Experimental Physics at Lepton Colliders

CERN Summer Student Lecture, 2019

Lecture 1

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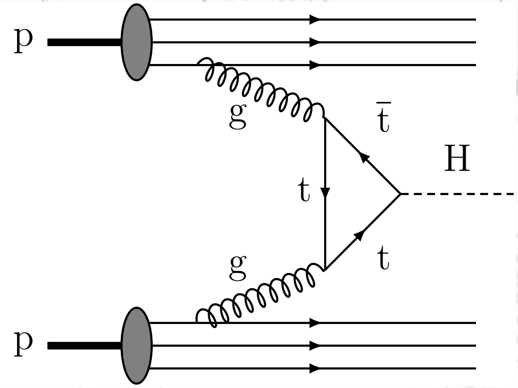
Physics at (Future) Lepton Colliders

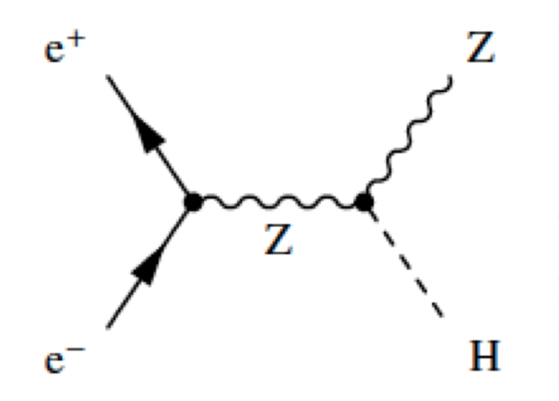
- Lecture 1 (Wednesday 31 July, 9:15)
  - Introduction: Why Lepton Colliders ?
  - Where we stand: Status of the Standard Model
  - An experimental strategy for the future: e^+e^- colliders
  - Precision Higgs Physics
  - Rounding off: Summary and Conclusions

- Lecture 2 (Thursday 1 August, 10:25)
  - Electroweak Precision Physics: FCC-ee
  - High Energy e^+e^- Physics: CLIC
  - Thinking out of the box: Muon colliders
  - Rounding off: Summary and Conclusions

Introduction:
Why Lepton colliders ?

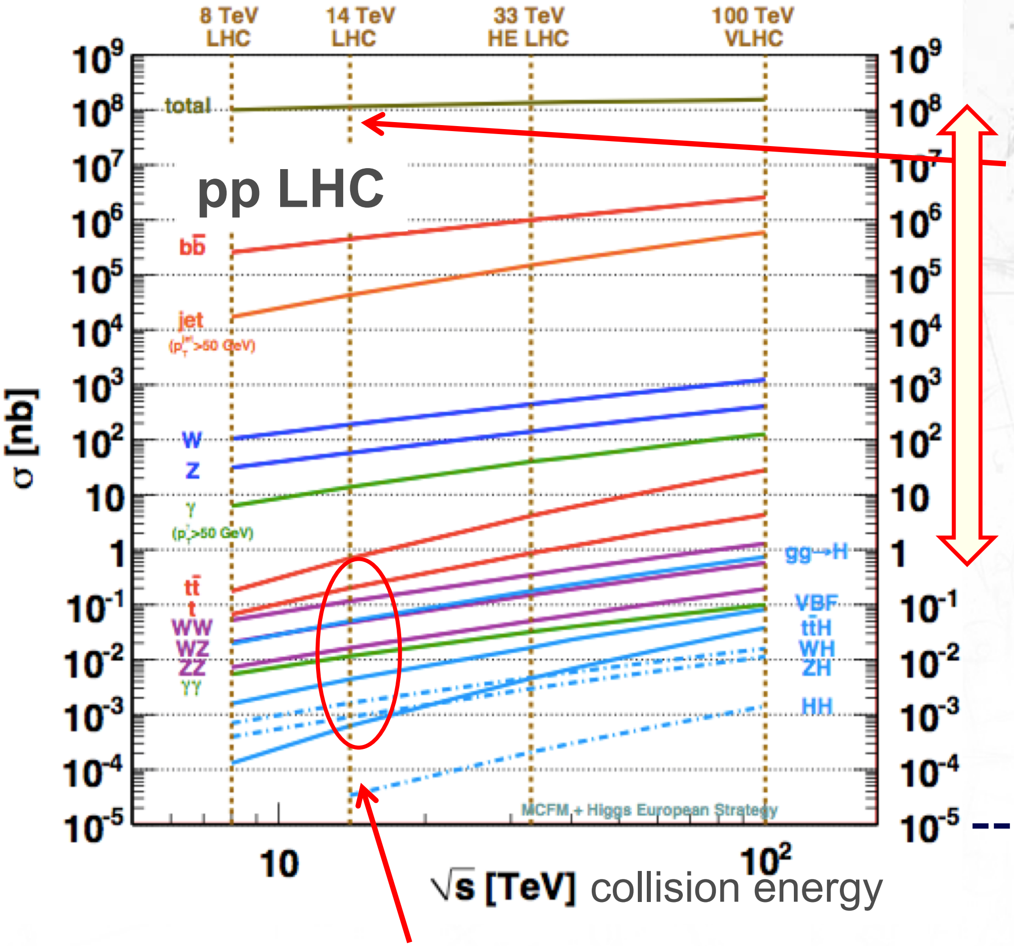
pp collisions vs. e^+e^- collisions (1)





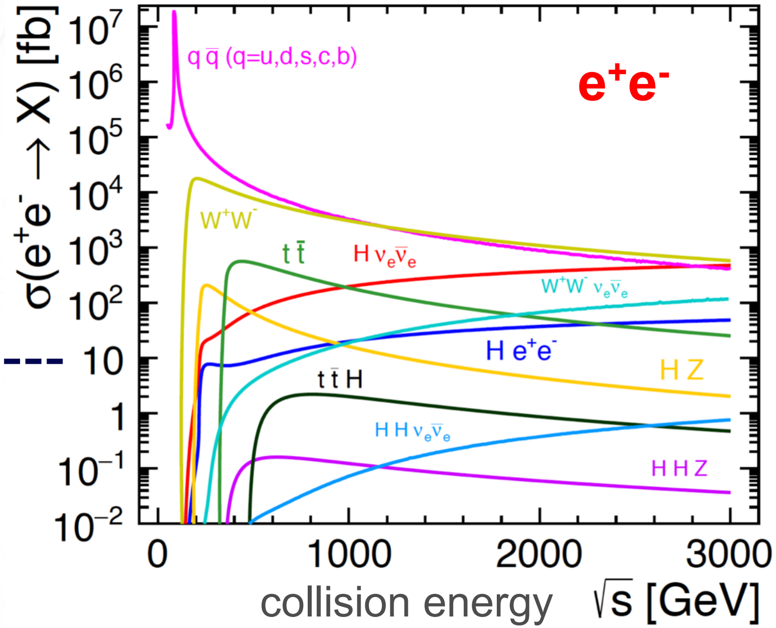
p-p collisions	e^+e^- collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined (E, $\mathbf{p}$), polarisation → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	**Clean experimental environment** → Trigger-less readout → Low radiation levels
High cross-sections for **colored-states**	Superior sensitivity for **electro-weak states**
High-energy **circular** pp colliders feasible	- At lower energies ($\lesssim$ 350 GeV) , **circular** e^+e^- colliders can deliver **very large luminosities.** - Higher energy e^+e^- requires **linear** collider.

pp collisions vs. e^+e^- collisions (2)



LHC total cross section factor > 100 million !!

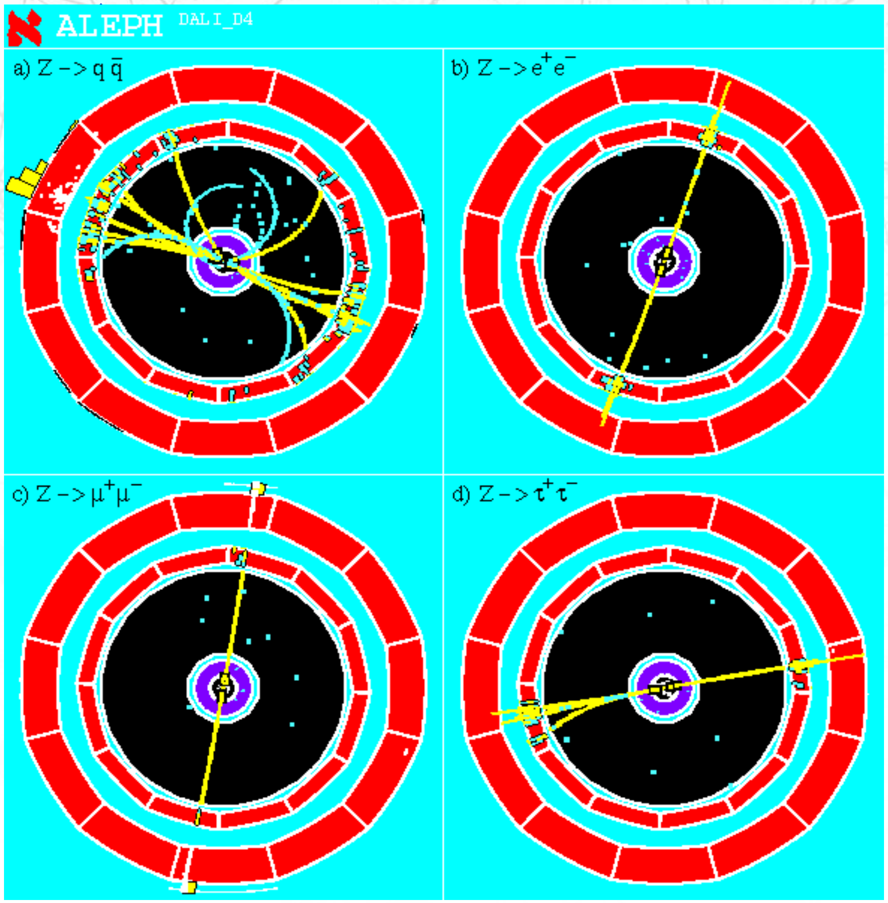
At LHC, much of the interesting physics needs to be found among a huge number of collisions



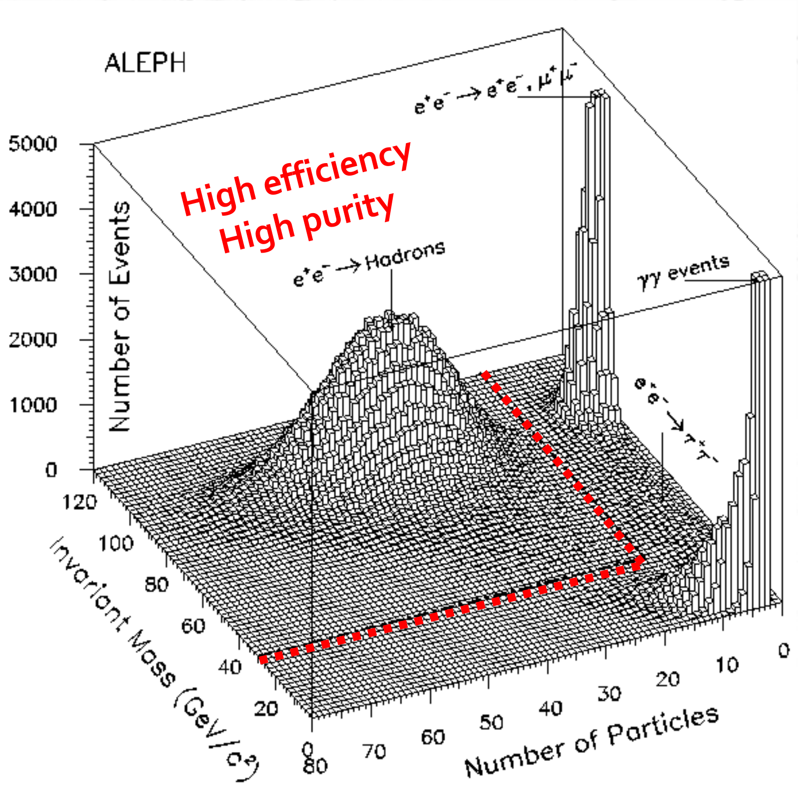
e^+e^- events are “clean”

e^+e^- collisions (1)

- No pile-up collisions, no underlying event
  - Final state is clean and cosy, triggering is easy (100% efficient)



Analysis is a waking dream



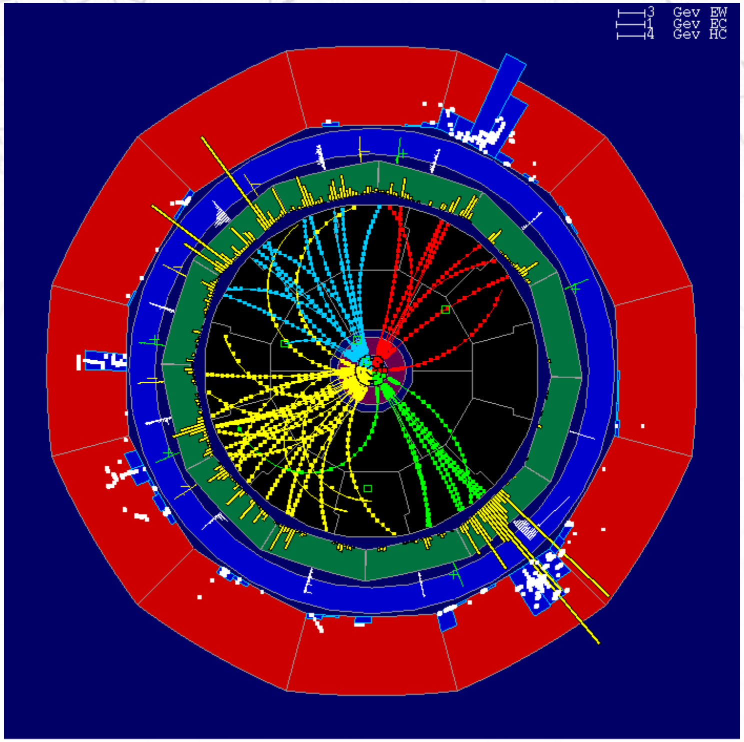
High efficiency
High purity

- No huge QCD cross section: All events are signal.

e^+e^- collisions (2)

- Electrons are leptons, i.e., elementary particles: no underlying event
  - ❑ Final state has known energy and momentum: ($\sqrt{s}$, 0, 0, 0)

- Example: an $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$ candidate
  - ❑ Four jets in the event and nothing else
  - ❑ Total energy and momentum are conserved
    - ❖ $E_1 + E_2 + E_3 + E_4 = \sqrt{s}$
    - ❖ $p_1^{x,y,z} + p_2^{x,y,z} + p_3^{x,y,z} + p_4^{x,y,z} = 0$
  - ❑ Jet directions ($\beta_i = p_i/E_i$) are very well measured



$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ \beta_1^x & \beta_2^x & \beta_3^x & \beta_4^x \\ \beta_1^y & \beta_2^y & \beta_3^y & \beta_4^y \\ \beta_1^z & \beta_2^z & \beta_3^z & \beta_4^z \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} \sqrt{s} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

- ❑ Jet energies (and di-jet masses, m_W) determined analytically by inverting the matrix
  - ❖ No systematic uncertainty related to jet energy calibration
    - ▪ A lot of Z are available anyway to calibrate and align everything

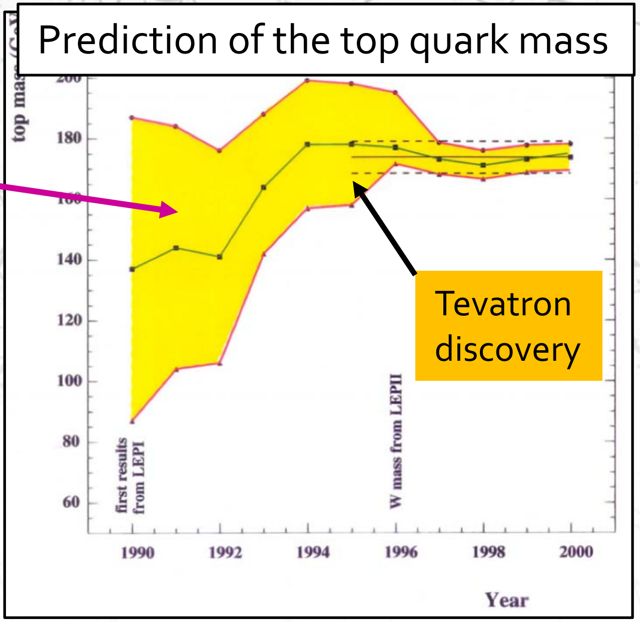
A look the rear mirror…

- Historic overview over important discoveries

Year	Discovery	Experiment	$\sqrt{s}$ [GeV]	Observation
1974	**c quark** (m~1.5 GeV)	e^+e^- ring (SLAC) Fixed target (BNL)	3.1 8	$\sigma(e^+e^- \to J/\Psi)$ $J/\Psi \to \mu^+\mu^-$
1975	**τ lepton** (m=1.777 GeV)	e^+e^- ring (SPEAR/SLAC)	8	$e^+e^- \to \tau^+\tau^-$ $e^+\mu^-$ events
1977	**b quark** (m~4.5 GeV)	Fixed target (FNAL)	25	$\Upsilon \to \mu^+\mu^-$
1979	**gluon** (m = 0)	e^+e^- ring (PETRA/DESY)	30	$e^+e^- \to qqg$ Three-jet events
1983	**W, Z** (m ~ 80, 91 GeV)	$p\bar{p}$ ring (SPS/CERN)	900	$W \to \ell\bar{\nu}$ $Z \to \ell^+\ell^-$
1989	**Three neutrino generations**	e^+e^- ring (LEP/CERN)	91	Z-boson lineshape *measurement*
1995	**t quark** (m=173 GeV)	$p\bar{p}$ ring (Tevatron/FNAL)	1960	Two semileptonic t-quark decays
2012	**Higgs boson** (m=125 GeV)	pp ring (LHC/CERN)	8000	$H \to \gamma\gamma$, $H \to Z^*Z \to 4\ell$

