From LHC to ILC

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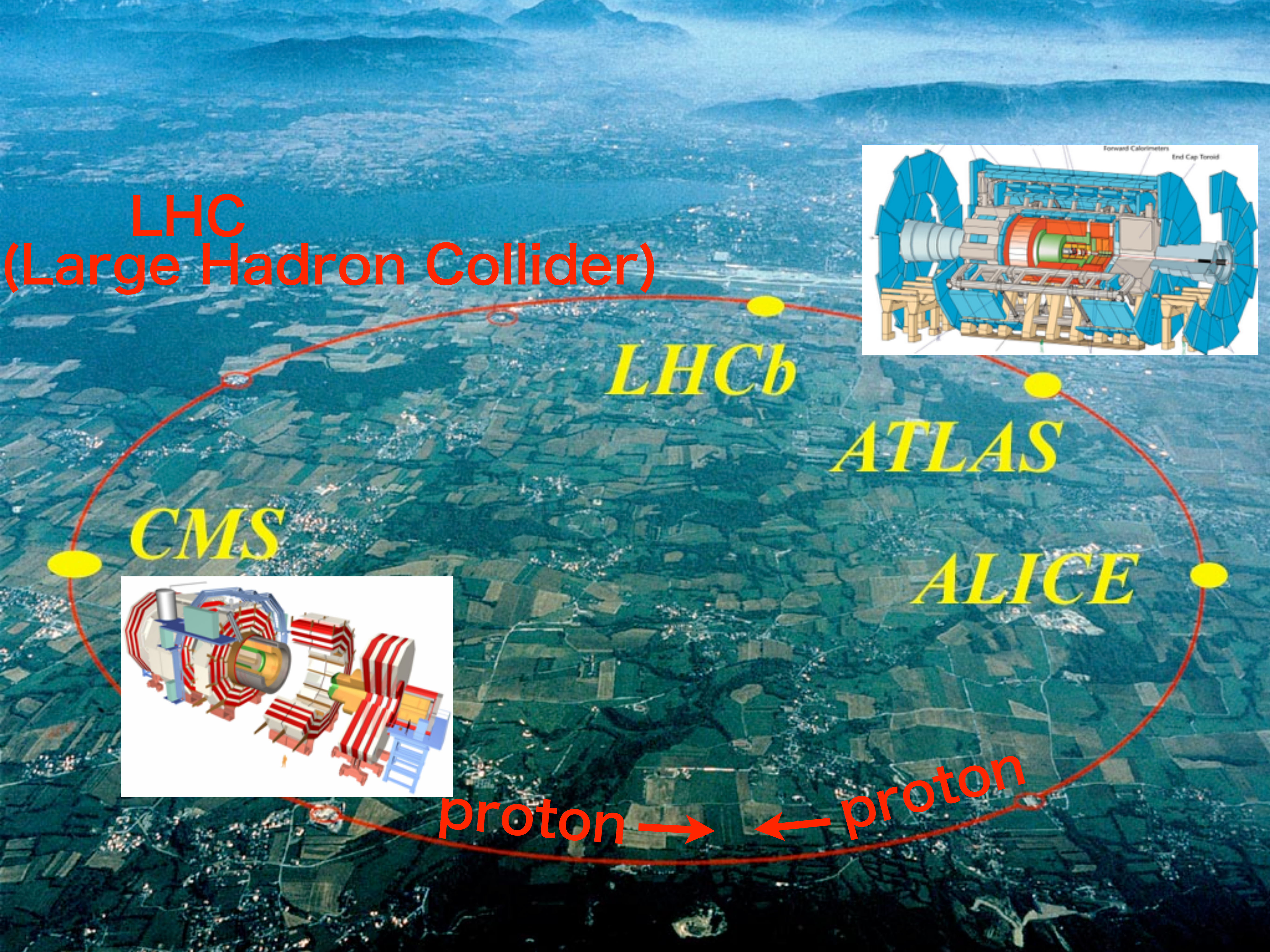
Yonsei-Saga Partnership Lecture 2015

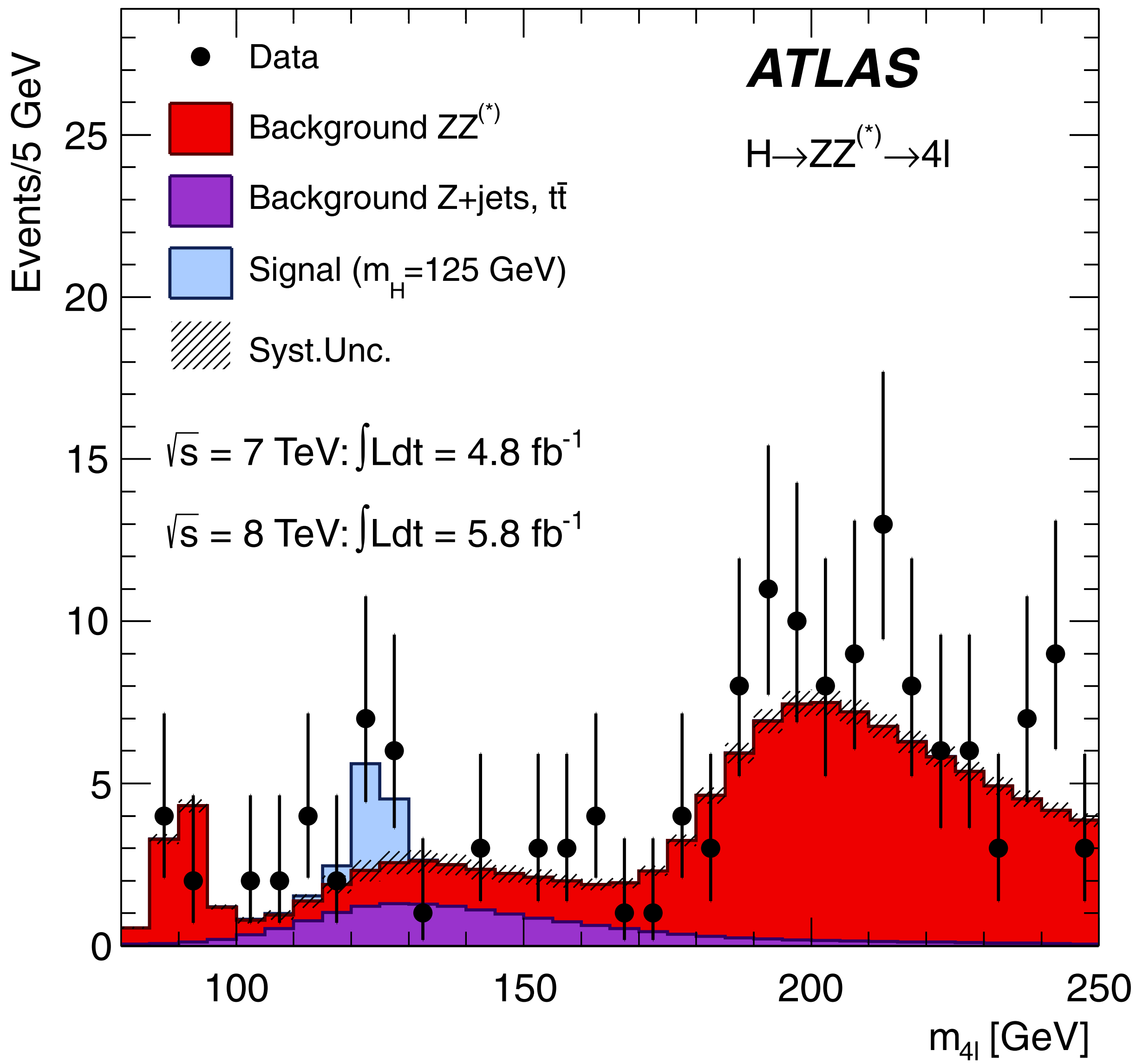
Contents

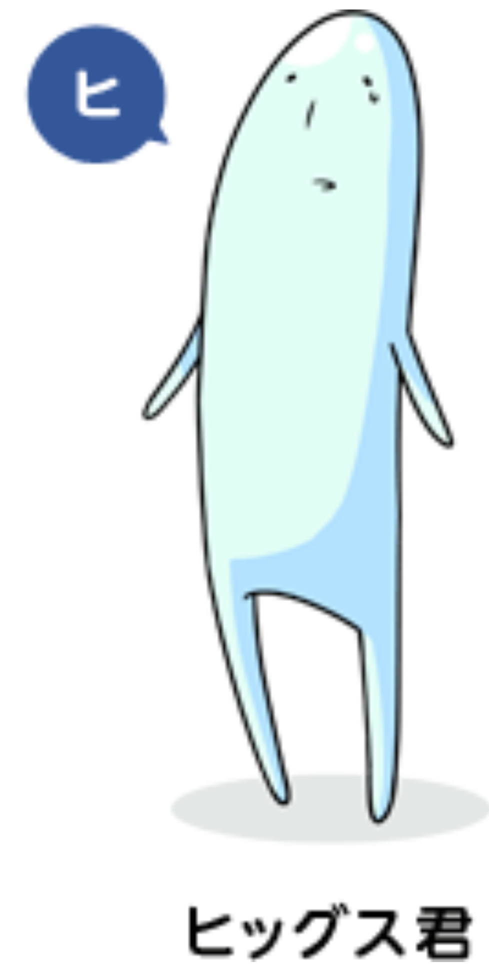
- About LHC results (just quickly)
- Importance of ILC
- ILC Detectors


LHC
(Large Hadron Collider)
LHCb
ATLAS
CMS
ALICE
Forward Calorimeters
End Cap Toroid
proton
proton

Higgs boson discovery

4/Jul/2012

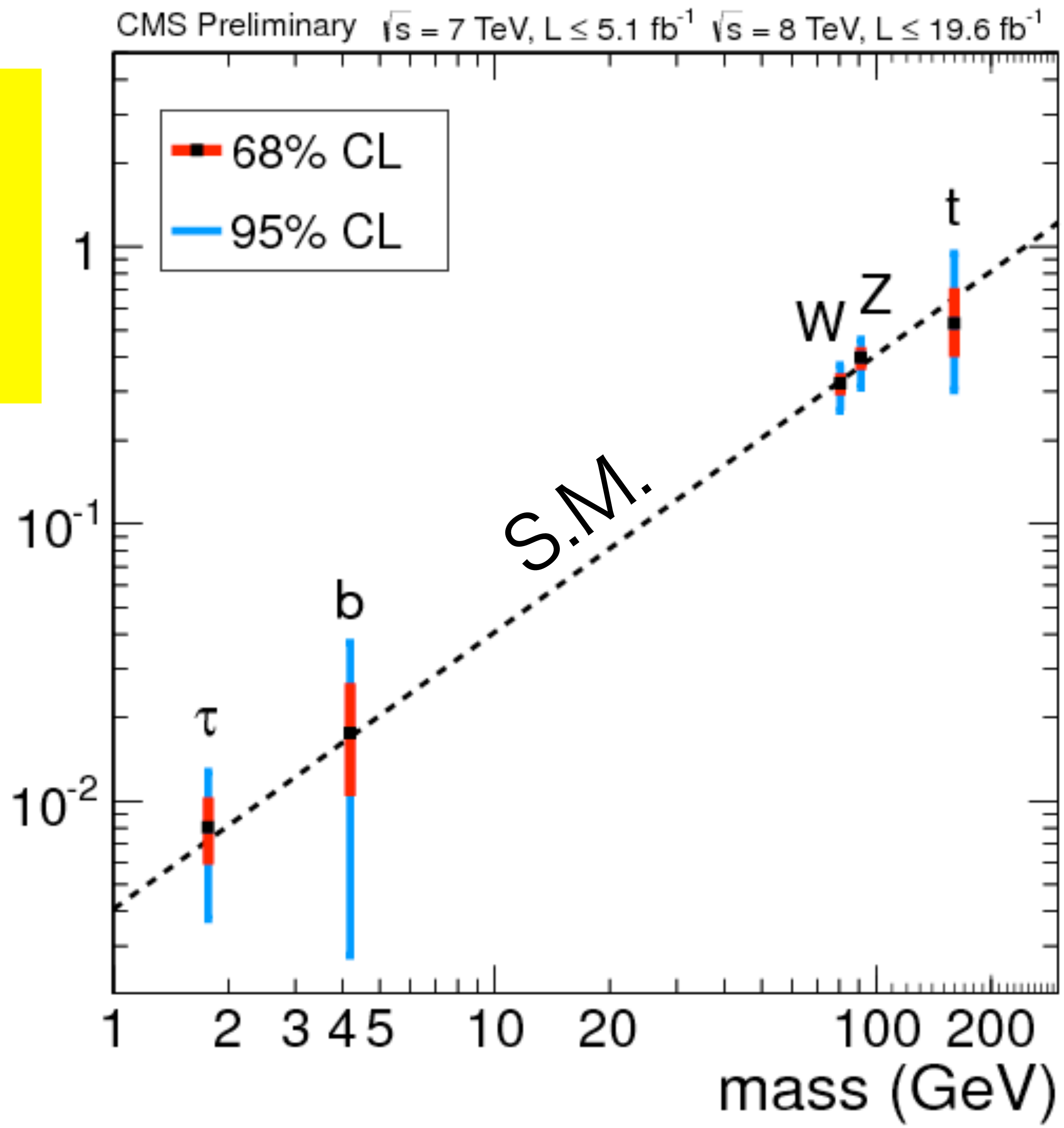




mass of Higgs candidate events

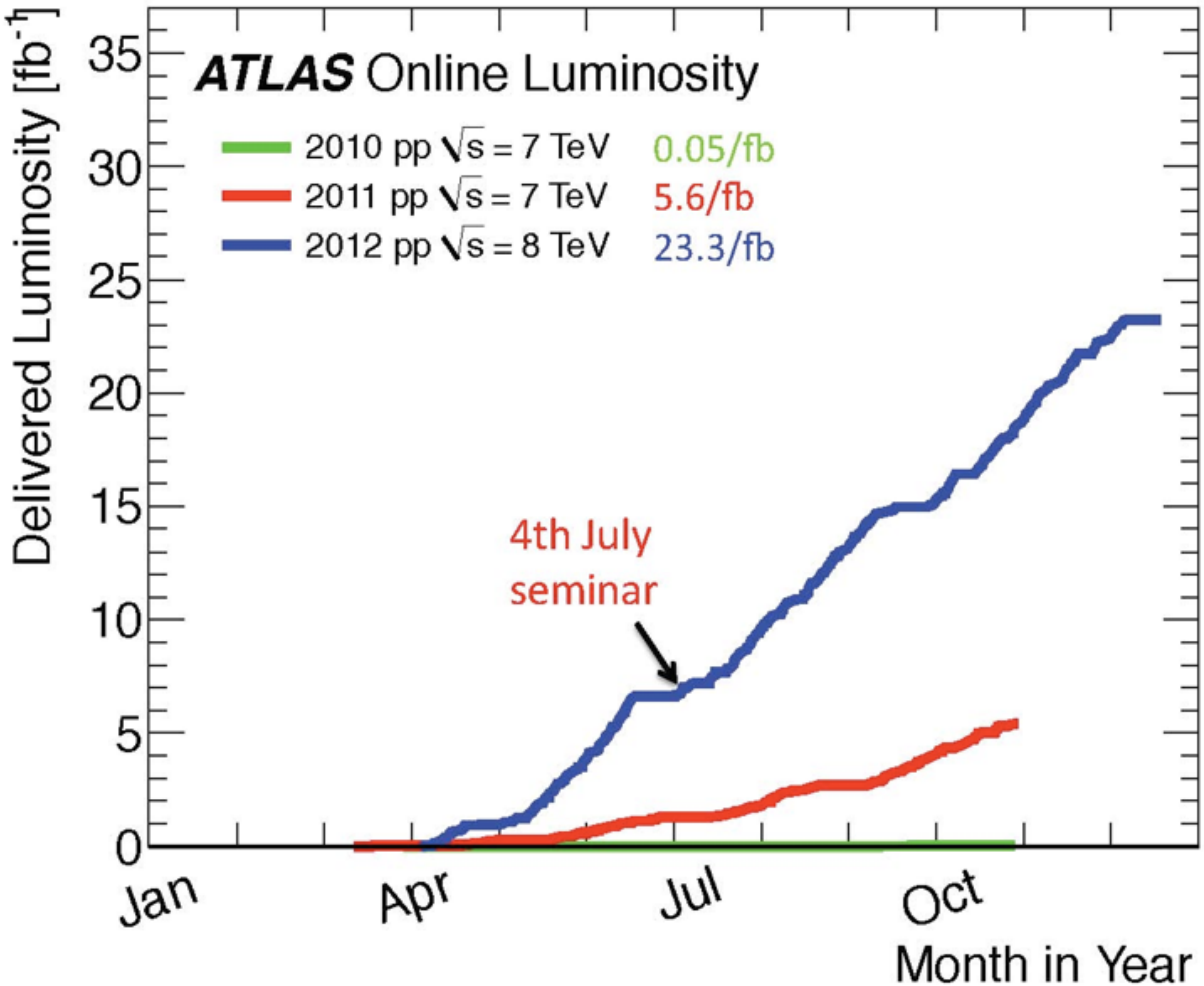
Higgs is actually the origin of mass!

