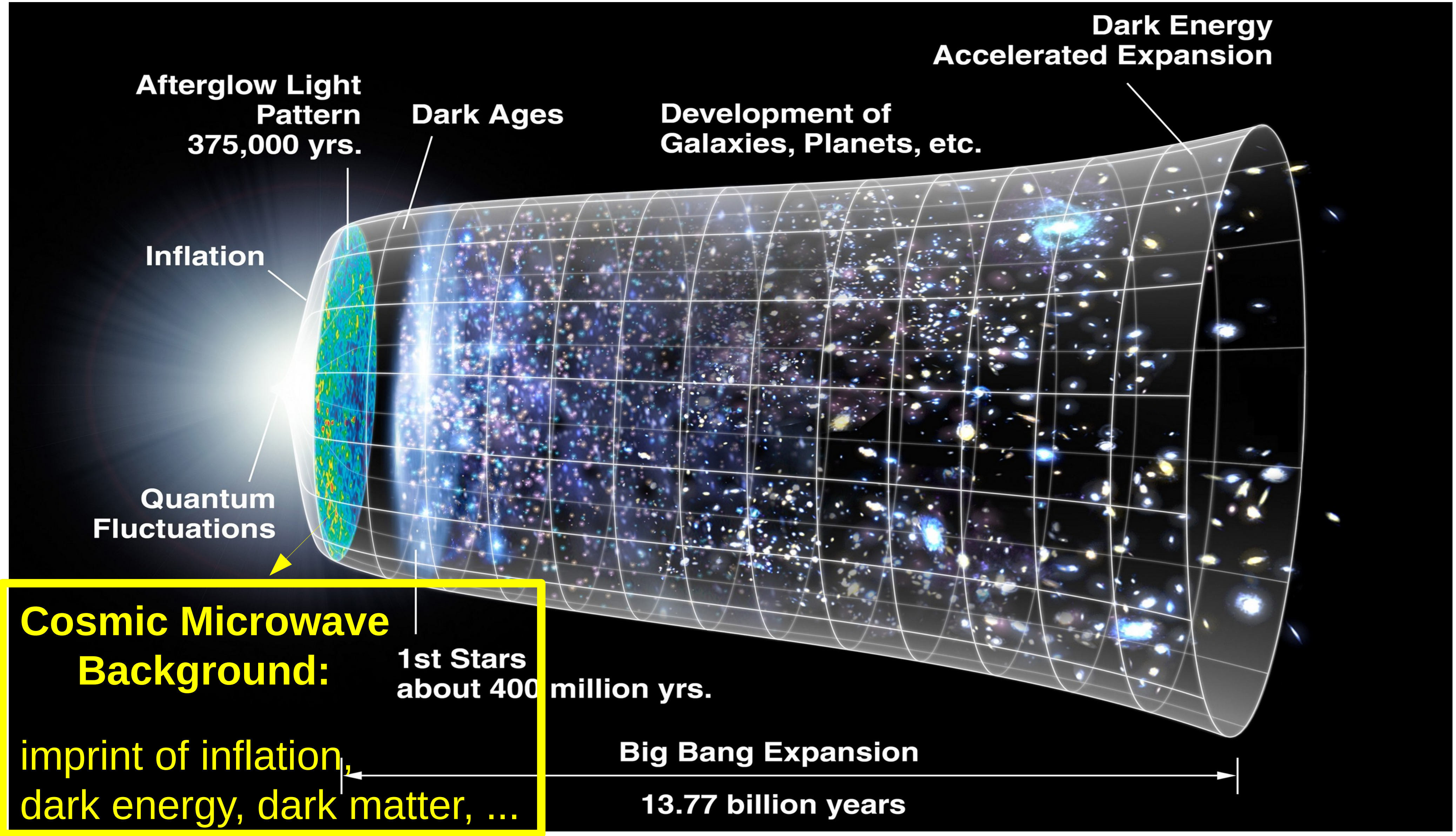
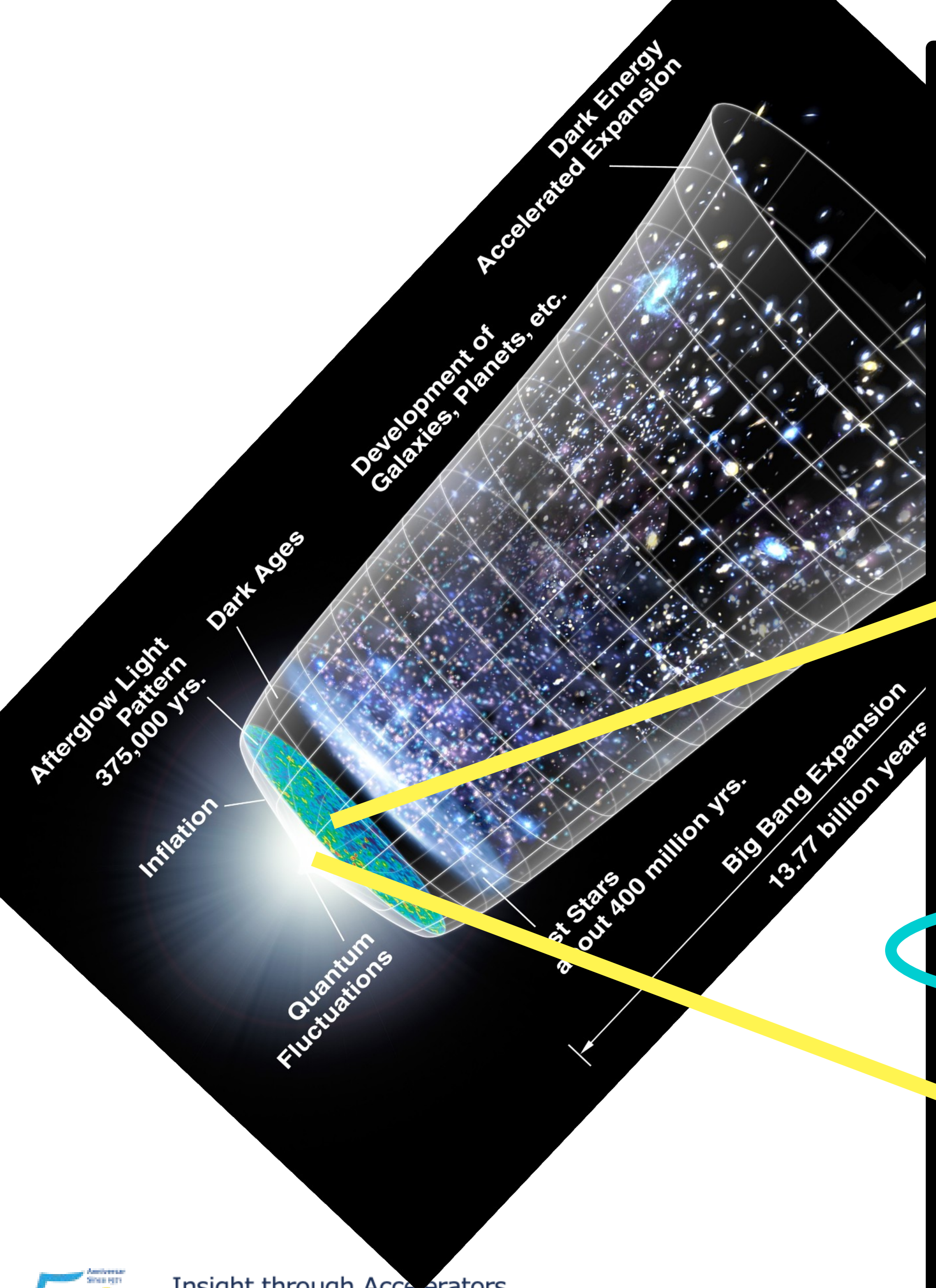
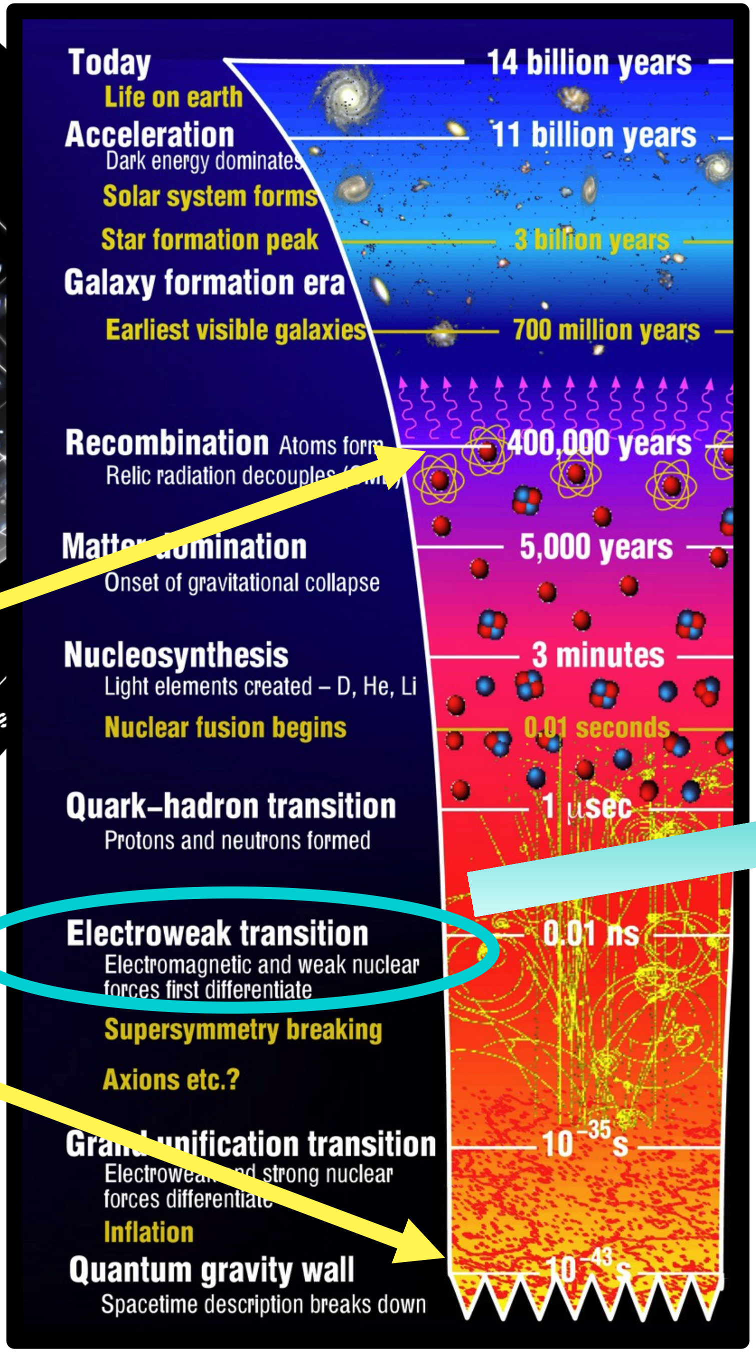
International Linear Collider

Daniel Jeans IPNS / KEK 2023/March


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
Cosmic Microwave
Background:
imprint of inflation,
dark energy, dark matter, ...
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years



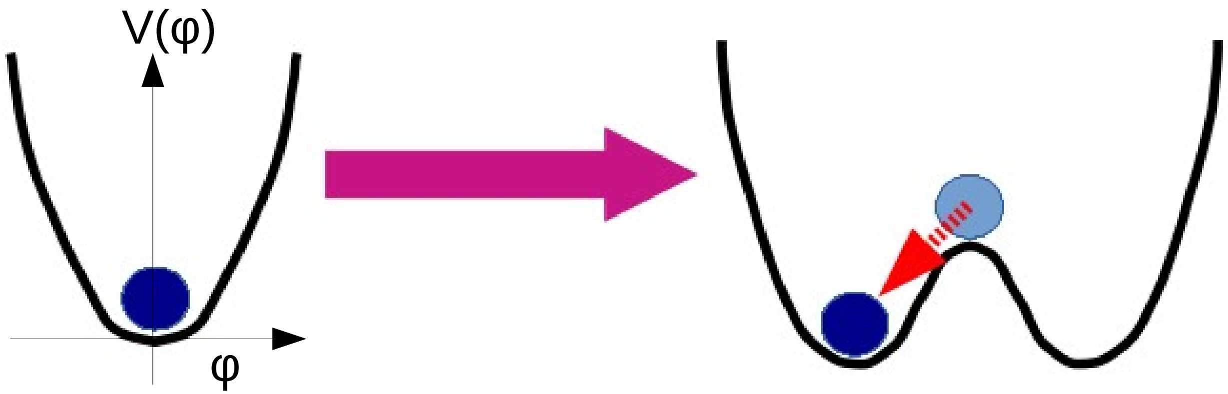


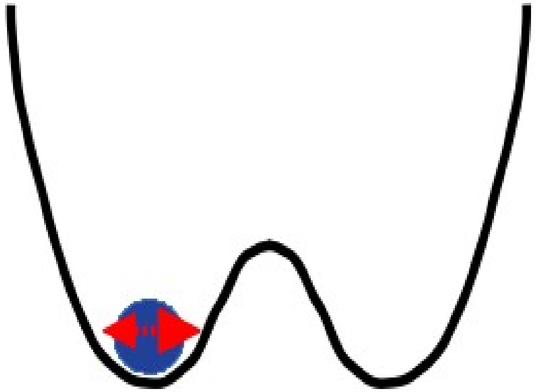
Electro-weak transition

Electro-weak physics should contain imprint of physics at much higher energy

Electro-weak transition

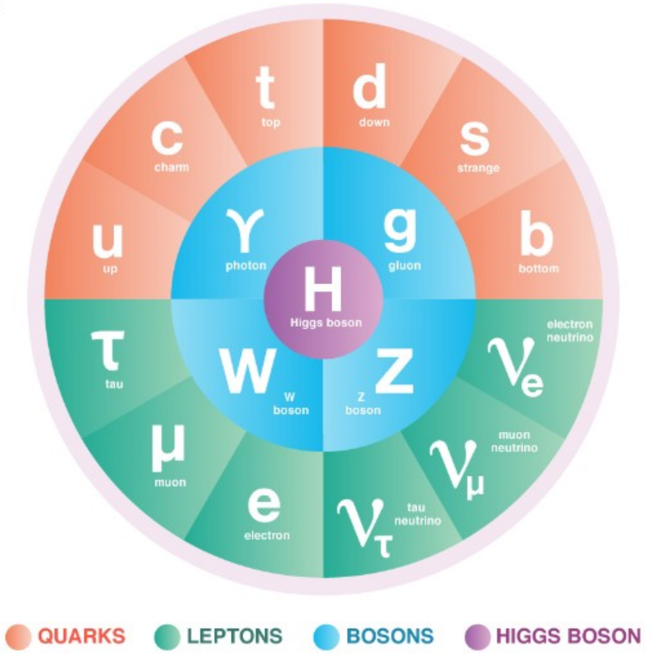
Higgs potential changes shape

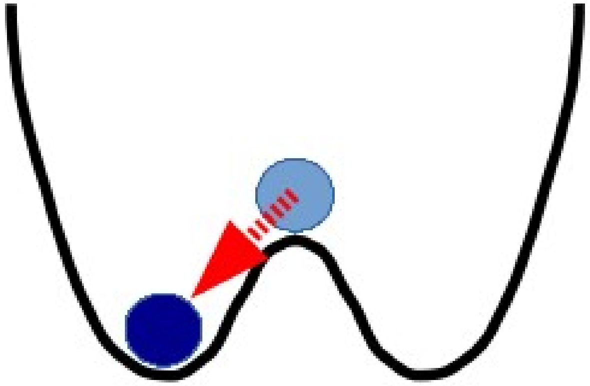




Higgs particle: excitation of Higgs field

different to all other
fundamental particles
not “matter”, not “force”, no spin

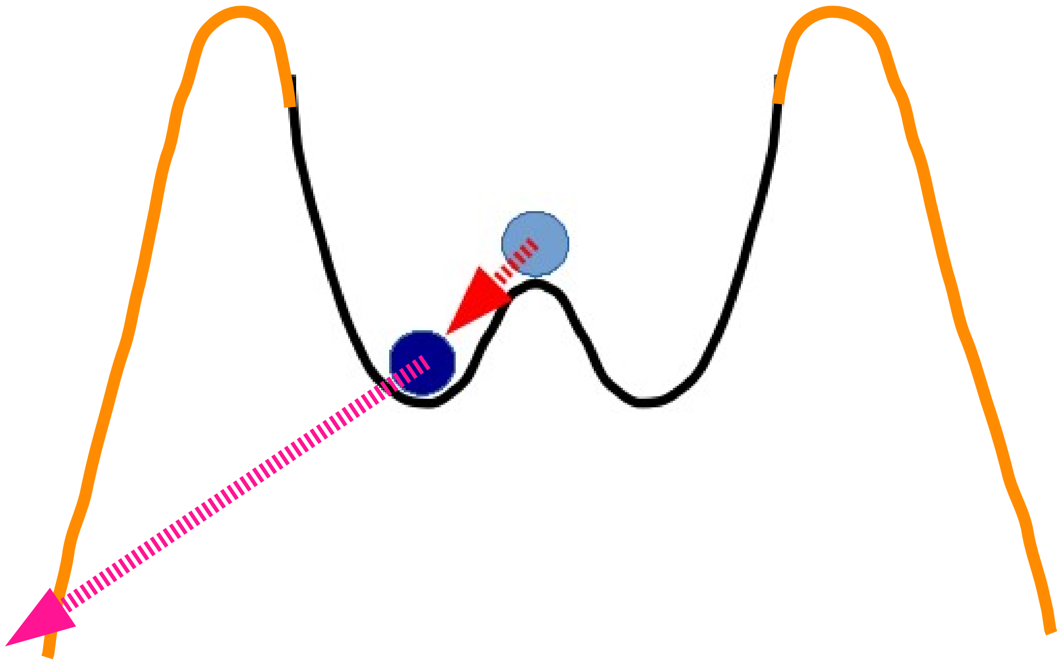




why did the transition happen ?

how fast did it happen ?

did it cause the universe’s
anti-matter to disappear ?



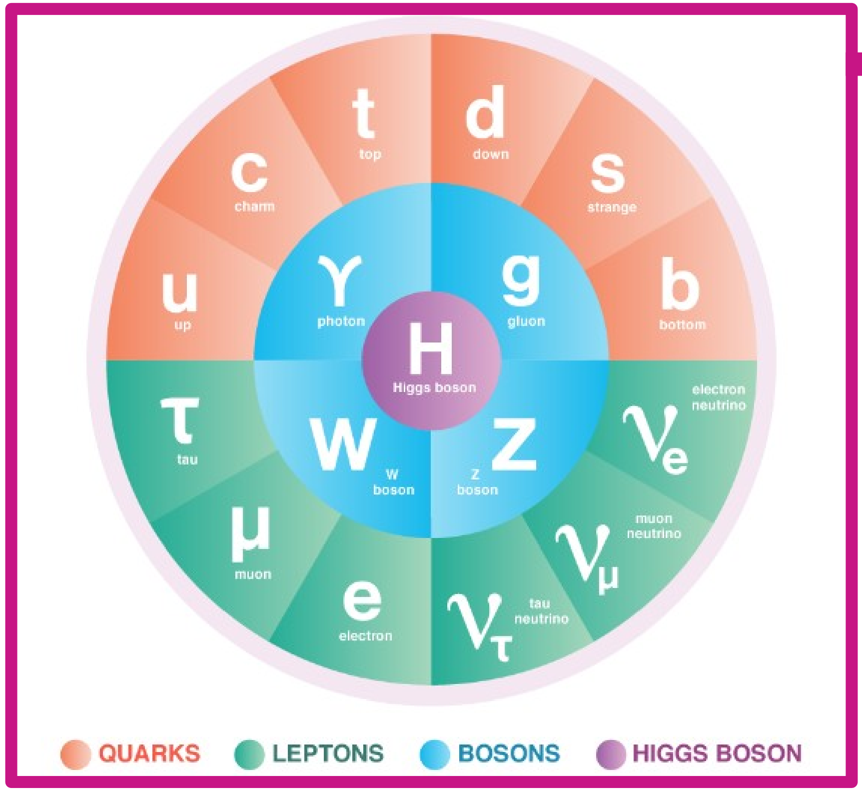
Is the Higgs potential as we expect

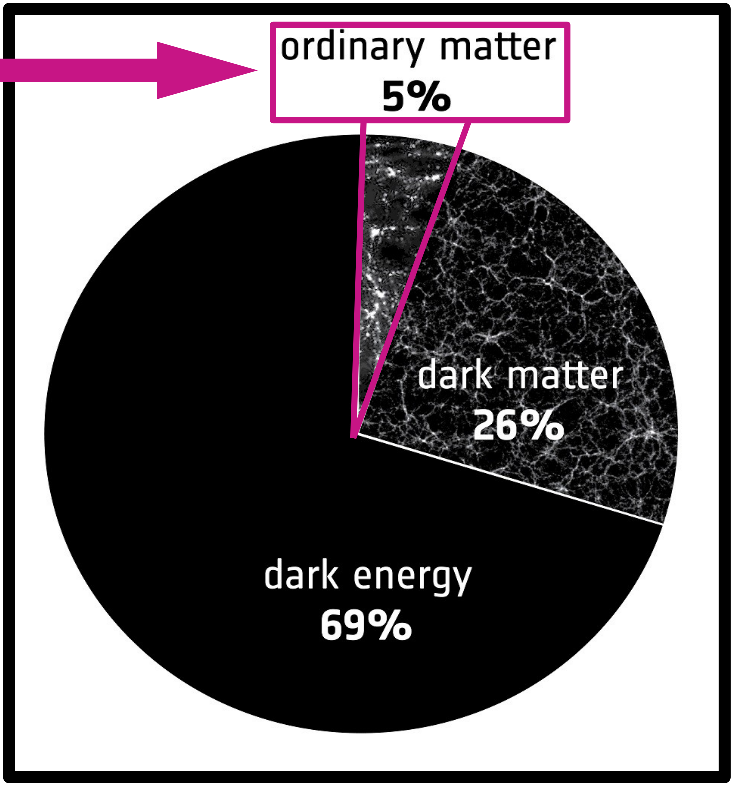
is our current vacuum
really stable ?

might our vacuum
spontaneously decay ?

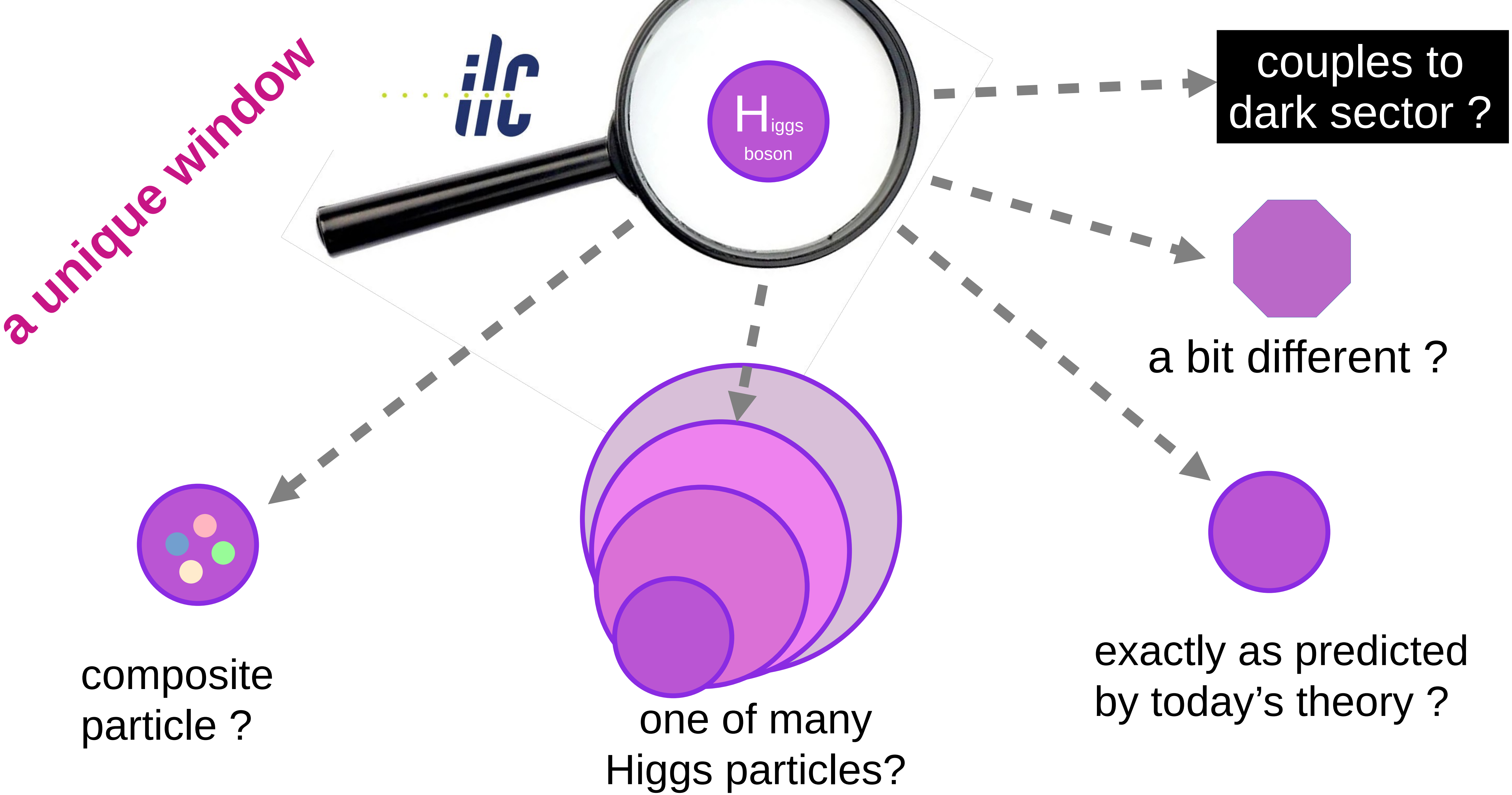
we've observed all particles of the **Standard Model**

...but they describe only a small fraction of our universe



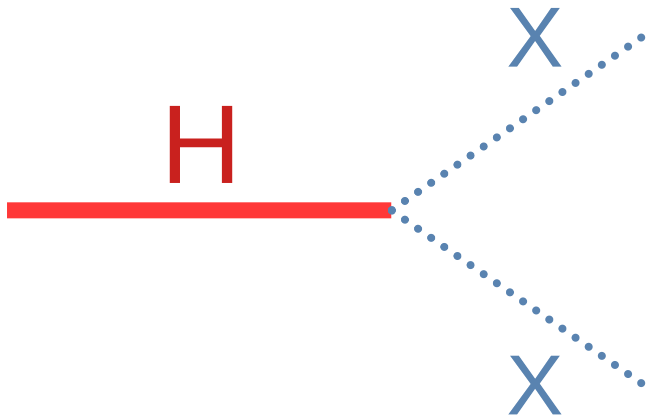


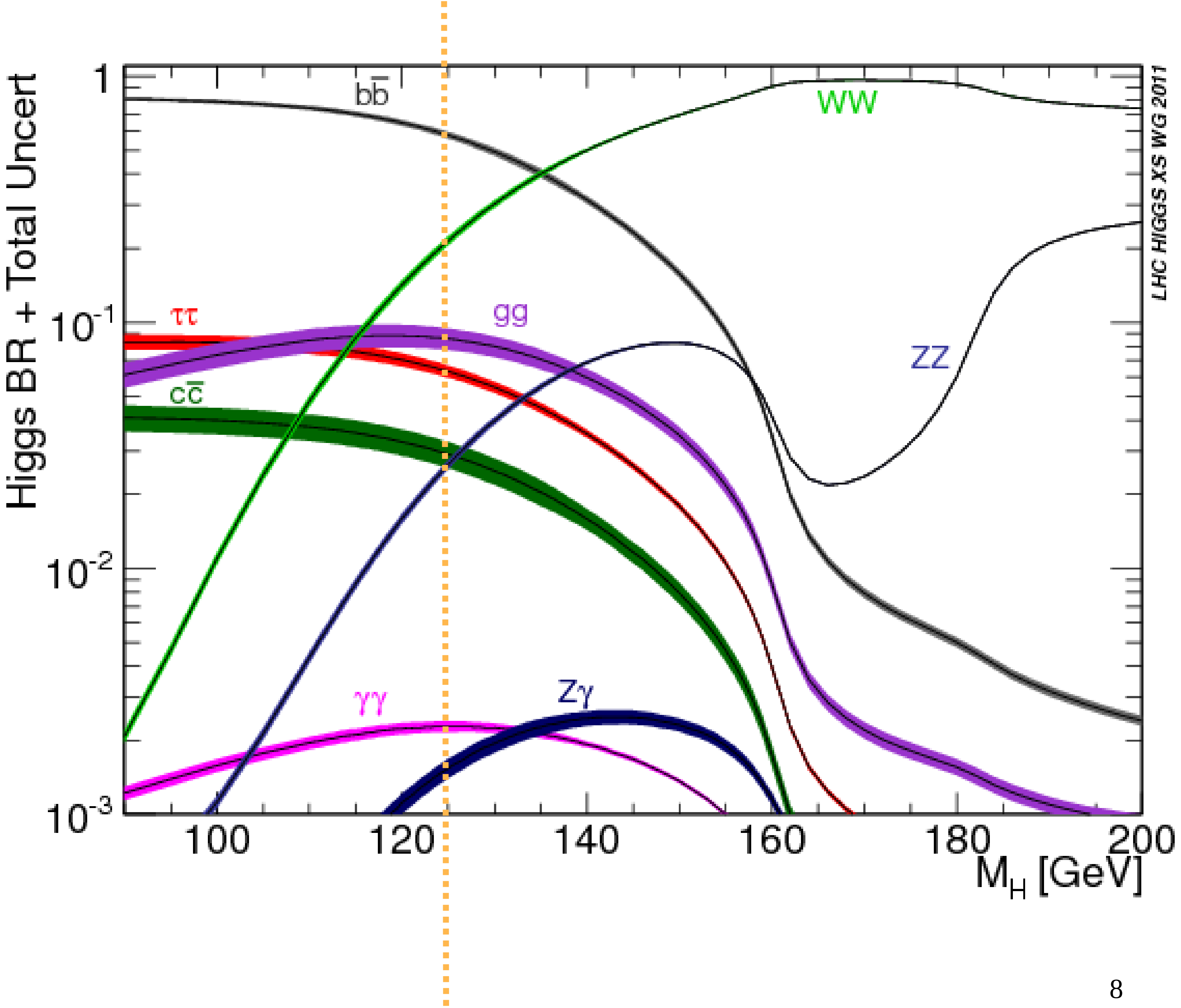
To be honest, we understand very little !


a unique window
ilc
Higgs boson
couples to
dark sector ?
a bit different ?
composite
particle ?
one of many
Higgs particles?
exactly as predicted
by today's theory ?

