ILC Physics and Detectors

XVI Workshop on High Energy Physics Phenomenology

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RCAPP

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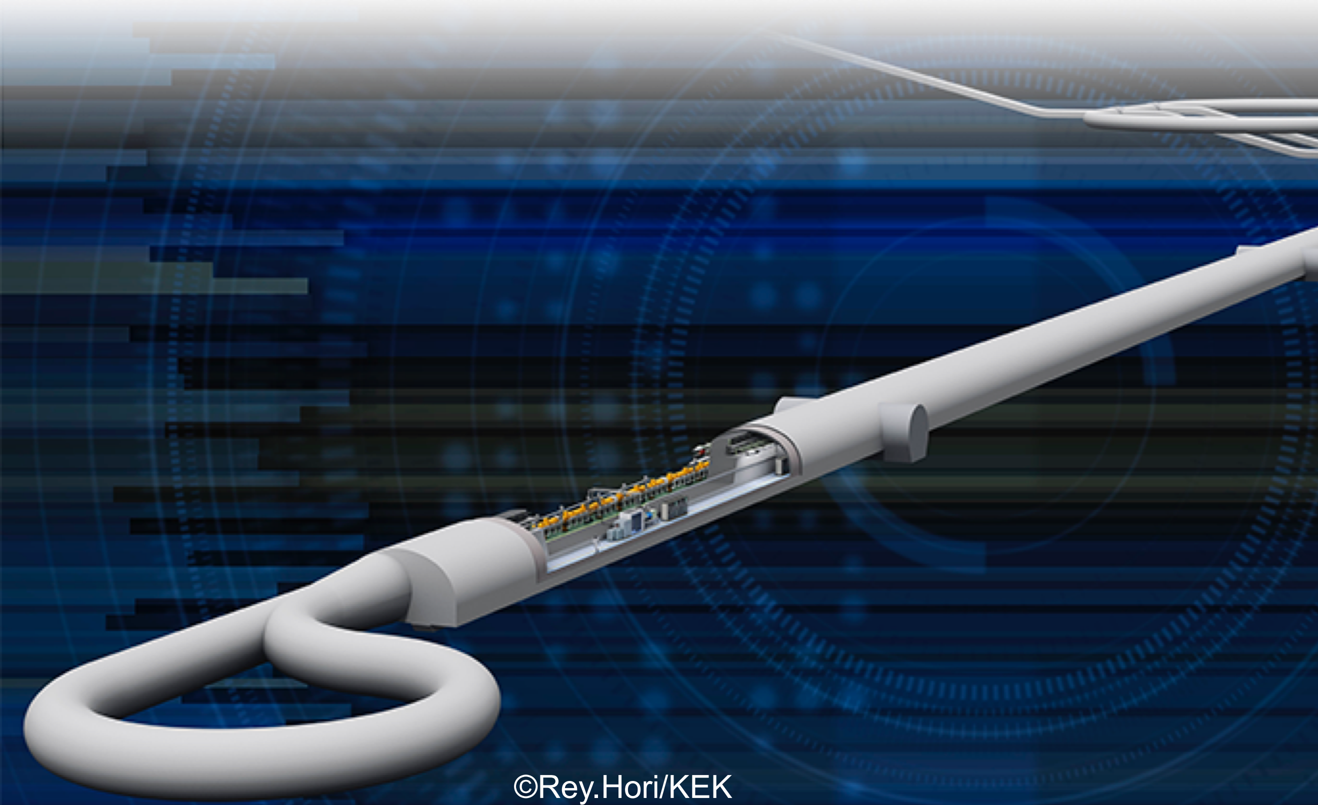
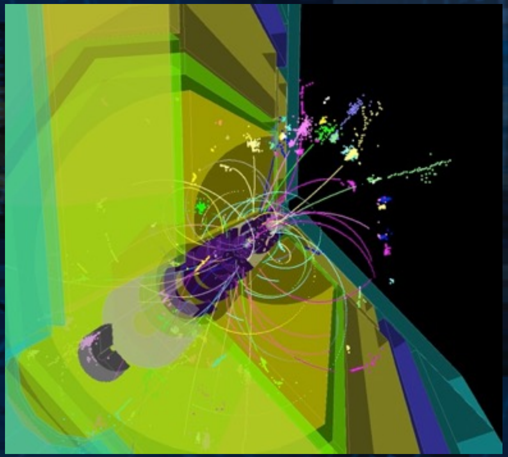
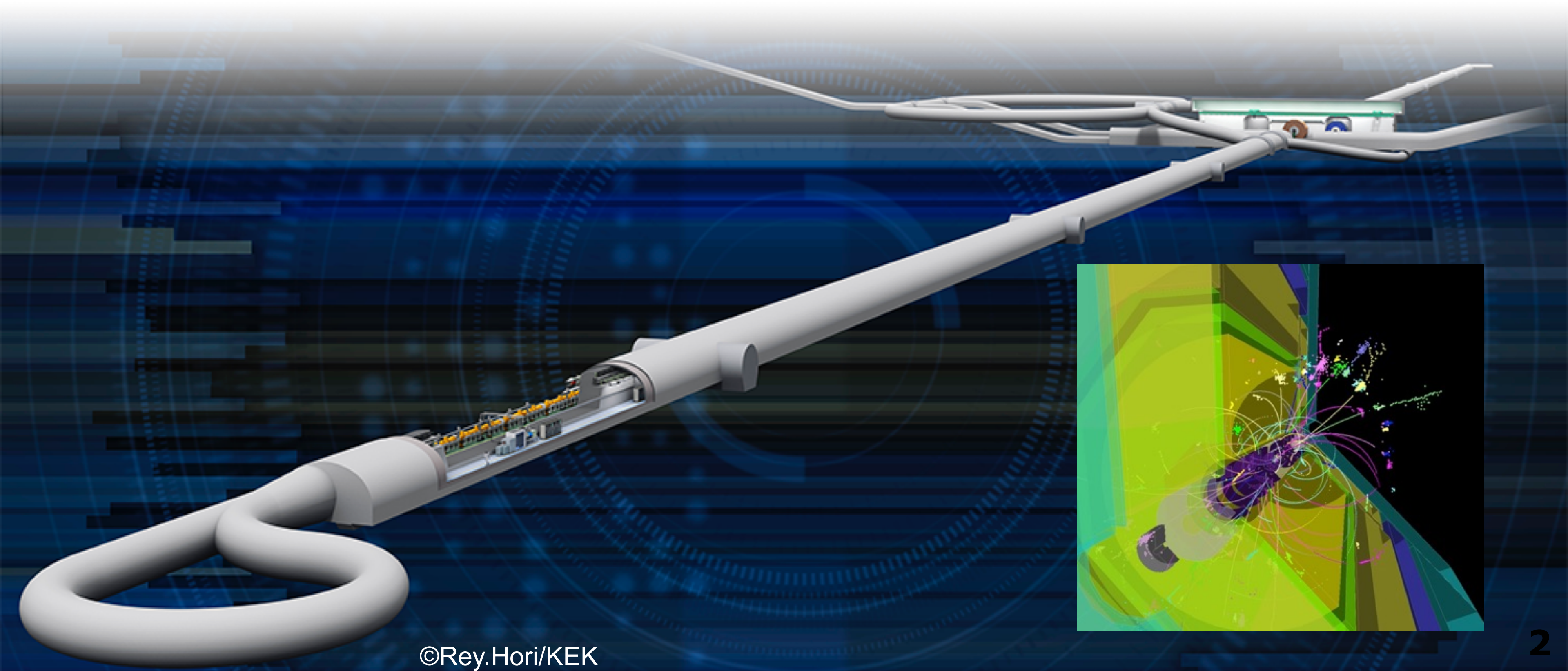


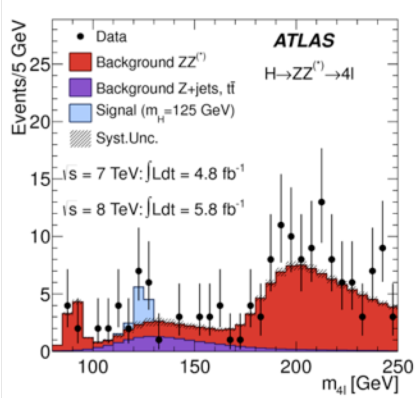


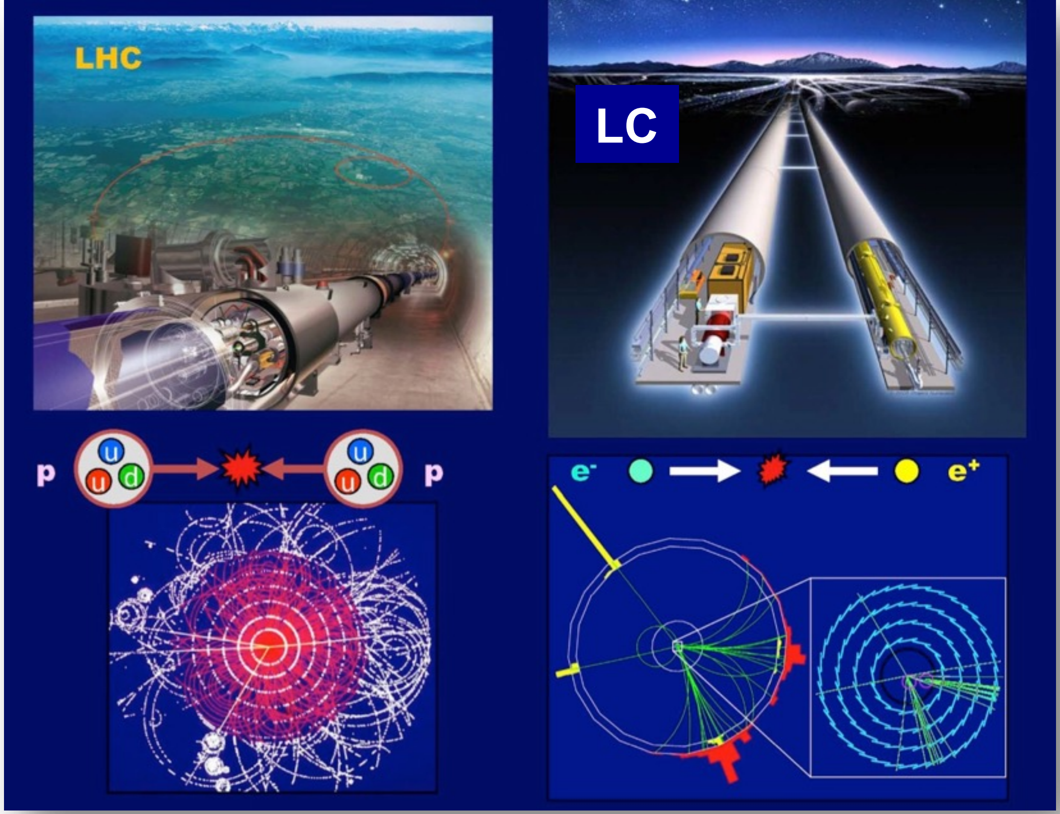
- **Physics**
- Detectors



Why e^+e^- colliders ?

Hadron colliders and e^+e^- colliders are complementary/synergetic.





- **Hadron colliders** are powerful in producing heavy particles:
  - LHC Run 1 (7-8 TeV): **discovered the Higgs boson** in 2012.
  - LHC Run 2 and Run 3 (13~14 TeV): extend discovery region but no signals so far.
  - HL-LHC (~10 time more integrated luminosity) will further extend the region.
- **e^+e^- colliders** are very good at precision measurements. **High precision measurements of the Higgs boson** at a **future e^+e^- collider** gain more importance than ever:
  - To reveal **Symmetries and basic principles** behind them
  - To obtain information of **Yet-undiscovered particles**

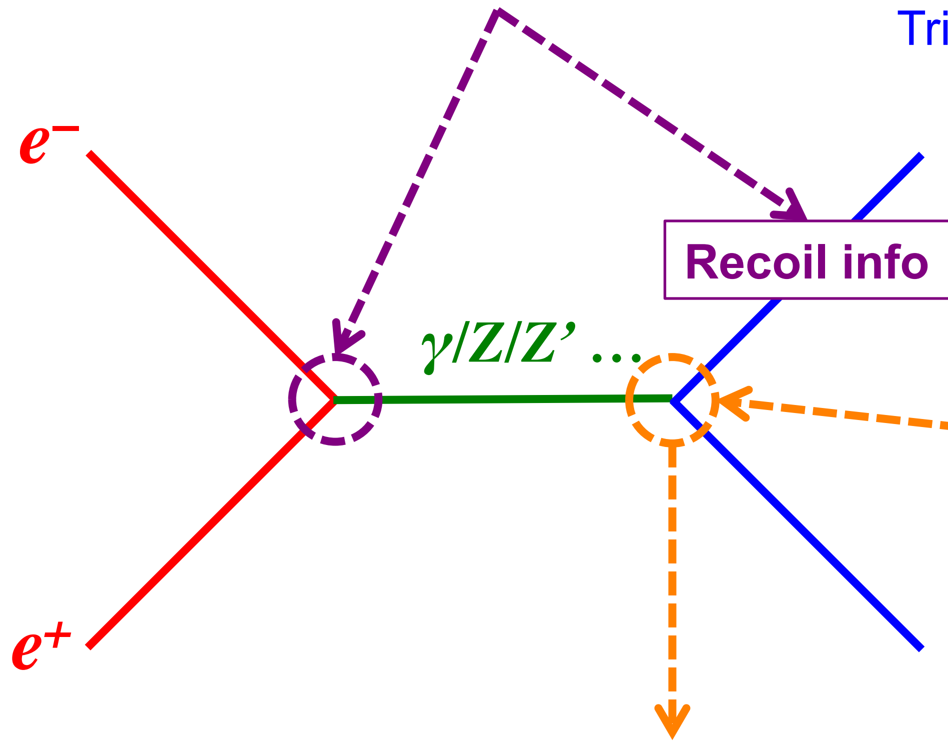
+ Potential of **Direct discovery of BSM phenomena** that are difficult for LHC to handle.

Characteristics of ILC

Beam
Tunable energy
Polarization
$P_{electron} = \pm 80\%$
$P_{positron} = \pm 30\%$

