Physics at future e^+e^- colliders

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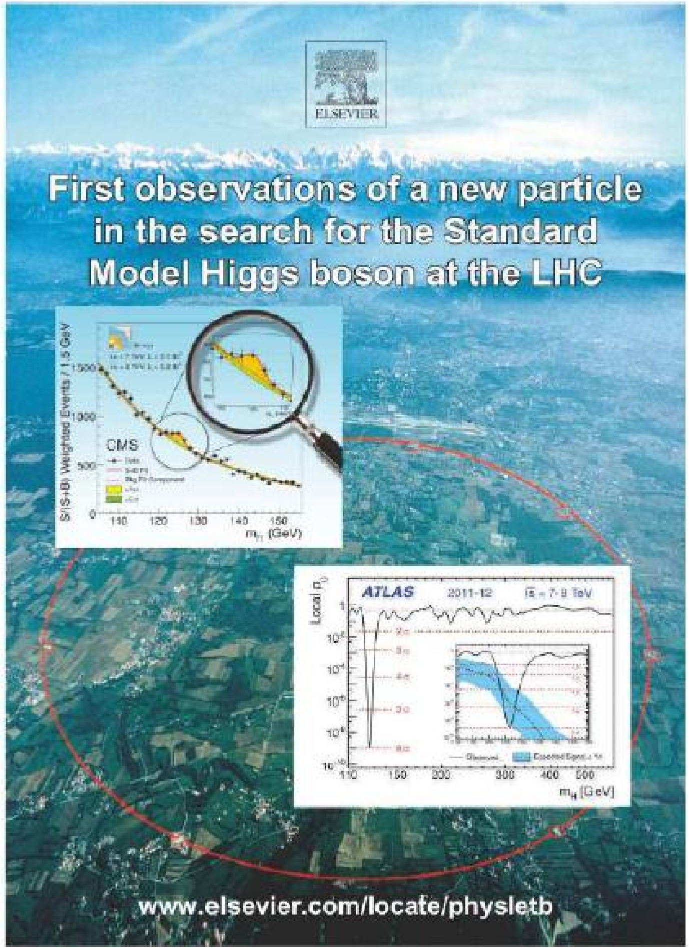
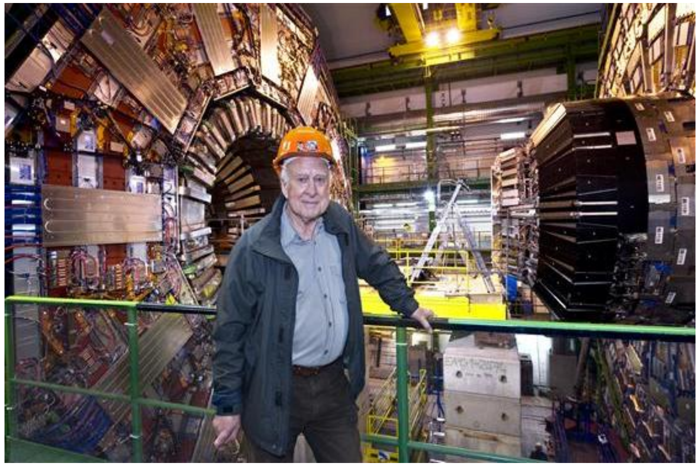
(DLNP)

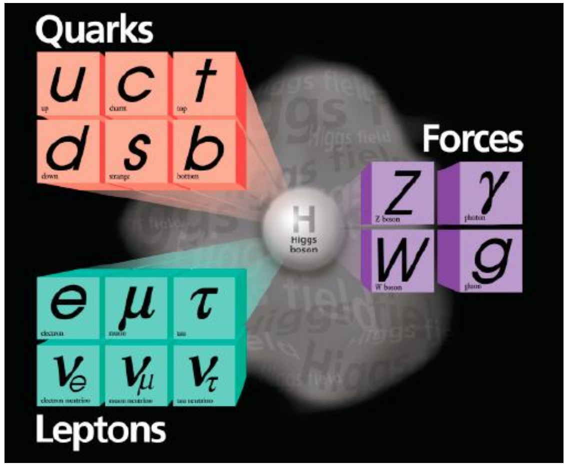
Higgs discovery: success of experiment, triumph of theory





End of physics?

- With the discovery of Higgs boson, Standard Model is now complete
- Does it mean that now we fully understand the structure of Nature?
- It seems very unlikely



Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

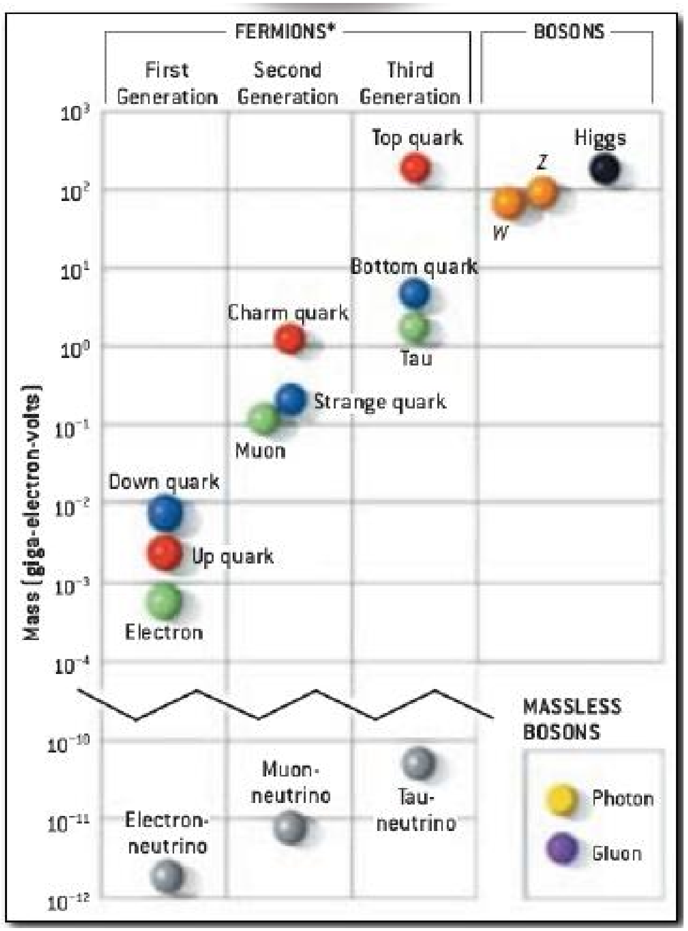
Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

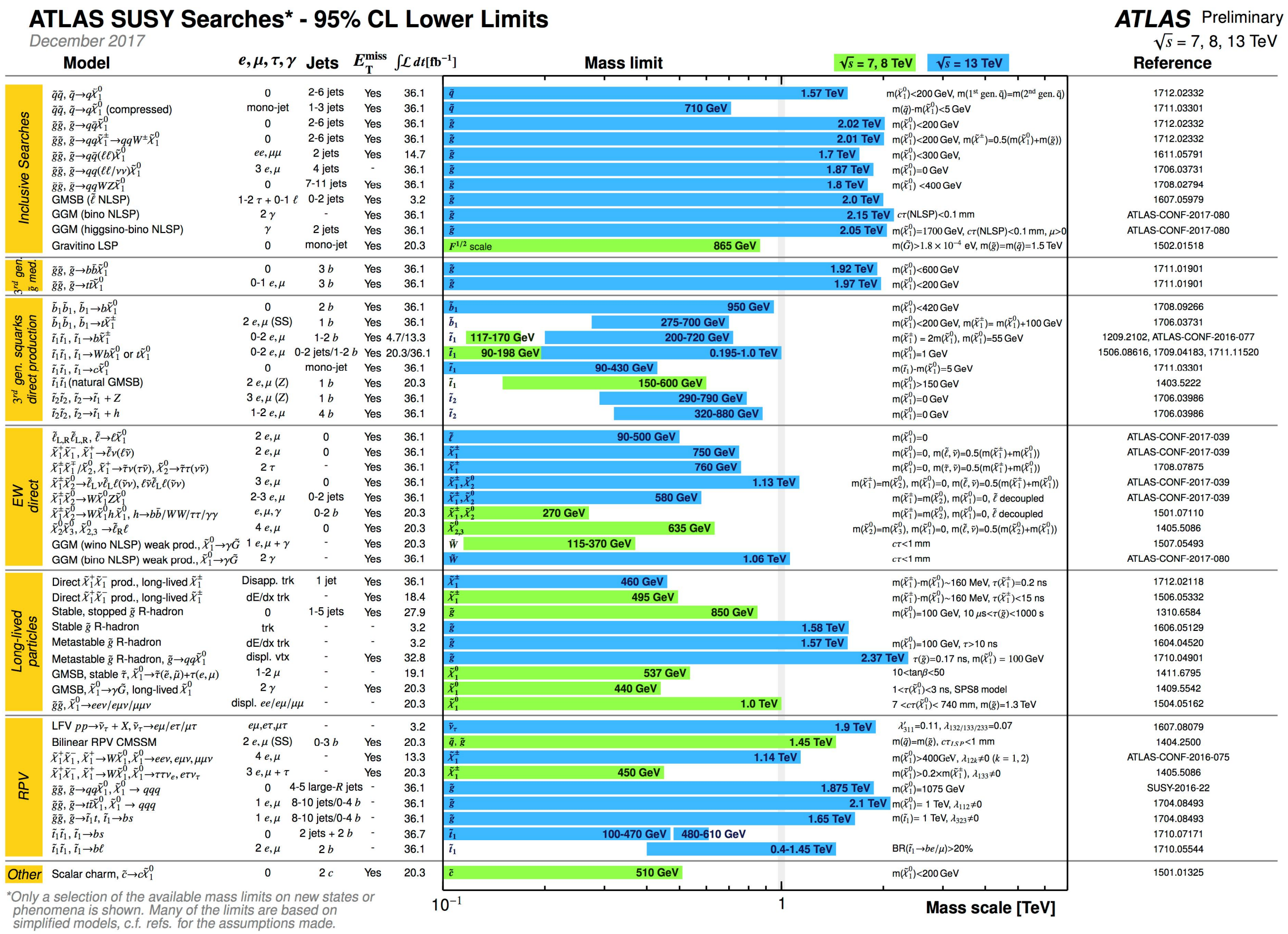
Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Still many puzzles remain

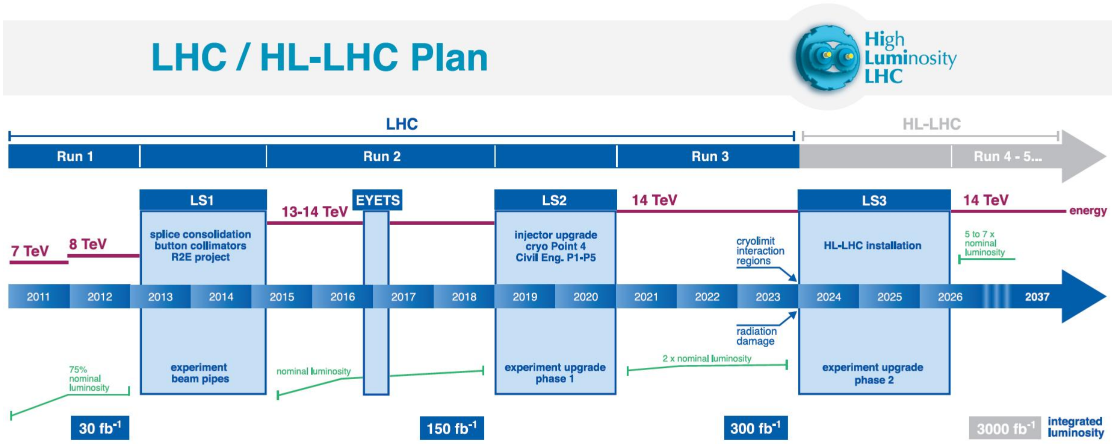
- Masses of charged fermions are GeVs, masses of neutrinos are milli-eVs
- Who would believe that this happened randomly, just by tossing a coin?
- Electroweak scale is 10^2, Plank scale is 10^{19}
- Clearly, the Nature is trying to send us a message…
- …but we still have to decode this message!



LHC: no hint of new physics so far



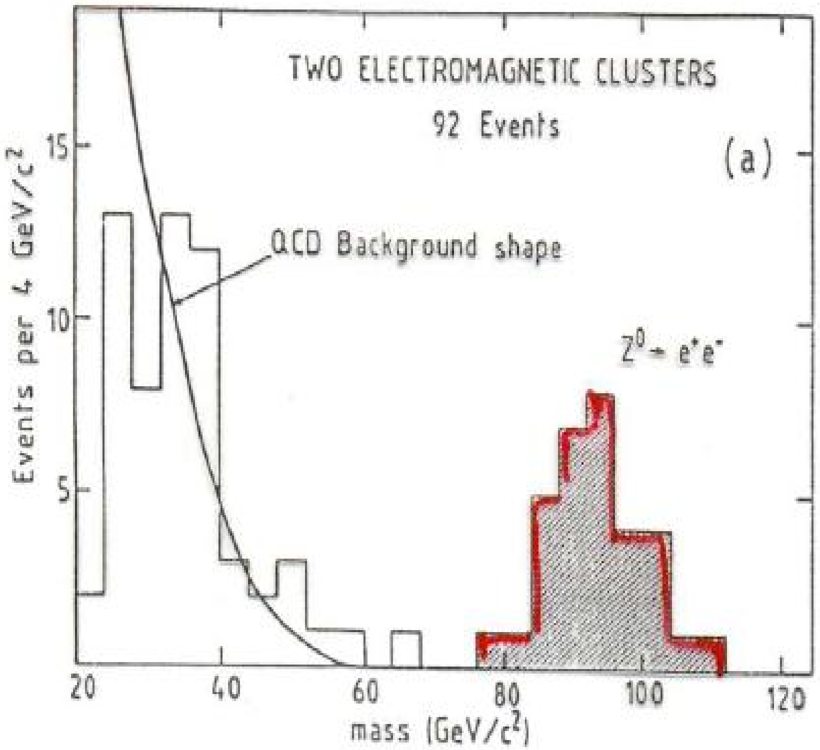
What after the LHC?

