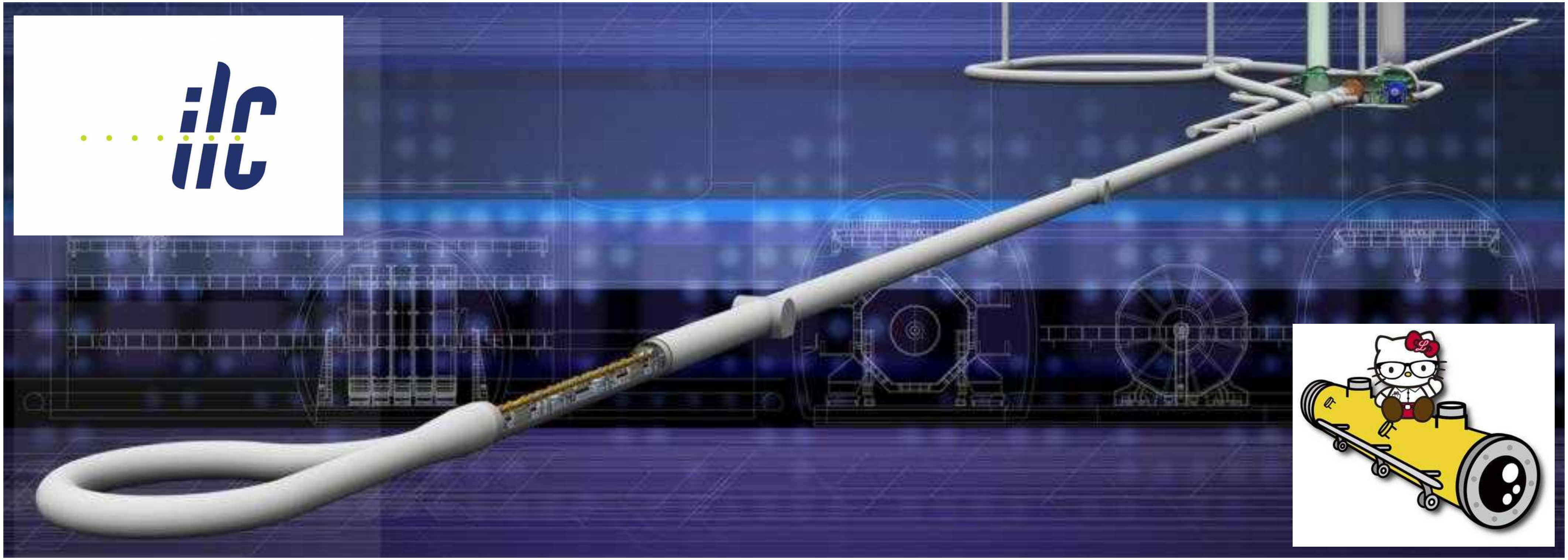
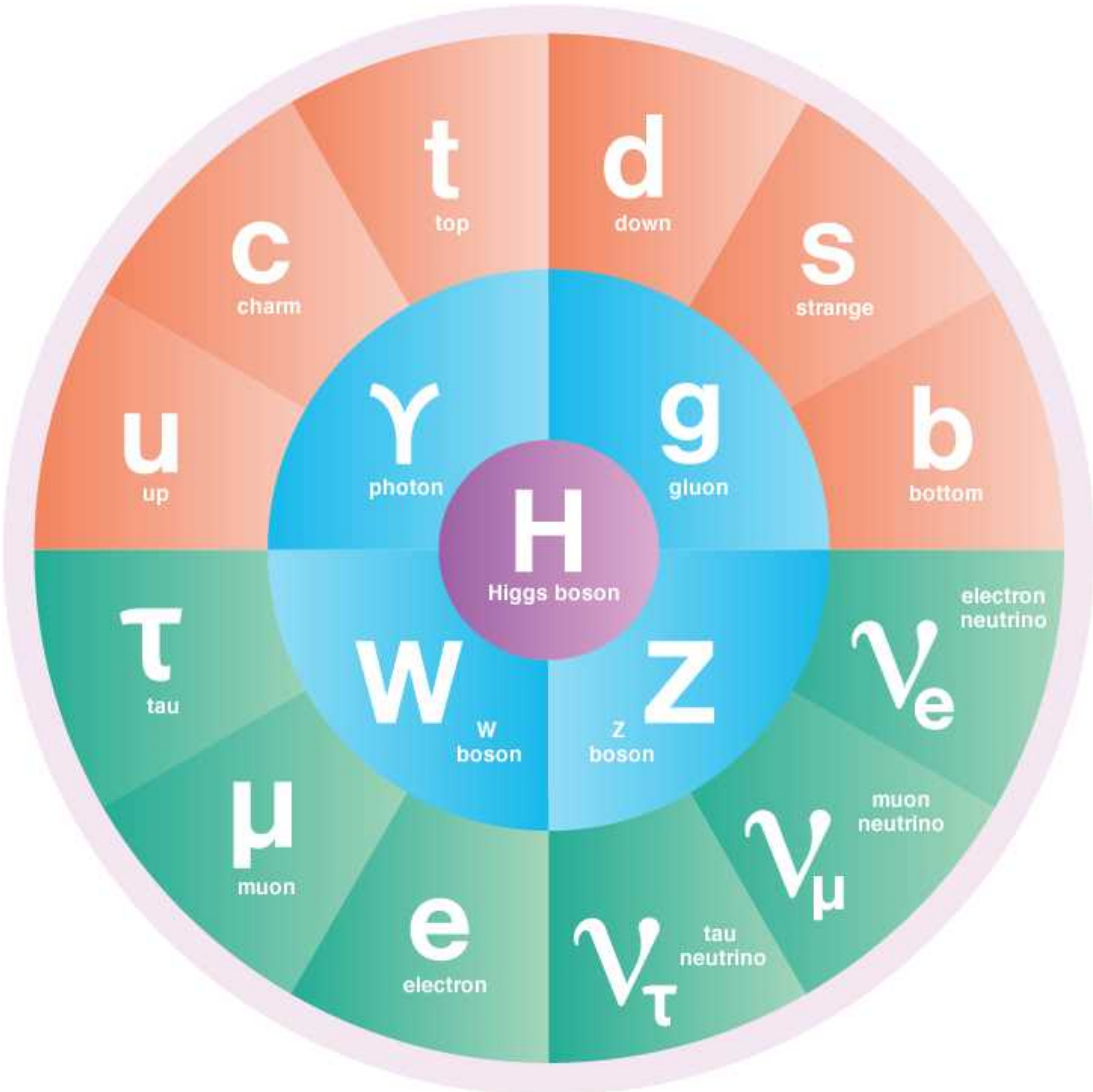
International Linear Collider
physics and detectors