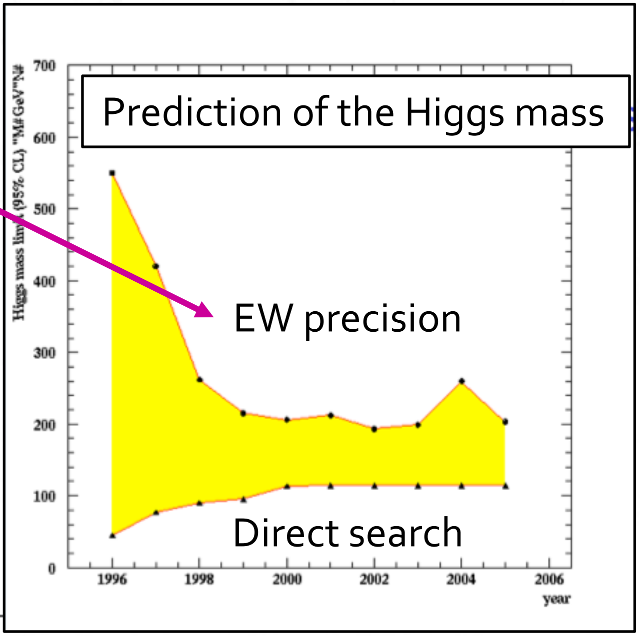
Indirect evidence from Precision Measurements

- Top quark
  - 1990-1994: Mass predicted from quantum loops
    - m_{top}(pred.) = 178.0 ± 10 GeV
  - 1995: Discovered at the Tevatron (DØ, CDF) ✓
    - Today: m_{top}(obs.) = 173.23± 0.7 GeV


Prediction of the top quark mass

Tevatron discovery

- Higgs boson
  - 1996-2011: Mass predicted from quantum loops
    - m_{Higgs}(pred.) = 98^{+25}_{-21} GeV
  - 2012: Discovery at the LHC (ATLAS, CMS) ✓
    - Today: m_{Higgs}(obs.) = 125.09 ± 0.24 GeV

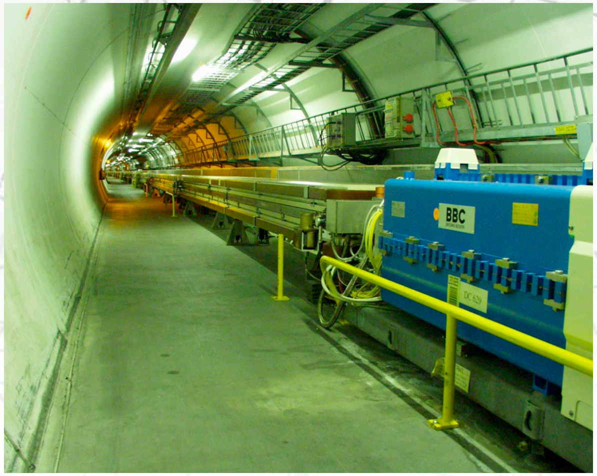

Prediction of the Higgs mass

EW precision

Direct search

- Lesson:
  - Precision measurements interpreted via quantum loop corrections can give very strong constraints on particles at higher masses than what can be directly probed!

LEP and the Rise of Precison



- 27 km circumference e^+e^- collider
  - "LEP tunnel", now "LHC tunnel"
- 1989-1995: Operation as *Z factory* at $\sqrt{s} \simeq 91$ GeV
  - 1989: Only three species of light, active neutrinos:

    $\boxed{\nu_e,\ \nu_\mu,\ \text{and}\ \nu_\tau}$

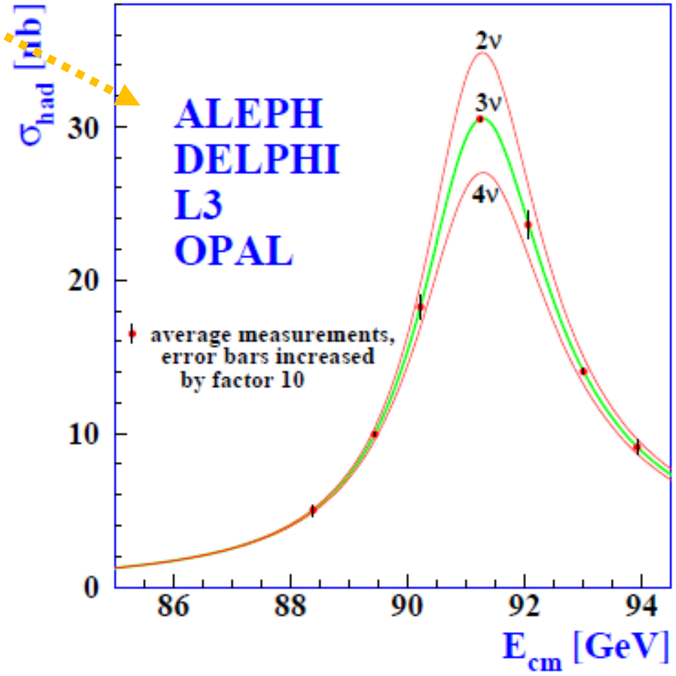
    - $e^+e^- \to Z \to$ hadrons at LEP1; measurement of the Z boson lineshape
  - After 5 years at LEP1: per-mille level precision

    $N_\nu = 2.984 \pm 0.008$

    $\Gamma_Z = 2495.2 \pm 2.3$ MeV

    $m_Z = 91187.5 \pm 2.1$ MeV

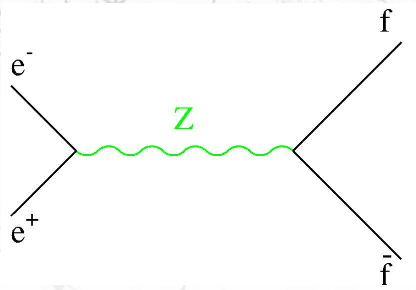
    $\alpha_s = 0.1190 \pm 0.0025$



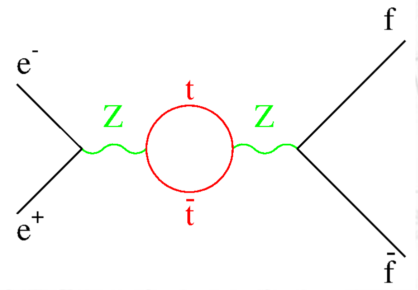
- 1996-2000: Operation at WW threshold and above
  - W mass
  - Higgs search
    - Just missed it…

Why precision measurements are interesting

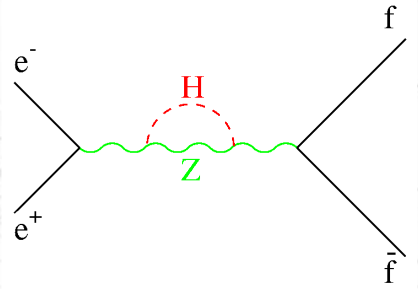
- Electroweak observables can be calculated / predicted with precision
  - They are sensitive to heavier particles through quantum corrections



Tree level



$0.002 \times \frac{m_t^2}{m_W^2} \simeq 1\%$



$-0.0006 \times \left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right)$

[small correction]

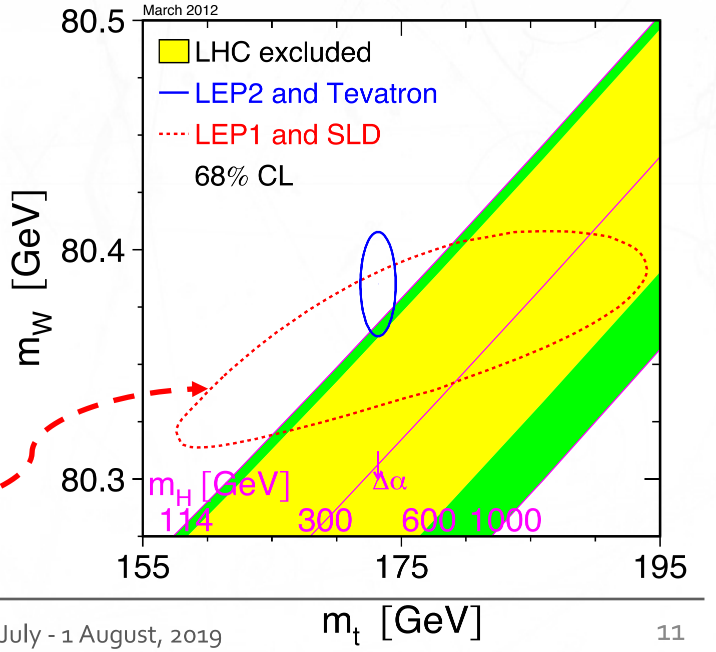
- Example: $\Gamma_Z \to \Gamma_Z \times (1+\Delta\rho)$

$$\Delta\rho = 0.0020 \times \frac{m_t^2}{m_W^2} - 0.0006 \times \left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \ldots$$

- Similarly, $m^2_W = m^2_Z \cos^2\theta_W^{eff} (1+\Delta\rho)$

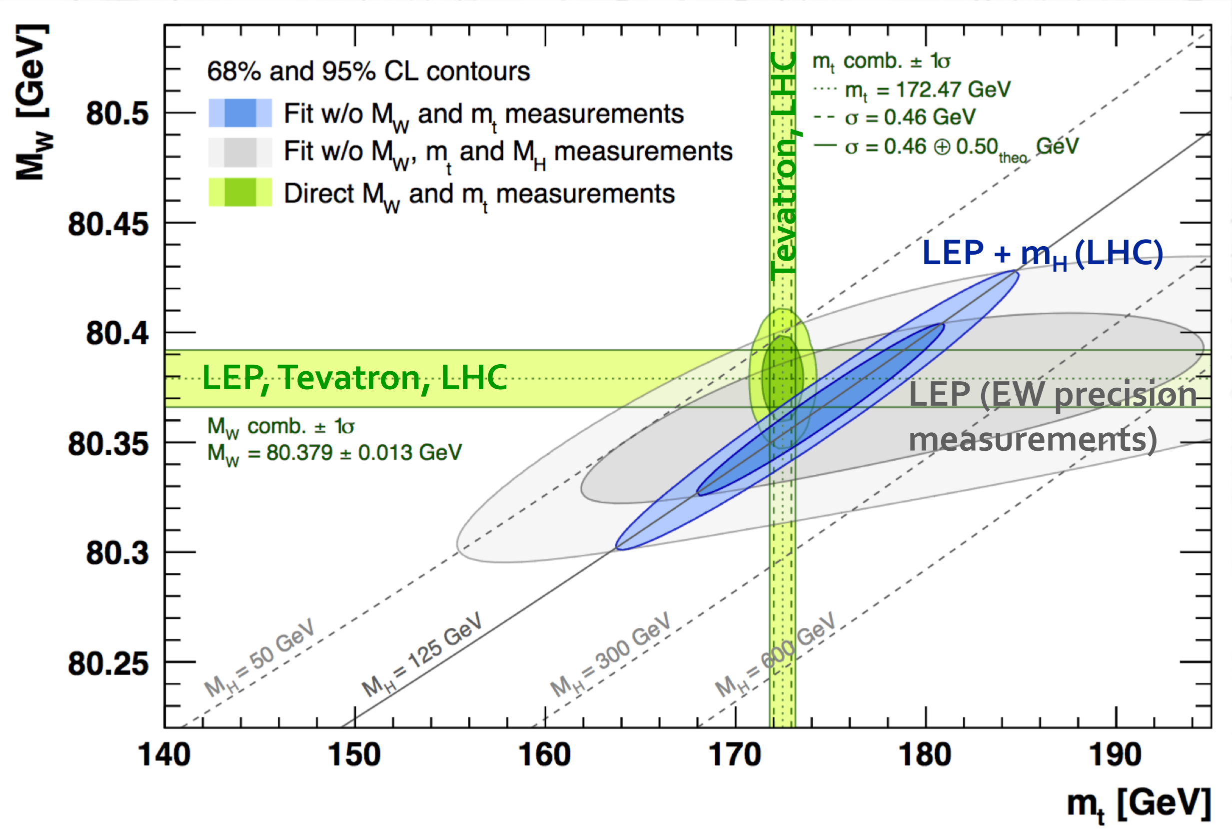
  ($\sin^2\theta_W^{eff}$ from, e.g., asymmetries)

- Precict m_W and m_{top} from Z measurements



Precison measurements

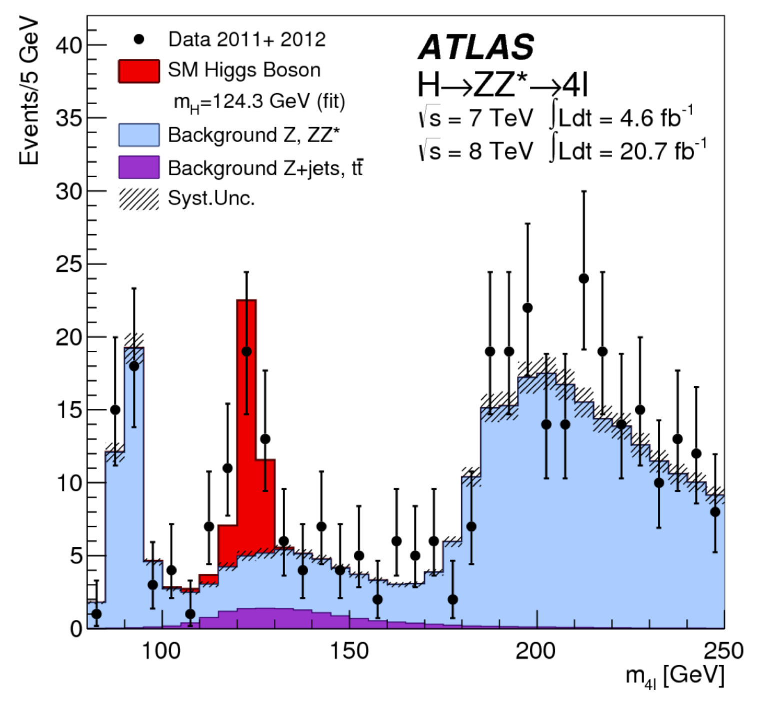
- With m_{top}, m_W and m_H known, the Standard Model has nowhere to go

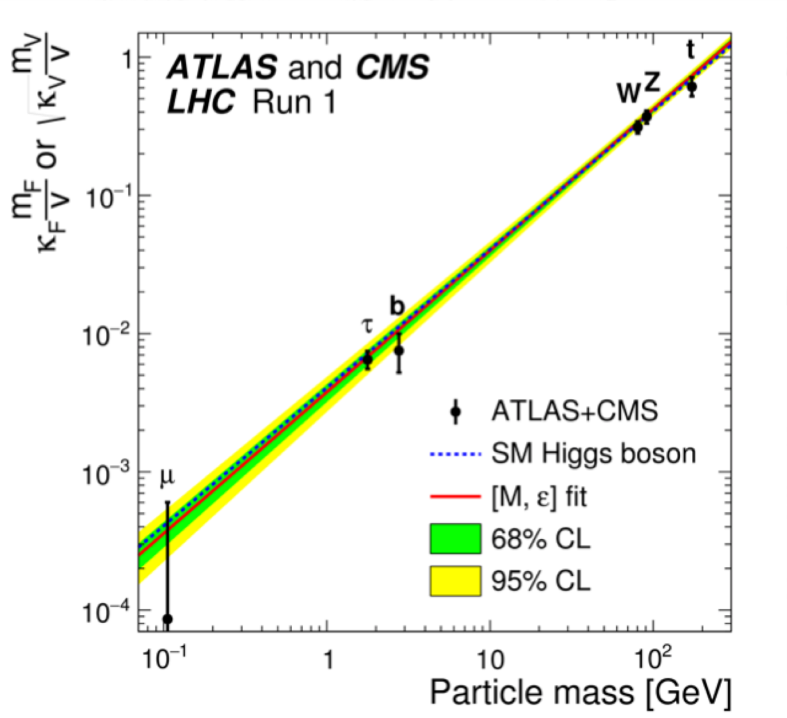


- ❑ Within current precision direct and indirect constraints are consistent
  - ❖ No evidence for the need for BSM physics
- ❑ But what if measurements precisions were improved ?
  - ❖ Strong incentive to significantly improve the precision of all measurement

