Future e^+e^- Accelerator-based Experiments

Asia–Europe–Pacific School of
High Energy Physics
at Quy Nhon, Vietnam

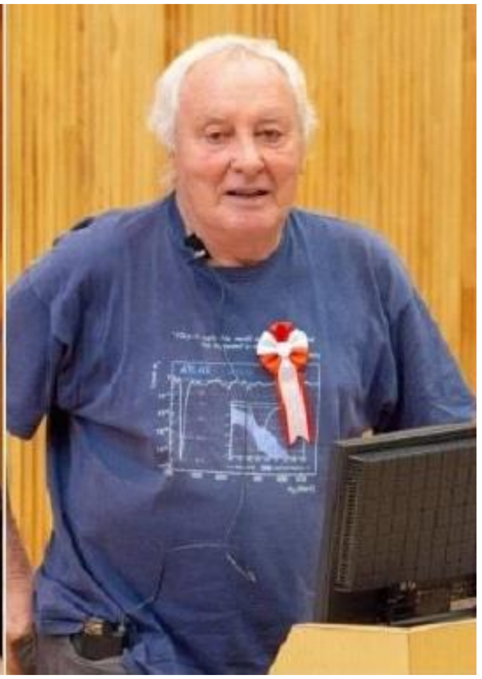
16 September 2018

Sachio Komamiya
Waseda University
The University of Tokyo

I collected information on ILC, CLIC, CEPC, and FCCee from these leading physicists

Shinichiro Michizono
KEK, for ILC

Lyn Evans, CERN
for LCC

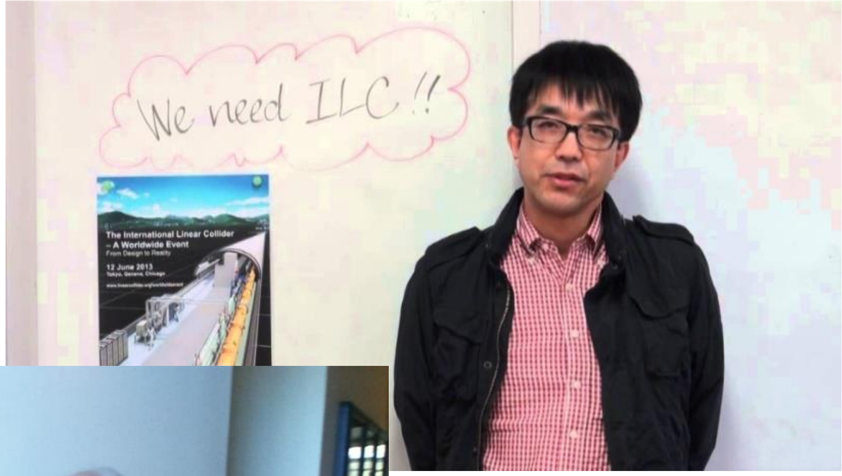


Steinar Stapnes, CERN
For CLIC

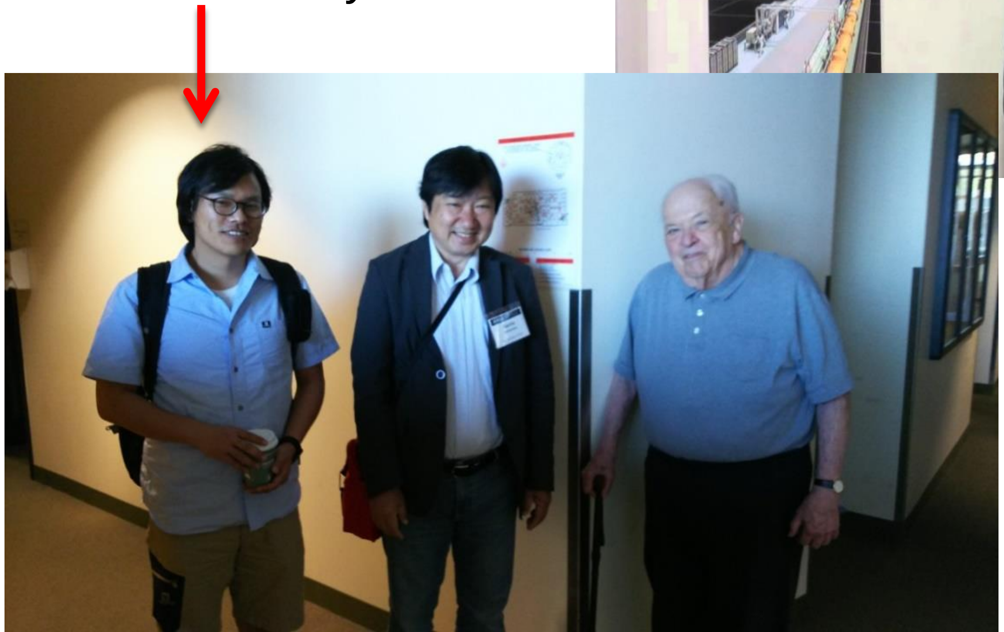
Yifang Wang, IHEP
for CEPC

Phil Burrows, Oxford
For CLIC

Keisuke Fujii, KEK
for LCC Physics



Junping Tian
The University of Tokyo
for LCC Physics



Alain Blondel, Geneva
for FCCee

Menu

1. A short History of e^+e^- Physics

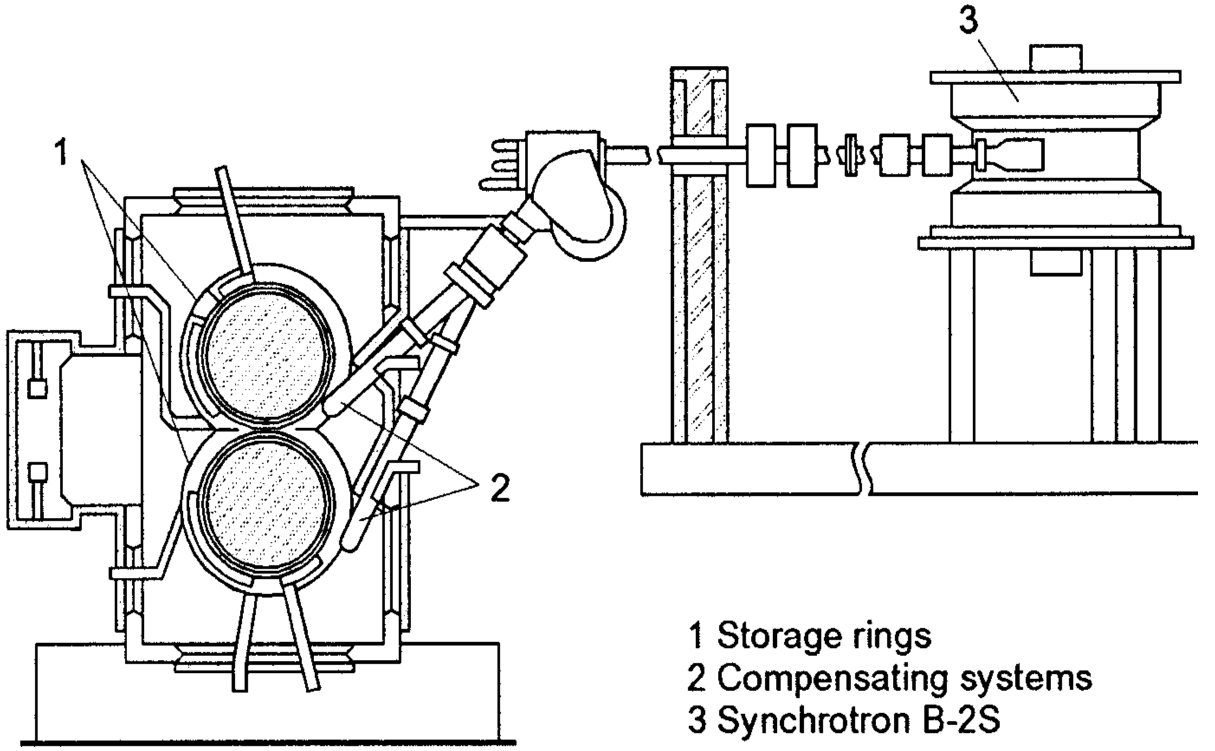
2. Higgs Boson Physics

3. Beyond the Higgs Boson

4. Future e+e- Colliders: ILC, CLIC, CEPC and FCCee

5. Summary

A short History of e^+e^- Physics



Vepp-1 1965

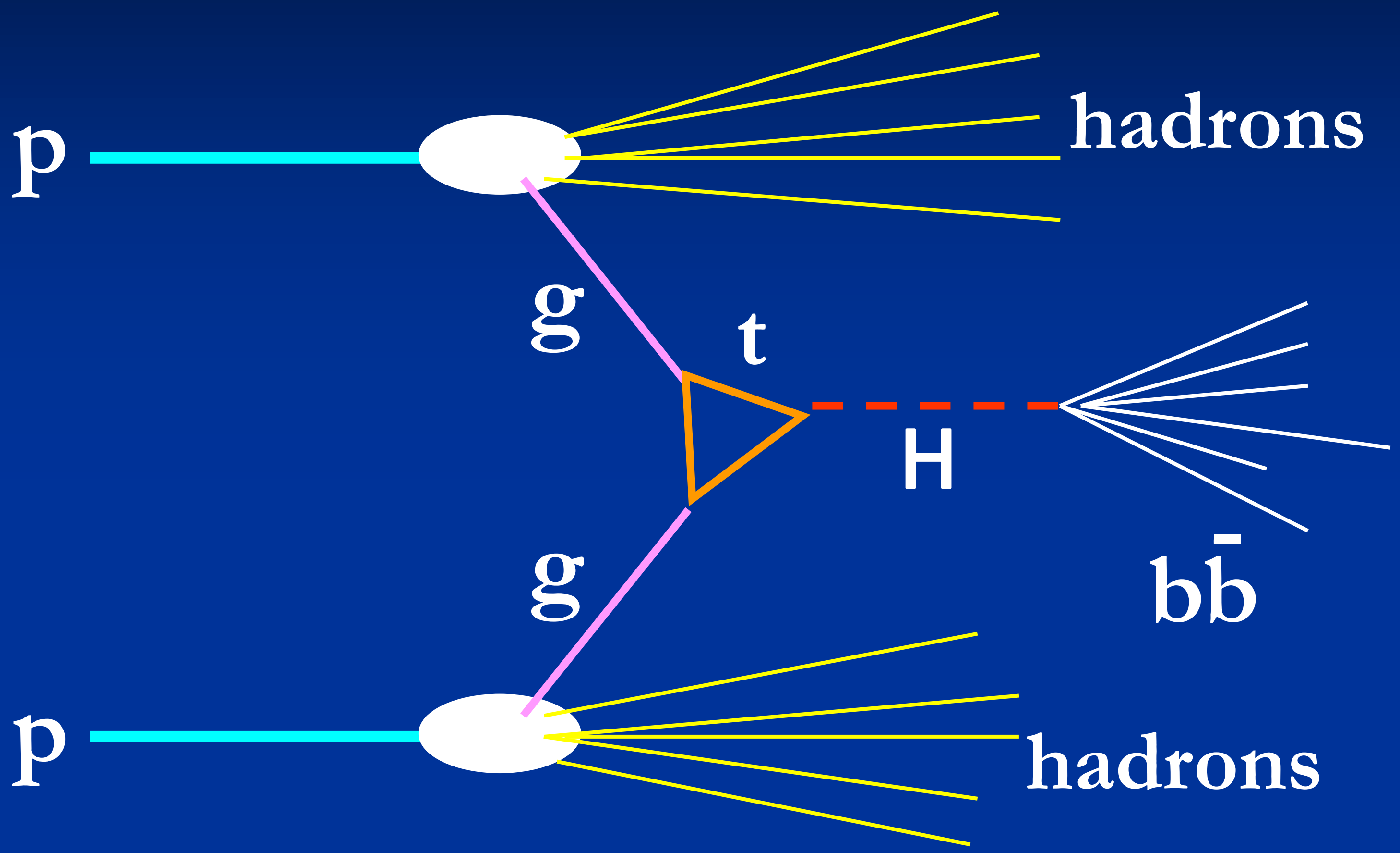
Ecm= 2x0.16 GeV

L= 3×10^{27}[cm^{-2} s^{-1}]

- G.Budker Vepp-1,2 e^-e^-
- G.K.O'Neill (radiation dumping) Princeton-MIT
- F.Amman ADONE
- B.Richter SPEAR
- G.Voss DORIS

We do need both pp and e^+e^- colliders

Proton-Proton Collider

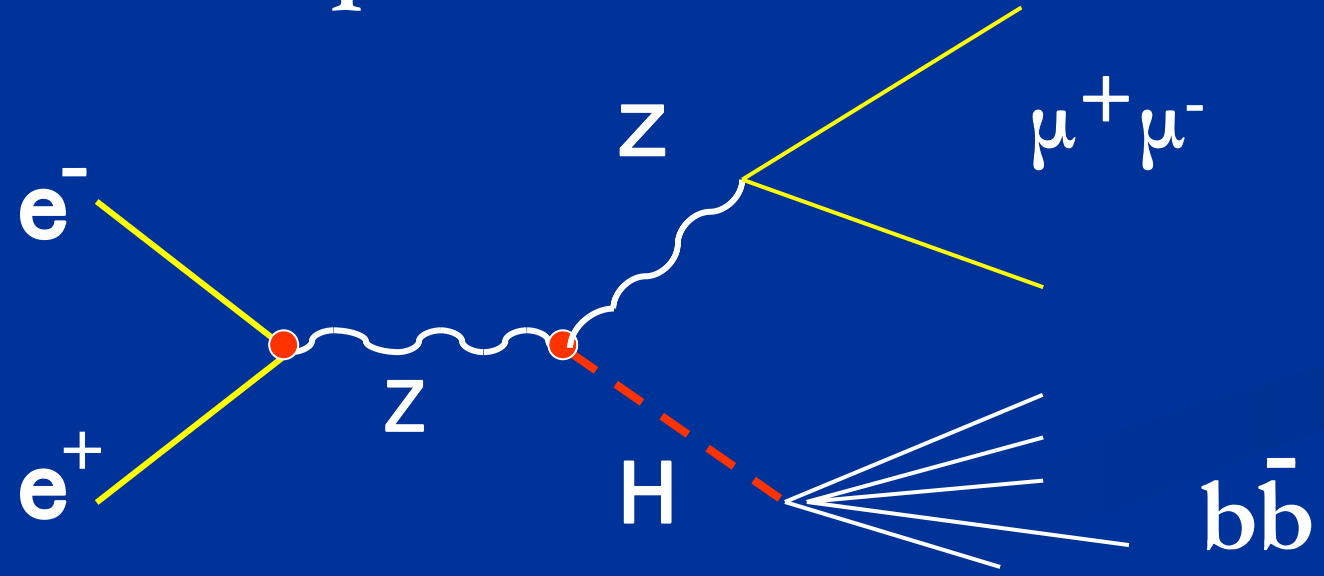


Ex. Higgs Boson

Proton is a composite particle ⇒ processes are complicated
NNLO O(10%)

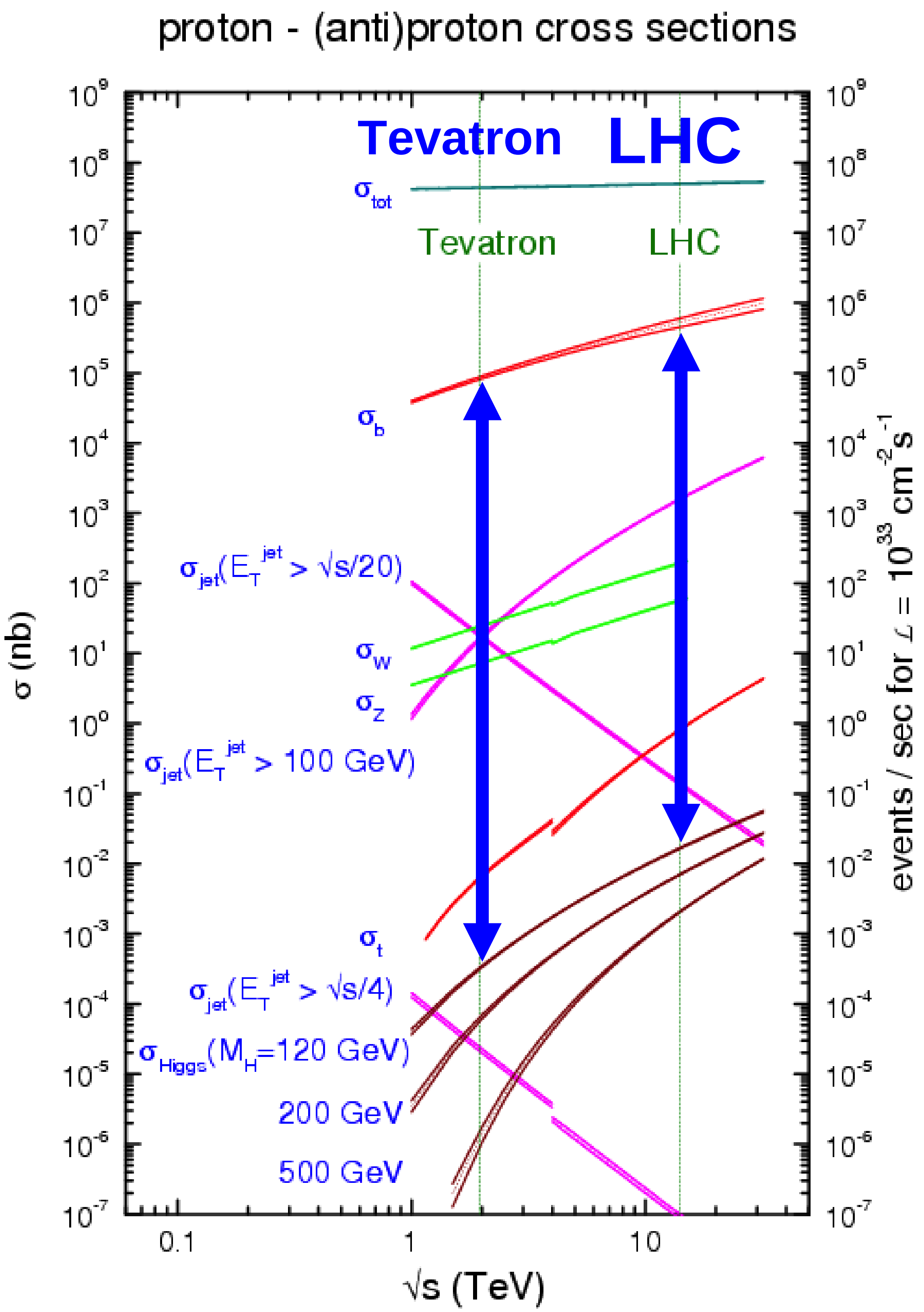
High radiation High event rate
⇒ need a high-tech detector and powerful computing system
BUT Very high energy can be achieved by the current accelerator technology

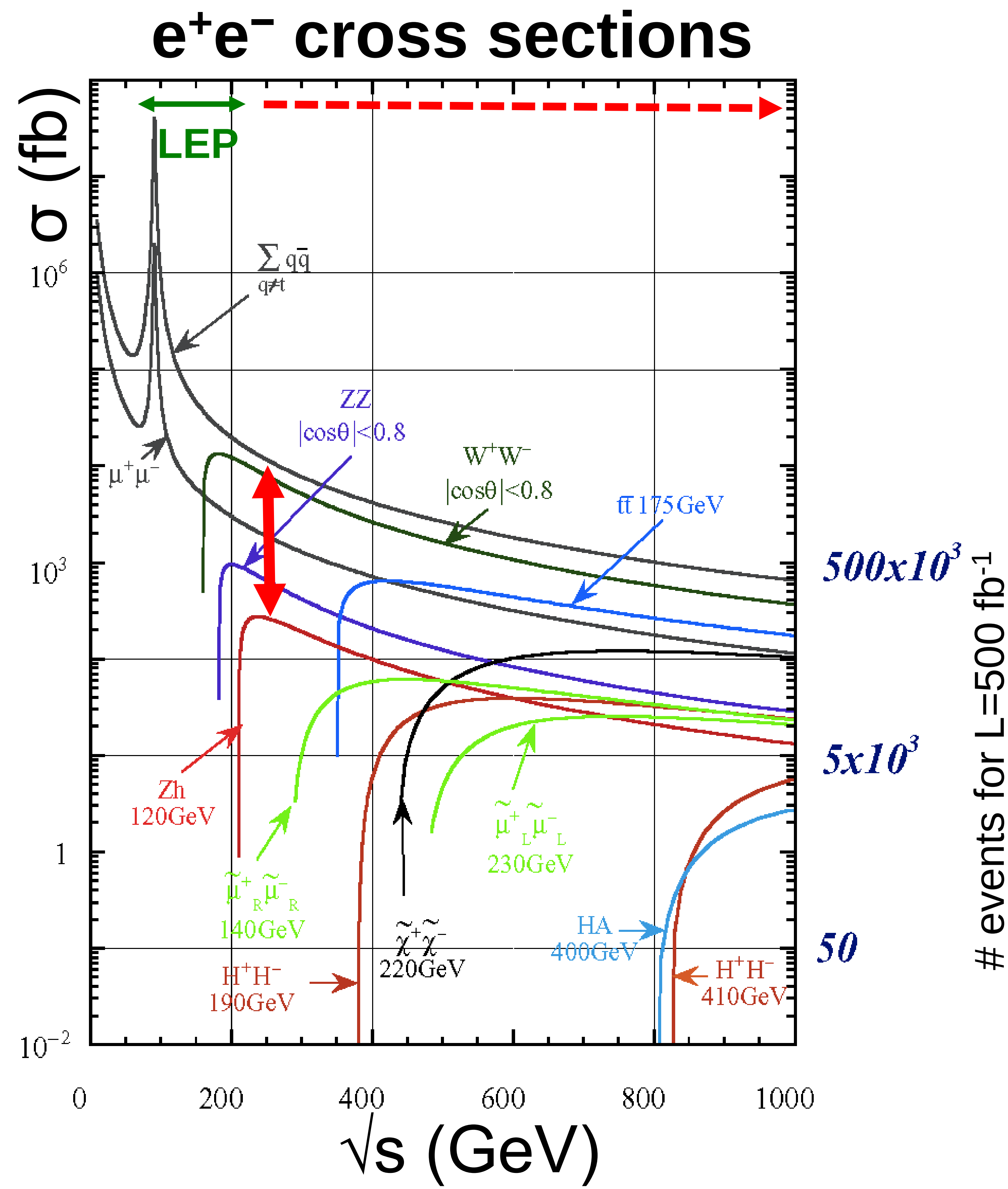
Electron-positron collider



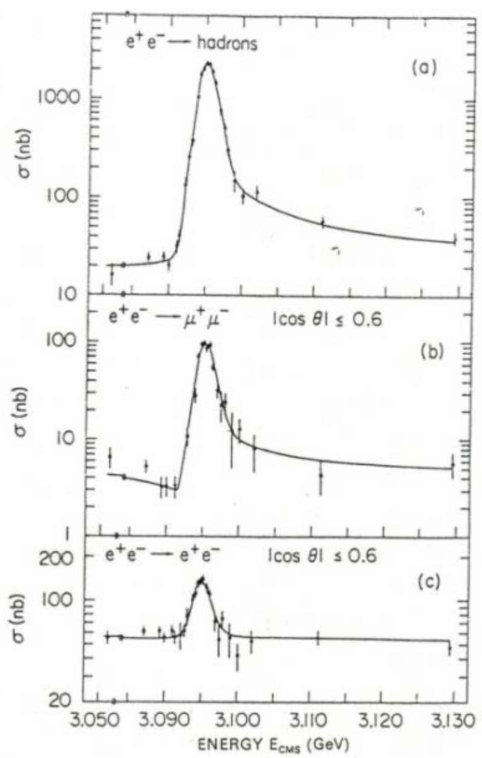
Electron and positron are pont-like elementary particles
⇒ Clean environment.
Processes are simple.
Prediction：O(1%)
State-of-the-are detector can be build

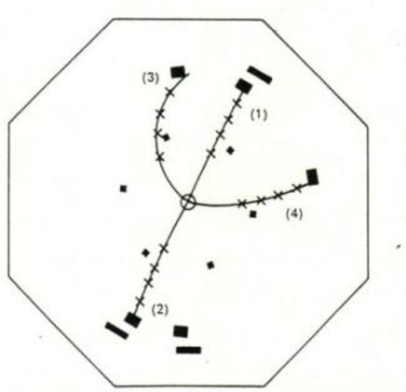
Cross Sections

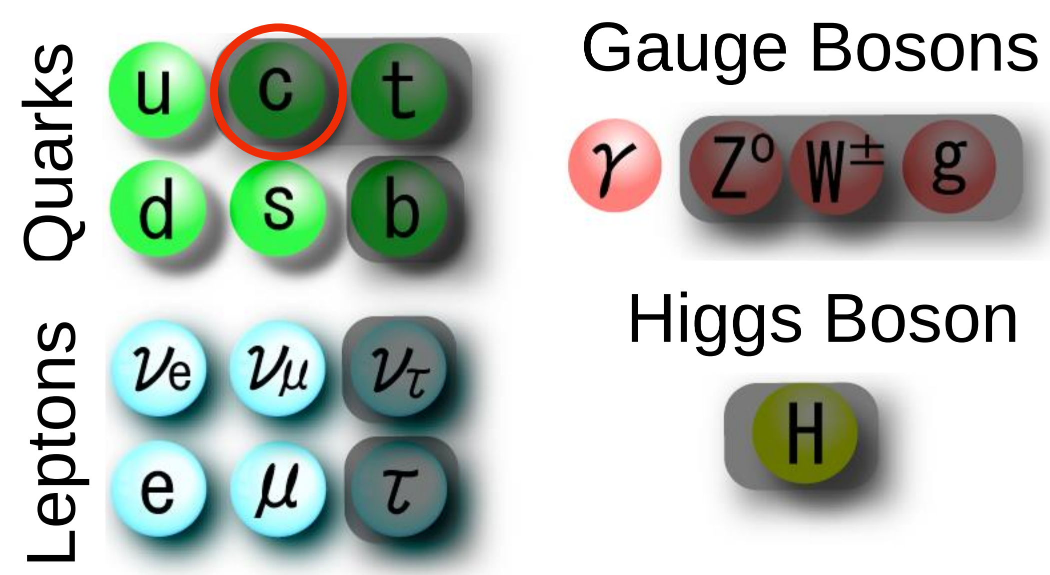


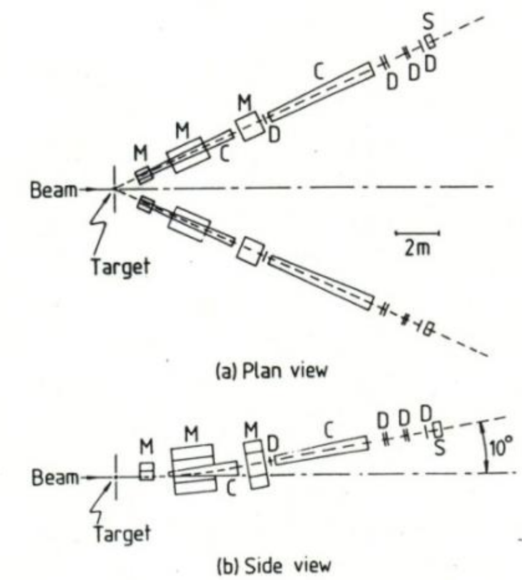


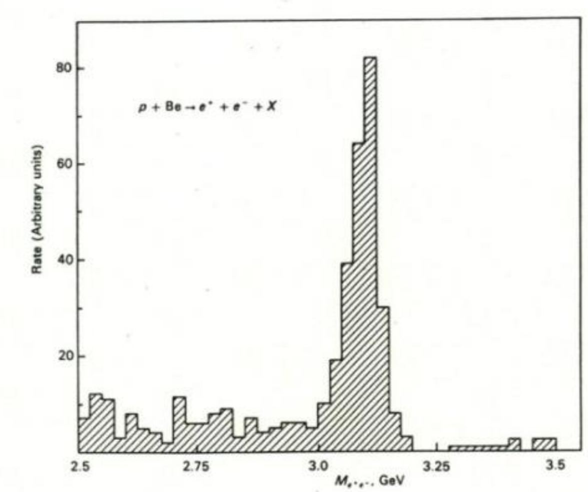
There was a revolution in particle physics！
The 1974 November Revolution
Discovery of J/ψ（charm quark）











$J/\psi = c\bar{c}$ bound state

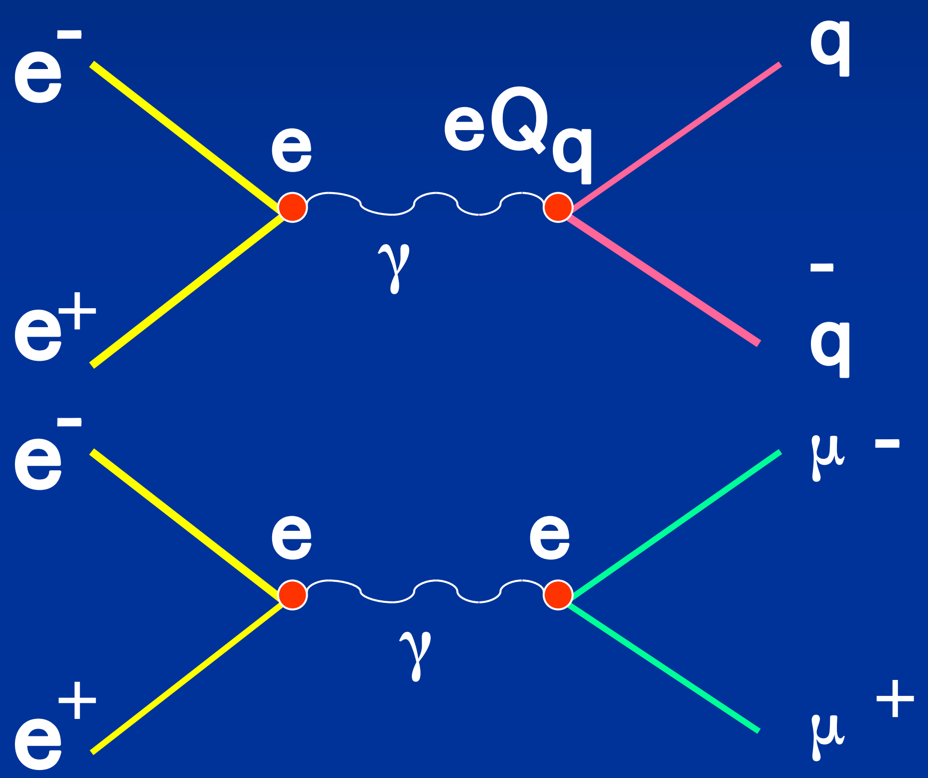
It becomes evident even for experimental physicists that quarks and leptons are the elementary particles of the same level. ⇒ base of The Standard Model

$e^+e^- \rightarrow \psi$ SLAC
Richter et al.

$J \rightarrow e^+e^-$ BNL
Ting（丁）et al.

R-value

How many types of quarks ?

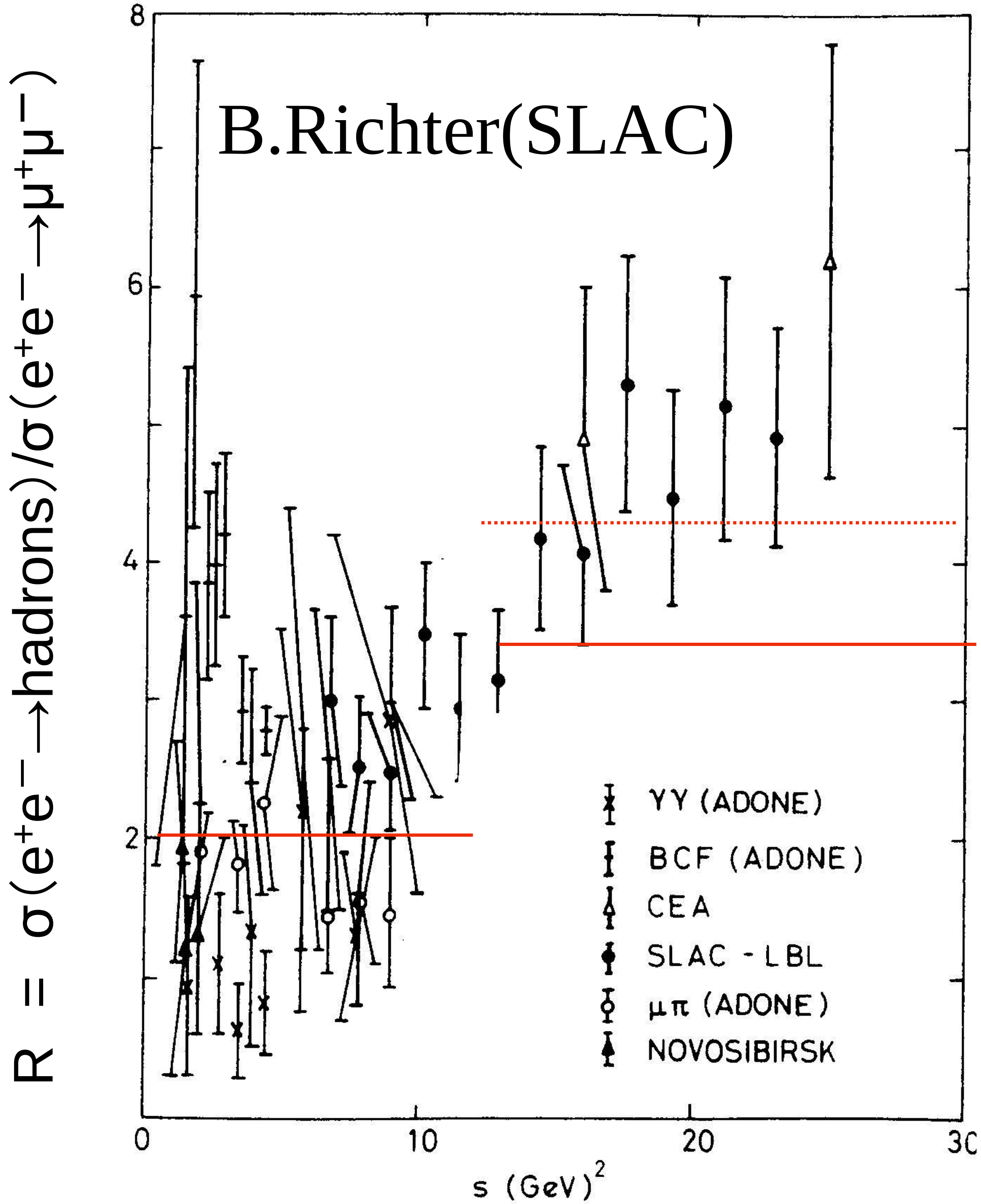


$$\sigma(ee \longrightarrow q\bar{q}) \sim \sum_q e^4 Q_q^2$$

$$\sigma(ee \longrightarrow \mu^+\mu^-) \sim e^4$$

$$R = \frac{\sigma(ee \longrightarrow q\bar{q})}{\sigma(ee \longrightarrow \mu\mu)} = \sum_q Q_q^2 = \begin{cases} 2/3 & \text{uds} \\ 2 & \text{uds x3} \\ 4/9 & \text{udsc} \\ 4/3 & \text{udsc x 3} \end{cases}$$

Eve of the November Revolution



R looks monotone increasing function with s (= Ecm²). Parton model must be wrong

B.Richter

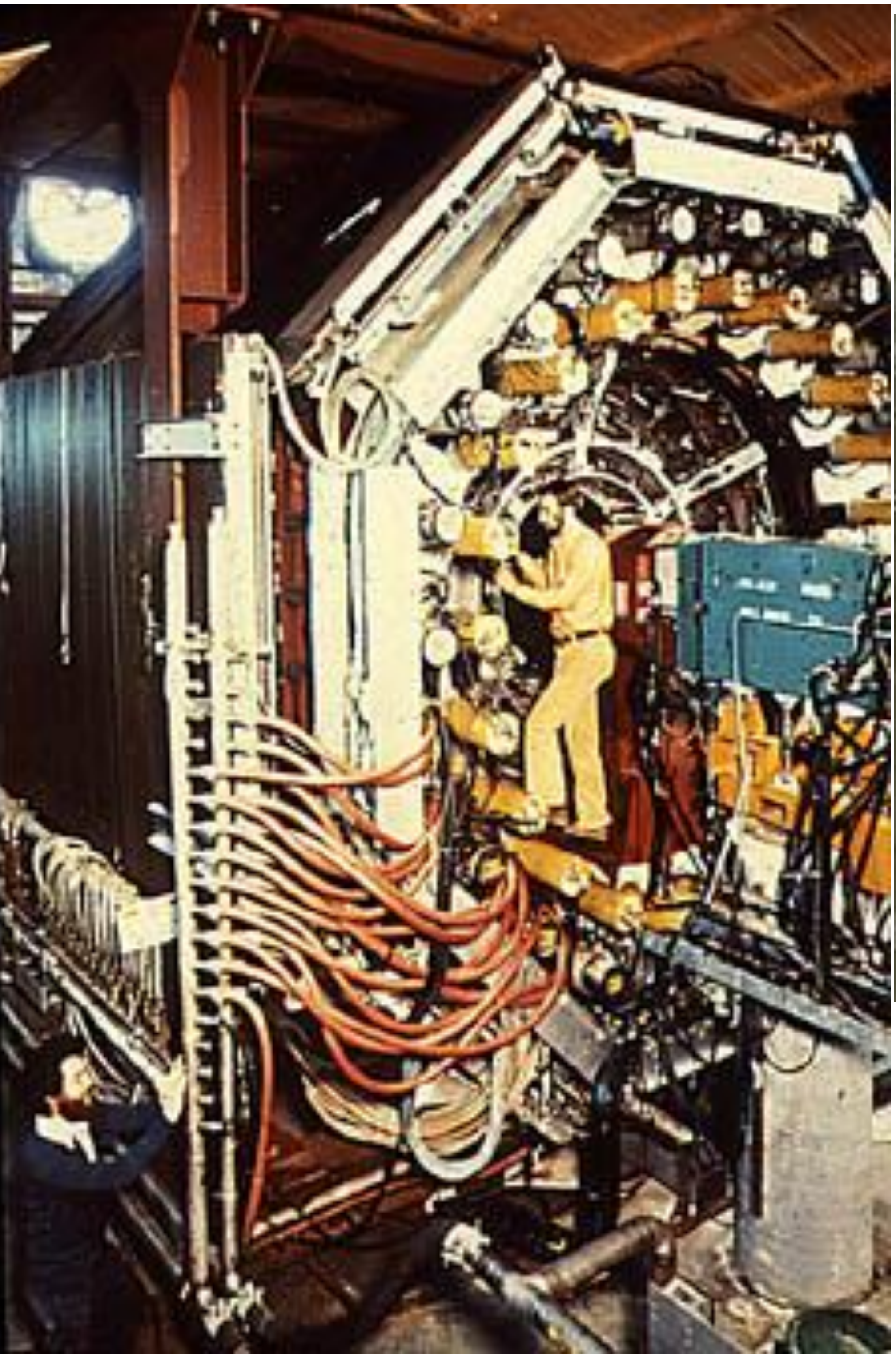
Theoretical Predictions of the R-value ICHEP 1974 Summer in London

J.Ellis (CERN)

Table of Values of R

Value	Model	Source
0.36	Bethe-Salpeter bound quarks	Bohm et al, ref 42
2/3	Gell-Mann-Zweig quarks	
0.69	Generalized vector meson dominance	Renard, ref 49
∿1	Composite quarks	Raitio, ref 43
10/9	Gell-Mann-Zweig with charm	Glashow et al, ref 31
2	Coloured quarks	
2.5 to 3	Generalized vector meson dominance	Greco, ref 30
2 to 5	" " " "	Sakurai, Gounaris, ref 47
$3^{1}/3$	Coloured charmed quarks	Glashow et al, ref 31
4	Han-Nambu quarks	Han and Nambu, ref 32
5.7±0.9	Trace anomaly and ρ dominance	Terazawa, ref 27
$5.8^{+3.2}_{-3.5}$	Trace anomaly and ε dominance	Orito et al, ref 25
6	Han-Nambu with charm	Han and Nambu, ref 32
6.69 to 7.77	Broken scale invariance	Choudhury, ref 18
8	Tati quarks	Han and Nambu, ref 32
8 ± 2	Trace anomaly and ε dominance	Eliezer, ref 26
9	Gravitational cut-off, universality	Parisi, ref 40
9	Broken scale invariance	Nachtmann, ref 39
16	$SU_{12} \times SU_{12}$) gauge models	Fritzsch & Minkowski, ref 34
$35^{1}/3$	$SU_{16} \times SU_{16}$) gauge models	Fritzsch & Minkowski, ref 34
∿5000	High Z quarks)	Yock, ref 73
70 – 203	Schwinger's quarks)	Yock, ref 73
∞	∞ of partons	Cabibbo and Karl, ref 9; Matveev and Tolkachev, ref 35; Rozenblit, ref 36