higgs coupling



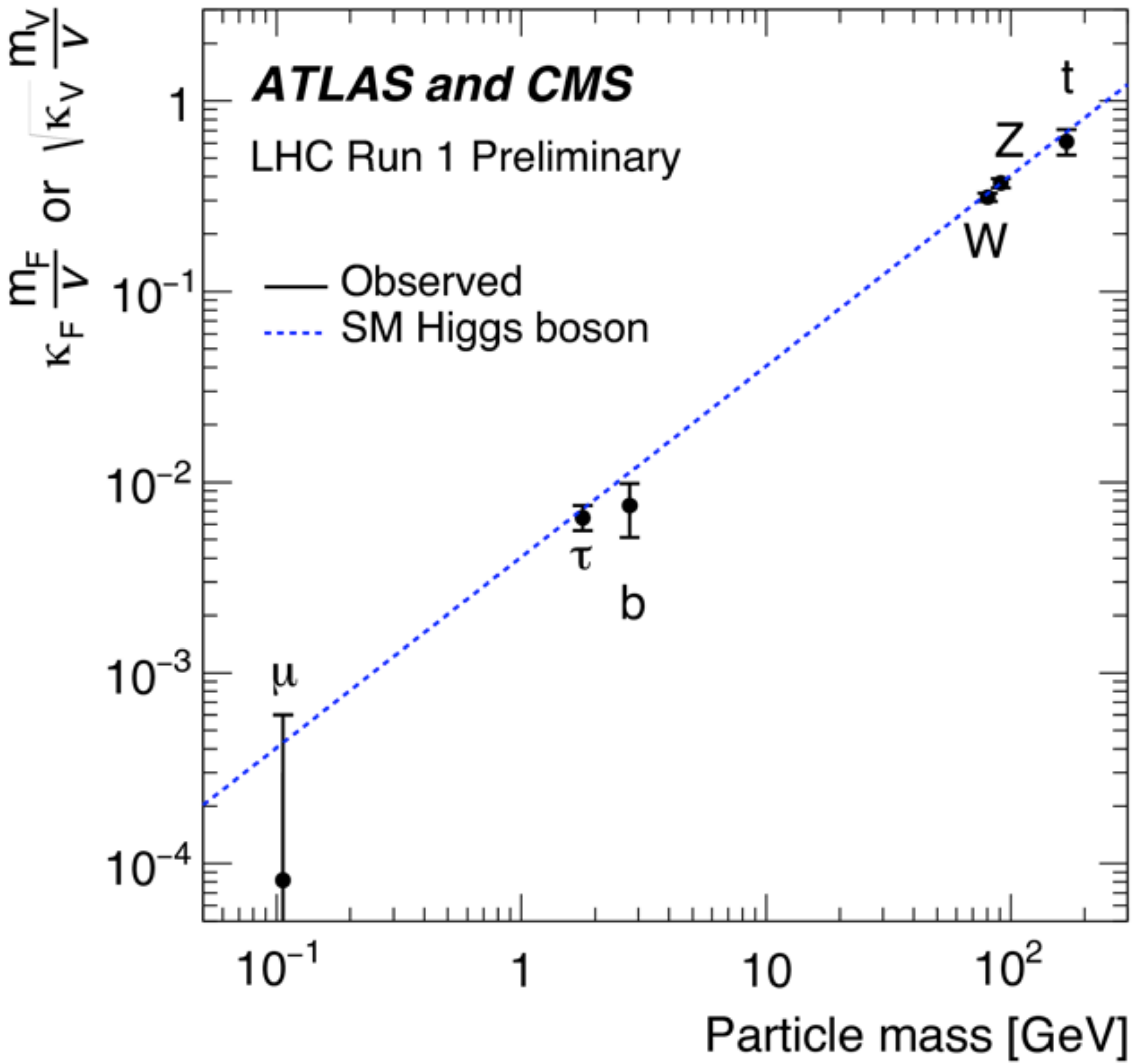
early LHC results

Luminosity

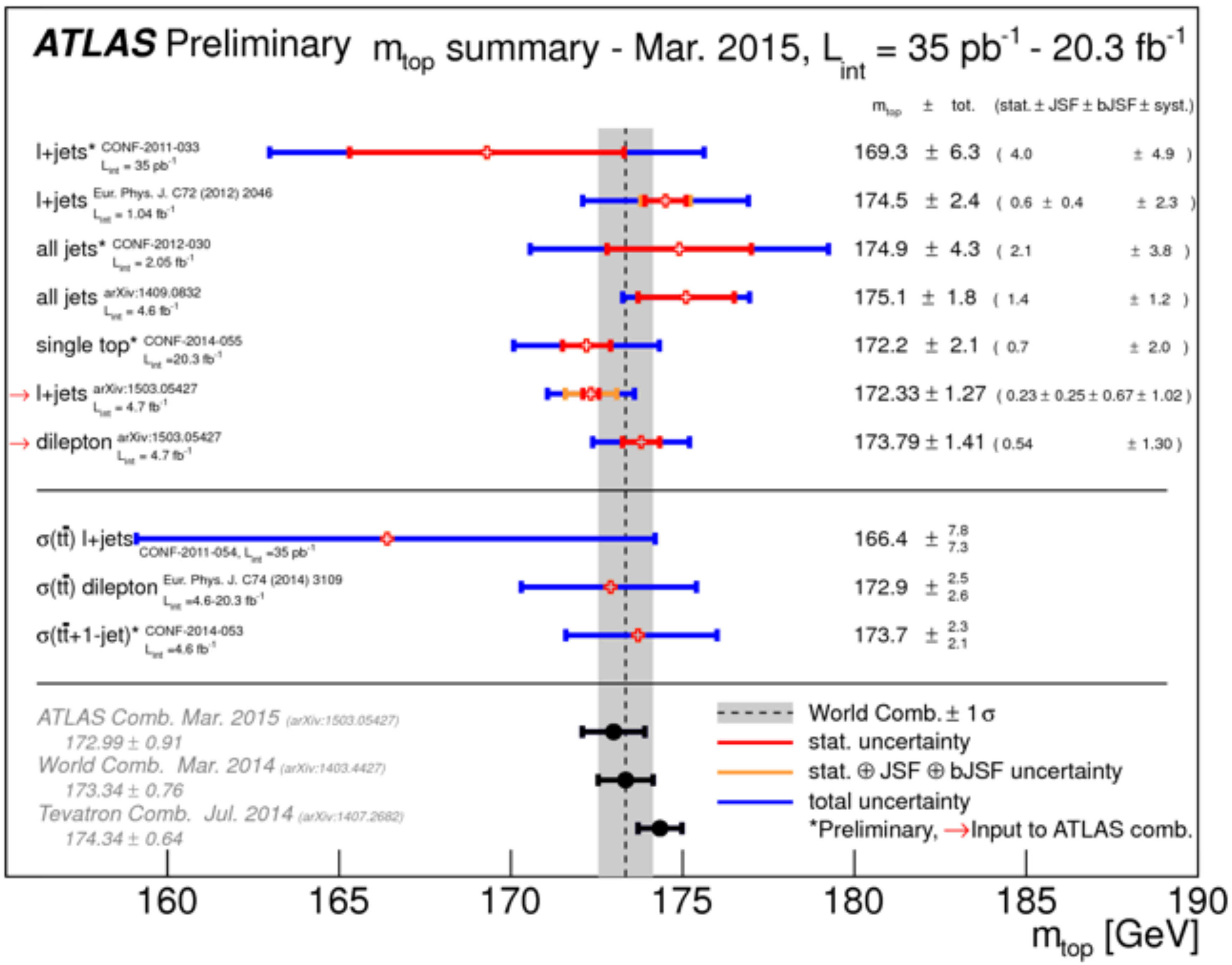


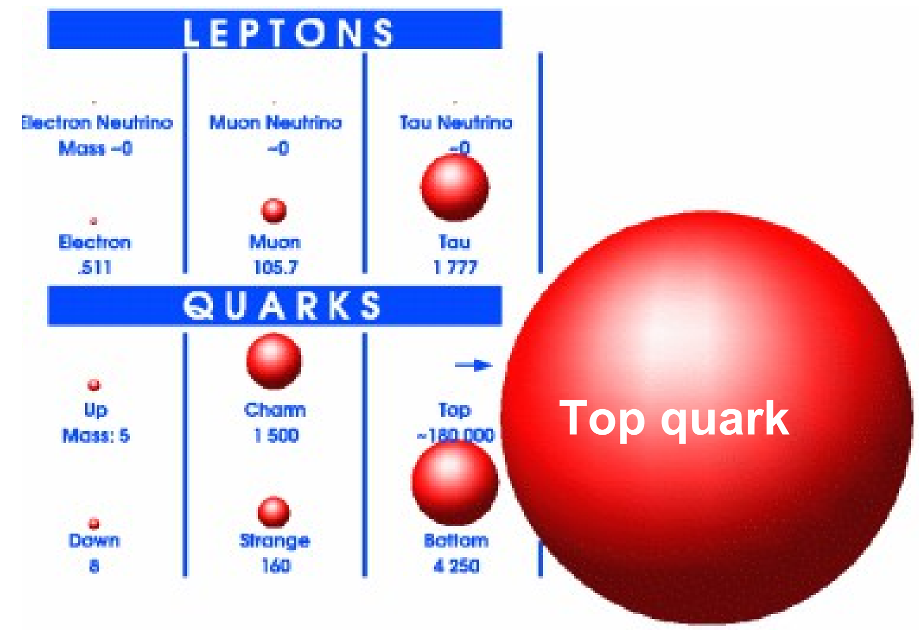
ATLAS Online Luminosity
2010 pp √s = 7 TeV
0.05/fb
2011 pp √s = 7 TeV
5.6/fb
2012 pp √s = 8 TeV
23.3/fb
4th July
seminar
Delivered Luminosity [fb-1]
0
5
10
15
20
25
30
35
Jan
Apr
Jul
Oct
Month in Year

Higgs couplings



Top quark mass



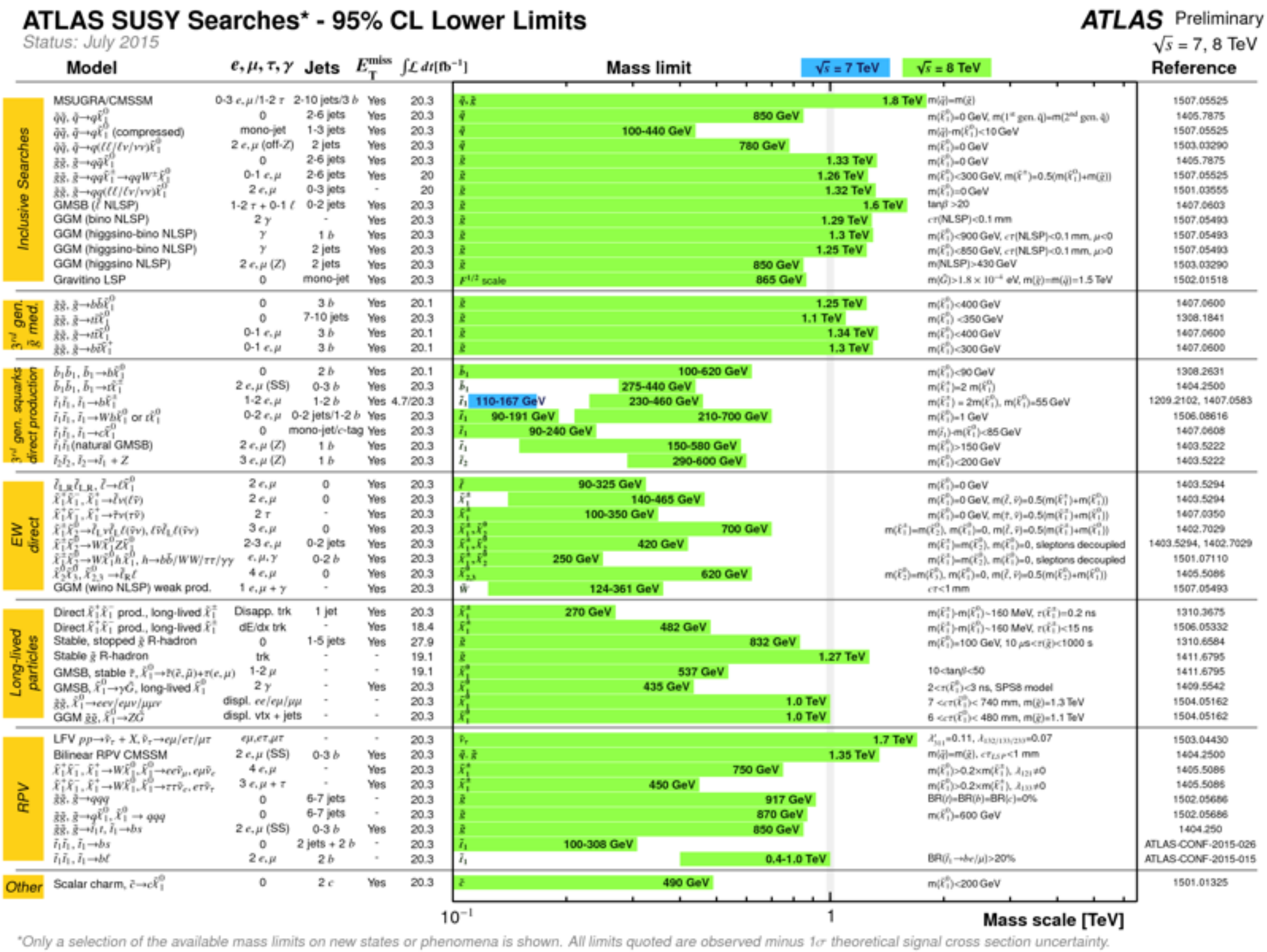


heaviest of the SM particle

↓

the strongest coupling with Higgs sector

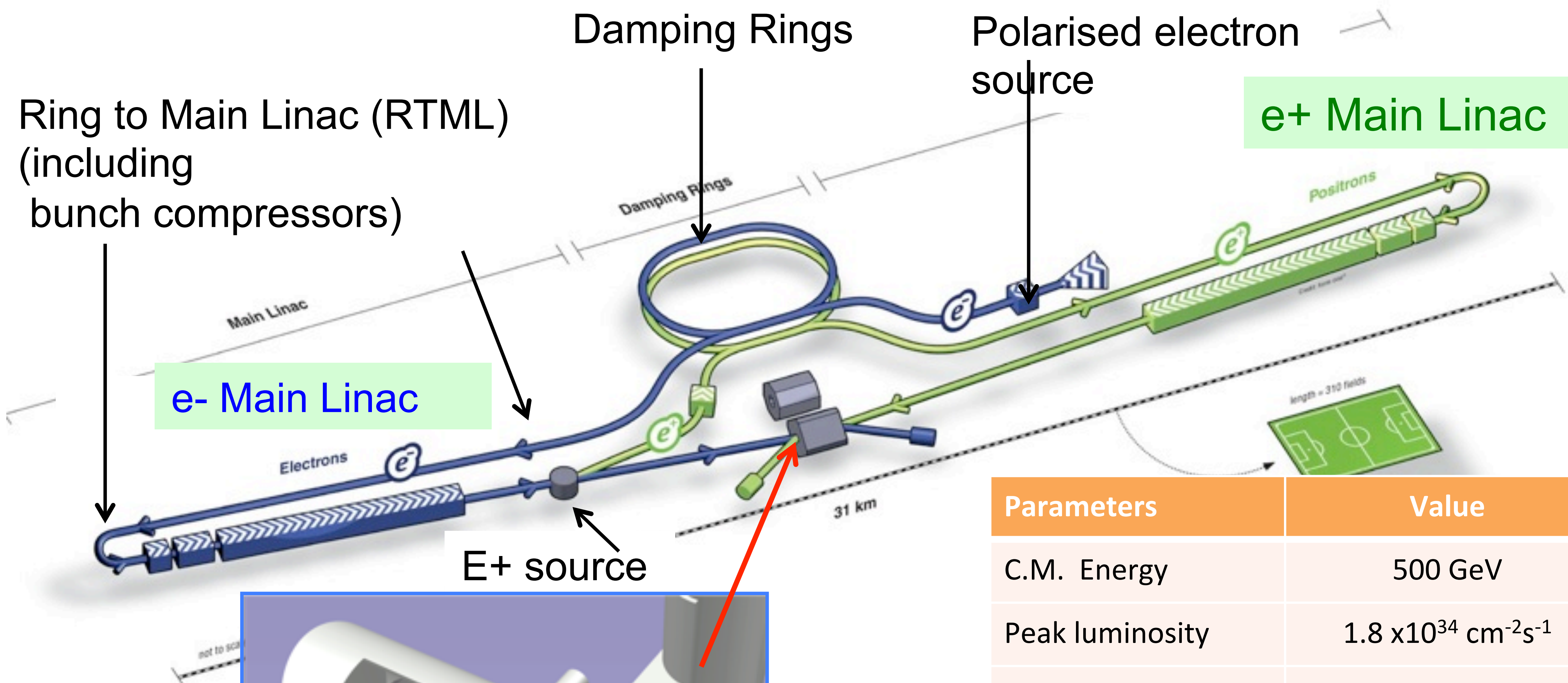
SUSY search

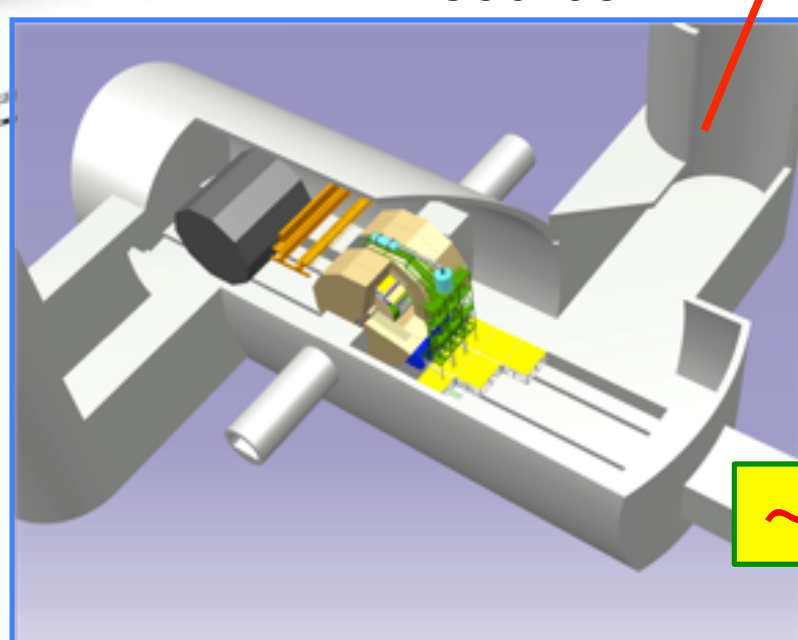


ATLAS SUSY Searches* - 95% CL Lower Limits
Status: July 2015
ATLAS Preliminary
$\sqrt{s}$ = 7, 8 TeV
Model
e, μ, τ, γ
Jets
E_T^{miss}
$\int \mathcal{L}\, dt [fb^{-1}]$
Mass limit
$\sqrt{s}$ = 7 TeV
$\sqrt{s}$ = 8 TeV
Reference
Inclusive Searches
3rd gen. $\tilde{g}$ med.
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Other
10^{-1}
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

ILC

ILC Accelerator in TDR





～achieved

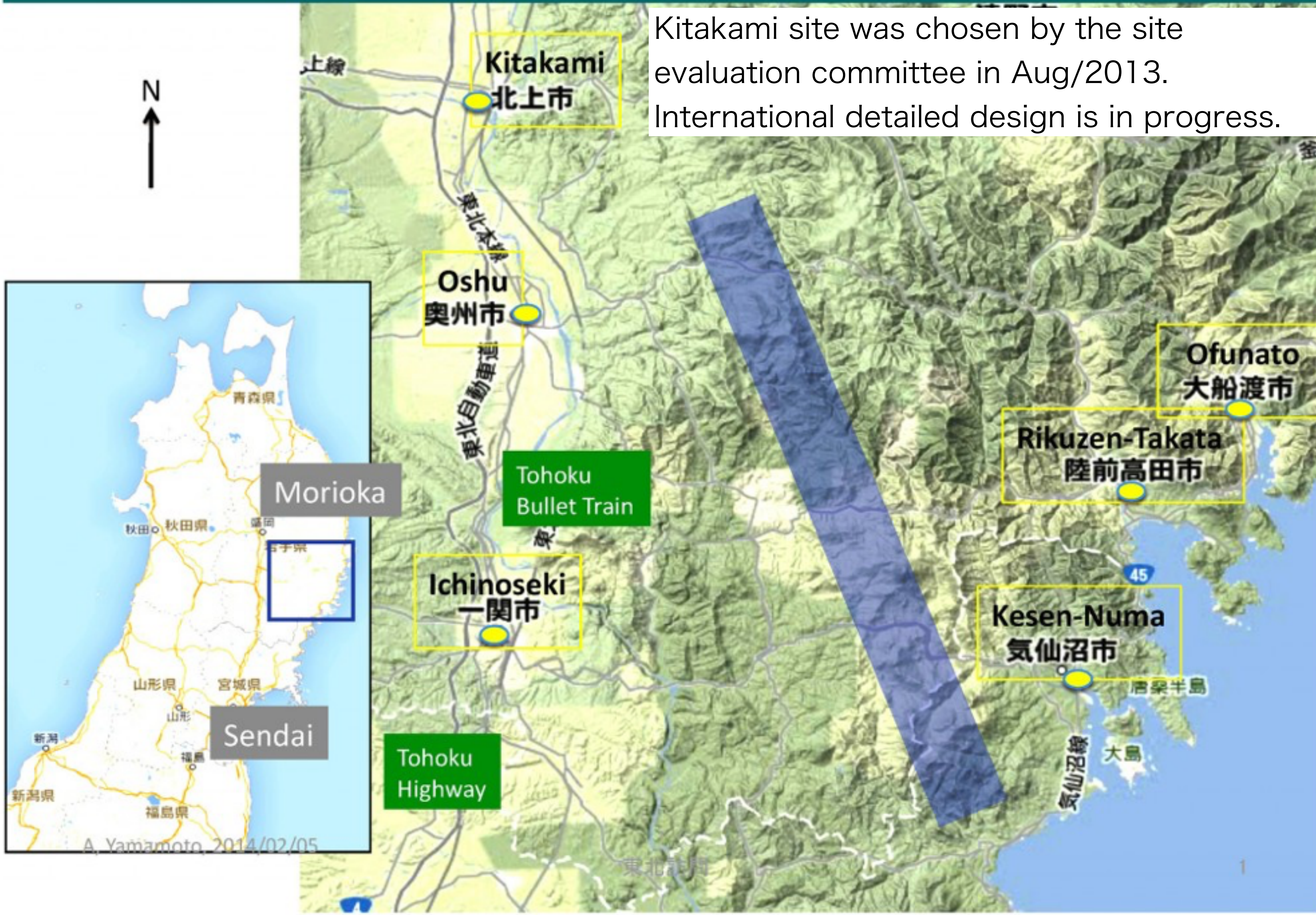
Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} cm^{-2}s^{-1}
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
FF beam size (y)	**5.9** nm
E gradient in SCRF acc. cavity	**31.5** MV/m +/-20% Q_0 = 1E10

4

From slides by Prof. Komamiya @ JPS

ILC Candidate site in Kitakami, Tohoku

Kitakami site was chosen by the site evaluation committee in Aug/2013.
International detailed design is in progress.



Summary of the International Linear Collider (ILC) Advisory Panel's Discussions to Date (Jun/2015)

http://www.mext.go.jp/b_menu/shingi/chousa/shinkou/038/gaiyou/1360593.htm

Recommendation 1: The ILC project requires huge investment that is so huge that a single country cannot cover, thus it is indispensable to share the cost internationally. From the viewpoint that the huge investments in new science projects must be weighed based upon the scientific merit of the project, a clear vision on the discovery potential of new particles as well as that of precision measurements of the Higgs boson and the top quark has to be shown so as to bring about novel development that goes beyond the Standard Model of the particle physics.

New particles detectable by ILC only are also important, i.e. comprementary to LHC

Summary of the International Linear Collider (ILC) Advisory Panel's Discussions to Date (Jun/2015)

http://www.mext.go.jp/b_menu/shingi/chousa/shinkou/038/gaiyou/1360593.htm

Recommendation 2: Since the specifications of the performance and the scientific achievements of the ILC are considered to be designed based on the results of LHC experiments, which are planned to be executed through the end of 2017, it is necessary to closely monitor, analyze and examine the development of LHC experiments . Furthermore, it is necessary to clarify how to solve technical issues and how to mitigate cost risk associated with the project.

LHC Run2 results on new physics are important to ILC

Summary of the International Linear Collider (ILC) Advisory Panel's Discussions to Date (Jun/2015)

http://www.mext.go.jp/b_menu/shingi/chousa/shinkou/038/gaiyou/1360593.htm

Recommendation 3: While presenting the total project plan, including not only the plan for the accelerator and related facilities but also the plan for other infrastructure as well as efforts pointed out in Recommendations 1 & 2, it is important to have general understanding on the project by the public and science communities.

