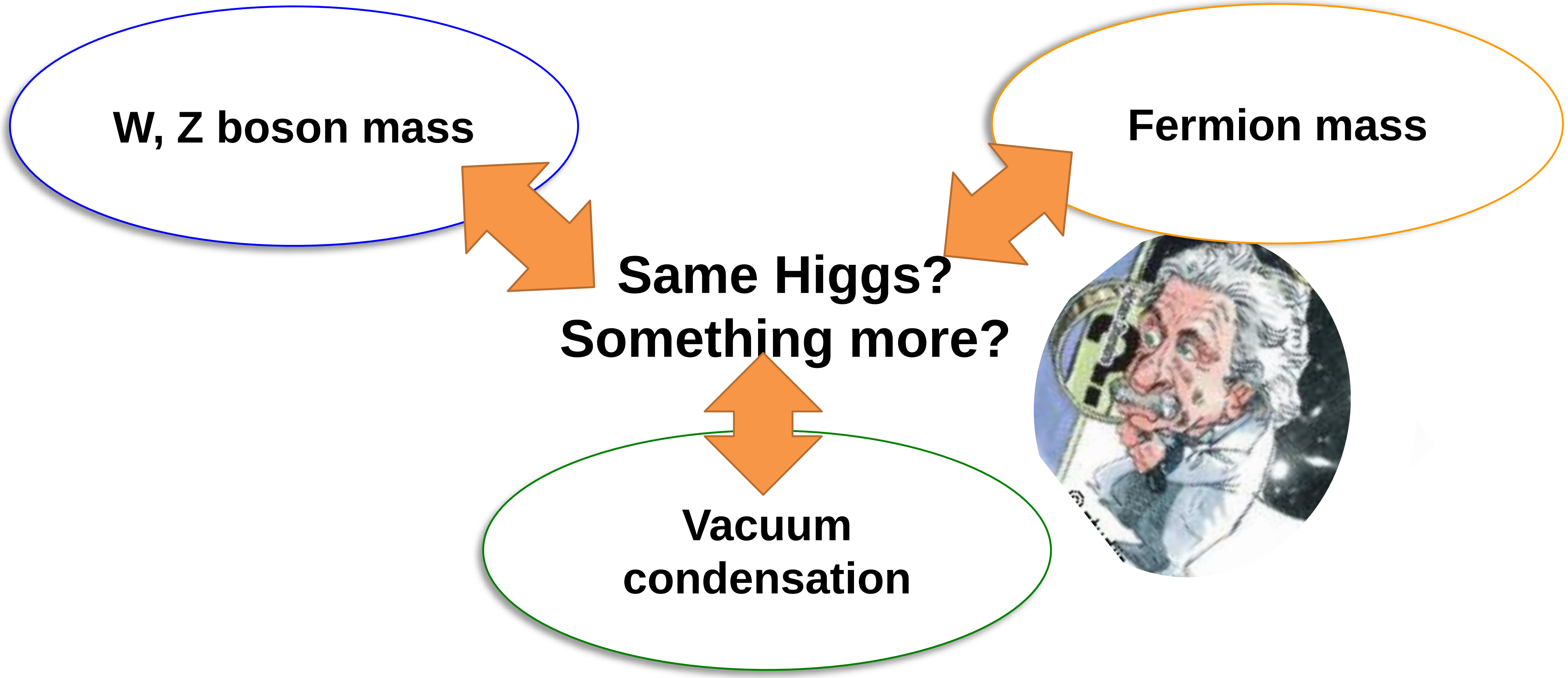
ILC physics to detector

LC13 Trento, Italy

Tohoku Univ. Eriko Kato

Why the Higgs Boson?

The Higgs boson plays a unique role in the SM:



SM contains the simplest possible Higgs sector.

There is no known principle for this simplicity.

➢We need to investigate the structure of the Higgs sector!

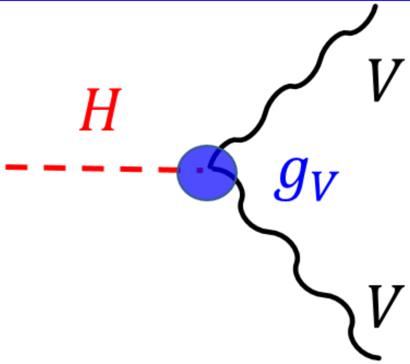
So where shall we start?

For details
Higgs physics session

Completely new type of interactions

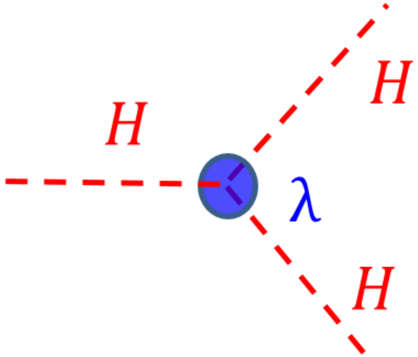
Explain...

HVV coupling



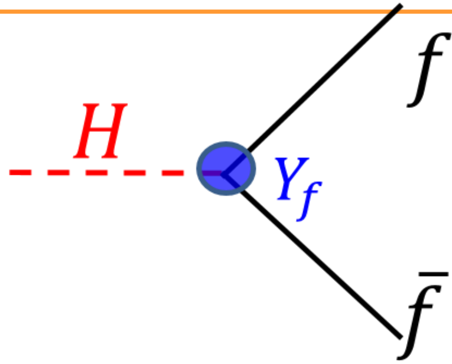
W, Z boson mass

Higgs self-coupling



Vacuum condensation

Yukawa coupling



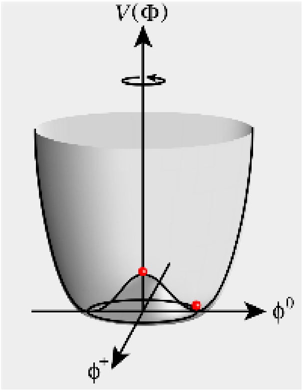
Fermion mass

Higgs couplings deviate from SM certain ways depending on the **structure of the Higgs sector** and it's **underlying dynamics**

- Higgs coupling measurements with high precision might point the direction towards New Physics!

What will we be looking at the ILC ?

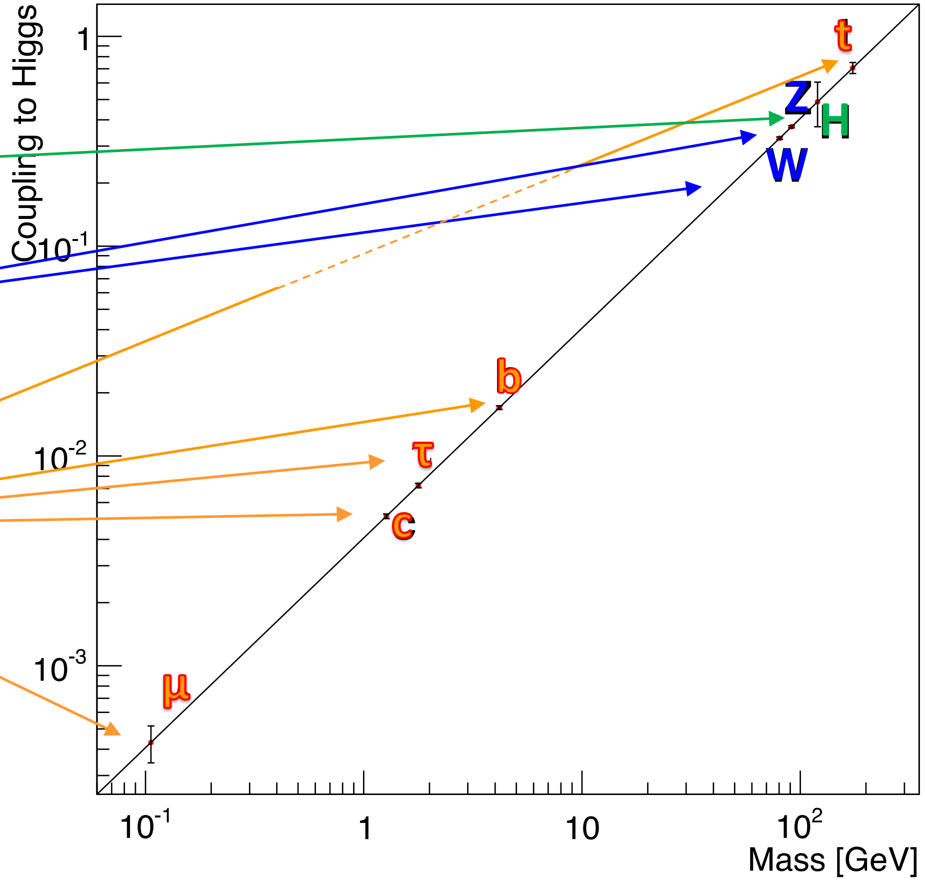
Model independent measurements of absolute Higgs couplings



Higgs *HHH*

Gauge *HVV*

Yukawa *Hff*

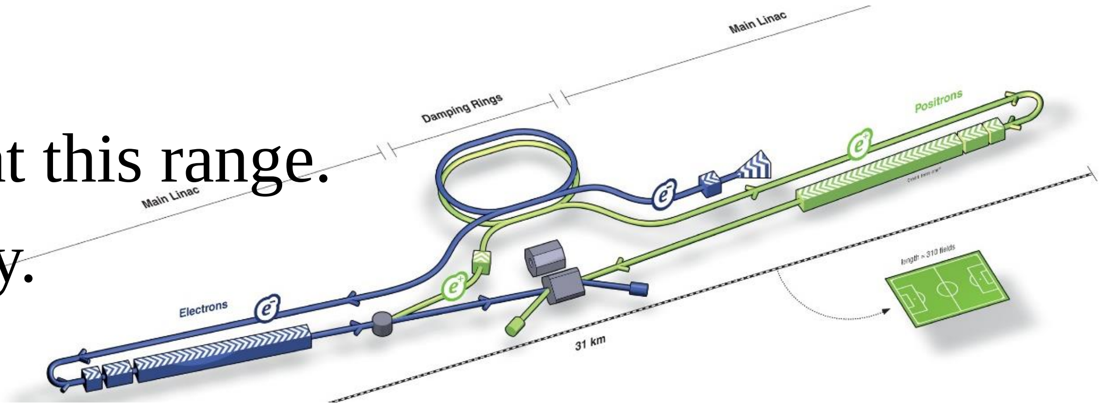


➢ Verify mass coupling relations.

➢ Precision is the key to probing New Physics

ILC, the machine

- E_{CM}: 250GeV - 1TeV
  - major Higgs couplings are all accessible at this range.
  - Tunable energy. Focus on optimum energy.