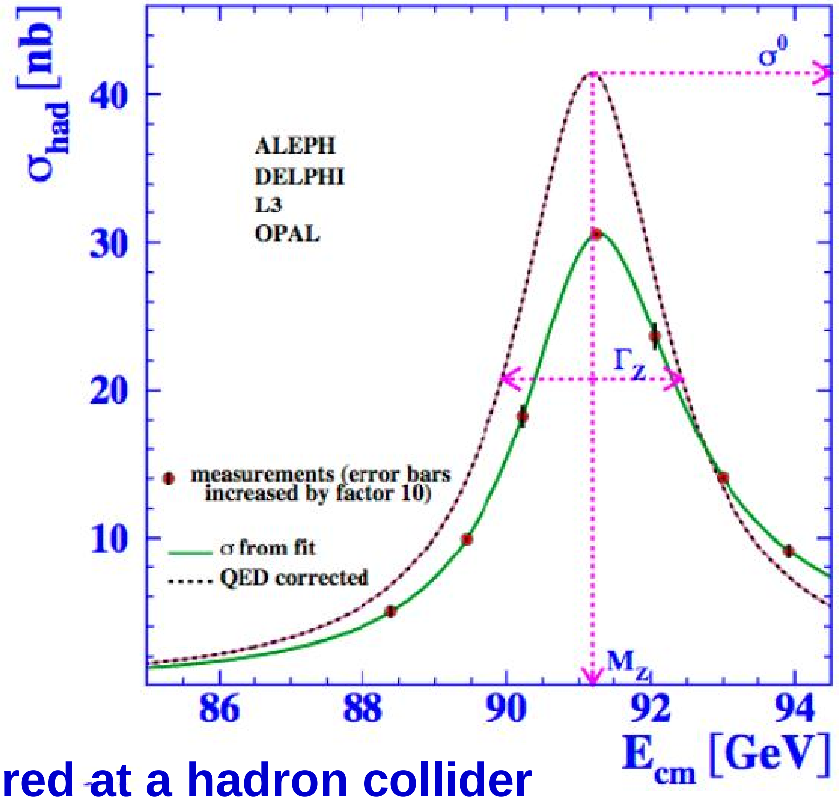


- Possible extension to HE-LHC (33 TeV)
- Or build a brand new collider!
- Hadron or lepton collider?

1982-83 SPS
Discovery of W and Z
$\sigma(M_Z)$ = 2 GeV

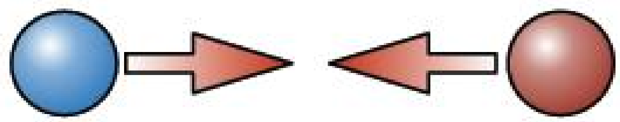
1989-95 LEP
Precision study of Z
$\sigma(M_Z)$ = 2 MeV



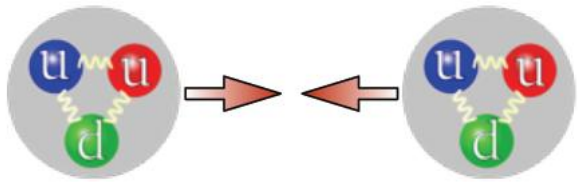


1995: top quark discovered at a hadron collider
2012: Higgs boson discovered at a hadron collider

Choice of collider type



- e^+e^- collisions
- Point-like particles
- Total annihilation: initial state known
- Decent background
- Limited in energy, but – precision!

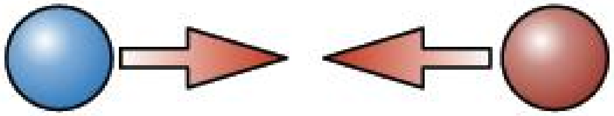


- pp(bar) collisions
- Composite particles
- Random energy of the hard interaction
- High background
- Highest energy frontier – discovery!

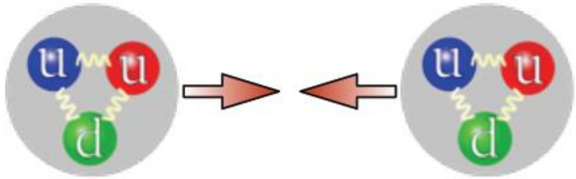
Choice of e^+e^- collider scheme

- e^+e^- circular colliders are limited in energy by the synchrotron radiation due to the beam curvature
- Either you build a tunnel of enormous size…
- Or you build a linear collider with enormous acceleration gradient
- Linear collider: advantage in energy
- Circular collider: re-use for a next pp-collider

Future collider candidates

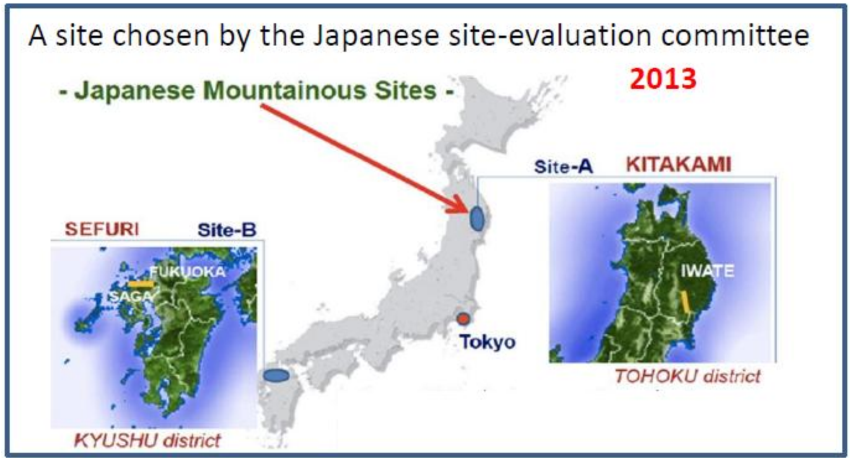


- ILC: 20 (30?) km, 250 (500?) GeV, Higgs factory (Giga-Z possible)
- CLIC: 50 km, 3000 GeV, Higgs, Top, discoveries
- CEPC: 100 km, 250 GeV, Higgs physics + Giga-Z
- FCC: 100 km, 350 GeV, Higgs + Tera-Z

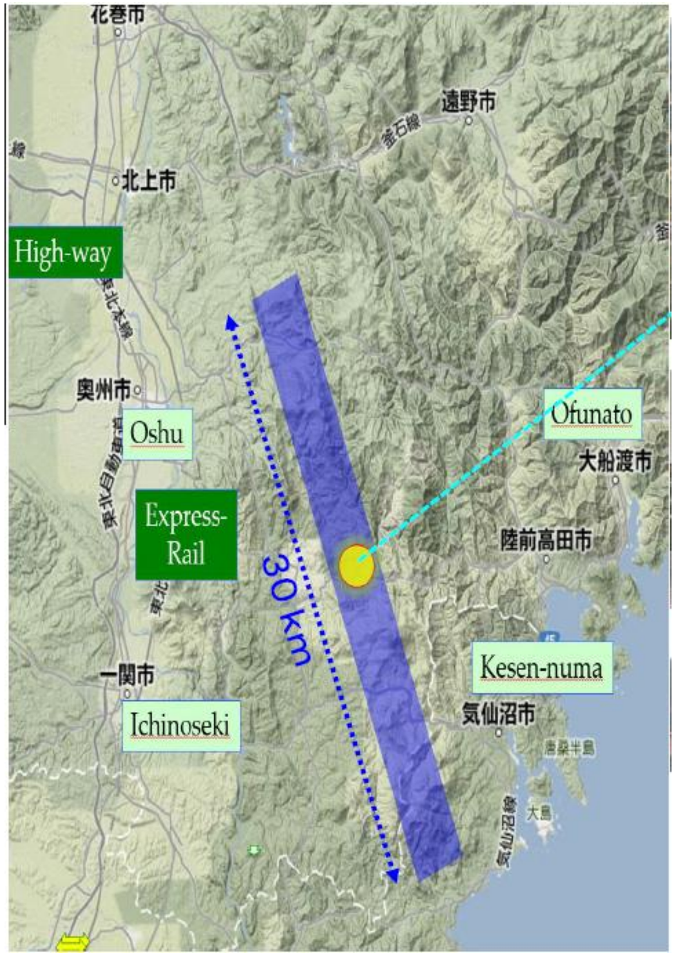


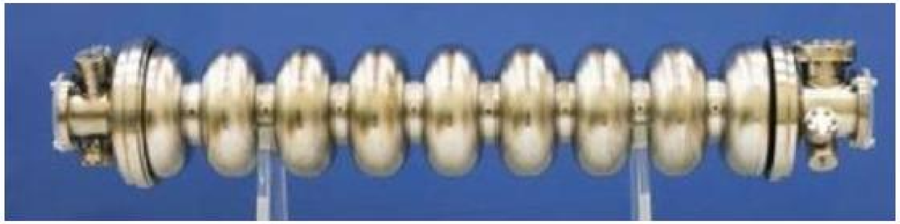
- HL LHC:
  14 TeV, 3 ab^{-1}
- HE-LHC:
  33 TeV, 2 ab^{-1}
- CEPC-pp:
  70 TeV, 10 ab^{-1}
- FCC-pp:
  100 TeV, 5 ab^{-1}

ILC



- Initial baseline: 500 GeV, possible extension to 1000 GeV
- After “cost optimization”: 250 GeV, extension to 500 GeV unlikely
- Cost down from $8G to $4G





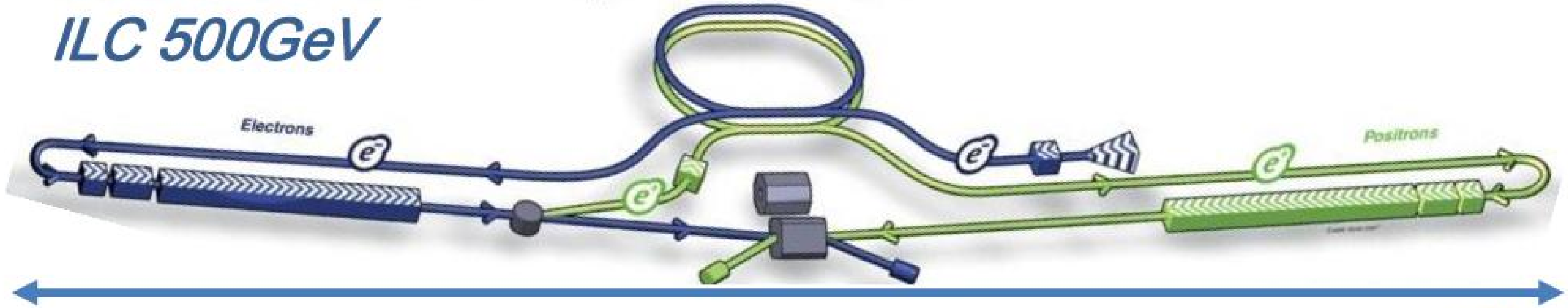
Cost reduction by technological innovation

Innovation of Nb (superconducting) material process: decrease in material cost

Innovative surface processing for high efficiency cavity by FNAL: decrease in number of cavities