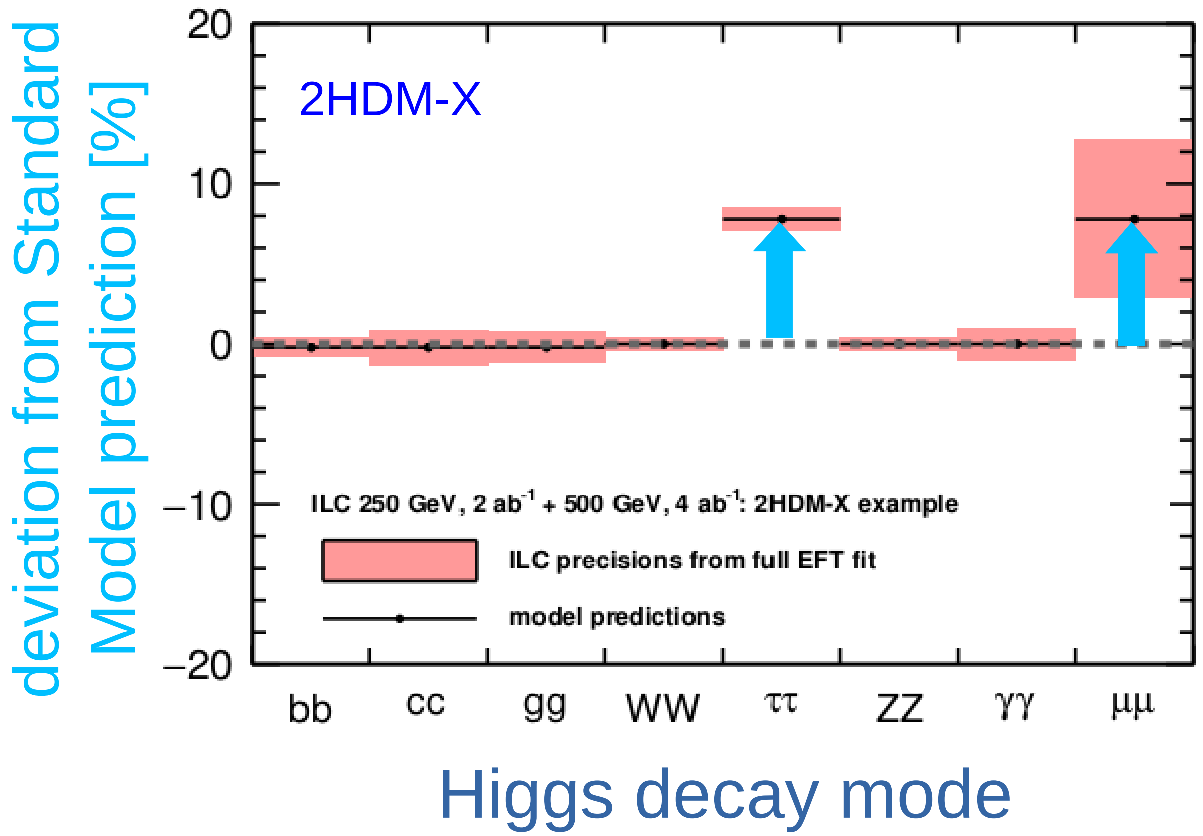
Higgs decay branching fractions

as predicted in the Standard Model



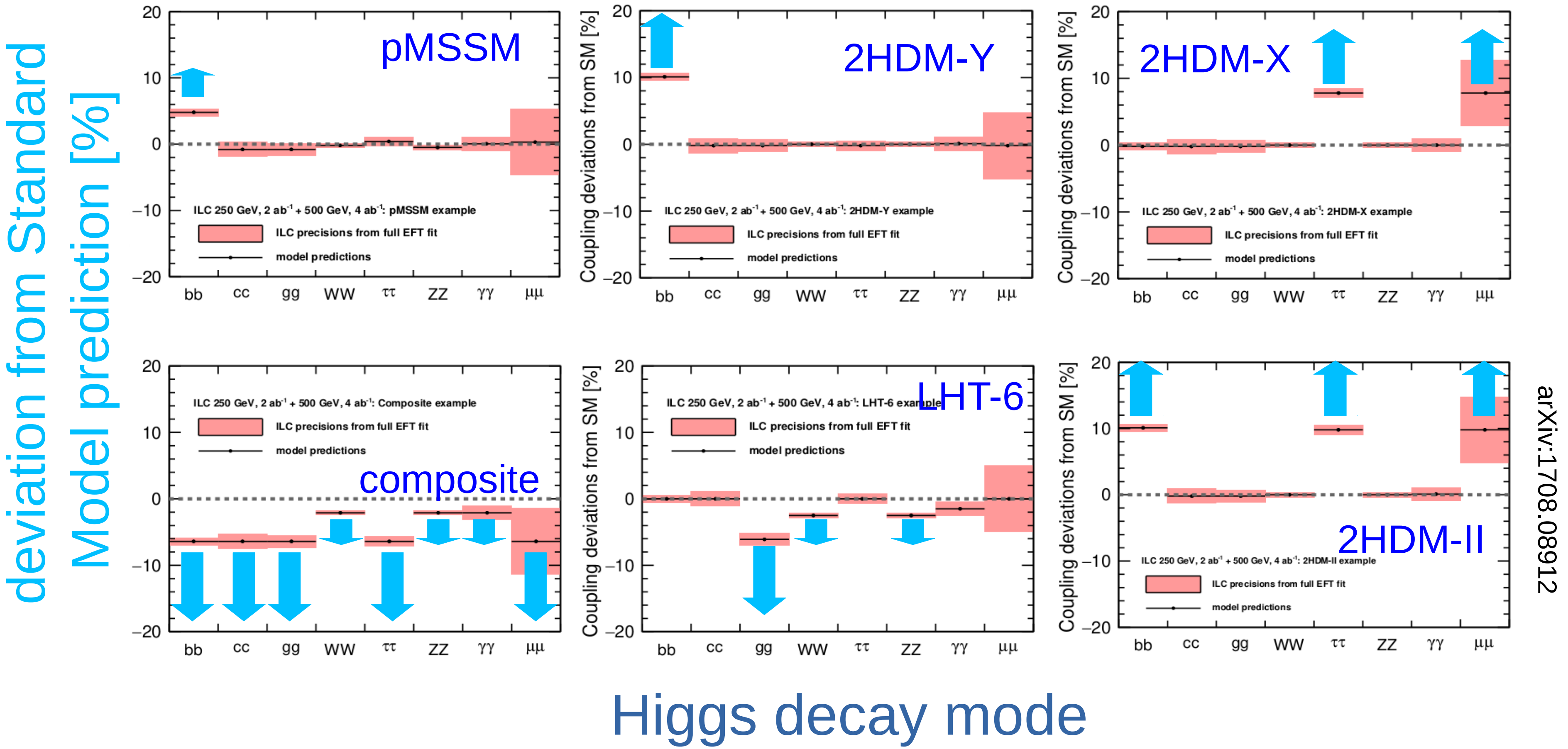


Deviations in Higgs couplings from BSM physics



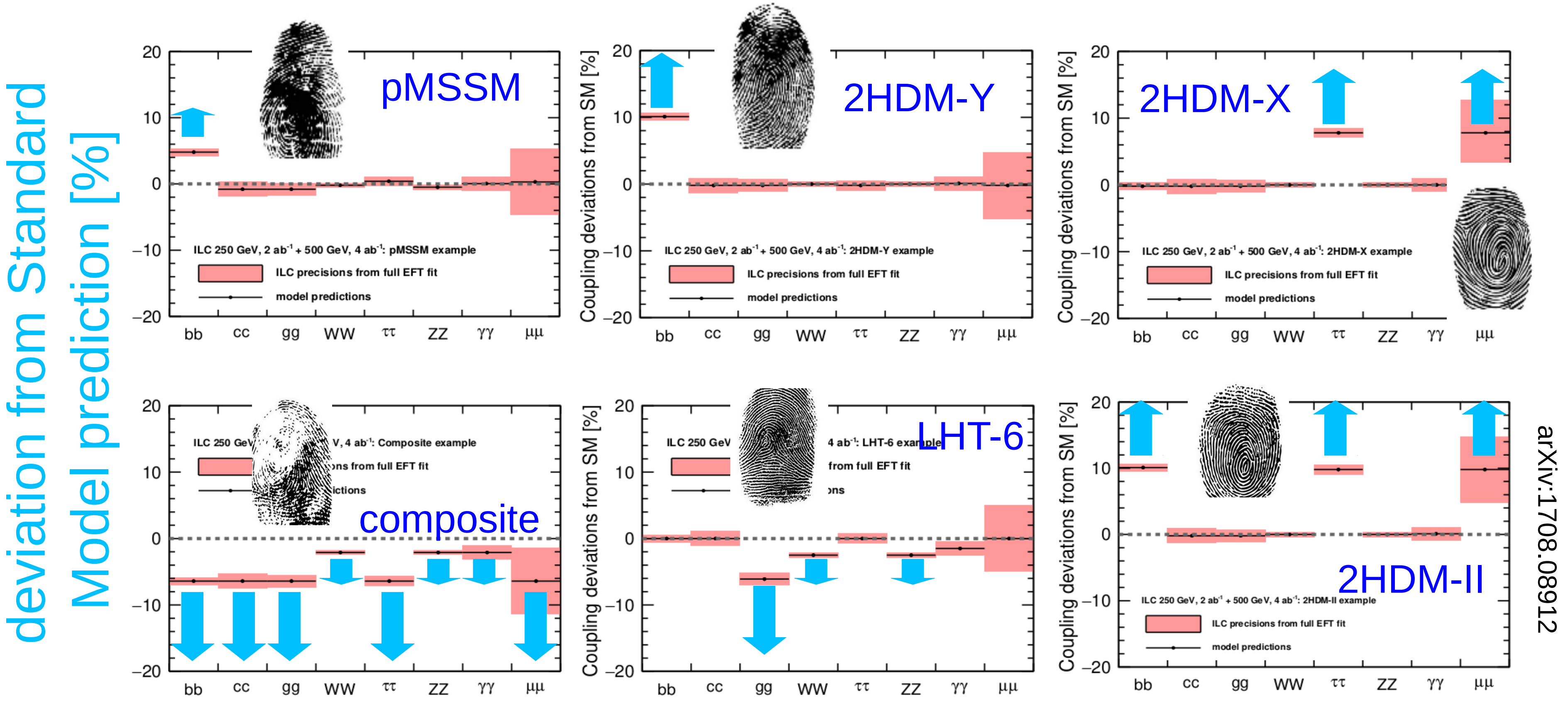
new physics @ TeV-scale → few % deviations

Deviations in Higgs couplings from BSM physics



→ different BSM models give different deviations

Deviations in Higgs couplings from BSM physics



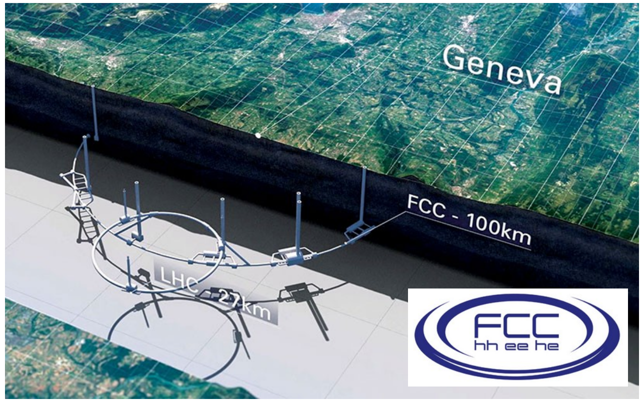
precision Higgs measurements → fingerprints of deeper physics

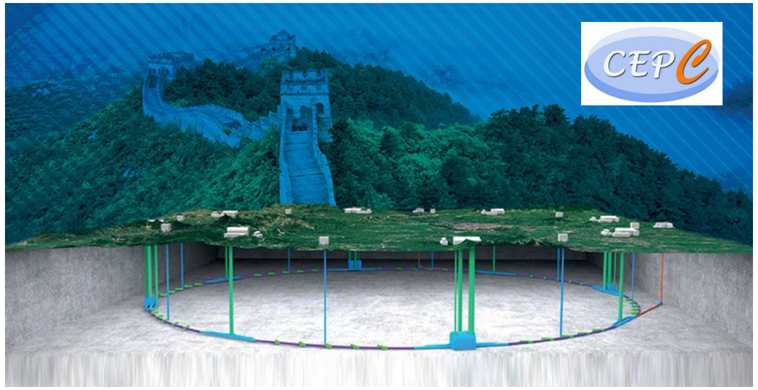
~1% precision needed for ~TeV new physics

“Higgs Factory”

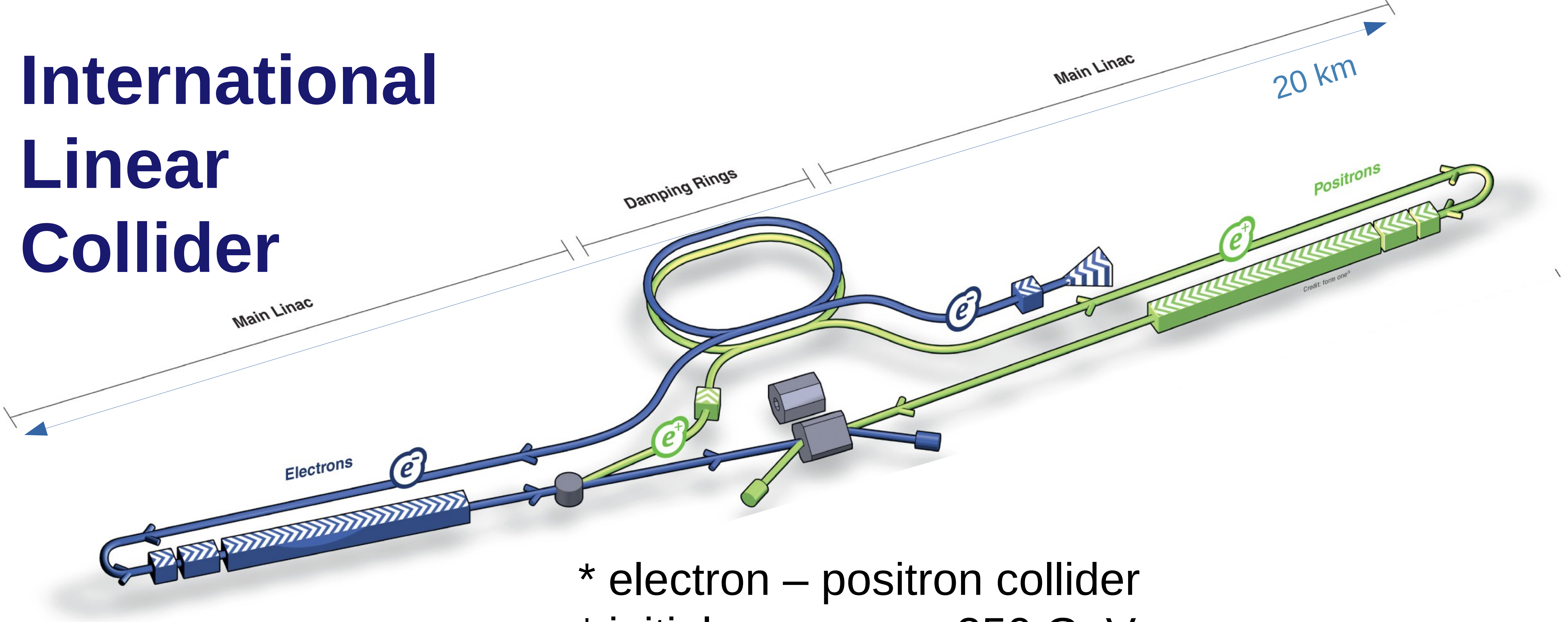
based on an electron – positron collider

→ high precision measurements of
Higgs particle and other topics





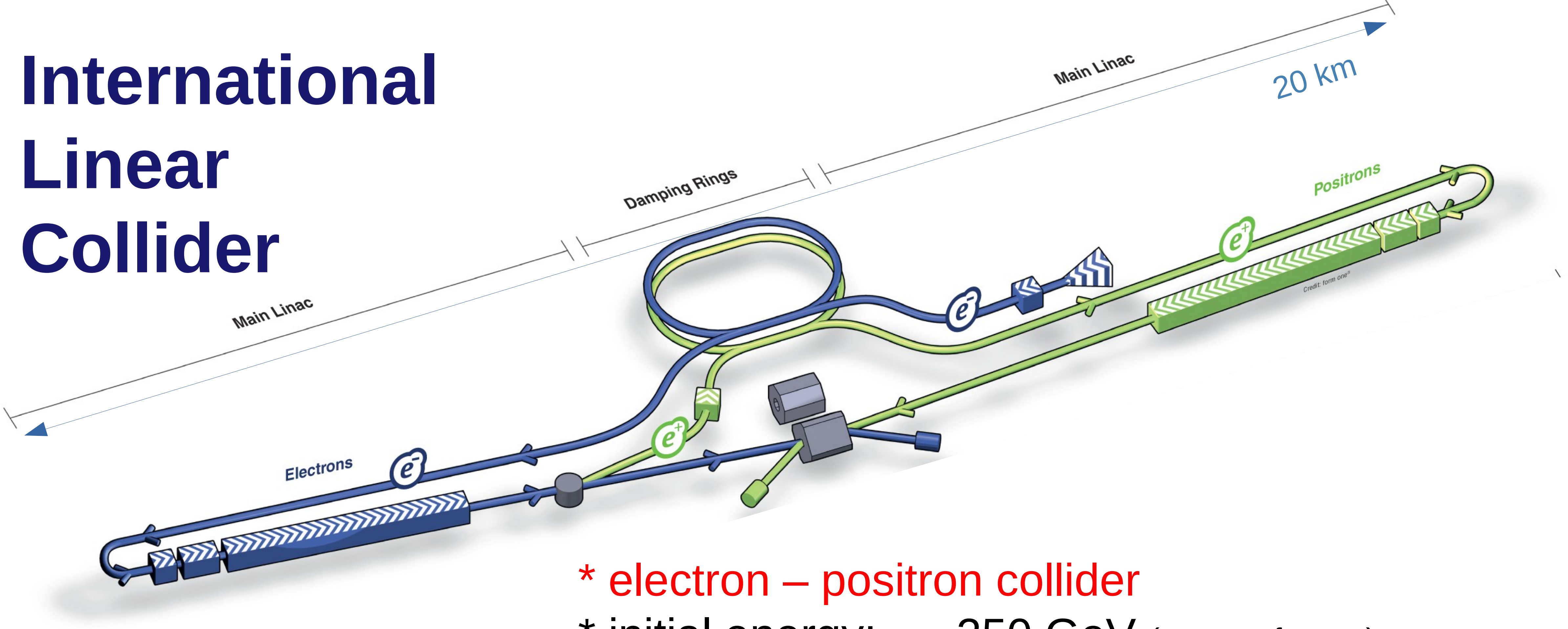
International Linear Collider



* electron – positron collider
* initial energy: 250 GeV (centre of mass)
* initial luminosity: 1.35 x 10^{34} cm^{-2} s^{-1}
* polarised beams
* future upgrades in energy and luminosity

~1M Higgs bosons

International Linear Collider



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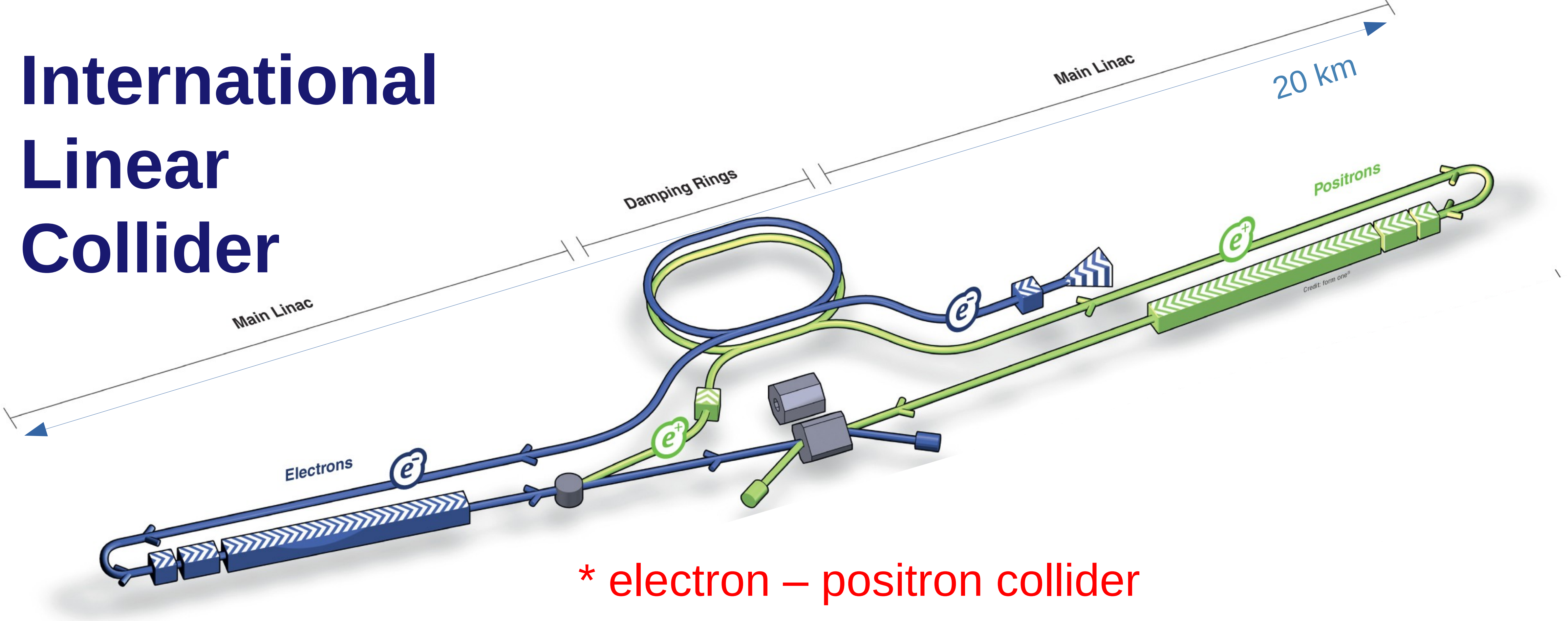


* electron – positron collider

why ?