Physics at ILC

- Precise measurement of Higgs
    - Higgs coupling → Sensitivity to new physics
    - Higgs self coupling → E > 500GeV is required
- Search for new particles
    - Direct search → High energy is required
    - Indirect search → High precision
    - Its nature → High precision & polarized beam
- Precise measurement of Top
    - Top mass → high precision, E>350GeV
    - Coupling → high precision & polarized beam with >350GeV

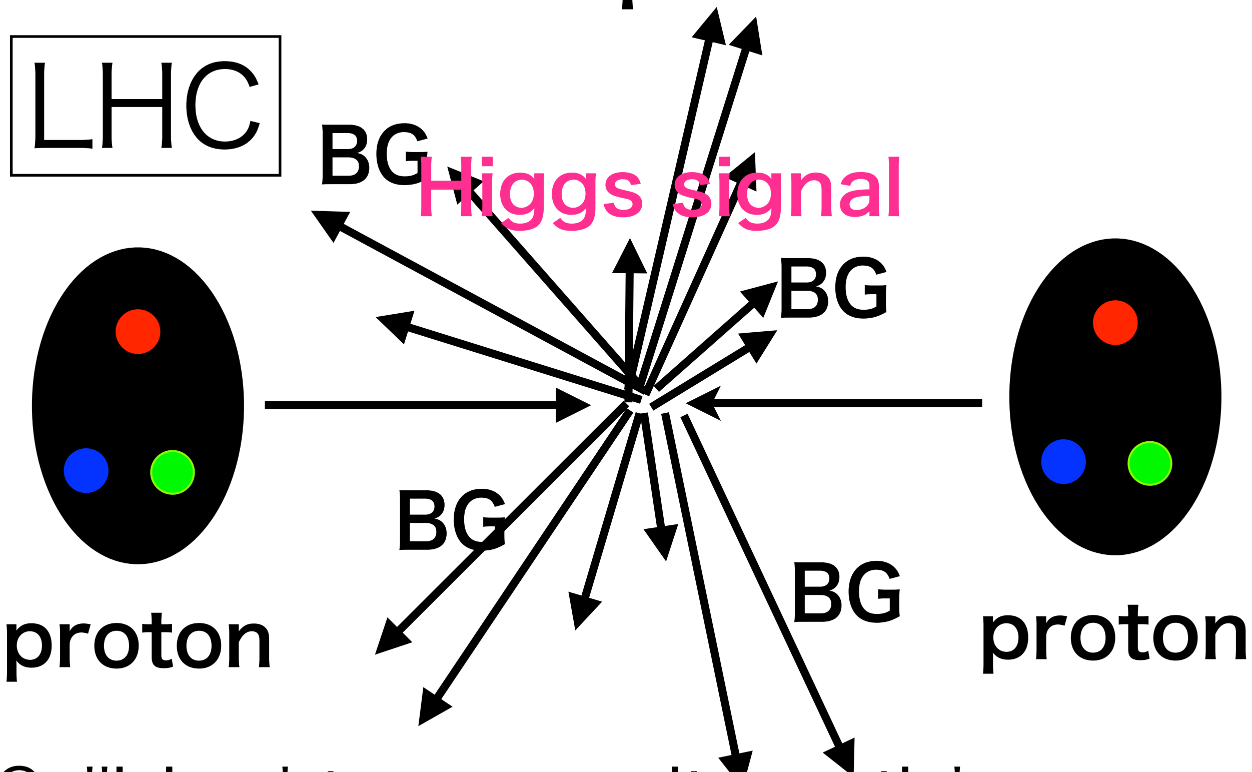
Therefore,

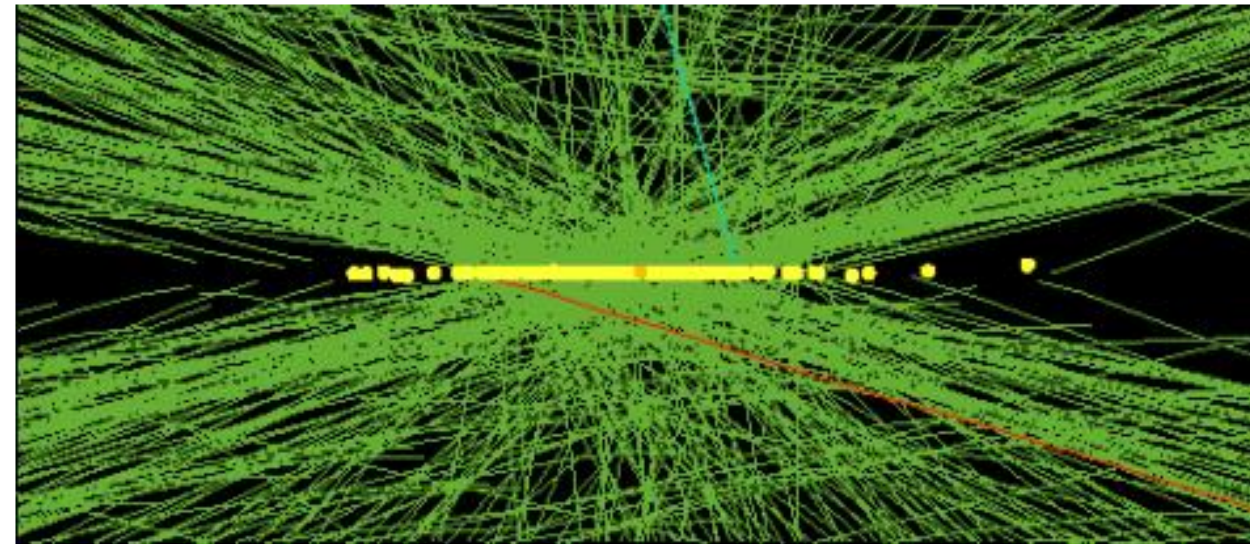
We need e^+e^- collider
with energy 350-500GeV (or higher)

Yes, we need ILC!

Comparison btw. LHC and ILC

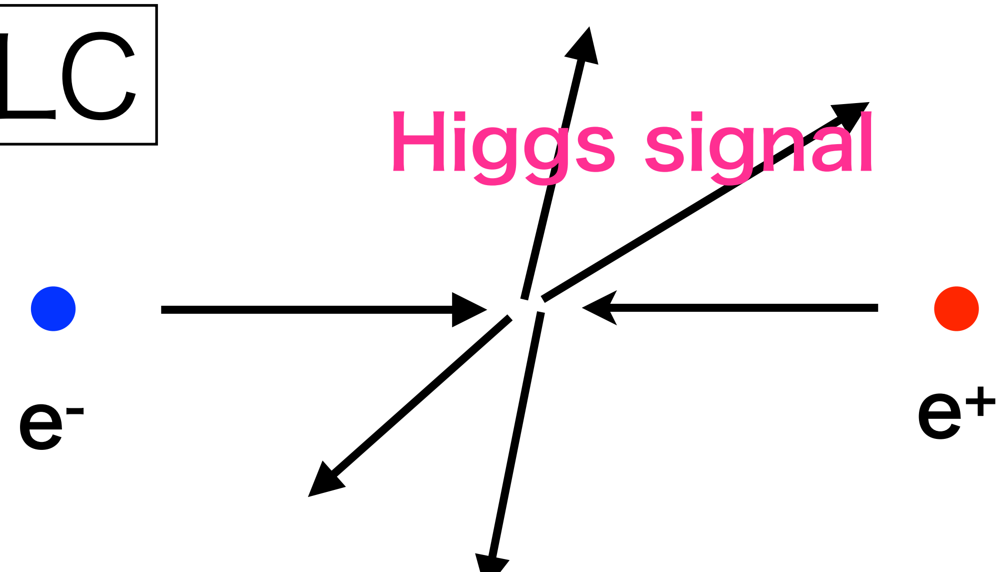
LHC

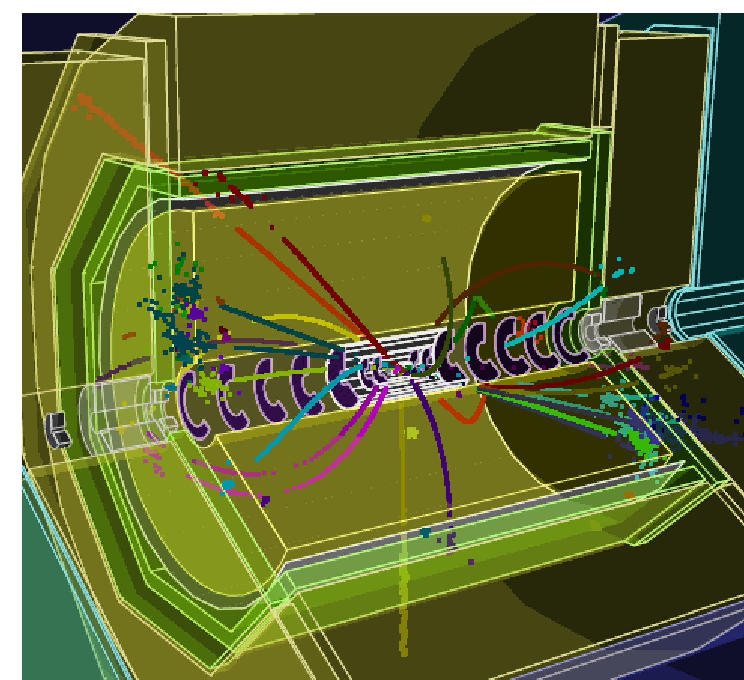




- Collision btw composite particles
- only a part of proton energy contributes
- energy frontier → new particles, new phenomena

ILC





- Collision btw elementary particles → clean signal, suited for precise measurement
- Collision energy is well controlled. Energy scan is possible.
- Discovery potential up to E_{cm}

Merits of the ILC

Clean experiment

- Low background (S:B=**1:10^2 @ ILC**, **1:10^8~10^9 @ LHC**)
- Low pileup (0.7 per bunch crossing @ ILC 500GeV)
- Whole energy is used for collision
  → 4-momentum conservation can be used
  → simple mass measurement
- Low radiation environment allows more idealistic detector design

Accelerator technology established

- High gradient Superconducting RF cavities
- Final beam focusing

Merit of the ILC

Low energy loss with less synchrotron radiation

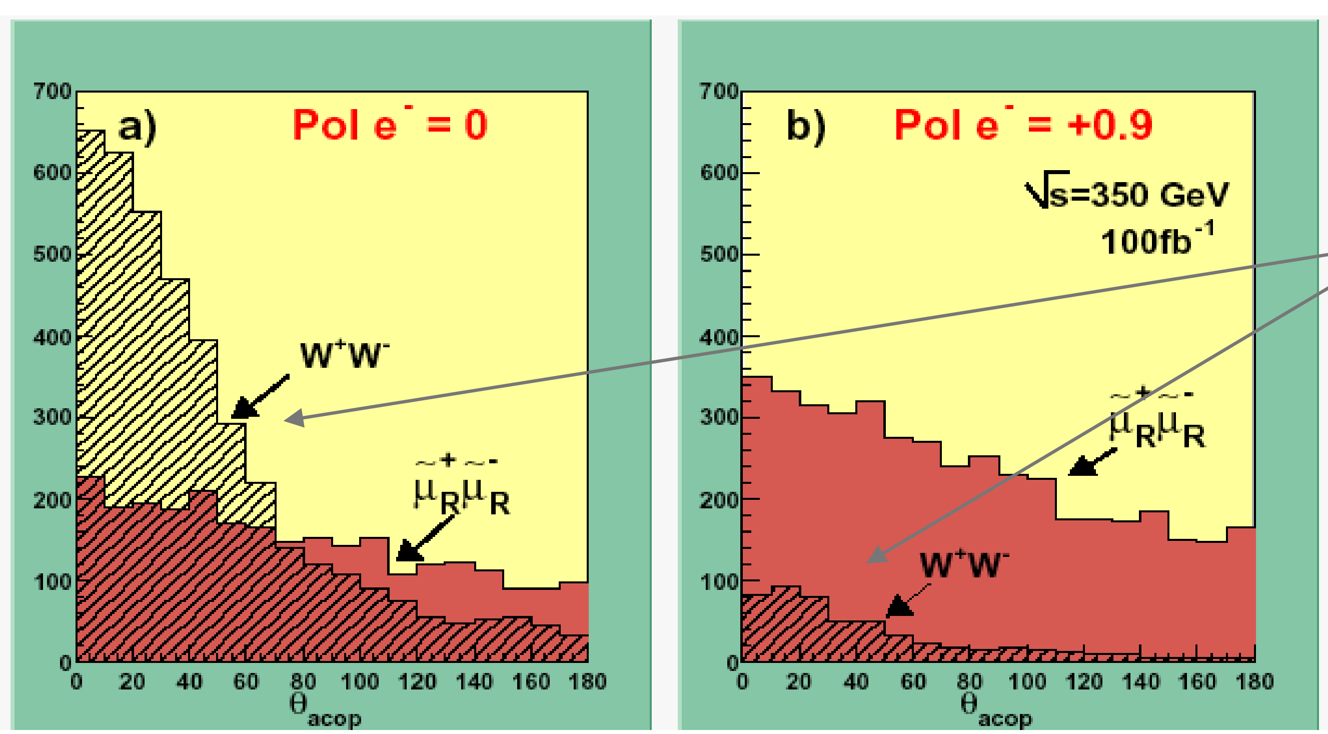
- Energy loss per cycle at ring accelerator: $\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$

Energy extension

- Longer accelerator for higher energy
- Future R&D will further improve gradient of cavity

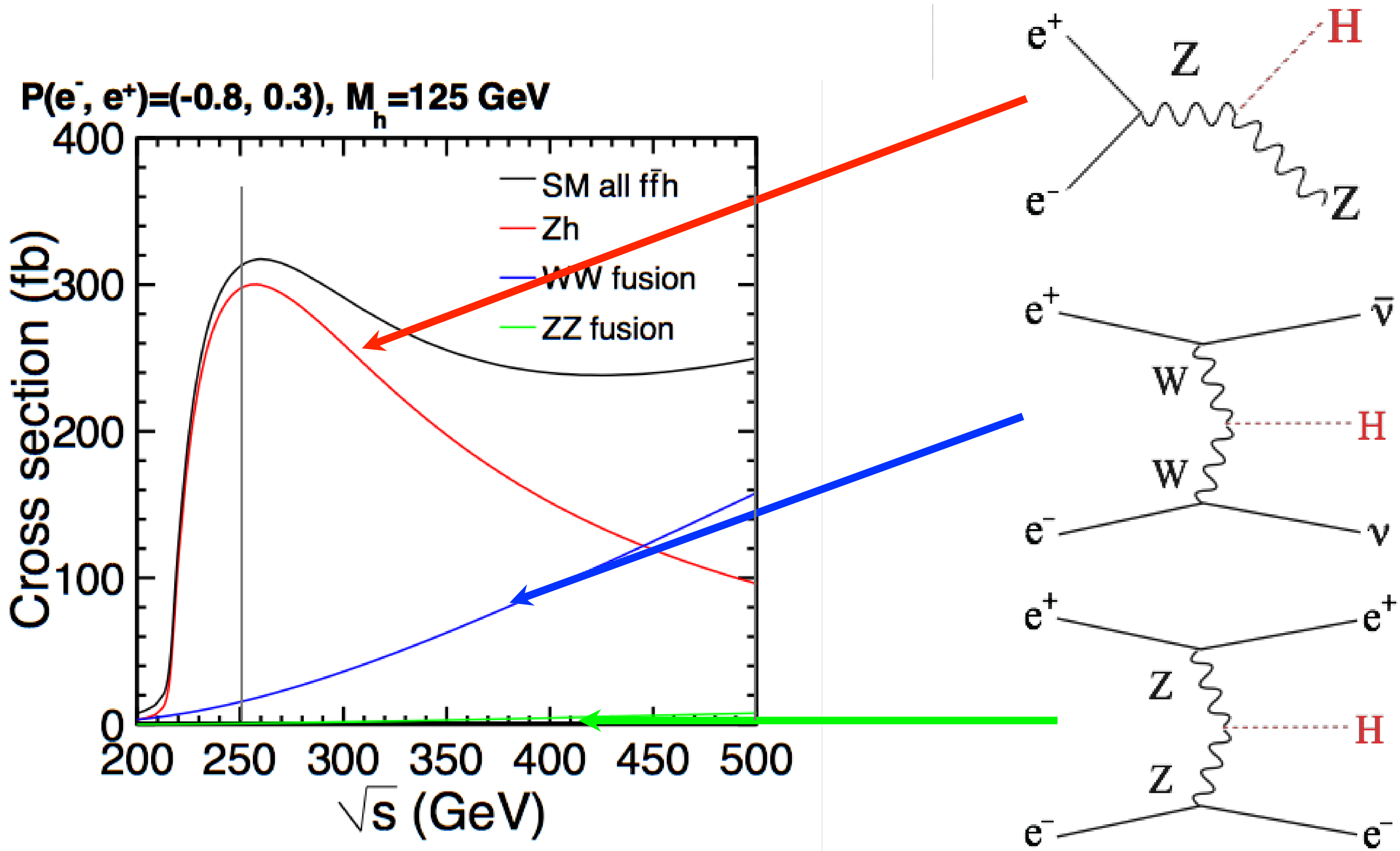
Spin polarized beam

- control of signal-to-background ratio
- measurement of various (right-handed, left-handed) couplings



Suppress standard model WW pair by using right-handed electron

Higgs generation at ILC



number of expected Higgs events

√s	σ (e⁺e⁻→XH)	σ (e⁺e⁻→ννH)	luminosity	# of ZH	# of ννH
250GeV	318fb	36.6fb	$500fb^{-1}$	~160,000	~18,000
500GeV	95.5fb	163fb	$500fb^{-1}$	~48,000	~80,000