Elementary process
Well-understood at LEP
Theoretical uncertainty <1%

Detection
Low background
Highly granular sensors
Trigger free operation

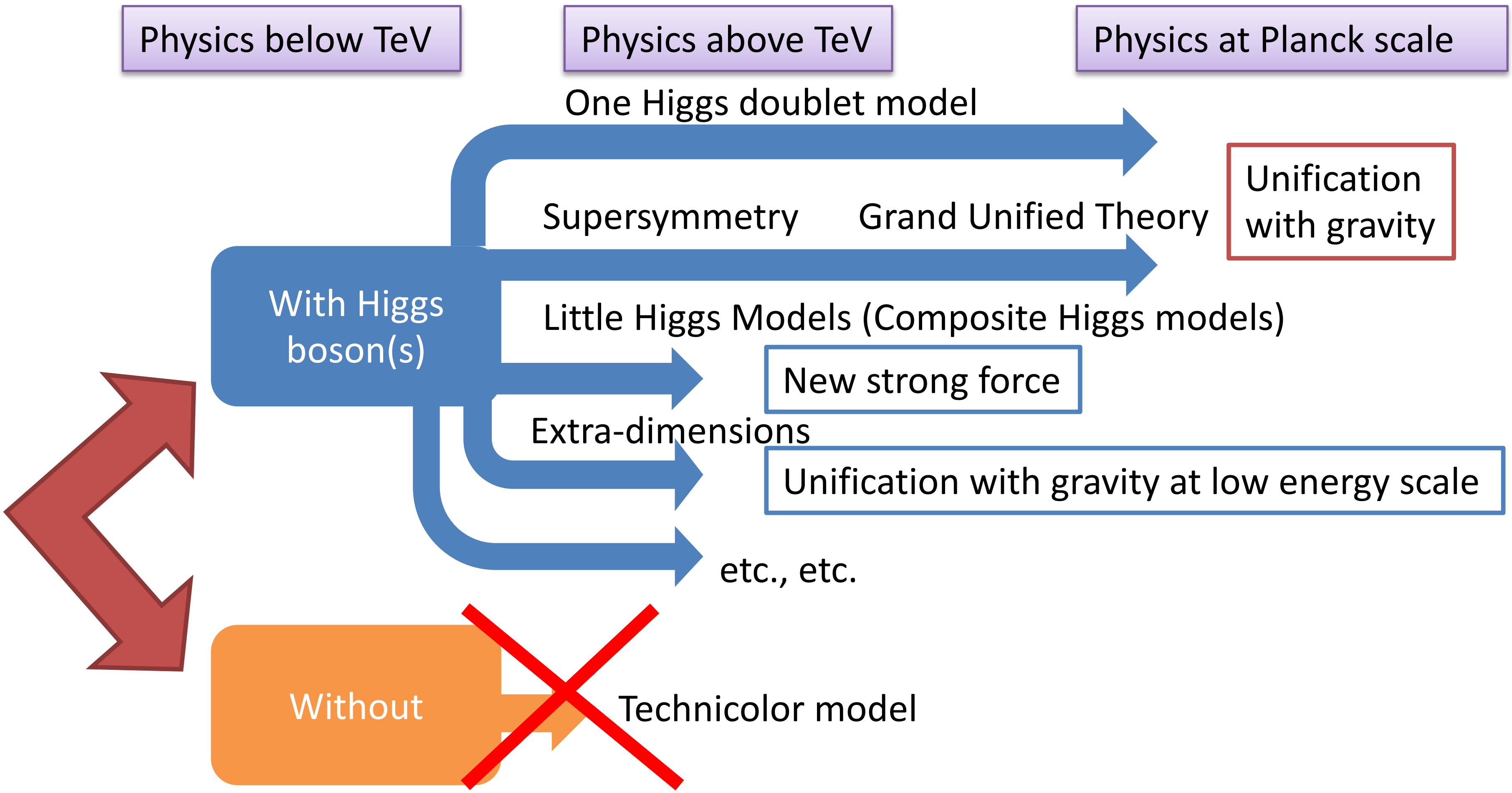


Production
Higgs boson
@250GeV
Di-bosons,
New particles

Top Quark, Di-Higgs,
New Particles
with energy upgrade

Determine: Mass, J/CP, Couplings, etc
Discover: New Physics & New Principles

Higgs boson is the portal to new physics

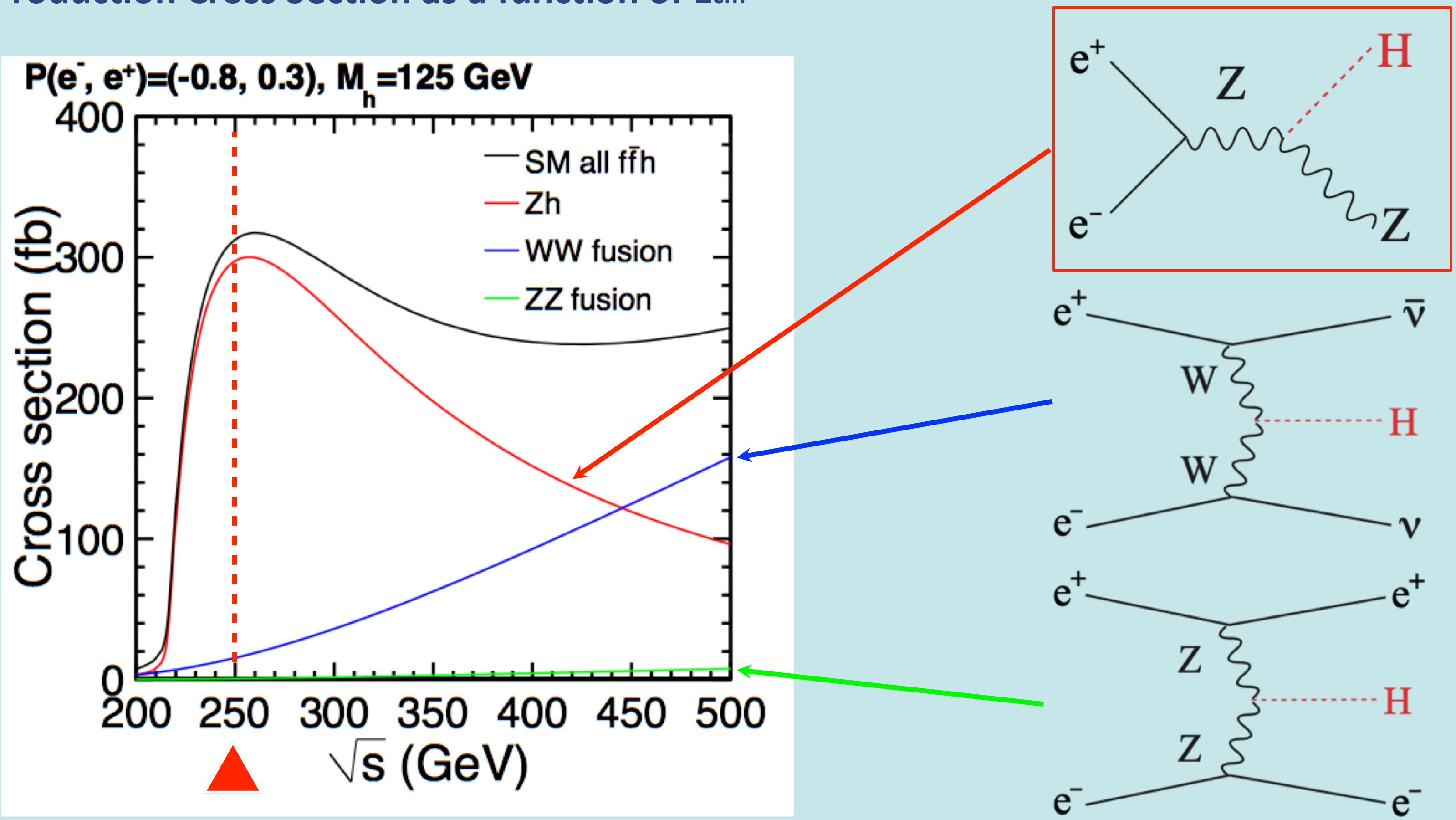


The property of the Higgs boson depends on how the Higgs field is incorporated in particle physics models beyond the TeV scale.

250 GeV is a special energy

Single Higgs production cross section at maximum

Production Cross Section as a function of E_{cm}



250 GeV: cross section maximum (~0.5 Million events for 2 ab^{-1})

Mass-produce Higgs bosons and study them in detail.

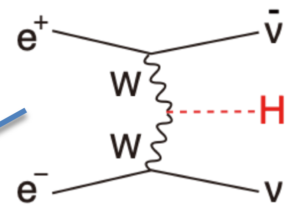
Recent Development: EFT Analysis

Potential drawback at 250 GeV:

It was said that Γ_h (Higgs total width) necessary for absolute coupling normalization requires E_{CM} > 350 GeV.

$$\Gamma_h = \frac{\Gamma(h \to WW^*)}{BR(h \to WW^*)}$$

$$\Gamma(h \to WW^*) \propto \sigma(\nu\bar{\nu}h)$$



cross section: small@250GeV

Solution: *EFT* (*Effective Field Theory*) to relate hZZ and hWW couplings

LHC Run II results suggest that 250 GeV is likely in the validity range of the EFT

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}$$

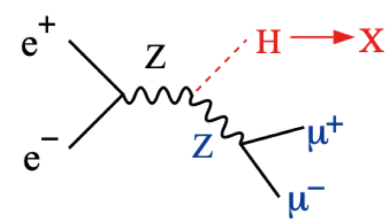
SU(2)xU(1) inv. dim.6 operators

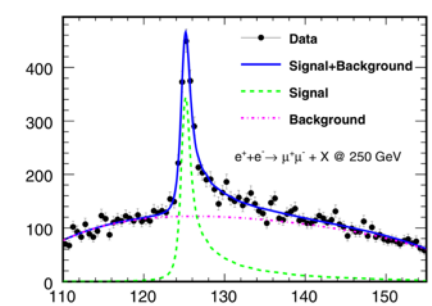
 # EFT coefficients to decide: 17 @ ILC

This ILC number is quite tractable.

Beam polarization doubles the number of usable observables.

The importance of ***the σ_{Zh} measurement by recoil mass technique*** remains the same.



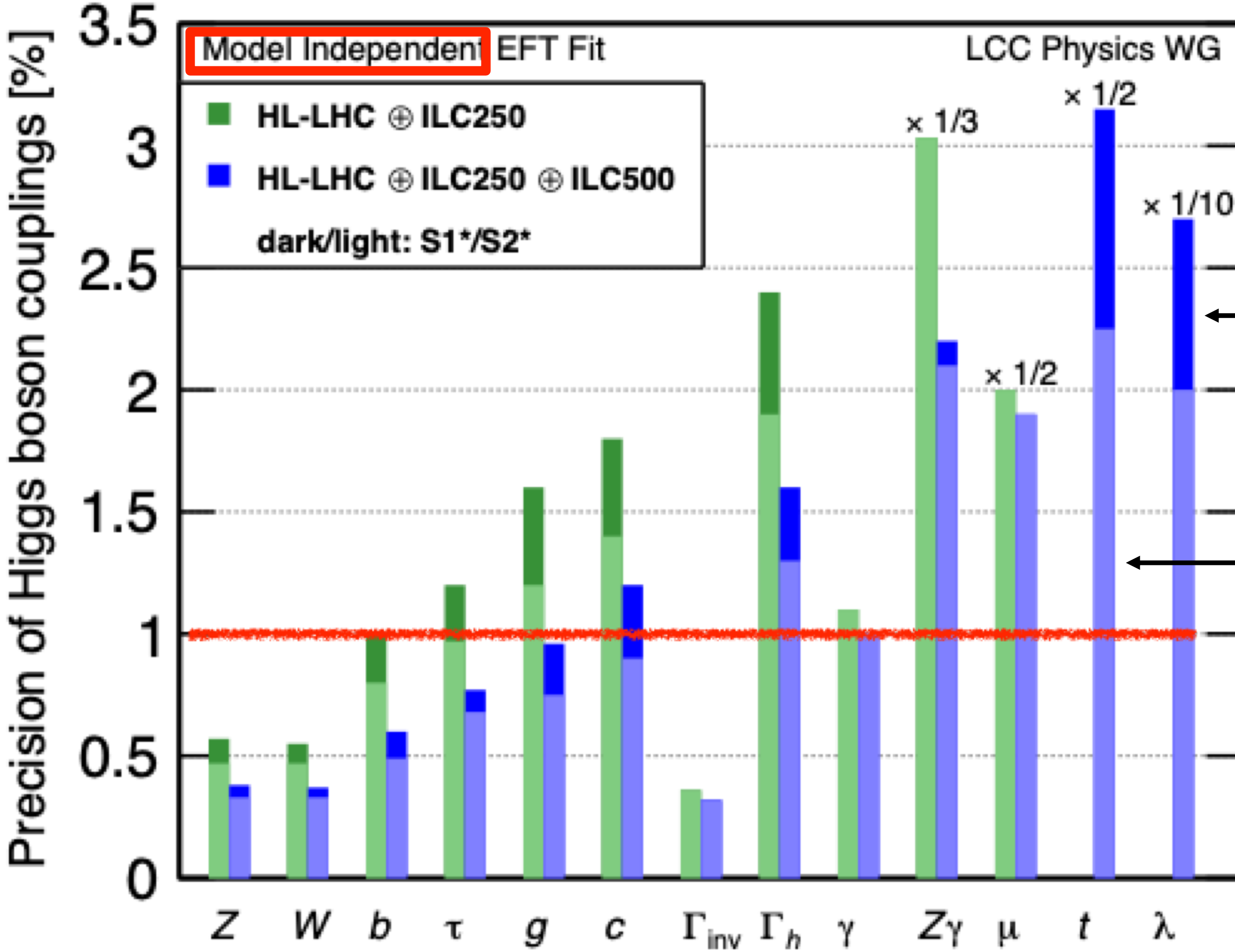


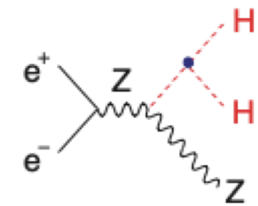
W_L and Z_L are NGBs from the Higgs sector. All the SM processes with W and Z can be used to constrain the EFT coefficients.

Absolute and model-independent Higgs coupling measurements possible with the 250 GeV data alone.

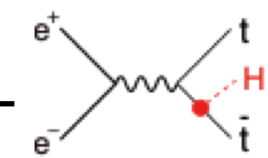
Higgs coupling measurements at ILC

arXiv: 1901.09829



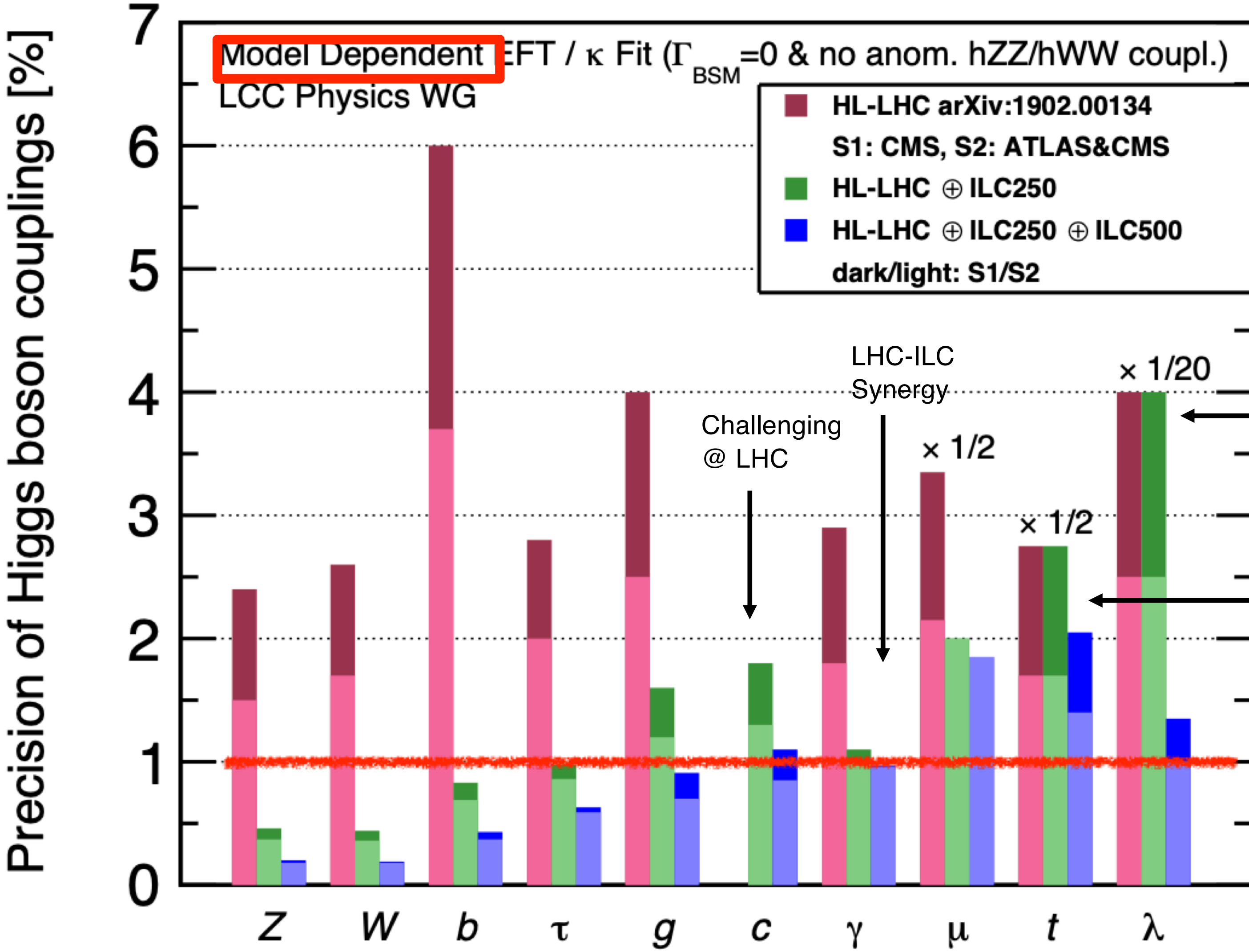


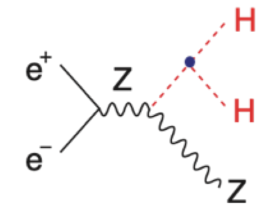
Self-coupling
Not accessible at 250 GeV.
Can reach 26% at 500 GeV.



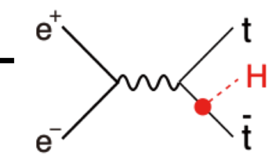
Top Yukawa
Not accessible at 250 GeV.
Can reach 3% at 550 GeV.

ILC allows model-independent fit to extract all the major Higgs couplings !





Self-coupling
Not accessible at 250 GeV.
Can reach 26% (15%) for λ=1(2) at 500 GeV.



Top Yukawa
Not accessible at 250 GeV.
Can reach 3% at 550 GeV.

FIG. 1. Projected Higgs boson coupling uncertainties for the LHC and ILC using the model-dependent assumptions appropriate to the LHC Higgs coupling fit. The dark- and light-red bars represent the projections in the scenarios S1 and S2 presented in [9, 10]. The scenario S1 refers to analyses with our current understanding; the scenario S2 refers to more optimistic assumptions in which experimental errors decrease with experience. The dark- and light-green bars represent the projections in the ILC scenarios in similar S1 and S2 scenarios defined in [6]. The dark- and light-blue bars show the projections for scenarios S1 and S2 when data from the 500 GeV run of the ILC is included. The same integrated luminosities are assumed as for Figure 2. The projected uncertainties in the Higgs couplings to μμ, tt, and the self-coupling are divided by the indicated factors to fit on the scale of this plot.