LHC is proton+proton …

proton - proton

protons are composite: quarks and gluons
→ wide spectrum of q-q , q-g , g-g collision energies

debris from collision of remainder of protons

dominated by QCD interactions

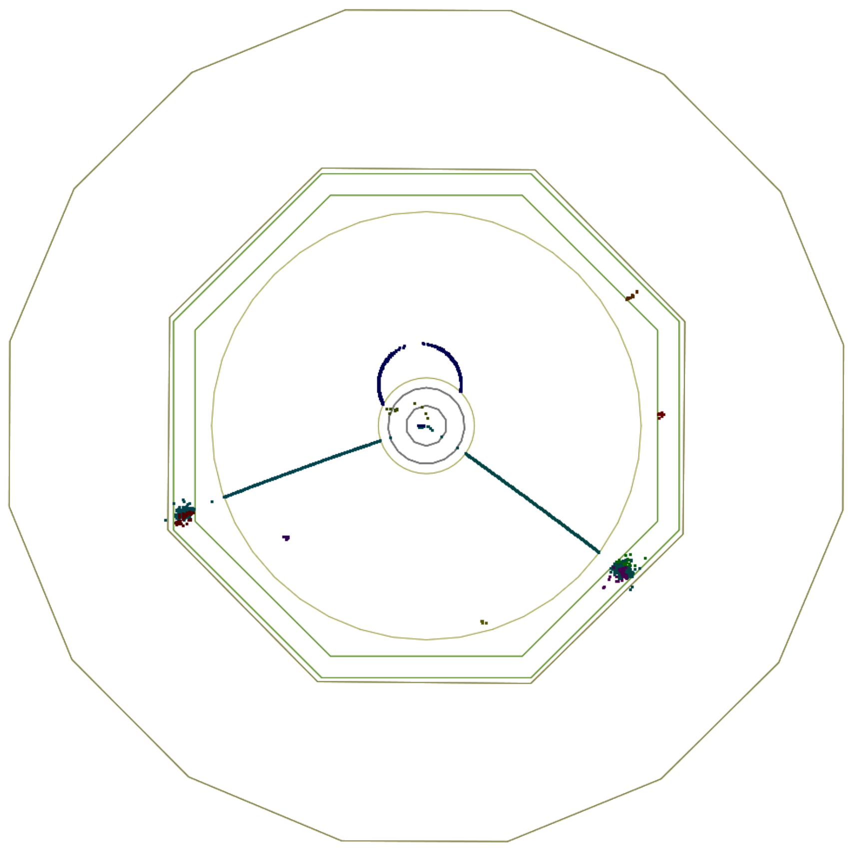
e+ e-

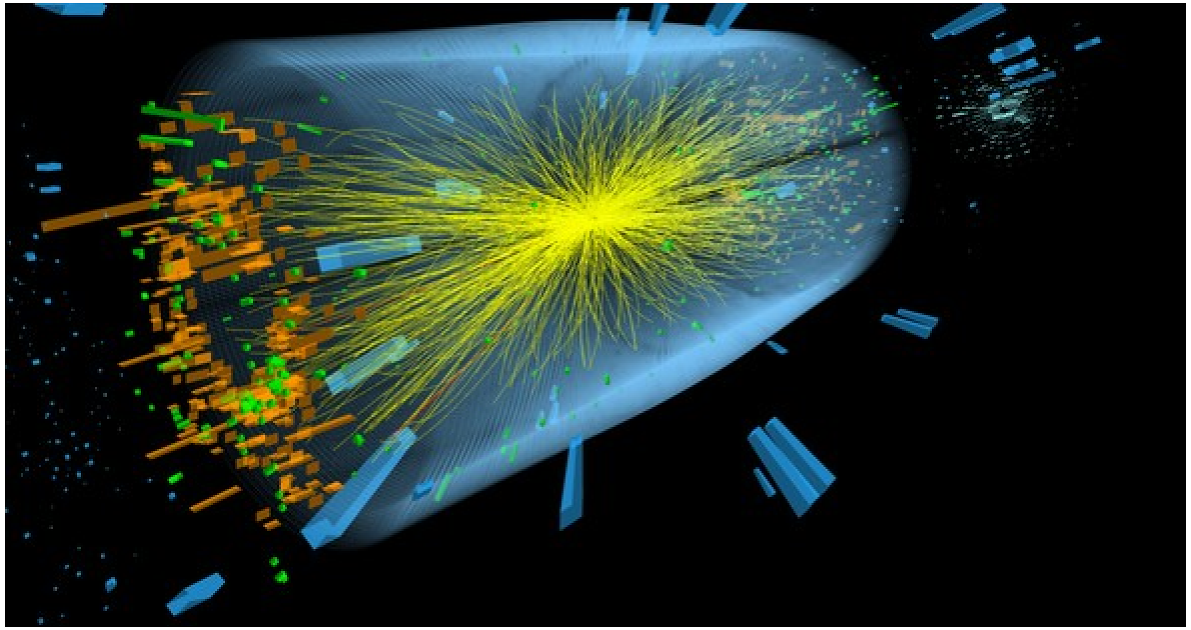
elementary particles: each collisions has “fixed” energy

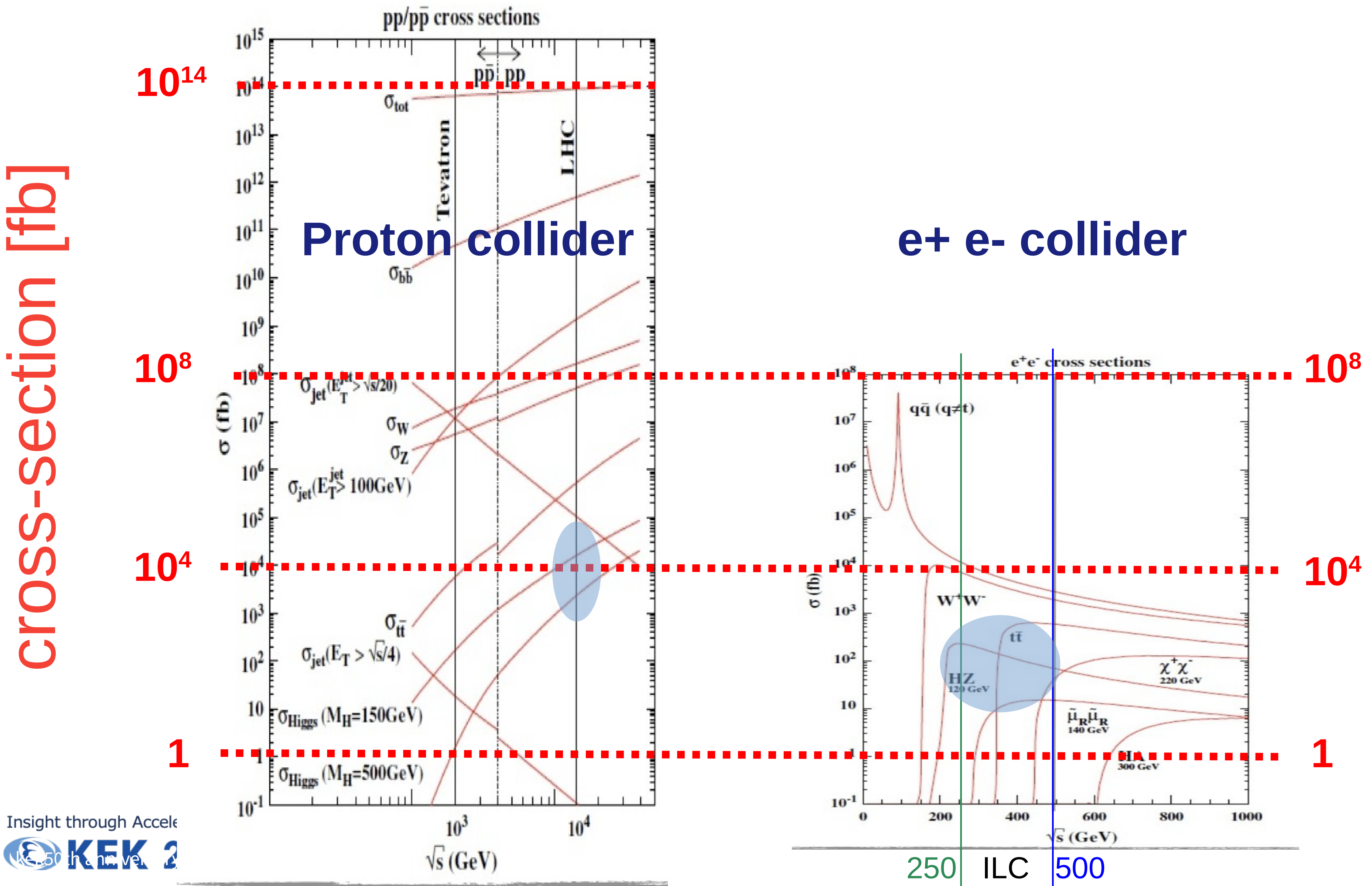
almost no “debris”: clean events, easy to analyse

dominated by Electro-Weak interactions

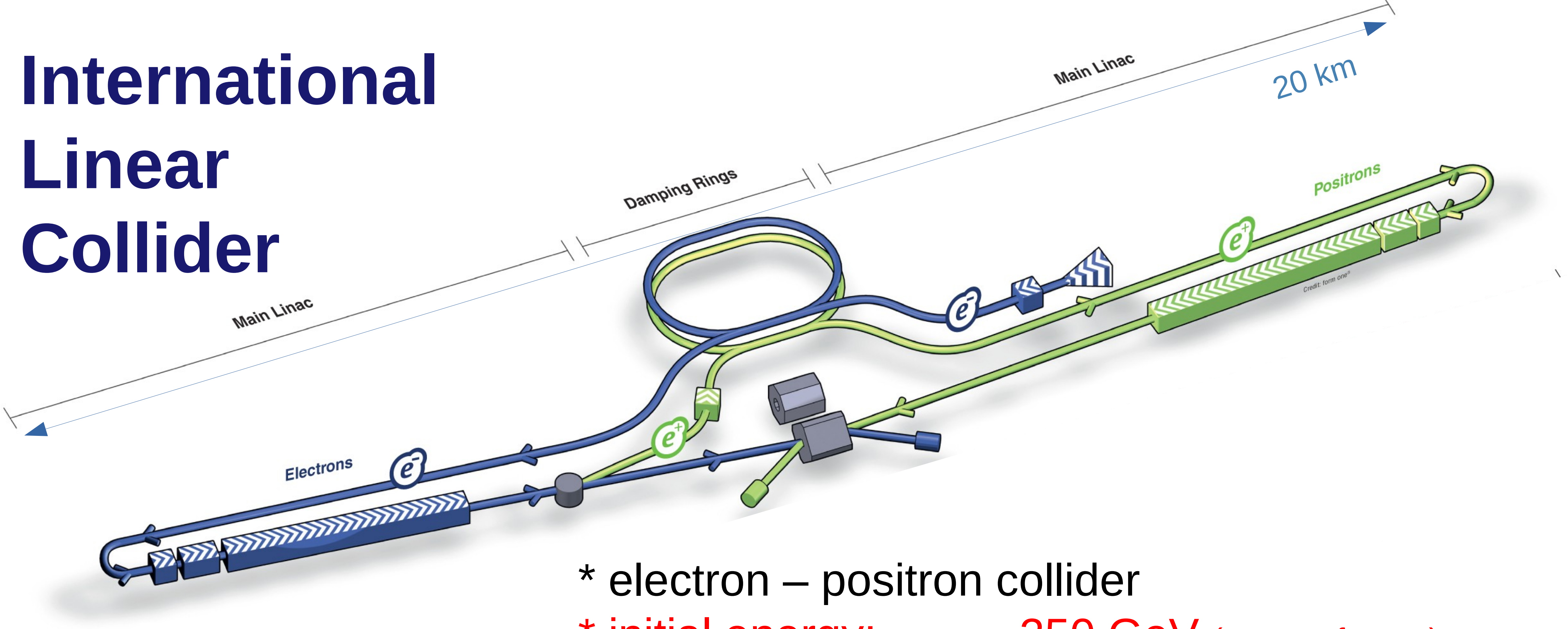
Insight through Accelerators. KEK 2021






cross-section [fb]
Proton collider
e+ e- collider
10^{14}
10^8
10^4
1
pp/p$\bar{p}$ cross sections
p$\bar{p}$ pp
Tevatron
LHC
σ_{tot}
$\sigma_{b\bar{b}}$
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/20)$
σ_W
σ_Z
$\sigma_{jet}(E_T^{jet} > 100GeV)$
$\sigma_{t\bar{t}}$
$\sigma_{jet}(E_T > \sqrt{s}/4)$
$\sigma_{Higgs}(M_H=150GeV)$
$\sigma_{Higgs}(M_H=500GeV)$
σ (fb)
$\sqrt{s}$ (GeV)
e+e- cross sections
$q\bar{q}$ (q≠t)
W^+W^-
$t\bar{t}$
HZ 120 GeV
$\chi^+\chi^-$ 220 GeV
$\tilde{\mu}_R\tilde{\mu}_R$ 140 GeV
HA 300 GeV
250
ILC
500

International Linear Collider



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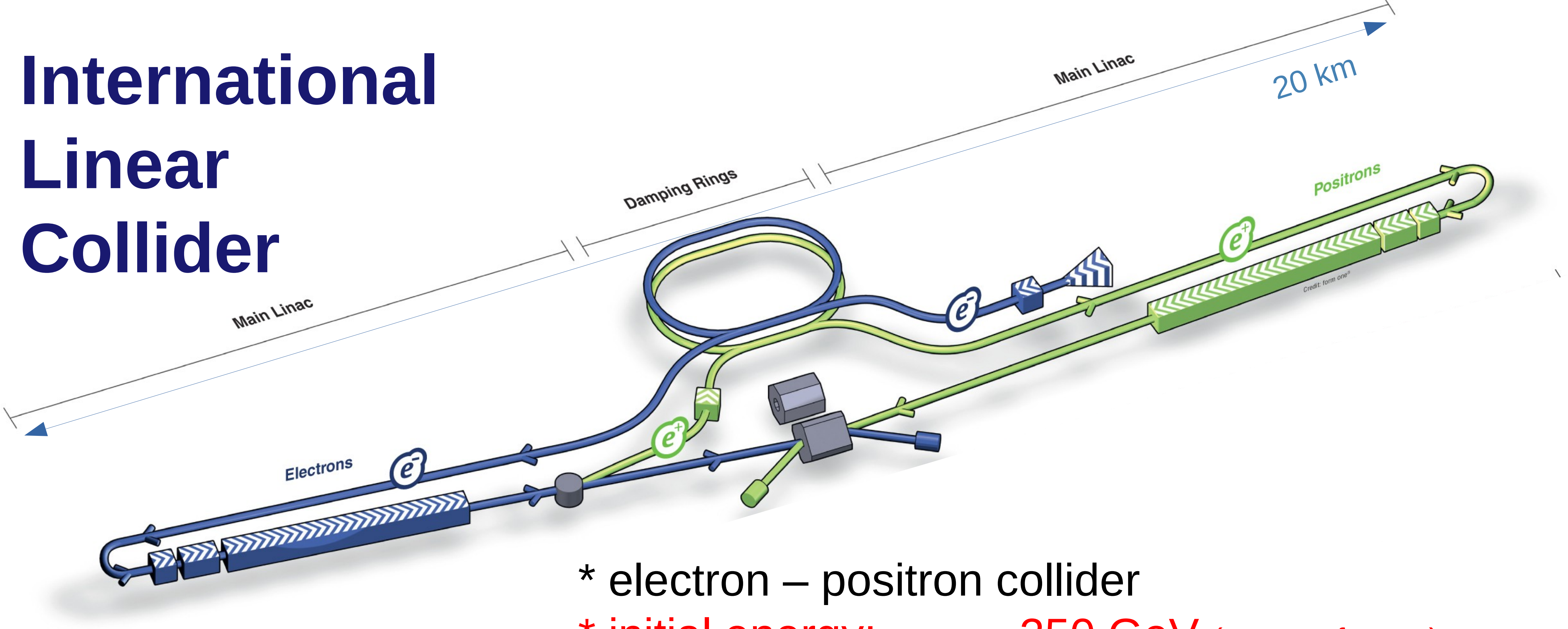
* polarised beams
* future upgrades in energy and luminosity

~1M Higgs bosons

International Linear Collider

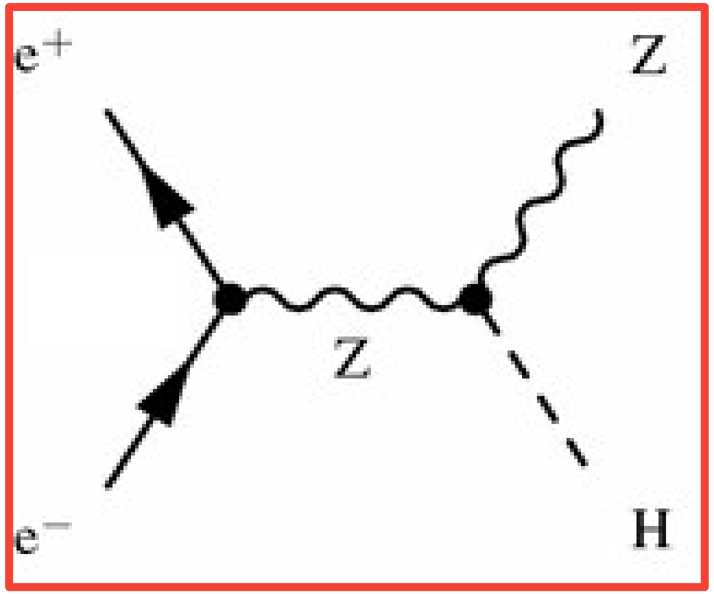


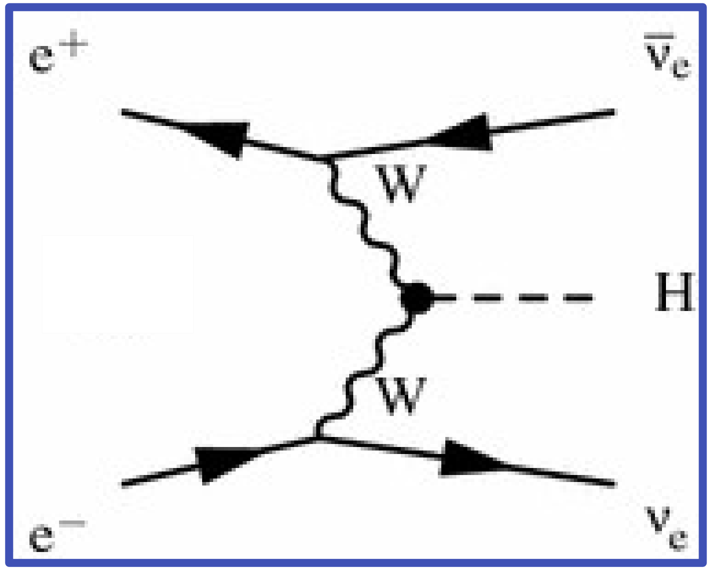
* electron – positron collider

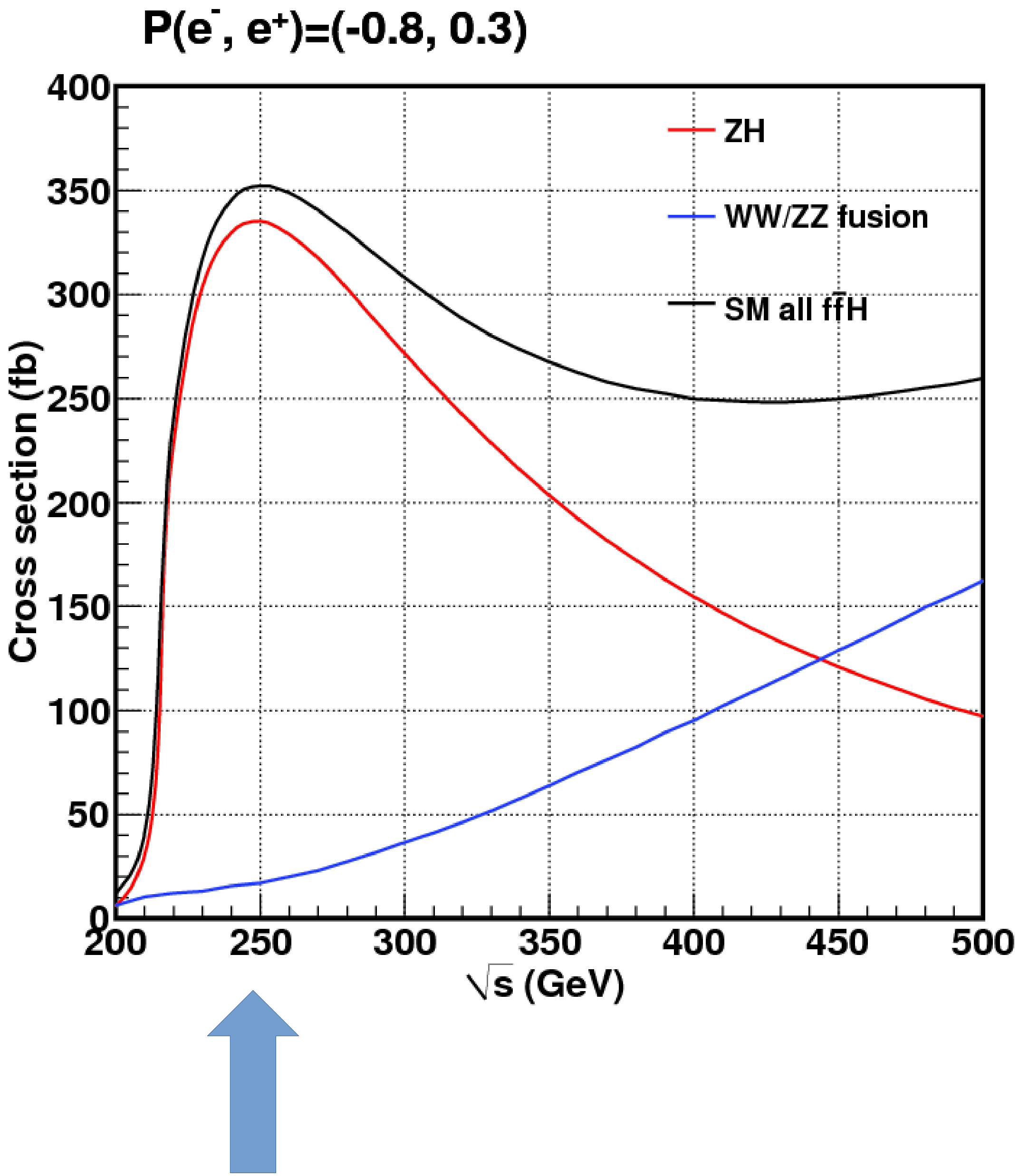
* initial energy: 250 GeV (centre of mass)

why ?

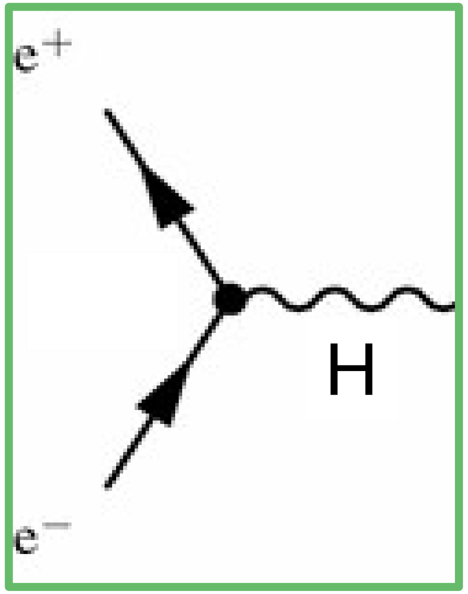
LHC runs at 14 TeV…


e+
Z
Z
e−
H


e+
$\bar{\nu}_e$
W
H
W
e−
ν_e

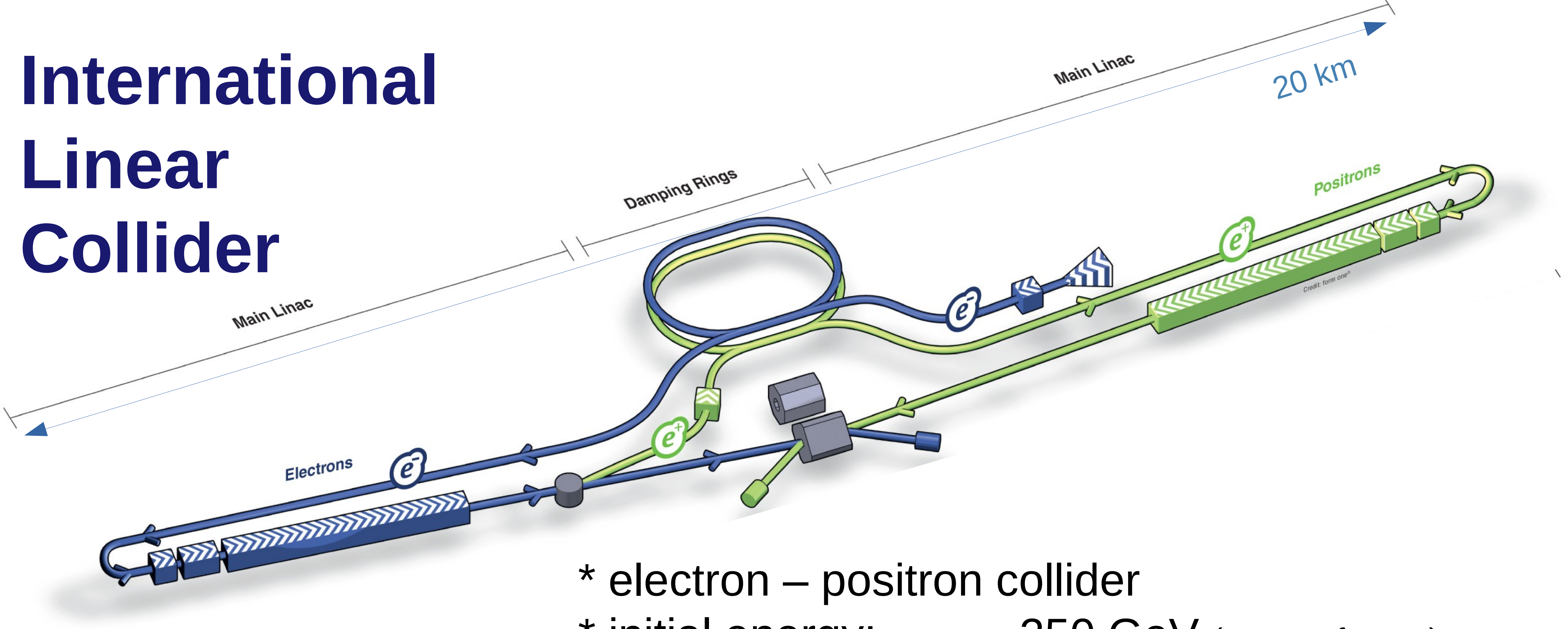

P(e-, e+)=(-0.8, 0.3)
ZH
WW/ZZ fusion
SM all ff̄H
Cross section (fb)
400
350
300
250
200
150
100
50
0
200
250
300
350
400
450
500
√s (GeV)

what about this process ?



what energy is needed ?