- Other traits
  - Polarization (for e-/e+) : ±80%/±30% @250 - 500GeV
    ±80%/±20% @1TeV

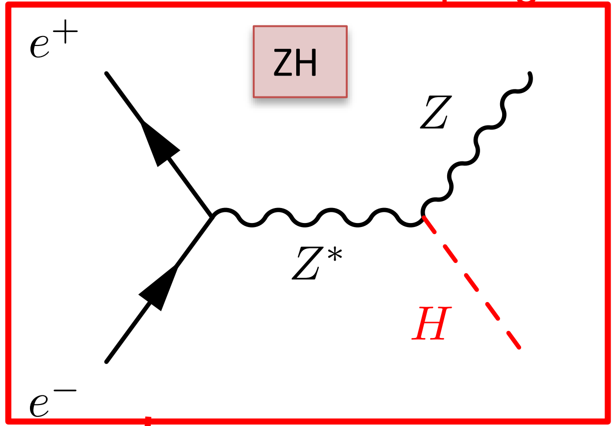
Staging strategy

E_{CM} (GeV)		250	350	500	1000
# of Running years		3	(1)	3	3
Canonical	$\int \mathcal{L} dt$ (fb^{-1})	250	(110)	500	1000
Lumi-up	$\int \mathcal{L} dt$ (fb^{-1})	1150	—	1600	2500

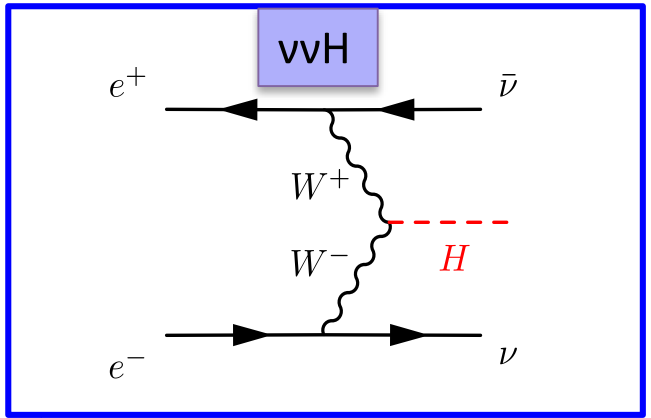
➢ Tunable energy, luminosity and polarization are keys to achieving precision.

ILC, a Higgs factory

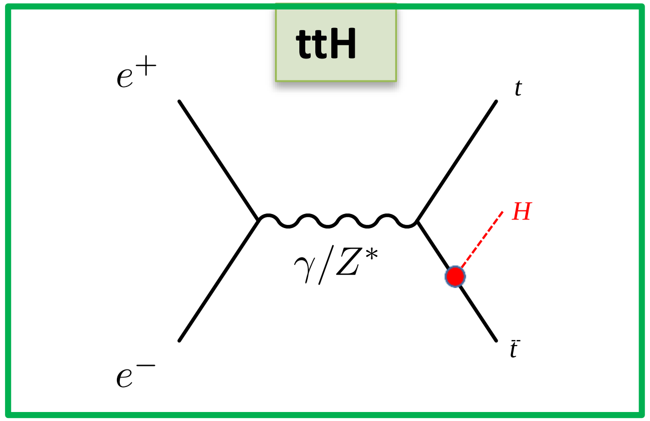
Higgs-strahlung
peaks around 250 GeV
Absolute HZZ coupling

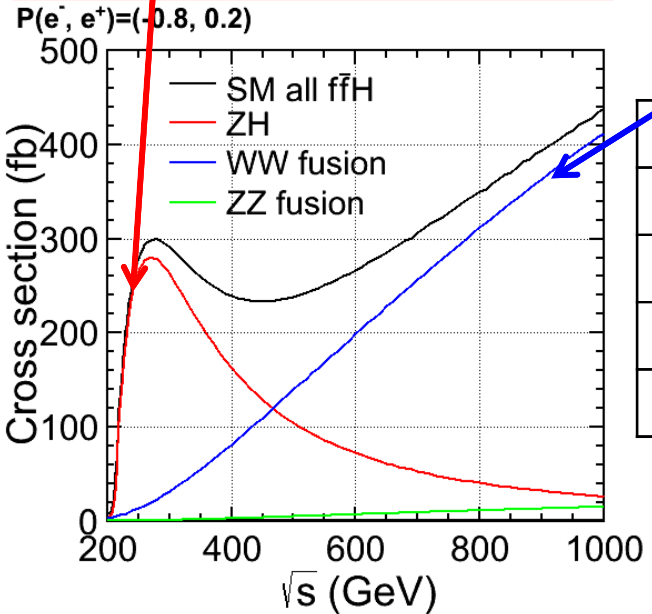


WW fusion
dominates at high energies
Absolute HWW coupling



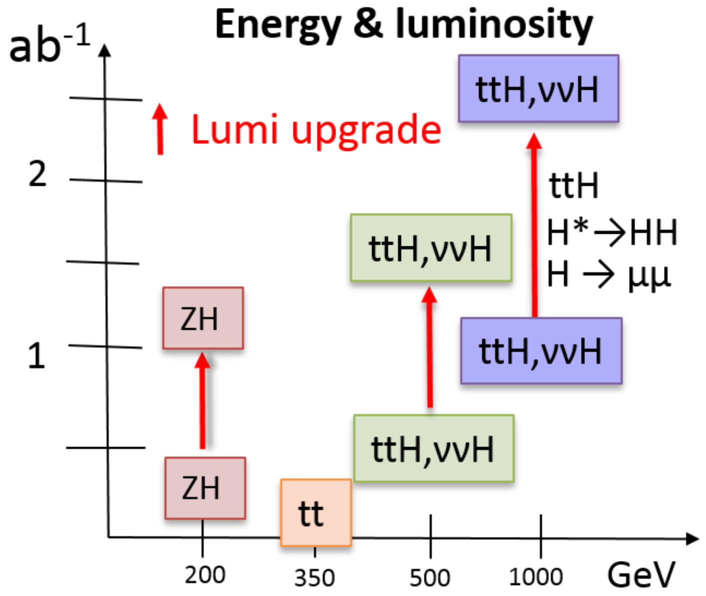
ttH production
Top Yukawa coupling





	250 GeV	500 GeV
$\sigma(e^+e^- \rightarrow ZH)$	303 fb	100 fb
$\sigma(e^+e^- \rightarrow \nu\nu H)$	16 fb	150 fb
# Higgs (canonial)	80,000	125,000
# Higgs (lumi-up)	368,000	400,000

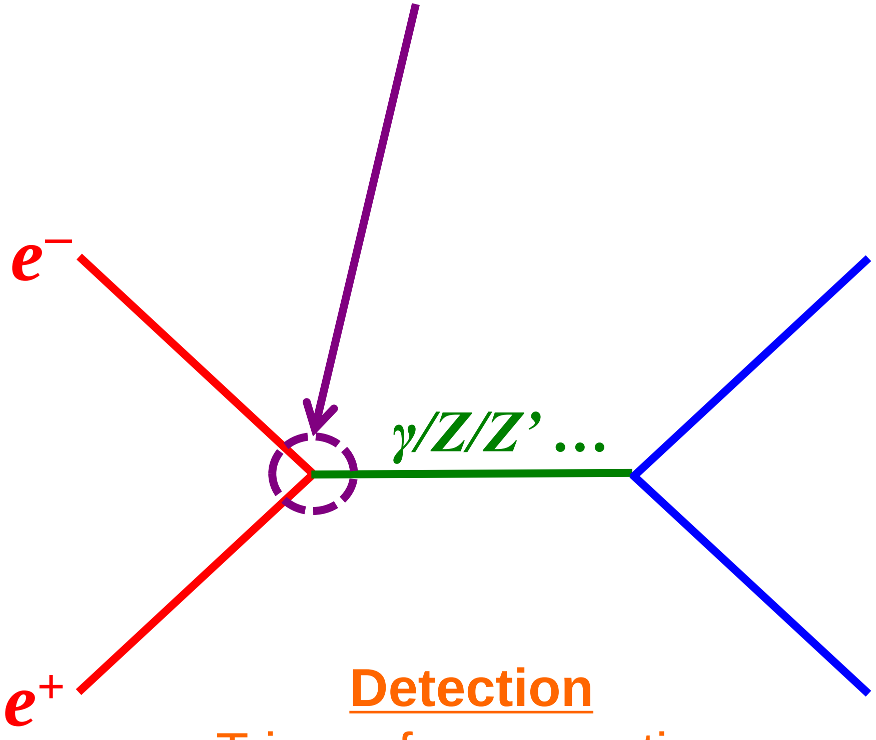
ILC is a Higgs Factory



Weapons for hunting down the Higgs@ILC

<ILC characteristics>

Elementary process



Beam
Tunable energy
High energy
High luminosity
Polarization

Production

Detection
Trigger free operation

Weapons for hunting down the Higgs@ILC

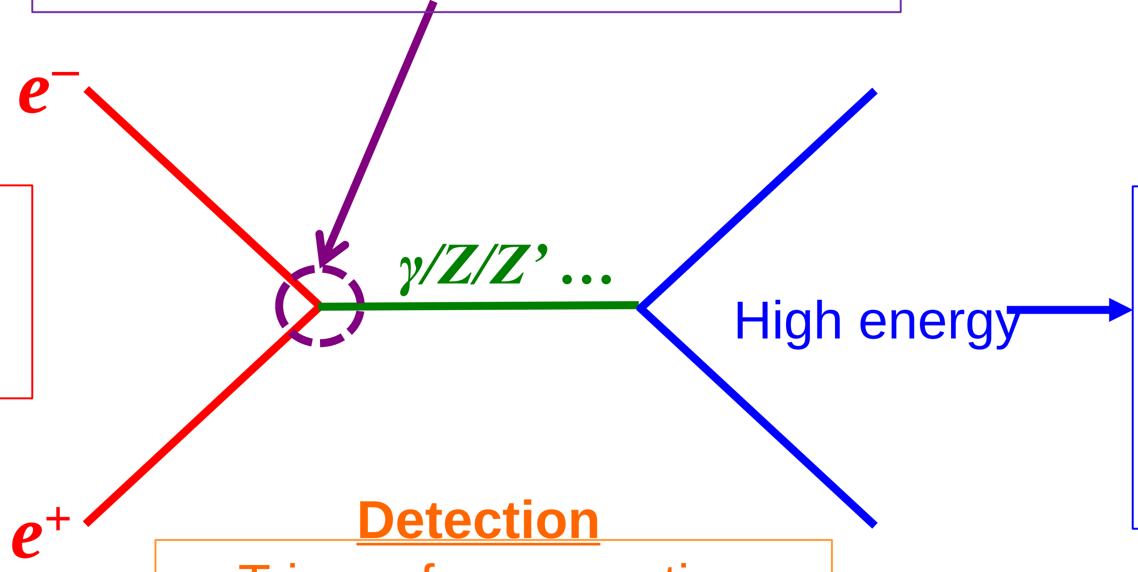
<ILC weapons used for analysis>

Elementary process

Low background
theoretically and experimentally
Well-understood

Beam

High luminosity → Precision
Polarization → BG suppression
Tunable → energy Threshold



