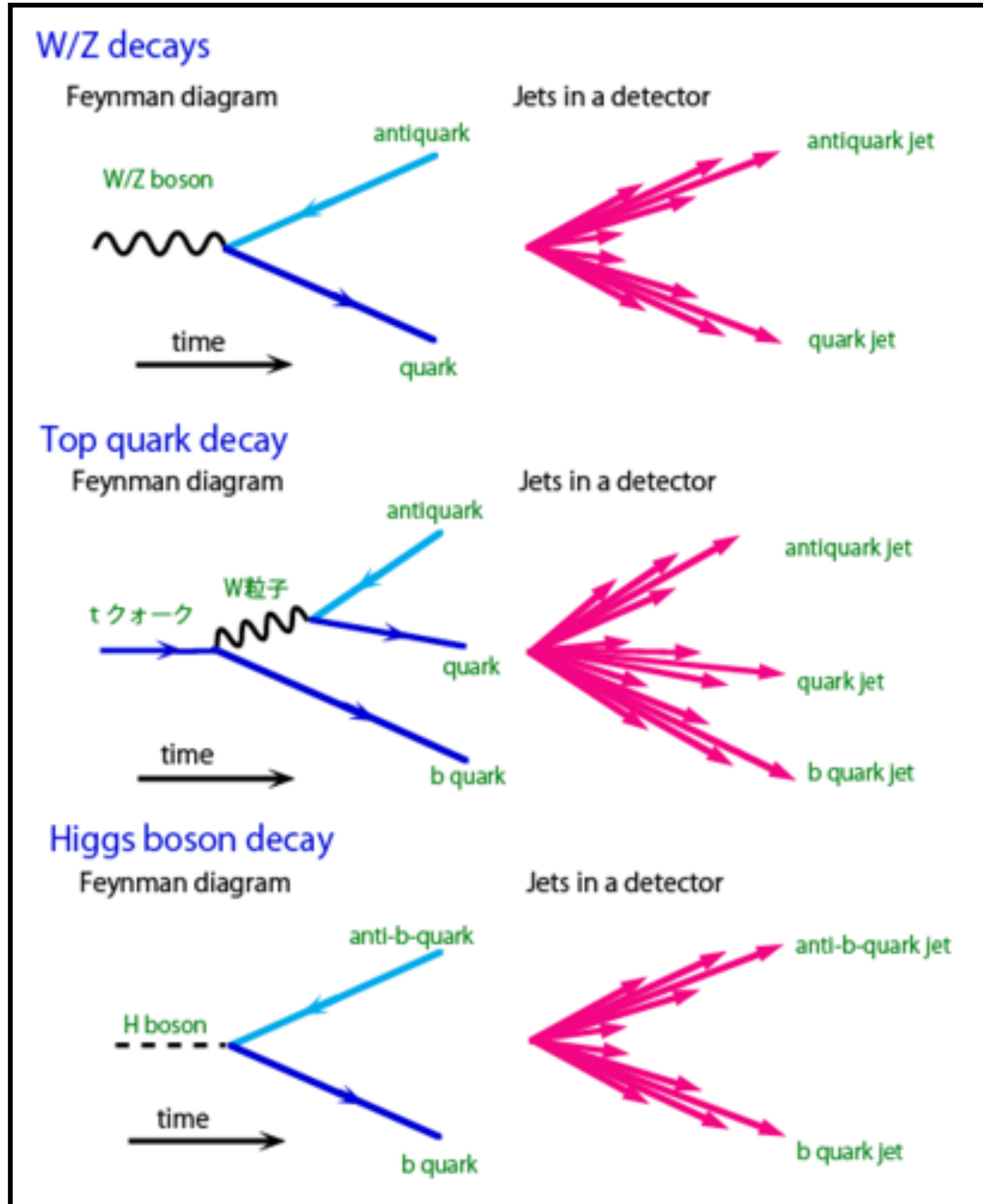
Beam polarization acts as luminosity doubler !

Reconstruction of Jets

View events as viewing Feynman diagrams

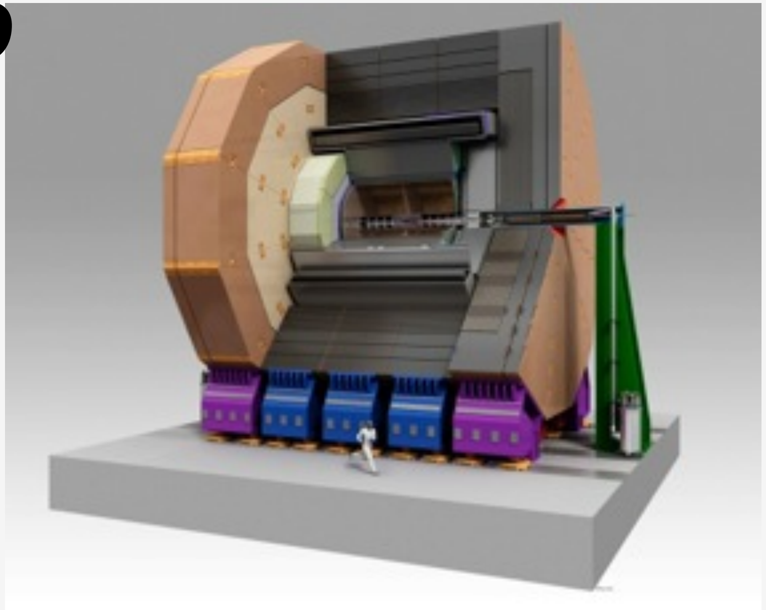






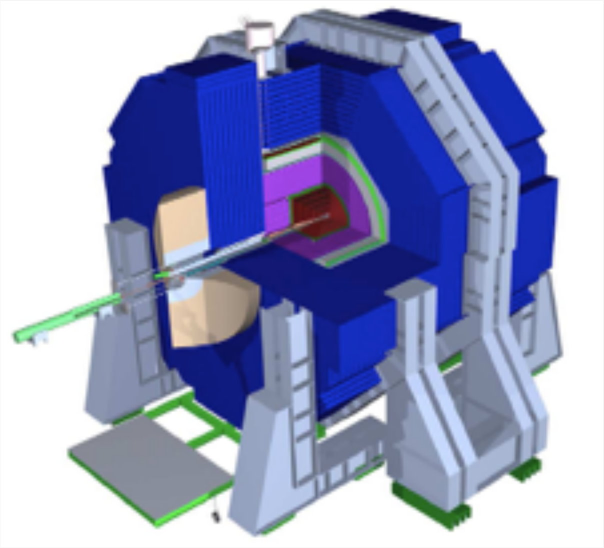
Detailed Baseline Design Document

ILD



- Large R with TPC tracker
  - 32 countries, 151 institutions, ~700 members
  - Most members from Asia and Europe
  - B=3.5T, TPC + Si trackers
  - ECal: R=1.8m

SiD

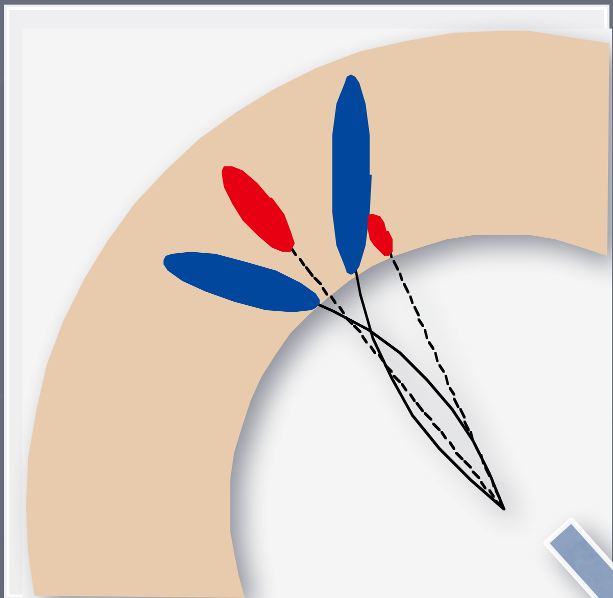


- High B with Si strip tracker
  - 18 countries, 77 institutions, ~240 members
  - Mostly American
  - B=5T, Si only tracker
  - ECal : R=1.27m

Both detector concepts are optimized for Particle Flow Analysis

Particle Flow Analysis

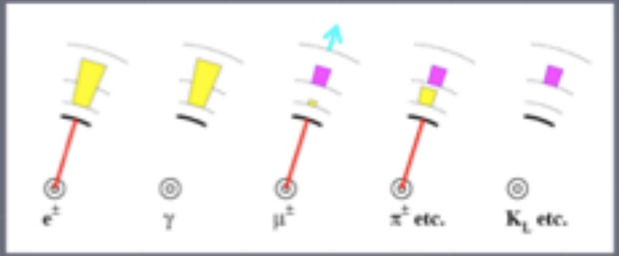
How to measure jet energies precisely?



Charged Particles

Tracker's resolution is much better than that from calorimetry

Use tracking devices



Neutral Particles

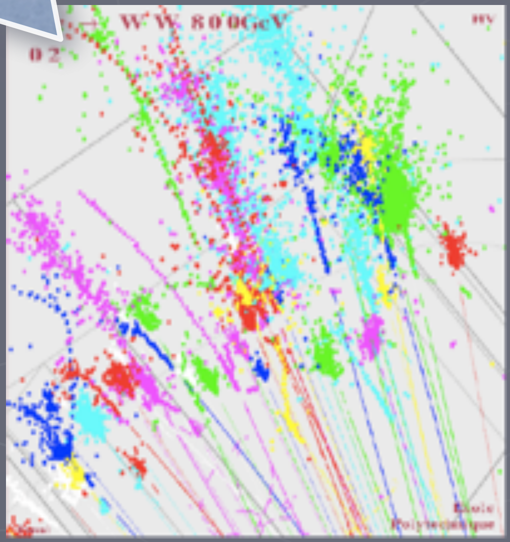
Use calorimetry

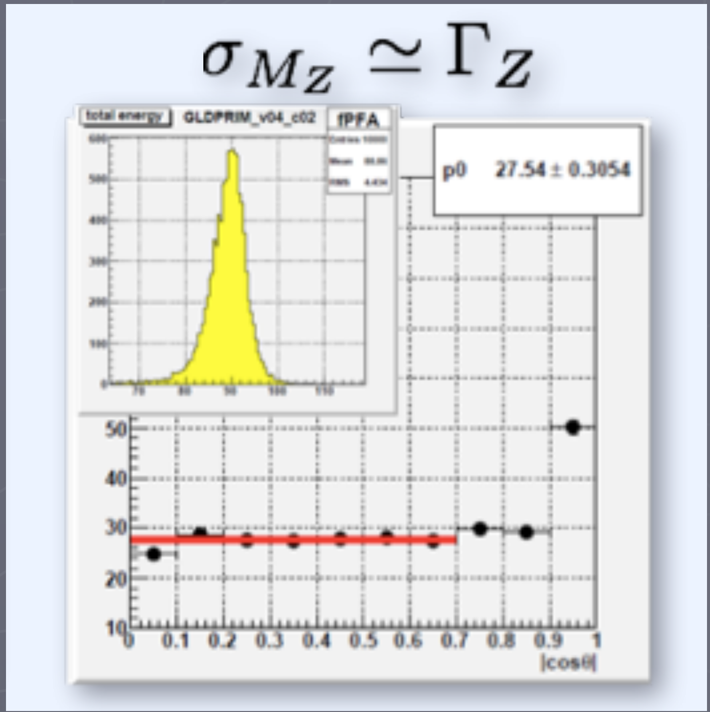
PFA

Remove charged particle signals in calorimeters

Needs 1-to-1 matching of tracks and calorimeter clusters

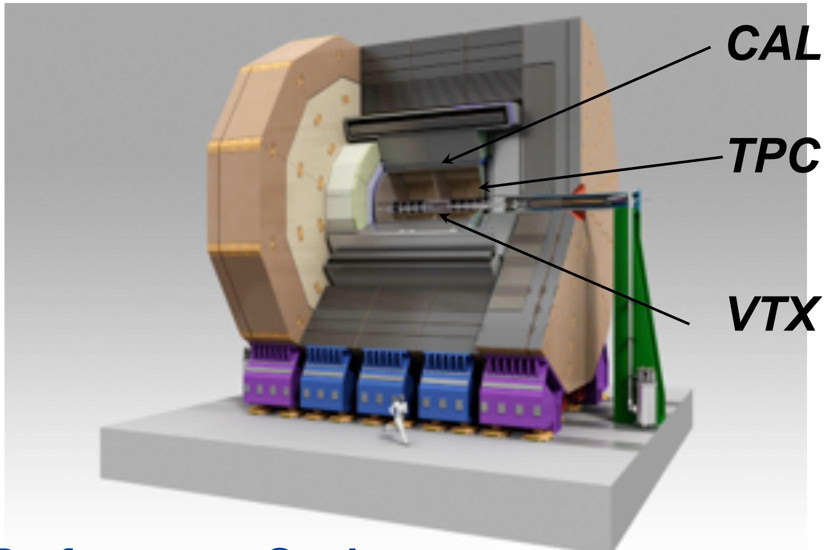
Needs ultra-high granularity calorimeter





Detector R&D : ILD

Component R&D



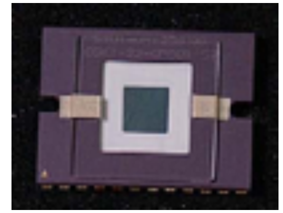
Performance Goal as compared to LHC detectors

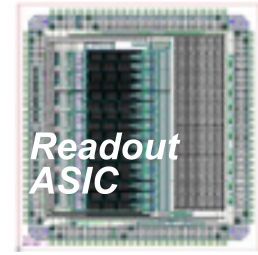
Vertex resolution	2-7 times better
Momentum resolution	10 times better
Jet energy resolution	2 times better

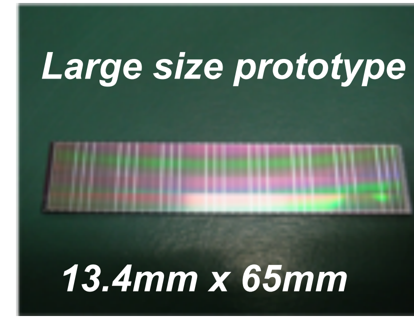
The key is ultra high granularity!

Detector	ILC	ATLAS	Granularity
Vertex Det.	5×5μm	400×50μm	x 800
Tracker	1×6mm	13mm	x 2.2
EM Calorimeter	Silicon: 5×5mm Scintillator : 5×45mm	39×39mm	x 61 x 7

Vertex Detector R&D



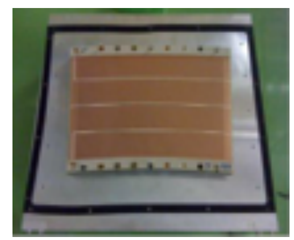




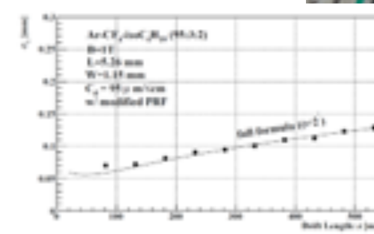
6um pixel now working!

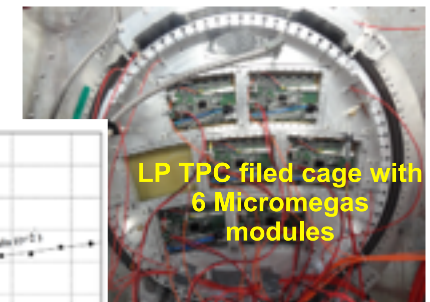
Proof of principle for sensor technology finished!
Now R&D on ladder, support structure, and 2-phase CO_2 cooling system.

TPC R&D



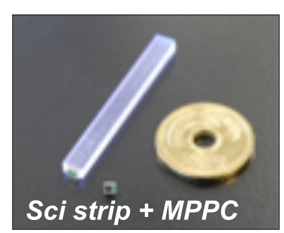
Spatial resolution
Asian GEM module

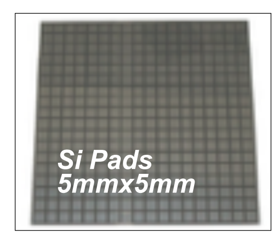


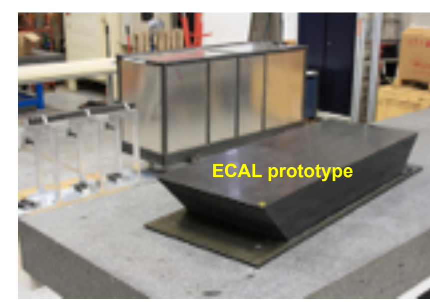


Both GEM and Micromegas modules have achieved the performance goal: point resolution < 100um (3.5T)

Calorimeter R&D







Test beam data well reproduced by MC simulation, one-particle energy resolution has reached performance goal!

Higgs at ILC

With the machine and the detector we will be able to tackle the mystery of symmetry breaking!

LC 250-500

Why 250-500 GeV?

Three well known thresholds

ZH @ 250 GeV (~M_Z+M_H+20GeV) :

- Higgs mass, width, J^{PC}
- Gauge quantum numbers
- Absolute measurement of HZZ coupling (recoil mass) -> couplings to H (other than top)
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g, γ (loop)

ttbar @ 340-350GeV (~2mt) : ZH meas. Is also possible

- Threshold scan --> theoretically clean mt measurement:$\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$
  --> test stability of the SM vacuum
  --> indirect meas. of top Yukawa coupling
- A_{FB}, Top momentum measurements
- Form factor measurements

γ γ → HH @ 350GeV possibility

vvH @ 350 - 500GeV :

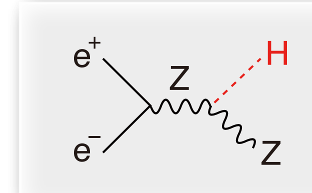
- HWW coupling -> total width --> absolute normalization of Higgs couplings

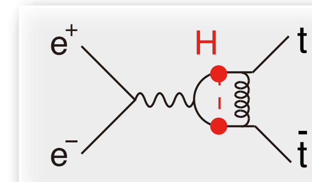
ZHH @ 500GeV (~M_Z+2M_H+170GeV) :

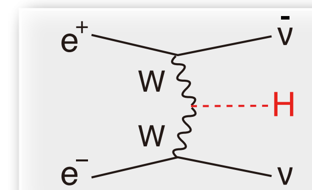
- Prod. cross section attains its maximum at around 500GeV -> Higgs self-coupling

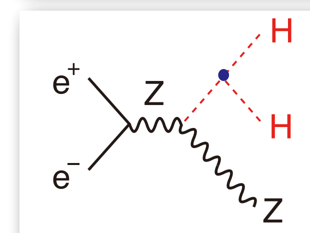
ttbarH @ 500GeV (~2mt+M_H+30GeV) :

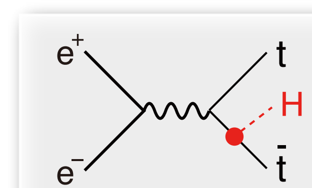
- Prod. cross section becomes maximum at around 800GeV.
- QCD threshold correction enhances the cross section -> top Yukawa measurable at 500GeV concurrently with the self-coupling







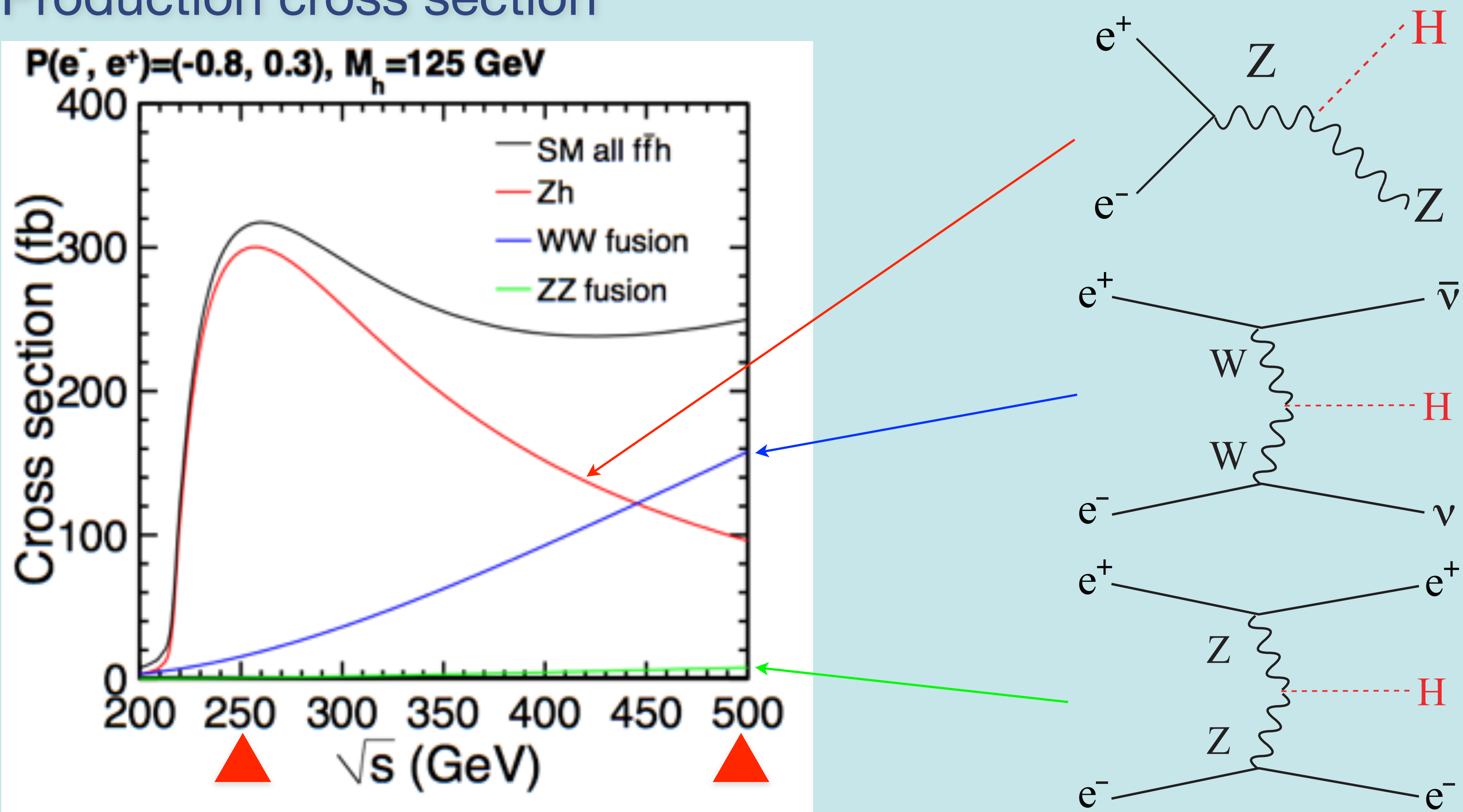




We can complete the mass-coupling plot at ~500GeV!

Main Production Processes
Single Higgs Production

Production cross section



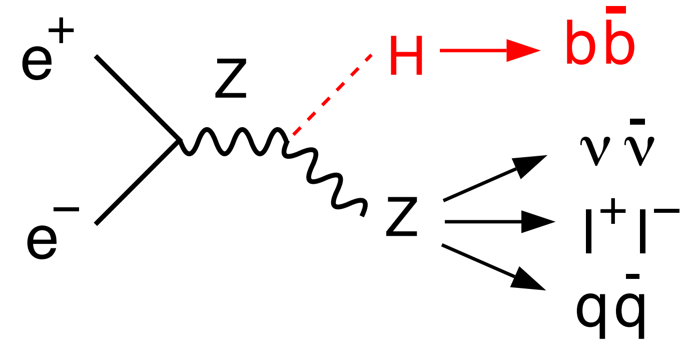
ZH dominates at 250 GeV
(~80k ev: 250 fb^{-1})

vvH takes over at 500 GeV
(~125k ev: 500 fb^{-1})

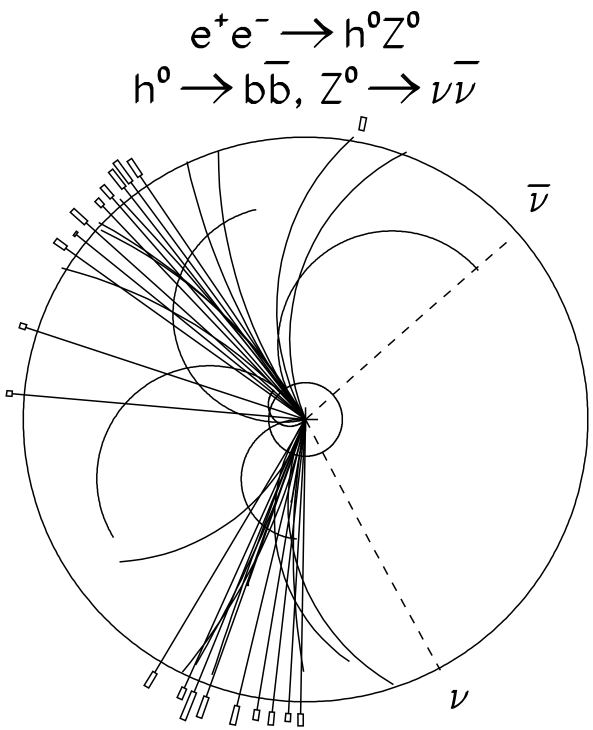
Possible to rediscover the Higgs in one day!

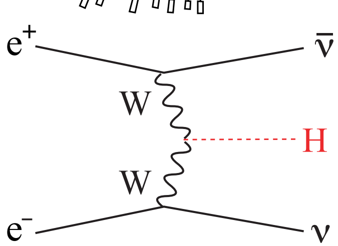
Higgs Signals

3 modes depending on how Z decays

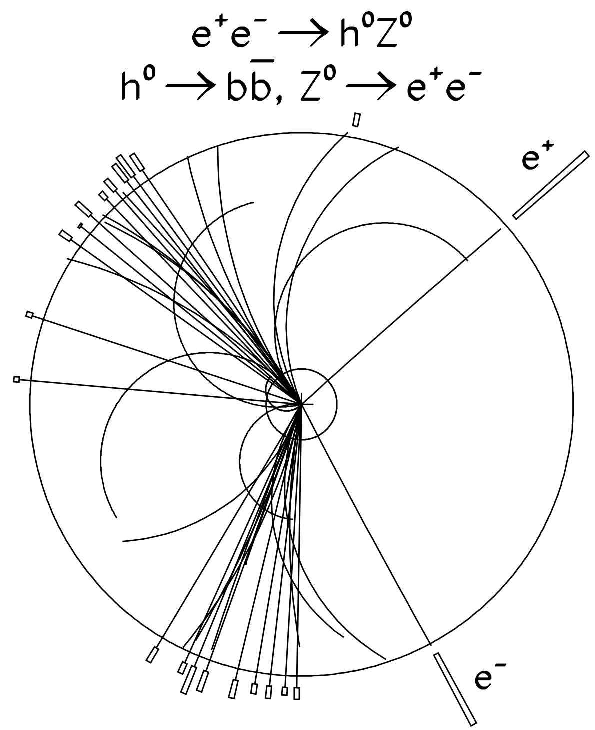


$Z \rightarrow \nu\bar{\nu}$

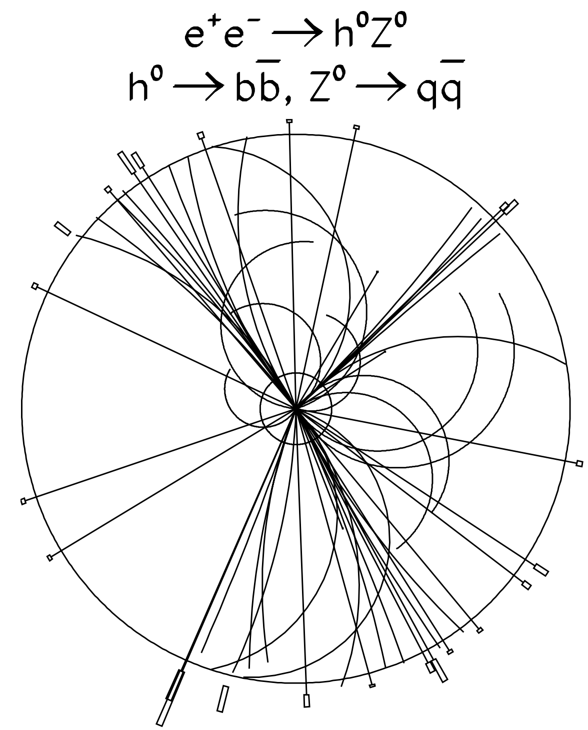




$Z \rightarrow l^+l^-$



$Z \rightarrow q\bar{q}$

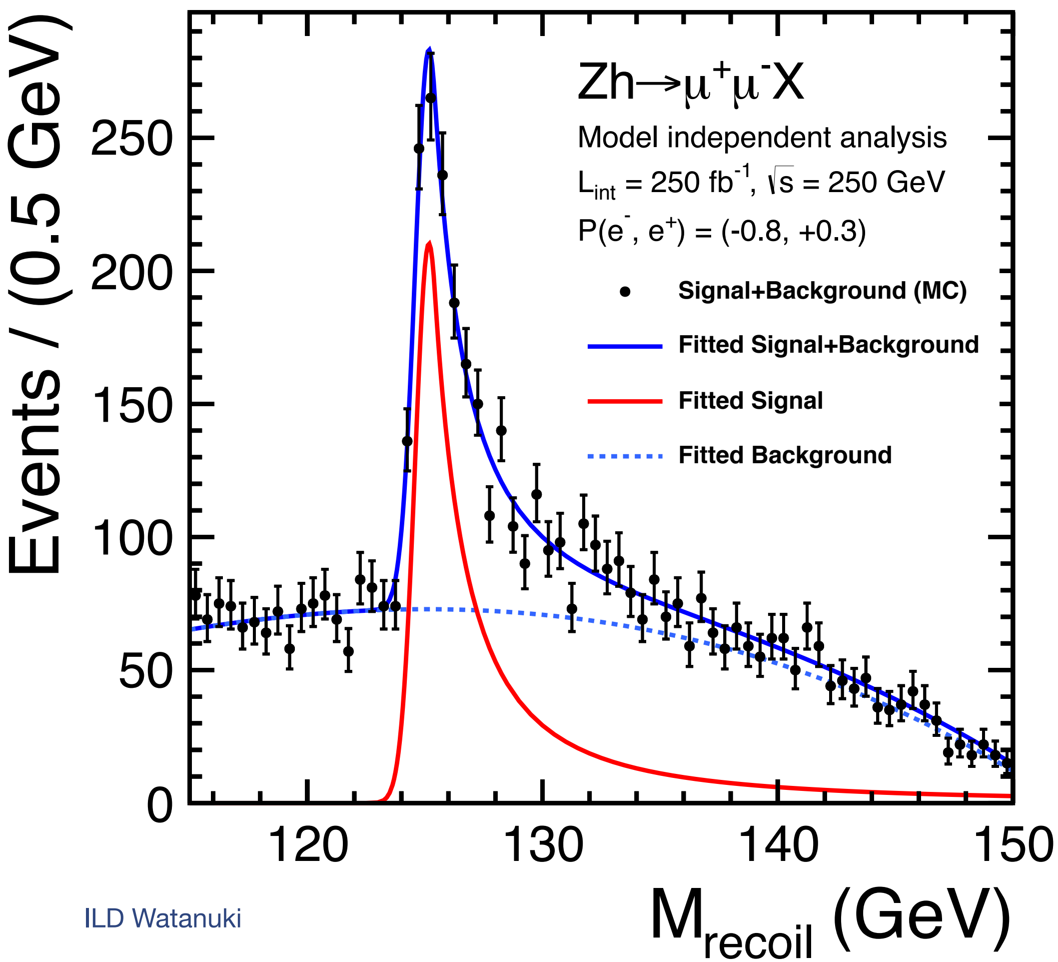


ILC 250

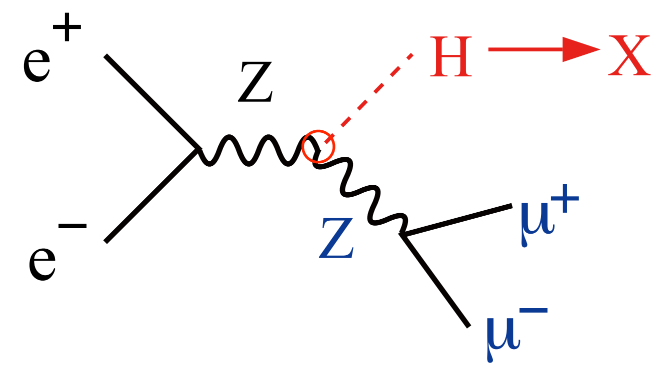
Recoil Mass Measurement

The flagship measurement of ILC 250

Recoil Mass



ILD Watanuki



$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

Invisible decay detectable!