Kyushu University, Dec 12
Daniel Jeans, IPNS/KEK

The Standard Model of Particle Physics



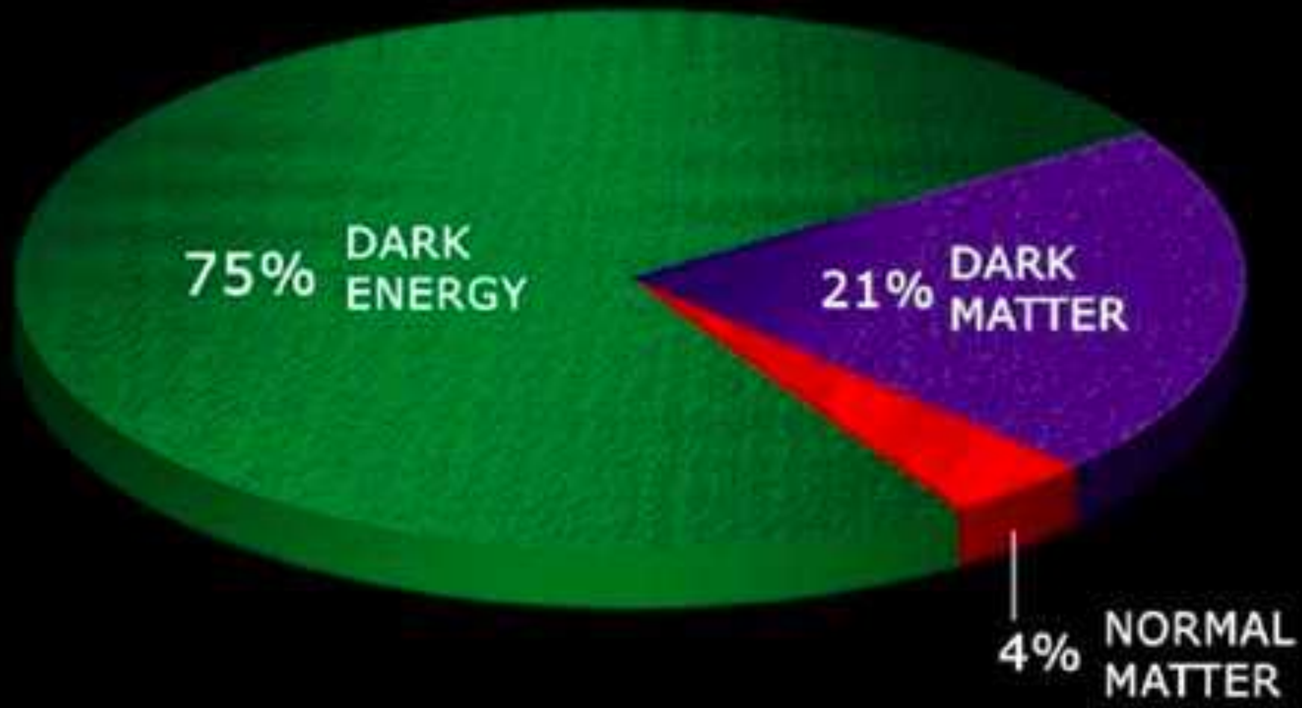
quarks

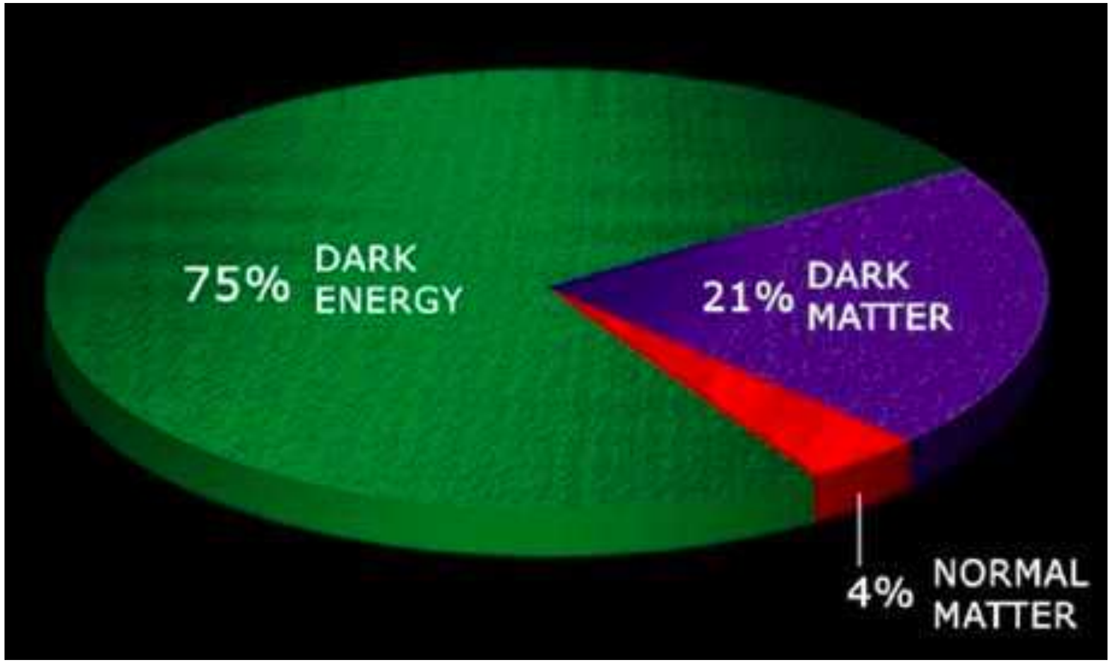
leptons

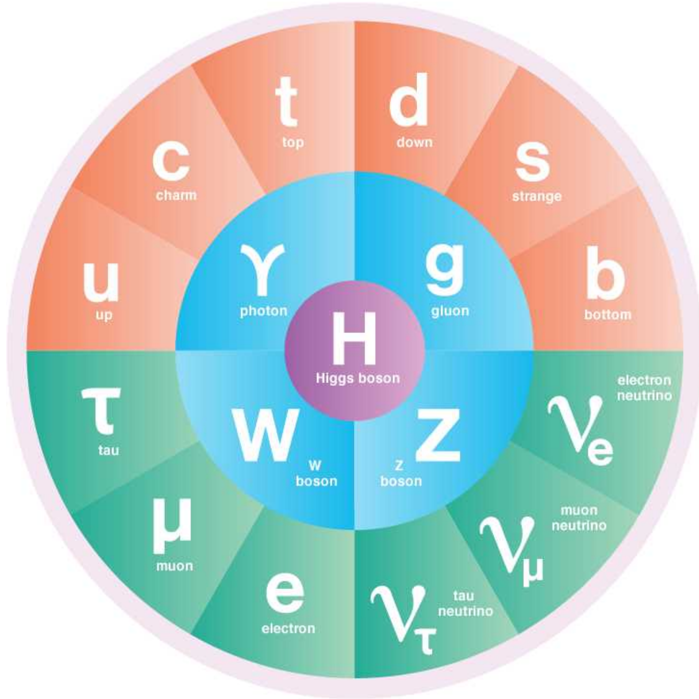
gauge bosons

Higgs boson

The Standard Model of Cosmology







these Standard Models leave important unanswered questions

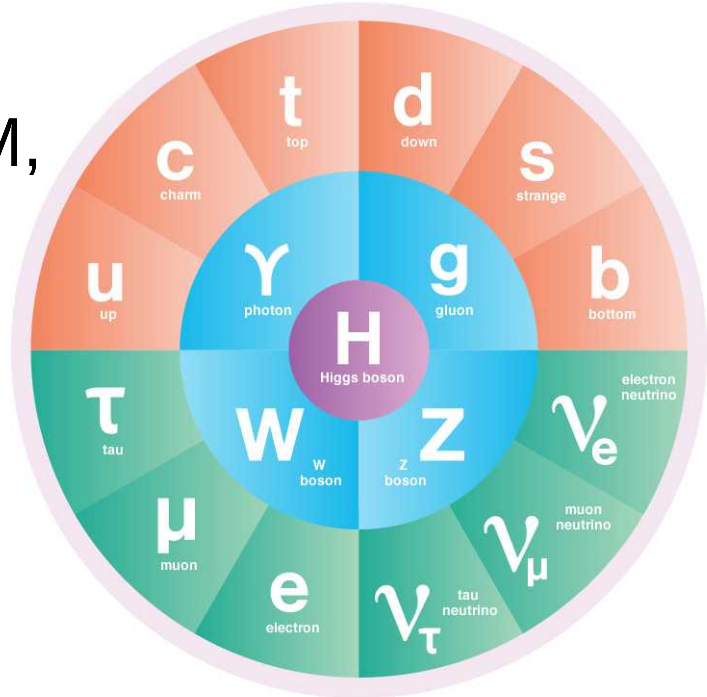
→ Nature of dark matter and energy

→ Why a matter-dominated universe ?
CP violation mechanism in early universe

→ What lies between E-W (~100 GeV) and Plank (10^{19} GeV) scales ?
how are they insulated from each other?

Higgs boson

most recently discovered particle of SM,
(probably) least well measured



Higgs is unique, in class of its own

not a matter fermion
not a gauge boson

In the SM, the Higgs boson's properties (decay width, branching ratios, ...)
depend on only its mass

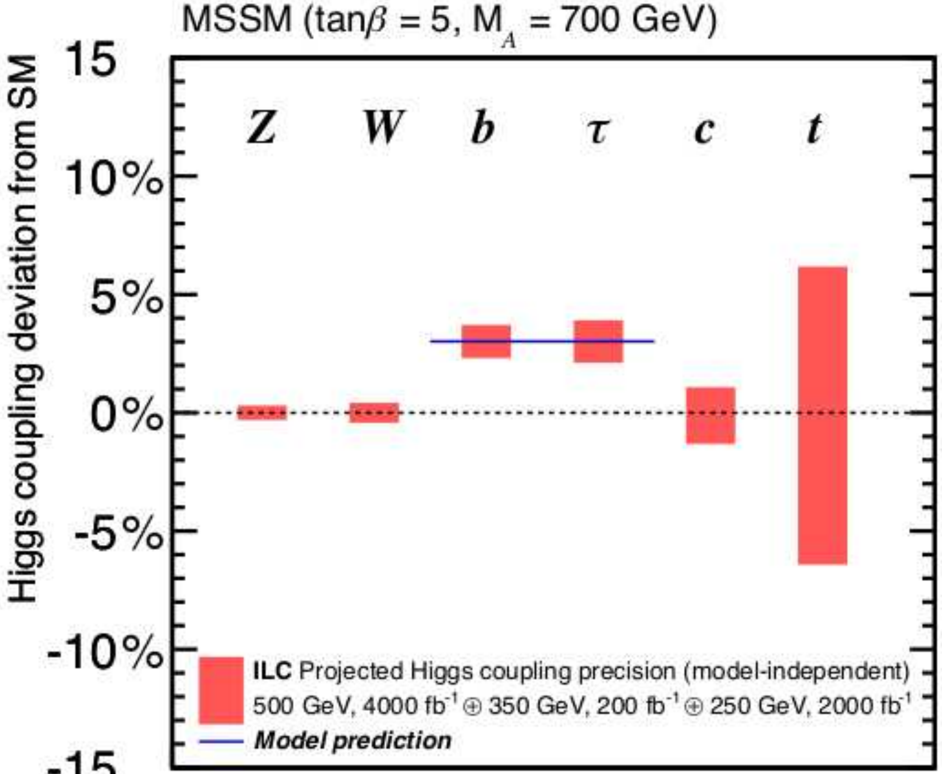
The Higgs sector is (arguably) the most promising place to find
new physics beyond the Standard Model

is Higgs really elementary ?
is there really only a single type of Higgs boson ?
does Higgs also give mass to dark matter ?
is CP violated in Higgs interactions ?
what lies beyond the SM ?

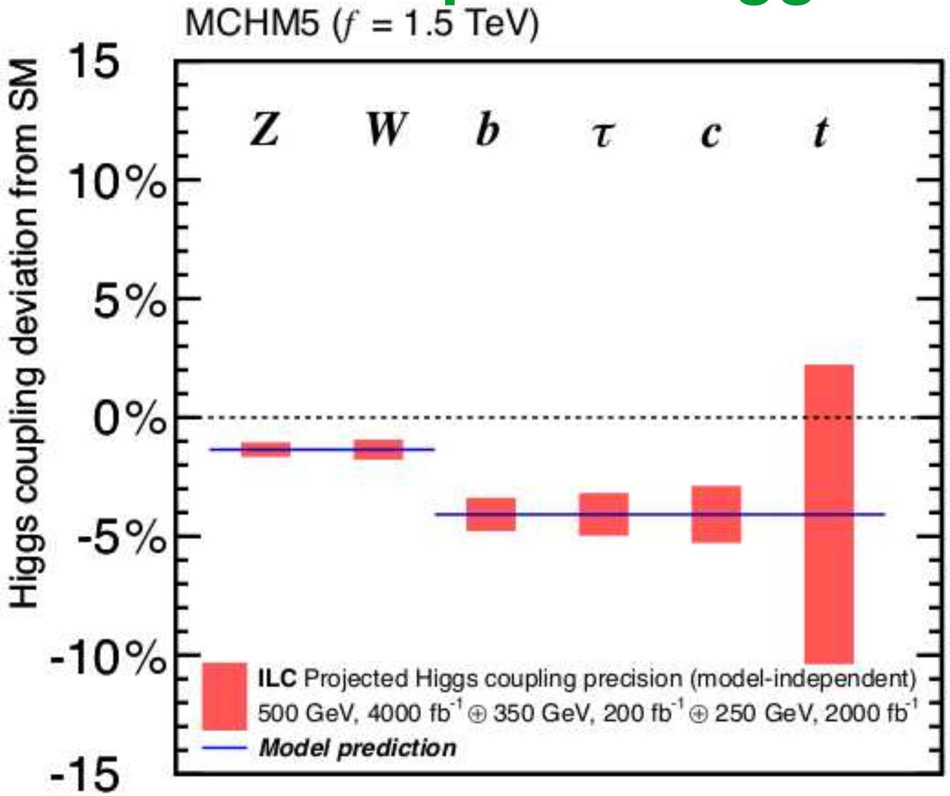
An example:

In SM, Higgs couples to particles purely according to their masses
In many models of physics beyond the SM, this relation is altered

e.g. **SUSY**



Composite Higgs



arXiv:1506.05992

By measuring such deviations, we can hope to reveal the <u>nature</u> of underlying physics, and its <u>energy scale</u>

Measurement of the Higgs boson's properties presents unique opportunity to probe for physics beyond the Standard Model

For physics at ~TeV scale,
expect few %-level variations in
Higgs boson properties

Large Hadron Collider

Running at design energy

surpassed design luminosity

[last week: end "run 2" ; "run 3" from 2021-2023]

→ Higgs boson discovery

→ first "sketch" of its properties

→ 300 fb^{-1}

High-luminosity LHC [2026 – mid 2030s]:

same collision energy, higher luminosity

→ 3000 fb^{-1}

→ increasingly detailed picture of Higgs

→ ultimate precision of ~few % on many Higgs boson couplings

→ same order as "expected" deviations

largely dominated by systematic uncertainties

To move beyond LHC precision on Higgs boson properties, require new approach

electron – positron collisions

Long history in particle physics of such synergy between hadron and lepton colliders

e.g. W, Z bosons discovered in hadron collider (SppS) measured in detail at lepton colliders LEP, SLC

b quark discovered in proton fixed target collisions measured in detail at KEKB, PEP-II, SuperKEKB

