Linear Colliders

the Higgs boson microscopes

Mila Pandurovic

Vinca Institute of Nuclear sciences
Belgrade, Serbia

University of Pavia

22. March 2018

Outline

- Introduction
- Standard model of particle physics
- Open questions
- Motivation for new machine in high energy physics
- The synergy of hadron and lepton colliders
- Linear Collider options: ILC and CLIC
- Accelerator design
- Detectors for ILC
- Physics program of linear colliders
- Summary

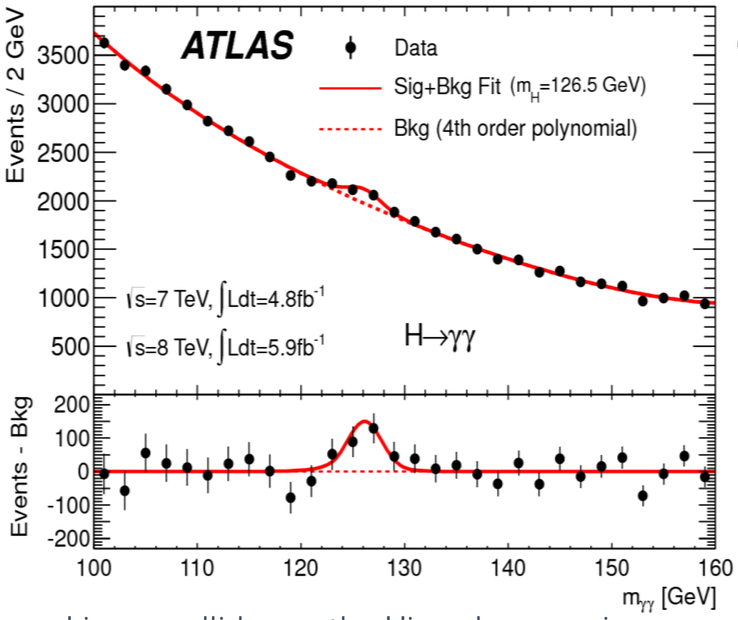
LHC discovery

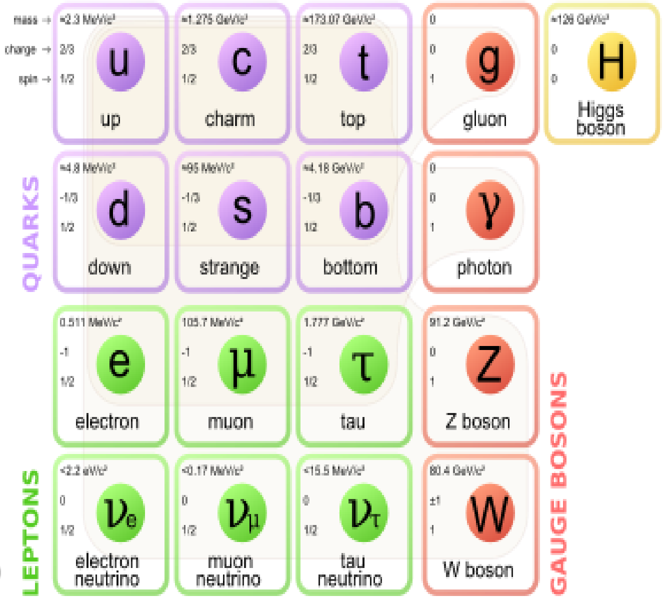
2013. Standard model has passed the exam again:

New resonance

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs

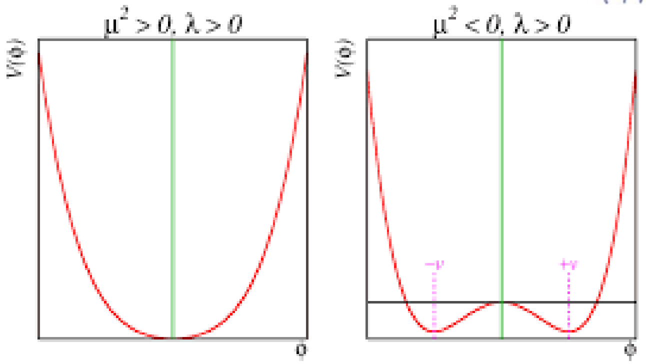
"For the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"





Interaction	Weak	Electromagnetic Electroweak	Strong
Particles which are "mediators"	$W^+, W^- Z^0$	γ (photon)	Gluon
No of "mediators"	3	1	8
Strength of the force	10^{-16}	10^{-3}	1

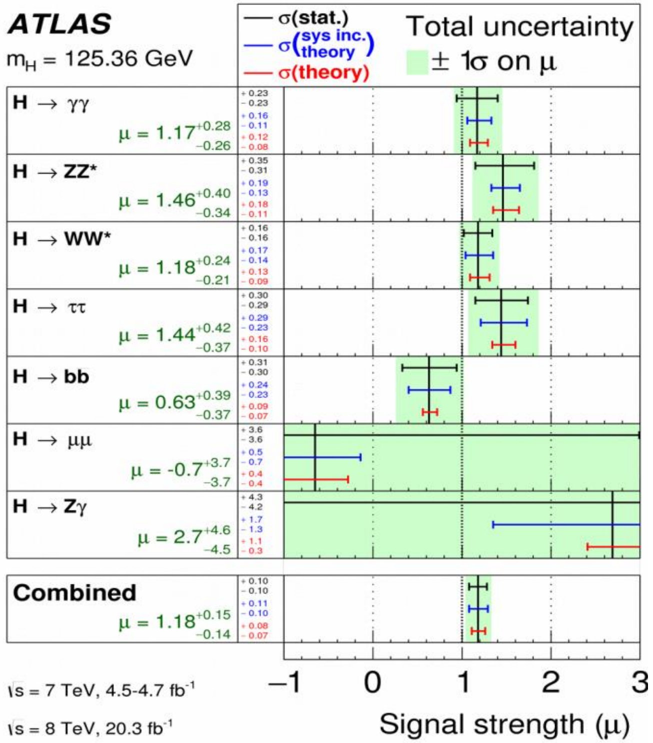
Open questions of particle physics

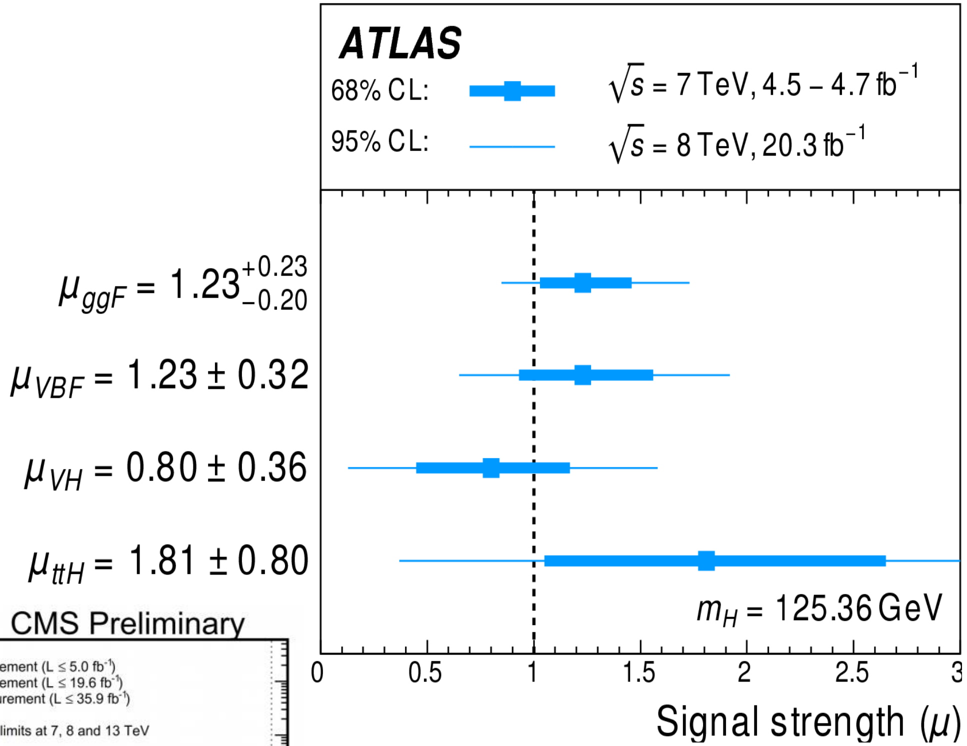


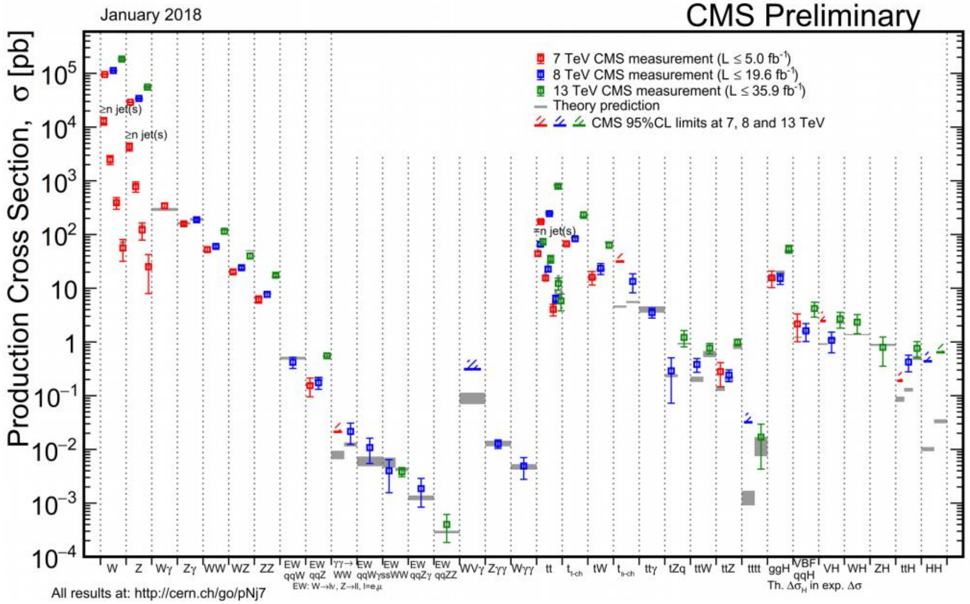
- Still there are many open questions that directly connected to the properties of the Higgs boson in relation to the new physics
  - The SM does not explain why was the symmetry broken!
  - Gravity is not included
    - Hierarchy Problem – why the gravity is 'so much weaker' then the other forces
  - At the high energy the Higgs boson mass becomes 'infinite' (the problem of "naturalness")
  - Matter/Anti-Matter asymmetry
  - Dark matter, ...

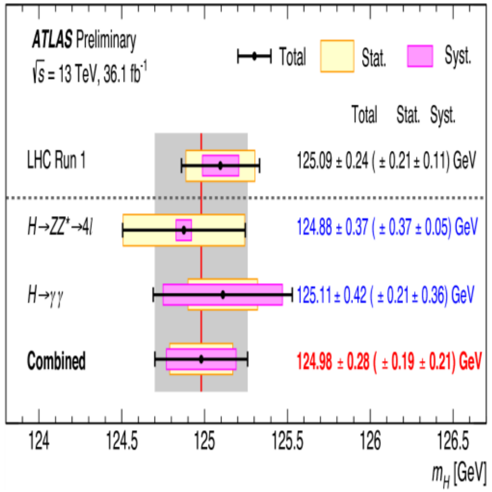
- In order to answer at least a part of these questions several paths of Physics Beyond Standard model has been developed
  - SuperSymetrical models (SUSY)
  - Models with Extra Dimensions
  - Composite Higgs models ...