$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$ $\quad m_H = 125\,\mathrm{GeV}$

$$\Delta\sigma_H/\sigma_H = 2.6\%$$

$$\Delta m_H = 30\,\mathrm{MeV}$$

$$BR(\text{invisible}) < 1\%\,@\,95\%\,\text{C.L.}$$

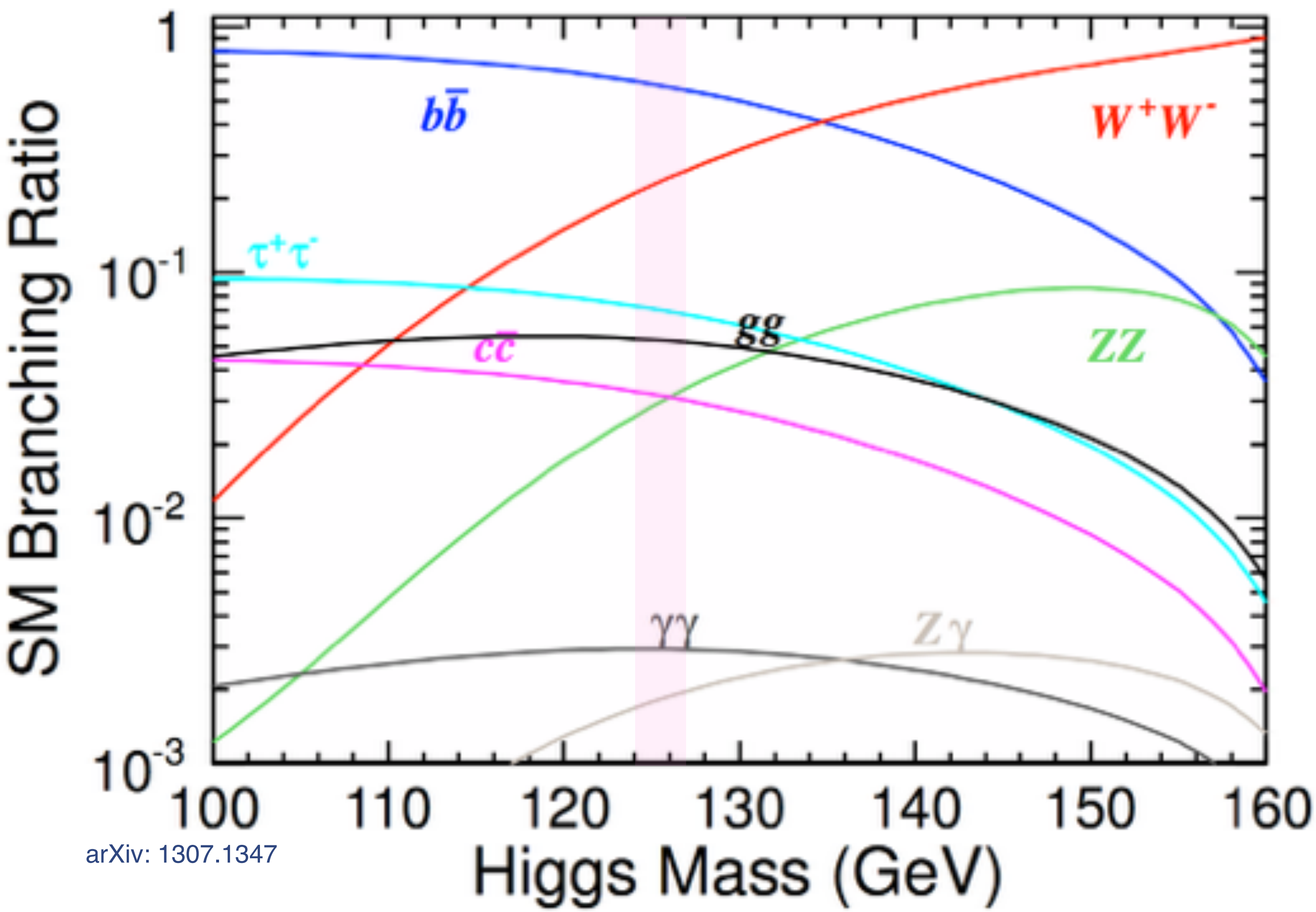
scaled from mH=120 GeV

Model-independent absolute measurement of σ_{ZH} (the HZZ coupling)

σ x BR Measurements

for b, c, g, tau, WW*, ...

DBD Physics Chap.



arXiv: 1307.1347

$$250\,\mathrm{fb}^{-1}@250\,\mathrm{GeV}$$
$$m_H = 125\,\mathrm{GeV}$$

scaled from mH=120 GeV

	@250GeV
process	ZH
Int. Lumi. [fb	250
Δσ/σ	2.6%
decay mode	ΔσBr/σBr
$H \to bb$	1.2%
$H \to cc$	8.3%
$H \to gg$	7%
$H \to WW^*$	6.4%
$H \to \tau\tau$	4.2%
$H \to ZZ^*$	18%
$H \to \gamma\gamma$	34%

preliminarily

What we measure is not BR itself but σxBR.

To extract BR from σxBR, we need σ from the recoil mass measurement.
--> Δσ/σ=2.6% eventually limits the BR measurements.
--> If we want to improve this situation, we need more data at 250GeV.
We need to seriously think about luminosity upgrade scenario.

Total Width and Coupling Extraction

One of the major advantages of the LC

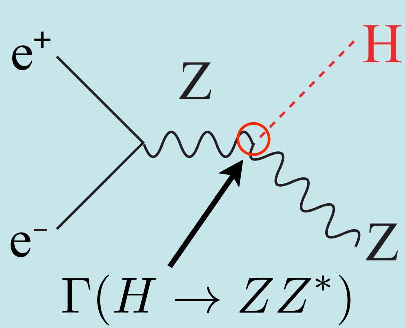
To extract couplings from BRs, we need the total width:

$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$

To determine the total width, we need at least one partial width and corresponding BR:

$$\Gamma_H = \Gamma(H \to AA)/BR(H \to AA)$$

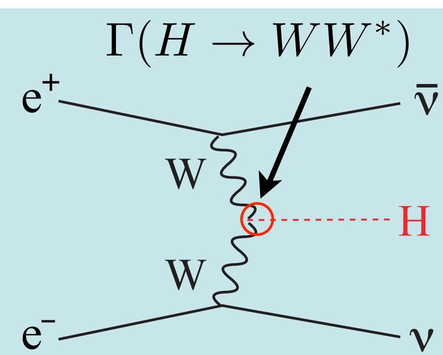
In principle, we can use A=Z, or W for which we can measure both the BRs and the couplings:



$BR(H \to ZZ^*)$

BR=O(1%): precision limited by low stat. for H->ZZ* events

$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$
$\Delta\Gamma_H/\Gamma_H \simeq 20\%$



$BR(H \to WW^*)$

More advantageous but not easy at low E

$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$
$\Delta\Gamma_H/\Gamma_H \simeq 11\%$

C.F.Durig, Helmholtz Alliance 6th WS, Dec. 2012

ILC 500

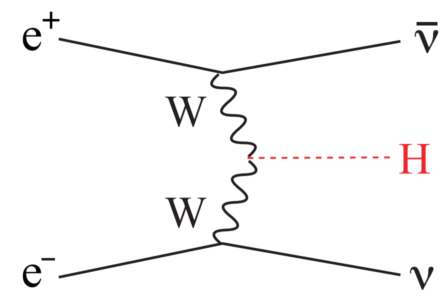
Width and BR Measurements at 500 GeV

Addition of 500GeV data to 250GeV data

E	independent measurements	relative error
250	σ_{ZH}	2.6%
	$\sigma_{ZH} \cdot Br(H \to b\bar{b})$	1.2%
	$\sigma_{ZH} \cdot Br(H \to c\bar{c})$	8.3%
	$\sigma_{ZH} \cdot Br(H \to gg)$	7%
	$\sigma_{ZH} \cdot Br(H \to WW^*)$	6.4%
	$\sigma_{ZH} \cdot Br(H \to \tau^+\tau^-)$	4.2%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to b\bar{b})$	10.5%
500	σ_{ZH}	3%
	$\sigma_{ZH} \cdot Br(H \to b\bar{b})$	1.8%
	$\sigma_{ZH} \cdot Br(H \to c\bar{c})$	13%
	$\sigma_{ZH} \cdot Br(H \to gg)$	11%
	$\sigma_{ZH} \cdot Br(H \to WW^*)$	9.2%
	$\sigma_{ZH} \cdot Br(H \to \tau^+\tau^-)$	5.4%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to b\bar{b})$	0.66%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to c\bar{c})$	6.2%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to gg)$	4.1%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to WW^*)$	2.4%

$$250\,\mathrm{fb}^{-1}@250\,\mathrm{GeV}$$
$$+500\,\mathrm{fb}^{-1}@500\,\mathrm{GeV}$$
$$m_H = 125\,\mathrm{GeV}$$

ILD DBD Full Simulation Study



comes in as a powerful tool!

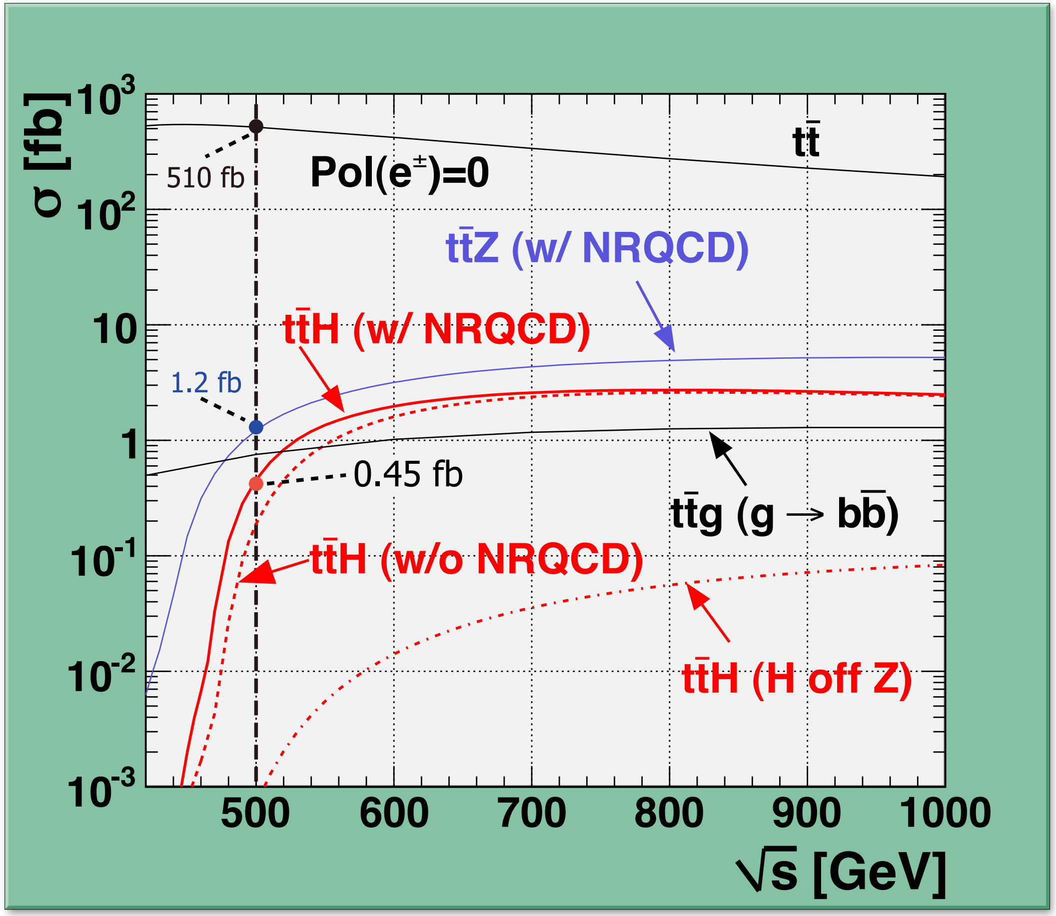
$$\Delta\Gamma_H/\Gamma_H \simeq 5\%$$

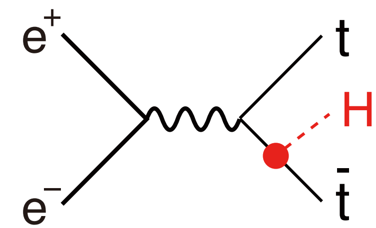
Mode	ΔBR/BR
bb	2.2 (2.9)%
cc	5.1 (8.7)%
gg	4.0 (7.5)%
WW*	3.1 (6.9)%
τ τ	3.7 (4.9)%

The numbers in the parentheses are as of $250\,\mathrm{fb}^{-1}@250\,\mathrm{GeV}$

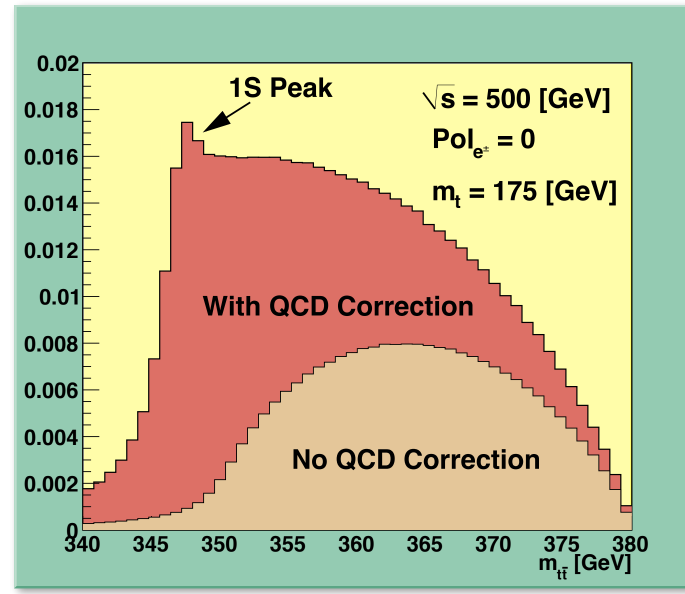
Top Yukawa Coupling

The largest among matter fermions, but not yet directly observed





H-> bb



A factor of 2 enhancement from QCD bound-state effects

Cross section maximum at around Ecm = 800GeV

Philipp Roloff, LCWS12

Tony Price, LCWS12

DBD Full Simulation

$$1\,\mathrm{ab}^{-1}@500\,\mathrm{GeV} \qquad m_H = 125\,\mathrm{GeV}$$

$$\Delta g_Y(t)/g_Y(t) = 9.9\%$$

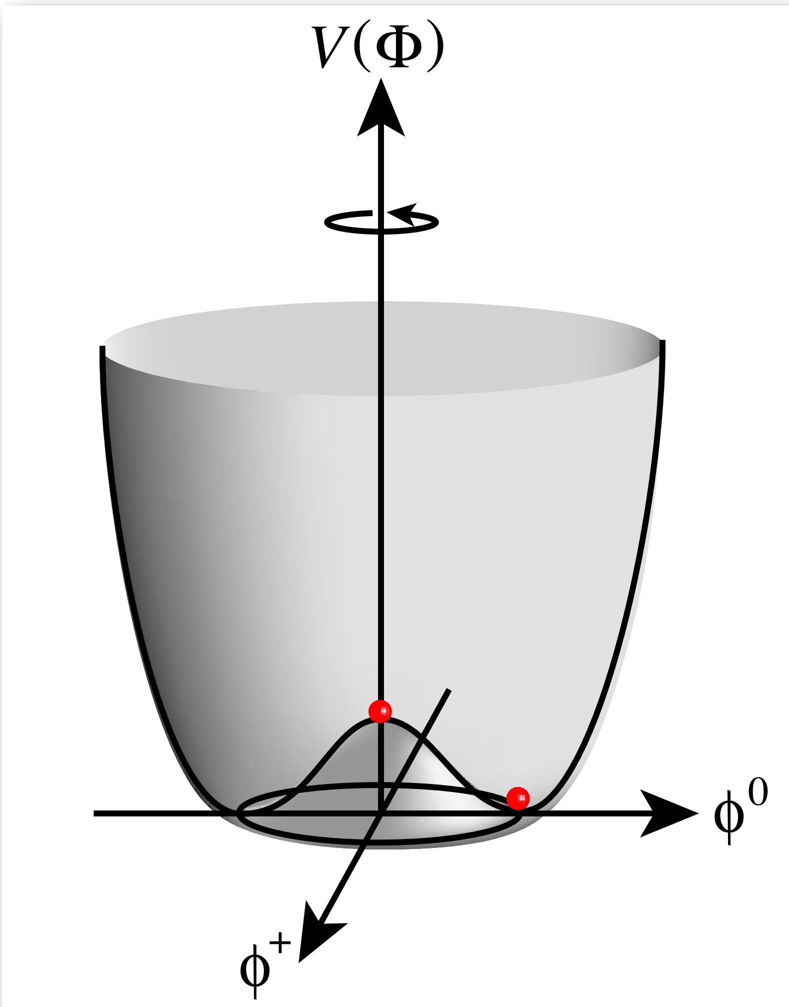
Tony Price, LCWS12

scaled from mH=120 GeV

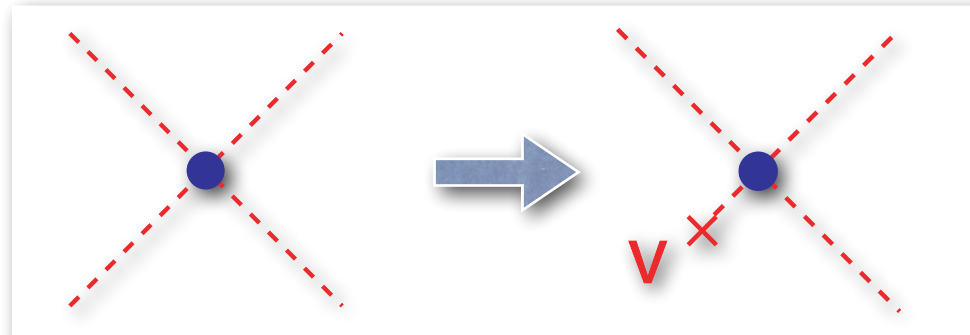
Notice σ(500+20GeV)/σ(500GeV) ~ 2
Moving up a little bit helps significantly!

Higgs Self-coupling

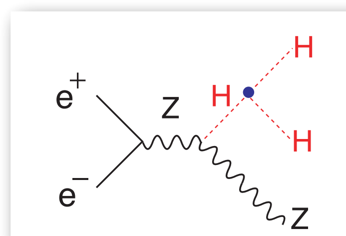
What force makes the Higgs condense in the vacuum?

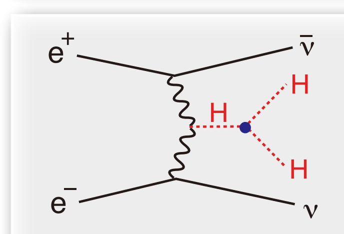


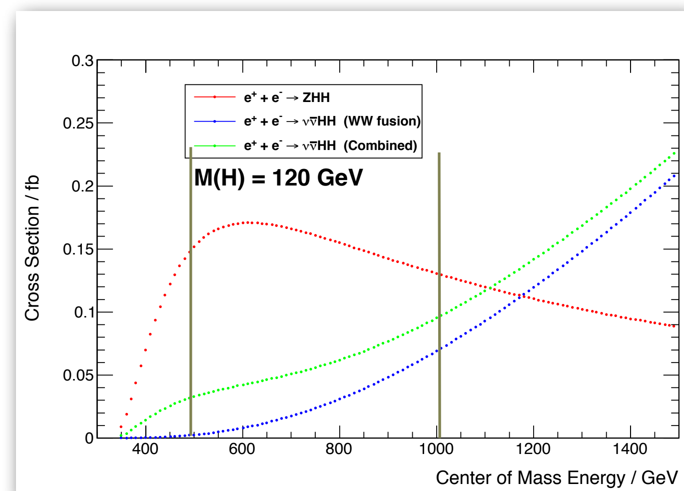
We need to measure the Higgs self-coupling



= We need to measure the shape of the Higgs potential

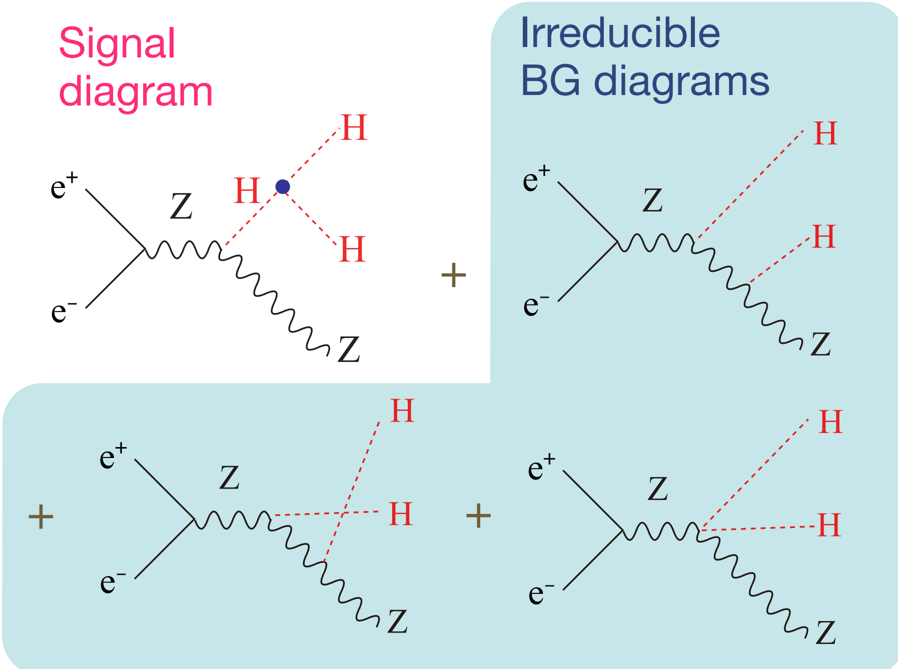






The measurement is very difficult even at ILC.

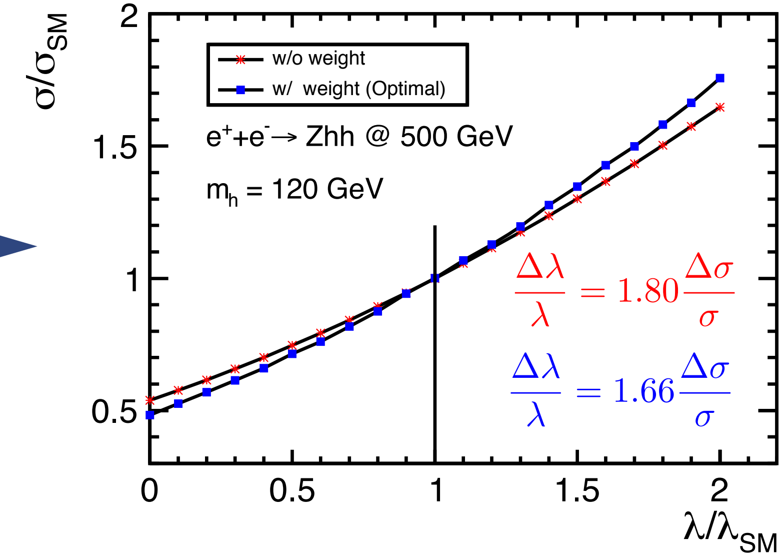
The Problem : BG diagrams dilute self-coupling contribution

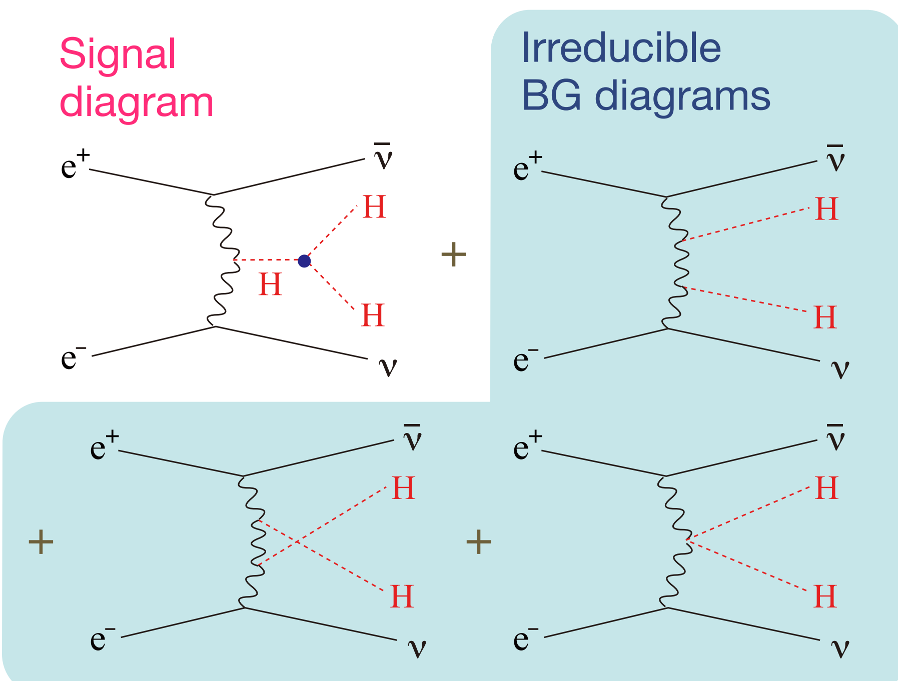


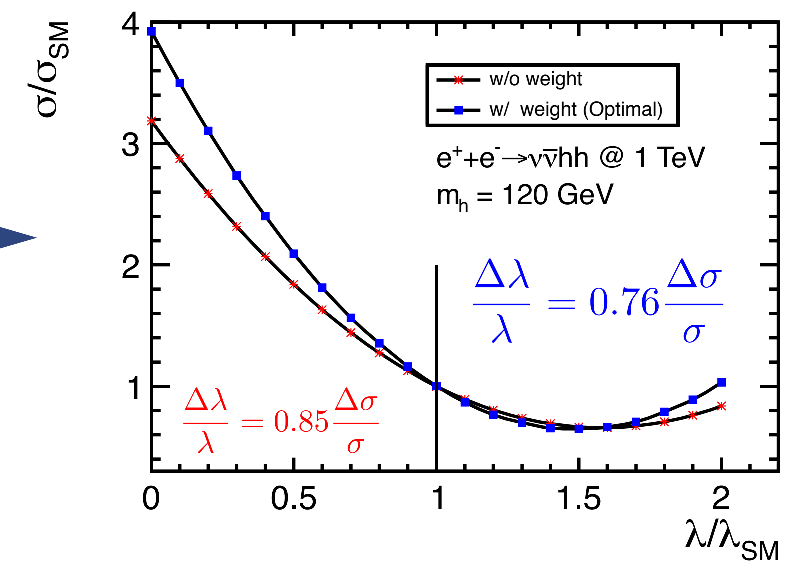
$$\sigma = \lambda^2 S + \lambda I + B$$

$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

F=0.5 if no BG diagrams







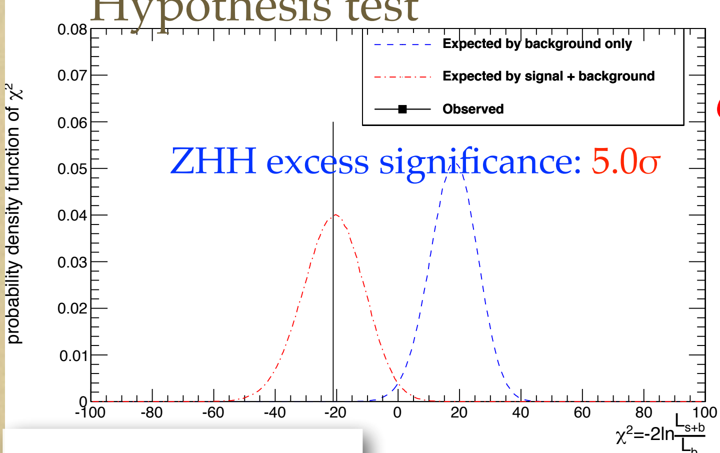
Junping Tian LC-REP-2013-003

Higgs self-coupling @ 500 GeV (combined)

P(e-,e+)=(-0.8,+0.3) $e^+ + e^- \to ZHH$ $M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

Energy (GeV)	Modes	signal	background (tt, ZZ, ZZH/ ZZZ)	significance	
				excess (I)	measurement (II)
500	$ZHH \to (l\bar{l})(b\bar{b})(b\bar{b})$	3.7	4.3	1.5σ	1.1σ
		4.5	6	1.5σ	1.2σ
500	$ZHH \to (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	8.5	7.9	2.5σ	2.1σ
500	$ZHH \to (q\bar{q})(b\bar{b})(b\bar{b})$	13.6	30.7	2.2σ	2.0σ
		18.8	90.6	1.9σ	1.8σ

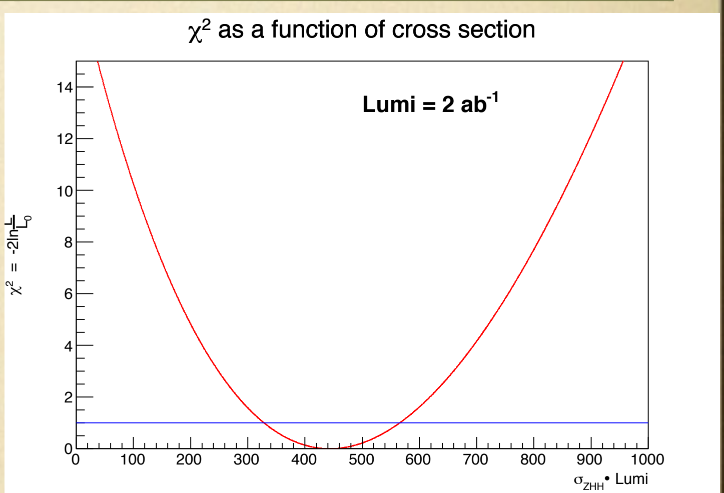
Hypothesis test

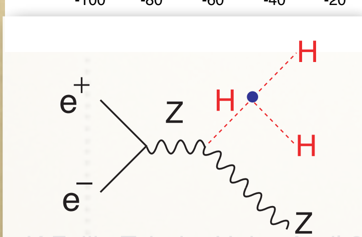


$$\sigma_{ZHH} = 0.22 \pm 0.06 \text{ fb}$$

$$\frac{\delta\sigma}{\sigma} = 27\%$$

$$\frac{\delta\lambda}{\lambda} = 44\%$$





(cf. 80% for qqbbbb at the LoI time)

ILC 1000

Higgs Physics at Higher Energy

Self-coupling with WBF, top Yukawa at xsection max., other higgses, ...

vvH @ at >1TeV：> 1ab^{-1} (pol e$^+$, e$^-$)=(+0.2,-0.8)

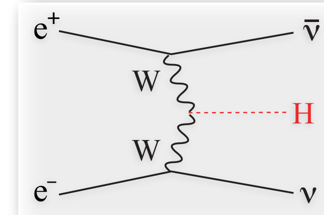
- allows us to measure rare decays such as H -> $\mu^+ \mu^-$, ...
- further improvements of coupling measurements

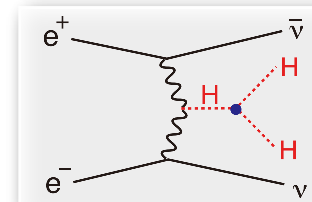
vvHH @ 1TeV or higher： 2ab^{-1} (pol e$^+$, e$^-$)=(+0.2,-0.8)

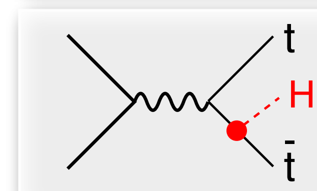
- cross section increases with Ecm, which compensates the dominance of the background diagrams at higher energies, thereby giving a better precision for the self-coupling.
- If possible, we want to see the running of the self-coupling (very very challenging).