International Linear Collider



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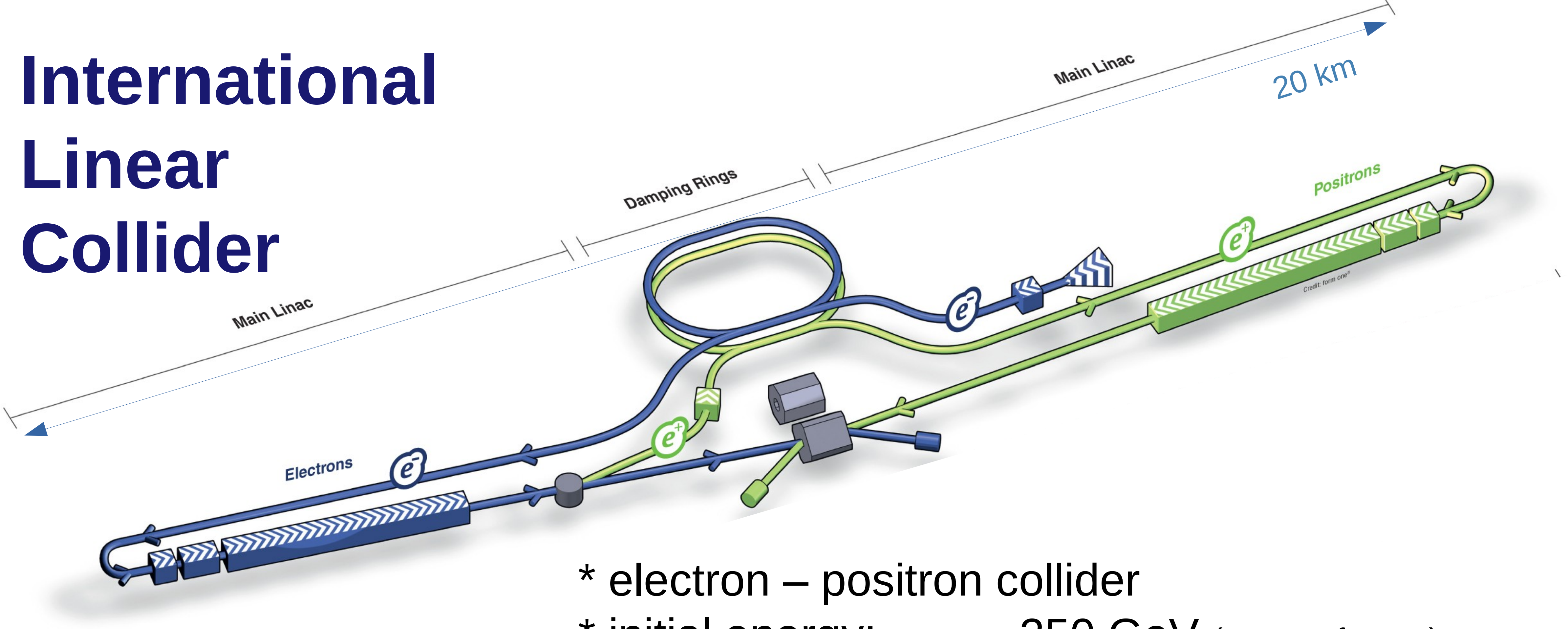
~1M Higgs bosons

International Linear Collider



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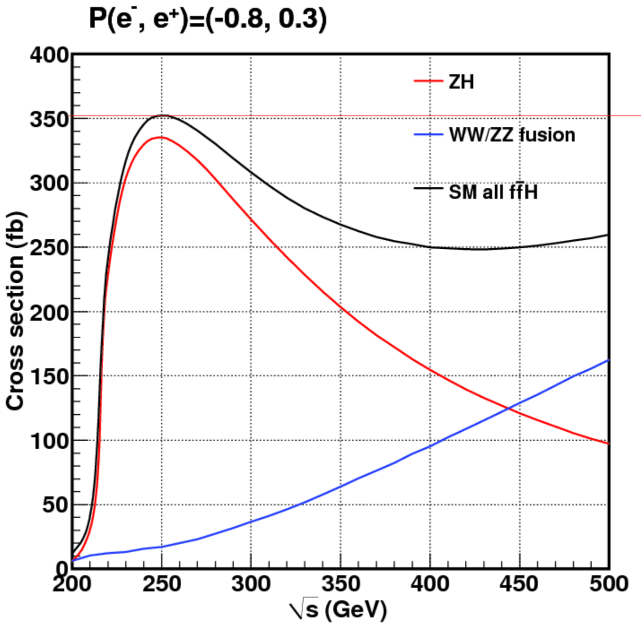
what is luminosity?

```
Number of Higgs bosons   = cross-section * integrated luminosity

                         = cross-section * running time * luminosity
```

need enough luminosity to get enough Higgs bosons in a reasonable time



350 fb = 350 x 10^{-15} x 10^{-24} cm^2 = 3.5 x 10^{-37} cm^2

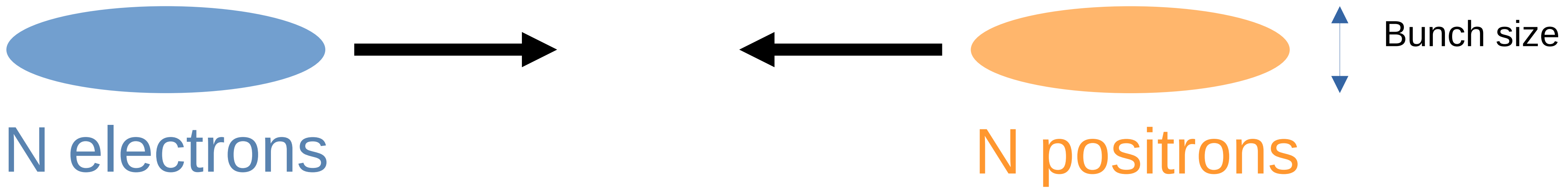
luminosity: 1.35 x 10^{34} cm^{-2} s^{-1}

→ 4.7 x 10^{-3} Higgs s^{-1}

→ one Higgs every 3~4 minutes

→ 150k per year (if running continuously)

(after a few years,
plan to upgrade luminosity
to increase this rate)



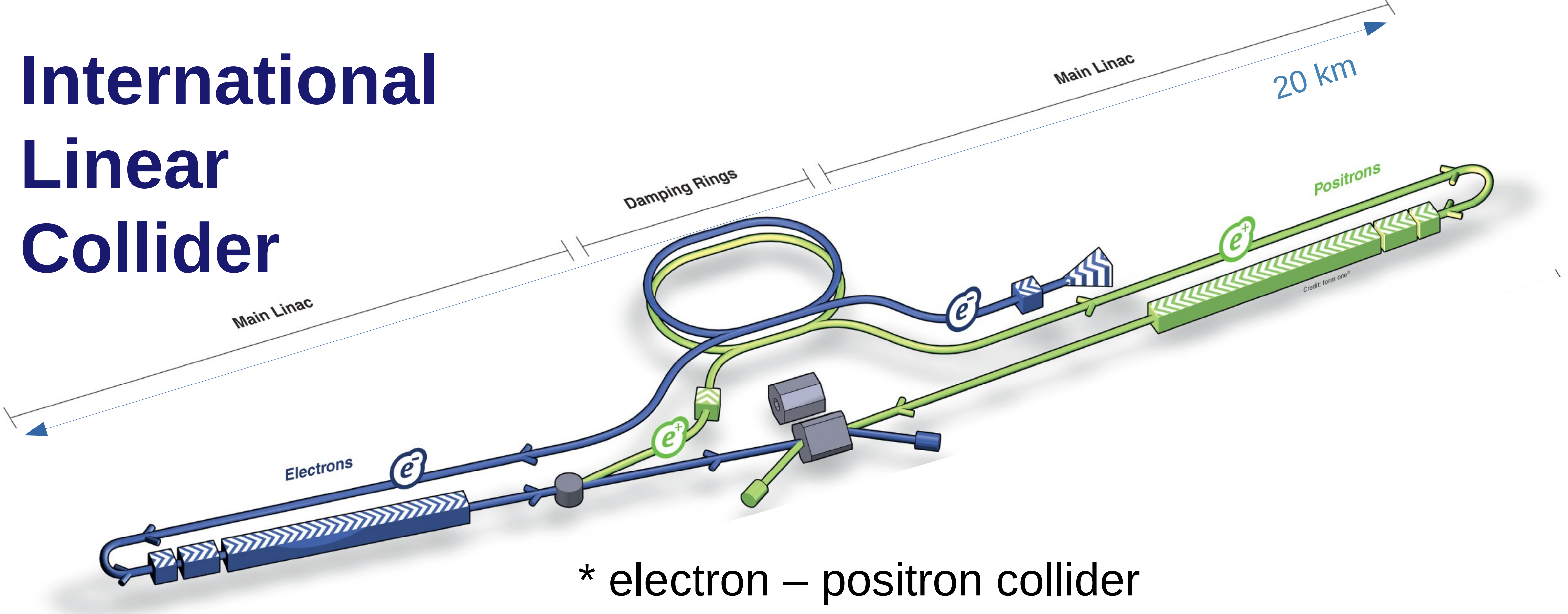
$$\text{Luminosity} \sim \frac{(\text{repetition rate})\ N\ N\ (\text{enhancement factor})}{\text{bunch\_size}_{(\text{vertical})}\ \text{bunch\_size}_{(\text{horizontal})}}$$

Large N ~ 10^{10}

Large repetition rate ~ 6500 / s

Small bunch size ~ 7 nm (vertical) ~ 500 nm (horizontal)

International Linear Collider



* electron – positron collider
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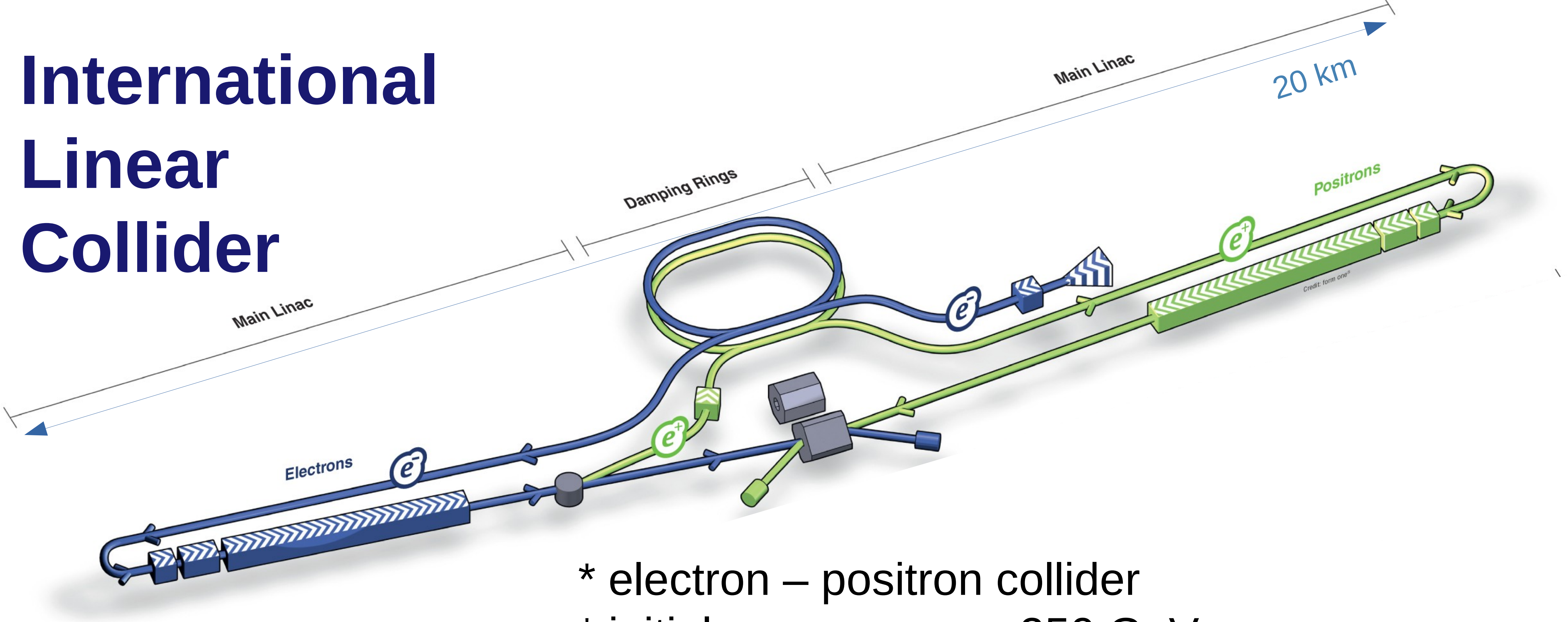
~1M Higgs bosons

International Linear Collider



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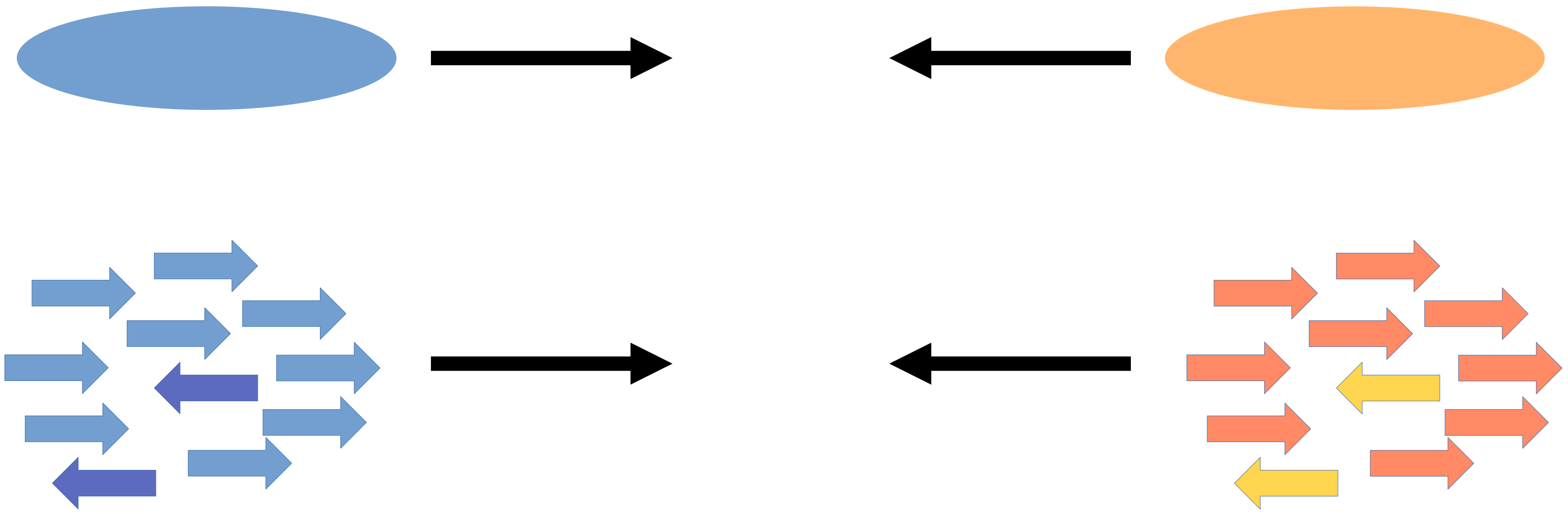
* polarised beams

what is beam polarisation ?
what's good about it ?

What is beam polarisation?



mostly positive helicity

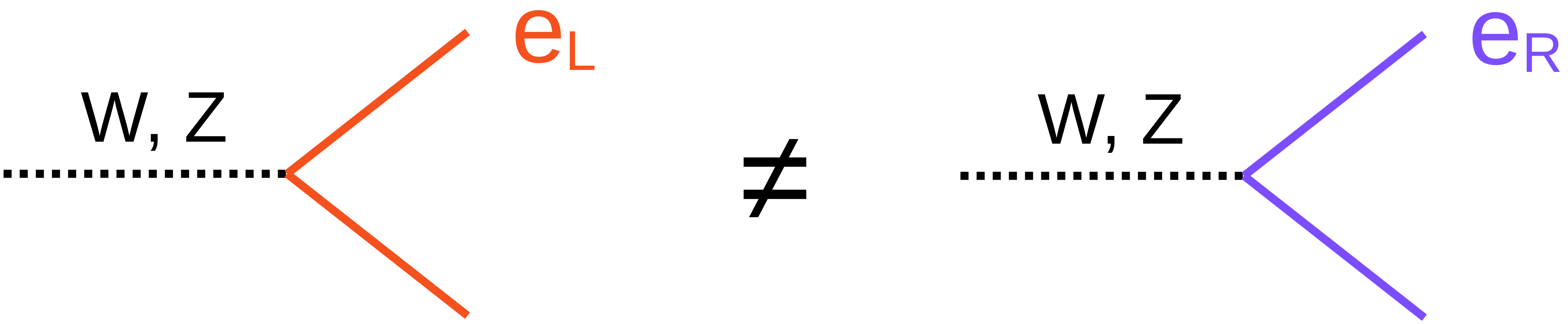
mostly negative helicity

if highly relativistic:

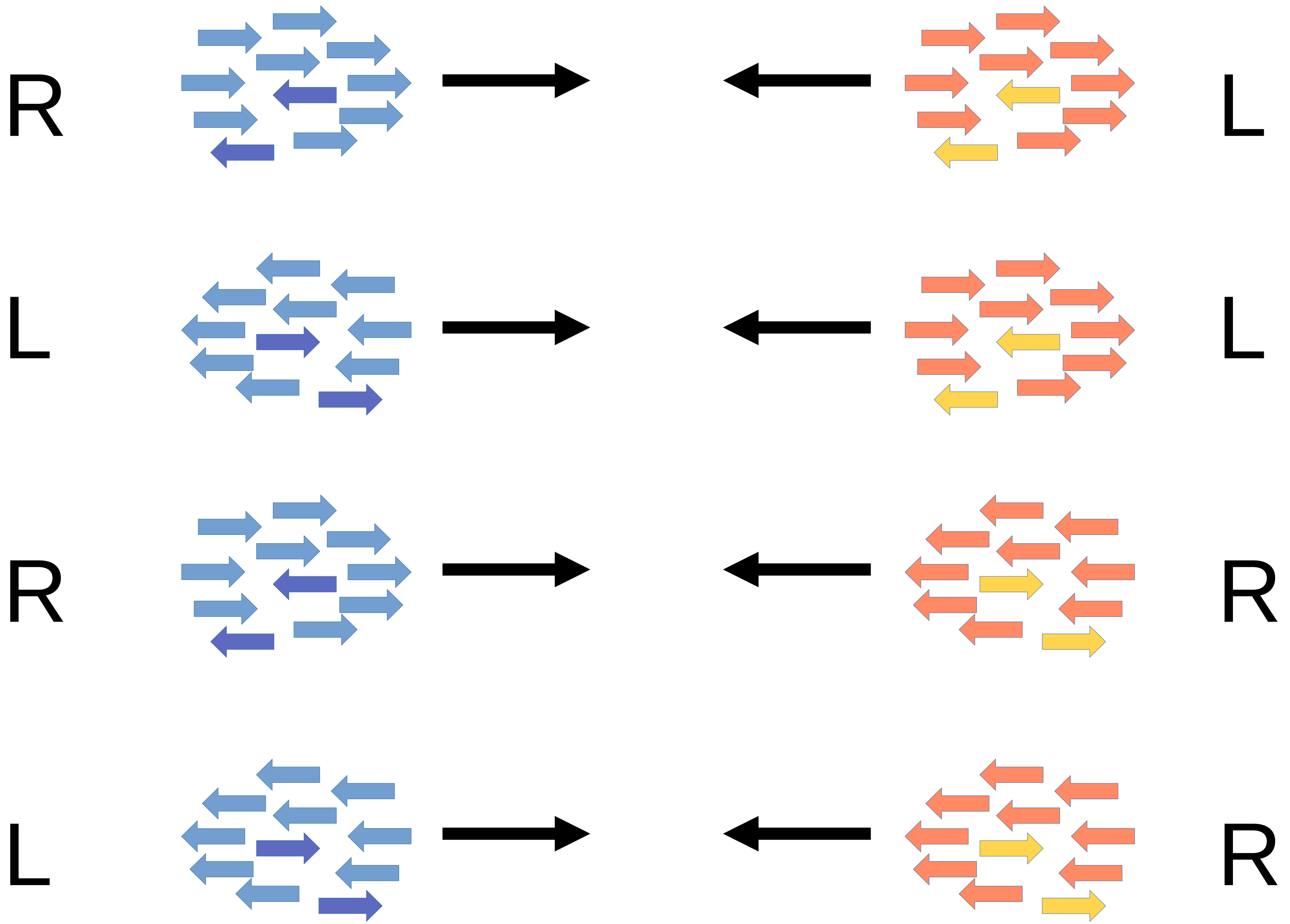
mostly **right-handed**

mostly **left-handed**

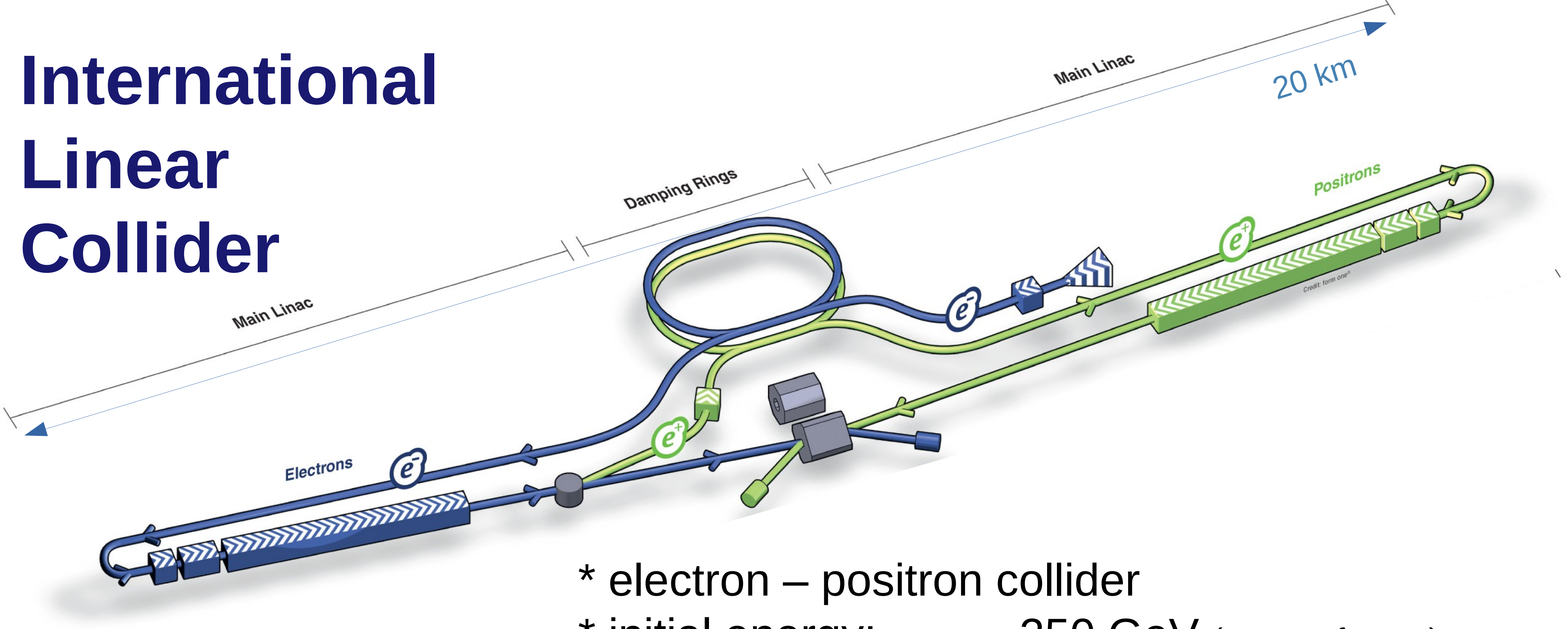
In the electro-weak interactions,
Left and Right-handed fermions are different particles



flipping the beam polarisations → 4 different experiments!



International Linear Collider



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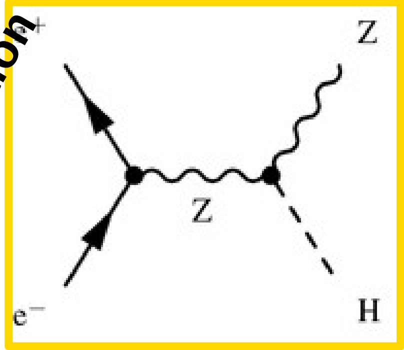
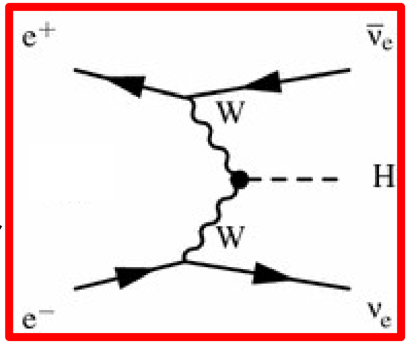
why increase the energy ?

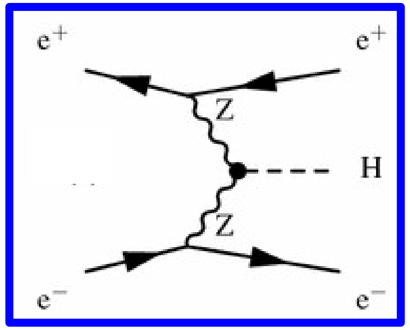
Higgs production in electron-positron collisions

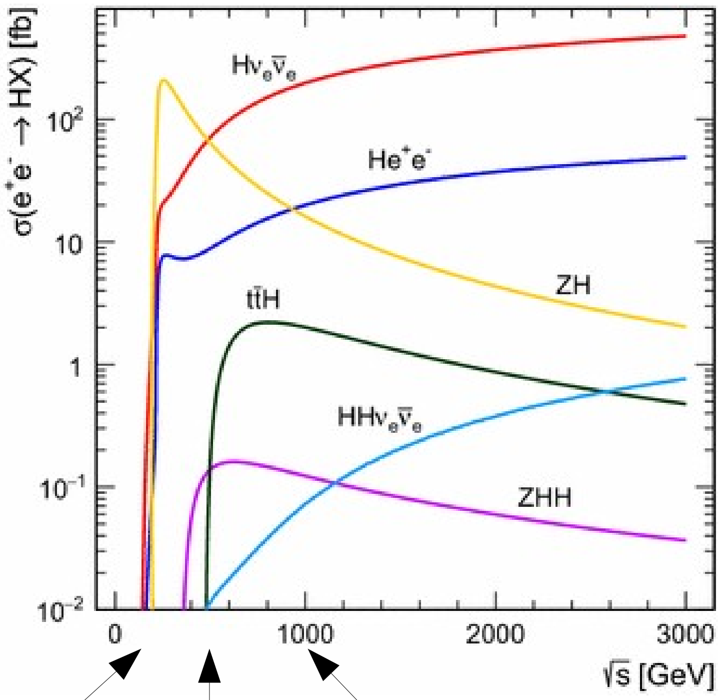
associated Higgs production



ZZ & WW fusion





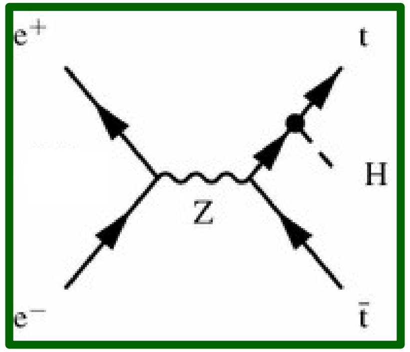


250 500 1000 GeV

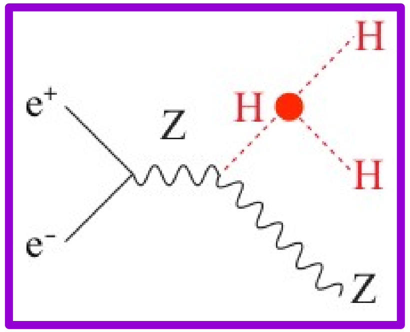
Higgs studies can start at **250 GeV**

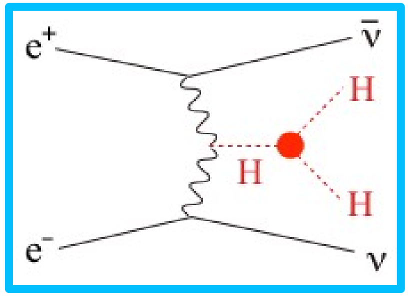
full set of Higgs measurements:
add ~**500** & ~**1000 GeV**

top quark Yukawa

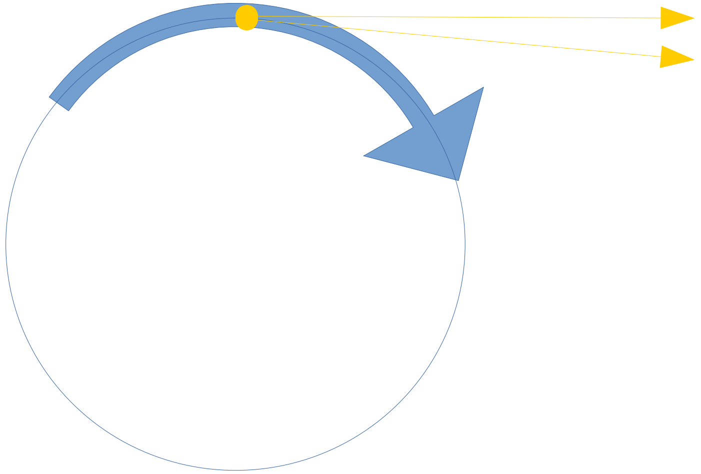


Higgs boson self-coupling





Circular collider (electron-positron)



Energy loss by synchrotron radiation:

power loss ~ $E^4 / (m^4 r^2)$

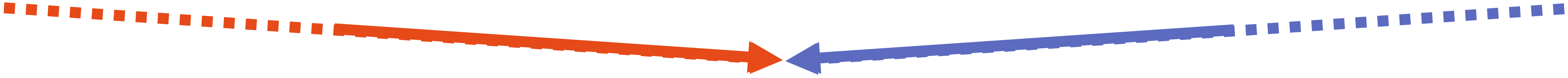
E: energy
m: particle mass
r: ring radius

→ practically limits the maximum beam energy
→ difficult to increase energy in a ring

unless what ?