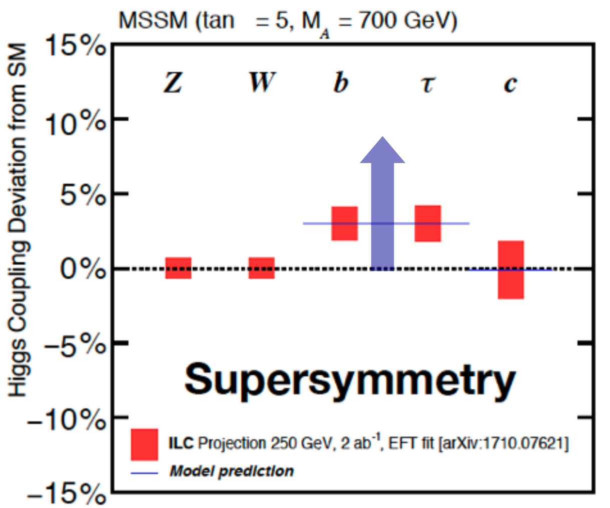
With ILC, we can reach our goal of 1%-level precisions for all the major couplings.

We need to study Higgs couplings

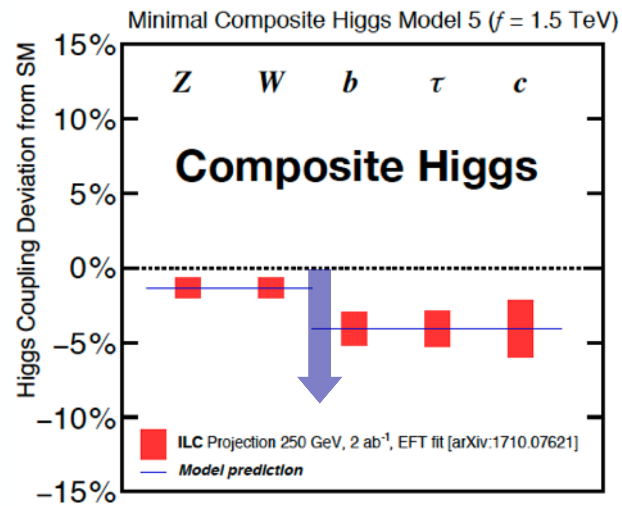
Higgs as a window for BSM

- fingerprint BSM by patterns of deviations

—> measure as many couplings as possible



Upward shift only for down-type fermions



Downward shift for all the couplings

deviation is typically small, 1-10% for m_{BSM}~1TeV

—> need 1% or below measurement

5

Different models predict different deviation patterns

→ *Deviation pattern tells us which way to go.*

Sensitivity to BSM

ILC not only shows us the general direction but points to a specific direction

9 sample models and expected deviations (%)

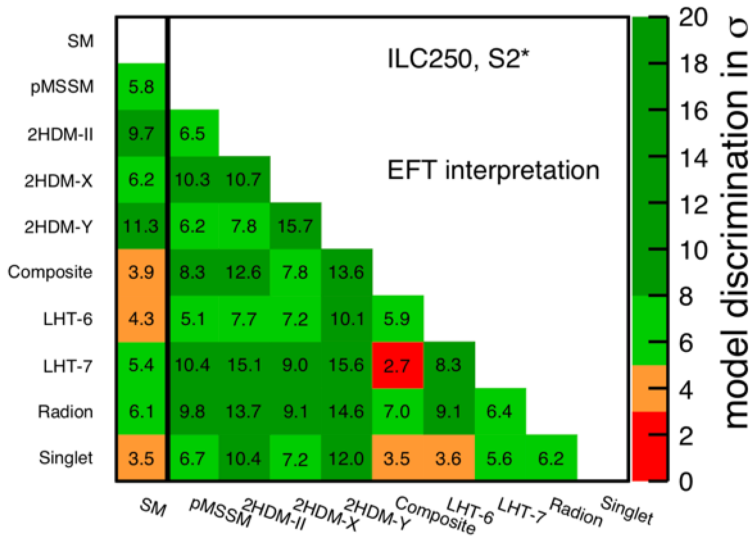
arXiv: 1710.07621

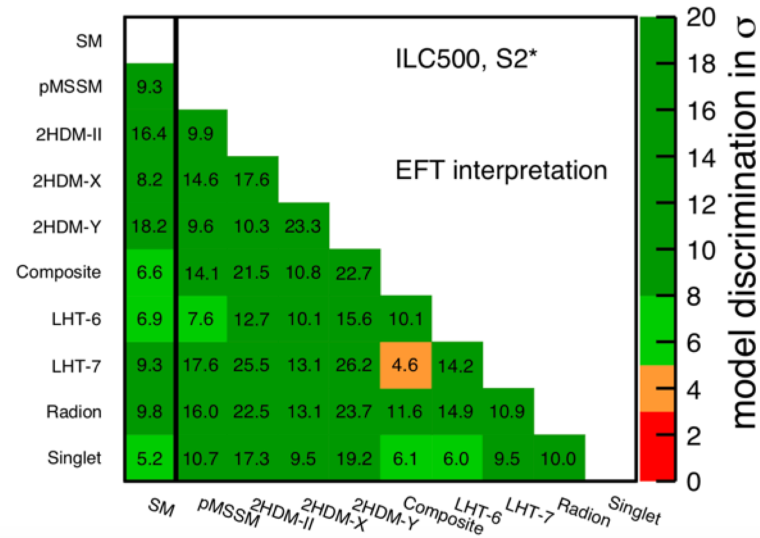
	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [37]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [38]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [38]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [38]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [39]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [40]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [41]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [42]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [43]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

All new particles unlikely to be within the reach of the HL-LHC
→ The only probe would be precision measurements of the Higgs couplings

Expected deviations are at most 10% or so
Needs high precision to see the deviations
→ *Different new physics models predict different deviation patterns*
→ *We can discriminate the models !*

Discrimination power in σs





$$n \simeq \sqrt{\chi^2}$$

> 3σ sensitivities to most models @ 250 GeV

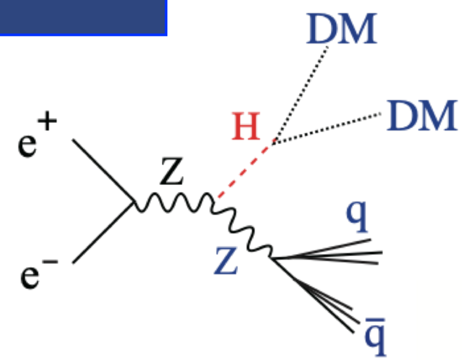
> 5σ sensitivities to almost all models @ 500 GeV

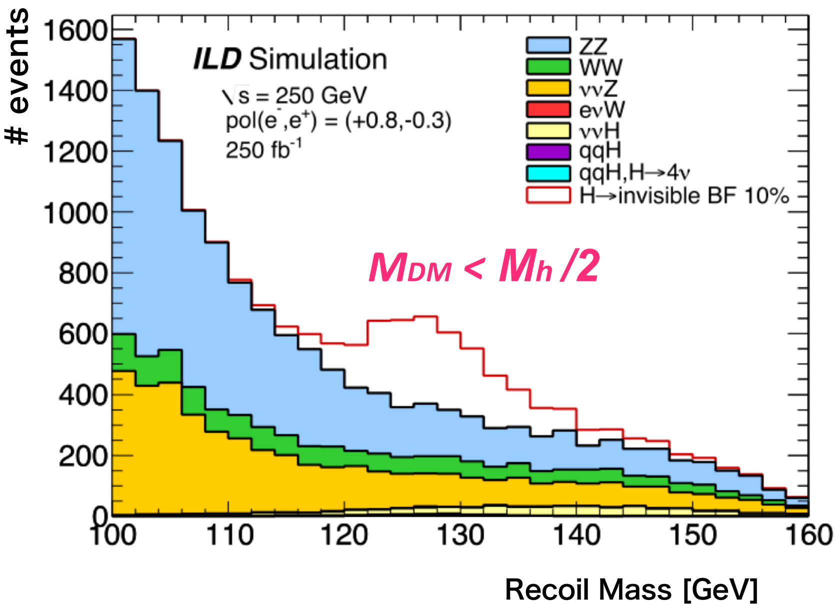
WIMP Dark Matter Search @ ILC

Weakly **I**nteracting **M**assive **P**article

1. Higgs Invisible Decay

Effective when the Dark Matter particle interacts with the Higgs boson





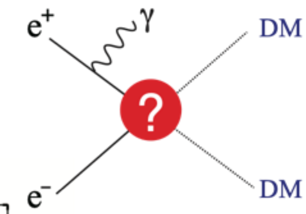
Possible to access BR_{inv} to 0.3%!

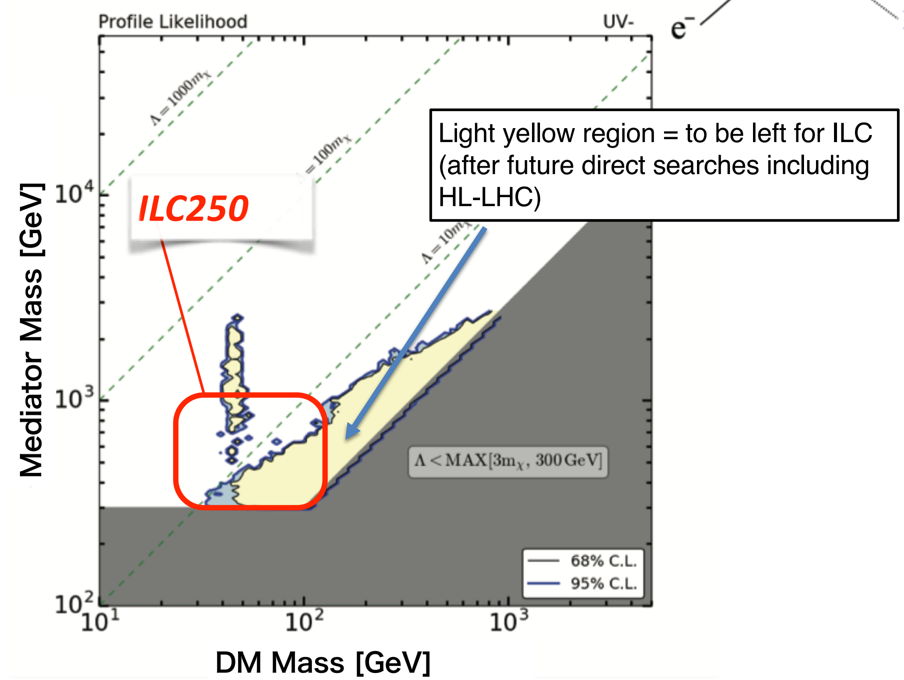
O(10) more sensitive than HL-LHC

2. Mono-photon Search

Sensitive to various types of Dark Matter particles

Effective in particular for DM particles which couple mostly to EW gauge bosons and leptons and hence difficult to find at the LHC.

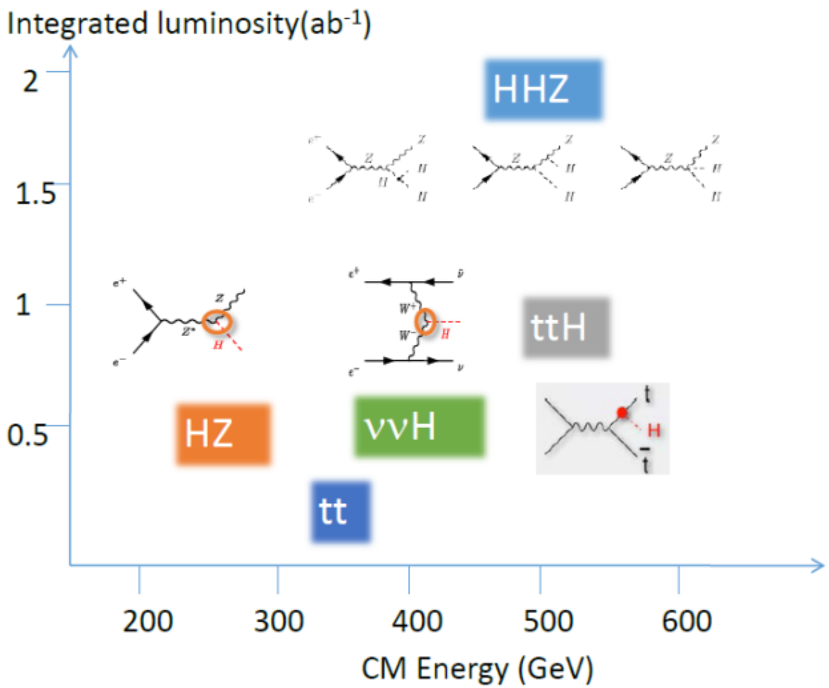




Significant chunk of region remains for ILC250!

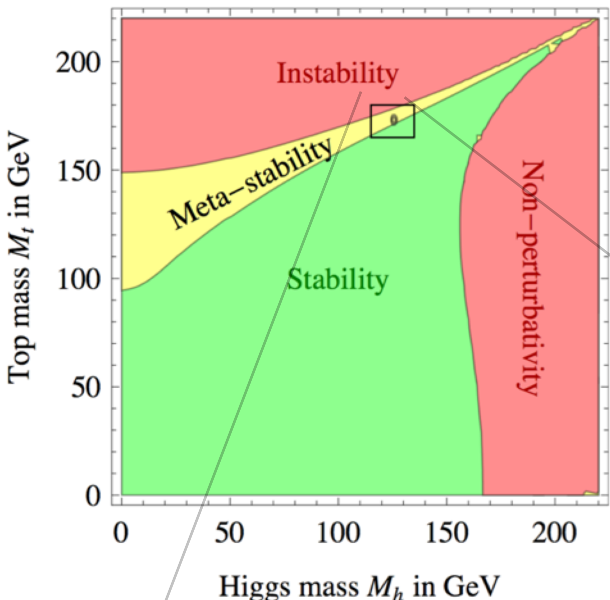
Physics beyond 250 GeV ILC

- Important measurements
  - Top mass at the top threshold
  - Higgs self coupling, ttH coupling beyond 500 GeV
  - Top anomalous coupling
  - Extension of new particle search areas

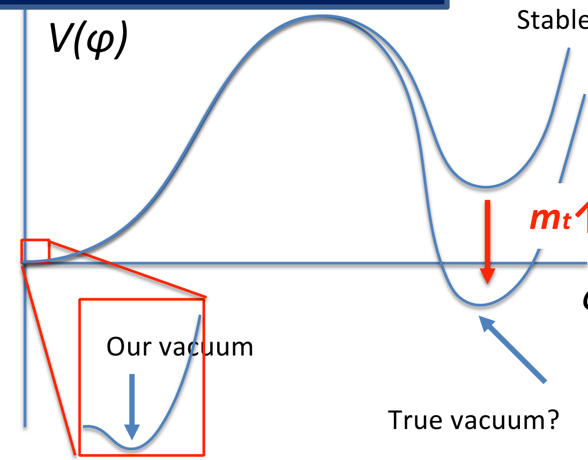


The energy upgrade path can be decided based on the outcome of 250 GeV ILC.

Top mass and SM vacuum stability



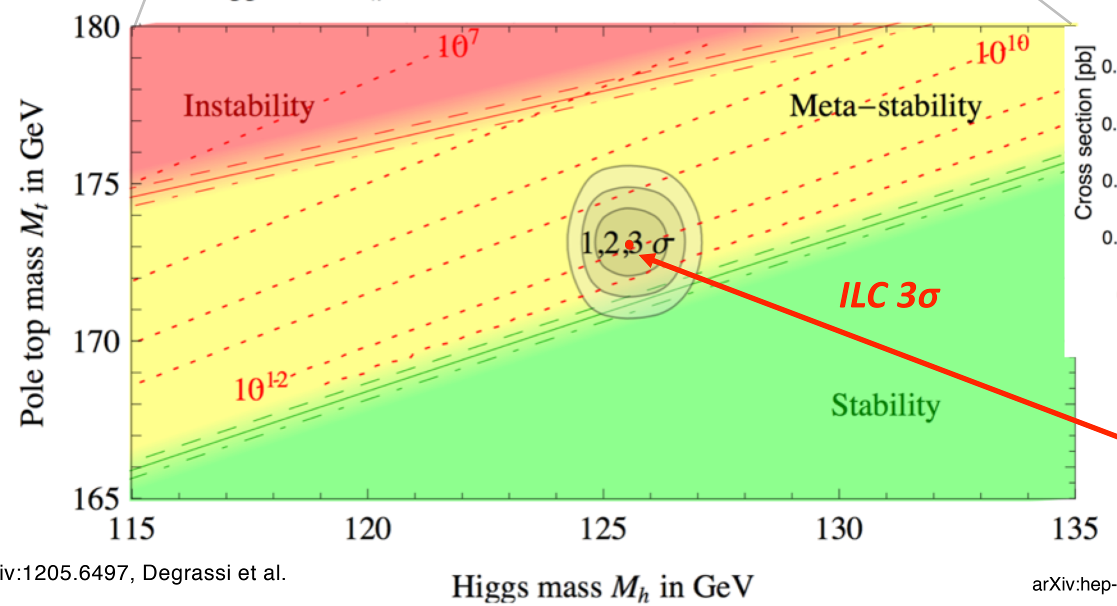
Vacuum stability is dependent on the top mass, as the Top-Yukawa coupling may drive the 4-point Higgs self-coupling negative.
→ True vacuum could be somewhere else at high ϕ value.