$e^+ e^-$

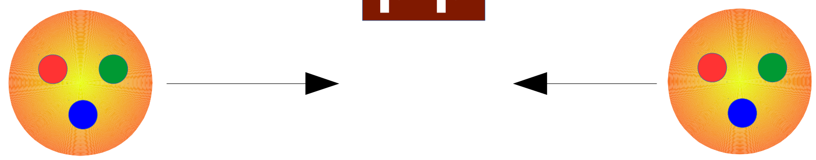
elementary particles

known, fixed energy

“democratic” occurrence of different interactions

little debris → clean events

p p

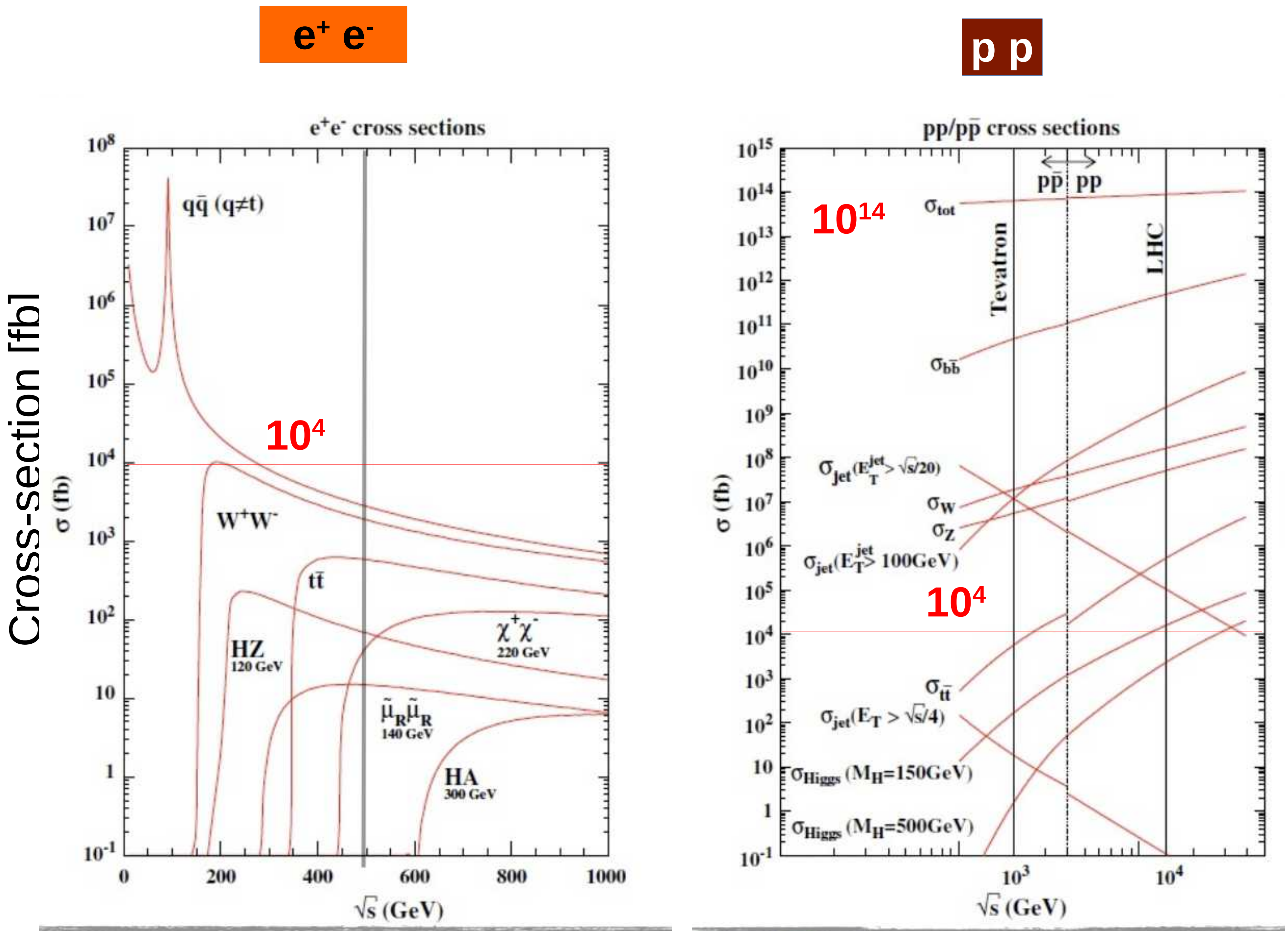


composite particles:
collisions between quarks, gluons

each carries fraction of proton momentum
→ wide spectrum of energies

dominated by QCD interactions;
electro-weak processes rare

debris: proton remnants

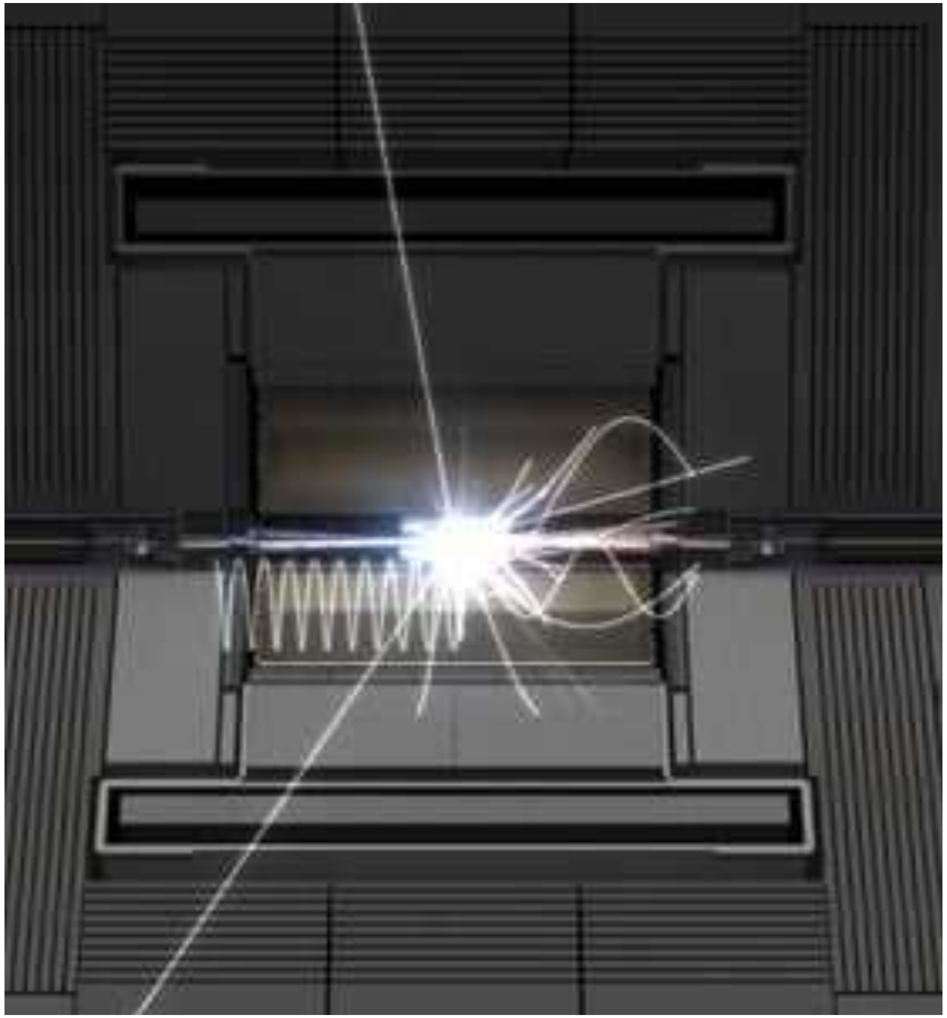


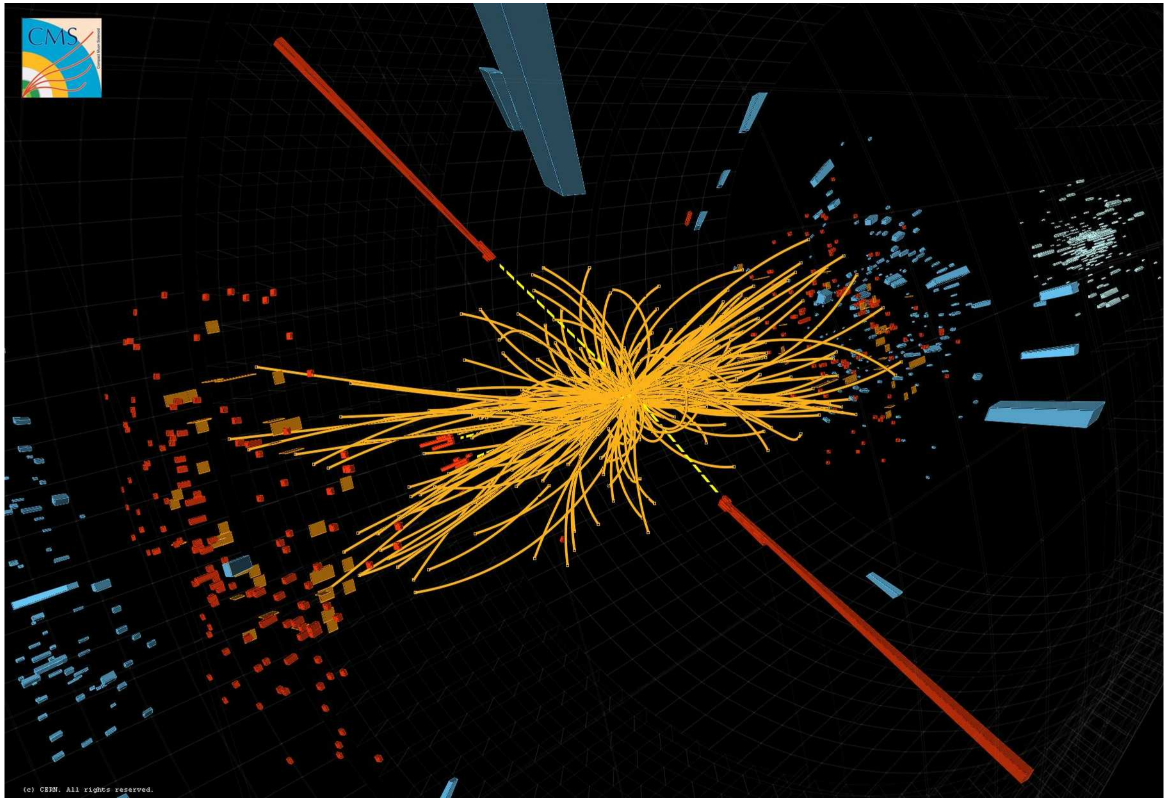
G. Weiglein et al. / Physics Reports 426 (2006) 47–358

Contrasting experimental environments

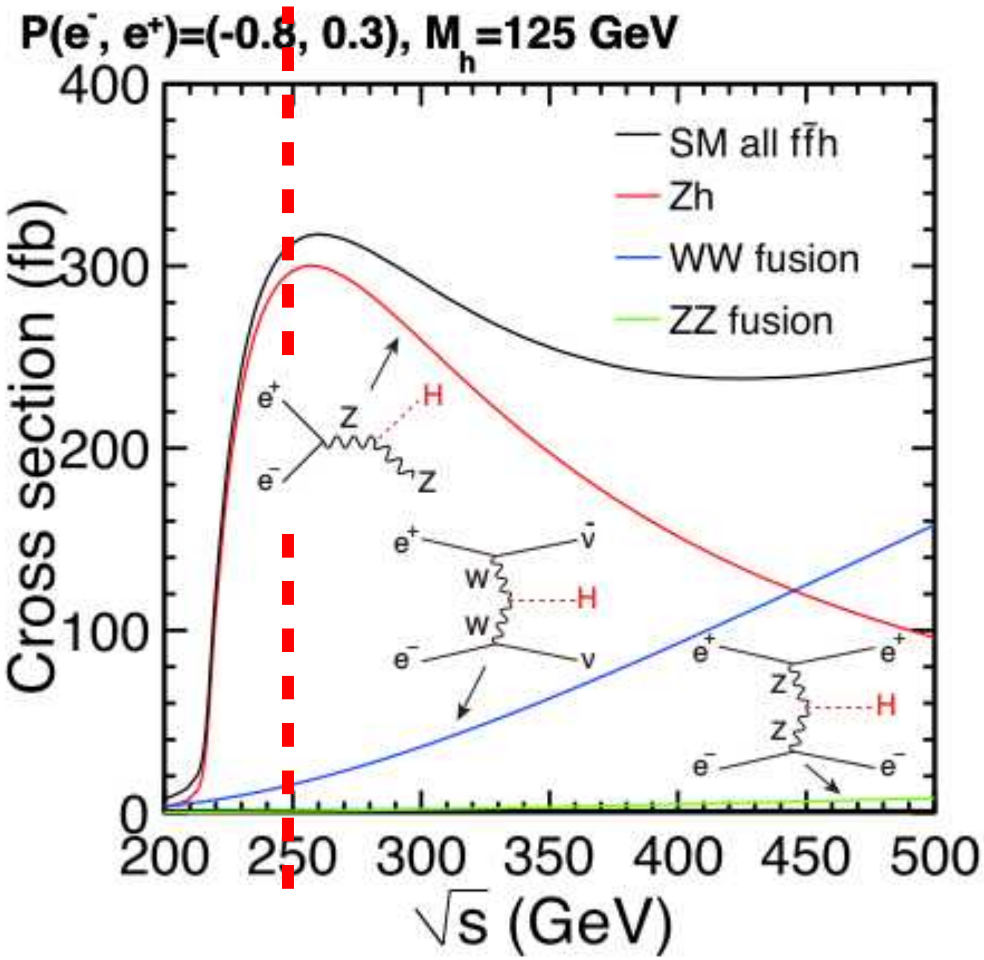
$e^+ e^-$

p p





Higgs boson production in electron-positron collisions



initial ILC luminosity
$L \sim 10^{34}\ cm^{-2}\,s^{-1} \sim 100\ fb^{-1}\ yr^{-1}$

peak cross-section ~300 fb
→ ~30,000 events/yr

total: 2000 fb^{-1} @ 250 GeV:
~0.6 M Higgs events

Higgs-strahlung
radiate H from Z

WW-fusion

ZZ-fusion

Higgs-strahlung process is particularly powerful

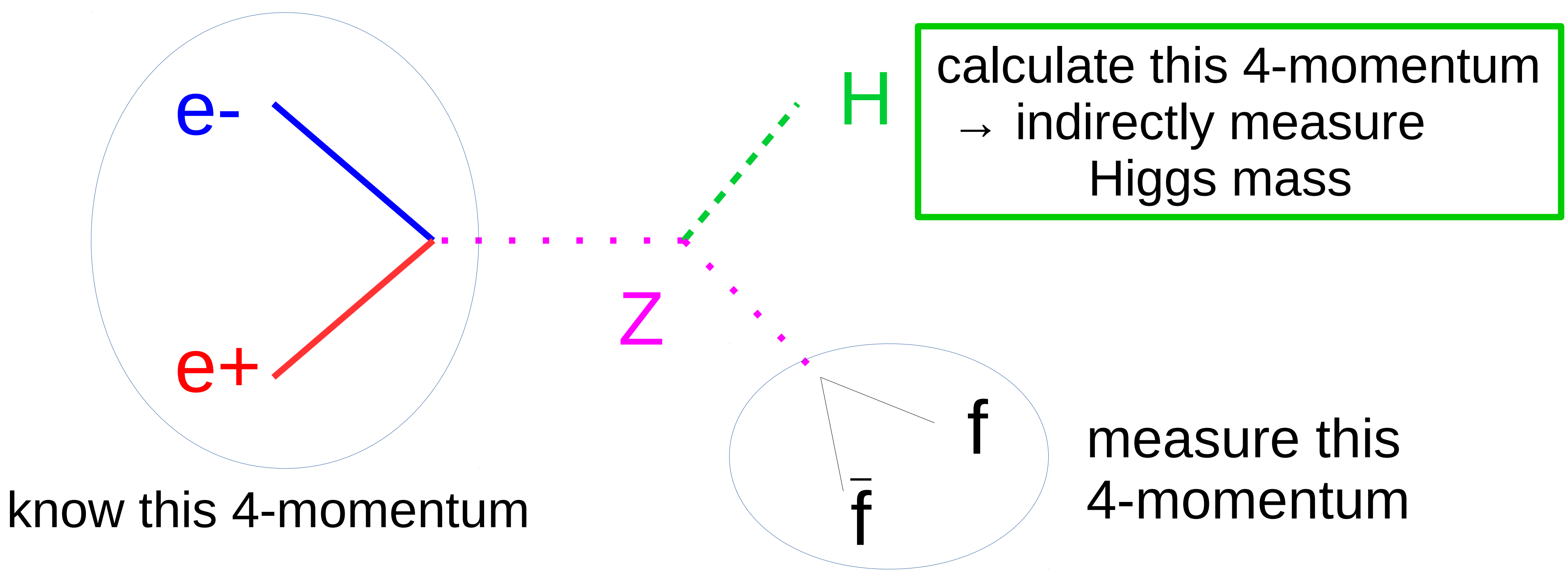
Higgs can be selected by looking **only** at Z decay products