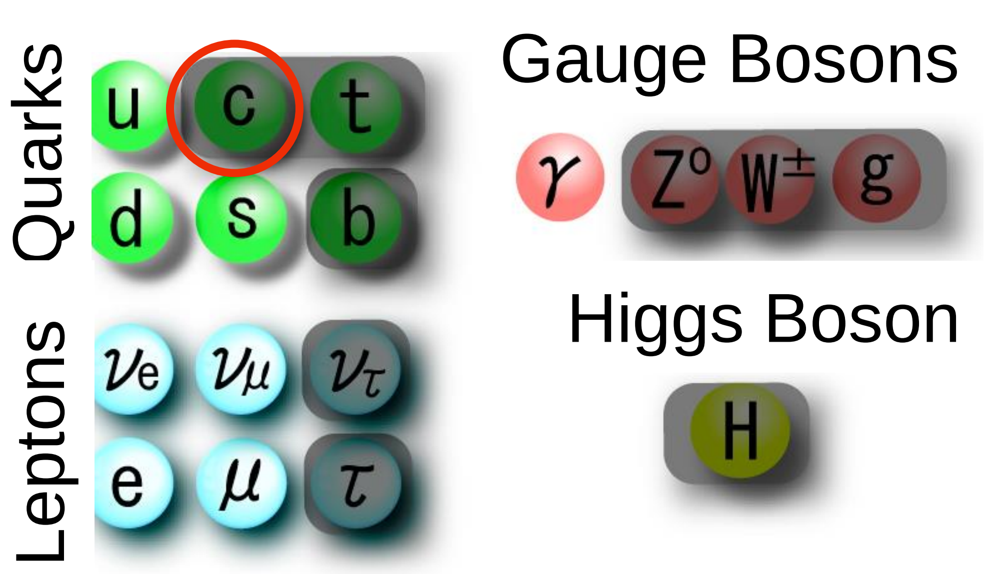
The November Revolution



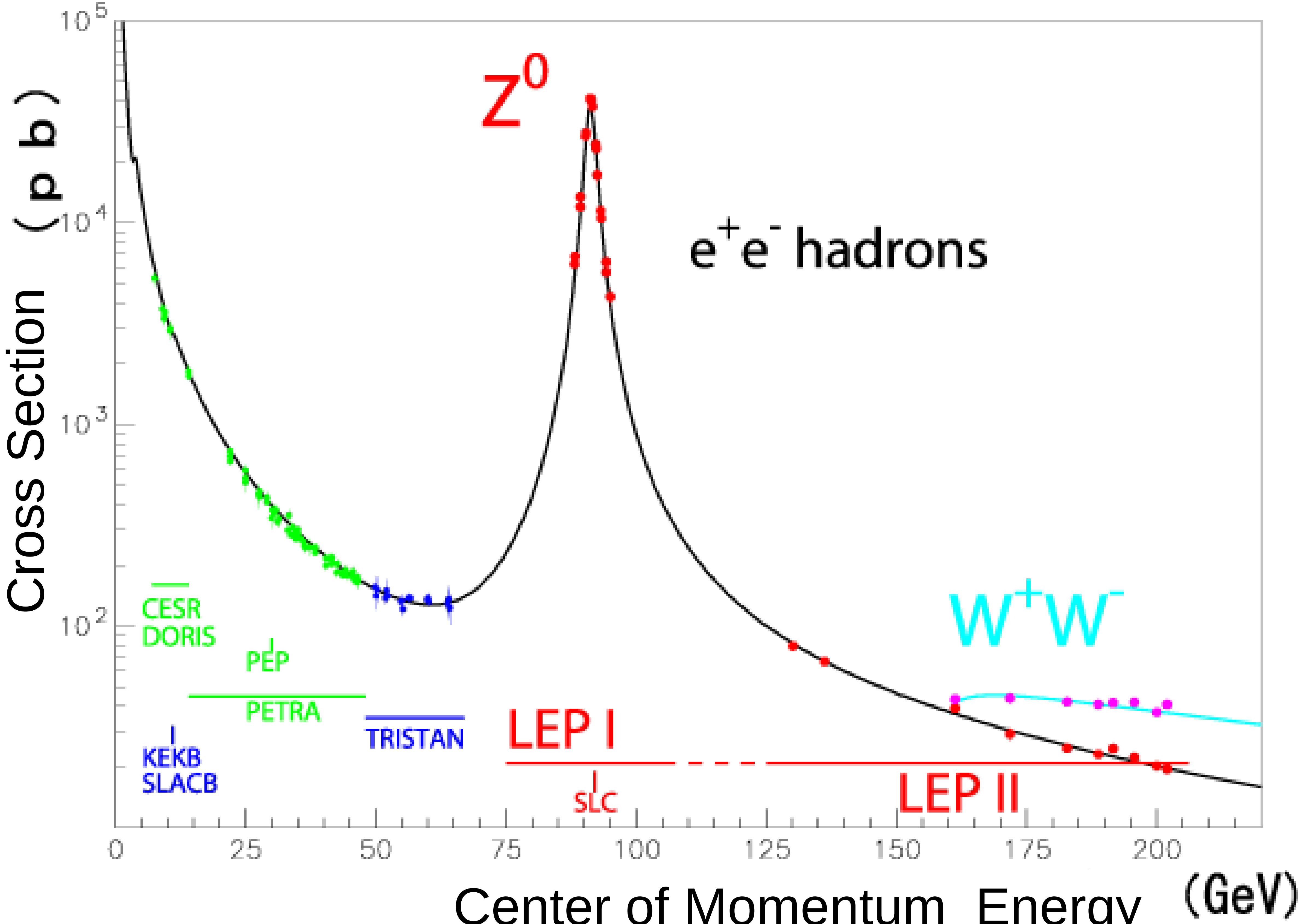
Concept of 4πDetector

B.Richter

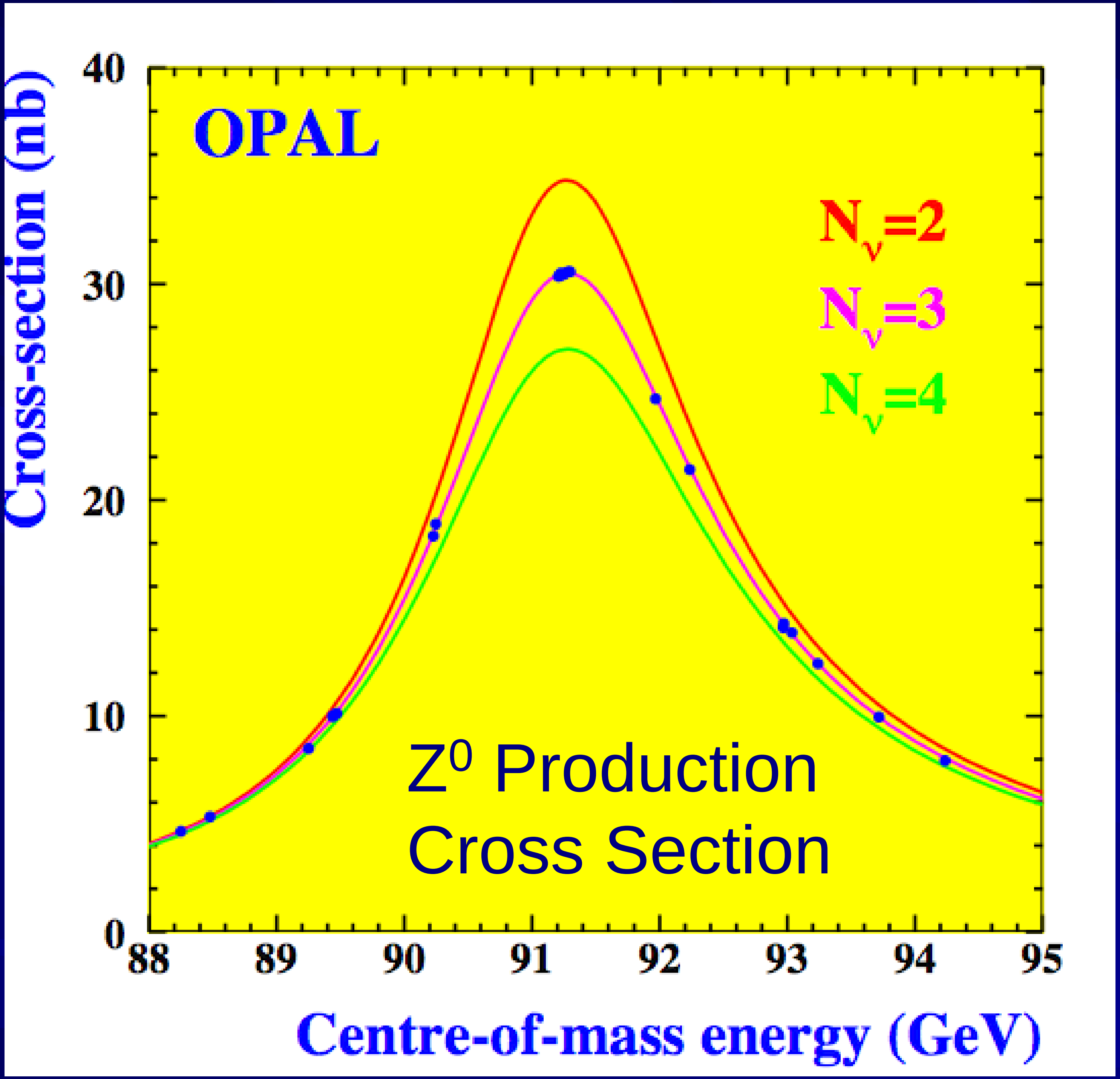
Data analysis with a wine glass

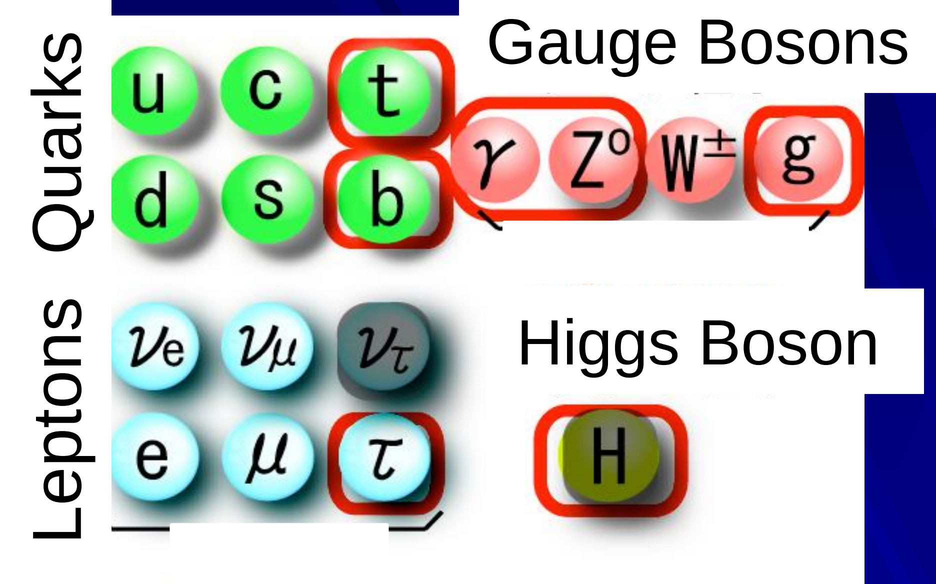


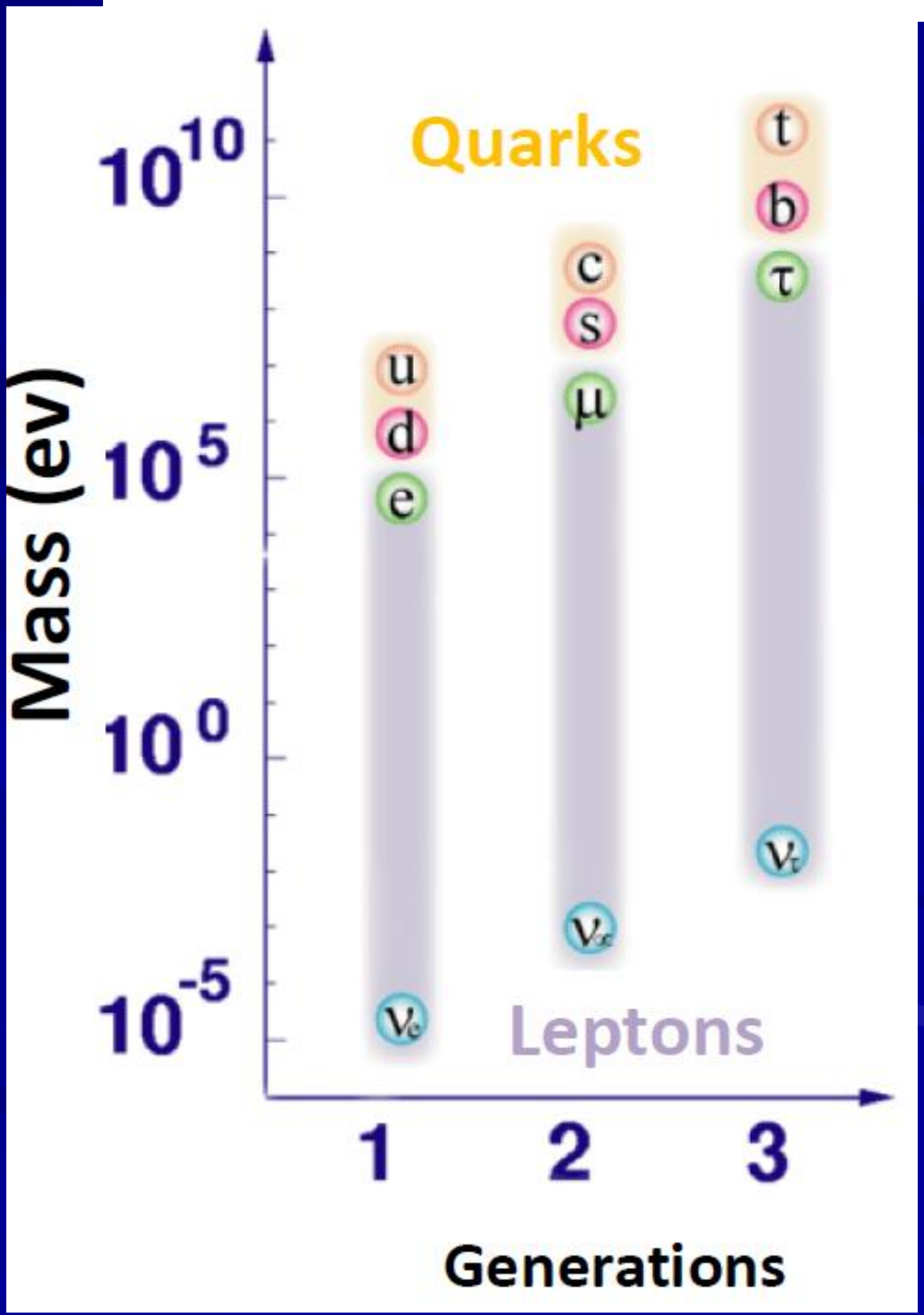
LEP e+e- Collicer at CERN (1990s)



Number of Generations



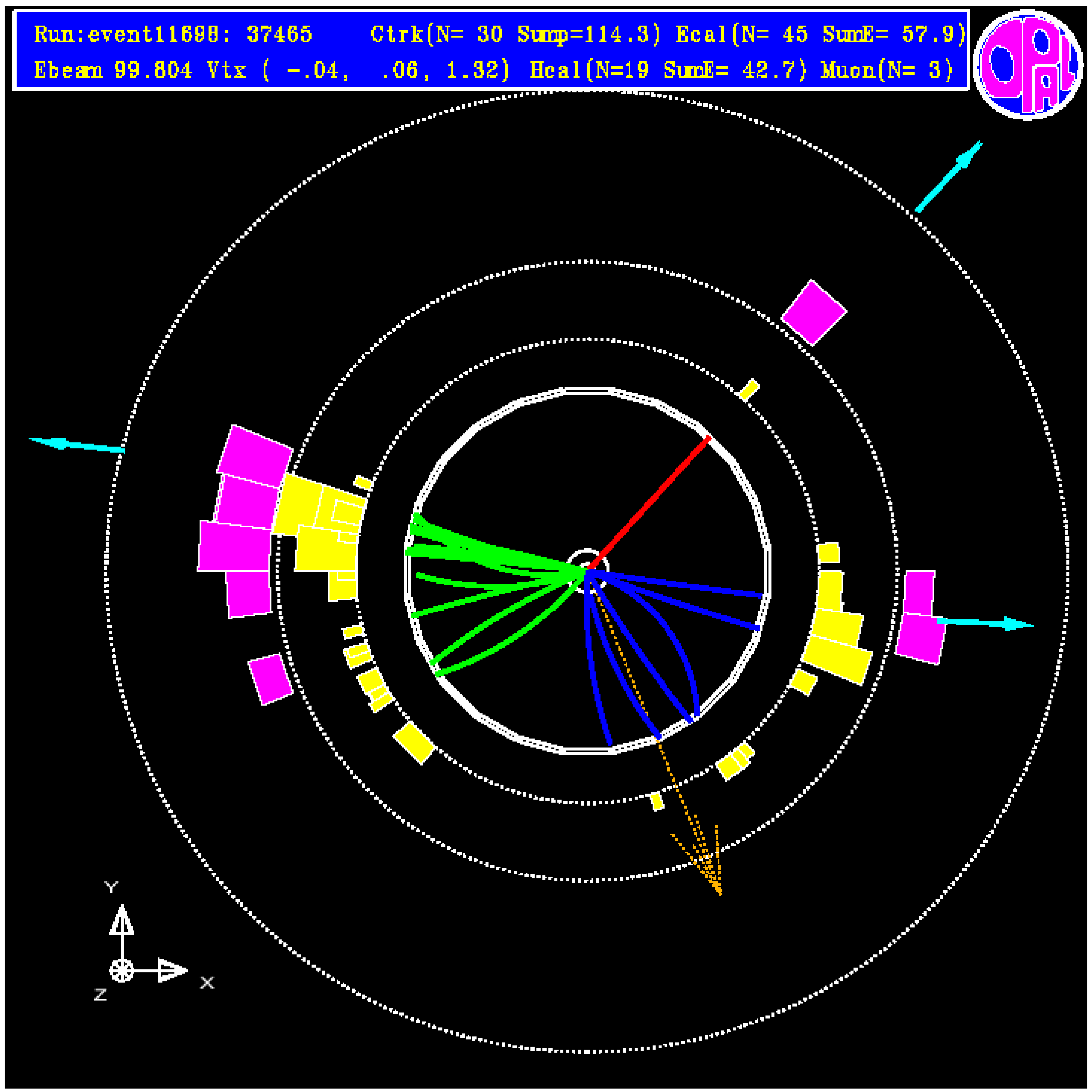


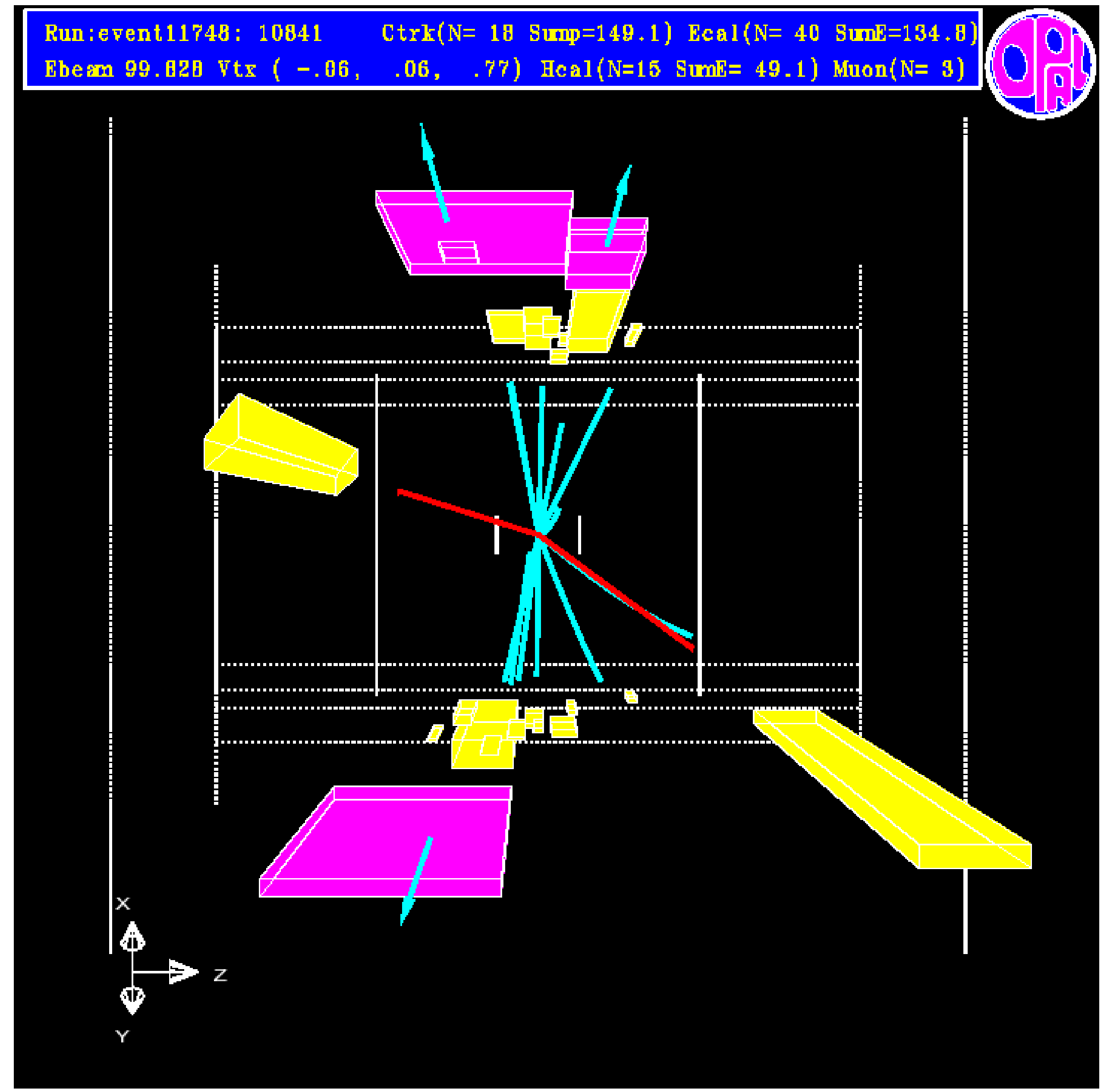


- **Number of Generatons = 3**

  N=2.9841 +- 0.0083 **(LEP)**

Precise Measurement of Weak Gaoge Bosons at LEP-II



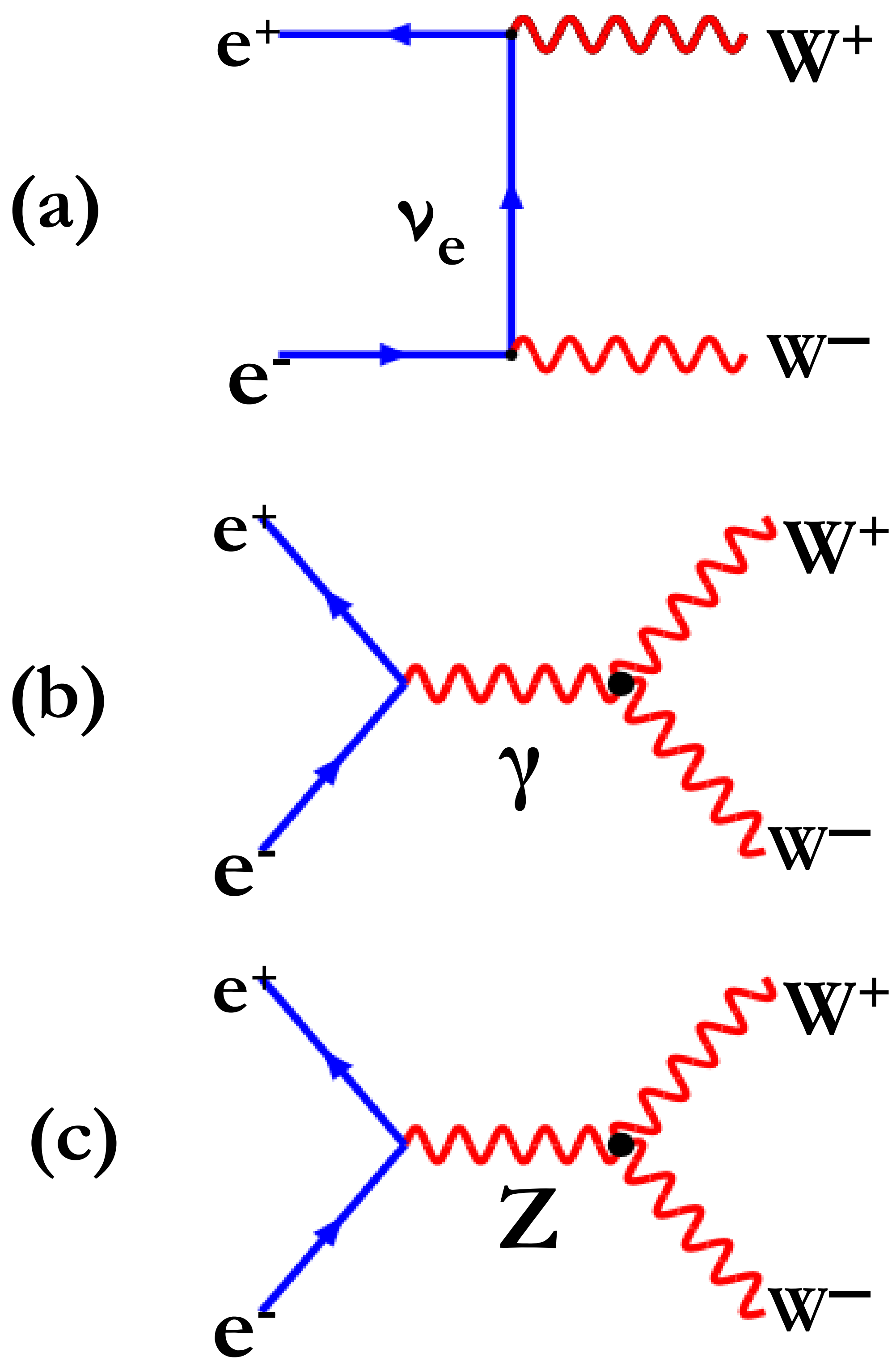


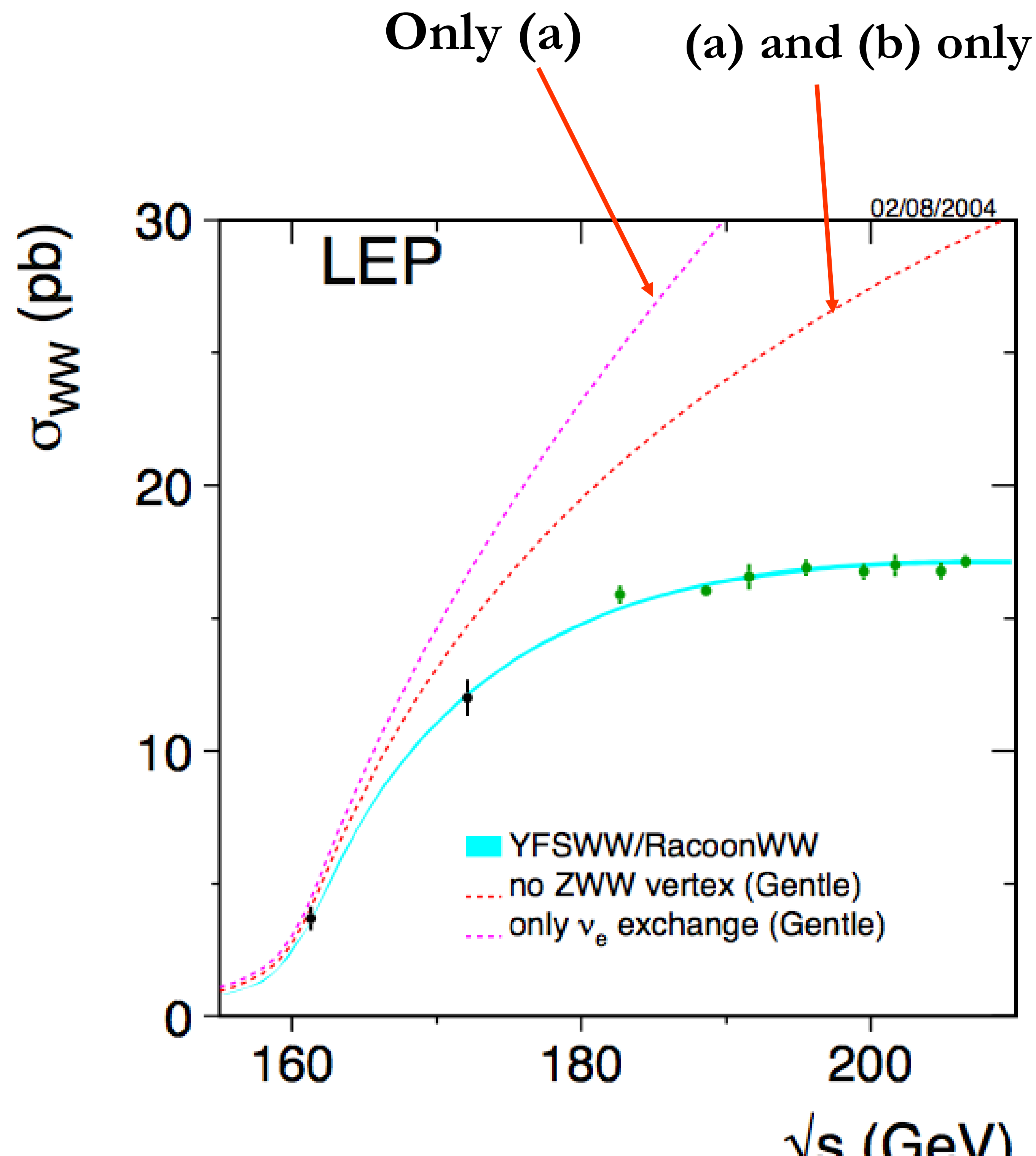
$e^+e^- \longrightarrow W^+W^- \longrightarrow \mu^+\nu_\mu + q\bar{q}$

$e^+e^- \longrightarrow Z^0Z^0 \longrightarrow e^+ e^- + q\bar{q}$

Precise Measurement of Weak Gauge Bosons

Proof of the Electroweak Gauge Principle



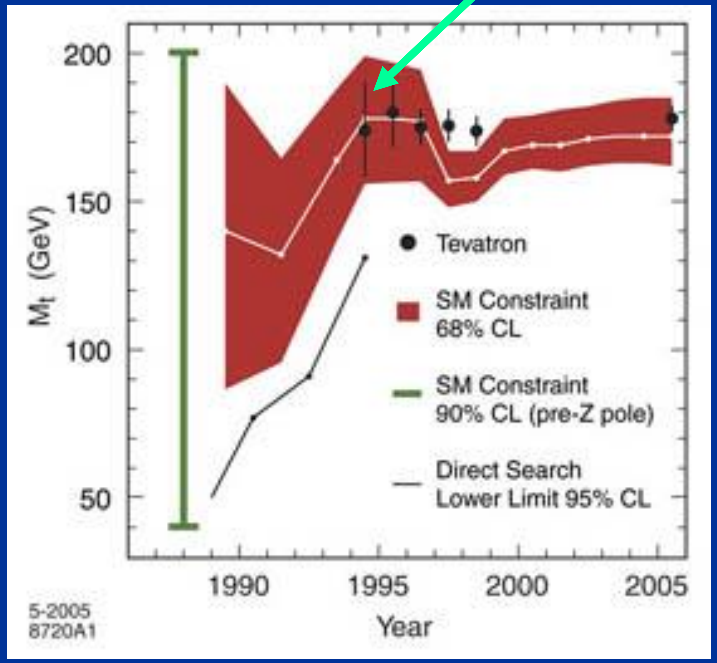


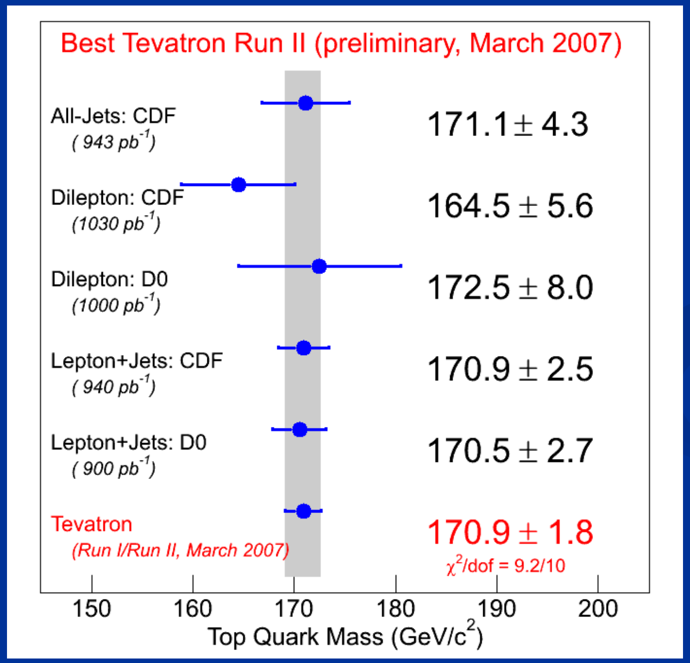
Complementarity and synergy between hadron and e^+e^- colliders (based on the experimental facts)

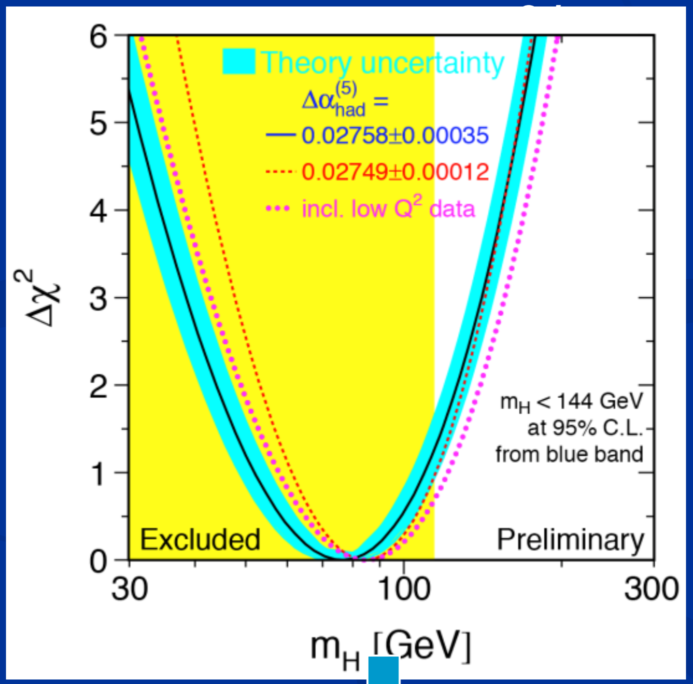
Story of Top Quark and Higgs Boson

From precise electro-weak measurements at LEP, top mass was predicted → **Discovery to Top** → Higgs mass is restricted into a narrow mass range using precise top mass and LEP/SLC electro-weak data 114 GeV $< M_H <$ 160 GeV

Precise Measurement of Top mass at the TEVATRON







Discovery of Higgs at LHC

Precise measurements of Higgs properties at **ILC,…**

The Standard Model of Elementary Particles

(1) Matter Fermions (J=1/2)

Quarks			Leptons		
u	c	t	ν_e	ν_μ	ν_τ
d	s	b	e	μ	τ

+anti-quarks +anti-leptons

(2) Gauge Bosons (J=1)

Elecro-Magnetic Interaction	γ	(Photon)
Weak Interactions	$W^+ W^- Z^0$	(Weak Bosons)
Strong Interaction	g (8-types)	(Gluons)

(3) Origin od Masses (J=0) H^0 (Higgs Boson)

Higgs Boson Physics

Robert Brout

Determine the direction of particle physics
beyond the Standard Model
from precise measurements of the Higgs Boson

What is the Mass ?

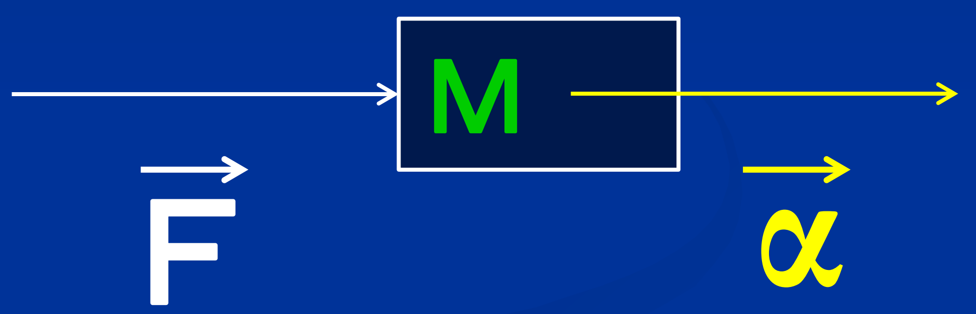
Newton`s Second Low

$$\vec{F} = M\vec{\alpha}$$

M:Mass (Inertial Mass)

$\vec{\alpha}$: Acceleration

$\vec{F}$: Force



The acceleration vector of an body is proportional to vector sum of Force on the object The constant of the proportionality is the (Inertial) Mass

For stopped objects:

A heavy objects hardly move. A light objects easily move.

Mass is an indicator of resistance to change the constant motion

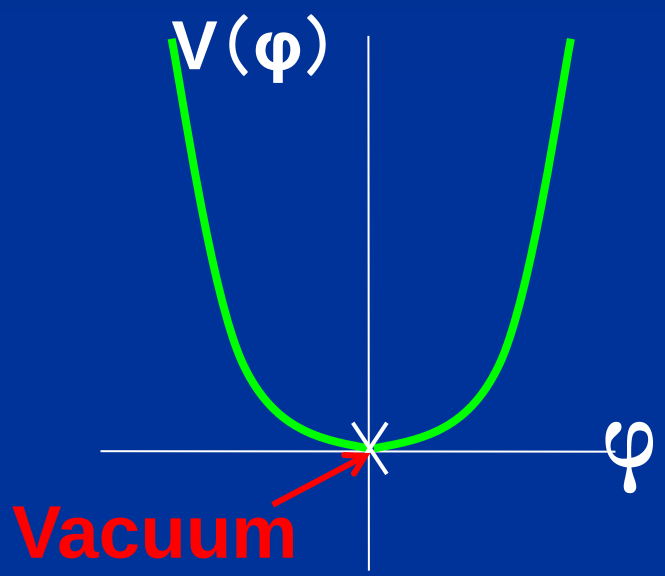
Higgs Boson and the Vacuum

Englert Higgs

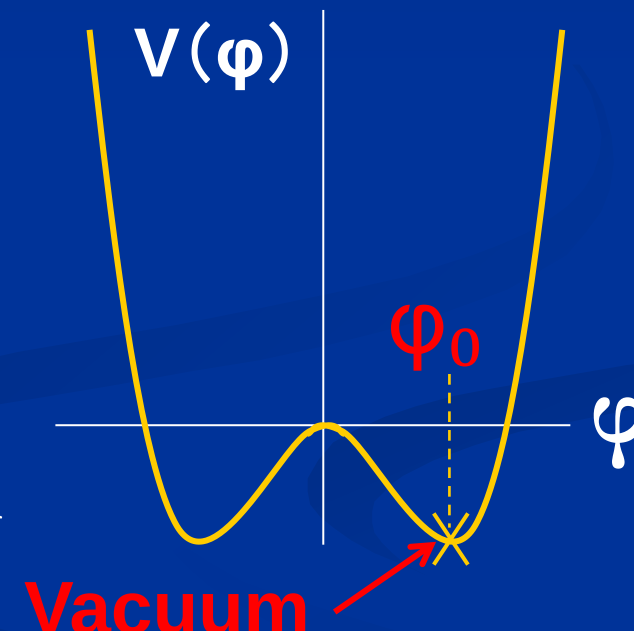
Higgs Boson has the same quantum number with Vacuum

⇒ Higgs field in the vacuum transits from $\varphi=0$ to $\varphi=\varphi_0$.

Phase transition



The universe cooled down during expansion



Early Universe

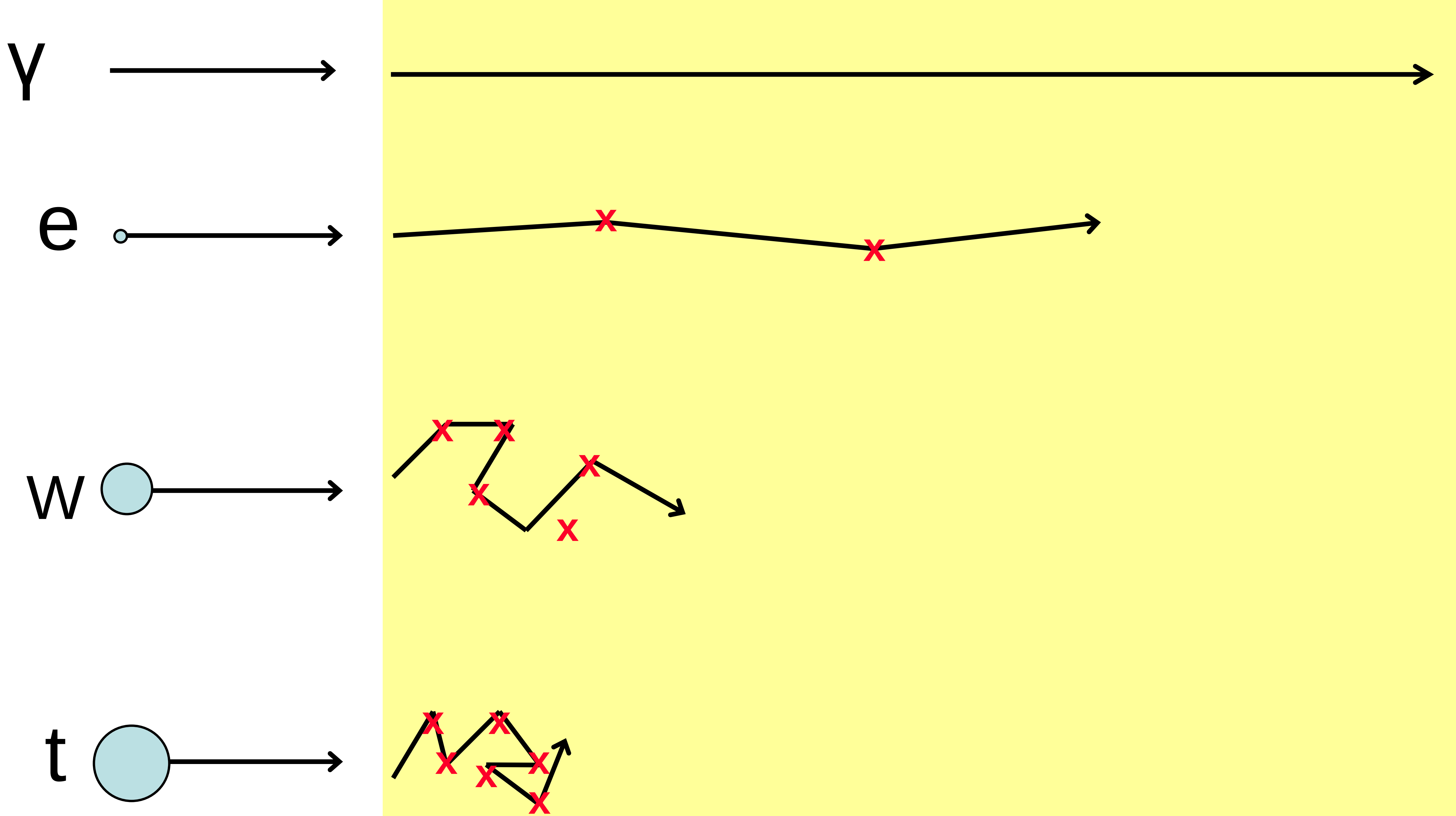
Higgs Field φ_0 fills the vacuum

At the Vacumm（The lowest potential point）$\varphi\neq0$.

The symmetry breaks down（Brout, Englert, Higgs ）

This situation happens if there is Supersymmetry：Inoue et al.（Kyushu U.）

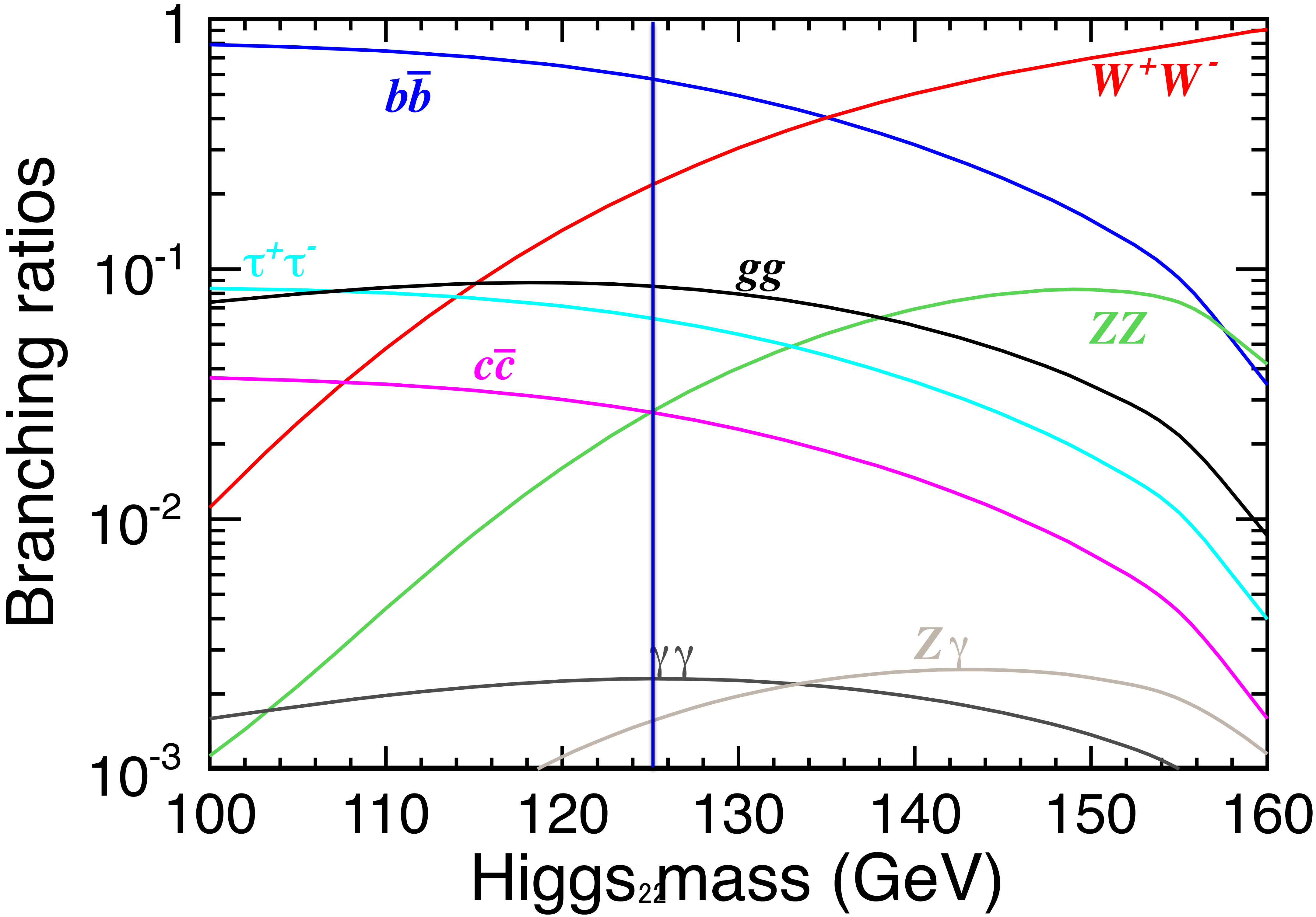
Particles collide with the Higgs field which is filled in the vacuum.
They obtain inertial mass..