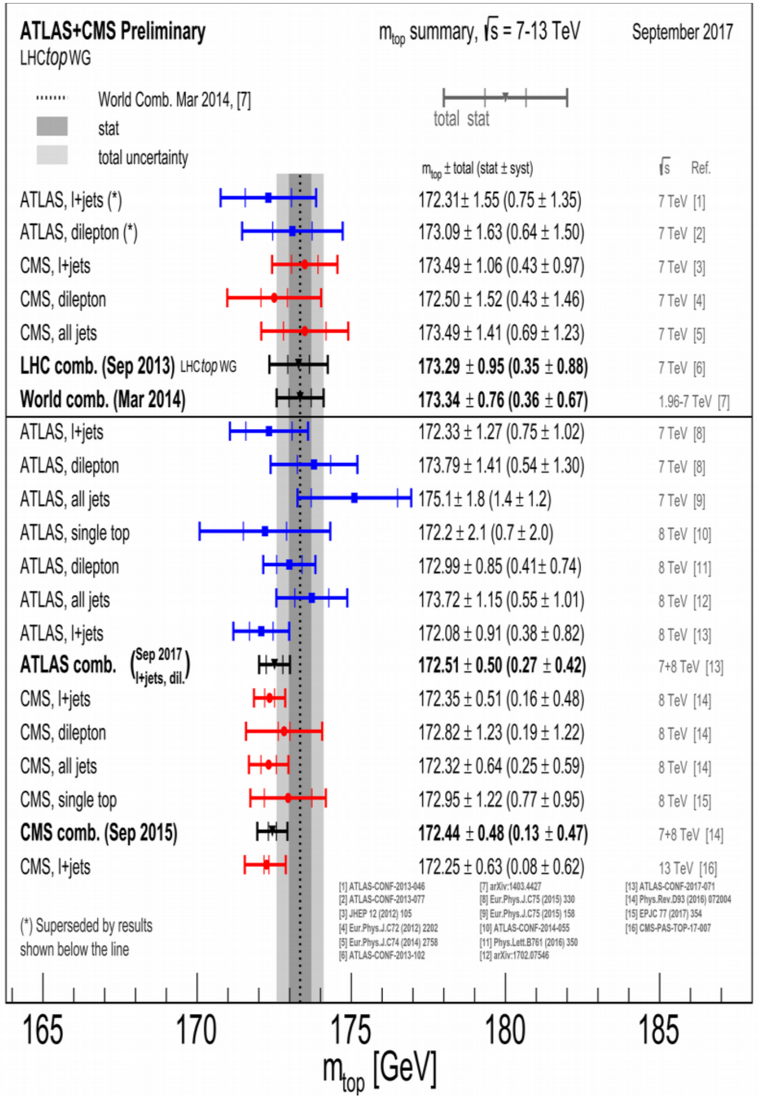
Success of LHC



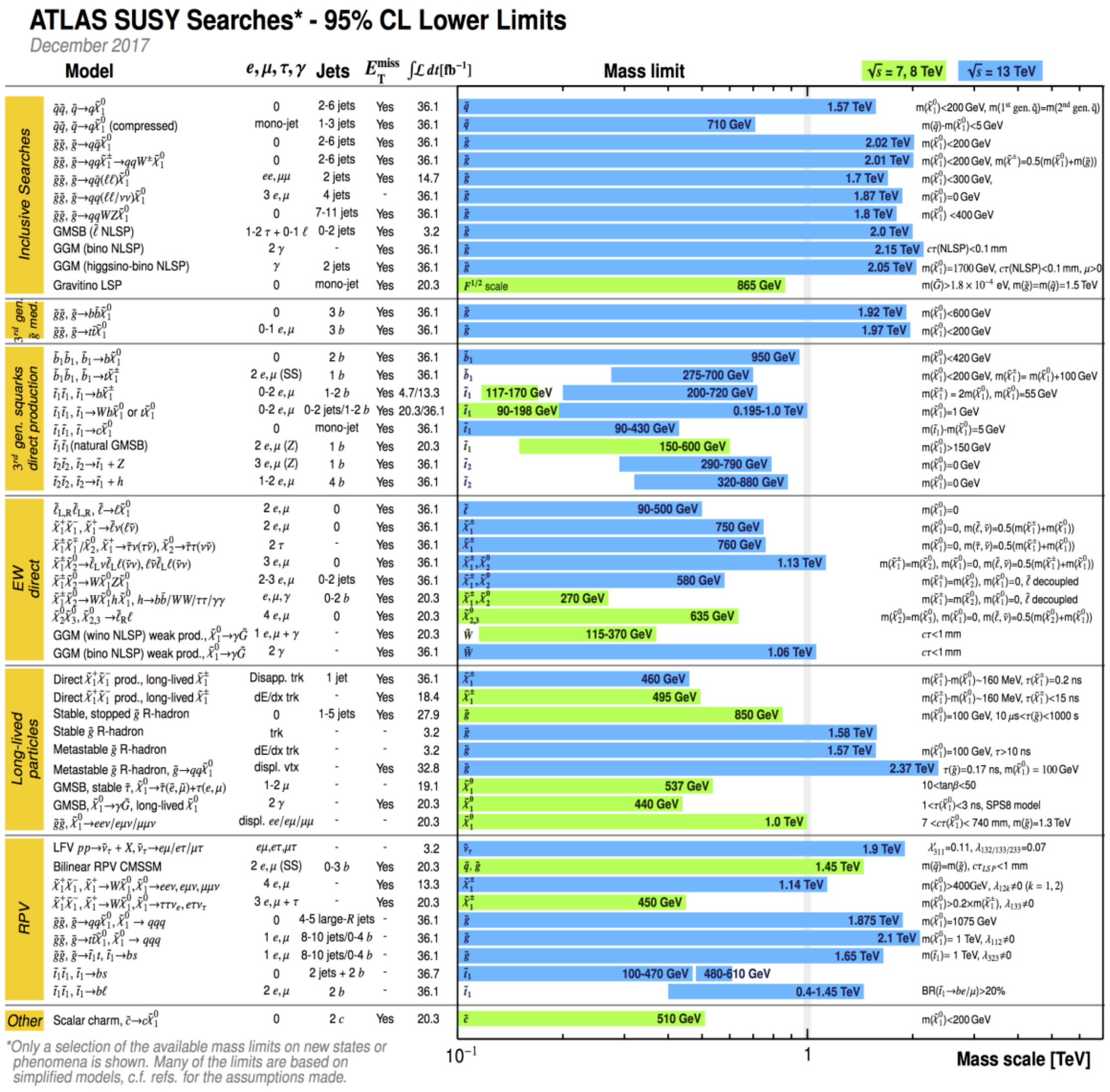


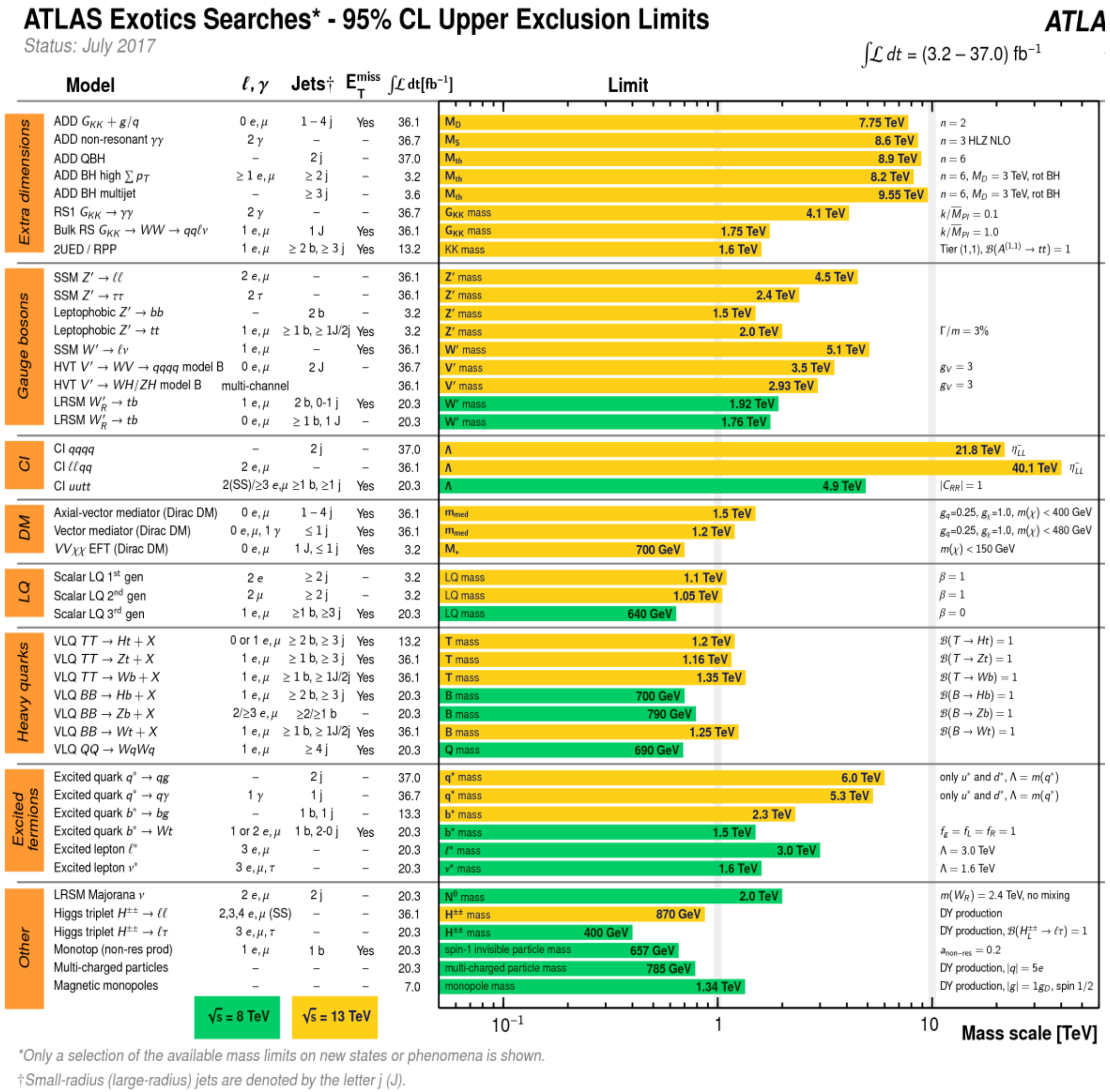






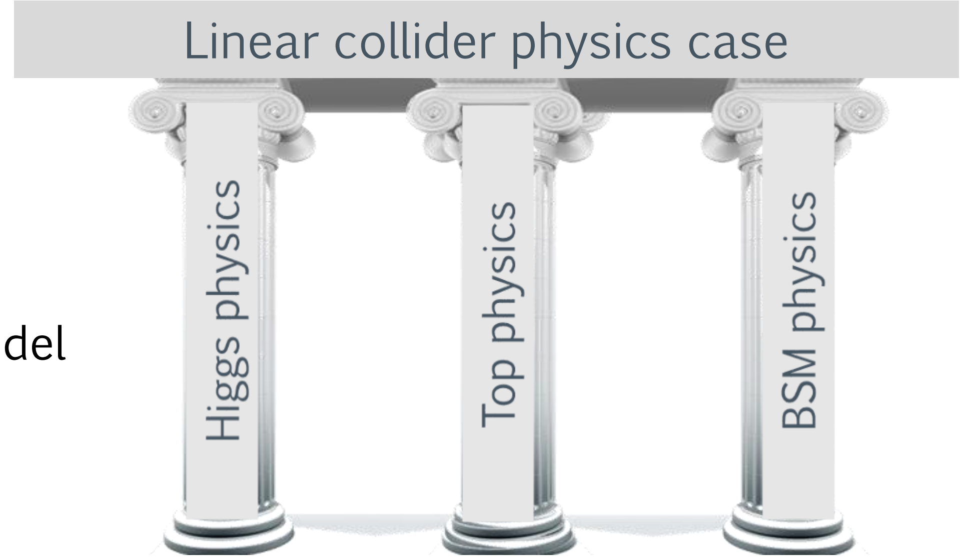
Standard model holds!





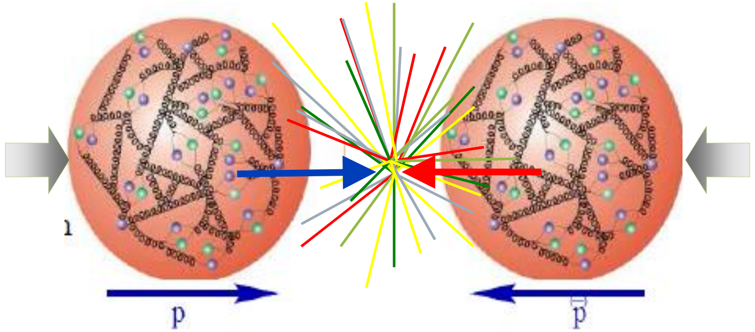
New machine in high energy physics

- What can we learn by studying Higgs bosons and top quarks in electron-positron collisions?
- Which precision measurements can hint to new physics at very high scales?
- Do lepton colliders have the potential to make direct observations if the LHC has found nothing so far?
- Higgs physics
  - Higgs couplings
  - Higgs mass
  - Total Higgs decay width
  - CP properties
- Top precision physics
  - Top couplings
  - Top mass
- The search for New Physics beyond the Standard Model
  - Extended gauge theories
  - Theories with extra dimensions
  - SUSY …

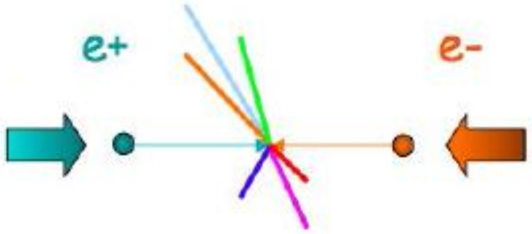


Complementarity of hadron and lepton colliders

DISCOVERY



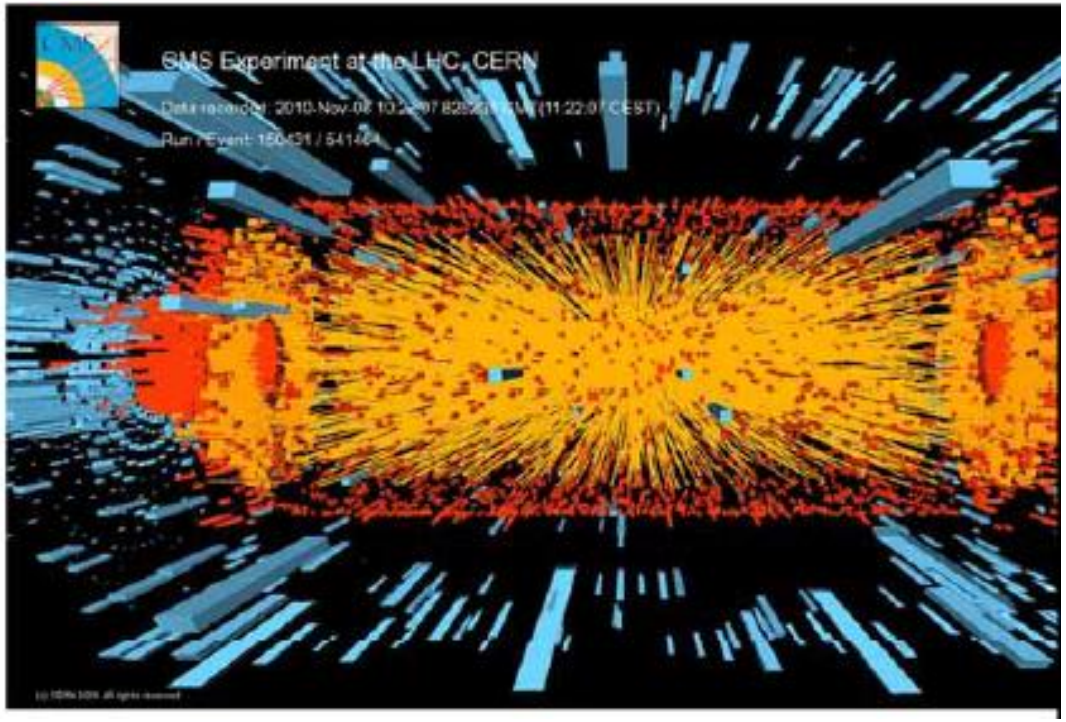
HIGH PRECISION



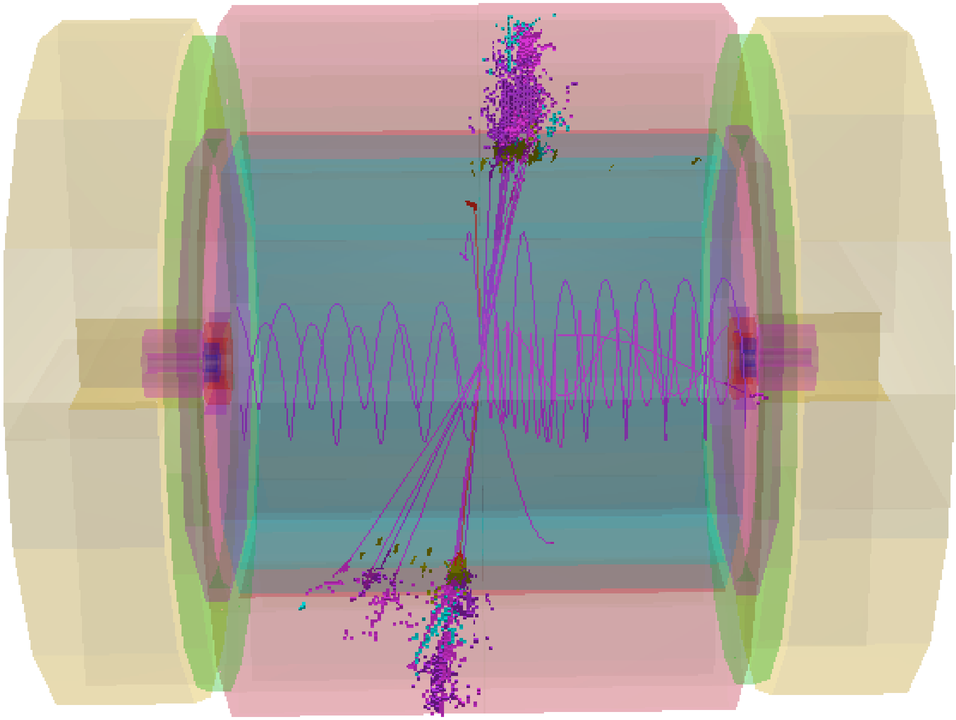
HADRON COLLIDERS	LEPTON COLLIDERS
Initial state not known event by event	Initial state precisely known
Partons carry a fraction of energy	Full energy available for the collision
High QCD background	Clean experimental conditions
Multilevel trigger schemes	Triggerless readout
High cross section for colored states	Superior sensitivity for electro-weak states
/	Possibility of beam polarization

Event display

Large Hadron Collider

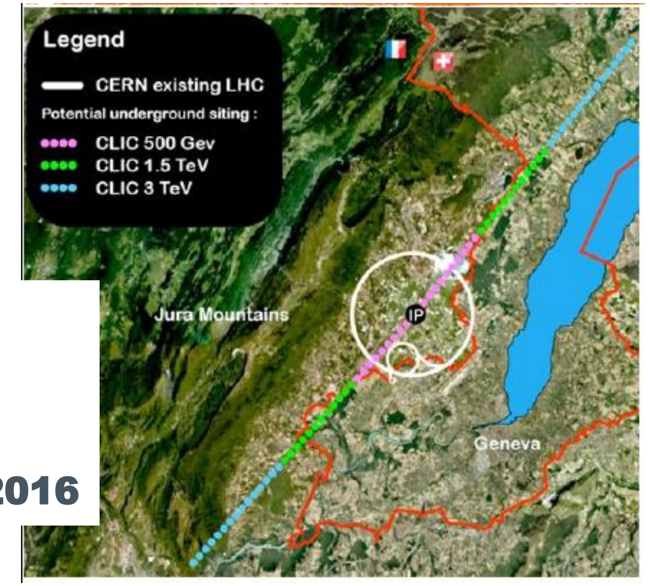


Linear colliders



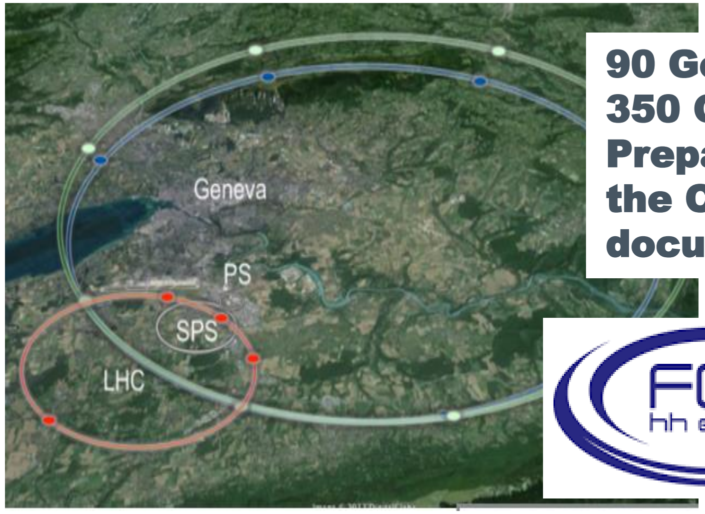
Current options of electron-positron colliders

250 GeV
500 GeV
1 TeV
TDR 2013



380 GeV
1.5 GeV
3 TeV
CDR 2012
Updated baseline 2016

250 GeV
Z pole, WW
1 TeV
preCDR published
Full CDR mid 2018



90 GeV
350 GeV
Preparation of the CDR document 2018

Energy and luminosity

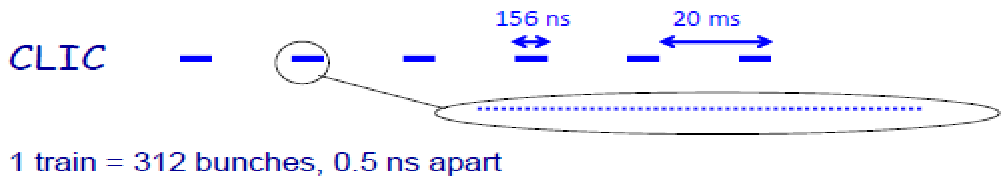
- Most important parameters of the collider:
  - Energy Luminosity
- Luminosity is the 'capability of the collider to produce collisions'

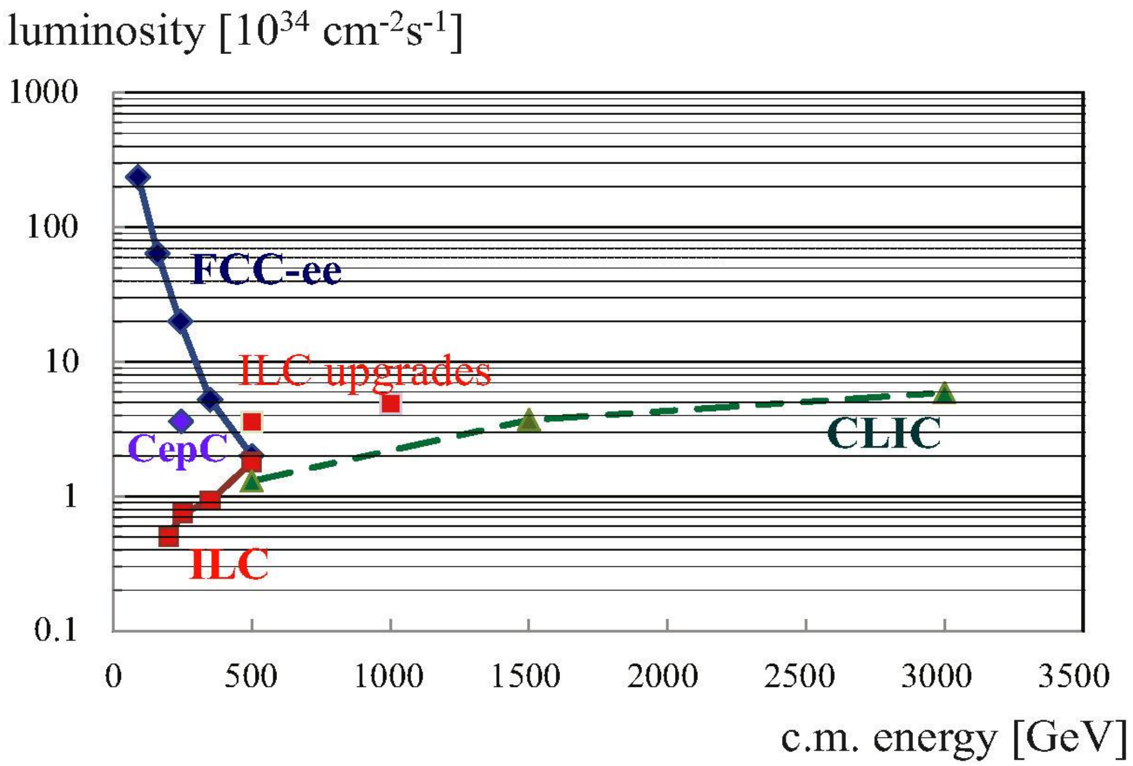
$$N = \mathcal{L} \cdot \sigma_{process}$$

- At linear colliders the increase in luminosity is achieved by beam focusing to nanometer sizes!