Staging

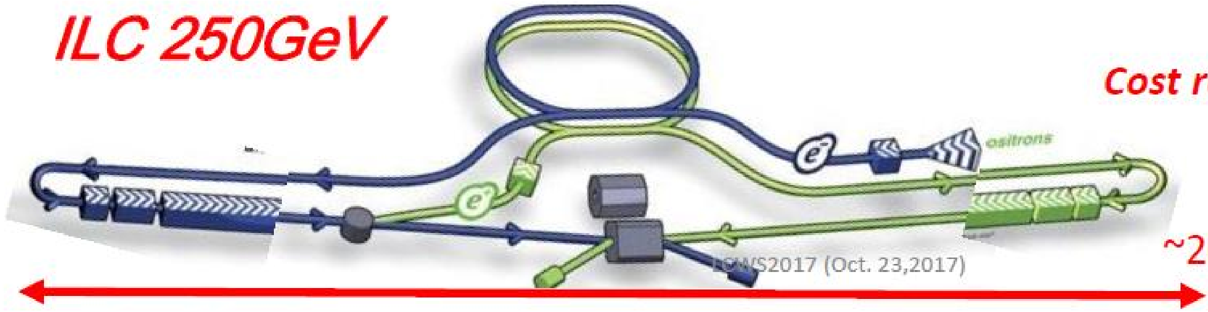
ILC 500GeV



~31km

ILC 250GeV

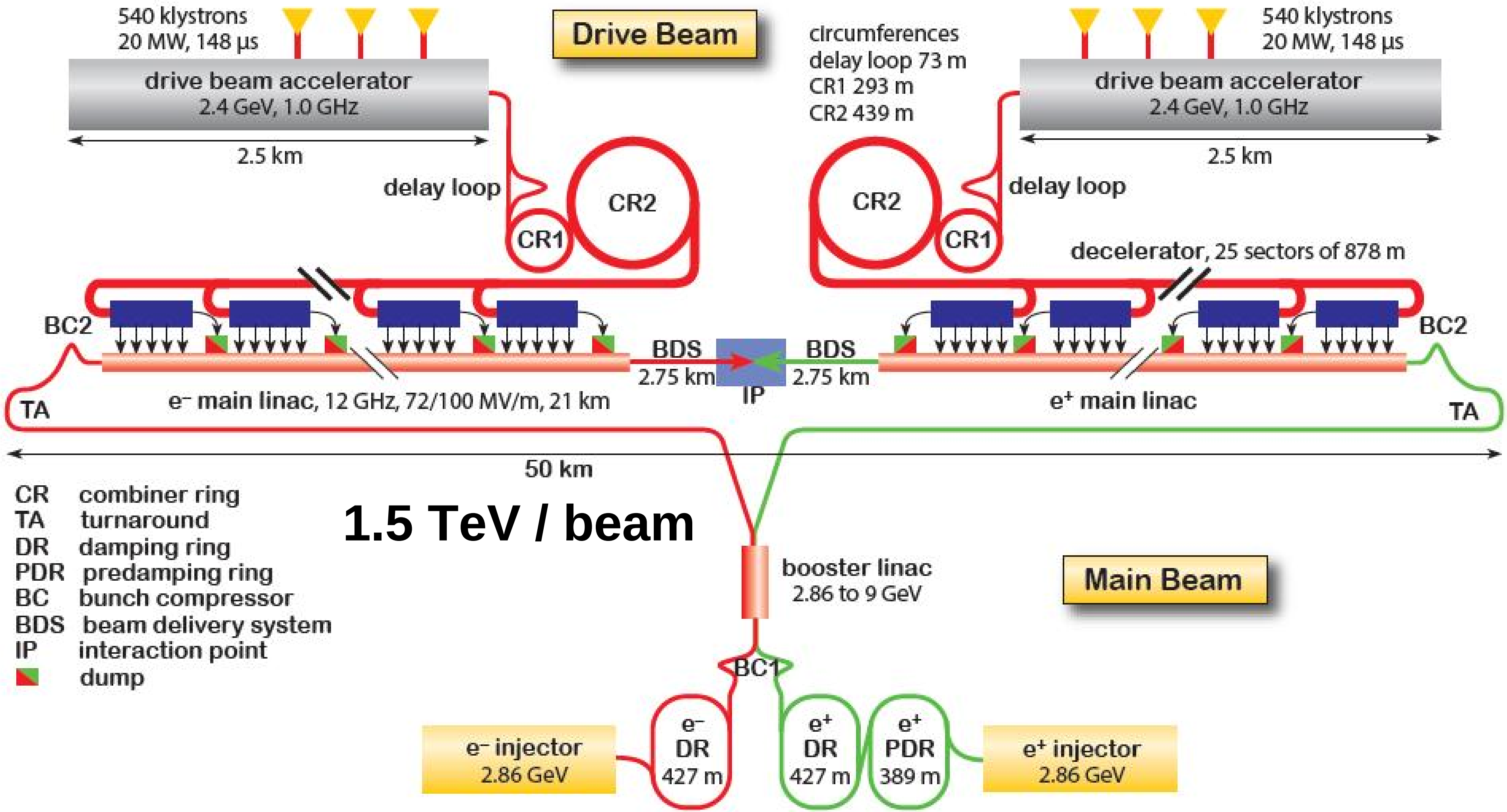
Cost reduction by compact ILC

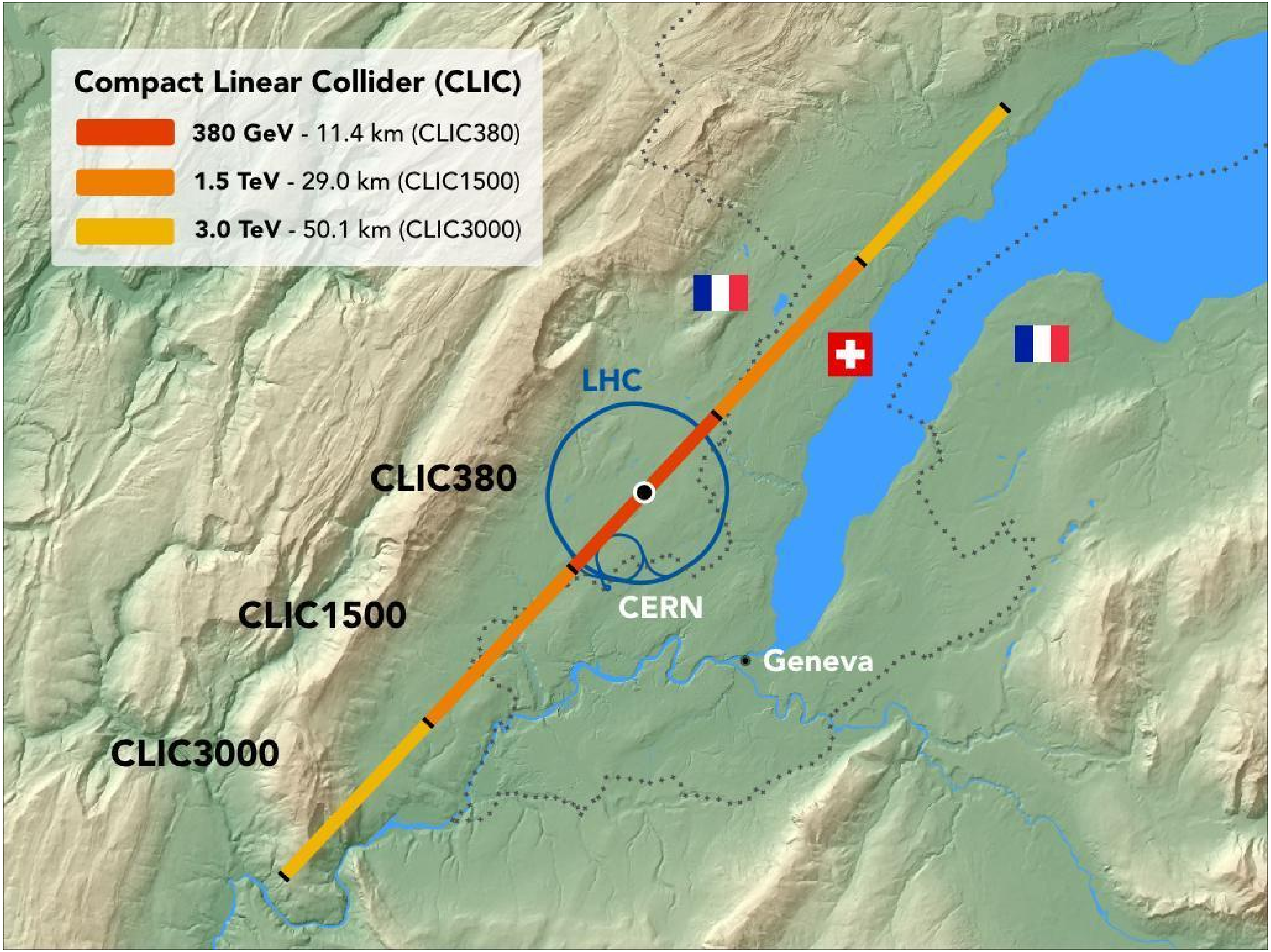


~20km

10

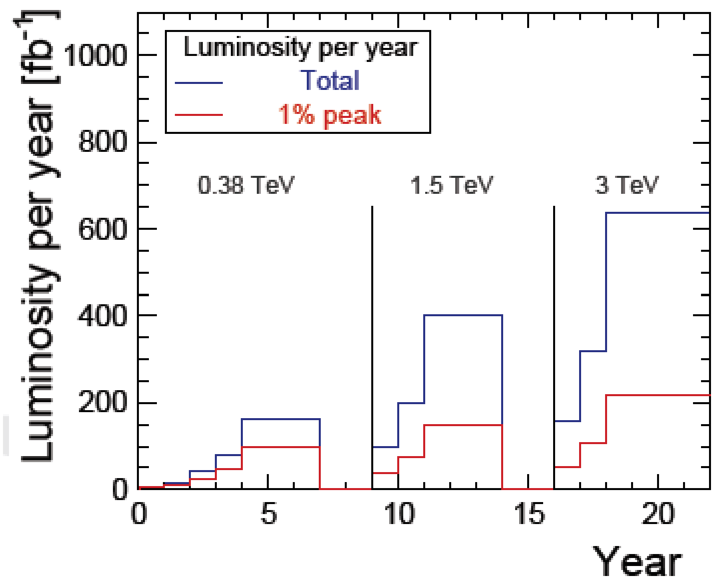
CLIC layout (3 TeV)





Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva

CLIC running baseline



Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\mathrm{int}}$ (fb^{-1})
1	380 350	500 100
2	1500	1500
3	3000	3000

CEPC/SppC

e^+e^- Higgs (Z) factory

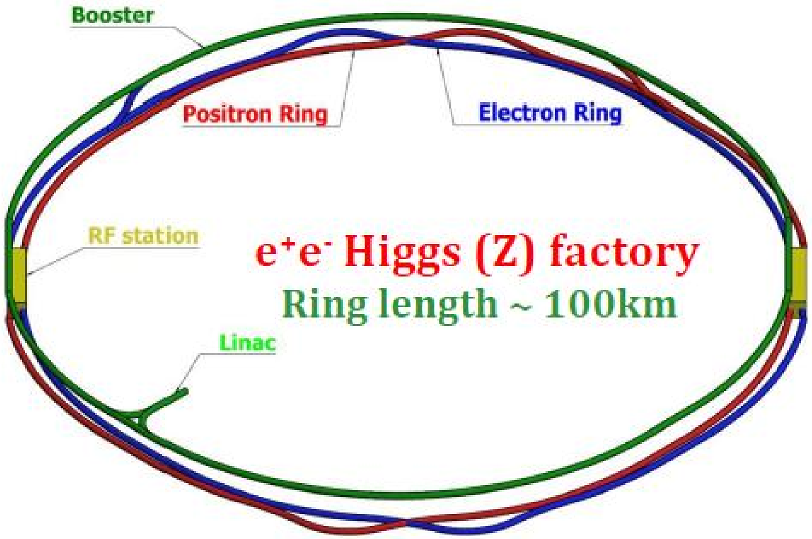
$E_{cm} \approx 240$GeV, luminosity $\sim 2\times10^{34}$ $cm^{-2}s^{-1}$, 2IP, 1M H in 10 years
at the Z-pole 10^{10}Z bosons/yr

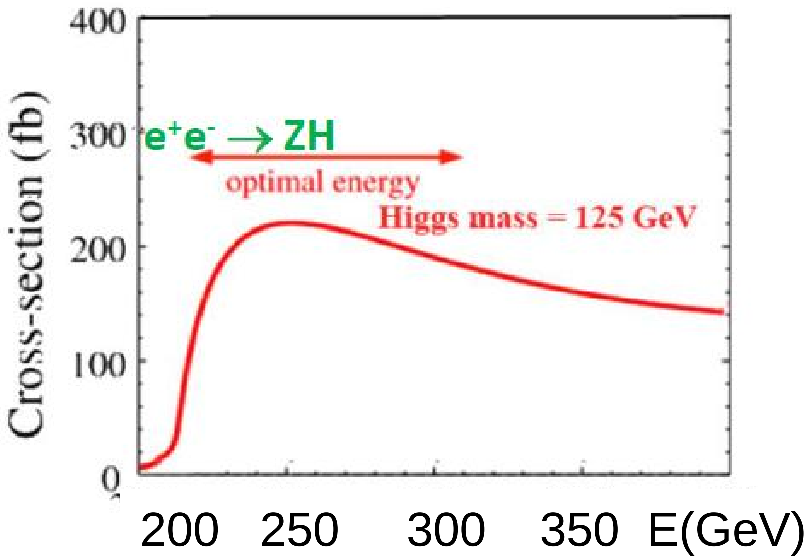
Precision measurement of the Higgs boson (and the Z boson)

Higgs precision 1% or better

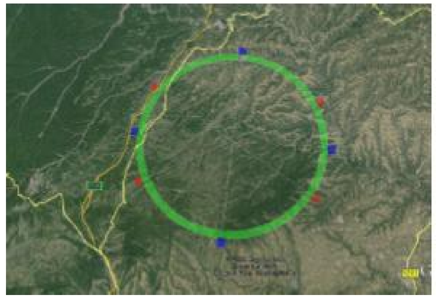
Upgradable to pp collision with $E_{cm} \approx$ 50-100 TeV (with ep, HI options)

A discovery machine for BSM new physics





CEPC site



1) QingHuangDao, Hebei（completed preCDR）

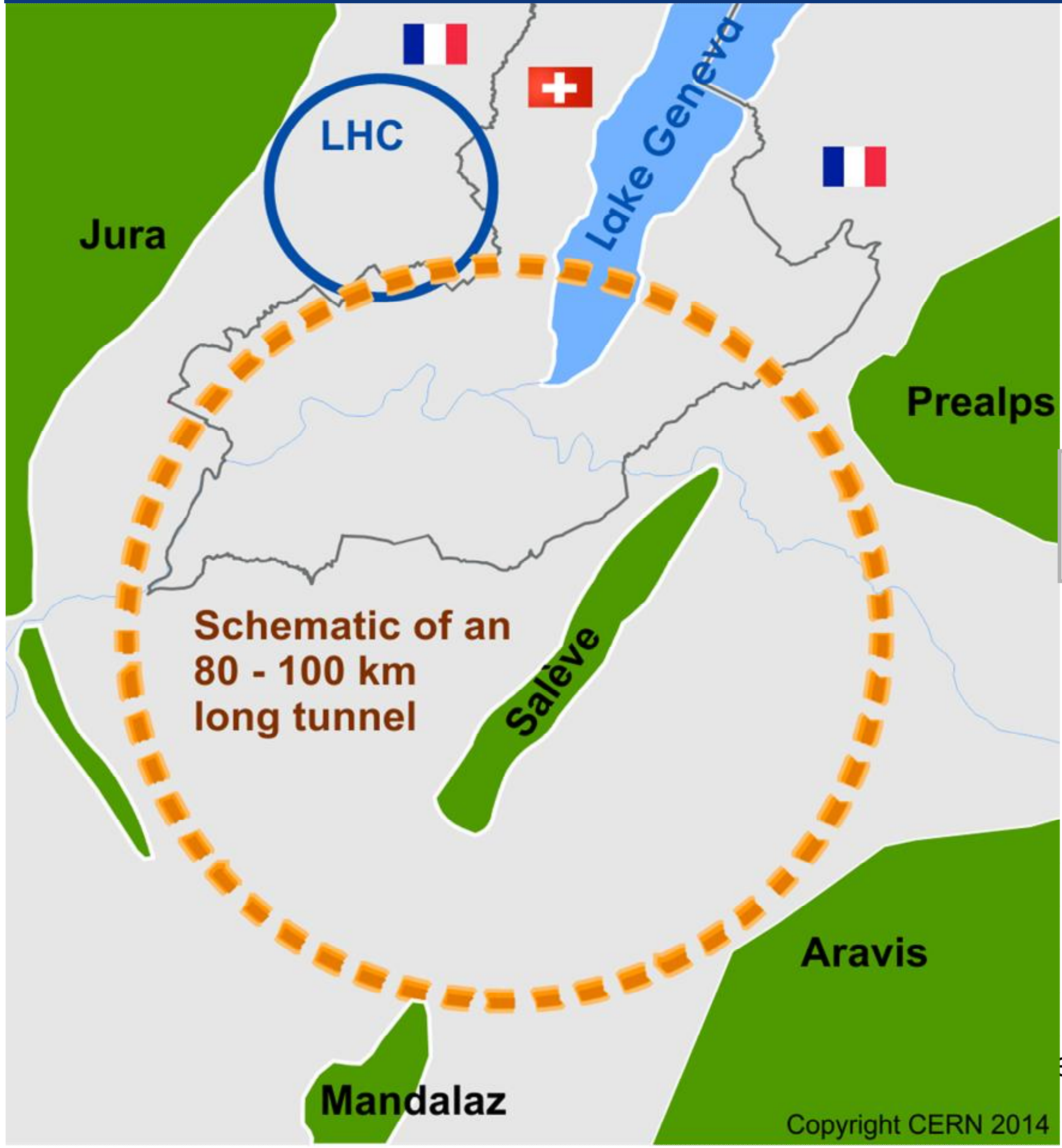
2) Huangling, Shaanxi（2017.1 signed contract to exp.）

