Higgs and Top physics

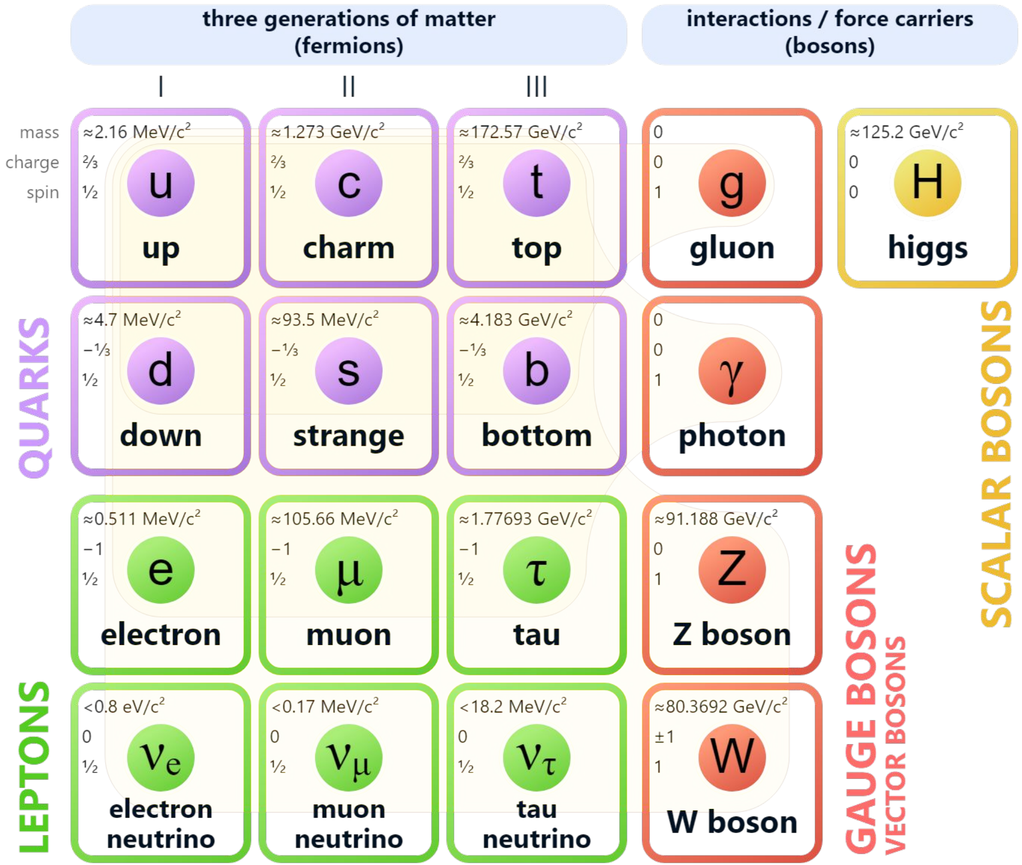
The Standard Model

Theoretical framework describing the fundamental particles and their interactions (excluding gravity)

Particle spectrum consists of bosons (force carriers) and fermions

All particles have been discovered and measured over the past decades, making the Standard Model complete

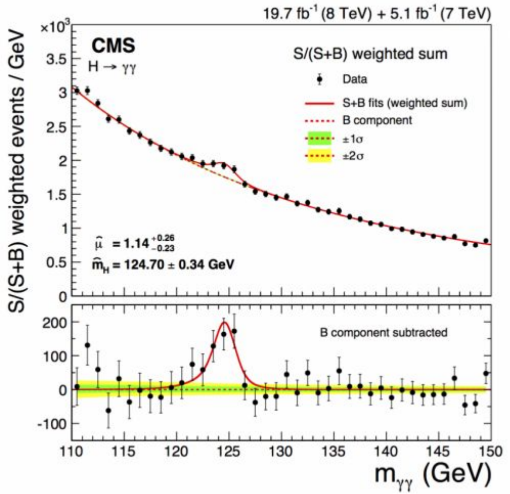
- W/Z bosons extensively studied at LEP
- Top discovered in 1996 at the Tevatron
- Higgs recently discovered in 2012 at the LHC
- Both Top/Higgs only being studied at hadron colliders



The present landscape

Key achievements of the Standard Model (SM)