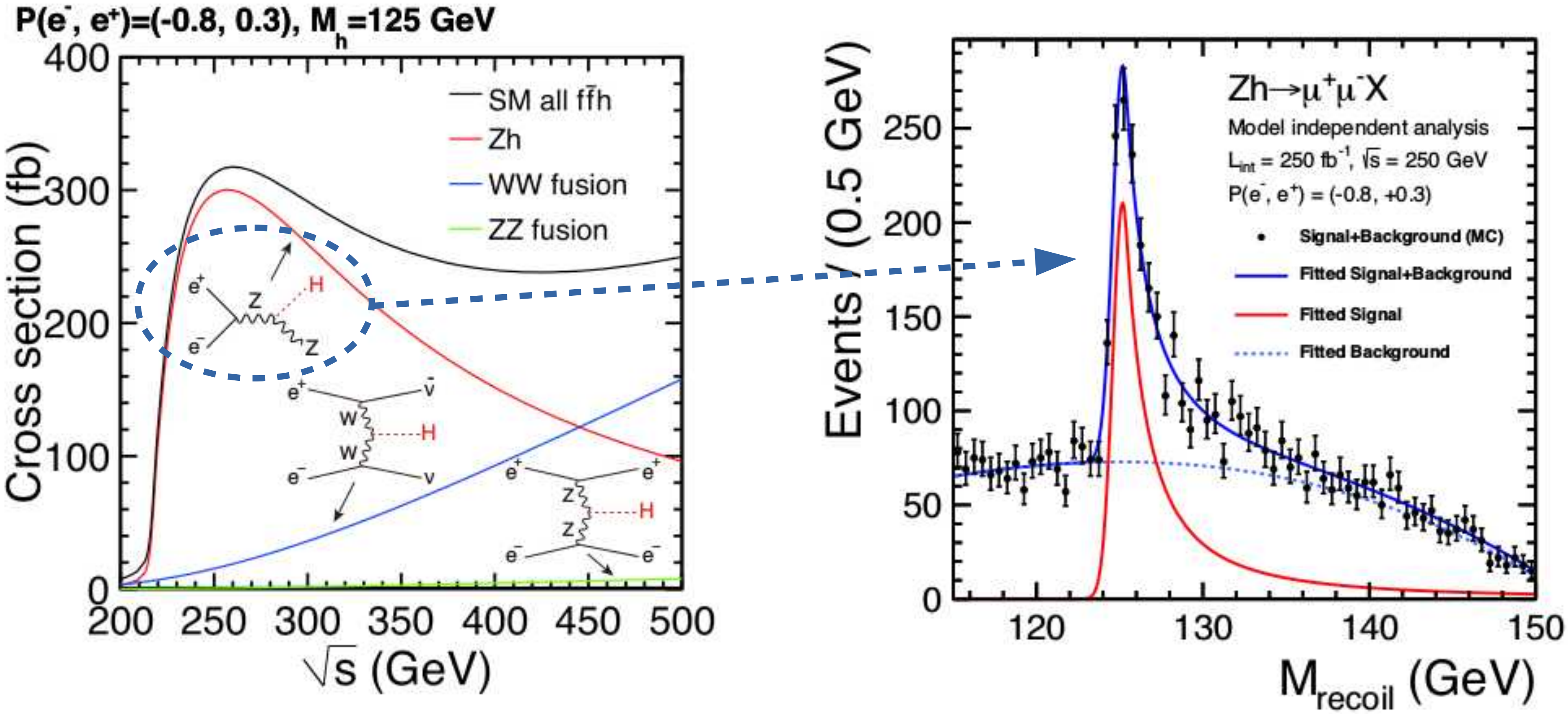
we know initial e^+e^- 4-momentum (lepton collider)

we precisely measure 4-momentum of Z

→ we can trivially extract 4-momentum of "H"

select Higgs events with **no decay mode bias** (e.g. invisible Higgs)



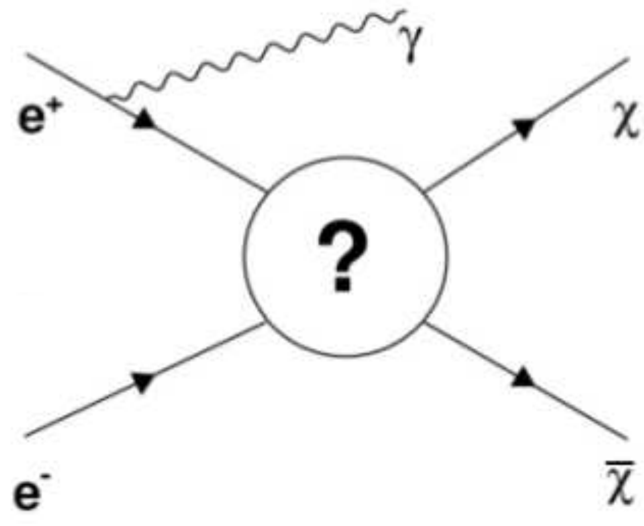


count total number of produced Higgs events, and extract Higgs mass without looking at Higgs decay products

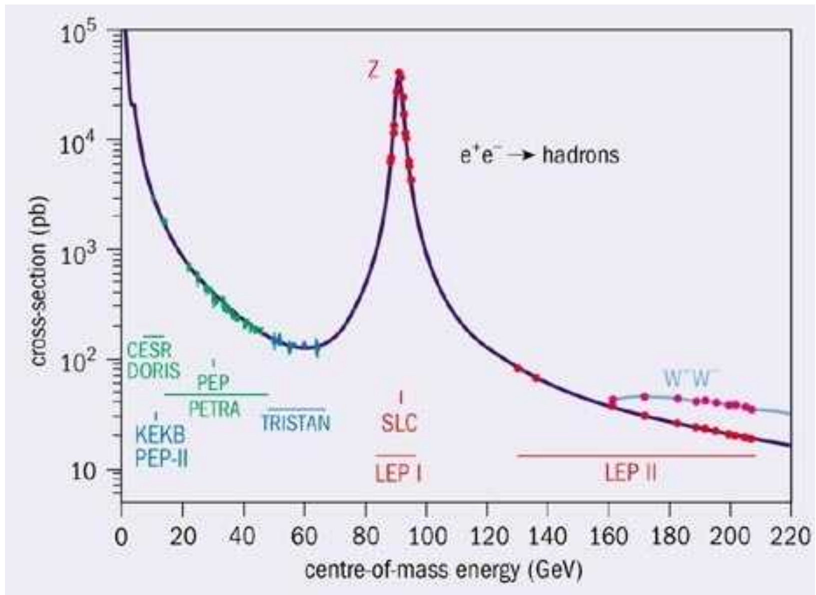
→ not affected by e.g. invisible / unexpectedly weird Higgs decays
→ “model independent”

In addition to Higgs physics, ILC will

search for direct production of new particles
- helped by clean experimental environment
- cover "blind-spots" of LHC experiments
  - low energy (e.g. < 1 GeV) signals
  - invisible signatures
- models total event rate
  - → trigger-less operation
  - → analyse all collisions



wide range of electroweak measurements
- orders of magnitude more lumi. than LEP2
- wider energy range, polarised beams
  - → stringent constraints on,
    or observation of,
    new physics at high scales (~ 10 TeV)



ilc

International Linear Collider project

initiated in 2005 under auspices of the

International Committee for Future Accelerators ICFA

→ amalgamation of several regional,
linear collider studies using different technologies

→ superconducting RF technology selected

Reference Design Report (2007)

Global Design Effort
lead by B. Barish

Technical Design Report (2013)

signed by 2800+ people from 400+ institutes from ~50 countries

Niobium 1.3 GHz superconducting accelerating structures
average gradient 31.5 MV/m, operated at 2 K

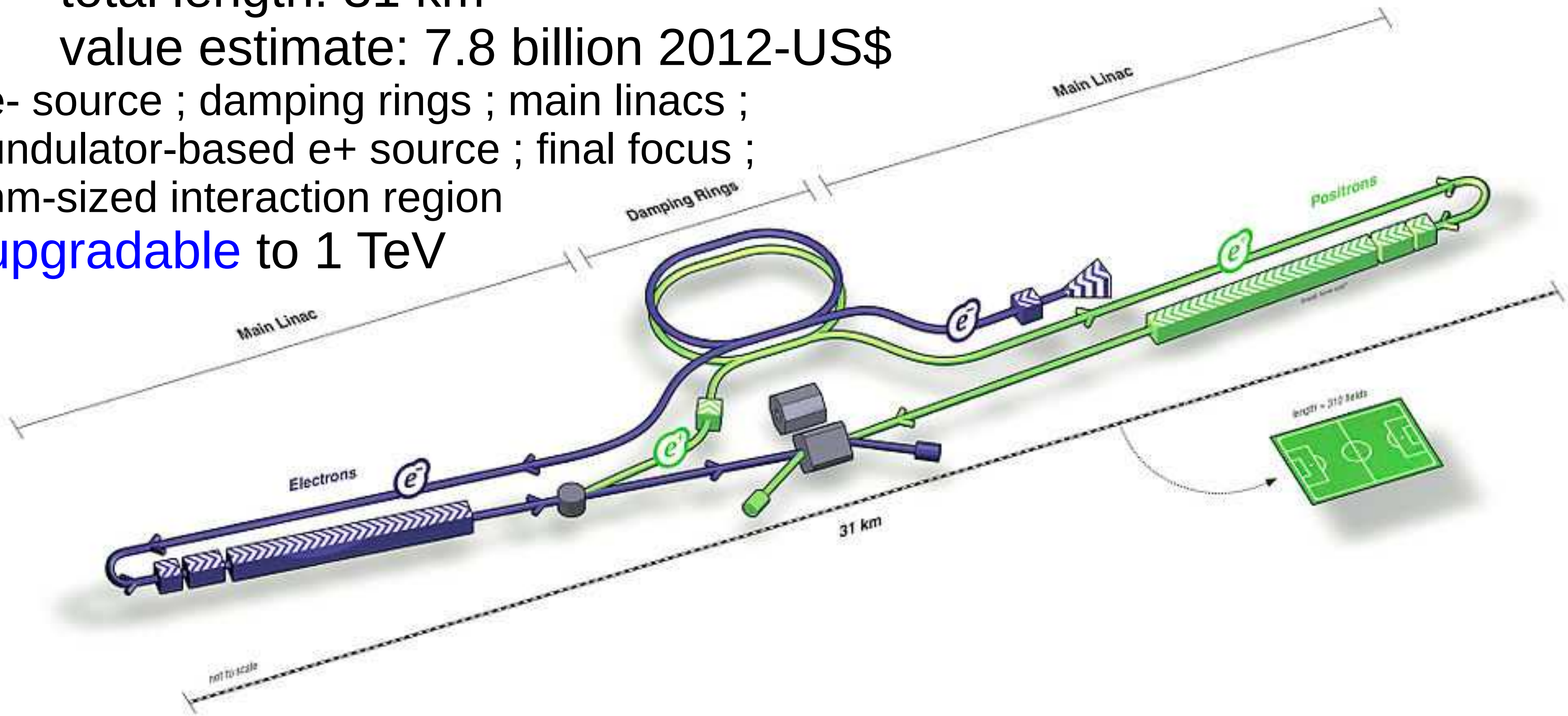
Technical Design Report (2013)

e+ e- collisions : C.M.E ~ 250 → 500 GeV , L ~ 10^{32} cm^{-2} s^{-1}
with longitudinally polarised beams : e- 80%, e+ 30%

500 GeV machine:
total length: 31 km
value estimate: 7.8 billion 2012-US$

e- source ; damping rings ; main linacs ;
undulator-based e+ source ; final focus ;
nm-sized interaction region

upgradable to 1 TeV



changes to design only via formal change review process
→ stable, well-controlled, mature project

Accelerating technology is mature

production of niobium cavities in industry;
being used / developed in several other contexts:
e.g. light sources at DESY (E-XFEL), SLAC (LCLS-II), Shanghai

E-XFEL has been successfully built, commissioned, now running smoothly

17.5 GeV in 2 km
@ ~24 MV/m

10~20% of one ILC arm

Since 2016, proposing initial ILC250 stage,
maximum collision energy 250 GeV

“Higgs factory” – precision measurement of Higgs

Significantly reduced cost compared to ILC500

ILC will be upgradable to higher energies,
if and when the scientific case is sufficiently strong
→ extend tunnel
→ improved accelerating technology