3) ShenShan, Guangdong, （completed in August, 2016)

CEPC schedule

- CEPC data-taking starts before the LHC program ends
- Possibly con-current with the ILC program

Future Circular Collider (FCC)



International FCC collaboration (CERN as host lab) to study:

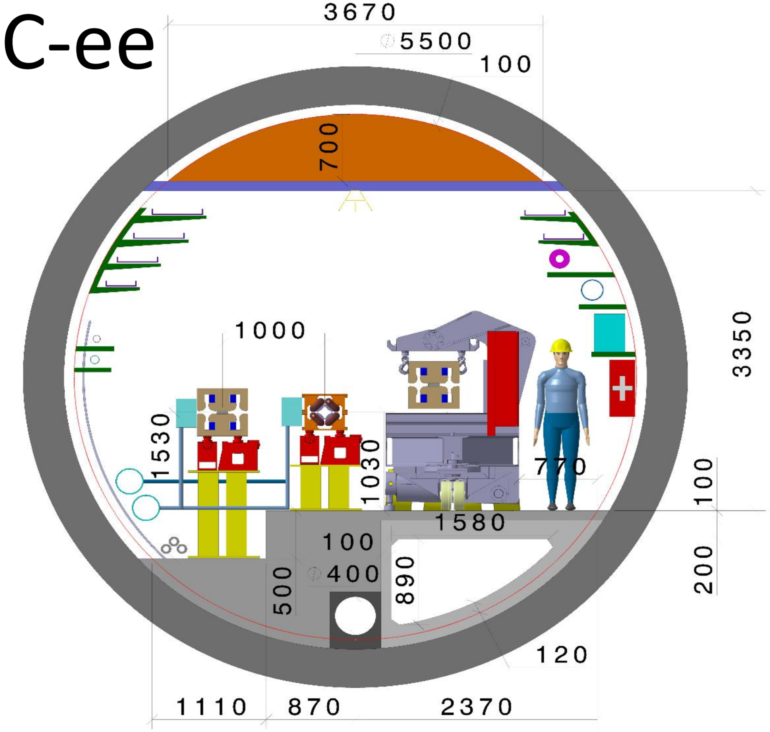
- ***pp*-collider (*FCC-hh*)** → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

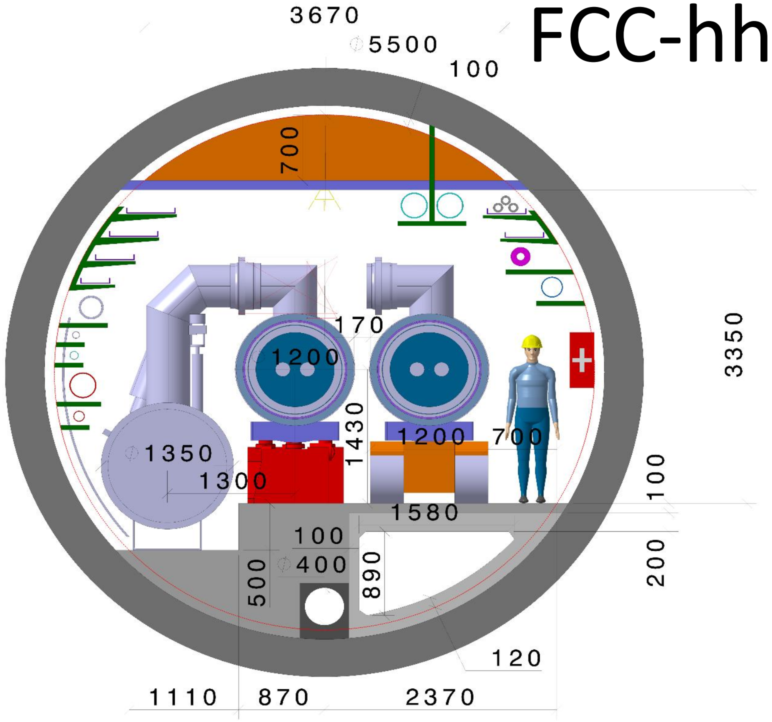
- **~100 km tunnel infrastructure** in Geneva area, site specific
- ***e*$^{+}$*e*$^{-}$ collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology

FCC tunnel

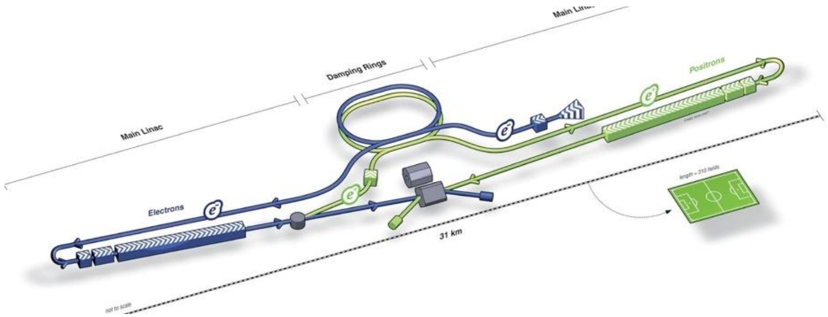
FCC-ee



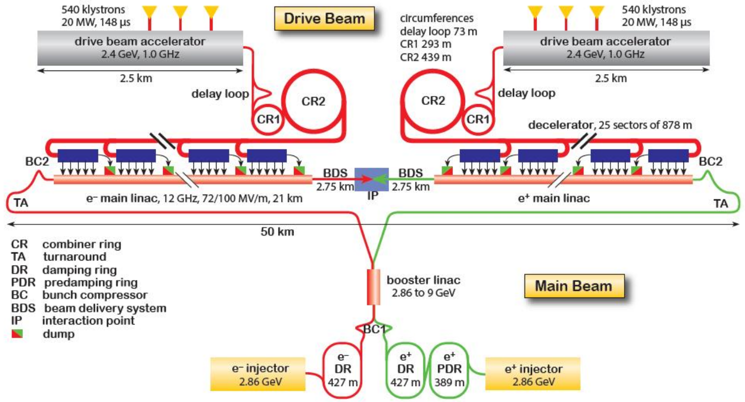
FCC-hh



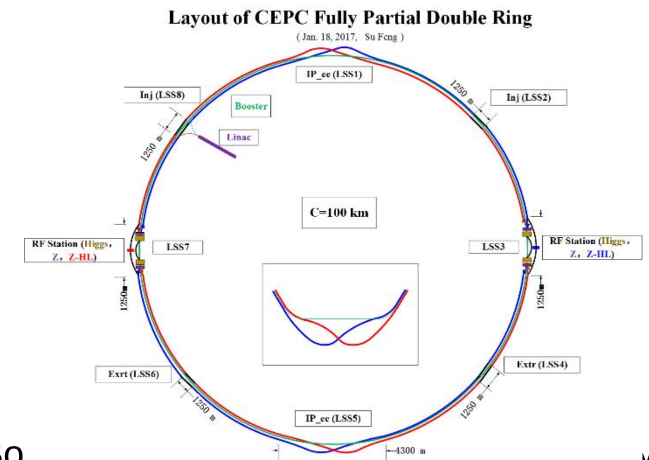
ILC (2030) **$ 4-5G**



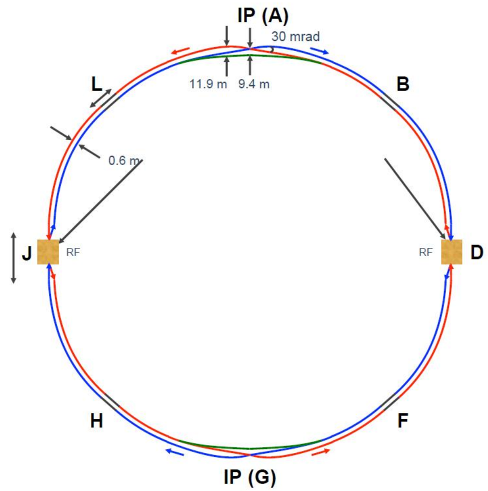
CLIC (2035) **$ 6.7G (380 GeV)**
$13G (3000 GeV)



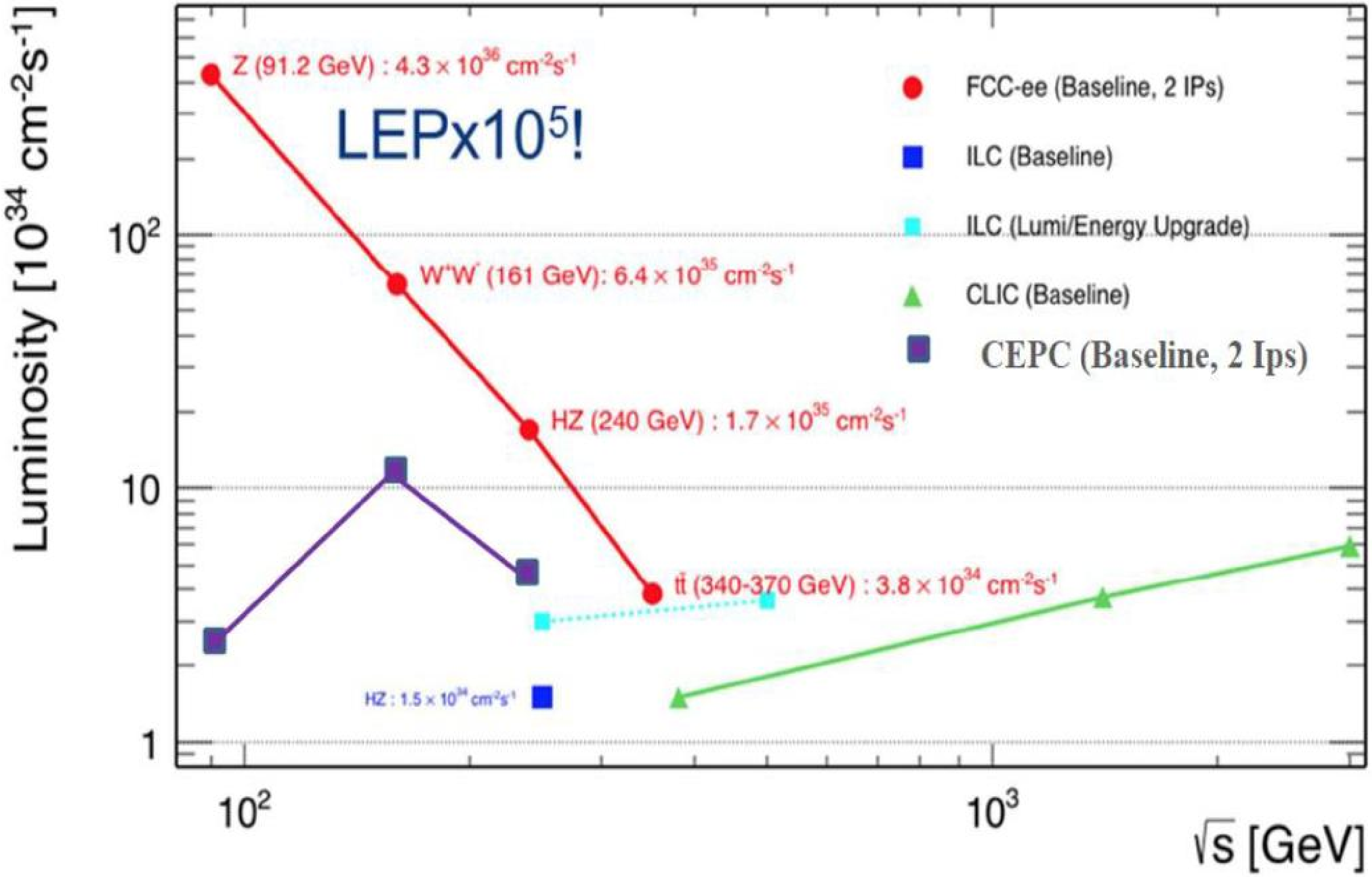
CEPC (2030) **$ 5.5G**



FCC-ee (2039) **$???**



Comparison of e^+e^- projects



Energy landmarks of ee colliders

- 91 GeV: repeat LEP1 experiments
  - "Tera-Z": full LEP1 data every 5 min !!!!!!!!!!!!!!!
- 161 GeV: $E=2xM_W$, threshold scan
  - repeat 1996 at LEP2, 1000x lumi
- 240-250 GeV: Higgs factory
- 350 GeV: $E=2xM_t$, threshold scan
- 400 GeV: maximum top-pair cross-section
- 500-3000 GeV: discovery of new physics!