Electrical power ~ E^4

Linear Collider

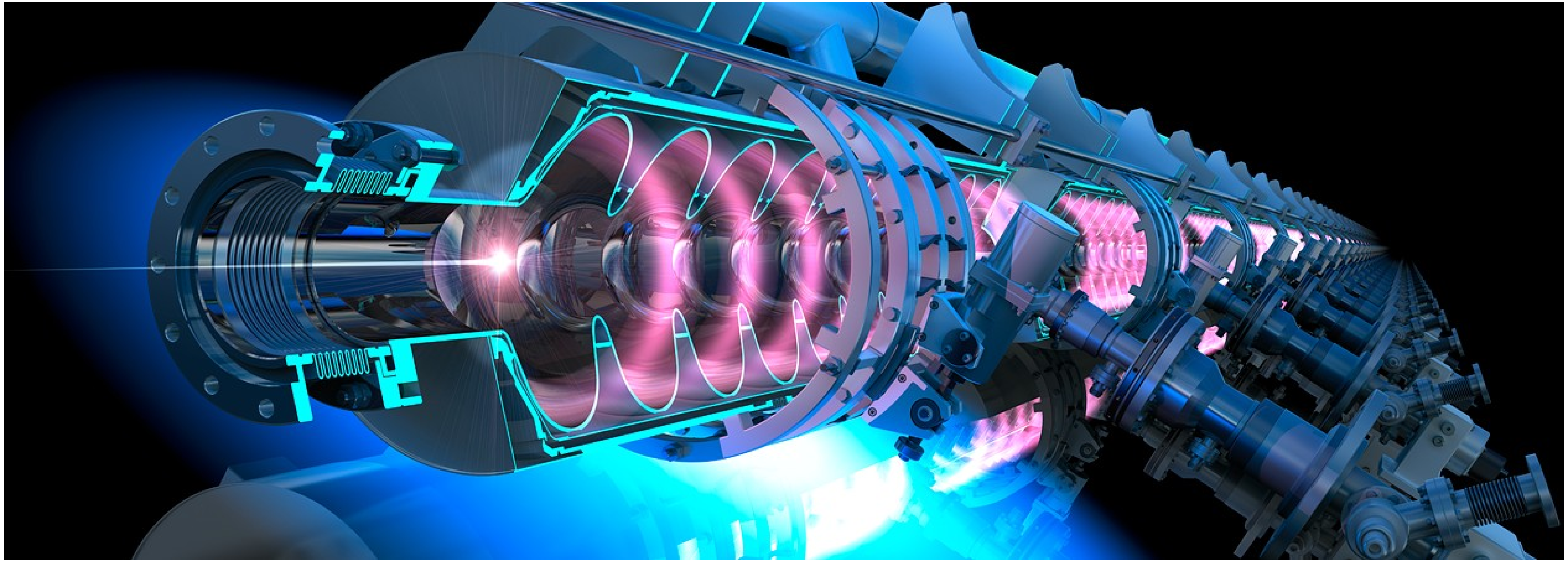


Beam energy limited by tunnel length
→ easy to extend (reusing existing tunnel)

Electrical power ~ E

ILC technology

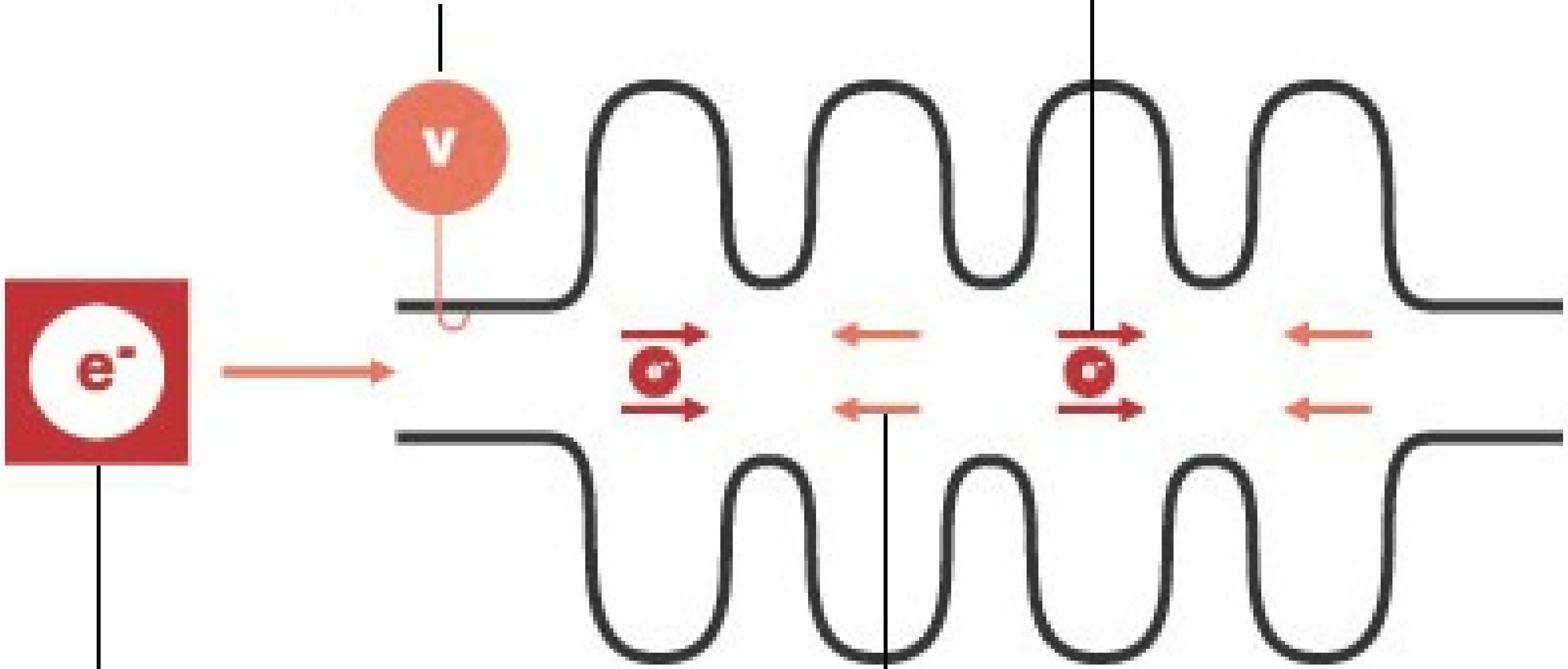
Key Technology:
Super-Conducting Radio Frequency acceleration



accelerate electrons through 30~35+ million volts every meter

A voltage generator induces an electric field inside the rf cavity. Its voltage oscillates with a radio frequency of 1.3 Gigahertz or 1.3 billion times per second.

The electrons always feel a force in the forward direction.



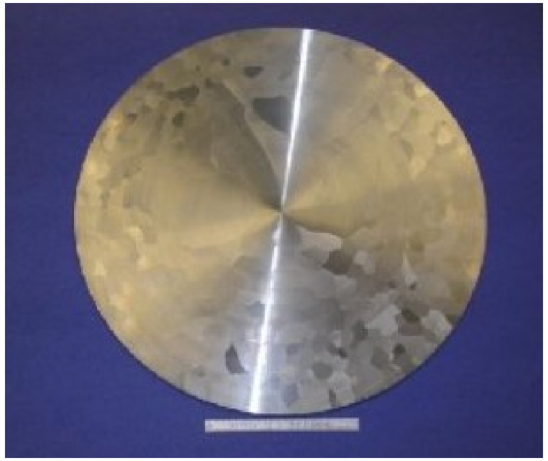
An electron source injects particles into the cavity in phase with the variable voltage.

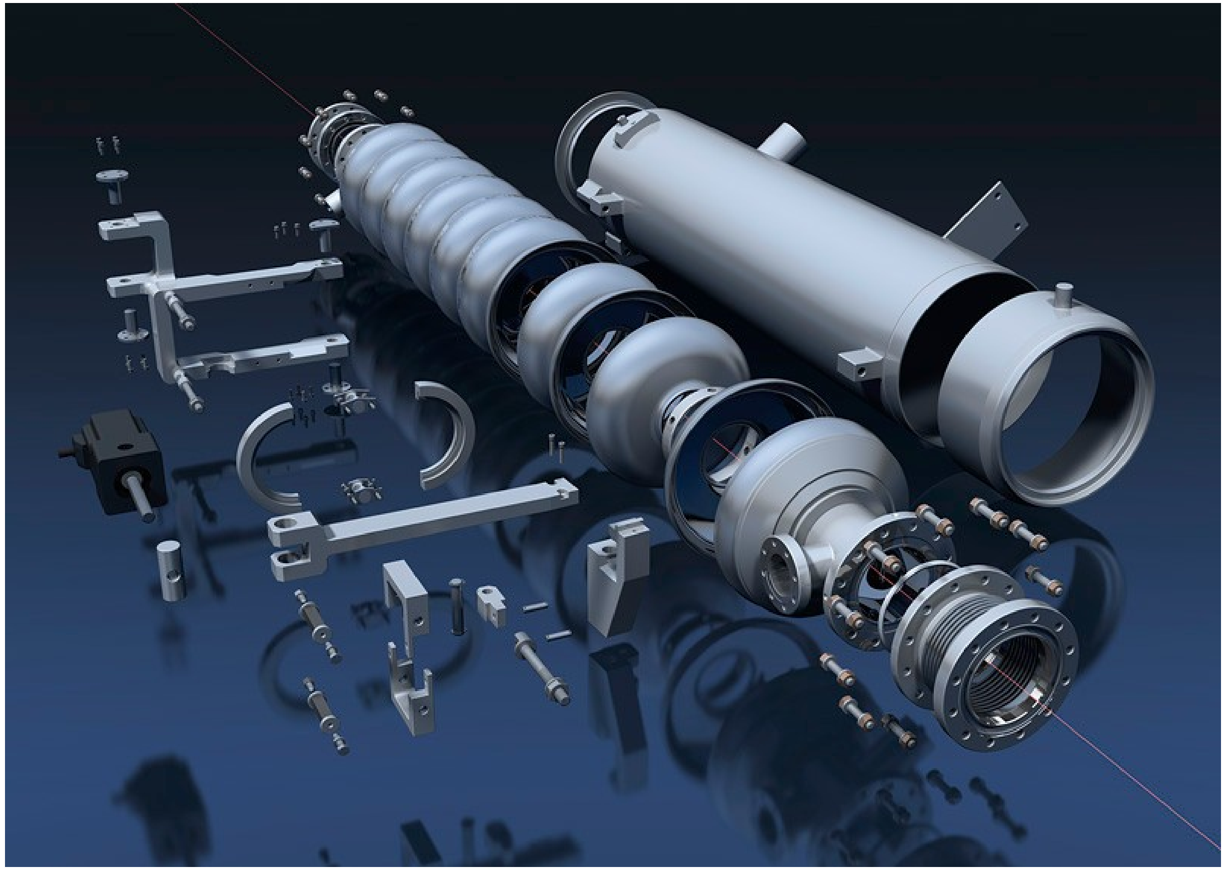
The electrons never feel a force in the backward direction.

Super-Conducting cavities for ILC

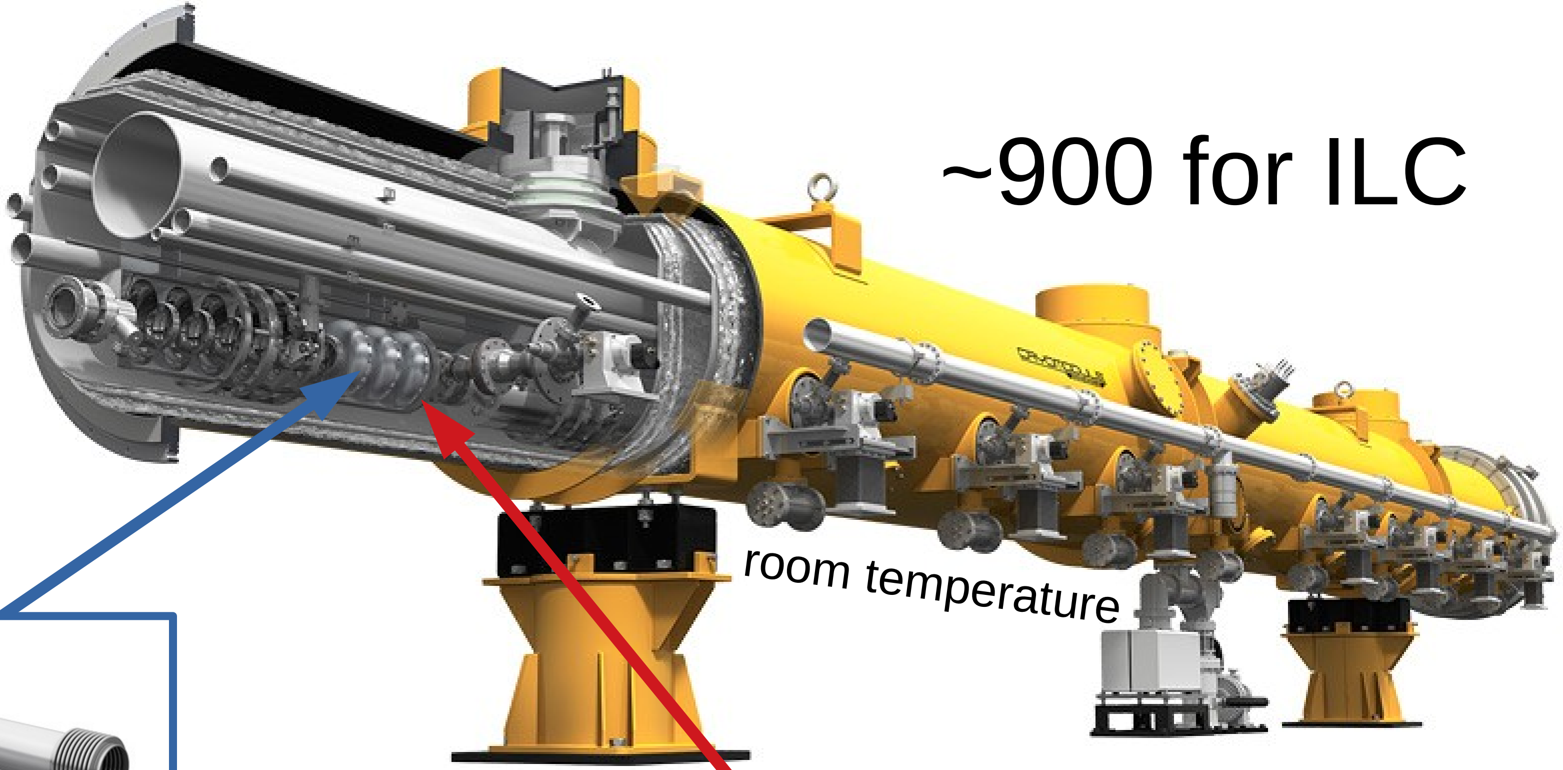
Super-conductor → dramatically reduce heating
→ more efficient

Niobium :
good superconductor

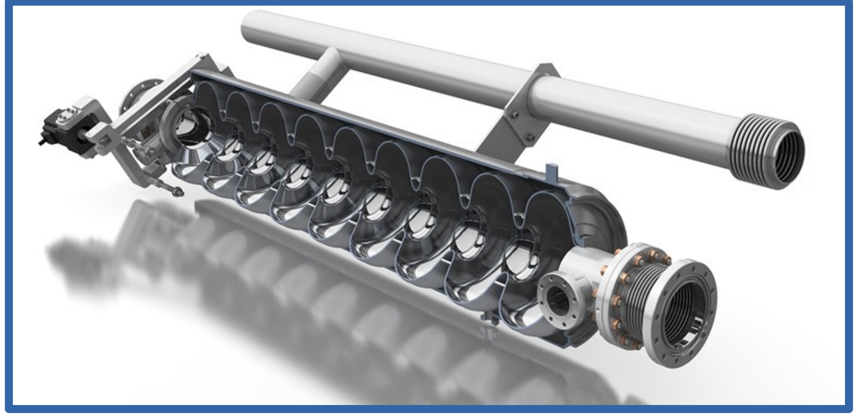




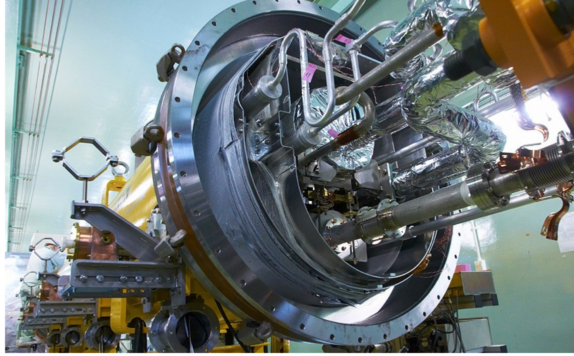
cryomodule

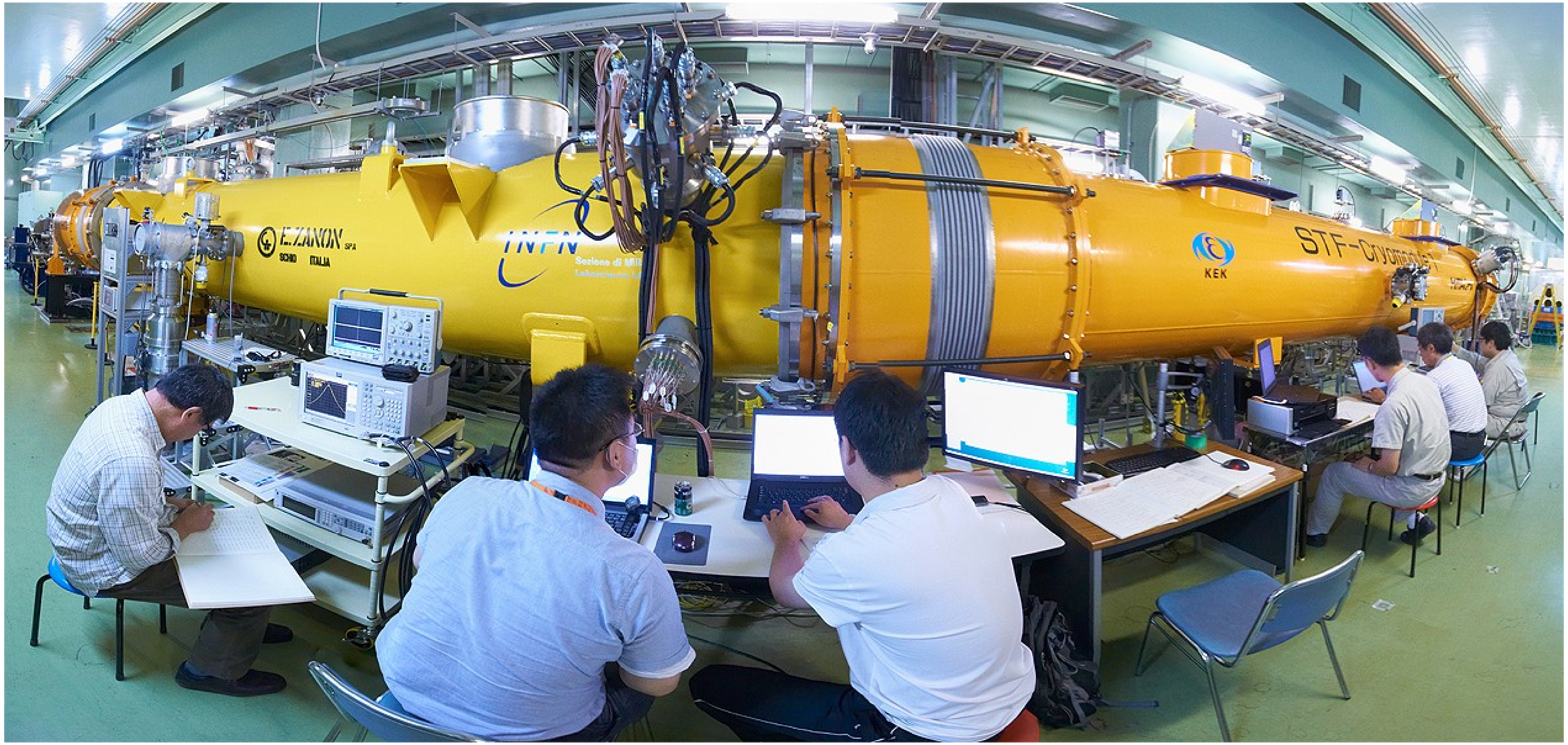


keep at 2K (–271°C)



~7,800 for ILC





Superconducting Test Facility (STF)

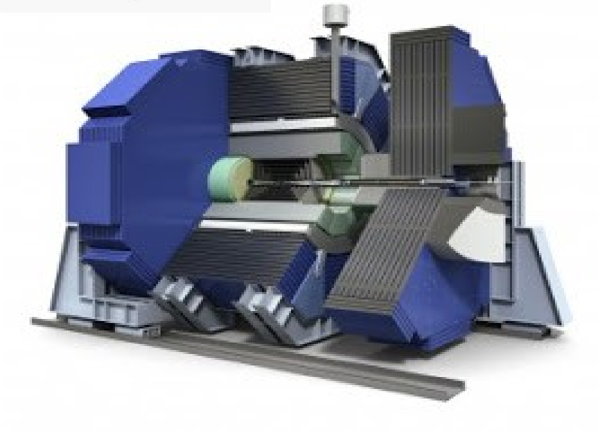
3 km of “ILC-like” technology

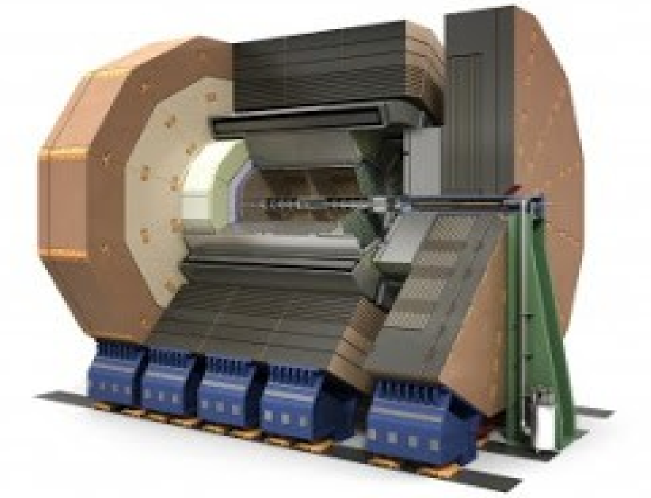
European XFEL @ DESY

cryomodule at FNAL, destined for LCLS-II @ SLAC

Experiments at ILC

two international groups developing detectors for ILC





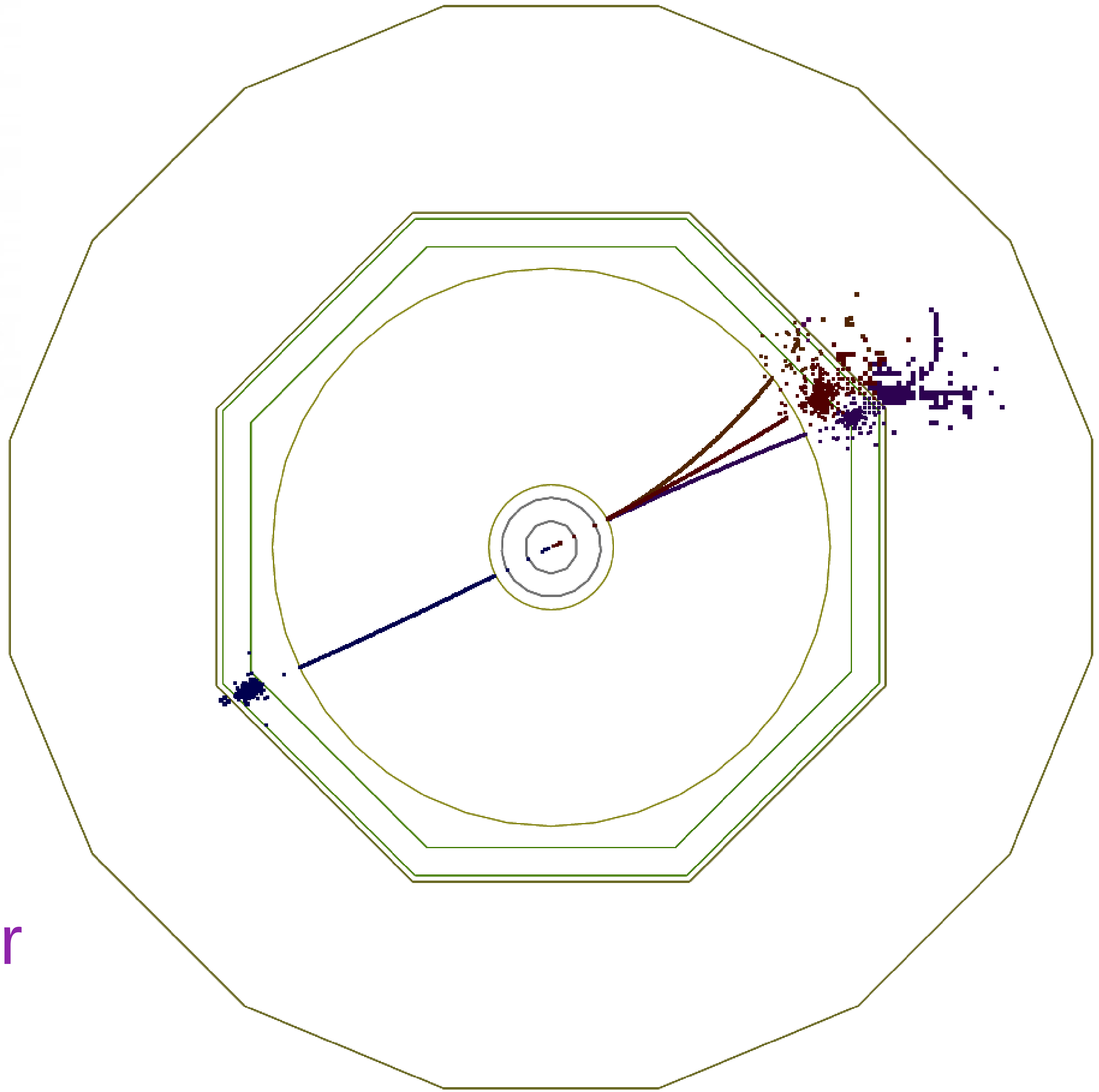
design detectors with unprecedented precision
→ enable ILC program