ILC detector design

ILC detector design

general purpose: address wide range of physics analyses

- charged **lepton**, **photon**, **hadron** measurement and identification
- highly **hermetic**

lepton collider : relatively low event rates, clean environment

- trigger-less readout: collect all detector signals

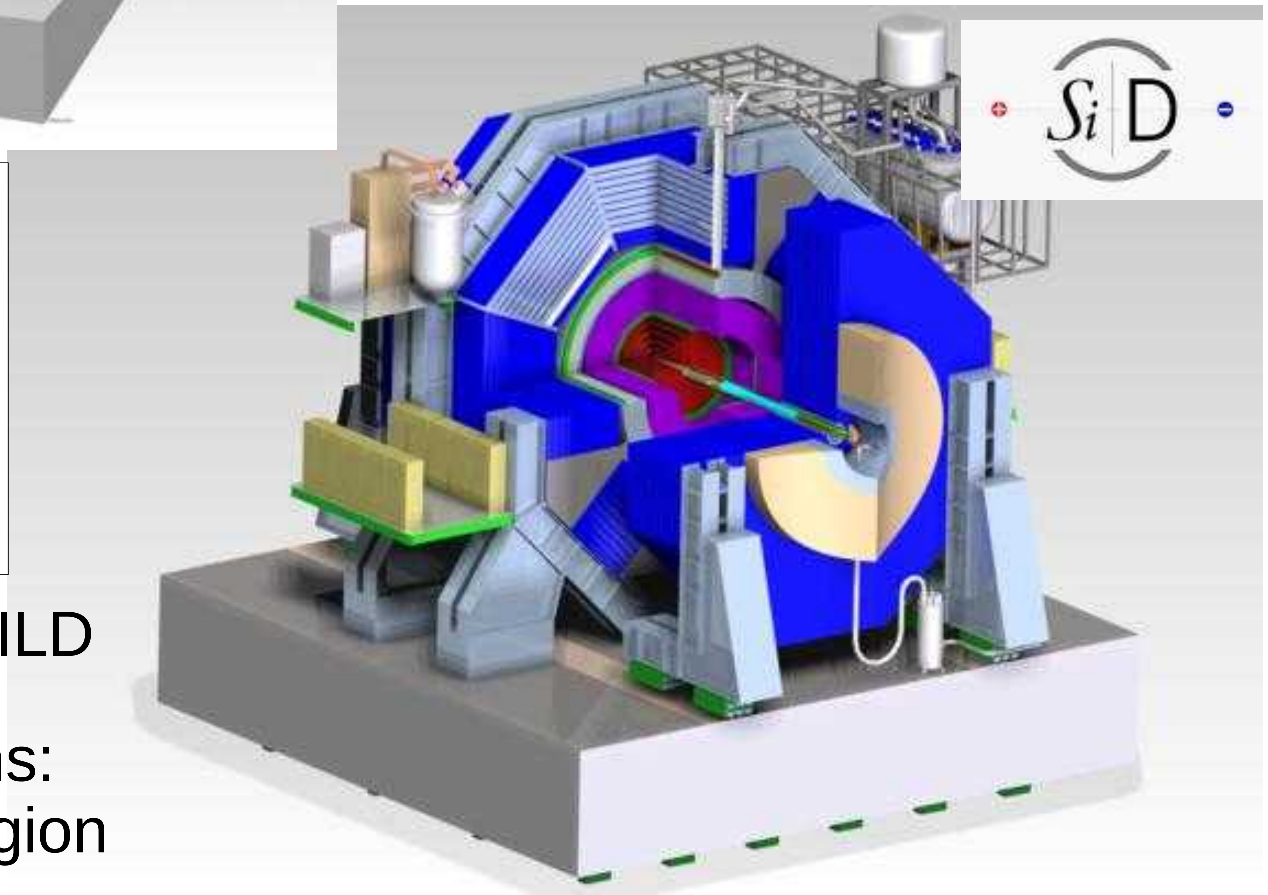
- designed for particle flow (PFA) reconstruction
  - measure every particle in final state,
  - optimal combination of sub-detector information

- high precision, low material trackers
  - momentum resolution
  - displaced tracks from b, c, τ

- analysis of dominant hadronic decays of W, Z, H essential
  - precise jet energy measurement by PFA
  - calorimeters with highly granular readout

ILD

pixel vertex detector
large TPC + silicon strips
high granularity calorimeters
3.5 T field

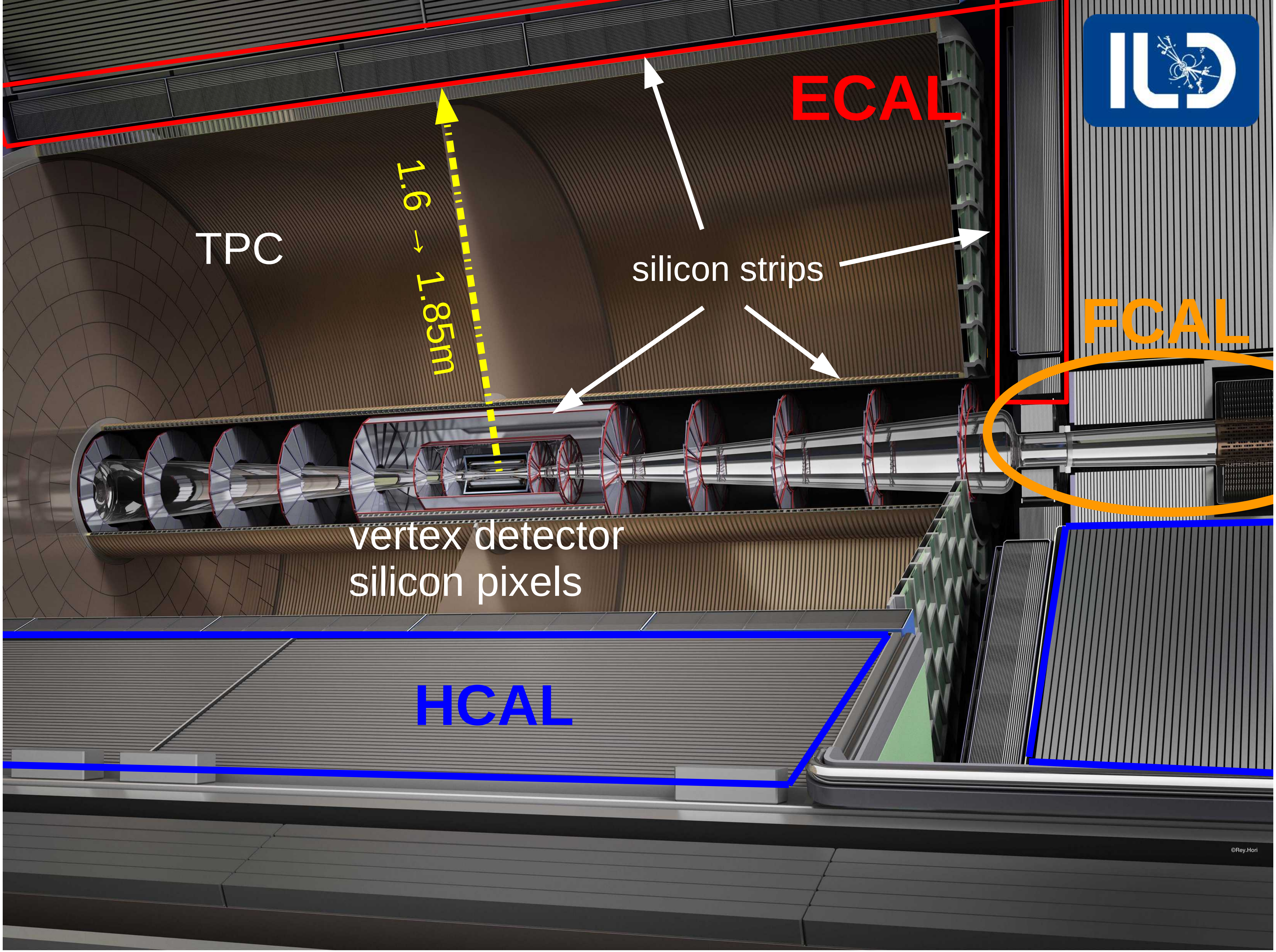


SiD

pixel vertex detector
silicon-only tracking system
high granularity calorimeters
5 T field

SiD somewhat smaller than ILD

detectors placed on platforms:
move in/out of interaction region



ECAL
ILD
TPC
1.6 → 1.85m
silicon strips
FCAL
vertex detector
silicon pixels
HCAL
©Rey.Hori

typical detector performance

(from detailed simulations and prototyping)

charged track momentum resolution

$dp_T / p_T \sim 3 \times 10^{-5}\, p_T$

→ important for “recoil” H mass measurement

charged track impact parameter resolution

$\sigma_{d0} \sim 5\ \mu m \oplus (\ 10\ \mu m / p\ [GeV]\ \sin^{3/2}\theta\ )$

→ important for identification of b, c, and τ decays

hadronic jet energy resolution

$\sigma_E / E \sim 3 \rightarrow 5\ \%$ over wide energy range

→ optimal combination of tracking and calorimeter

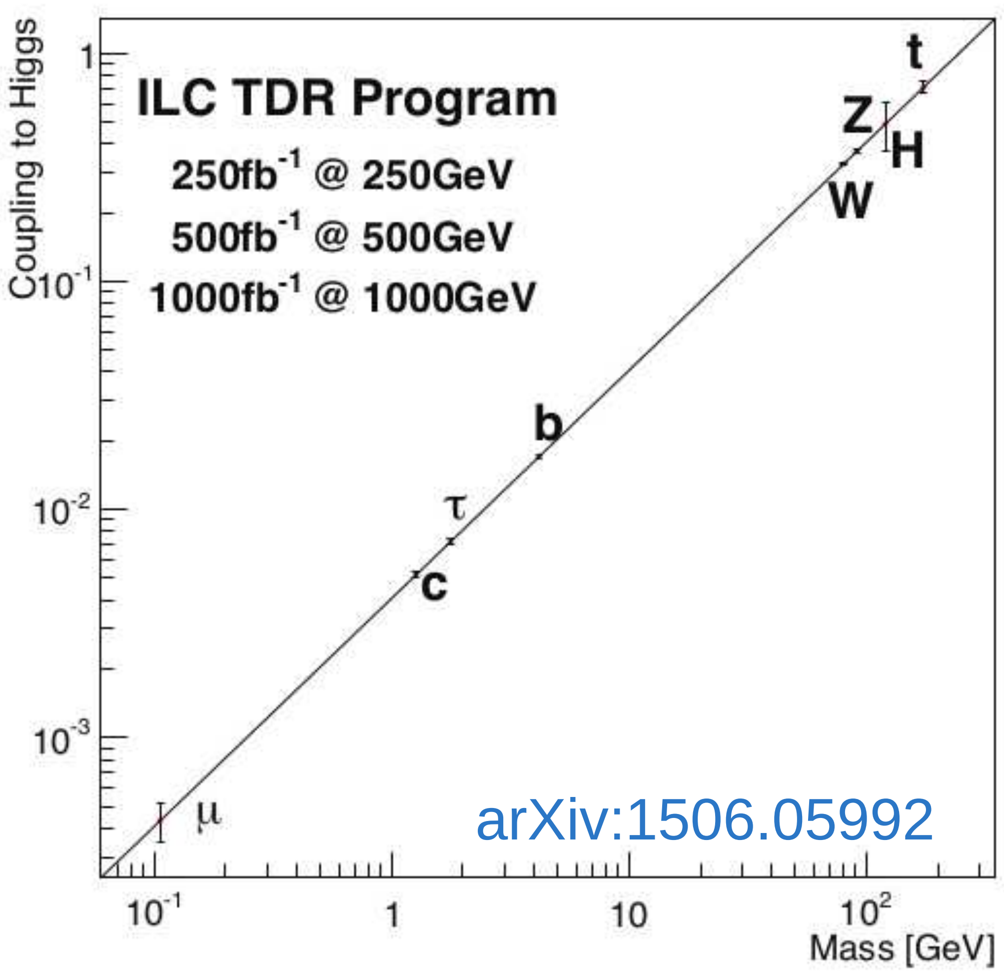
→ important for measurement of hadronic final states

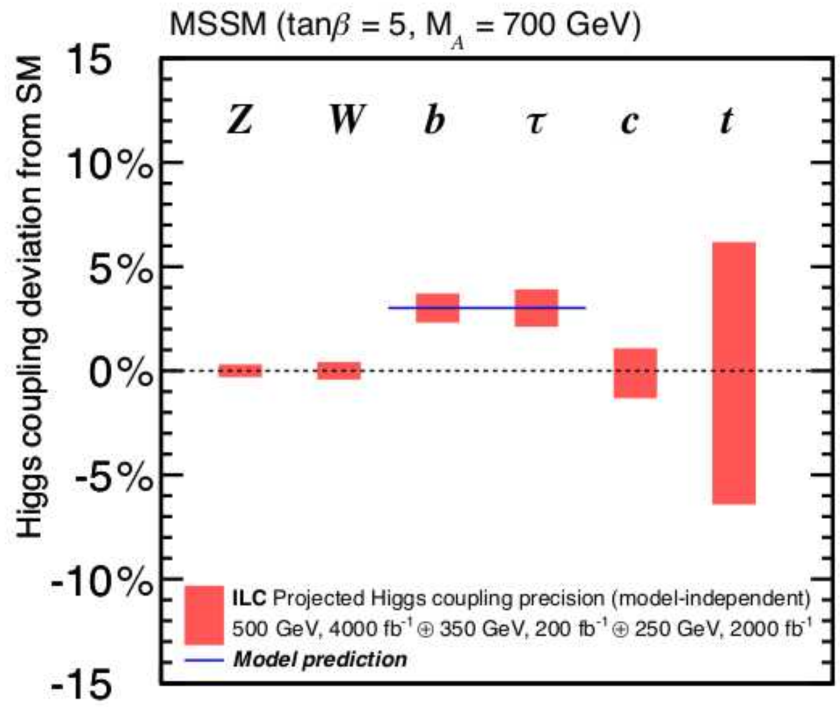
covers almost 4π solid angle

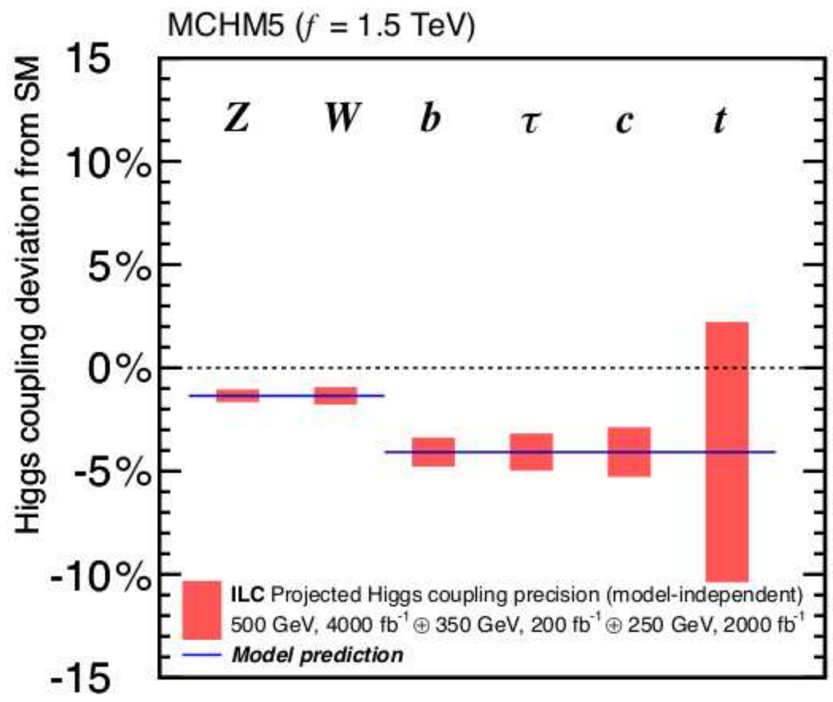
→ important for “missing momentum” searches