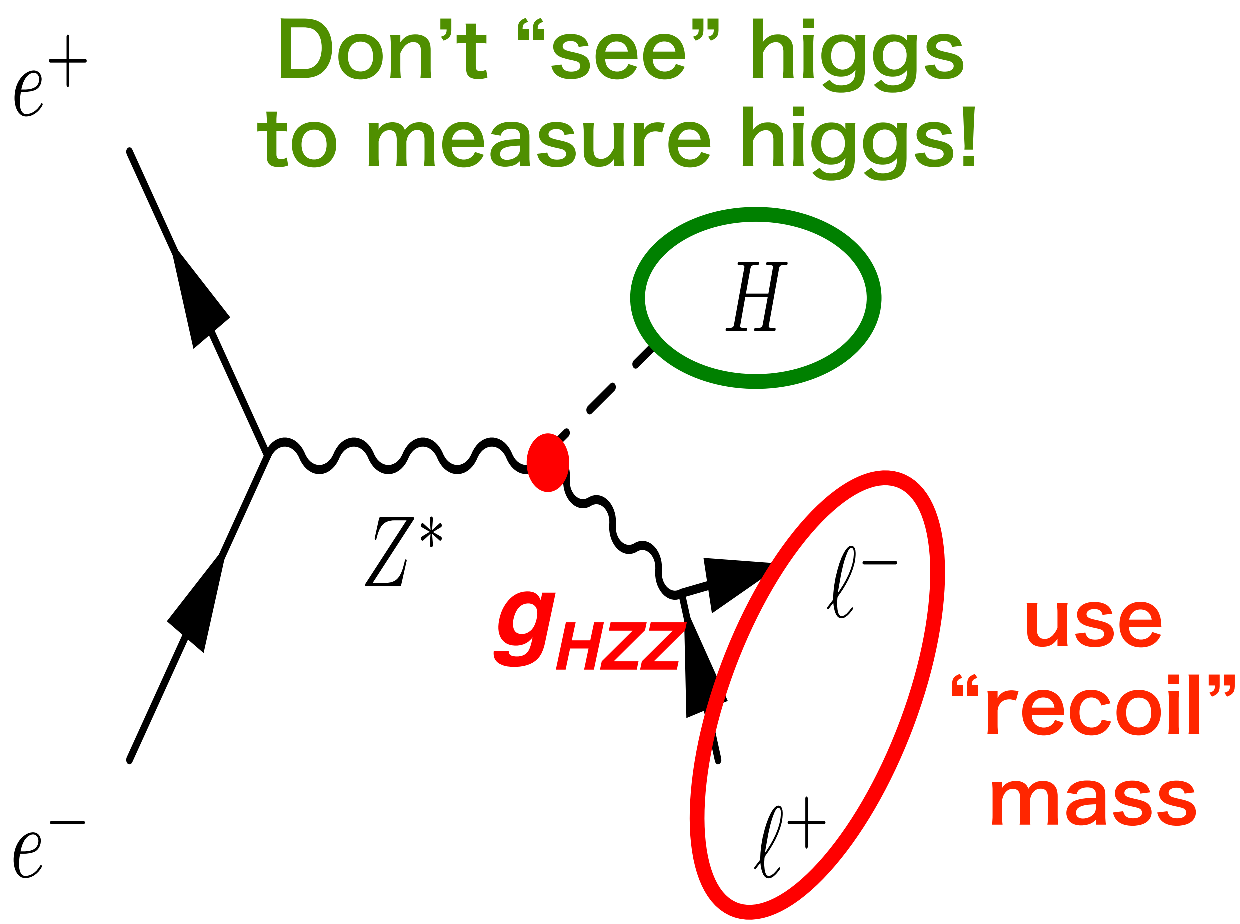
Figures from slides by M. Kurata @ JPS

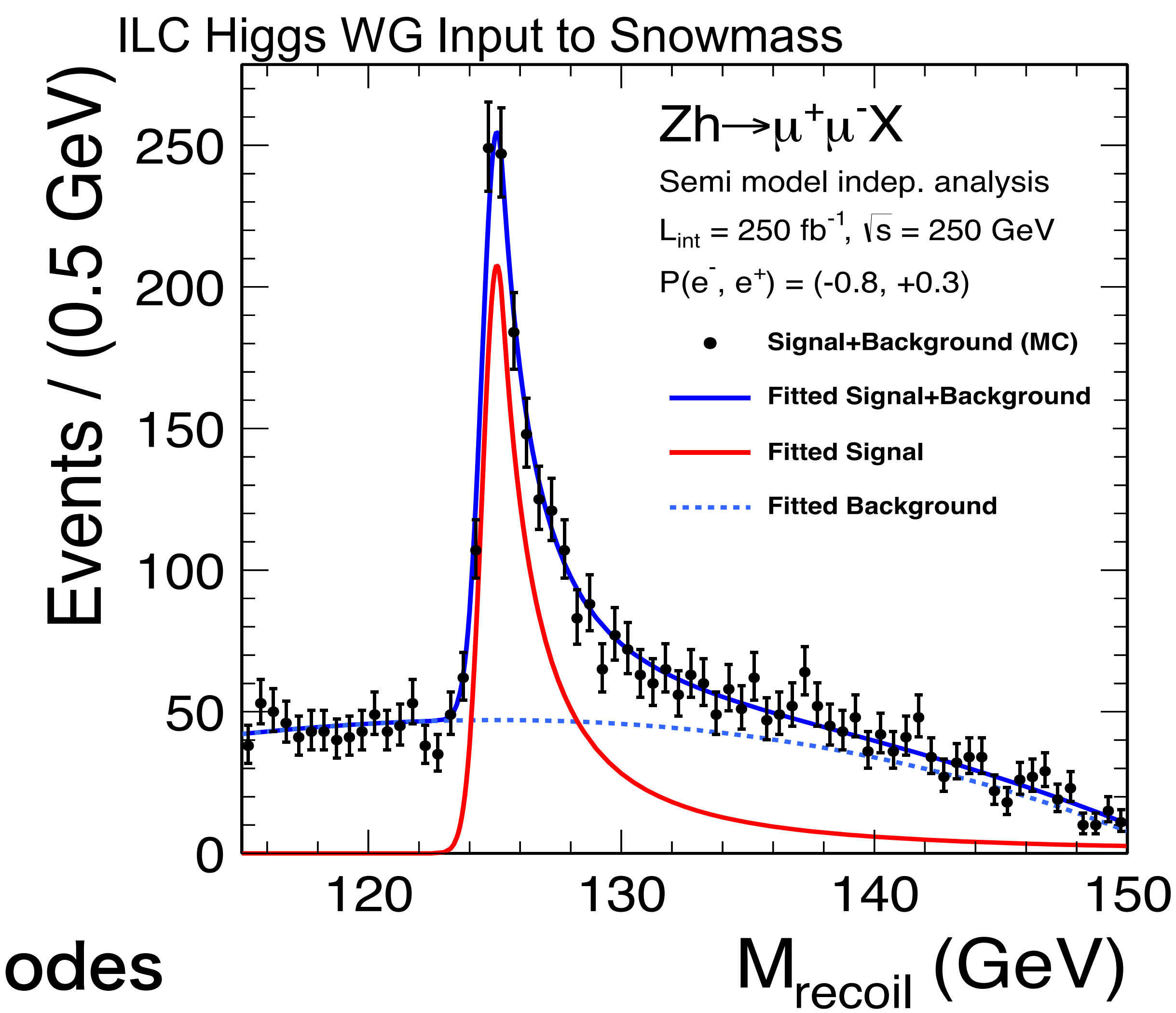
Measurement of Higgs production cross section

Recoil mass measurement:

$$m^2_{recoil} = (\sqrt{s} - E_{ll})^2 - |\vec{p}_{ll}|^2$$

$e^+e^- \to ZH \to l^+l^-X$





measure σ(ZH) independent of decay modes

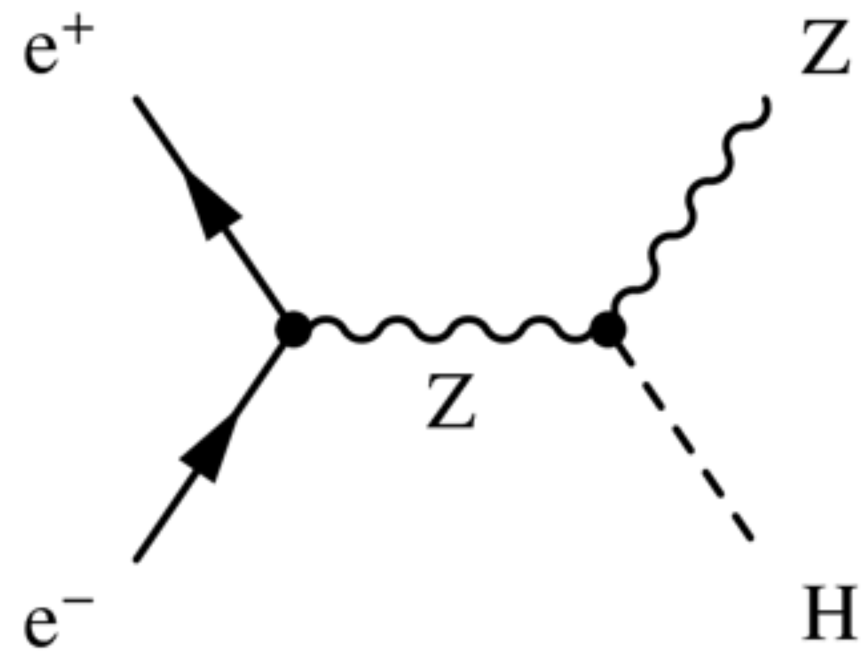
Precision @ (250GeV+350GeV+500GeV)

Runtime	Δm_H	Γ (int.) (95%C.L.)
8yrs.	25MeV	0.5%
20yrs.	15MeV	0.3%

Possible only at ILC!

Figures from slides by M. Kurata @ JPS

Measurement of Higgs production cross section



- In LHC, obtained measurements are of σ (total cross section) x BR (branching ratio).
- In ILC, with the recoil mass measurement, total cross section σ is obtained → Direct measurements of BR are possible!

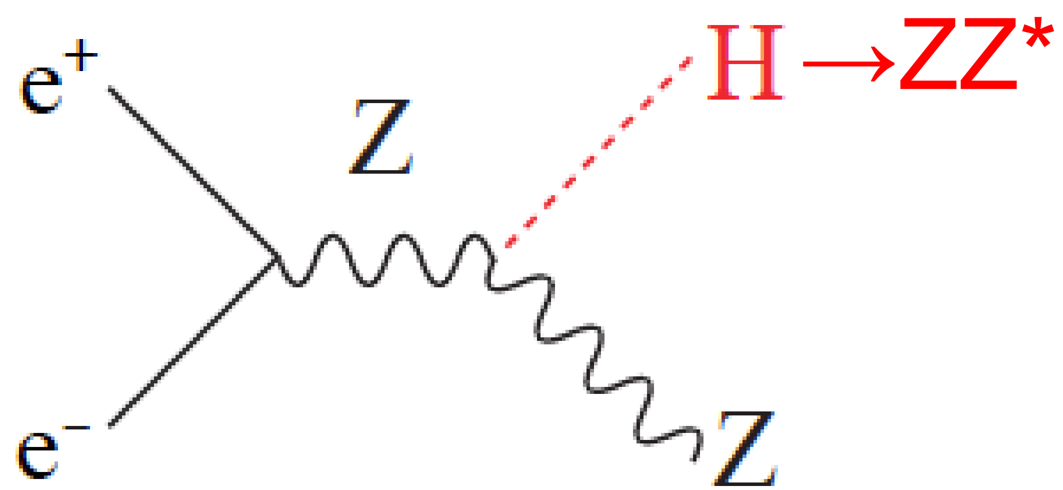
H→ZZ

- Higgs coupling measurements are also important
- For coupling measurements, total decay width is necessary.

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

- **Total decay width of Higgs** can be obtained at ILC if you know Γ and BR for some decay process.
- For example, H→ZZ.

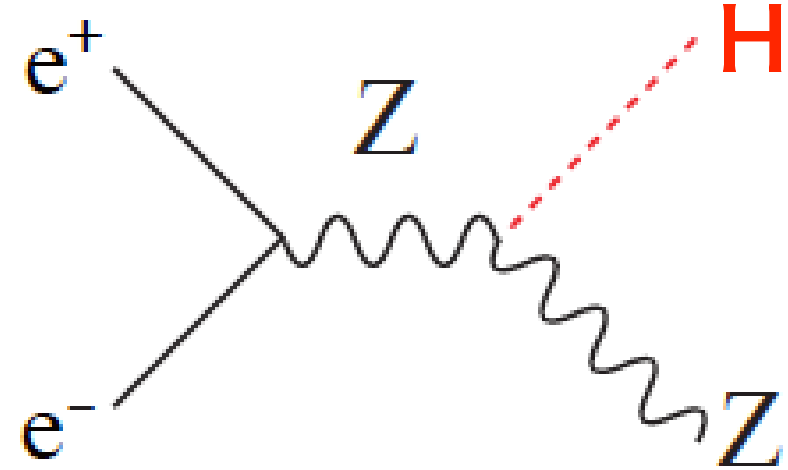
$$\Gamma_H = \frac{\Gamma_{H \to ZZ^*}}{Br(H \to ZZ^*)}$$



- Unfortunately, H→ZZ* is difficult because of low statistics (Br(ZZ*)~2%)

H→WW

- Better way is to use H→WW

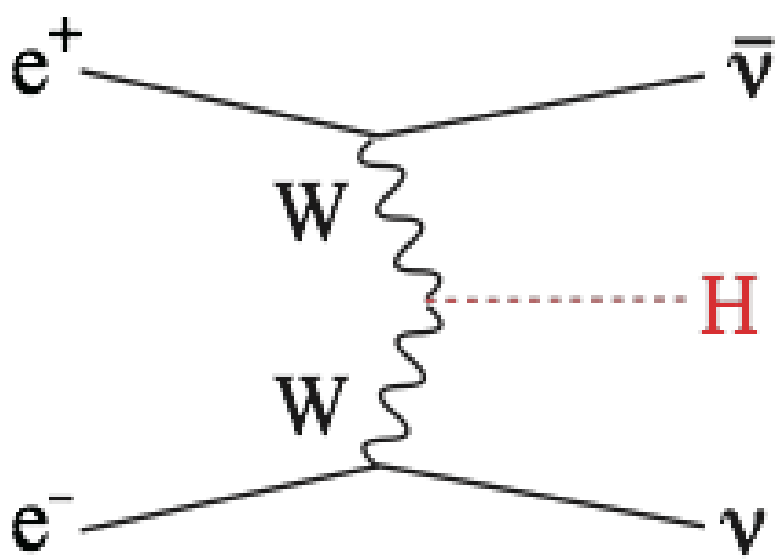


H→WW*

$\sigma_{ZH} \times BR(H \to WW^*)$

recoil mass measurement $\to \sigma_{ZH}$

} $BR(H \to WW^*)$



→WW*

$\Gamma_{H \to WW^*}$

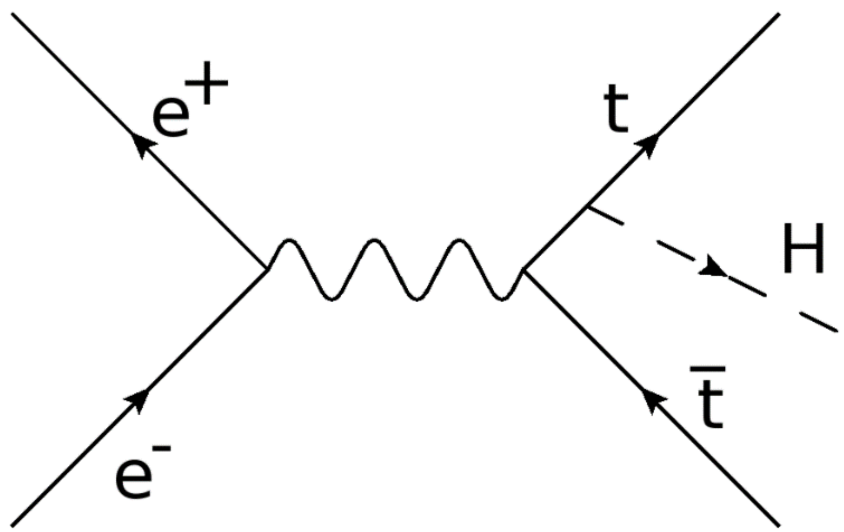
$$\Gamma_H = \frac{\Gamma_{H \to WW^*}}{Br(H \to WW^*)}$$

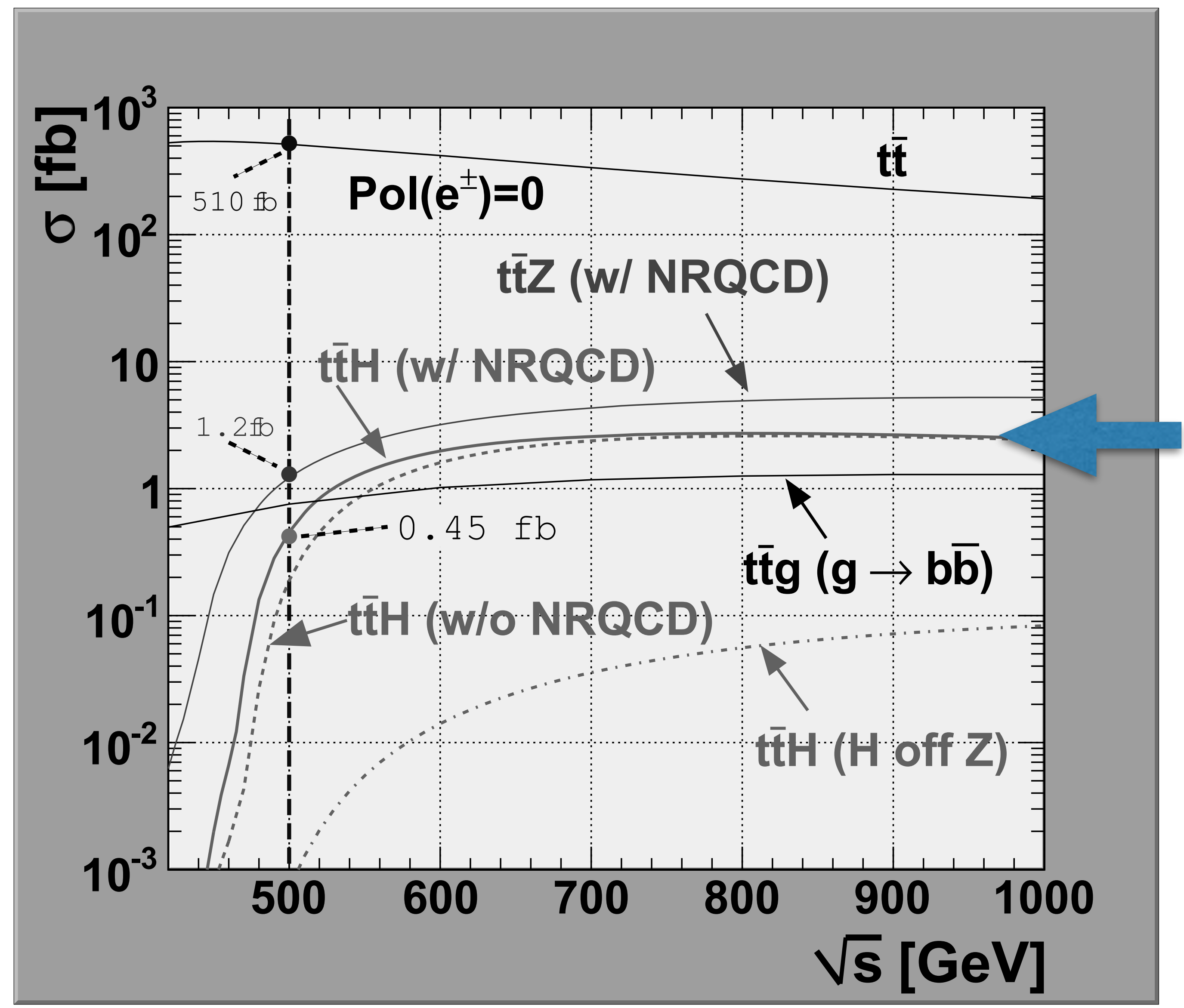
Precision of total width measurement

Runtime	8yrs.	20yrs.
$\Delta\Gamma_H/\Gamma_H$	3.8%	1.8%

Top Yukawa coupling

- HAA coupling is obtained from σ_{ZH} by recoil mass measurement and ($\sigma_{ZH} \times BR$ or $\sigma_{\nu\bar{\nu}H} \times BR$).
- However, Higgs cannot decay to top quarks ($m_H < 2m_t$)
- Use ttH decay mode.





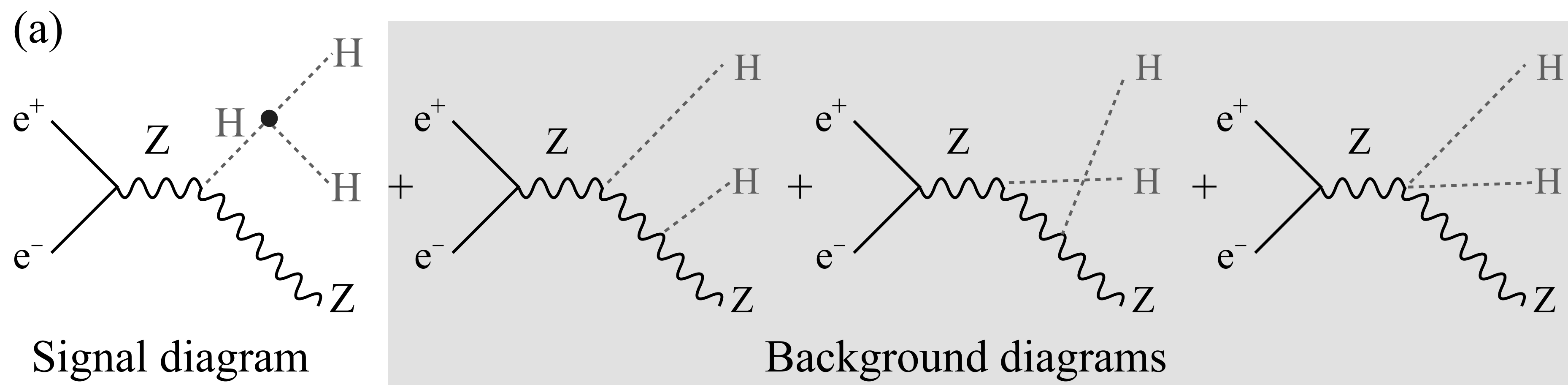
- Cross section increases at √s = 500GeV rapidly.

Figures from Prof. K. Fujii's lecture note

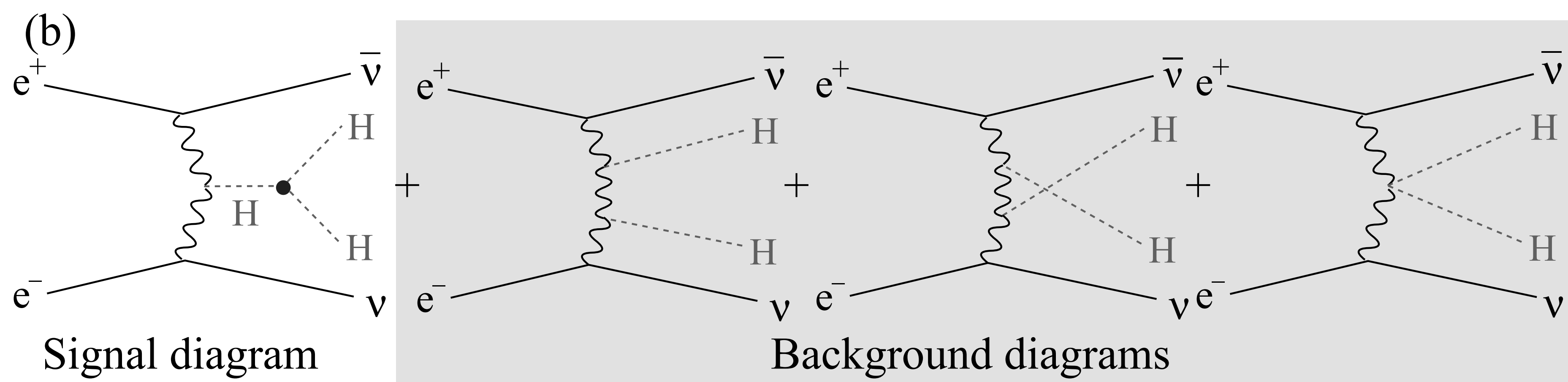
Higgs self coupling

- Important to understand Higgs potential shape and the origin of the symmetry breaking.