Sources of precision

- Statistical error
  - Increase collider luminosity
- Systematic error
  - Novel detector technologies, improved analysis methods
- Theoretical error
  - More precise calculations, higher perturbative order, include polarization
- Parametric error
  - Better measurement of external parameters

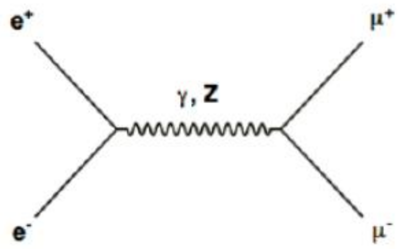
Physics at 91 GeV

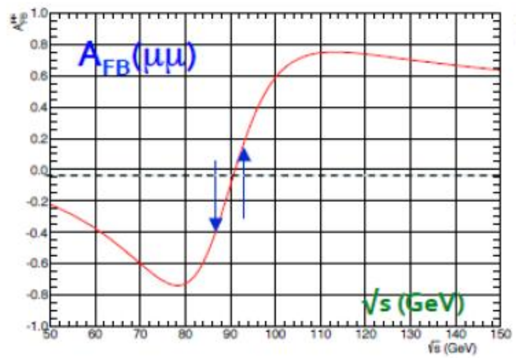
- 10^{12} Z bosons per year means increase of LEP1 statistics by a factor of 100000, statistical error reduced by factor 300
- In principle, should improve all systematic and theoretical errors by the same factor
- Seems impossible. Factor 50 as a VERY optimistic estimate
- Only the measurements that were statistically dominated at LEP1 can fully exploit the hyper-high luminosity of Tera-Z
  - Example: $A_{FB}(ee\to\mu\mu)$

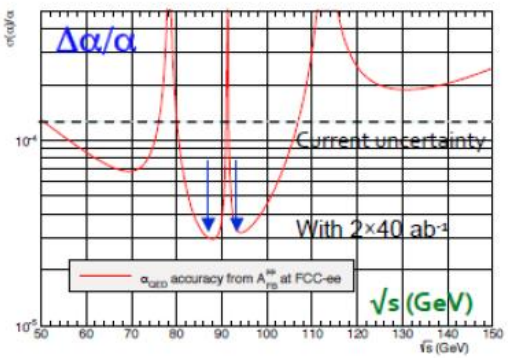
Example: $A_{FB}(ee\to\mu\mu)$

- **Forward-Backward asymmetry : $\alpha_{QED}(m_Z)$**

P. Janot et







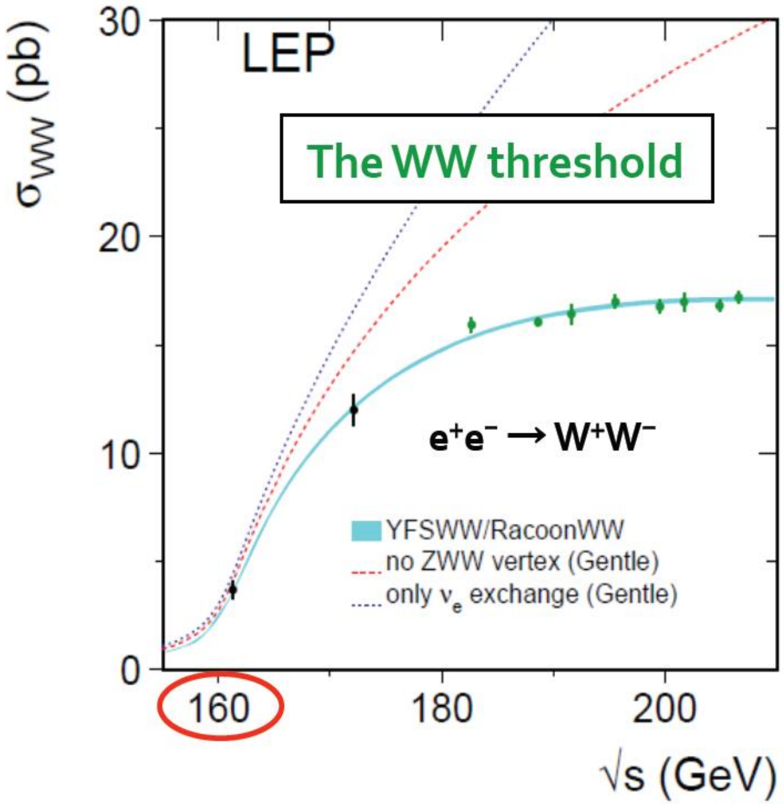
From γ-Z interference:

$$A_{FB}^{\mu\mu} = \frac{N_F^{\mu+} - N_B^{\mu+}}{N_F^{\mu+} + N_B^{\mu+}} \approx f(\sin^2\vartheta_W^{eff}) + \alpha_{QED}(s)\frac{s - m_Z^2}{2s}\, g(\sin^2\vartheta_W^{eff})$$

- Measure $\alpha_{QED}(m_Z)$ with A_{FB} at $\sqrt{s}$ = 87.9 and 94.3 GeV
  - To match statistical error
    - Predict AFB with a precision of ~10^{-5} at these energies
    - Predict IFI effects (ISR+FSR interference) to ~ few 10^{-4}

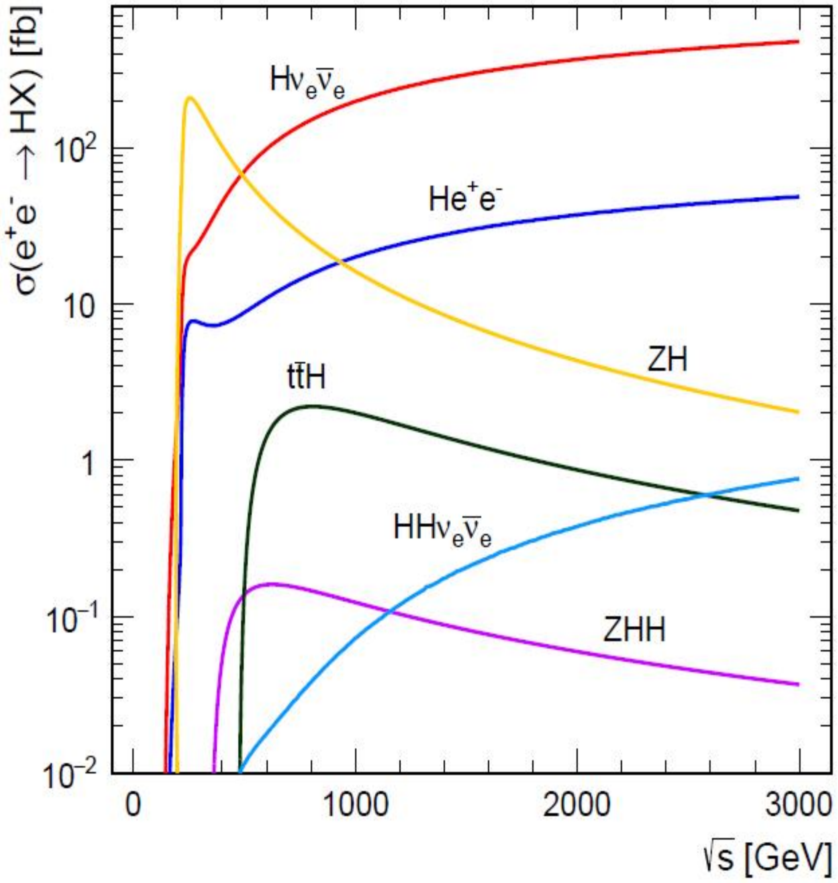
S. Jadach et al.

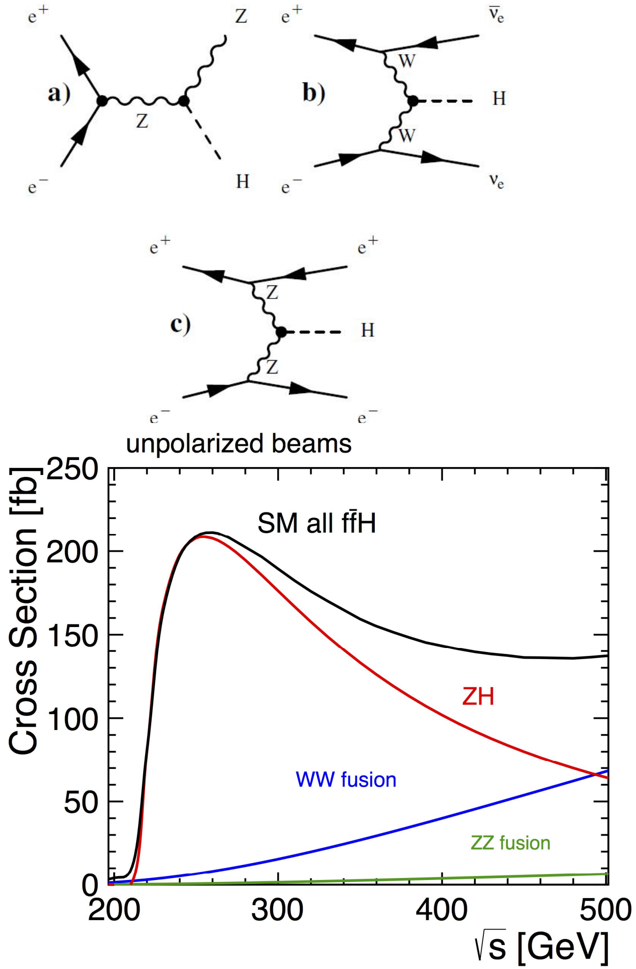
Physics at 161 GeV



- LEP2 spent only few weeks at 161 GeV
  - The dream was Higgs…
- Measurement of M_W at hadron colliders AND at LEP mainly from reconstruction of W decay products
  - Systematics-dominated
- Threshold scan at ee collider gives M_W with completely different (and small) systematics (E_{CM}!!)
- Weinberg angle: $M_W/M_Z=\sin\theta_W$

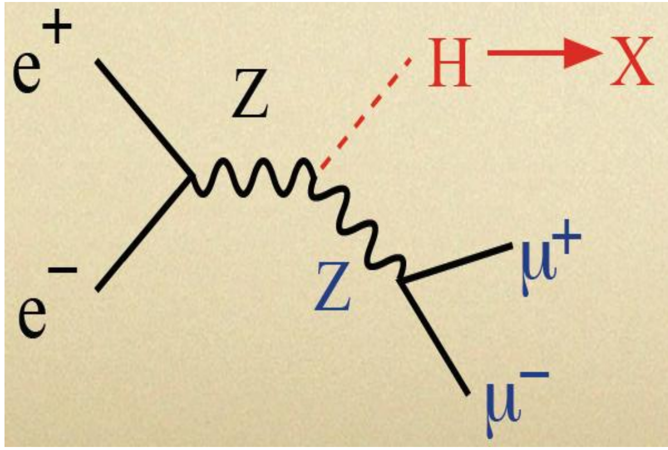
Physics at 250 GeV

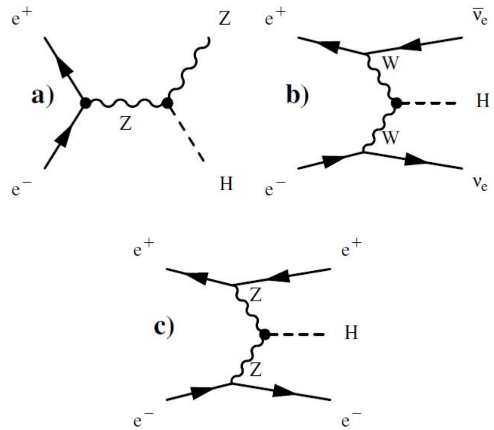




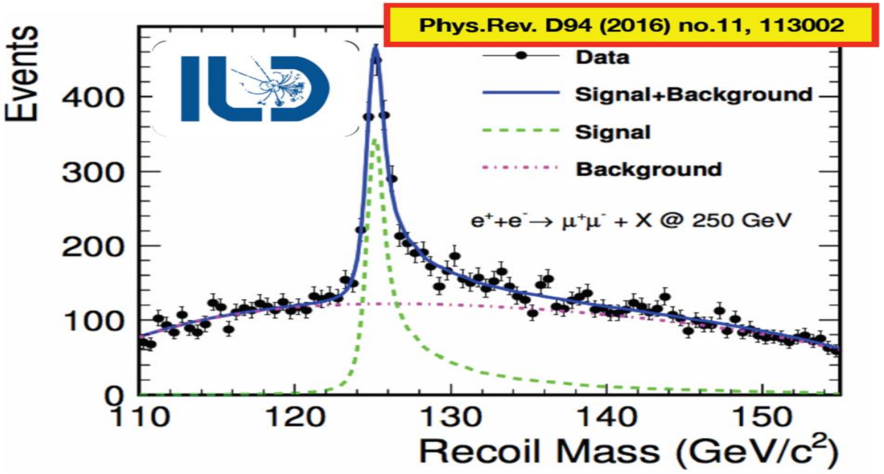
Model-independent Higgs

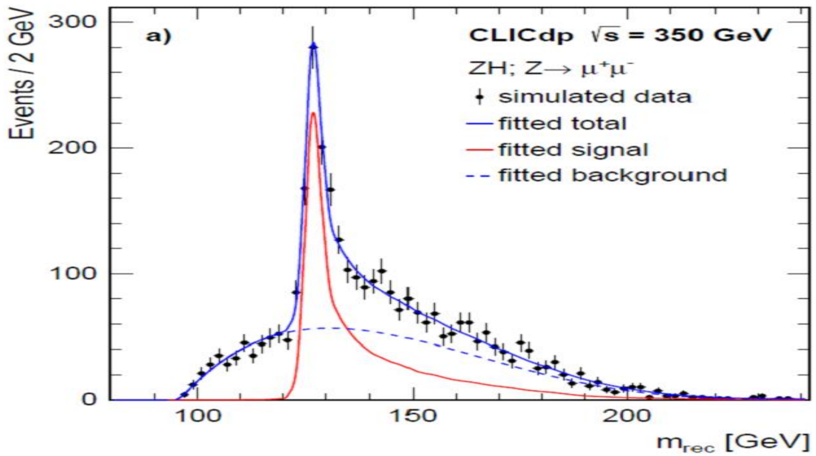
- At 250 GeV we look for events $ee \to HZ \to H\mu\mu$
- Muon pair is used as a tag, and we look at the mass recoiling against Z
- If recoil mass is 125 GeV, this is Higgs, for sure
- We don't need to reconstruct Higgs! It may be even invisible decay
- Model independent measurement!