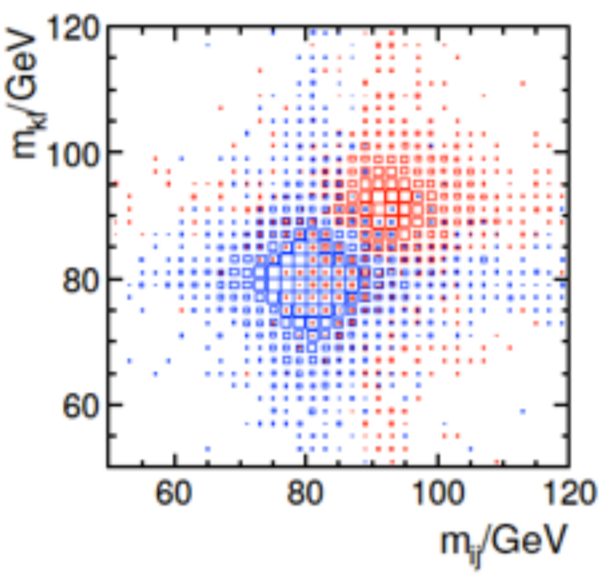
ttbarH @ 1TeV： 1ab^{-1}

- Prod. cross section becomes maximum at around 800GeV.









Obvious but most important advantage of higher energies in terms of Higgs physics is, however, its higher mass reach to other Higgs bosons expected in extended Higgs sectors and higher sensitivity to $W_L W_L$ scattering to decide whether the Higgs sector is strongly interacting or not.

In any case we can improve the mass-coupling plot by including the data at 1TeV!

Independent Higgs Measurements at ILC

Canonical ILC program

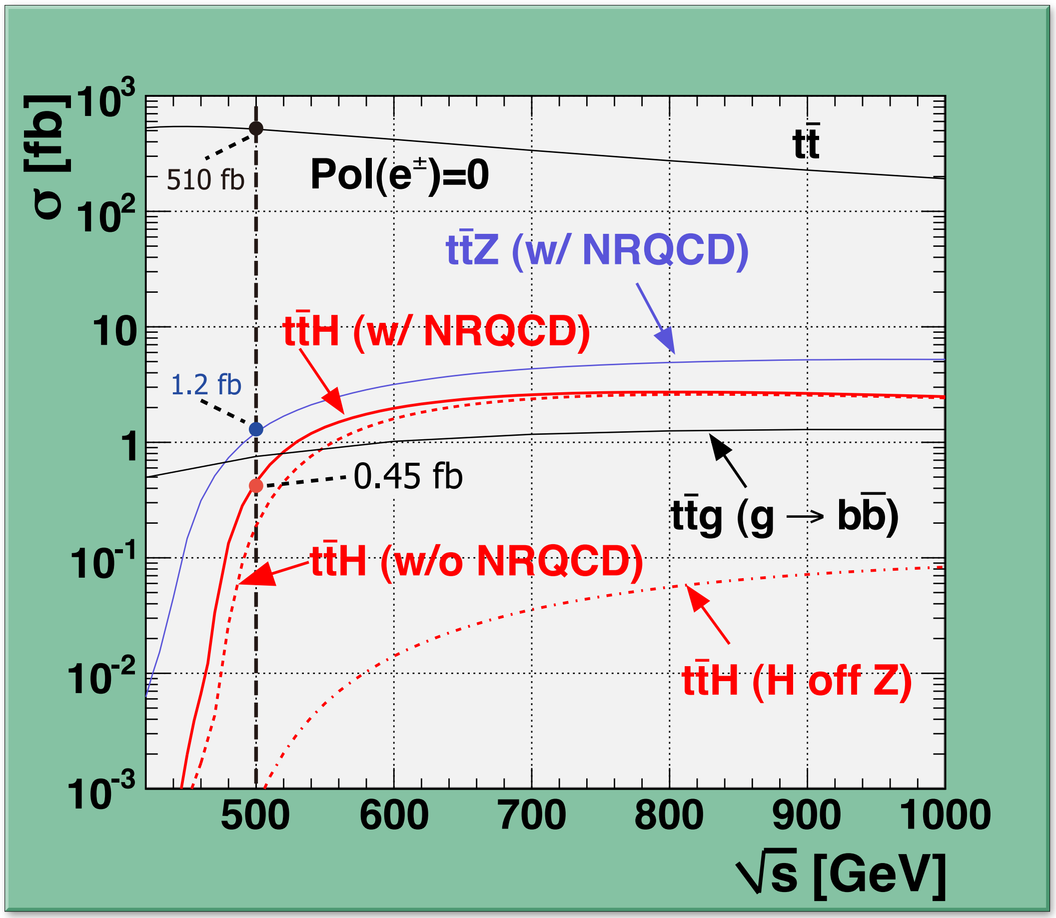
250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

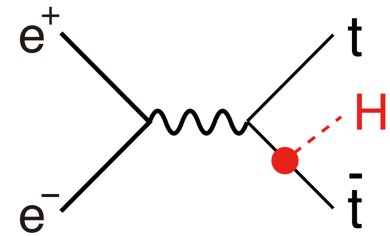
$(M_H = 125\ \mathrm{GeV})$

Ecm	250 GeV		500 GeV		1 TeV
luminosity [fb	250		500		1000
polarization (e	(-0.8, +0.3)		(-0.8, +0.3)		(-0.8, +0.2)
process	ZH	vvH(fusion)	ZH	vvH(fusion)	vvH(fusion)
cross section	2.6%	-	3%	-	
	σ·Br	σ·Br	σ·Br	σ·Br	σ·Br
H→bb	1.2%	10.5%	1.8%	0.66%	0.32%
H→cc	8.3%		13%	6.2%	3.1%
H→gg	7%		11%	4.1%	2.3%
H→WW*	6.4%		9.2%	2.4%	1.6%
H→ττ	4.2%		5.4%	9%	3.1%
H→ZZ*	18%		25%	8.2%	4.1%
H→γγ	34%		34%	19%	7.4%
H→μμ	100%	-	-	-	31%

Top Yukawa Coupling at 1TeV

The largest among matter fermions, but not yet observed





H-> bb

Similar significance in both modes

8-jet mode: 7.9σ (TMVA)

L+6-jet mode: 8.4σ (TMVA)

Tony Price & Tomohiko Tanabe: ILD DBD Study

$$1\,\mathrm{ab}^{-1}@500\,\mathrm{GeV} \qquad m_H = 125\,\mathrm{GeV}$$
$$\Delta g_Y(t)/g_Y(t) = 9.9\%$$

Tony Price, LCWS12 — scaled from mH=120 GeV

$$1\,\mathrm{ab}^{-1}@1\,\mathrm{TeV} \qquad m_H = 125\,\mathrm{GeV}$$
$$\Delta g_Y(t)/g_Y(t) = 3.1\%$$

ILD / SiD DBD Studies

Cross section maximum at around
Ecm = 800GeV

Tony Price & Tomohiko Tanabe: ILD DBD Study
Philipp Roloff & Jan Strube: SiD DBD Dtudy

DBD Full Simulation

DBD full simulation

Higgs self-coupling @ 1 TeV

P(e-,e+)=(-0.8,+0.2) $e^+ + e^- \to \nu\bar{\nu}HH$ $M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

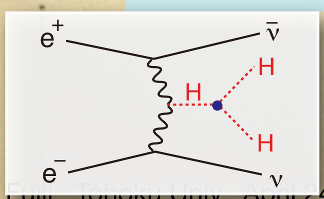
	Expected	After Cut
ννhh (WW F)	272	35.7
ννhh (ZHH)	74	3.88
BG (tt/ννZH)	7.86×10	33.7
significance	0.3	4.29

- better sensitive factor
- benefit more from beam polarization
- BG tt x-section smaller
- more boosted b-jets

$$\frac{\Delta\sigma}{\sigma} \approx 23\% \qquad \frac{\Delta\lambda}{\lambda} \approx 18\%$$

Double Higgs excess significance: > 7σ

Higgs self-coupling significance: > 5σ



ILD DBD Study (Junping Tian)

HHH Prospects

Scenario A: HH-->bbbb, full simulation done
Scenario B: by adding HH-->bbWW*, full simulation ongoing,
expect ~20% relative improvement
Scenario C: color-singlet clustering, future improvement,
expected ~20% relative improvement (conservative)

HHH	500 GeV			500 GeV + 1 TeV		
Scenario	A	B	C	A	B	C
Canonical	104%	83%	66%	26%	21%	17%
LumiUP	58%	46%	37%	16%	13%	10%

ILC 250+500+1000

Model-independent Global Fit for Couplings

33 σxBR measurements (Y_i) and σ_{ZH} ($Y_{34,35}$)

$$\chi^2 = \sum_{i=1}^{35} \left(\frac{Y_i - Y_i'}{\Delta Y_i} \right)^2$$

$$Y_i' = F_i \cdot \frac{g^2_{HA_iA_i} \cdot g^2_{HB_iB_i}}{\Gamma_0} \qquad (A_i = Z, W, t)$$

$$(i = 1, \cdots, 33) \qquad (B_i = b, c, \tau, \mu, g, \gamma, Z, W : \text{decay})$$

$$F_i = S_i \, G_i \qquad G_i = \left(\frac{\Gamma_i}{g_i^2} \right)$$

$$S_i = \left(\frac{\sigma_{ZH}}{g^2_{HZZ}} \right), \left(\frac{\sigma_{\nu\bar{\nu}H}}{g^2_{HWW}} \right), \text{ or } \left(\frac{\sigma_{t\bar{t}H}}{g^2_{Htt}} \right)$$

- The recoil mass measurement is the key to unlock the door to this completely model-independent analysis!
- Cross section calculations (S_i) do not involve QCD ISR.
- Partial width calculations (G_i) do not need quark mass as input.

We are confident that the total theory errors for S_i and G_i will be at the 0.1% level at the time of ILC running.

Model-independent Global Fit for Couplings

Baseline ILC program

250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

(M_H = 125 GeV)

P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV   P(e-,e+)=(-0.8,+0.2) @ 1 TeV

coupling	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	1.3%	1%	1%
HWW	4.8%	1.1%	1.1%
Hbb	5.3%	1.6%	1.3%
Hcc	6.8%	2.8%	1.8%
Hgg	6.4%	2.3%	1.6%
Hττ	5.7%	2.3%	1.6%
Hγγ	18%	8.4%	4%
Hμμ	91%	91%	16%
Γ	12%	4.9%	4.5%
Htt	-	14%	3.1%
HHH	-	83%(*)	21%(*)

) With H->WW (preliminary), if we include expected improvements in jet clustering it would become 17%!

Coupling Measurements

Hypothetical HL-ILC

250 GeV: 1150 fb^{-1}
500 GeV: 1600 fb^{-1}
1 TeV: 2500 fb^{-1}

(M_H = 125 GeV)

P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV   P(e-,e+)=(-0.8,+0.2) @ 1 TeV

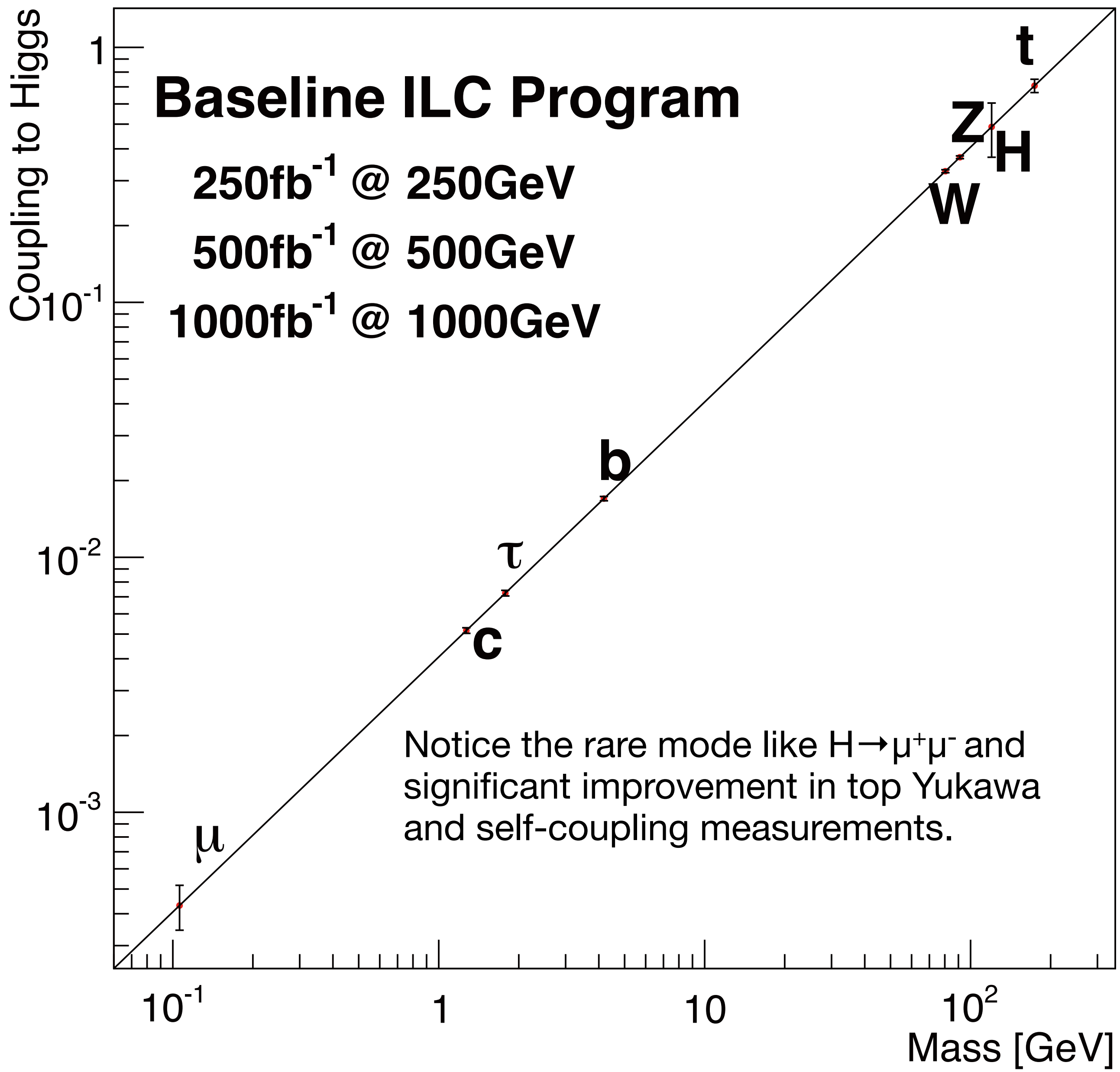
coupling	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	0.6%	0.5%	0.5%
HWW	2.3%	0.6%	0.6%
Hbb	2.5%	0.8%	0.7%
Hcc	3.2%	1.5%	1%
Hgg	3%	1.2%	0.93%
Hττ	2.7%	1.2%	0.9%
Hγγ	8.2%	4.5%	2.4%
Hμμ	42%	42%	10%
Γ	5.4%	2.5%	2.3%
Htt	-	7.8%	1.9%

HHH	-	46%(*)	13%(*)

) With H->WW (preliminary), if we include expected improvements in jet clustering, it would become 10%!

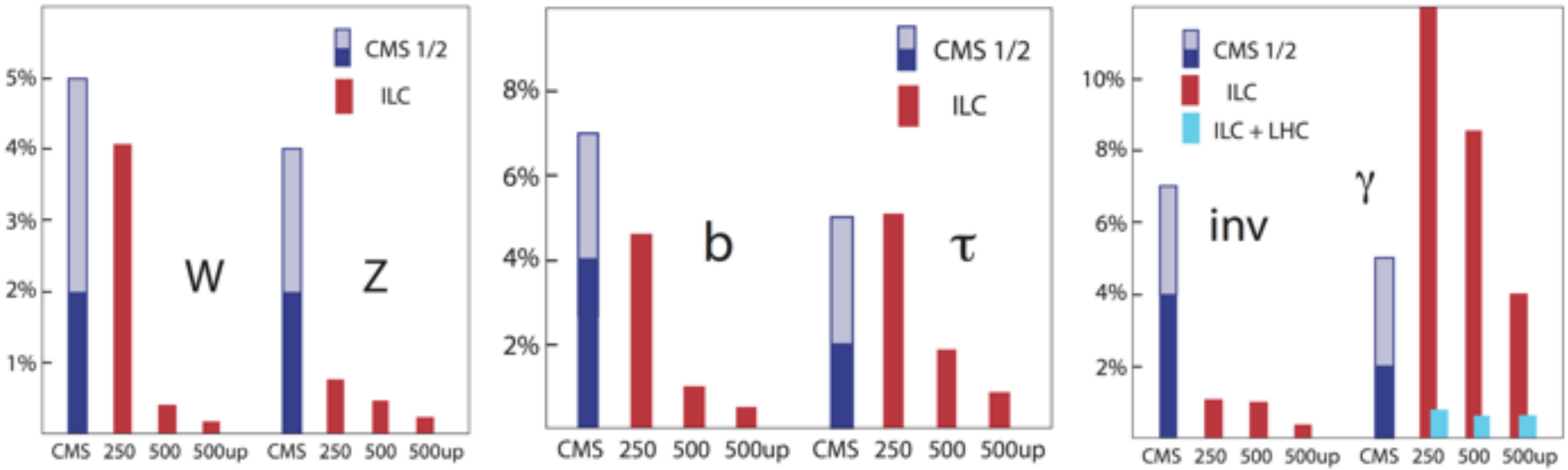
Mass Coupling Relation

After Baseline ILC Program



LHC + ILC

M. Peskin, LCWS 2013
arXiv: 1312.4974



ILC greatly improves the LHC precisions and provides the necessary precision for the fingerprinting

For rare decays such as H → γγ, there is powerful synergy of LHC and ILC!

Expected Precision and Deviation

Combined Fit with LHC data

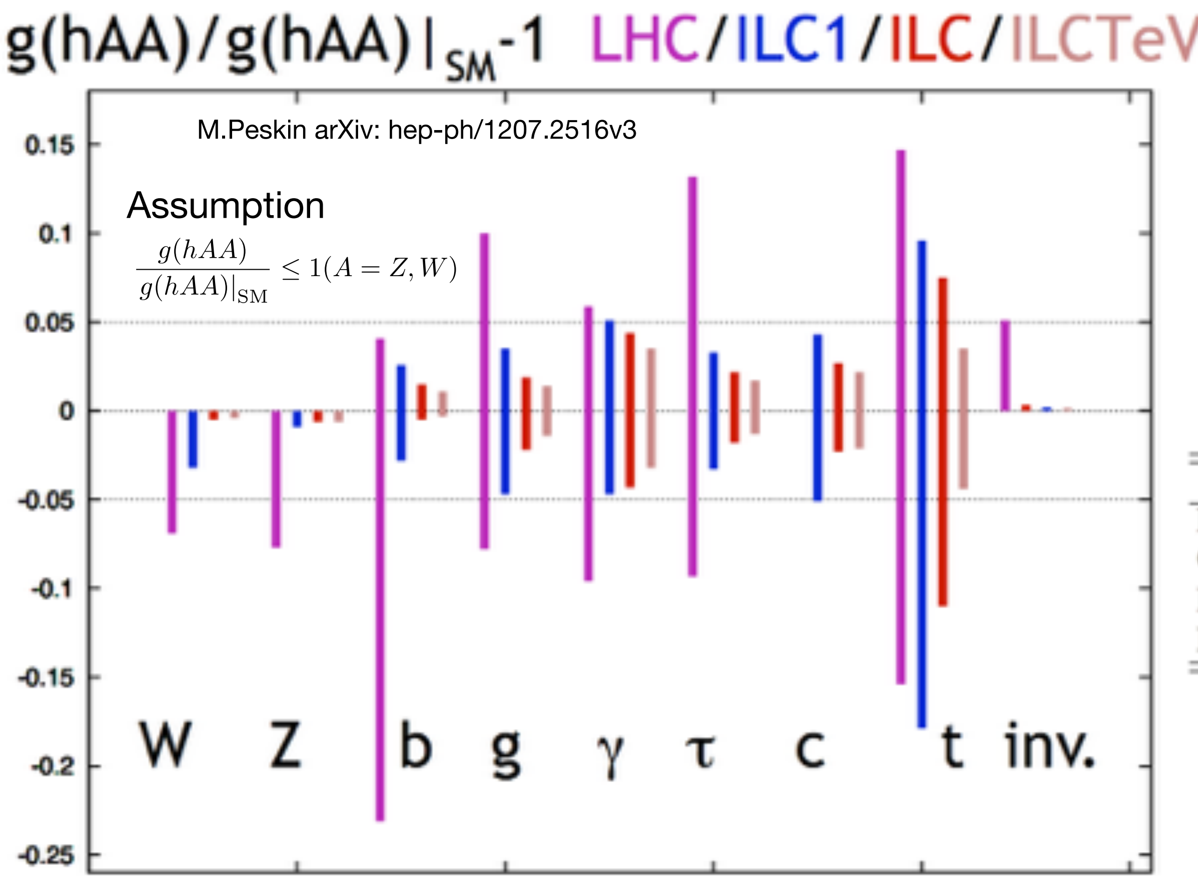


Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC program up to 500 GeV with 500 fb^{-1} ('ILC'), and for a program with 1000 fb^{-1} for an upgraded ILC at 1 TeV ('ILCTeV'). More details of the presentation are given in the caption of Fig. 1. The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

Assumed Luminosities

LHC = LHC14TeV: 300fb^{-1}

HLC = ILC250: 250fb^{-1}

ILC = ILC500: 500fb^{-1}

ILCTeV = ILC1000: 1000fb^{-1}

Maximum deviation when nothing but the 125 GeV object would be found at LHC

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	10%[a], 100%[b]
LHC 14 TeV, 3 ab^{-1}	8%	10%	15%

R.S.Gupta, H.Rzehak, J.D.Wells arXiv: 1206.3560v1

Mixing with singlet

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \frac{g_{hff}}{g_{h_{SM}ff}} = \cos\theta \simeq 1 - \frac{\delta^2}{2}$$

Composite Higgs

$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\%(1\ \mathrm{TeV}/f)^2$$

$$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \mathrm{TeV}/f)^2 & \text{(MCHM4)} \\ 1 - 9\%(1\ \mathrm{TeV}/f)^2 & \text{(MCHM5)} \end{cases}$$

SUSY

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

Fingerprinting is possible or we will get lower bounds on the BSM scale!

Model-dependent Global Fit for Couplings

7-parameter fit

Model Assumptions

$\kappa_c = \kappa_t$ and $\Gamma_{\text{tot}} = \sum_{i \in \text{SM decays}} \Gamma_i^{\text{SM}} \kappa_i^2$

$\kappa_i := g_i / g_i(\text{SM})$

Results

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.2%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.50%	0.3%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%	0.51%	0.4%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.9%

Snowmass Higgs WG Report (Draft)

Finger Printing

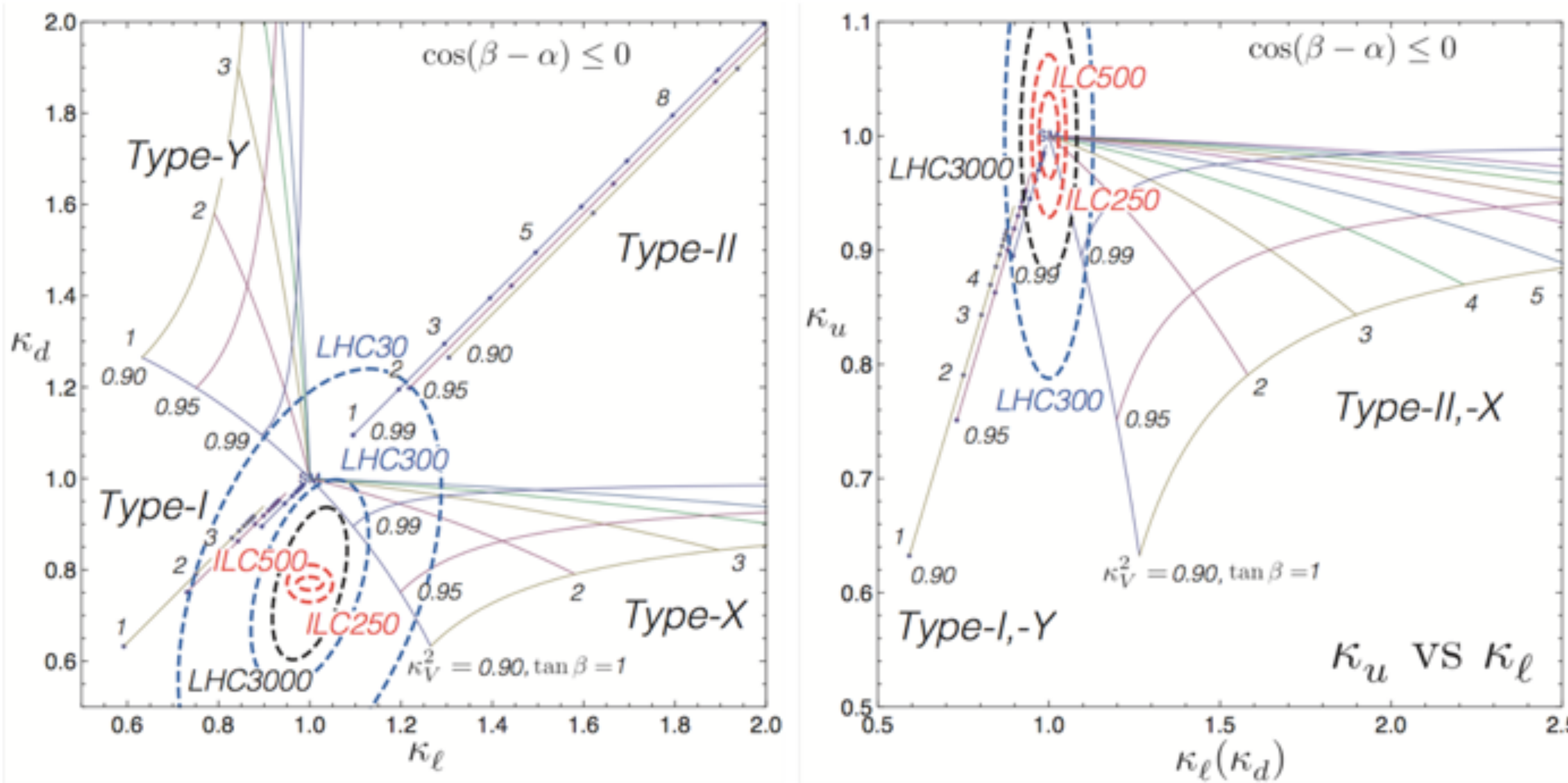


Figure 1.17. The deviation in $\kappa_f = \xi_h^f$ in the 2HDM with Type I, II, X and Y Yukawa interactions are plotted as a function of $\tan\beta = v_2/v_1$ and $\kappa_V = \sin(\beta - \alpha)$ with $\cos(\beta - \alpha) \leq 0$. For the illustration purpose only, we slightly shift lines along with $\kappa_x = \kappa_y$. The points and the dashed curves denote changes of $\tan\beta$ by one steps. The scaling factor for the Higgs-gauge-gauge coupling constants is taken to be $\kappa_V^2 = 0.99, 0.95$ and 0.90. For $\kappa_V = 1$, all the scaling factors with SM particles become unity. The current LHC constraints, expected LHC and ILC sensitivities on (left) κ_d and κ_ℓ and (right) κ_u and κ_ℓ are added.