$$\mathcal{L} = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x\sigma_y}$$

- At circular collider luminosity is increased by longer beam circulation

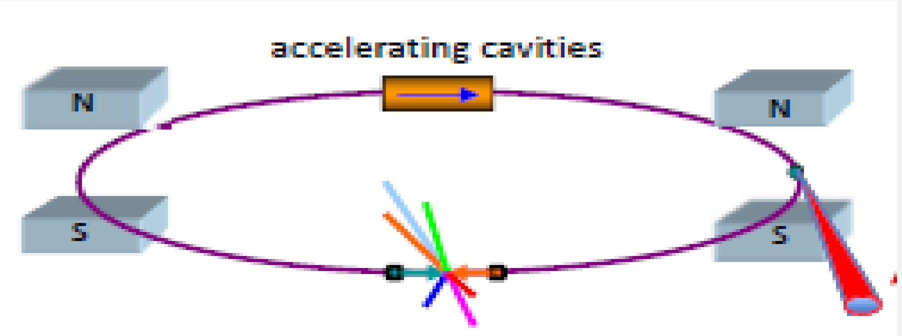




Parameters		units	ILC(RDR)	CLIC(3 TeV)
Repetition rate	F_{rep}	Hz	5	50
Number of particles in a bunch	N	10^9	20	3.7
Number of bunches / train	N_b		2625	312
Bunch spacing	T_b	ns	360	0.5

Electron-positron colliders

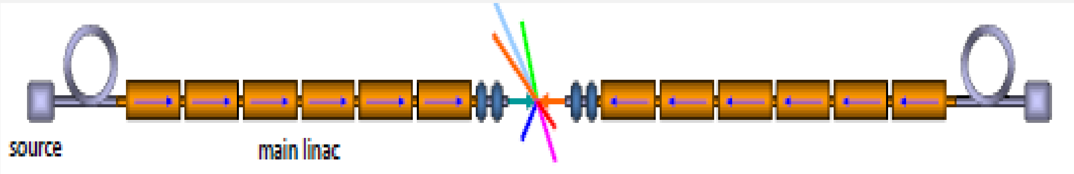
Circular



- Beam circulates a long time
- Smaller number of accelerating cavities
- Many bending magnets
- Radiation losses due to circulation

$$\Delta E_{sync} \approx \frac{E^4}{m^4 R}$$

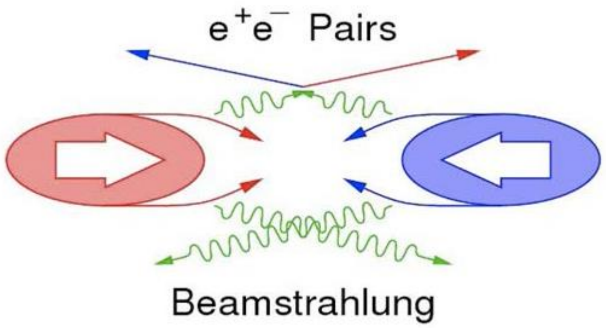
Linear Collider

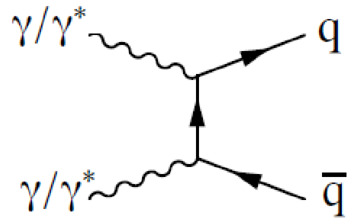


- Small number of magnets
- Many accelerating cavities
- Beam passes only once!
- High energy high accelerating gradient
- Small beam sizes - beamstrahlung

Energy losses of the beam

- At linear colliders the beams are separated in bunches of nm size
- Very dense bunches imply high electric field inside a bunch
- The field is influencing the particles in the opposite bunch, causing them to emit the radiation called beamstrahlung
- Converted e^+e^- pairs – high doses deposited in the forward detectors
- $\gamma\gamma$ to hadrons – influences event reconstruction
- Beamstrahlung radiation leads to important energy loses

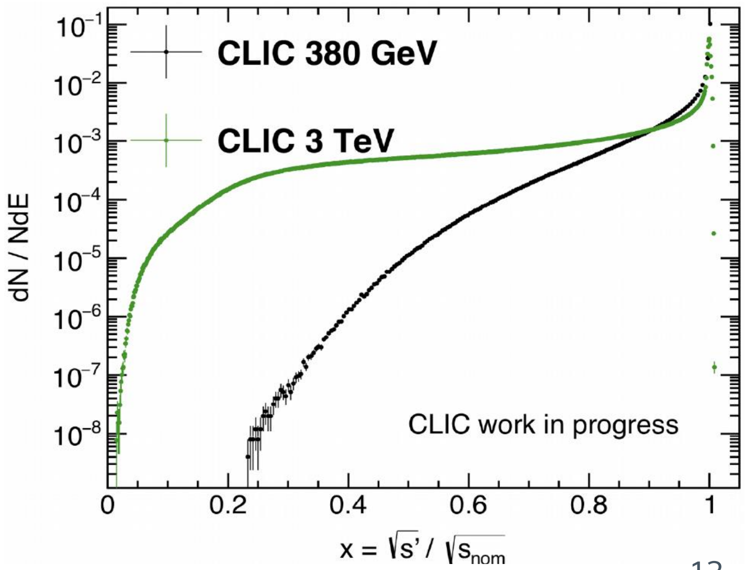




TRADEOFF: $\delta E = \frac{N^2}{(\sigma_x+\sigma_y)\sigma_z}$ vs luminosity $\mathcal{L} = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x\sigma_y}$

$\Rightarrow$ FLAT BEAMS

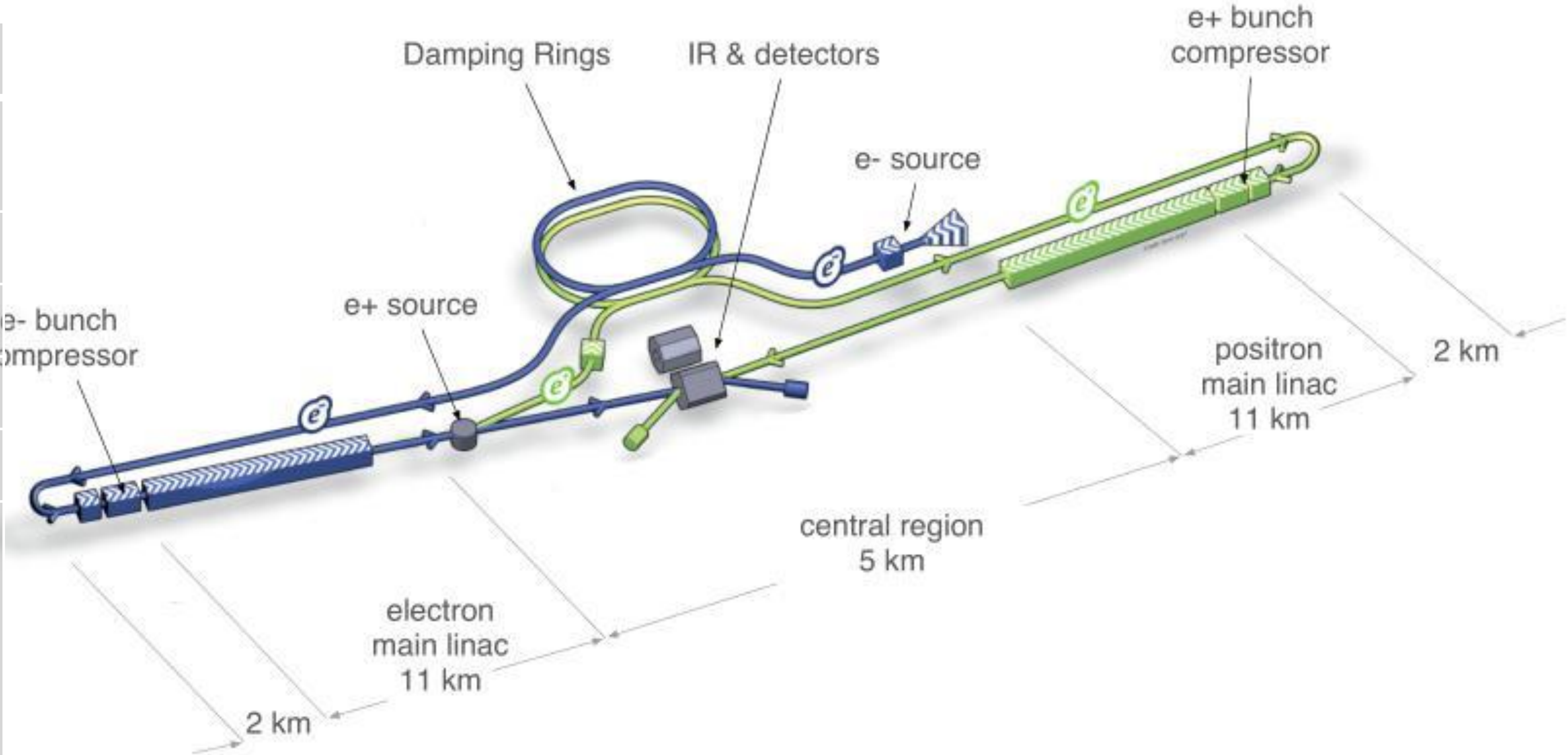
Beam sizes at IP	ILC 500 GeV [nm]	CLIC 3 TEV [nm]
σ_x	474	45
σ_y	5.9	1



ILC

- International Linear Collider (ILC) is one the most advanced concept for a future energy frontier e^+e^- collider

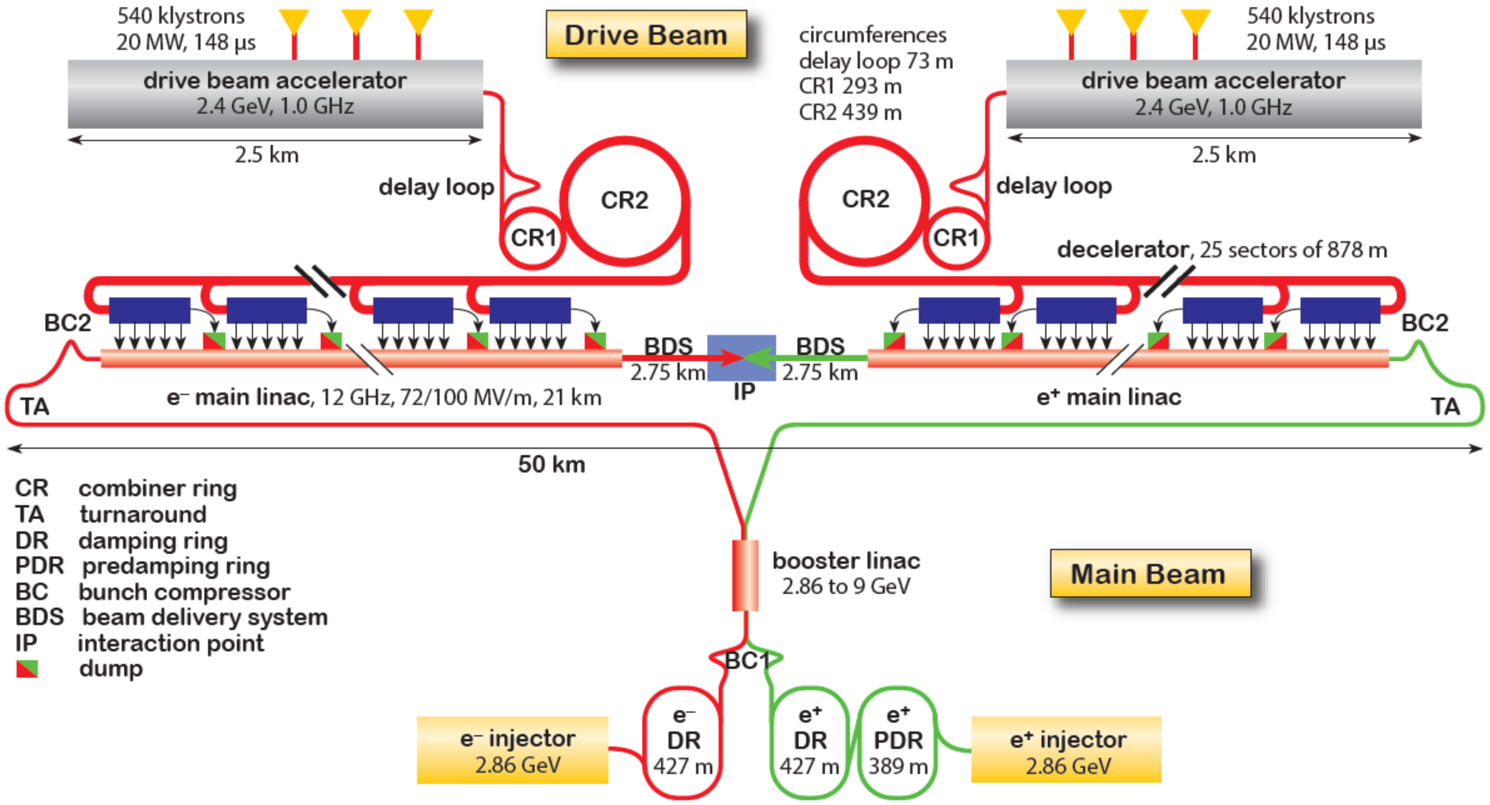
ILC
Superconducting RF cavities
'cold' machine
32 MV/m
31 km
2.0×10^{-34}
Higgs factory 250 GeV 500 GeV case upgradable to 1 TeV (considering staged approach)



CLIC

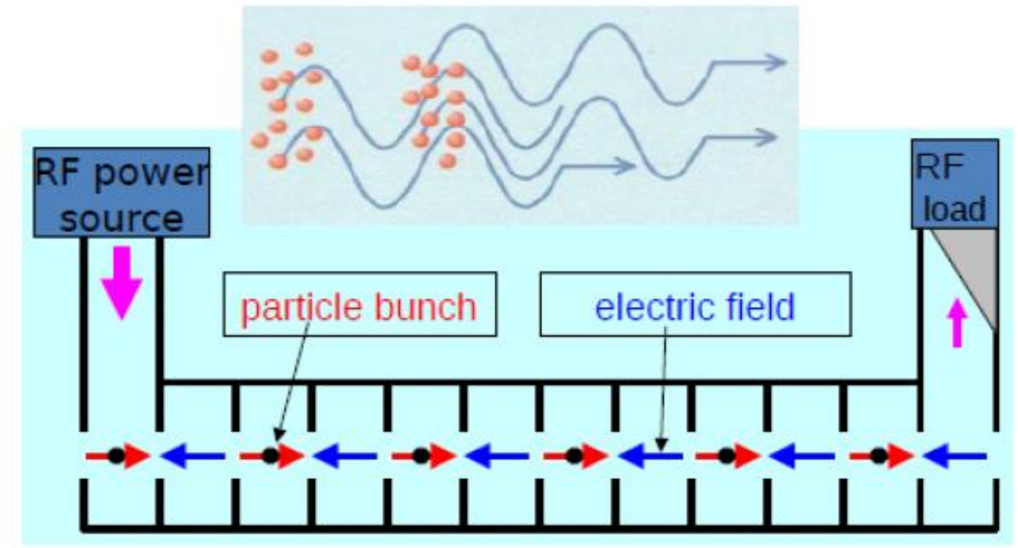
- Staged machine with three center-of-mass energies: 350/380 GeV, 1.5 TeV, 3.0 TeV
- The operating energy can be adapted to possible LHC discoveries at 13/14 TeV

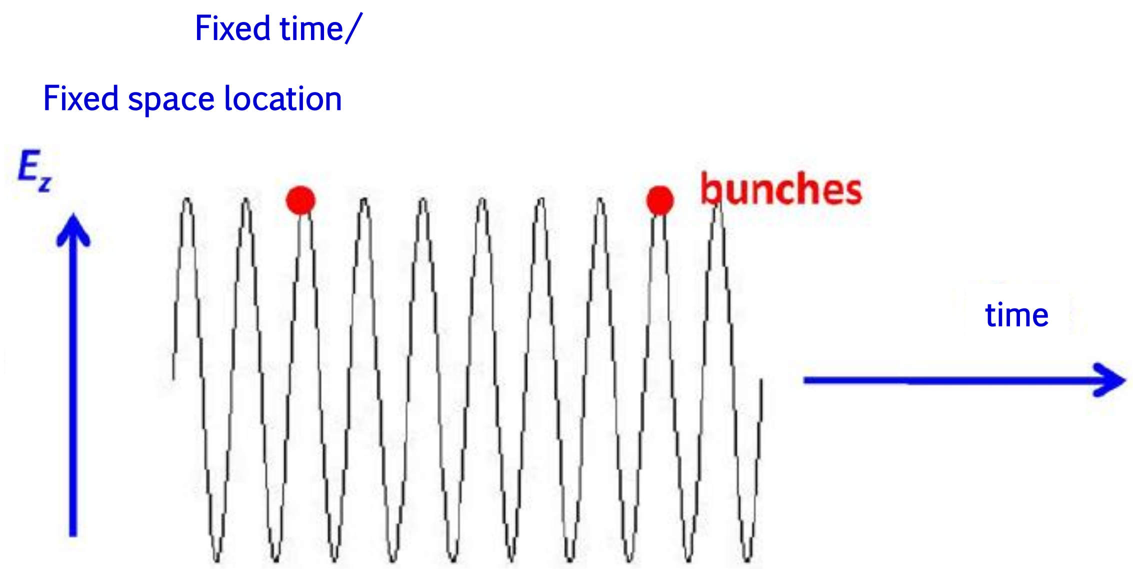
CLIC
Two-beam acceleration scheme
Operating at room temperature
100 MV/m
51.1 km
1.5 - 5.9 x 10^{-34}
3 TeV
Staged construction and operation: 380 GeV 1.5 TeV 3.0 TeV



Principle of particle acceleration

- Both proposed future colliders, ILC and CLIC, use the use the radio-frequency (RF) acceleration principle





Accelerating structures

- The RF acceleration is the technology which could provide TeV range e+/e- collisions in the near future
- New types of

ILC "L-band" (1.3 GHz, or 20 cm)

superconducting cavity, standing wave (ILC)

average gradient 31.5MV/m

- CLIC
  - "X-band" (11-12 GHz, ~2.6 cm),
  - normal conducting cavity, traveling wave