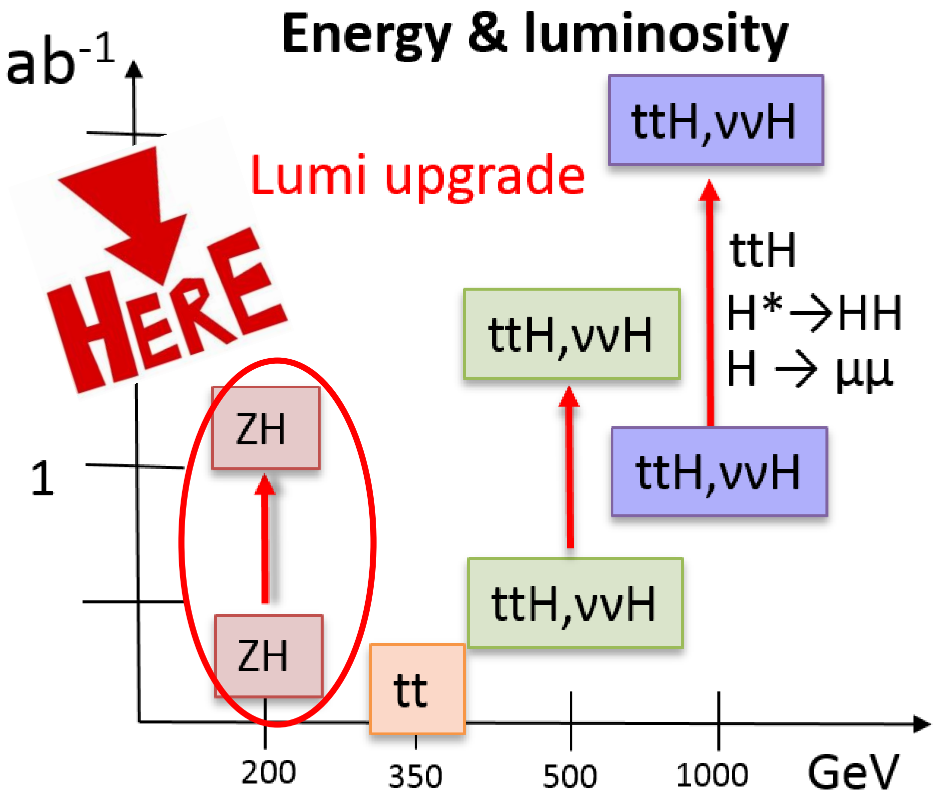
Production

Higgs
(incl ttH,HHH)
Top pair
New particles
…

Detection

Trigger free operation
→ Minimum biased

➢ Model independent precision measurement of absolute couplings become possible



HIGGS COUPLING MEAS.@250GEV

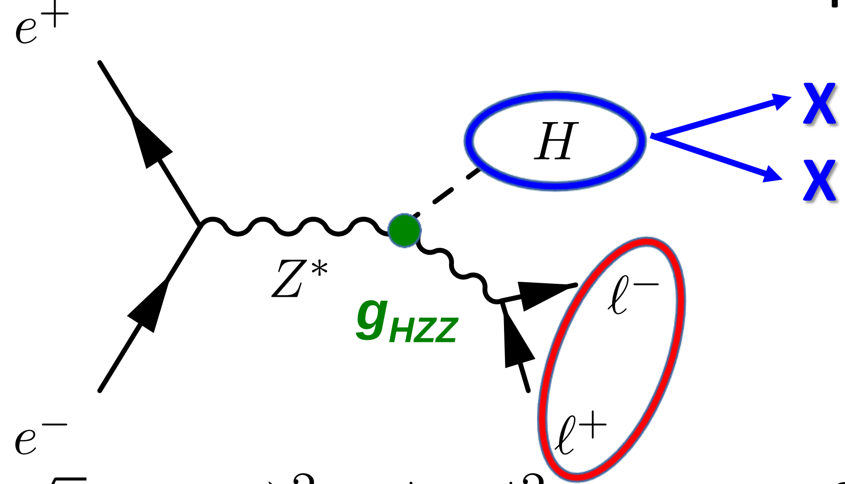
Key to absolute Higgs couplings @250GeV

Higgs recoil measurements

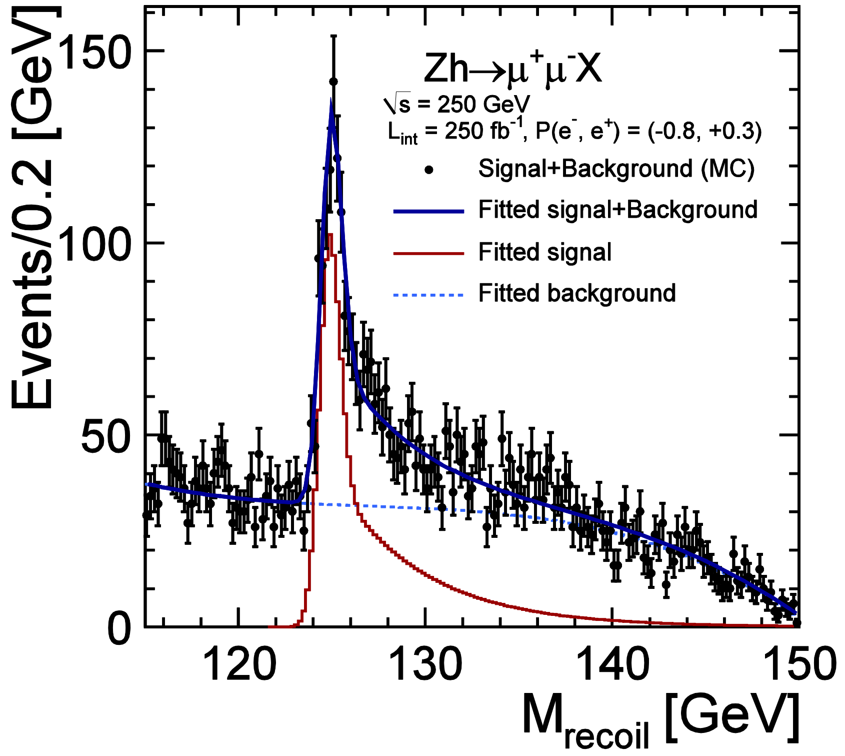
Capture Higgs w/o looking at its decay product!

Even Invisible decay is detectable

Absolute measurement of HZZ couplings



$$m^2_{\text{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2 \qquad \sigma_{ZH} \propto g^2_{HZZ}$$



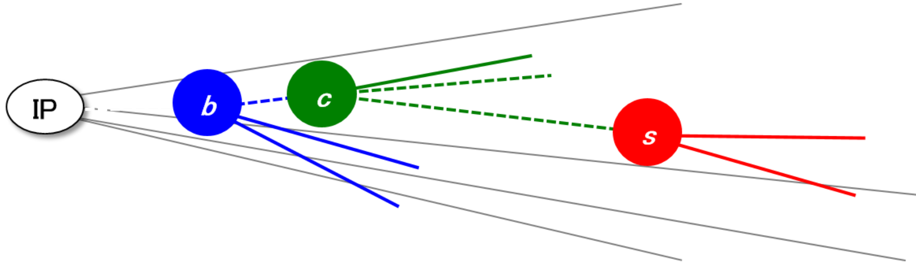
Precision	250 fb^{-1}	1150 fb^{-1}
σ_{ZH}	2.6%	1.3%
g_{HZZ}	1.3%	0.7%

$$Br(H \to XX) = \frac{\sigma_{ZH} Br(H \to XX)}{\sigma_{ZH}} \propto g^2_{HXX}$$

- σ_{ZH}, g_{HZZ} are the keys to model independent meas. of absolute Higgs couplings

Branching ratio measurement

$$Br(H \to XX) = \frac{\sigma_{ZH} Br(H \to XX)}{\sigma_{ZH}} \propto g_{HXX}^2$$



Br(H→cc,bb,gg) measurement

Become bkg. Of each other.

- ➢ Precise flavor tagging(b, c tagging) is essential.

Flavor tagging

of Lepton tracks

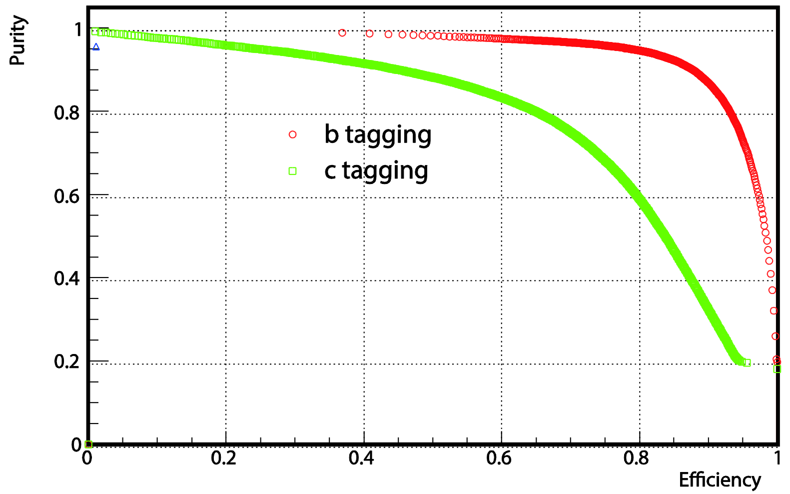
Decay length($c\tau_b \approx$ 450-500 mm, $c\tau_c \approx$ 100-300 mm)

Mass ($m_b \approx$ 5 GeV, $m_c \approx$ 2 GeV)

H→ττ,VV

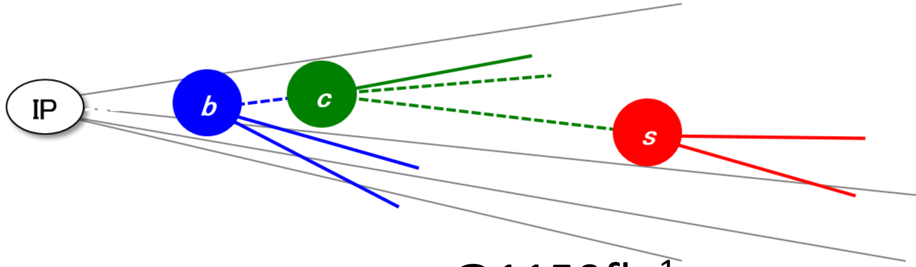
Mass etc.

Flavor tagging
@Z→qq 91GeV



Branching ratio measurement

$$Br(H \to XX) = \frac{\sigma_{ZH} Br(H \to XX)}{\sigma_{ZH}} \propto g_{HXX}^2$$



Br(H→cc,bb,gg) measurement

Become bkg. Of each other.

- ➢ Precise flavor tagging(b, c tagging) is essential.