Discovery of the Higgs Boson 2012 July

Decay Branching Fraction for the 125 GeV Higgs Boson

Rich in variety of decay modes ⇒ Very lucky situation



Higgs Boson

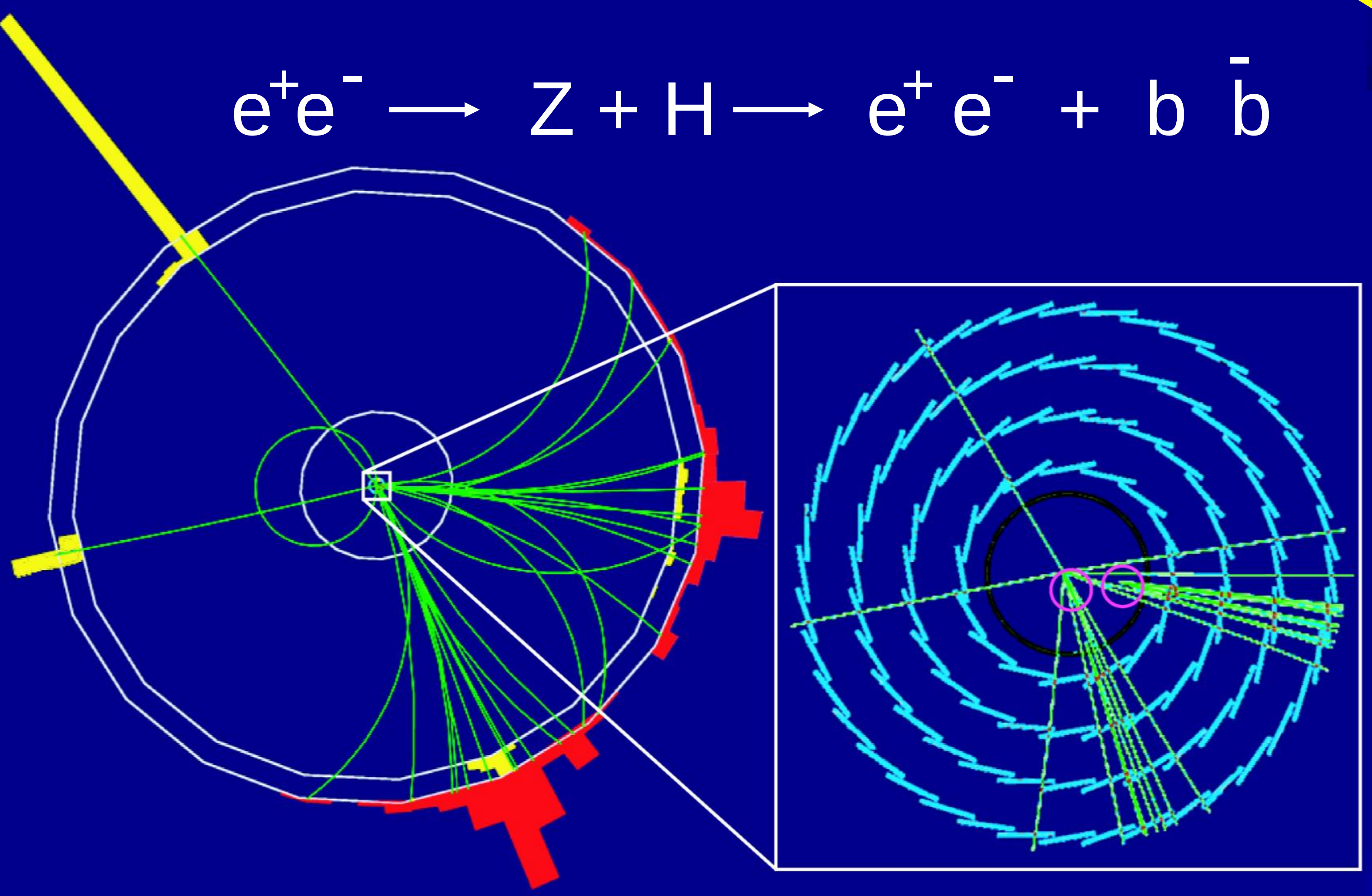
Precise measurement of Higgs Boson
⇒Deduce Principal Low in the Nature

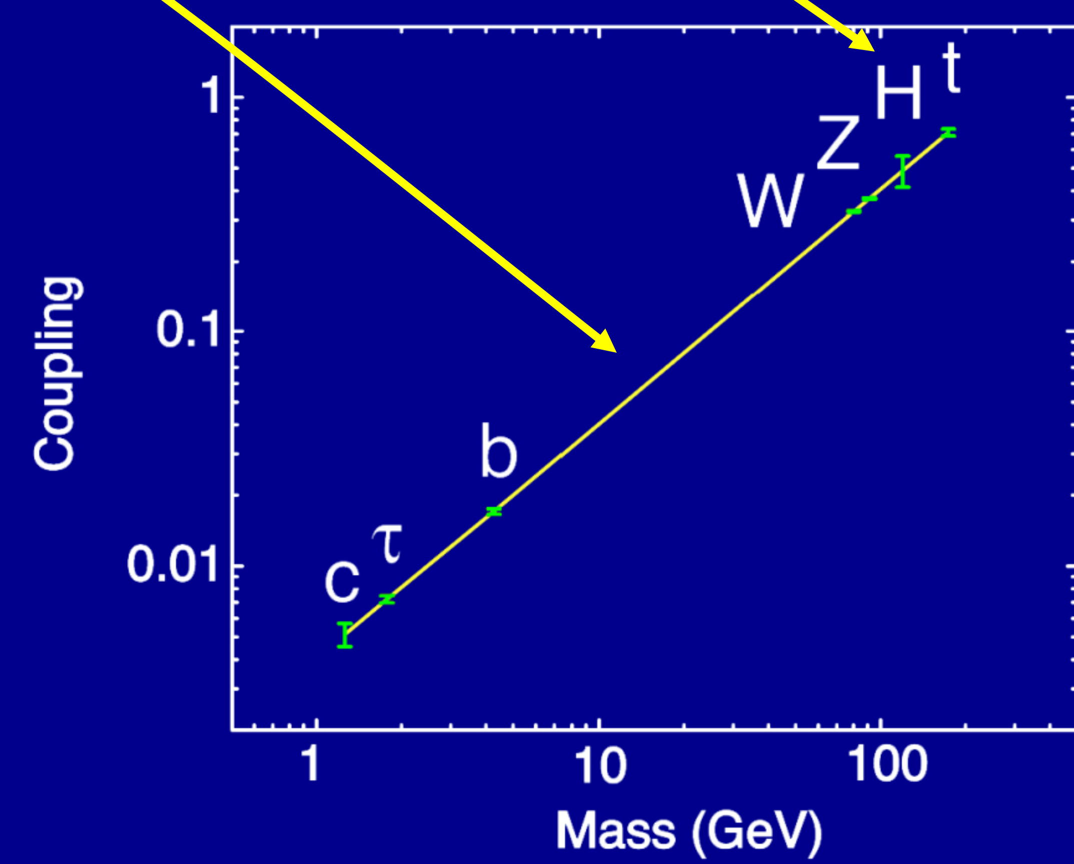
$e^+ e^-$ Higgs Boson Factory

$O(10^5)$ such events will be collected and studied.

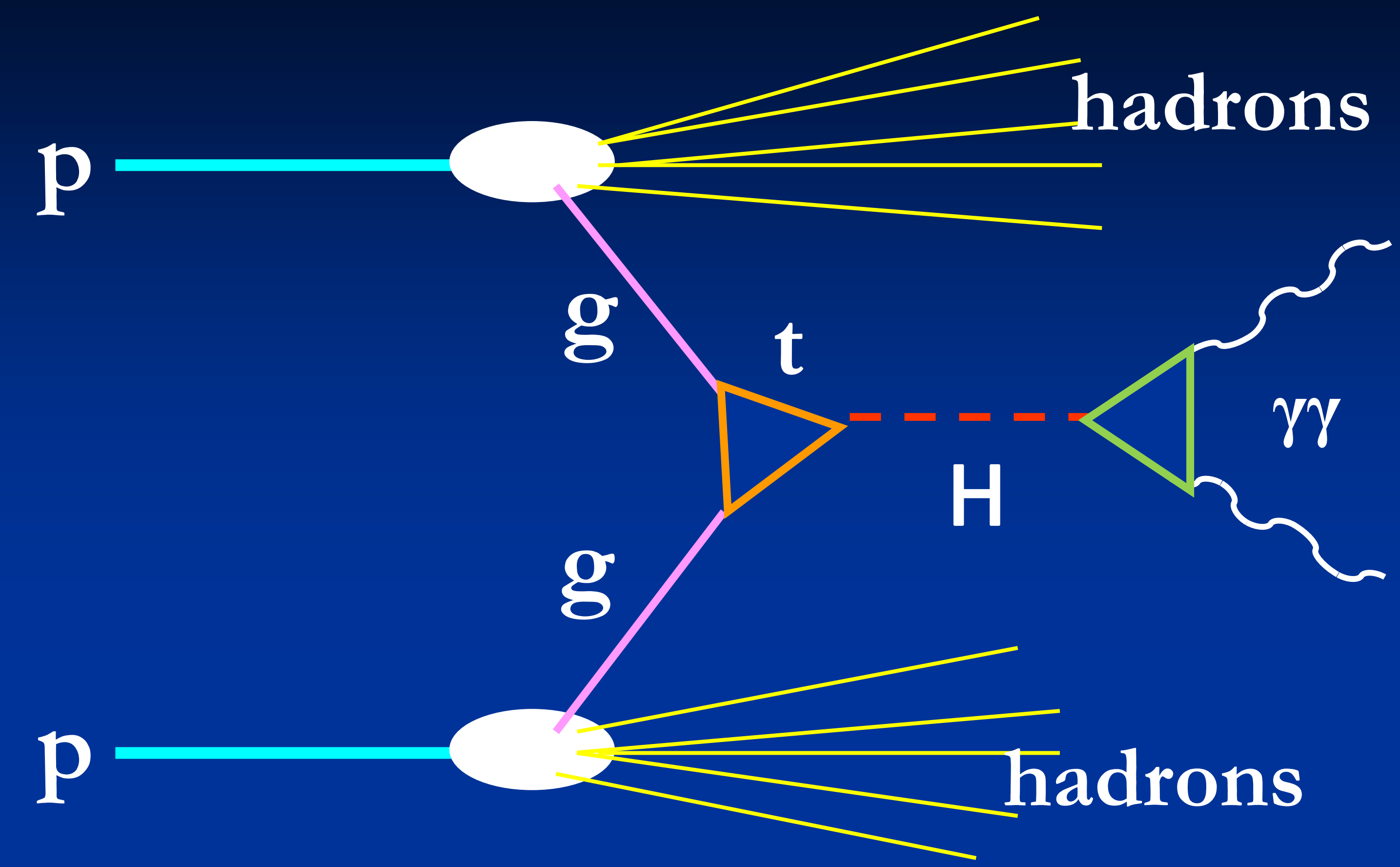
Origin of mass ⟷ Structure of the 'vacuum`.

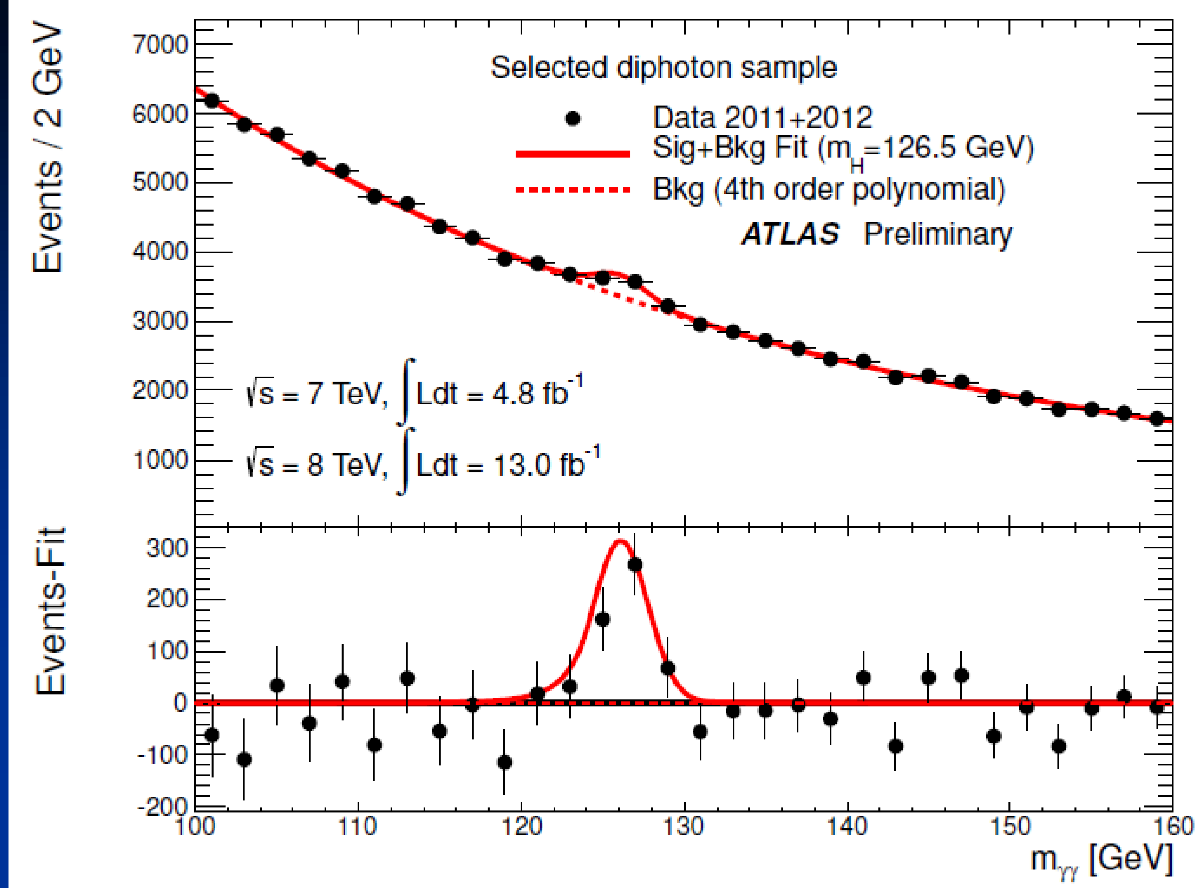
$e^+e^- \longrightarrow Z + H \longrightarrow e^+ e^- + b\ \bar{b}$



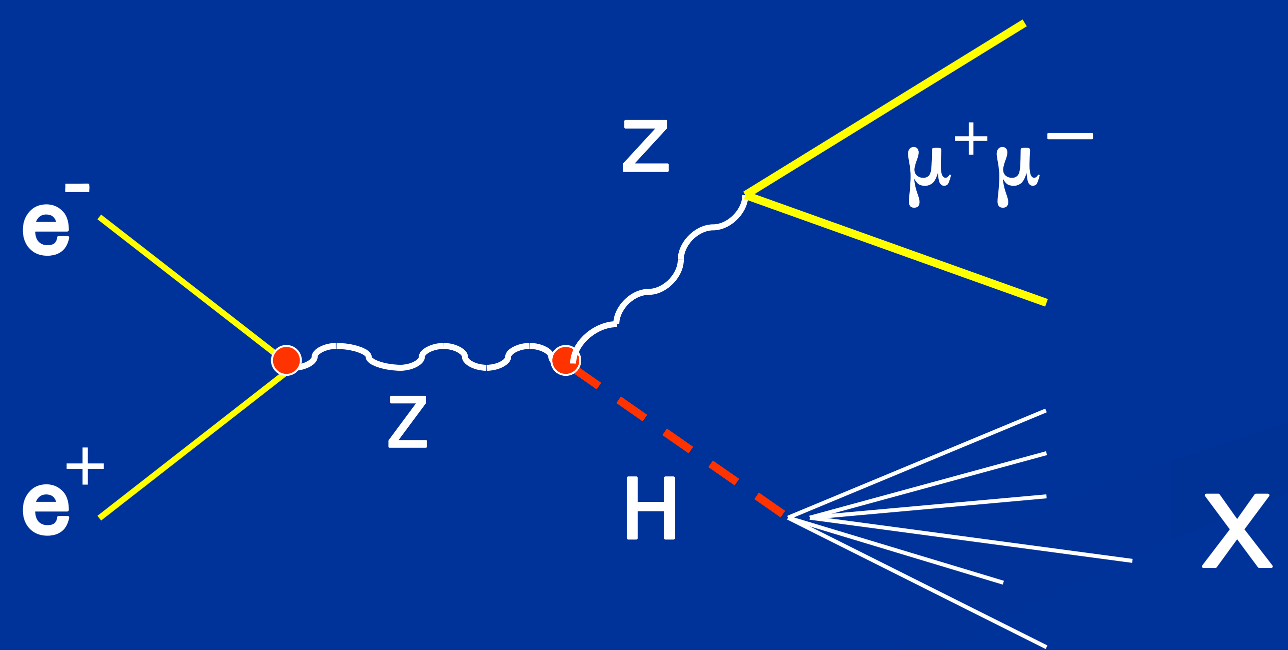


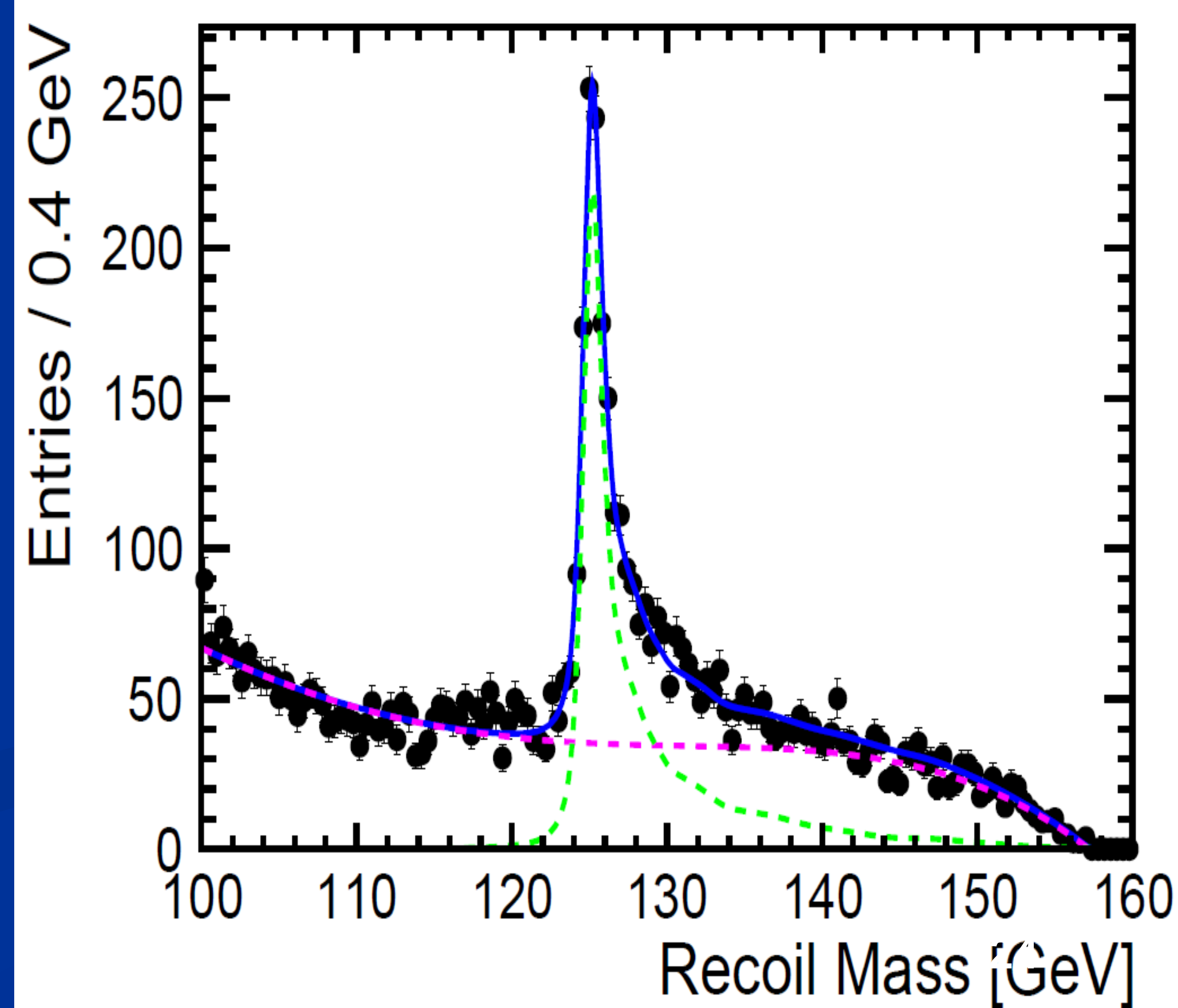
LHC $H\to\gamma\gamma$ Invariant mass of $\gamma\gamma$





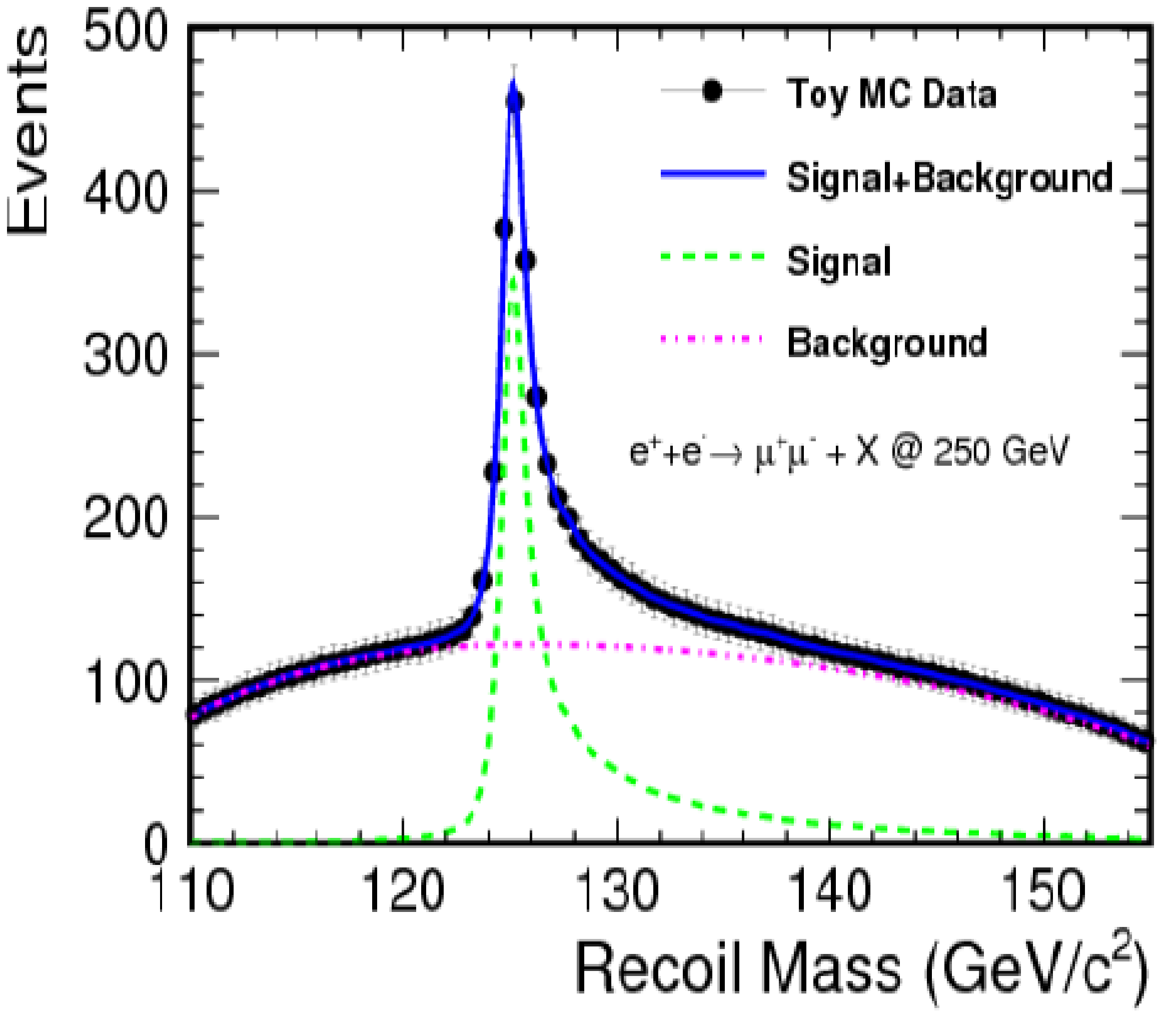
ILC Recoil mass of $Z(\mu^+\mu^-)$

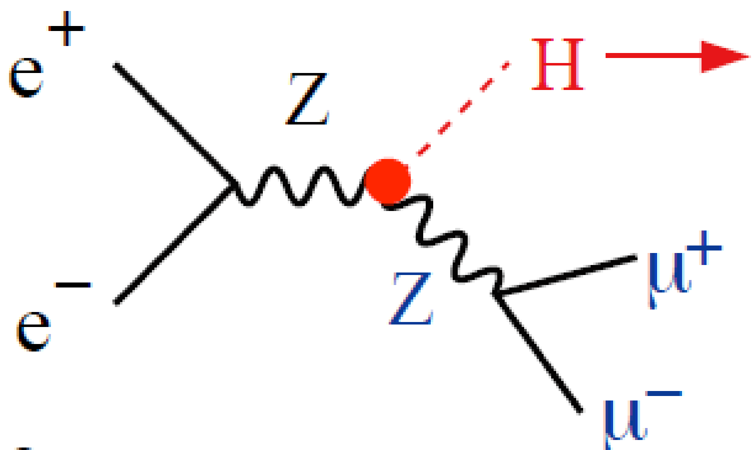




the key of model independence: meas. inclusive σ_{ZH}

Yan, et al, Phys.Rev. D94 (2016) 113002;
Thomson, Eur.Phys.J. C76 (2016) 72





$$M_X^2 = (p_{CM} - (p_{\mu^+} + p_{\mu^-}))^2$$

- well defined initial states at e+e-
- recoil mass technique —> tag Z only
- Higgs tagged without looking into H decay
- absolute cross section of e^+e^- —> ZH
- absolute HZZ coupling can be given

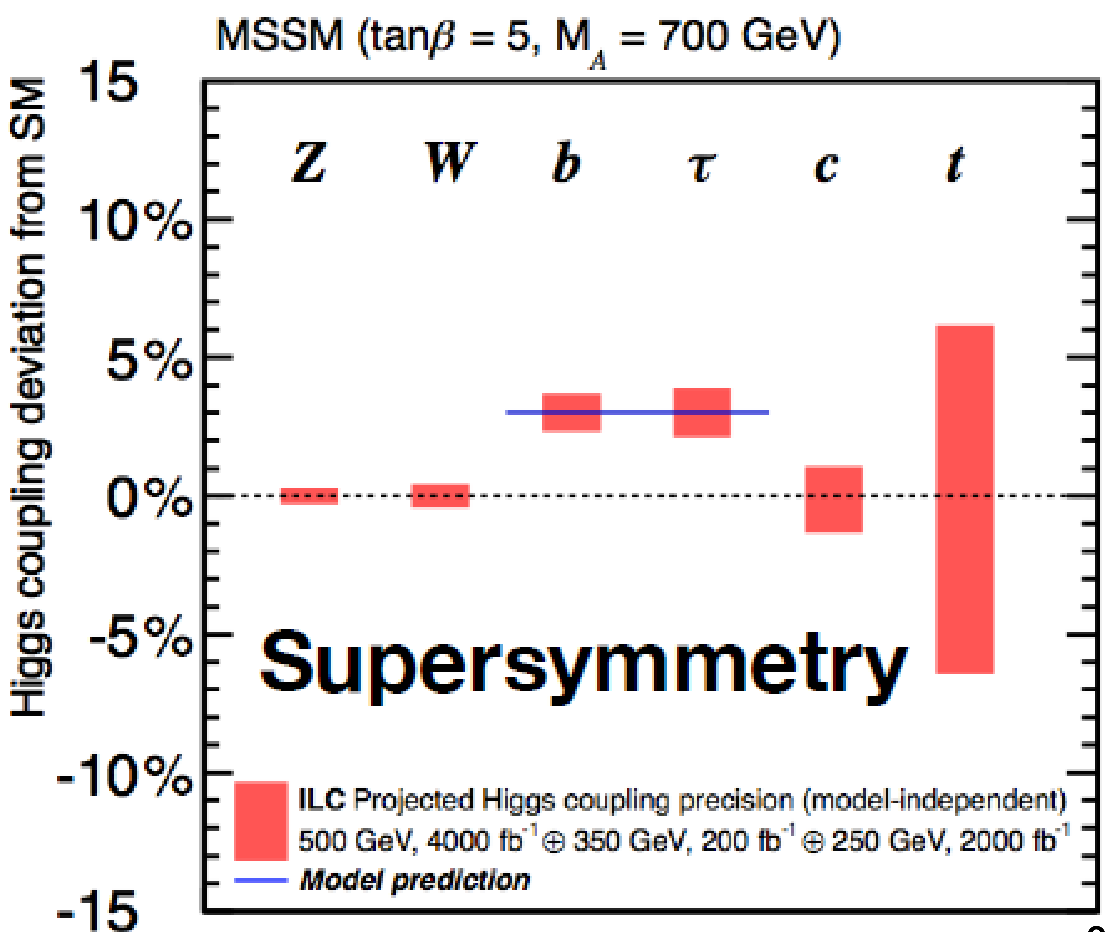
$\Delta m_H = 14\text{MeV}$ $\quad \delta g_{HZZ} \sim 0.38\%$ $\qquad Y_1 = \sigma_{ZH} \propto g_{HZZ}^2$

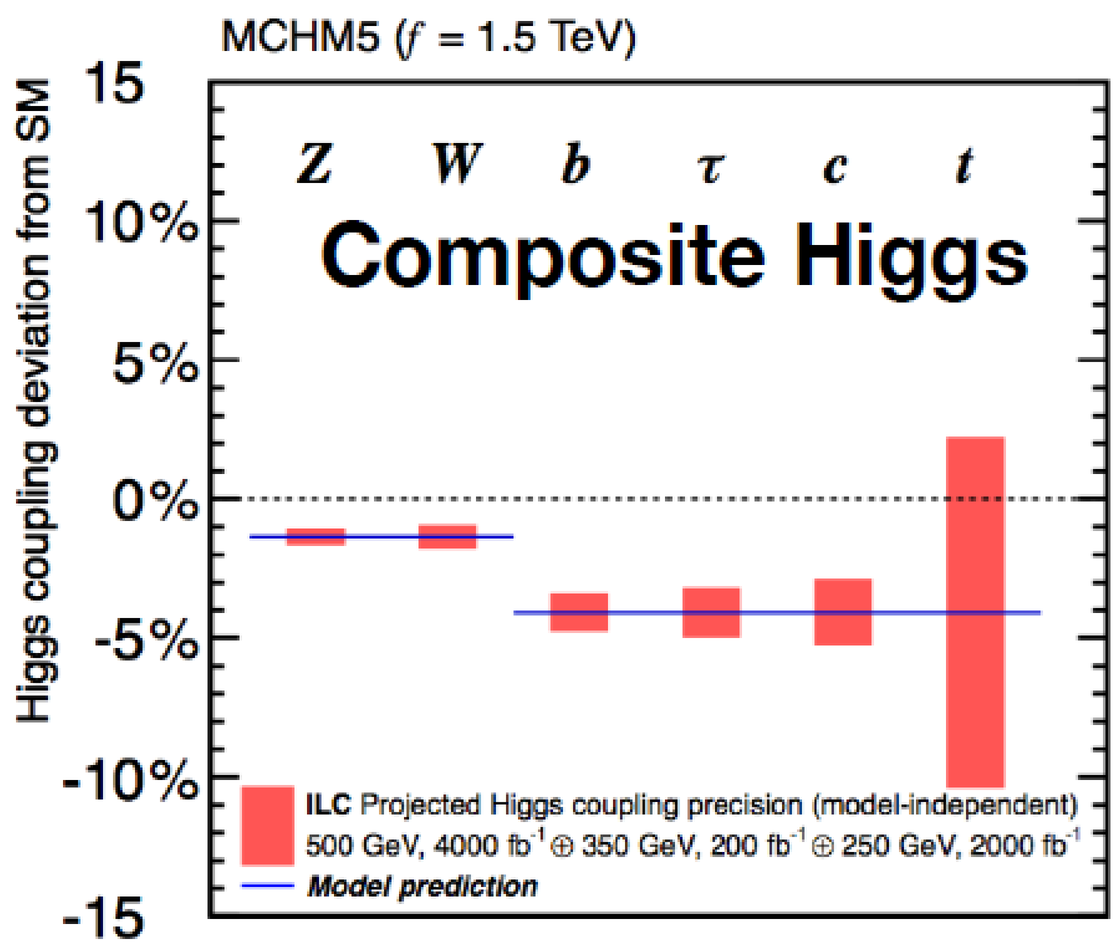
- meas. of σ_{ZH} doesn't depend on how Higgs decays
- meas. of σ_{ZH} doesn't depend on underlying models on HZZ vertex

why precision higgs physics

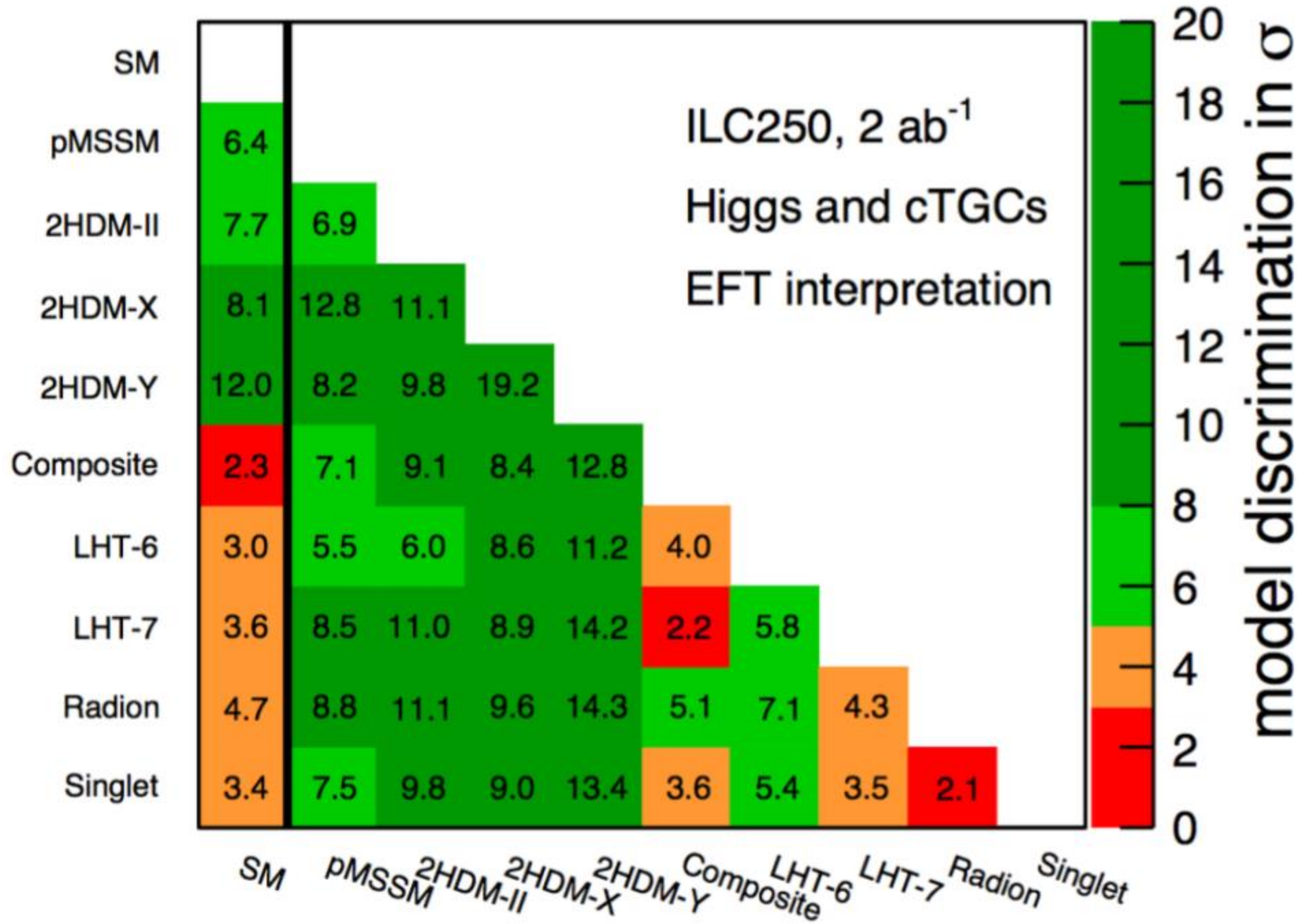
- Haber's decoupling limit, deviation ~ m_h^2/M^2.
  —> $\Delta g/g$ ~ O(1%) for M ~ 1 TeV
- fingerprint BSM by patterns of deviations
  —> measure as many couplings as possible

challenging at LHC





Once a deviation from the Standard Model prediction in the couplings are seen, types of new physics could be differentiated from the deviation pattern



◎Significance of model discrimination
◎For Models which cannot be directly discovered at LHC
◎Most of the models can be discriminated by 3 σ or more.

Results of the full EFT analysis should be better than these ones.

CP violation in the Higgs sector

Matter-antimatter asymmetry in the universe is evident.

Cosmic rays overwhelmingly composed of matter (protons)

No intense outbursts of electromagnetic radiation from annihilation of clouds of matter with those of anti-matter

$N_B/N_\gamma \sim 10^{-9}$ $N_{\bar{B}}/N_\gamma \sim 10^{-13}$

Sakharov's conditions of baryon-antibaryon asymmetry:

- Baryon number violation
- C-symmetry violation and CP-symmetry violation
- Interactions out of thermal equilibrium

CP-violation phase in CKM matrix of quark sector is too small to explain the baryon-antibaryon asymmetry in the universe. Similarly, CP-violation phase in PMKS matrix of neutrino sector is also too small.