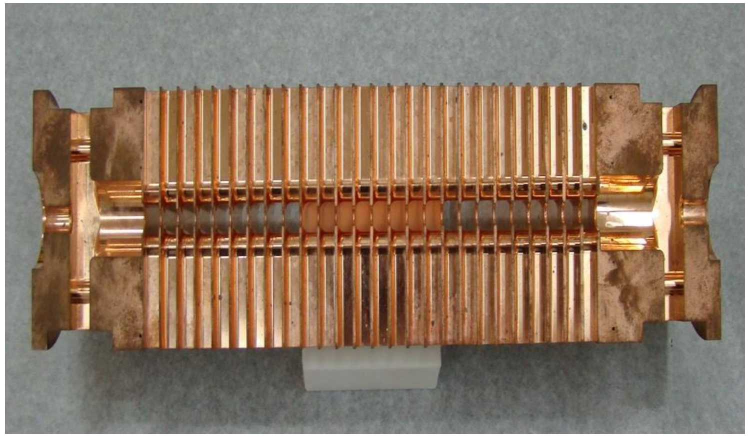
  Gradient 72/100MV/m

380GeV/3TeV accelerator

22/50 km length

20,600 /140000 modules

A 9-cell SCL-band structure



20-cell NC cavity

Power production for acceleration ILC

- The RF power electron linear accelerators is provided by 10MW multi-beam klystrons (MBK)
- Two alternative methods of transporting the RF microwave power to the accelerating structures are considered
- The first is a Distributed Klystron Scheme (DKS)
  - each klystron drives 39 cavities
  - the klystrons and modulators are distributed along the entire length of the SCRF linear accelerators (linacs), in the same tunnel

The second is a novel Klystron Cluster Scheme (KCS)

  - All the klystrons are located in ‘clusters’ in surface buildings located periodically along the linacs

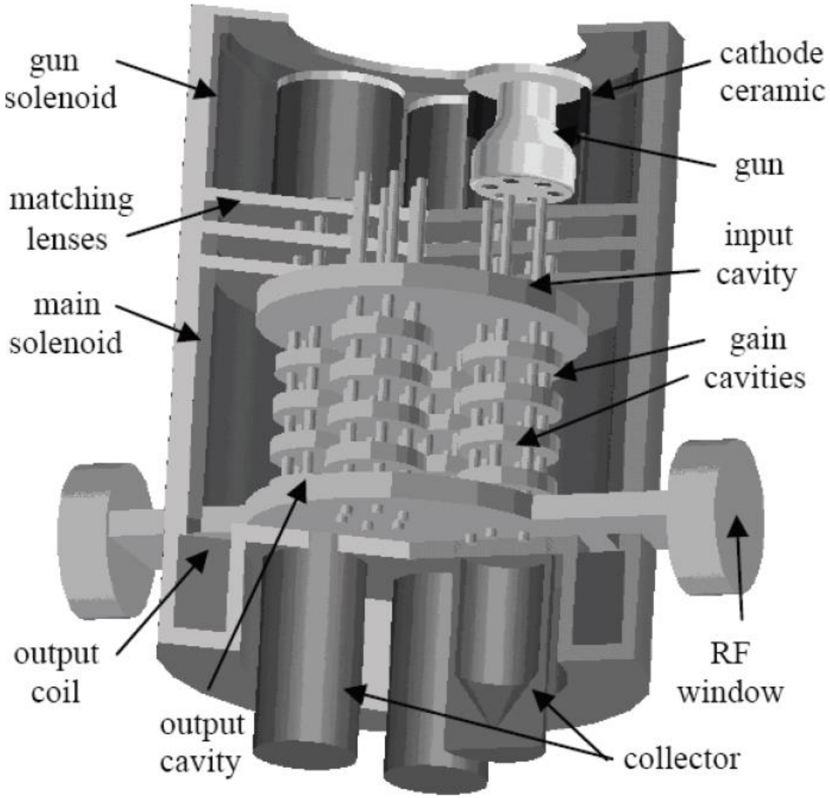


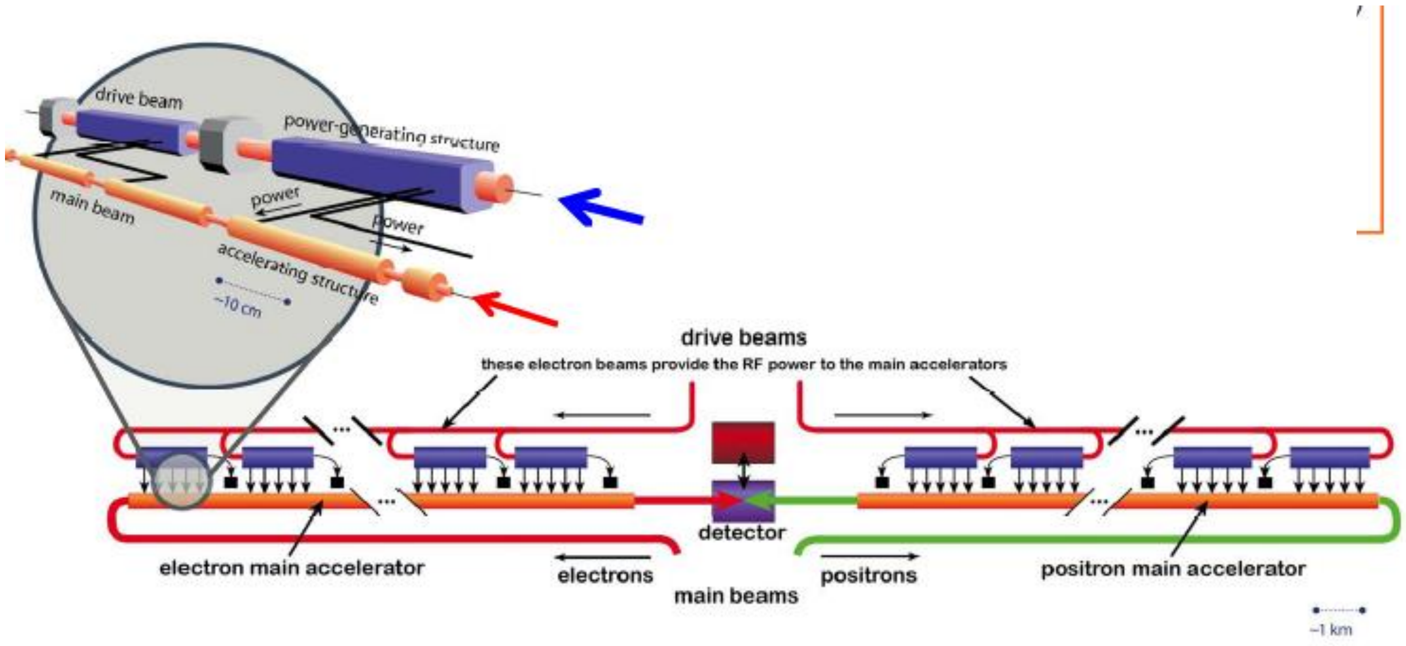
Figure 1: Layout of ILC MBK.

Power production for acceleration CLIC

- New acceleration scheme: Two beam technique

- Drive beam supplies RF power
  - 12 GHz bunch structure
  - High current 100A
  - Low energy 2.4 GeV to 240 MeV

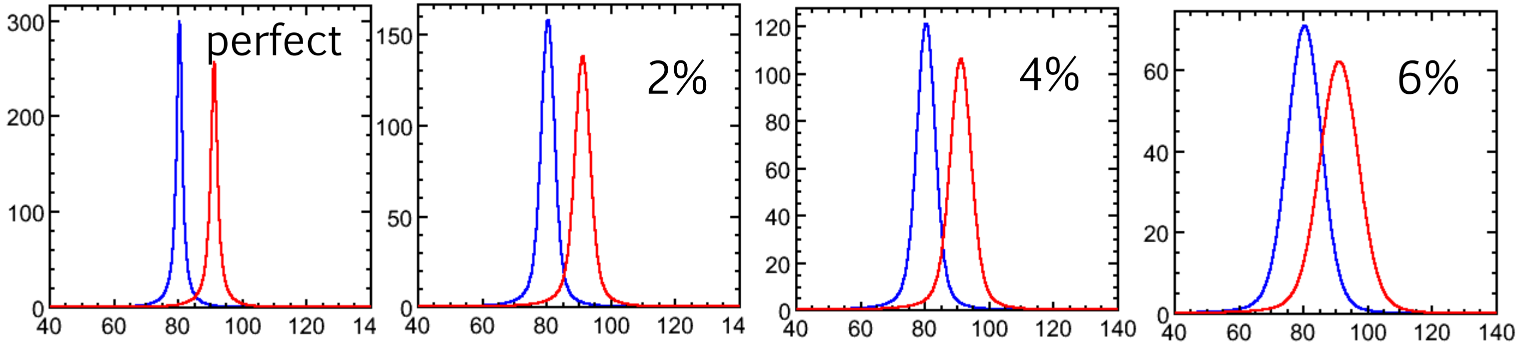
- Main beam for physics
  - Lower current 1.2A
  - High energy 9 GeV to 1.5TeV



- **CLIC will be operating at high gradient level (100 MV/m) at the highest energy stage of 3 TeV**
- Two beam technique demonstrated at CERN, CLIC CTF3 test facility

Detector requirements: jet energy resolution

- Certain physics processes of interest are setting the necessary precision goal of the measurement that has to be achieved in specific subdetectors
- Very high technical challenges!
- Jet energy resolution: Calorimeters
- measurement: separation of W and Z bosons, multijet final states $HZ \rightarrow q\bar{q}q\bar{q}q\bar{q}$
- Gauge boson widths set the natural limit for minimum jet energy resolution
- $m_Z = 91.2$ GeV $\Gamma_Z \sim 2.5$ GeV $\mathrm{m_W} = 80.4$ GeV $\Gamma_W = 2.1$ GeV

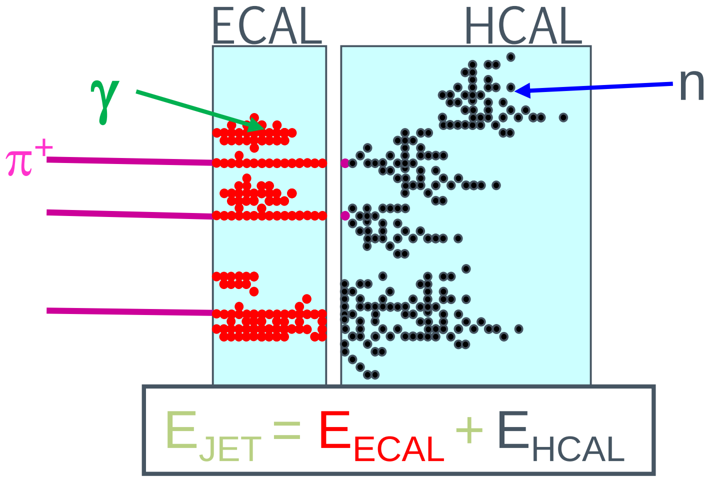


$\sigma_E/E \sim \frac{30\,\%}{\sqrt{E}}$, E<100 GeV and 3.5 - 4.0 % E>100GeV

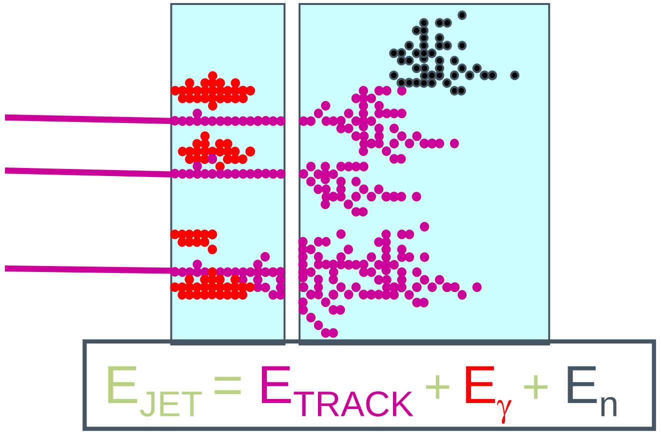
Particle flow algorithm

- Jet composition: 60 % charged hadrons 30 % photons 10 % neutral hadrons

- CLASICAL CALORIMETRY
  - Jet energy measurement exclusively using electromagnetic and hadronic calorimeters
  - HCAL intrinsically has very low resolution $\sigma_{\mathrm{E}}/E \sim \frac{60\ \%}{\sqrt{E}}$
  - This resolution limits overall jet energy resolution



PARTICLE FLOW CALORIMETRY
  - Measure only neutral hadrons in HCAL
  - Photons in ECAL $\sigma_{\mathrm{E}}/E \sim \frac{20\ \%}{\sqrt{E}}$
  - Charged hadrons in the TRACKER



Detector requirements: momentum and impact parameter

- Momentum resolution: TRACKER
  measurement: Higgs mass measurements
  Higgs decay to muons

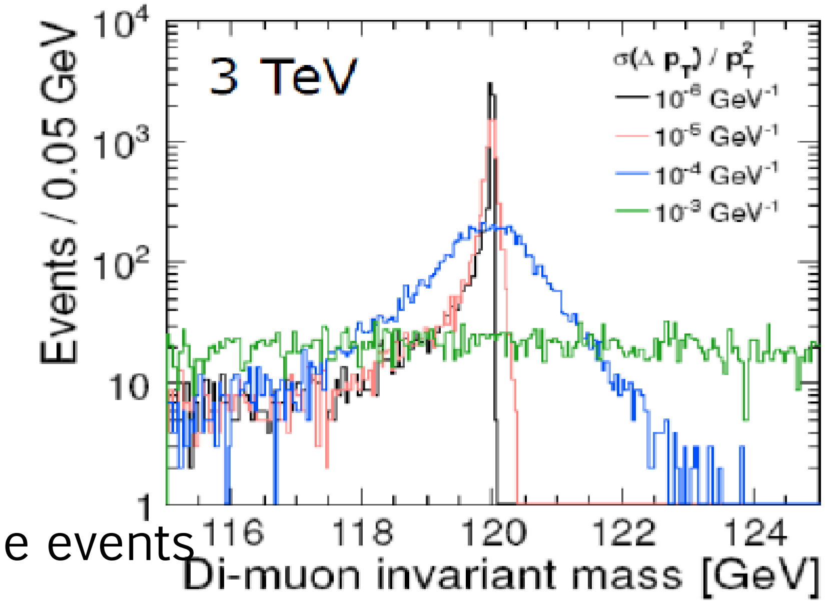
  $\sigma_{pt}/p^2_t \sim$ 2/5 x 10^{-5} GeV^{-1} CLIC/ILC

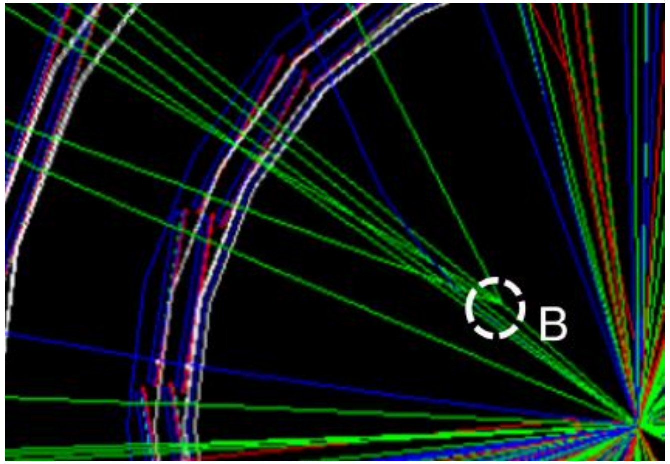
- Impact parameter resolution: VERTEX DETECTOR
  measurement: identifying beauty and charm heavy quarks in the events

  $\sigma_{r\varphi} \sim 5\ \mu m \oplus 10/(p\,[\mathrm{GeV}] \cdot \sin^{3/2}\theta)$