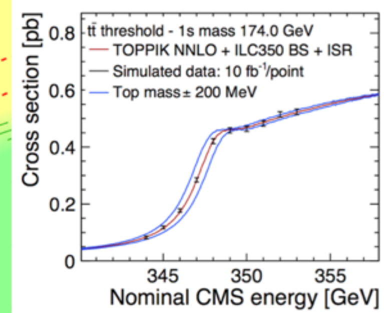


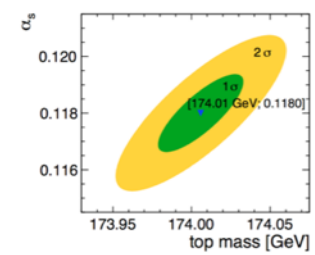
To answer this, we need precision m_t measurement!

At LHC, theory error limits the precision to ~500 MeV.

TTbar Threshold Scan @ILC allows very clean measurement of theoretically well defined m_t







$$\Delta m_t(\overline{MS}) \lesssim 50\,\mathrm{MeV}$$
$$\Delta m_H = 14\,\mathrm{MeV}$$

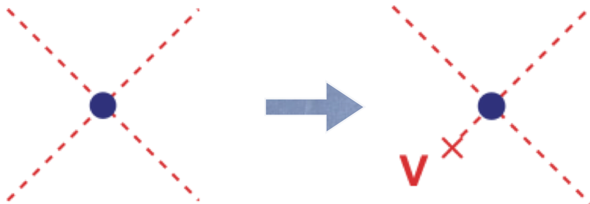
ILC pinpoints the vacuum location

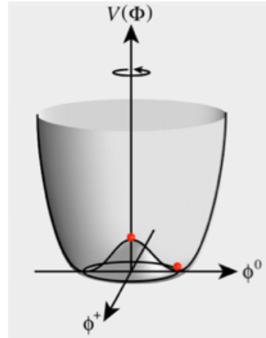
arXiv:1205.6497, Degrassi et al.

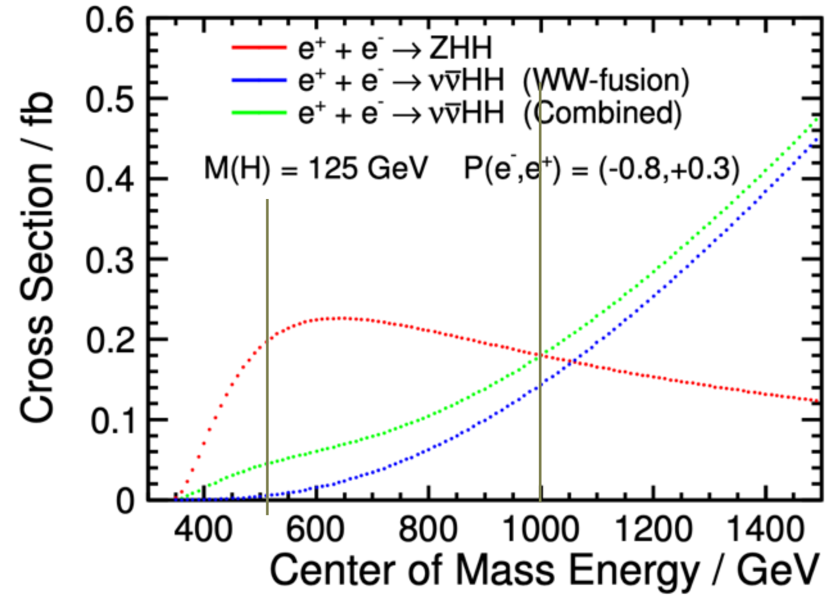
arXiv:hep-ph/1502.01030: Quark mass relation to 4-loop order
arXiv:hep-ph/1506.06864: NNNLO QCD
arXiv:hep-ph/1506.06542: possibility of MSbar mass to 20MeV

Higgs Self-Coupling

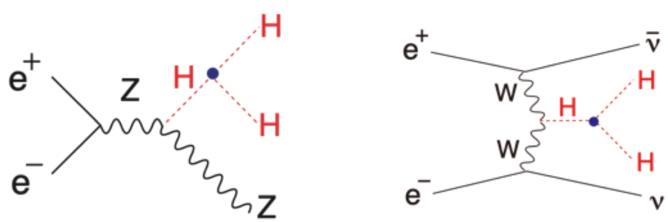
The ***Higgs cubic self-coupling*** is at the heart of EWSB, so should be measured in its own right!







There are ***two ways to measure it*** at ILC



Challenging even at ILC because of

- Small cross section
- ***Presence of irreducible BG diagrams that dilute the self-coupling contribution!***
- ***Separation of BSM effects that appear other than in self-coupling (possible in EFT: same impossible at LHC)***

ILC

	500 GeV	+ 1 TeV
Snowmass	46%	13%
H20	**26%**	10%

H20 arXiv: 1506.07830

J. Tian, LC-REP-2013-003

C. Dürig @ ALCW16

M. Kurata, LC-REP-2014-025

CLIC

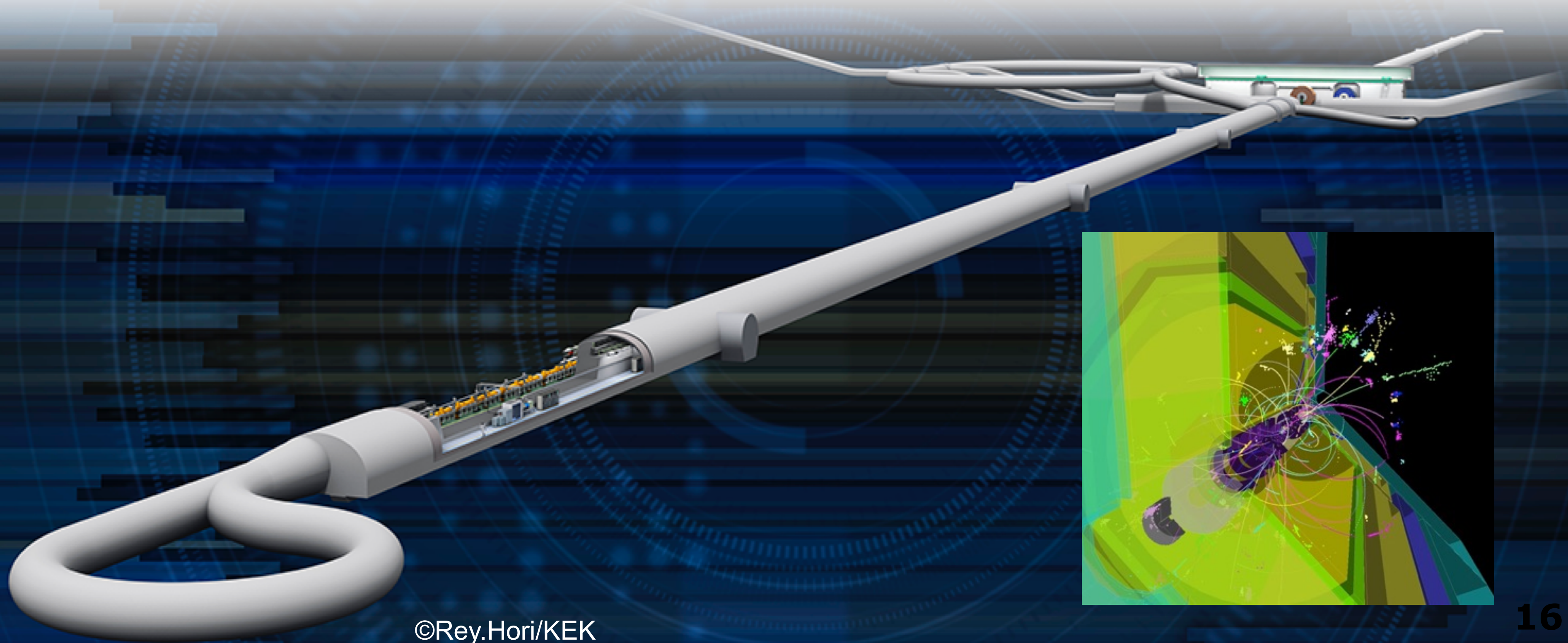
1.4 TeV (1.5 ab^{-1})	+3 TeV (2 ab^{-1})
21%	10%

(arXiv: 1307.5288)

Ongoing effort ***towards O(10)% measurement***

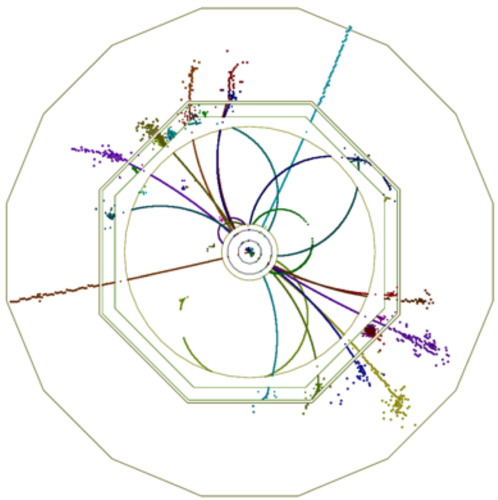
If +100% deviation as possible in EWBG scenario, $\Delta\lambda/\lambda$=14%!

- Physics
- **Detectors**



Particle detectors

We want to understand what is happening in particle collisions, ideally at the level of Feynman diagrams.



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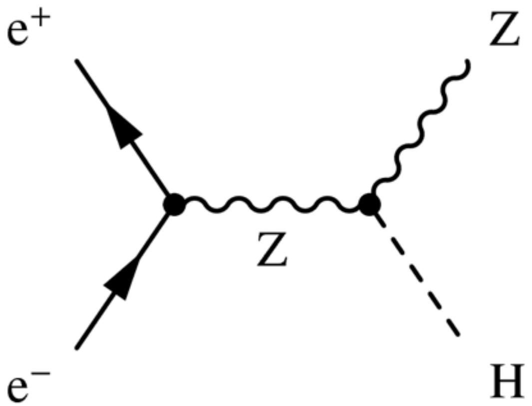
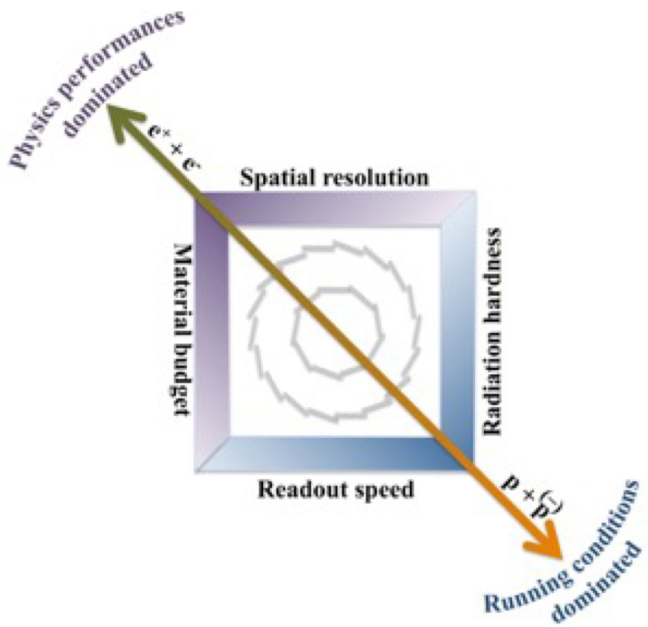


- **Future experiments require very challenging detectors in many aspects.**
- **The requirements depend on collision types, energies, and luminosities.**



Challenges of future lepton colliders

Maximize physics performance in much cleaner experimental conditions

- Moderate radiation level: ~ 100 kRad+10^{11} n_{eq}/cm^2 at inner vertex layer (ILC)

--> Pursue ultimate detector performance

$\sigma_{IP} = a \oplus b/p\sin^{3/2}\theta$

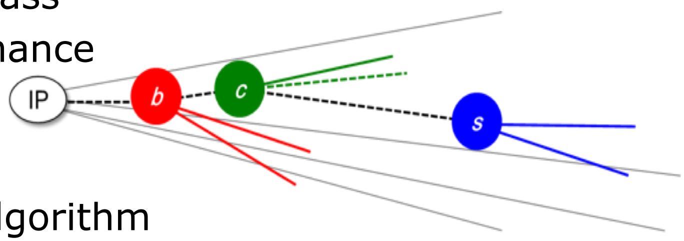
x	LEP	SLC	LHC	ILC
a [μm]	25	8	12	5
b [μm GeV/c]	70	33	70	10

Vertex Detector:

- Excellent IP resolution for efficient b, c jet tagging
- Much smaller pixel size, much less material budget

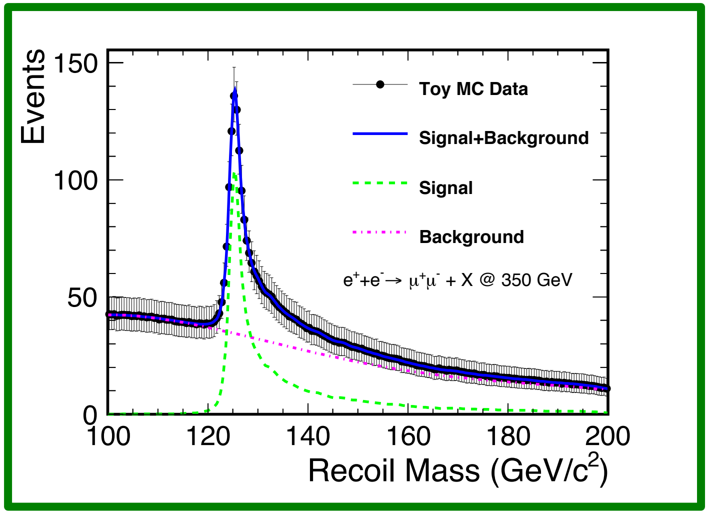
Central Tracker:

- High momentum resolution to reconstruct Higgs recoil mass
- Low material budget, not to degrade calorimeter performance

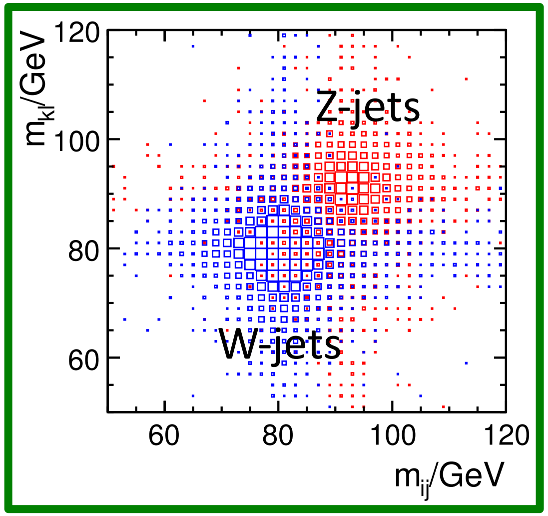


Calorimetry:

- High jet-energy resolution to separate W-jets and Z-jets
- A promising solution: high granularity for Particle Flow Algorithm



Higgs recoil mass Using only a lepton-pair from Z^0

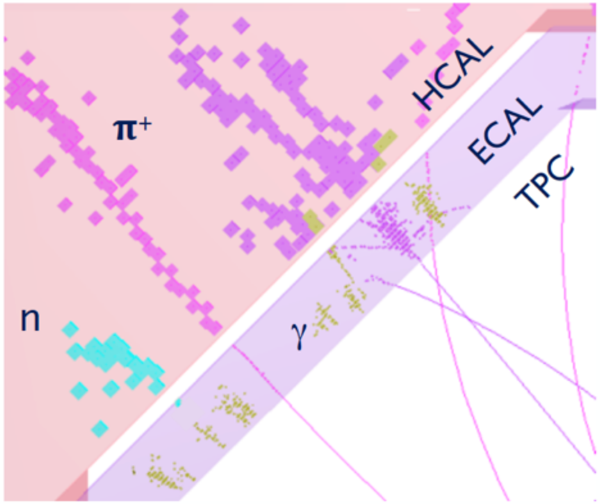


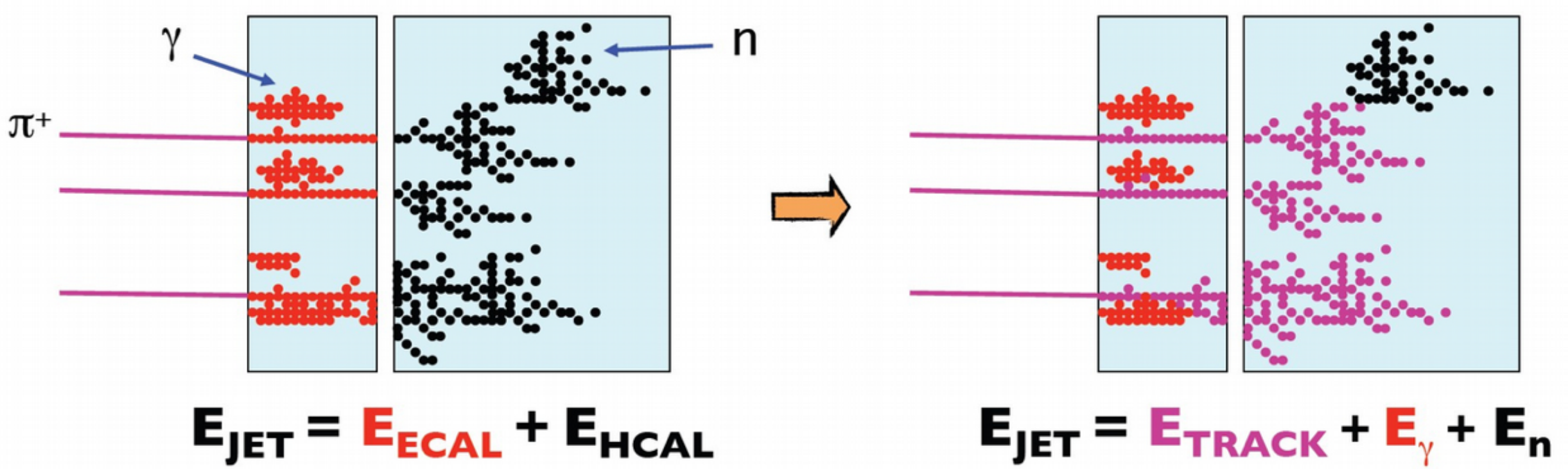
Separation of ννWW and ννZZ events

Particle flow approach

PFA uses best energy measurement for each particle to reconstruct **jet energy** with no overlaps:

- **Charged tracks (~60%)**
  → tracker: $\sigma_{1/p_T} \approx 2 \times 10^{-5}$ (GeV)
- **Photons (~30%)**
  → ECAL: $\sigma_E/E \approx 15\% / \sqrt{E}$ (GeV)
- **Neutral hadrons (~10%) → HCAL: $\sigma_E/E \approx 60\% / \sqrt{E}$ (GeV)**





It is essential to separate calorimeter clusters at particle level

→ Calls for highly granular calorimeters

PFA: Granularity is the key

Jet energy resolution

$$(\sigma_{jet})^2=(\sigma_{tracks})^2+(\sigma_{ECAL})^2+(\sigma_{HCAL})^2 +(\sigma_{loss})^2+(\sigma_{confusion})^2$$

Confusion term originates from overlap of shower clusters in calorimeter

Material for absorbers

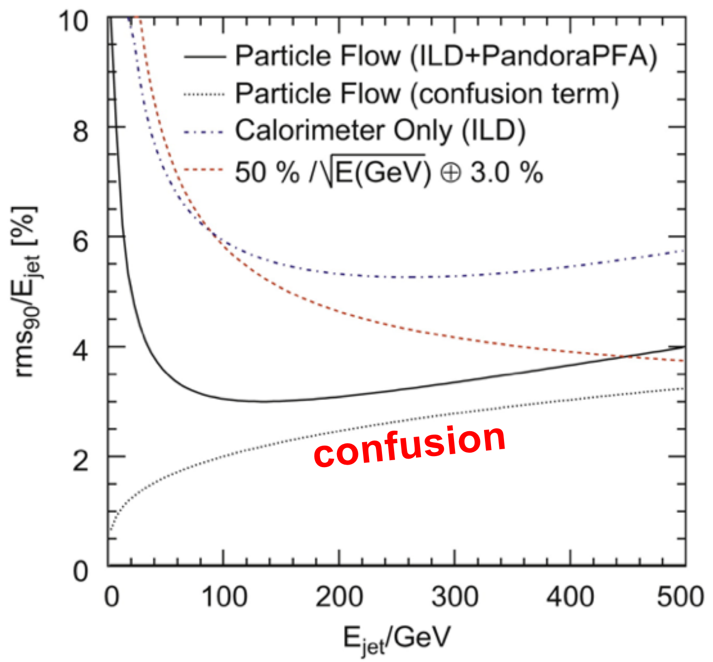
- ECAL: Tungsten
- HCAL: Steel or Tungsten

Thin active layers

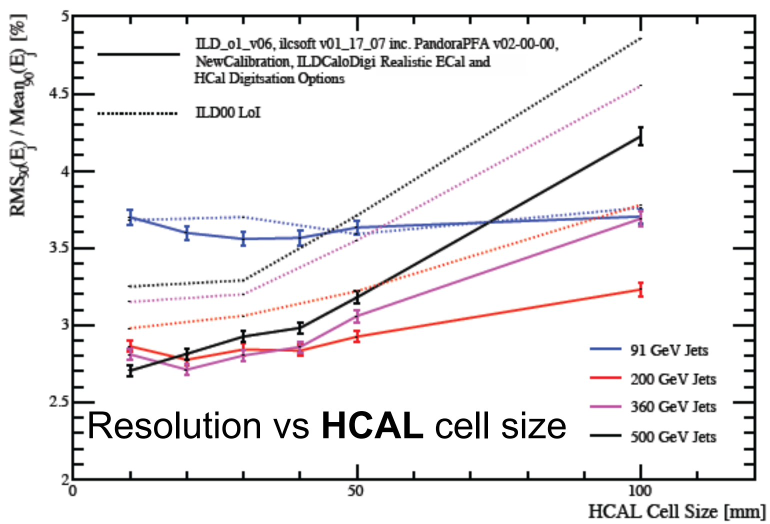
- Sensor and frontend electronics integrated

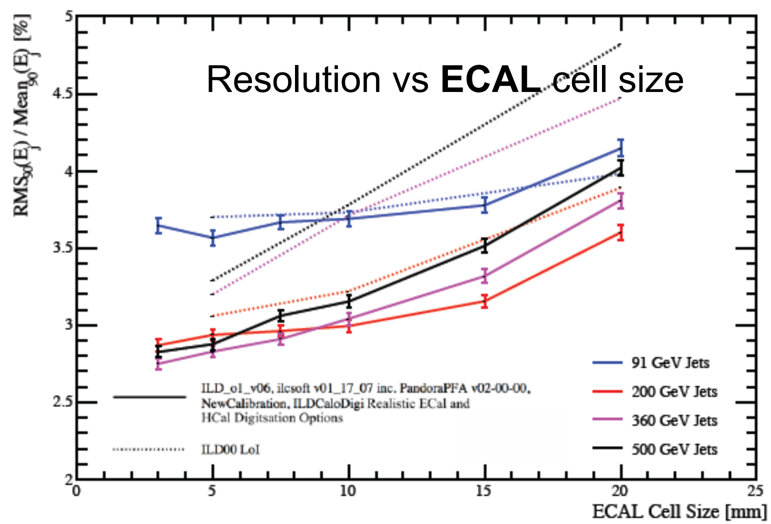
Optimized granularity (cell size) for ILC

- ECAL ~ 0.5x0.5 cm²
- HCAL ~ 3x3 cm² (analog readout)

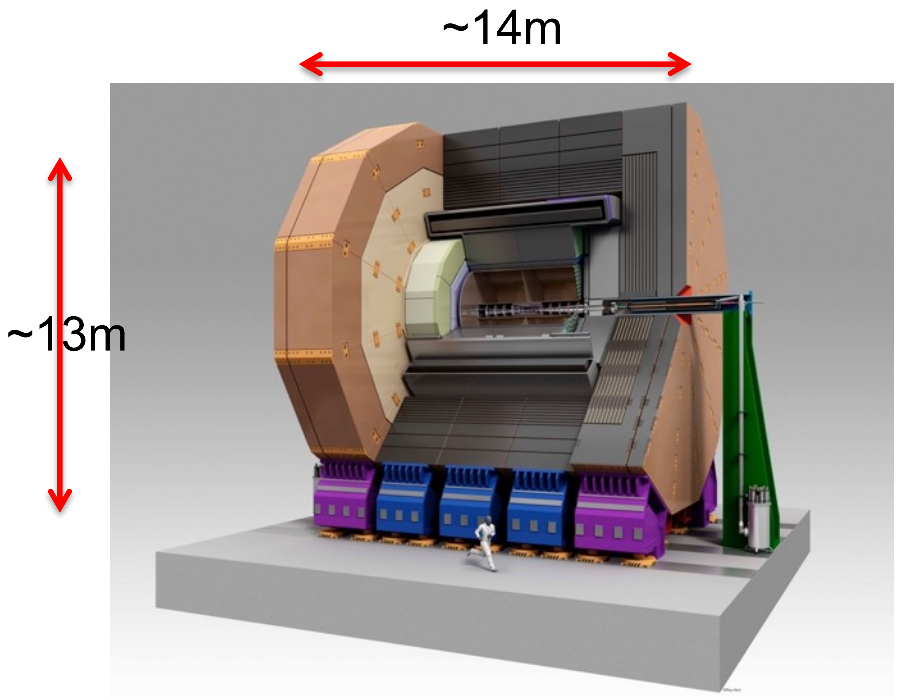


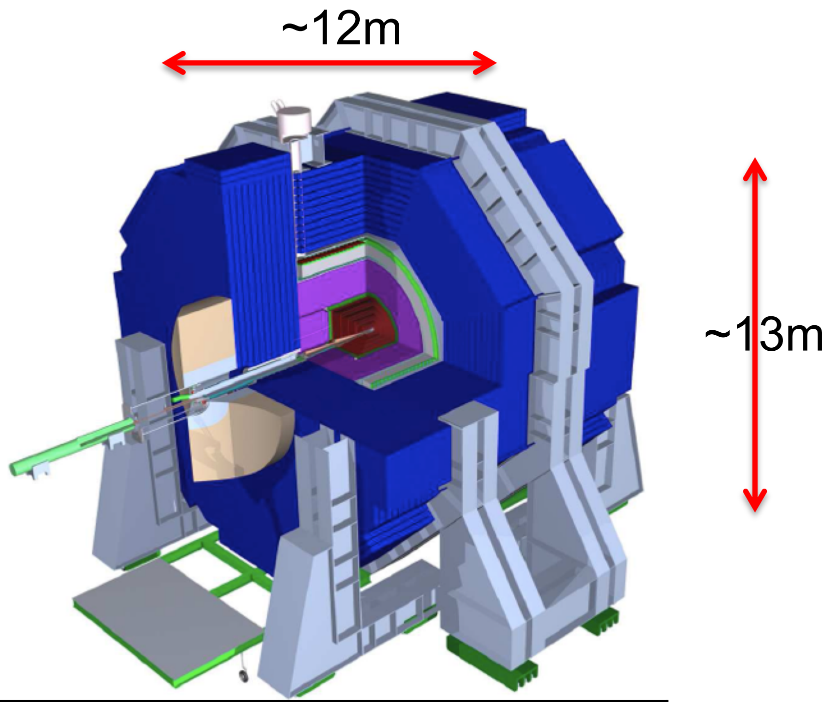
From M.A. Thomson
Nucl. Instrum. Meth. A611 (2009) 25.





S. Green
LCWS15

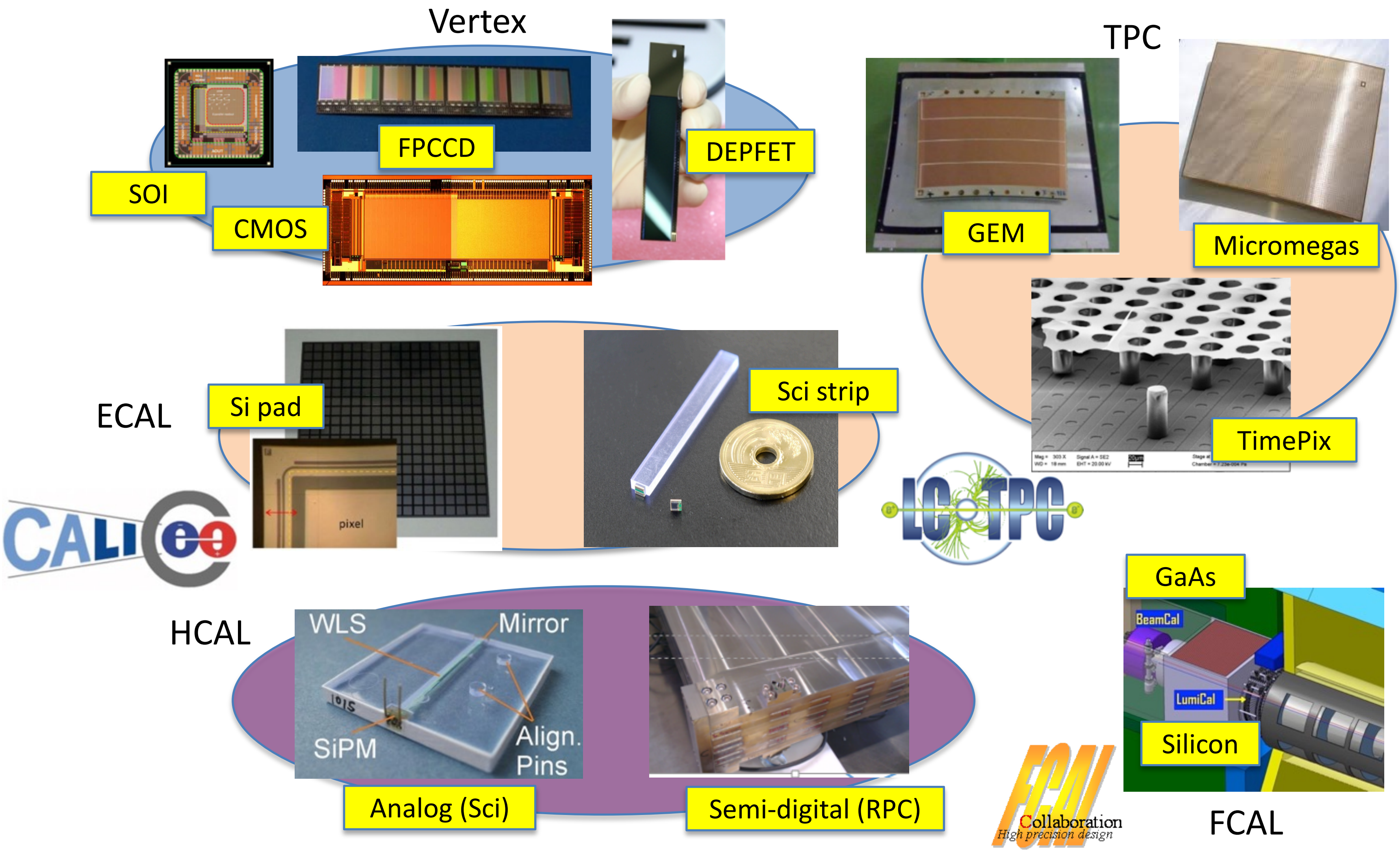




ILD	SiD
Both optimized for PFA PFA Performance $\sim B \cdot R_{ECAL,inner}^2$ (two-track separation @ ECAL)	
B = 3.5 T	**B = 5 T**
$R_{ECAL,inner}$ **= 1.8 m**	$R_{ECAL,inner}$ **= 1.27 m**
Si + TPC tracking	Tracking: Si only
Share interaction point via push-pull	

Note: DBD (Detailed Baseline Design) of the two detectors were published together with the accelerator TDR in 2013. ILD has been re-optimizing the design since 2013. IDR (ILD Design Report) summarizing the effort will be published soon.