CP violation in other sectors (Higgs sector ?, Mixing in SUSY particles. …) are very interesting.

determine Higgs CP (admixture)

- find CP-violating source in Higgs sector —> EW baryongenesis
- essential to understand structures of all Higgs couplings

through H—>$\tau^+\tau^-$

$$L_{Hff} = -\frac{m_f}{v} H \bar{f} (\cos \Phi_{CP} + i\gamma^5 \sin \Phi_{CP}) f$$

$$\Delta\Phi_{CP} \sim 3.8^\circ$$

D.Jeans @ LCWS16

through HZZ/HWW

$$L_{HVV} = 2C_V M_V^2 (\frac{1}{v} + \frac{a}{\Lambda}) H V_\mu V^\mu + C_V \frac{b}{\Lambda} H V_{\mu\nu} V^{\mu\nu} + C_V \frac{\tilde{b}}{\Lambda} H V_{\mu\nu} \tilde{V}_{\mu\nu}$$

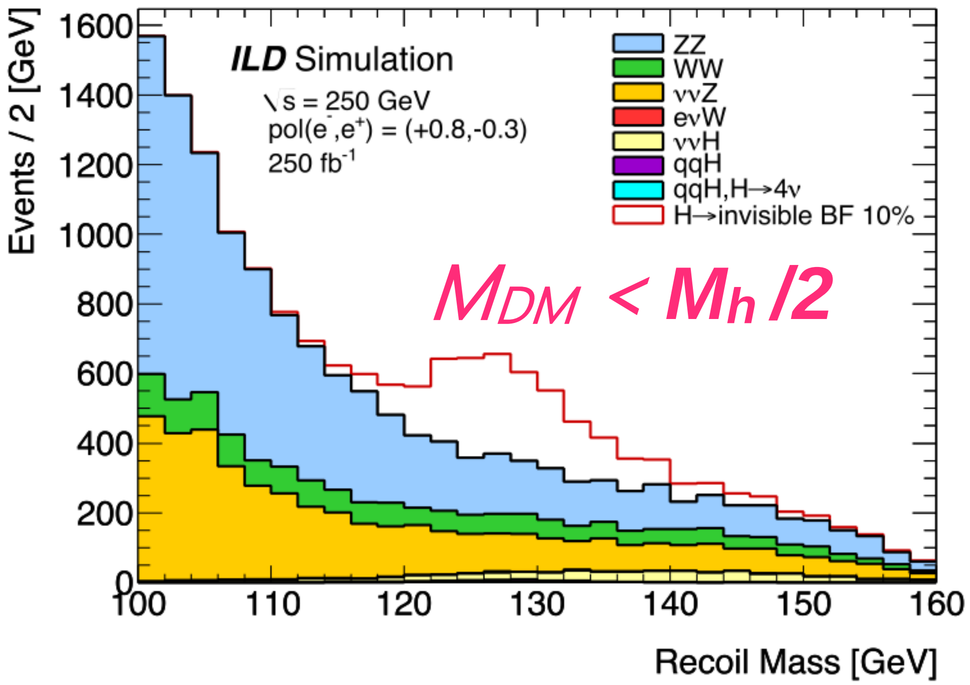
(CP-odd)

$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV) T.Ogawa @ LCWS16

Invisible/Exotic Higgs Decays

By making maximum use of Z-tagged Higgs bosons, all kinds of invisible/exotic decays can be searched for with high sensitivity

Invisible Higgs Decay



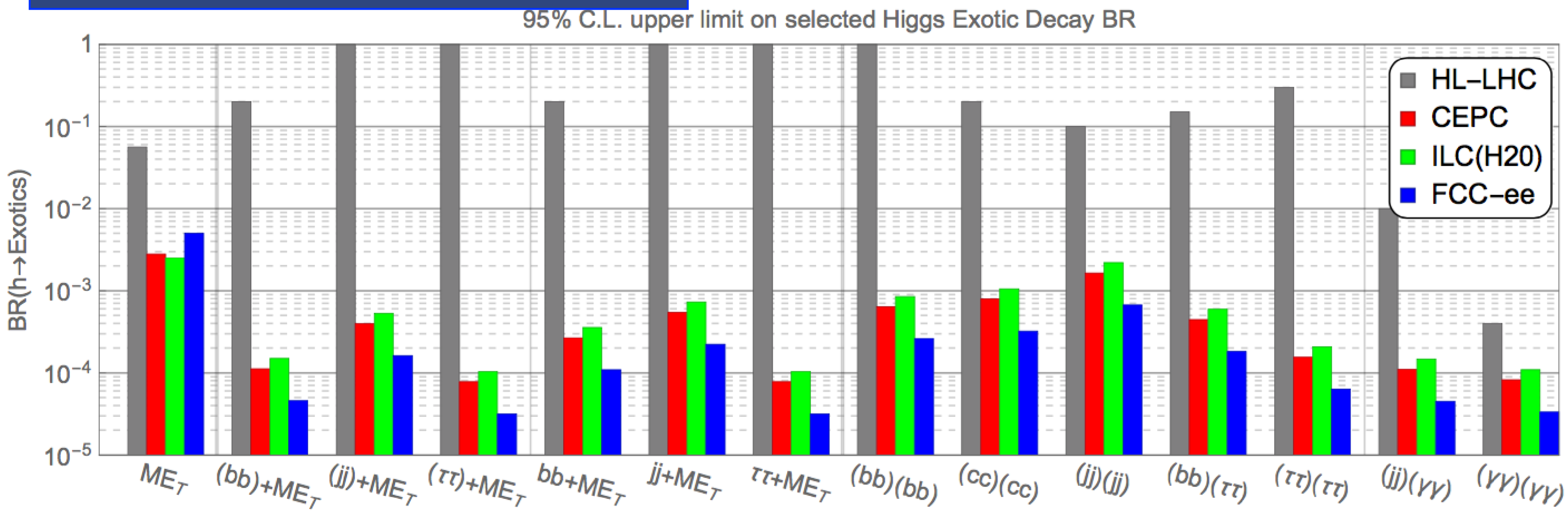
BR(H→invis.) < 0.3% at 95%CL 2ab^{-1}@ 250GeV

An attractive way to build a model of Dark Matter = to assume a "Hidden Sector"

Invisible / Exotic Higgs Decays = ideal hunting ground for

Higgs Portal	Neutrino Portal
$\epsilon \lvert\varphi\rvert^2 \lvert\hat{S}\rvert^2$	$\epsilon\, L^\dagger \cdot \varphi \hat{N}$

Exotic Higgs Decays



Liu, Wang, Zhang
arXiv: 1612.09284

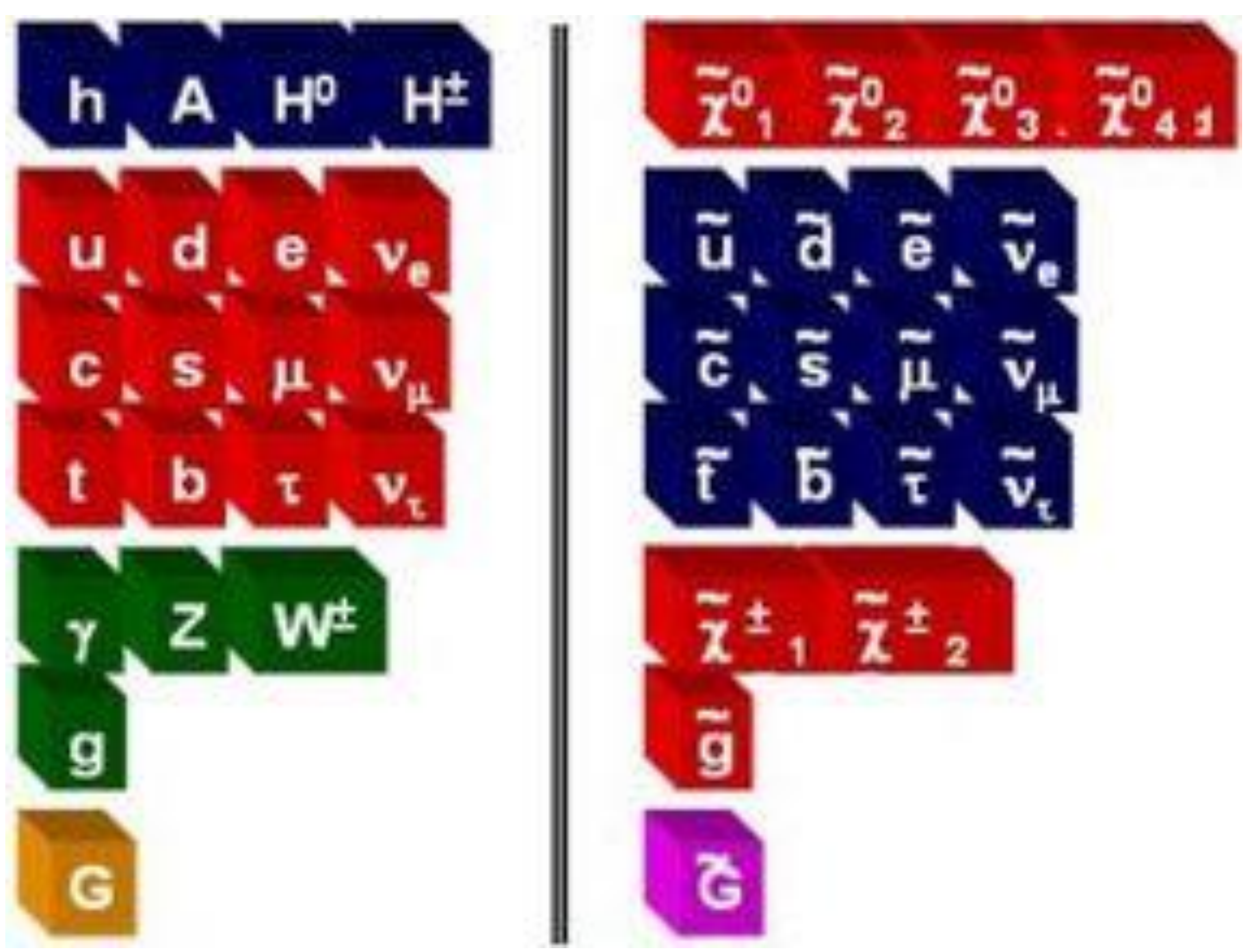
Liu, Wang, Zhang
arXiv: 1612.09284

BR= 0.1%
→ >500 events
2ab^{-1}@ 250GeV

Depending on which way to go, the answers to other big questions like dark matter, baryon asymmetry of the universe, neutrino masses/mixings, dark energy, ··· also change.

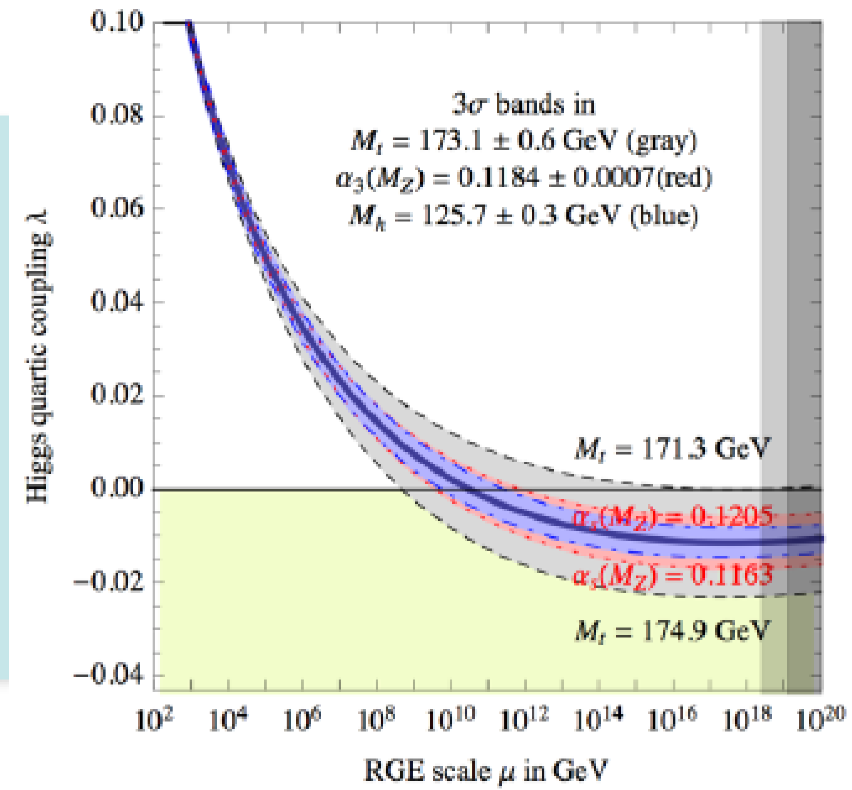
250 GeV ILC decides the future direction of particle physics.

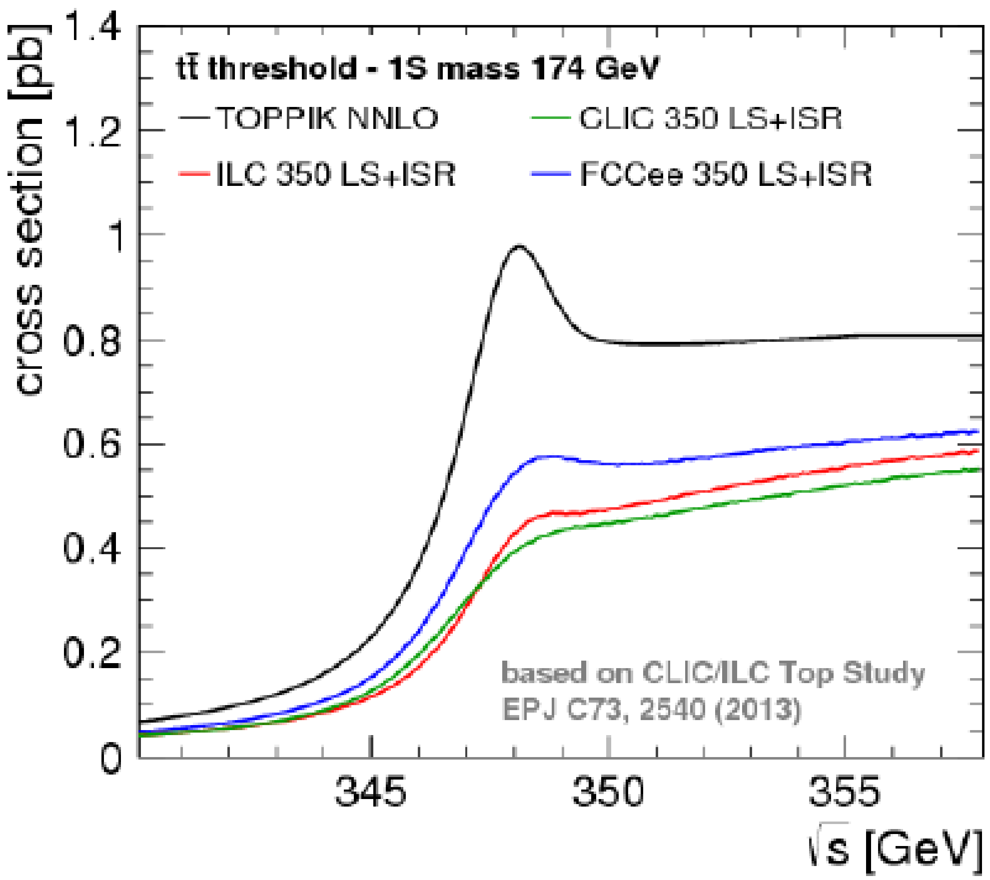
Beyond the Higgs Boson



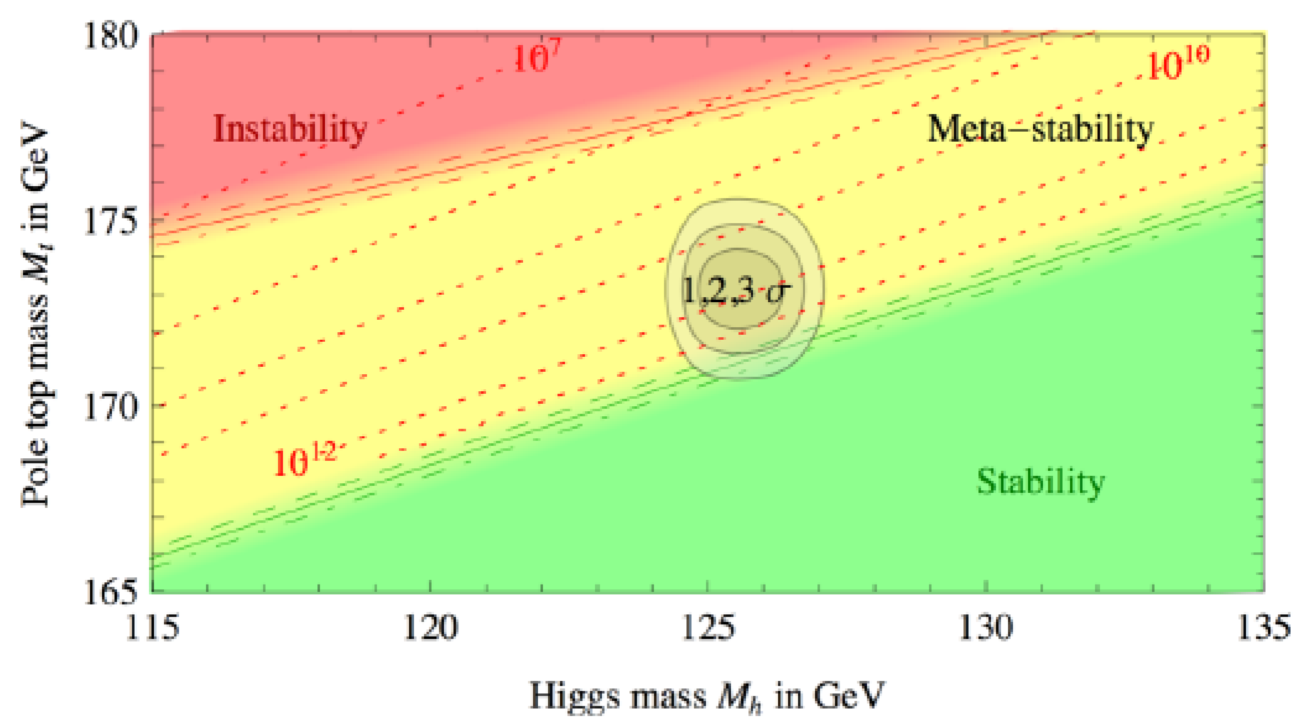
vacuum stability

- λ runs < 0? top mass precision crucial for vacuum stability
- at e+e-: top-pair threshold scan, much lower theory error
- Δm_t(MS-bar) ~ 50 MeV (Δm_H=14MeV)





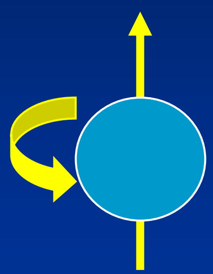
Degrassi et al, JHEP 1208 (2012) 098



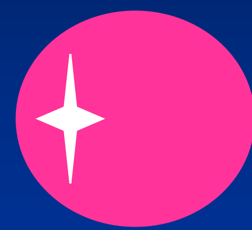
Δm_t ~ 300 MeV (HL-LHC) This can be enough for this purpose

Supersymmetry (SUSY) solves miltiple problems

Fermions ⟷ Bosons

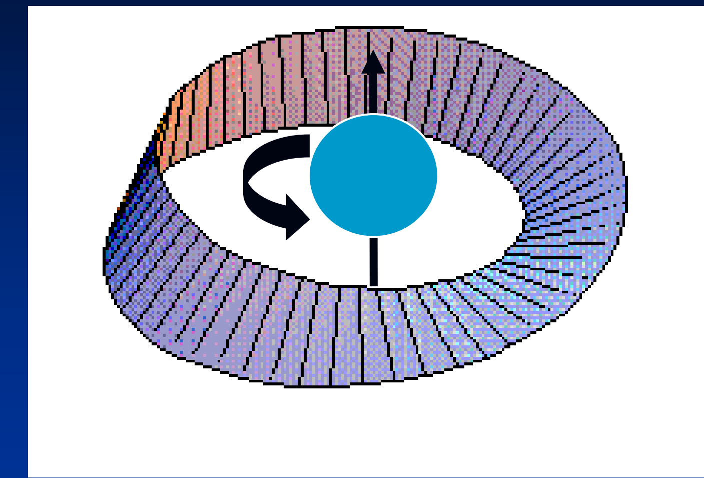


electron
spin =1/2



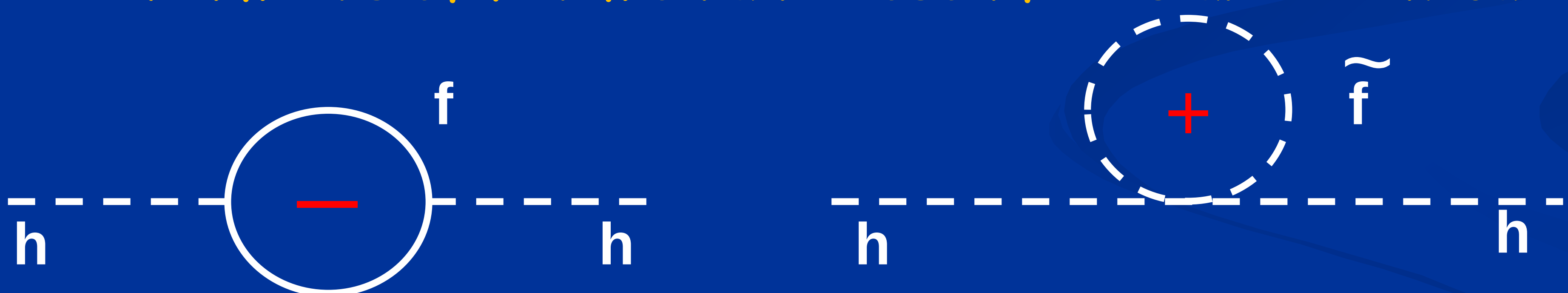
selectron
spin = 0

Supersymmetric
partner of electron



Wave function of
spin1/2 Fermion

- Stabilization of Higgs Boson Mass due to a cancellation
  ⇒ Numbers of Fermion and Boson fields are identical

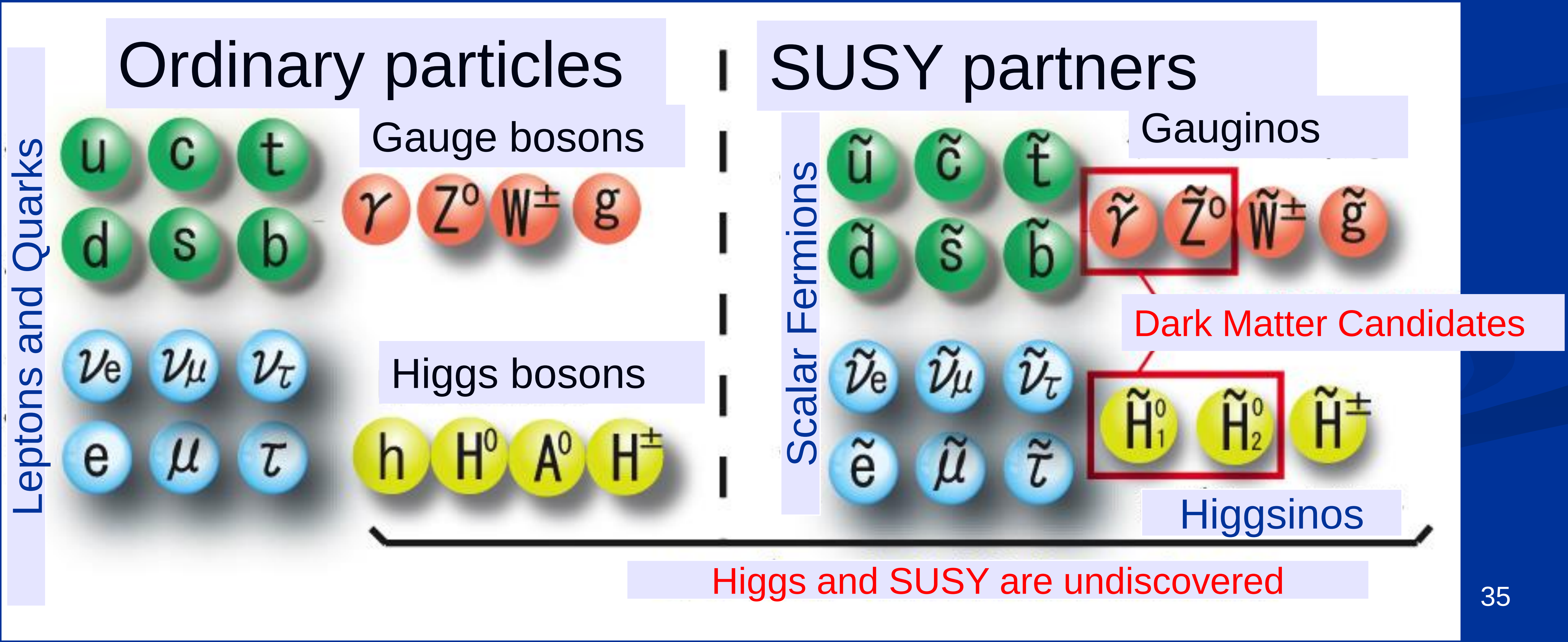


- The lightest SUSY particle is a good candidate of the Dark Matter
  ⇒ We gain the understanding of the structure of the universe
- SUSY is a space-time symmetry
  It plays a crucial role for the unification of 3 forces with gravity
  Number of extra-dimensions in the string theory is determined

Supersymmetry (SUSY)

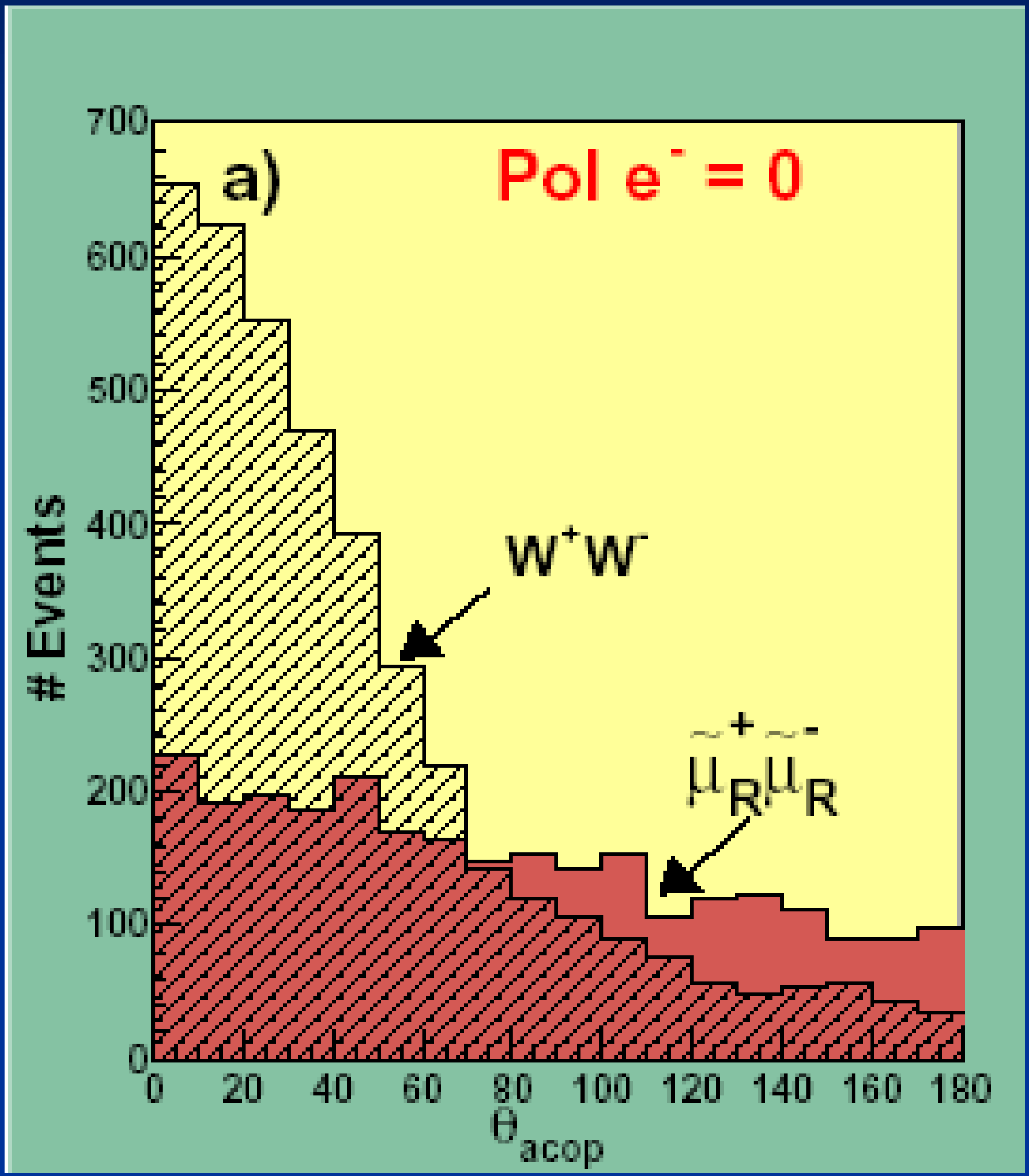
- Every Elementary Particle has SUSY partner, their masses $\lesssim$ TeV

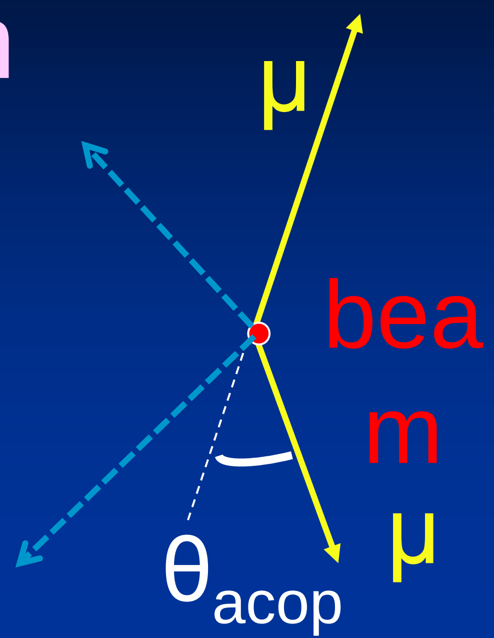
⇒ The value of the SUSY discovery is that for the Anti-particles

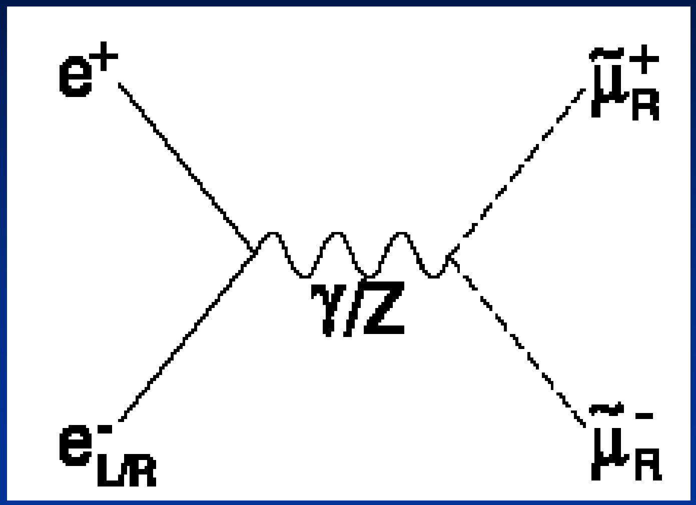


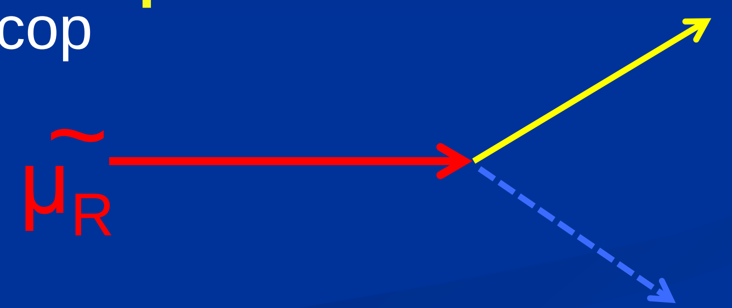
Power of electron polarization at ILC

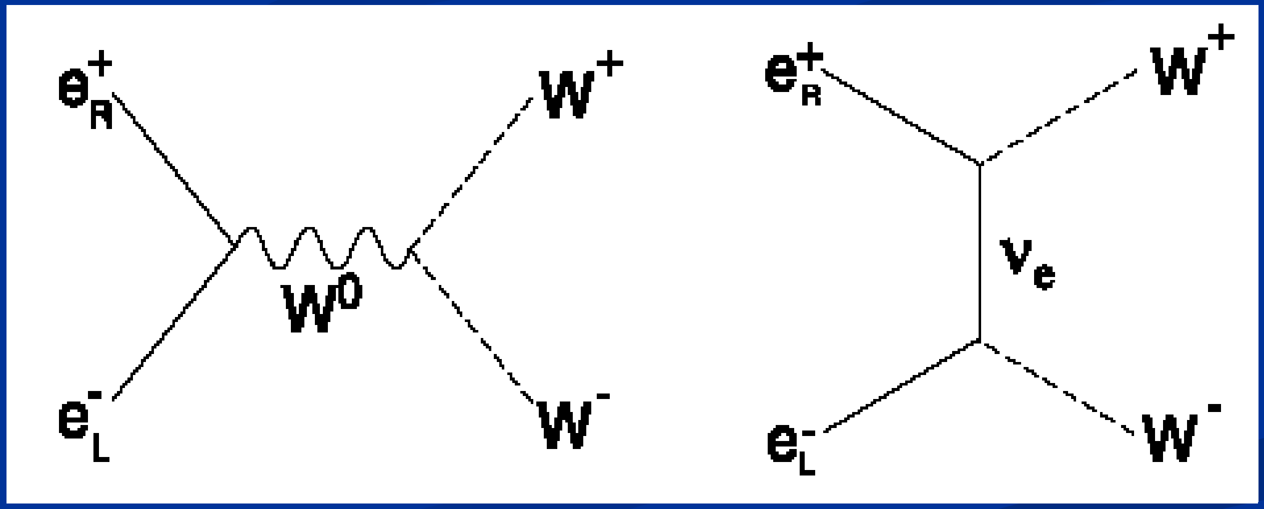
Scalar muon production









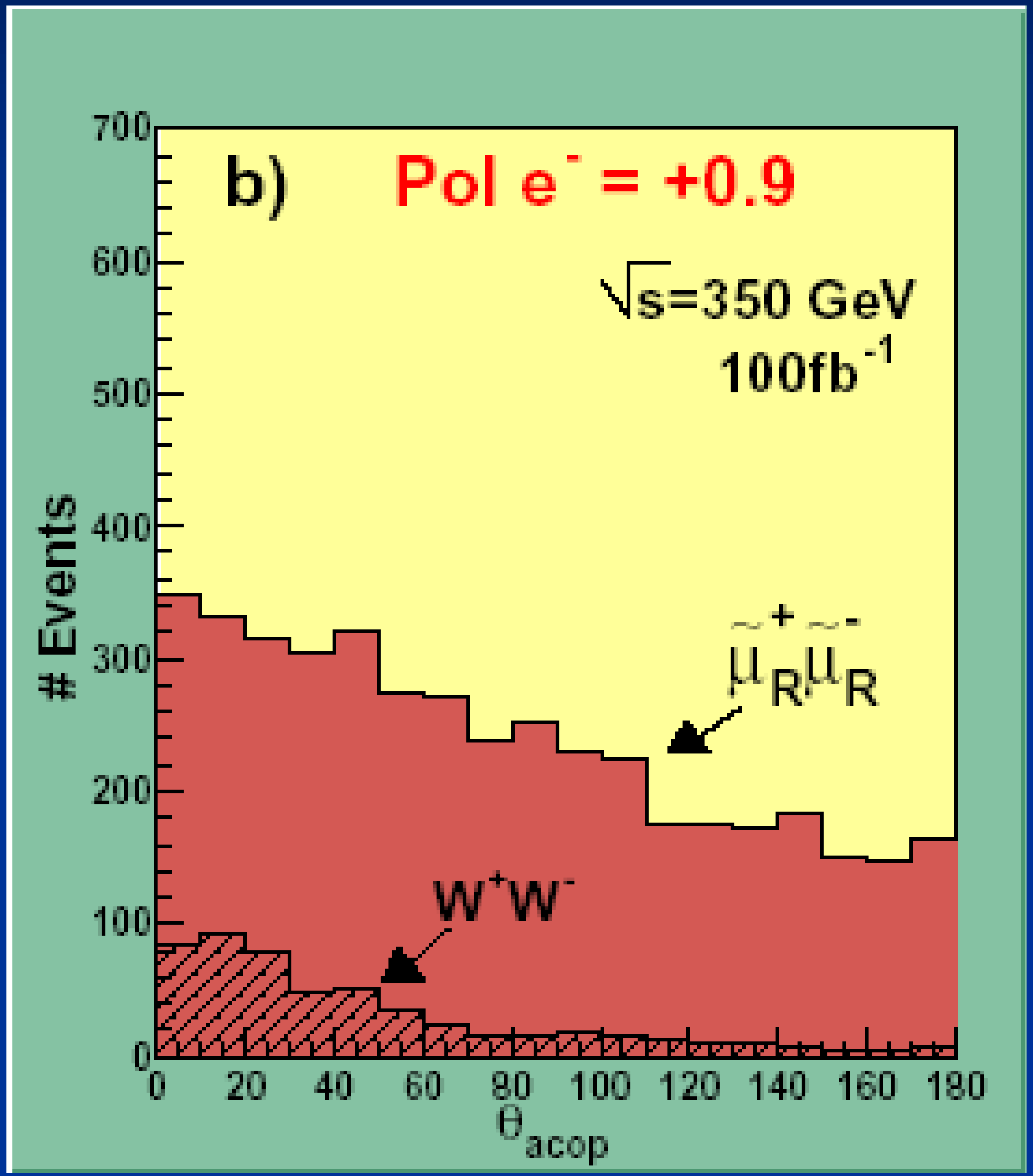


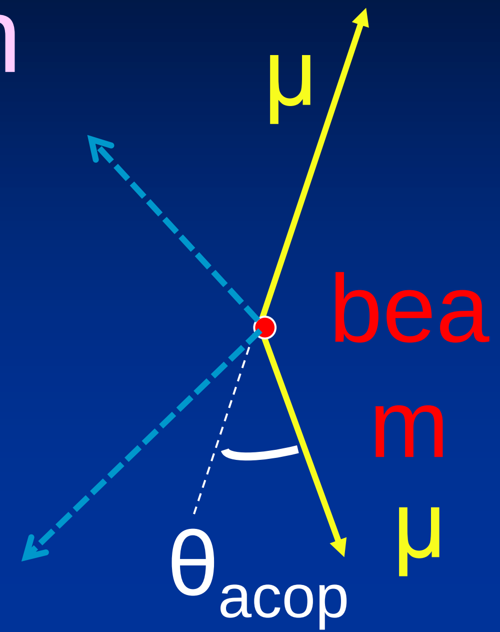
Unpolarized

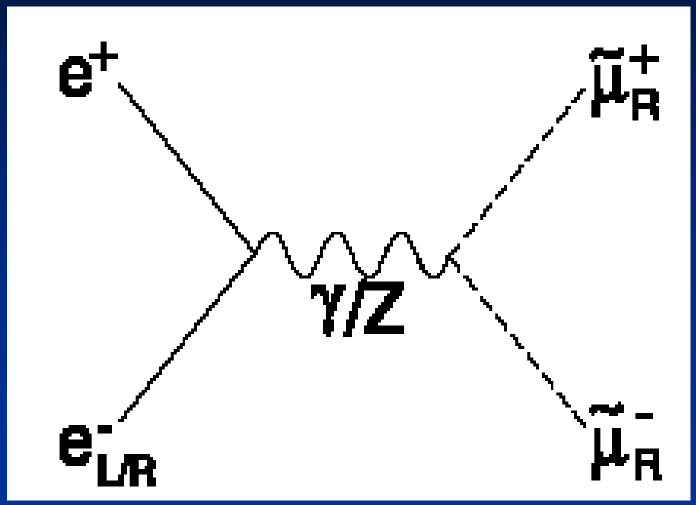
Background signal

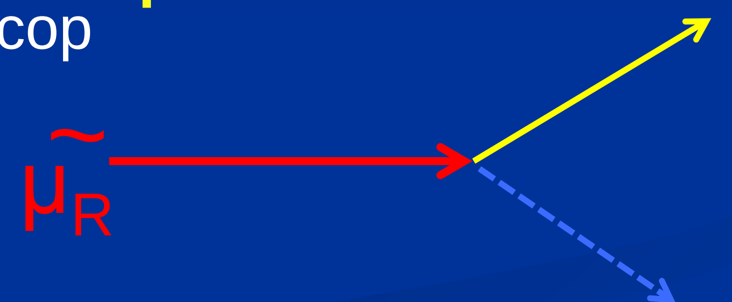
Power of electron polarization at ILC

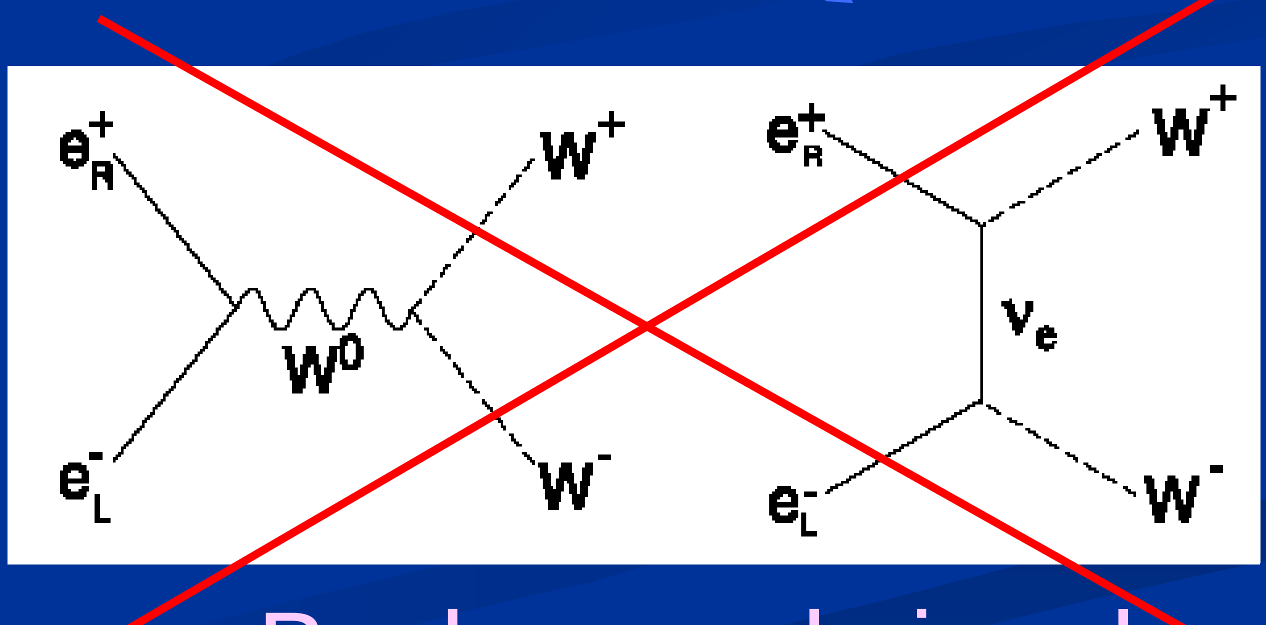
Scalar muon production









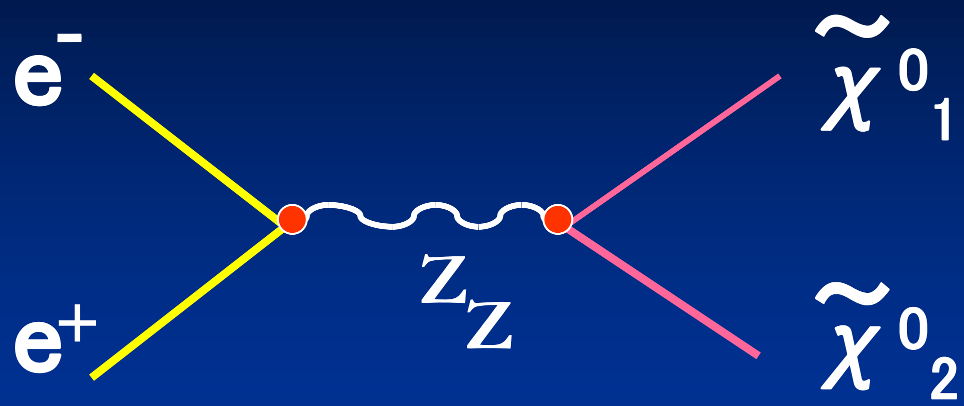


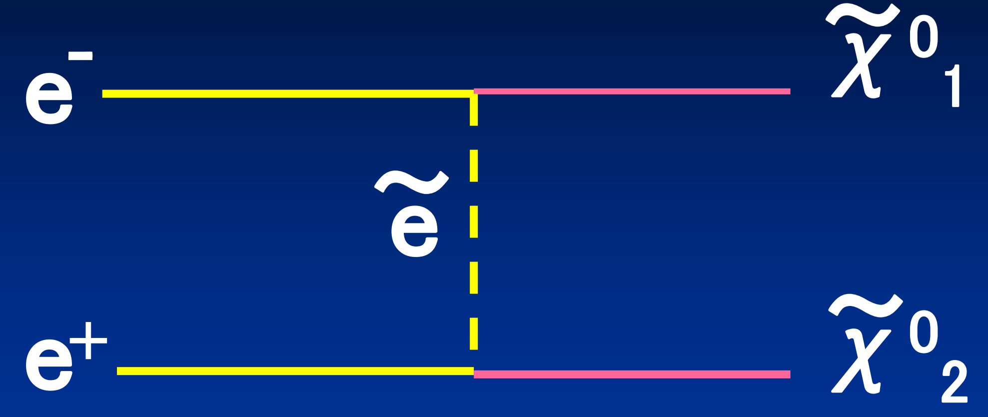
Polarized (90% e^-_R)