Where we stand:
Status of the Standard Model

"The" Higgs



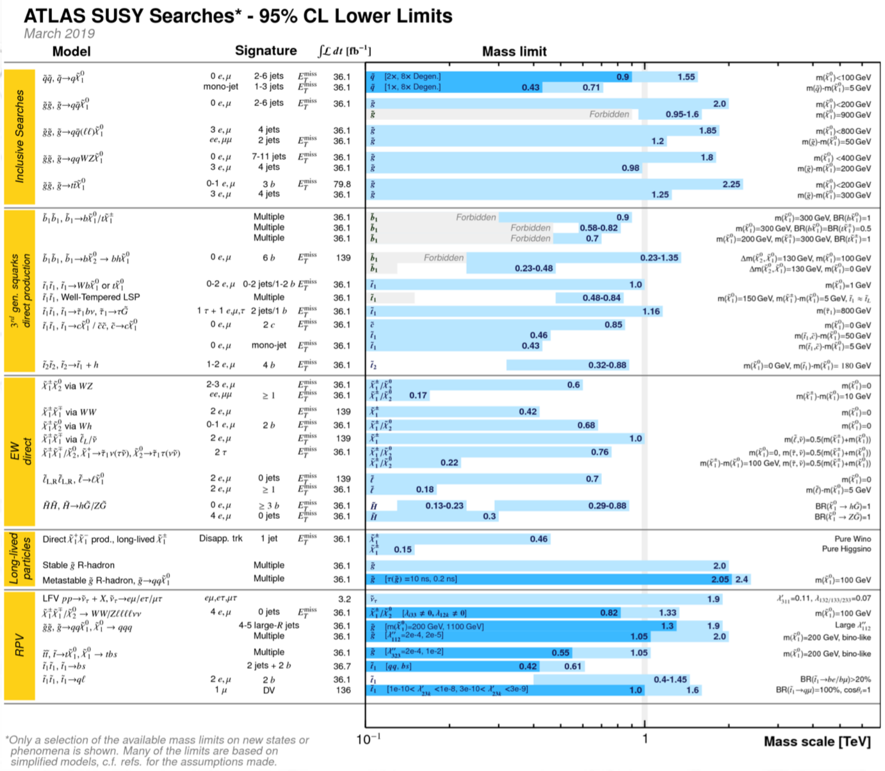


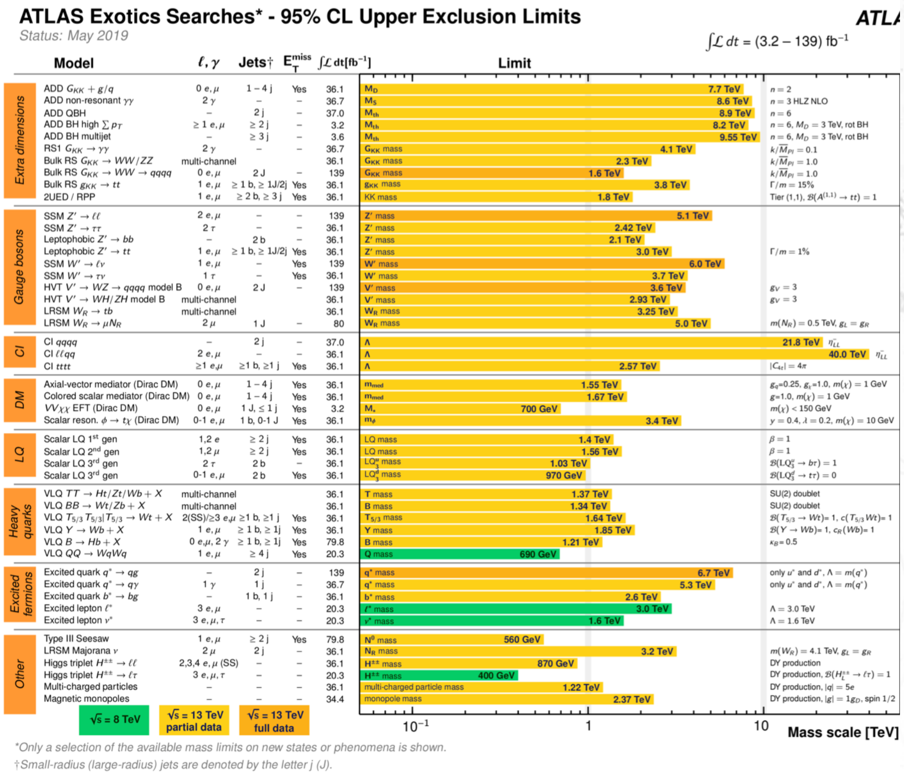
Discorered at the LHC in 2012…

…and to current precision, looks pretty Standard Model like

- But is the current precision "good enough" ?
  - At which level (if any) do we expect deviations from SM predictions to appear?

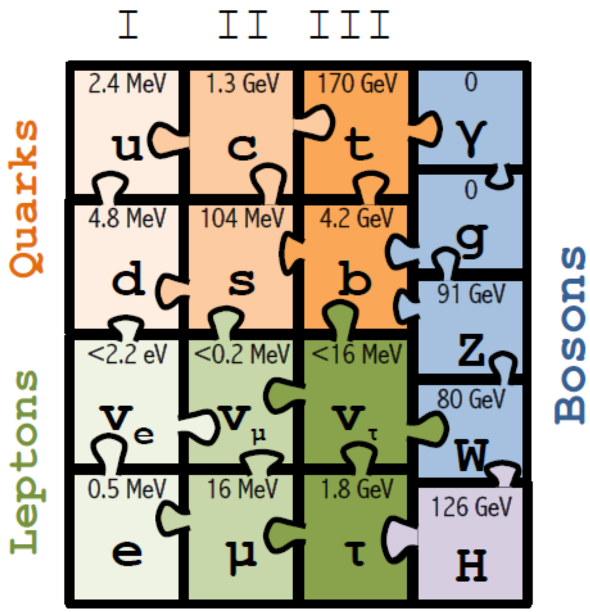
BSM Searches



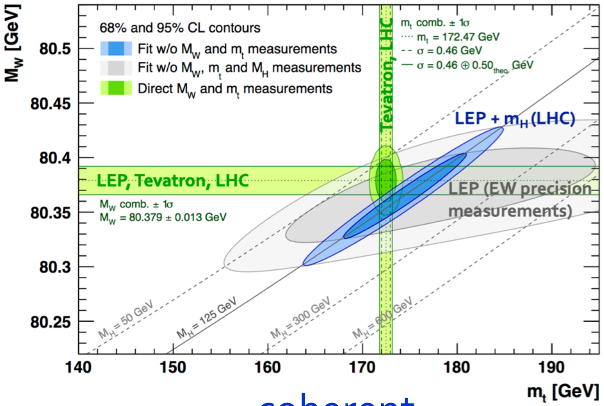


- So far, no indications for new BSM physics up to several hundred GeV
  - However: in flavour physics, tensions observed between LHCb data and SM predicitions

Standard Model Complete…



complete



coherent

With the Higgs boson, the Standard Model as a theory of particles and their interactions is now

- ✓ complete
- ✓ coherent
- ✓ predictive to all energies

Is this the end ?

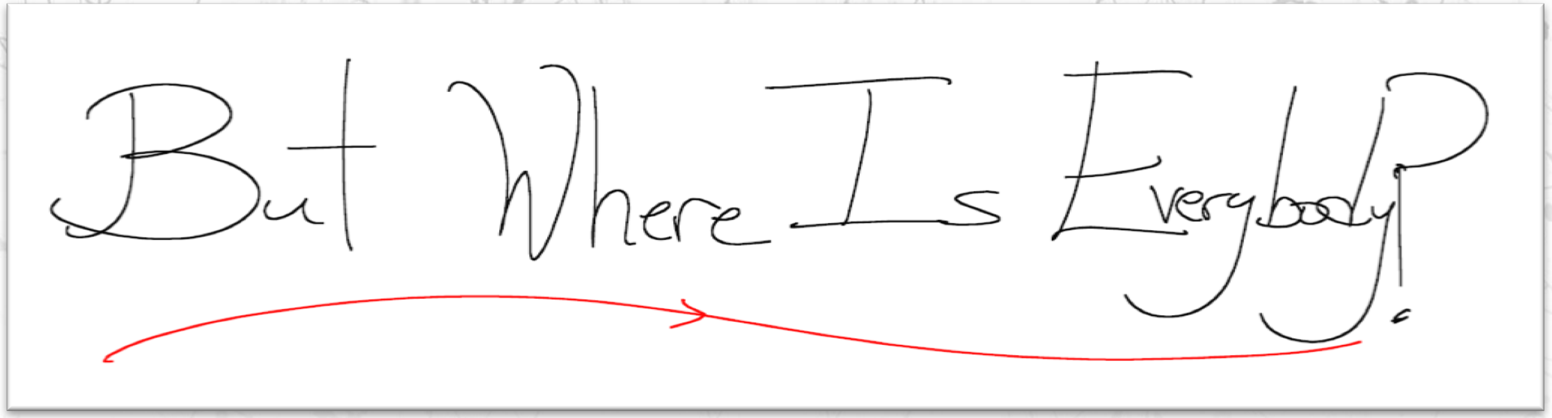
…most likely not… !?

Many unanswered questions based on experimental observations?

- ☐ Why 3 generations of fermions ?
- ☐ What is the origin of neutrino masses and oscillations ?
- ☐ What is the composition of dark matter ?
- ☐ What is the origin of the matter-antimatter asymmetry in the Universe [BAU] ?
- ☐ Why is gravity so weak ?
- ☐ Why is the Higgs boson so light ?
  - so-called "naturalness" or "hierarchy" problem
- ☐ What is the origin of the Universe's accelerated expansion ?

New Physics ?

- Many diverse theoretical ideas to extend the Standard Model (with new particles)



But Where Is Everybody?

- Is new physics at larger masses ? Or at smaller couplings ? Or both ?
  - Only way to find out: *go look*, following the historical approach:
    - Direct searches for new heavy particles
      - ⇒ Need colliders with *larger energies*

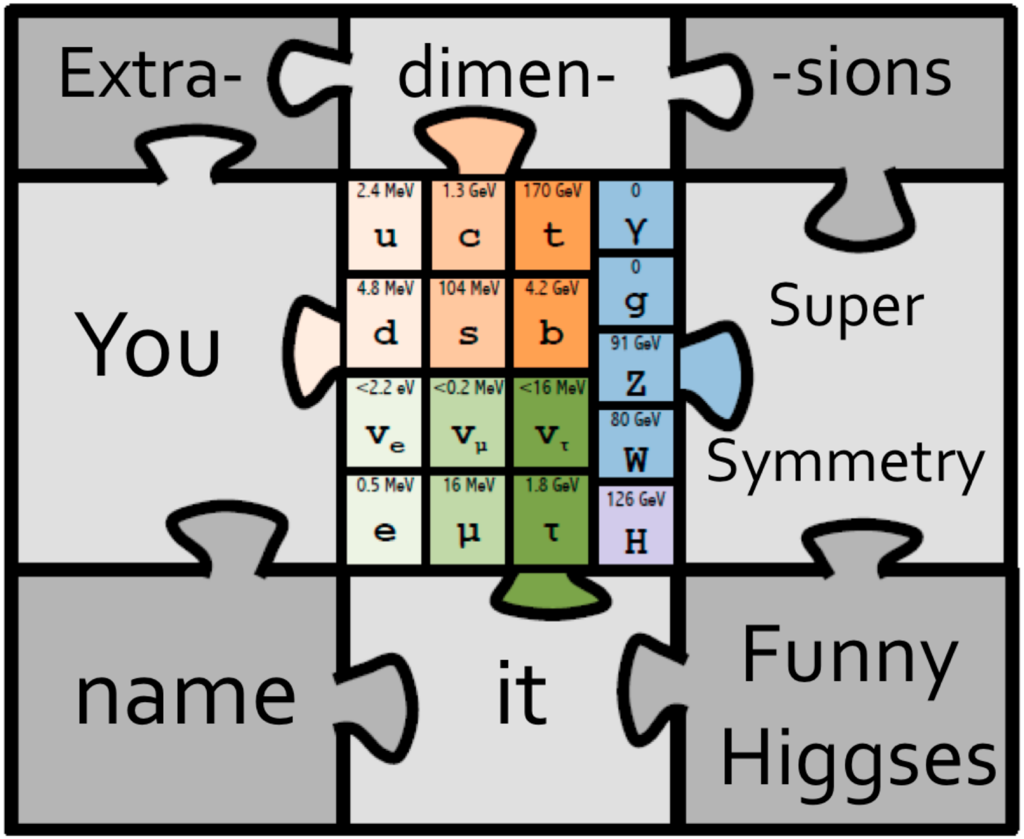
Energy frontier

    - Searches for the imprint of New Physics at lower energies, e.g. on the properties of Z, W, top, and Higgs particles
      - ⇒ Need colliders / measurements with *unprecedented accuracy*

Precision frontier

Energy vs Precision

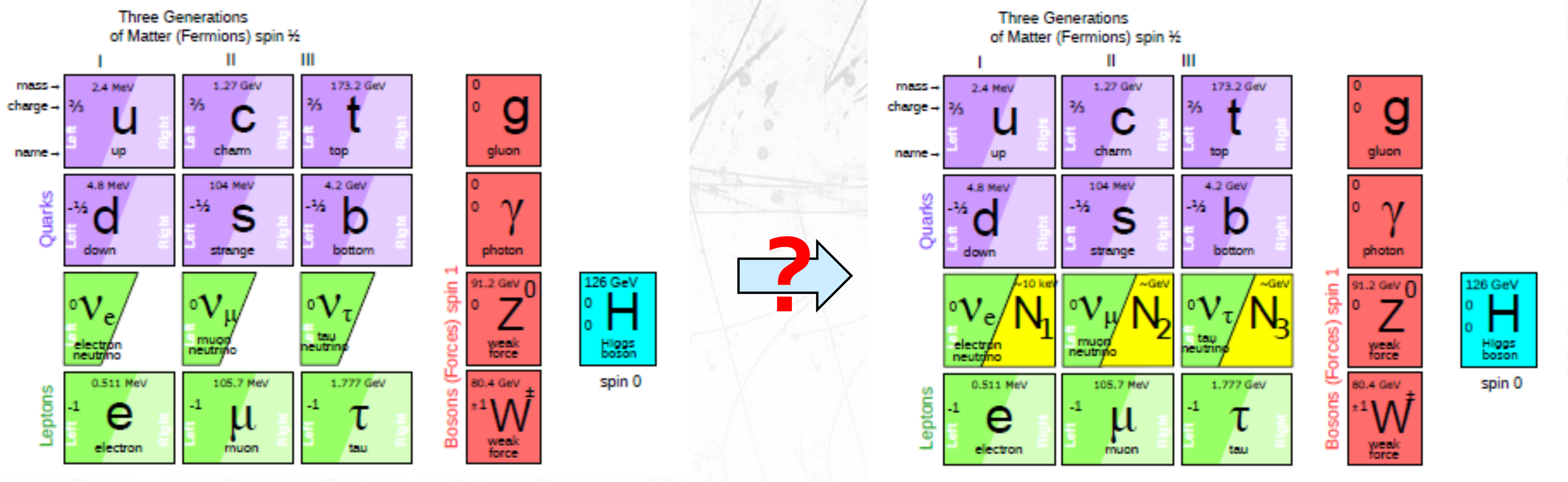
- Many ideas lean towards higher-energy replicas of the standard theory



- ❑ Direct searches at larger energies may be the key – but how much larger ?
  - ❖ Rare decays and precise measurements may also unveil these extension's imprints

Precision vs Energy

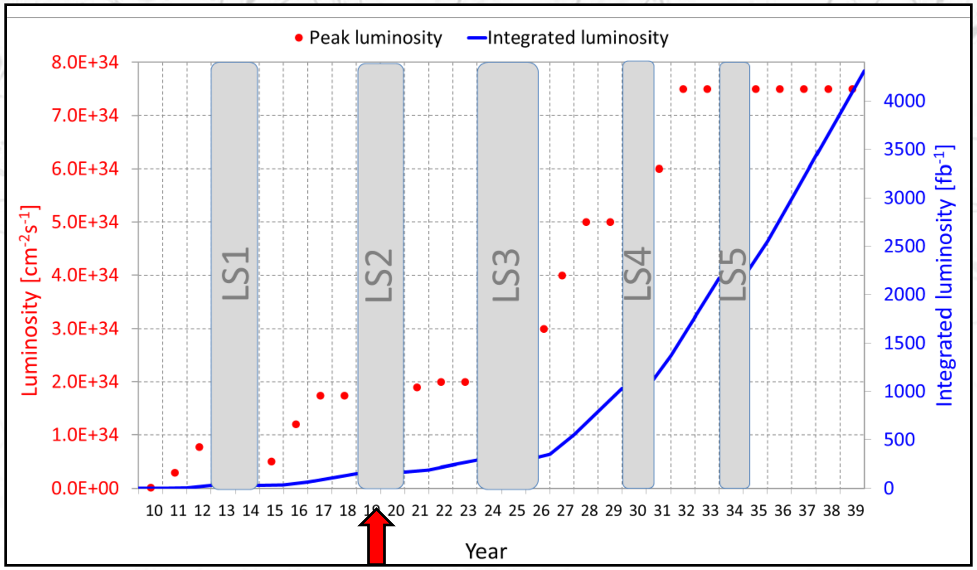
- The Standard Model is complete ? Obviously three pieces missing !