Higgs mass measurement

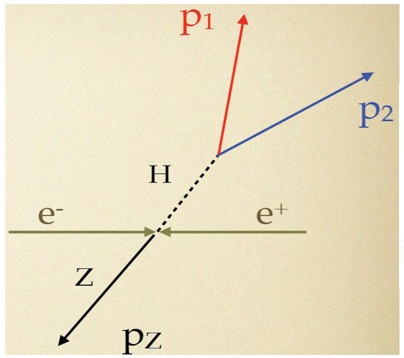




- At ILC/FCC/CEPC Higgs mass can be measured with 15-20 MeV precision as a mass recoiling against a dymuon in ee→HZ events
- The method relies on well defined kinematics of the initial ee system
- CLIC precision is only 110 MeV because of large beamspread and long tail of beamstrahlung
- We plan to apply a new method in CLIC environment

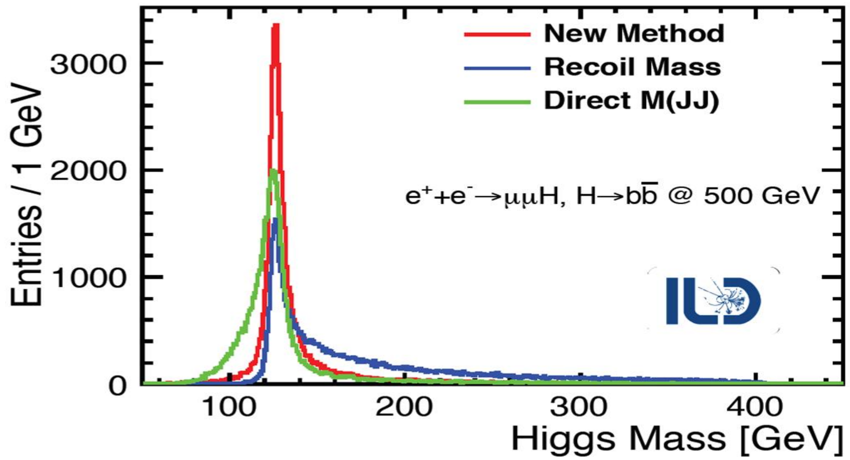
New method for M_H

- Measured muon tracks define Z kinematics
- For the b-jets from H→bb only directions (but not energies) are measured
- Zero p_T of the initial state is assumed (reasonable!)
- No assumption on p_Z of initial system is nedeed!
- Especially good for the CLIC environment!

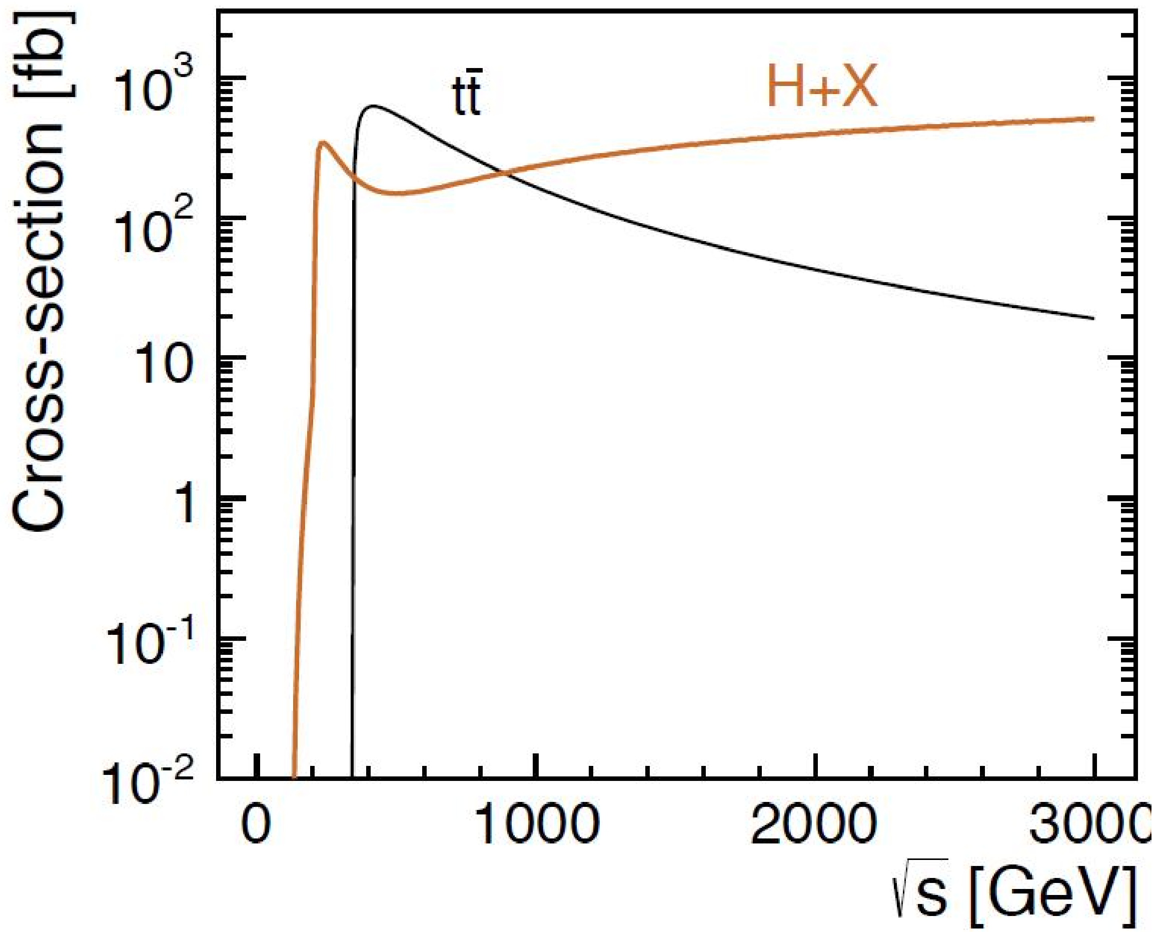


$$p_1 = \frac{p_T^{\mu\mu}}{\sin\theta_1}\frac{\sin(\phi_2 - \phi^{\mu\mu})}{\sin(\phi_2 - \phi_1)}$$

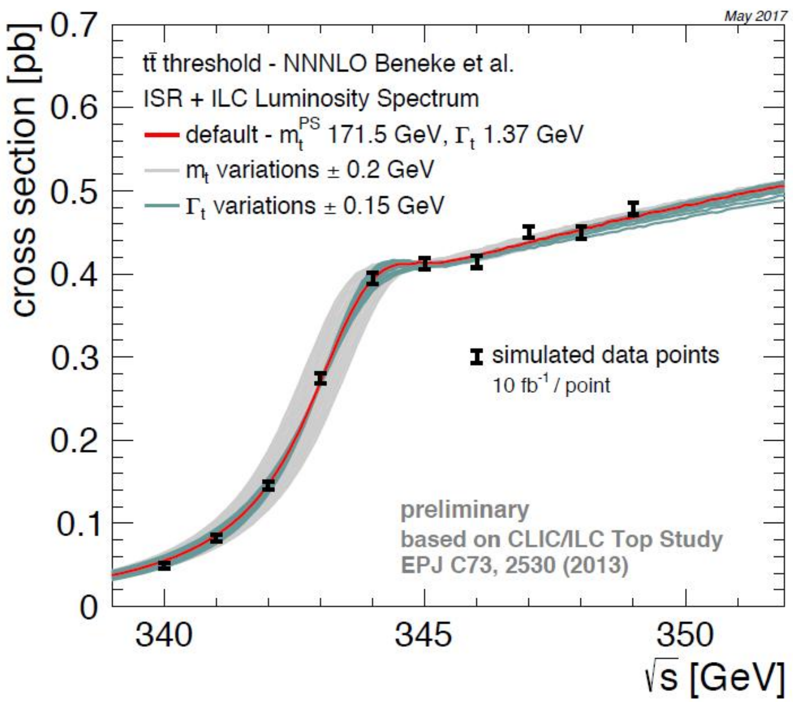
$$p_2 = \frac{p_T^{\mu\mu}}{\sin\theta_2}\frac{\sin(\phi_1 - \phi^{\mu\mu})}{\sin(\phi_1 - \phi_2)}$$



Top quark physics



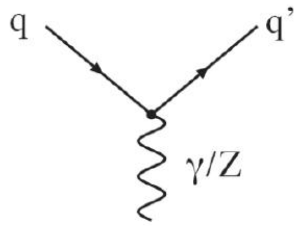
M_t: threshold scan at 350 GeV

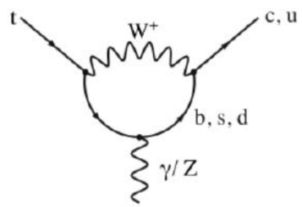


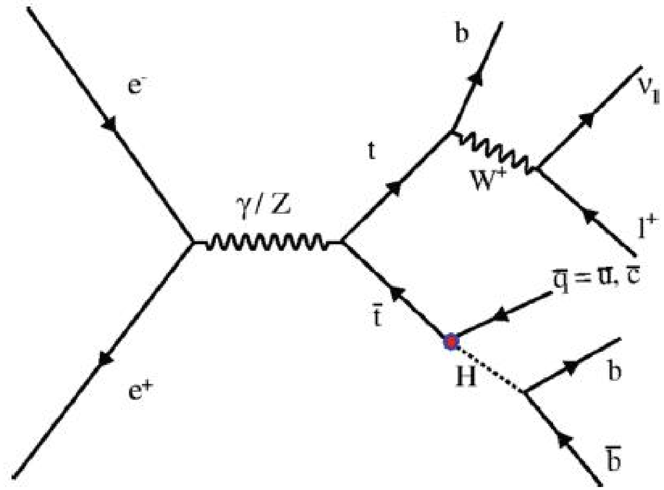
- 10 points, 10fb^{-1} each (1 year running at 350 GeV)
- Cross-section curve directly sensitive to the top mass, width, Yukawa coupling, strong coupling constant
- $\delta(m_t)$=±20MeV(stat) ±40MeV(syst) ±40 MeV(scale)
- $\delta(\Gamma_t)$=±45MeV(stat) ±60MeV(scale)

Top at 380 GeV: rare decays

- The FCNC decays $t \to c\gamma/cZ/cg/cH$ have negligible branchings in the Standard Model (10^{-12}-10^{-14})
- Currently 2 channels are under study: $t \to c\gamma$ and $t \to cH$
- Signal: for $ee \to tt$ one top decays anomalously, another decay is standard, $t \to Wb$
- CLIC sensitivity: $Br<1 \cdot 10^{-4}$ (Expected HL-LHC: $2 \cdot 10^{-4}$)

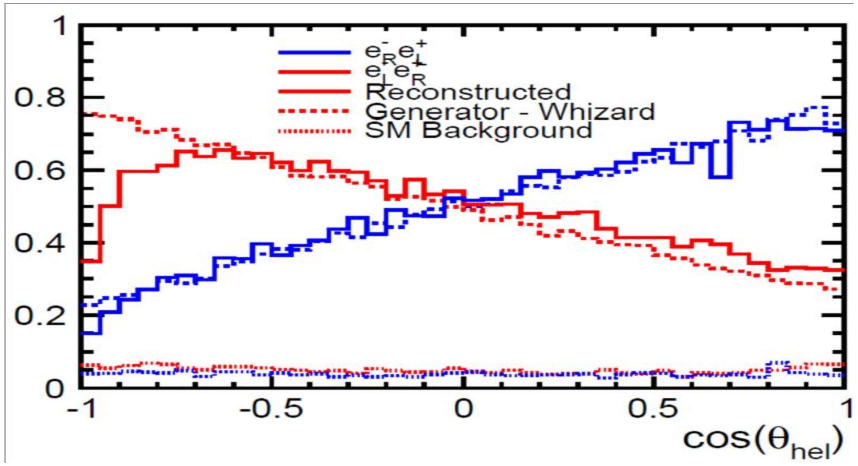


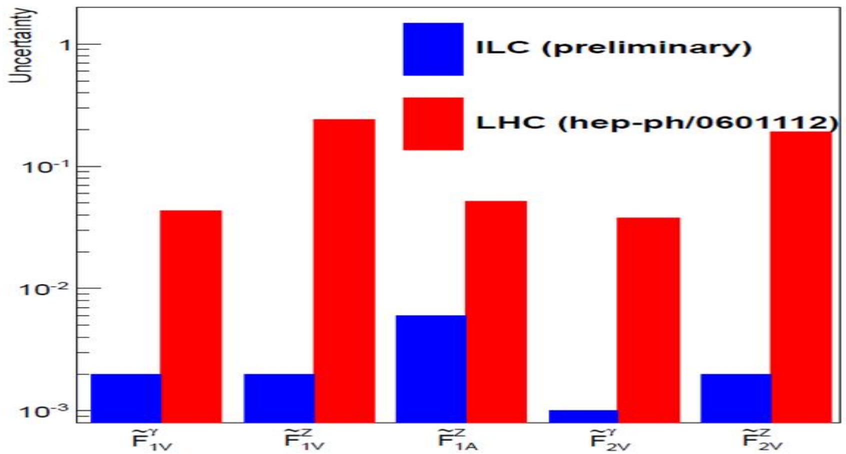




Top polarization at E≥380 GeV

- Fermion pair production described by 3 observables: cross-section σ, asymmetry A_{FB}, polarization P
- $P=(N_R-N_L)/(N_R+N_L)$
- Only accessible via distribution of decay products
- Only available for τ and t