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

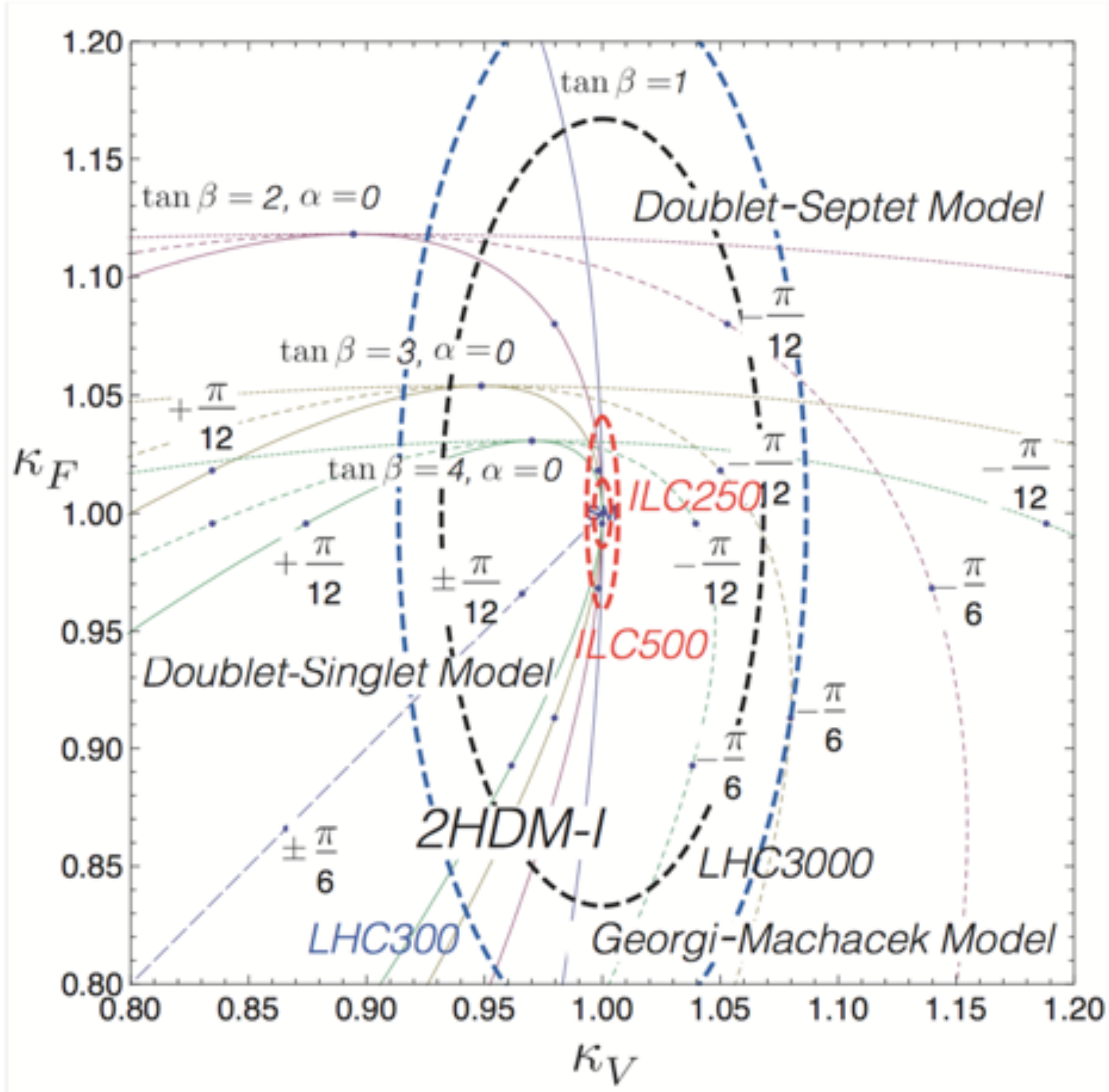
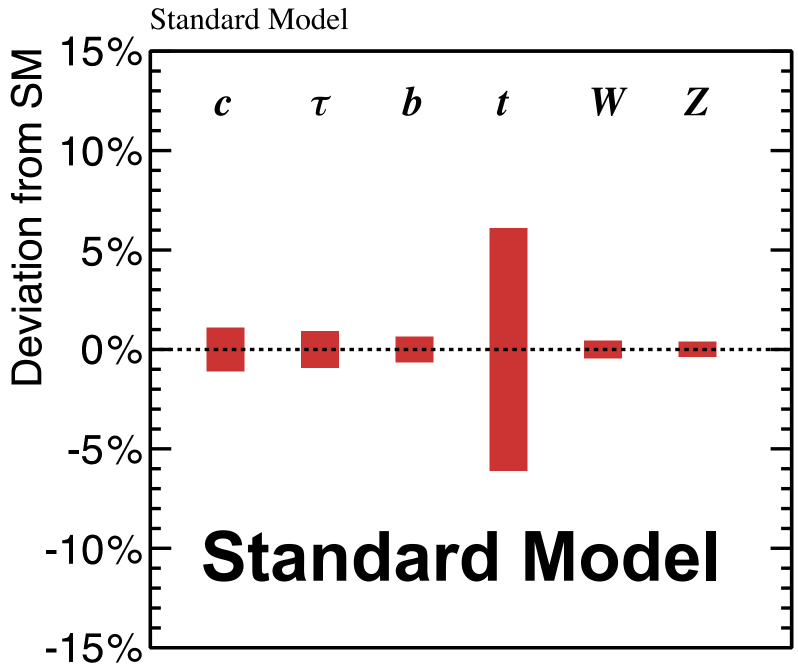


Figure 1.18. The scaling factors in models with universal Yukawa coupling constants.

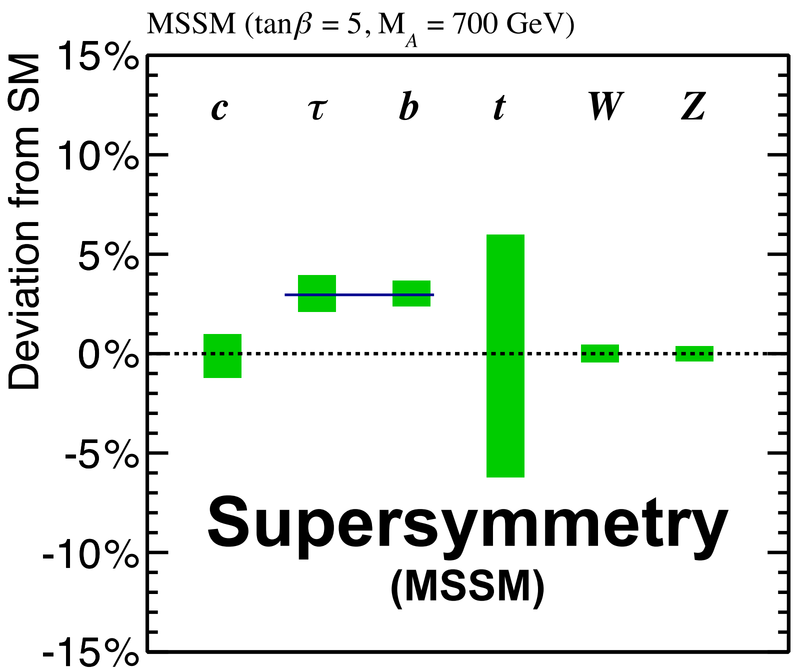
Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

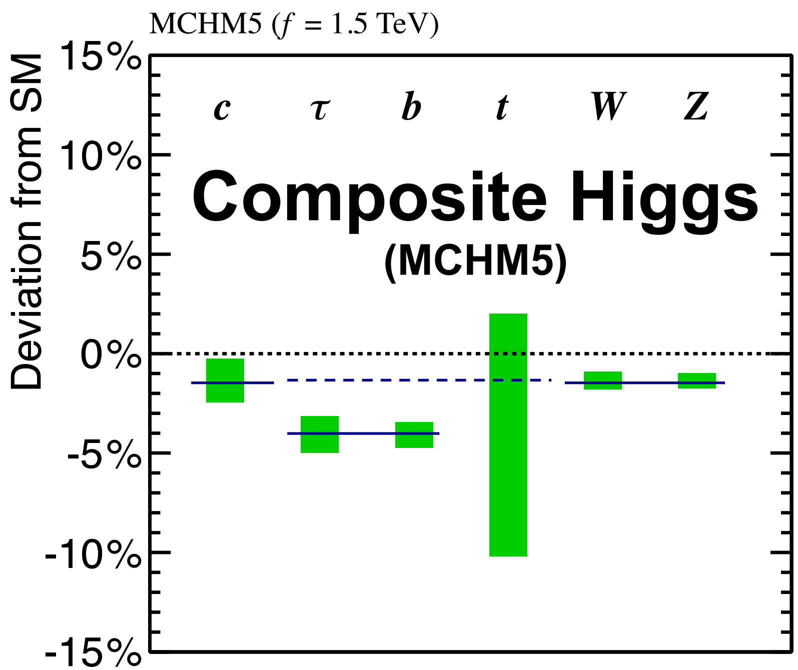
Impact of BSM on Higgs Sector

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



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



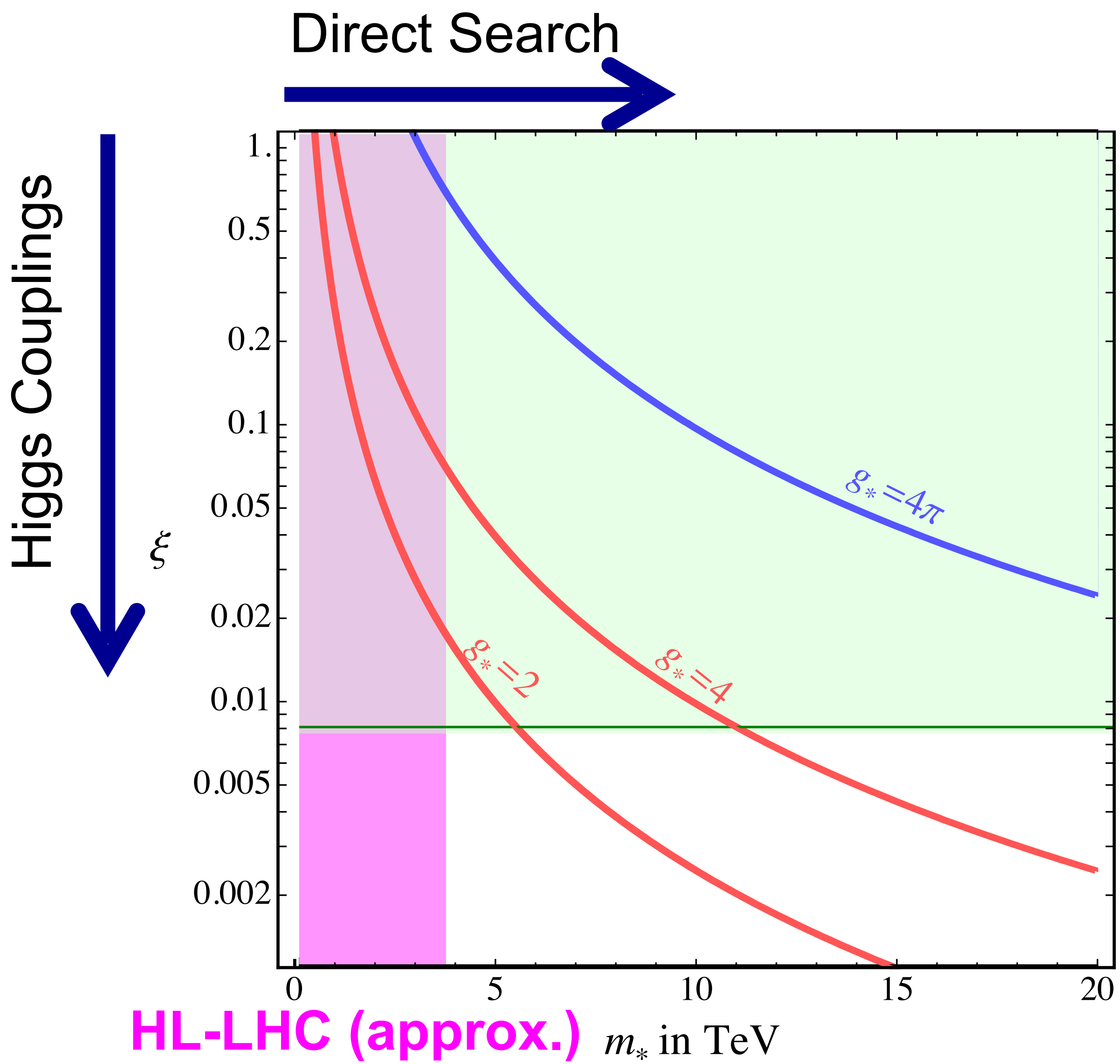


Composite Higgs: Reach

Complementary approaches to probe composite Higgs models

- Direct search for heavy resonances at the LHC
- Indirect search via Higgs couplings at the ILC

Comparison depends on the coupling strength (g_*)



$$\xi = \frac{g_*^2}{m_*^2} v^2$$

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \sqrt{1-\xi}$$

ILC

$$\frac{\Delta g_{hVV}}{g_{hVV}} = 0.4\%$$

Self-Coupling

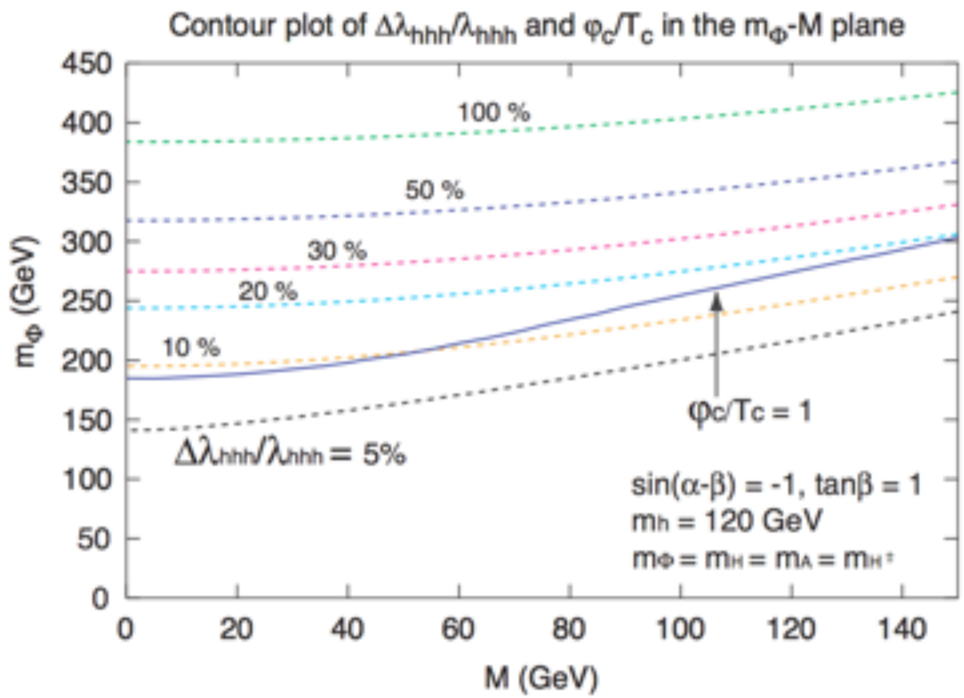
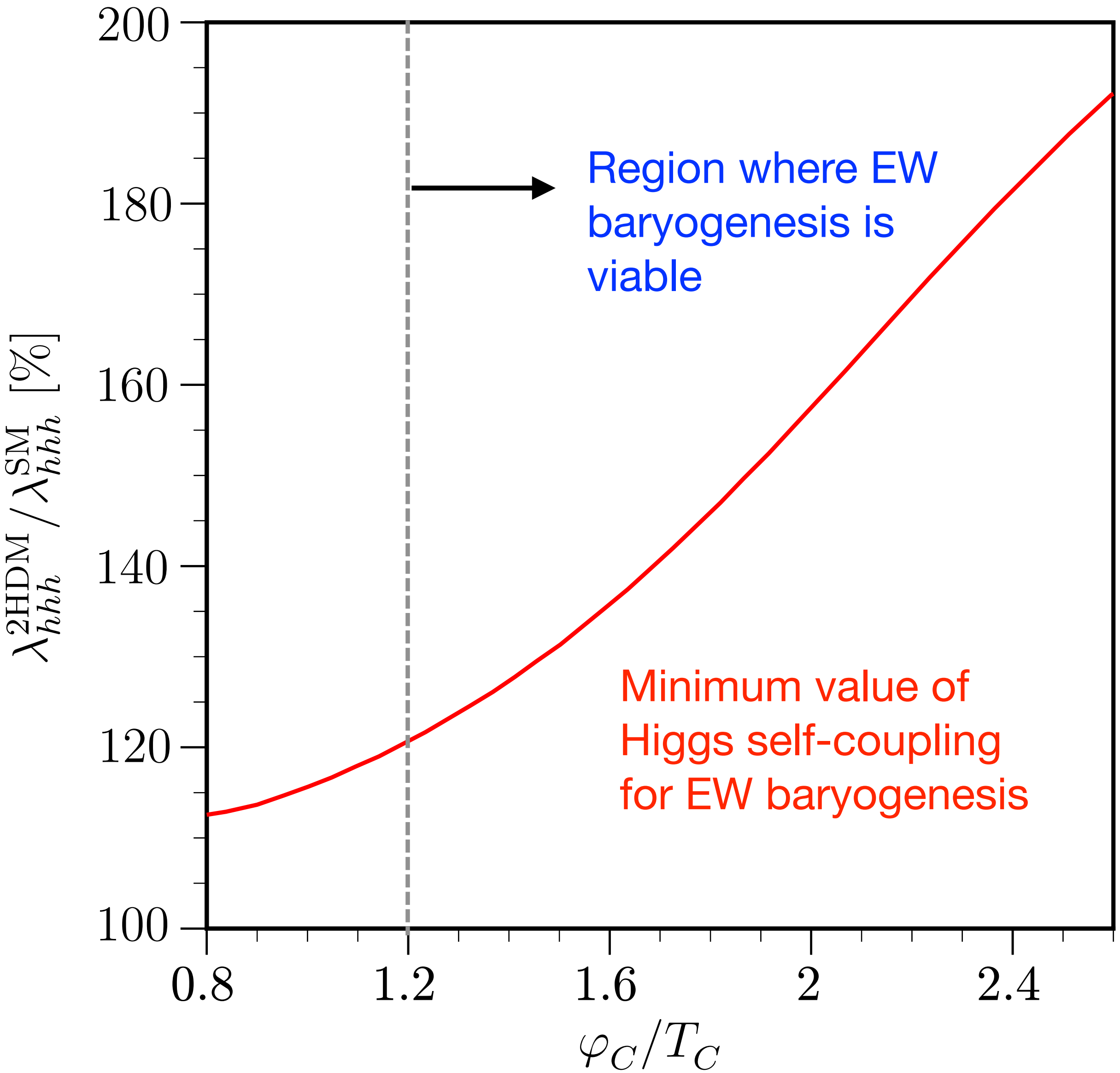


Figure 1.21. The region of strong first order phase transition ($\varphi_c/T_c > 1$) required for successful electroweak baryogenesis and the contour plot of the deviation in the triple Higgs boson coupling from the SM prediction [11], where m_Φ represents degenerated mass of H, A and $H^\pm$ and M is the soft-breaking mass of the discrete symmetry in the Higgs potential.

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

Electroweak Baryogenesis



Senaha, Kanemura

Example:
Electroweak baryogenesis in a Two Higgs Doublet Model

Large deviations in Higgs self-coupling are generally predicted in EW baryogenesis scenarios.

ILC can test the idea of baryogenesis occurring at the electroweak scale.

Conclusions

- The primary goal for the next decades is to uncover the secret of the EW symmetry breaking. This will open up a window to BSM and set the energy scale for the E-frontier machine that will follow LHC and ILC.
- Probably LHC will hit systematic limits at O(5-10%) for most of σ×Br measurements, being not enough to see the BSM effects if we are in the decoupling regime.
  Moreover, we need some model assumption to extract couplings from the LHC data.
- The recoil mass measurements at ILC unlocks the door to a fully model-independent analysis. To achieve the primary goal we hence need a 500 GeV LC for self-contained precision Higgs studies to complete the mass-coupling plot
  - starting from $e^+e^- \to ZH$ at Ecm = 250GeV,
  - then ttbar at around 350GeV,
  - and then ZHH and ttbarH at 500GeV.
- The ILC to cover up to 500 GeV is an ideal machine to carry out this mission (regardless of BSM scenarios) and we can do this ***completely model-independently*** with staging starting from 250GeV. We may need more data depending on the size of the deviation. Lumi-upgrade possibility should be always kept in our scope.
- If we are lucky, some extra Higgs boson or some other new particle might be within reach already at ILC 500. Let's hope that the upgraded LHC will make another great discovery in the next run.
- If not, we will most probably need the energy scale information from the precision Higgs studies. Guided by the energy scale information, we will go hunt direct BSM signals with a new machine, if necessary.

Last but Not Least

- In this talk I have been focusing on the case where X(125GeV) alone would be the probe for BSM physics, but there is a good chance for the higher energy run of LHC to bring us more.

- It is also very important to stress that ILC, too, is an energy frontier machine. It will access the energy region never explored with any lepton collider. There can be a zoo of new uncolored particles or new phenomena that are difficult to find at LHC but can be discovered and studied in detail at ILC.

- For instance

  - Natural SUSY : naturalness prefers μ not far above 100GeV

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

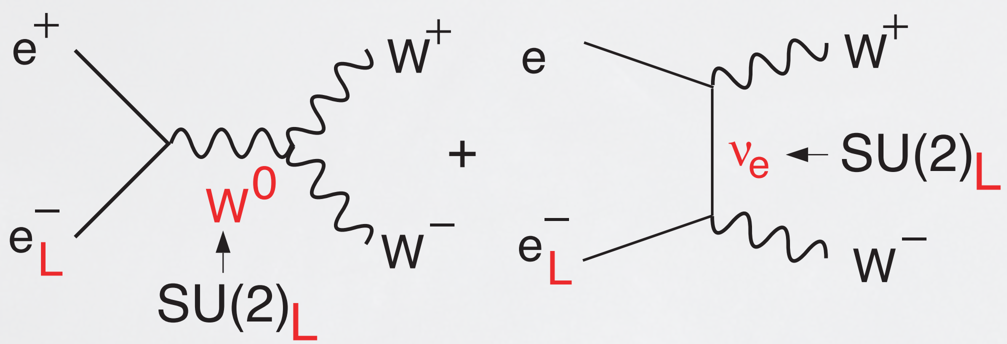
    --> light chargino/neutralinos will be higgsino-dominant and nearly degenerate
    --> typically Δm of a few GeV or less (very difficult for LHC)
    --> Δm as small as 50MeV possible with ISR tagging at ILC
    --> If Δm=800MeV --> possible to measure m to 1.5GeV and Δm to 20MeV
    --> ILC will also be a Higgsino factory!

  - Possible anomalies in precision studies of properties of top, W/Z, and two-fermion processes

SUSY

Power of Beam Polarization

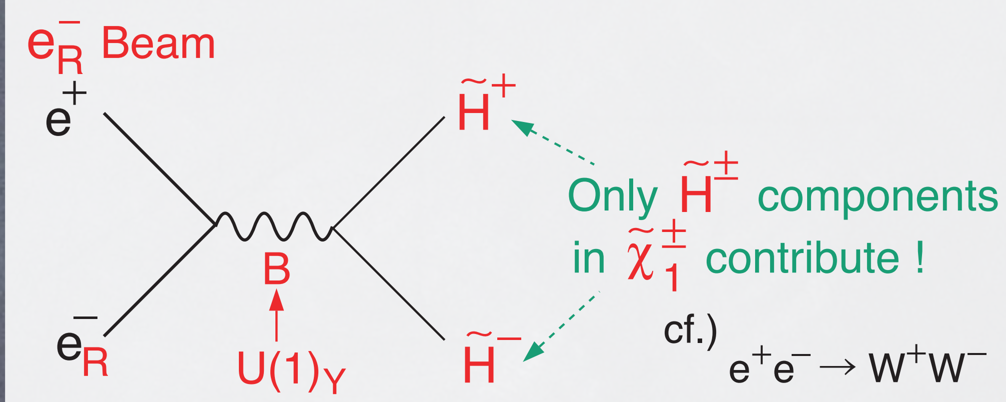
W^+W^- (Largest SM BG)



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

BG Suppression

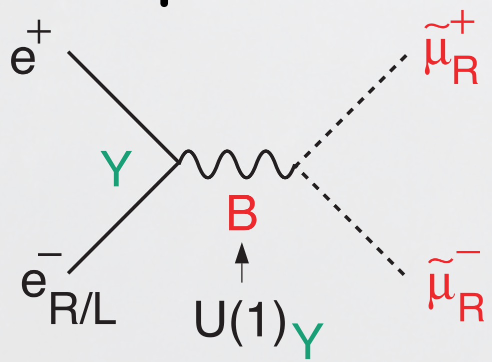
Chargino Pair



$$\tilde{\chi}^{\pm}_1 = \bigcirc \cdot \tilde{W}^{\pm} + \bullet \cdot \tilde{H}^{\pm}, \quad \bullet = \langle \tilde{H}^{\pm} | \tilde{\chi}^{\pm}_1 \rangle$$

Decomposition

Slepton Pair



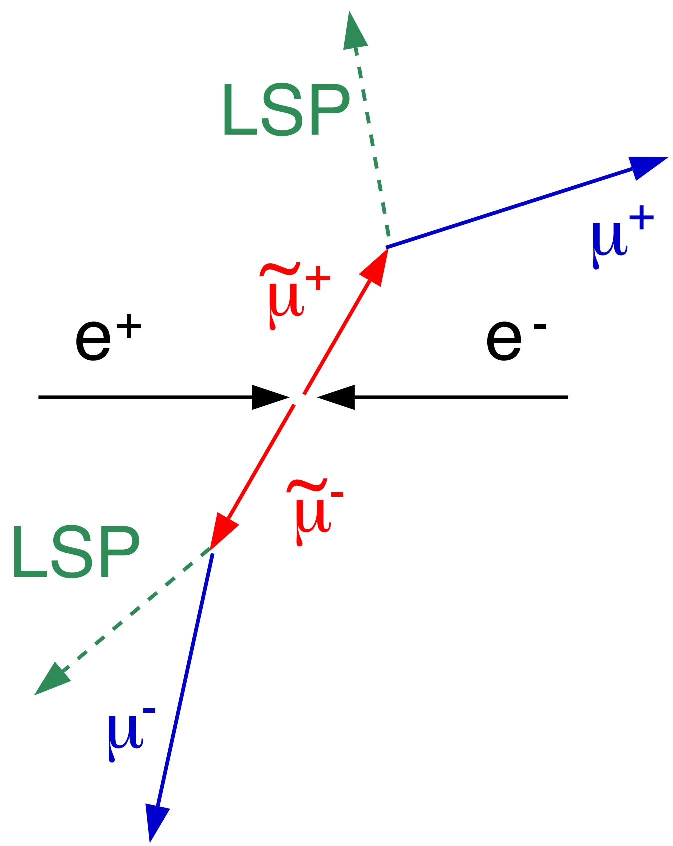
$$\begin{cases} Y_L = -1/2 : e^-_L \\ Y_R = -1 \quad : e^-_R \end{cases}$$

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

Signal Enhancement

SUSY Signals

e.g.) Smuon pair production



LSP (Lightest SUSY Particle)

Stable

Invisible, since it interacts only very weakly with material

↓

Missing transverse momentum

↓

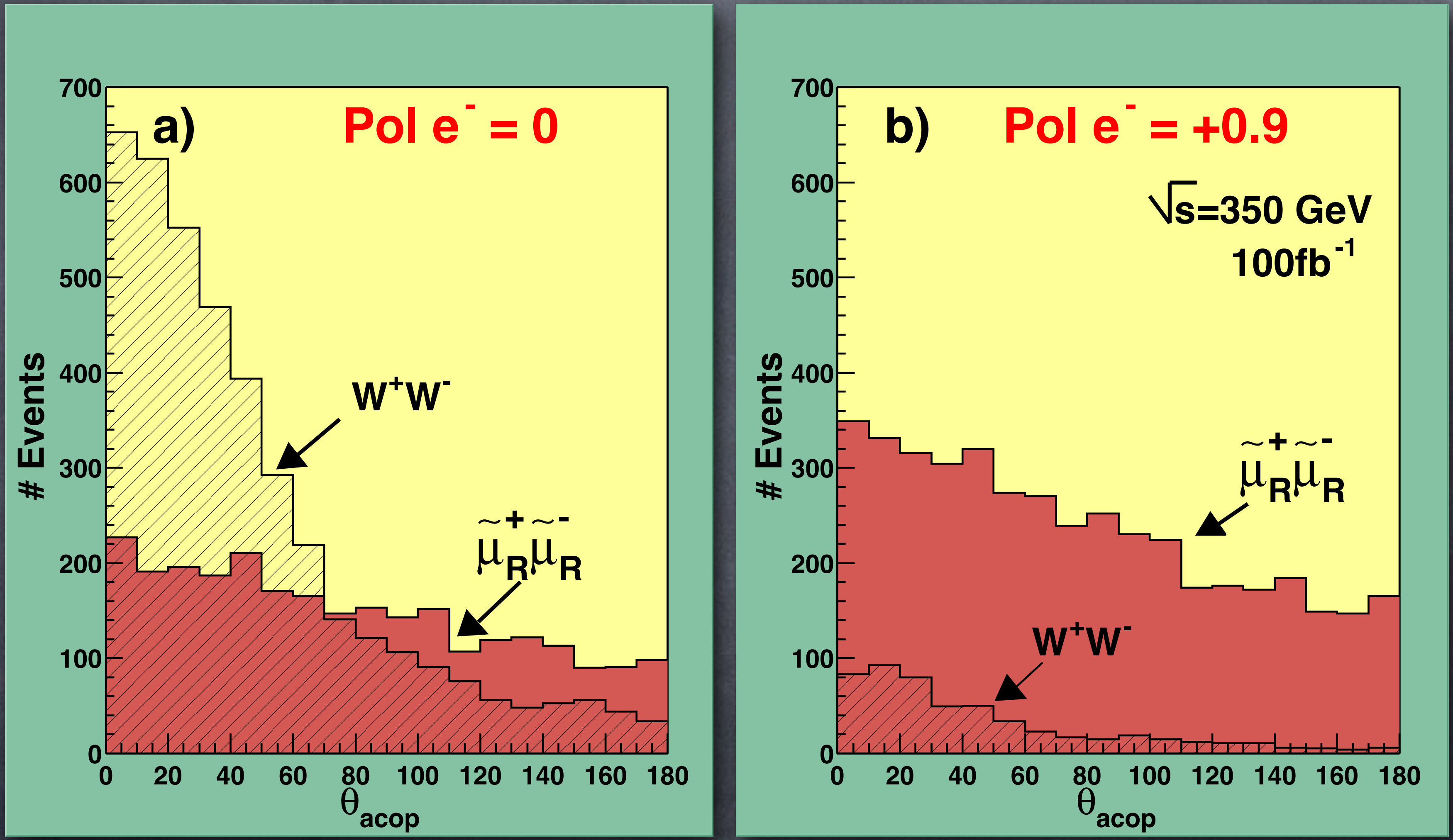
Non-back-to-back muon pairs

Quantity useful for events with missing Pt (Acoplanarity)