- Three right-handed neutrinos ?
  - Extremely small couplings, nearly impossible to find but could explain nearly everything !
    - Small m_ν (see-saw), DM (light N_1), and BAU (leptogenesis)
  - Need very-high-precision experiments to unveil
    - Could cause a slight reduction (increase) in the Z (H) invisible decay width
    - Could open exotic Z and Higgs decays: Z, H → $\nu_i N_i$
      - Possibly measurable / detectable in precision e^+e^- collisions
      - Most likely out of reach for hadron colliders (small couplings)

Where we are heading

- The LHC is still pretty much in its childhood
  - Factor 30 more luminosity to be collected

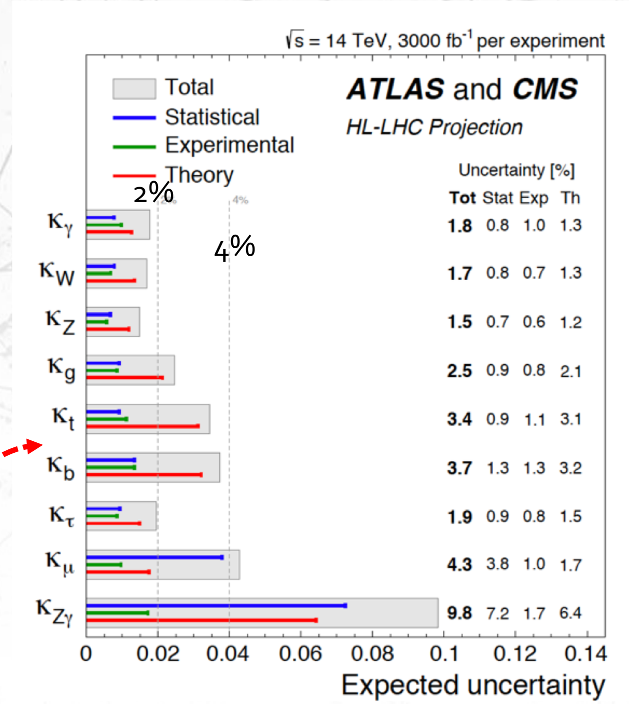


- Until the end of HL-LHC (~2037 !)
  - Exciting search programme for New Physics
    - Stop: 1.5 TeV; squarks/gluinos: 3 TeV; Z′: 7 TeV; etc., etc.
  - Important precision measurement
    - Higgs couplings to 2-4%
    - Top quark mass to 200 MeV
    - W boson to 10 MeV ?
    - Flavour physics measurements

Be prepared for the unexpected

Precision Higgs physics – The need for a Higgs Factory

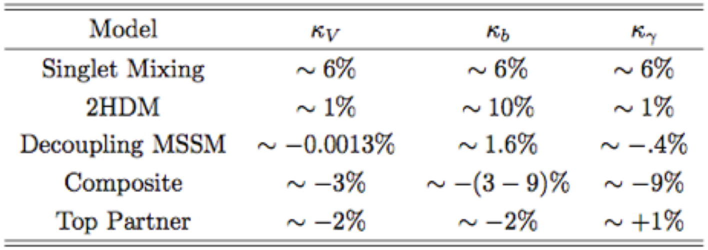
- The Higgs boson is different from all other SM particles
  - May possibly open window to *new physics ?*
  - Study precisely its properties to look for possible deviations
- The (HL-)LHC is already a "*Higgs factory*"
  - Fabulous statistics
    - At HL-LHC, > 10^8 Higgs bosons produced in ATLAS + CMS
  - Main challenge is backgrounds
    - Many decay modes are hard to identify
  - Expected HL-LHC precisions at the "few percent level"
- Is this precision good enough to make a "discovery" ?



- Higgs couplings are sensitive to New Physics (NP)
  - Expected deviations from SM coupling strengths depend on NP scale:

$$\frac{g_{HXX}}{g_{HXX}^{SM}} \approx 1 + \delta \times \left(\frac{1\,\mathrm{TeV}}{\Lambda_{\mathrm{NP}}} \right)^2$$

with **δ** =



Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

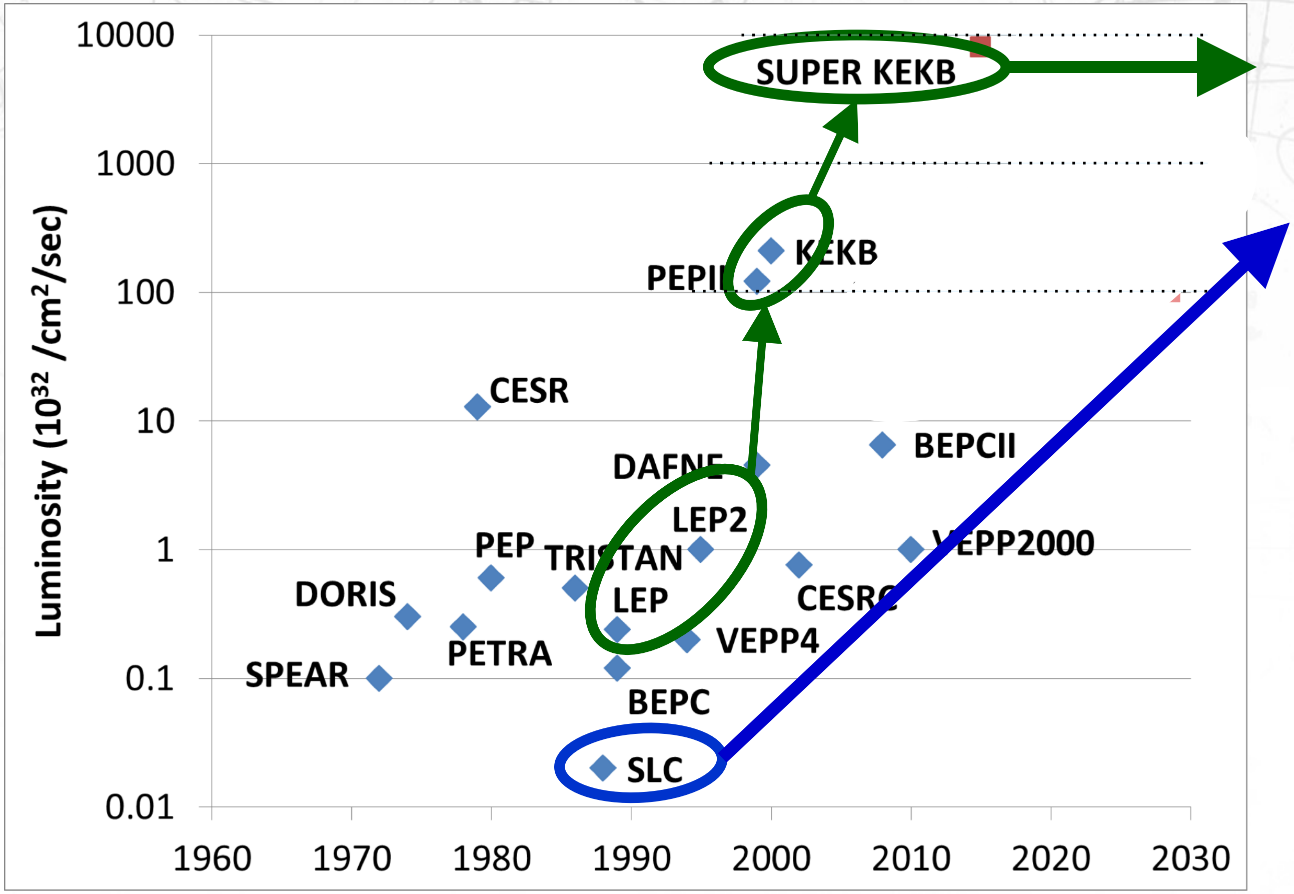
- Need a <u>*minimum*</u> of 1% precision on couplings for a 5σ discovery if Λ_{NP} = 1 TeV
  - And better for heavier New Physics

Need a precision Higgs factory

An experimental strategy for the future:
e^+e^- colliders

Precision requires luminosity

- So far, all e^+e^- colliders except SLC (at SLAC) have been circular
  - Over time there has been a dramatic increase in luminosity
- The next e^+e^- collider will be …



Circular ?

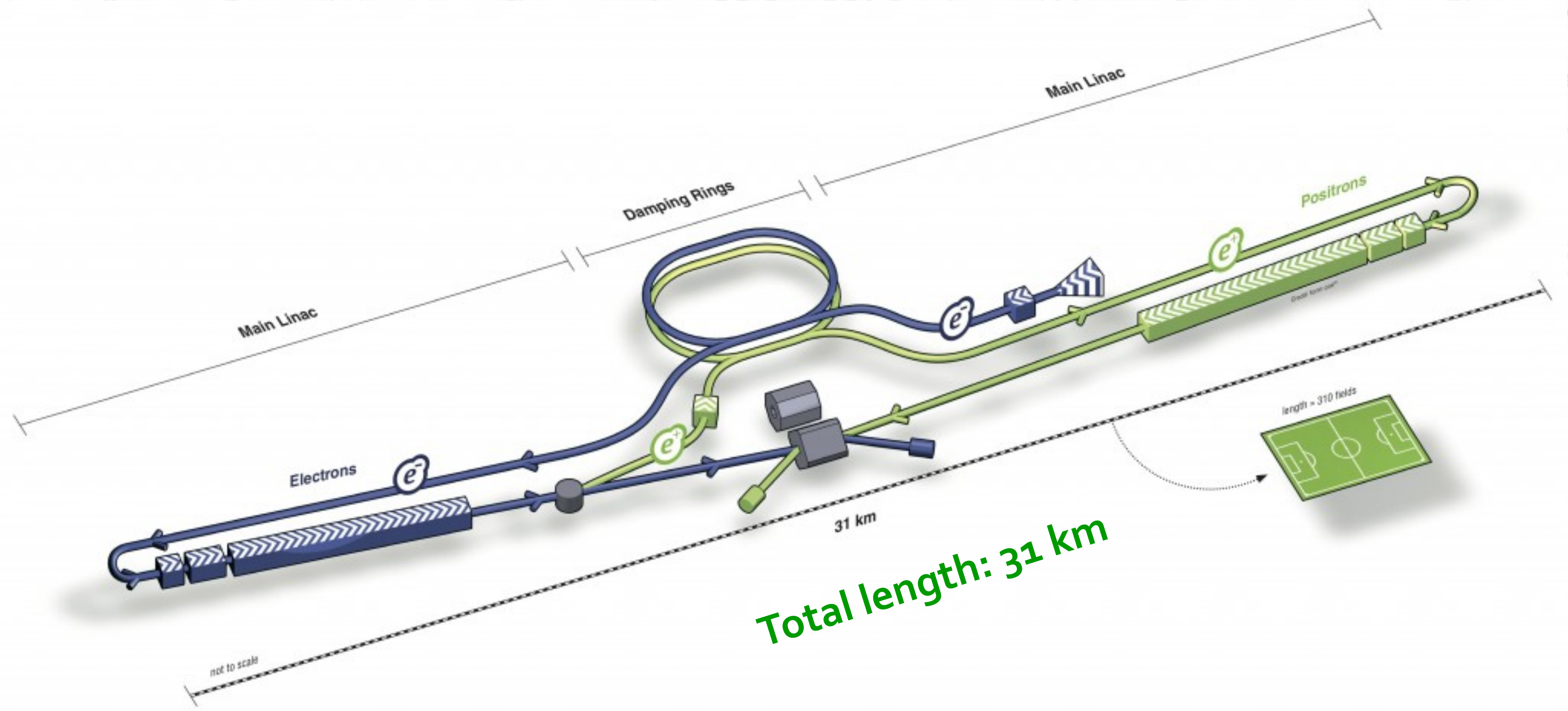
FCC-ee, CEPC

Linear ?

ILC, CLIC

Linear or Circular ? (1)

- For 20 years, there was only one future e^+e^- collider project on the market
  - ☐ A 500 GeV e^+e^- linear collider, now called "ILC", proposed in the early 1990's

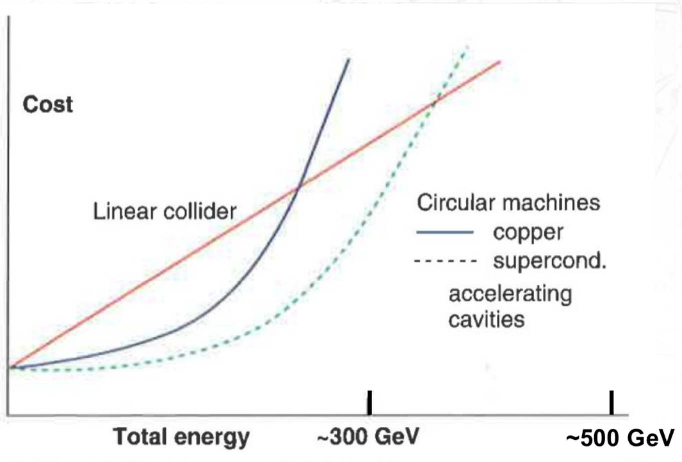


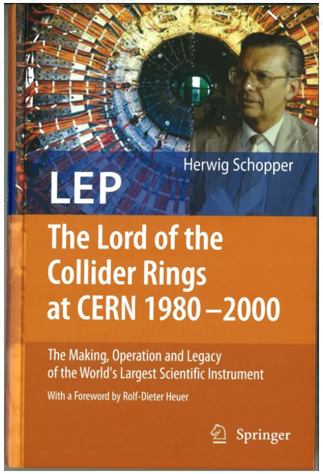
Total length: 31 km

  - ☐ Why not a 500 GeV circular collider ?

Linear or Circular ? (2)

- Why not a 500 GeV circular collider ?
  - Synchrotron radiation in circular machines
    - Energy lost per turn grows like $\boxed{\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4}$, e.g., 3.5 GeV per turn at LEP2
      - Must compensate with *R* and accelerating cavities ⟶ Cost grows like E^4 too

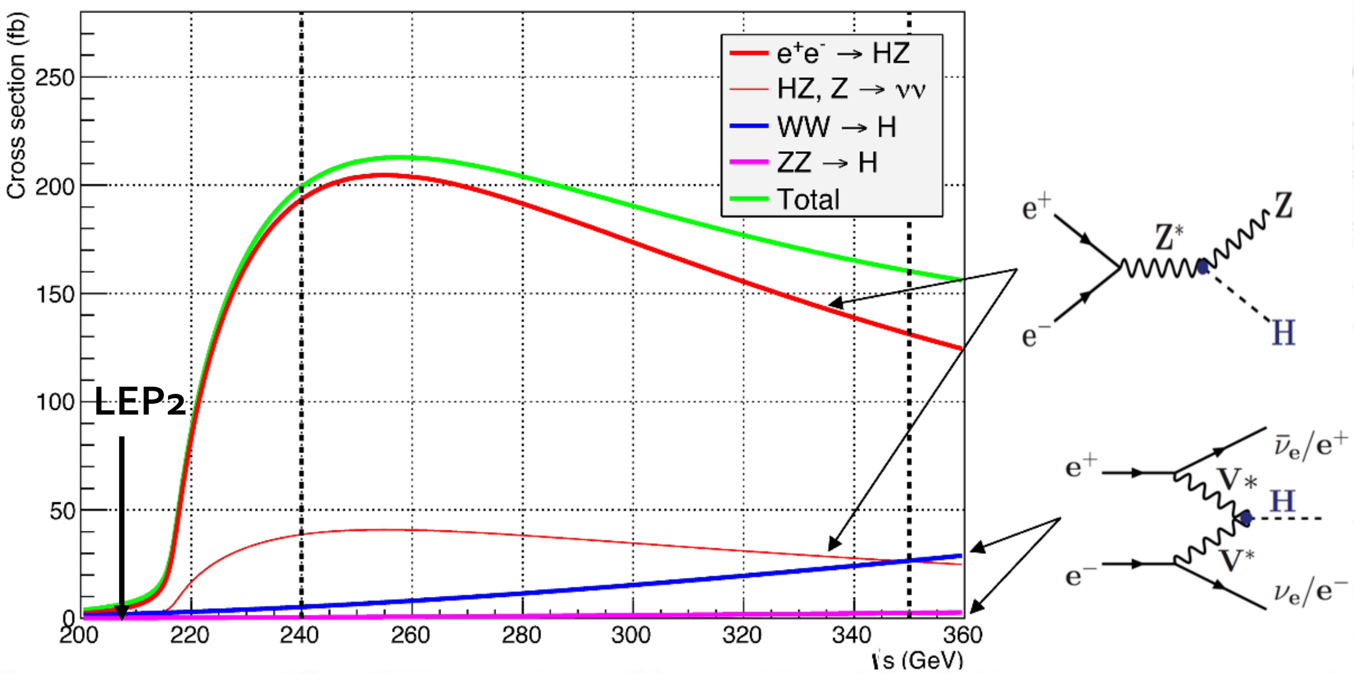




- "Up to a centre-of-mass energy of 350 GeV at least, a circular collider with superconducting accelerating cavities is the cheapest option", Herwig Schopper
- At and above 500 GeV, a e^+e^- collider can only be linear

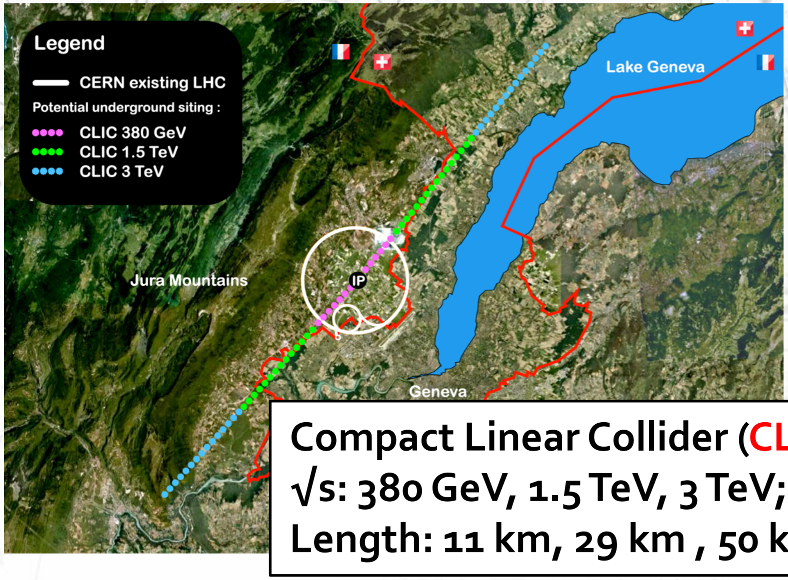
The Revival of Circular e^+e^- Colliders