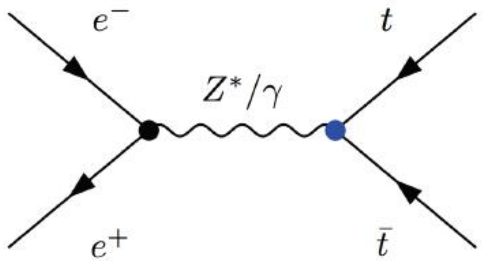




Top electroweak couplings

$$\Gamma^{t\bar{t}X}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\underbrace{F^X_{1V}(k^2)}_{\text{vector}} + \gamma_5 \underbrace{F^X_{1A}(k^2)}_{\text{axial}}\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(i\underbrace{F^X_{2V}(k^2)}_{\text{tensor}} + \gamma_5 \underbrace{F^X_{2A}(k^2)}_{\text{CPV}}\right)\right\}$$

- Observables to distinguish Z and γ couplings:
  - Energy dependence of the cross-section
  - Forward-backward charge asymmetry
  - Beam polarization asymmetry (P_{e^-} = ±80%)
  - Top quark polarization
  - Spin correlation
- Deviations from SM can be parameterized in terms of New Physics, e.g. in the EFT language



$$F^Z_{1,V} - F^{Z,SM}_{1,V} = \frac{1}{2}\left(\underline{C^{(3)}_{\varphi Q} - C^{(1)}_{\varphi Q} - C_{\varphi t}}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2}\underline{C^V_{\varphi q}}\frac{m_t^2}{\Lambda^2 s_W c_W}$$

$$F^Z_{1,A} - F^{Z,SM}_{1,A} = \frac{1}{2}\left(\underline{-C^{(3)}_{\varphi Q} + C^{(1)}_{\varphi Q} - C_{\varphi t}}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2}\underline{C^A_{\varphi q}}\frac{m_t^2}{\Lambda^2 s_W c_W}$$

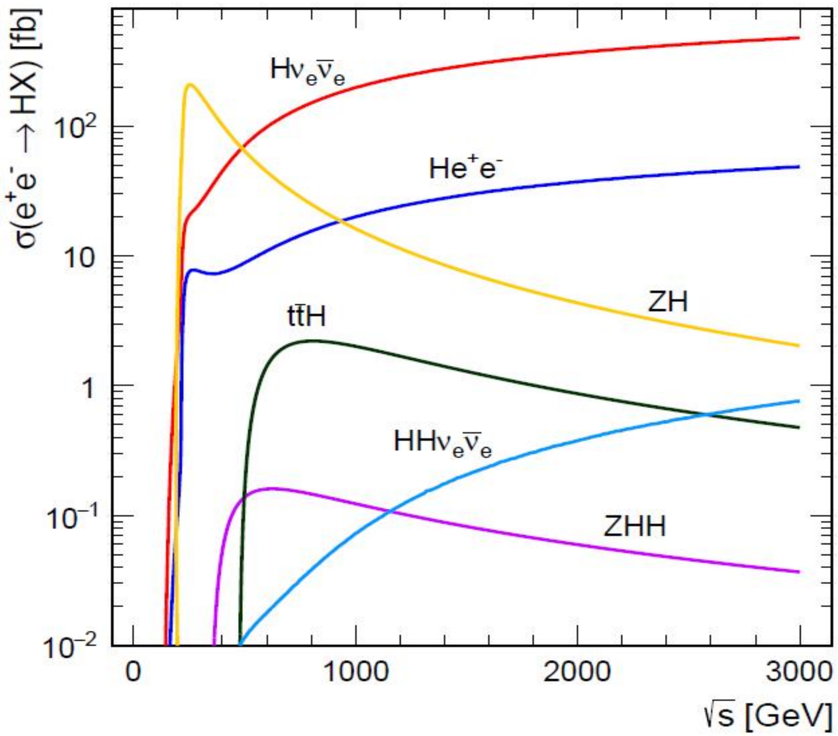
$$F^Z_{2,V} = \left(\underline{\mathrm{Re}\{C_{tW}\}c_W^2 - \mathrm{Re}\{C_{tB}\}s_W^2}\right)\frac{4m_t^2}{\Lambda^2 s_W c_W} = \mathrm{Re}\{\underline{C_{uZ}}\}\frac{4m_t^2}{\Lambda^2}$$

$$F^\gamma_{2,V} = \left(\underline{\mathrm{Re}\{C_{tW}\} + \mathrm{Re}\{C_{tB}\}}\right)\frac{4m_t^2}{\Lambda^2} = \mathrm{Re}\{\underline{C_{uA}}\}\frac{4m_t^2}{\Lambda^2}$$

$$[F^Z_{2,A}, F^\gamma_{2,A}] \propto [\mathrm{Im}\{C_{tW}\}, \mathrm{Im}\{C_{tB}\}]$$

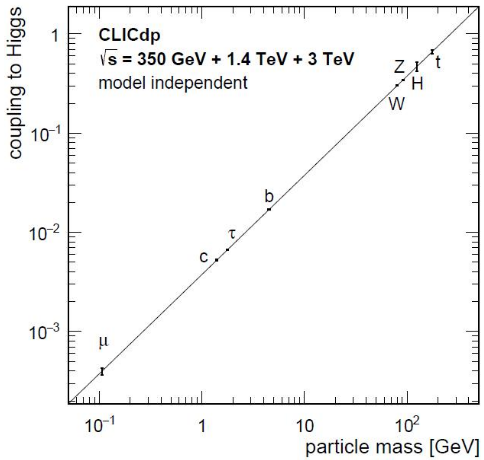
Higgs physics at 3000 GeV

About 1M Higgses will be reconstructed at CLIC

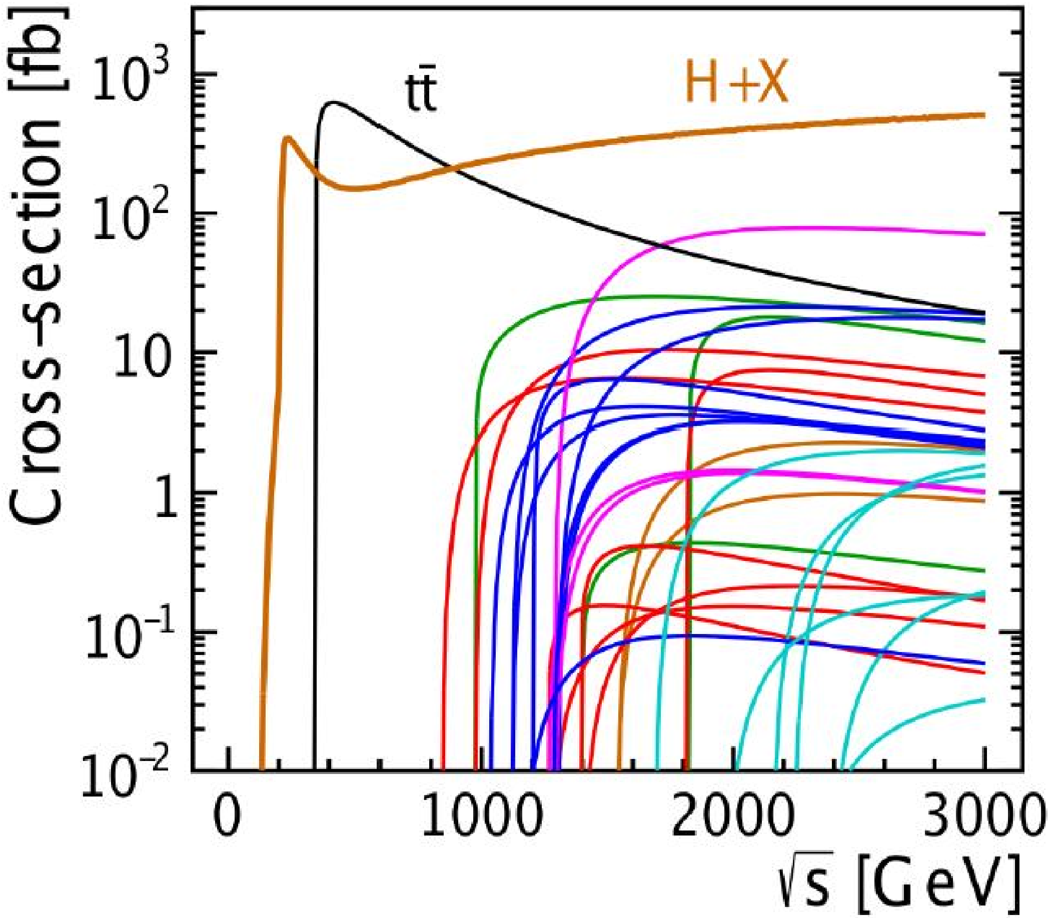


Self-coupling HHH ≈20%!

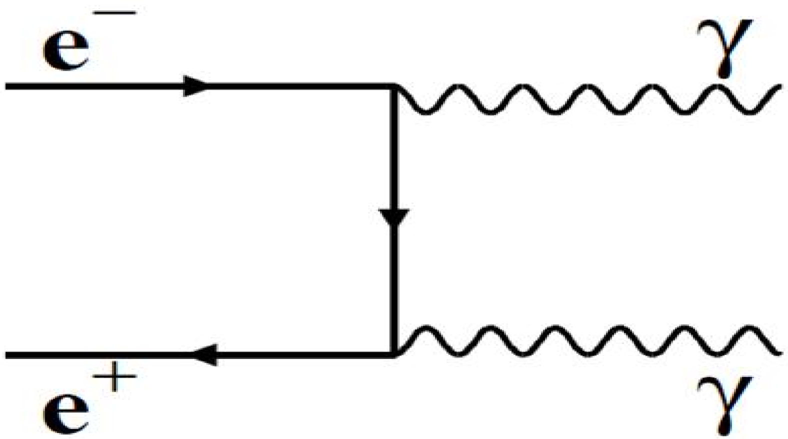
Parameter	Relative precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV + 1.5 ab^{-1}	+ 3 TeV + 2 ab^{-1}
κ_{HZZ}	0.6 %	0.4 %	0.3 %
κ_{HWW}	1.1 %	0.2 %	0.1 %
κ_{Hbb}	1.8 %	0.4 %	0.2 %
κ_{Hcc}	5.8 %	2.1 %	1.7 %
$\kappa_{H\tau\tau}$	3.9 %	1.5 %	1.1 %
$\kappa_{H\mu\mu}$	–	14.1 %	7.8 %
κ_{Htt}	–	4.1 %	4.1 %
κ_{Hgg}	3.0 %	1.5 %	1.1 %
$\kappa_{H\gamma\gamma}$	–	5.6 %	3.1 %
$\kappa_{HZ\gamma}$	–	15.6 %	9.1 %
$\Gamma_{H,md,derived}$	1.4 %	0.4 %	0.3 %

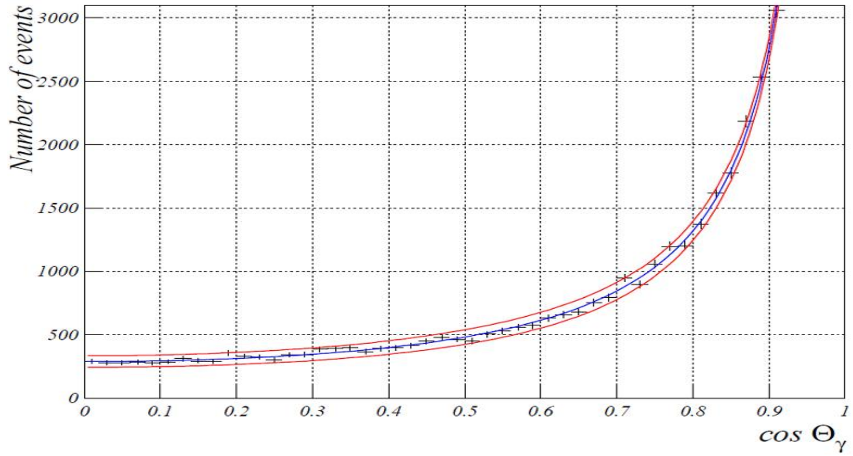


New physics at 3000 GeV



Electron radius from ee→γγ

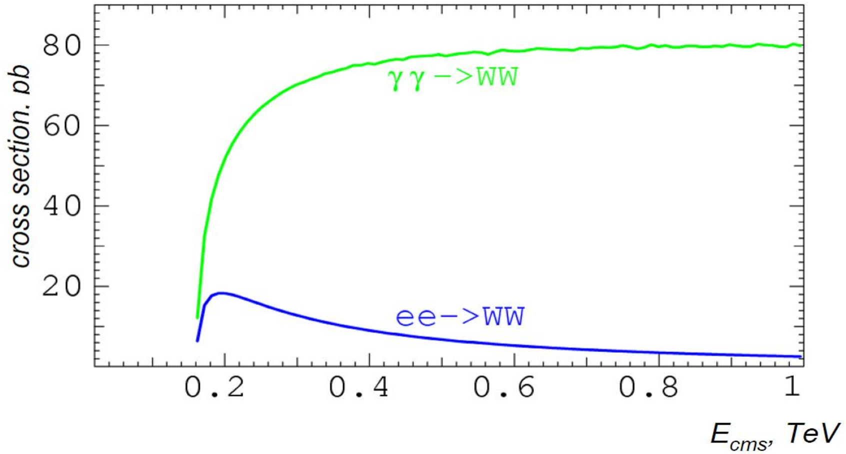


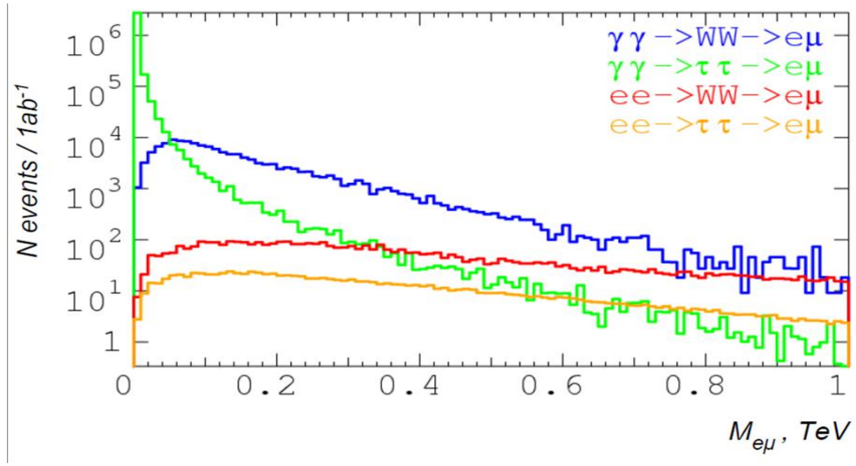


	LEP limit	CLIC expectation
$\Lambda_{\pm}$ (QED cut-off) Electron radius	364 GeV 4.6×10^{-17} cm	6-6.5 TeV $(3 - 3.5) \times 10^{-18}$ cm
Λ' (contact interactions)	831 GeV	18-20 TeV
M_s (extra dimensions)	933 GeV	15-17 TeV
M_{e^*} (excited electron)	248 GeV	4.5-5.0 TeV