θ_{acop} = π - (opening angle of the muon pairs projected to the plane perpendicular to beam axis)

Slepton Studies

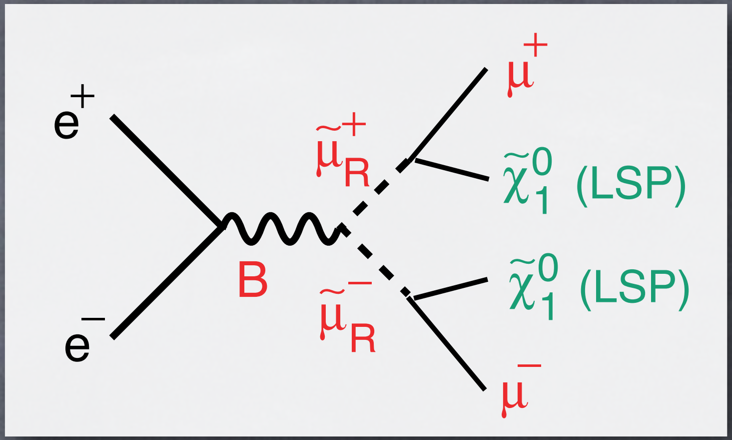
Signal=acoplanar lepton pairs

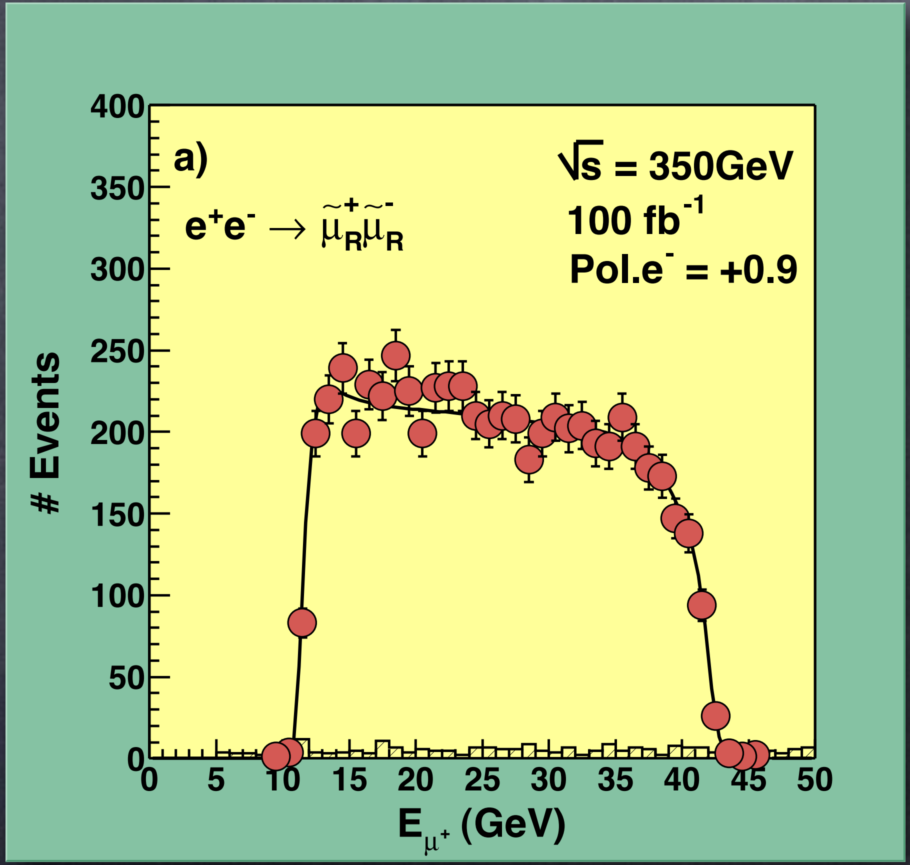


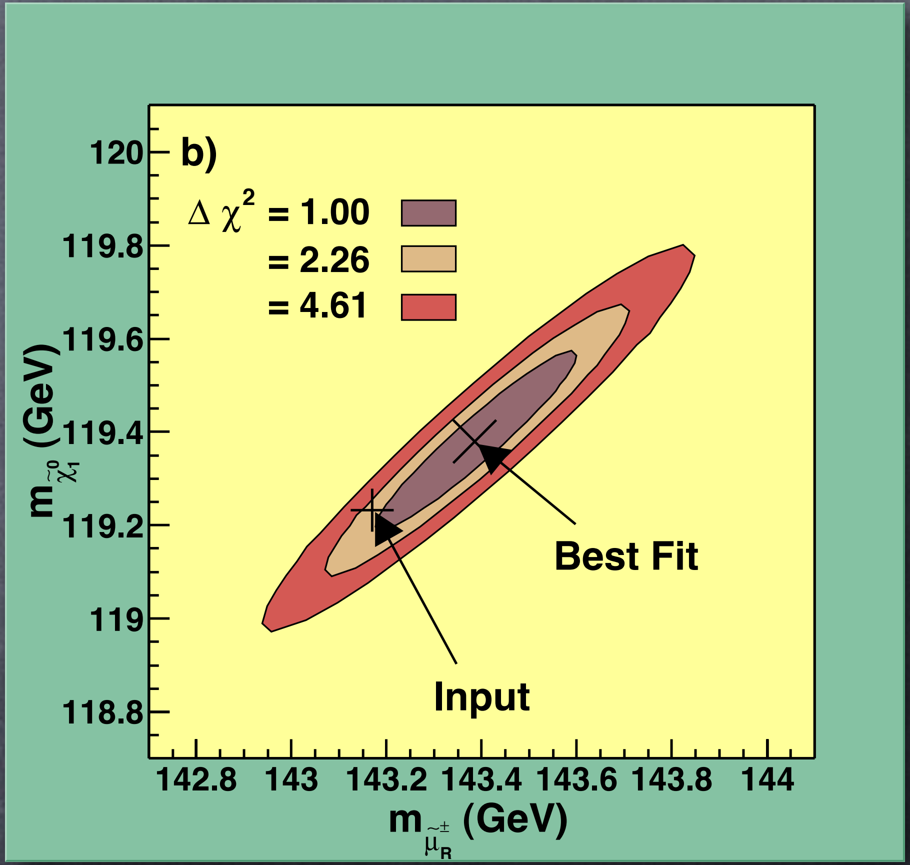
Thanks to beam polarization, we can get very clean sample

Mass Measurement

Endpoint measurements







O(0.1%) measurement is possible!

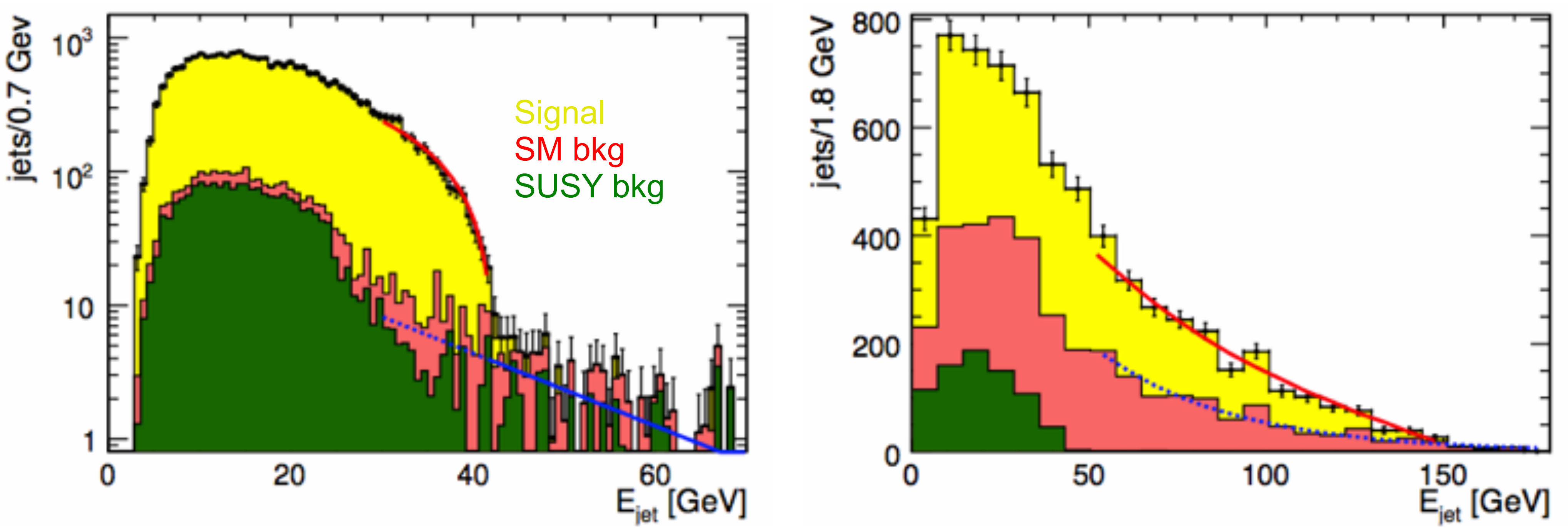
Slepton decays to DM with small mass differences

Study of stau pair production at the ILC

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

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

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



Stau1 mass resolution ~0.1%

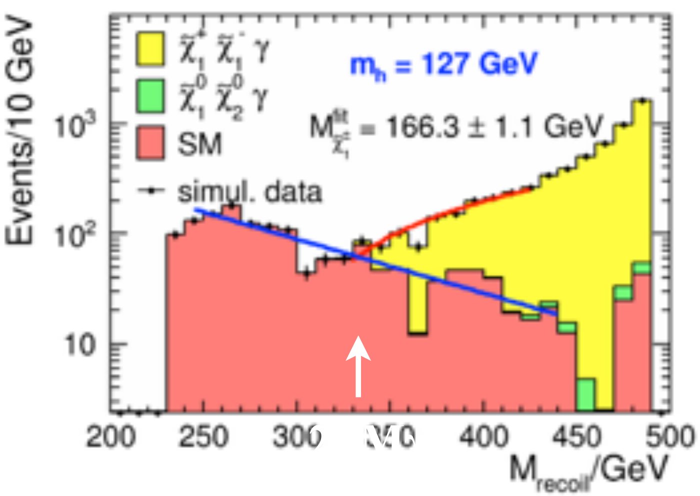
Stau2 mass resolution ~3%

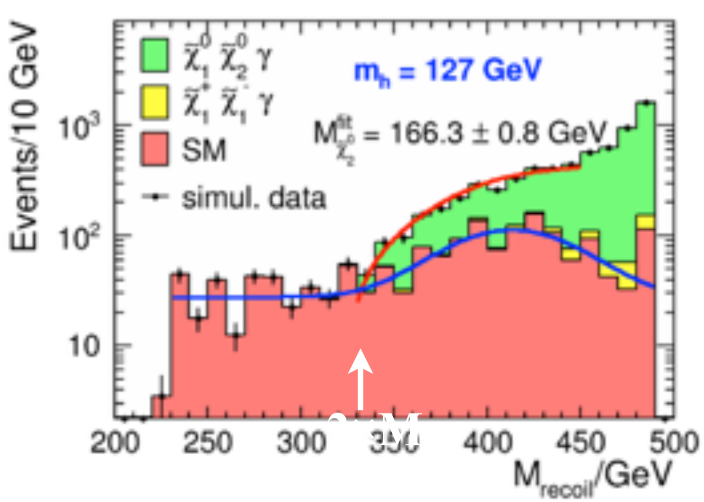
→ LSP mass resolution ~1.7%

Higgsinos in Natural SUSY (ΔM<a few GeV)

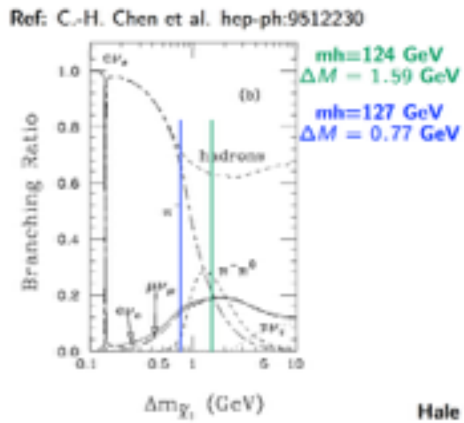
Hale Sert
ECFA LCWS 2013, DESY

$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$$
$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0\gamma$$





ISR Tagging



Only very soft particles in the final states → Require a hard ISR to kill huge two-photon BG!

Conclusion

Hale Sert

- Light Higgsinos are well motivated by naturalness
- It is a challenging scenario for LHC
- Separation of Higgsinos at the reconstructed level is possible at the ILC
- Assumed
  - $\sqrt{s} = 500$ GeV
  - $\int \mathcal{L}dt = 500\ fb^{-1}$ with $P(e^+,e^-) = (+30\%, -80\%)$ and $P(e^+,e^-) = (-30\%, +80\%)$ each
- Statistical uncertainities for $P(e^+,e^-) = (+30\%, -80\%)$

m_h=124 GeV

- $\delta(\sigma \times BR) \approx 3\ \%$ $\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_2^0}) \approx 2.1(3.7)$ GeV $\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 70$ MeV

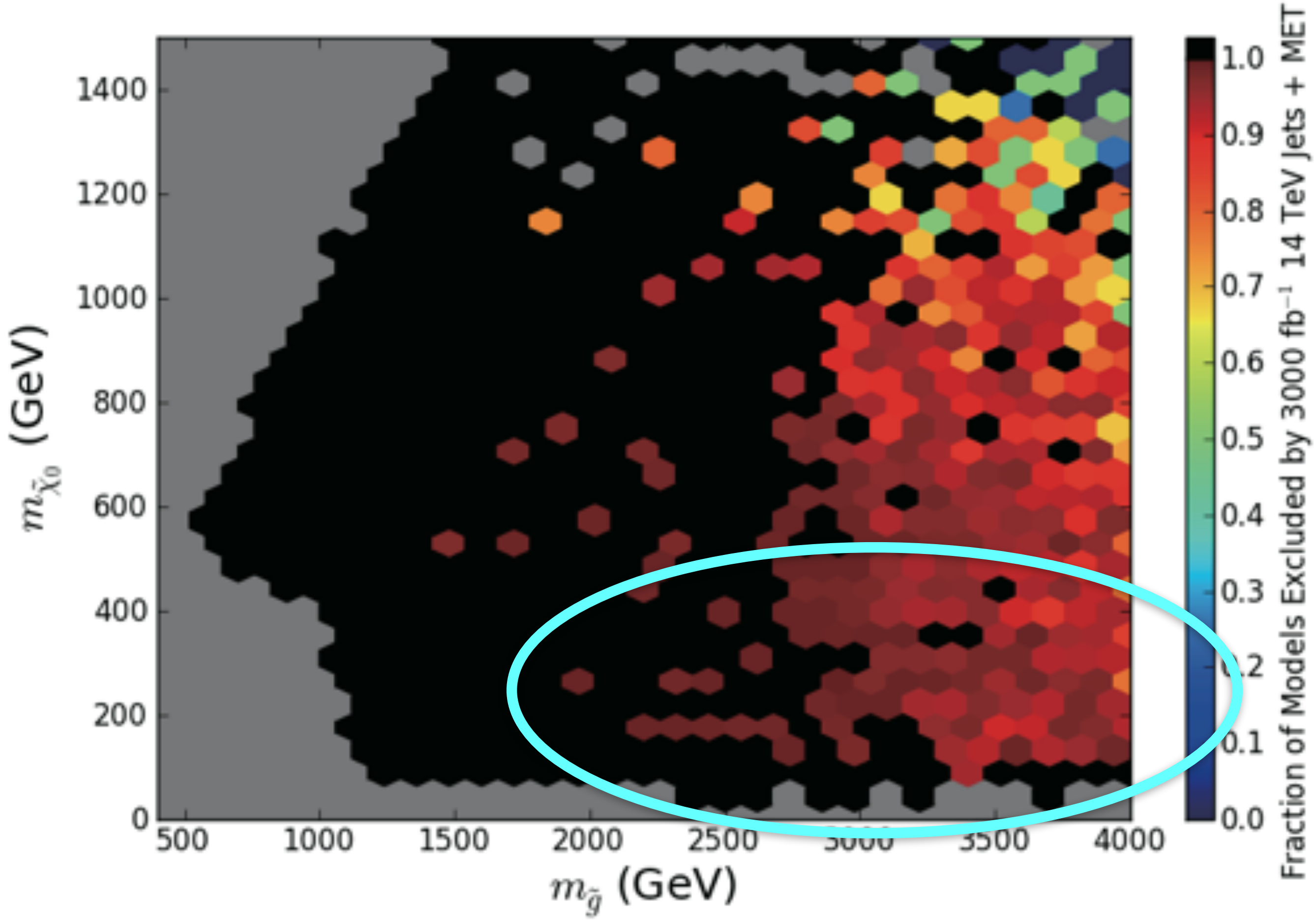
m_h=127 GeV

- $\delta(\sigma \times BR) \approx 1.5\ \%$ $\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_2^0}) \approx 1.5(1.6)$ GeV $\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 20$ MeV

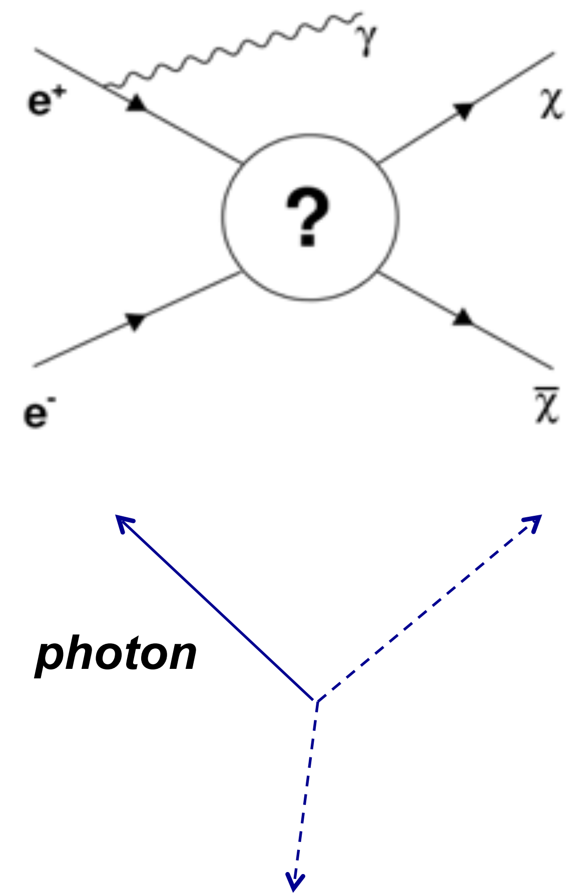
Dark Matter Production

LHC 14 TeV, 3000 fb-1, Jets+MET analysis only
pMSSM Neutralino DM expected exclusion

Cahill-Rowley, Hewett, Ismail, Rizzo [arXiv:1307.8444]



ILC:
single photon search

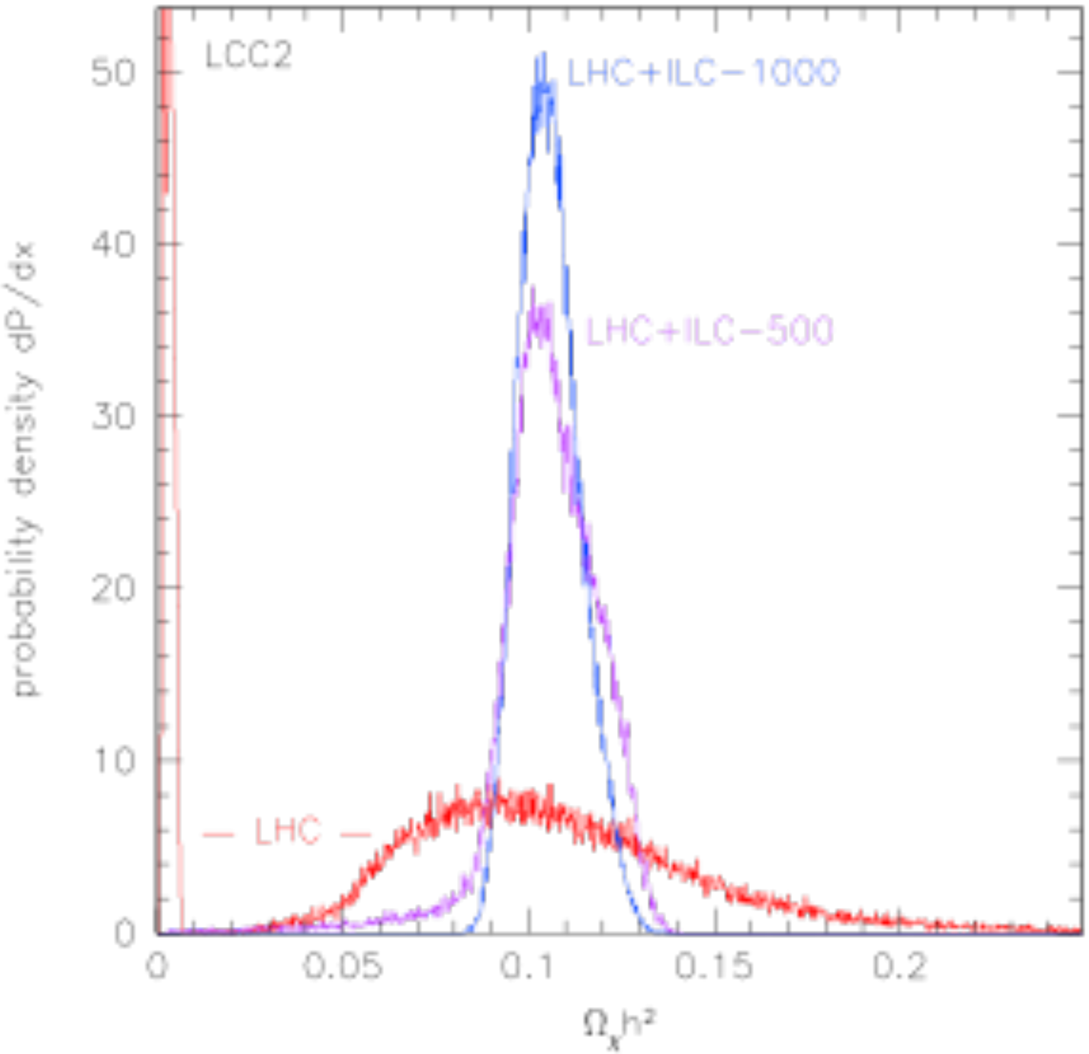


Loopholes of HL-LHC → Hunting ground of ILC

DM Relic Abundance

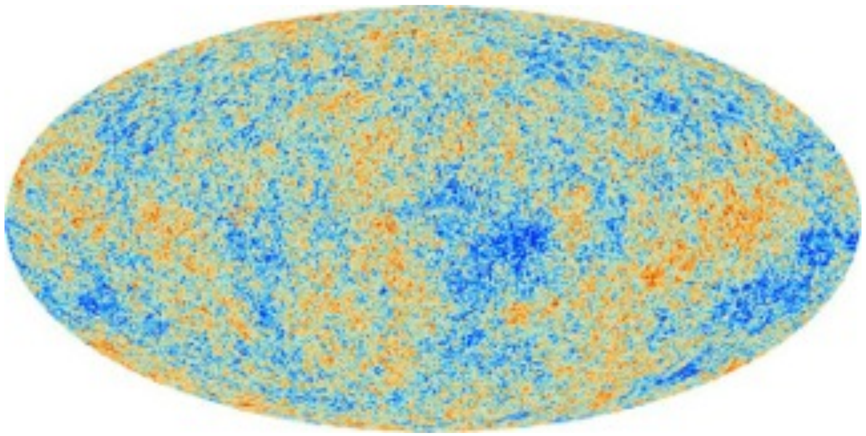
WMAP/Planck

$$\Omega_\chi h^2 = 0.1199 \pm 0.0027$$



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

ESA/Planck

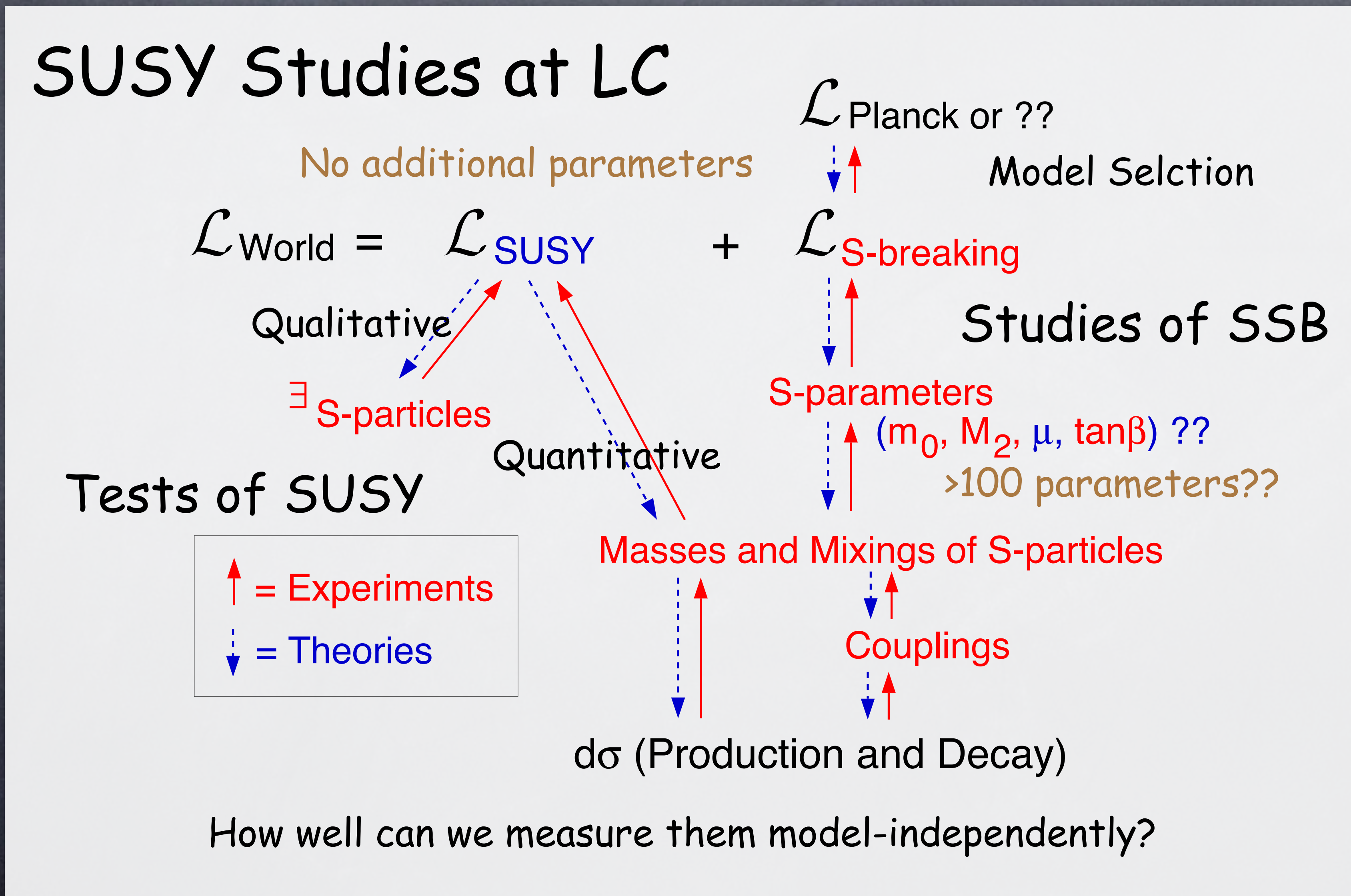


Once a DM candidate is discovered, crucial to test consistency with the measured DM relic abundance.