Expected physics performance

Higgs couplings at ILC

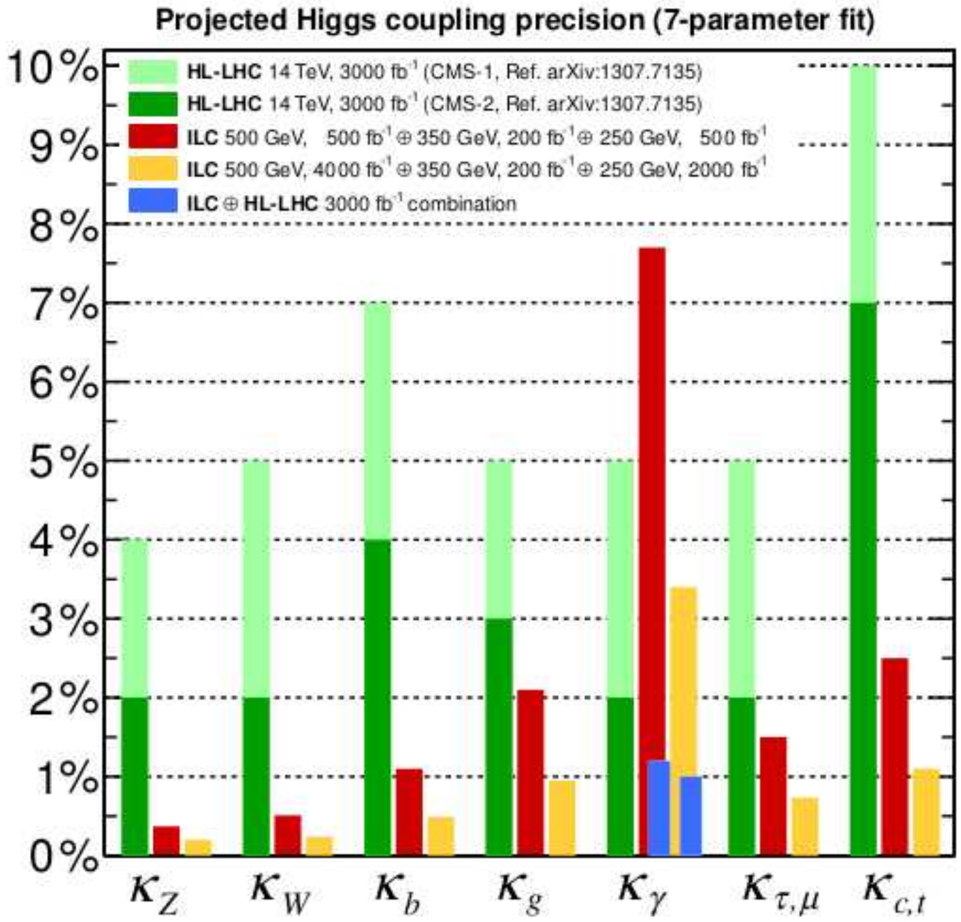




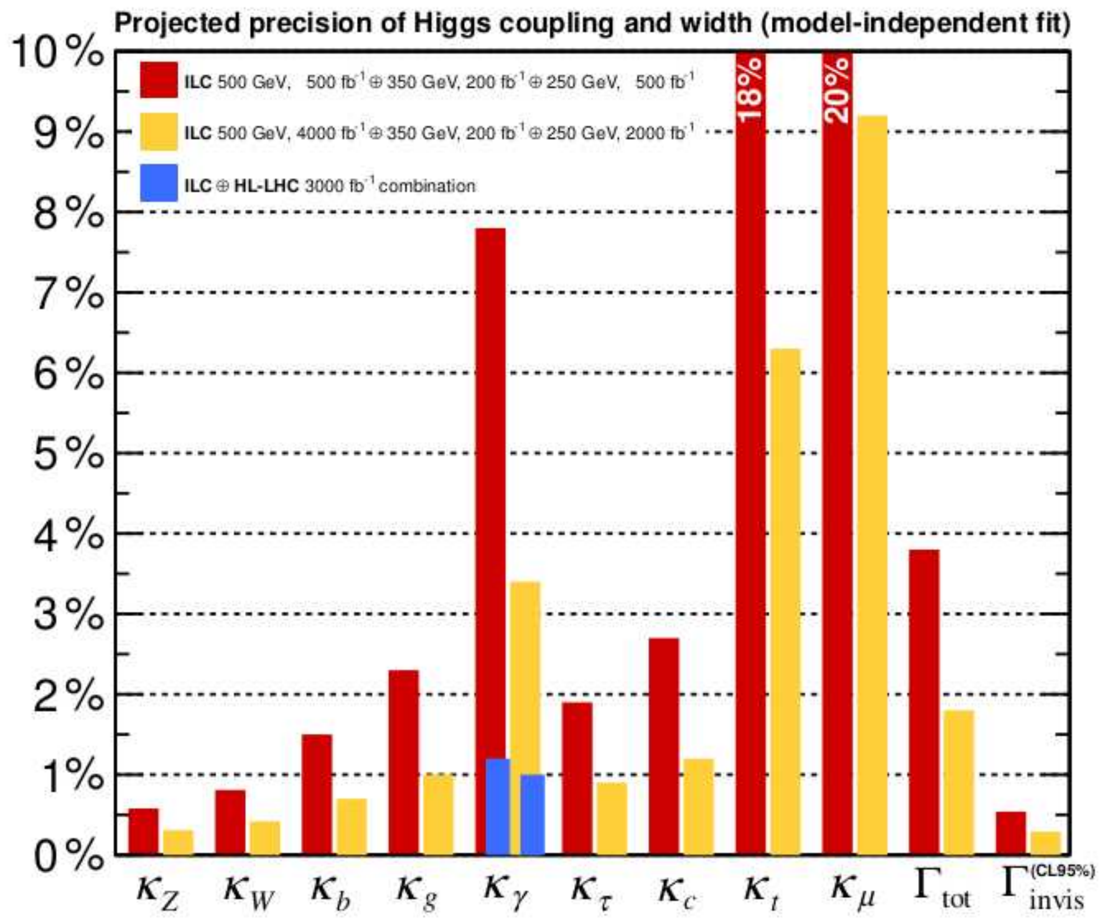


Higgs couplings precisions at ILC

Model-dependent a la LHC
compared to CMS HL-LHC

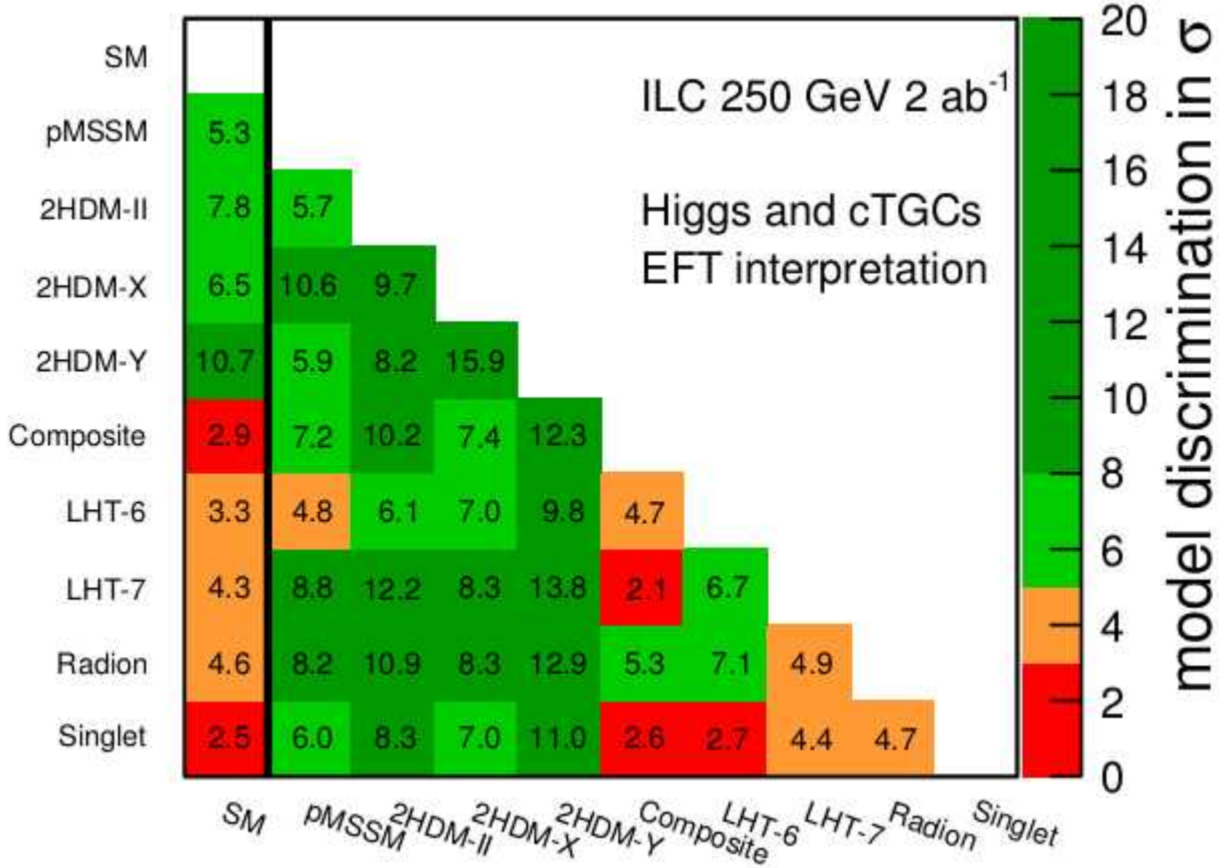


Model-independent



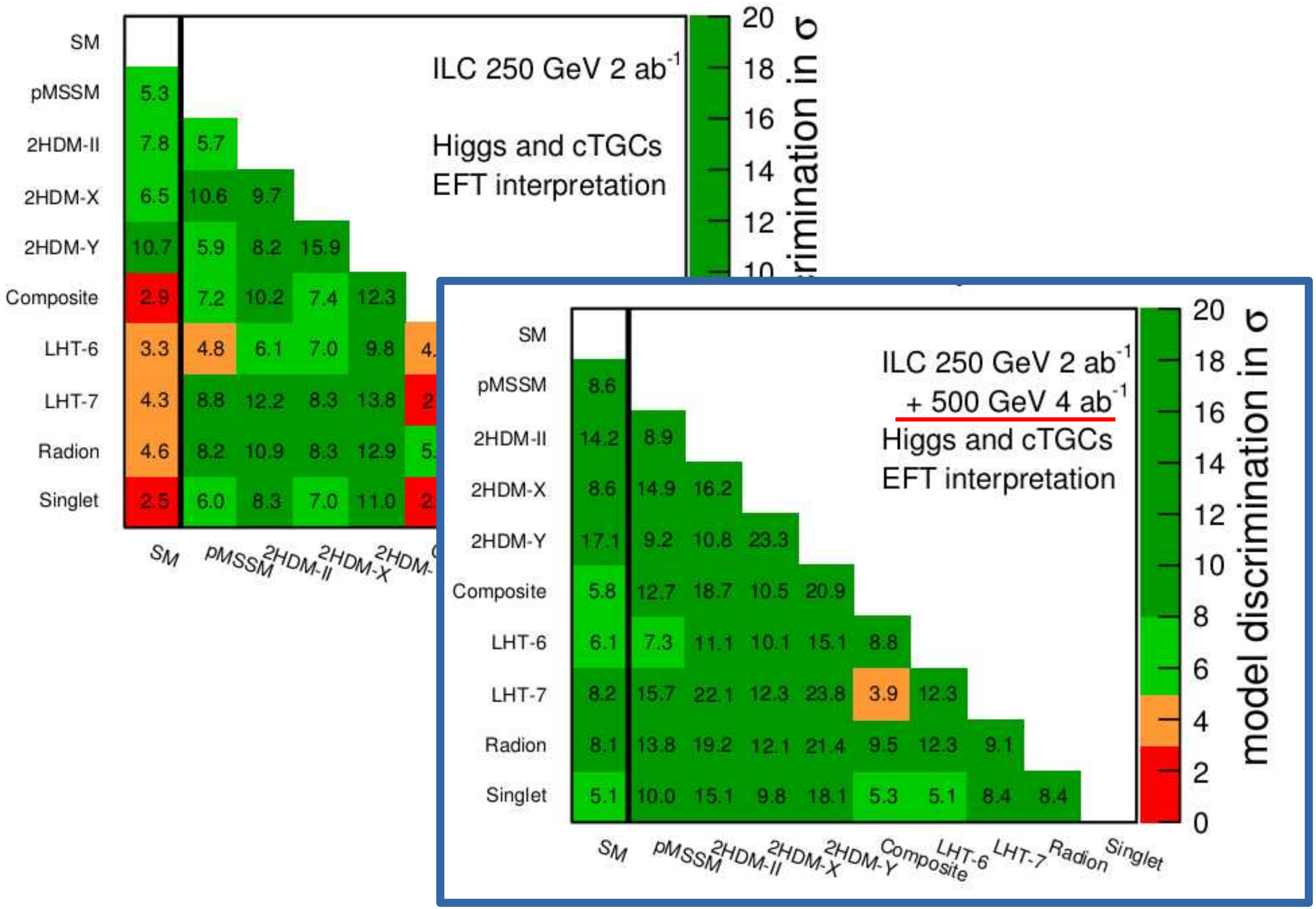
HL-LHC **initial 8 years of ILC** **full 20 year program** arXiv:1506.05992

- %-level measurements or better in most cases
- Strong synergies with HL-LHC in some cases
- significant improvements with respect to HL-LHC prospects
- several key measurements ~impossible at LHC



new particles associated with these models
not in reach of HL-LHC

Barklow et al, Phys.Rev. D97 (2018) no.5, 053003



Barklow et al, Phys.Rev. D97 (2018) no.5, 053003

Another example:

Our matter-dominated universe requires source of CP violation in early universe

Cannot be accounted for by current known sources of CP violation

Electro-weak baryogenesis at the Electro-Weak breaking scale ?