σ peak at $\sqrt{s}$ = 500GeV



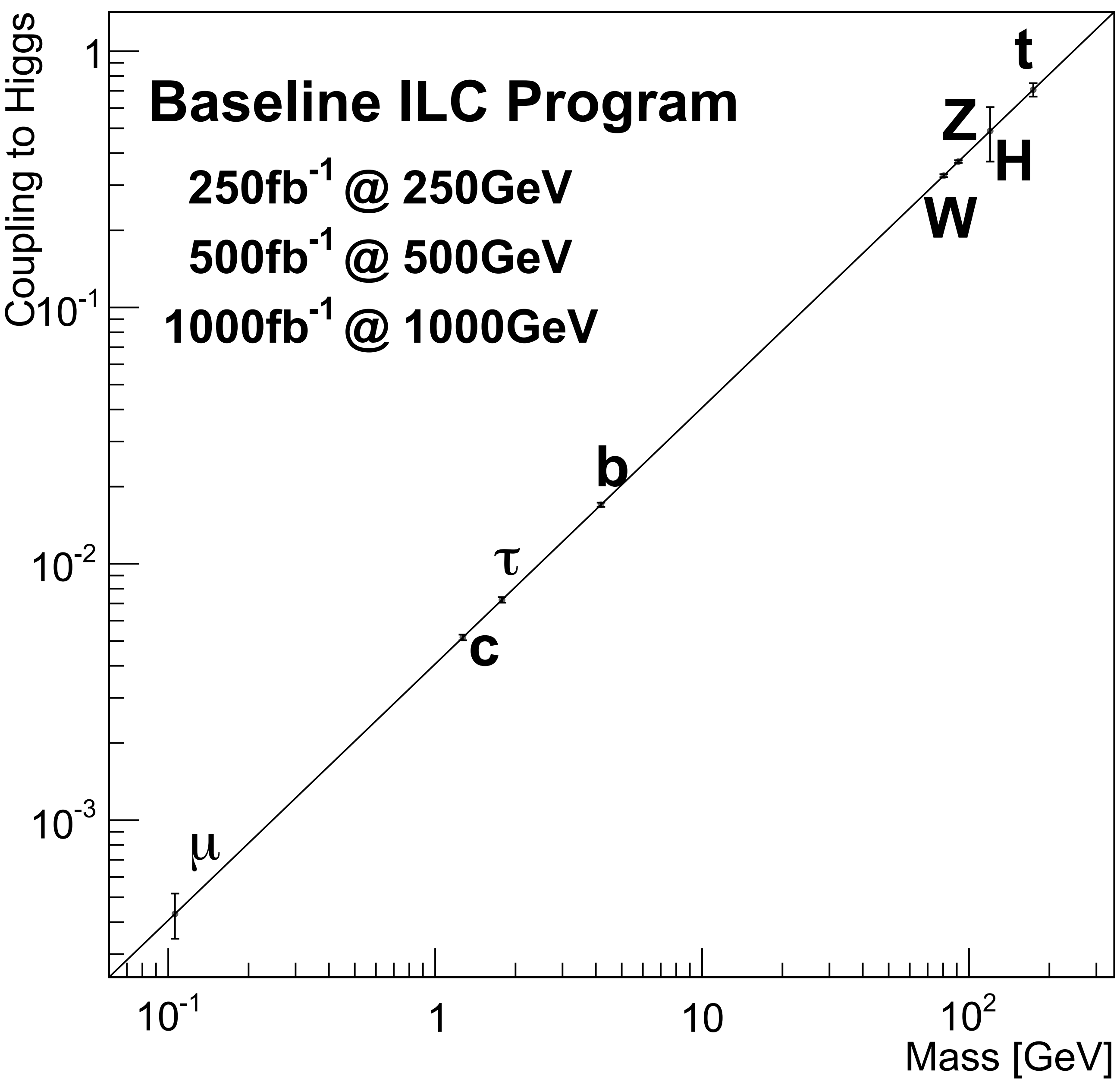
larger σ at $\sqrt{s}$ > 1.2TeV



Hard task because of background.
1TeV run would be necessary for this.

Figures from Prof. K. Fujii's lecture note

Higgs coupling accuracy



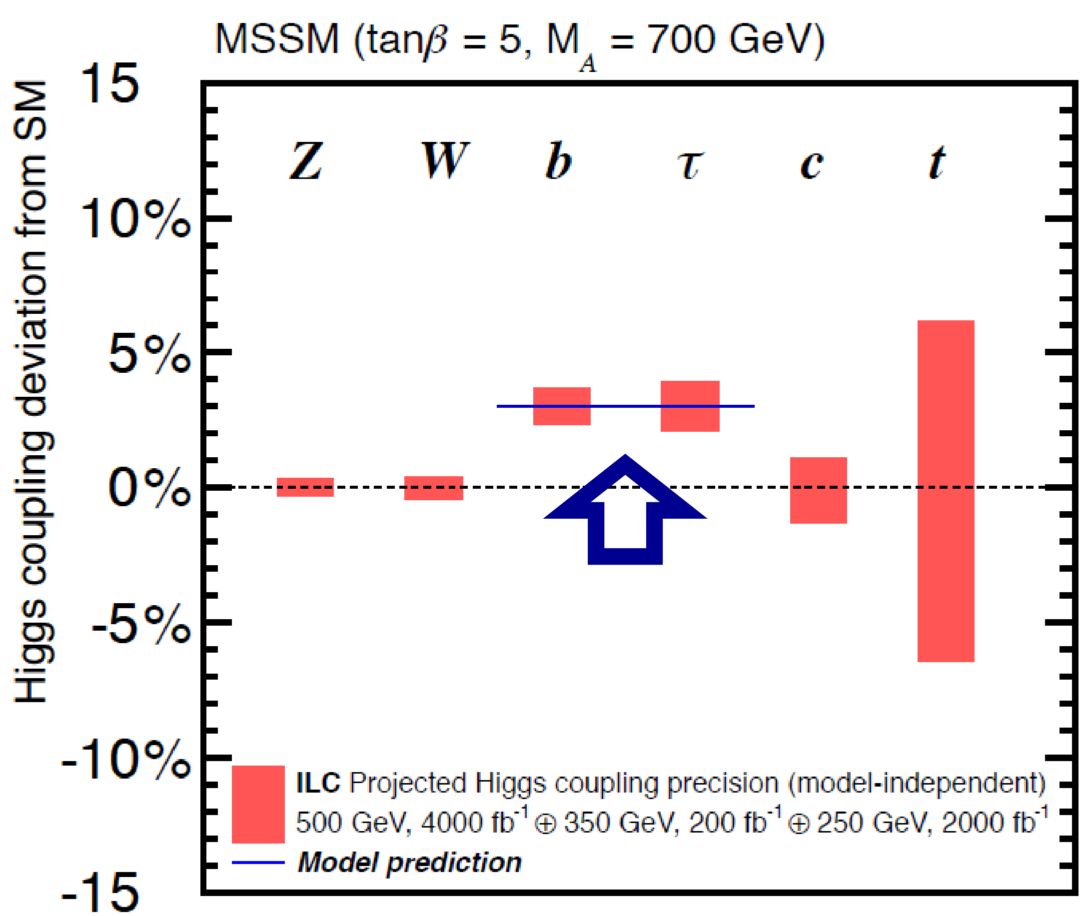
coupling	$\sqrt{s}$ (GeV) 250	250+500	250 + 500 + 1000
hZZ	0.6%	0.5%	0.5%
hWW	2.3%	0.6%	0.6%
hbb	2.5%	0.8%	0.7%
hcc	3.2%	1.5%	1.0%
hgg	3.0%	1.2%	0.93%
$h\tau\tau$	2.7%	1.2%	0.9%
$h\gamma\gamma$	8.2%	4.5%	2.4%
$h\mu\mu$	42%	42%	10%
Γ_0	5.4%	2.5%	2.3%
htt	-	7.8%	1.9%
hhh	-	46%(*)	13%(*)

Figures from Prof. K. Fujii's lecture note

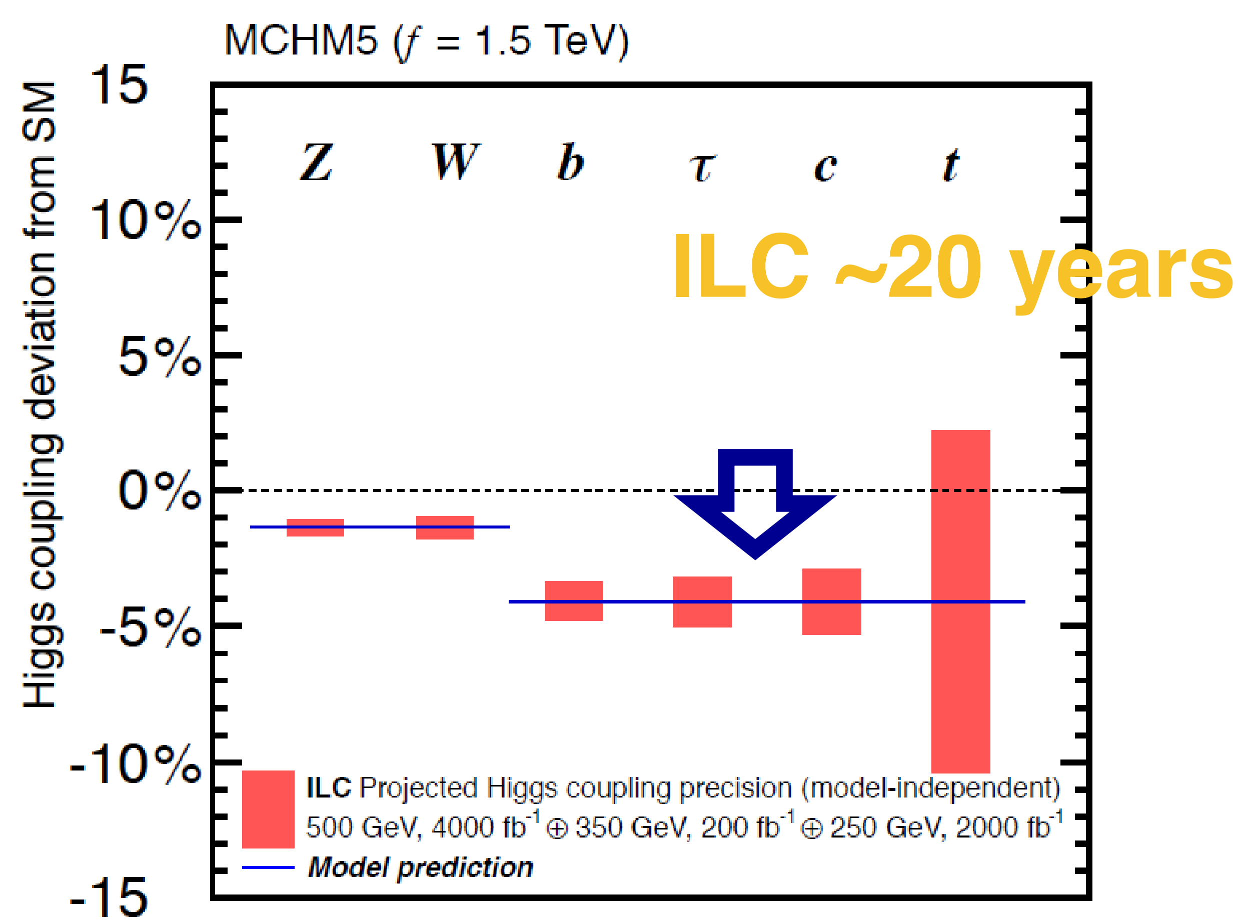
Sensitivity to new physics

- Precise measurement of higgs coupling opens window to new physics.
- From deviation pattern, we can identify which kind of physics is behind.

Supersymmetry (MSSM)

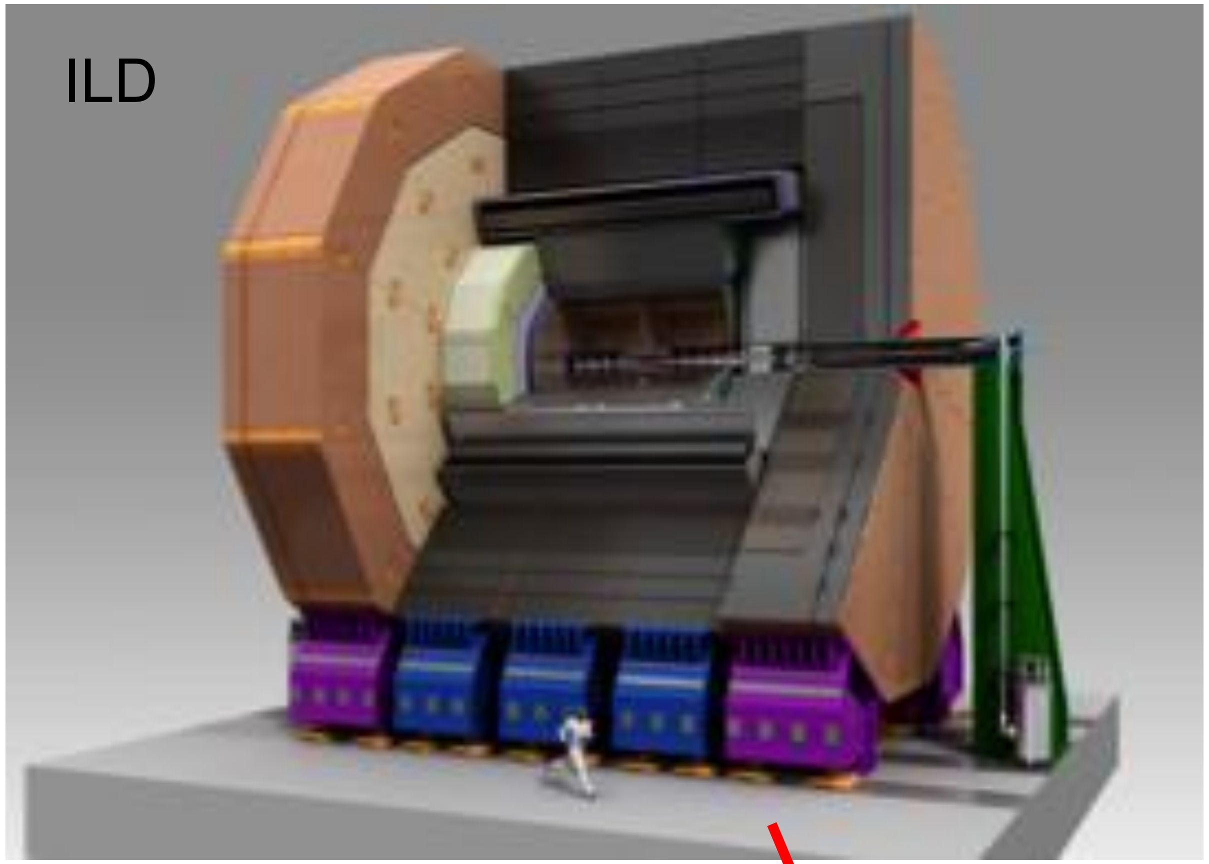


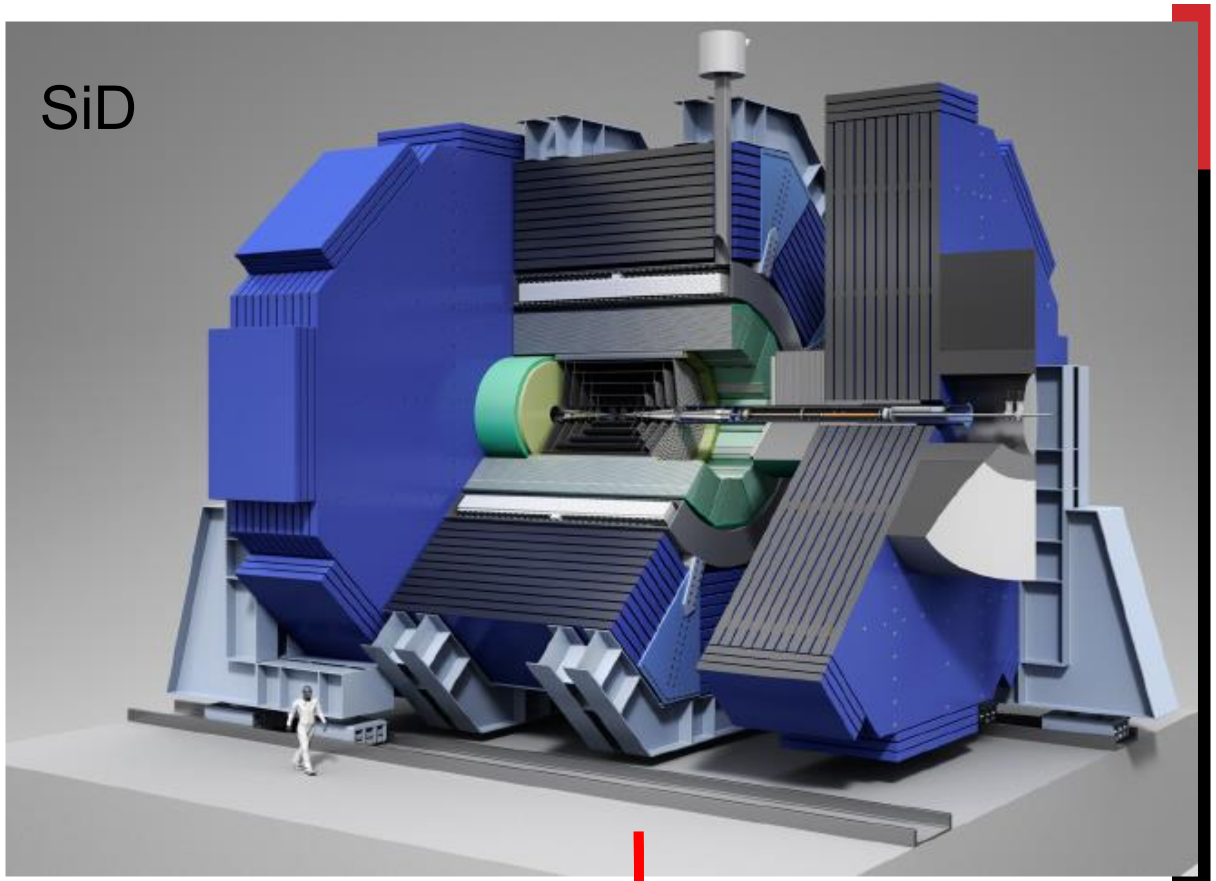
Composite Higgs (MCHM5)



Figures from slides by M. Kurata @ JPS

ILC detectors





	ILD (International Large Detector)	SiD (Silicon Detector)
Height x Length	16 m x 14 m	14 m x 11 m
Weight	14,000 t	10,100 t
Magnetic field	3.5 T	5 T
ECAL inner radius	1.8 m	1.3 m
Tracker	TPC	Silicon strip

Saga U. joins

From slides by M. Kurata @ JPS

ILC detector (ILD)

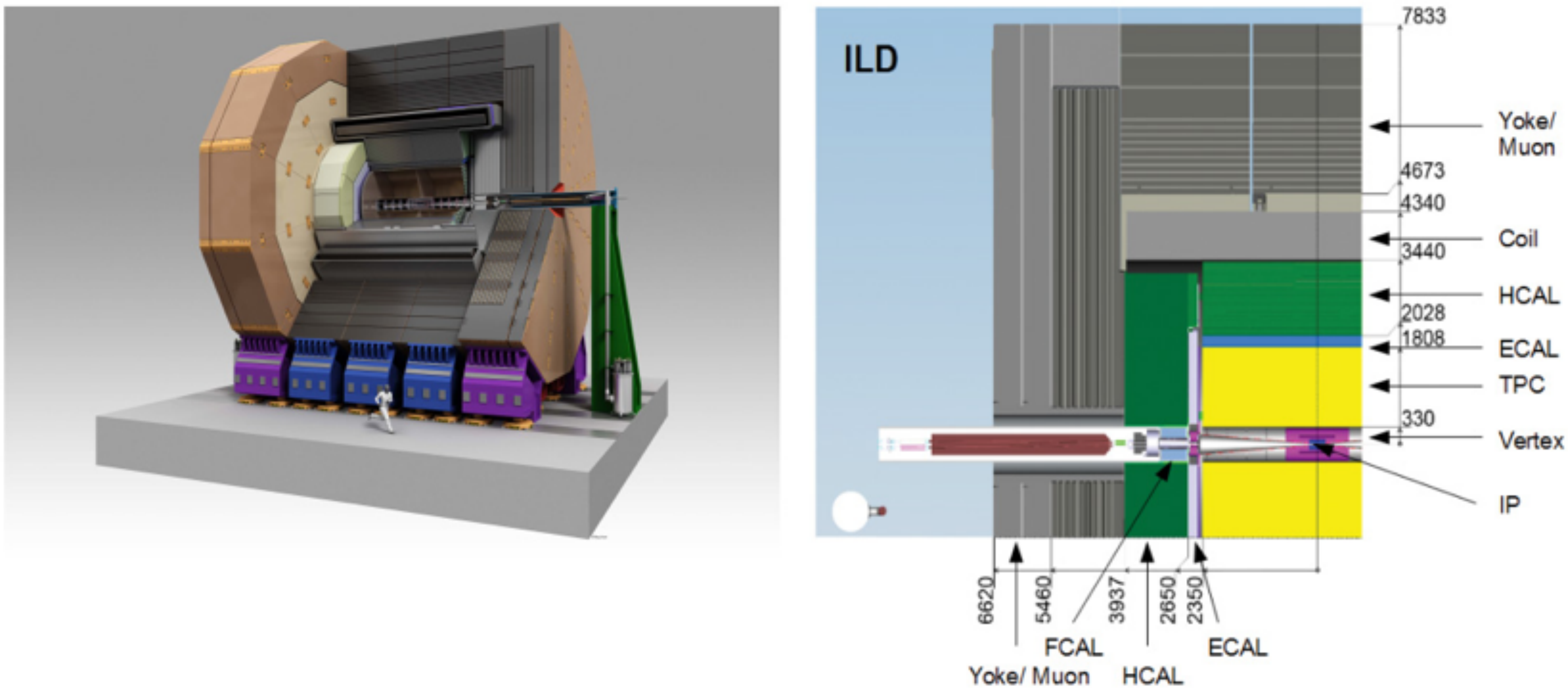


Figure 4.6. Views of the ILD detector concept. The interaction point in the quadrant view (right) is in the lower right corner of the picture. Dimensions are in mm.