→ ILC precise measurements of mass and cross sections

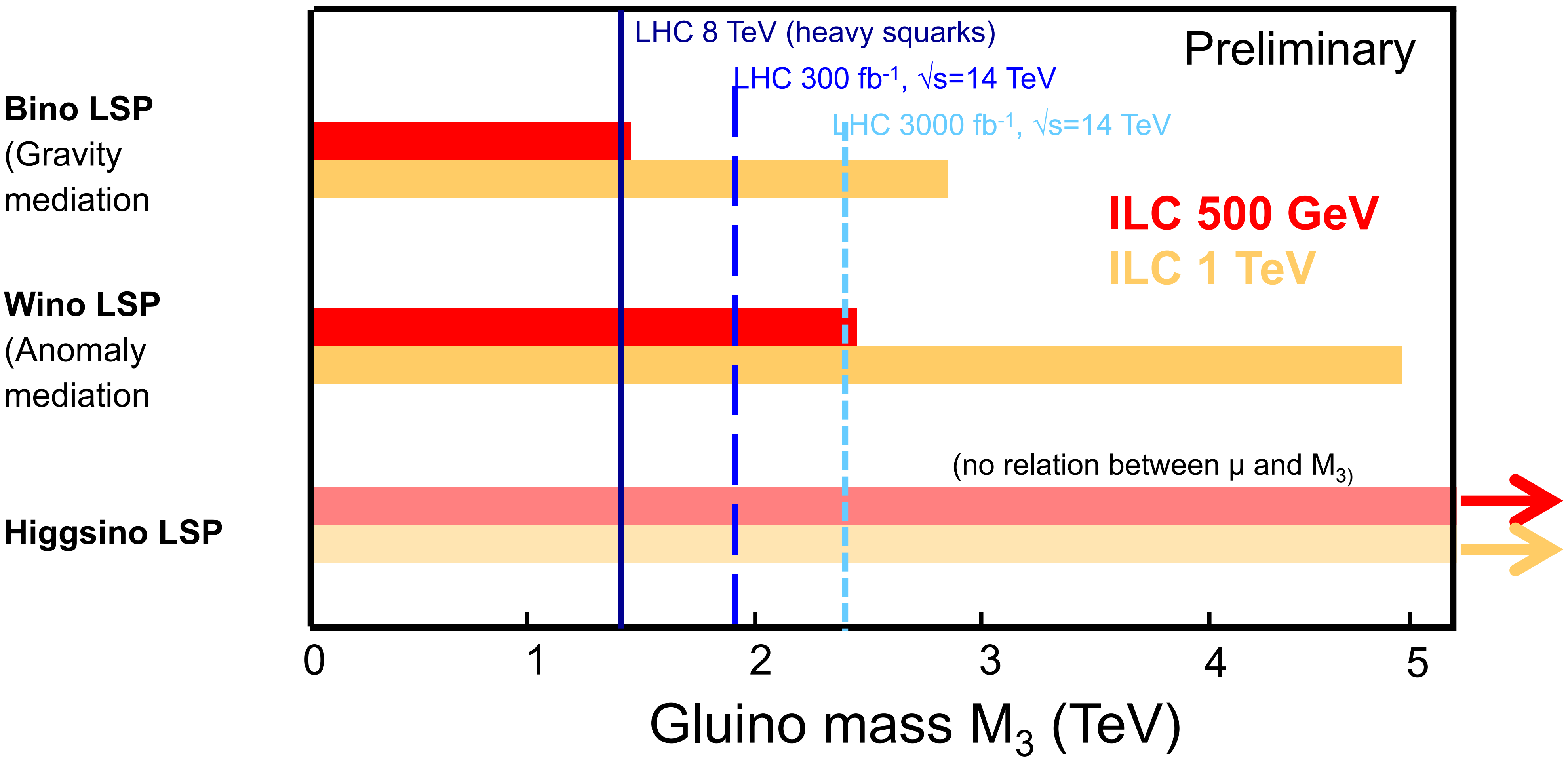
Supersymmetry

Standard BSM



Sensitivity to SUSY

Gluino search at LHC
Chargino/Neutralino search at ILC
→ Comparison assuming gaugino mass relations

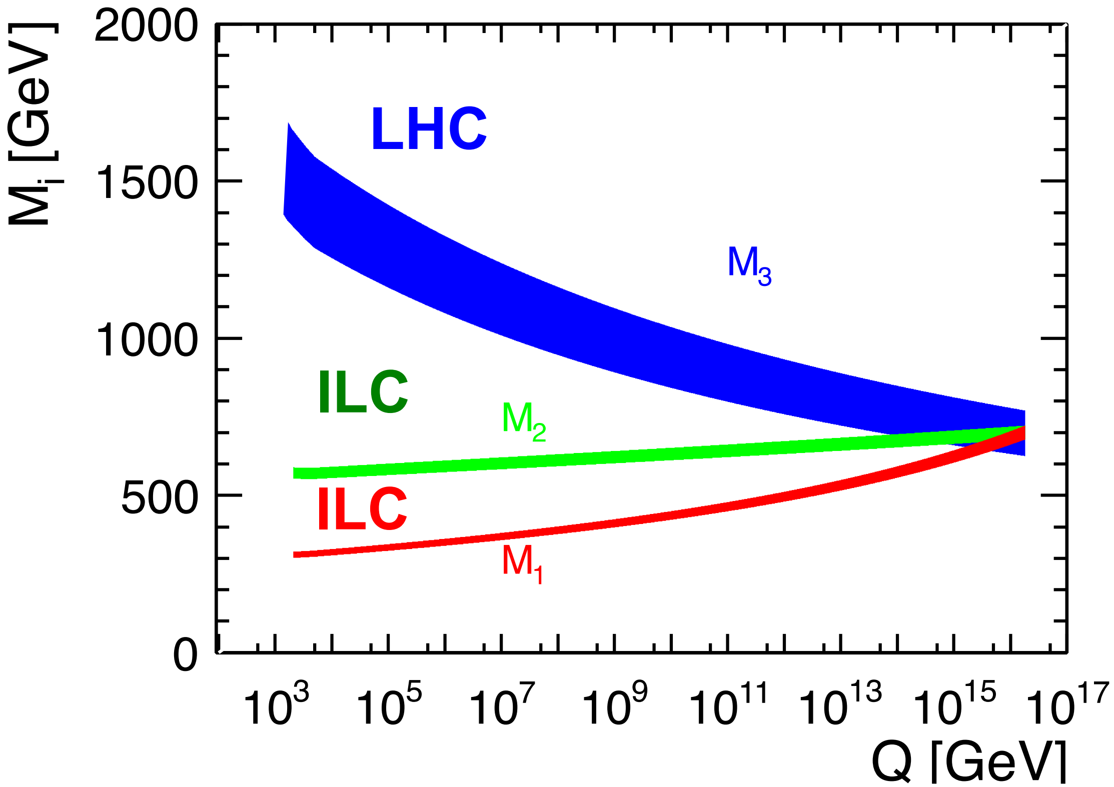


* Assumptions: MSUGRA/GMSB relation $M_1 : M_2 : M_3 = 1 : 2 : 6$; AMSB relation $M_1 : M_2 : M_3 = 3.3 : 1 : 10.5$

Gaugino mass relation

- Chargino/Neutralino @ ILC → probe M_1-M_2 gaugino mass relation
- Gluino @ LHC → test of gaugino mass relation by ILC-LHC complementarity
- Gives a prediction of the gluino mass scale
- Discrimination of SUSY spontaneous symmetry breaking scenarios

Gaugino mass unification:
Higgsino-like LSP scenario
By Baer, List



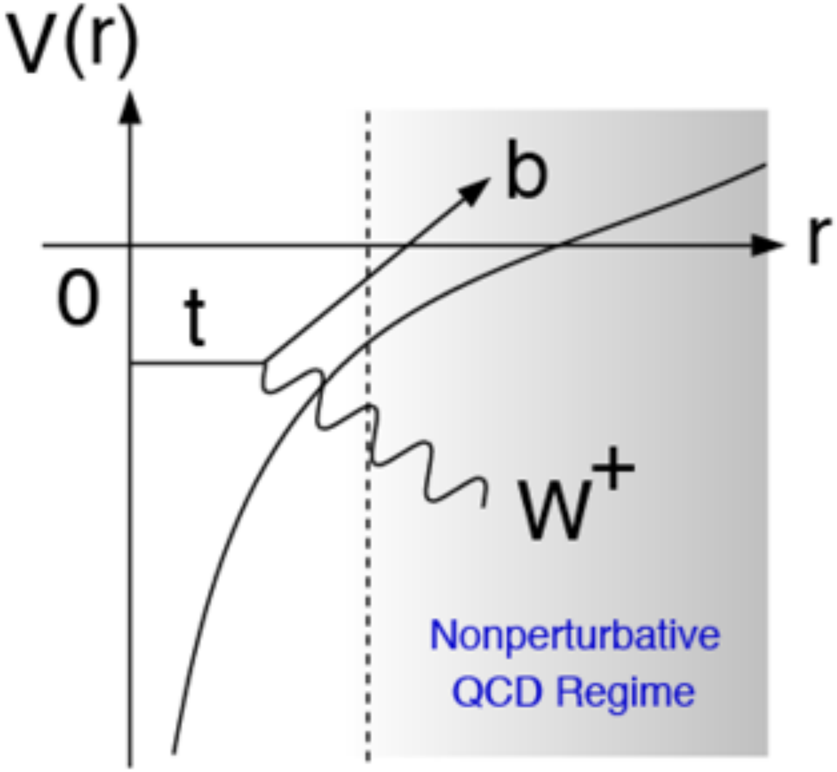
LHC: gluino discovery
→ mass determination

ILC: Higgsino discovery
→ M1, M2 via mixing between Higgsino and Bino/Wino

Top

Top Quark

The heaviest in the SM particles

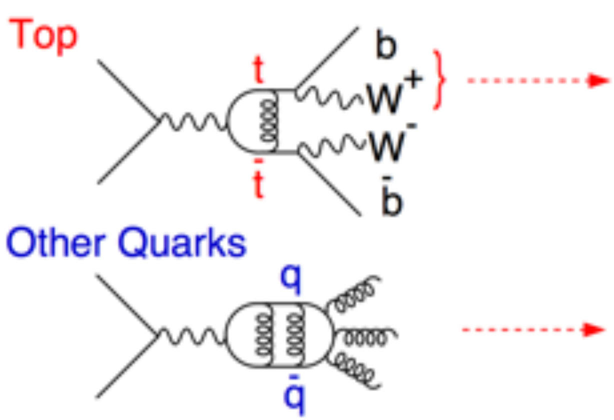


$\Gamma_t \approx 1.4$ GeV for $m_t = 175$ GeV

Because of this large width, the top and the anti-top pair created at r=0 decay before entering the non-perturbative QCD regime.

Γ_t acts as an infrared cutoff

Reliable cross section calculation from first principle (perturbative QCD) as first shown by Fadin-Khoze!



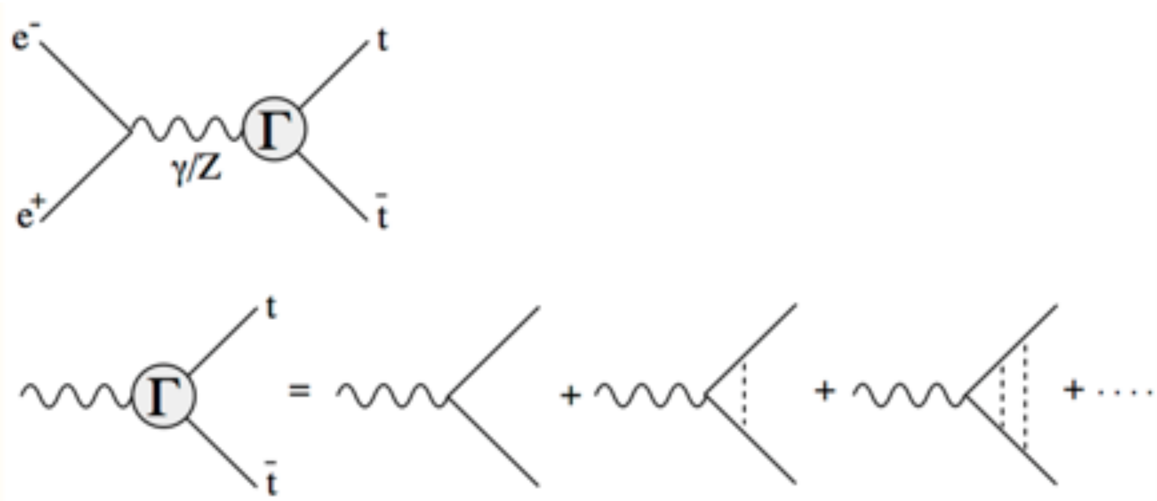
$p_{top} = p_{bW} = p_{3Jets}$

We cannot measure p_q in the onium!

The first chance to measure momentum space wave function of a (remnant of) quarkonium state.

Top Quark

Threshold Region



At threshold both the top quark and the anti-top quark are slow and stay close to each other, allowing multiple exchange of Coulombic gluons.

⇒ Leading contribution

The threshold correction factor (bound-state effect) denoted by Γ satisfies the Bethe-Salpeter equation which reduces to Schroedinger's equation:

$$\left[H - \left(E + \frac{i}{2}\Gamma_{\ominus}\right)\right] G = 1$$

in the non-relativistic limit. The operator G is related to Γ through

$$\Gamma_V^k \simeq -\left(\frac{1}{D_t} + \frac{1}{D_{\bar{t}}}\right) \cdot \tilde{G}(\boldsymbol{p}; E) \cdot \gamma^k$$

$$\tilde{G}(\boldsymbol{p}; E) \equiv \langle \boldsymbol{p} \,|\, G \,|\, \boldsymbol{x} = \boldsymbol{0} \rangle$$

for vector part

$$\Gamma_A^k \simeq -\left(\frac{1}{D_t} + \frac{1}{D_{\bar{t}}}\right) \cdot \left(\frac{\tilde{F}^l(\boldsymbol{p}; E)}{m_t}\right) \cdot \sigma^{kl}\gamma^5$$

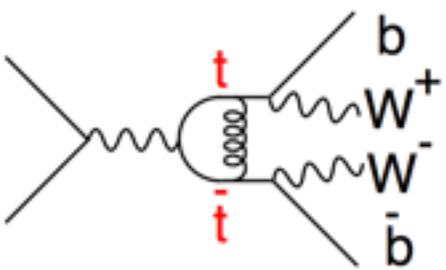
$$\tilde{F}^l(\boldsymbol{p}; E) \equiv \langle \boldsymbol{p} \,|\, G \cdot \hat{p}^l \,|\, \boldsymbol{x} = \boldsymbol{0} \rangle$$

for axial vector part

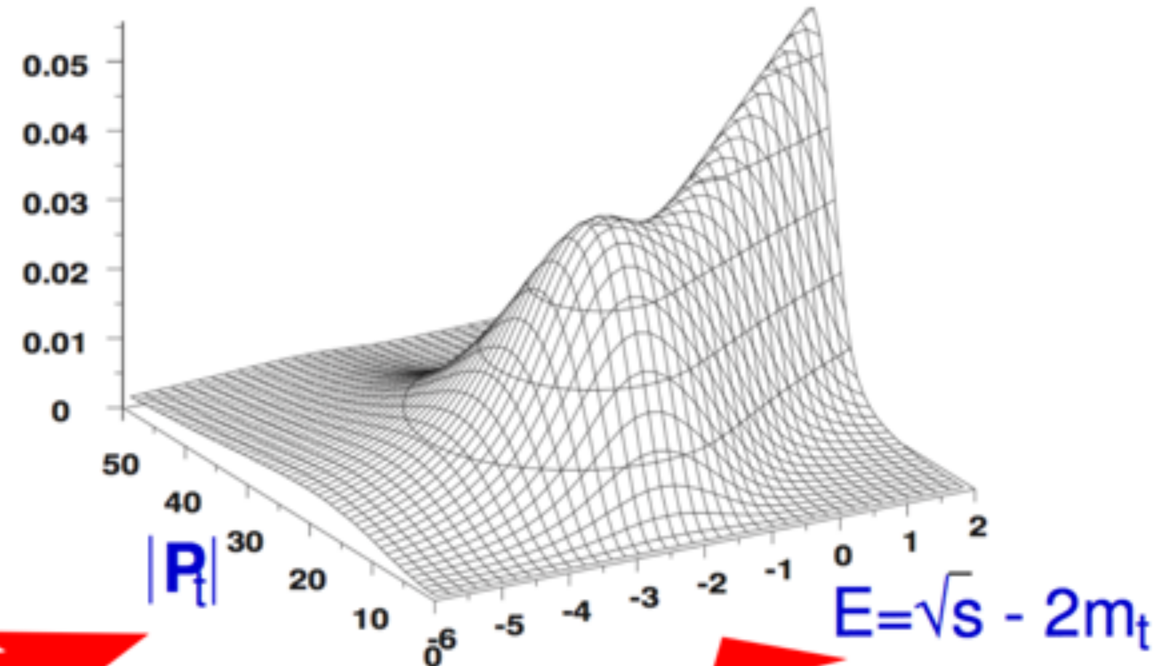
Top Quark

Threshold Region

How to access G experimentally



$p_{top} = p_{bW} = p_{3jets}$



Momentum Dist.

$$\frac{d\sigma_{t\bar{t}}}{d\,|\boldsymbol{p}|} \propto |\langle \boldsymbol{p}\,|\,G\,|\,\boldsymbol{x}=\boldsymbol{0}\,\rangle|^2$$

$$\simeq \left|\sum_n \frac{\phi_n(\boldsymbol{p})\Psi_n^*(\boldsymbol{0})}{E-E_n+i\Gamma_n/2}\right|^2$$

momentum space wave fun.

Threshold Scan

$$\sigma_{t\bar{t}} \propto Im\,\langle \boldsymbol{x}=\boldsymbol{0}\,|\,G\,|\,\boldsymbol{x}=\boldsymbol{0}\,\rangle$$

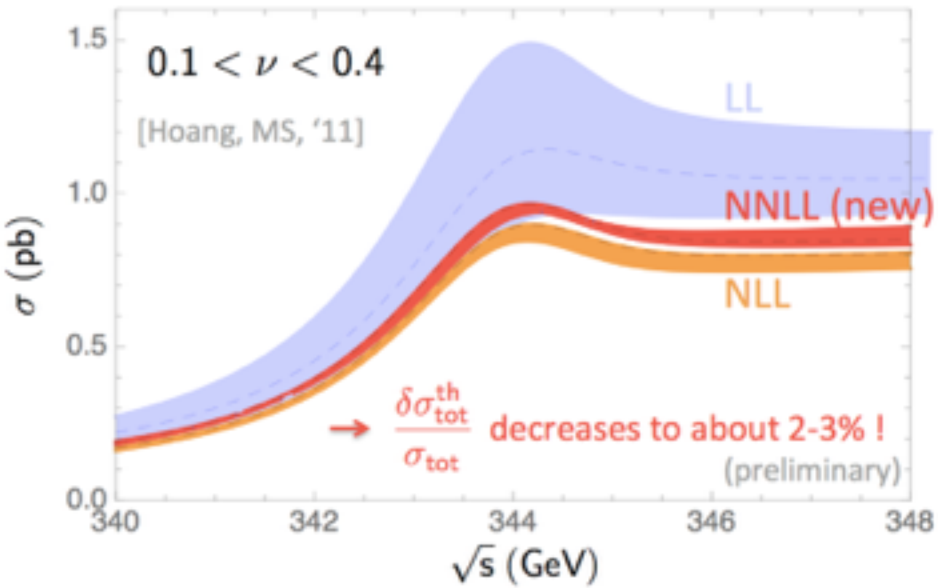
$$\simeq Im\sum_n \frac{|\Psi_n(\boldsymbol{0})|^2}{E-E_n+i\Gamma_n/2}$$

wave function at origin

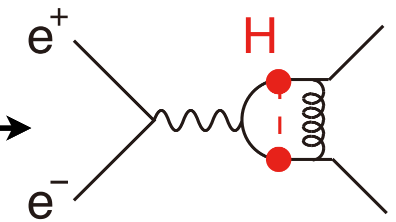
Top Quark

Threshold Scan

M.Stahlhofen Top Phys WS 2012



Theory improving! →

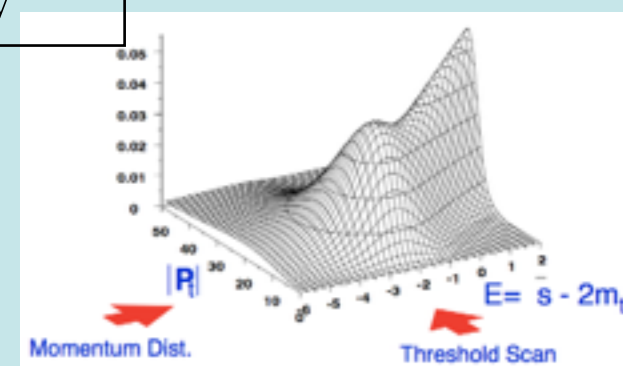


~10% effect

Expected accuracies

$$\Delta m_t = 34\,\mathrm{MeV}$$
$$\Delta\alpha_s(m_Z) = 0.0023$$
$$\Delta\Gamma_t = 42\,\mathrm{MeV}$$

Threshold scan alone

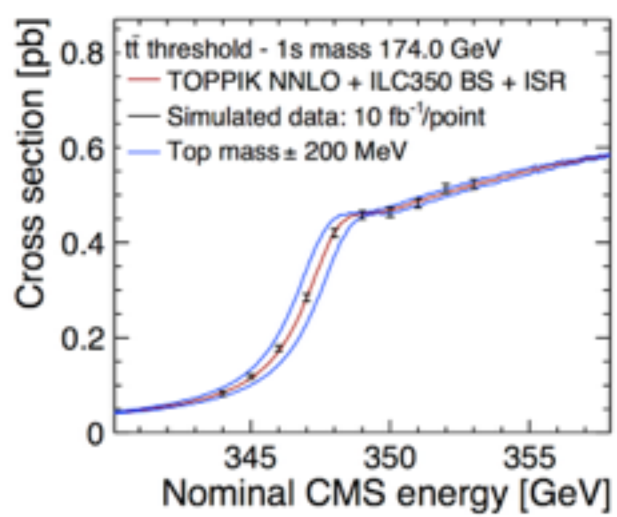


+ A_{FB} & Top Momentum

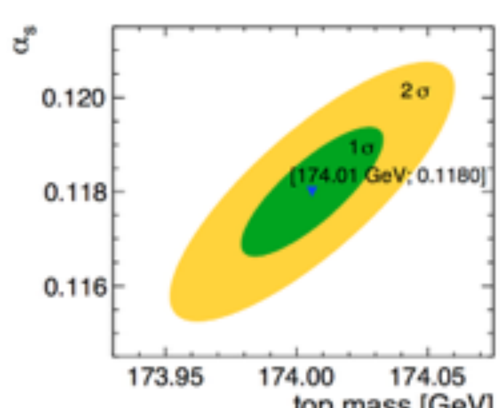
$$\Delta m_t = 19\,\mathrm{MeV}$$
$$\Delta\alpha_s(m_Z) = 0.0012$$
$$\Delta\Gamma_t = 32\,\mathrm{MeV}$$

arXiv:hep-ph/0601112v2

$$\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$$



F.Simon Top Phys WS 2012



Shinya Kanemura

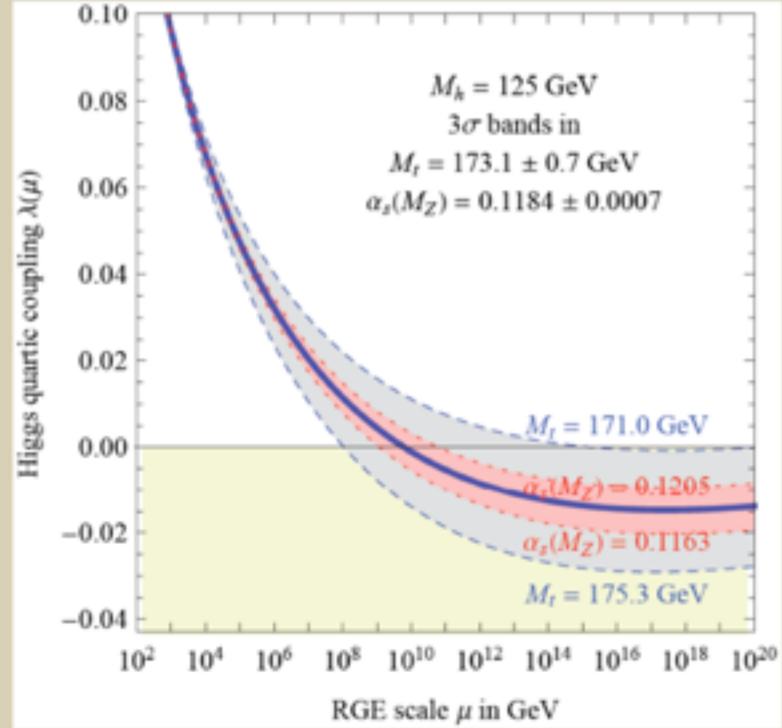
Vacuum Stability of the SM

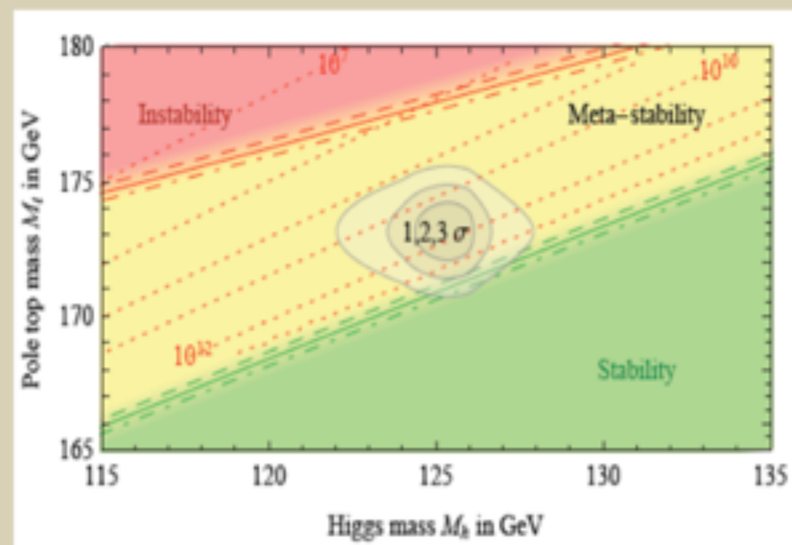
With the discovered 126 GeV Higgs boson, λ becomes negative below Planck Scale

Cut off $\Lambda = 10^7 - 10^{15}$ GeV
large uncertainty comes from large Δm_t

At ILC, $\Delta m_t \approx 30$ MeV is expected
Cutoff Λ can be better determined

At Planck Scale, $\lambda(M_{pl}) < 0$, but the theory satisfies the condition of the meta-stable vacuum





arXiv:1205.6497, Degrassi et al

Top Quark

Open Top Region

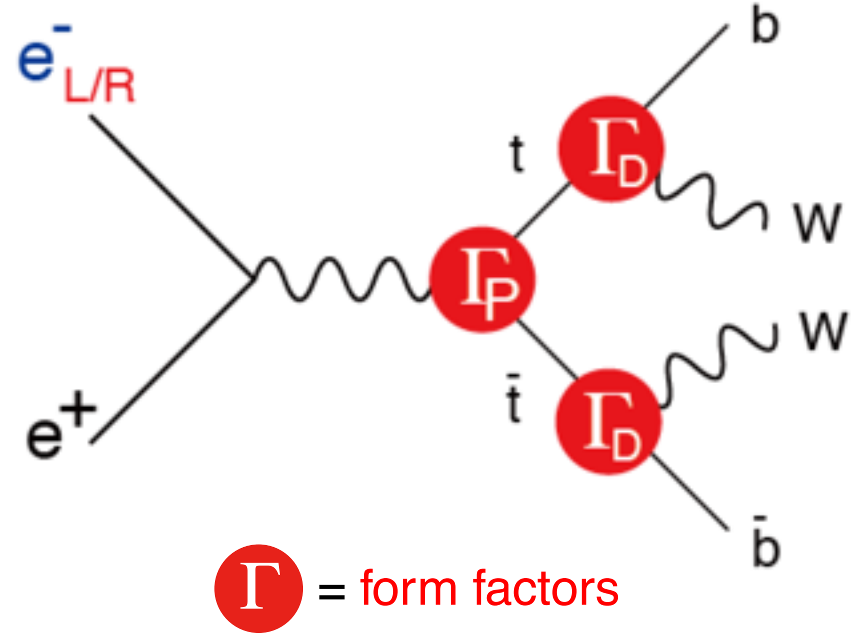
Key points

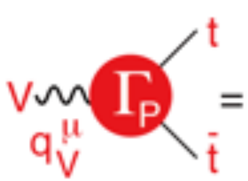
$\Gamma_t \approx 1.4$ GeV for $m_t = 175$ GeV

The top decays before forming a top hadron.

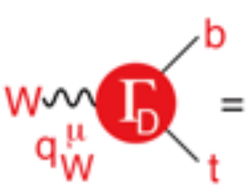
Top spin is measurable by angular analysis of decay products.

+ Polarized beams are available at ILC





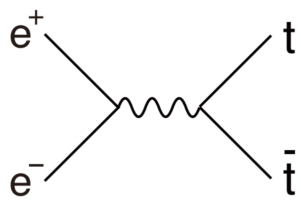
$$= \quad \mathcal{L}_{\rm int}^{ttV} = g_W \left[V_\mu \bar{t} \gamma^\mu \left(F_{1L}^V P_L + F_{1R}^V P_R \right) t - \frac{1}{v} (\partial_\nu V_\mu) \bar{t} \sigma^{\mu\nu} \left(F_{2L}^V P_L + F_{2R}^V P_R \right) t \right] + \text{h.c.}$$

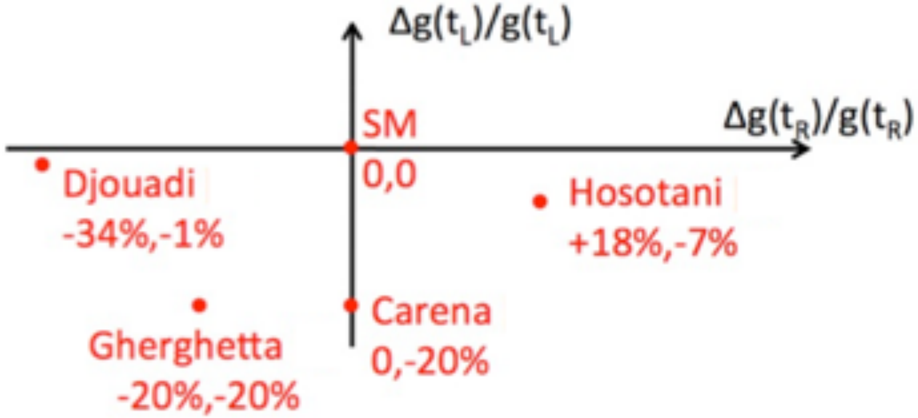


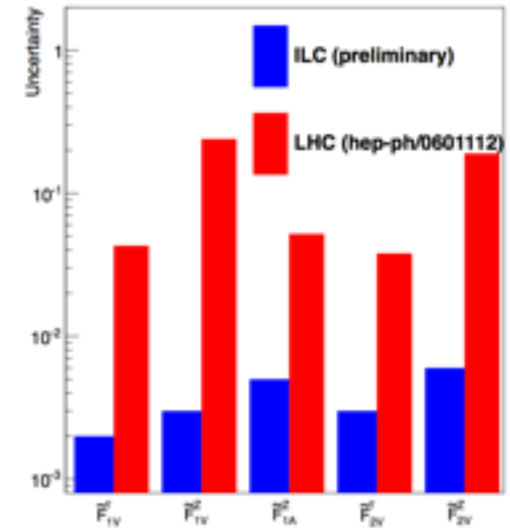
$$= \quad \mathcal{L}_{\rm int}^{tbW} = \frac{g_W}{\sqrt{2}} \left[W_\mu^- \bar{b} \gamma^\mu \left(F_{1L}^W P_L + F_{1R}^W P_R \right) t - \frac{1}{v} (\partial_\nu W_\mu^-) \bar{b} \sigma^{\mu\nu} \left(F_{2L}^W P_L + F_{2R}^W P_R \right) t \right] + \text{h.c.}$$

Top Quark

Anomalous Couplings in Open Top Production at 500 GeV







LAL 11-222

Figure 34: *Predictions of various groups [40,42–44] on deviations from Standard Model couplings of the t quark within Randall-Sundrum Models. The cartoon is taken from [47].*

Coupling	LHC [40] $\mathcal{L} = 300$ fb^{-1}	e^+e^- [52] $P_{e^-} = \pm 0.8$	e^+e^- [45] $\mathcal{L} = 500$ fb^{-1}, $P_{e^-,+} = \pm 0.8, \mp 0.3$
$\Delta \widetilde{F}^{\gamma}_{1V}$	$^{+0.043}_{-0.041}$	$^{+0.047}_{-0.047}$, $\mathcal{L} = 200$ fb^{-1}	$^{+0.002}_{-0.002}$
$\Delta \widetilde{F}^{Z}_{1V}$	$^{+0.24}_{-0.62}$	$^{+0.012}_{-0.012}$, $\mathcal{L} = 200$ fb^{-1}	$^{+0.002}_{-0.002}$
$\Delta \widetilde{F}^{Z}_{1A}$	$^{+0.052}_{-0.060}$	$^{+0.013}_{-0.013}$, $\mathcal{L} = 100$ fb^{-1}	$^{+0.006}_{-0.006}$
$\Delta \widetilde{F}^{\gamma}_{2V}$	$^{+0.038}_{-0.035}$	$^{+0.038}_{-0.038}$, $\mathcal{L} = 200$ fb^{-1}	$^{+0.001}_{-0.001}$
$\Delta \widetilde{F}^{Z}_{2V}$	$^{+0.27}_{-0.19}$	$^{+0.009}_{-0.009}$, $\mathcal{L} = 200$ fb^{-1}	$^{+0.002}_{-0.002}$

Table 3: Sensitivities achievable at 68.3% CL for the CP-conserving t quark form factors $\widetilde{F}^{X}_{1V,A}$ and $\widetilde{F}^{X}_{2V}$ defined in (1), at LHC and at the ILC. The assumed luminosity samples and, for ILC, beam polarization, are indicated. In the LHC studies and in the study [52], only one form factor at a time is allowed to deviate from its SM value. In study [45] the form factors are allowed to vary independently.