- Hermeticity: FORWARD REGION
  measurement: missing energy signatures

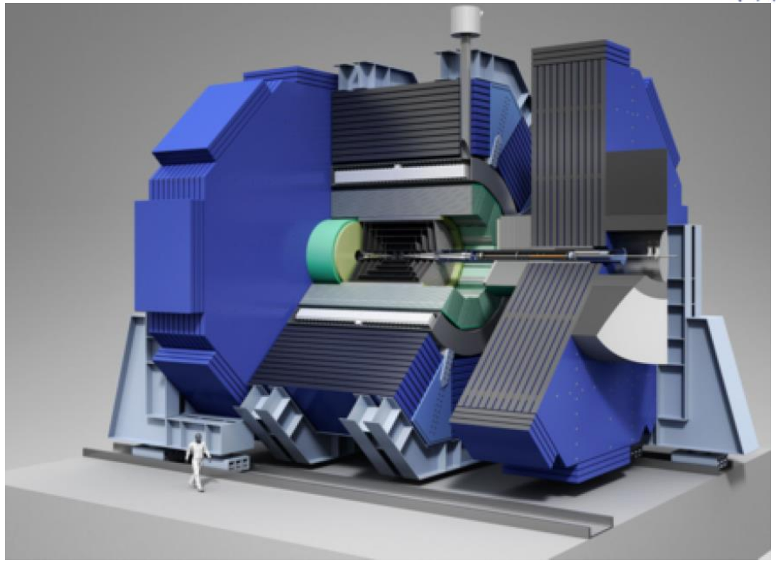
- ~ 5 - 10 mrad

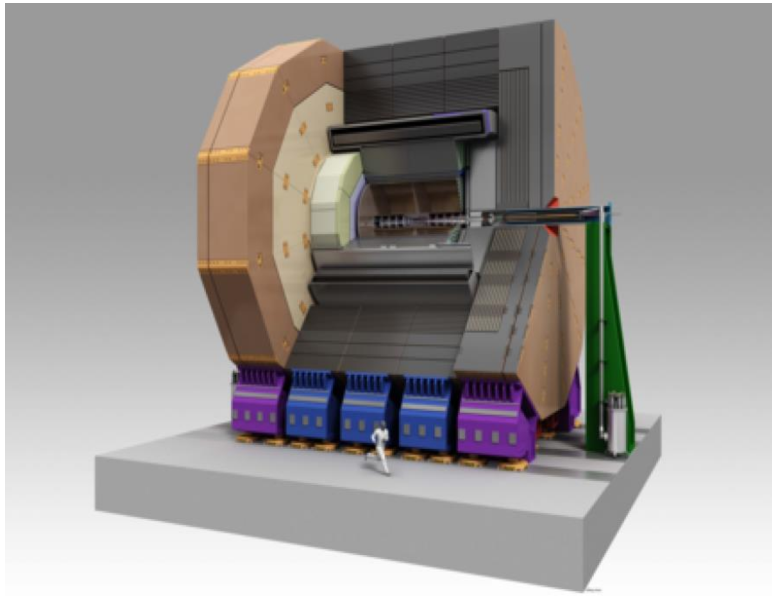




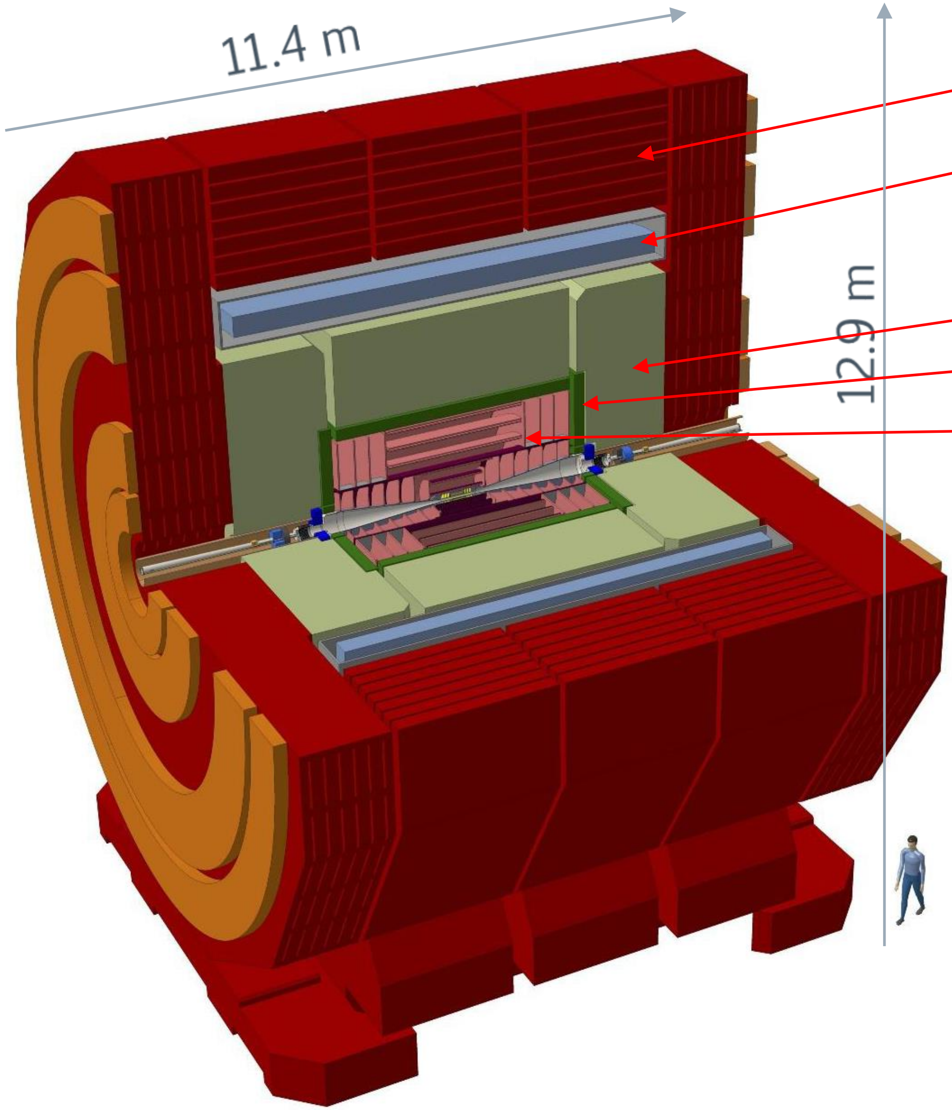
ILC detectors

- Two detector concepts for ILC: SiD & ILD
- Both designs optimized for particle flow calorimetry for the best jet energy reconstruction
- Push-pull operation
- Silicon Detector (SiD): B=5 T
  - vertex Si pixel ECAL Si/W
  - HCAL glassRPC/Fe Muon: Sc
  - tracking detector Si
- Cost-constrained detector with silicon tracking
- Time-stamping on single bunch crossings
- International Large Detector (ILD)
- Large detector optimized for good energy and momentum resolution
  - Tracking gaseous (TPC) for excellent pattern recognition an dE/dx capability
  - vertex Si pixel ECAL Si/W HCAL Sc or gaseous /Fe
  - Muon RPC or SC strips





New CLIC detector model



- Iron return yoke instrumented with muon detectors (RPC)
- 4 T superconducting solenoid magnet
- Fine grained calorimetry system
  - HCAL Sc/W , 60 layers, 7.5 λ_i
  - ECAL Si/W , 40 layers, 22 X_0
- Tracker – Si - 7μm single point resolution
- Vertex Si pixel

The optimized detector model after full detector simulation

- Cost optimization
- Physics performance of CLIC_ILD and CLIC_SiD very similar
- Background conditions are not favorable at 3 TeV for TPC

$\Rightarrow$ one detector, all silicon tracking

Physics program at lepton colliders

A full set of the full simulation studies have been performed at the ILC and CLIC

The result has proven that all of these measurements can be performed at the both proposed colliders, with the precision that is much higher then at Large Hadron Collider LHC

- Higgs factory
- 250 GeV 0.5 ab-1 :
- Standard model Higgs physics measurement
- 350 GeV **tt threshold scan ~** 200 fb^{-1}

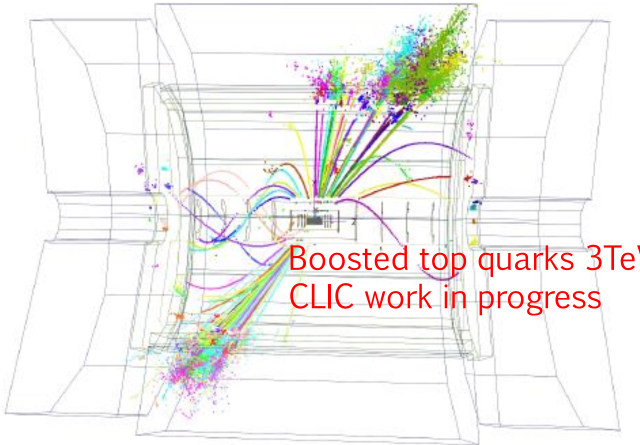
- 500 GeV 0.5 ab-1
- **Top-Yukawa coupling ttH , Higgs self coupling**
- Rare Higgs decays
- Top quark physics

- 1 TeV
- BSM physics
- Higgs self coupling
- Rare Higgs decays
- Top-Yukawa coupling

- **Three construction stages optimized for physics runs**
- 380 GeV 0.5 ab-1 :
- Standard model Higgs physics measurement
- Top physics
- **tt threshold scan ~350 GeV 100 fb^{-1}**

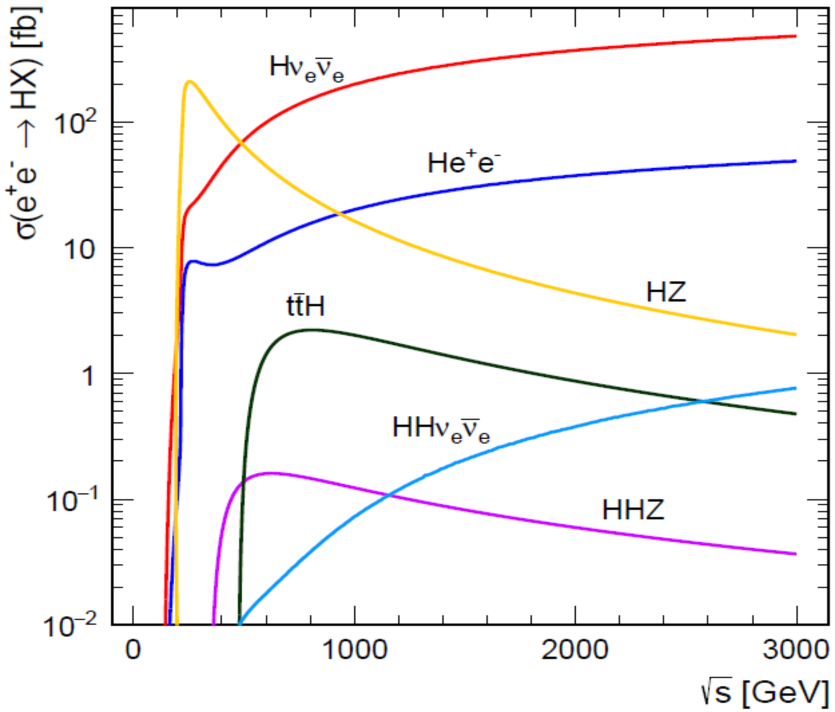
- 1.5 TeV 1.5 ab-1
- BSM physics
- **Top-Yukawa coupling ttH , Higgs self coupling**
- Rare Higgs decays
- Top quark physics

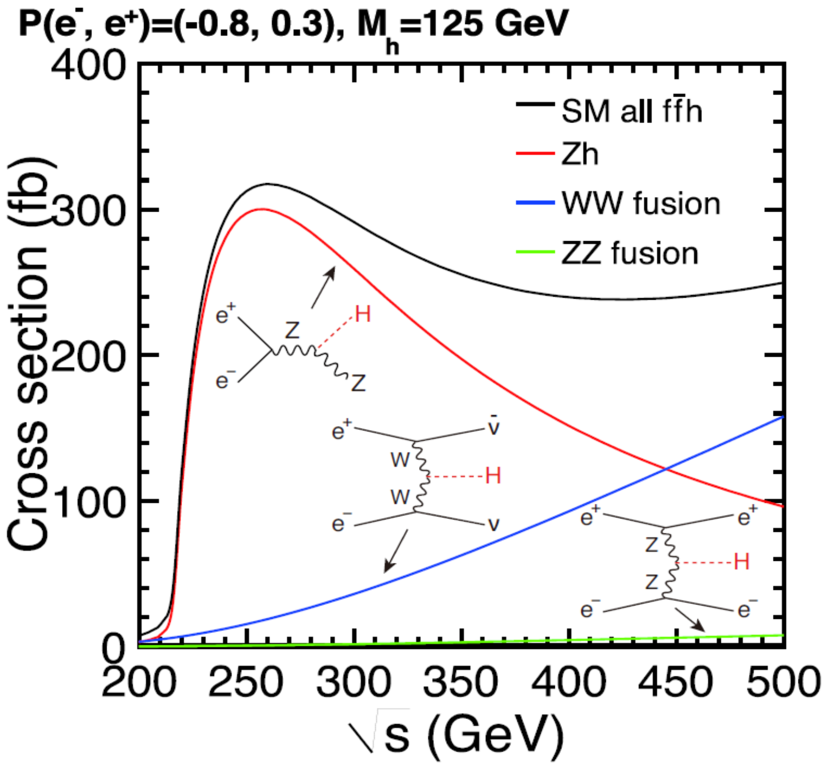
- 3 TeV 3.0 ab^{-1}
- BSM physics
- Higgs self coupling
- Rare Higgs decays
- Top quark physics

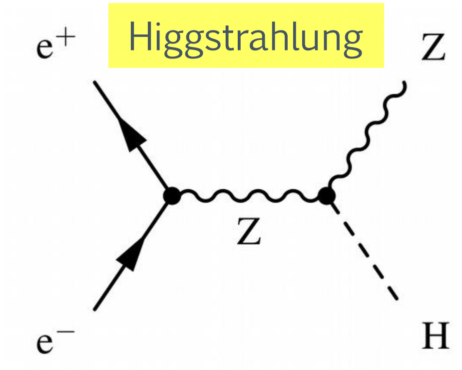


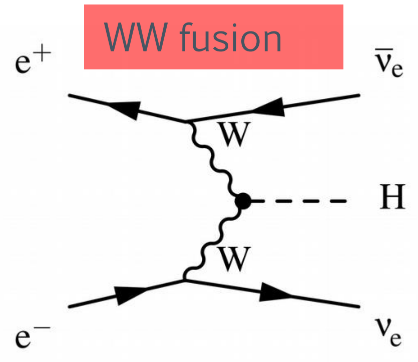
Higgs Physics

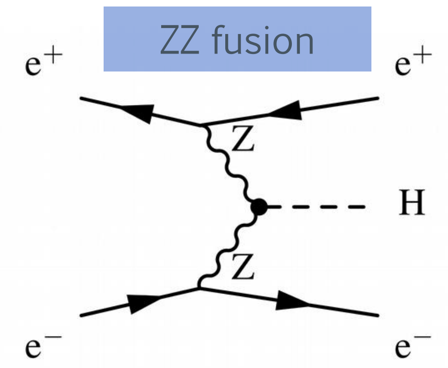
CLIC unpolarized beams









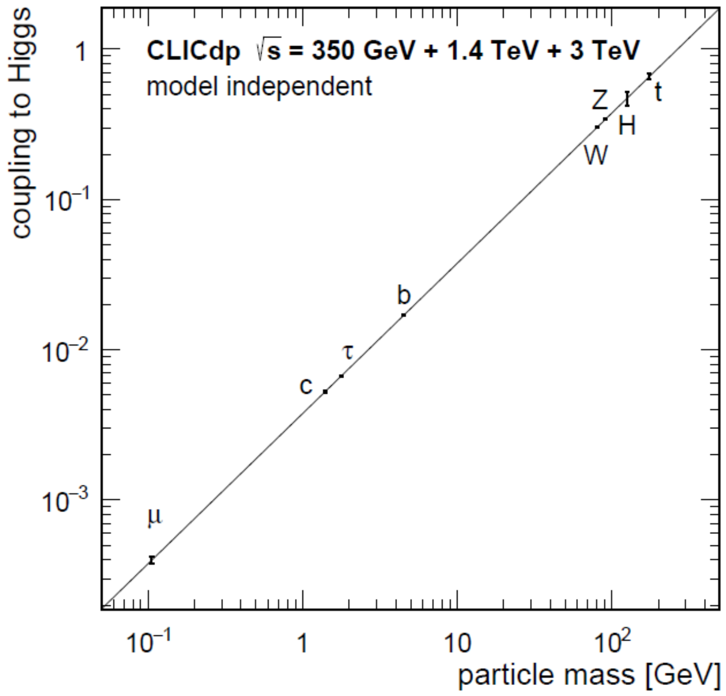


Higgs couplings

- The measurement of the Higgs boson couplings provide a strong test for the Standard model
- The deviation from the linearity of couplings vs. masses would be the sign of new physics⇒ necessary to achieve high precision of the measurement
- Measurement of the Higgs-self couplings is the only way to access the Higgs potential

$$V = \mu^2(\phi^+\phi) + \lambda(\phi^+\phi)^2 \Rightarrow \lambda = \frac{m_H^2}{V}$$

- Higgs couplings measurements at CLIC
  - Yukawa couplings(c, τ, b, top, μ)
  - Gauge couplings (W,Z)
  - Self coupling
  - Effective couplings for loop induced decays ($H \to \gamma\gamma$, $H \to Z\gamma$)

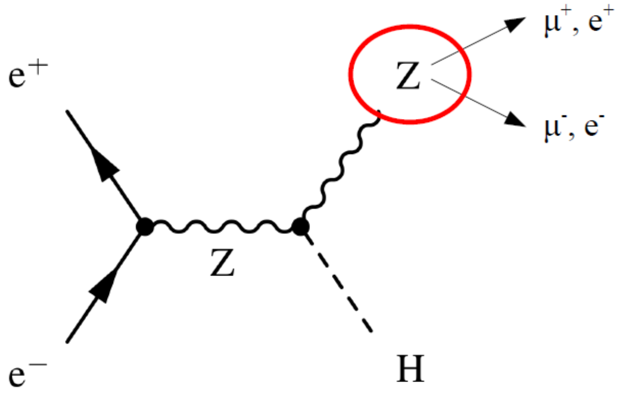


Higgs boson couplings: New physics signatures

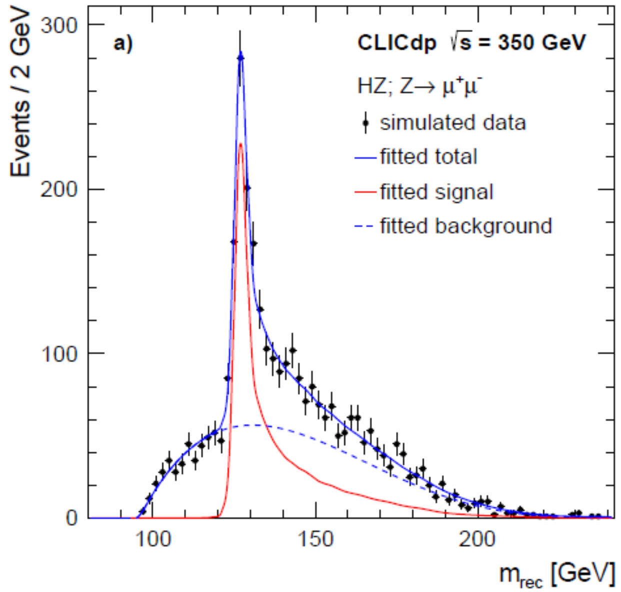
Mass & J^{CP} $\quad M_h \quad \Gamma_h \quad J^{\mathrm{CP}}$	New CP violating source
L_{Higgs} $\quad hhh: \ -6i\lambda v = -3i\frac{m_h^2}{v}, \quad hhhh: \ -6i\lambda = -3i\frac{m_h^2}{v^2}$	Self couplings Higgs potential large deviations - baryogenesis
L_{Gauge} $\quad W^+_\mu W^-_\nu h: \ i\frac{g^2 v}{2}g_{\mu\nu} = 2i\frac{M_W^2}{v}g_{\mu\nu}, \quad W^+_\mu W^-_\nu hh: \ i\frac{g^2}{2}g_{\mu\nu} = 2i\frac{M_W^2}{v^2}g_{\mu\nu},$ $Z_\mu Z_\nu h: \ i\frac{g^2+g'^2 v}{2}g_{\mu\nu} = 2i\frac{M_Z^2}{v}g_{\mu\nu}, \quad Z_\mu Z_\nu hh: \ i\frac{g^2+g'^2}{2}g_{\mu\nu} = 2i\frac{M_Z^2}{v^2}g_{\mu\nu}$	Gauge couplings (W,Z) Higgs singlet, composite Higgs
L_{Yukawa} $\quad h\bar{f}f: \ -i\frac{y^f}{\sqrt{2}} = -i\frac{m_f}{v}$	Fermion-Yukawa couplings: multiple Higgs doublets - 2HDM? Top-Yukawa couplings – top compositeness
L_{Loop} $\quad h\gamma\gamma \quad hgg \quad h\gamma Z$	Effective couplings for loop induced decays heavy vector like particles

Model independent σ(HZ)