$\gamma\gamma \rightarrow$ WW at 3000 GeV

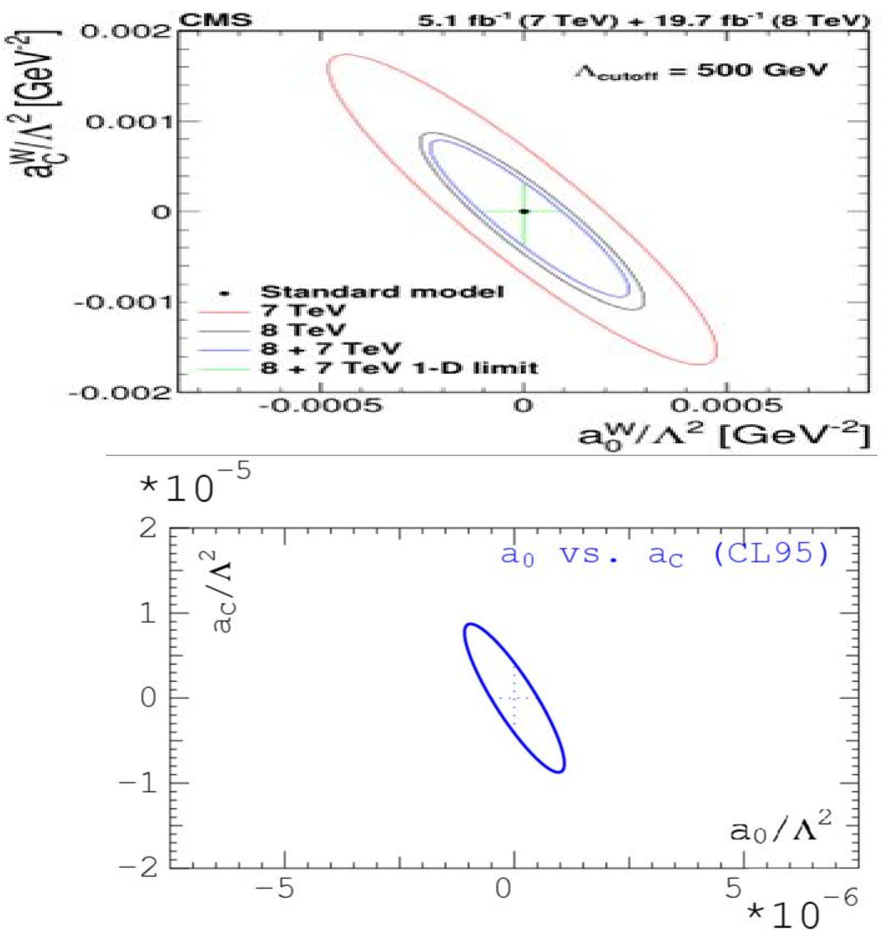
- At CLIC energies, most WW pairs are produced in collisions of $\gamma\gamma$ rather than e^+e^-
- Our generator-level study show that even with simplest eμ final state $\approx 10^4$ events can be selected with 10% background level





Quartic WWγγ coupling

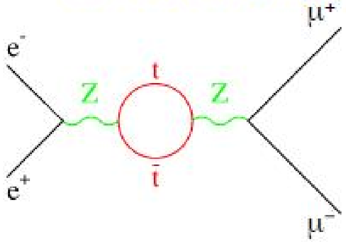
- SM includes quartic couplings WWWW, WWZZ, WWγγ and WWZγ couplings
- Anomalous WWγγ was searched at LEP (new physics excluded up to few GeV) and at LHC (100-200 GeV)
- Our generator-level study shows that CLIC can improve LHC limit by an order of magnitude

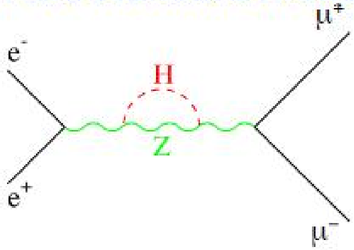


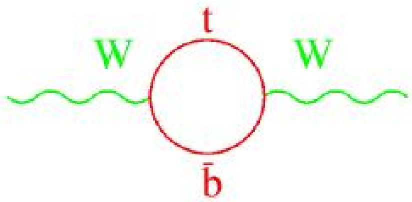
Precision means discovery!

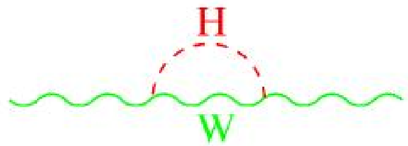
Electroweak observables are sensitive to heavy particles in "loops"

- For example, in the standard model: $\Gamma(Z \to \mu^+\mu^-)$ or m_W









$$\Gamma_{ll} = \frac{G_F}{\sqrt{2}} \frac{m_Z^3}{24\pi} \left(1 + \left[\frac{1}{4} - \sin^2 \theta_W^{eff} \right]^2 \right) \times (1 + \Delta\rho)$$

$$m_W^2 = \frac{\pi \alpha_{QED}(m_Z^2)}{\sqrt{2} G_F \sin^2 \theta_W^{eff}} \times \frac{1}{1 - \Delta r}$$

$$\boxed{\Delta\rho = \frac{\alpha}{\pi} \frac{m_t^2}{m_Z^2} - \frac{\alpha}{4\pi} \mathrm{Log} \frac{m_H^2}{m_Z^2} + \cdots \approx 1\%}$$

$$\boxed{\Delta r = -\frac{\cos^2 \vartheta_W}{\sin^2 \vartheta_W} \Delta\rho + \frac{\alpha}{3\pi} \left[\frac{1}{2} - \frac{1}{3} \frac{\sin^2 \vartheta_W}{1 - \tan^2 \vartheta_W} \right] \mathrm{Log} \frac{m_H^2}{m_Z^2} + \cdots \approx 1\%}$$

- With precise measurements of the Z mass, Z width, and Weinberg angle [+ $\alpha_{QED}(m_Z)$]
  - LEP was able to predict m_{top} and m_W (with uncertainty for unknown m_H)
- With the discovery of the top (Tevatron) at the right mass
  - LEP was able to predict m_H

Precision of theory

- At the next-generation ee colliders the experimental precision will be improved by 1-2 orders of magnitude
- The measurements must be confronted to theoretical calculations
- Corresponding improvement of calculations is an absolute necessity

- After LEP

$$M_W = 80.3593 \pm 0.0056_{m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm 0.0040_{\rm theo}$$

$$\sin^2\theta^{\ell}_{\rm eff} = 0.231496 \pm 0.000030_{m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\rm had}} \pm 0.000010_{\alpha_S} \pm 0.000002_{M_H} \pm 0.000047_{\rm theo}$$

Precision of theory

- At the next-generation ee colliders the experimental precision will be improved by 1-2 orders of magnitude
- The measurements must be confronted to theoretical calculations
- Corresponding improvement of calculations is an absolute necessity

◆ After FCC-ee

$$M_W = 80.3593 \pm 0.0002_{m_t} \pm 0.0001_{M_Z} \pm 0.0004_{\Delta\alpha_{\rm had}}$$

0.0005

$$\pm 0.0001_{\alpha_S} \pm 0.0000_{M_H} \pm 0.0040_{\rm theo}$$

$$\sin^2\theta^{\ell}_{\rm eff} = 0.231496 \pm 0.0000015_{m_t} \pm 0.000001_{M_Z} \pm 0.000006_{\Delta\alpha_{\rm had}}$$

0.000006

$$\pm 0.0000014_{\alpha_S} \pm 0.000000_{M_H} \pm 0.000047_{\rm theo}$$

Beam polarization

Consider s-channel processes (ee→ff)

		e^-	e^+	Contibution due to polarization
$J_Z = 0$	σ_{RR}	$\Rightarrow$	$\Leftarrow$	$\frac{1+P_{e^-}}{2}\frac{1+P_{e^+}}{2}$
	σ_{LL}	$\Leftarrow$	$\Rightarrow$	$\frac{1-P_{e^-}}{2}\frac{1-P_{e^+}}{2}$
$J_Z = 1$	σ_{RL}	$\Rightarrow$	$\Rightarrow$	$\frac{1+P_{e^-}}{2}\frac{1-P_{e^+}}{2}$
	σ_{LR}	$\Leftarrow$	$\Leftarrow$	$\frac{1-P_{e^-}}{2}\frac{1+P_{e^+}}{2}$

P_{e-} = -1:
100% left-polarized e-
P_{e+} = -1:
100% right-polarized e+

$$\sigma_{ij}^{meas} = \sigma_0 (1 - P_{e-} P_{e+})(1 + A_{LR} P_{eff})$$

$$P_{eff} = \frac{P_{e-} - P_{e+}}{1 - P_{e-} P_{e+}}$$

σ_0 - unpolarized cross section

Most sensitive to weak mixing angle: A_{LR}

$$A_{LR} = \frac{A_{LR}^{meas}}{P} = A_e = \frac{2 v_e a_e}{v_e^2 + a_e^2}$$

(independent of the final state)

$$\frac{v_e}{a_e} = 1\text{-}4 \sin^2 \theta_{eff}^{lept}$$

Importance of polarization

- Luminosity of SLC was 1/50 of LEP1. Still, SLC measured some EW observables (A_{LR}, $\sin^2$) with precision similar to LEP, thanks to polarized beams
- CLIC and ILC are designed with 80% beam polarization. Much more difficult at circular machines
- Theoretical calculations must take into account beam polarization

Full threatment of polarization

$$
\begin{aligned}
|\mathcal{M}|^2 = &\frac{1}{4}\Big\{(1-P^{||}_{e-})(1+P^{||}_{e+})|\mathcal{H}_{-+}|^2 + (1+P^{||}_{e-})(1-P^{||}_{e+})|\mathcal{H}_{-+}|^2 \\
&+ (1-P^{||}_{e-})(1-P^{||}_{e+})|\mathcal{H}_{--}|^2 + (1+P^{||}_{e-})(1-P^{||}_{e+})|\mathcal{H}_{++}|^2 \\
&- 2P^{T}_{e-}P^{T}_{e+}\Big[\cos(\phi_- - \phi_+)\,\mathrm{Re}(\mathcal{H}_{++}\mathcal{H}^{*}_{--}) + \cos(\phi_- + \phi_+ - 2\phi)\,\mathrm{Re}(\mathcal{H}_{-+}\mathcal{H}^{*}_{+-}) \\
&+ \sin(\phi_- + \phi_+ - 2\phi)\,\mathrm{Im}(\mathcal{H}_{-+}\mathcal{H}^{*}_{+-}) + \sin(\phi_- - \phi_+)\,\mathrm{Im}(\mathcal{H}_{++}\mathcal{H}^{*}_{--})\Big] \\
&+ 2P^{T}_{e-}\Big[\cos(\phi_- - \phi)\Big((1-P^{||}_{e+})\,\mathrm{Re}(\mathcal{H}_{+-}\mathcal{H}^{*}_{--}) + (1+P^{||}_{e+})\,\mathrm{Re}(\mathcal{H}_{++}\mathcal{H}^{*}_{-+})\Big) \\
&+ \sin(\phi_- - \phi)\Big((1-P^{||}_{e+})\,\mathrm{Im}(\mathcal{H}_{+-}\mathcal{H}^{*}_{--}) + (1+P^{||}_{e+})\,\mathrm{Im}(\mathcal{H}_{++}\mathcal{H}^{*}_{-+})\Big)\Big] \\
&- 2P^{T}_{e+}\Big[\cos(\phi_+ - \phi)\Big((1-P^{||}_{e-})\,\mathrm{Re}(\mathcal{H}_{-+}\mathcal{H}^{*}_{--}) + (1+P^{||}_{e-})\,\mathrm{Re}(\mathcal{H}_{++}\mathcal{H}^{*}_{+-})\Big) \\
&- \sin(\phi_+ - \phi)\Big((1-P^{||}_{e-})\,\mathrm{Im}(\mathcal{H}_{-+}\mathcal{H}^{*}_{--}) + (1+P^{||}_{e-})\,\mathrm{Im}(\mathcal{H}_{++}\mathcal{H}^{*}_{+-})\Big)\Big]\Big\},
\end{aligned}
$$

where $\mathcal{H}_{++}$, $\mathcal{H}_{--}$,$\mathcal{H}_{+-}$,$\mathcal{H}_{-+}$ — helicity amplitudes.

G. Moortgat-Pick et al. Phys. Rept. 460 (2008) 131–243

MC generator with polarization

- Currently there is no MC generator with polarization at complete 1-loop level
- Our group plans to create a generator with polarization for the most important e^+e^- processes at complete 1-loop EW level, with leading EW contributions up to 3 loops and leading QCD contributions up to 4 loops
- For Bhabha this work is already at a rather advanced stage

$$\sigma^{\text{1-loop}} = \sigma^{\text{Born}} + \sigma^{\text{virt}}(\lambda) + \sigma^{\text{soft}}(\lambda, \omega) + \sigma^{\text{hard}}(\omega)$$

Summary

- It is widely believed that the next big machine will be an e^+e^- collider
- It will deliver a wonderful physics and improve the LHC precision by 1-2 orders of magnitude
- There are 4 mature collider project: CEPC, FCC, ILC, CLIC.
- JINR experimentalists are participating in CLIC
- JINR theoreticians are developing tools that will be necessary for any of those projects