Flavor tagging

of Lepton tracks

Decay length($c\tau_b \approx$ 450-500 mm, $c\tau_c \approx$ 100-300 mm)

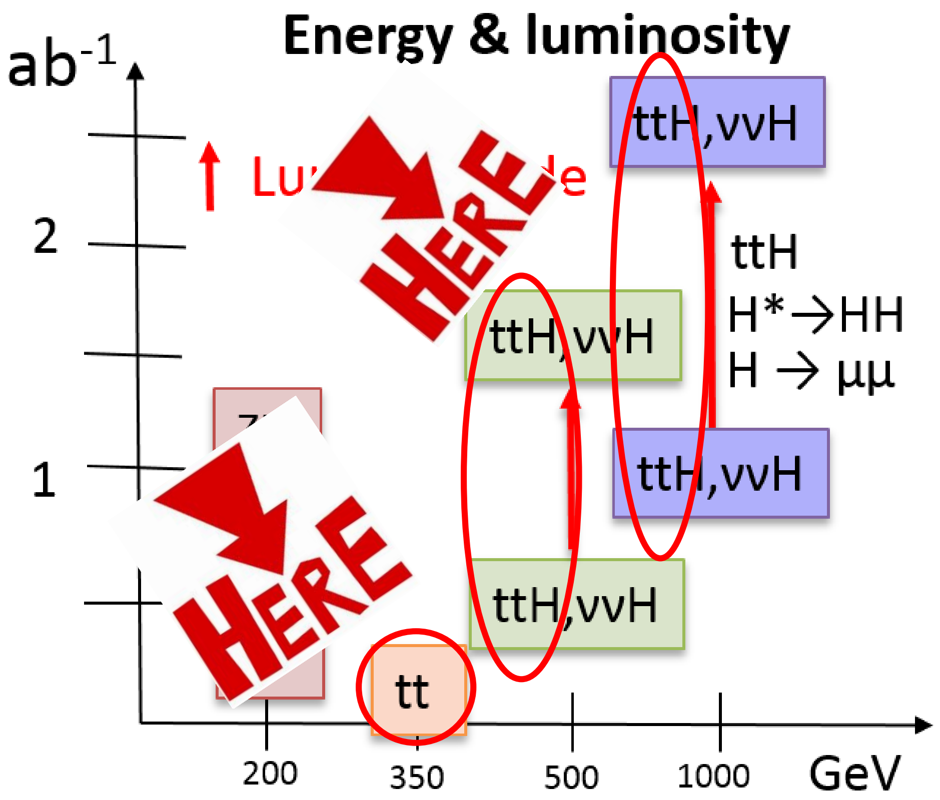
Mass ($m_b \approx$ 5 GeV, $m_c \approx$ 2 GeV)

H→ττ,VV

Mass etc..

@1150fb^{-1}

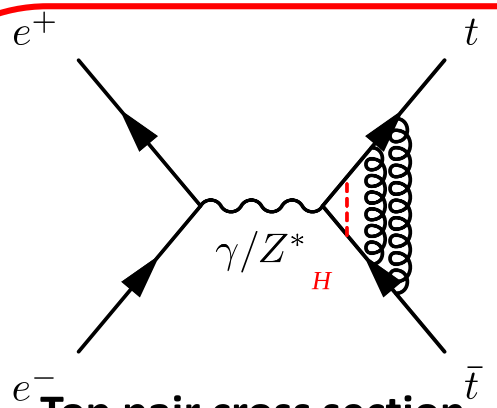
σZH	
Cross section	1.2%
σZH*Br	
H→bb	0.56%
H→cc	3.9%
H→gg	3.3%
H→WW*	3.0%
H→ττ	2.0%
H→ZZ*	8.8%
H→γγ	16%
H→inv	<0.44%



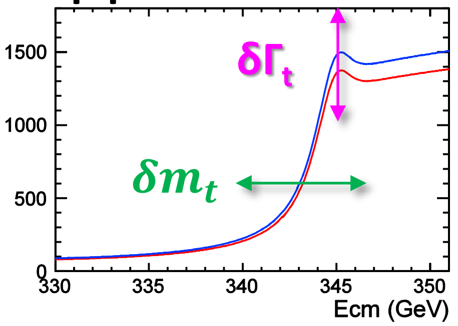
TOP YUKAWA COUPLING MEAS.@ILC

Top Yukawa coupling

Top pair threshold 350GeV



Top pair cross section



w/ g_{ttH}

w/o g_{ttH}

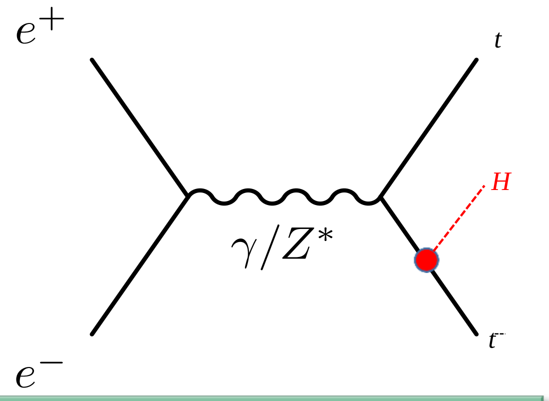
$\delta\Gamma_t$: 21MeV

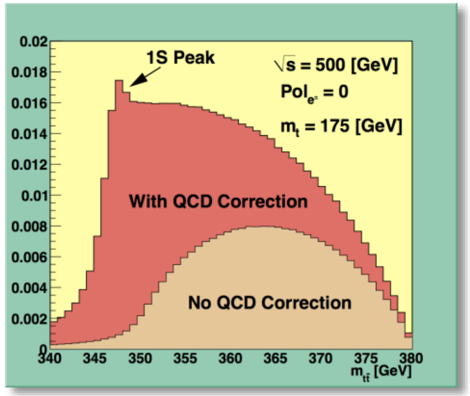
$\delta m_t(\overline{MS})$: 16(stat) + 54($\alpha_s$)MeV

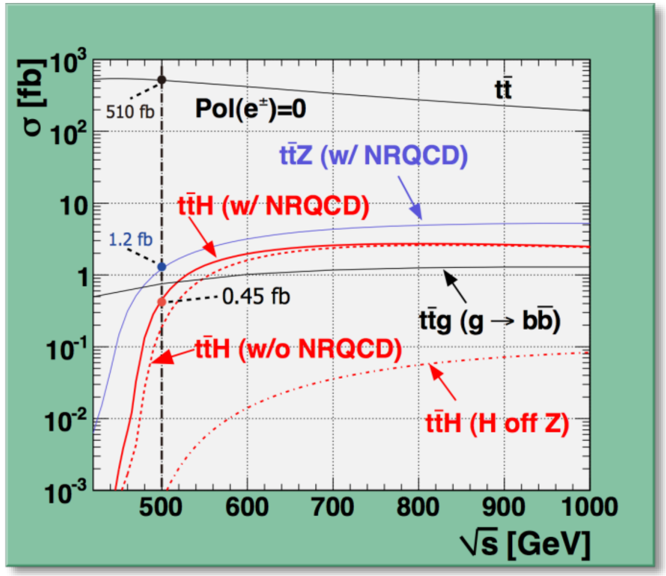
$\Delta g_{ttH}/g_{ttH}$	350GeV
220 fb^{-1}	4.2%

※Δ(Exp) only.

Open top 500GeV & 1TeV



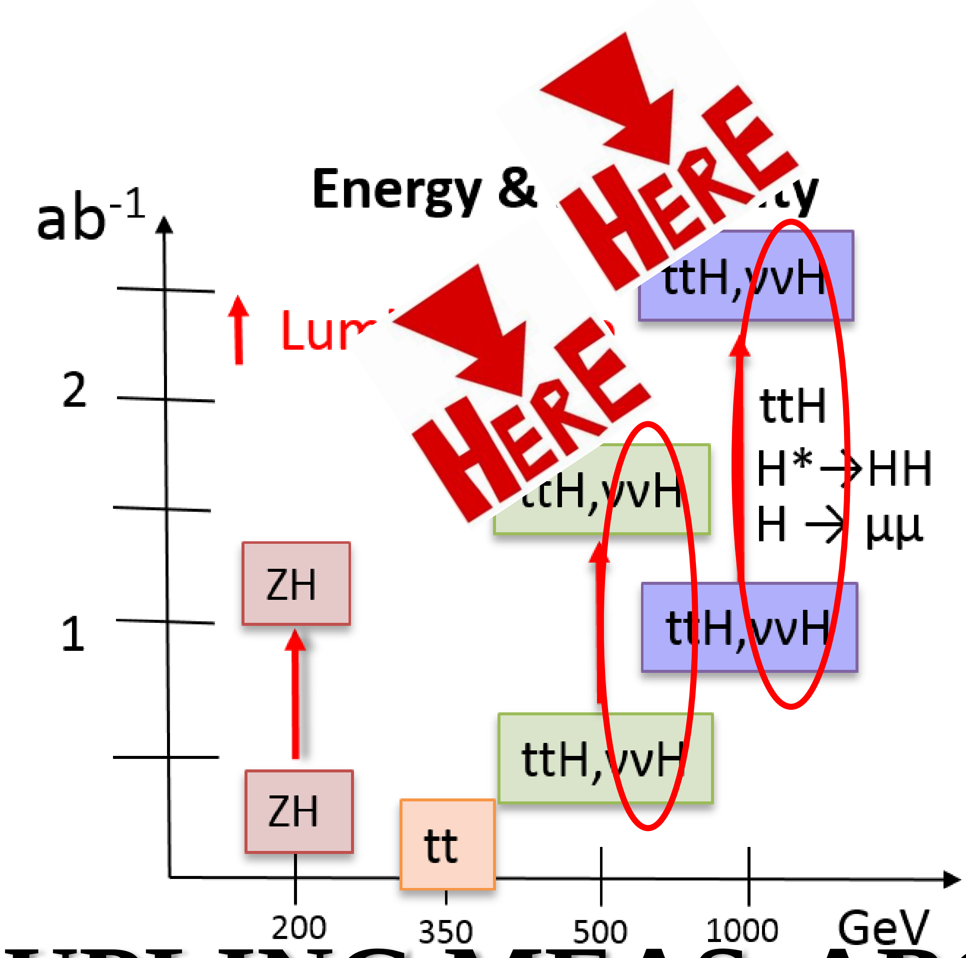




factor of 2 enhancement from QCD bound-state effects @500GeV

$\Delta g_{ttH}/g_{ttH}$	500GeV	+1TeV
Canonical	14%	3.2%
Lumi up	7.8%	2.0%

Main BG:ttZ, tbW, ttg(g→bb)