Background signal

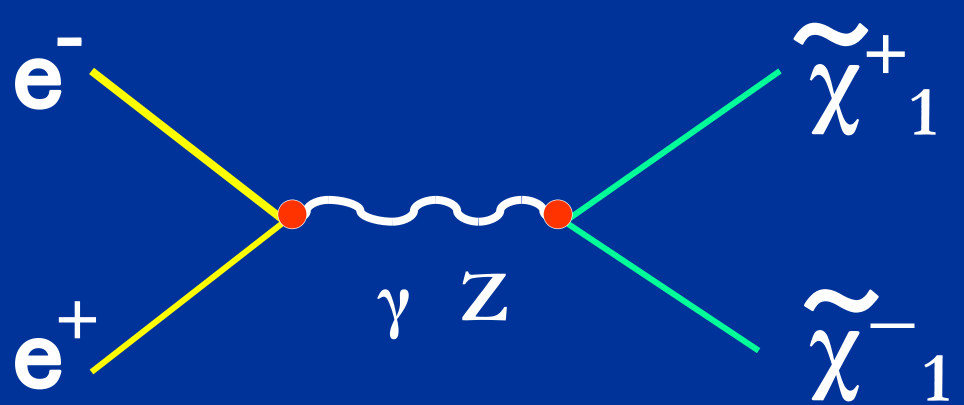
Possible Dark Matter Searches at e+e-

The lightest and the next lightest SUSY particles

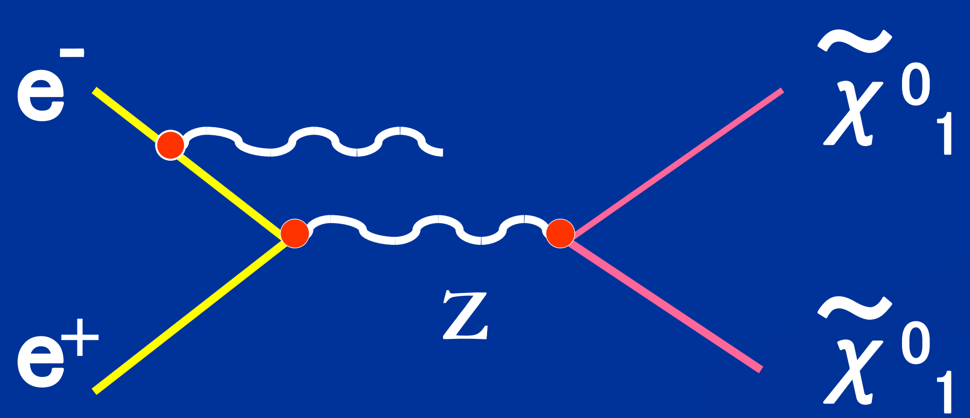


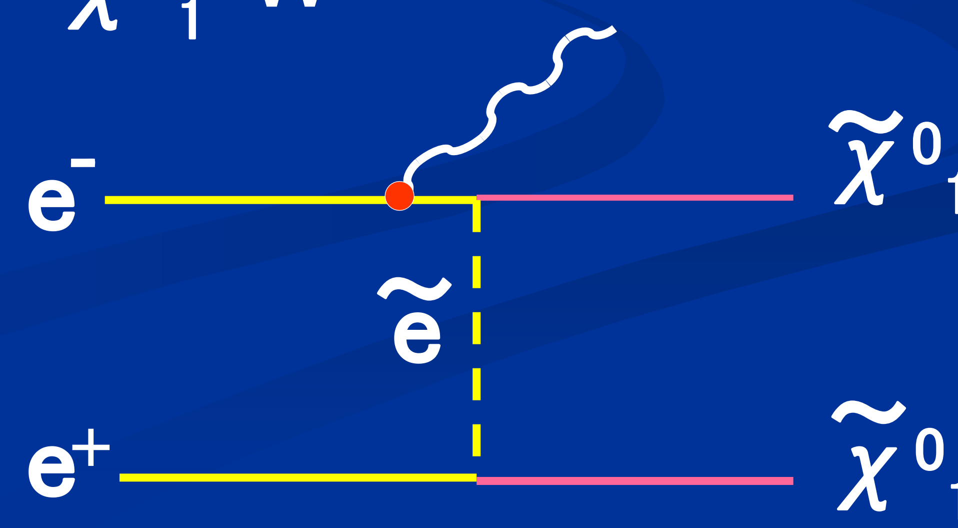


$$\tilde{\chi}^0_1 \; \tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 \; \tilde{\chi}^0_1 \, Z \quad \text{or} \quad \tilde{\chi}^0_1 \; \tilde{\chi}^0_1 \, h$$



$$\tilde{\chi}^+_1 \; \tilde{\chi}^-_1 \rightarrow \tilde{\chi}^0_1 \, W^+ \; \tilde{\chi}^0_1 \, W^-$$



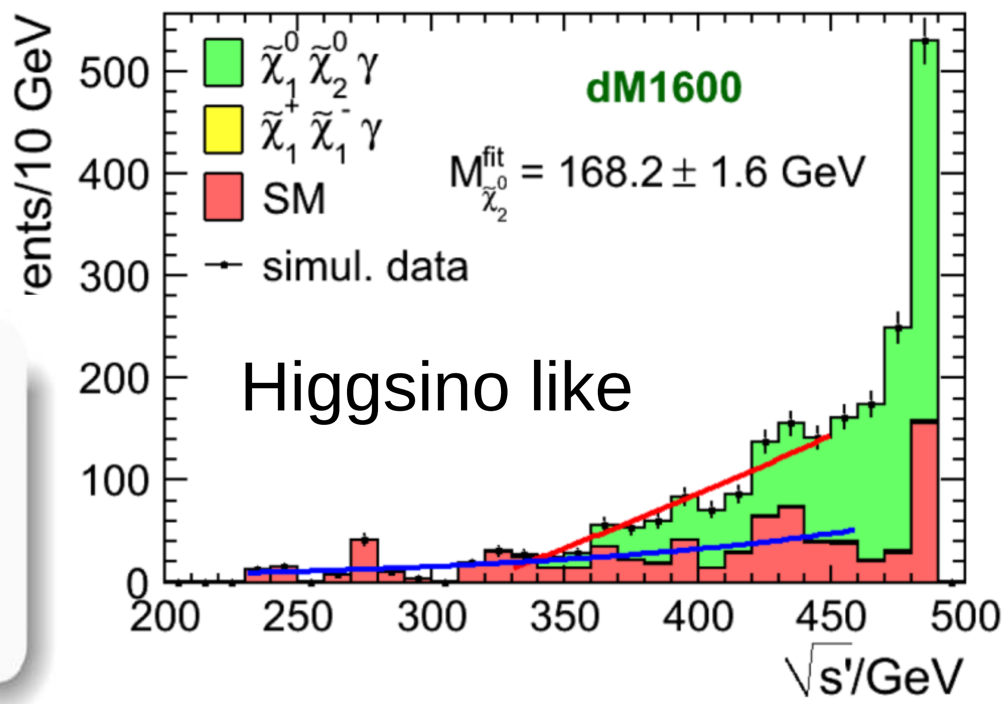


Search for Light SUSY Particles (Dark Matter Candidate)

Tag the Initital State Radiation

$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \gamma$$

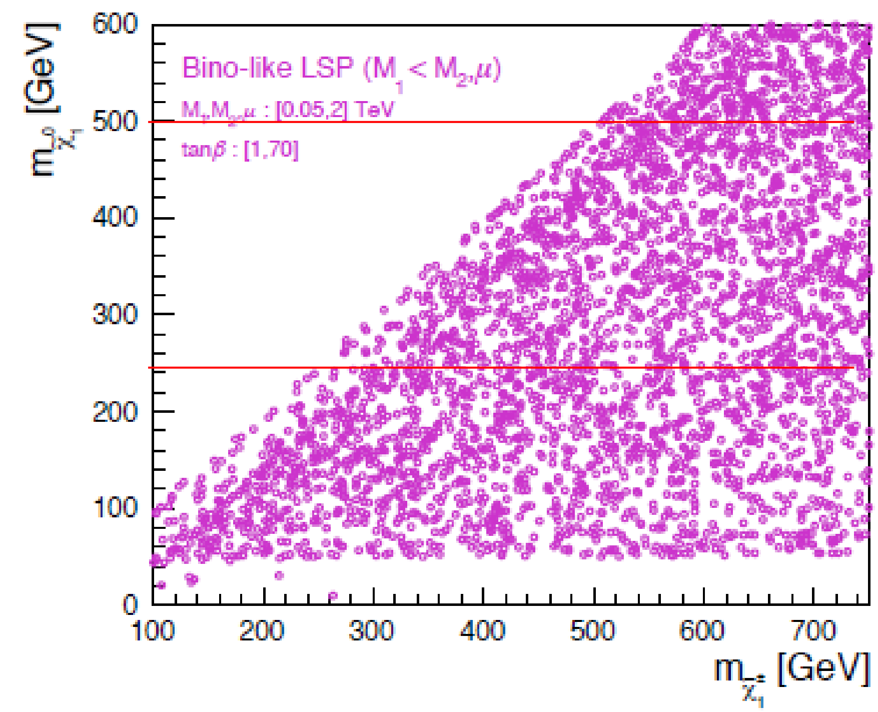
$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \gamma$$



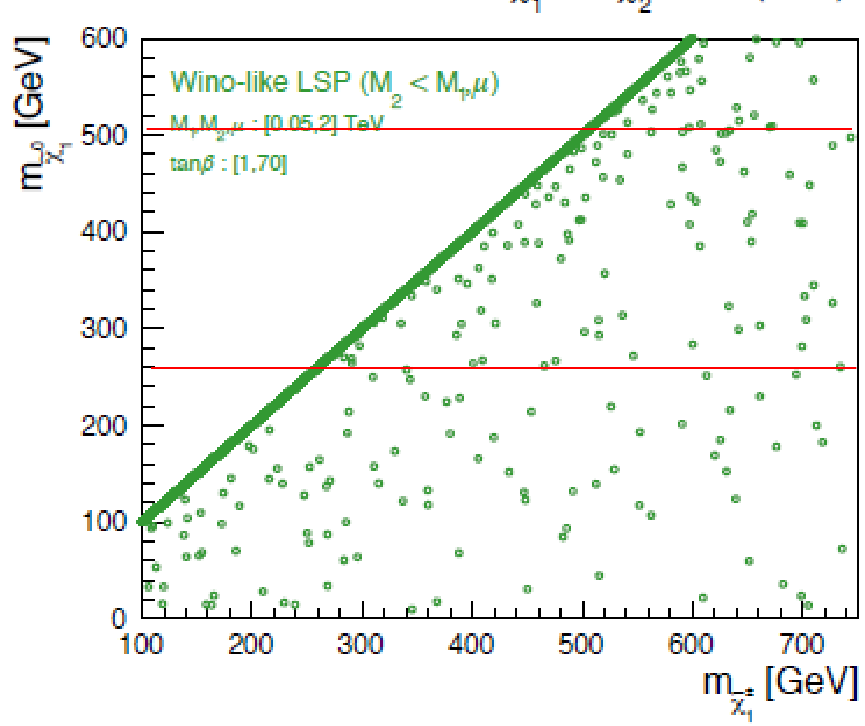
$(M_1, M_2, \mu, \tan\beta)$ point is randomly chosen
$0.05 < M_1, M_2, \mu < 2$ TeV,
$1 < \tan\beta < 70$
Calculate LSP and the lightest chargino masses

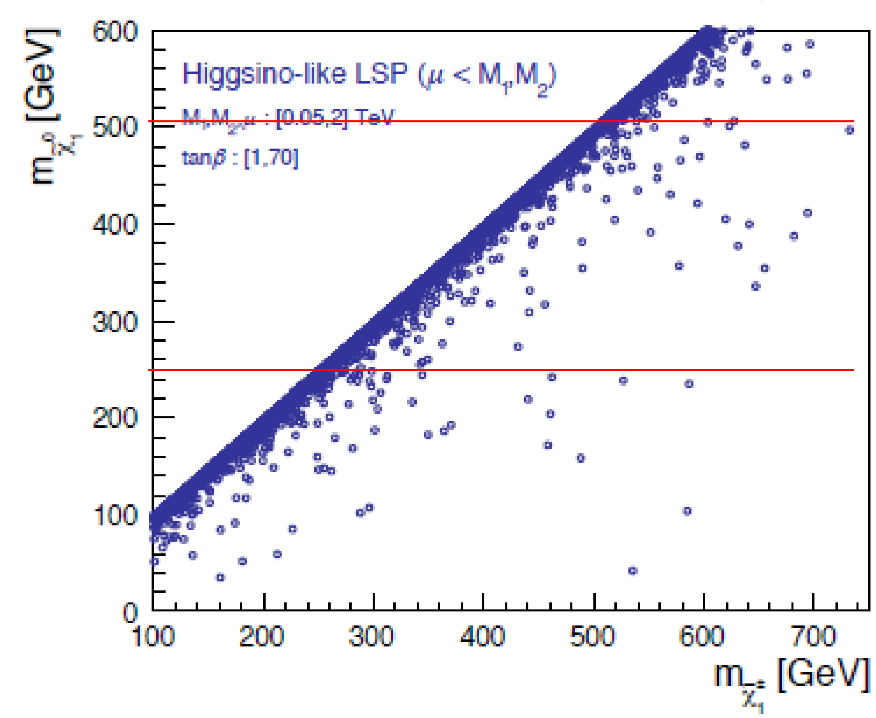
LSP

Bino-like	$M_1 < M_2, \mu$
Wino-like	$M_2 < M_1, \mu$
Higgsino-like	$\mu < M_1, M_2$



$\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ Mass (GeV)





WIMP Dark Matter Search @ ILC

Weakly Interacting Massive Particle

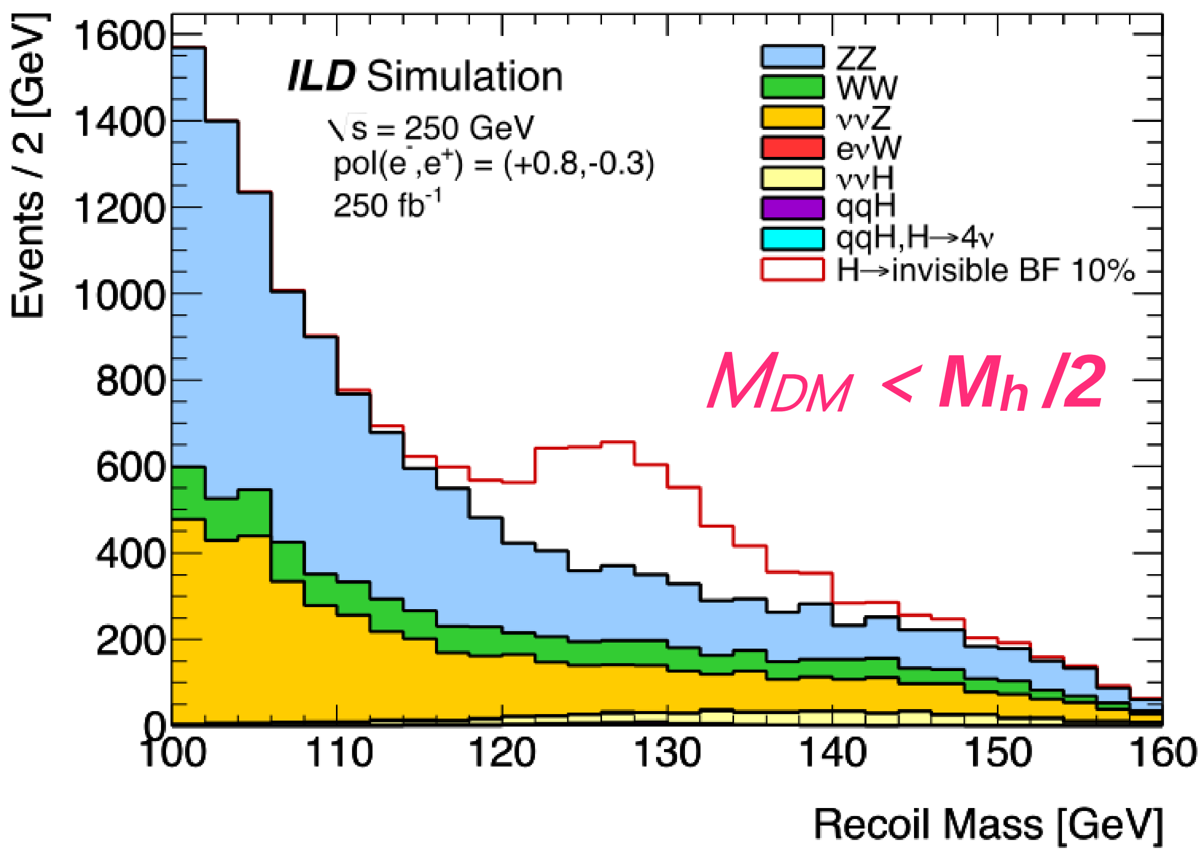
1. Decay of a new particle to Dark Matter (DM)

Dark Matter (DM) has a charged partner in many new physics models.

SUSY: The Lightest SUSY Particle (LSP) = DM → Its partner decays to a DM.

- Events with missing Pt (example: light chargino: challenging at LHC if mass difference is small)

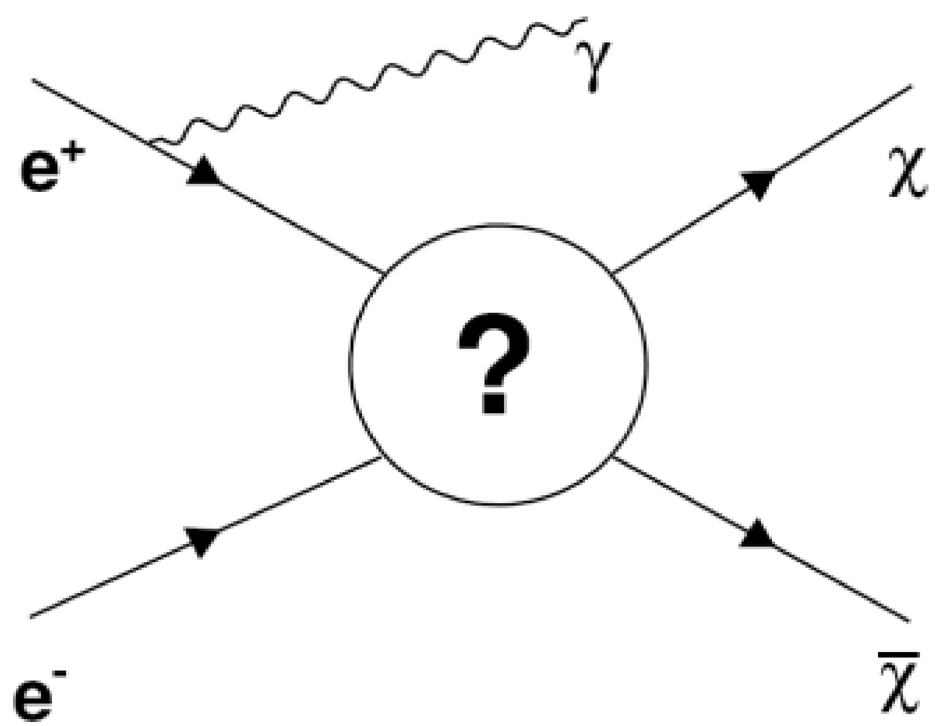
2. Higgs Invisible Decay



Possible to access BR_{inv} to 0.3%!

Possible to access BR_{inv} to 0.3%!

3. Mono-photon Search



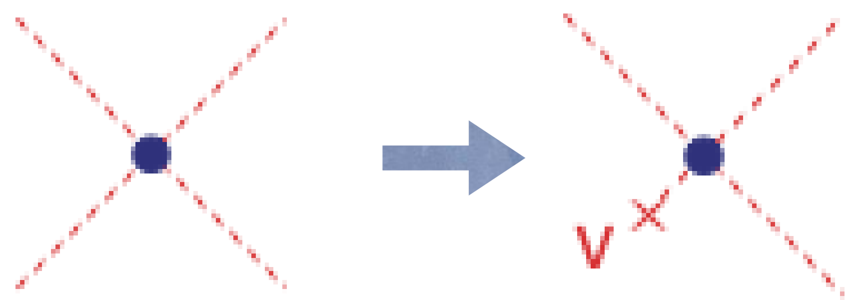
Possible to access DM to ~E_{cm}/2!

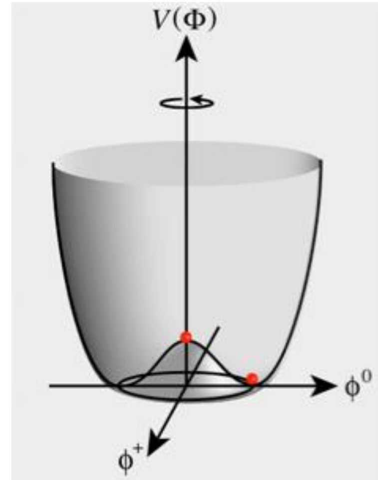
Possible to access DM to ~E_{cm}/2!

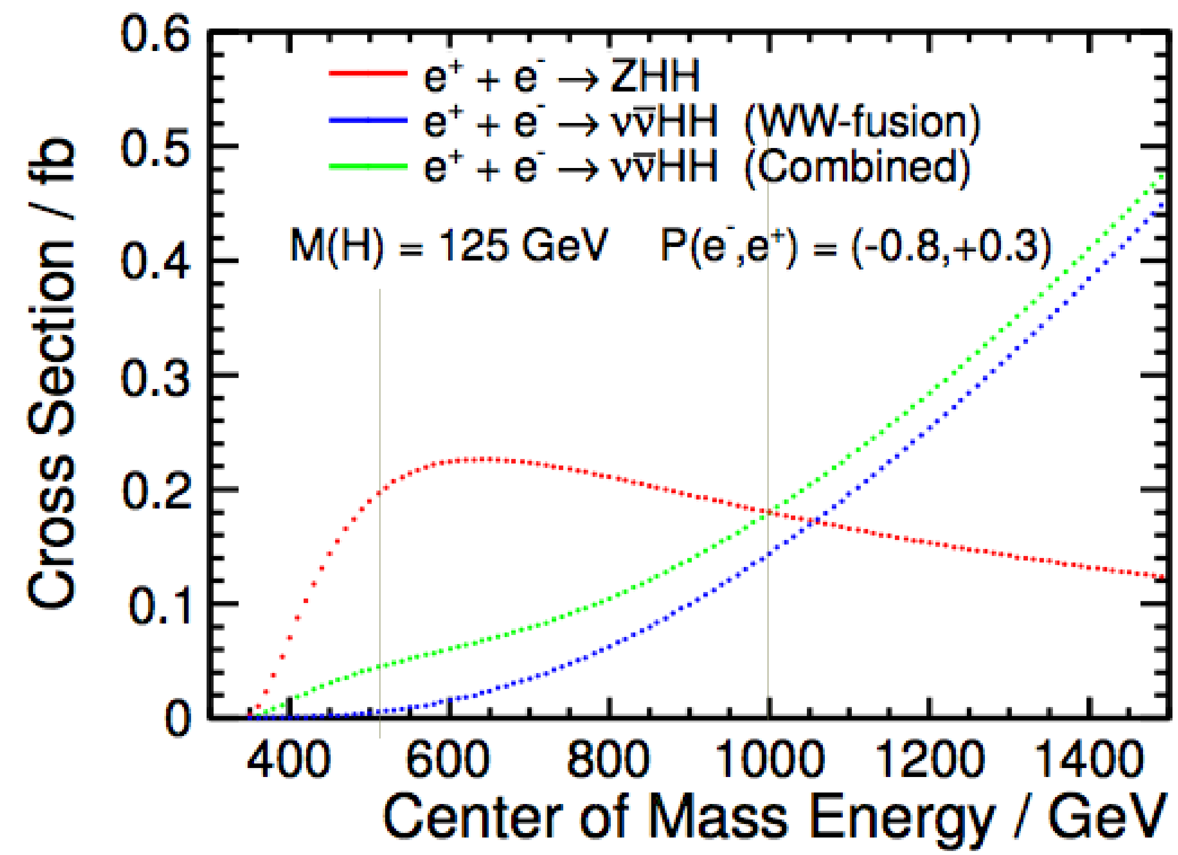
Look for dark matter mainly couples to leptons and gauge bosons

Higgs Self-Coupling

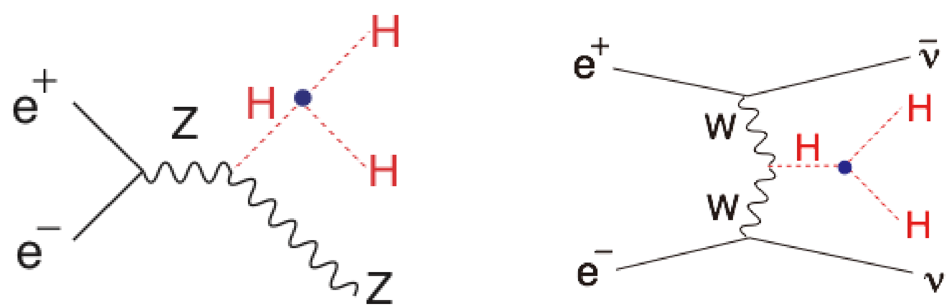
The ***Higgs cubic self-coupling*** is at the heart of EWSB, so should be measured in its own right!







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: 1506.07870

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***

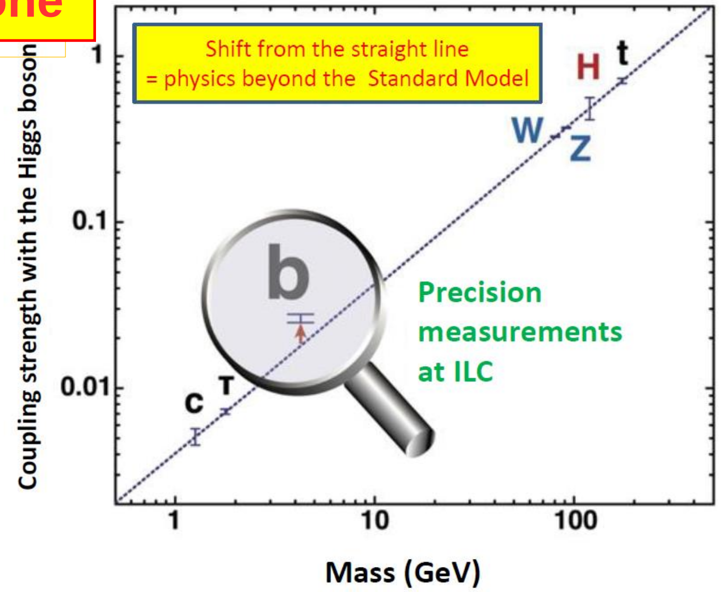
Ongoing effort ***towards O(10)% measurement***

So many physics can be done

Higgs precise measurements
- **Definitely possible at ILC**

Higgs boson is so special

Inclusive cross section : $e^+e^- \to H\ (Z \to e^+e^-)$
Inclusive cross section: $e^+e^- \to H\ (Z \to \mu^+\mu^-)$
Inclusive cross section: $e^+e^- \to H\ (Z \to q\ q)$
Z angular distribution : $e^+e^- \to H\ (Z \to e^+e^-)$
Z angular distribution : $e^+e^- \to H\ (Z \to \mu^+\mu^-)$
Z angular distribution : $e^+e^- \to H\ (Z \to q\ q)$
Partial production cross sections
$e^+e^- \to (H \to b\ b)\ (Z \to e^+e^-)$
$e^+e^- \to (H \to c\ c)\ (Z \to e^+e^-)$
$e^+e^- \to (H \to g\ g)\ (Z \to e^+e^-)$
$e^+e^- \to (H \to \tau^+\tau^-)\ (Z \to e^+e^-)$
$e^+e^- \to (H \to \mu^+\mu^-)\ (Z \to e^+e^-)$
$e^+e^- \to (H \to W\ W)\ (Z \to e^+e^-)$
$e^+e^- \to (H \to Z\ Z)\ (Z \to e^+e^-)$
$e^+e^- \to$ (H → invisible) $(Z \to e^+e^-)$
$e^+e^- \to$ (H → "exotic") $(Z \to e^+e^-)$
$e^+e^- \to (H \to b\ b)\ (Z \to \mu^+\mu^-)$
$e^+e^- \to (H \to c\ c)\ (Z \to \mu^+\mu^-)$
$e^+e^- \to (H \to g\ g)\ (Z \to \mu^+\mu^-)$
$e^+e^- \to (H \to \tau^+\tau^-)\ (Z \to \mu^+\mu^-)$
$e^+e^- \to (H \to \mu^+\mu^-)\ (Z \to \mu^+\mu^-)$
$e^+e^- \to (H \to W\ W)\ (Z \to \mu^+\mu^-)$
$e^+e^- \to (H \to Z\ Z)\ (Z \to \mu^+\mu^-)$
$e^+e^- \to$ (H → invisible) $(Z \to \mu^+\mu^-)$
$e^+e^- \to$ (H → "exotic") $(Z \to \mu^+\mu^-)$
$e^+e^- \to (H \to b\ b)\ (Z \to q\ q)$
$e^+e^- \to (H \to c\ c)\ (Z \to q\ q)$
$e^+e^- \to (H \to g\ g)\ (Z \to q\ q)$
$e^+e^- \to (H \to \tau^+\tau^-)\ (Z \to q\ q)$
$e^+e^- \to (H \to \mu^+\mu^-)\ (Z \to q\ q)$
$e^+e^- \to (H \to W\ W)\ (Z \to q\ q)$
$e^+e^- \to (H \to Z\ Z)\ (Z \to q\ q)$
$e^+e^- \to$ (H → invisible) $(Z \to q\ q)$
$e^+e^- \to$ (H → "exotic") $(Z \to q\ q)$
Inclusive cross sec.: $e^+e^- \to \gamma\ H$
Photon angular dist.: $e^+e^- \to \gamma\ H$
CP effects
$e^+e^- \to (H \to \tau^+\tau^-)\ (Z \to q\ q)$
$e^+e^- \to (H \to \tau^+\tau^-)\ (Z \to e^+e^-)$
$e^+e^- \to (H \to \tau^+\tau^-)\ (Z \to \mu^+\mu^-)$
$e^+e^- \to (H \to \tau^+\tau^-)\ (Z \to \nu\ \nu)$
$H \to (W \to q\ q)\ (W \to q\ q)$
$H \to (W \to q\ q)\ (W \to l\ \nu)$
$H \to (Z \to q\ q)\ (Z \to q\ q)$
$H \to (Z \to q\ q)\ (Z \to l\ l)$
$H \to (Z \to l\ l)\ (Z \to l\ l)$



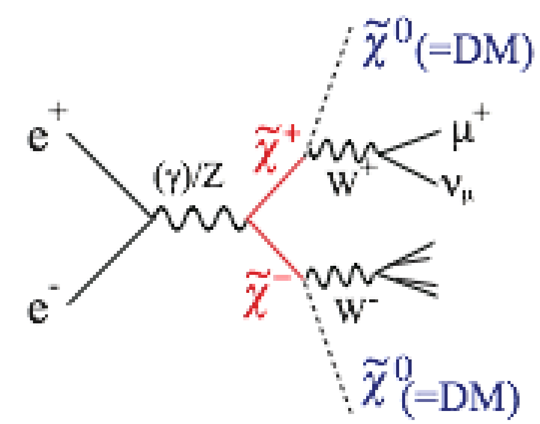
Precise measurement Elctroweak
- Definitely possible at ILC
- 3 orders of magnitude better than LEP
- Closely related to Higgs precise meas.
- Polarization is essential

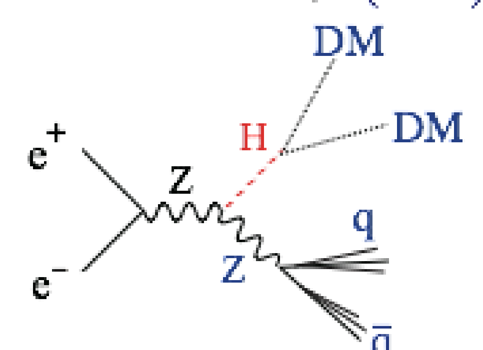
Cross section: $e^+e^- \to (W \to q\ q)\ (W \to q\ q)$
Cross section: $e^+e^- \to (W \to q\ q)\ (W \to l\ \nu)$
Cross section: $e^+e^- \to (W \to l\ \nu)\ (W \to l\ \nu)$
W boson decay branching, mass width
$e^+e^- \to (W \to q\ q)\ (W \to q\ q)$
$e^+e^- \to (W \to q\ q)\ (W \to l\ \nu)$
CP conserving triple gauge coupling
$e^+e^- \to (W \to q\ q)\ (W \to l\ \nu)$
CP violating triple gauge coupling
$e^+e^- \to (W \to q\ q)\ (W \to l\ \nu)$
Cross section : $e^+e^- \to (Z \to q\ q)\ (Z \to q\ q)$
Cross section: $e^+e^- \to (Z \to q\ q)\ (Z \to l\ l)$
Cross section: $e^+e^- \to (Z \to l\ l)\ (Z \to l\ l)$
CP conserving anomalous triple gauge boson coupling:
$e^+e^- \to (Z \to q\ q)\ (Z \to q\ q)$
$e^+e^- \to (Z \to q\ q)\ (Z \to l\ l)$
$e^+e^- \to (Z \to l\ l)\ (Z \to l\ l)$
CP violating anomalous triple gauge boson coupling :
$e^+e^- \to (Z \to q\ q)\ (Z \to q\ q)$
$e^+e^- \to (Z \to q\ q)\ (Z \to l\ l)$
$e^+e^- \to (Z \to l\ l)\ (Z \to l\ l)$
Cross section: $e^+e^- \to \gamma\ Z$
Photon angular distribution: $e^+e^- \to \gamma\ Z$
Cross section: $e^+e^- \to \gamma\ \gamma$
Angular distribution: $e^+e^- \to \gamma\ \gamma$

This is just an example for ILC, but for all other e^+e^- colliders are similar

New particle searches
- possibility of direct observation of new particles

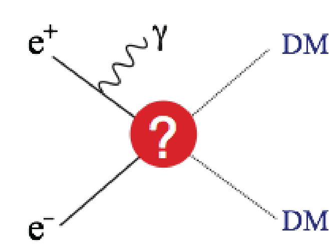
New Higgs boson searches
$e^+e^- \to (Z \to e^+e^-) + X$
$e^+e^- \to (Z \to \mu^+\mu^-) + X$
$e^+e^- \to (Z \to q\ q) + X$
$e^+e^- \to A\ H$
Singly charged Higgs boson searches
$e^+e^- \to H^-\ H^+$, $H \to \tau^+\ \nu$, c s , c b
$e^+e^- \to W^-H^+$
Doubly charged Higgs boson searches
$e^+e^- \to W^+\ W^+ + X$
$e^+e^- \to e^+e^+ + X$ $\quad$ $e^+e^- \to \mu^+\mu^+ + X$
$e^+e^- \to \tau^+\ \tau^+ + X$
Ecited lepton searches
Long lived particle searches
Heavy ion particle searches
New particle searches
$e^+e^- \to e\ e + X$ $\quad$ $e^+e^- \to \mu\ \mu + X$
$e^+e^- \to \tau\ \tau + X$ $\quad$ $e^+e^- \to e\ \mu + X$
$e^+e^- \to e\ \tau + X$ $\quad$ $e^+e^- \to \mu\ \tau + X$
$e^+e^- \to b\ b + X$ $\quad$ $e^+e^- \to c\ c + X$
$e^+e^- \to q\ q + X$ $\quad$ $e^+e^- \to b\ c + X$
$e^+e^- \to b\ q + X$ $\quad$ $e^+e^- \to c\ q + X$
$e^+e^- \to g\ g + X$ $\quad$ $e^+e^- \to e\ q + X$
$e^+e^- \to \mu\ q + X$ $\quad$ $e^+e^- \to \tau\ q + X$
$e^+e^- \to W + X$ $\quad$ $e^+e^- \to Z + X$
$e^+e^- \to \gamma + X$

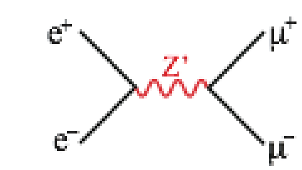




2- Fermion processses
- Possibility of new force discovery
- **Statistics is 3 times higher than LEP**
- Polarization is very important

Cross sections and angular distributions
$e^+e^- \to e^+e^-$ $\quad$ $e^+e^- \to \mu^+\mu^-$
$e^+e^- \to \tau^+\tau^-$
$e^+e^- \to b\ b$ $\quad$ $e^+e^- \to c\ c$
$e^+e^- \to s\ s$ $\quad$ $e^+e^- \to q\ q$
Decay branching fractions of τ
Polarization of τ
Lifetime of τ
Composite particles of quark and lepton
Lepto-quarks
Search for extra-dimensions





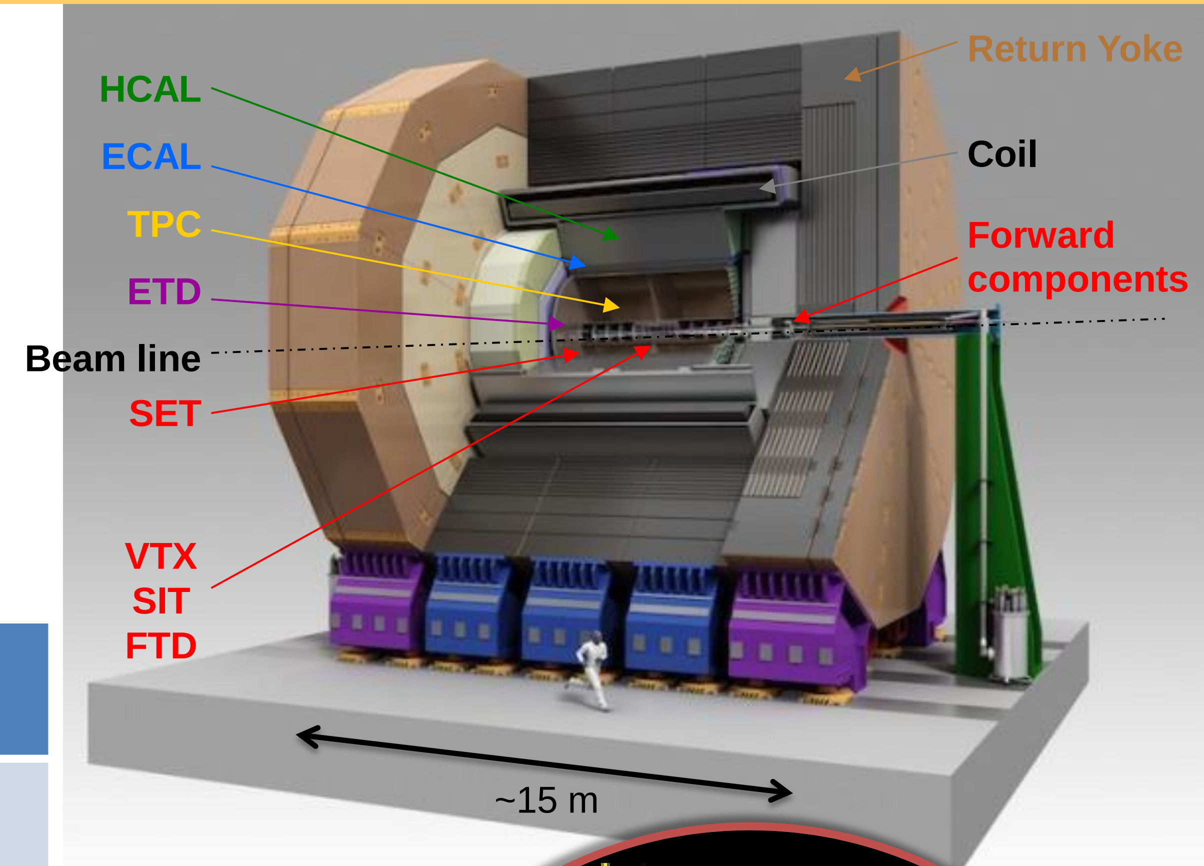
QCD Nuclear Physics
- **Definitely possible at ILC**
- **Detailed understanding of bkg**
- **Important for new particle searches**

Measurement of $\alpha_S\ (q^2)$
$e^+e^- \to$ b b, b b g, b b g g
$e^+e^- \to$ c c, c c g, c c g g
$e^+e^- \to$ q q, q q g, q q g g

Measurement of fragmentation functions
b, c, s, q, gluon
Particle correlations in hadronic system
Production and decay of b,c,s,u,d-baryons、and mesons
Search for exotic hadrons:
tetra-quark、penta-quark、
glueball、etc.
Jet production in the two photon processes
Production and decay of b,c,s,u,d-baryons and mesons in two photon preocesses
Lepton production in two photon processes

ILC Detector R&D (ILD, SiD)

- **Vertex Detector: pixel detectors & low material budget**
- **(Time Projection Chamber: high resolution & low material budget, MPGD readout)**
- **Calorimeters: high granularity sensors, 5x5mm^2 (ECAL)、3x3cm^2 (HCAL)**



Sensor Size	ILC	ATLAS	Ratio
Vertex	5×5 mm^2	400×50 mm^2	x800
Tracker	1×6 mm^2	13 mm^2	x2.2
ECAL	5×5 mm^2 (Si)	39×39 mm^2	x61

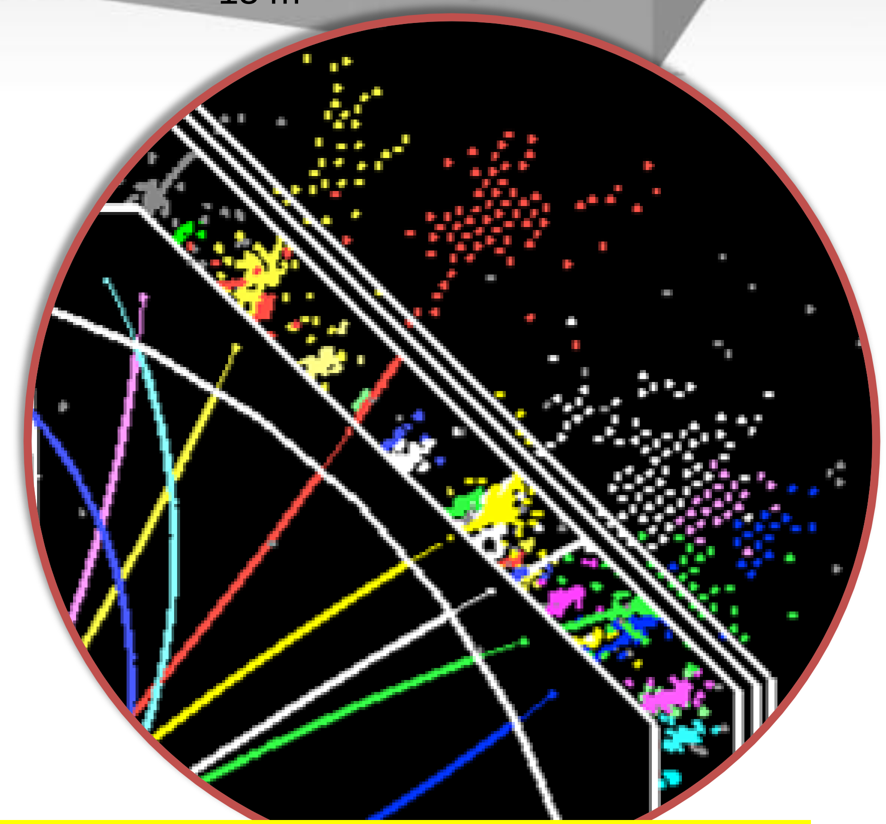
Particle Flow Algorithm

Charged particles → Tracker,

Photons → ECAL, Neutral Hadrons → HCAL

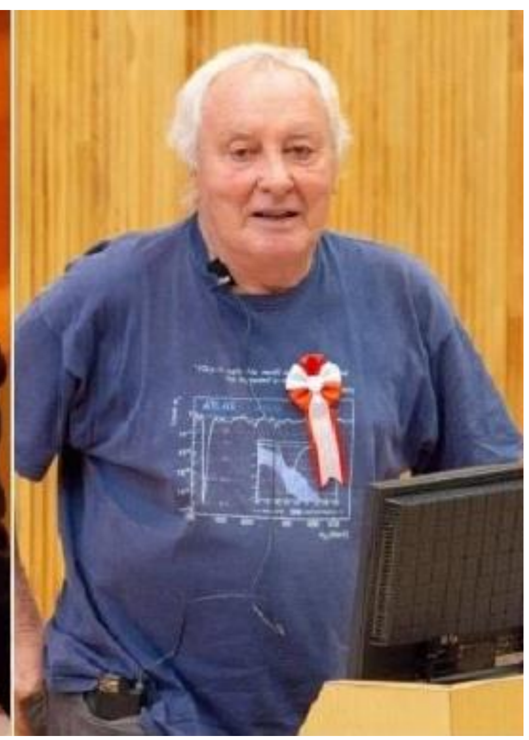
Separate calorimeter clusters at particle level

→use *best* energy measurement for *each* particle.