Many R&D studies are ongoing for state-of-the-art detectors of Linear Colliders



This page shows just a part of R&D activities

Linear Collider Detector R&D Report

http://linearcollider.web.cern.ch/physics-detectors/working-group-detector-rd-liaison

LINEAR COLLIDER COLLABORATION

Detector R&D Report

VERSION 2018.2

Editors

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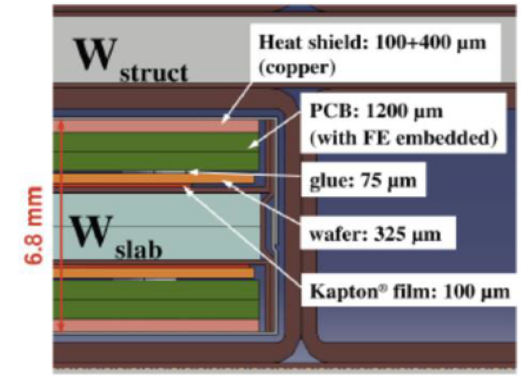
November 9, 2018

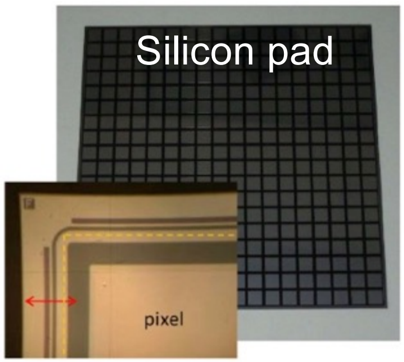
LINEAR COLLIDER COLLABORATION

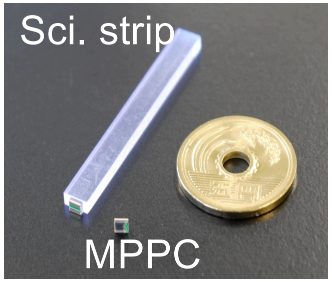
- By LCC Physics and Detectors
- Summary of LC-related detector R&D efforts
- For each effort, it describes
  - Introduction
  - Institutions involved
  - Milestones achieved
  - Challenges
  - Future plans
- Continuously updated

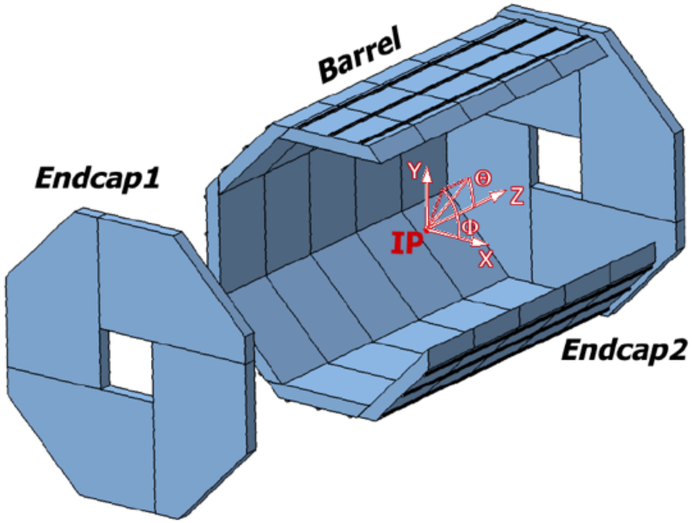
High granularity ECAL

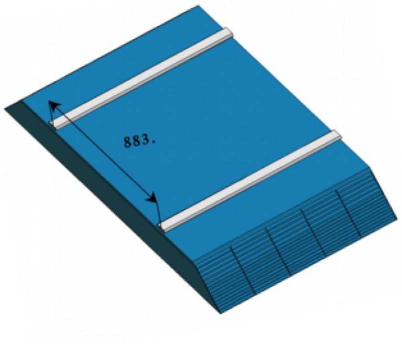
- Each module = carbon-fiber + W structure with alveoli where detector elements (slabs) slide in.
- Slab = Si matrices of PIN diodes (5 x 5 mm^2) glued to PCB with embedded electronics (SKIROC) on both sides of W wrapped into carbon fiber.
- Alternative idea is to use scintillator strips with SiPM readout for sensitive layers
- SiD ECAL will use highly segmented hexagonal Si sensors with readout by KPiX ASIC

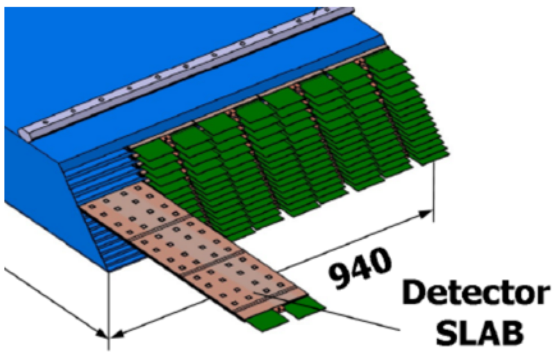








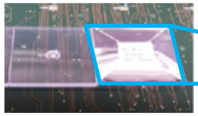
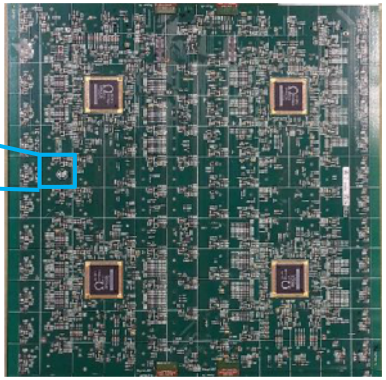




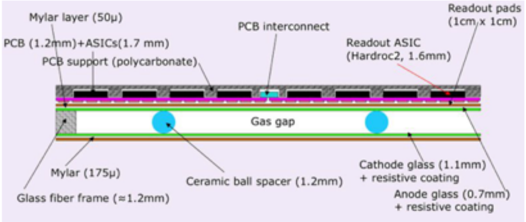
High granularity HCAL

Two promising approaches have been studied by CALICE

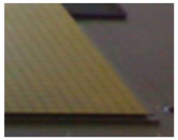
- **Analog HCAL**
  - Active layer: scintillator tiles (3x3 cm^2) readout using SiPM
  - Readout ASIC: SPIROC (OMEGA)
  - Physics prototype demonstrated performance
  - (ILD, SiD, CLIC)
- **(Semi-)Digital HCAL**
  - RPC with 1x1 cm^2 pads, with digital (1-bit) or semi-digital (2-bit) readout
  - Other detector options: MicroMEGAS, GEM, THGEM
  - Readout ASIC: HARDROC (OMEGA)
- Physics prototypes validated the concept and demonstrated performance
- Technological prototypes demonstrate scalability to the full detector

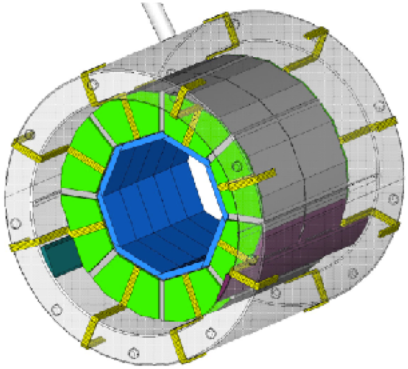
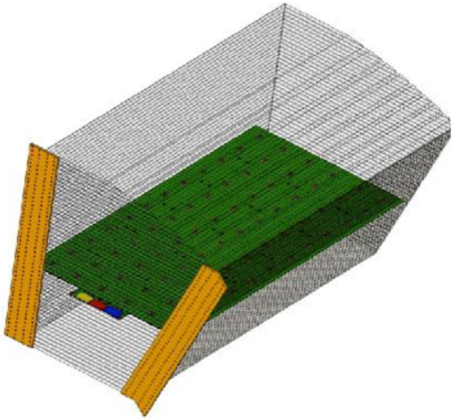
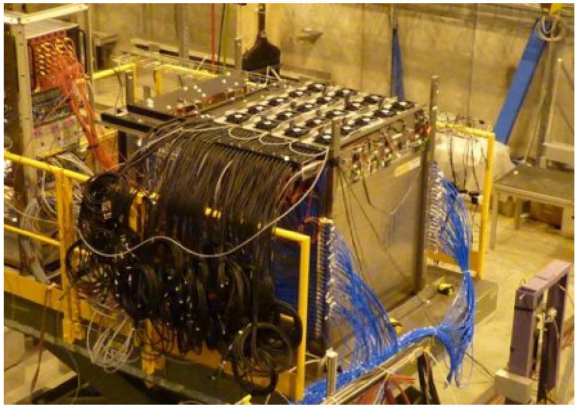



AHCAL unit

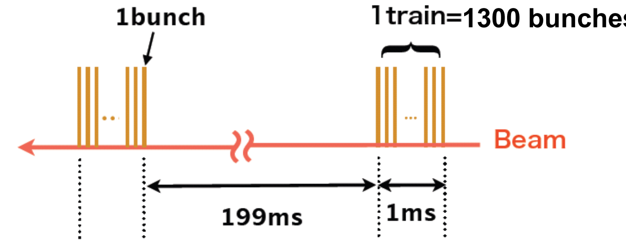


RPC for SDHCAL

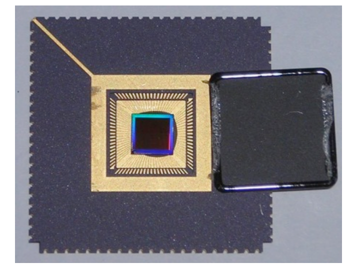




Vertex Detector

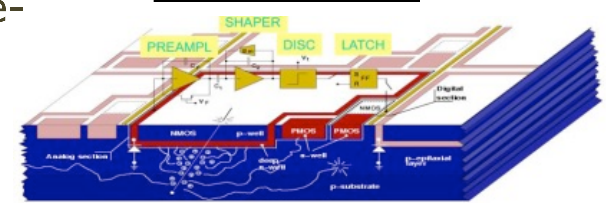


- Requirements
  - ILC beam: 1300 bunches with 554 ns intervals
  - **<3%** occupancy in innermost layer R=16mm
  - position resolution **<3µm**
  - **0.3%** X_0 per double layer (x3 = 6 layers)
- A variety of promising technology options
  - Fast readout during a bunch-train, to reduce bunches to be overlaid
    - CMOS–type, DEPFET, 3D-sensor
  - Readout between bunch trains
    - FPCCD with very small pixels to reduce hit occupancy ($5 \times 5 \mu m^2$, bonus: better resolution)
    - Chronopixel to provide single-bunch crossing time-stamping
    - SOFIST based on SOI technology
- More R&D for spatial resolution, material budget, readout speed, radiation hardness:
  - Vertex detector is the last to be installed.

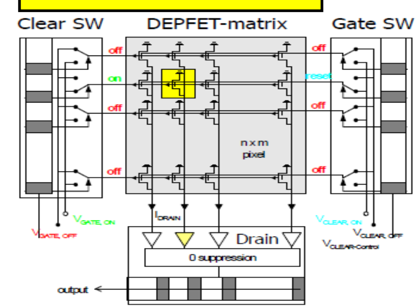
Chronopixel



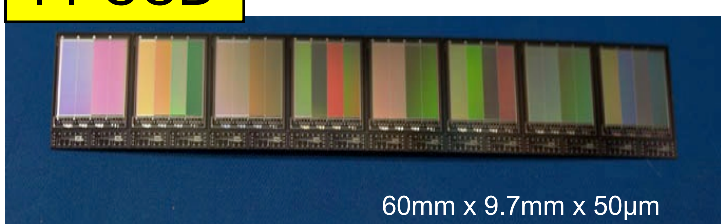
3D-sensor



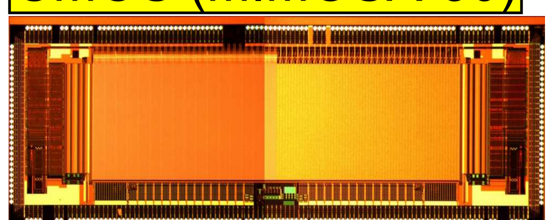
DEPFET



FPCCD



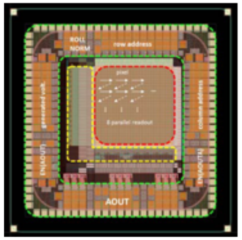
CMOS (MIMOSA-30)



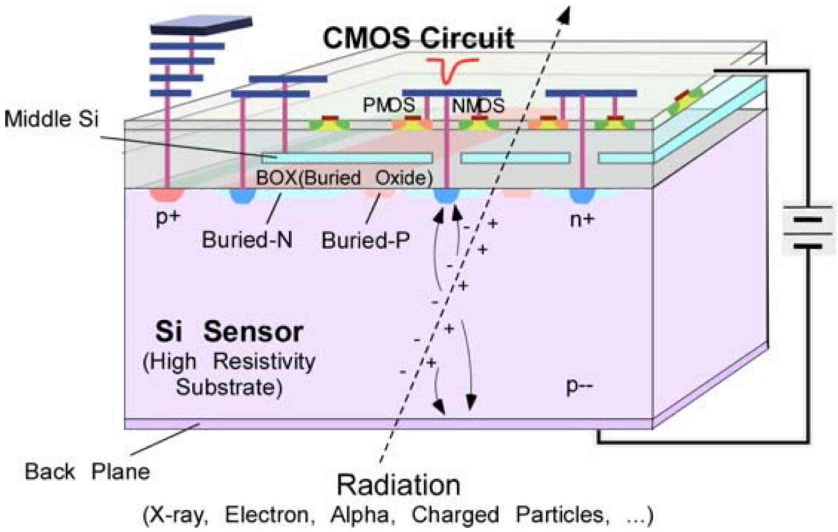
SOI (Silicon on Insulator)

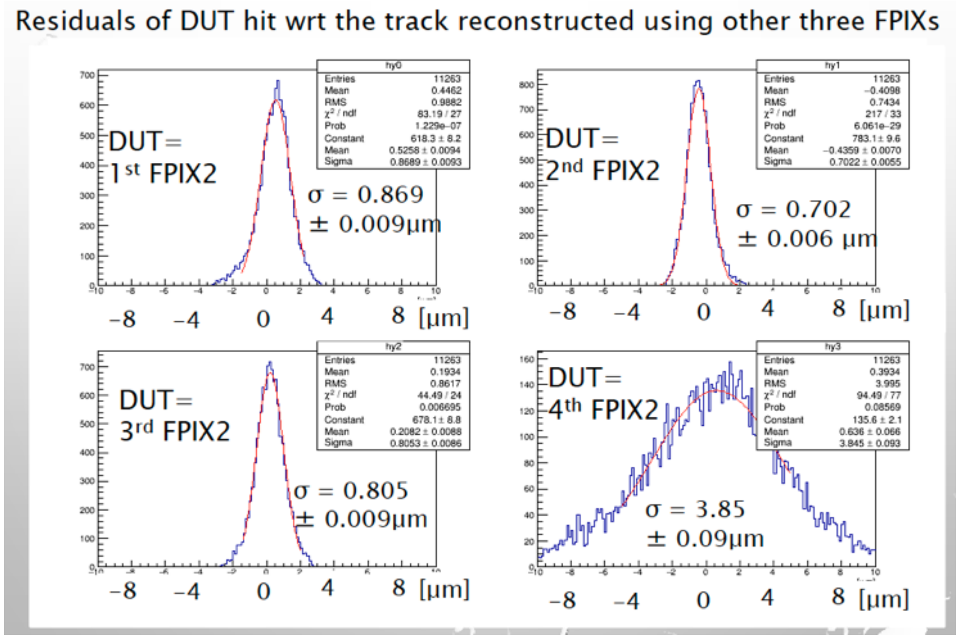
A next generation technology developed by KEK and Tsukuba-U

- CMOS circuit fabricated above the silicon layer on the wafer.
- CMOS circuit fully isolated from each other and from the wafer.
- Fully depleted CMOS sensors possible
- FPIX2 chip with 8 μm pixel size tested at FNAL TB
  → **intrinsic spatial resolution < 1 μm** achieved !!



FPIX2 chip





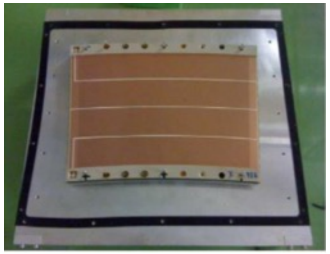
K. Hara@TIPP2017

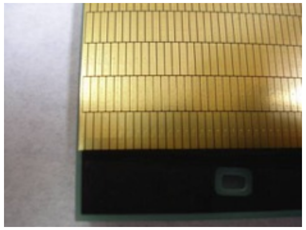
Time Projection Chamber

- Requirements
  - rφ resolution **<100μm**
  - ~**200** measurement points
  - Material budget **5%** X_0 (barrel), **25%** $\mathbf{X_0}$ (endcap)
    → thin endplate
- Technology options
  - **GEM** + Pad readout
  - **Micromegas** + resistive Pad readout
  - **GEM/Micromegas** + Si pixel readout

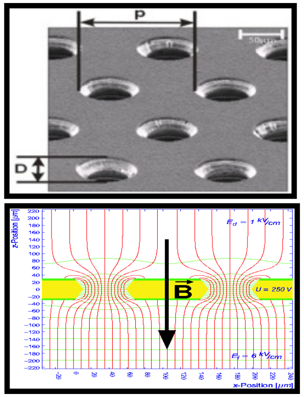
→ Micro-Pattern Gas Detector (MPGD)