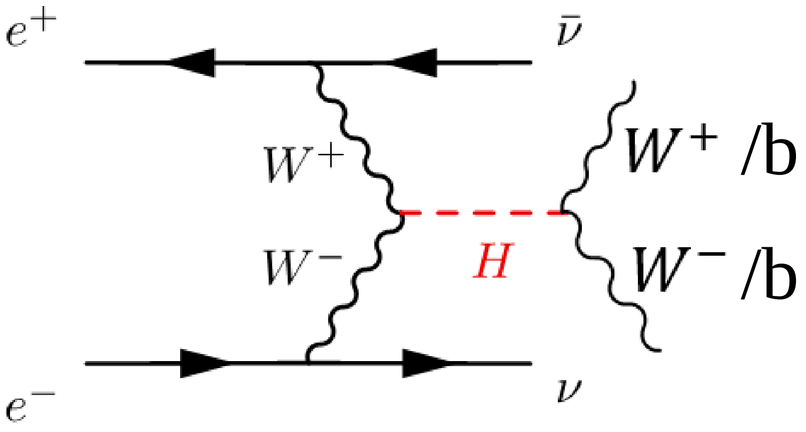
HIGGS COUPLING MEAS. ABOVE 500GEV

Key to Higgs couplings

above 500GeV

WW fusion

dominates at high energies



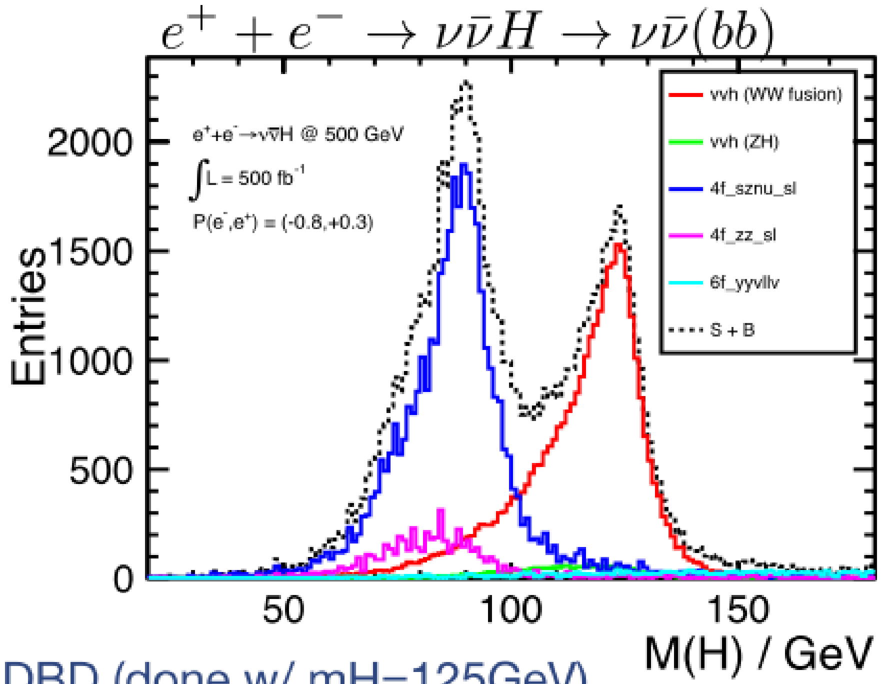
absolute normalization g_{HWW}

$$\sigma_{\nu\nu H} Br_{(H\to bb)} \sim g^2_{HWW} Br_{(H\to bb)}$$

$$\Gamma_{tot} = \frac{\Gamma_{HWW}}{Br(H\to WW^*)} \propto \frac{g^4_{HWW}}{\sigma_{\nu\nu H} Br(H\to WW^*)}$$

g_{HWW} gives Higgs total width Γ_{tot}

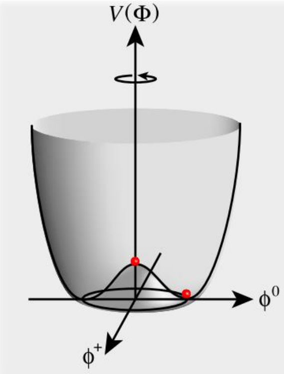
absolute normalization of other couplings g_{HXX}



DBD (done w/ mH=125GeV)

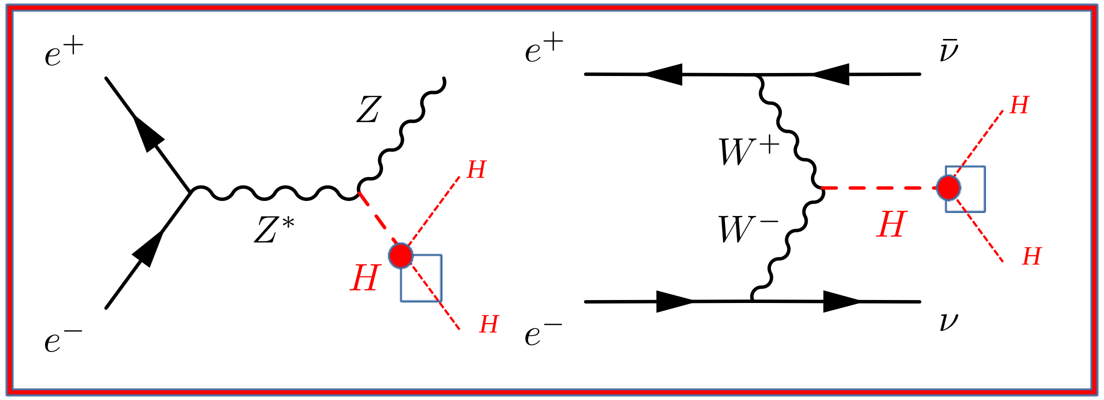
Precision	500 fb^{-1}	2500 fb^{-1}
g_{HWW}	1.4%	0.7%
Γ_{tot}	~6%	~3%

Higgs self coupling

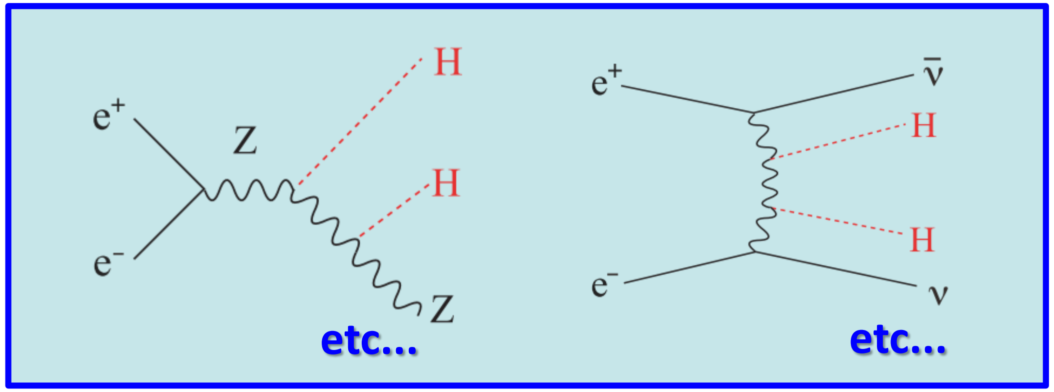


- What makes the Higgs condense in the vacuum?
  - We need to measure Higgs self-coupling λ, the shape of the Higgs potential

500 GeV~ Higgs Self-Coupling



Many Irreducible diagrams



500GeV

$$\frac{\Delta\lambda}{\lambda} = 1.66 \frac{\Delta\sigma}{\sigma}$$

1TeV

$$\frac{\Delta\lambda}{\lambda} = 0.76 \frac{\Delta\sigma}{\sigma}$$

Coupling accuracy diluted(F=0.5 if no BG diagrams)

Δλ/λ	500GeV	+1TeV
Canonical	83%	21%
Lumi up	46%	13%

※HH→bbbb, bbWW combined

σ_{ZHH} ~0.13fb, large BG→high polarization & luminosity effective

Higgs Coupling Precision

(model-independent)

Facility		ILC		ILC(LumiUp)
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)
Γ_H	11%	5.9%	5.6%	2.7%
BR_{inv}	$< 0.69\%$	$< 0.69\%$	$< 0.69\%$	$< 0.32\%$
κ_γ	18%	8.4%	4.1%	2.4%
κ_g	6.4%	2.4%	1.8%	0.93%
κ_W	4.8%	1.4%	1.4%	0.65%
κ_Z	1.3%	1.3%	1.3%	0.61%
κ_μ	–	–	16%	10%
κ_τ	5.7%	2.4%	1.9%	0.99%
κ_c	6.8%	2.9%	2.0%	1.1%
κ_b	5.3%	1.8%	1.5%	0.74%
κ_t	–	14%	3.2%	2.0%

➢ Overall, 1% or sub-persent accuracy can be achieved

Higgs Coupling Precision

(model-dependent)

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%	0.13%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.44%	0.22%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%
κ_d	10 – 13%	4 – 7%	0.93%	0.51%	0.51%	0.31%
κ_u	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.76%

Main assumption :

$$\frac{\Gamma_{tot}}{\Gamma_{tot}|_{\rm SM}} = \sum_i \kappa_i^2 Br_i|_{\rm SM}$$

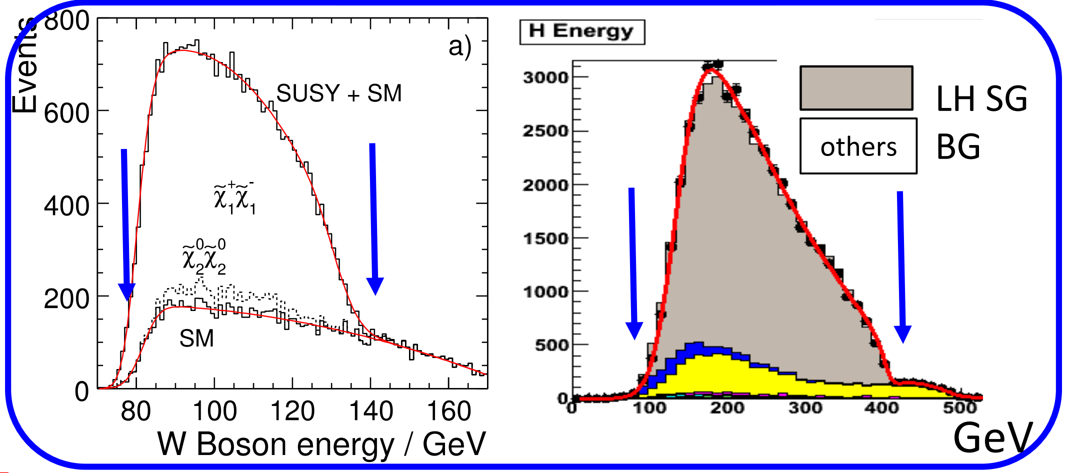
➢Overall, approximately one order better