- The measurement of the total cross-section of the Higgsstrahlung process $\Rightarrow g_{HZZ}$
- Measure only properties of the Z decay
  - Invariant mass of lepton pair identifies Z
  - Recoil mass identifies H
- Leptonic Z decays -the cleanest signature



$$m_{rec}^2 = s + m_Z^2 - 2E_Z\sqrt{s}$$

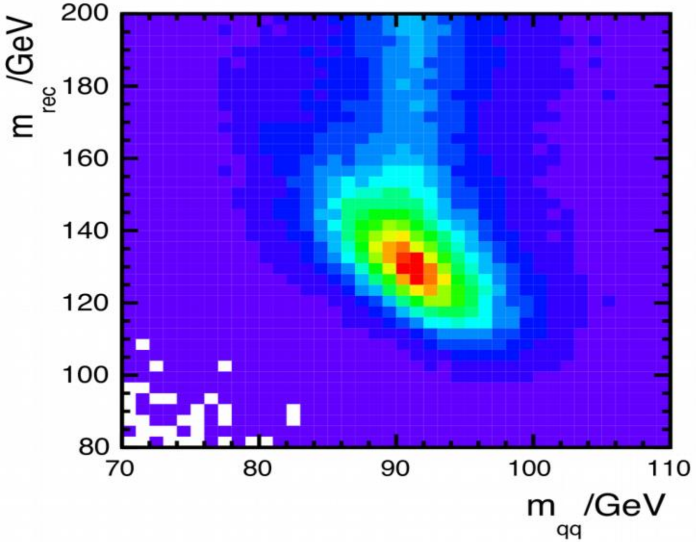


- Hadronic $Z \rightarrow q\bar{q}$ - high branching fraction ~ 70%
- almost model-independent measurement

$\Rightarrow$ Substantial improvement in precision possible

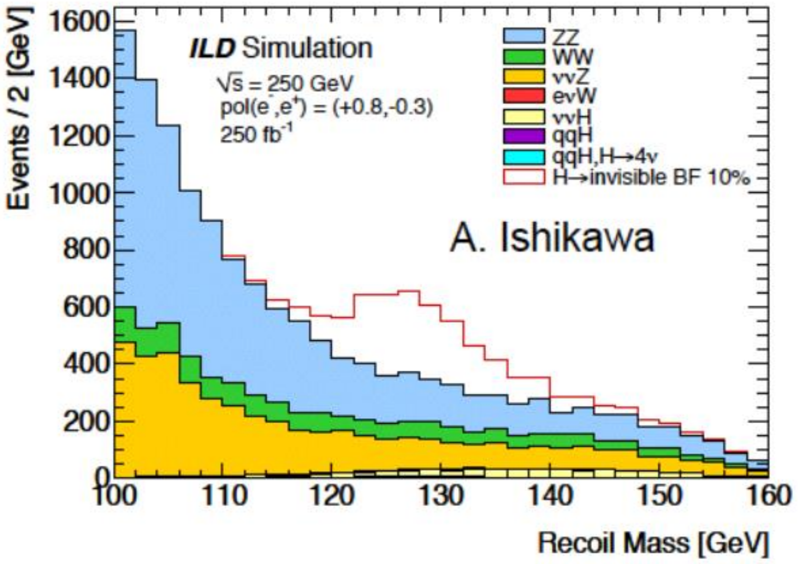
- Challenge: Z reconstruction depends on H-decay mode, H/Z separation

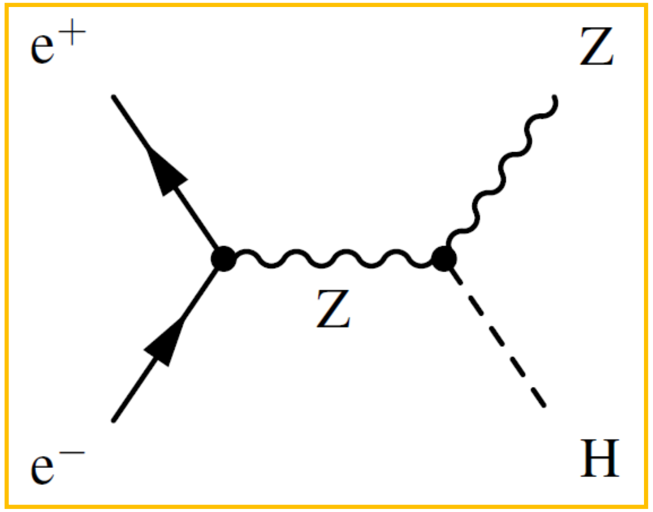
$$\Delta(\sigma_{HZ})/\sigma_{HZ} \approx 1.8\% \rightarrow \Delta(g_{HZZ})/g_{HZZ} \approx 0.9\%$$



Invisible Higgs decays

- The invisible Higgs decay process is highly suppressed in the SM
- However, many beyond SM scenarios allow for enhanced H →invisible decay modes
- Using recoil mass technique the invisible Higgs decays Branching fraction is measured to be less than a percent (0.4%) at 250 GeV (at the 95% confidence level) using combined leptonic and hadronic Z decays

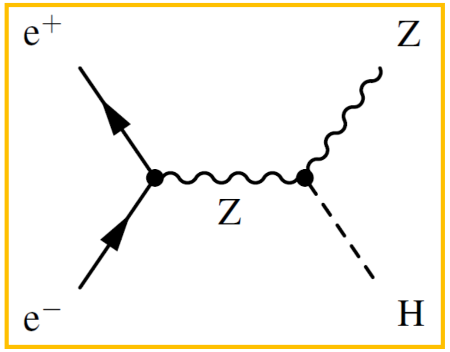




Higgs width

$$\sigma(HZ) \Rightarrow g^2_{HZZ}$$

- Lepton colliders: model independent measurement of absolute couplings of the Higgs to Z boson in Higgsstrahlung $\sigma(HZ)\sim g^2_{HZZ}$ and the total Higgs decay width

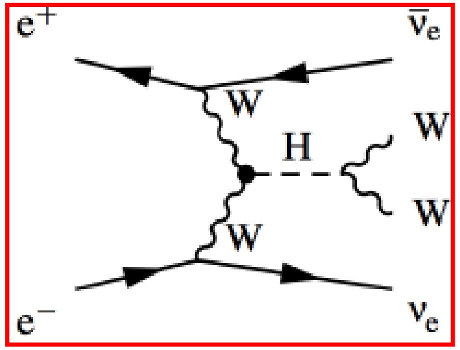


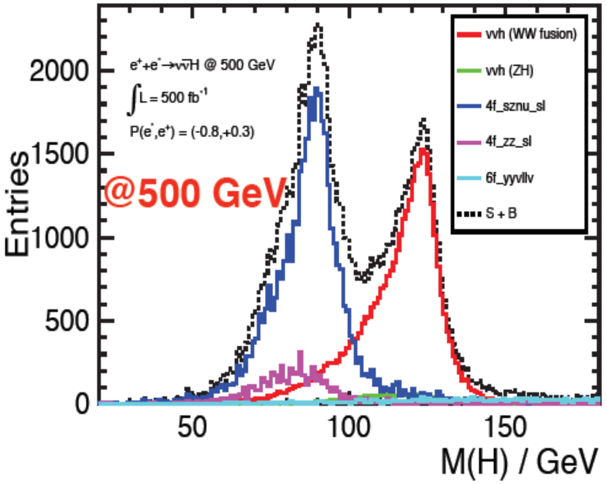
- Influences reachable precision on all other absolute Higgs couplings and the determination of total Higgs width

- Determine g_{HWW} from ratio of the Higgsstrahlung and WW-fusion using the same Higgs decay mode

$$\left(\frac{g_{HZZ}}{g_{HWW}}\right)^2 \propto \frac{\sigma(e^+e^- \to ZH) \text{ x } BR(H \to xx)}{\sigma(e^+e^- \to H\nu_e\nu_e) \text{ x } BR(H \to xx)}$$

$$\Rightarrow g^2_{HWW}$$





- Determine total Higgs width (Γ_H) from

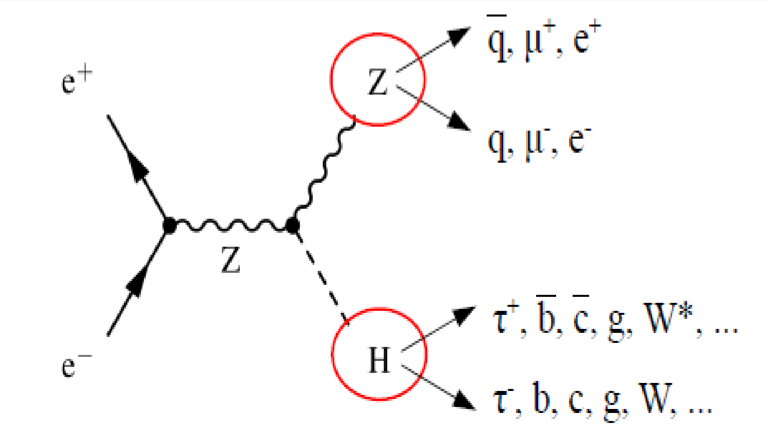
$$\sigma(e^+e^- \to H\nu\nu) \text{ x } BR\left(H \to WW^*\right) \propto \frac{g^4_{HWW}}{\Gamma_H}$$

$$\Rightarrow \Gamma_H$$

Other Higgs couplings

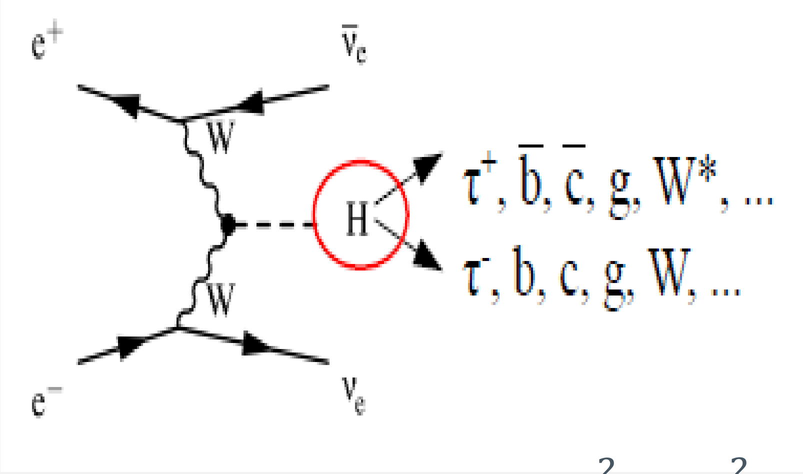
Decay mode	Branching ratio
$H \to b\bar{b}$	56.1 %
$H \to WW^*$	23.1 %
$H \to gg$	8.5 %
$H \to \tau^+\tau^-$	6.2 %
$H \to c\bar{c}$	2.8 %
$H \to ZZ^*$	2.9 %
$H \to \gamma\gamma$	0.23 %
$H \to Z\gamma$	0.16 %
$H \to \mu^+\mu^-$	0.021 %

$\sqrt{s} < 500\ GeV$

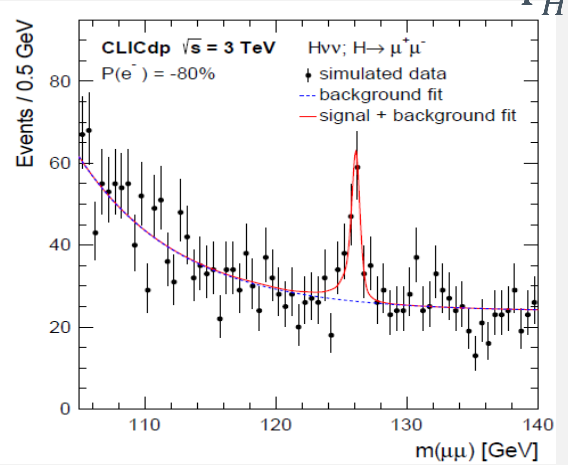


$$\sigma(HZ)xBR(H \to x\bar{x}) \sim \frac{g_{HZZ}^2 g_{x\bar{x}}^2}{\Gamma_H}$$

$\sqrt{s} \geq 500\ GeV$

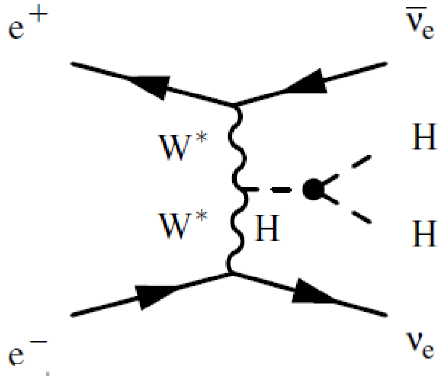


$$\sigma(H\nu_e\nu_e)xBR(H \to x\bar{x}) \sim \frac{g_{HWW}^2 g_{x\bar{x}}^2}{\Gamma_H}$$

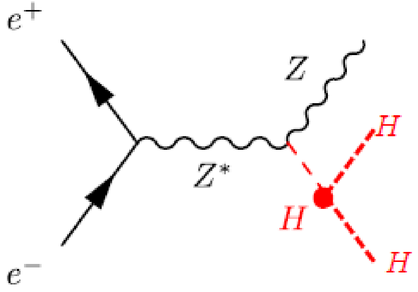


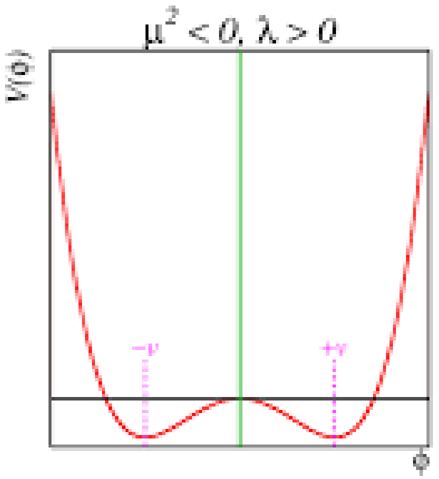
Higgs self-coupling

- Higgs boson can also couple to itself
- The determination of the Higgs self coupling is the way to access the Higgs potential
- New physics scenarios can enhance of selfcoupling λ of the SM value up to tens of percent



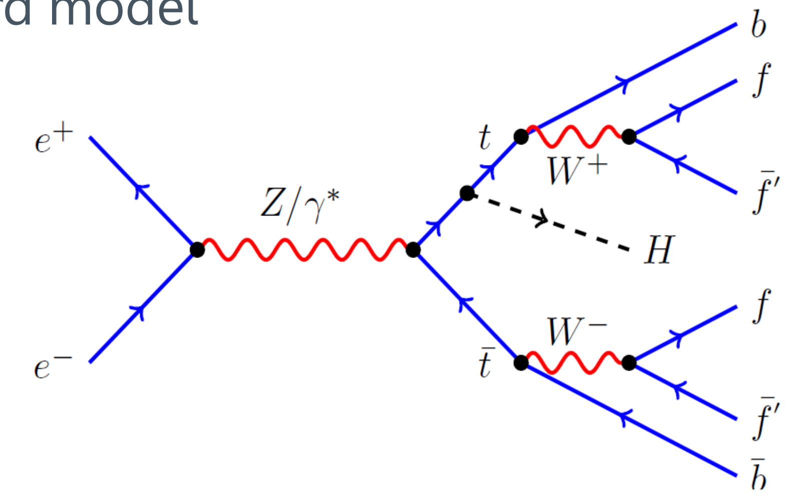
$$V = \mu^2(\phi^+\phi) + \lambda(\phi^+\phi)^2 \Rightarrow \lambda = \frac{m_H^2}{\nu}$$





Top-Yukawa coupling

- Is a coupling of top quark to a Higgs boson
- Because of very high mass top quark may play a special role in electroweak symmetry breaking
- High sensitivity to the physics beyond the Standard model



Combined fits

- From the measurements obtained at each energy stage the Higgs coupling parameters and total width are extracted by a global fit
- Model independent fit
  - Input: the cross sections of the specific Higgs decays (σxBR)
  - Output of the fit: absolute couplings and total Higgs width

$$\chi^2 = \sum_i \frac{\left(C_i / C_i^{SM} - 1\right)^2}{\Delta F_i^2}, \quad i = 1,10$$

- Model dependent
  - Input: the ratio between partial width of the studied Higgs decays, to one expected in SM

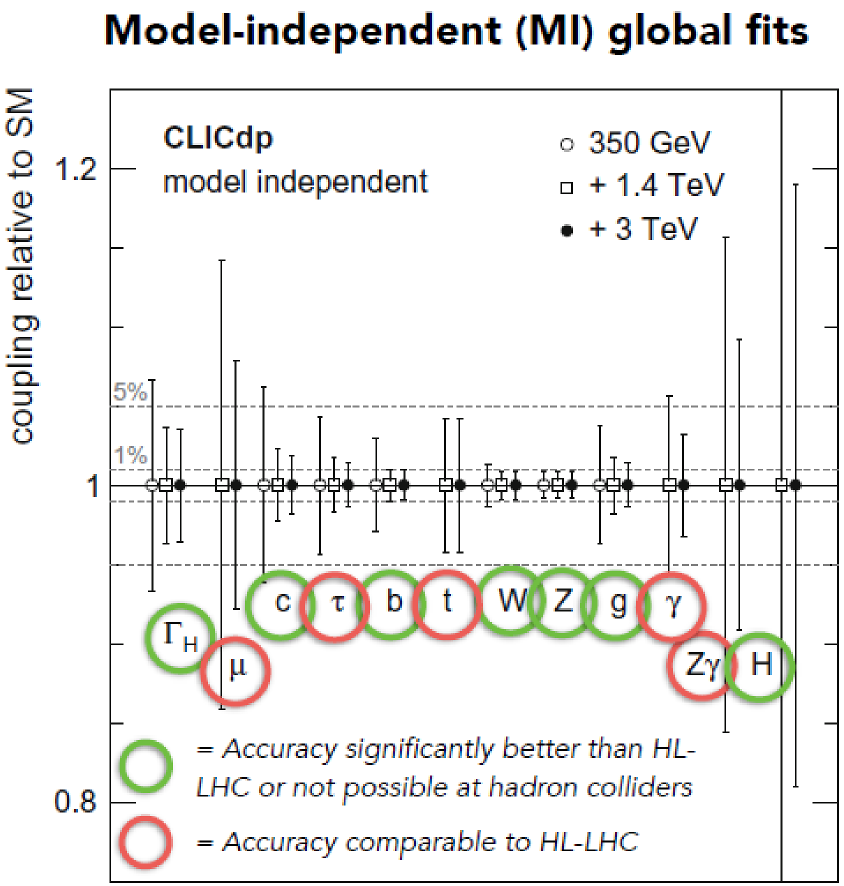
$$\kappa_{Hi} = \frac{\Gamma_{Hi}}{\Gamma_{Hi}^{SM}},$$