State-of-the-art detectors can be designed for ILC ⇒Prof. J. Haba's talk

Future e^+e^- Colliders



Future e^+e^- Colliders in the world (Energy Frontier)

Linear Colliders

ILC International Linear Collider 250 GeV (– 1 TeV)

CLIC Compact Linear Collider 380 GeV – 3 TeV

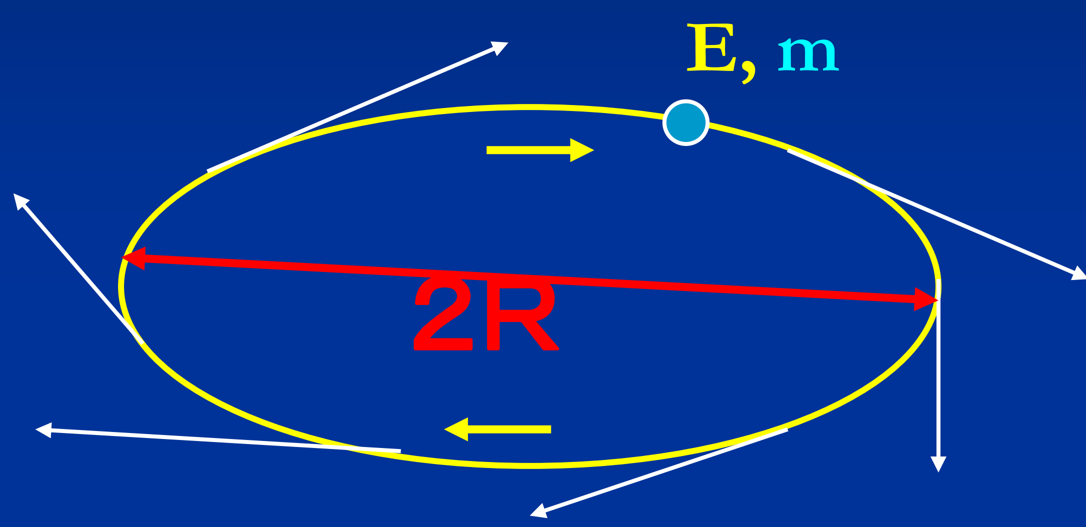
Circular Colliders

CEPC Circular Electron-Positron Collider 240 GeV Z, WW

FCCee Future Circular Collider (e+e-) 240-350 GeV Z, WW

Limit of High Energy Circular e+e- Colliders

Reaction is simple, experiment is clean   but…



Electron and positrons loose energy due to synchrotron radiation

Energy loss per trun ΔE is given by

$$\Delta E \propto (E/m)^4/R$$

E：particle energy
m：particle mass   R：radius

Like a bankruptcy by loan interest

Recover the energy loss and obtain higher collision energy

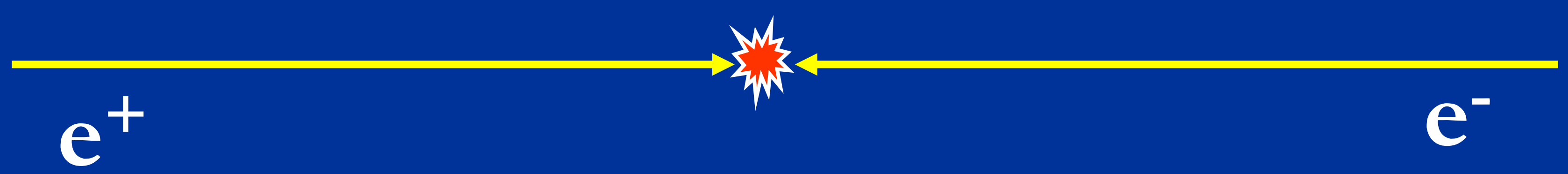
（1）Use heavier particle (proton mass/electron mass＝1800)⇒ LHC

（2） Larger radius ⇒ LEP（27km） ⇒ large radius

Electron Positron Linear Collider is inevitable

Large radius R ⇒ Ultimate radius R=∞ !

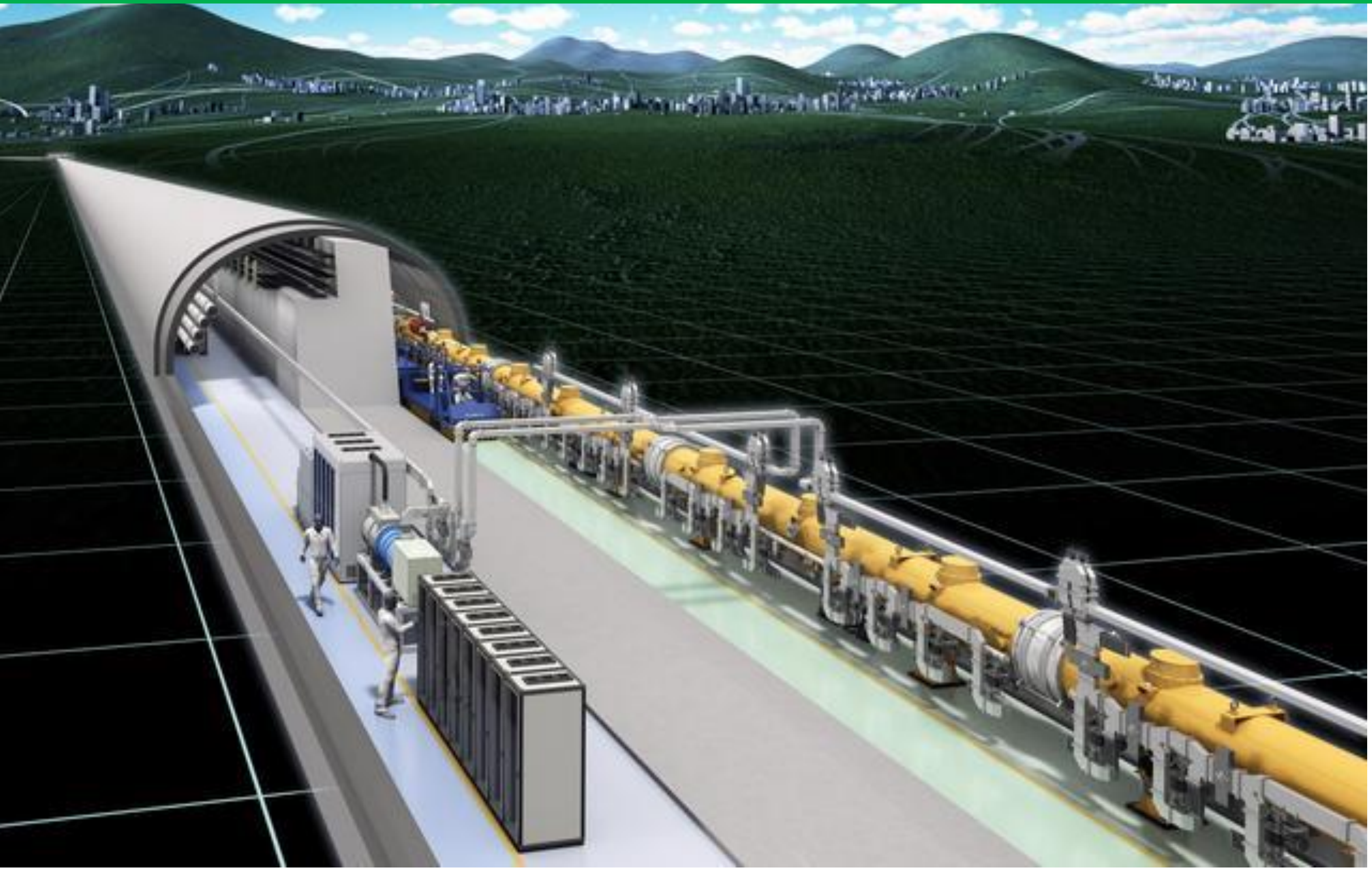
Straight beam line ⇒ No synchrotron radiation (Linear Collider)



Electrons are accelerated from one side positon from the other side. Collide the beams at the center

Reduce construction cost ⇒ High acceleration gradient
Reduce running cost (electric power) ⇒ Squeeze the beam size as small as possible at the interaction point
⇒ round beam is unstable ⇒ very flat beam

ILC (International Linear Collider)



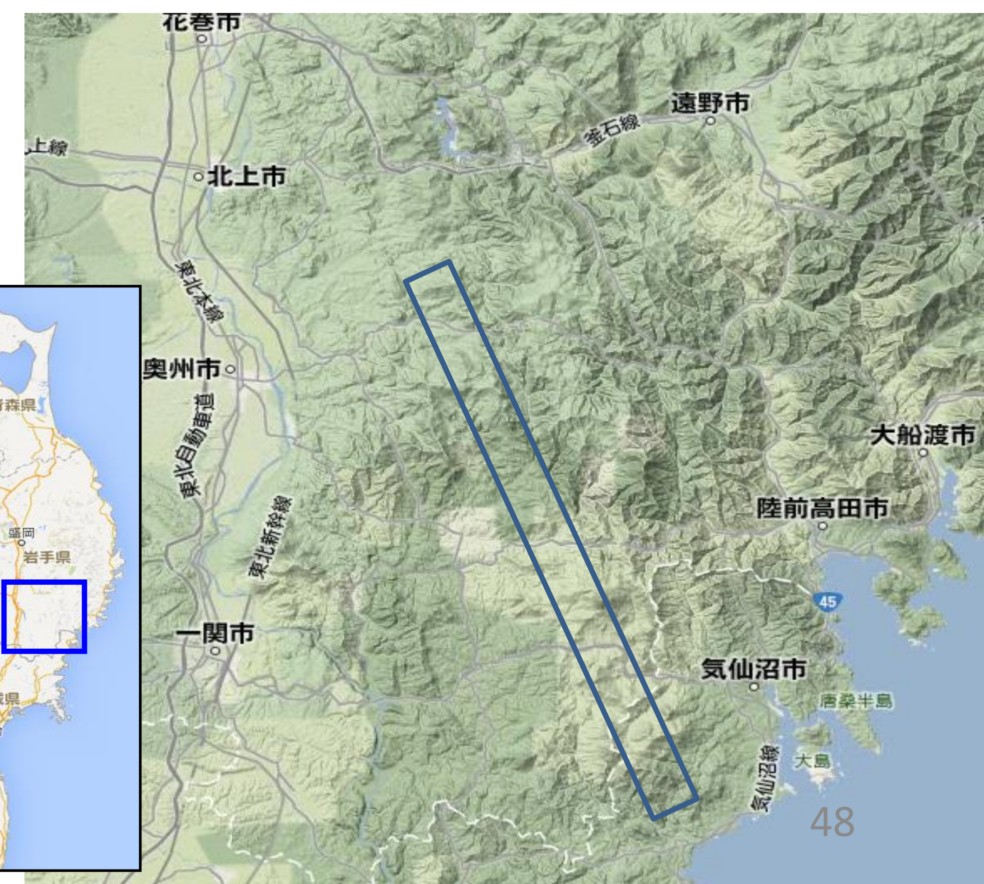
Advantages of linear colliders

(1) No energy loss due to synchrotron radiation
(c.f. Circular Colliders $-\Delta E/\text{turn} \propto (E/m)^4 R^{-1}$)
(2) Energy extendability: length, (gradient) ⇒ energy
(3) Beam Polarization

Discovery of the 125 GeV Higgs Boson at LHC in 2012
⇒ obvious physics target (Higgs is a portal of physics beyond the Standard Model)
⇒ triggered early construction of the ILC

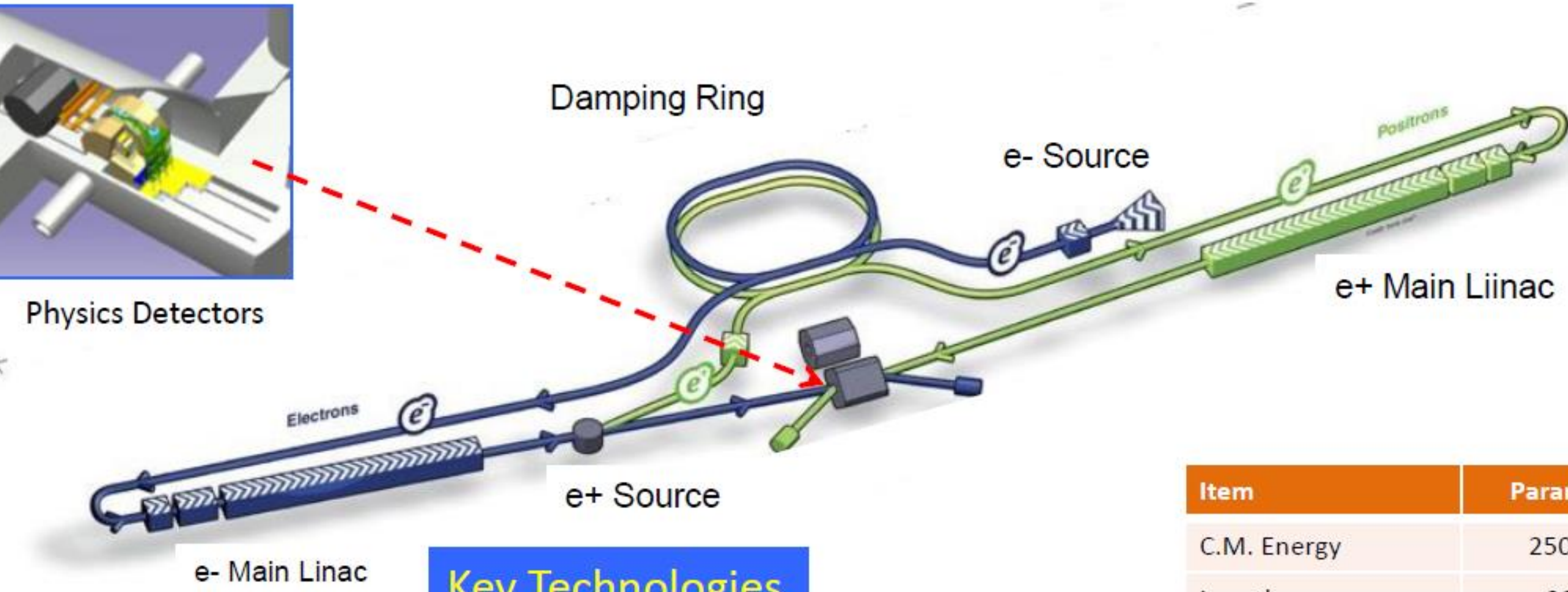
ILC Site Candidate Location in Japan: Kitakami

Earthquake-proof stable bedrock of granite. No faults cross the line.



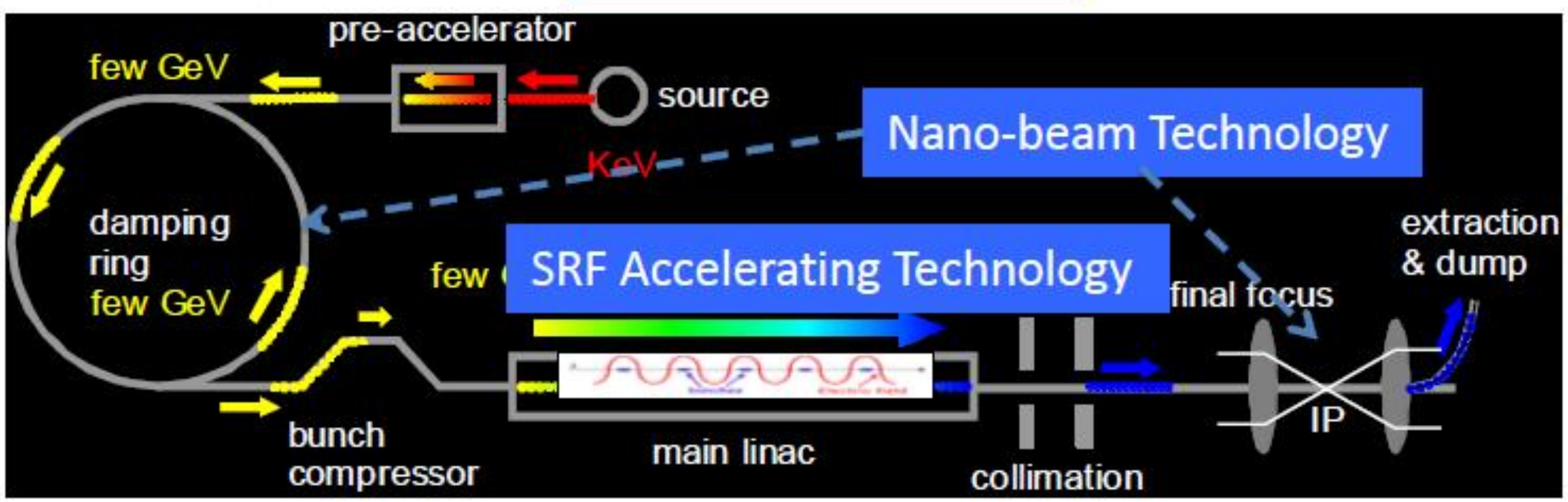
ILC250 Acc. Design Overview

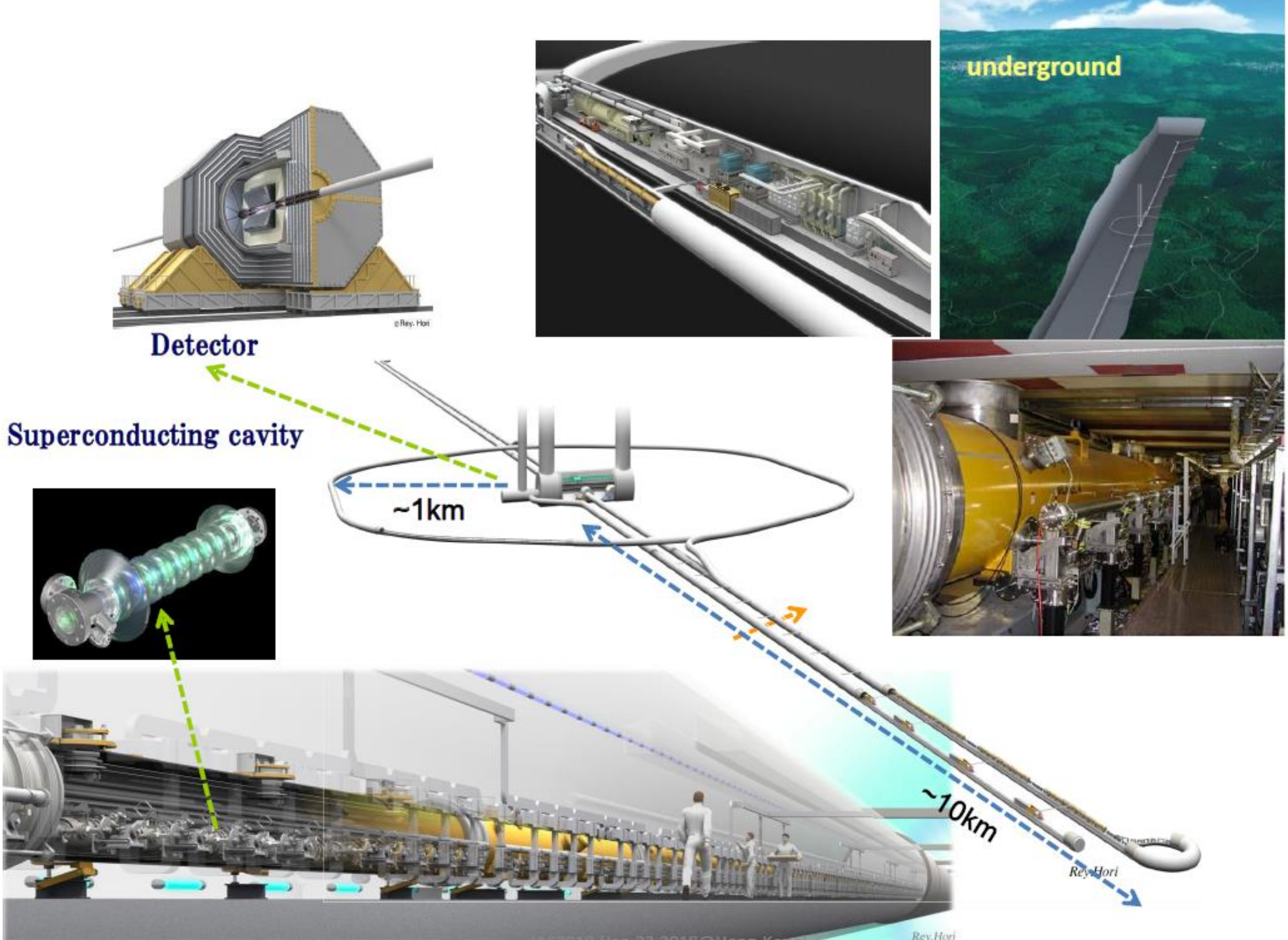
The most matured design



Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 $x10^{34}$ $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m Q_0 = $1x10^{10}$

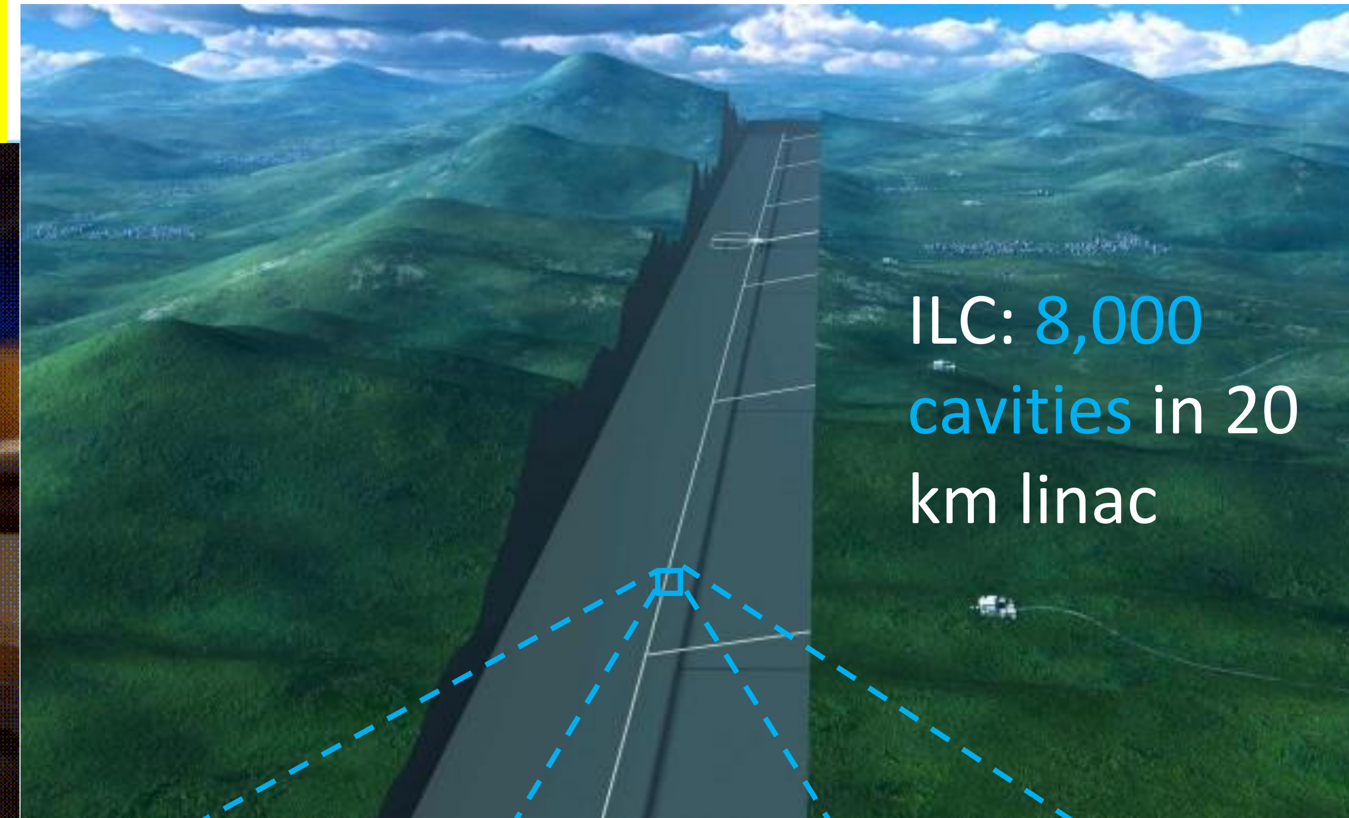
Key Technologies




underground
Detector
Superconducting cavity
~1km
~10km
Rey.Hori

○European XFEL (@DESY) is running now：10% scale linac of the ILC 250 GeV

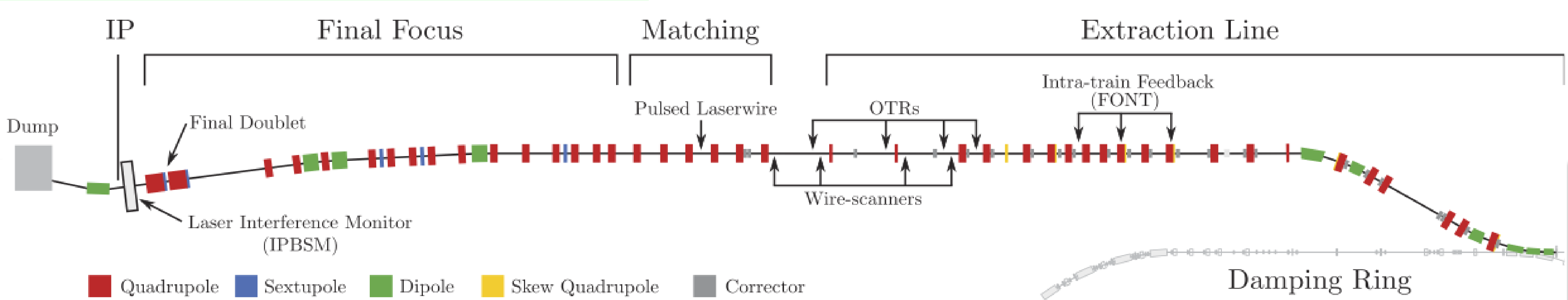
European XFEL(DESY), LCLS-II



○ATF2(@KEK): the same Optics as

Using the same fosusing optics as ILC
Vertical beam size of 41 nm is achieved
（Goal ：37 nm)

For beam size feedback 133 ns (Goal：< 300 ns)
Beam size measurement is still poor (<67 nm) due to BPM (goal *a few nm)

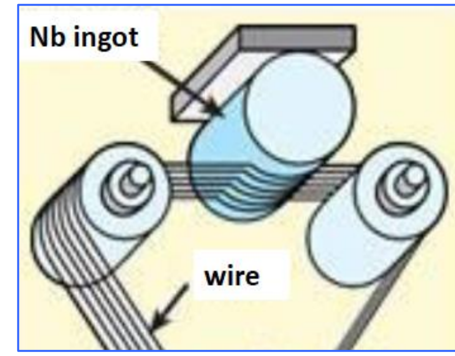


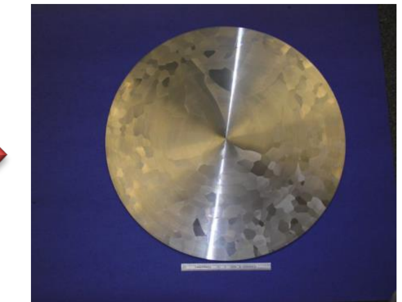
“DoE-MEXT ILC Discussion Group” was formed in October 2016

cost reduction and **management of the ILC lab** are the main issues

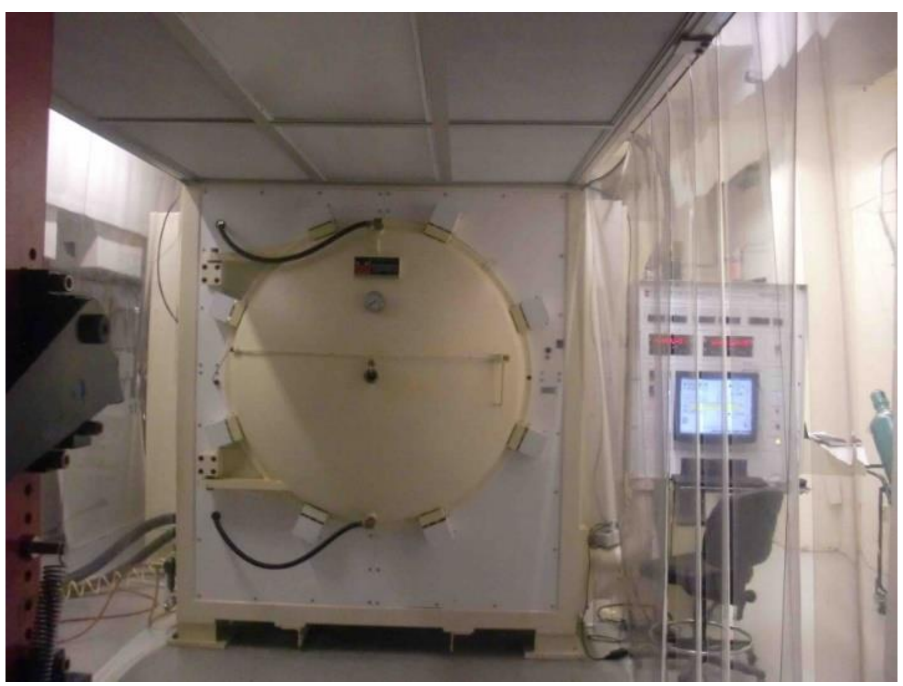
1. Cost reduction in Nb material preparation

- Optimize the ingot purity with a lower residual resistivity ratio (RRR).
- Simplify the manufacturing method such as forging, rolling, slicing and tube forming.

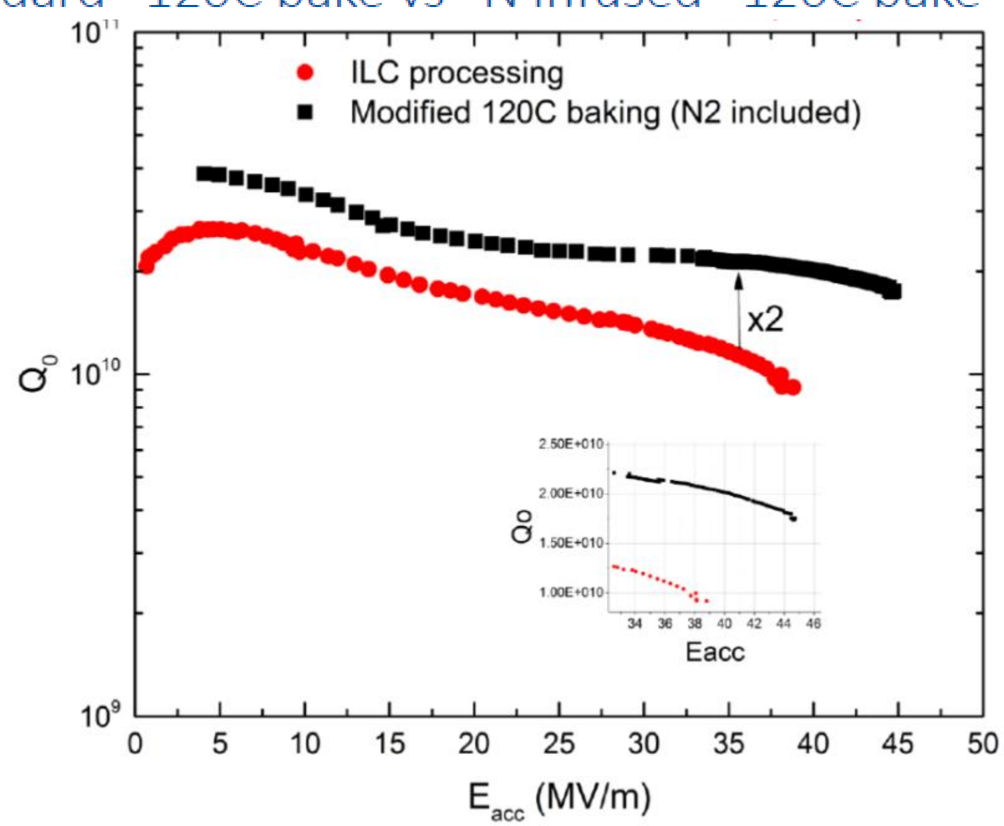




2. High-Q high-gradient SRC with nitrogen infusion at Fermilab



“standard” 120C bake vs “N infused” 120C bake



Achieved:
45.6 MV/m → 194 mT
with Q ~ 2×10^{10}
Q ~2.3×10^{10}
at 35MV/m

ILC spec:
Q = 0.8×10^{10}
at 35 MV/m

Increase in Q factor of two, increase in gradient ~15%

- **Confirm reproducibility of the nitrogen infusion method to improve Q and field gradient of SC RF cavity developed at Fermilab. ⇒ Understand the underlying physics**
- **High statistics test of the yield by fabricating 8 9-cell cavities.**

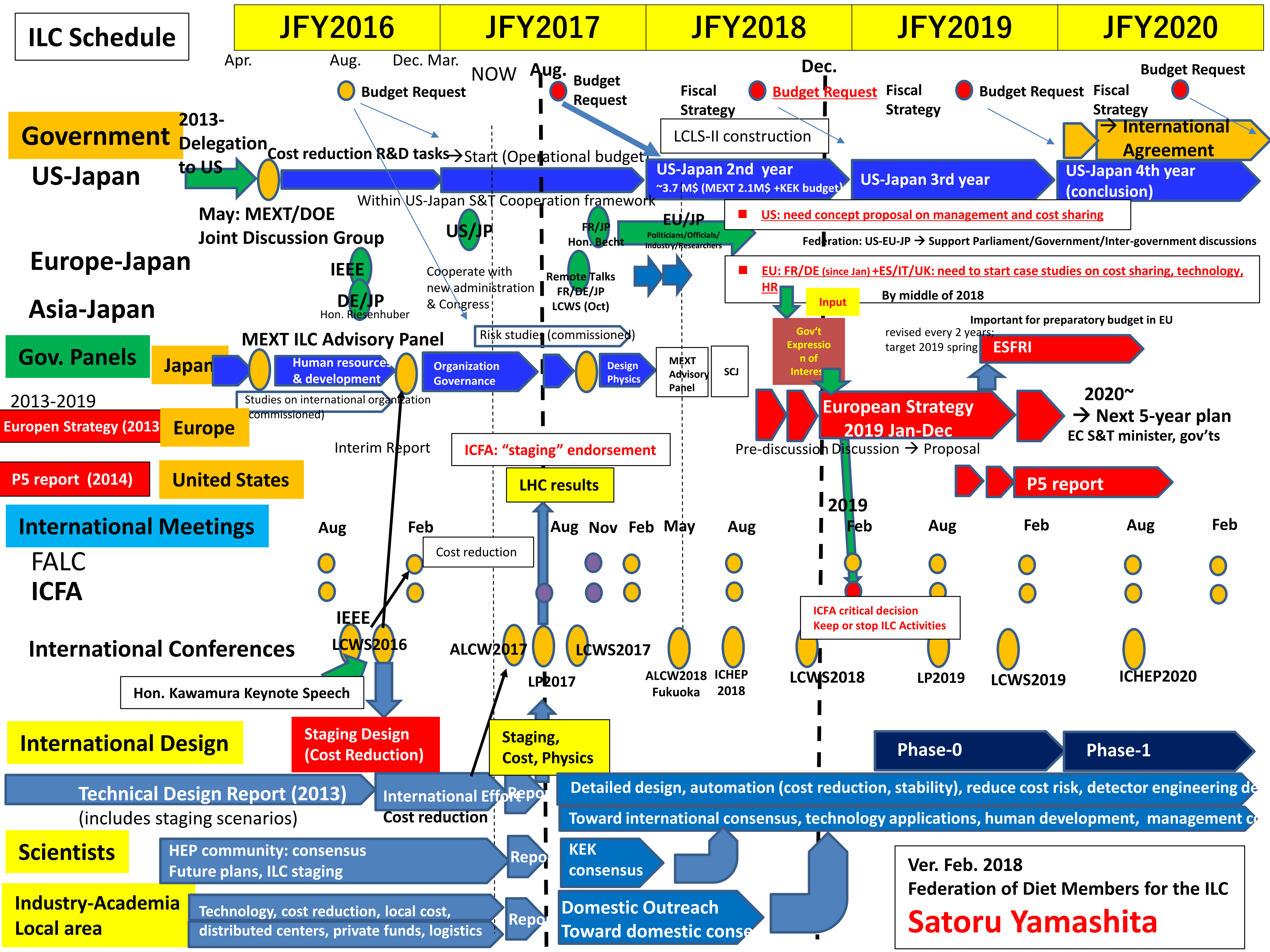
ILC Status & Recent Activities

- Project under serious consideration by the Japanese Government
  - Statement/Decision expected by the end of 2018
  - Japan is aware of the urgency and milestones (e.g., upcoming European Strategy Update)
- High level advisory panel and working groups were formed; studies completed and reports generated
  - Science Council of Japan will finalize extensive technical reviews in the coming 2-3 months.
- Encouraging interactions of Japanese Officials with agencies/ governments in the US and in Europe have taken place
- Strong ongoing efforts in Japan with outreach to public, media, science community and industry

July 5^{th}

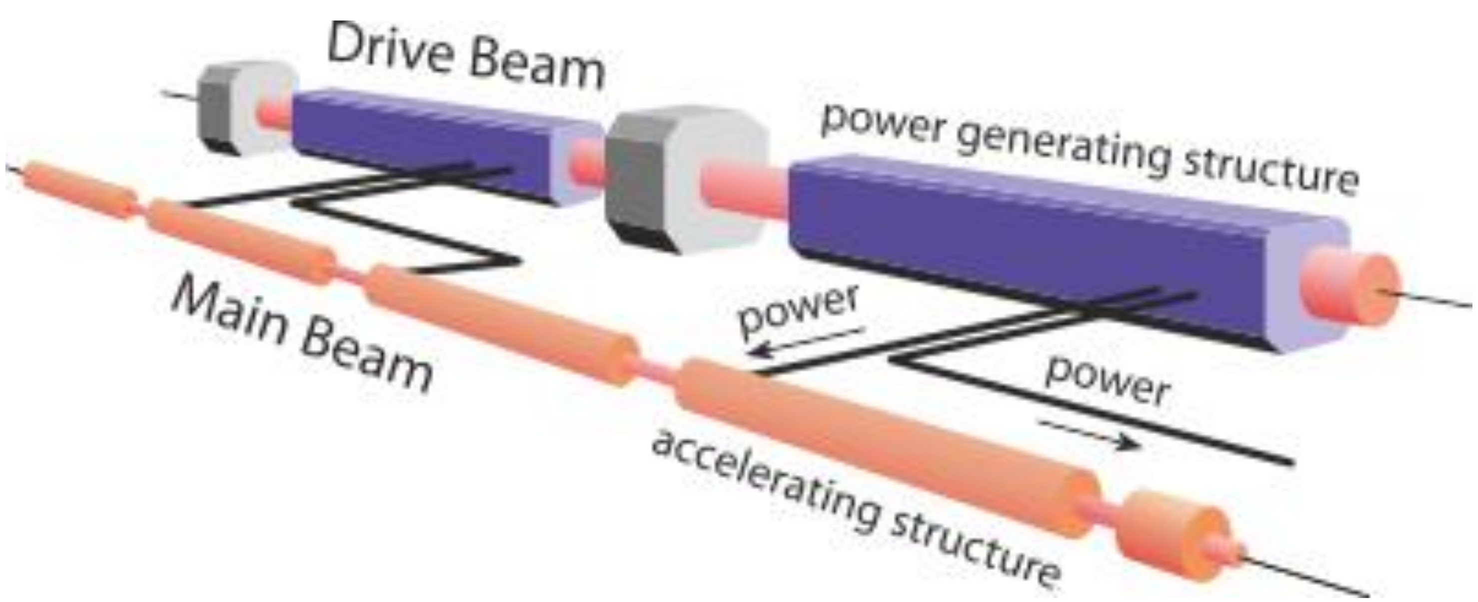
Meeting with Prime Minister Abe July 5^{th}

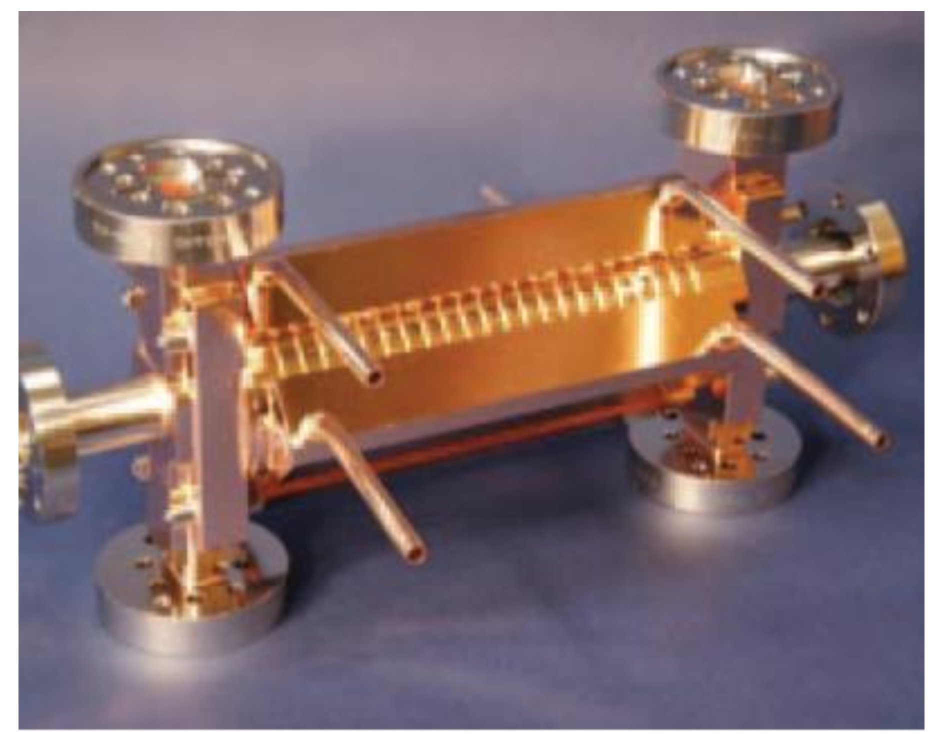
Prime Minister Abe
Deputy Chief Cabinet Secretary Nishimura
Deputy Chief Cabinet Secretary Nogami
Kawamura (Diet Budget committee chair)
Shionoya (LDP election chair)
Suzuki (Minister of Olympic)
Onodera (Minister of Defense)
Nishioka (AAA chair, MHI former CEO)
Takahashi (Tohoku, Tohoku electric former CEO
Yamashita