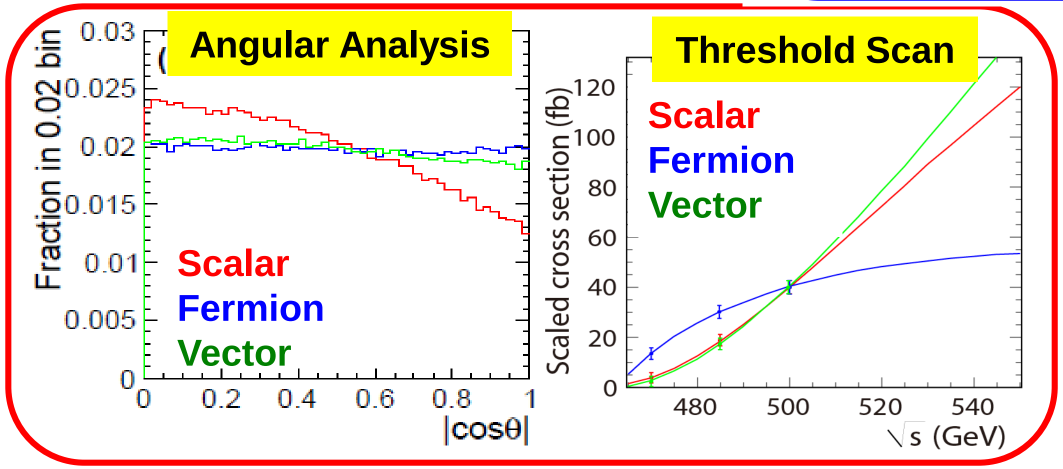
In the search of a new particle

<Of course if NP happens to be in our reach, we have various weapons to nail it!!>

- **kinematic edges** detection→Discovery + model independent mass measurement:
  - e.g. (SUSY) $e^+ e^- \rightarrow \chi_1^+ \chi_1^- \rightarrow \chi_1^0 \chi_1^0 W^+ W^-$
  - (Little Higgs) $e^+ e^- \rightarrow Z_H Z_H \rightarrow A_H A_H HH$
  - etc..
  - Mass measurement $\mathcal{O}(1)$ % order
- **Model Discrimination with spin** information
  - $X^+ X^- \rightarrow W^- W^+$ DMDM
  - X: spin 0, 1/2, 1

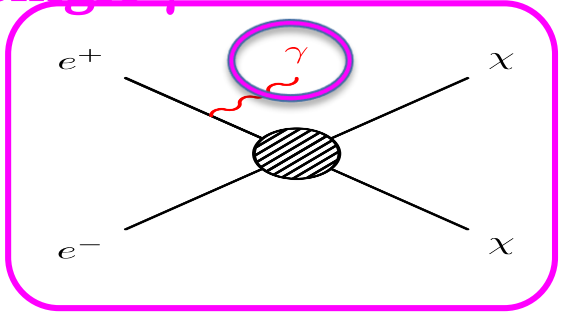
Energy distribution



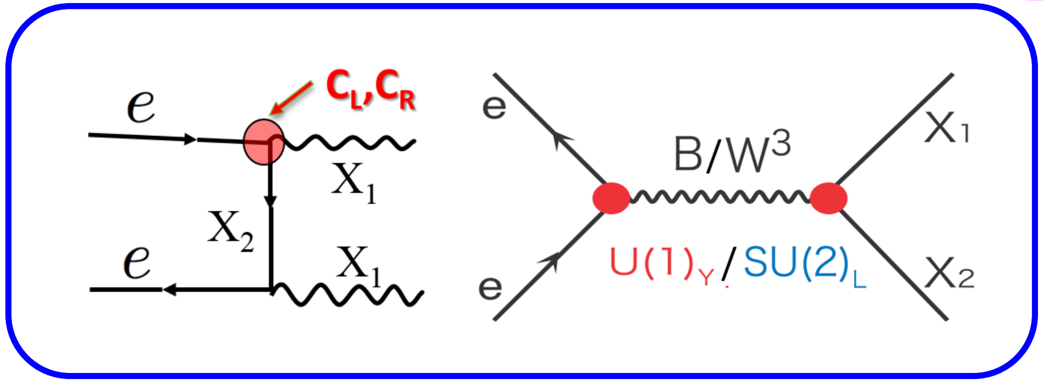


In the search of a new particle

- ILC sensitive to processes that involve **colorless particles**
  - e.g. light Chargino/neutralino higgsino-dominated→mass nearly degenerated
  - Even for sub-GeV mass differences, the charginos/neutralinos can be discovered / measured to O(1)% in mass.
- **DM + ISR**
  - Case where only DM is accessible@ILC → Can still discover w/ **single γ**



- **Polarization**
  - L&R-handed couplings measurement via cross section
  - New particle gauge charge



And more…

Challenges ~what drives technology~

Higgs self coupling, top Yukawa coupling

challenges

Small signal

Large background

(irreducible diagram + combinatorial background)

Key tools

Lumi-up grade
Polarization
} **accelerator**

Lepton selection
Flavor tagging
Mass resolution
} **Detector**
Jet energy resolution,
Momentum resolution,
Impact para. resolution

Higgs recoil measurements

challenges

Individually g_{HXX}(X:ff,VV,ll,inv etc) improve with the same factors as higgs self coupling & top Yukawa.

However..

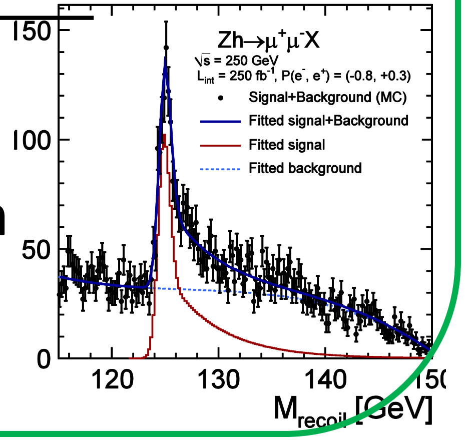
model independent precision upper-limit set by recoil precision

$$g_{HXX}^2 \propto \frac{\sigma_{ZH} Br(H \to XX)}{\sigma_{ZH}}$$

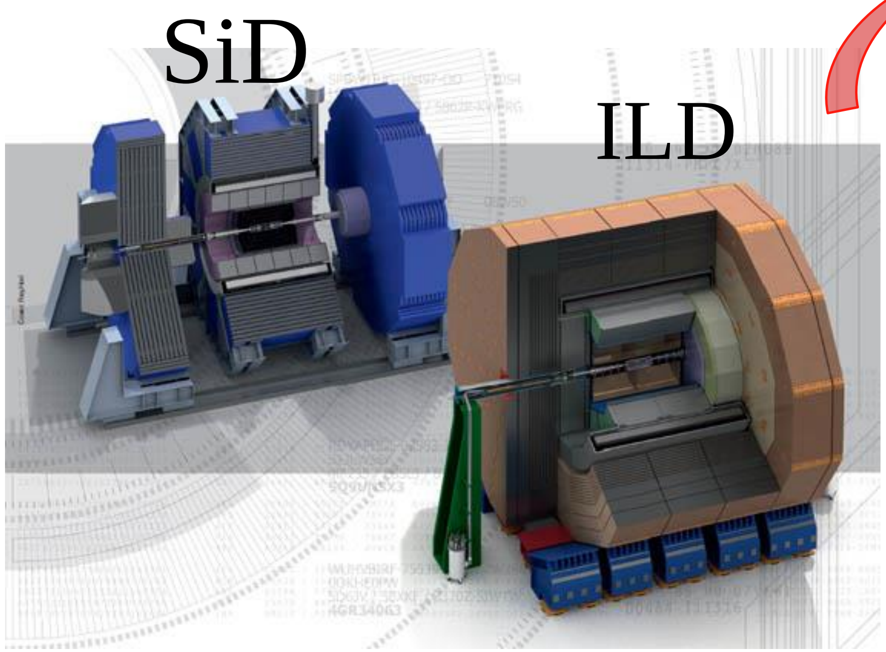
Key tools

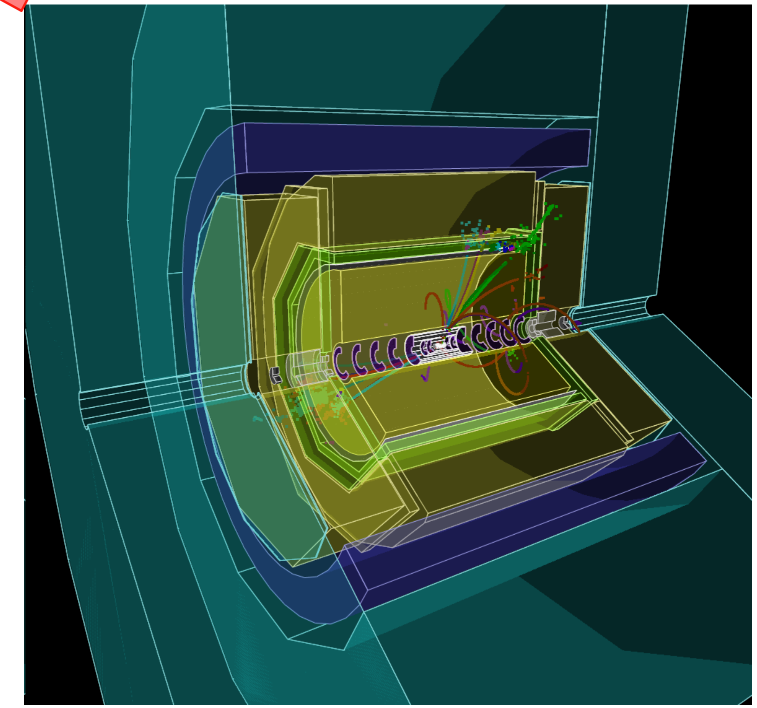
Momentum resolution

Statistics



➢ Physics is what drives technology to a precision we have never achieved before.