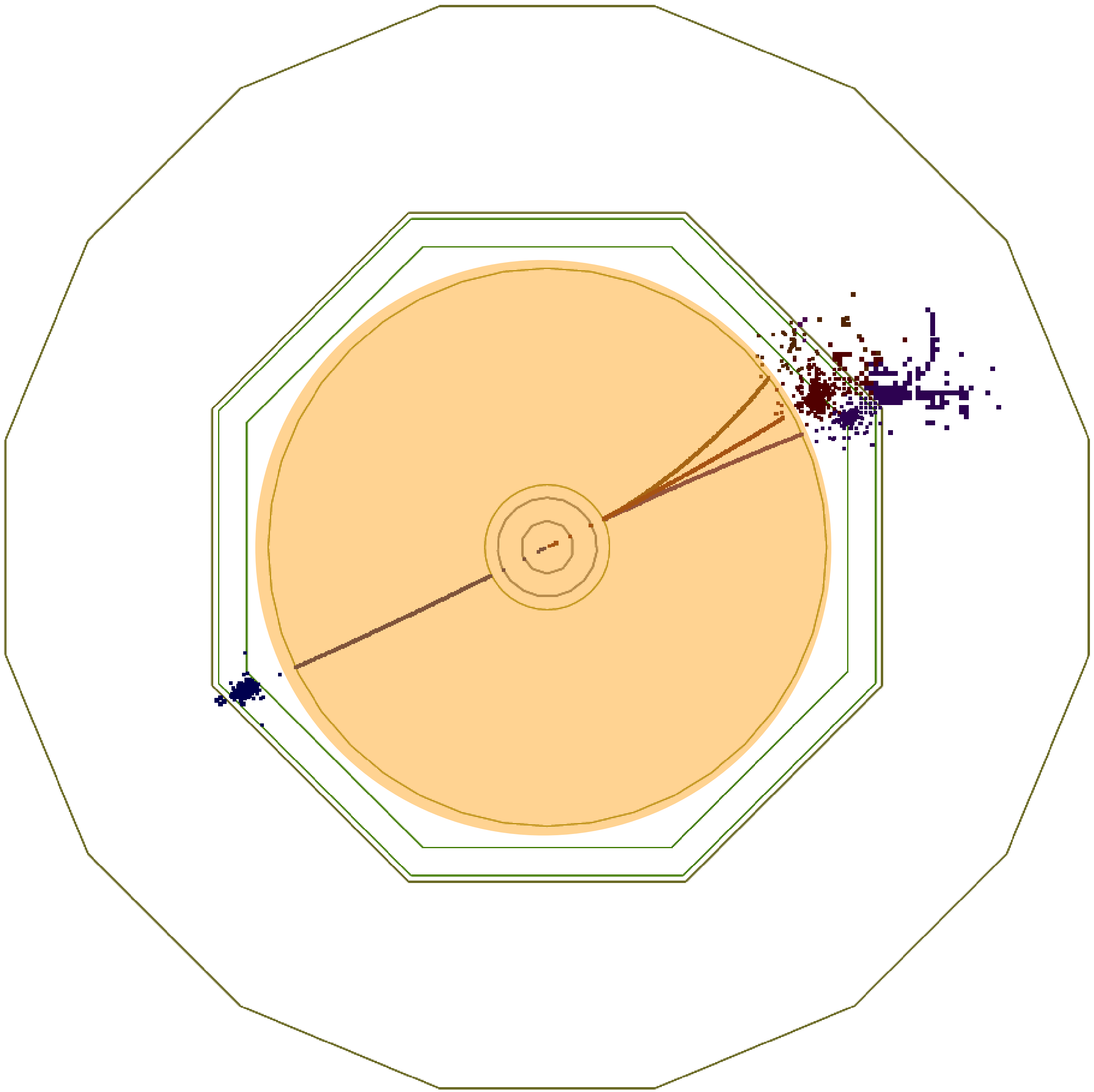
challenging requirements
to maximise physics harvest

→ efficiency, identification, resolution
→ hadronic jet resolution
→ angular coverage

technological advances
→ new technologies
→ low power, integrated electronics
→ compact devices
→ machine learning / AI
→ quantum sensors

Geant4
simulation
in ILD detector

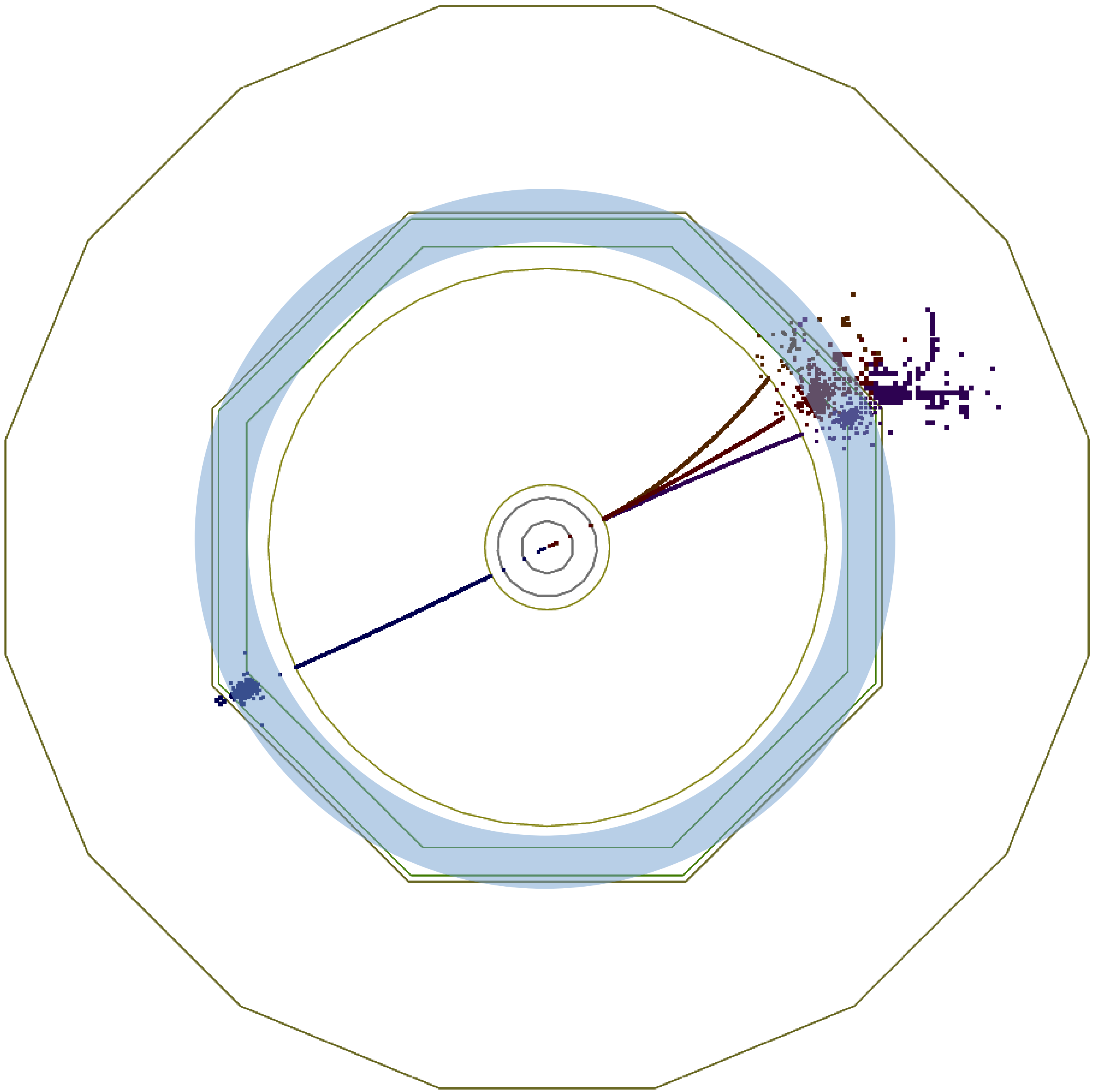




tracking detector

precise momentum of *charged* particles

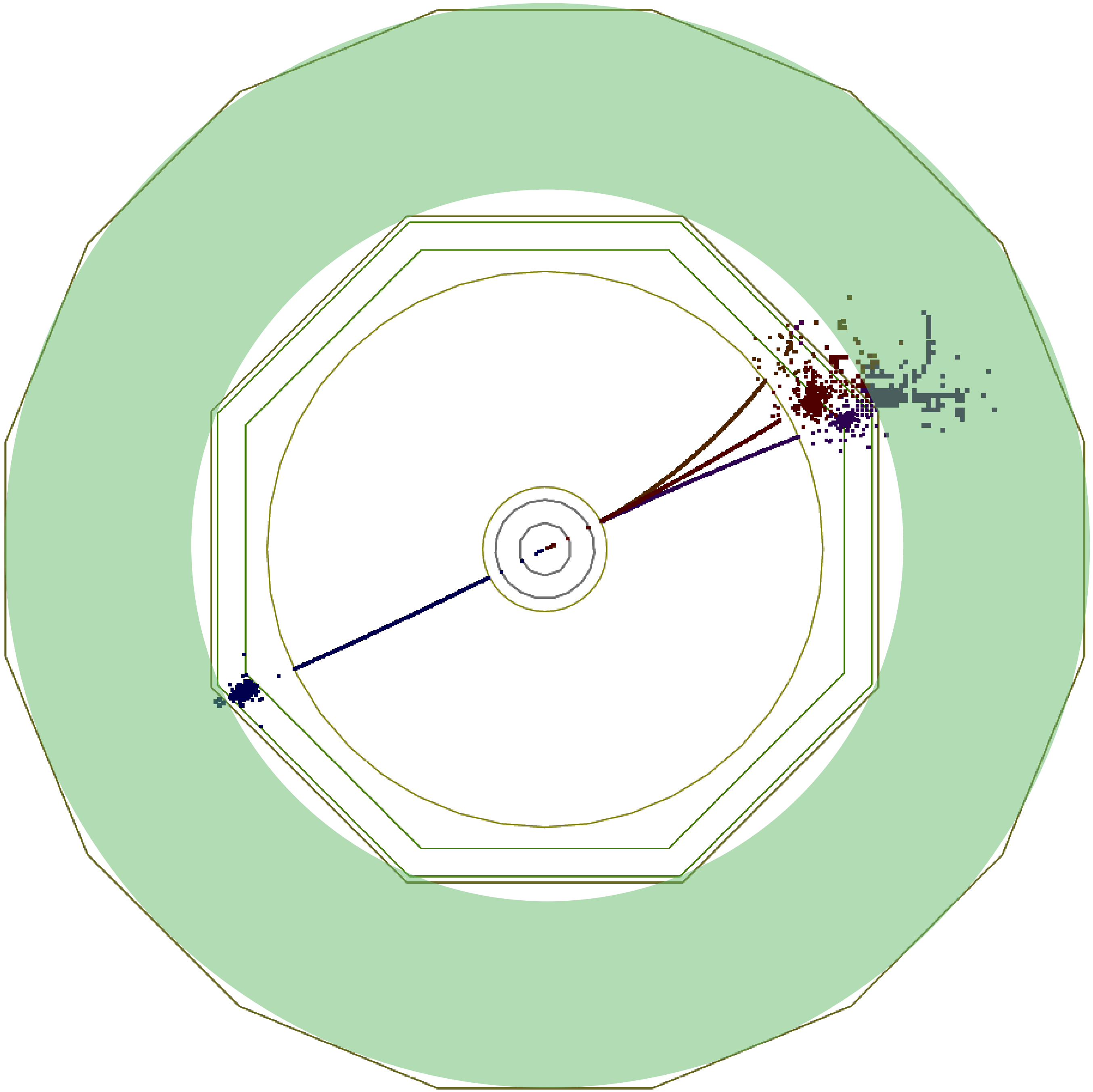
$d\,p_T / p_T \sim 3 \times 10^{-5}\,p_T$



electromagnetic calorimeter

reasonable precise measurement of
- **electrons, positrons,**
  - **photons**

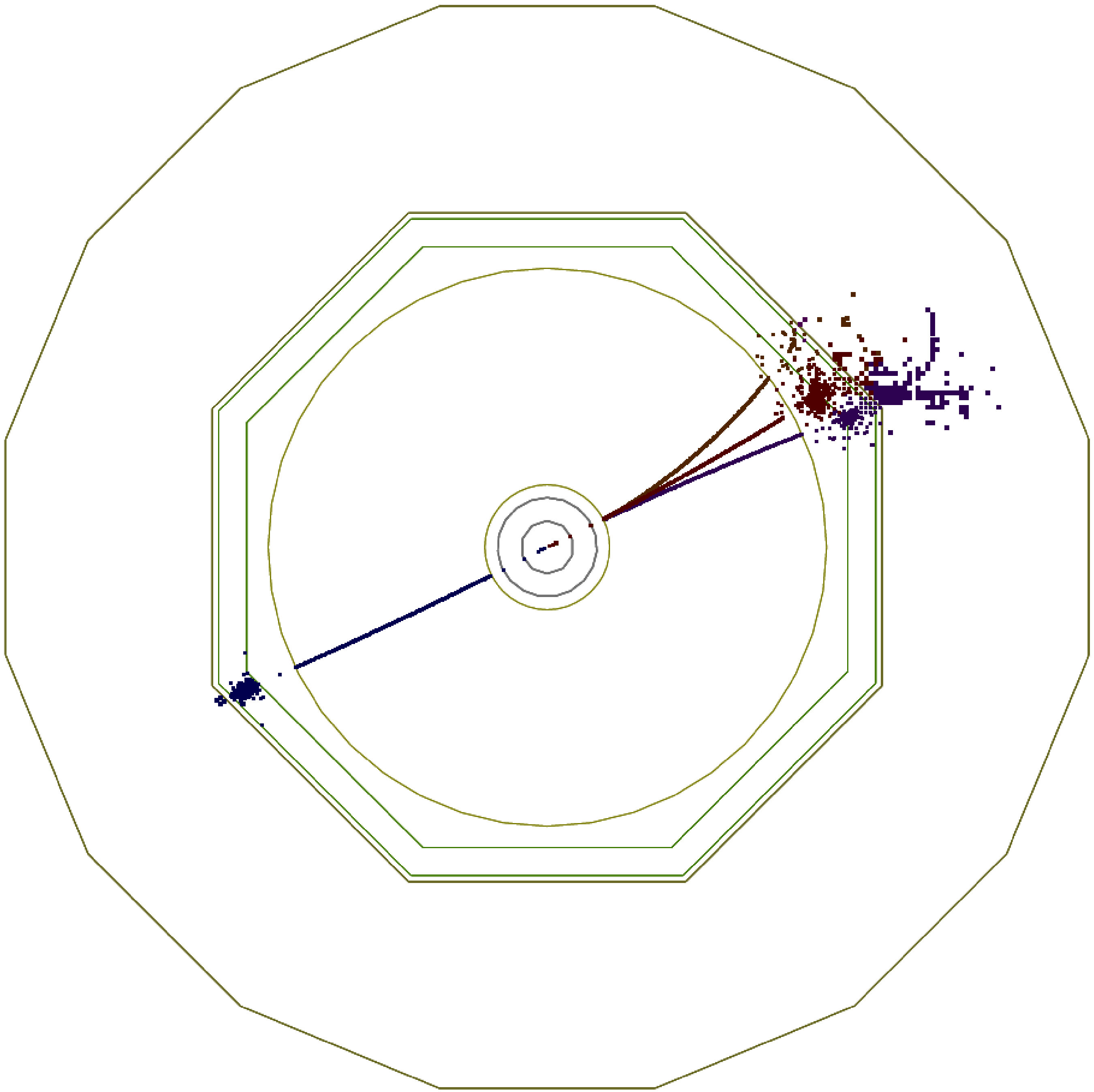
dE/E ~ 20% / √E



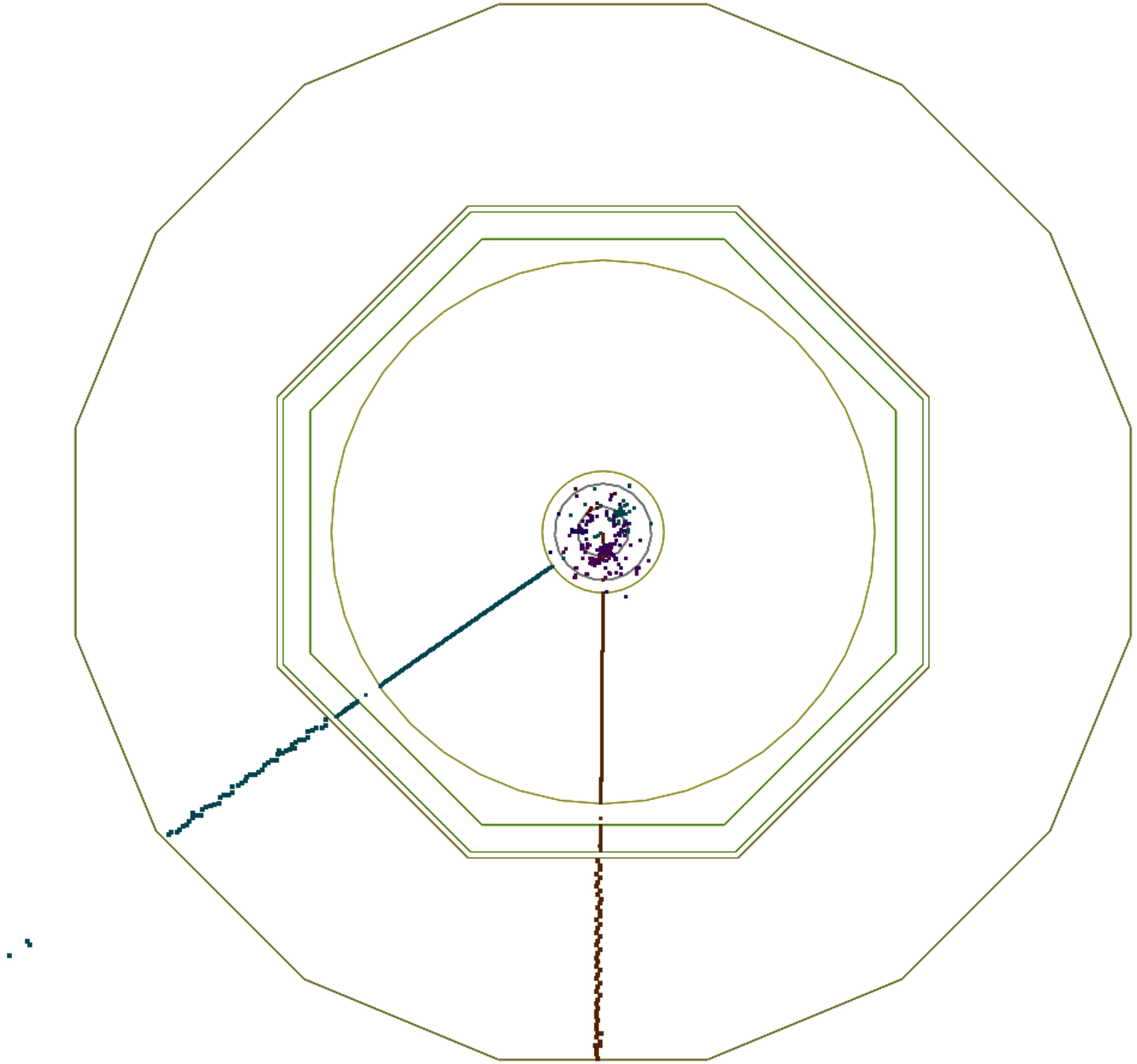
hadronic calorimeter

less precise measurement of charged and neutral hadron energies

dE/E ~ 50% / √E



what type of event ??



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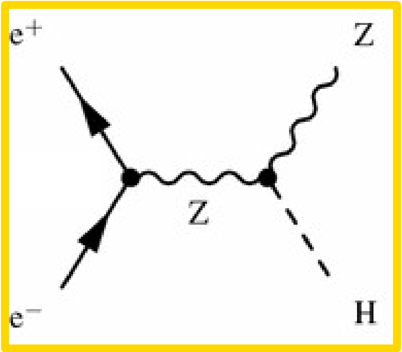
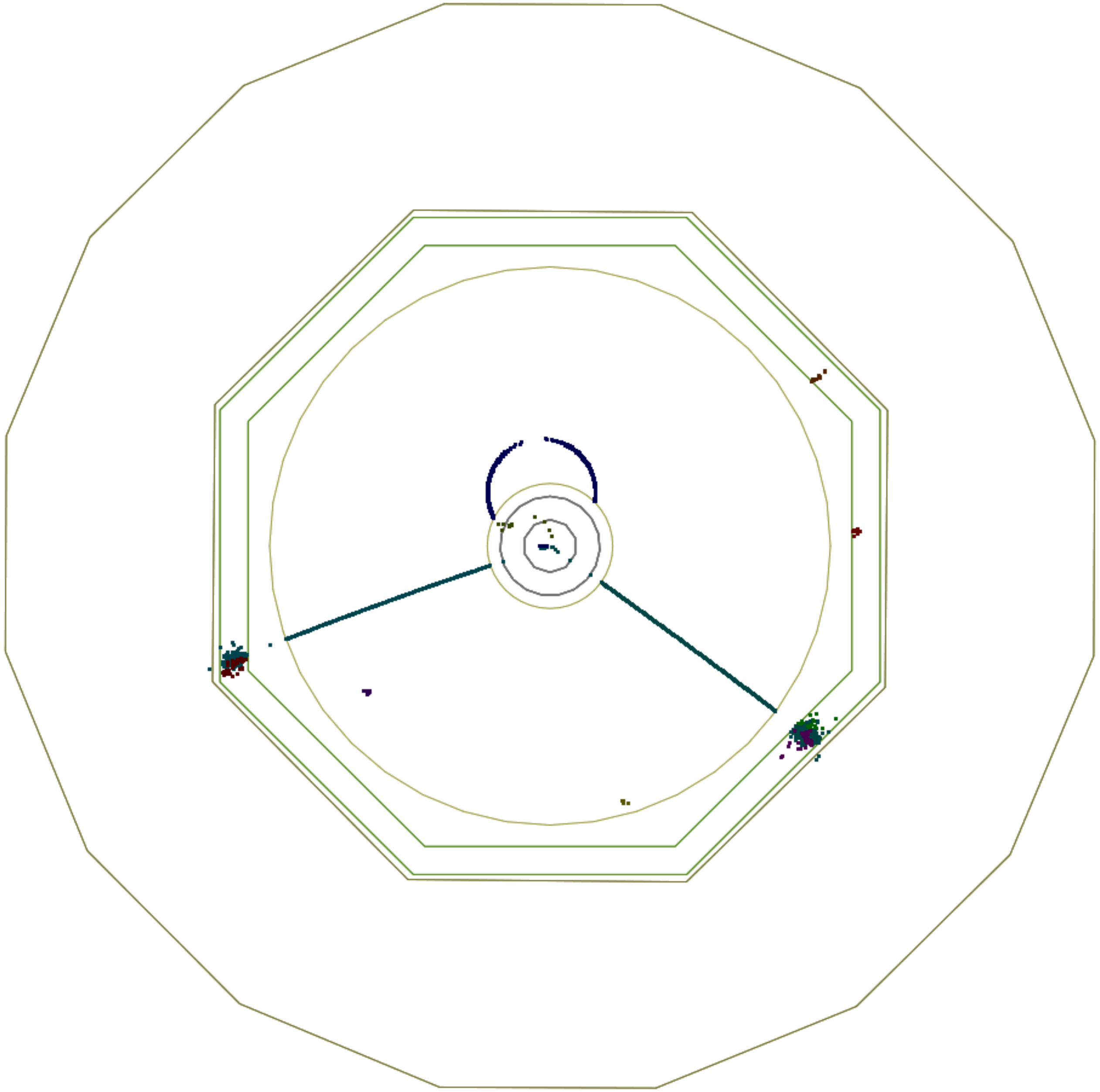