ILC Schedule
JFY2016
JFY2017
JFY2018
JFY2019
JFY2020
Apr.
Aug.
Dec. Mar.
NOW
Aug.
Dec.
Budget Request
Budget Request
Fiscal Strategy
Budget Request
Fiscal Strategy
Budget Request
Fiscal Strategy
Budget Request
Government
US-Japan
2013- Delegation to US
Cost reduction R&D tasks→Start (Operational budget)
LCLS-II construction
US-Japan 2nd year
~3.7 M$ (MEXT 2.1M$ +KEK budget)
US-Japan 3rd year
US-Japan 4th year (conclusion)
→ International Agreement
Within US-Japan S&T Cooperation framework
May: MEXT/DOE Joint Discussion Group
US/JP
FR/JP Hon. Becht
EU/JP
Politicians/Officials/ Industry/Researchers
US: need concept proposal on management and cost sharing
Federation: US-EU-JP → Support Parliament/Government/Inter-government discussions
Europe-Japan
IEEE
Cooperate with new administration & Congress
Remote Talks FR/DE/JP LCWS (Oct)
EU: FR/DE (since Jan) +ES/IT/UK: need to start case studies on cost sharing, technology, HR
Asia-Japan
DE/JP
Hon. Riesenhuber
Input
By middle of 2018
Gov't Expression of Interest
Important for preparatory budget in EU
revised every 2 years; target 2019 spring
ESFRI
Gov. Panels
MEXT ILC Advisory Panel
Risk studies (commissioned)
Japan
Human resources & development
Organization Governance
Design Physics
MEXT Advisory Panel
SCJ
2013-2019
Studies on international organization (commissioned)
Europen Strategy (2013)
Europe
European Strategy 2019 Jan-Dec
2020~ → Next 5-year plan EC S&T minister, gov'ts
Interim Report
ICFA: "staging" endorsement
Pre-discussion Discussion → Proposal
P5 report (2014)
United States
P5 report
LHC results
International Meetings
Aug
Feb
Aug
Nov
Feb
May
Aug
2019
Feb
Aug
Feb
Aug
Feb
FALC
ICFA
Cost reduction
ICFA critical decision Keep or stop ILC Activities
IEEE
LCWS2016
International Conferences
ALCW2017
LP2017
LCWS2017
ALCW2018 Fukuoka
ICHEP 2018
LCWS2018
LP2019
LCWS2019
ICHEP2020
Hon. Kawamura Keynote Speech
International Design
Staging Design (Cost Reduction)
Staging, Cost, Physics
Phase-0
Phase-1
Technical Design Report (2013)
(includes staging scenarios)
International Effort
Cost reduction
Report
Detailed design, automation (cost reduction, stability), reduce cost risk, detector engineering de
Toward international consensus, technology applications, human development, management c
Scientists
HEP community: consensus Future plans, ILC staging
Report
KEK consensus
Industry-Academia Local area
Technology, cost reduction, local cost, distributed centers, private funds, logistics
Report
Domestic Outreach Toward domestic conse
Ver. Feb. 2018
Federation of Diet Members for the ILC
Satoru Yamashita

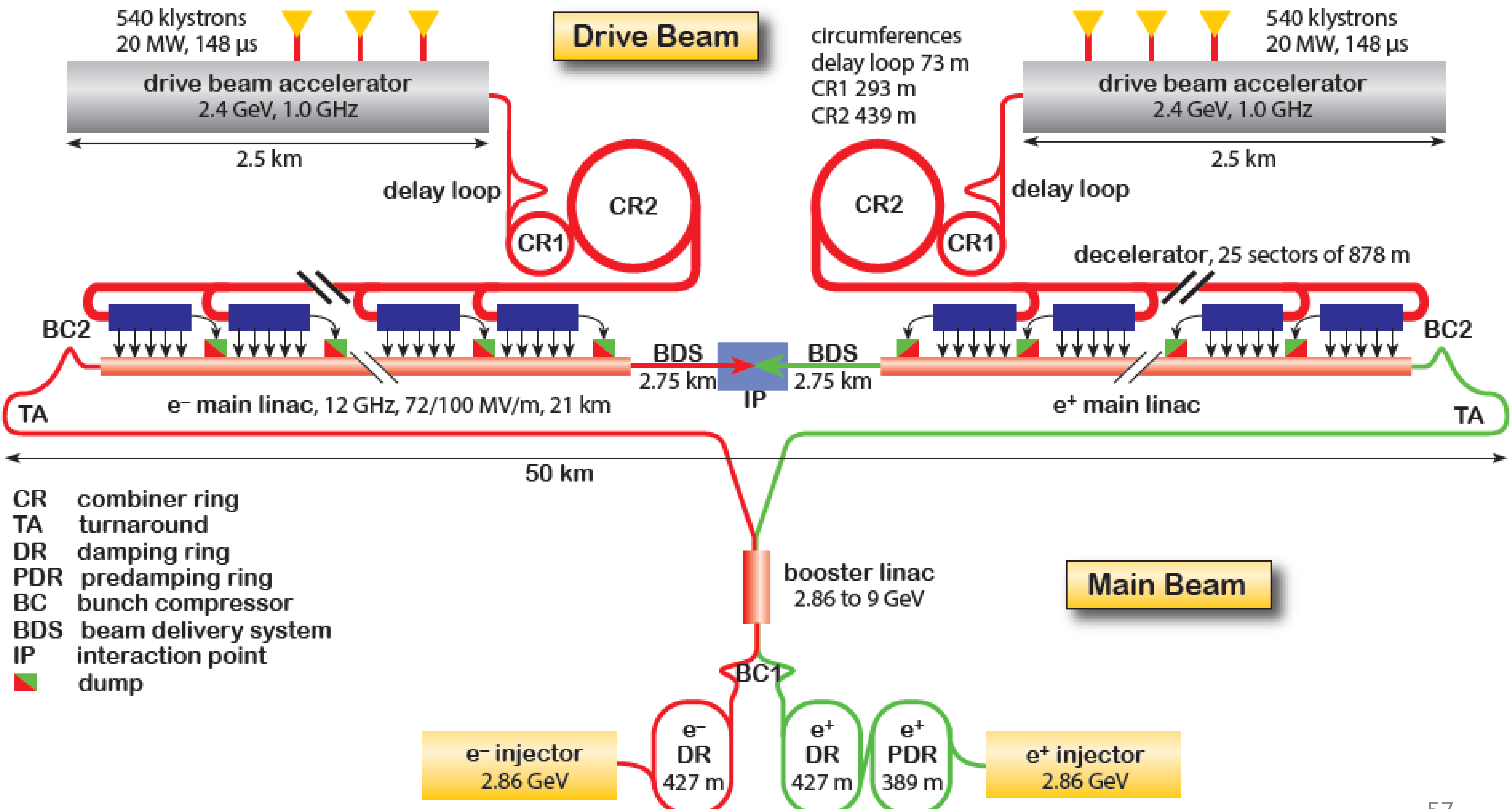
CLIC Compact Linear Collider

Use normal conducting high frequency RF system (X-band 12 GHz)
Two beams (drive beam → main beam) acceleration
- New acceleration system without using krystrons
- Efficient acceleration at high energy (> TeV region)

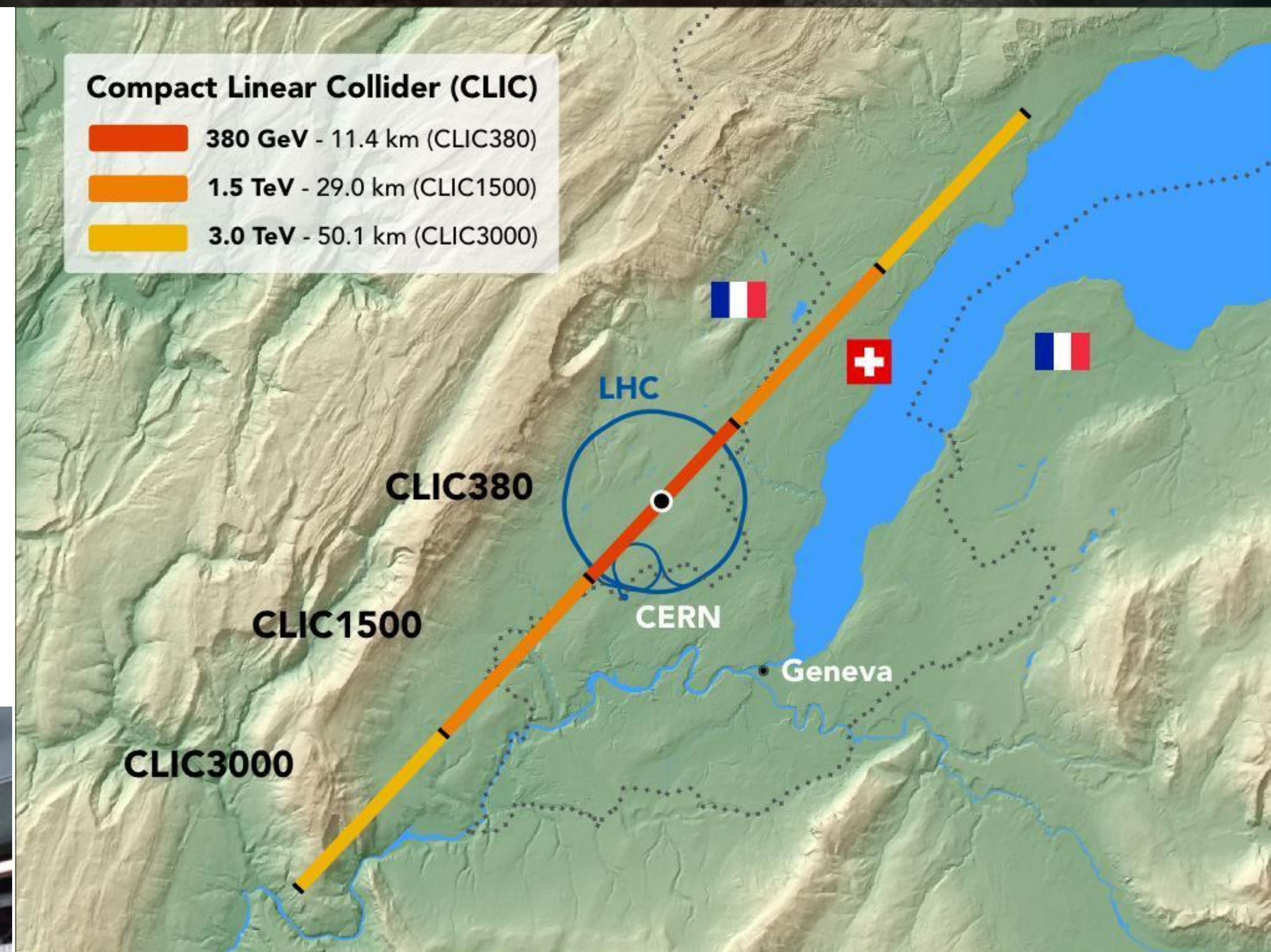


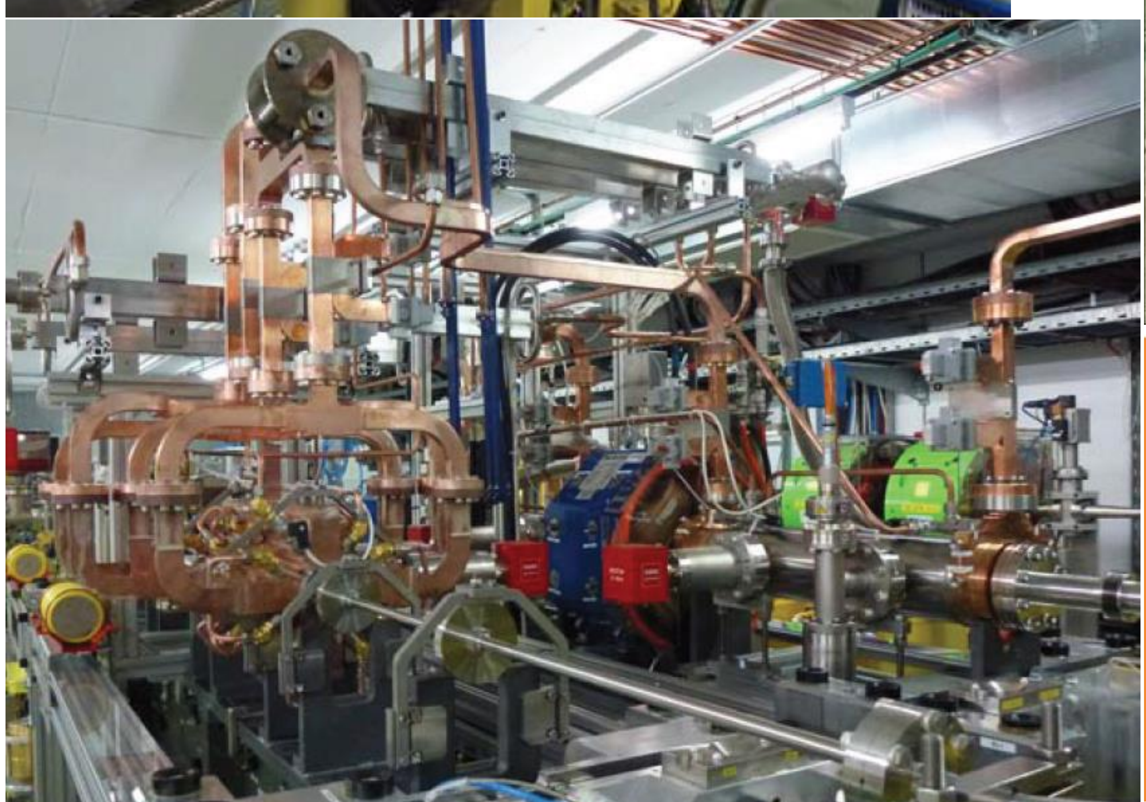


Schematics of CLIC 3 TeV



CTF3
(CLIC Test Facility 3)
at CERN





One possible location for CLIC is at CERN near Geneva. The CLIC acceleraator and detector would be situated in a tunnel deep underground, below the Franco-Swiss border.

Staged parameters for CLIC

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	$10^{34}\ \text{cm}^{-2}\text{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\ \text{cm}^{-2}\text{s}^{-1}$	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	920/20	660/20	660/20
Normalised emittance (at IP)	$\varepsilon_x/\varepsilon_y$	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589

CEPC Accelerator Design

6~10 GeV

LINAC

Electron

Positron

Booster

Energy Ramp
10 ->45/120GeV

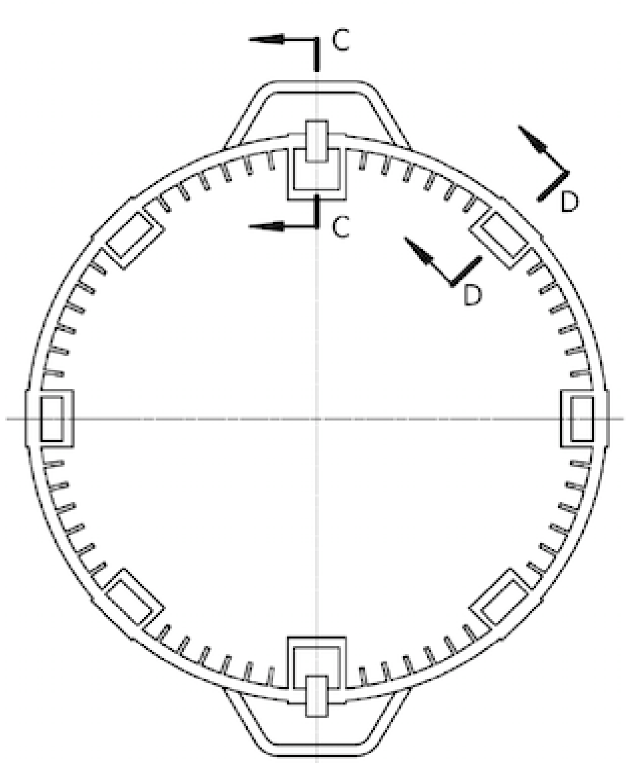
3 Machines in a tunnel:
- CEPC & booster
- SppC

Compatibility is the key

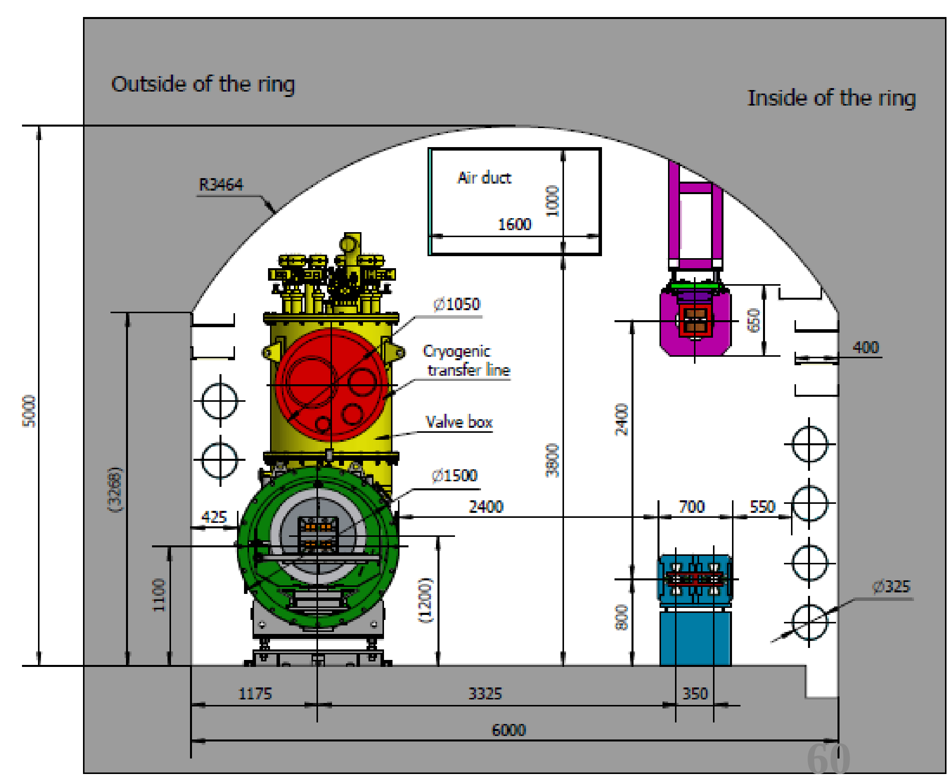
Storage Ring

45/120 GeV

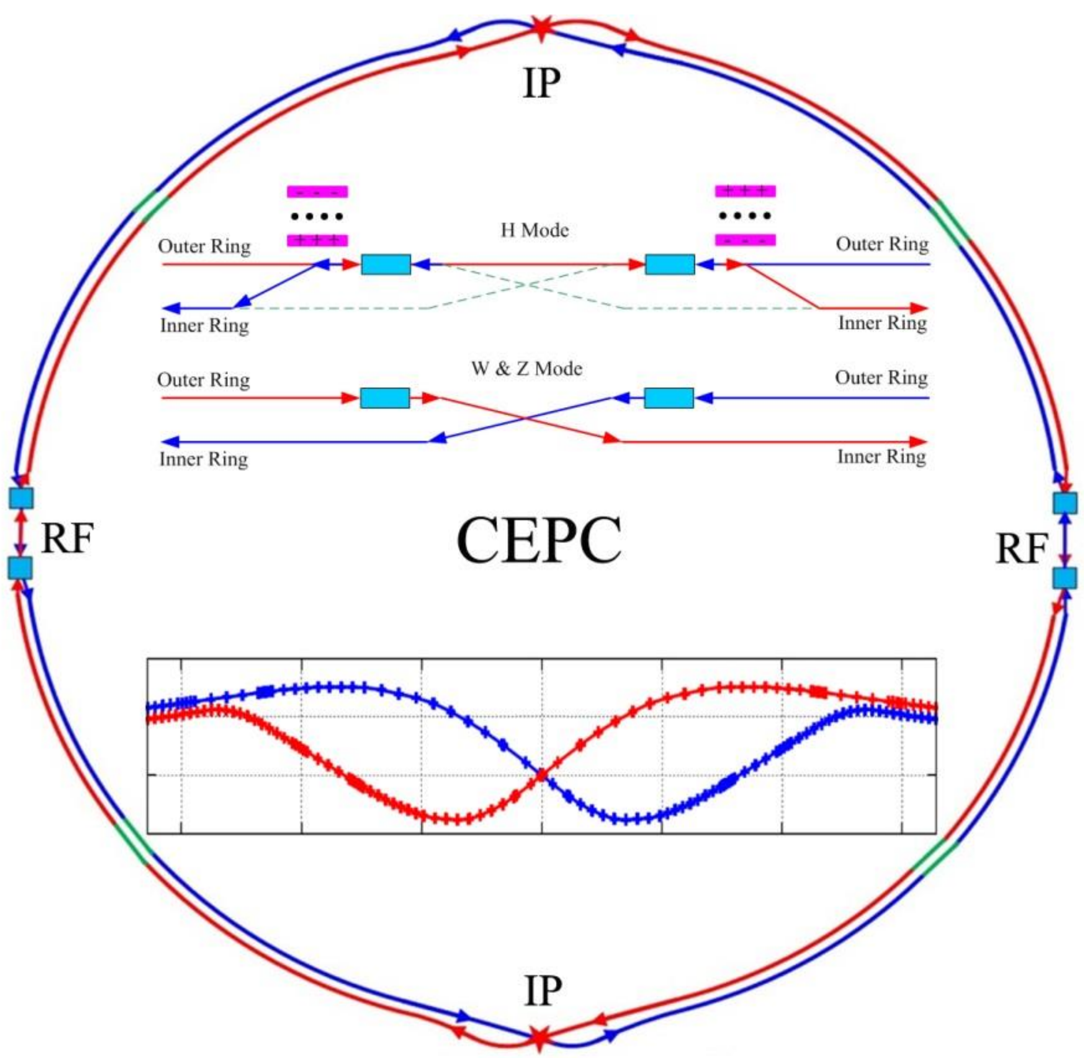
隧道俯视示意图

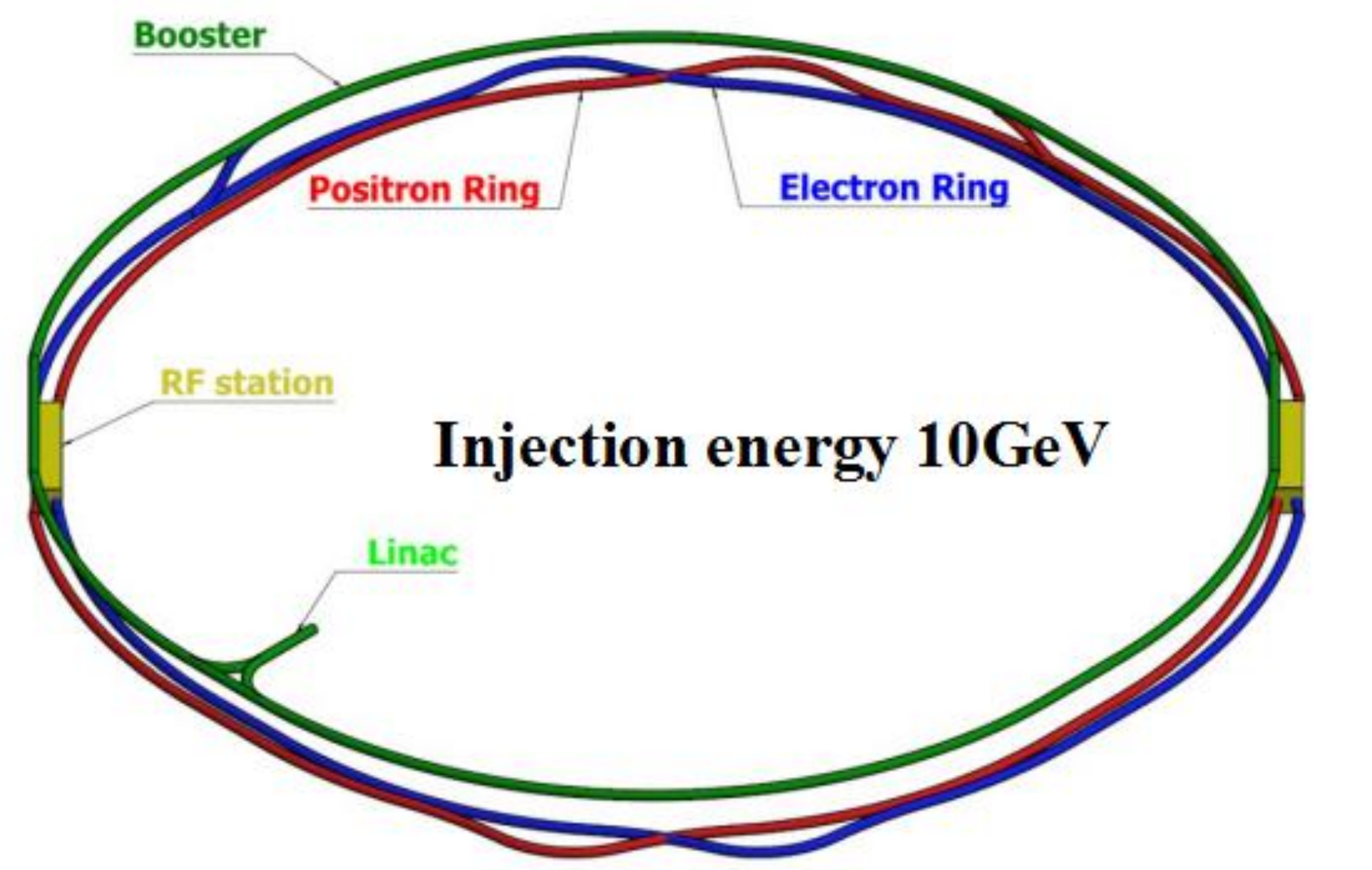


TUNNEL CROSS SECTION OF THE ARC AREA



CEPC CDR Basseline Layout

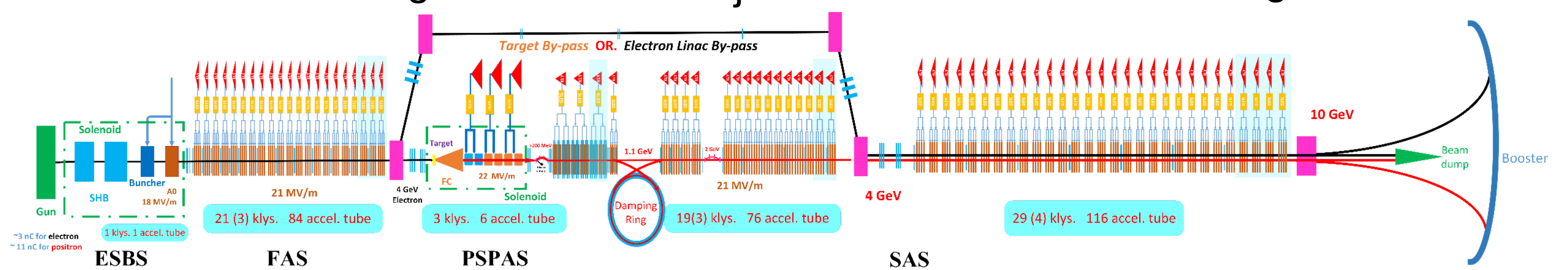




Collider ring

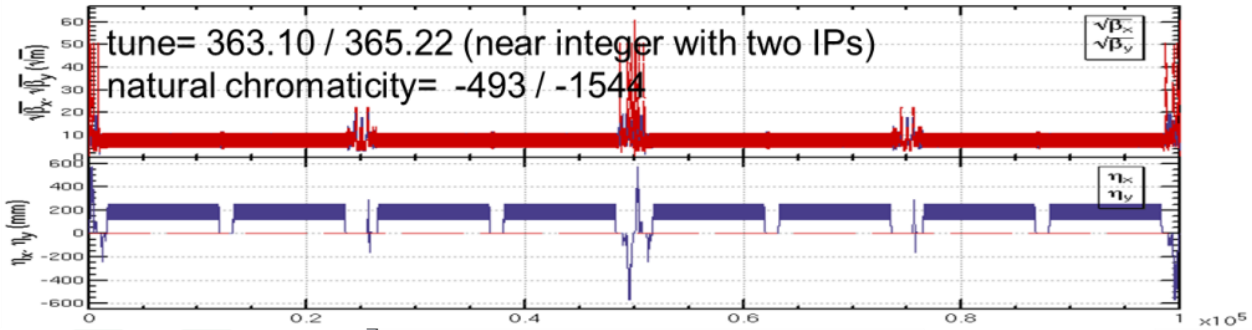
Linac injector

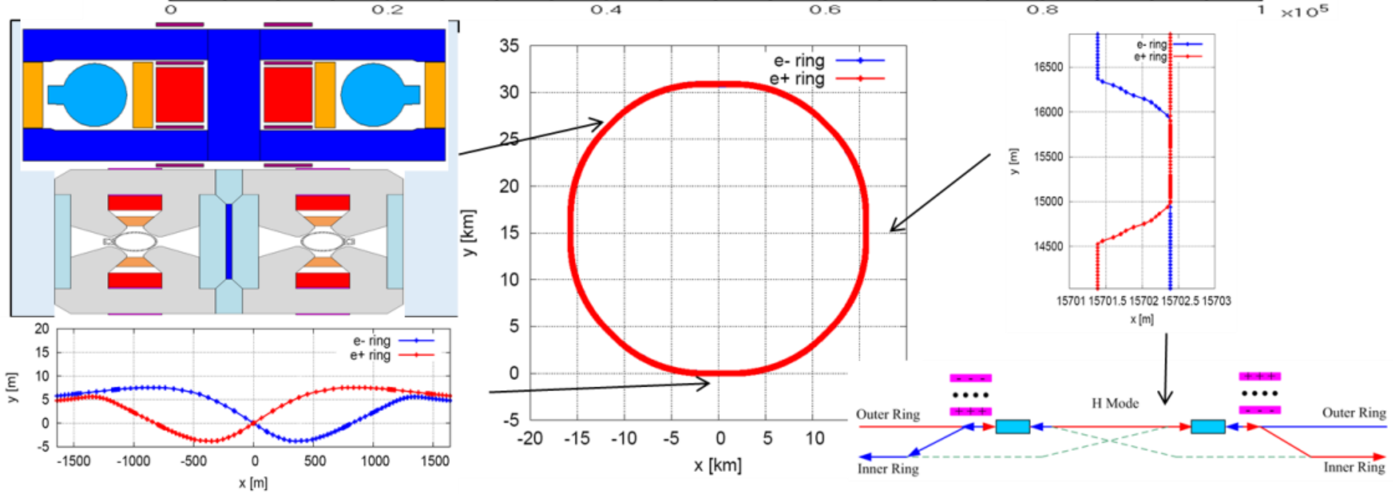
Booster ring

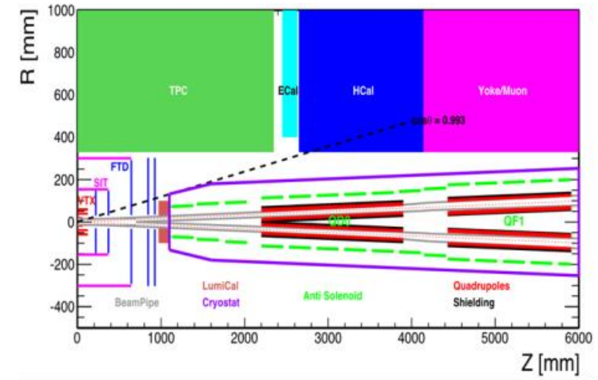


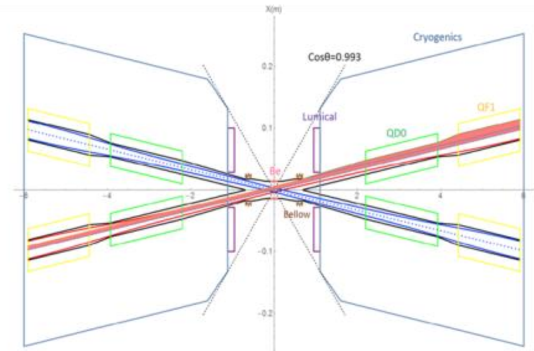
Baseline: 100 km, 30 MW; Upgradable to 50 MW, High Lumi Z
Try all means to cut cost down

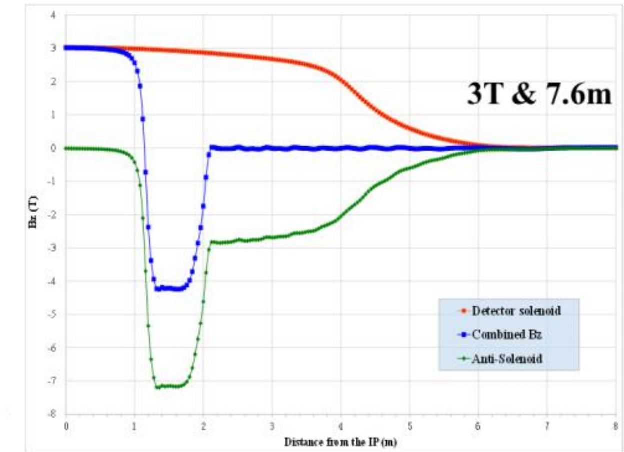
CEPC Collider CDR Design







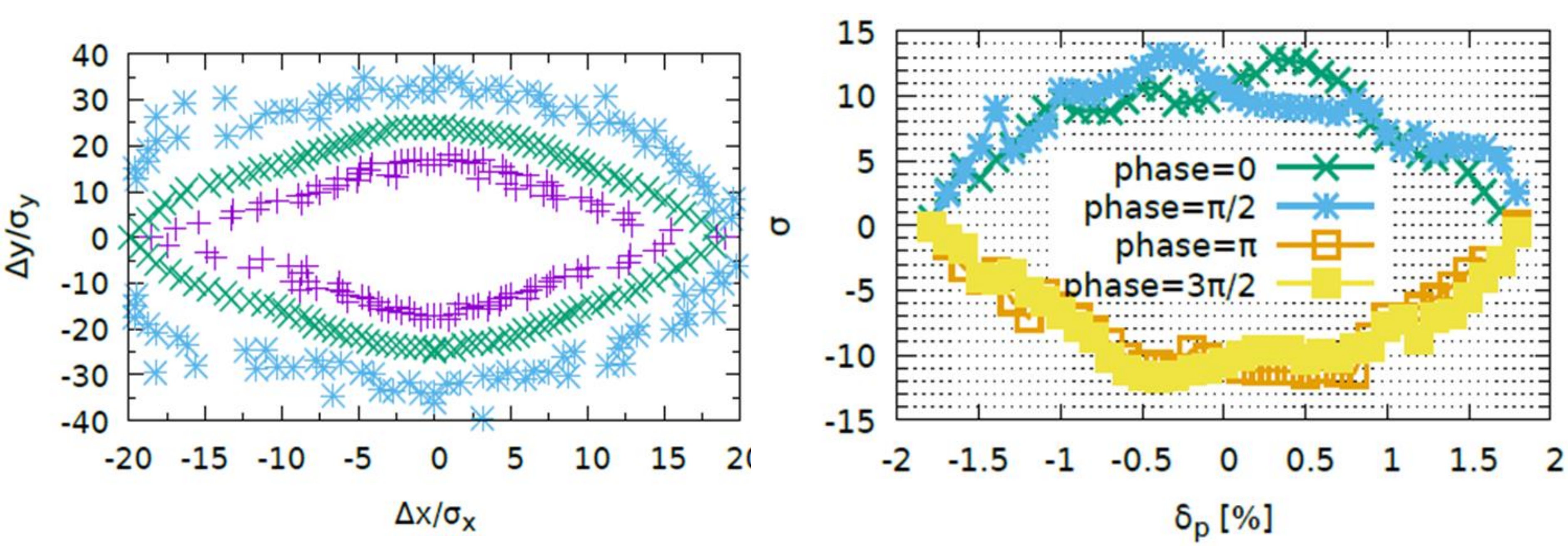


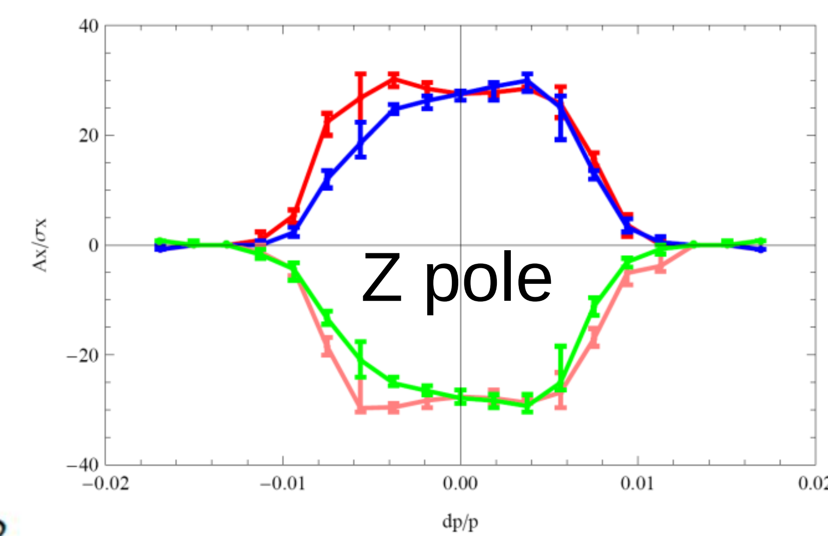


22 anti-Solenoid **sections with different inner coil diameters**

$\int B_z ds$ within 0~2.12m. Bz < 300Gauss away from 2.12m with local cancellation structure

The skew quadrupole coils are designed to make fine tuning of Bz over the QF&QD region instead of the mechanical rotation.





DAs of Higgs energy

DA of Z-Pole energy

Main Parameters

	Higgs	*W*	*Z（3T）*	*Z（2T）*
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	242 (0.68μs)	1524 (0.21μs)	12000 (25ns+10%gap)	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compact (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	3.26	5.9	8.5	
Betatron tune ν_x/ν_y	363.10 / 365.22			
Synchrotron tune ν_s	0.065	0.0395	0.028	
HOM power/cavity (2 cell) (kw)	0.54	0.75	1.94	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	1.35	0.4	0.23	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.29	0.35	0.55	
Lifetime _simulation (min)	100			
Lifetime (hour)	0.67	1.4	4.0	2.1
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP *L* ($10^{34}cm^{-2}s^{-1}$)	2.93	10.1	16.6	32.1

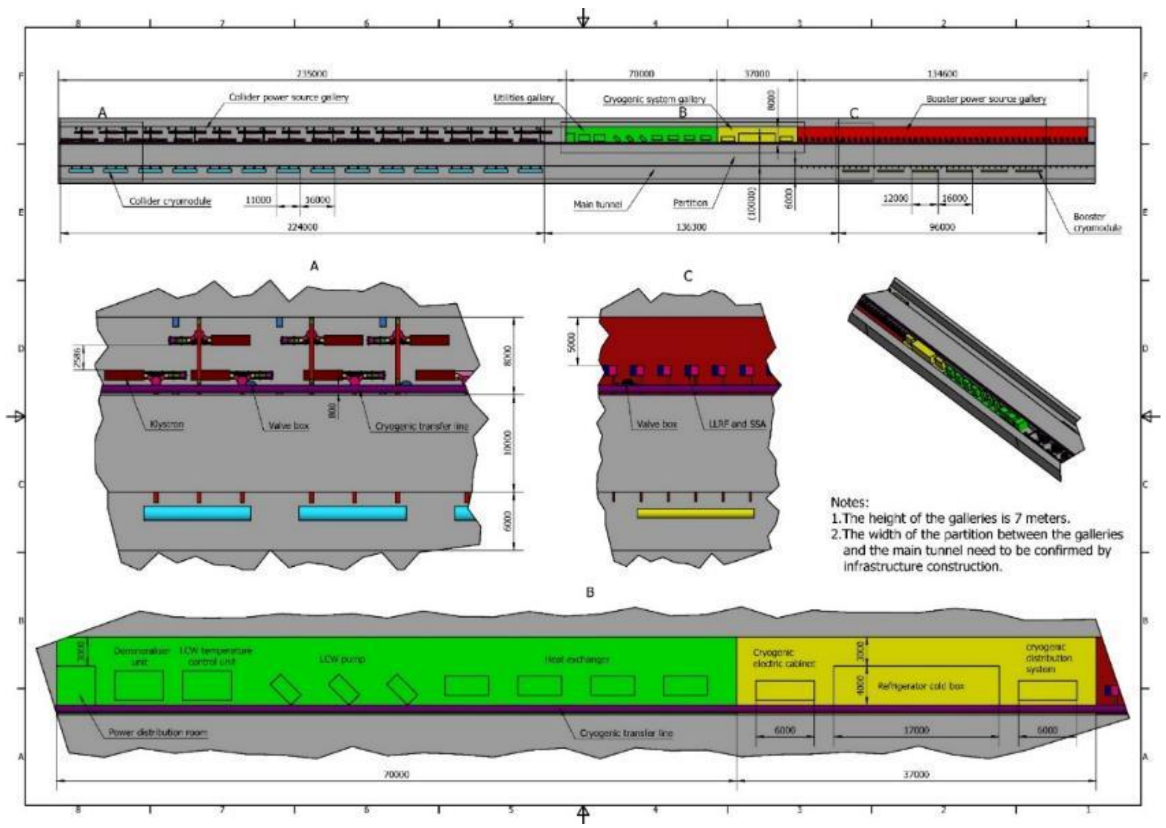
CEPC RF Layout

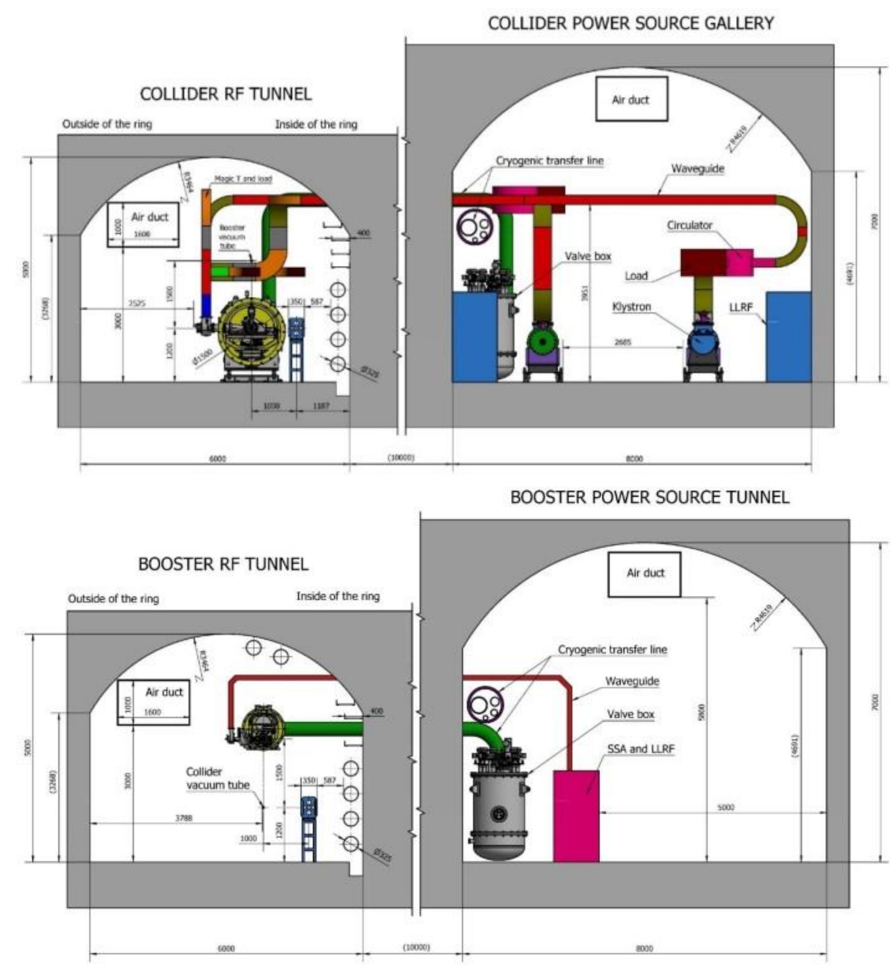
For 30 MW Higgs:

Collider: 240 650 MHz 2-cell cavities in 40 cryomodules (6 cav./ module).

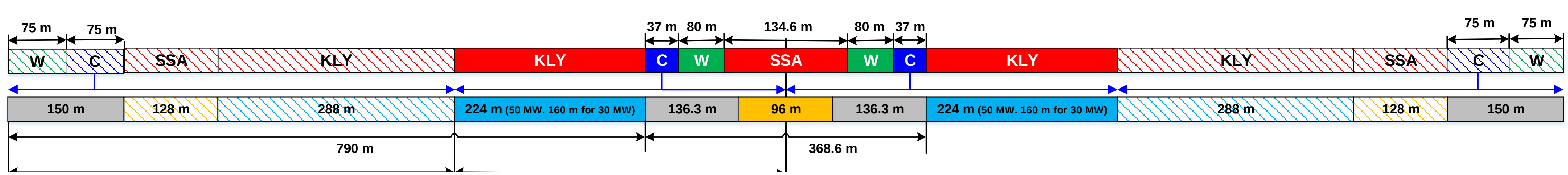
Booster: 96 1.3 GHz 9-cell cavities in 12 cryomodules (8 cav. / module).