Coupling	LHC [40] $\mathcal{L} = 300$ fb^{-1}	e^+e^- [51] $\mathcal{L} = 300$ fb^{-1}, $P_{e^-,+} = -0.8$
$\Delta \mathrm{Re}\, \widetilde{F}^{\gamma}_{2A}$	$^{+0.17}_{-0.17}$	$^{+0.007}_{-0.007}$
$\Delta \mathrm{Re}\, \widetilde{F}^{Z}_{2A}$	$^{+0.35}_{-0.35}$	$^{+0.008}_{-0.008}$
$\Delta \mathrm{Im}\, \widetilde{F}^{\gamma}_{2A}$	$^{+0.17}_{-0.17}$	$^{+0.008}_{-0.008}$
$\Delta \mathrm{Im}\, \widetilde{F}^{Z}_{2A}$	$^{+0.035}_{-0.035}$	$^{+0.015}_{-0.015}$

Table 4: Sensitivities achievable at 68.3% CL for the t quark CP-violating magnetic and electric dipole form factors $\widetilde{F}^{X}_{2A}$ defined in (1), at the LHC and at linear e^+e^- colliders as published in the TESLA TDR. The assumed luminosity samples and, for TESLA, the beam polarization, are indicated. In the LHC studies and in the TESLA studies, only one form factor at a time is allowed to deviate from its SM value.

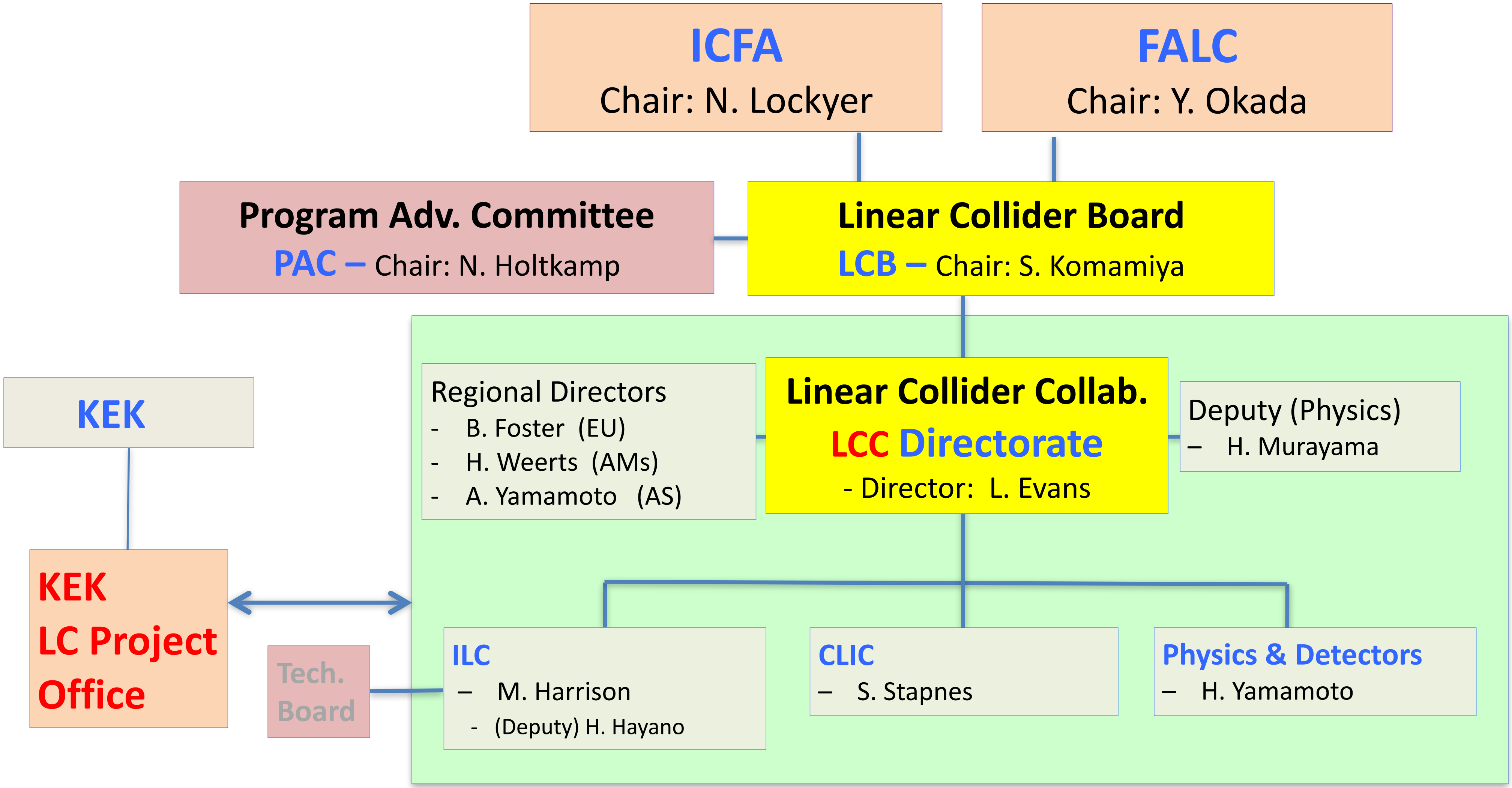
$$\Gamma^{ttX}_{\mu}(k^2, q, \bar{q}) = ie \left\{ \gamma_\mu \left(\widetilde{F}^{X}_{1V}(k^2) + \gamma_5 \widetilde{F}^{X}_{1A}(k^2) \right) + \frac{(q-\bar{q})_\mu}{2m_t} \left(\widetilde{F}^{X}_{2V}(k^2) + \gamma_5 \widetilde{F}^{X}_{2A}(k^2) \right) \right\}.$$

arXiv:hep-ph/1307.8265

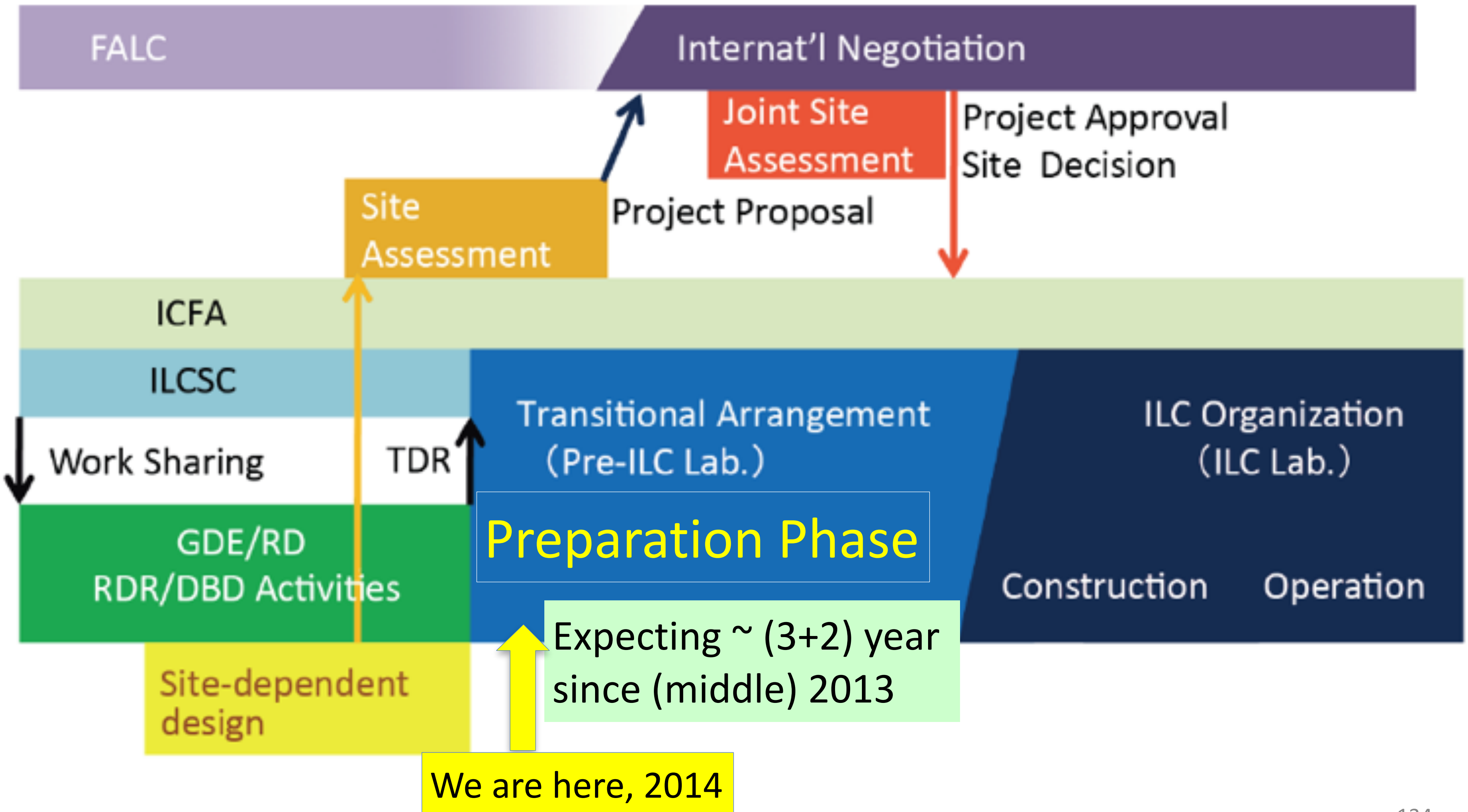
Whatever new physics is awaiting for us, clean environment, polarized beams, and excellent jet energy resolution to reconstruct W/Z/t/H in their hadronic decays will enable us to uncover the nature of the new physics through model-independent precision measurements and open up the way to ultra high scale physics!

Design to Reality

ILC in Linear Collider Collaboration

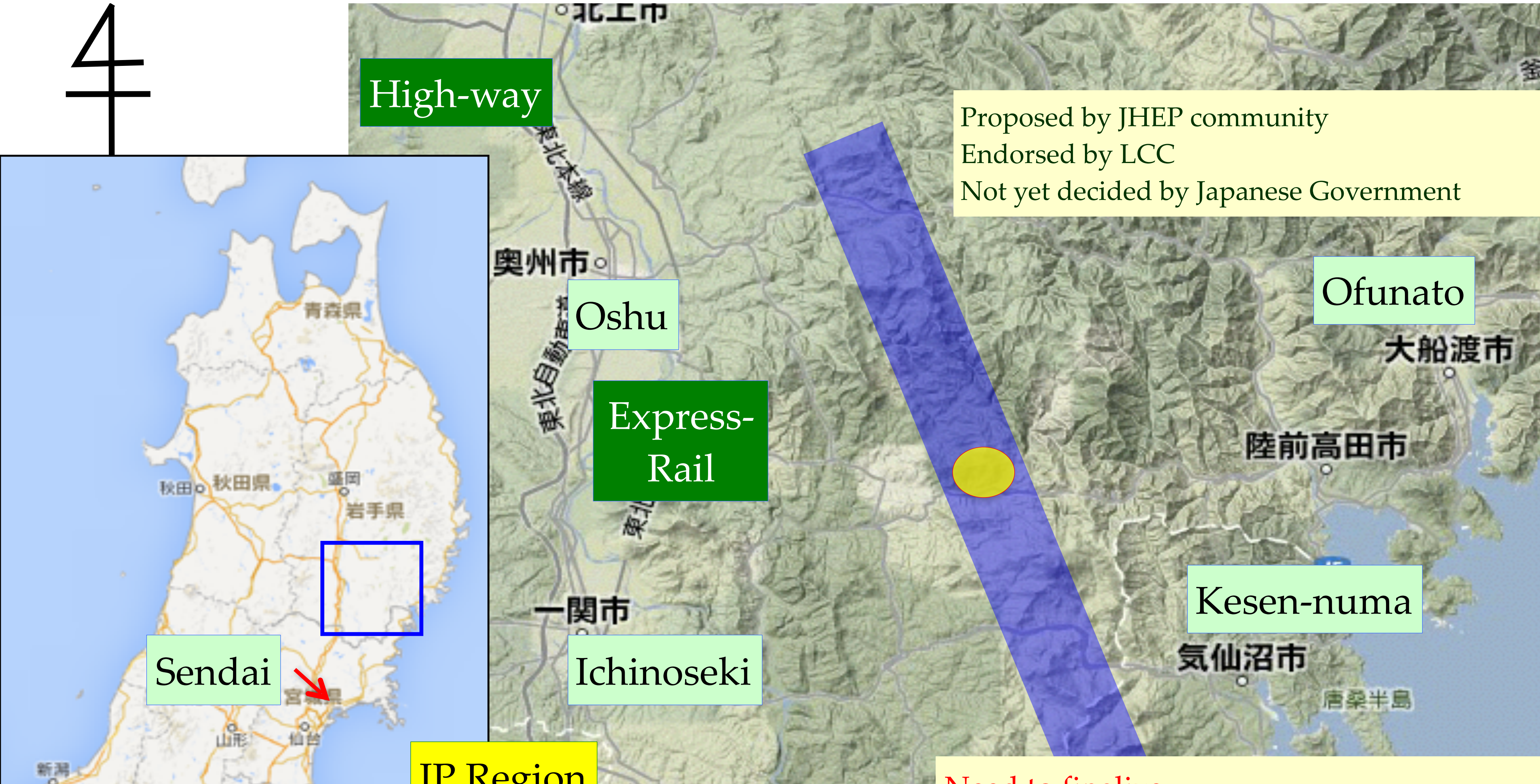


ILC Time Line: Progress and Prospect

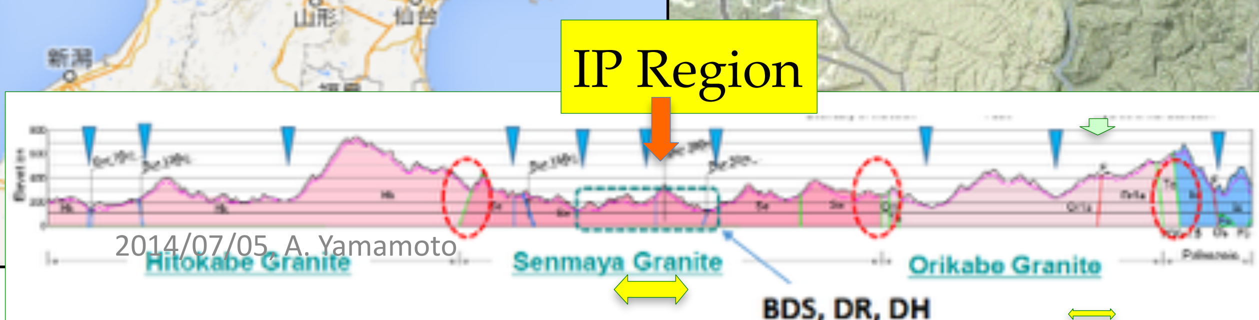


ILC Site Candidate Location in Japan: Kitakami Area

Establish a site-specific Civil Engineering Design - map the (site independent) TDR baseline onto the preferred site - assuming "Kitakami" as a primary candidate



Proposed by JHEP community
Endorsed by LCC
Not yet decided by Japanese Government



Need to finalize:

- IP / Linac orientation and length
- Access points and IR infrastructure
- Conventional Facilities and Siting (CFS)
- …

Global Status

Year	Global Status	Status in Japan
2012	- ***TDR "Draft" completed, and technically reviewed, and the cost estimate internally reviewed, in GDE***	
2013	- ***TDR Cost internationally and externally reviewed,*** - ***TDR published*** - ***"GDE" to "LCC"*** - ***European Strategy published***	- ***Candidate site by JHEP, unified,*** - ***Further study for q few year, recommended by SCJ (Science Council J.)***
2014	- - ***US-P5 recommendation published*** - - *Global supports well recognized*	- ***MEXT established ILC Task Force*** - ***ILC preparatory office starts at KEK*** - ***An official budget for the ILC investigation/preparation allocated, first time, in MEXT.***

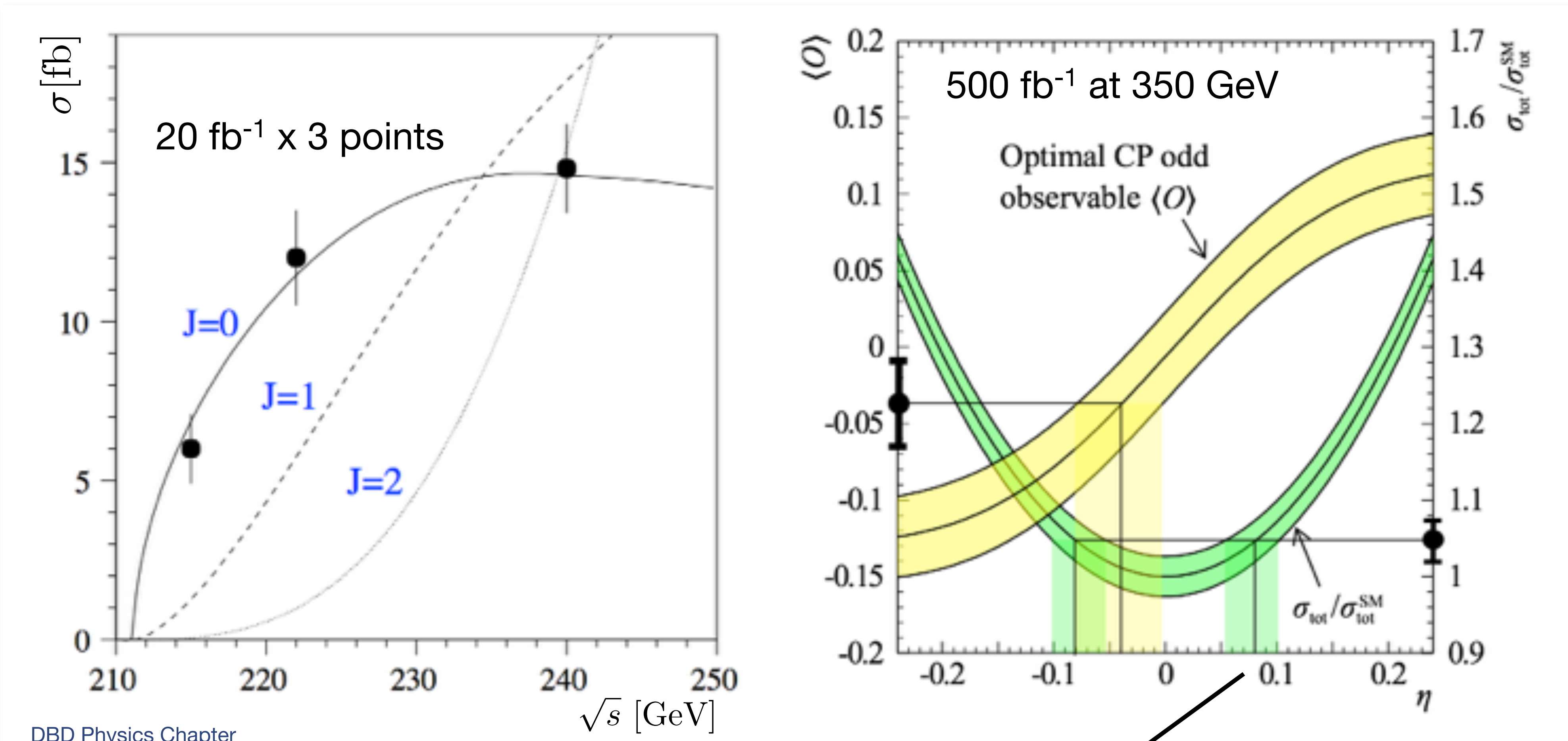
- ILC accelerator **technologies** have been sufficiently developed and matured for the project to move"from Design to Reality" in coming several years.
- **Global cooperation** needs to be further established,
- **LCC** is leading the project under supervision of ICFA and LCB
- Strong supports from EU and US, well recognized and acknowledged,

Backup

	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)	$+$	$-$	$-$	$+$	$-$	$+$

Spin and CP Mixing

Measurements that compliment those at LHC



Search for small CP-odd admixture to a few %

CP-odd ZHH coupling is loop-induced, may not be the best way, though.

SM Higgs BRs

arXiv: 1307.1347

Table 1.1. The Standard Model values of branching ratios of fermionic decays of the Higgs boson for each value of the Higgs boson mass m_h.

m_h (GeV)	$b\bar{b}$	$\tau^+\tau^-$	$\mu^+\mu^-$	$c\bar{c}$	$s\bar{s}$
125.0	57.7 %	6.32 %	0.0219 %	2.91 %	0.0246 %
125.3	57.2 %	6.27 %	0.0218 %	2.89 %	0.0244 %
125.6	56.7 %	6.22 %	0.0216 %	2.86 %	0.0242 %
125.9	56.3 %	6.17 %	0.0214 %	2.84 %	0.0240 %
126.2	55.8 %	6.12 %	0.0212 %	2.81 %	0.0238 %
126.5	55.3 %	6.07 %	0.0211 %	2.79 %	0.0236 %

Table 1.2. The Standard Model values of branching ratios of bosonic decays of the Higgs boson for each value of the Higgs boson mass m_h. The predicted value of the total decay width of the Higgs boson is also listed for each value of m_h.

m_h (GeV)	gg	$\gamma\gamma$	$Z\gamma$	W^+W^-	ZZ	Γ_H (MeV)
125.0	8.57 %	0.228 %	0.154 %	21.5 %	2.64 %	4.07
125.3	8.54 %	0.228 %	0.156 %	21.9 %	2.72 %	4.11
125.6	8.52 %	0.228 %	0.158 %	22.4 %	2.79 %	4.15
125.9	8.49 %	0.228 %	0.162 %	22.9 %	2.87 %	4.20
126.2	8.46 %	0.228 %	0.164 %	23.5 %	2.94 %	4.24
126.5	8.42 %	0.228 %	0.167 %	24.0 %	3.02 %	4.29

Systematic Errors

	Baseline	LumUp
luminosity	0.1%	0.05%
polarization	0.1%	0.05%
b-tag efficiency	0.3%	0.15%

arXiv: 1310.0763

Hunting Ground for Extra Higgs Bosons

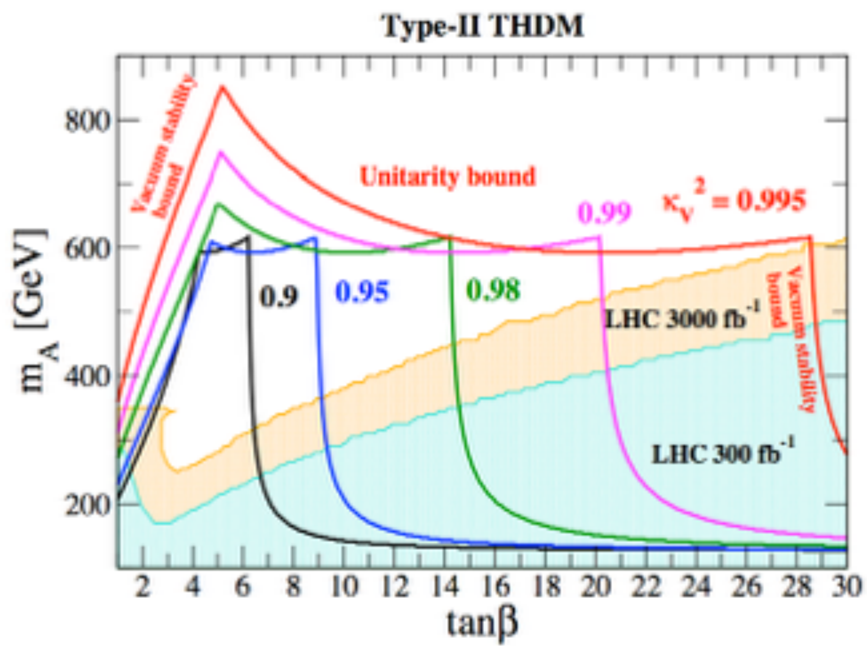
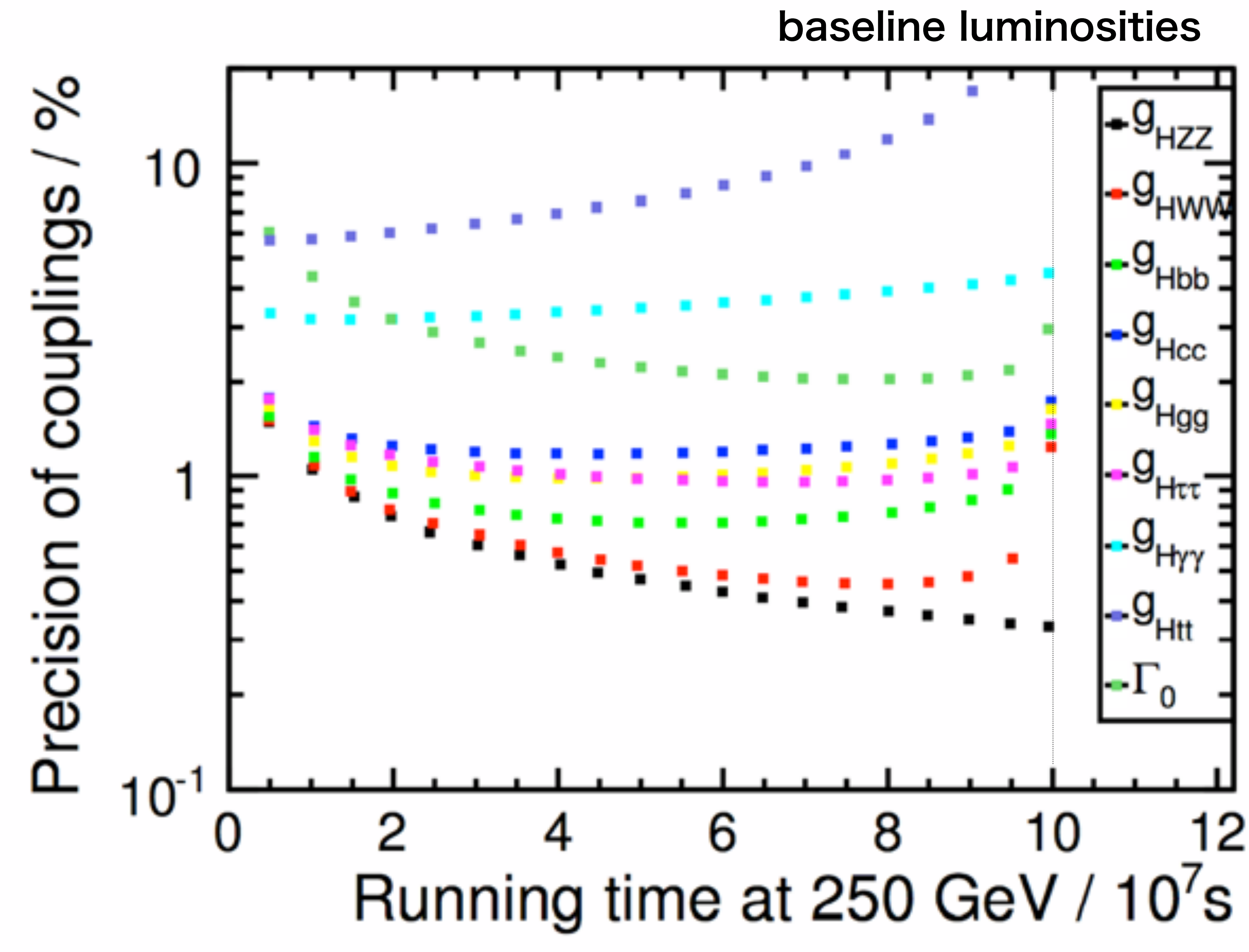


Figure 1.20. Regions below the curves are allowed by the constraints from unitarity and vacuum stability on the $\tan\beta$-m_A plane for each fixed value of κ_V^2 for $M = m_A = m_H = m_{H^+}$ in the Type II and Type X 2HDMs. Expected excluded parameter spaces are also shown by blue (orange) shaded regions from the gluon fusion production and associate production of A and H with bottom quarks and tau leptons at the LHC with the collision energy to be 14 TeV with the integrated luminosity to be 300 fb^{-1} (3000 fb^{-1}).