- Interest for circular collider projects grew up again after first LHC results
  - The Higgs boson is light – LEP2 almost made it: only moderate √s increase needed

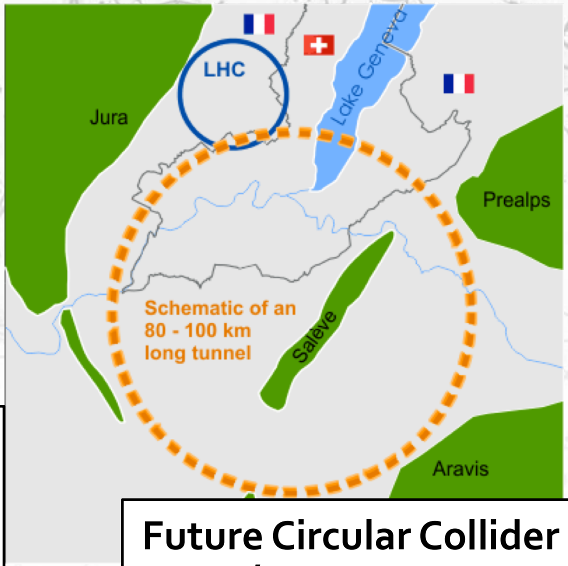


  - There seems to be no heavy new physics below 500 GeV
    - The interest of √s = 500 GeV (and even 1 TeV) is no longer quite that obvious
  - One way out: study with unprecedented precision the Z, W, H bosons and the top quark
    - Need to go up to the top-pair threshold (350+ GeV) anyway to study the top quark
    - Highest possible luminosities at 91, 160, 240 and 350+ GeV are needed

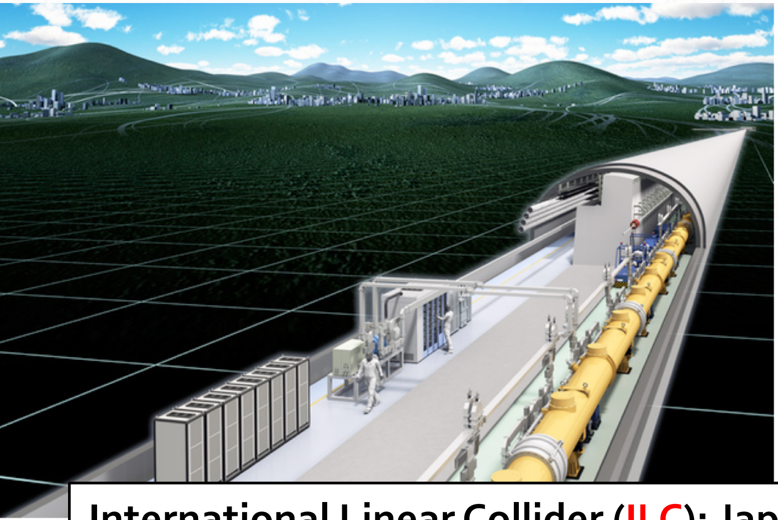
Studies of High-energy e^+e^- Colliders



Compact Linear Collider (CLIC): CERN
$\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV;
Length: 11 km, 29 km , 50 km

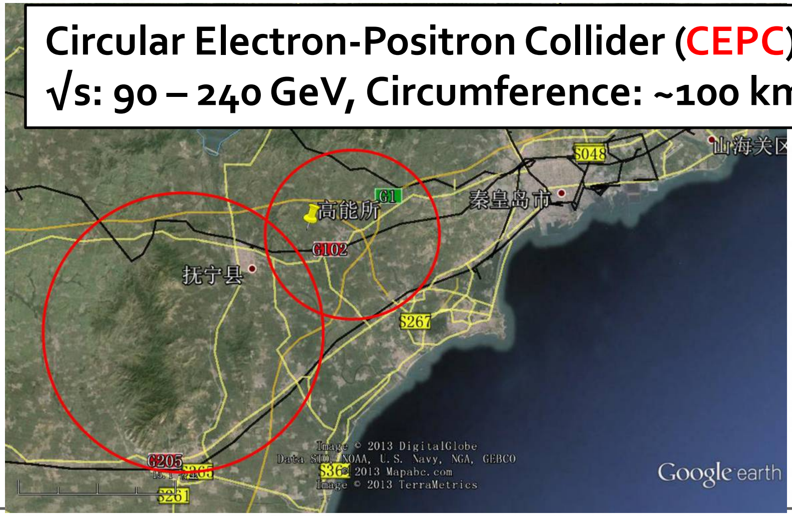


Future Circular Collider (FCC): CERN
e^+e^-, $\sqrt{s}$: 90 - 350 GeV; pp, $\sqrt{s}$: 100 TeV;
Circumference: 97.5 km

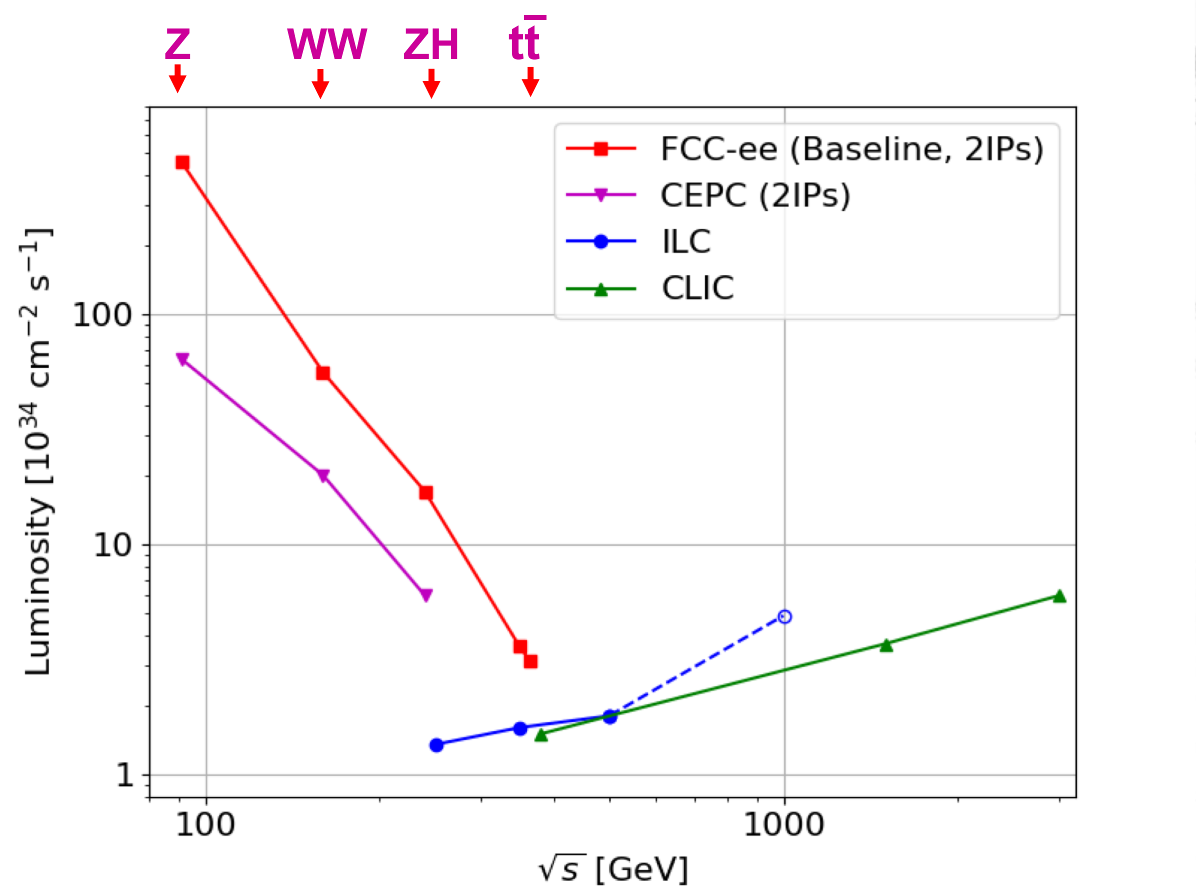


International Linear Collider (ILC): Japan
$\sqrt{s}$: 250 – 1000 GeV,
Now concentrating on $\sqrt{s}$ = 250 GeV,
Length: 21 km (250 GeV)

Circular Electron-Positron Collider (CEPC): China
$\sqrt{s}$: 90 – 240 GeV, Circumference: ~100 km



Projected Luminosities of e^+e^- Colliders



LEP@Z-pole:
$L = 0.01 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

0.01

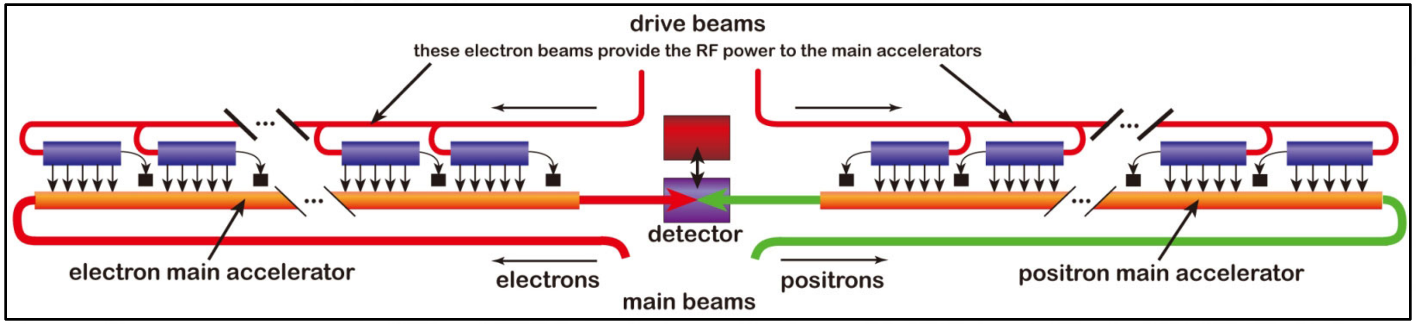
- Complementarity
  - ❑ Ultimate precision measurements (luminosity!) with circular colliders (FCC-ee)
  - ❑ Ultimate e^+e^- energies with linear colliders (CLIC)

ILC

- Originally designed for √s = 500 GeV, recently re-optimized for 250 GeV
  - Supported by 25 years of R&D and innovation
    - Complete technical design report delivered in 2013
      - In principle, ready for construction as soon as decision is taken
  - Machine has many technological challenges
    - ~10 km-long, high-gradient (31 MV/m), RF system
    - A very low β^* optics delivering small beam spot sizes at high intensity
      - Still to be demonstrated to be achievable
    - A positron source with no precedent
      - Performance cannot be verified before the construction is complete
    - A green-field project
  - Can deliver data to only one detector at a time
  - In principle upgradeable to √s = 1 TeV
    - And possibly more : CLIC or *plasma acceleration* later in the same tunnel (?)
  - No design to run at the Z pole

CLIC

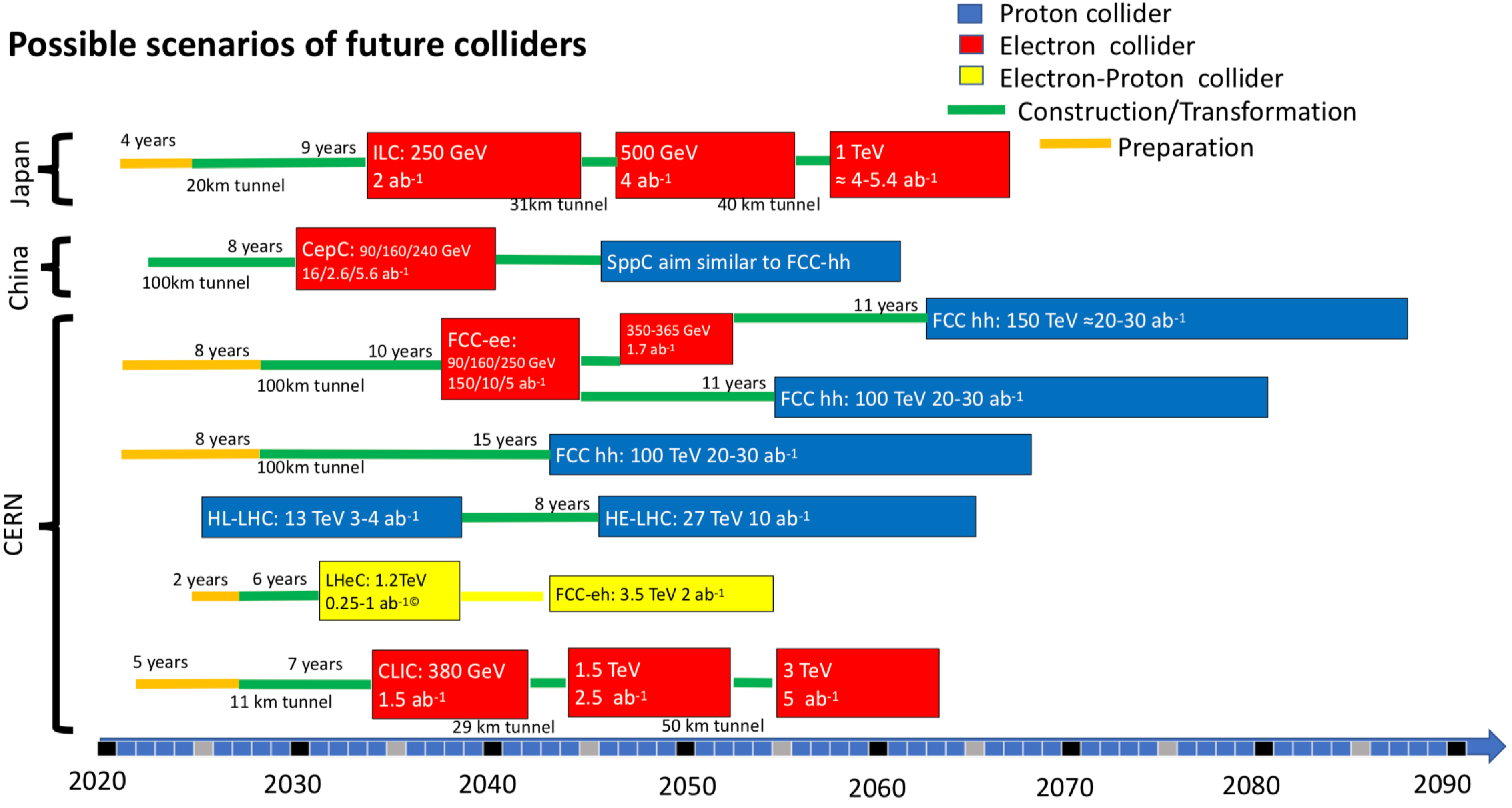
- Designed to reach the highest possible energies in e^+e^- collision
- In staging scenario, forseen to cover the three energy points $\sqrt{s}$ = 380, 1500, and 3000 GeV
  - More than 30 years of innovation and R&D
    - Very high acceleration gradient, 100 MV/m, from a 2-beam acceleration scheme
      - demonstrated via CLIC Test Facilities
    - Conceptual Design Report delivered in 2012
  - A number of technological challenges common with ILC
    - Very low β^* optics delivering small beam spot sizes at high intensity
    - Positron source with no precedent
  - Can deliver data to only one detector at a time
  - No design to run at the Z pole



FCC-ee

- Designed as highest luminosity Z, W, H, and top factory ($\sqrt{s}$=88-365 GeV)
  - Relatively young project: about six years old
    - Lots of progress – very solid design study (2014-2018)
      - Technology ready… on paper
      - Conceptual Design Report (CDR) published early this year
  - This machine has at least as many technological challenges as linear colliders
    - A high-power (200 MW), high-gradient (10 MV/m), 2 km-long, RF system
    - Loads of synchrotron radiation (100 MW) to deal with
    - A booster (for top up injection), and a double ring for e^+ and e^-
    - Optics with very low β^*, and large momentum acceptance
    - Transverse polarization for beam energy measurement
    - Two (possible four) experiments to serve
    - … and much more
  - Supported by 50 years of experience and progress with e^+e^- circular machines
    - Most of the above challenges starting to be addressed at SuperKEKB
      - FCC-ee will build on this experience
  - First step towards a 100 TeV proton-proton collider