For 50 MW Higgs: add 16 Collider modules.





RF Section A @ IP2 / LLS2 (length 1948.6 m)



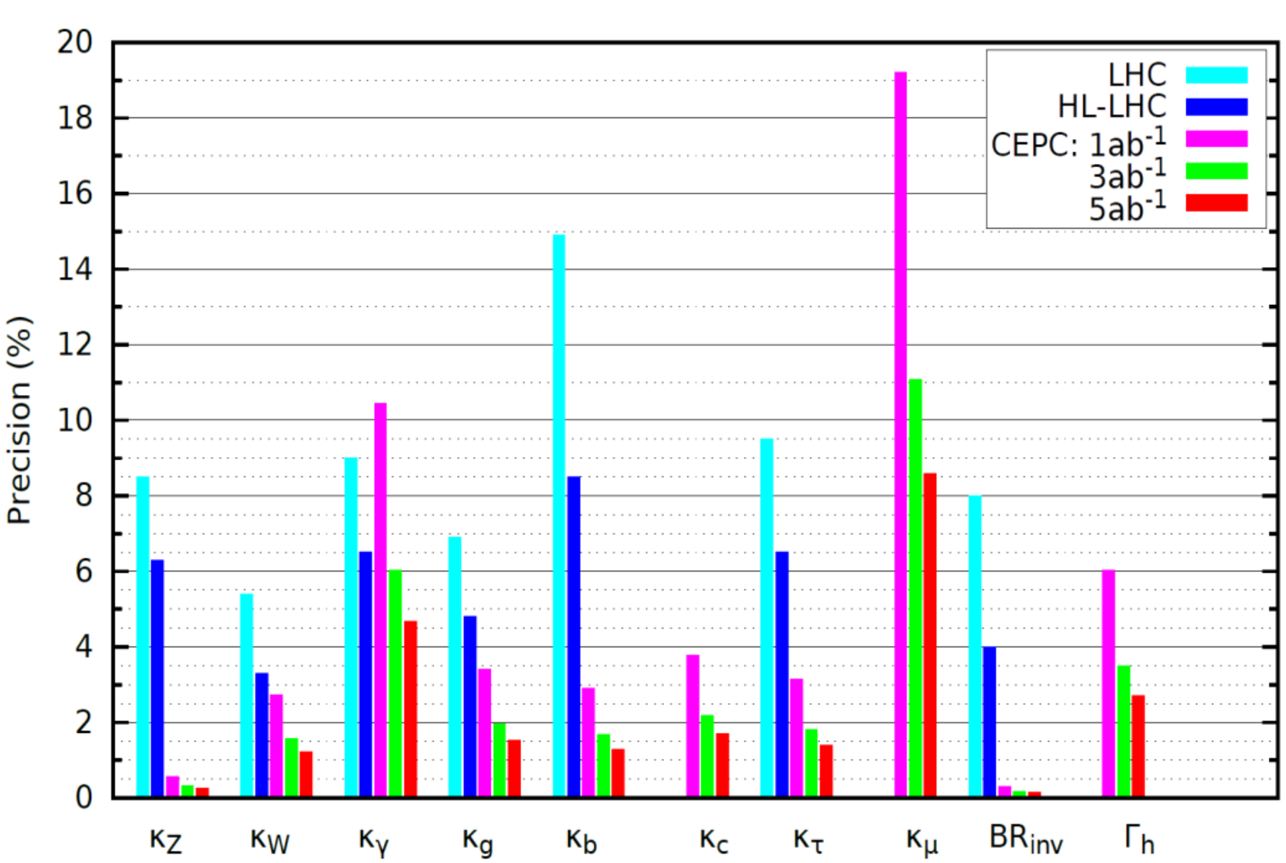
Precision Higgs Physics by CEPC

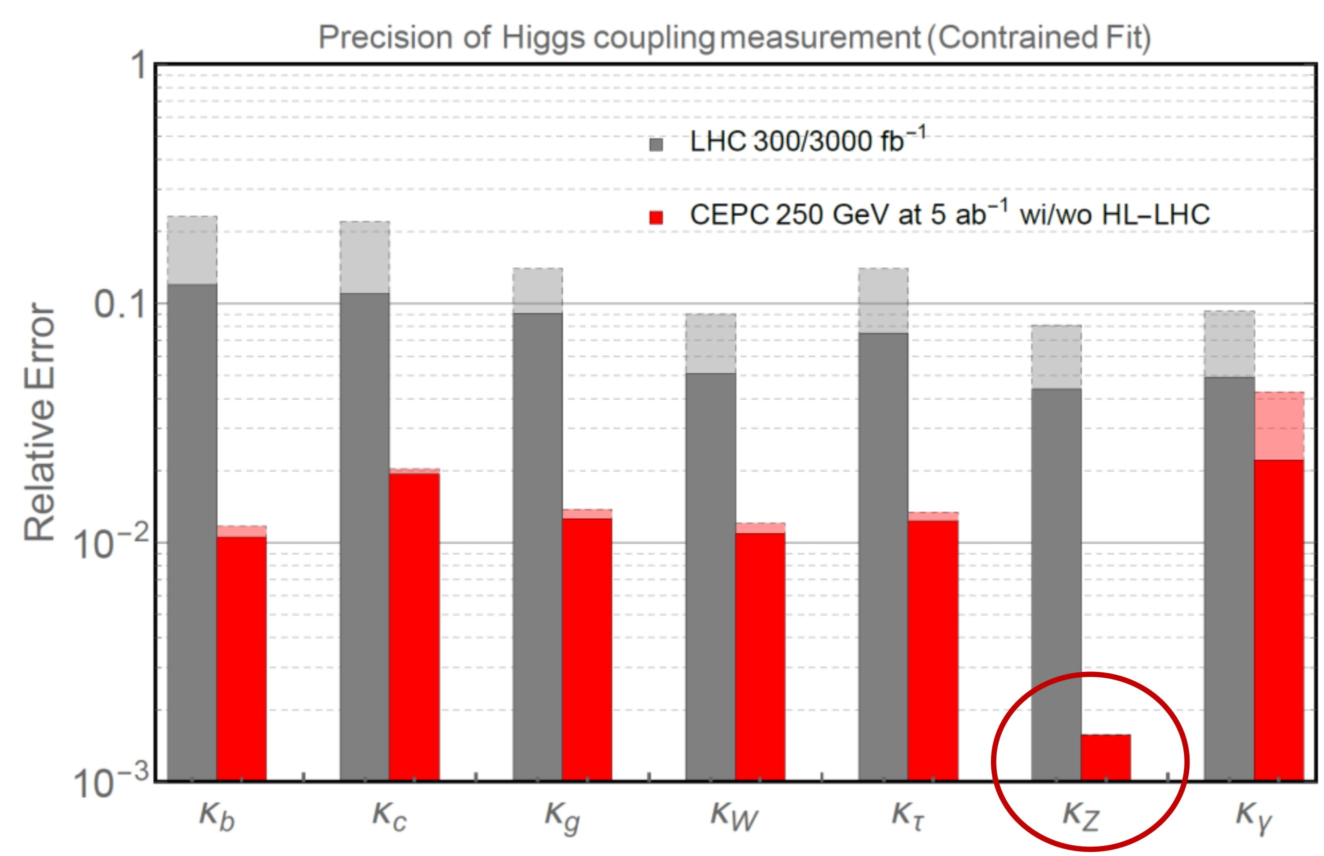
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{M^2}\mathcal{O}_{6,i} \qquad \delta \sim c_i \frac{v^2}{M^2}$$

A total of 10^6 Higgs
% precision ➔ M ~1 TeV
to new physics ➔ ~ ×10 over LHC

Only elementary particle
- with spin 0
- with non-gauge interactions

Related to "problems" of SM
A Step can not be skipped

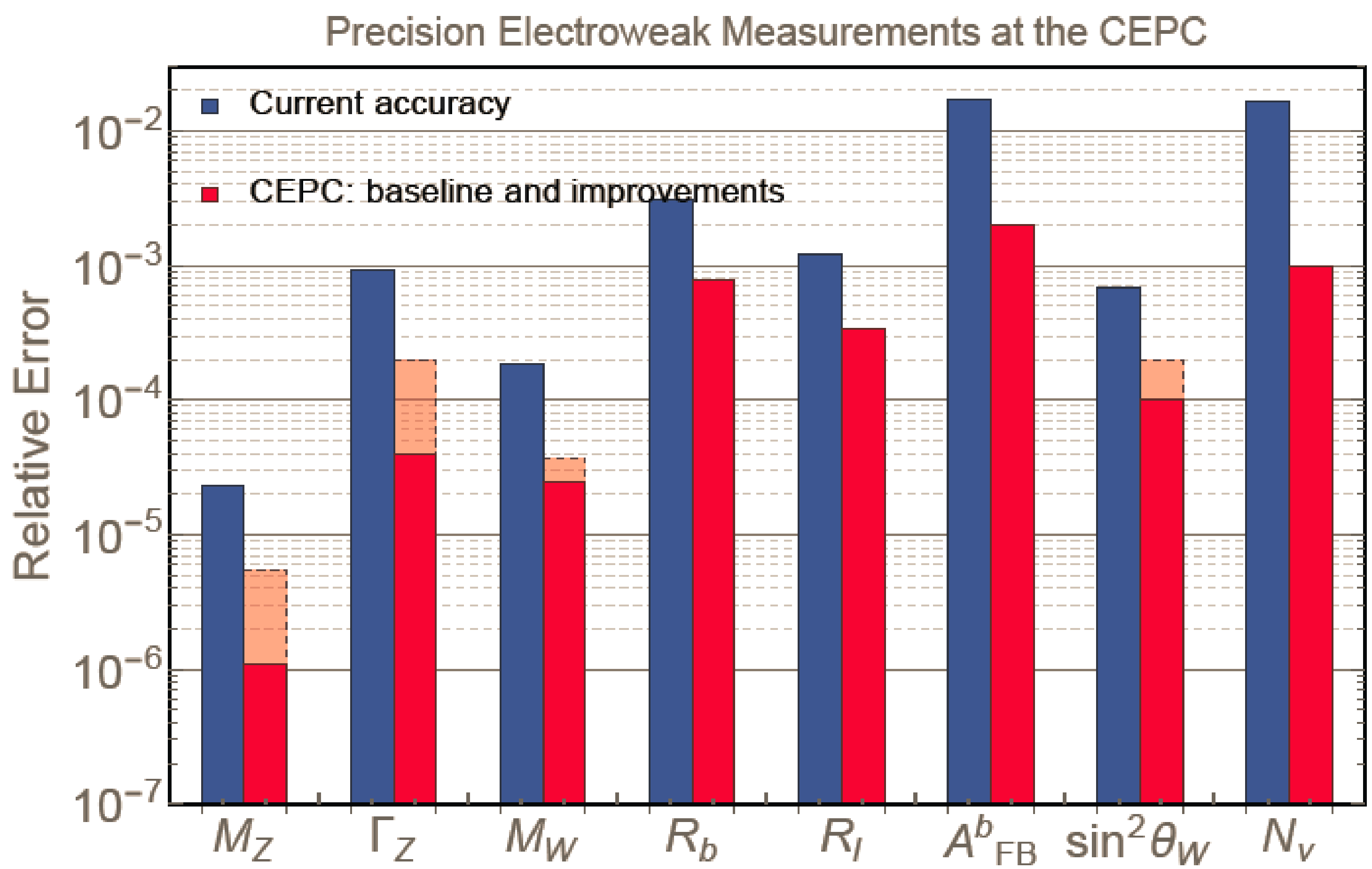


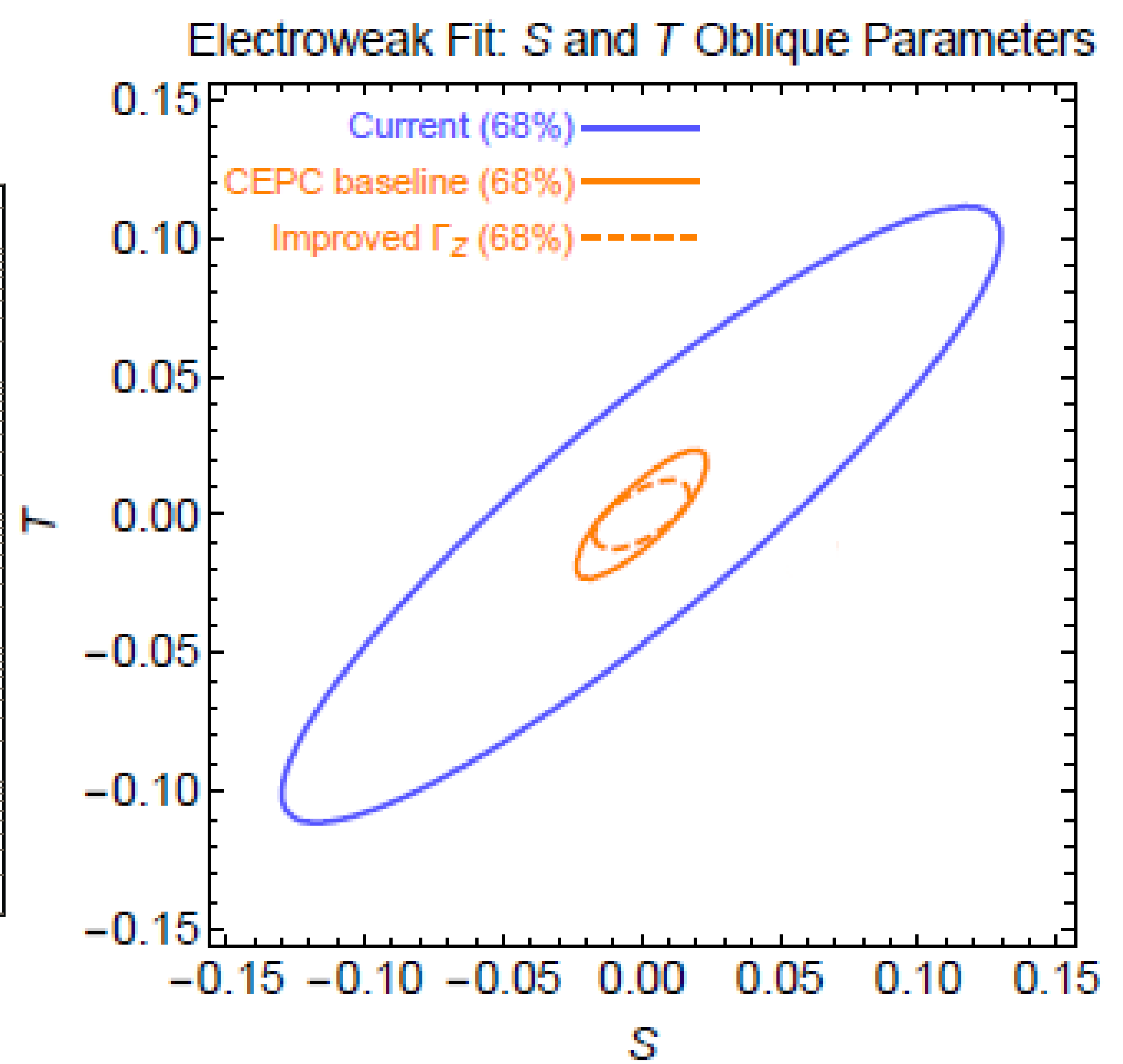


CEPC preCDR Volume 1 (p.9)

Improvement in Electroweak Precision

- A total of 10^{10} Z
- **A detailed study of Z & W to look for deviations from the Standard Model**
- **Can probe new physics up to ~ TeV， better than HL-LHC by a factor of 3**

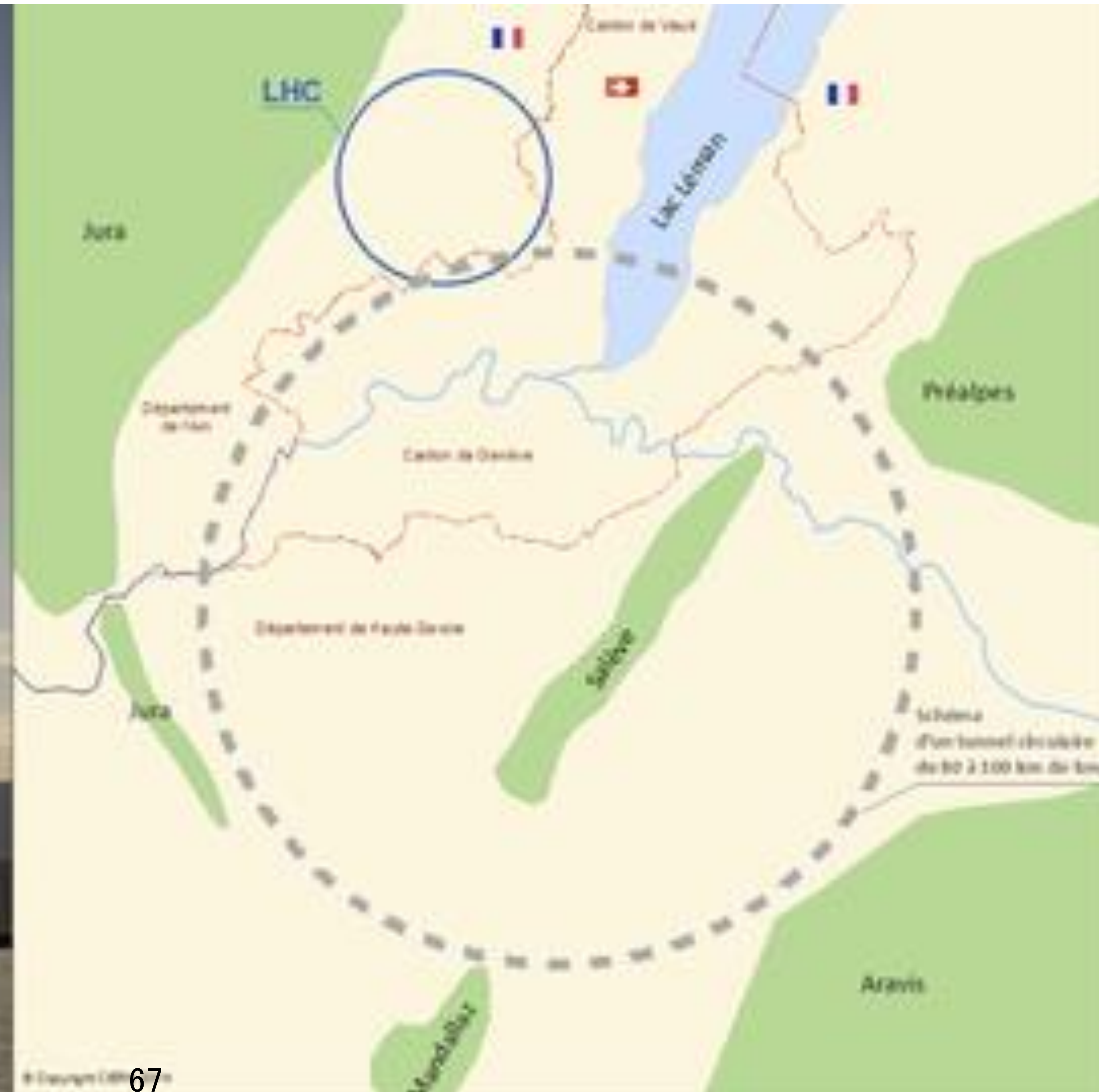




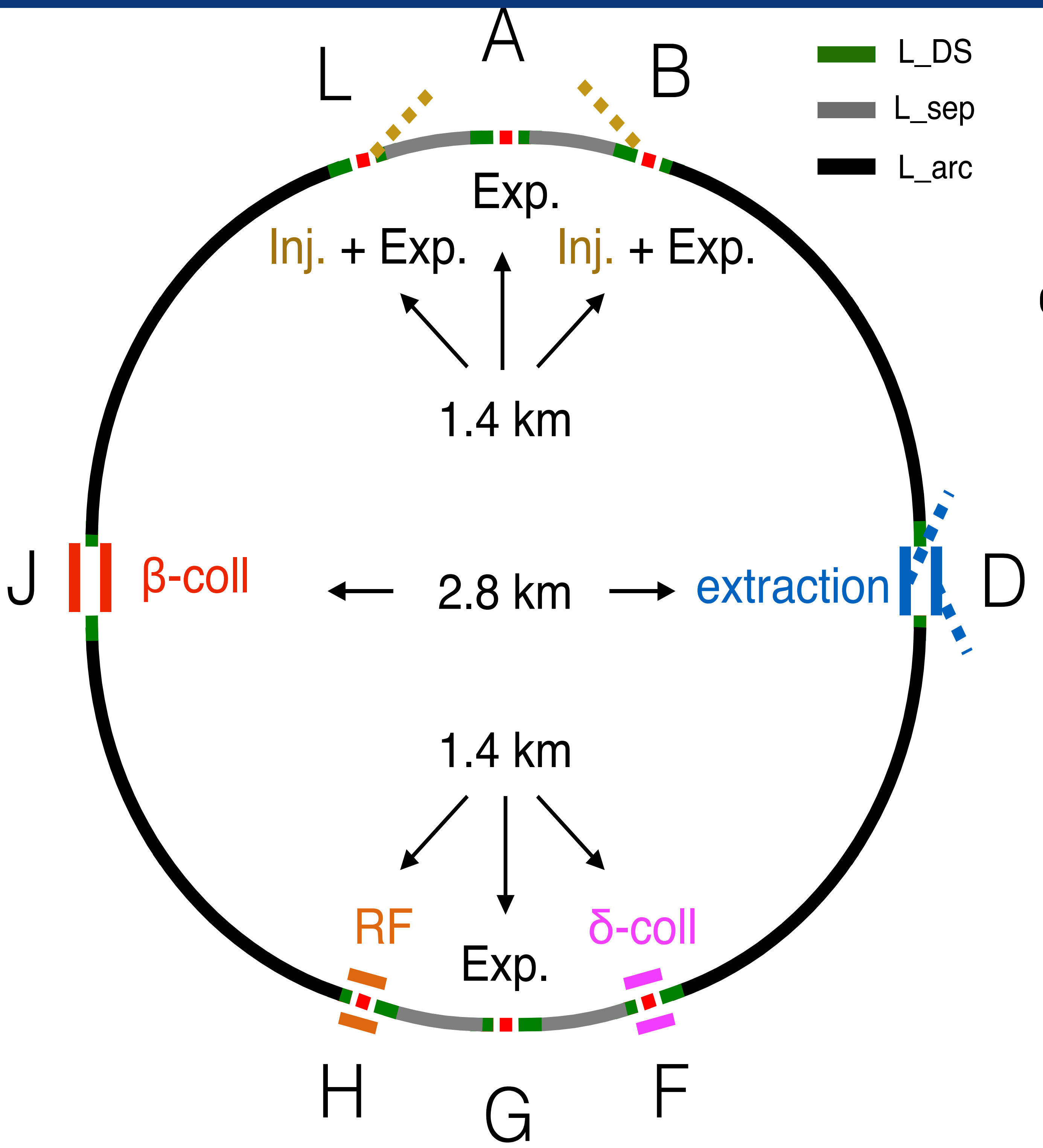
CEPC preCDR Volume 1 (p.10)

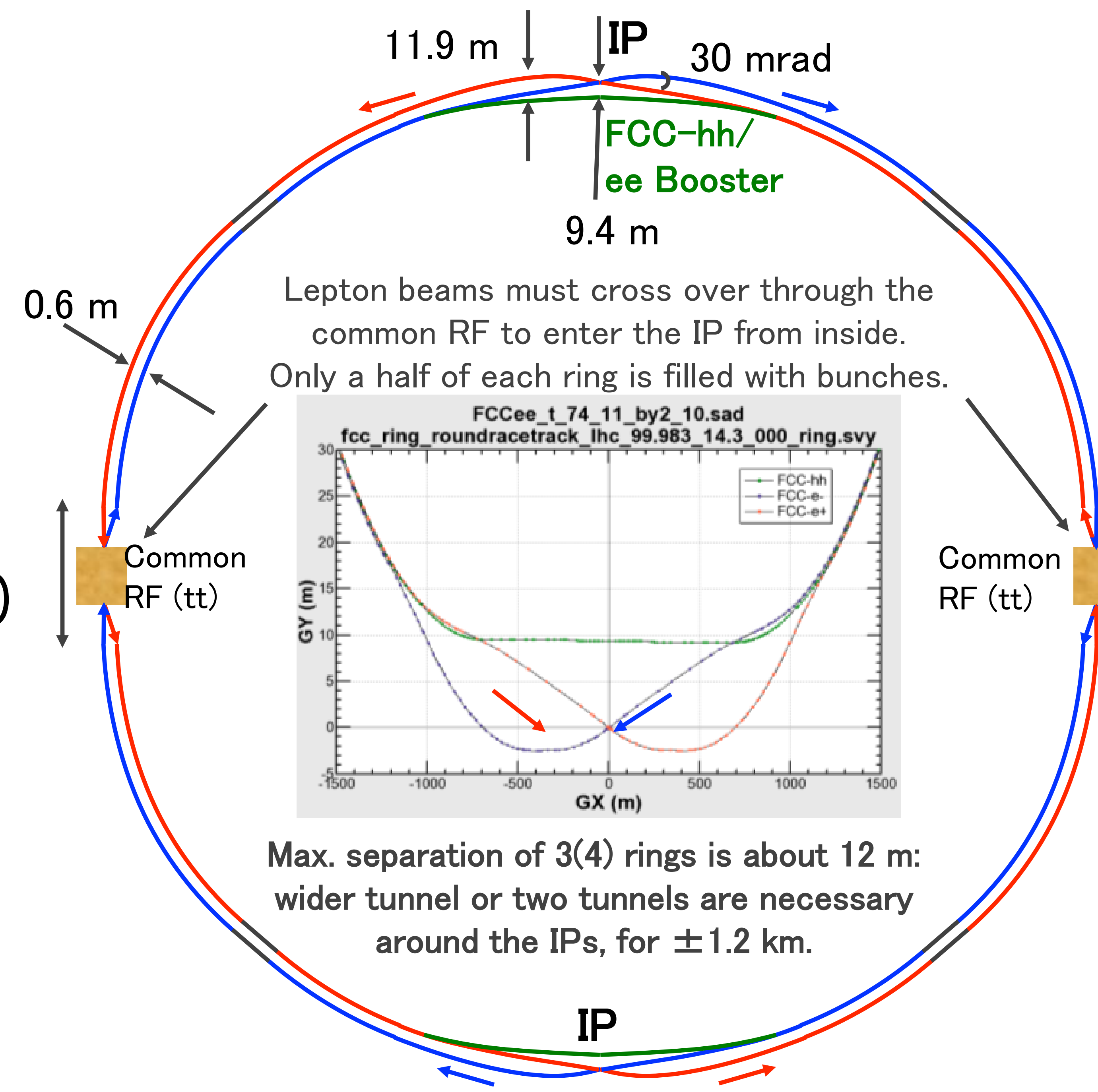
FCCee (TLEP)

Very high luminosity circular e^+e^- collider at CERN



common layouts for hh & ee





2 main IPs in A, G for both machines

FCC-ee 1, FCC-ee 2,

FCC-ee booster (FCC-hh footprint)

Asymmetric IR for ee, limits SR to expt

IMPLEMENTATION AND RUN PLAN

"Ampere-class" machine

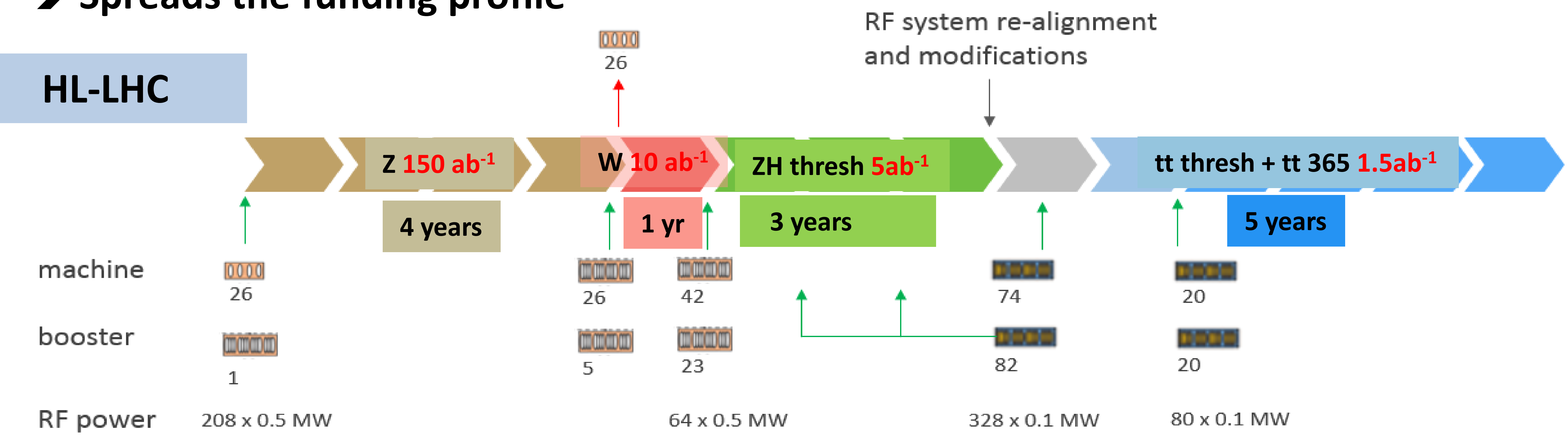
	V_tot (GV)	n_bunch	I_beam (mA)
Z	0.2	91500	1450
W	0.8	5260	152
H	3	780	30
t	10	81	6.6

"high gradient" machine

Three sets of RF cavities for FCCee & Booster:

- **Installation as LEP (≈30 CM/winter)**
- **high intensity (Z, FCC-hh): 400 MHz mono-cell cavities, ≈ 1MW source**
- **high energy (W, H, t): 400 MHz four-cell cavities, also for W machine**
- **booster and t machine complement: 800 MHz four-cell cavities**
- **Adaptable 100MW, 400MHz RF power distribution system +High effciency**

➔ Spreads the funding profile



indicative: total ~15 years

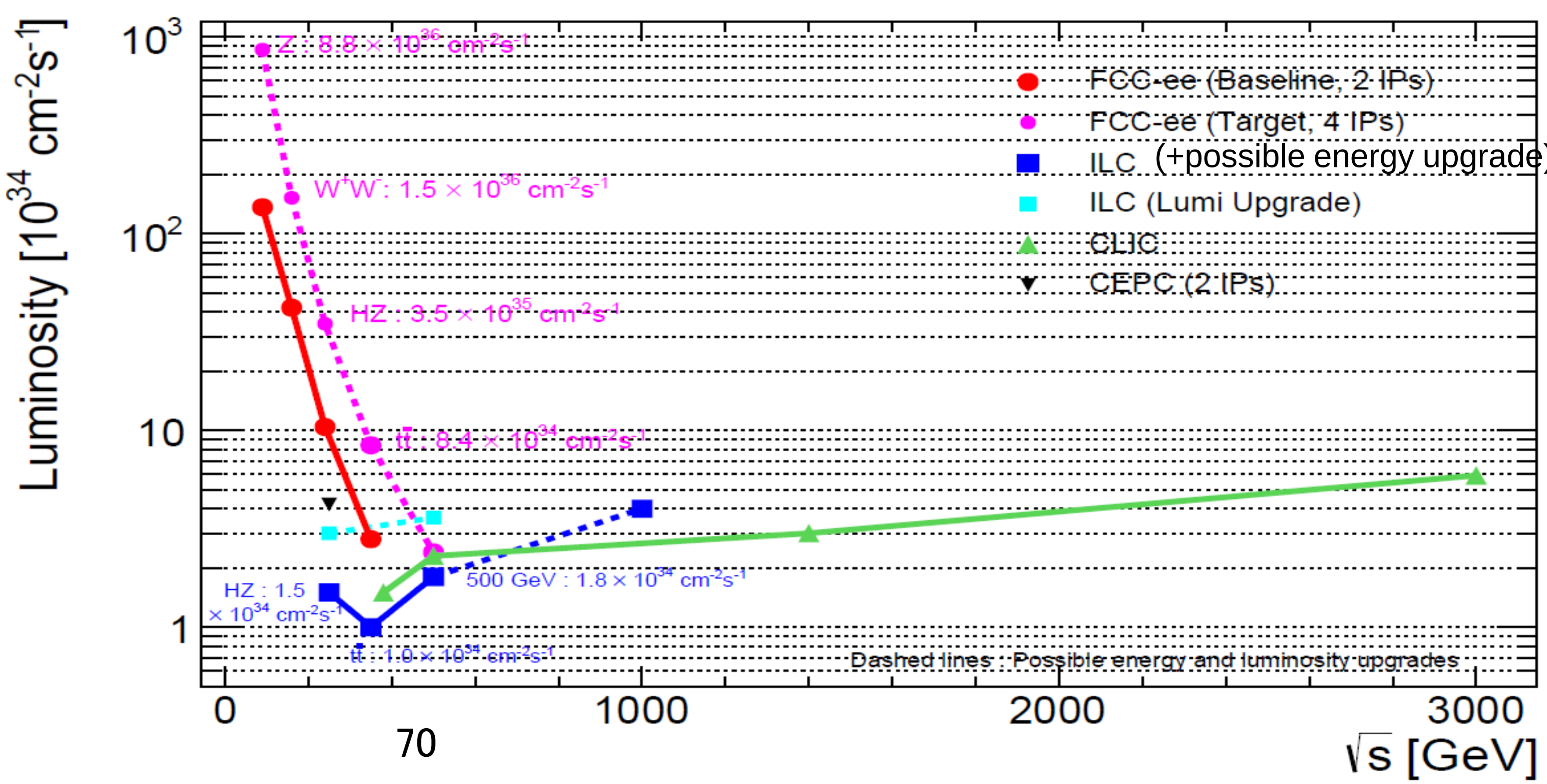
O(1/3) of the machine cost comes O(10) years after start

FCCee machine parameters

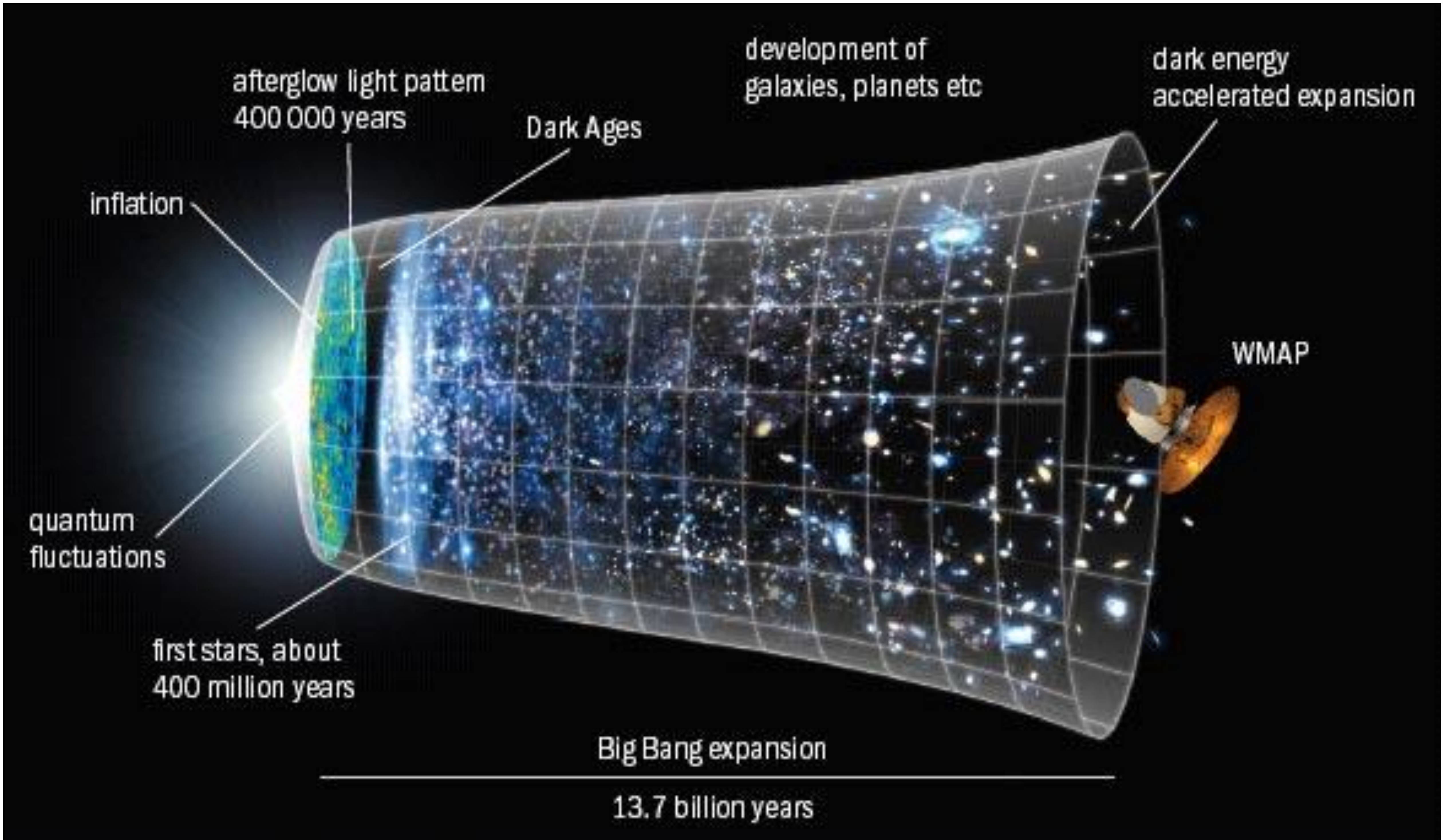
parameter	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
arc cell optics	60/60	90/90	90/90	90/90
momentum compaction [10^{-5}]	1.48	0.73	0.73	0.73
horizontal emittance [nm]	0.27	0.28	0.63	1.45
vertical emittance [pm]	1.0	1.0	1.3	2.7
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	2
length of interaction area [mm]	0.42	0.5	0.9	1.99
tunes, half-ring (x, y, s)	(0.569, 0.61, 0.0125)	(0.577, 0.61, 0.0115)	(0.565, 0.60, 0.0180)	(0.553, 0.59, 0.0350)
longitudinal damping time [ms]	414	77	23	6.6
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.10	0.44	2.0	10.93
RF acceptance [%]	1.9	1.9	2.3	4.9
energy acceptance [%]	1.3	1.3	1.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.15 / 0.20
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.5 / 3.3
Piwinski angle (SR / BS)	8.2 / 28.5	6.6 / 15.3	3.4 / 5.3	1.39 / 1.60
bunch intensity [10^{11}]	1.7	1.5	1.5	2.8
no. of bunches / beam	16640	2000	393	39
beam current [mA]	1390	147	29	5.4
luminosity [10^{34} $cm^{-2}s^{-1}$]	230	32	8	1.5
beam-beam parameter (x / y)	0.004 / 0.133	0.0065 / 0.118	0.016 / 0.108	0.094 / 0.150
luminosity lifetime [min]	70	50	42	44
time between injections [sec]	122	44	31	32
allowable asymmetry [%]	±5	±3	±3	±3
required lifetime by BS [min]	29	16	11	10
actual lifetime by BS (“weak”) [min]	> 200	20	20	25

Luminosity is very high !

Luminosity of e+e- Colliders



Summary



afterglow light pattern
400 000 years
development of
galaxies, planets etc
dark energy
accelerated expansion
Dark Ages
inflation
WMAP
quantum
fluctuations
first stars, about
400 million years
Big Bang expansion
13.7 billion years

Big Questions in the Particle Physics

(1) Mechanism of the elecroweak symmetry breaking ?

We know the negative value of μ^2 of the Higgs potential makes spontaneous symmetry breaking and the elementary particles obtain masses. We do not know the mechanism to make μ^2 negative.

SUSY ? Composite Higgs ???

(2) Why we have so many free parameters in the SM (quark and lepton masses mixing matrices, three different gauge interactions) ? Neutrino masses << Top quark mass

GUTS ? Flavor problem ? Neutrino mass (Dirac/Majorana fermion)?

(3) What is the Dark Matter ?

SUSY ? Axion (CP problem of QCD)?

(4) Why there is matter-antimatter asymmetry in the universe?

Lepto-genesis ? EW phase transition ? CP in Higgs or other sectors ?

(5) What is the Dark Energy ? What caused the Inflation ?

We know that the expansion of the universe is accelerating.

(6) How to implement Gravity in the quantum theory ?

Supergarvity ?? Superstring ??

You are extremely lucky because there are so may important questions in particle physics to be solved by the next generation in the near future.

Which problems can be solved by the e^+e^- colliders ? Really new discoveries cannot be guaranteed. Probably,

(1) Mechanism of the EW symmetry breaking,

(3) Origin of the Dark matter,

(4) Origin of the Matter-antimatter asymmetry

can be solved.

Even if you cannot believe or cannot understand predictions by a great theorist for new particles or phenomena, you pretend to listen to him/her and try to experimentally search for them. Then you might discover a totally unexpected new great physics.

(Serendipity)

Examples of Serendipity

Prediction of π-meson（Yukawa)

⇒ Discovery of muon in cosmic rays (C.D. Anderson)

Prediction of proton decay by GUT（Georgi and Glashow）

⇒ Discovery of neutrino from a supernova SN1987 (Koshiba)

Westward voyage from Europe may reach India（Toscanelli）

⇒ Discovery of the American Continent (Columbus)

History tells that Hadron colliders and e+e- colliders are not only complementary but also synergy between them is extremely important.

Also interactions between high energy particle physics and non-accelerator astro-particle physics help to understand particle physics and cosmology.

Finally, we do need e+e- collider(s).

This year is a critical time for realizing the ILC in Japan.

The international community including ICFA (International Committee for Future Accelerators) is working very hard towards the realization of the ILC.

CEPC, CLIC, and FCCee are in the que of the e+e- colliders.

SEARCH FOR NEW PARTICLES

S. KOMAMIYA
ICEPP, UNIV. OF TOKYO

LEPTONS + QUARKS
HIGGS BOSONS
SUPER SYMMETRY
COMPOSITENESS ETC.

RESULTS ARE FROM

ENERGY FRONTIER COLLIDERS
LEP e^+e^- COLLIDER
TEVATRON $p\bar{p}$ COLLIDER
AS WELL AS HERA, TRISTAN, CESR.

NEW PARTICLE SEARCHES AT ENERGY FRONTIER

COMPLIMENTARY

★ HADRON COLLIDERS
- HIGHEST POSSIBLE MASS RANGE CAN BE ACCESSIBLE
- NEW PARTICLES PRODUCED BY STRONG INTERACTION HAVE LARGE σ $(t, \tilde{g}, \tilde{q} \cdots)$
- BACKGROUND RATE IS VERY HIGH (SOFT HADRON PROCESSES, STRONG INT.)
- ENERGY IS CARRIED AWAY BY SPECTATOR PARTONS

ISR → $Sp\bar{p}S$ → TEVATRON → LHC

★ e^+e^- COLLIDERS
- EVENTS ARE CLEAN, PREDICTION IS RELIABLE, LARGE S/N RATIO.
- ENERGY IS LIMITED BY SYNCROTRON RADIATION $\propto E^4/\rho$
  ⇒ LINEAR COLLIDERS

⋯> ADONE → SPEAR → DORIS → PETRA, PEP → TRISTAN → SLC, LEP → LEP II → LINEAR COLLIDERS

■ IN ADDITION TO THE TWO COMPLIMENTARY TYPES OF COLLIDERS NEW PARTICLES/PHENOMENA ARE SEARCHED AT

e p	HERA → LHC ?
B factory	DORIS II → CESR → KEK / SLAC
τ-c factory	BEBC → SPAIN