CP violation in Higgs sector ?

CP violation in Higgs? Motivation

Is the 125 GeV Higgs a CP eigenstate ?

$$h_{125} = \cos\psi_{CP}\, h^{CPeven} + \sin\psi_{CP}\, A^{CPodd}$$ [e.g. extra Higgs doublets]

pure CP even: $\psi_{CP} = 0$ [Standard Model]

odd: $\psi_{CP} = \pi/2$ [excluded at LHC]

or a mixture?

Do Higgs couplings conserve CP ?

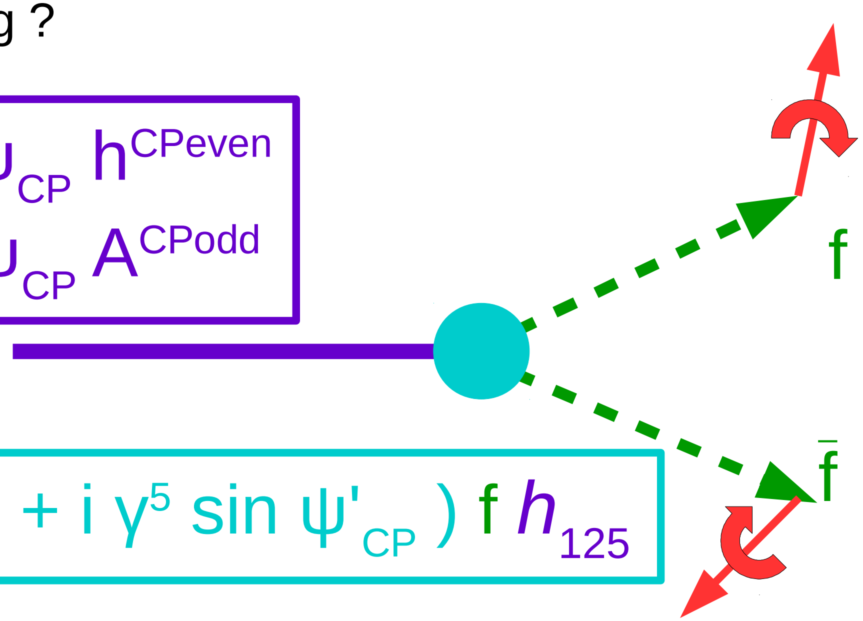
e.g. coupling to fermions: $L \sim g\, \bar{f}\, (\cos\psi_{CP} + i\,\gamma^5 \sin\psi_{CP})\, f\, H$

CP conserving coupling $\psi_{CP} = 0$ [Standard Model]

maximally violating $\psi_{CP} = \pi/2$

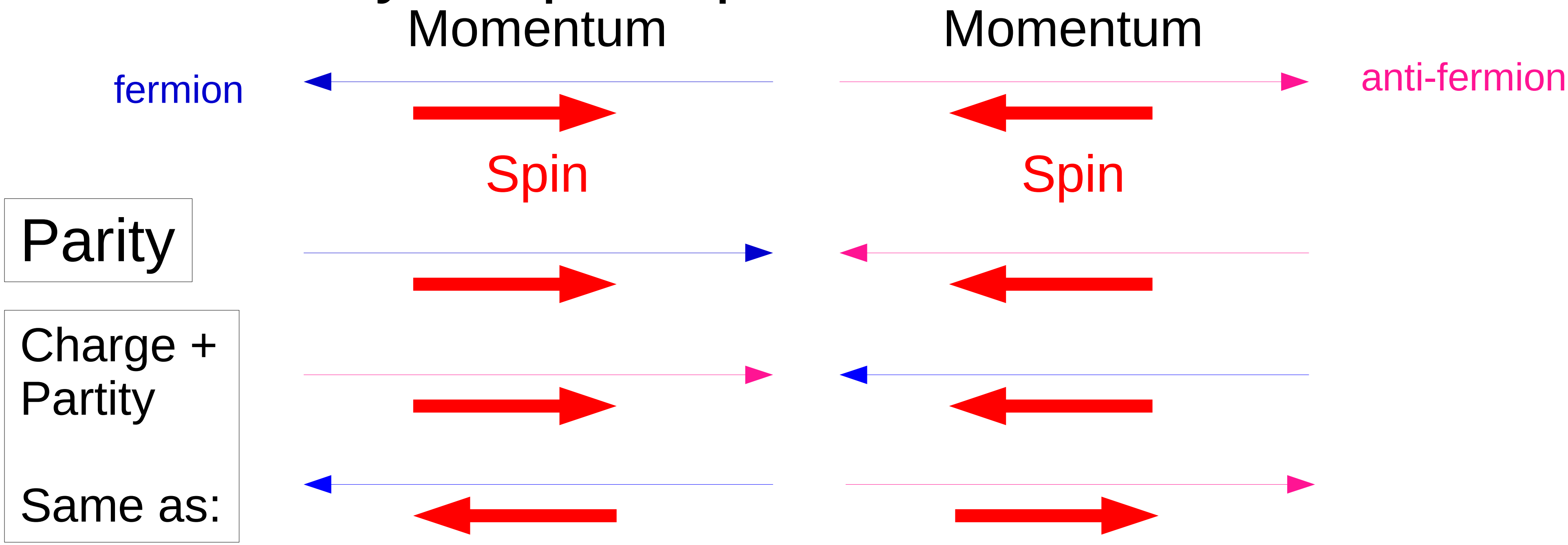
or partially violating ?

$$h_{125} = \cos\psi_{CP}\, h^{CPeven} + \sin\psi_{CP}\, A^{CPodd}$$



$$g\, \bar{f}\, (\cos\psi'_{CP} + i\,\gamma^5 \sin\psi'_{CP})\, f\, h_{125}$$

Decay of spin-0 particle into 2 fermions:



CP eigenstates of CP: $|f\bar{f}\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$ ← CP even

$|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$ ← CP odd

general state: $|f\bar{f}\rangle = |\uparrow\downarrow\rangle + e^{2i\psi} |\downarrow\uparrow\rangle$

<u>Correlation between fermion spins carry CP information</u>

At ILC, we can probe CP of Higgs bsons
in its decays to tau leptons [fermions]

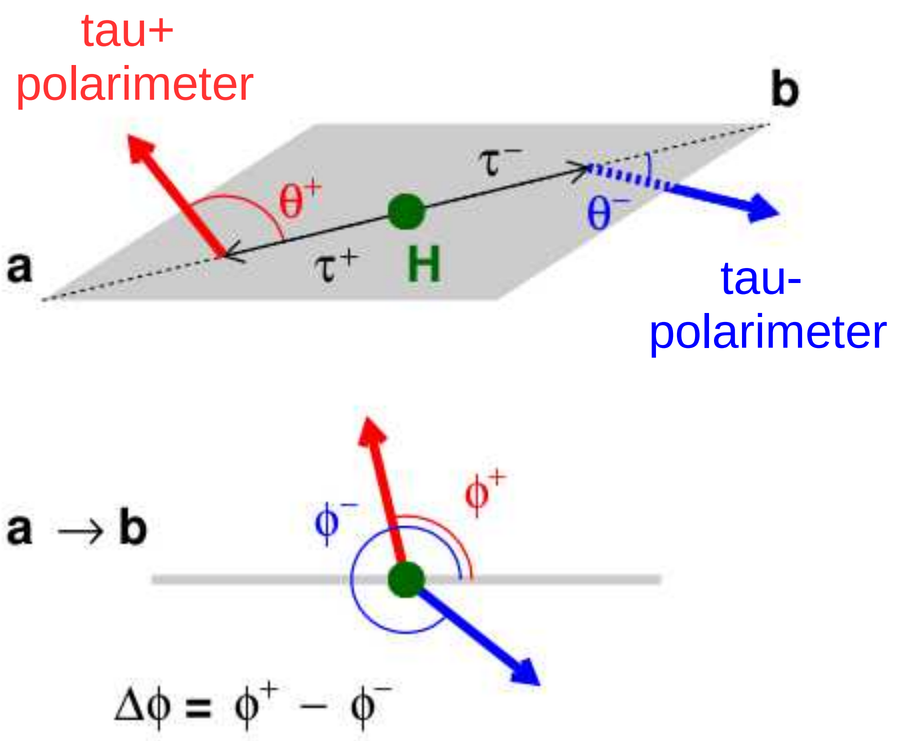
Higgs often decays to taus

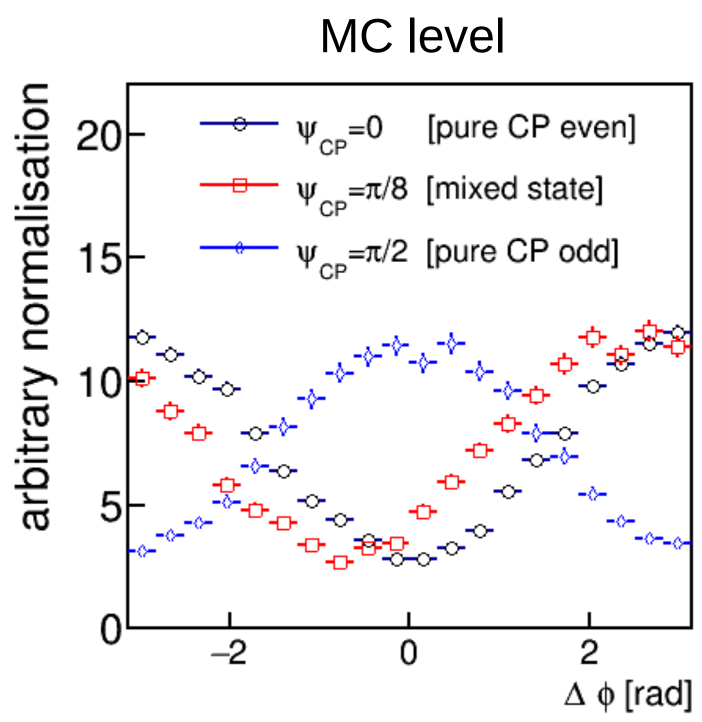
Taus have short lifetime
→ reconstruct decay kinematics
→ most probable spin direction
[polarimeter vector]

h is a spin 0 state:

$| f \bar{f} \rangle = |\uparrow\downarrow\rangle + e^{2i\psi} |\downarrow\uparrow\rangle$

[ψ = 0 CP even,
$\pi/2$ CP odd]

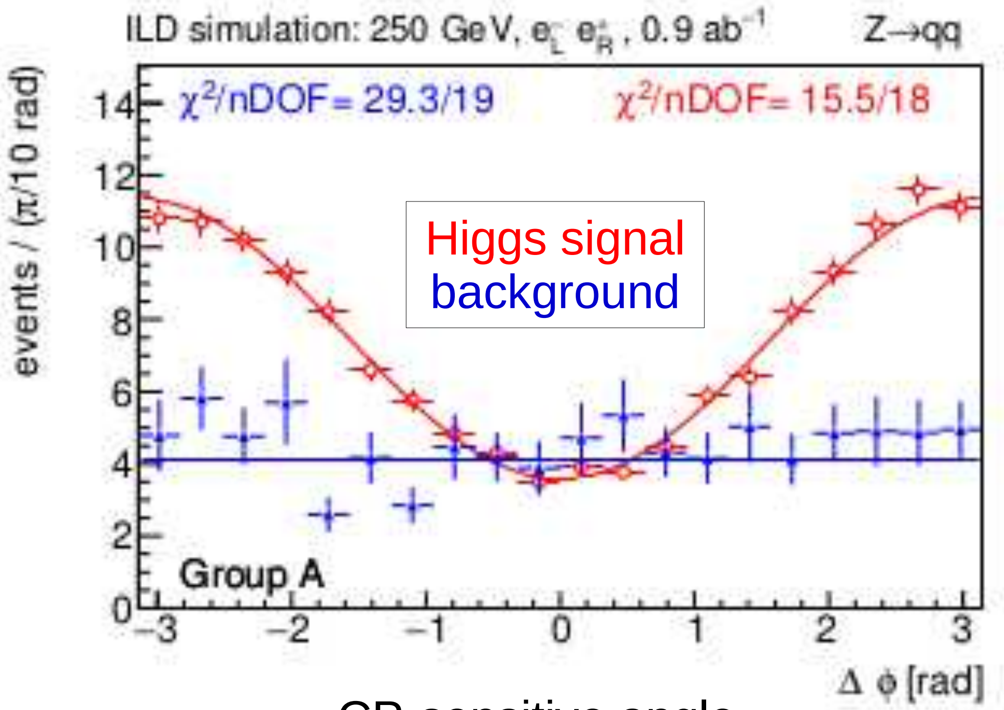




distribution of Δφ is sensitive to
CP mixing angle ψ_{CP}

Clean ILC environment and high precision detector allow excellent reconstruction of tau lepton decays, including their spin direction

Full detector simulation
Realistic reconstruction



CP-sensitive angle

Phase of signal distribution
→ CP mixing angle

$L \sim g \bar{f} (\cos \psi_{CP} + i \gamma^5 \sin \psi_{CP}) f H$

At ILC250, will measure ψ_{CP} to precision of 75 mrad (~4 deg.)