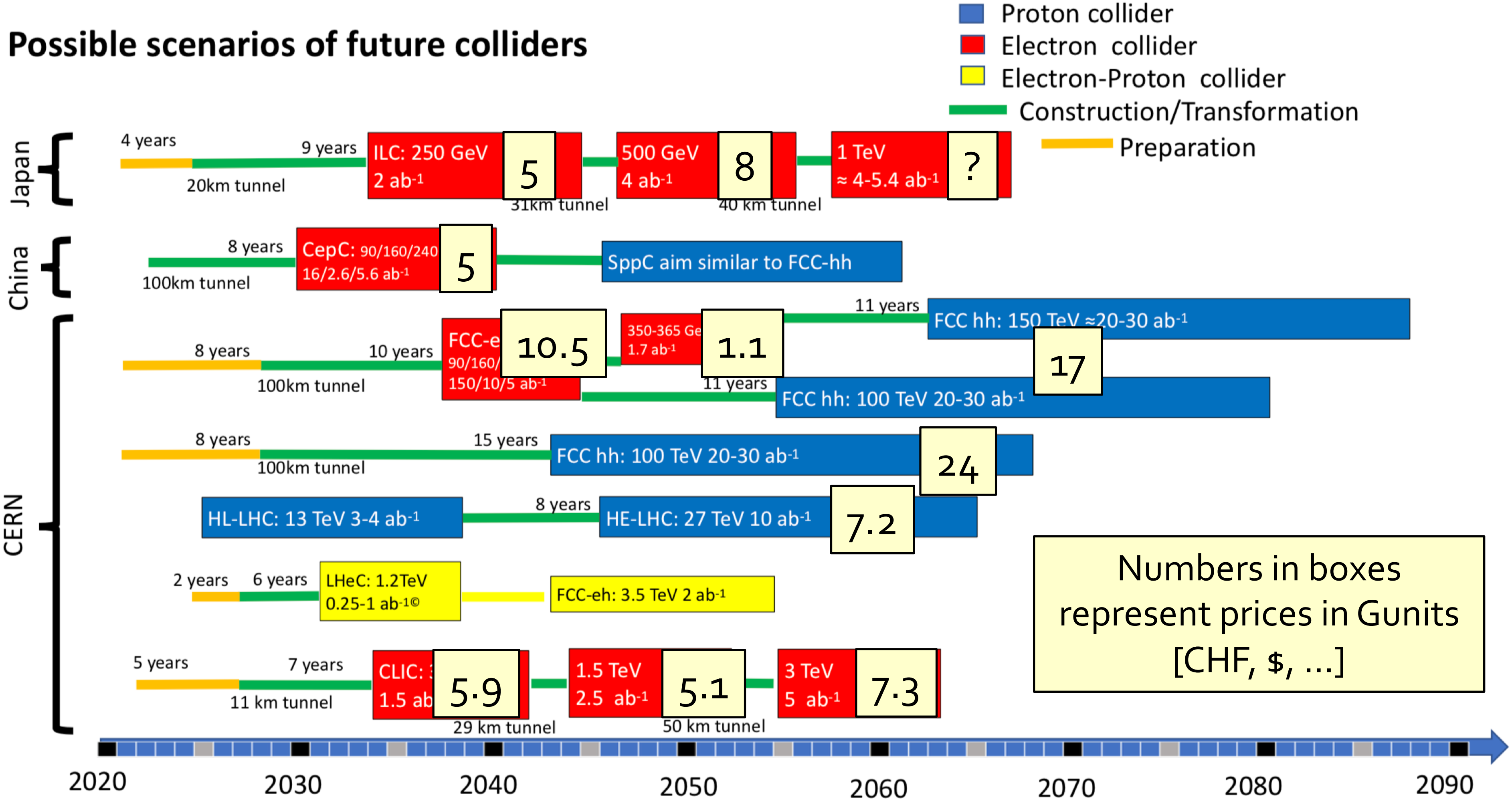
Landscape of proposed future colliders


Possible scenarios of future colliders

13/05/2019 UB

Landscape of proposed future colliders

Possible scenarios of future colliders



Numbers in boxes represent prices in Gunits [CHF, $, …]

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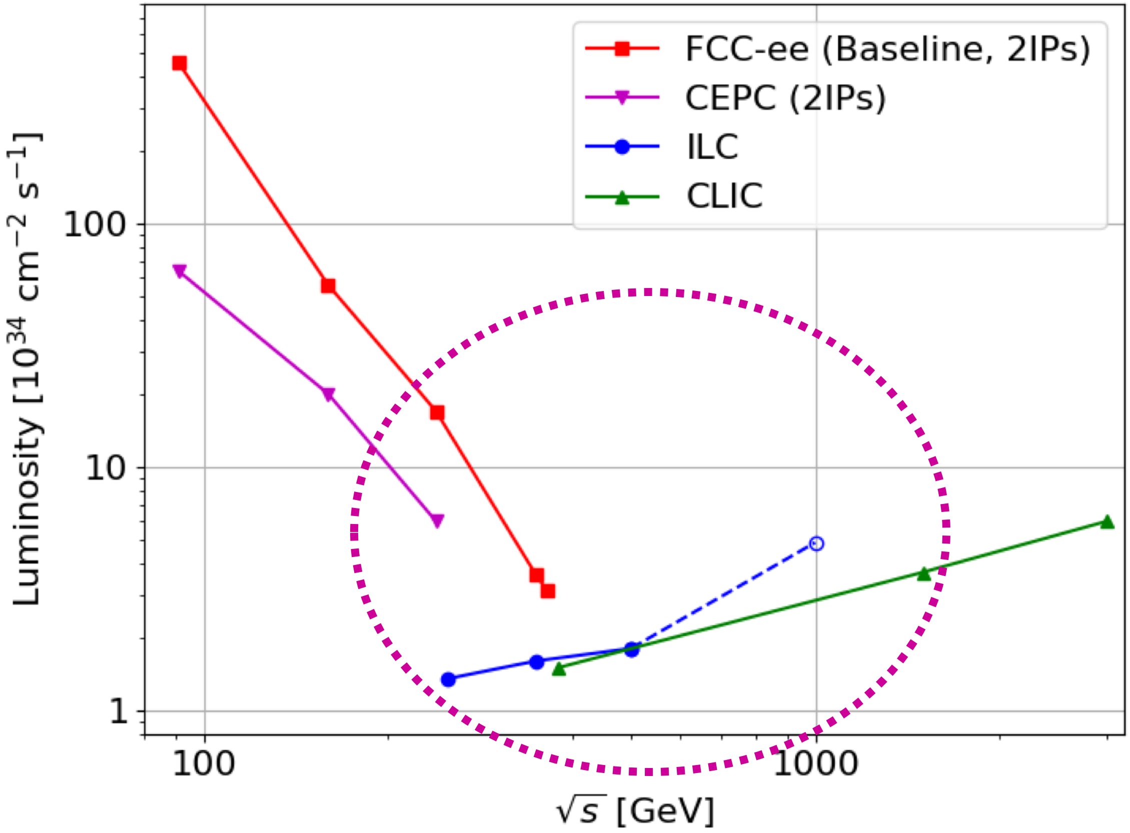
Precision Higgs Physics



Scenarios I have chosen to discuss / compare

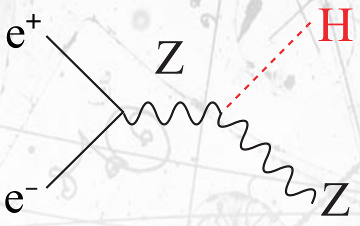
Facility	CEPC_{240}	FCC-ee_{365}	ILC_{500}	CLIC_{1500}
$\sqrt{s}$ [GeV]	240	240 / 365	250 / 350 / 500	380 / 1500
$\mathcal{L}$ [ab^{-1}]	5.6	5 / 1.5	2.0 / 0.2 / 4.0	1.0 / 2.5
# years	7	9	22	17
Polarisation	no	no	yes	yes
# Higgs (× 10^3)	1100	1000 / 240	500 / 40 / 800	150 / 600

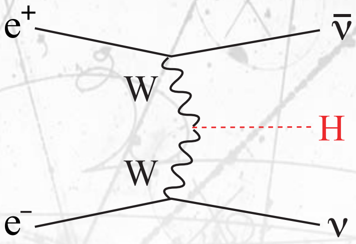
- The landscape is complicated; not easy to make a "fair" comparison:
  - CEPC: no *current* plans to go beyond $\sqrt{s}$ = 240 GeV
    - However, clearly technically feasible
  - FCC-ee: Both $\sqrt{s}$ = 240 and 365 GeV included in baseline project
    - The energy upgrade of FCC is the FCC-hh, which will bring ultimate precisions
  - ILC: Current baseline is 250 GeV only; but clearly an upgrade to 500 GeV is understood/hoped for
    - However, more than a factor two on price, and long time scale (Σ = 22 years)
  - CLIC: Have (arbitrarity) included the two first stages leaving out the the 3 TeV run
    - Regard the 3 TeV run as an "energy upgrade" comparable somehow to FCC-hh

Higgs Production

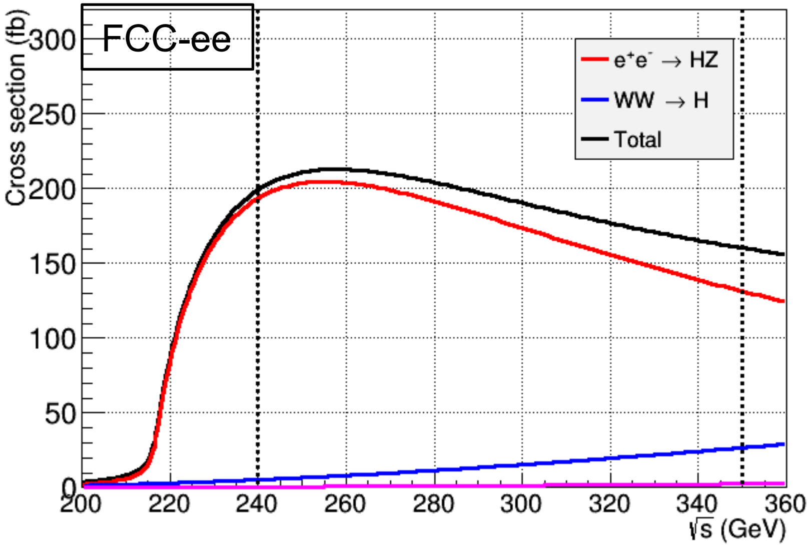
- Dominant production processes for $\sqrt{s} \leq 500$ GeV

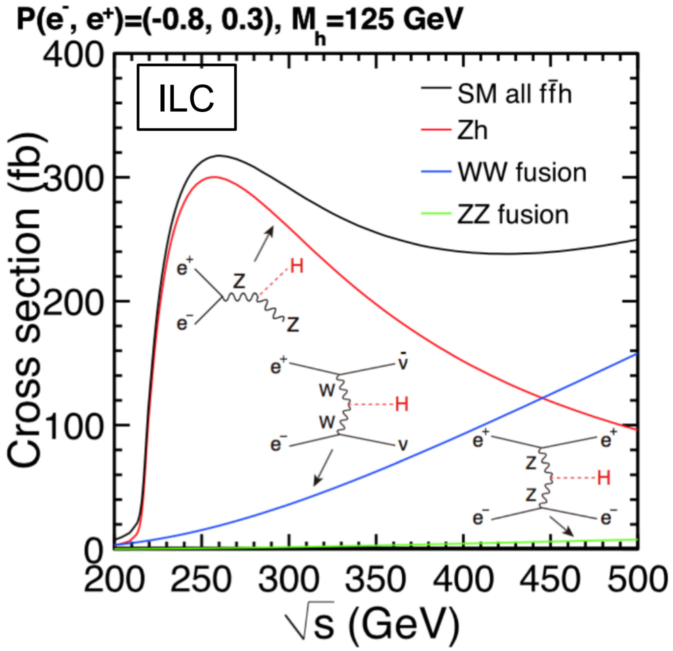
Higgs-strahlung





Boson fusion

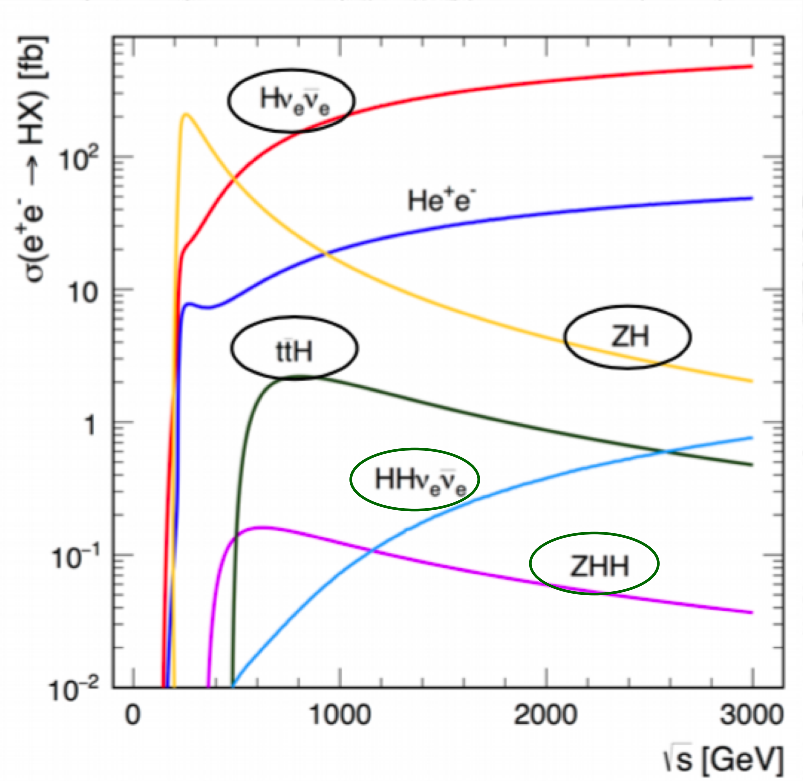




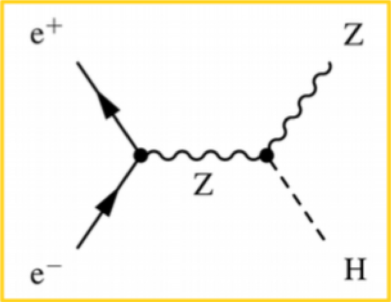
- **Effect of beam polarization**
  - **Higgs-strahlung cross section multiplied by $1 - P_- P_+ - A_e \times (P_- - P_+)$**
  - **Boson fusion cross section multiplied by $(1 - P_-) \times (1 + P_+)$**

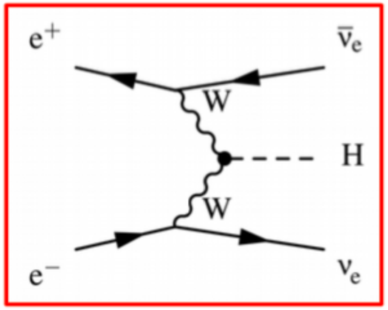
(exercise)

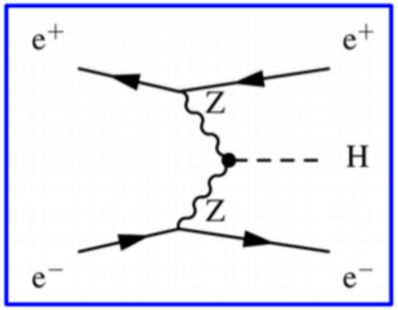
Moving to higher energies

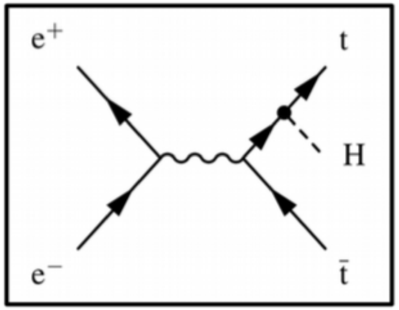


- Higgsstrahlung: $e^+e^- \to ZH$
  - ❑ $\sigma \sim 1/s$, dominant up to ≈ 450 GeV
- WW fusion: $e^+e^- \to H\nu_e\bar{\nu}_e$
  - ❑ $\sigma \sim \log(s)$, dominant above 450 GeV
  - ❑ Large statistics at high energy
- $t\bar{t}H$ production: $e^+e^- \to t\bar{t}H$
  - ❑ Accessible ≥ 500 GeV, maximum ≈ 800 GeV
  - ❑ Direct extraction of top Yukawa coupling
- ZHH and $HH\nu_e\bar{\nu}_e$ production
  - ❑ From 500 GeV (ZHH) and ≈800 GeV ($HH\nu_e\bar{\nu}_e$), dual Higgs production
  - ❑ Sensitivity to Higgs self coupling





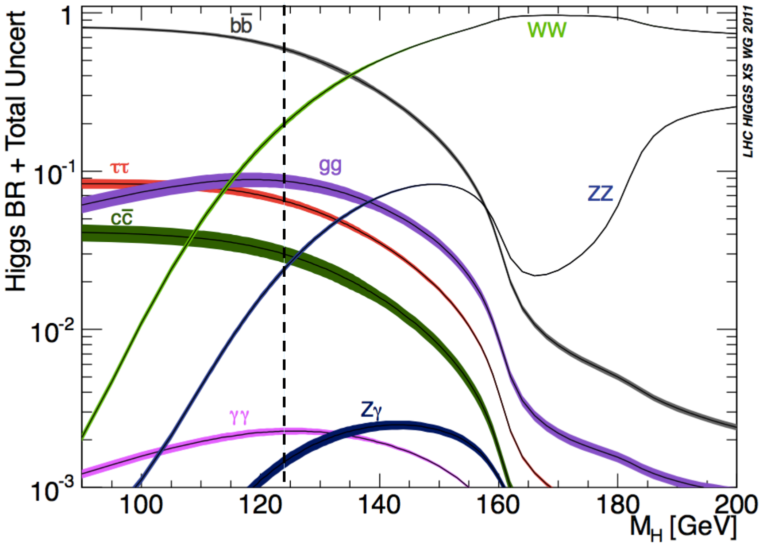




Higgs Decays

- Plan is to run at $\sqrt{s}$ = 240-250 GeV and 350-500 GeV in order to
  - Determine all Higgs couplings in a model-independent way
  - Infer the Higgs total decay width
  - Evaluate (or set limits on) the Higgs invisible or exotic decays
    - Through the measurements of $\sigma(e^+e^- \rightarrow H + X) \times BR(H \rightarrow YY)$

with Y = b, c, g, W, Z, γ, τ, μ, invisible



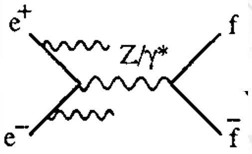
m_H = 125 GeV

Decay	BR [%]
bb	57.7
ττ	6.32
cc	2.91
μμ	0.022
WW	21.5
gg	8.57
ZZ	2.64
γγ	0.23
Zγ	0.15
ΓH [MeV]	4.07