ILC detector (ILD)

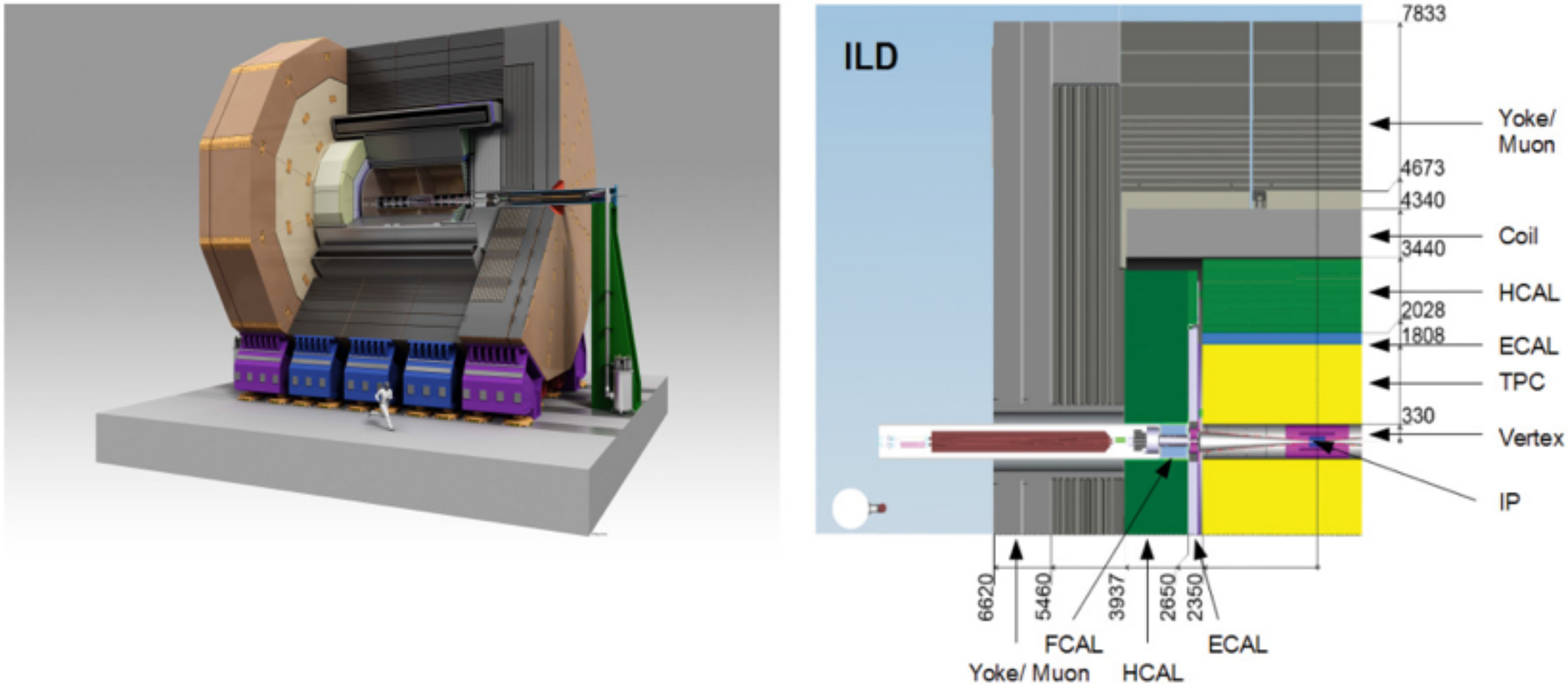


Figure 4.6. Views of the ILD detector concept. The interaction point in the quadrant view (right) is in the lower right corner of the picture. Dimensions are in mm.

Vertex detector

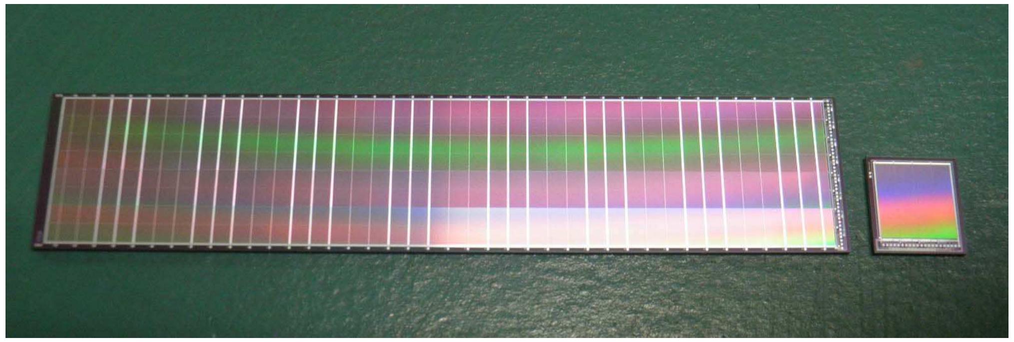
High precision and low material pixel detector

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

space for cooling pipe is limited in ILD

→ 2-phase CO_2 cooling under study.

Fine Pixel CCDs w/ 6um pixel pitch



62.4×12 mm^2 and 6×6 mm^2

ILC detector (ILD)

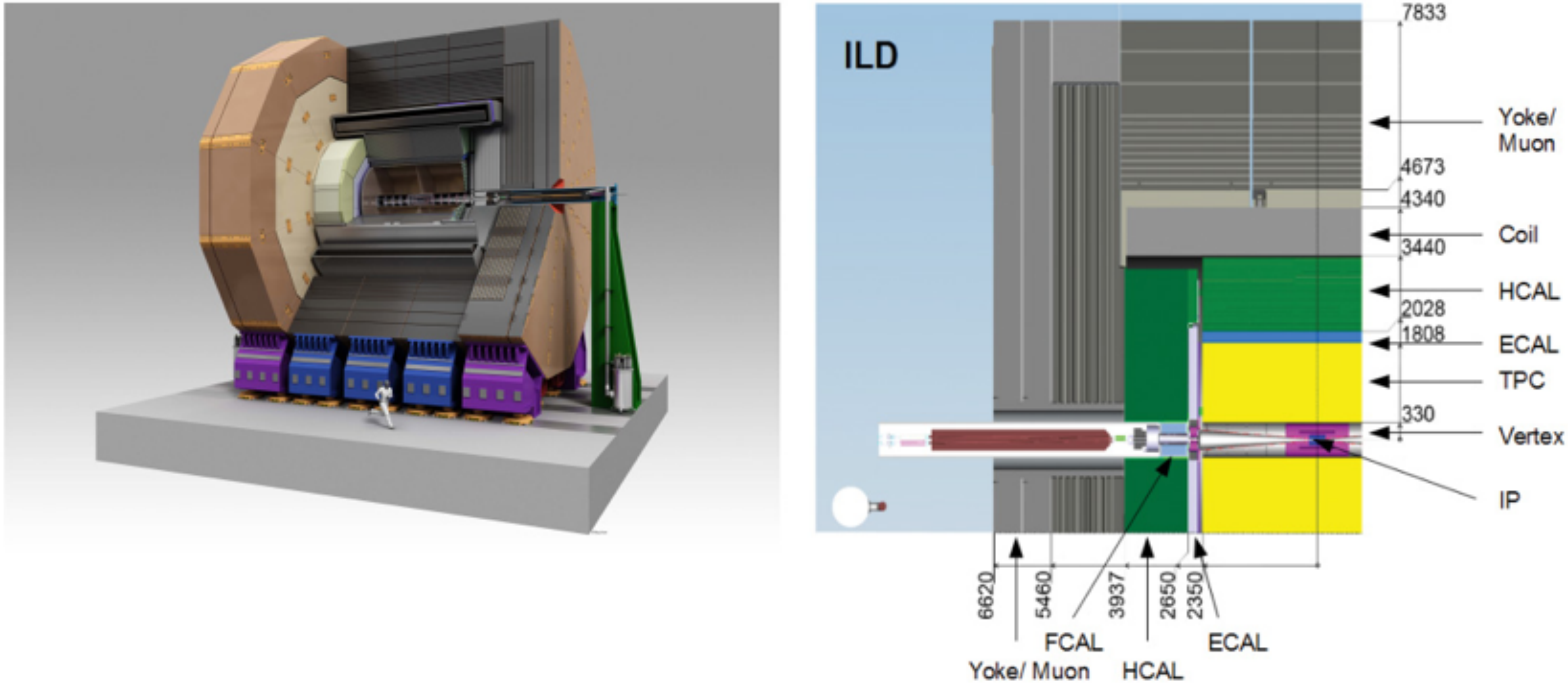


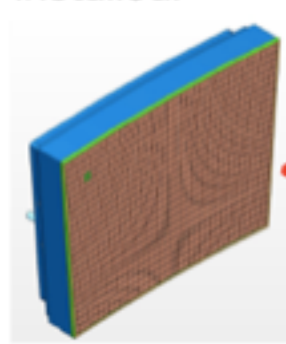
Figure 4.6. Views of the ILD detector concept. The interaction point in the quadrant view (right) is in the lower right corner of the picture. Dimensions are in mm.

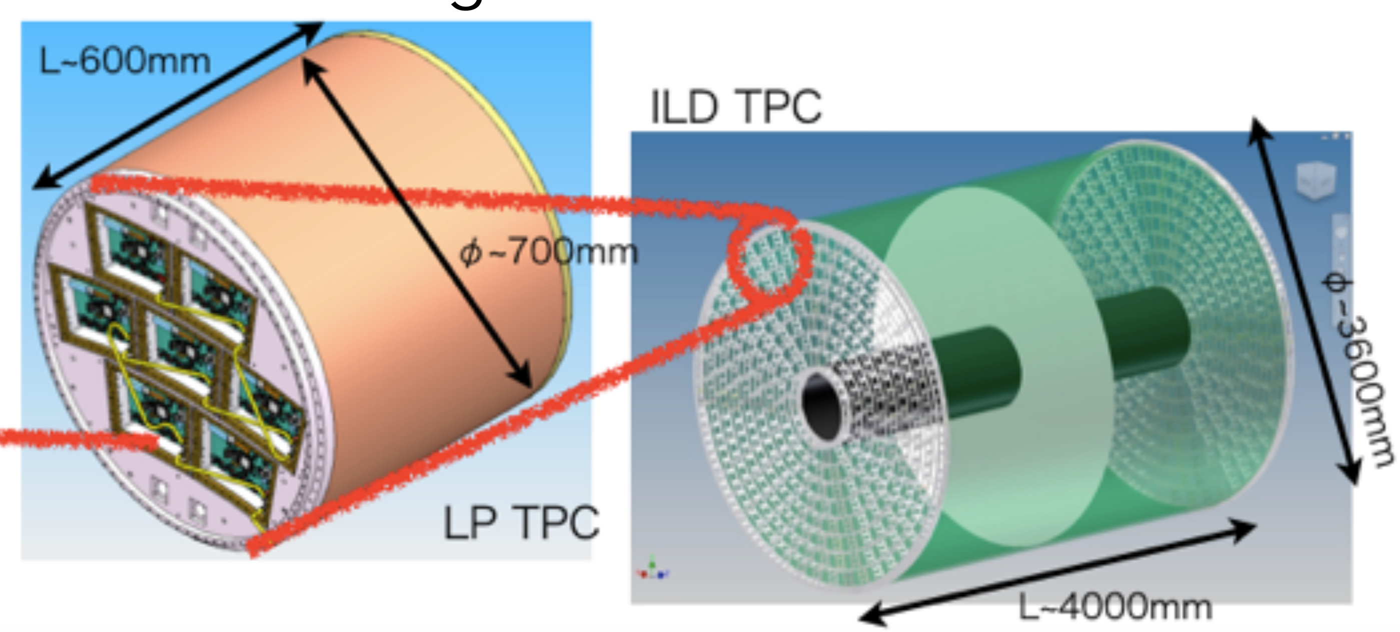
Tracking — Time-Projection Chamber

High resolution, low material and continuous tracking.

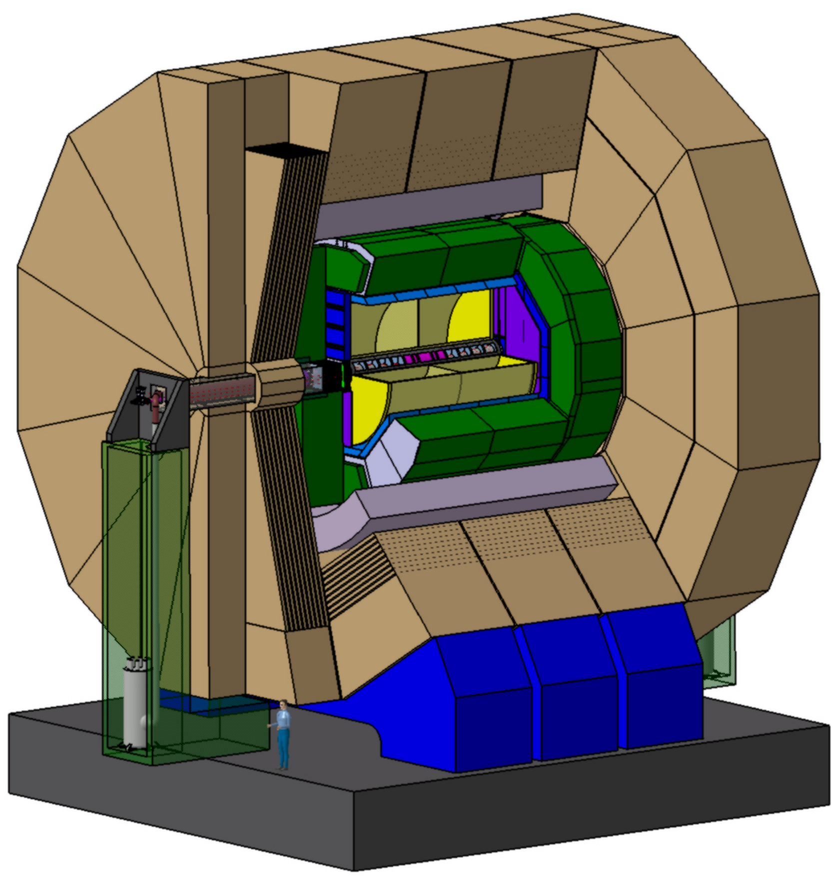
$\sigma_{1/p_T} \sim 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$

7 readout modules
with the size of ~230 x 170mm²
can be installed.



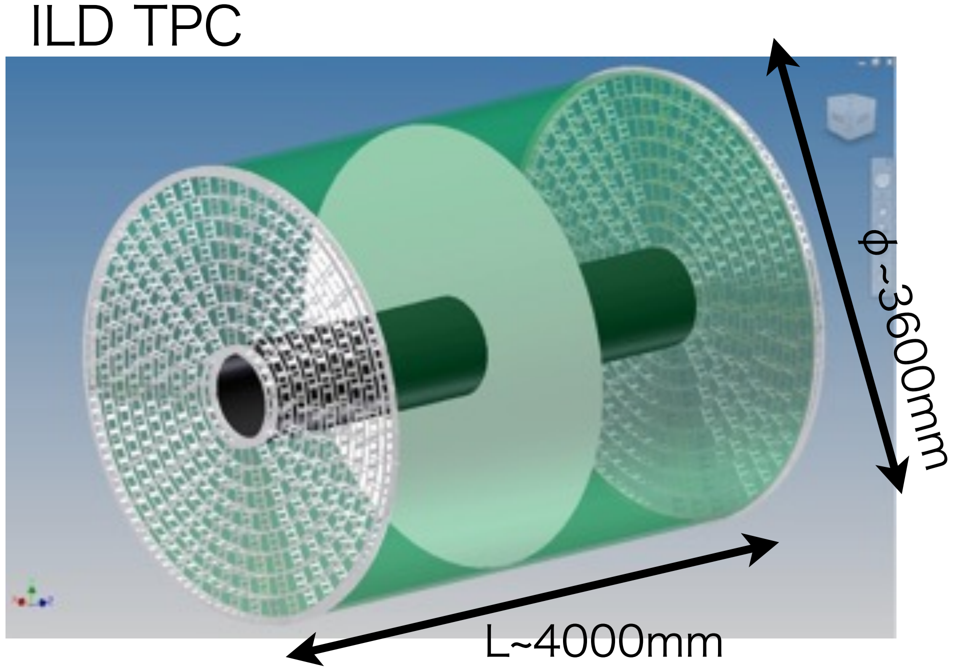


TPC for the ILD Detector at the ILC

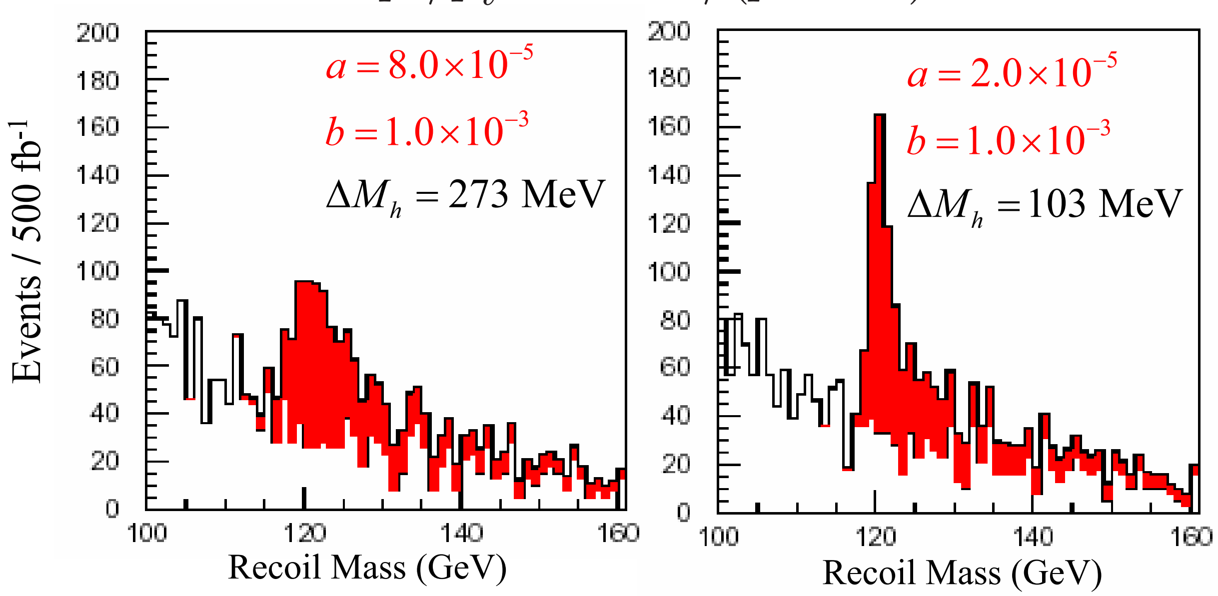


- The ILD Concept: One of two detector concepts validated to proceed to the TDR stage for the planned International Linear Collider (ILC).
- Precision physics measurements at the ILC requires:
  - Good Momentum Resolution of
    $\delta(1/p_t) \sim 9 \times 10^{-5}$/GeV/c @ 3.5T (TPC only: 1/10 of LEP)
    $\delta(1/p_t) \sim 2 \times 10^{-5}$/GeV/c @ 3.5T (complete ILD tracking)
  - Good spatial resolution of σ_{point} in $r\phi$ < 100μm @ 3.5T
- Why TPC as the ILD central tracker?
  - Good momentum resolution and pattern recognition with ~200 measurement points per track.
  - Low material budget provides good energy resolution in calorimeters.
- MPGD (GEM or Micromegas) as amplification device.