  - Constraints: total Higgs width is constrained by the Standard model

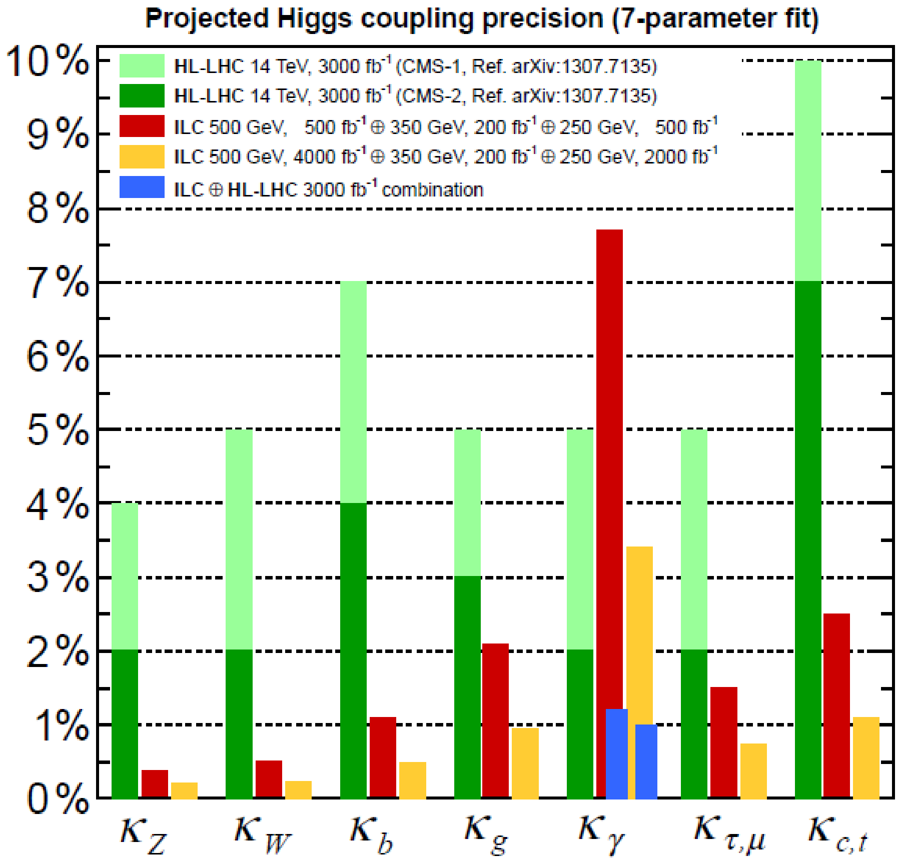
Assumption no invisible Higgs decays

Couplings results

Model independent



Model dependent

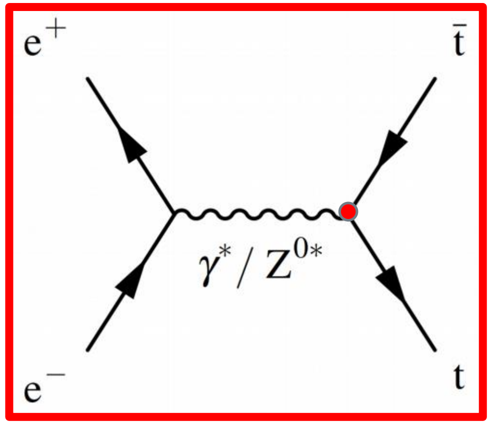


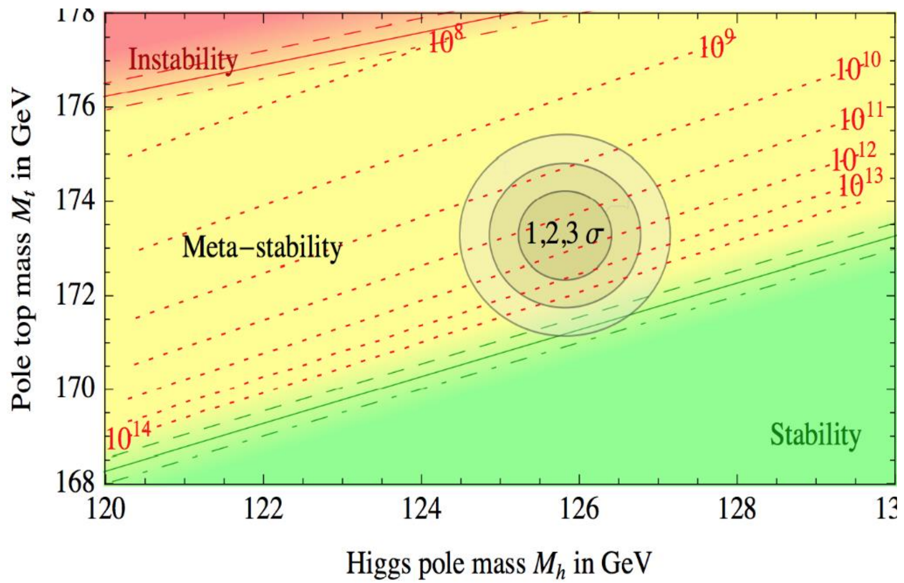
Top quark physics

- Top quark couples most strongly with Higgs field closest insights to the electroweak symmetry breaking
- Loop contributions to the processes that can be studied with high precision show sensitivity to BSM signals
- Uncertainty of the top mass, along with the uncertainty on the Higgs boson mass, is one of the key inputs to the studies of the SM vacuum stability

Dedicated measurements:

- Top quark mass
  - Top quark threshold scan
  - Direct reconstruction
- Top -Yukawa coupling
- Probe of new physics
  - Top quark electroweak couplings
  - Top quark production asymmetries
  - CP violation in top sector

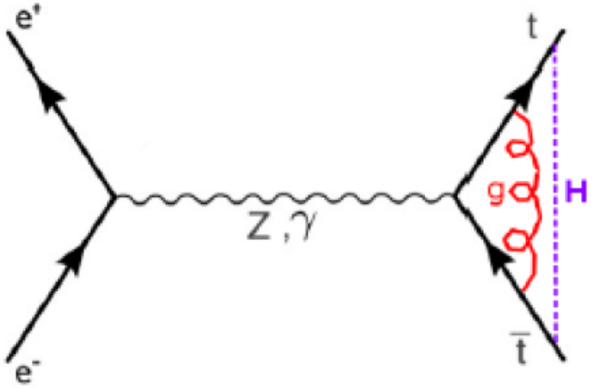


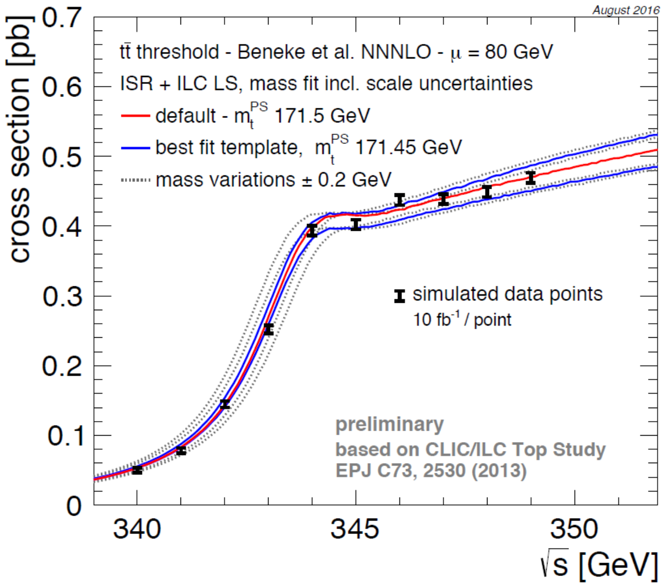


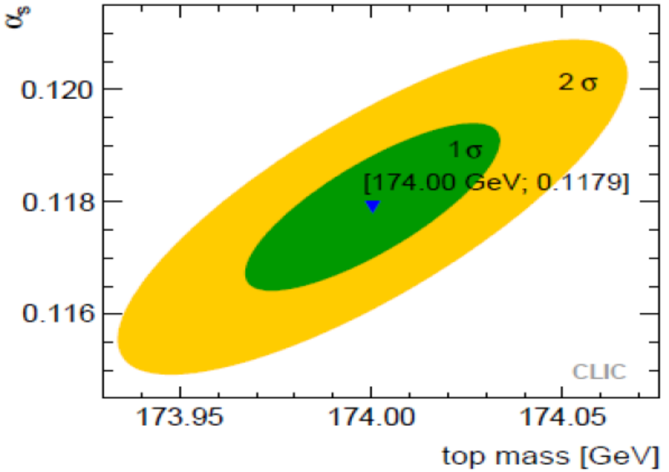
Top quark threshold scan

- At linear collider they can be produced in pairs
- The minimum required energy for production is $(\mathrm{E} > 2m_t) \Rightarrow$ 'threshold'

- Near the production threshold the production cross-section is showing the resonant behavior
- measurements
  - m_t *top quark mass*
  - Γ_t *top width*
  - α_S *stron coupling constant*
  - y_t *top – Yukawa coupling*

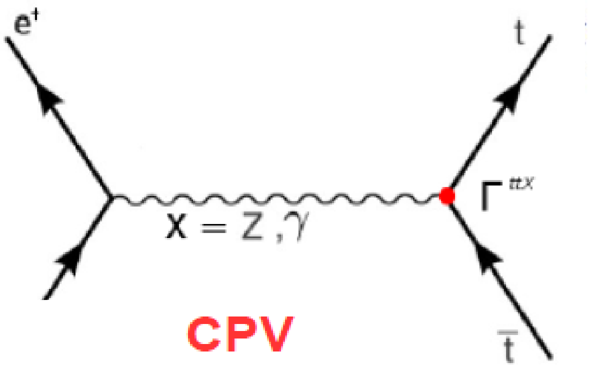






- Measurement at different center-of-mass energies in the tt production threshold region (data also useful for Higgs physics)
- Ten scan point, 100 fb^{-1}
- Expected precision on 1S mass: ≈50 MeV (dominated by theory NNNLO scale uncertainty)

Top electroweak couplings

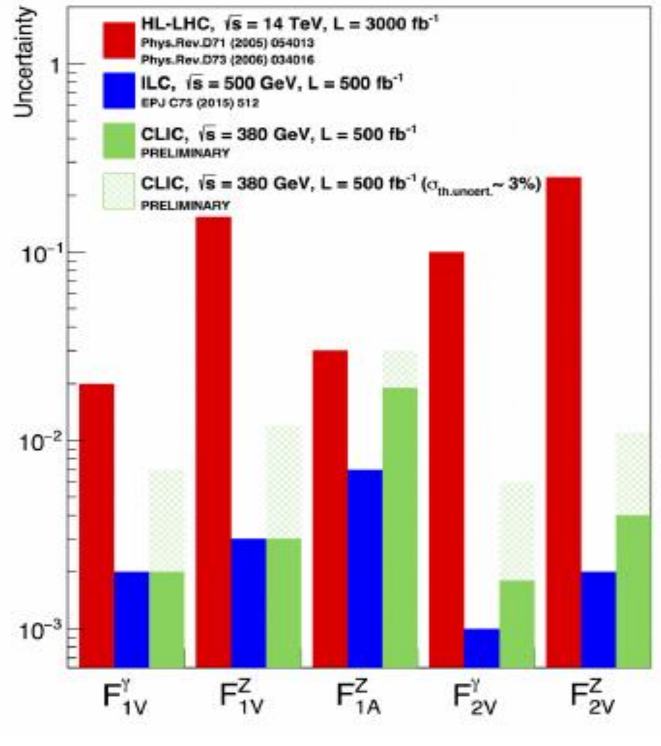


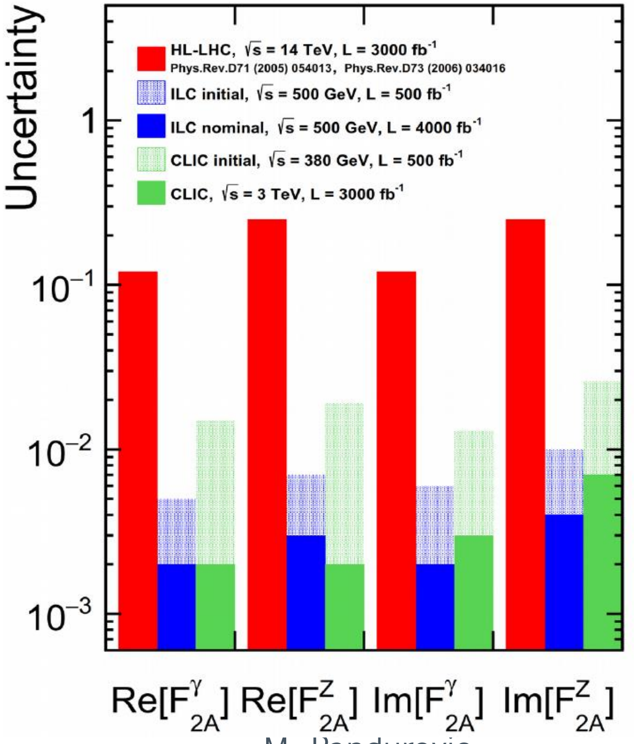
- At lepton collider top quark pairs are produced in pairs via Z/γ
- General form of coupling can be represented as:

CP conserving

CPV

$$\Gamma_\mu^{ttV}(k^2,\, q,\, \bar{q}) = -ie\left\{\gamma_\mu \left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right)\right\}$$



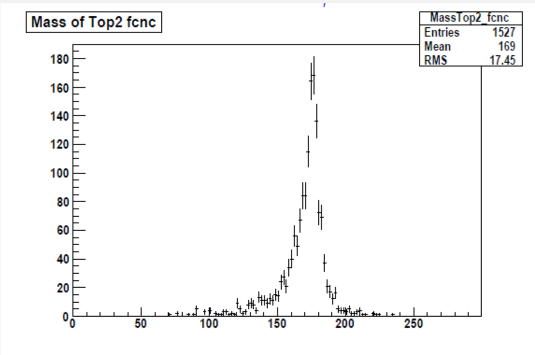


- Verticies ttZ and $tt\gamma$ are sensitive to the new physics
- Coupling determination:
- Measurement:
  - A_{FB} *forward backward assymetry*
  - A_{LR} *left right assymetry*
  - $\sigma_{t\bar{t}}$ *production cross section*

Top quark measurements

FCNC top decays

- In the Standard Model, FCNC top decays are strongly suppressed
- $BR(t \to c\gamma) = 2 \cdot 10^{-14}$
- $BR(t \to cZ) = 1 \cdot 10^{-14}$
- $BR(t \to cH) = 3 \cdot 10^{-15}$



- Significant enhancement possible in many new physics scenarios

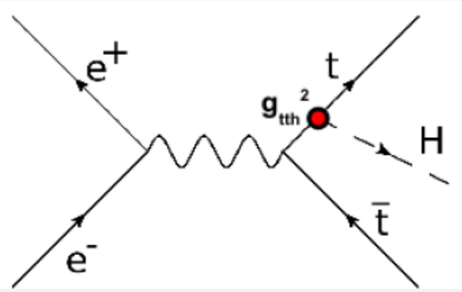
Ongoing CLIC

Model	2HDM	MSSM	$\not R$ SUSY	LH	Q singlet	RS
$BR(t \to c\,\gamma)$	10^{-6}	10^{-6}	10^{-5}	10^{-7}	$8 \cdot 10^{-9}$	10^{-9}
$BR(t \to c\,h)$	10^{-2}	10^{-4}	10^{-6}	10^{-5}	$4 \cdot 10^{-5}$	10^{-4}

Top-Yukawa coupling

- Direct access to top-Yukawa coupling at energies above 500 GeV
- $t \to bW, H \to b\bar{b} \Longrightarrow multi\ jet\ signature$
- complex reconstruction

$$\frac{\Delta y_t}{y_t} \approx C\,\frac{\Delta\sigma}{\sigma}$$



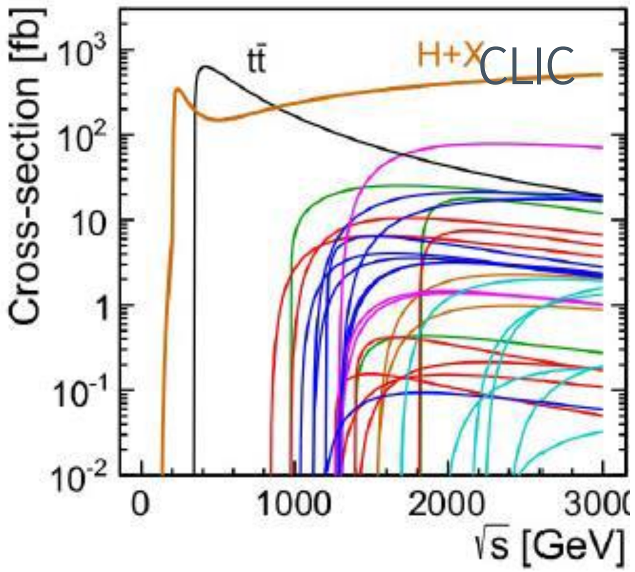
$ILC\ 1TeV\ \ C = 0.52$

$CLIC\ 3\ TeV\ \ C = 0.53$

Collider	LHC		ILC	ILC	CLIC
CM Energy [TeV]	14	14	0.5	1.0	1.4
Luminosity [fb^{-1}]	300	3000	1000	1000	1500
Top Yukawa coupling κ_t	(14 – 15)%	(7 – 10)%	10%	4%	4%

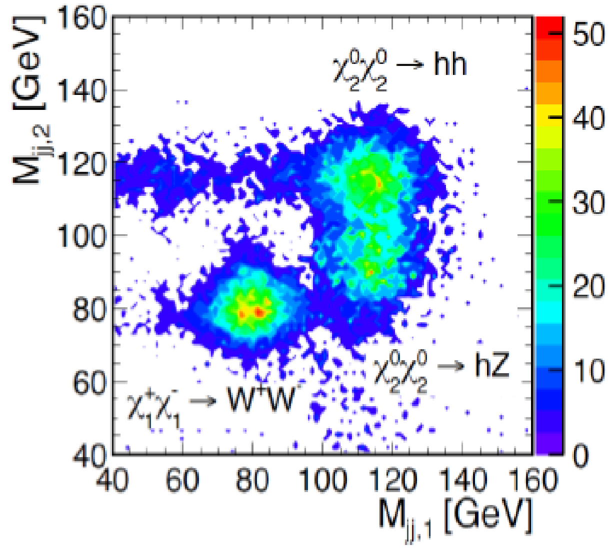
Beyond Standard Model searches

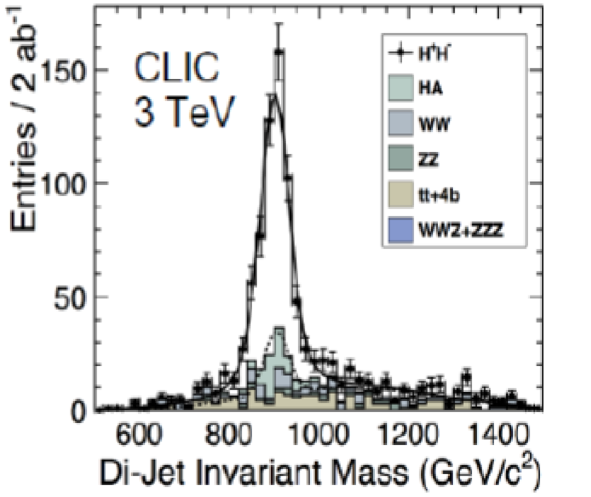
- Linear colliders have a significant discovery potential for the physics Beyond Standard Model
- **Direct searches**
  - Direct reconstruction of new particles
  - Possible observation of the new phenomena
  - Kinematic limit at the of 0.5/1.5 TeV for ILC/CLIC