GEM	Micromegas	Pad



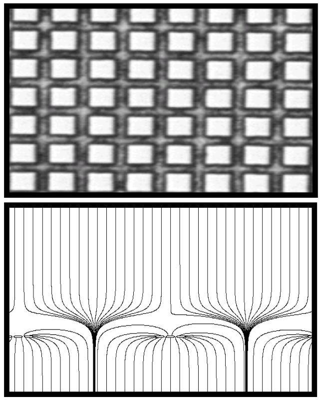


GEM



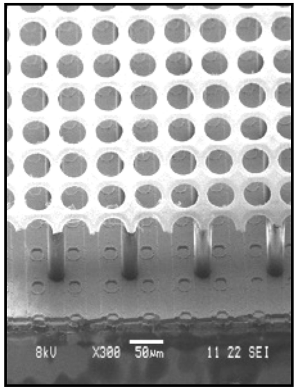
140um pitch

Micromegas

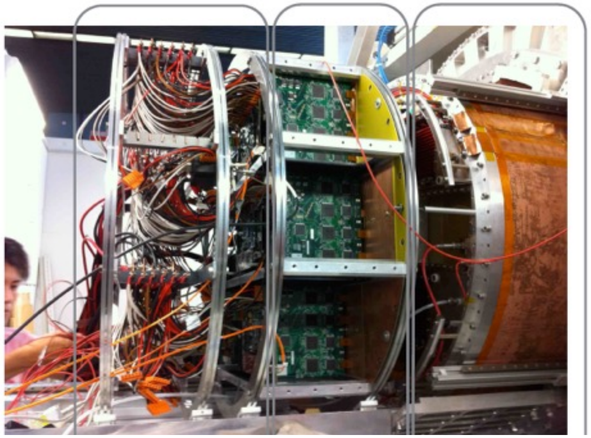


50um pitch

Ingrid TimePix

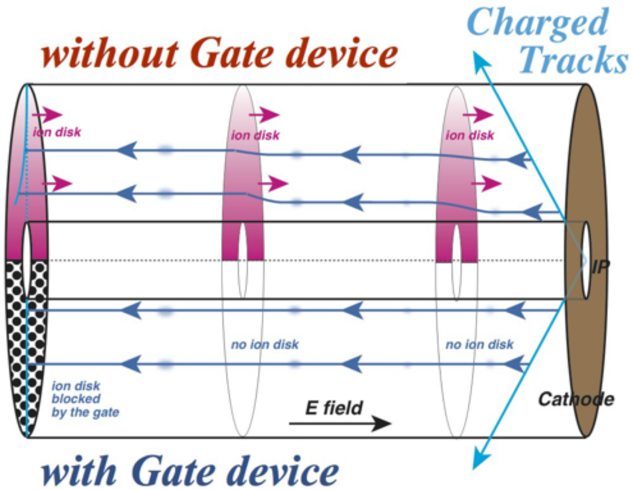


50um pitch



LCTPC Large prototype tested at DESY

Gating GEM for LC-TPC

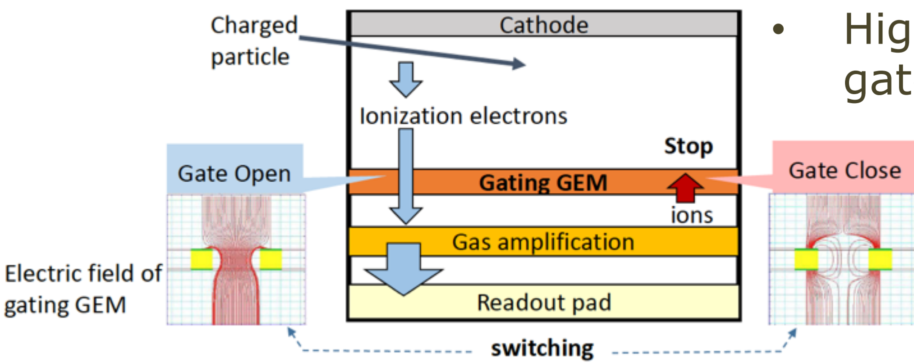


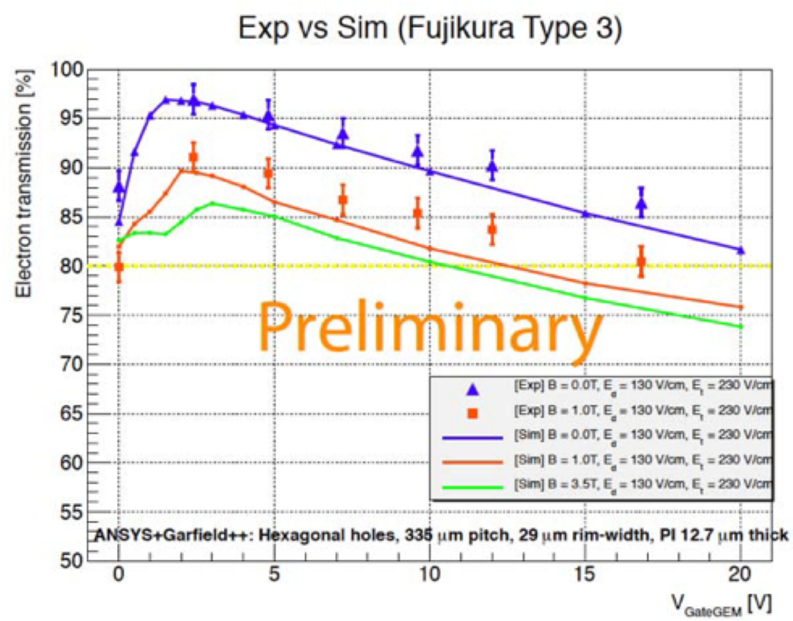
ILC has a special bunch structure (5 Hz, 1ms bunch train)

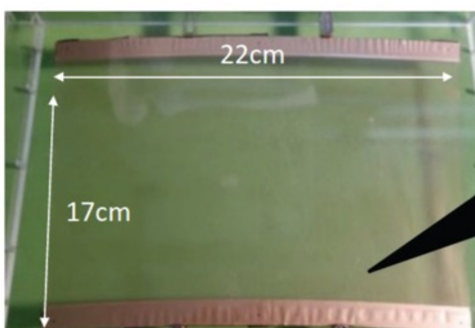
- 3 disks of IBF may slowly move from anode to cathode → distortion of the electric field
- **IBF must be completely blocked** (<0.01%) to achieve spatial resolution < 100 μm

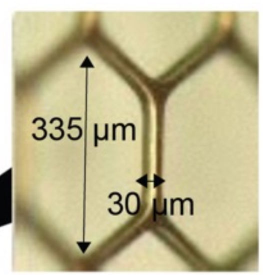
Gating GEM above the MPGD is developed

- High electron transparency (> 80 %) when the gate is OPEN.
- High blocking power for positive ions when the gate is CLOSED.





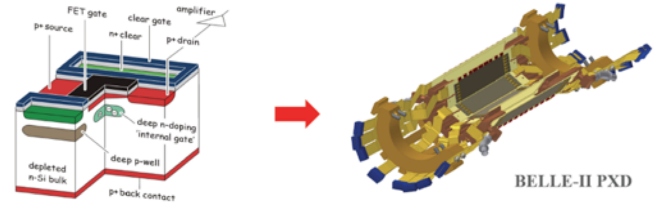




Fujikura Ltd.

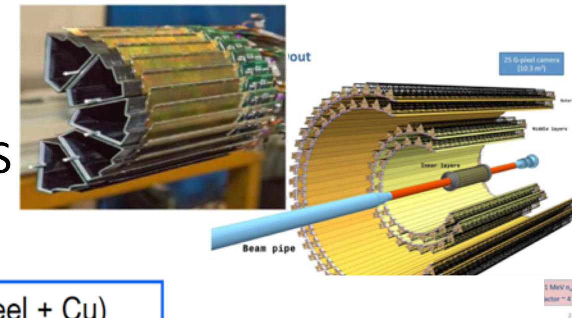
Application to other experiments

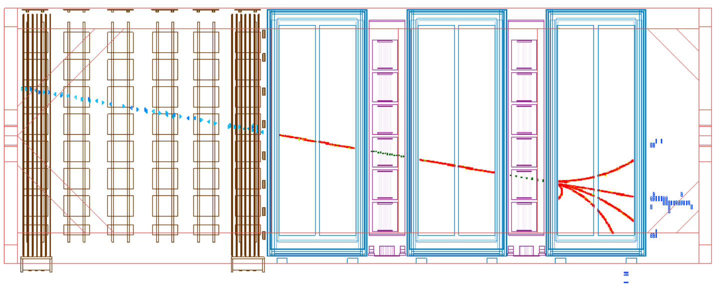
DEPFET → BELLE-II PXD



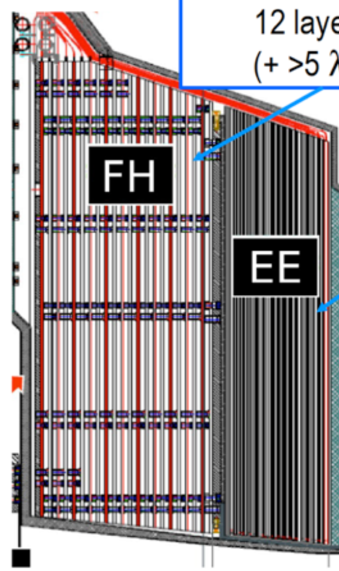
TPC with Micromegas
→ T2K near detector

CMOS-Pixel
→ STAR-PXL, ALICE-ITS





CALICE SiW Calorimeter
→ CMS HL-LHC Endcap Calorimeter
(ATLAS & ALICE under consideration)



FH: Si+(Steel + Cu)
12 layers, >3.5 λ
(+ >5 λ from BH)

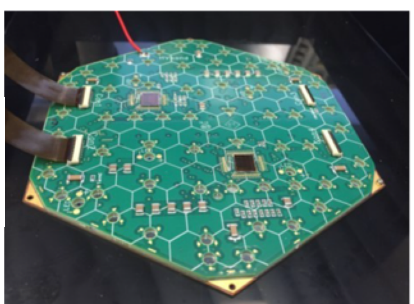
EE: Si+W/Cu
28 layers, ~26 X_0 (1.5 λ)
- 10 x 0.65 X_0 +
- 10 x 0.88 X_0 +
- 8 x 1.26 X_0

Operation at -30°C via CO_2 Cooling
(to mitigate Si leakage current)

Table 3.2: Parameters of the EE and FH.

	EE	FH	Total
Area of silicon (m^2)	380	209	589
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7
Number of Si planes	28	12	40

Modules
with 2x6 or 8" Hexagonal Si sensors,
PCB, FE chip, on W/Cu baseplate



Many other applications in Material Science, Life science, Medical instruments, …

The ILD concept group

61 Institutes / 338 members have signed the ILD documents of 2019 (input to EPPSU, ILD Design Report)
The numbers may grow once Japan makes the decision. Hope more Indian institutes to join.
ILD spokesperson: T. Behnke (DESY), deputy: K. Kawagoe (Kyushu)

Summary

Physics

- A consensus among the high energy physics community: a Higgs Factory is the highest priority for the next global machine.
- ILC at 250 GeV promises excellent performance as a Higgs Factory. Electron polarizations are a essential tool.
- ILC 250 also offers various opportunities for discoveries, for example dark matter search.
- Future energy upgrade path should be decided based on the outcome of the 250GeV program.

Detectors

- Unprecedented resolutions required for ILC Detectors.
- PFA is an effective guiding principle for design.
- To realize the goals, new technologies/ideas are needed.
- Since the TDR in 2012, many progresses have been made. However, still there are many holes in the R&Ds.
- Now is the good time to plug in to ILC detector R&Ds.

Backup slides

Example of Non-Higgs Process that plays an important role in the EFT fit

$e^+e^- \to W^+W^-$ (Triple Gauge Couplings)

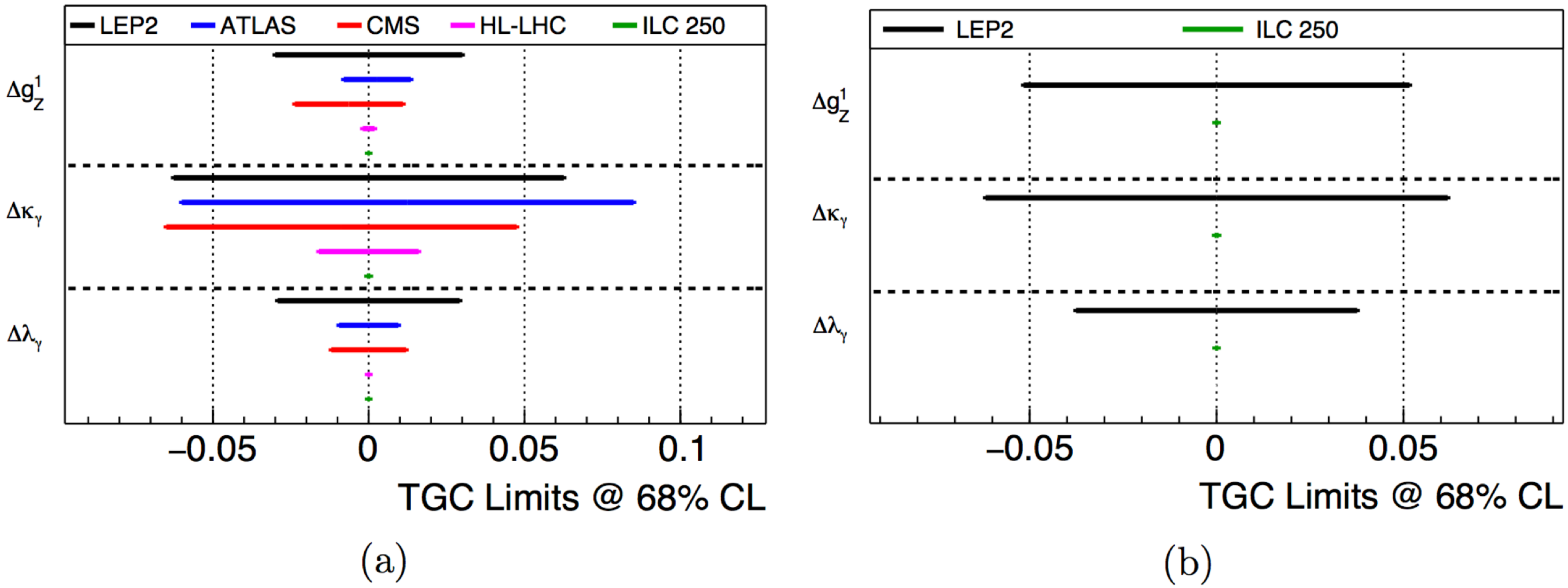


Figure 11: TGC precisions for LEP 2, Run1 at LHC, HL-LHC and the ILC at $\sqrt{s} = 250$ GeV with 2000 fb^{-1} luminosity (ILC 250) using one parameter fits (a) and for LEP 2 and ILC 250 using three parameter fits (b).

Significant improvements from HL-LHC and LEP2 !

Comparison with other Higgs factory proposals

Proposals of future energy frontier accelerators

Comparisons

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

D. Schulte Higgs Factories, Granada 2019 5

From "Accelerator Summary"
at Open Symposium towards updating the European Strategy for Particle Physics May 13-16, 2019, Granada, Spain