ILD TPC

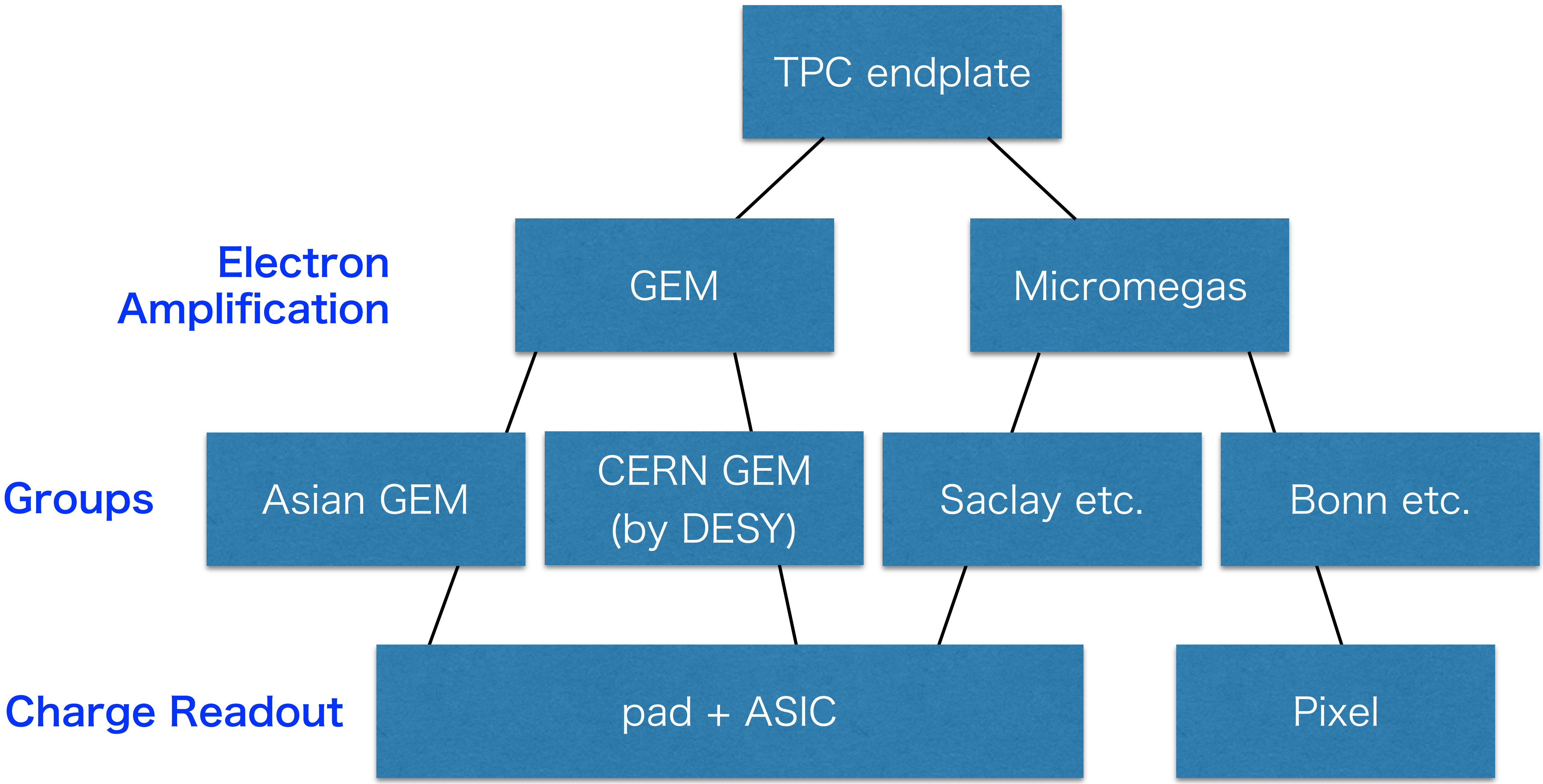


$$\delta p_t / p_t^2 = a \oplus b/(p_t \sin\theta)$$



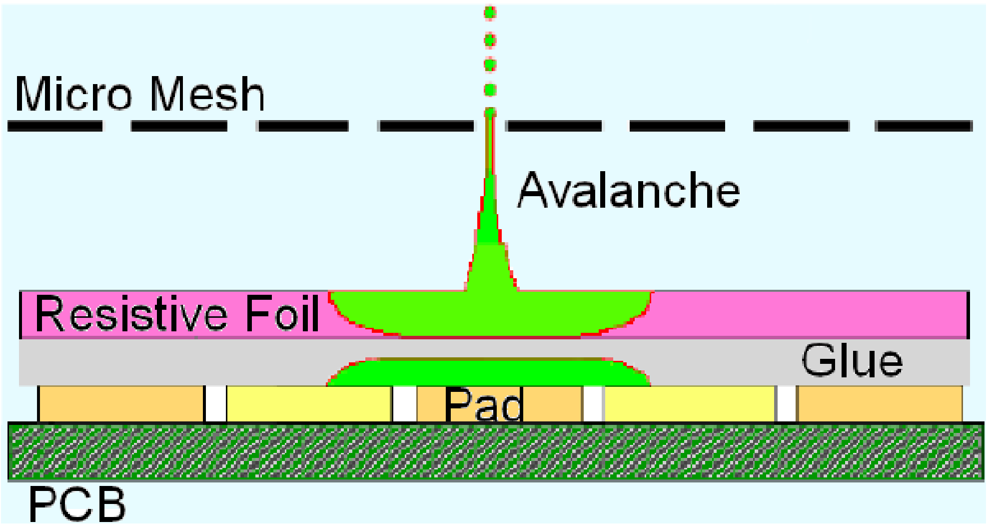
Higgs recoil mass reconstruction from muon pair decay of Z for different momentum resolution (ILC Reference Design Report Vol.4)

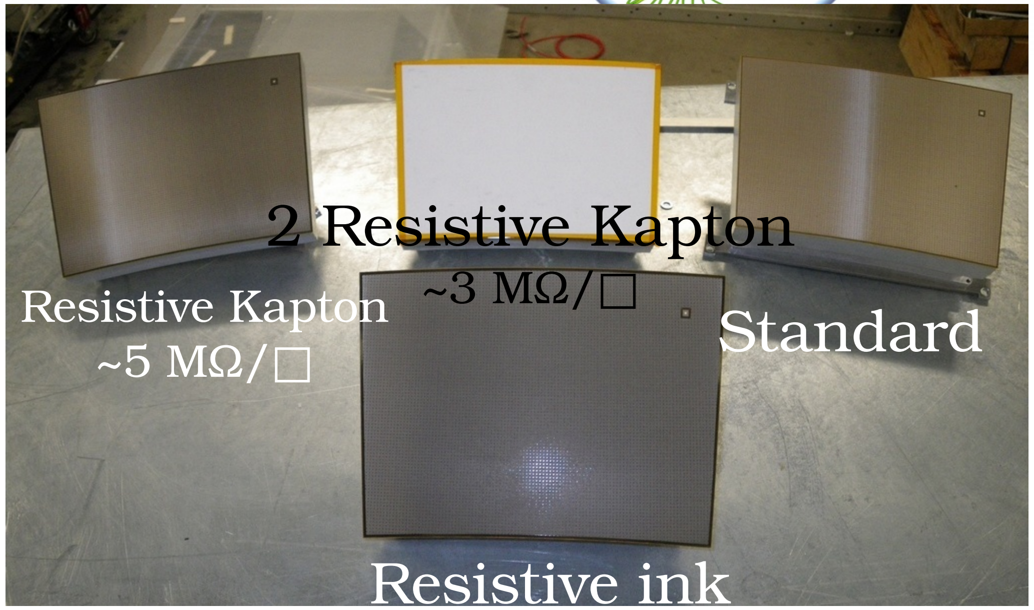
Candidates for endplate readout technology

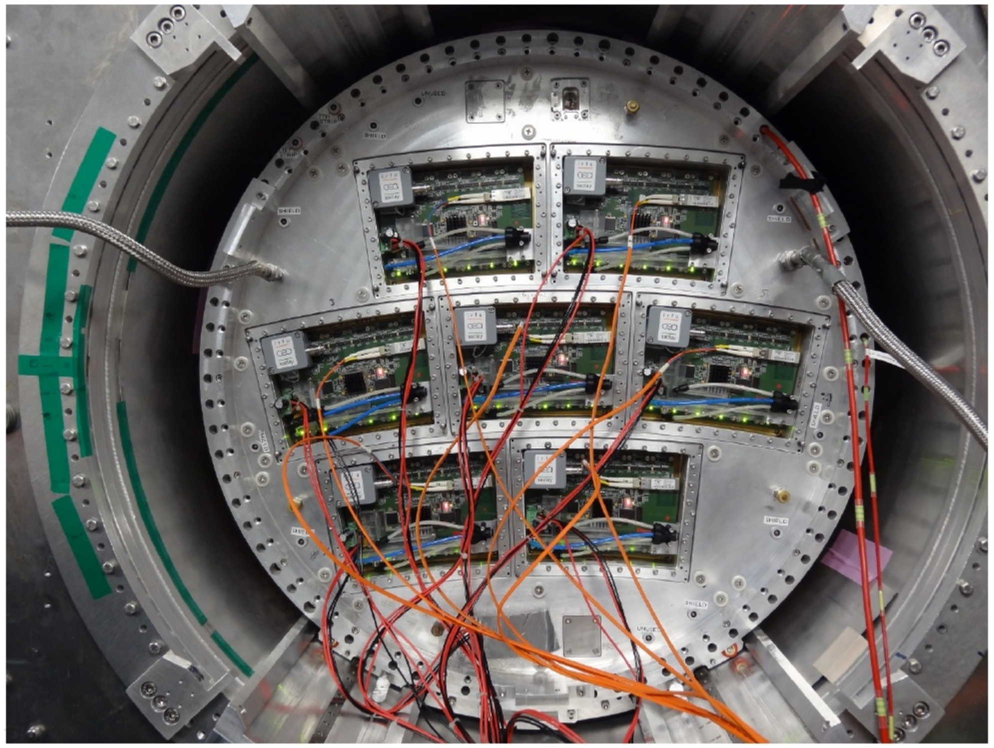


Micromegas Modules

Micromegas give rather thin signals
→ hits are collected by one pad
→ degrades spatial resolution
=> use resistive layer to spread signal over several pads!





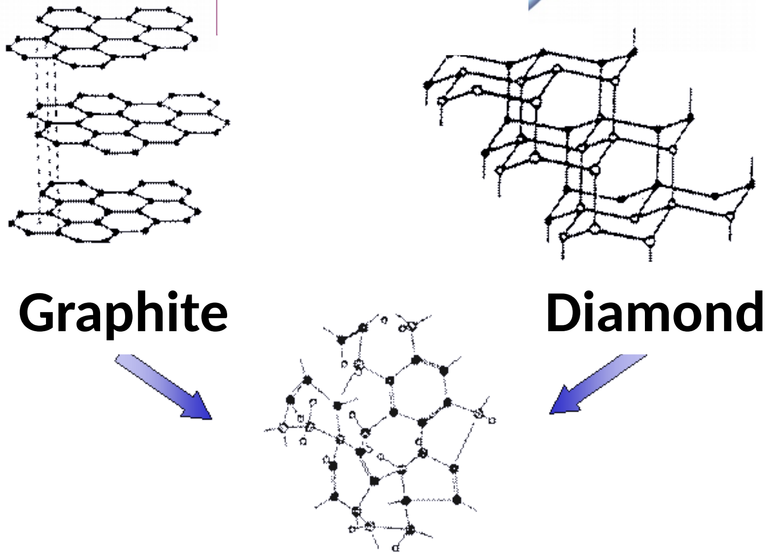


Modules have large pads (3×7 mm²)
1728 channels per module
connected to AFTER electronics.
Several resistive layers have been tested
9 modules built in a miniseries.

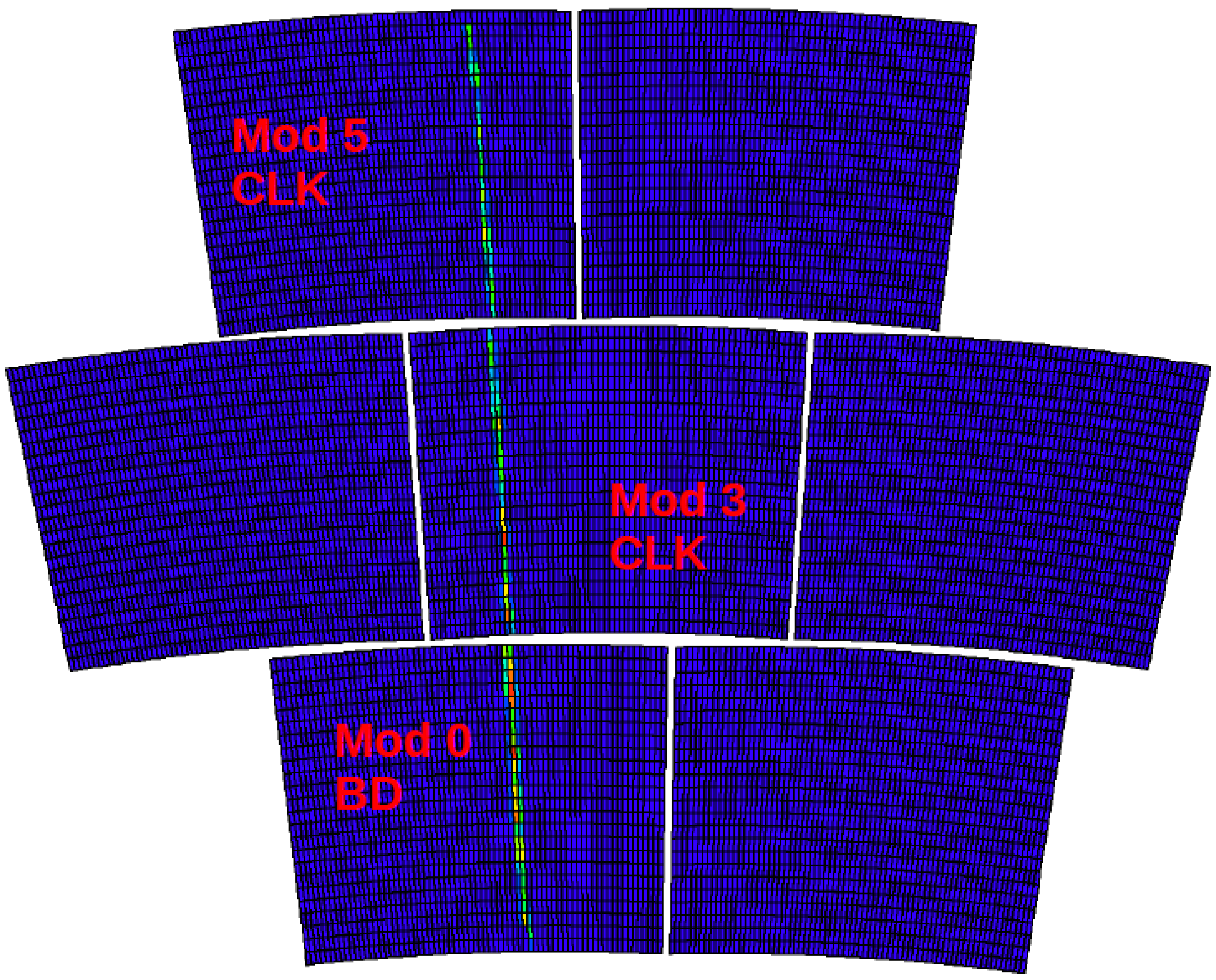
New Resistive Layer

Black Diamond (BD)/ Diamond like Carbon (DLC)

often used as a layer on tools to harden surface and as lubricant



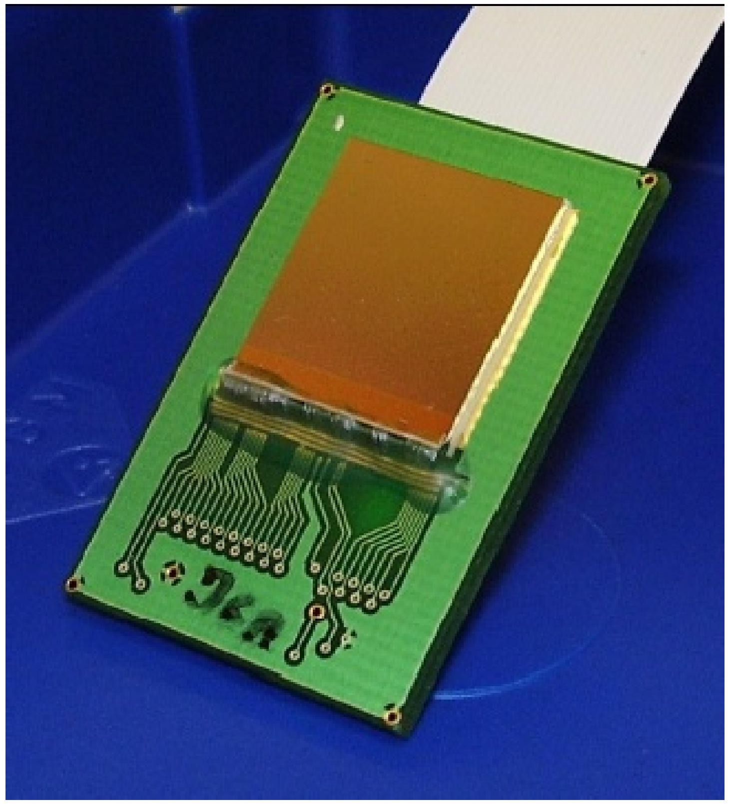
Black diamond' and Carbon-loaded kapton



BD layer was produced in Japan by A. Ochi: 100 nm on a kapton foil

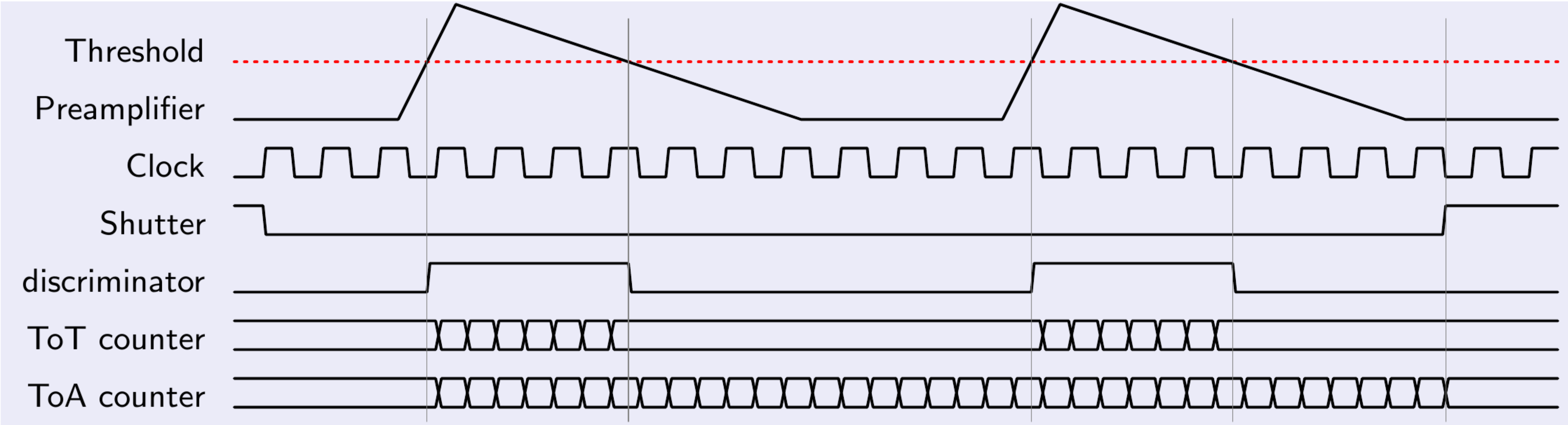
Two modules with BD were tested this year with 5 CLK ones (carbon loaded kapton).