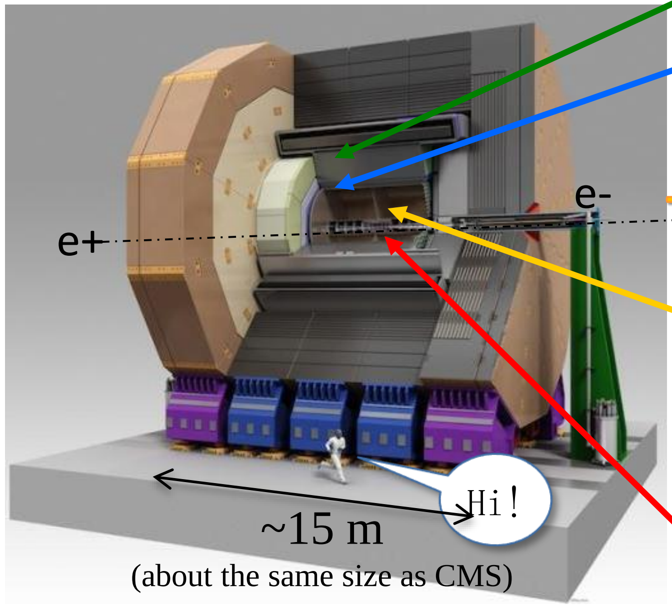




TO DETECTOR(FOCUSING ON ILD)

International Large Detector (ILD)

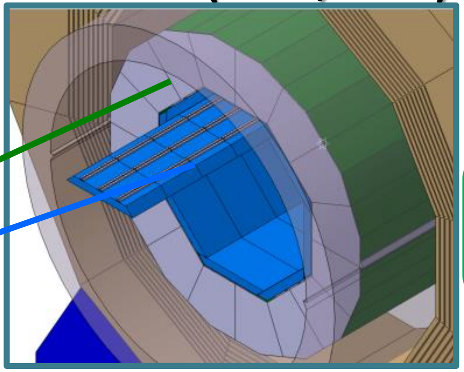
International Large Detector(ILD)



Low Background
Trigger free operation
Low radiation environment

Main detector components

CALorimier(ECAL,HCAL)

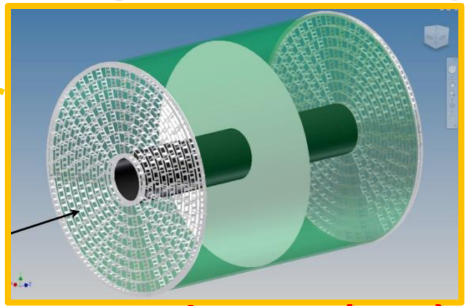


Energy resolution

$$\frac{\sigma_E}{E} \sim 3-4\% \sim 30\%/\sqrt{E}$$

@100GeV

Time Projection Chamber(TPC)

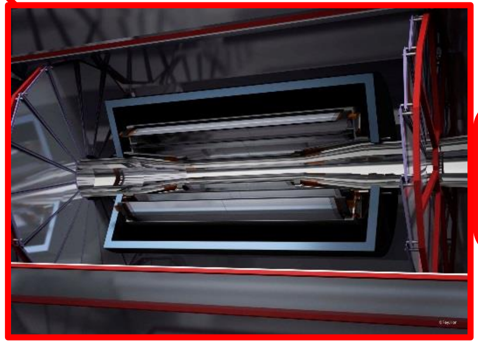


Momentum resolution

$$\sigma_{1/P_T} \sim 2\times10^{-5}\ [1/\mathrm{GeV}]$$

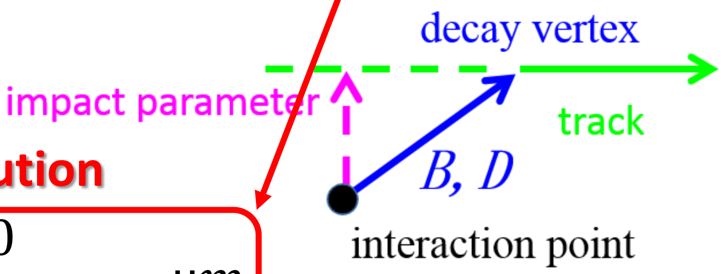
Determined by physics!

VerTeX detector(VTX)



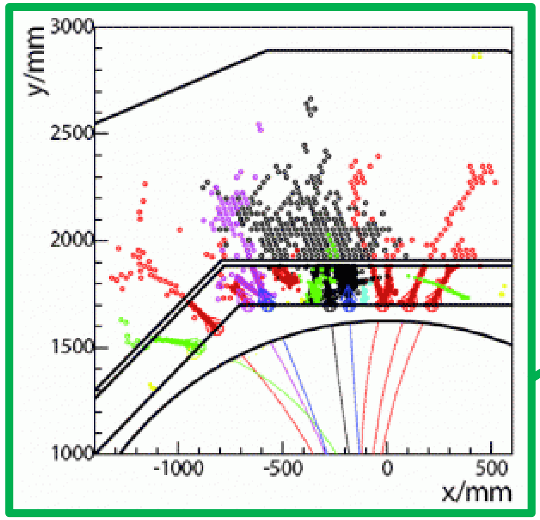
Impact parameter resolution

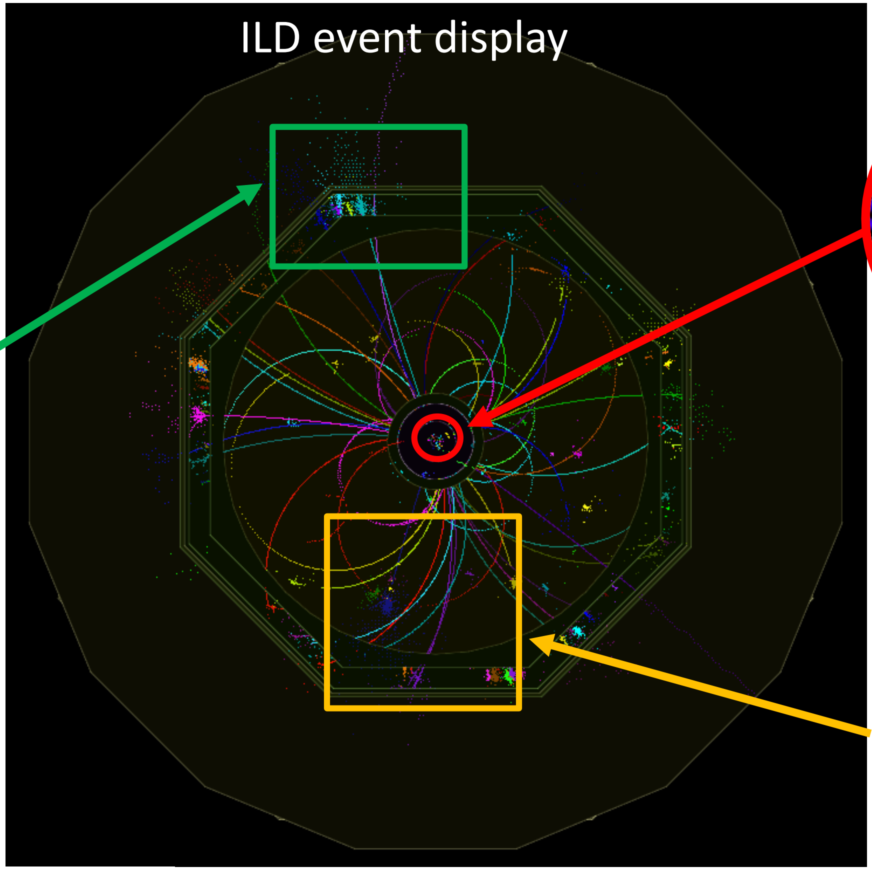
$$\sigma_{r\phi} = 5\mu m \oplus \frac{10}{p(GeV\ sin^{3/2}\theta)}\ \mu m$$



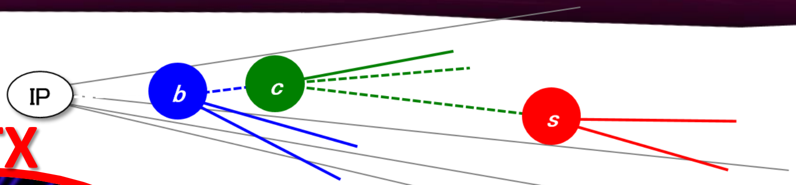
Physics to design

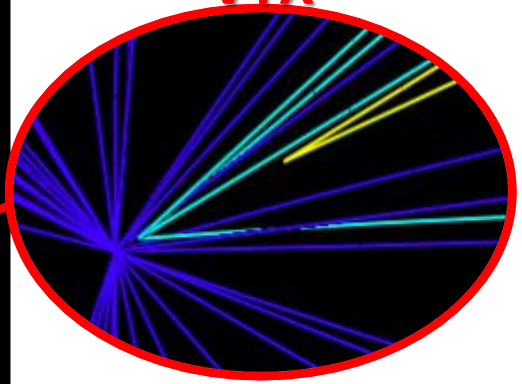
CALORIMETER





VTX





Is this c, b, or sth else?

<HHH coupling>

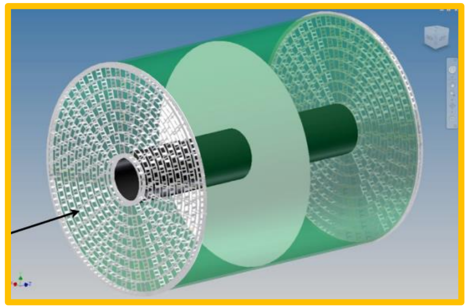
SG: ZHH $\rightarrow q_1\bar{q_2}b\bar{b}b\bar{b}$

BG: $t\bar{t} \rightarrow bq_1\bar{q_2}\bar{b}q_3\bar{q_4}$

<Hcc coupling>

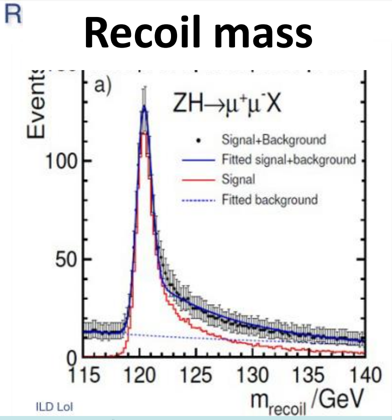
SG: H $\rightarrow c\bar{c}$,BG: H $\rightarrow b\bar{b}$