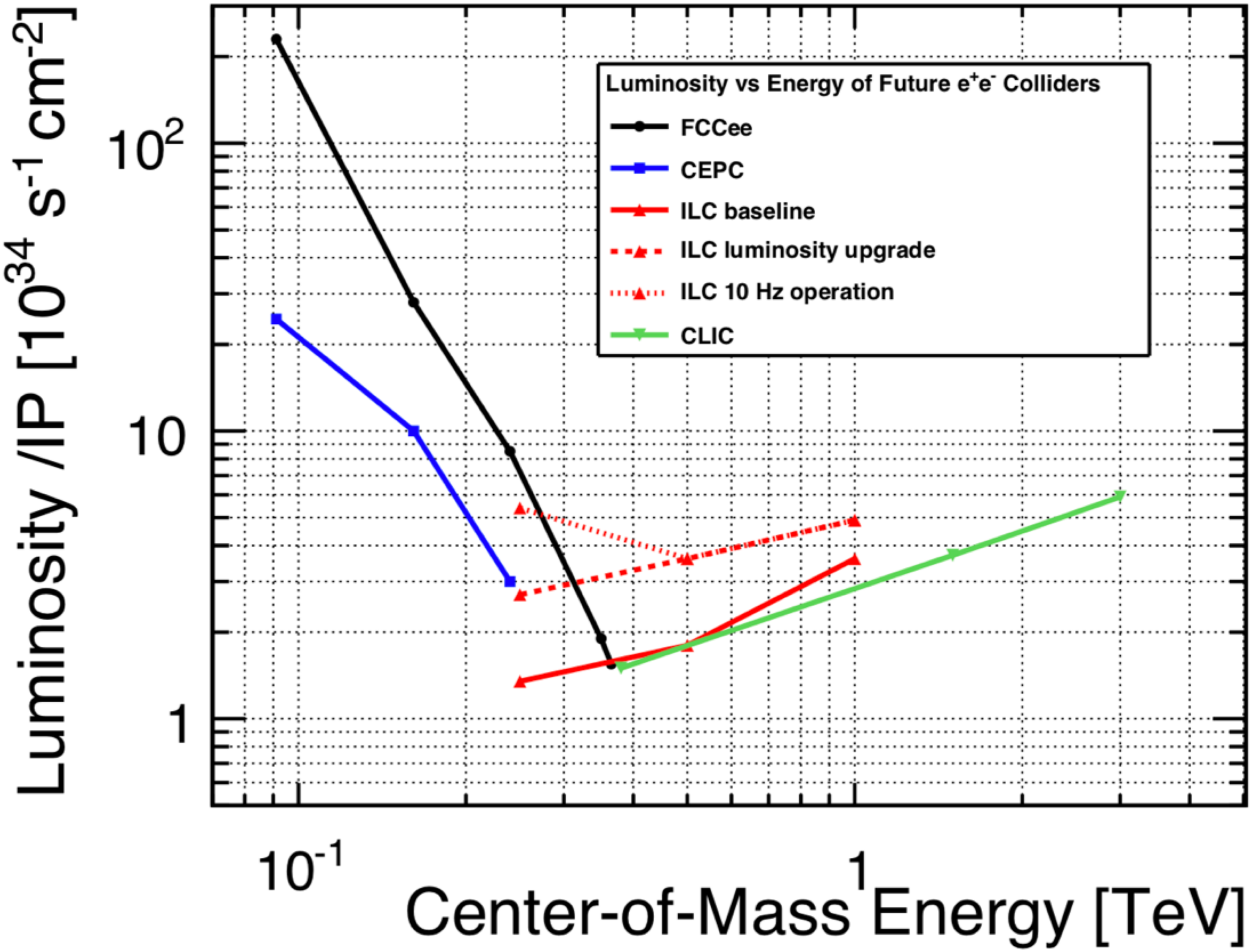
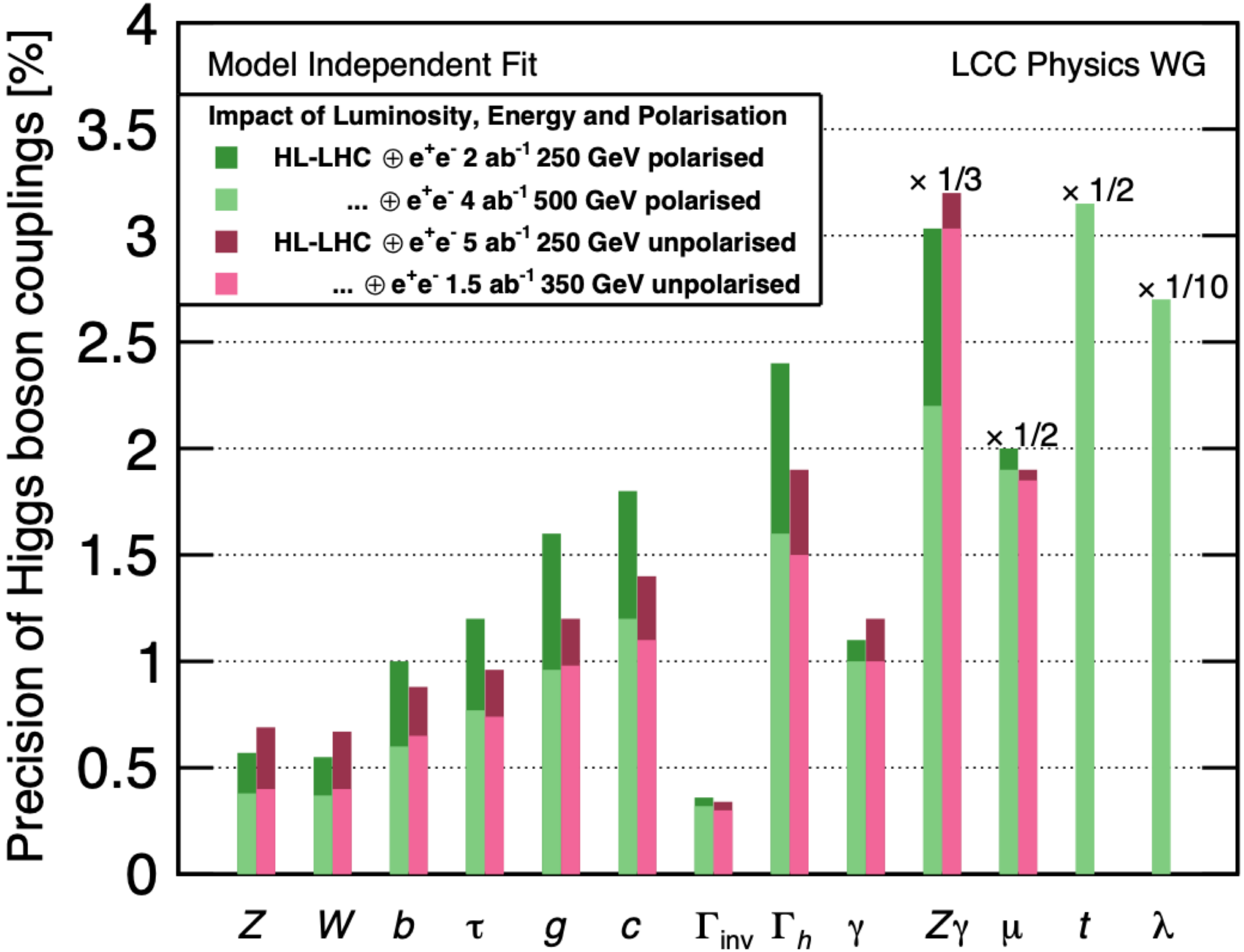


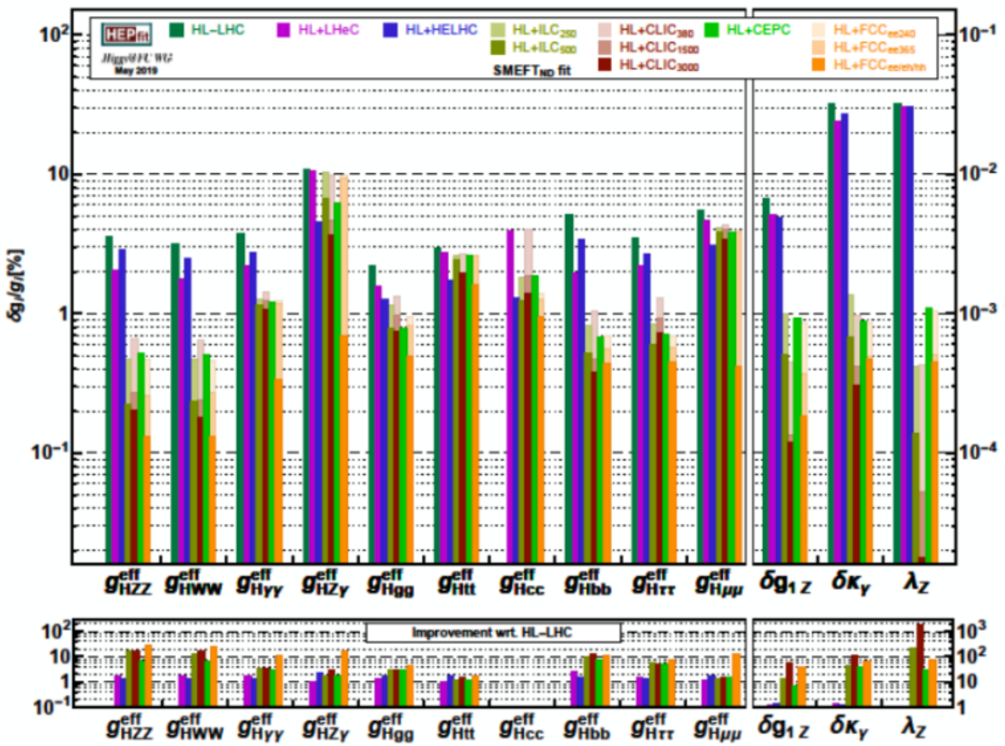
Figure 1: The luminosities of the ILC as functions of energy. Those of other e^+e^- colliders are also shown. The numbers are per IP, while the effect of polarization is not included.

Power of Polarization



Polarized 2 ab^{-1} is roughly equivalent to unpolarized 5 ab^{-1}.

Comparison of Colliders: EFT



Effective Higgs couplings

- Constraints approach 0.1% precision for gauge bosons
- Major improvement w.r.t. HL-LHC for many colliders for fermions

Trilinear gauge couplings

- Will achieve precision 10^{-3}-10^{-4}
- About 2-3 orders of magnitude better than LEP

arXiv:1905.03764

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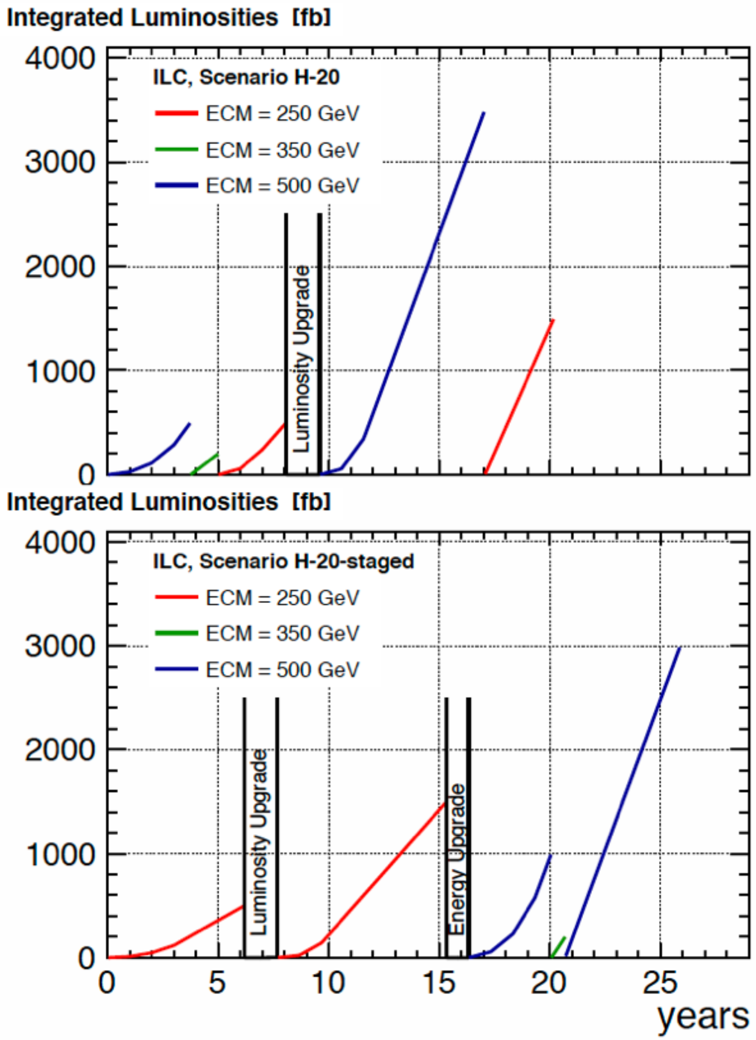
From “Summary: Electroweak Session” at Open Symposium towards updating the European Strategy for Particle Physics, May 13-16, 2019, Granada, Spain

“ All electron-positron colliders achieve major (and comparable) improvements in their first stage already in proving Higgs sector compared to HL-LHC “

The ILC running scenarios discussed in 2015

scenario:
example



ILC500
H20

ILC250
H20 staged

top physics starts
after > 16y
in total ~ 6y longer

59

Requirements for ILC Detectors

- **Vertex Detector: pixel detectors & low material budget**

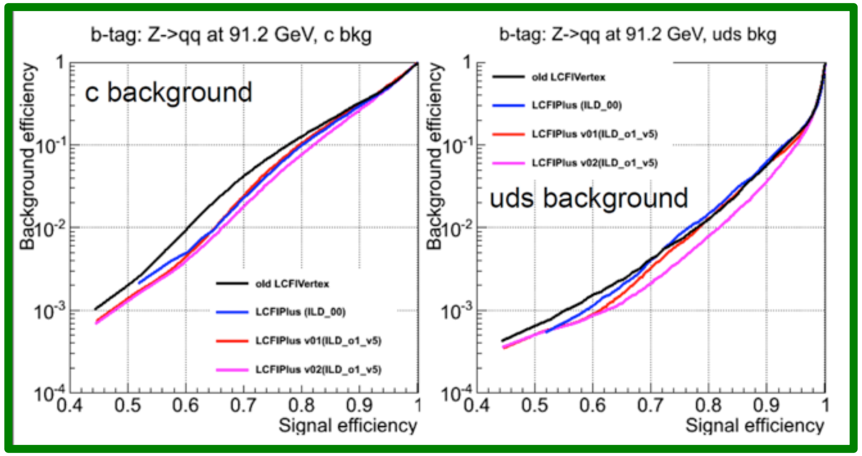
$$\sigma_{ip} = 5\mu m \oplus 10\mu m / p \sin^{3/2}\theta$$

- **Central Tracker: high resolution & low material budget, (TPC+)Silicon**

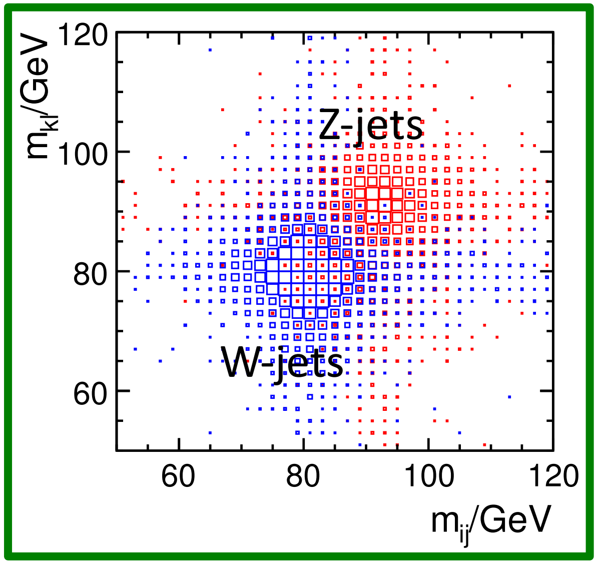
$$\sigma(1/pT) = 2\times 10^{-5}/\text{GeV}$$

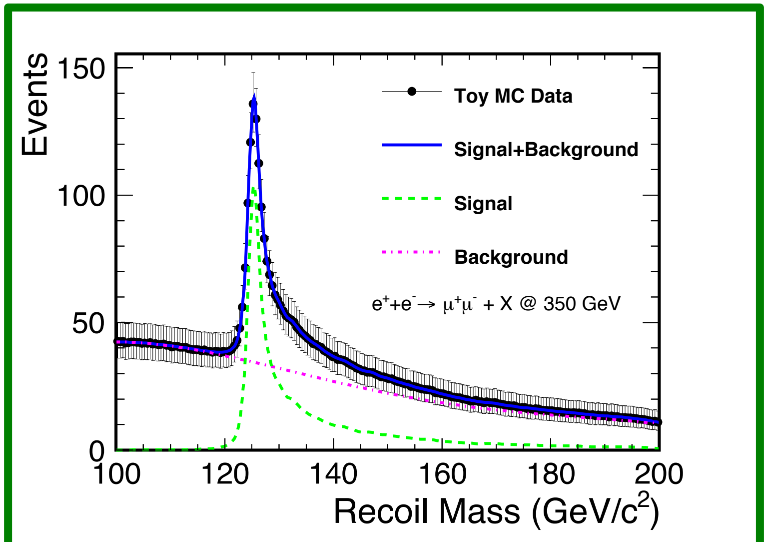
- **Calorimeters: high granularity & particle flow to realize high jet-energy resolution to separate W jets and Z jets**

$$\sigma_E / E = 30\% / \sqrt{E(\text{GeV})}$$



Vertex: Jet-flavor tagging

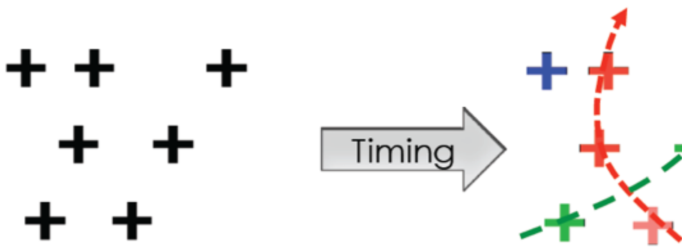


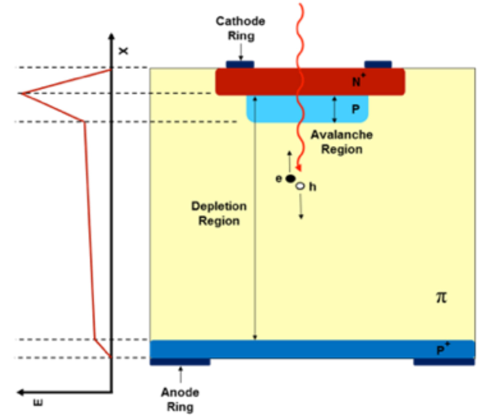


Tracker: reconstruct Higgs recoil mass
Using only a lepton-pair from Z^0

Low-Gain Avalanche Diode (LGAD)

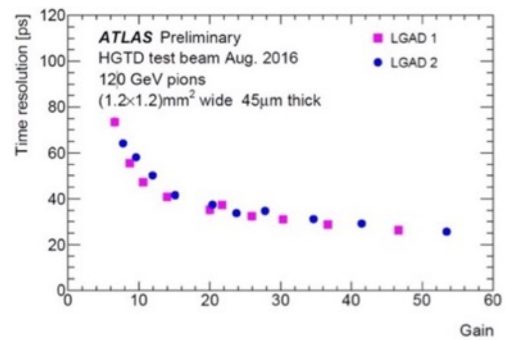
Precision timing of each point along the track can mitigate pile-ups
→ Use only "time-compatible points" for pattern-recognition





LGAD: **thin** silicon detector with **low gain** multiplication for **precise timing** measurement

- High electric field to accelerate electrons for multiplication, by highly doped p^+ region
- Moderate internal gain to reduce shot noise.
- 4 suppliers: **CNM**, FBK, HPK, Micron
- Both strip and pad detectors are possible



ATLAS HGTD (High Granularity Timing Detector) in front of endcap calorimeter

- 4 LGAD layers with 1.3 x 1.3 mm² sensor size
- Goal: 30 ps resolution for MIP

Use of precision timing detector at ILC

- Efficient to Particle-ID at low momentum