- **Indirect searches**
  - Precision measurements of sensitive observables reveal a signs of new physics, comparing to the SM expectations
  - Kinematic limit is higher – several tens of TeV

BSM physics: direct measurement





SUSY

- Reconstruction of chargino and neutralino
- Separation of W/Z/h

Heavy Higgs boson

- Reconstruction of four heavy Higgs bosons which are almost degenerate in mass

$$e^+e^- \to HA \to b\bar{b}b\bar{b}$$
$$e^+e^- \to H^-H^+ \to t\bar{b}b\bar{t}$$

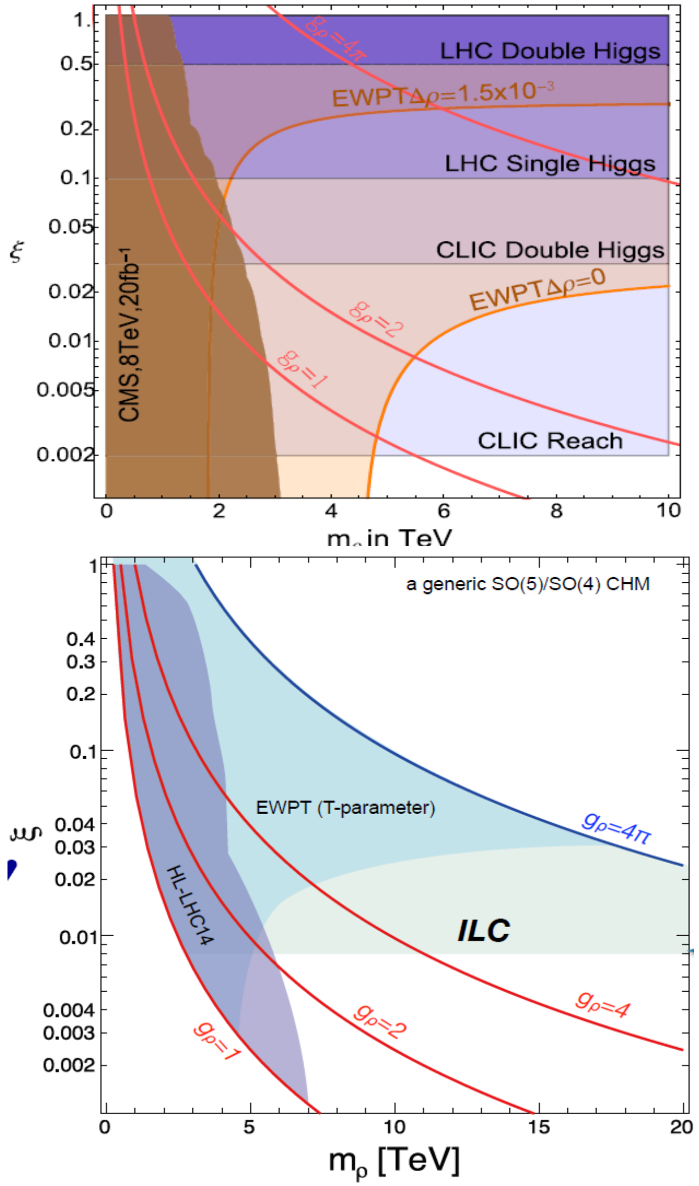
- Complex final state

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	0.6%
				$\tilde{\chi}_1^0$ mass	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	0.3%
				$\tilde{\chi}_1^0$ mass	1.0%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	0.4%
				$\tilde{\chi}_1^\pm$ mass	0.6%
3.0	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	II	$\tilde{\chi}_1^\pm$ mass	1.1%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\,h/Z^0\,\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	1.5%
3.0	Squarks	$\tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	I	$\tilde{q}_R$ mass	0.52%
3.0	Heavy Higgs	$H^0A^0 \to b\bar{b}b\bar{b}$	I	H^0/A^0 mass	0.3%
		$H^+H^- \to t\bar{b}b\bar{t}$		$H^\pm$ mass	0.3%
1.4	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\ell}$ mass	0.1%
				$\tilde{\chi}_1^0$ mass	0.1%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	0.1%
				$\tilde{\chi}_1^0$ mass	0.1%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	2.5%
				$\tilde{\chi}_1^\pm$ mass	2.7%
1.4	Stau	$\tilde{\tau}_1^+\tilde{\tau}_1^- \to \tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\tau}_1$ mass	2.0%
1.4	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	III	$\tilde{\chi}_1^\pm$ mass	0.2%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\,h/Z^0\,\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	0.1%

BSM physics: indirect measurements

Composite Higgs

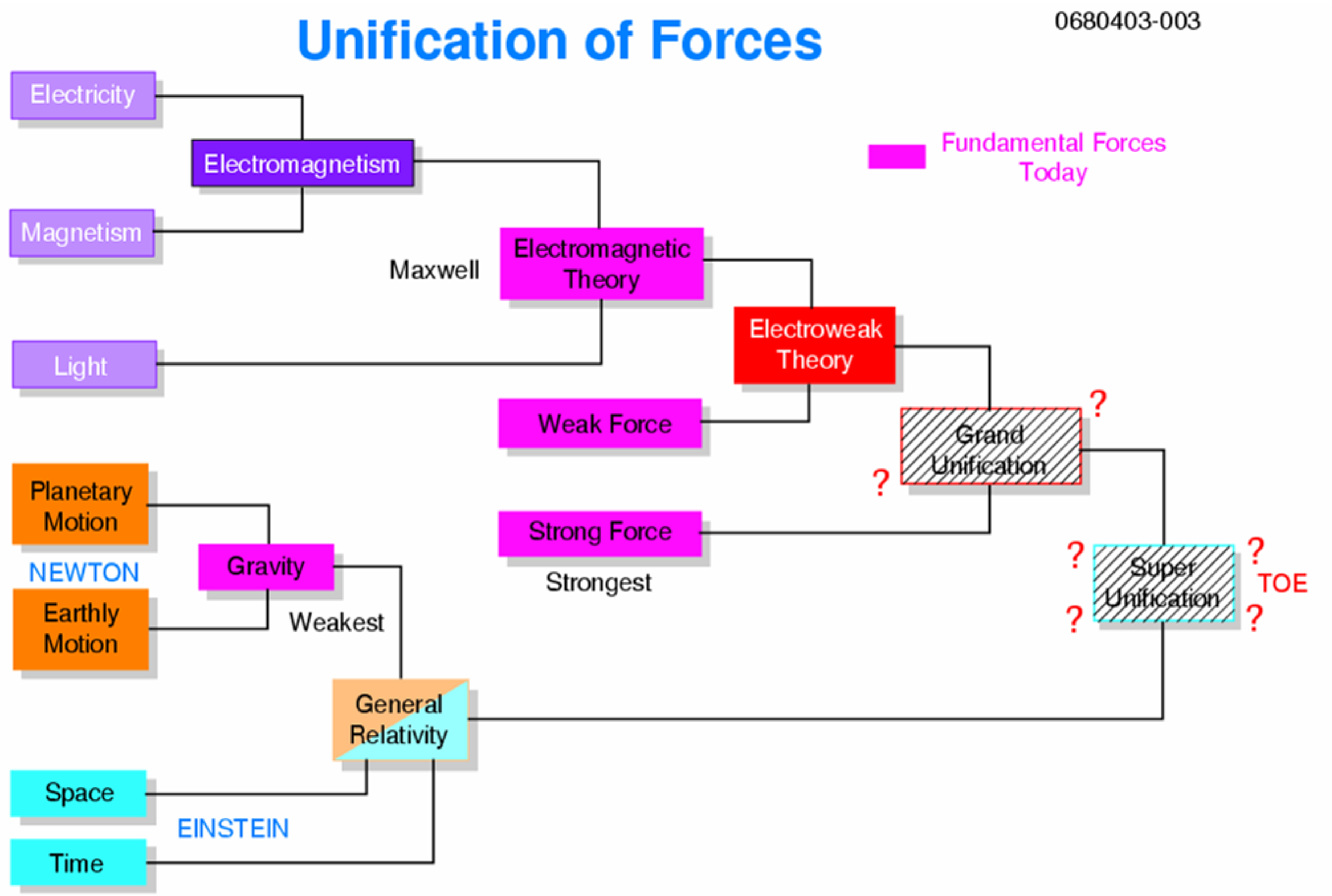
- These theories assume Higgs boson is not the fundamental but a composite particle which built out of fermions
  - Higgs is viewed as a bound state of fermions
  - Main consequence of this model is the existence of new particles that are excitations of the Higgs boson m_ρ
  - $4\pi f$ is the scale of compositeness
  - $\xi = \left(\frac{v}{f}\right)^2$ is the strength of Higgs interactions
- This theory solves the 'naturalness' problem: mass of SM Higgs boson at high energies becomes divergent
- At linear colliders we have better reach for the masses of new particles and at higher energies then the LHC



Summary

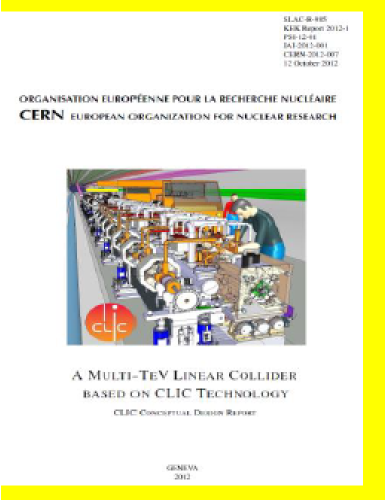
- The Higgs boson that has been discovered in 2012 has completed the SM particle spectrum and showed the way how the mechanism of electroweak symmetry breaking was realized
- Still many open questions:
  - why the electroweak symmetry was broken
  - question of asymmetry of matter and antimatter
  - The existence of dark matter and dark energy …
- In order to answer these question the high precision of the measurement of the sensitive observables is needed
- The necessary high precision is leading towards a next generation of electron positron colliders
- Performed physics studies show excellent potential of both linear colliders ILC and CLIC for high precision measurements, as well as large discovery potential for physics beyond the Standard model

Thank you for your attention


Unification of Forces
0680403-003
Electricity
Electromagnetism
Magnetism
Fundamental Forces Today
Maxwell
Electromagnetic Theory
Light
Electroweak Theory
Weak Force
Grand Unification
?
?
Planetary Motion
NEWTON
Earthly Motion
Gravity
Weakest
Strong Force
Strongest
Super Unification
?
?
?
?
TOE
General Relativity
Space
EINSTEIN
Time

CLIC timeline

CLIC aims to provide **multi-TeV electron-positron** collisions with high luminosity at affordable cost and power consumption


SLAC-R-985
KEK Report 2012-1
PSI-12-01
JAI-2012-001
CERN-2012-007
12 October 2012

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

A MULTI-TEV LINEAR COLLIDER BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

2012 CDR:
Shows feasibility of 3 TeV design

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

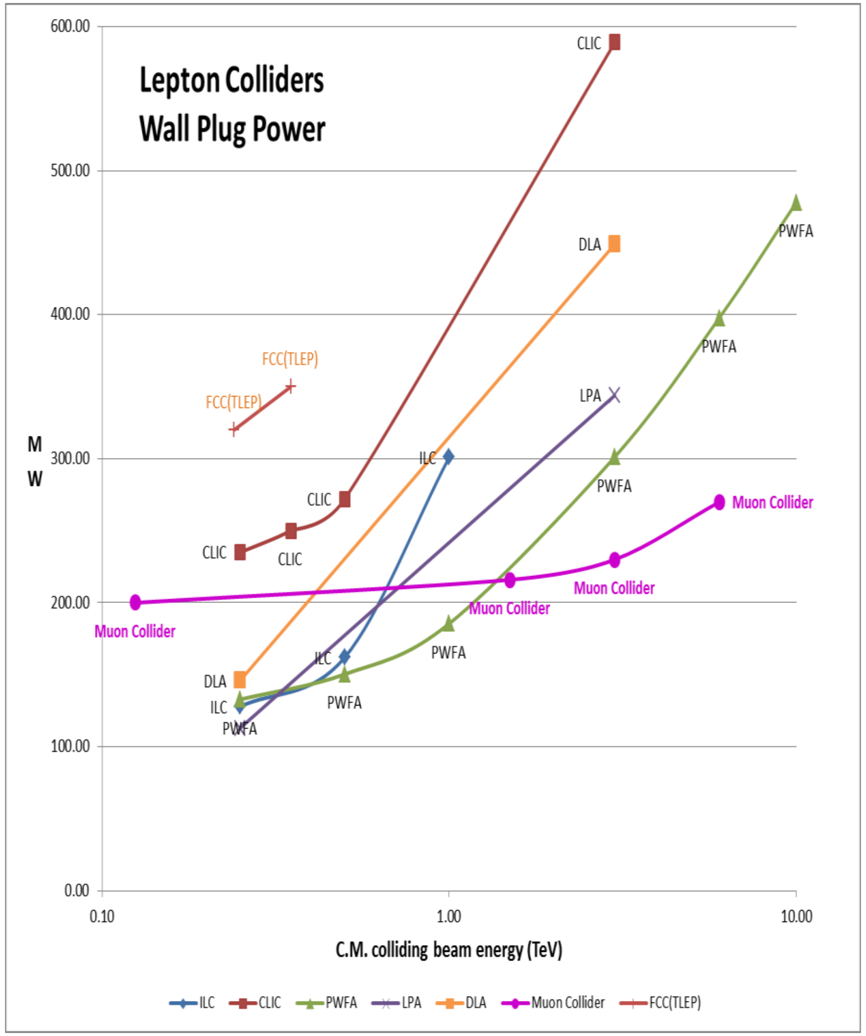
2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

Power consumption



Foundation of the Standard model

- The idea behind the formulation of the Standard model is the unification of forces and symmetry of the ‘equations of motion’
- First unification of forces under symmetry group U(1):

  electric and magnetic force
- Second unification: Glashow, Weinberg and Salam in 1960’s - the unification of the weak and electromagnetic force into electroweak under gauge group $SU(2) \times U(1)_Y$

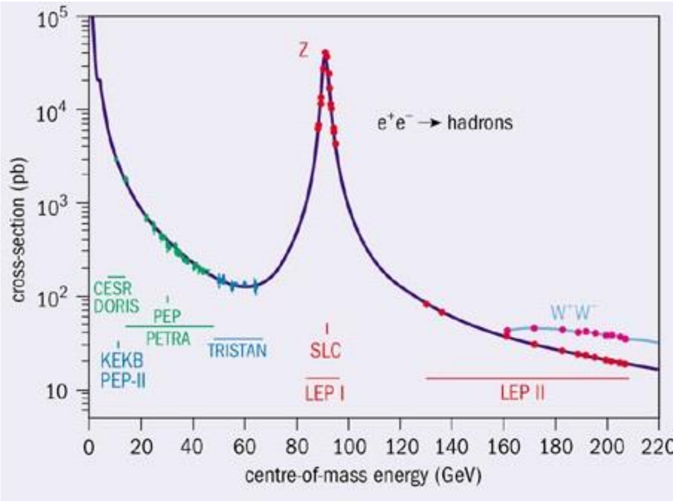
- Experimental confirmation of the electroweak theory: discovery of the W and Z bosons at UA1 and UA2 experiments at LEP, CERN – Nobel Prize 1973!
- Third unification $SU(3)_C x SU(2)_L x U(1)_Y$: Standard model

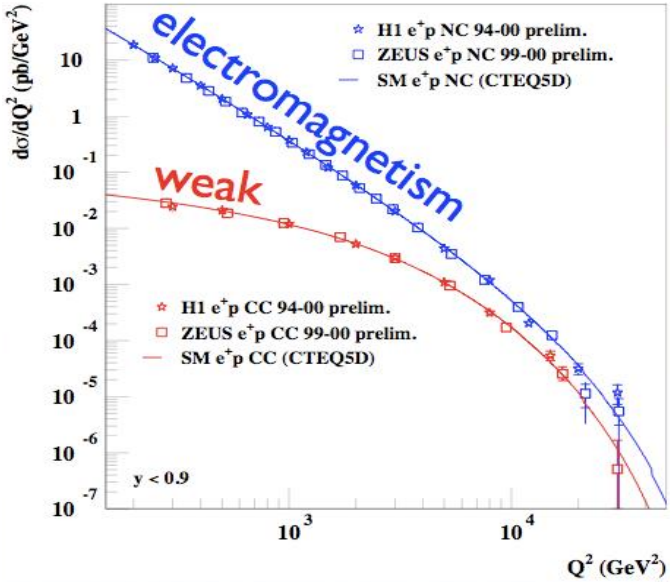
  mathematical unification weak, electromagnetic force and strong (color)

  physical unification is not yet proven

  Problem:

  according to the Standard Model ‘we’ are supposed to be massless!





Where did Higgs came from?

- Explicitly inserting massive term in the Standard model - breaks the gauge invariance

  Mathematical solution:

- introduce a new field with a potential that keeps the full Lagrangian invariant under symmetry, with the ground state which breaks the symmetry

$\Rightarrow$ Spontaneous symmetry breaking (SSB)

- In the presence of SSB, the gauge bosons associated acquire mass proportional to the gauge couplings and the vacuum expectation value
- Standard model assumes the Higgs field $\Rightarrow$ masses in SM
- The Higgs field

$$V = \mu^2(\phi^+\phi) + \lambda(\phi^+\phi)^2 \Rightarrow \lambda = \frac{m_H^2}{\nu}$$

- $\Rightarrow$ from symmetry an existence of the Higgs boson is predicted !!!