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

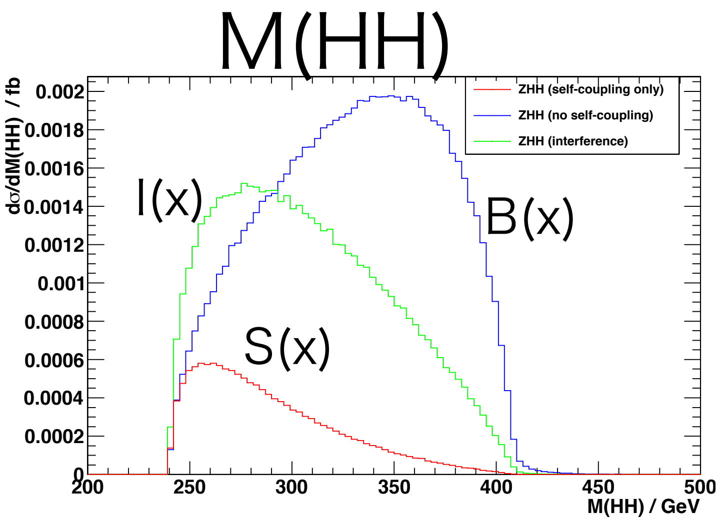
Coupling Precisions

Running Scenarios



Self-coupling Measurement

Weighting Method to Enhance the Sensitivity to λ

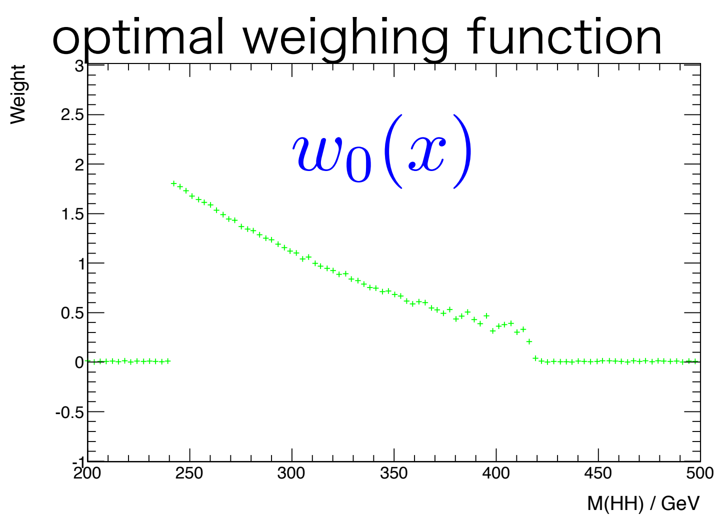


$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

irreducible — interference — self-coupling

Observable: weighted cross-section

$$\sigma_w = \int \frac{\mathrm{d}\sigma}{\mathrm{d}x} w(x)\mathrm{d}x$$



Equation for the optimal w(x) (variational principle):

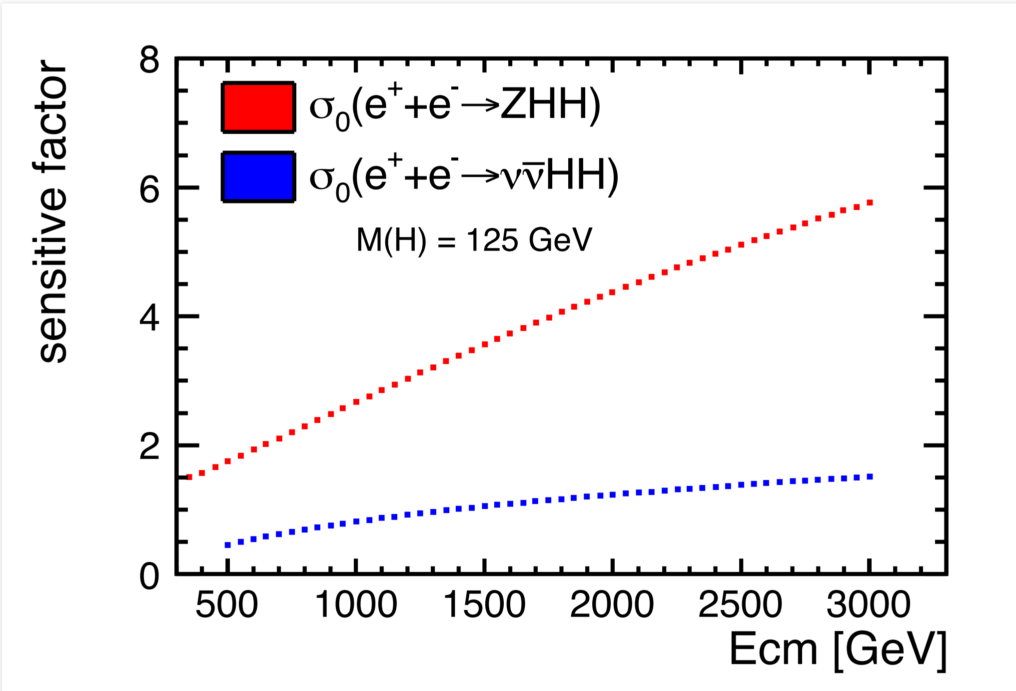
$$\sigma(x)w_0(x)\int (I(x)+2S(x))w_0(x)\mathrm{d}x = (I(x)+2S(x))\int \sigma(x)w_0^2(x)\mathrm{d}x$$

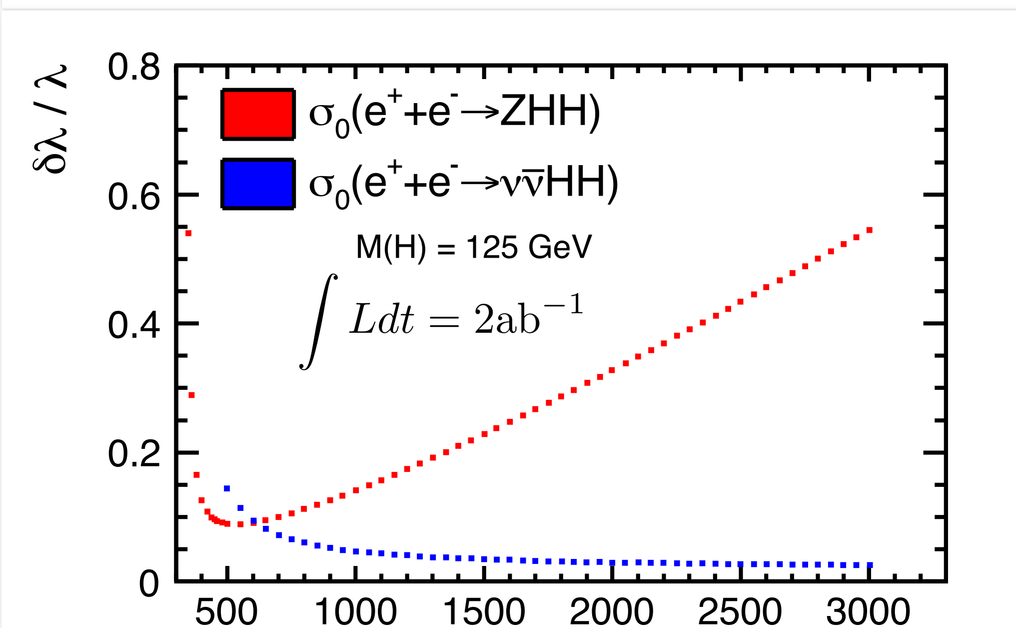
General solution:

$$w_0(x) = c \cdot \frac{I(x)+2S(x)}{\sigma(x)}$$

c: arbitrary normalization factor

Expected Coupling Precision as a Function of Ecm





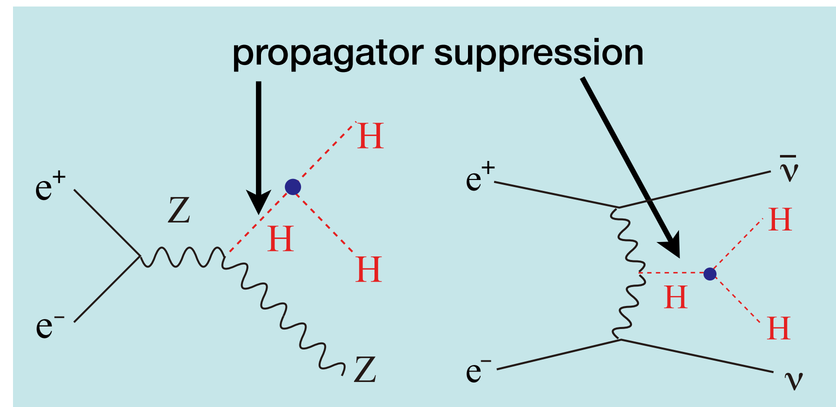
ILD DBD Study (Junping Tian)

Sensitivity Factor

$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

F=0.5 if no BG diagrams there

BG diagrams dominate at high E_{cm}



⇒ F grows quickly with Ecm !

Coupling Precision

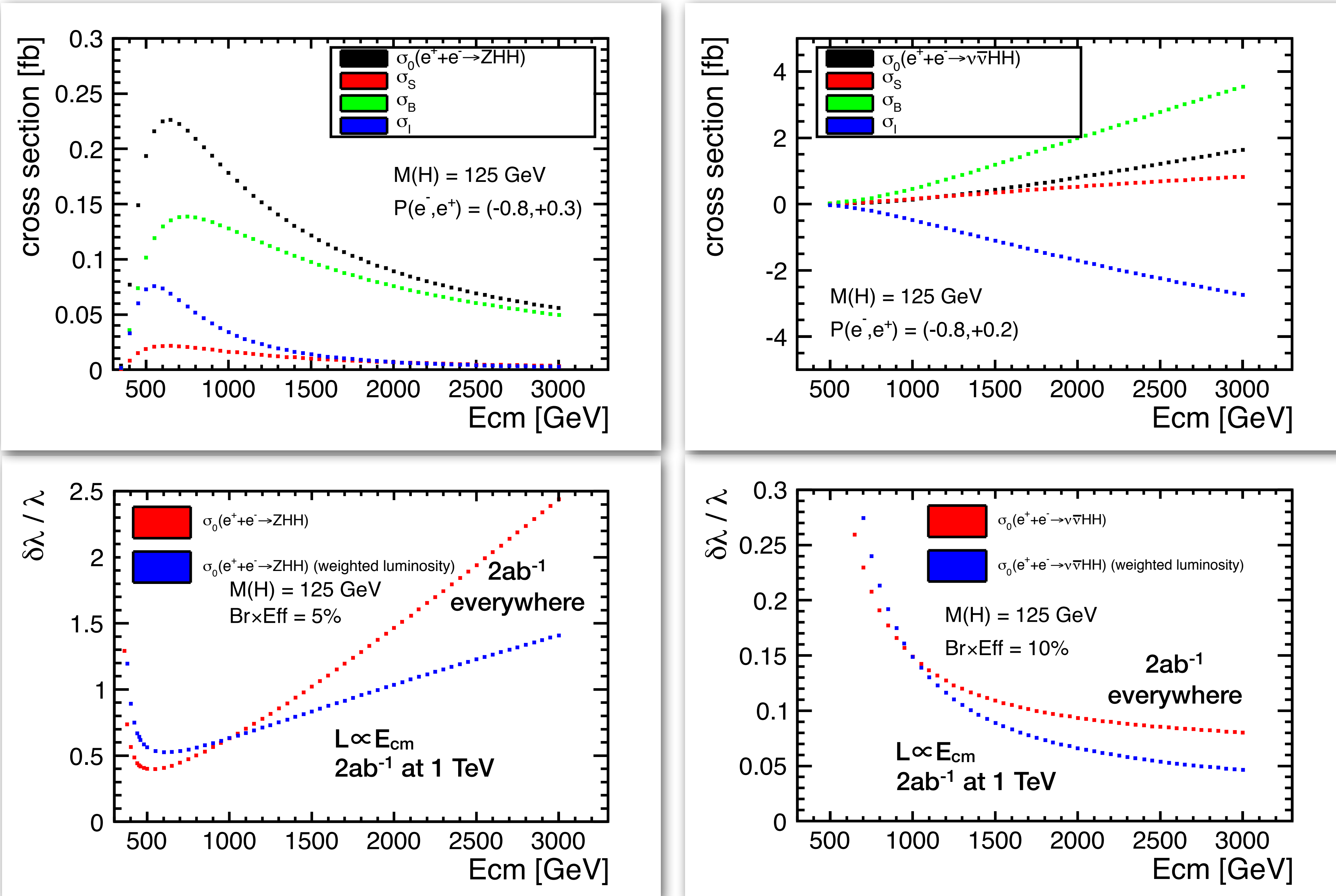
ZHH : optimal Ecm ~ 500 GeV

though the cross section maximum is at around Ecm = 600 GeV

ννHH :

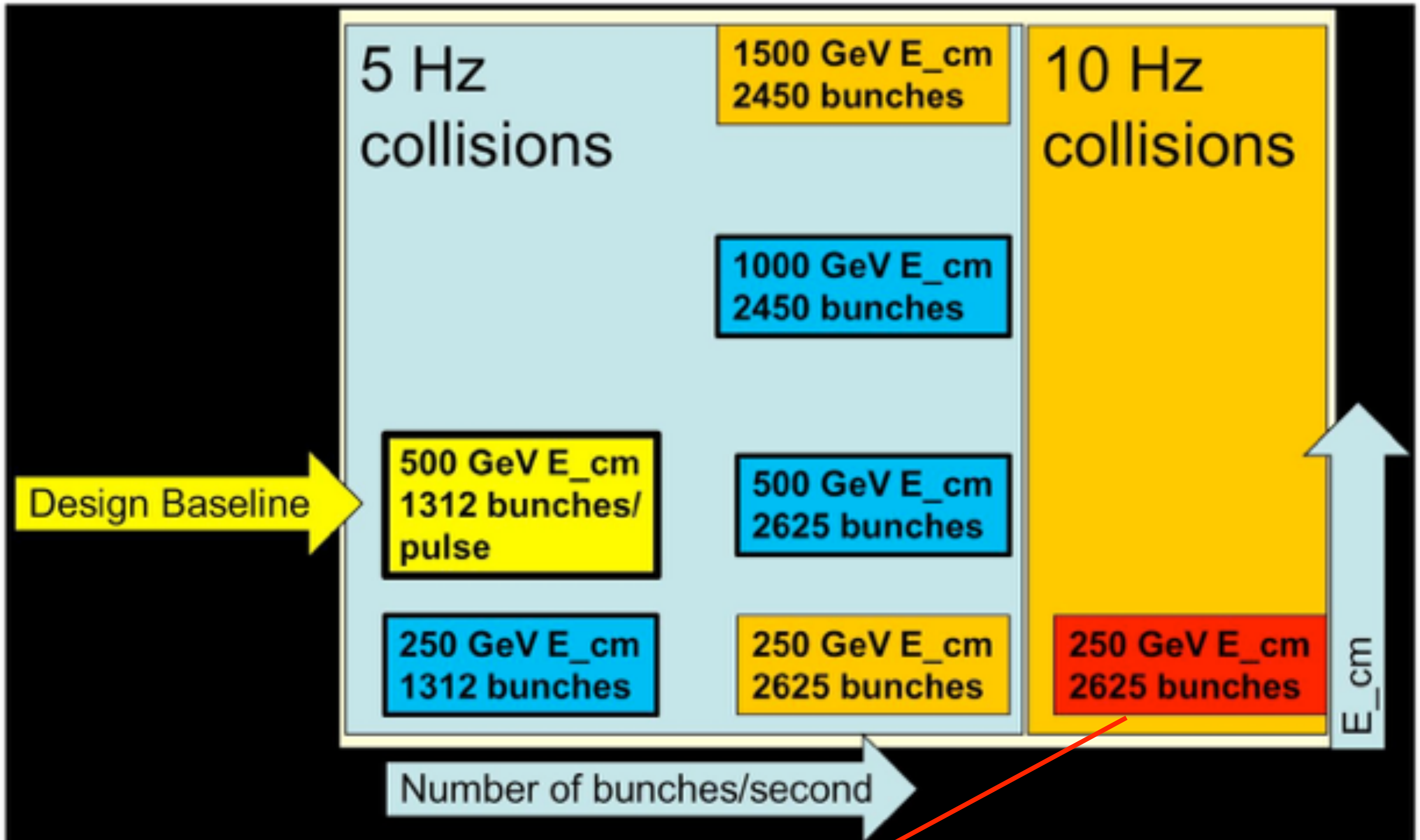
Precision slowly improves with Ecm

Expected Coupling Precision as a Function of Ecm



HL-ILC ?

ILC Stages and Upgrades



Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

x4 upgrade @250GeV

Blue: upgrade described in TDR

The current ILC design is rather conservative!

TDR

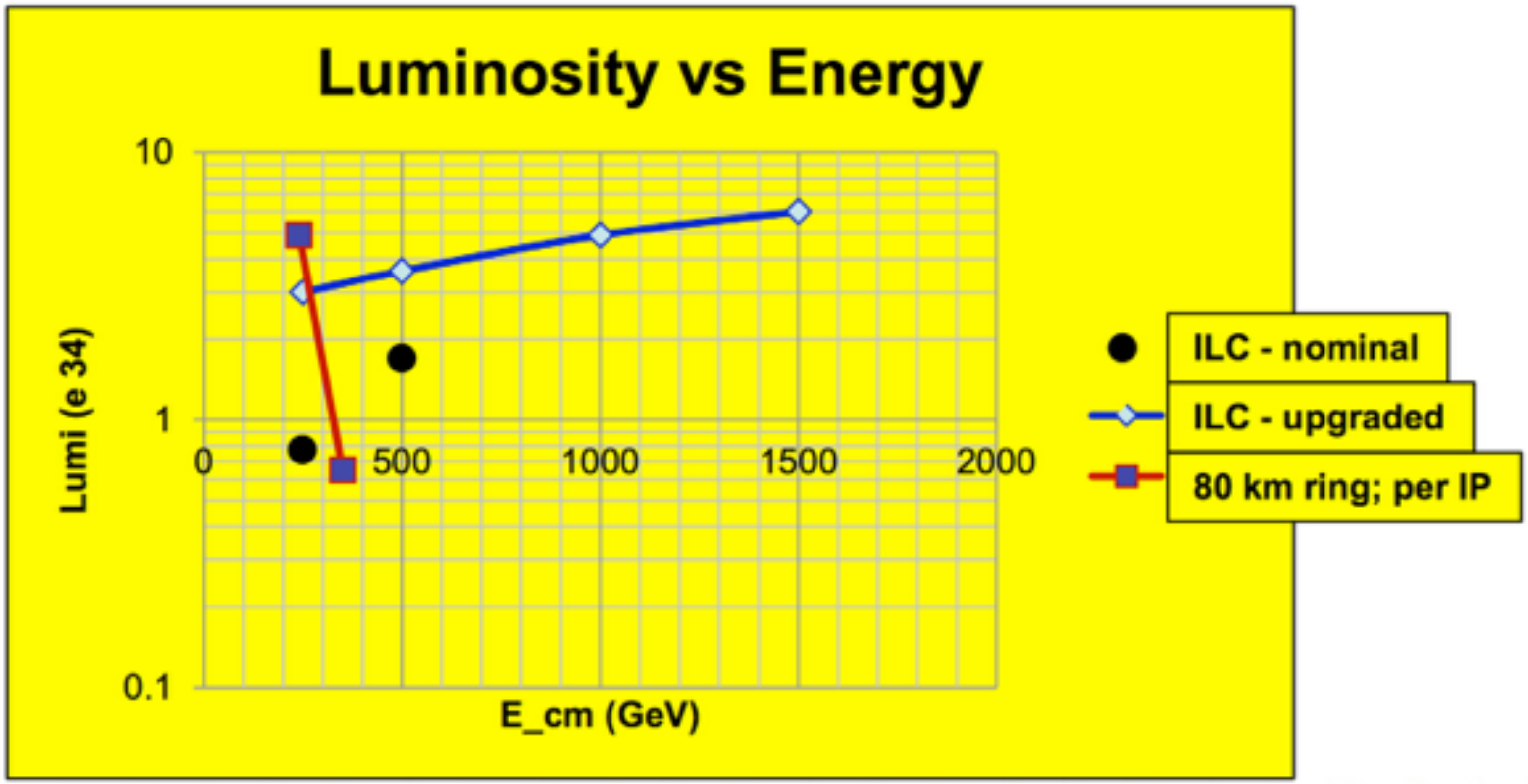
			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
Center-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	2625	2450	2450
Bunch population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

HL-ILC

			1st Stage Higgs Factory	Baseline ILC, after Lumi Upgrade	High Rep Rate Operation
Center-of-mass energy	E_{CM}	GeV	250	250	250
Collision rate	f_{rep}	Hz	5	5	10
Electron linac rate	f_{linac}	Hz	10	10	10
Number of bunches	n_{b}		1312	2625	2625
Pulse current	I_{beam}	mA	5.8	8.75	8.75
Average total beam power	P_{beam}	MW	5.9	10.5	21
Estimated AC power	P_{AC}	MW	129	160	200
Luminosity	L	$\times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.75	1.5	3.0

Nickname	Ecm(1) (GeV)	Lumi(1) (fb^{-1})	+	Ecm(2) (GeV)	Lumi(2) (fb^{-1})	+	Ecm(3) (GeV)	Lumi(3) (fb^{-1})	Runtime (yr)	Wall Plug E (MW-yr)
ILC(250)	250	250							1.1	130
ILC(500)	250	250		500	500				2.0	270
ILC(1000)	250	250		500	500		1000	1000	2.9	540
ILC(LumUp)	250	1150		500	1600		1000	2500	5.8	1220

High Luminosity ILC



Independent Higgs Measurements

Hypothetical HL-ILC

250 GeV: 250 fb^{-1}	250 GeV: 1150 fb^{-1}
500 GeV: 500 fb^{-1}	500 GeV: 1600 fb^{-1}
1 TeV: 1000 fb^{-1}	1 TeV: 2500 fb^{-1}

$(M_H = 125\ \mathrm{GeV})$

Ecm	250 GeV		500 GeV		1 TeV
luminosity · fb	250		500		1000
polarization (e-,e+)	(-0.8, +0.3)		(-0.8, +0.3)		(-0.8, +0.2)
process	ZH	vvH(fusion)	ZH	vvH(fusion)	vvH(fusion)
cross section	1.2%	-	1.7%	-	
	σ·Br	σ·Br	σ·Br	σ·Br	σ·Br
H-->bb	0.56%	4.9%	1%	0.37%	0.3%
H-->cc	3.9%		7.2%	3.5%	2%
H-->gg	3.3%		6%	2.3%	1.4%
H-->WW*	3%		5.1%	1.3%	1%
H-->ττ	2%		3%	5%	2%
H-->ZZ*	8.4%		14%	4.6%	2.6%
H-->γγ	16%		19%	13%	5.4%
H-->μμ	46.6%	-	-	-	20%

Coupling Measurements

Hypothetical HL-ILC

250 GeV: 1150 fb^{-1}
500 GeV: 1600 fb^{-1}
1 TeV: 2500 fb^{-1}

($M_H = 125$ GeV)

P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV   P(e-,e+)=(-0.8,+0.2) @ 1 TeV

coupling	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	0.6%	0.5%	0.5%
HWW	2.3%	0.6%	0.6%
Hbb	2.5%	0.8%	0.7%
Hcc	3.2%	1.5%	1%
Hgg	3%	1.2%	0.93%
Hττ	2.7%	1.2%	0.9%
Hγγ	8.2%	4.5%	2.4%
Hμμ	42%	42%	10%
Γ	5.4%	2.5%	2.3%
Htt	-	7.8%	1.9%

HHH	-	46%(*)	13%(*)

) With H->WW (preliminary), if we include expected improvements in jet clustering, it would become 10%!

Indirect BSM Searches

Two-Fermion Processes

Z' Search / Study

arXiv:0912.2806 [hep-ph]

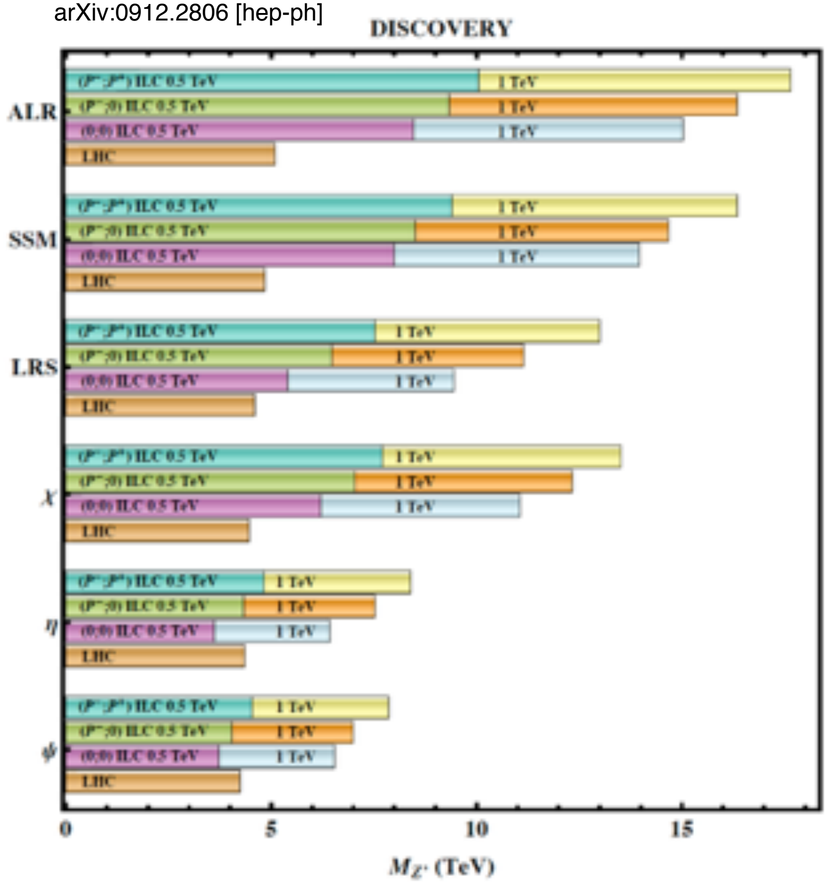
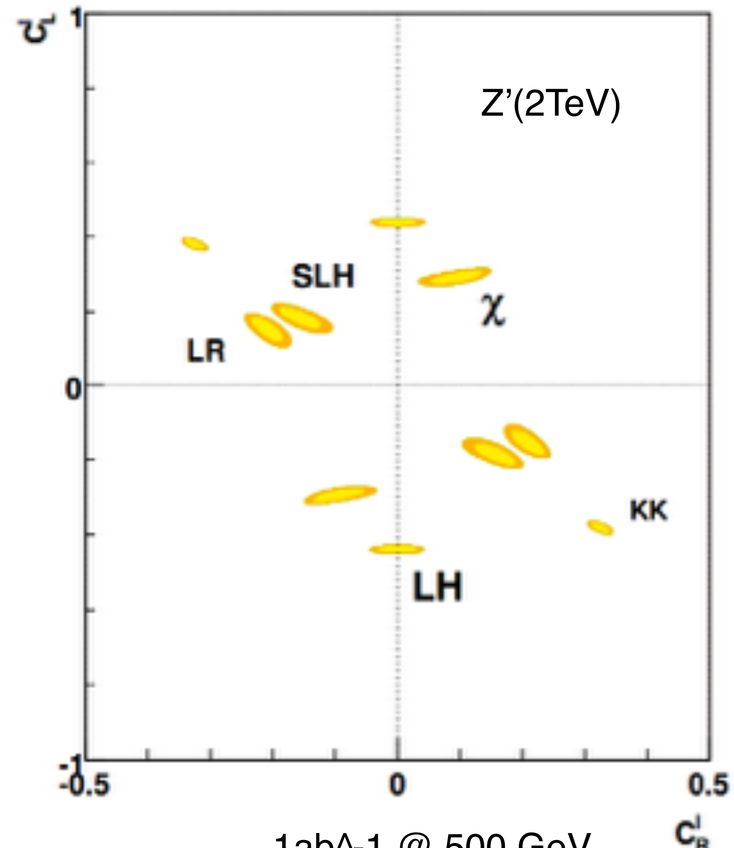


Figure 23: Sensitivity of the ILC to various candidate Z' bosons, quoted at 95% conf., with $\sqrt{s} = 0.5$ (1.0) TeV and $\mathcal{L}_{\rm int} = 500$ (1000) fb^{-1}. The sensitivity of the LHC-14 via Drell-Yan process $pp \to \ell^+\ell^- + X$ with 100 fb^{-1} of data are shown for comparison. For details, see [14].

hep-ph/0511335



1ab^-1 @ 500 GeV

ILC's Model ID capability is expected to exceed that of LHC even if we cannot hit the Z' pole.

Beam polarization is essential to sort out various possibilities.

Two-Fermion Processes

Compositeness

S. Riemann, LC-TH-2001-007

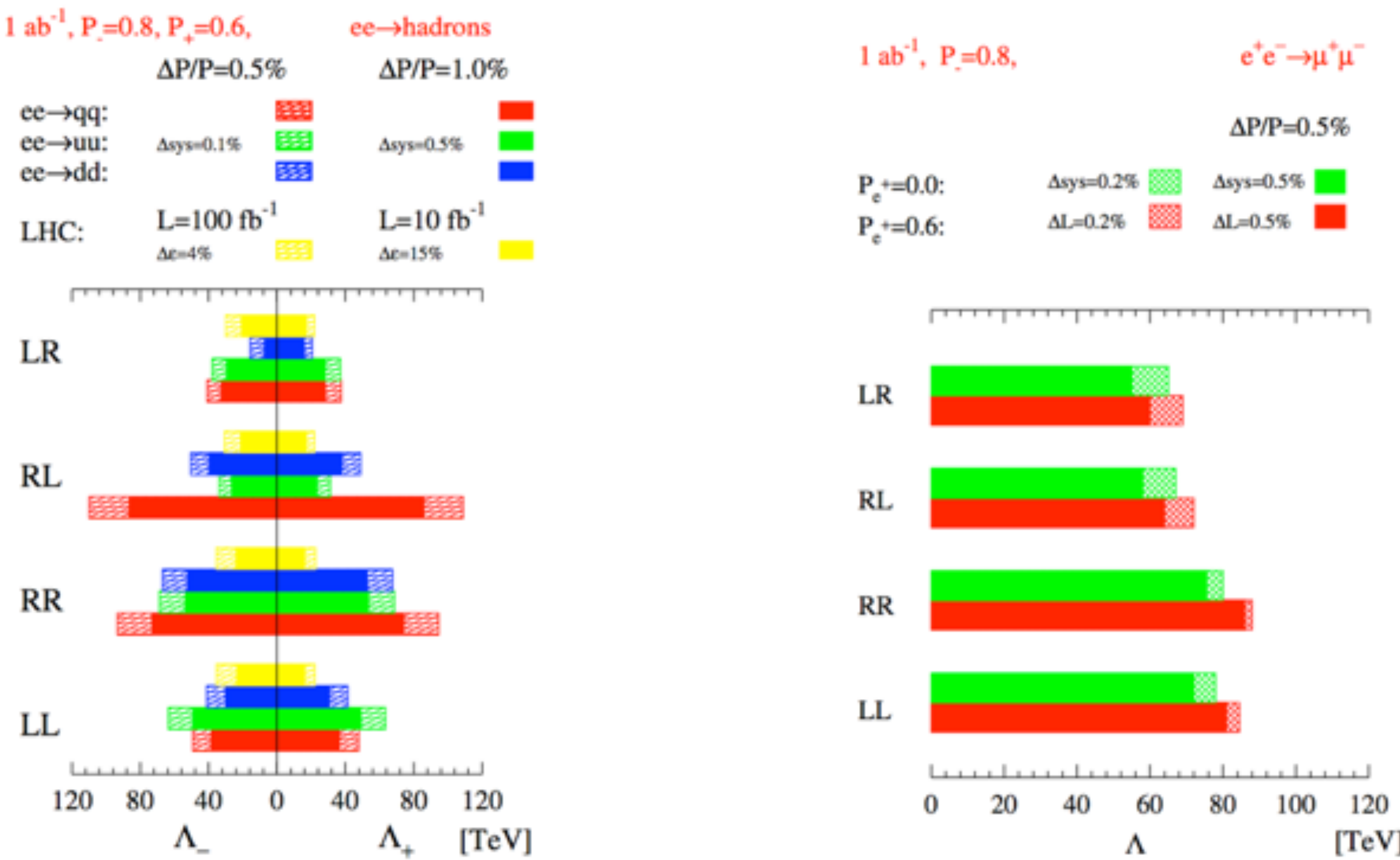


Figure 26: Sensitivities (95% c.l.) of a 500 GeV ILC to contact interaction scales Λ for different helicities in $e^+e^- \to$ hadrons (left) and $e^+e^- \to \mu^+\mu^-$ (right), including beam polarization [18].

Beam polarization is essential to sort out various possibilities.