- m_H = 125 GeV is a very good place to be for precision measurements !
  - All decay channels open and measurable – can test new physics from many angles

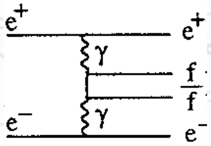
Higgs Backgrounds

- **Physics backgrounds are "small"**
  - For example, at $\sqrt{s}$ = 240 GeV



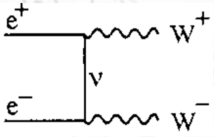
$e^+e^- \to q\bar{q}, l^+l^-$

60 pb



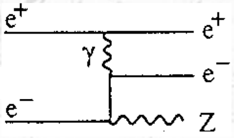
$\gamma\gamma \to q\bar{q}, \ell^+\ell^-$
m > 30 GeV

30 pb



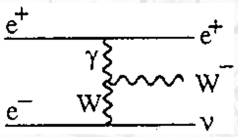
$e^+e^- \to W^+W^-$

16 pb



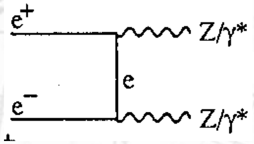
$e^+e^- \to Ze^+e^-$

3.8 pb



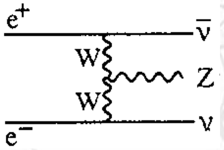
$e^+e^- \to We\nu$

1.4 pb



$e^+e^- \to ZZ$

1.3 pb



$e^+e^- \to Z\nu\bar{\nu}$

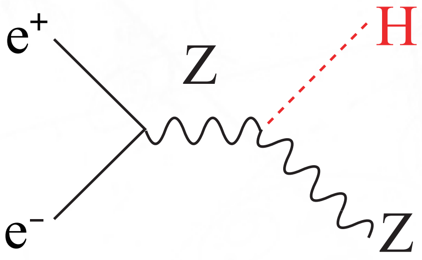
32 fb

- "Blue" cross sections decrease like 1/s
- "Green" cross sections increase slowly with s

Add $e^+e^- \to t\bar{t}$
for $\sqrt{s}$ > 345 GeV

0.6 pb

- To be compared to

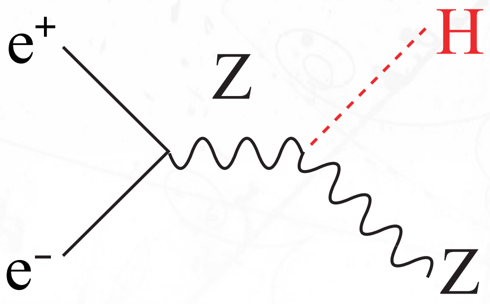


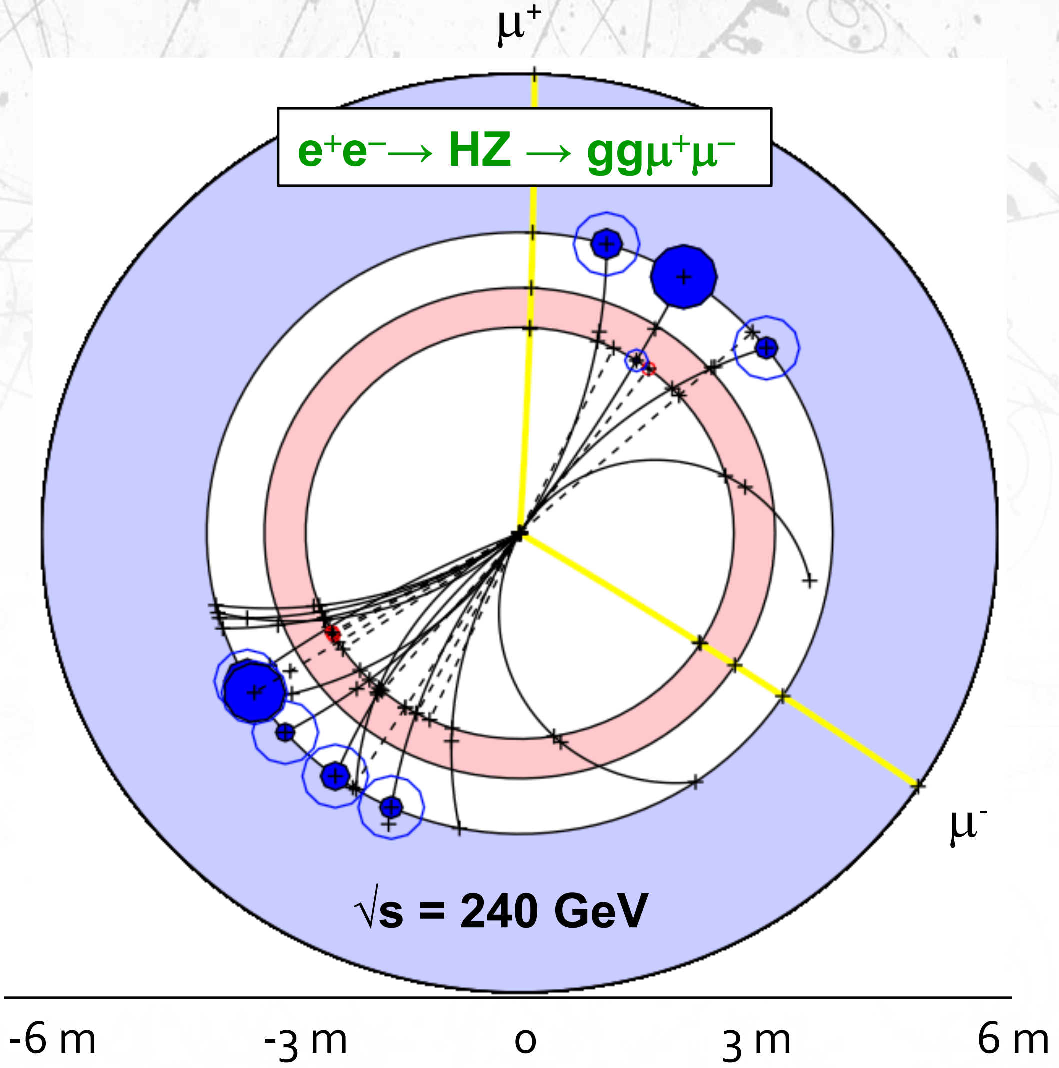
200 fb

- Only one to two orders of magnitude smaller
  - vs. 11 orders of magnitude in pp collisions
    - Trigger is 100% efficient
      - no need for trigger; all crossings are recorded
    - All Higgs events are useful and exploitable
    - Signal purity is large

Higgs Events

- Example of a Higgs boson event
  - Tagged with a Z boson
  - Very clean signature



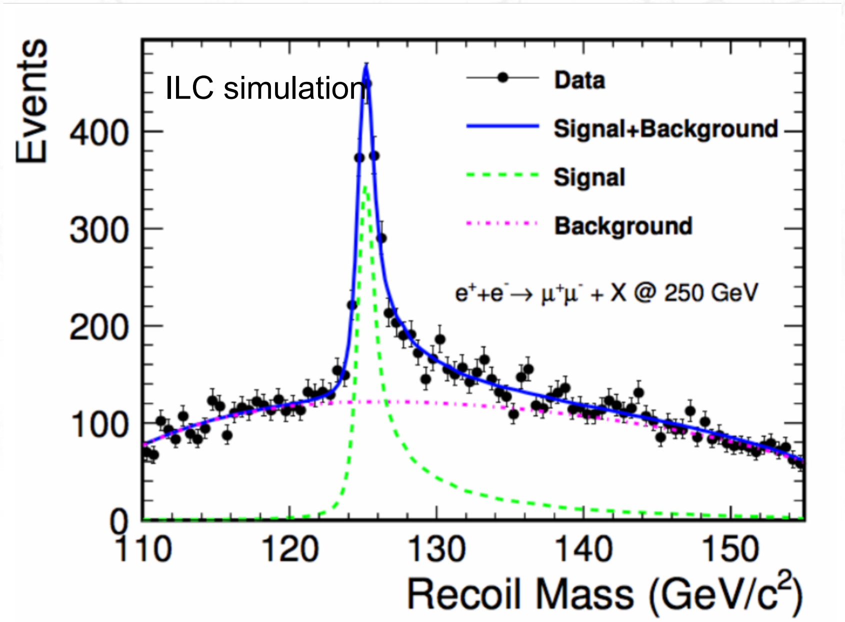


Higgs physics Analysis

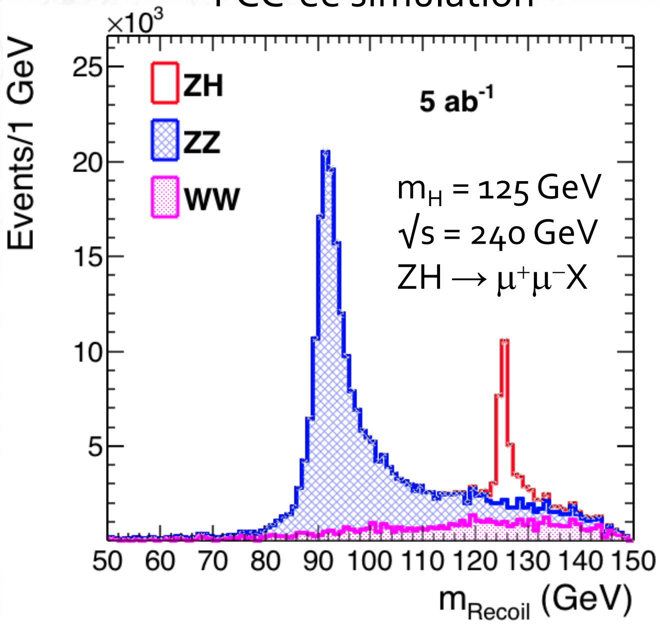
- **Example: Model-independent measurement of σ_{HZ} and g_{HZZ}**
  - The Higgs boson in HZ events is tagged by the presence of the $Z \to e^+e^-, \mu^+\mu^-$
    - Select events with a lepton pair ($e^+e^-, \mu^+\mu^-$) with mass compatible with m_Z
    - Apply total energy-momentum conservation to determine the "recoil mass"
      - $m_H^2 = s + m_Z^2 - 2\sqrt{s}\,(p_+ + p_-)$

Exercise !

    - Plot the recoil mass distribution – resolution proportional to momentum resolution
    - No requirement on the Higgs decays: measure $\sigma_{HZ} \times BR(Z \to e^+e^-, \mu^+\mu^-)$



FCC-ee simulation



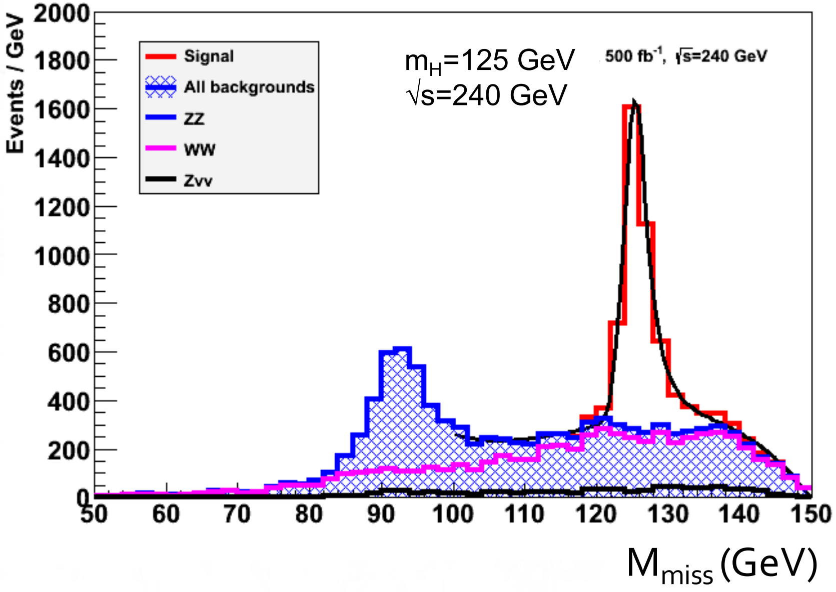
  - Provides an absolute measurement of g_{HZZ} and set required detector performance

Higgs physics Analysis

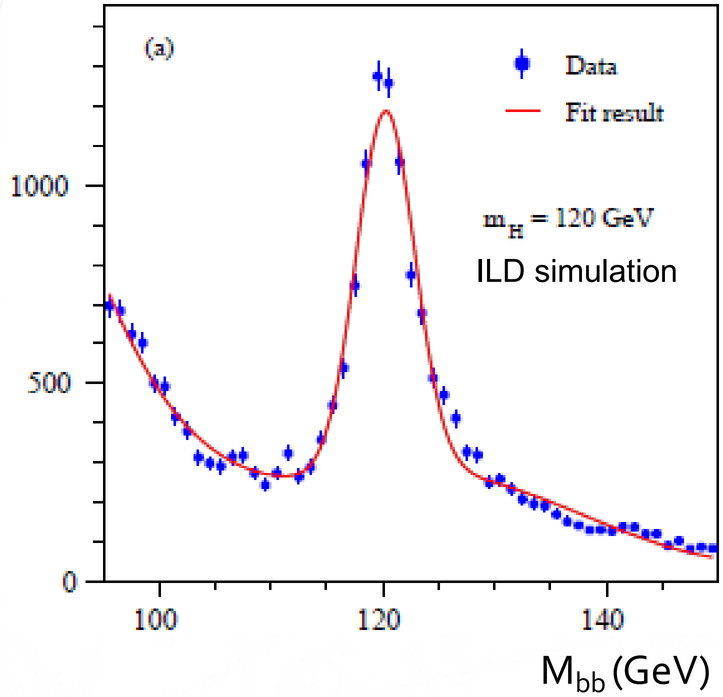
- Repeat the search in all possible final states
  - For all exclusive decays, YY, of the Higgs boson: measure $\sigma_{HZ} \times BR(H \to YY)$
    - Including invisible decays
      - event containing only the lepton pair with correct (m_{miss}, m_{recoil}), else empty
    - For all decays of the Z (hadrons, taus, neutrinos) to increase statistics
  - For the WW fusion mode ($H\nu\bar{\nu}$ final state): measure $\sigma_{WW\to H} \times BR(H \to YY)$

$ZH \to \ell^+\ell^-$ + nothing, 0.5 ab^{-1}

$BR(H \to invis) = 100\%$

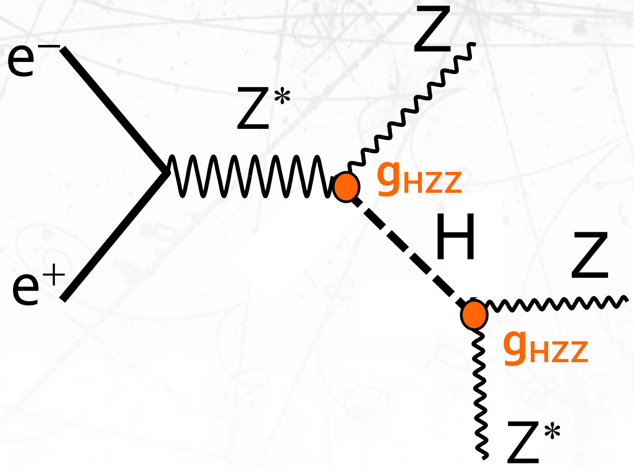


$ZH \to q\bar{q}\,b\bar{b}$, 0.25 ab^{-1}



Higgs total Width

- Indirect determination of the total Higgs decay width
  - From a counting of HZ events with H → ZZ at $\sqrt{s} = 240$ GeV
    - Measure $\sigma_{HZ} \times BR(H \to ZZ)$



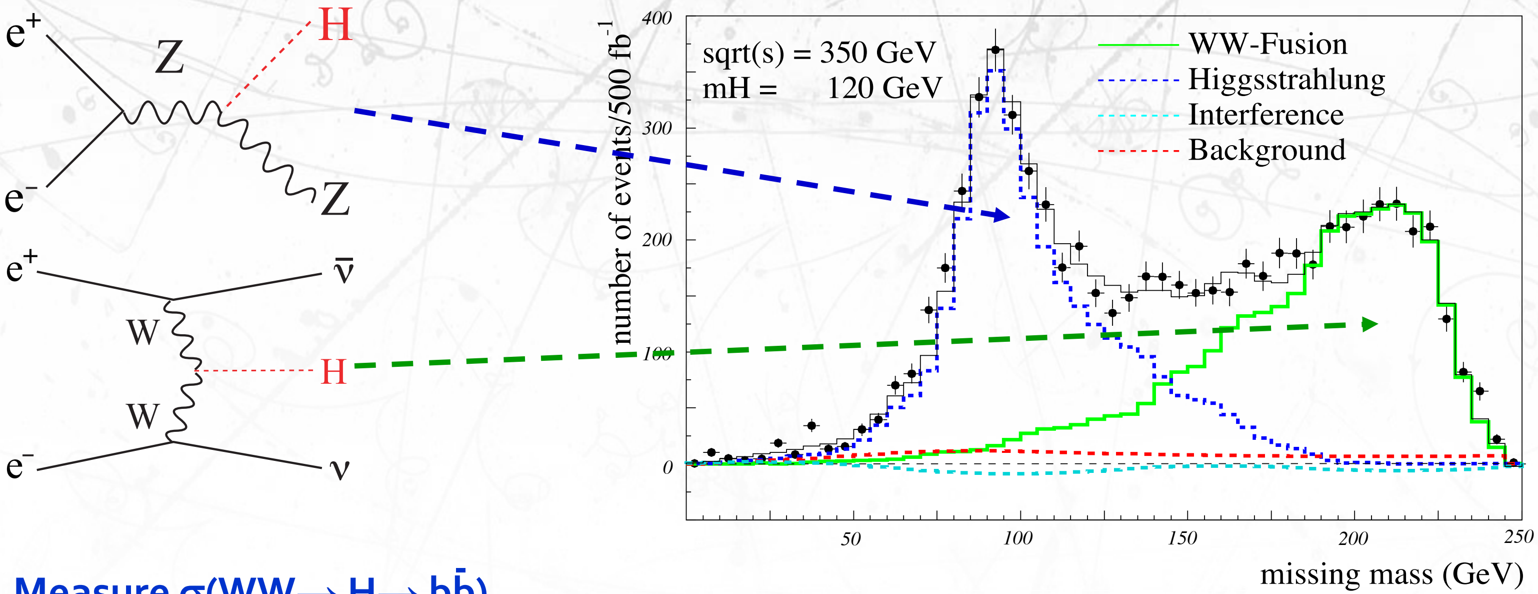
Final state with three Z's
Almost background free