TPC



momentum resolution

Recoil mass



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

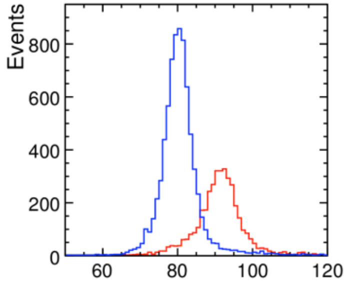
$$\Delta\sigma_H/\sigma_H = 2.5\%$$

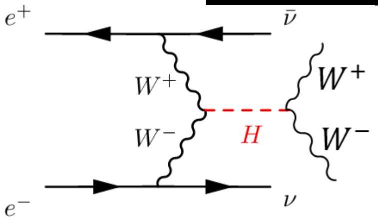
$$\Delta m_H = 30\,\mathrm{MeV}$$

Energy resolution

W, Z mass hadronic decay

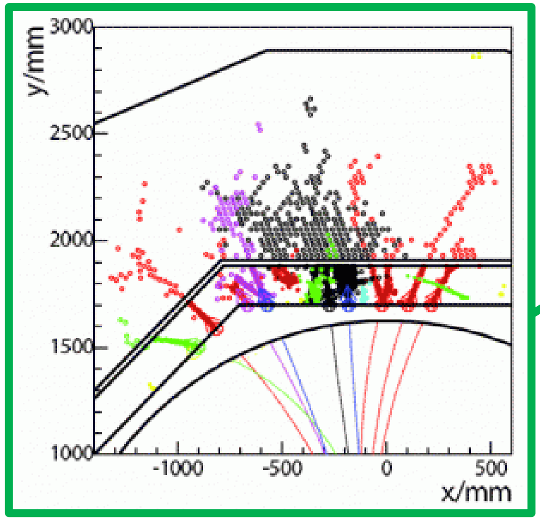
3σ separation

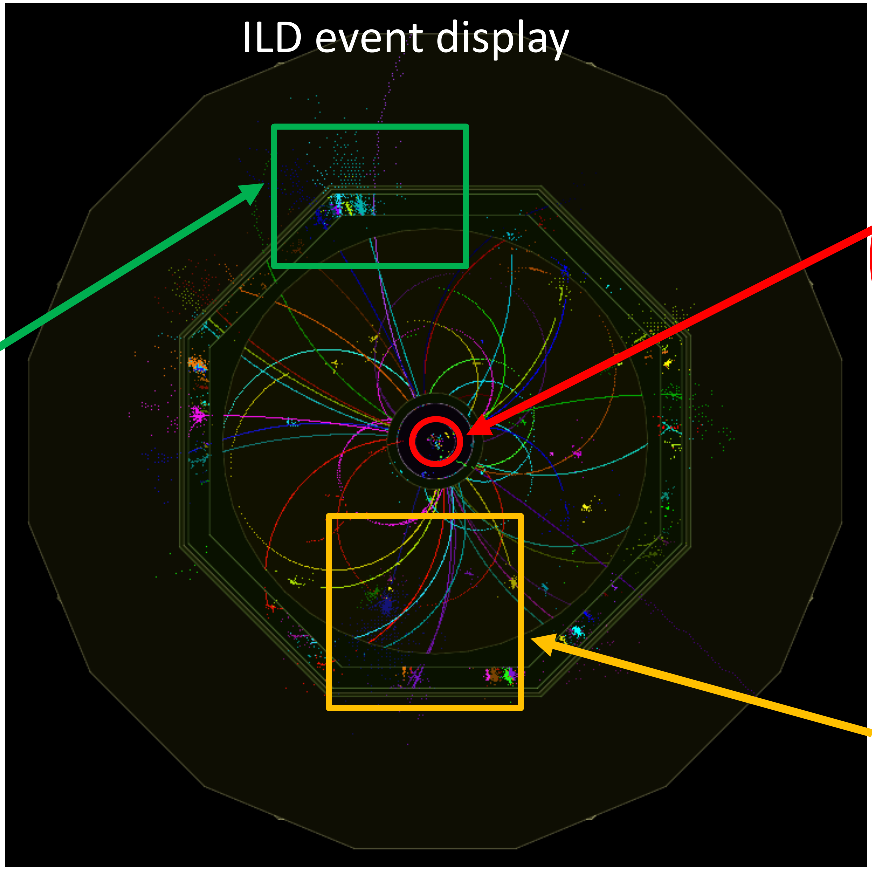




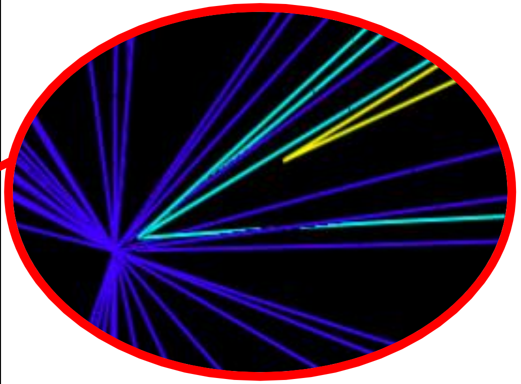
Challenges

CALORIMETER





VTX



Is this c, b, or sth else?

Many tracks

Many beam BG events

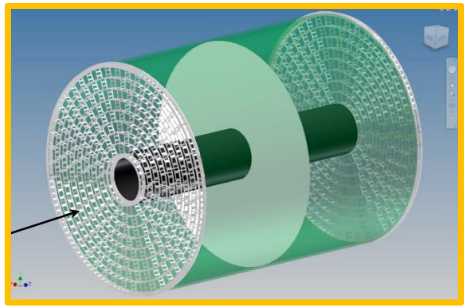
Position resolution

Close to IP

Fine segmented sensors

Low material

TPC



momentum resolution

Large # of space points

Low material

Energy resolution

$\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E_0}}$ for single jet

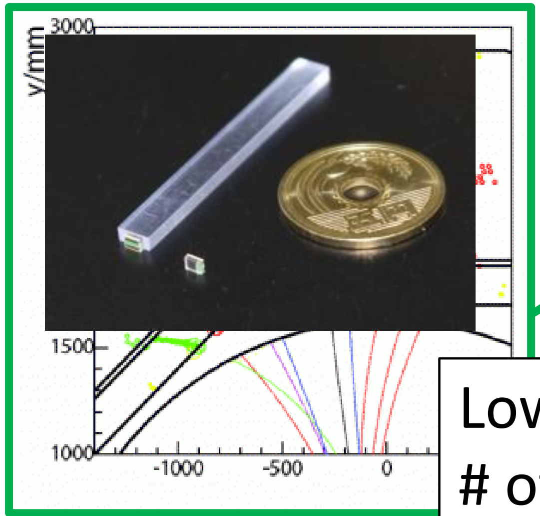
Boosted jet overlap

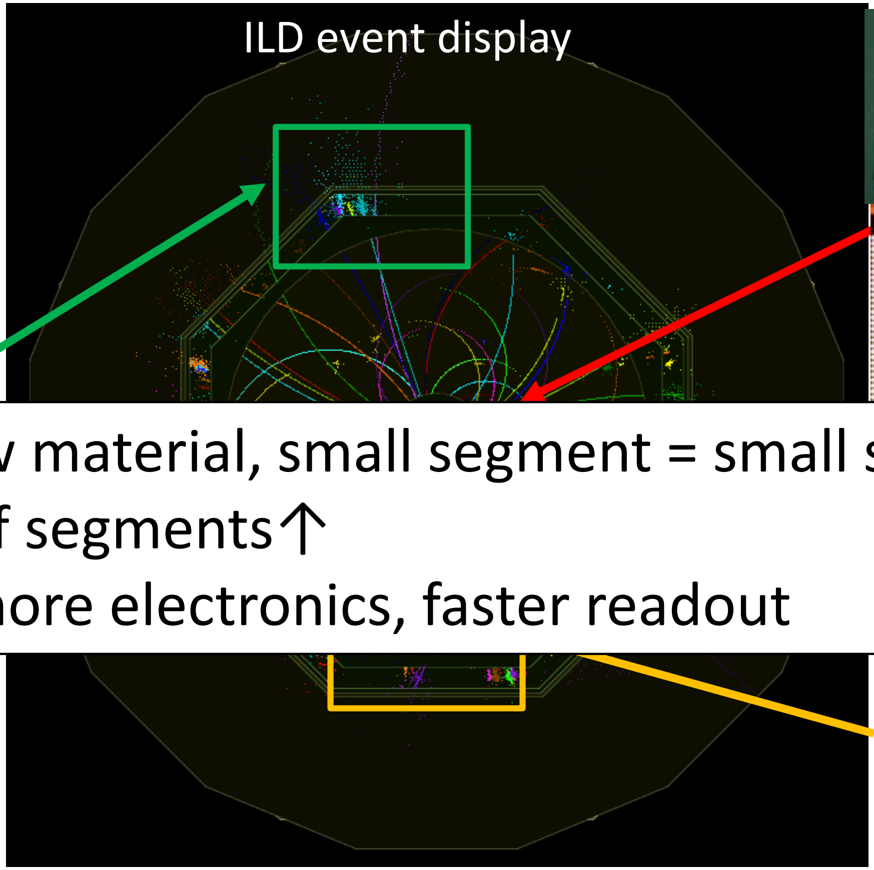
→compact shower

→fine granaralty, dense absorber

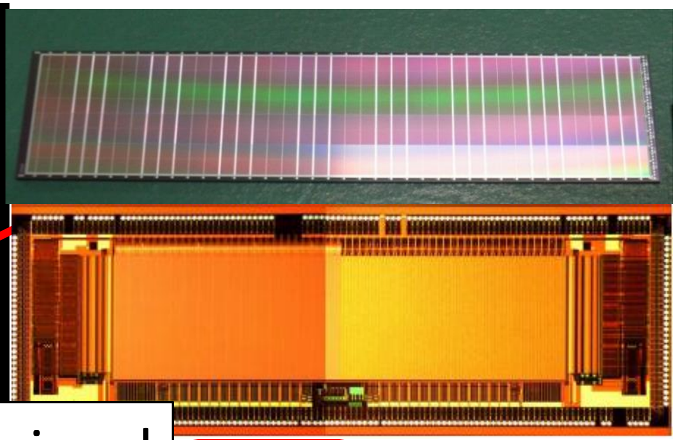
State of the art detector technology

CALORIMETER





VTX

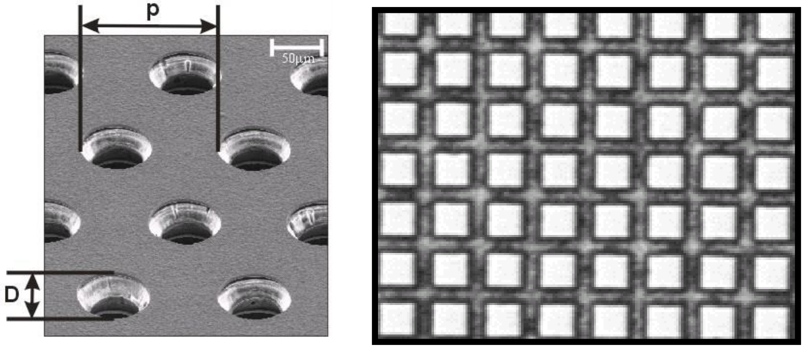


Small thin pixel
Low noise
Fast readout
Low Power

Low material, small segment = small signal
# of segments↑
= more electronics, faster readout

TPC

High gain
Fine granularity readout



Particle Flow Algorithm
Remove jets from HCAL
That aren't neutral hadrons

CAL	Fraction	$\sigma_E/\sqrt{E}$
HCAL	70%	55%
ECAL	30%	15%

PFA →

Fraction
10%
30%

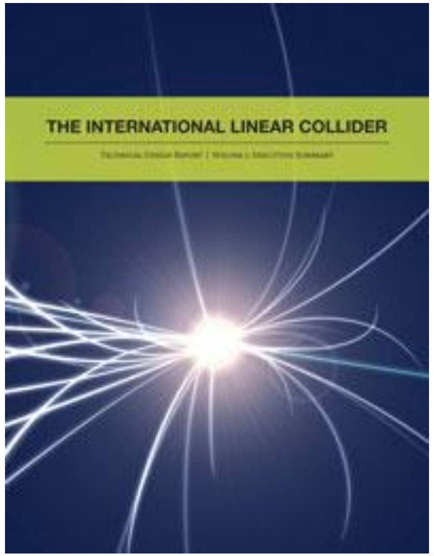
Summary

- ILC is capable of measuring absolute Higgs couplings model independently with high precision.
- Detector technology mature!

➢ We can start our journey to unveil the mystery of the Higgs right now!

Kitakami mountains announced as Japan candidate cite!

Technical Design Report Published!!



LCWS13 will be held at The University of Tokyo
11-15 November 2013 (registration is ongoing)
http://www.icepp.s.u-tokyo.ac.jp/lcws13/