@ 250 GeV



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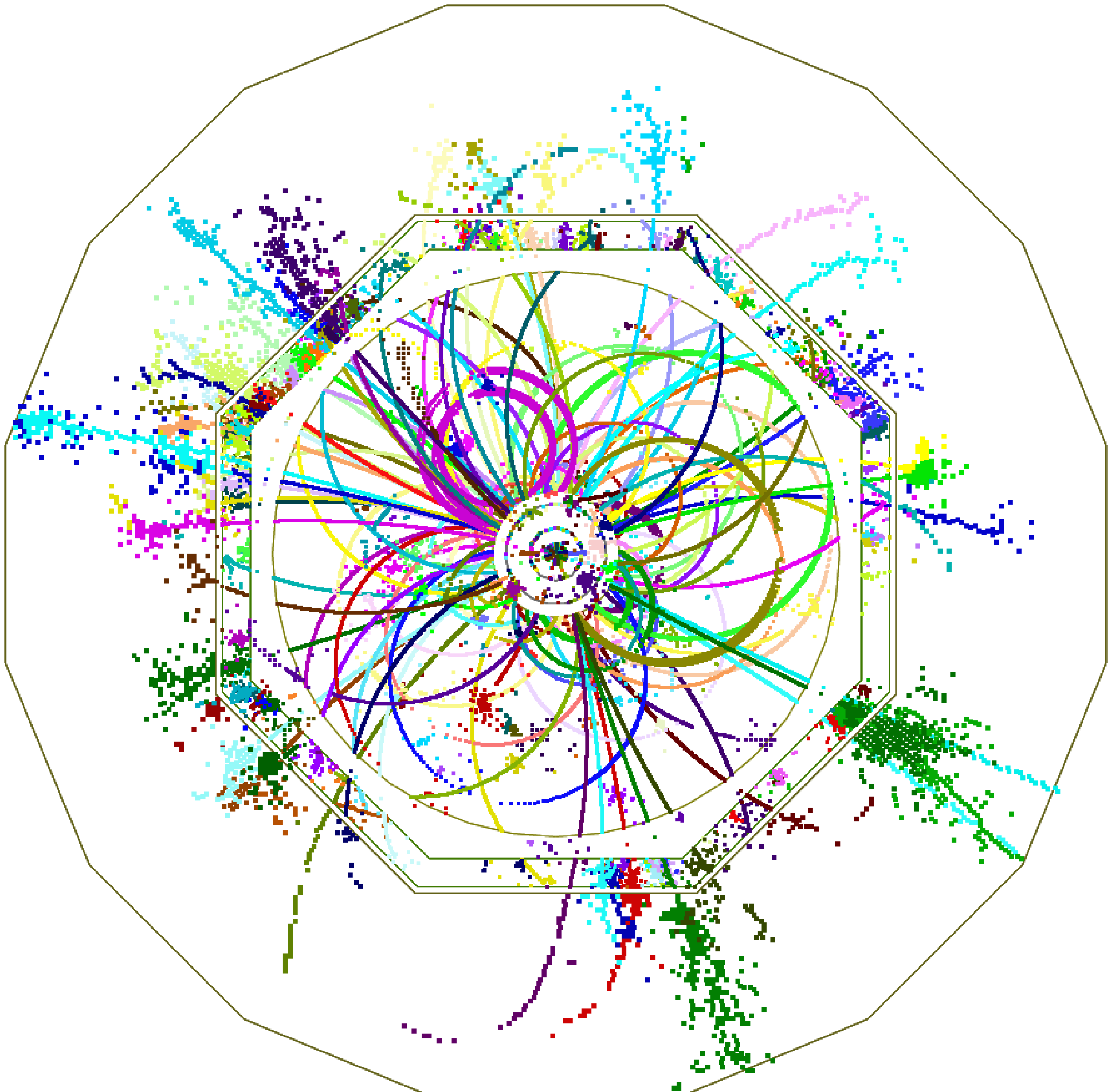

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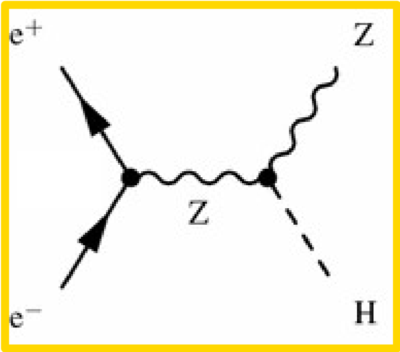
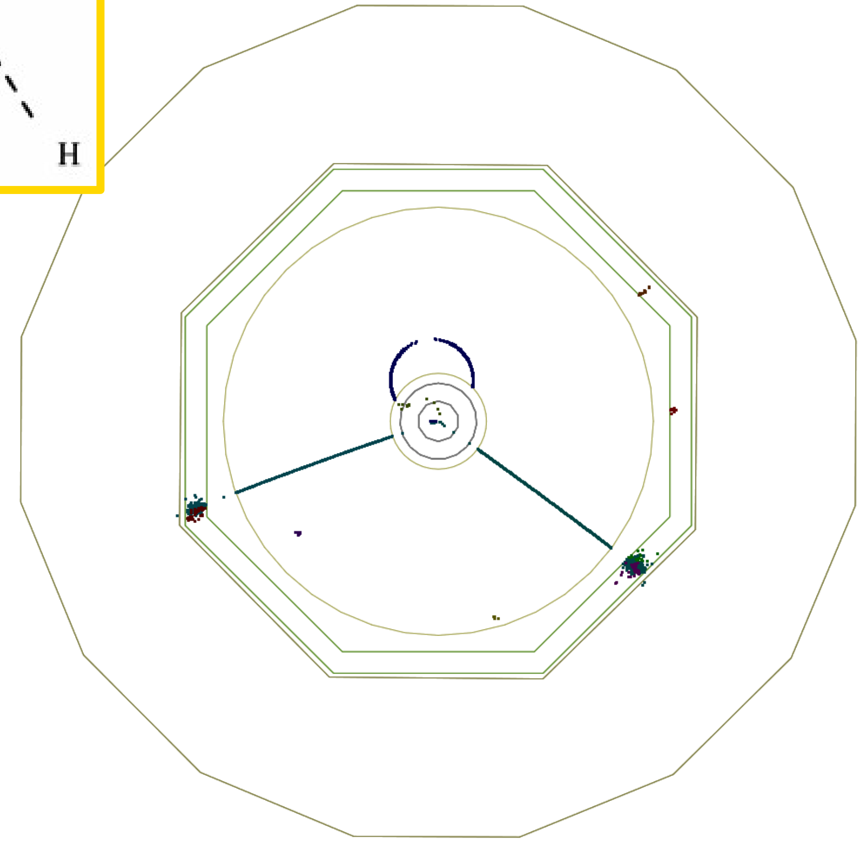
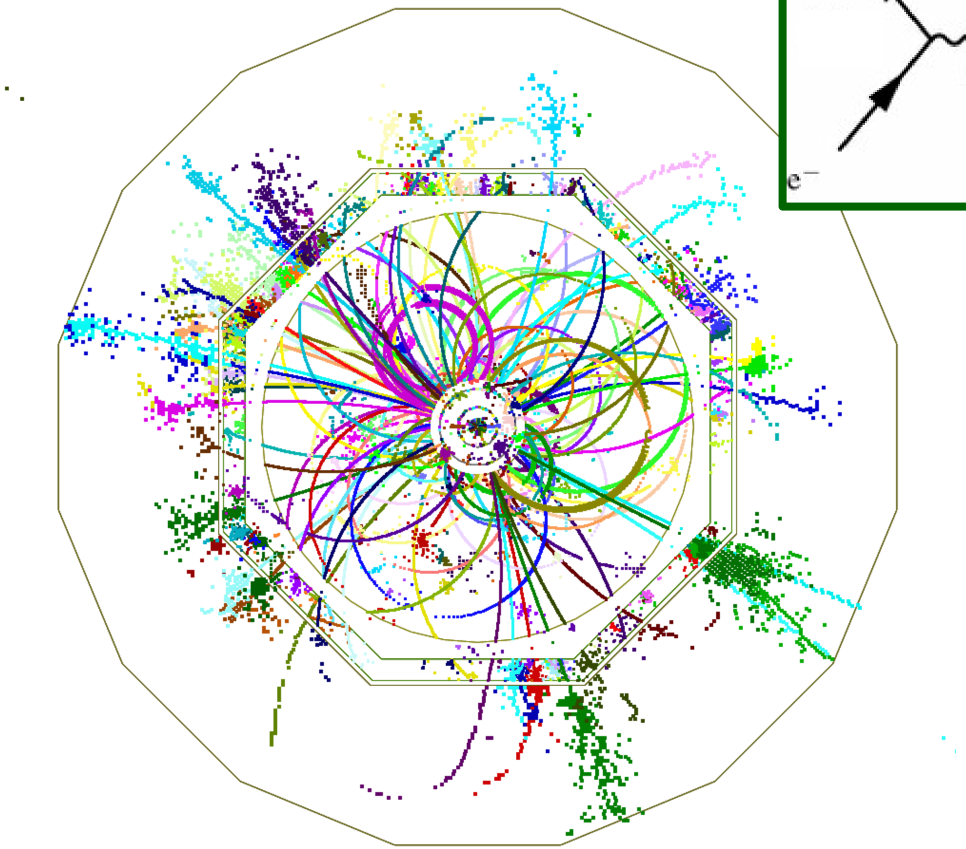
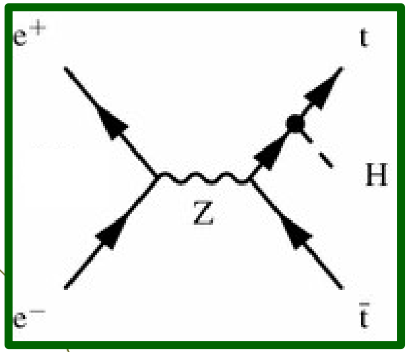




$e^+e^- \rightarrow e^+e^- h$ [invisible h decay]
@ 250 GeV





$e^+e^- \rightarrow tth$ [$tt \rightarrow 6q$, $h \rightarrow bb$]
@ 1000 GeV

Higgs-strahlung process is particularly powerful

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

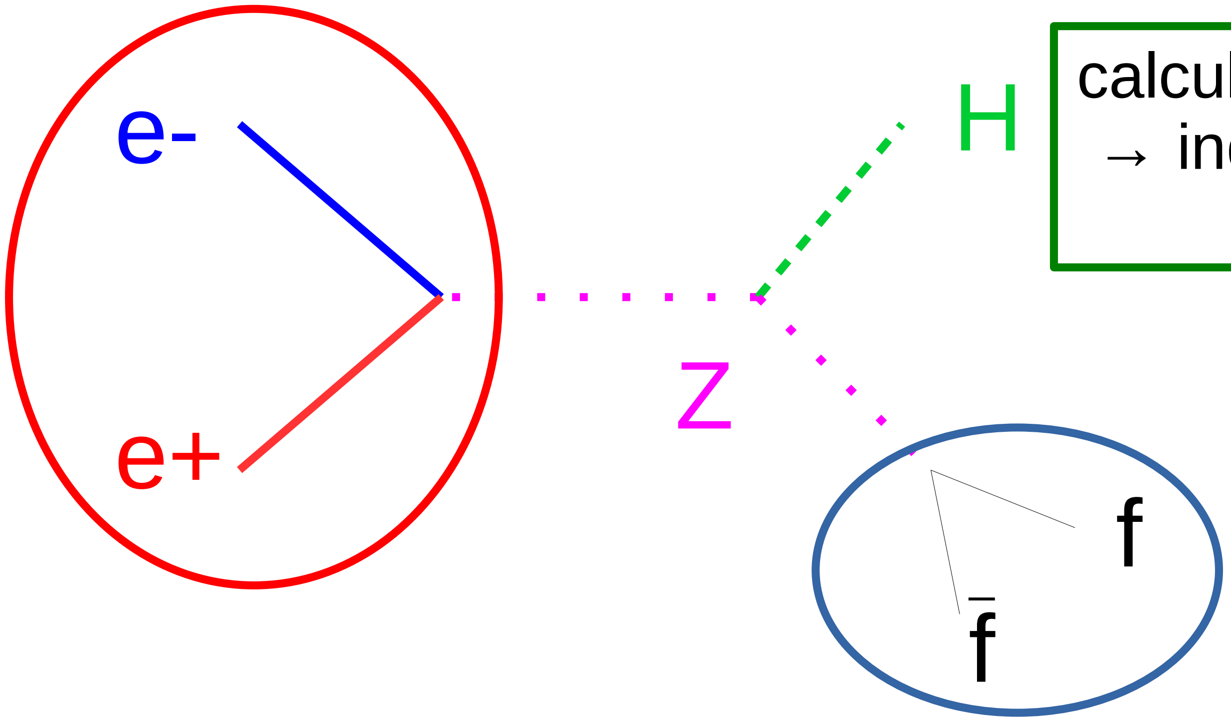
we know initial e^+e^- 4-momentum (at lepton collider)

we precisely measure 4-momentum of Z

→ we can trivially extract 4-momentum of “H”

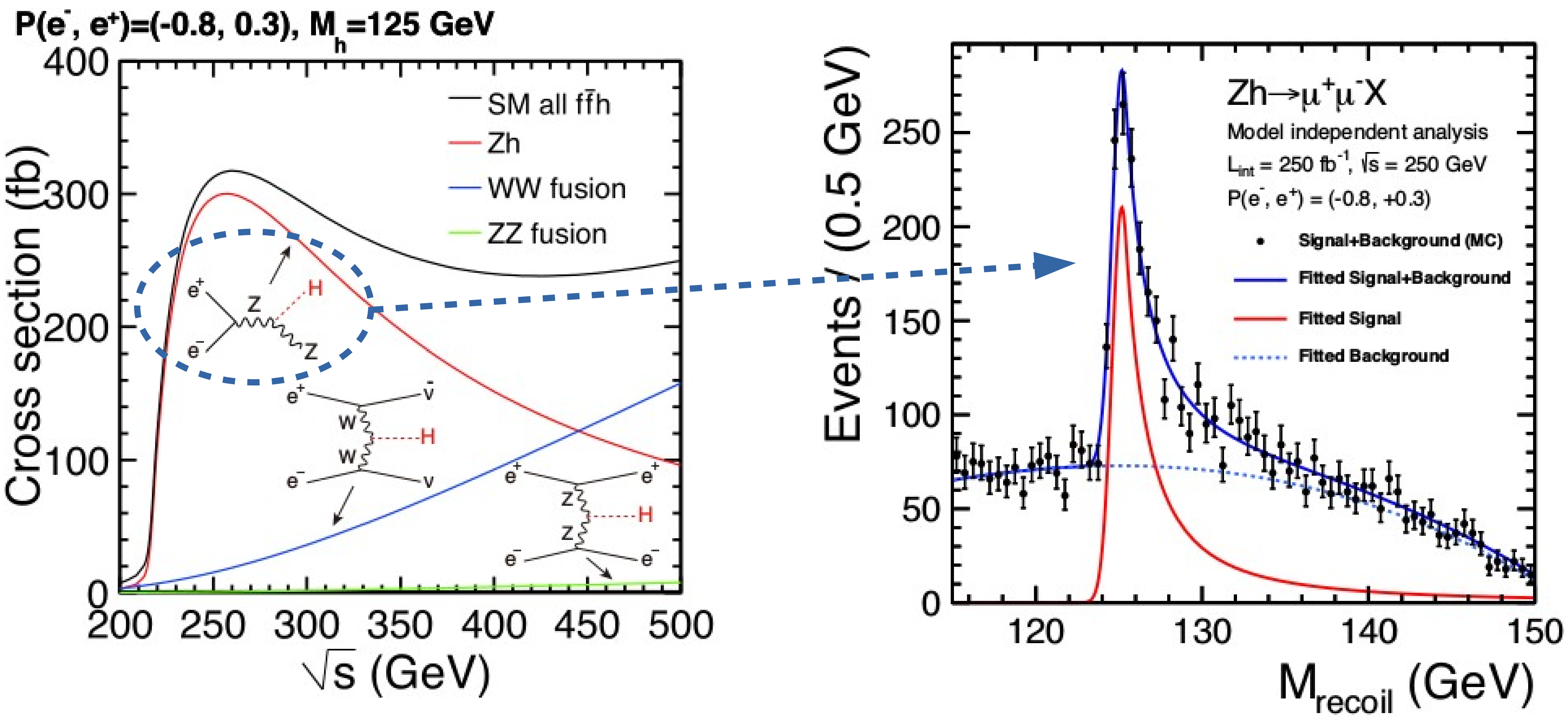
select Higgs events with **no decay mode bias** (e.g. invisible Higgs)

know this
4-momentum



calculate this 4-momentum
→ indirectly measure
Higgs mass

measure this
4-momentum



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

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

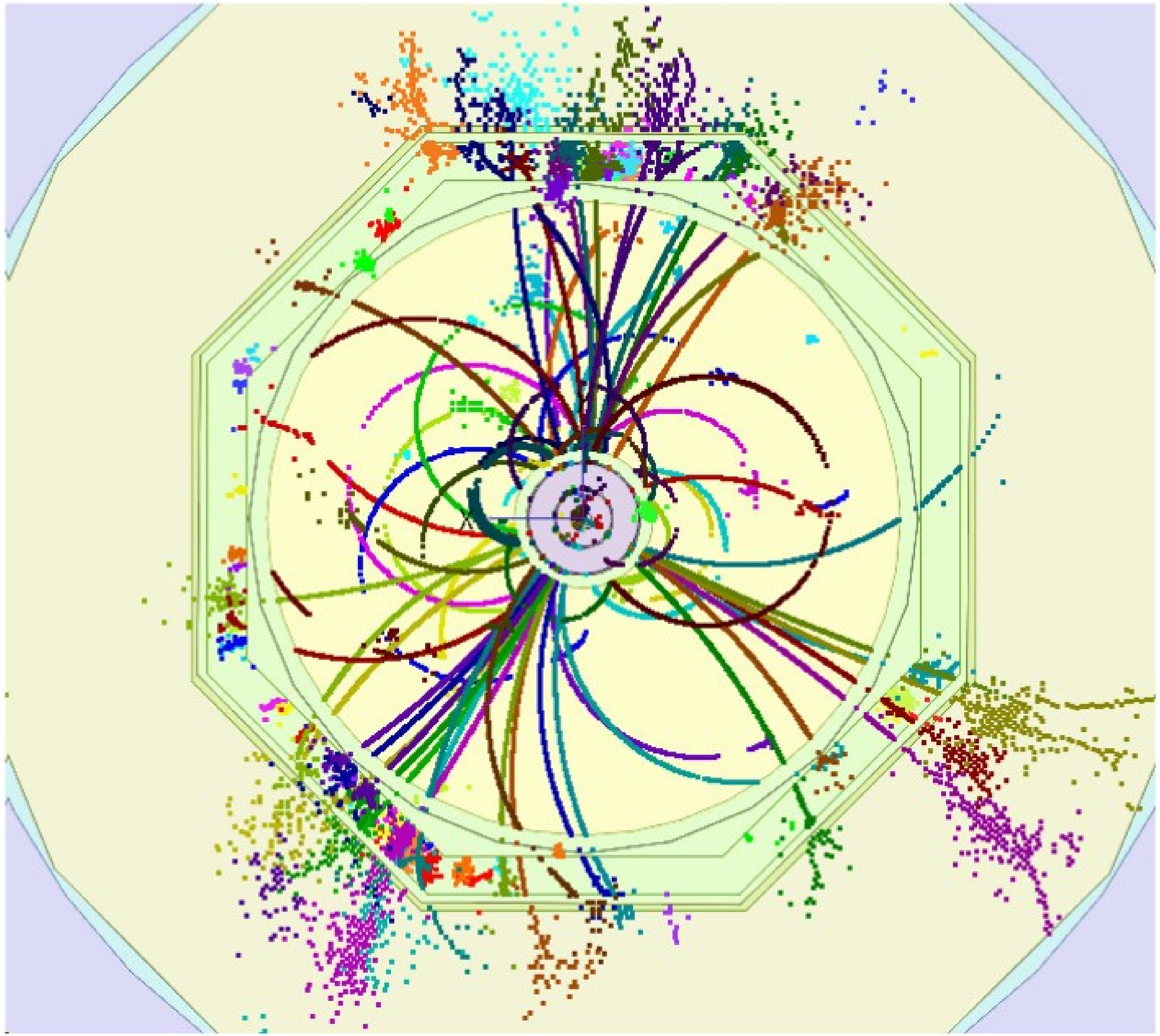
many processes will produce 1 or more W, Z, H

these usually (~70%) decay to $q\bar{q}$

→ shower

→ hadronise

→ jets



hadronic jet:

charged hadrons

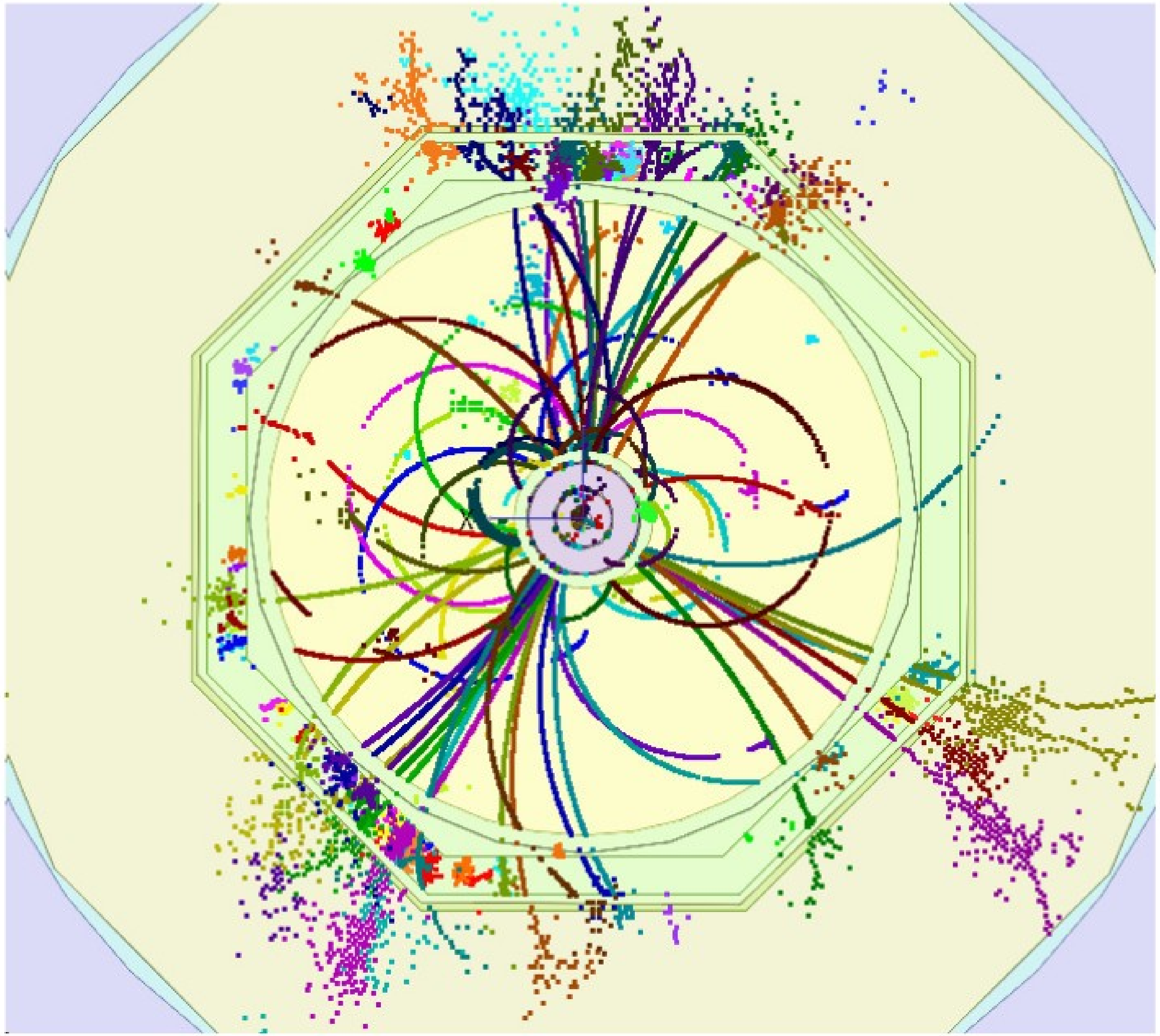
pions, kaons, protons …

photons

from pi0, eta, ... decays

neutral hadrons

K^0_L, neutrons, …



hadronic jet:

charged hadrons

pions, kaons, protons …

ave. ~65% of energy

photons

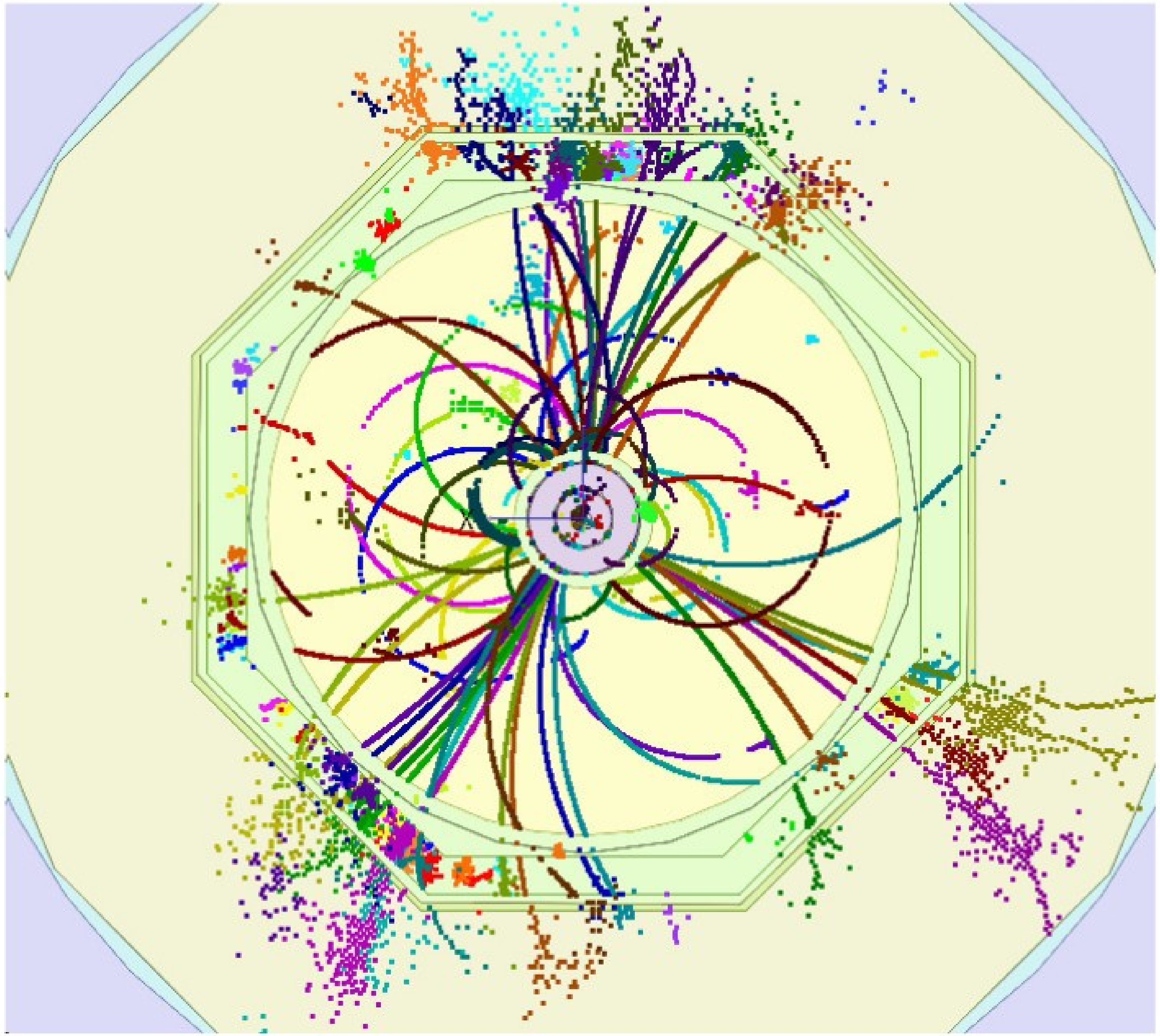
from pi0, eta, ... decays

ave. ~25% of energy

neutral hadrons

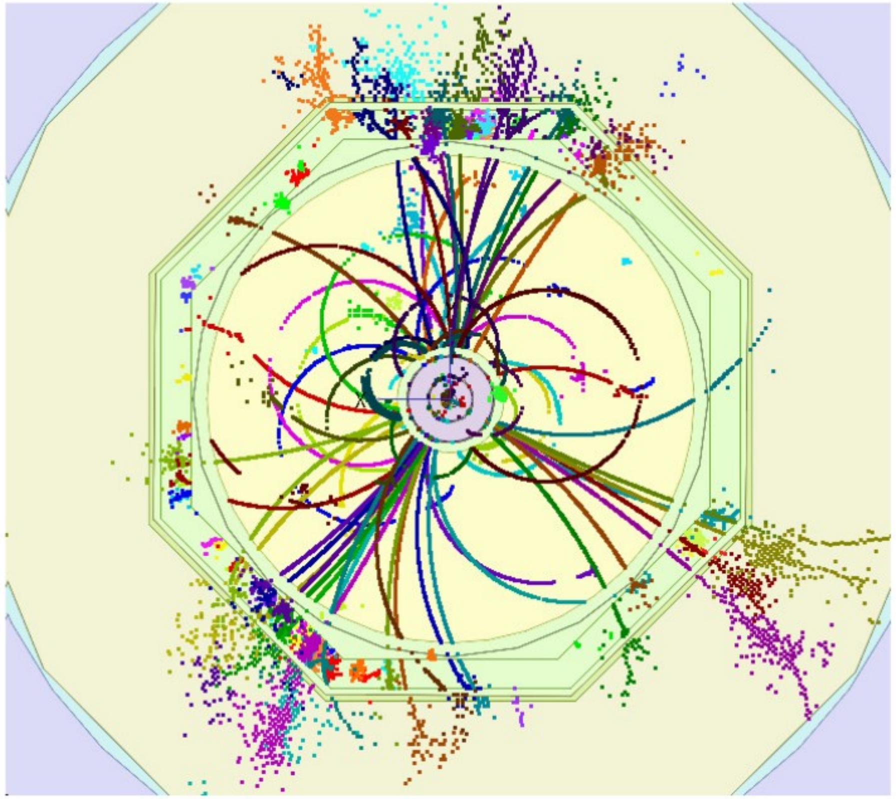
K^0_L, neutrons, …

ave. ~10% of energy



how should we measure jet energy ?