Measured with the $H\ell^+\ell^-$ final state
(see slide 41)

- σ_{HZ} is proportional to g_{HZZ}^2
- $BR(H \to ZZ) = \Gamma(H \to ZZ) / \Gamma_H$ is proportional to g_{HZZ}^2 / Γ_H
  - $\sigma_{HZ} \times BR(H \to ZZ)$ is proportional to g_{HZZ}^4 / Γ_H
- Infer the total width Γ_H

Higgs total Width

- **Indirect determination of the total Higgs decay width (cont'd)**
  - From a counting WW→ H→ $b\bar{b}$ events at 350-500 GeV in the $b\bar{b}\nu\bar{\nu}$ final state:



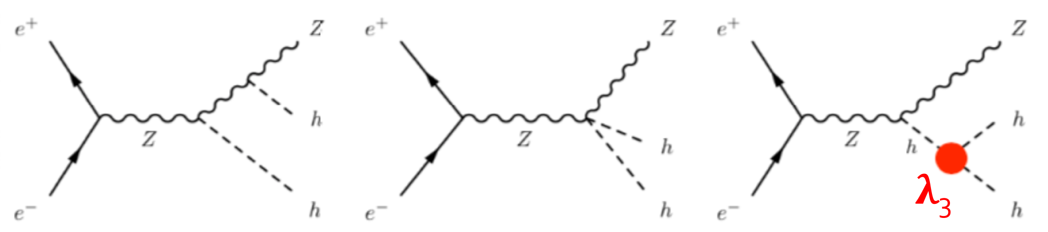
- Measure σ(WW→ H→ $b\bar{b}$)
- Take the branching ratios into WW and $b\bar{b}$ from σ_{HZ} and σ_{HZ} × BR(H → WW,$b\bar{b}$)
- Infer the total width

$$\boxed{\Gamma_H \propto \sigma_{WW\to H} / \mathrm{BR}(H \to WW) = \sigma_{WW\to H\to bb} / \mathrm{BR}(H \to WW) \times \mathrm{BR}(H \to bb)}$$

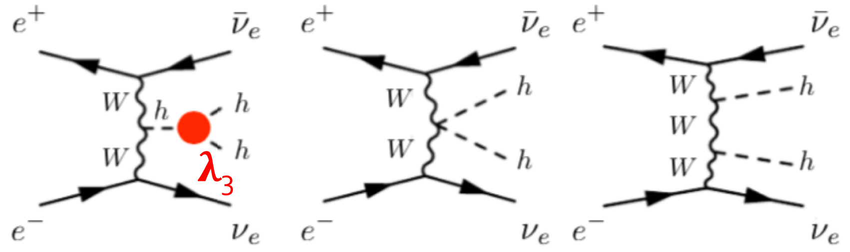
Higgs Self Coupling, λ_3

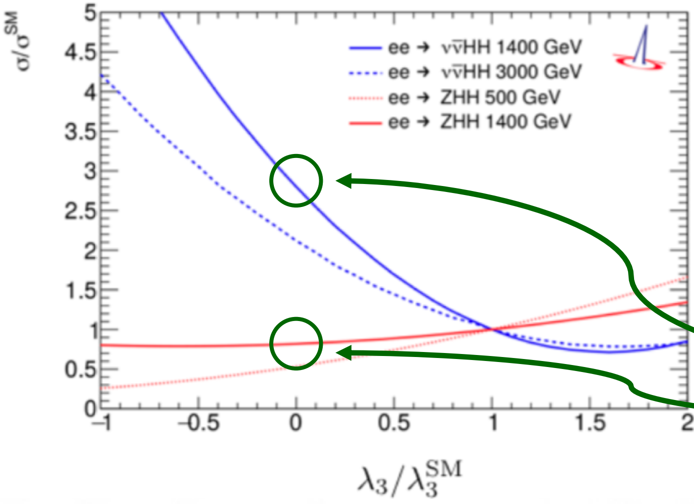
- Higgs self-coupling, λ_3, is a fundamental parameter of the SM whos value should be checked against prediction
  - Essentially dictates the shape of the Higgs potential
- For $\sqrt{s} \gtrsim 500$ GeV, access to di-Higgs production

From 500 GeV



From ≈800 GeV

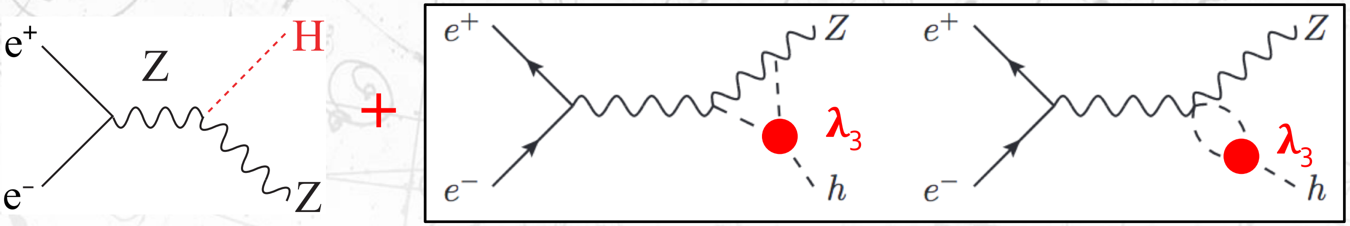




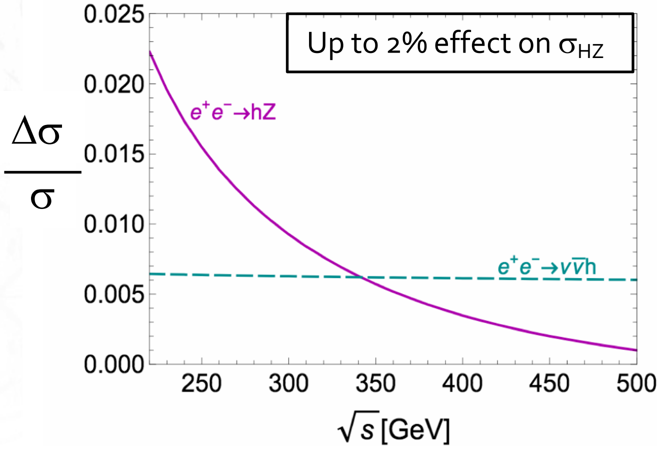
- In both cases, three interfering diagrams
  - Higgs self coupling, λ_3, extracted from fit to production cross section
    - At 1400 GeV: relatively strong dependence
    - At 500 GeV: weak(er) dependence

Higgs Self Coupling, λ_3

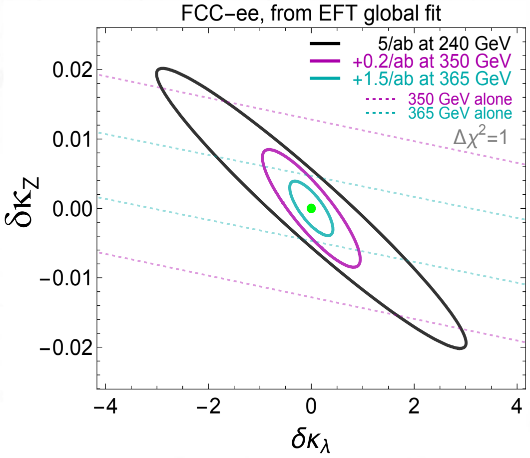
- At lower energies, no production of Higgs pairs
- But, loops including Higgs self coupling contribute to Higgs production



- Effect on σ_{ZH} and $\sigma_{\nu\nu H}$ of Higgs self coupling (λ_3 and hence $\kappa_\lambda=\lambda_3/\lambda_3^{SM}$) depends on $\sqrt{s}$



Up to 2% effect on σ_{HZ}



- Two energy points (240 and 365 GeV) lift the degeneracy between $\delta\kappa_Z$ and $\delta\kappa_\lambda$
  - Precision on λ_3 with 2 IPs at the end of the FCC-ee (91+160+240+365 GeV)
    - Global EFT fit (model-independent) : ±34% (3σ) ; in the SM : ±12%

Summary of Higgs Measurement Precisons

Coupling	HL-LHC	CEPC_{240}	FCCee_{365}	ILC_{500}	CLIC_{1500}
κ_W [%]	1.2	1.3	0.43	0.29	0.17
κ_Z [%]	1.0	0.13	0.17	0.23	0.26
κ_c [%]	SM	2.2	1.3	1.3	1.8
κ_t [%]	2.8	-	-	6.9	n.a.
κ_b [%]	2.7	1.2	0.67	0.58	0.48
κ_μ [%]	4.4	8.9	8.9	9.4	13
κ_τ [%]	1.6	1.3	0.73	0.7	1.3
κ_γ [%]	1.7	3.7	3.9	3.4	5.0
κ_g [%]	2.2	1.5	1.0	0.97	1.3
$\kappa_{Z\gamma}$ [%]	10	8.2	-	-	15
Γ_H [%]	~50	3.1	1.3	1.6	2.6
BR_{inv} [%]	$\lesssim 2$	< 0.27	< 0.19	< 0.22	< 0.62
BR_{EXO} [%]	SM	< 1.1	< 1.0	< 1.4	< 2.4
λ_3 (sngl-H/di-H)	- / 50	17 / -	19 / -	26 / 27	40 / 36

Model-independent results

Sensitive to new physics at tree level

Expected effects < 5% / Λ^2_{NP}

1% precision needed for $\Lambda_{\text{NP}} \sim 1\text{TeV}$

Sub-percent needed for $\Lambda_{\text{NP}} > 1\text{TeV}$

Sensitive to new physics in loops

Sensitive to light dark matter particles (sterile ν, χ, …) and to other exotic decays

Higgs self-coupling

Generally, a factors of 2–10 better than HL-LHC
Plus Model Independence

Rounding off …

Conclusions of the first lecture (1)

- The Standard Model is a complete theory of particles and their interactions
  - ❑ Theoretically complete since 40 years
  - ❑ Experimentally complete since 2012 with the discovery of the Higgs boson
  - ❑ Tested to be internally consistent at the quantum loop level via EW precision measts.
- The days of "guaranteed discoveries" are over, however, experimental observations suggest the existence of physics beyond the SM
  - ❑ Dark matter, matter-antimatter asymmetry, neutrino masses, …
  - ❑ However, we do not know where this new physics is hiding
    - ❖ At high(er) masses ➪ Energy Frontier / Precision Frontier
    - ❖ At small(er) couplings ➪ Precision Frontier
- e^+e^- colliders provide very clean experimental environments:
  - ❑ In particularly LEP has played (is still playing!) an important role in precision tests of SM
    - ❖ Z parameters from 10^7 Z decays; W parameters from 10^5 W decays
- Future e^+e^- colliders can be either linear or circular
  - ❑ Linear: necessary for energies > 500 GeV (synchrotron radiation)
  - ❑ Circular: superiour luminosity performance for energies $\lesssim$ 375 GeV

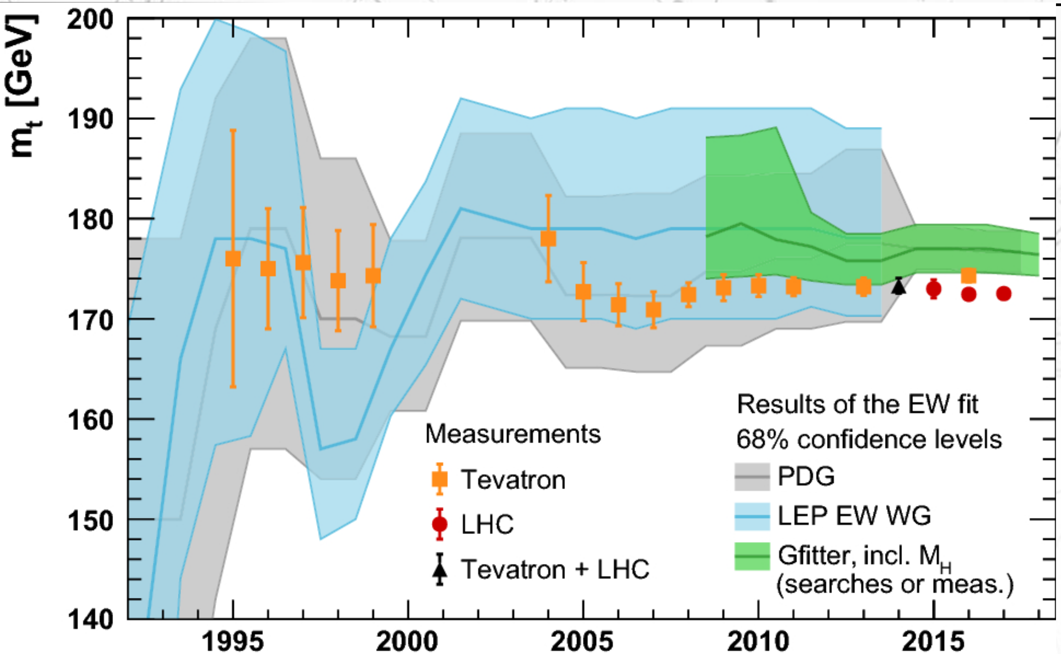
Conclusions of the first lecture (2)

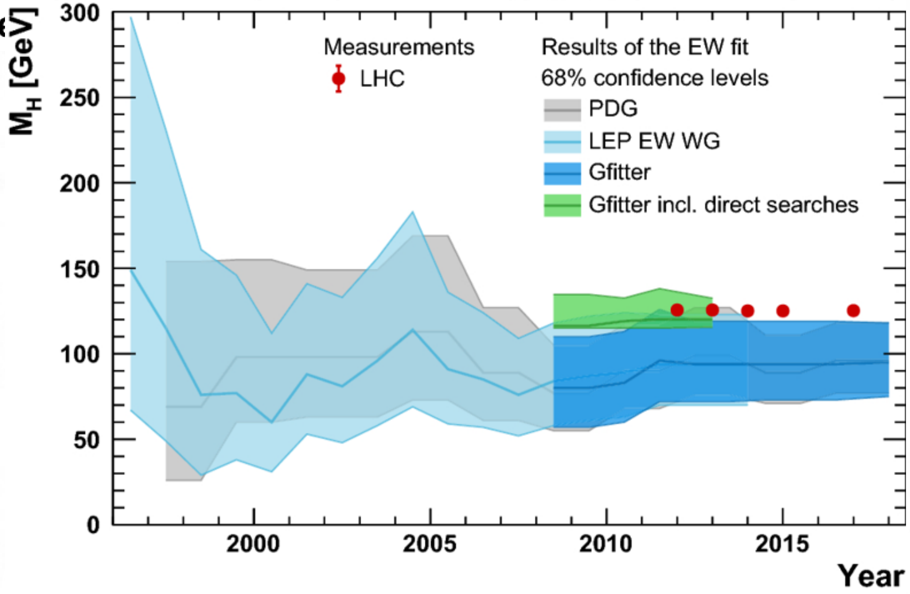
- A e^+e^- *Higgs Factory* can test the Higgs boson to the theoretical interesting sub-percent level
  - ~ 10^6 Higgs decays in an experimentally very clean environment
  - The Higgs boson in HZ events are tagged by the Z decay products
- The small mass of the Higgs boson allows two options for a *Higgs Factory*
  - A 250 – 500 GeV linear collider: ILC (also CLIC at $\sqrt{s}$ = 380 GeV and higher)
    - ILC now concentrating on $\sqrt{s}$ = 250 GeV
  - A 88 – 365 GeV circular collider: FCC-ee (also CEPC at $\sqrt{s}$ = 88 – 240 GeV)

- Tomorrow we will consider the potential of very high precison electroweak measurements at the FCC-ee and high-energy e^+e^- collisions at CLIC

End of the first lecture

Questions…


m_t [GeV]
200
190
180
170
160
150
140
1995
2000
2005
2010
2015
Ye
Measurements
Tevatron
LHC
Tevatron + LHC
Results of the EW fit
68% confidence levels
PDG
LEP EW WG
Gfitter, incl. M_H
(searches or meas.)


M_H [GeV]
300
250
200
150
100
50
0
2000
2005
2010
2015
Year
Measurements
LHC
Results of the EW fit
68% confidence levels
PDG
LEP EW WG
Gfitter
Gfitter incl. direct searches