- Higgs discovery and properties; appears to be SM-like (could be a different particle!)
- Precision measurements of SM parameters, including the top quark mass, W boson mass, and CP violation
- Excellent agreement of the SM with experimental data across large energy scale

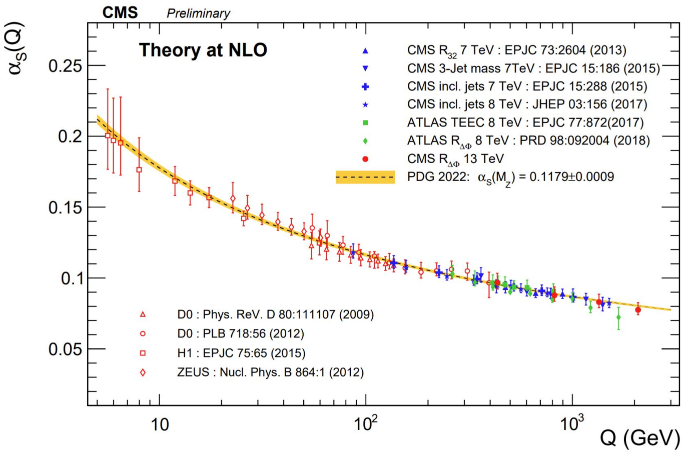


We know the SM is not sufficient – open questions in fundamental physics

- Nature of dark matter
- Matter-antimatter asymmetry: insufficient CP violation in SM
- Hierarchy problem
- Neutrino masses and oscillations
- Unification and quantum gravity: theories beyond the SM

But no direct indication of new physics at LHC (so far)

- What can HL-LHC do? Direct observation of new particles?
- What can future colliders do?
- What can precision physics do?



The power of precision measurements

Precision measurements allows to test the self-consistency of the SM

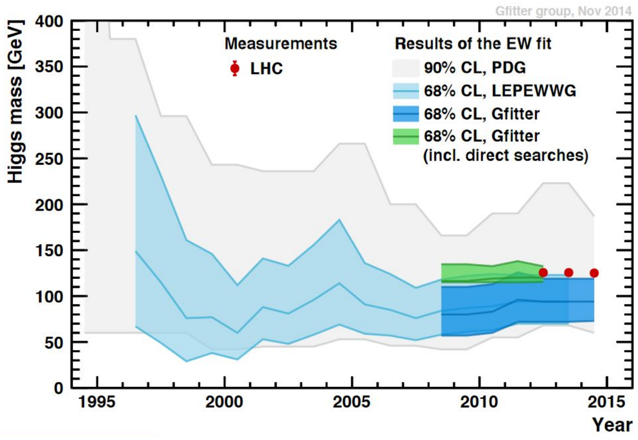
- Increased effort in performing precision physics at the LHC using large datasets with succes (recent examples α_s, W mass)
- LHC and HL-LHC will offer competitive precision physics

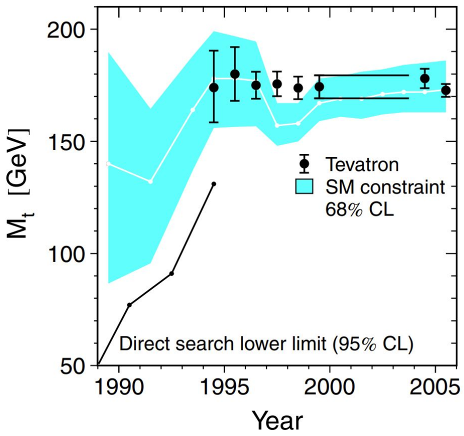
Electron-positron collider necessary to boost the precision measurements with order of magnitude(s)

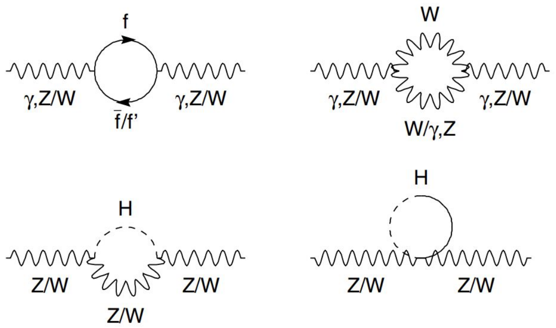
- Clean events, direct interpretation of results
- Higgs and Top to be studied precisely using e^+e^- machines