detector performance requirements



track momentum

impact parameter

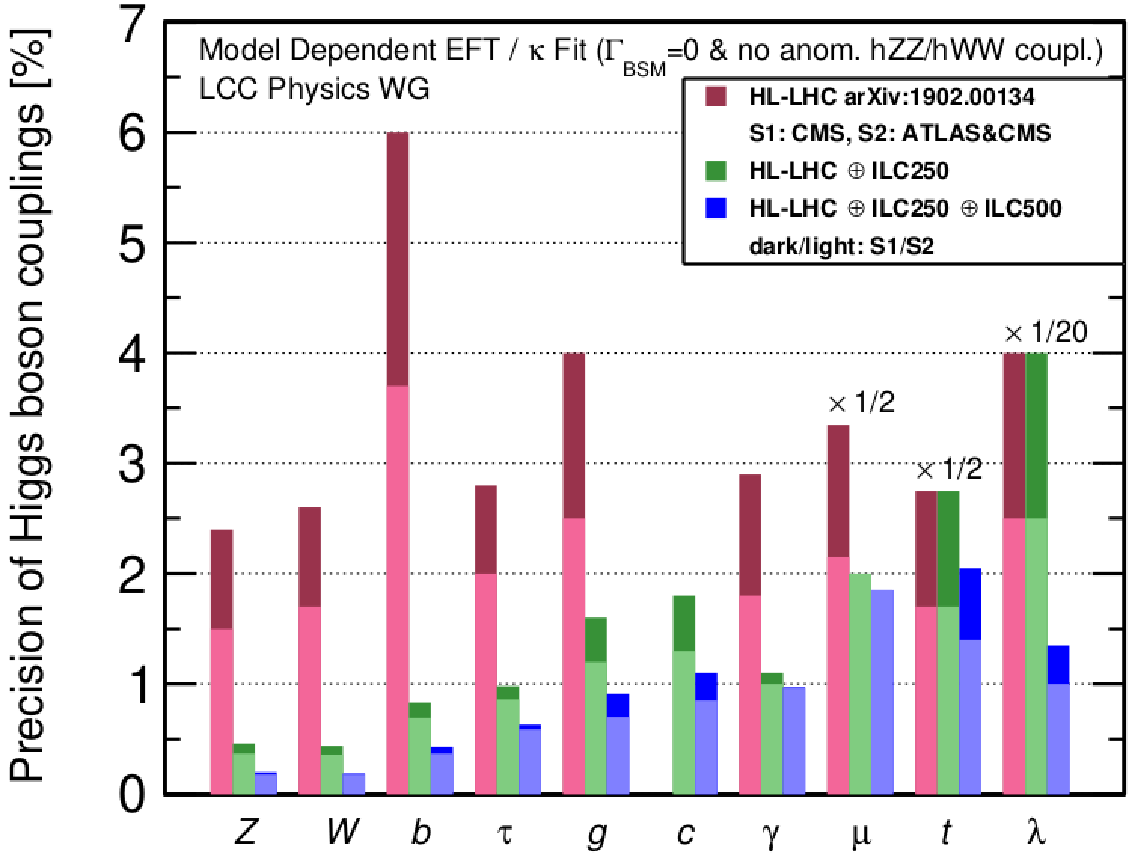
transparent tracker

jet energy

cover all solid angle around collision

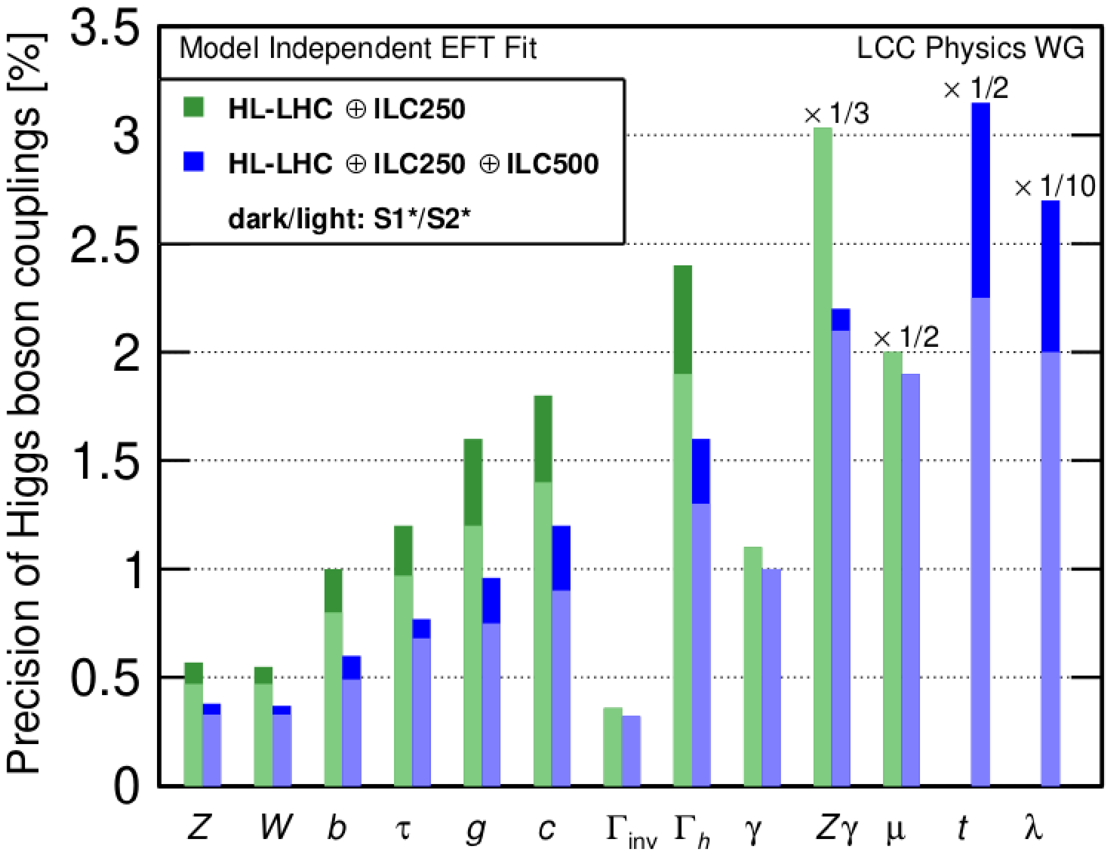
precision on Higgs boson couplings based on realistic simulation and analysis

compared to **HL-LHC-only**



Higgs coupling to …

model independent fit possible at ILC



arXiv:1903.01629

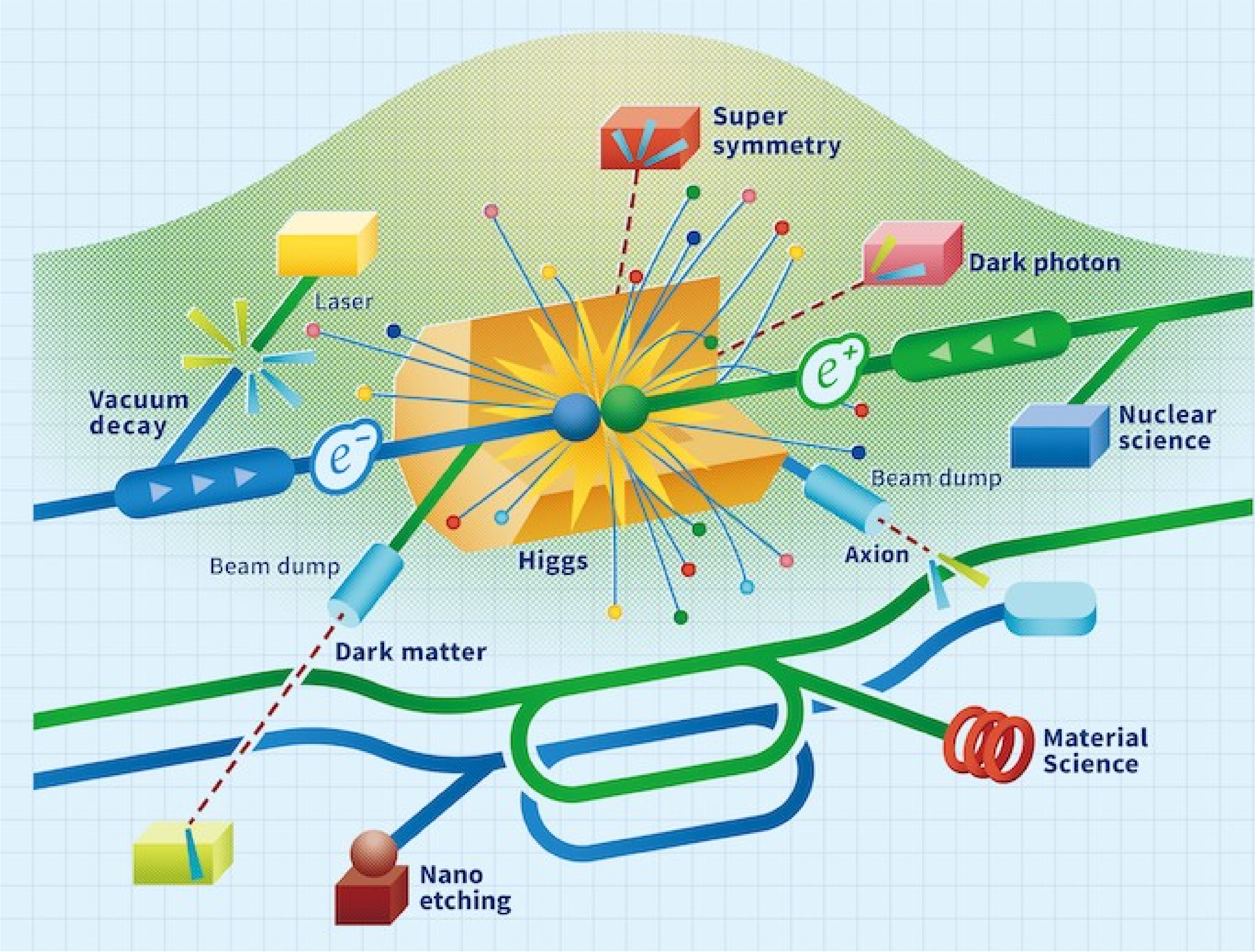
Insight through Accelerators.
KEK 2021

ILC facility

unique e^- & e^+ beams
high intensity
high energy
high quality

→ potential for studies
beyond Higgs,
beyond particle
physics

new ideas welcome !



Green ILC

linear accelerator and **super-conducting technology** were chosen because they minimize energy loss

none the less, ILC operation requires 111 MW (at 250 GeV) assuming current energy mix: 320 kton CO_2 per year

→ continue development of energy saving technologies for ILC

→ use of waste energy (heat) by local industry

→ encourage and prioritize renewable energy sources

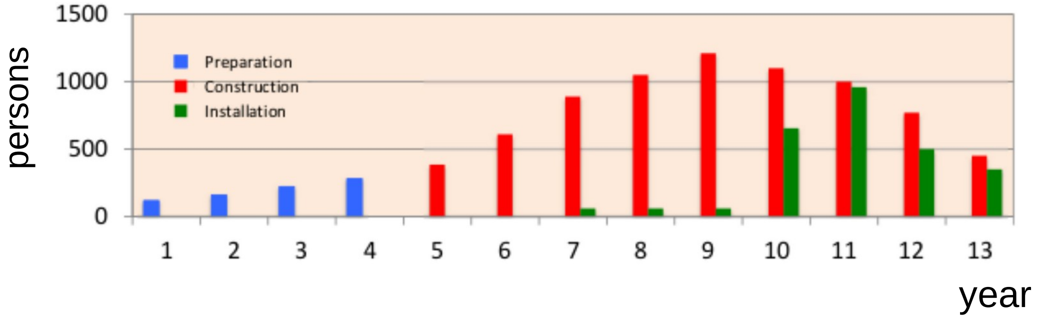
→ encourage local forestry industry: wooden construction

ILC project

ILC is a large project

many skilled human resources
extensive production facilities
construction 635.0 − 702.8 GJPY
annual operation 36.6 − 39.2 GJPY

Summary of the ILC Advisory Panel's Discussions to Date after Revision (2018)



→ a true international project is essential

IUPAP International Union of Pure and Applied Physics

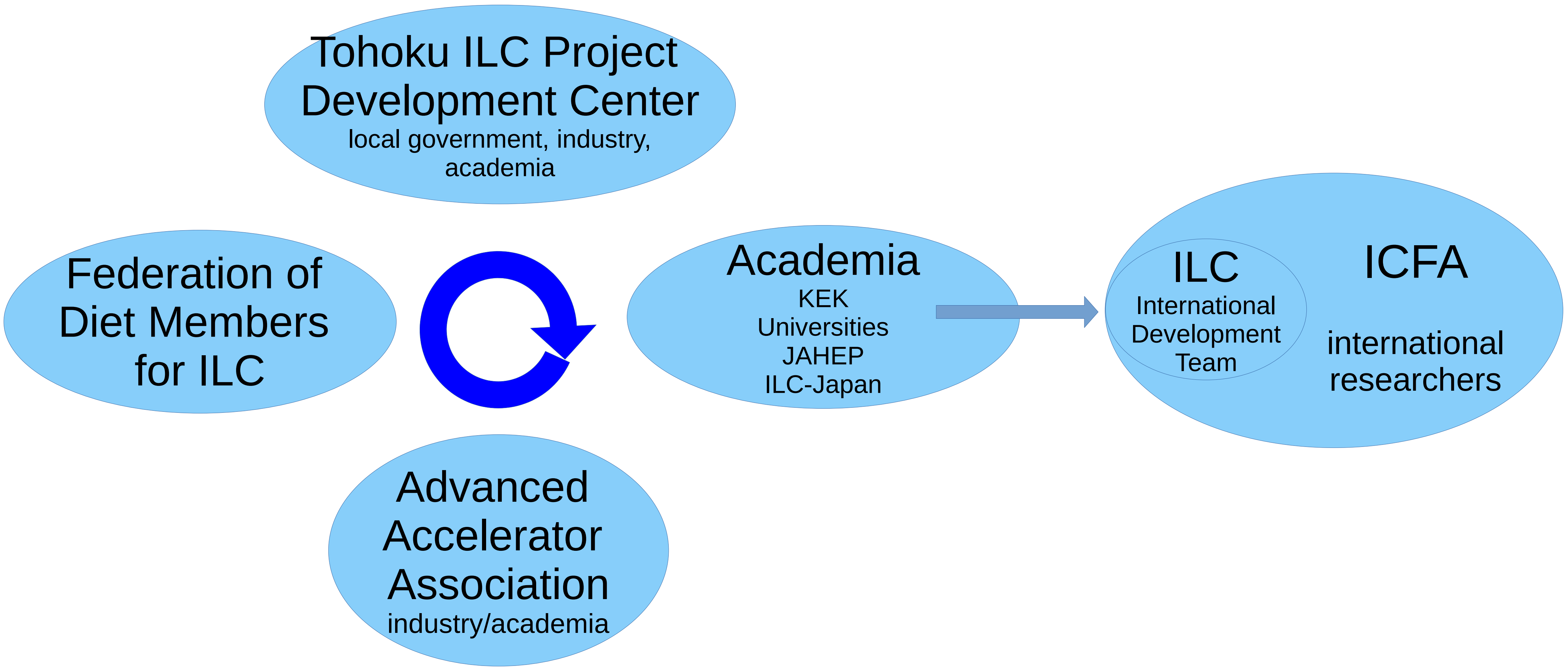
C11 Commission of Particles and Fields

ICFA International Committee for Future Accelerators

International Development Team

S. Henderson	**Chair**	USA
T. Schoerner-Sadenius	**Secretary**	Germany
K. Jakobs	[ECFA chair]	CERN Member States
F. Gianotti	[CERN DG]	CERN Member States
T. Behnke		CERN Member States
N. Lockyer	[FNAL director]	USA
J. Incandela		USA
Z. Huang		USA
I. Koop		Russia
V. Obraztsov		Russia
Y. Wang	[IHEP director]	China
G. Taylor		Other Countries
I. Bediaga		Other Countries
S. Krishnagopal		Other Countries
T. Mori		Japan
M. Yamauchi	[KEK DG]	Japan
M. Roney		Canada
H. Schellman	Chair of the IUPAP C-11 (ex officio)	

ILC project promotion



from late 1980s/’90s → several linear collider studies JLC, GLC, NLC, TESLA, ...

2005 — **ILC** Global Design Effort — technical design

2013 — Linear Collider Collab. — site-specific design

2020 — Internl. Develp. Team

~2 y — .... — set up pre-lab organisation

~4 y — **ILC pre-lab.** — engineering design, set up ILC lab.

~9 y — **ILC laboratory** — construction

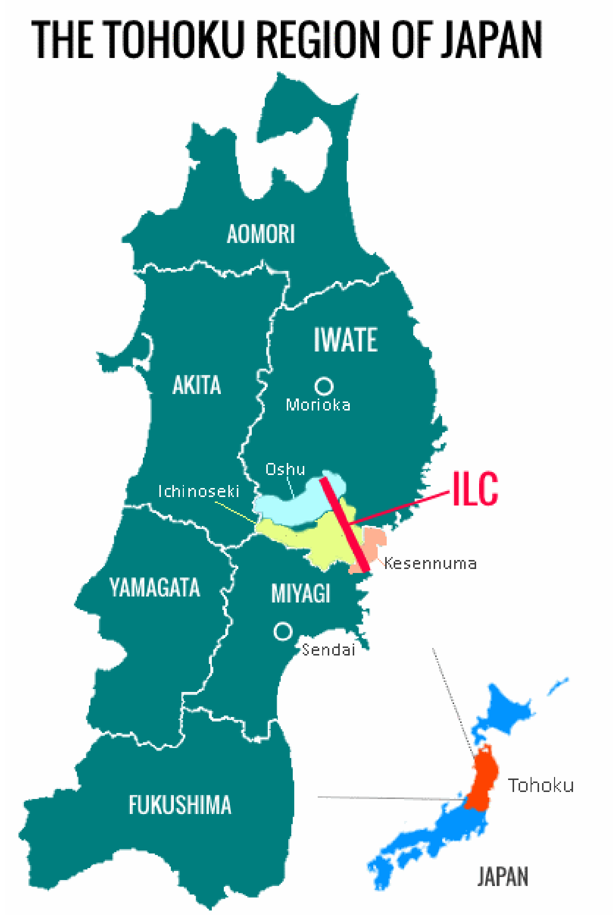
>20 y — operation & upgrades

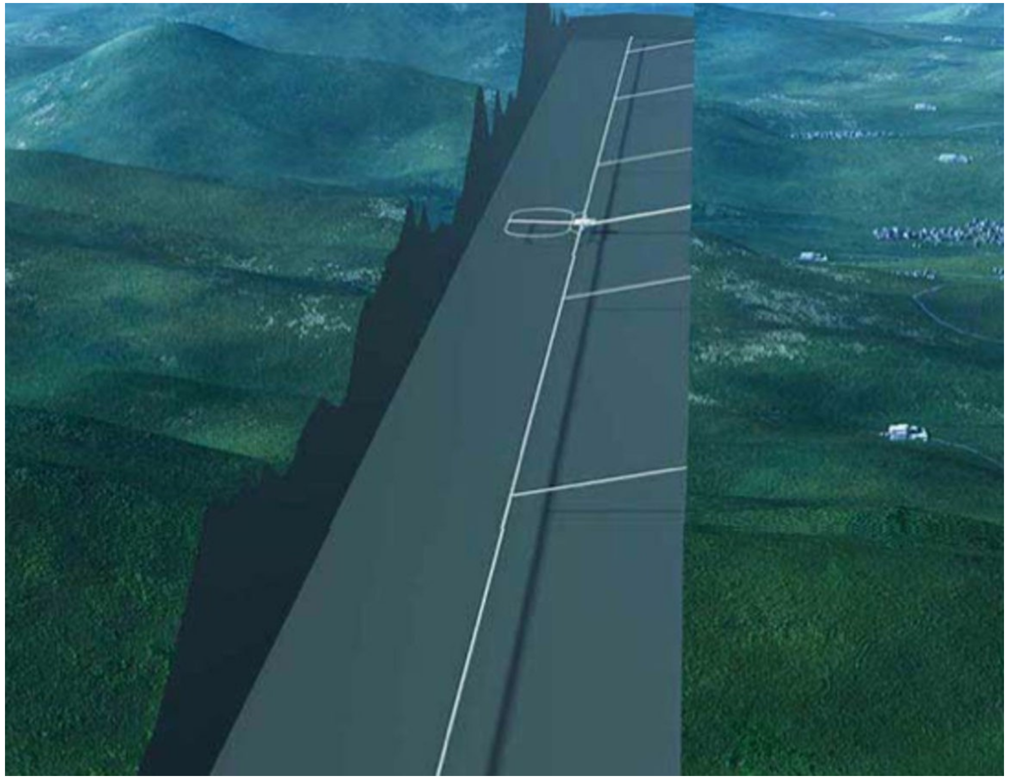
Strong consensus in world-wide HEP community for electron-positron Higgs factory (US, Europe, Japan, ...)

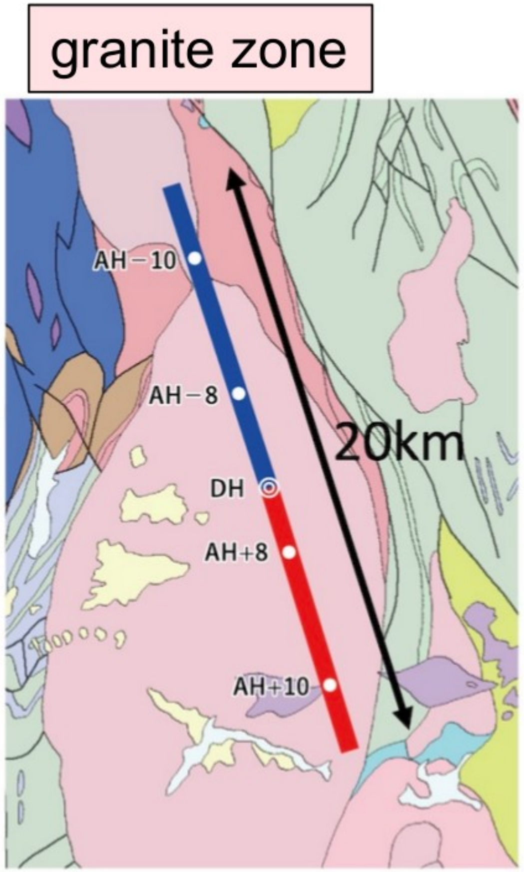
ILC is most technologically developed option

Japanese government considering
whether to host ILC in Japan

candidate ILC site







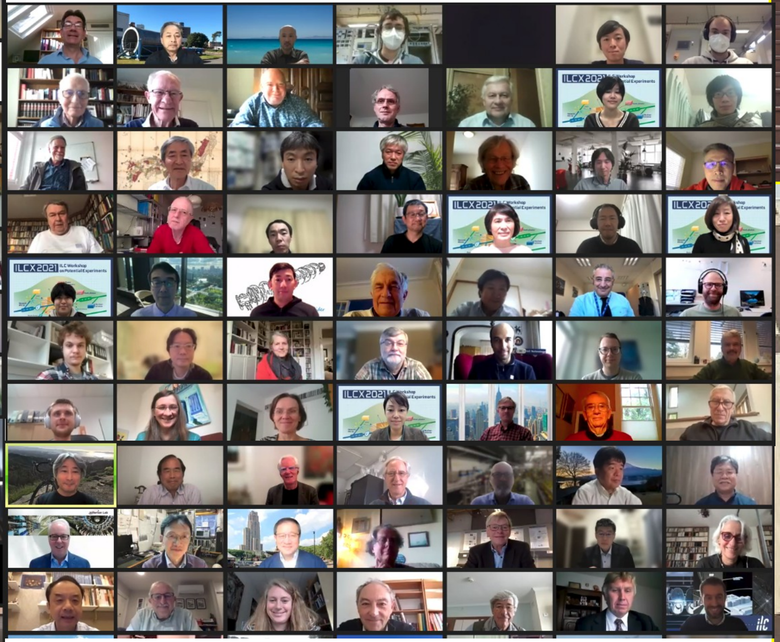
selected as candidate site by
scientists from Japan and abroad


international linear collider
国際リニアコライダーを東北に
Welcome to the ILC kitakami site!


ILCで大原を自慢の町に!!
〜夢と・希望と・未来をここに〜
We support the International-
Linear Collider Project.
ILC
Iwate
Ichinoseki

@Iwate_ilc
@ichinoseki_ilc
@Oshu_ILC
@ILCsupporters
@ilc_tsushin
@LCNewsLine

we want ilc !!



summary

Higgs particle presents a once-per-generation opportunity
to look into our universe's beginnings, perhaps its destiny

ILC uses technologies developed around the world
technologies have been proven

ILC is an ideal facility to enable this study of the Higgs
it requires joint effort from the worldwide community:
governments, local communities, industries, academia

Hosting ILC in Iwate/Japan/Asia will promote position at the forefront of
science, technology, culture, and society through the 21st century