Timepix

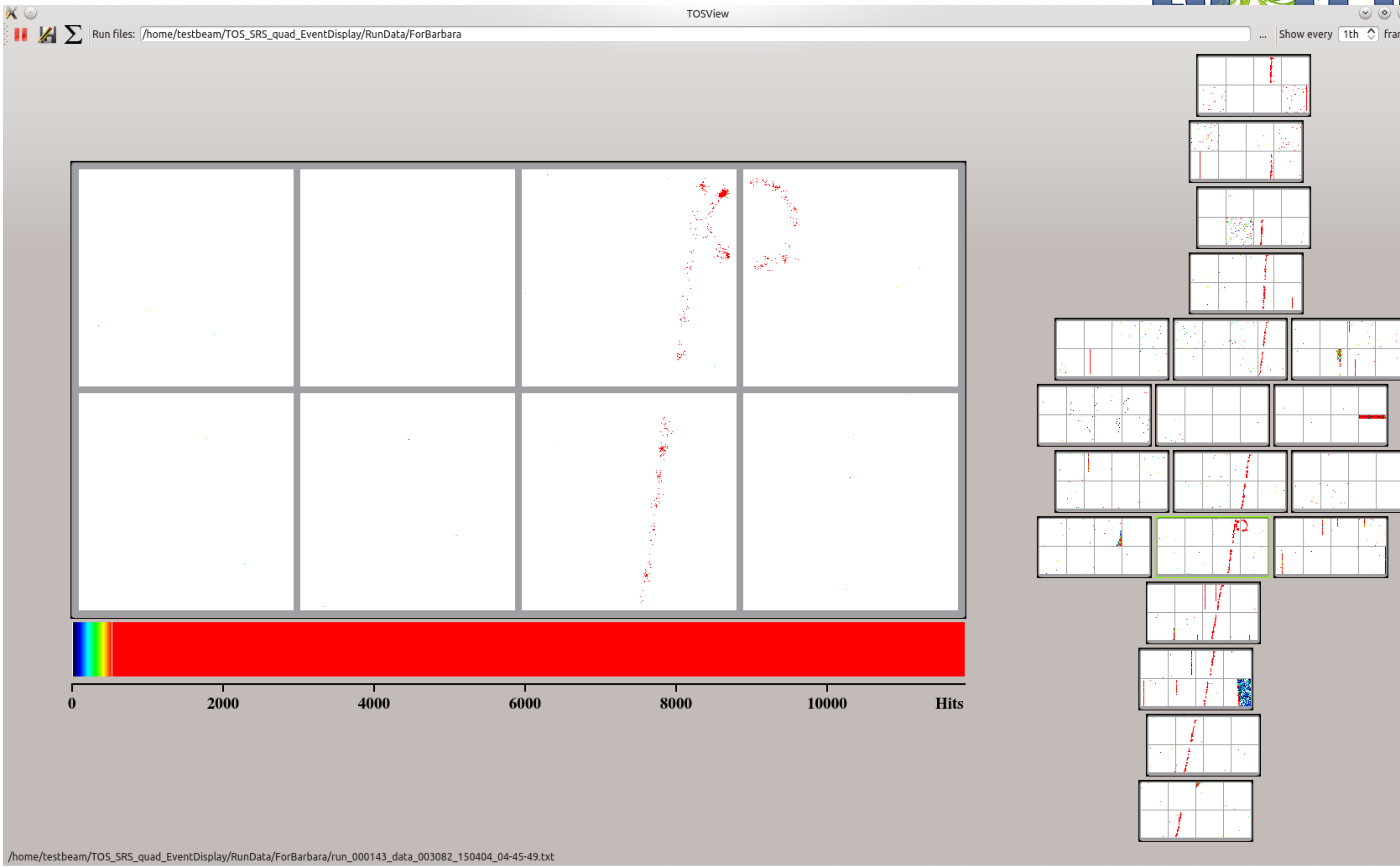


Number of pixels: 256 × 256 pixels
Pixel pitch: 55 × 55 μm²
Chip dimensions: 1.4 × 1.4 cm²
ENC: ~ 90 e⁻

Limitations: no multi-hit capability, charge and time measurement not possible for one pixel.
Each pixel can be set to one of these modes: TOT = time over threshold (charge)
Time between hit and shutter end.



Online Event Display (I)



ILC detector (ILD)

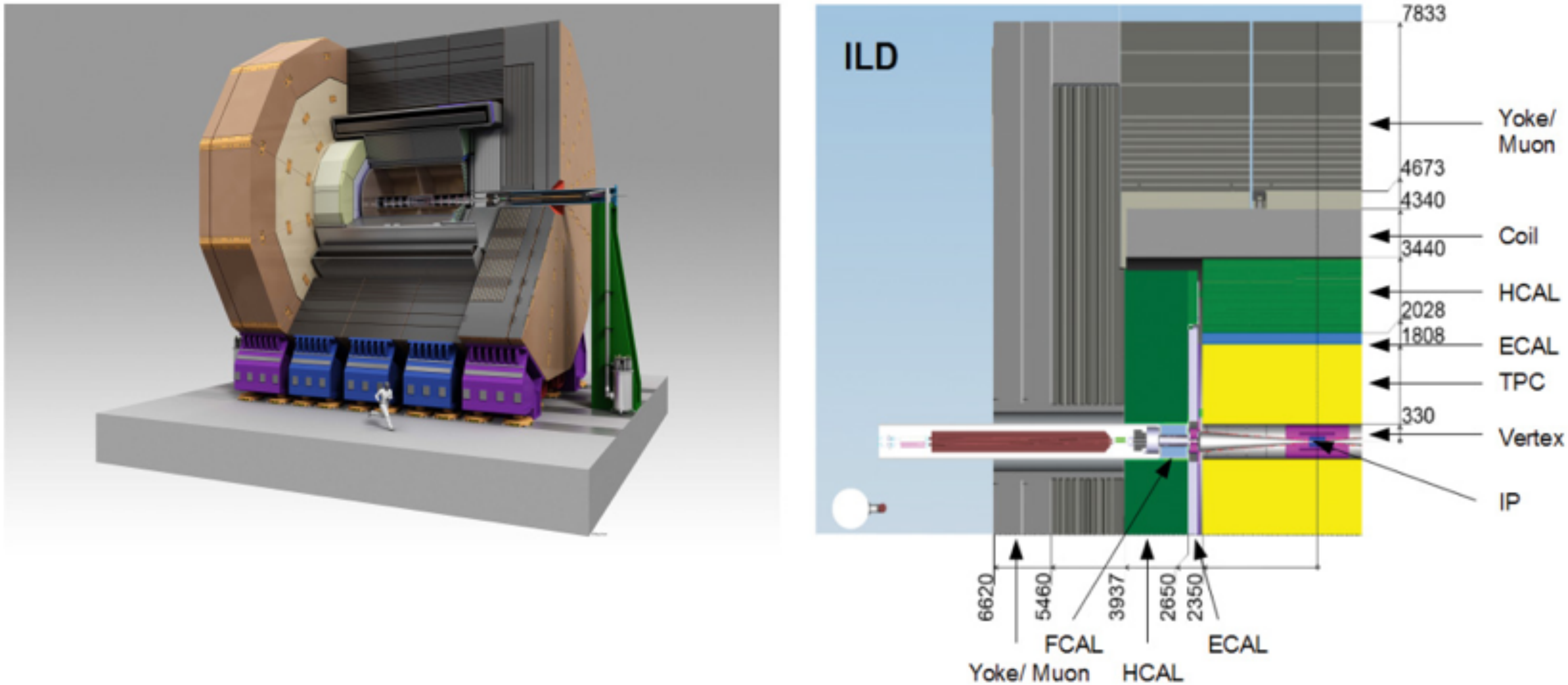


Figure 4.6. Views of the ILD detector concept. The interaction point in the quadrant view (right) is in the lower right corner of the picture. Dimensions are in mm.

Calorimeter

High precision sensors with 5x5mm^2 (ECAL), 3x3cm^2 (HCAL)

$\sigma_E/E \sim 3-4\%$ → measurement of m_W, m_Z (3σ separation)

ILC detector (ILD)

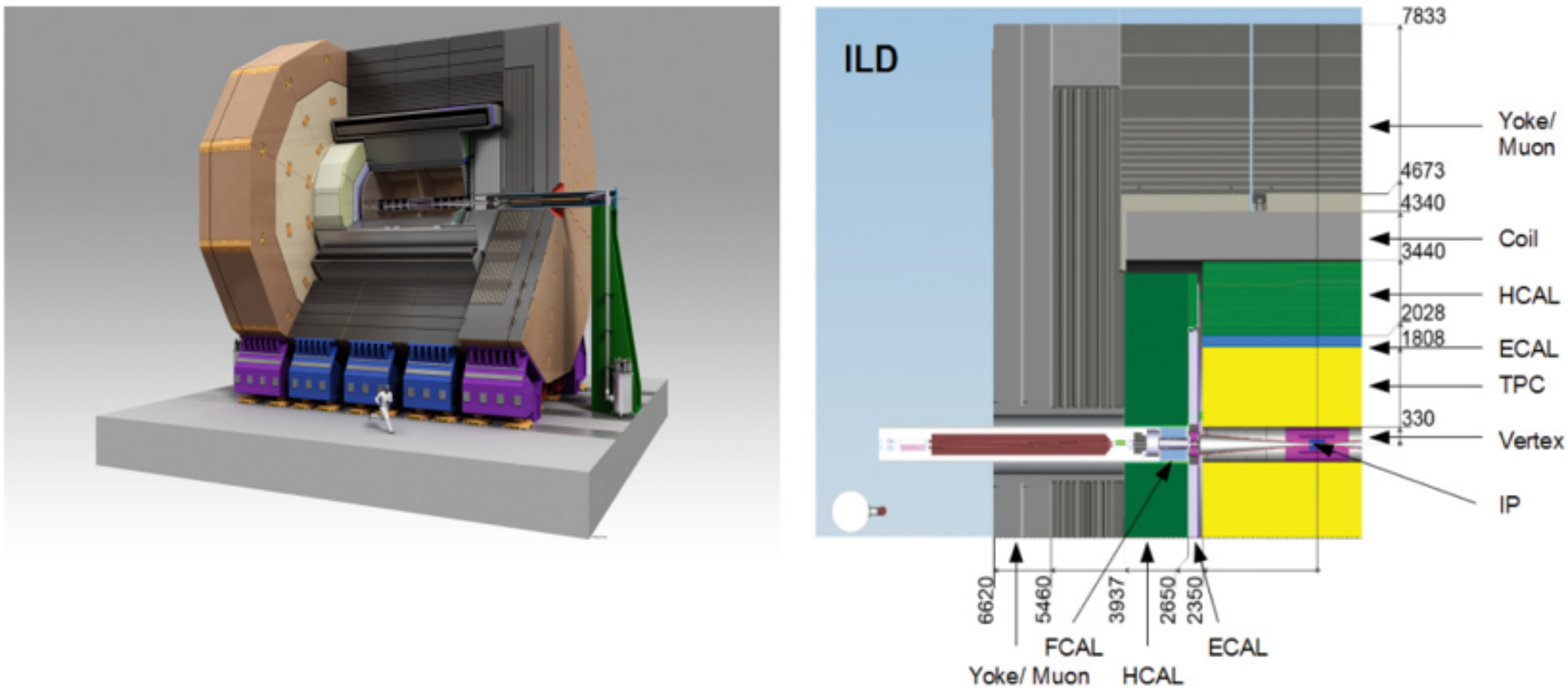
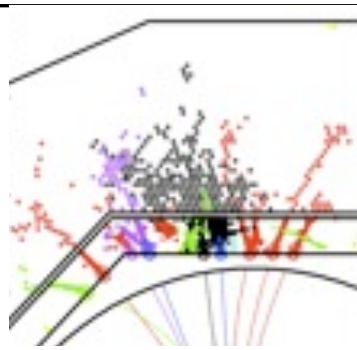


Figure 4.6. Views of the ILD detector concept. The interaction point in the quadrant view (right) is in the lower right corner of the picture. Dimensions are in mm.

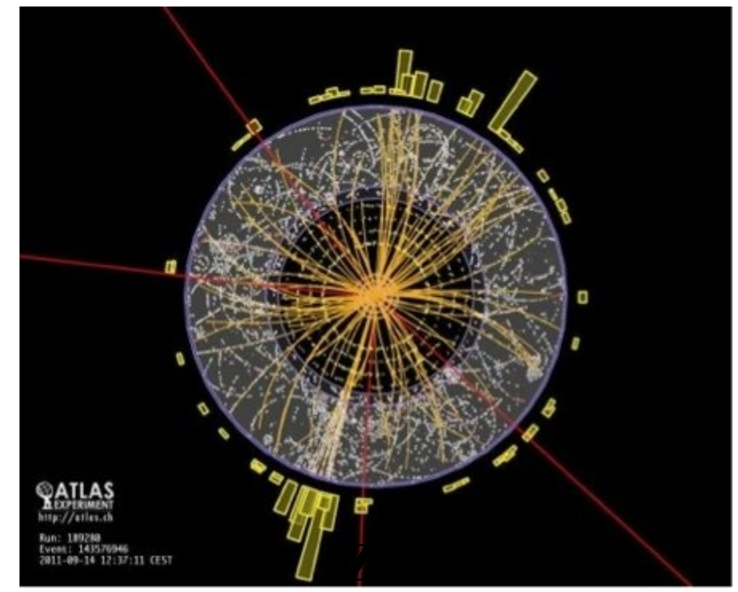
	ILC	ATLAS	precision ratio
vertex	5x5 um^2	400x50 um^2	x800
tracker	1x6 mm^2	13 mm^2	x2.2
ECAL	5x5 mm^2	39x39mm^2	x61

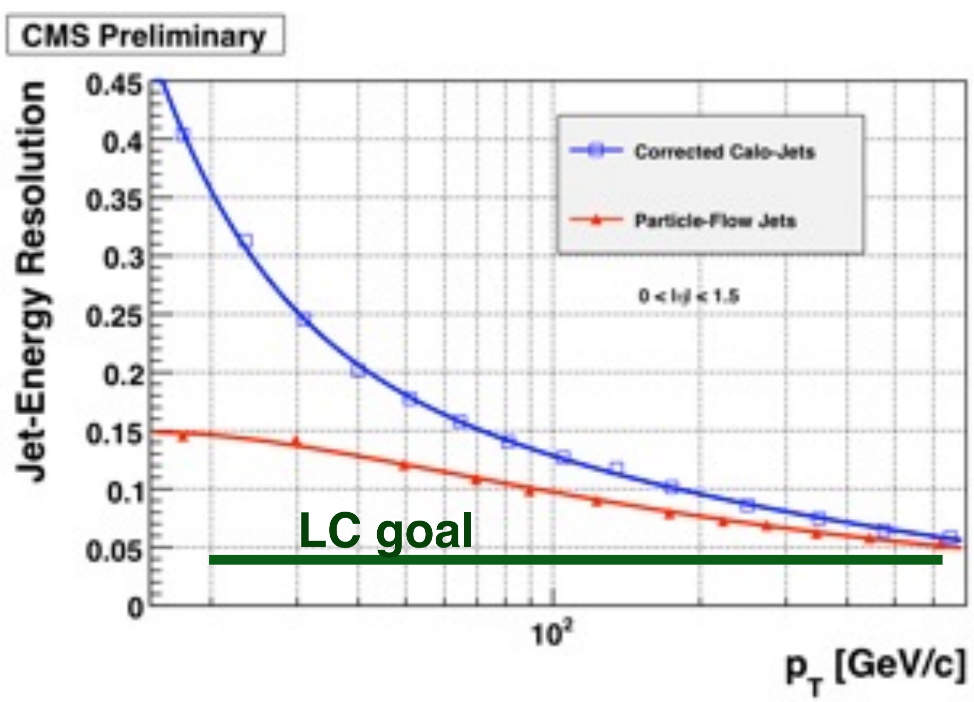
Particle Flow Algorithm (PFA)



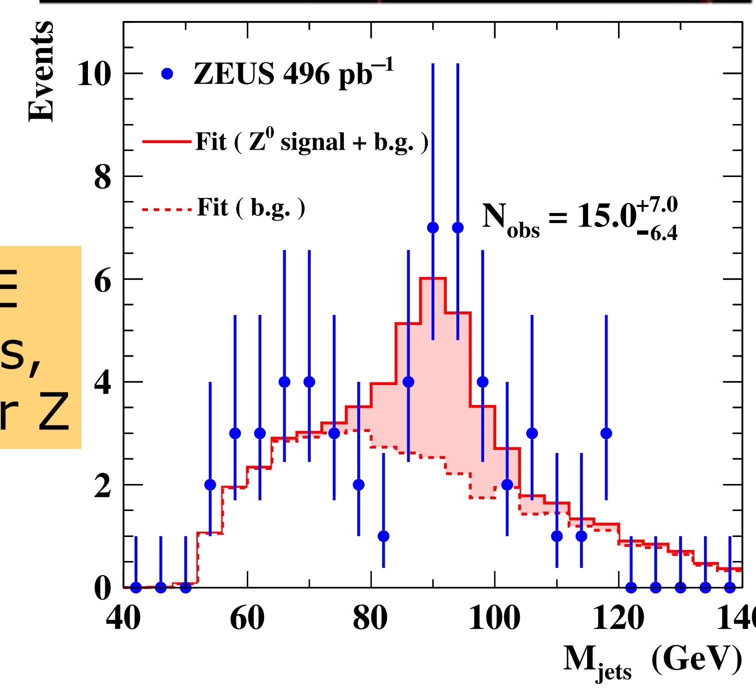
The jet energy challenge

- Jet energy performance of existing detectors is not sufficient for W Z separation
- E.g. CMS: ~ 100%/√E, ATLAS ~ 70%/√E
- Calorimeter resolution for hadrons is intrinsically limited
- Resolution for jets worse than for single hadrons
- It is not sufficient to have the world best calorimeter





35%√E
for pions,
6 GeV for Z



6

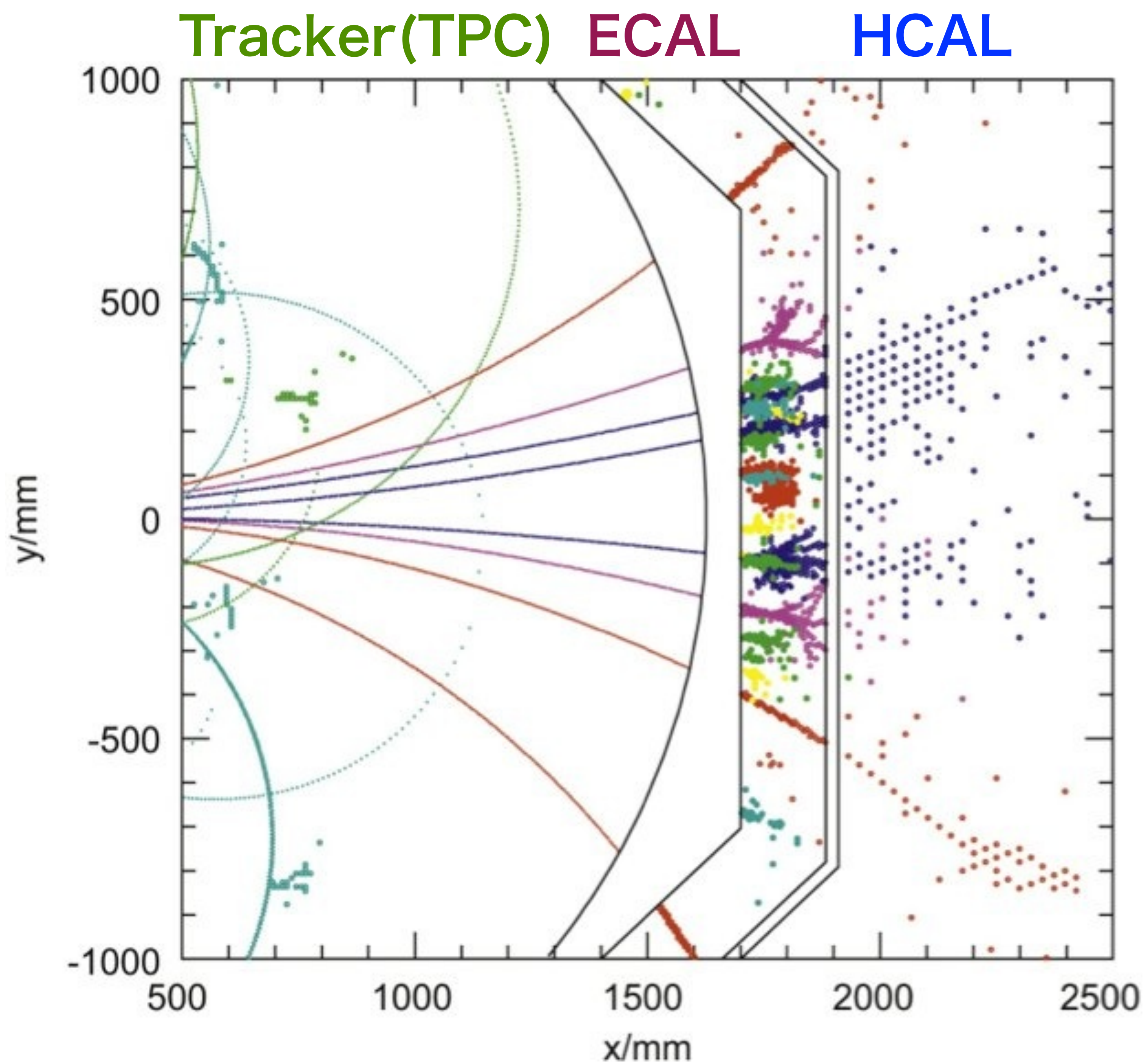
Slides by F. Sefkow

Particle Flow Algorithm (PFA)

Separate hit of each particle in calorimeter. Then, measure the particle energy using the detector with the best resolution for the particle.

- charged particles
  → Tracker
- photons
  → ECAL
- neutral hadrons
  → HCAL

For this purpose, there is no solenoid inside calorimeters.



Summary

- LHC run1 gave excellent results. Higgs discovery and measurement of its natures. Run2 will be further fruitful with possible discoveries.
- ILC will start after looking at ~3years of LHC run2 results. Precise measurements of Higgs and top quarks can open windows to new physics. In addition, ILC will have discovery potential that is not obtained by LHC.
- Detector studies for the most precise measurements ever are being performed.