Jeans, NIM A810 (2016) 51

Jeans, Wilson, Phys.Rev. D98 (2018) no.1, 013007

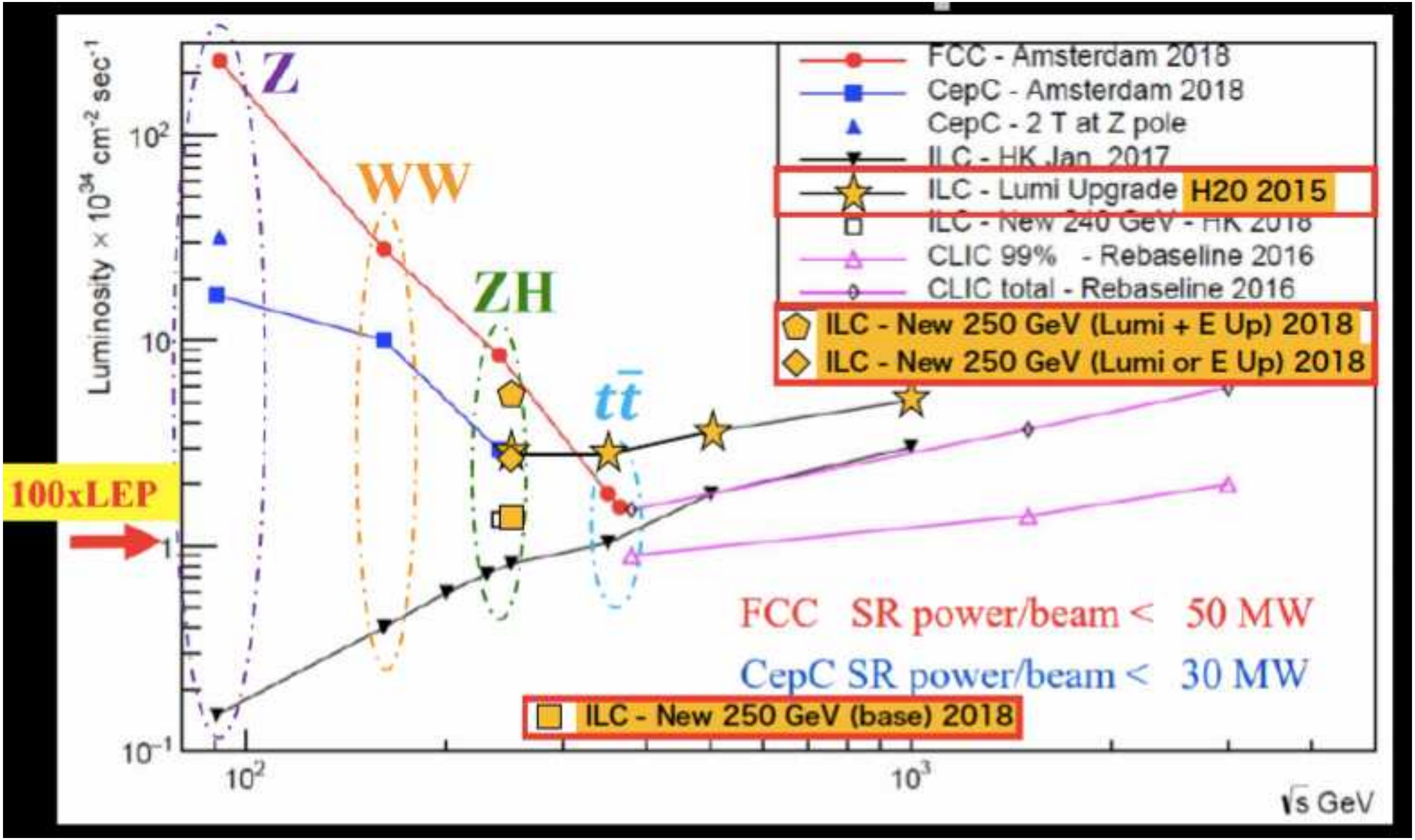
ILC: precision exploration of
- Higgs sector

Many other tests of Standard Model

- Electro-Weak sector
  - high luminosity, polarised beams

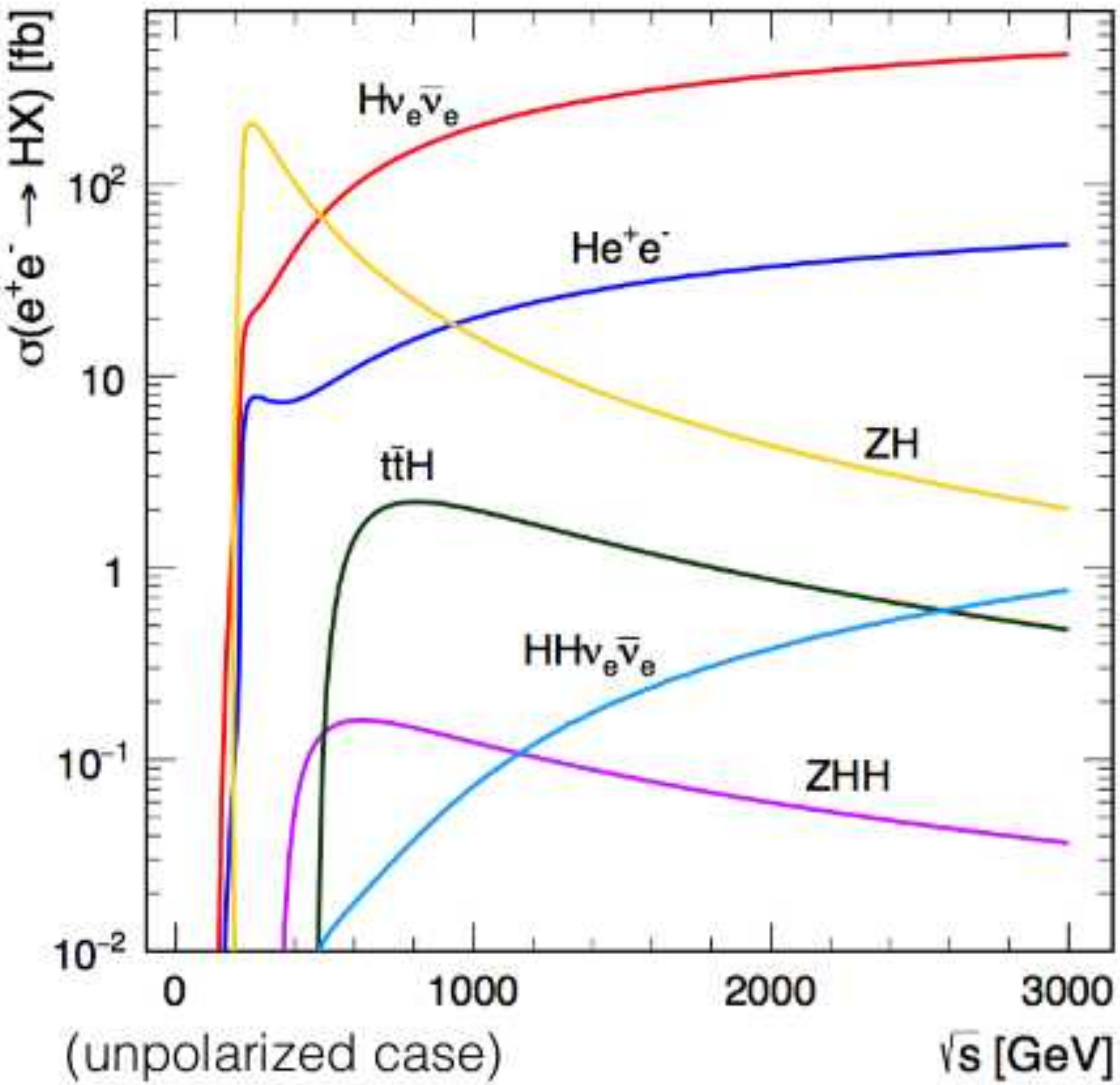
- QCD
  - clean environment

- New Particle Searches
  - trigger-less operation



G. Taylor, LCWS'18

Potential future ILC energy upgrades



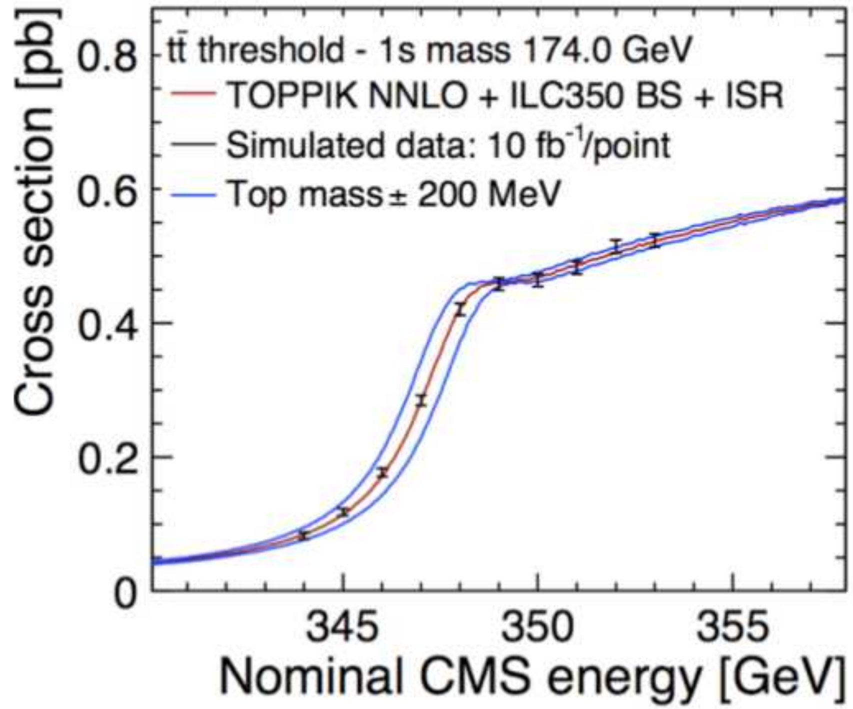
~ 350 GeV

make beautiful measurements of the **top** threshold scan of $e^+ e^- \to t \bar{t}$

experimentally precise,

theoretically well-understood

top quark mass measurement

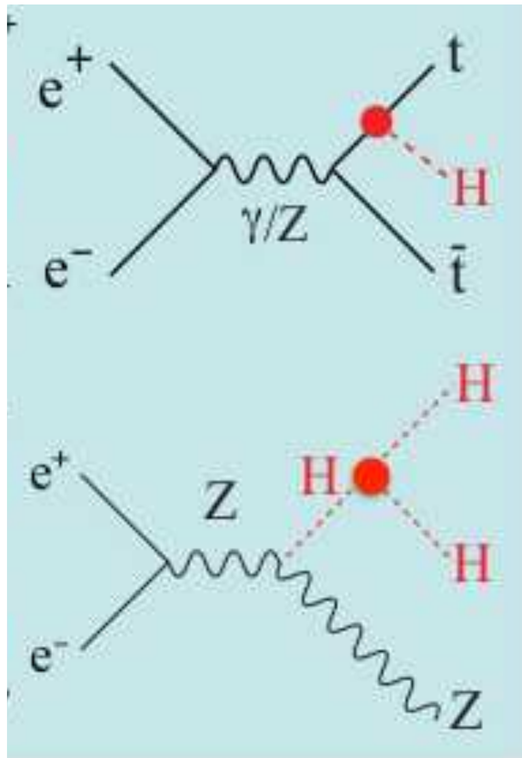


~500 – 600 GeV

Top quark electro-weak couplings

→ indirect probe of new physics

H t t-bar production → top Yukawa coupling



~ 1 TeV

Higgs self-coupling

→ clearer view of Higgs potential shape

Conclusion

The ILC will make wonderfully precise measurements of the Higgs and top sectors, and will search for new physics, both directly and indirectly

These measurements will help us along the correct BSM path

We are ready to build the ILC and its detectors

first “Higgs factory” stage at 250 GeV

The political process for this large, international project is now in a critical period → statement of interest before March ?

Can imagine a series of well-motivated upgrades to ILC's luminosity and energy over a period of 20-30 years