History shows that precision measurements can guide us toward future discoveries

- It may be our best opportunity to guide the search for new physics







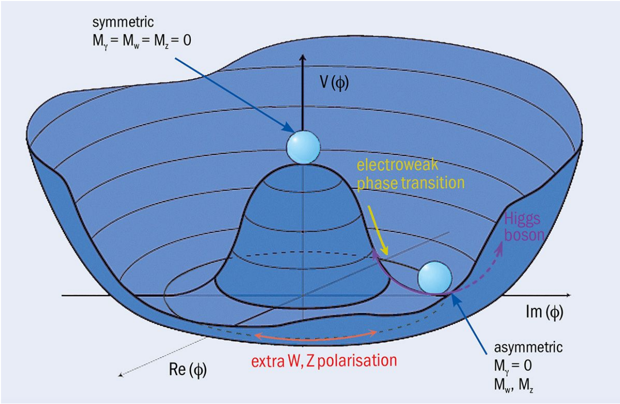
The Higgs boson

The Higgs mechanism is responsible for the mass of the elementary particles in the Standard Model (excluding neutrinos)

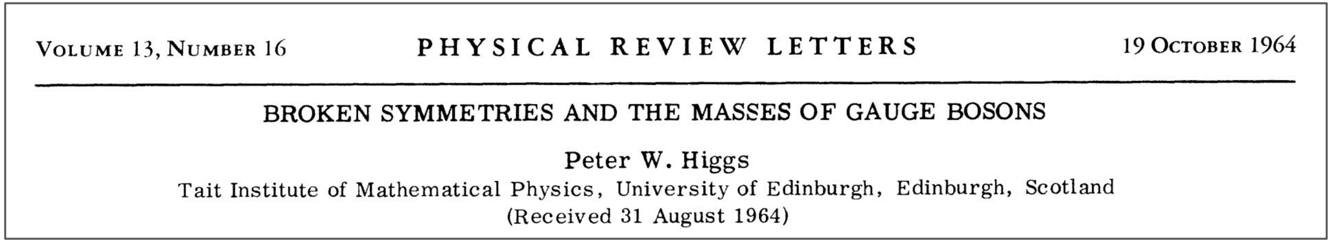
It is based on electroweak symmetry breaking

- Process through which the unified electroweak force separates into the electromagnetic and weak forces, as the Higgs field acquires a nonzero vacuum expectation value
- Giving mass to the W and Z bosons while leaving the photon massless
- Existence of a Higgs field H → Higgs boson
- Theory developed in 1964 by Higgs, Englert and Brout

Higgs potential



$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4$$


VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

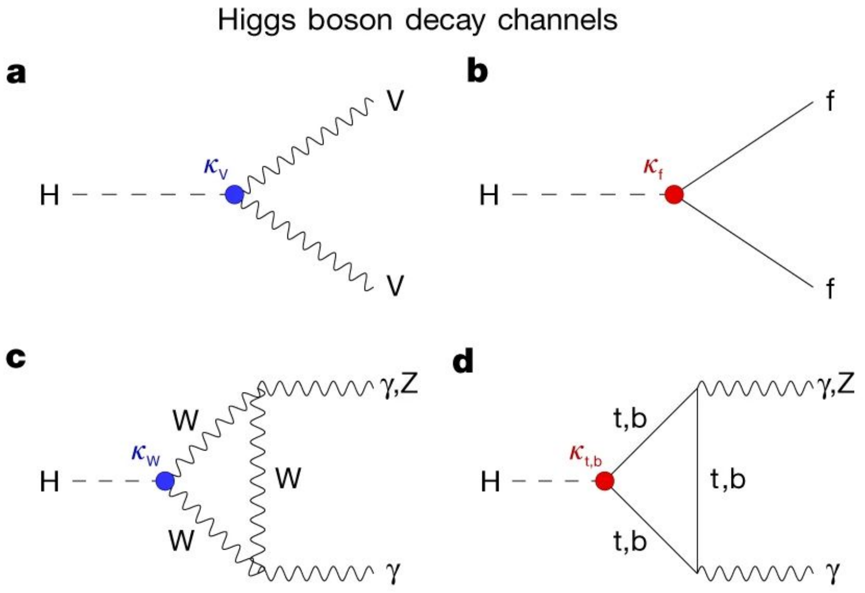
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

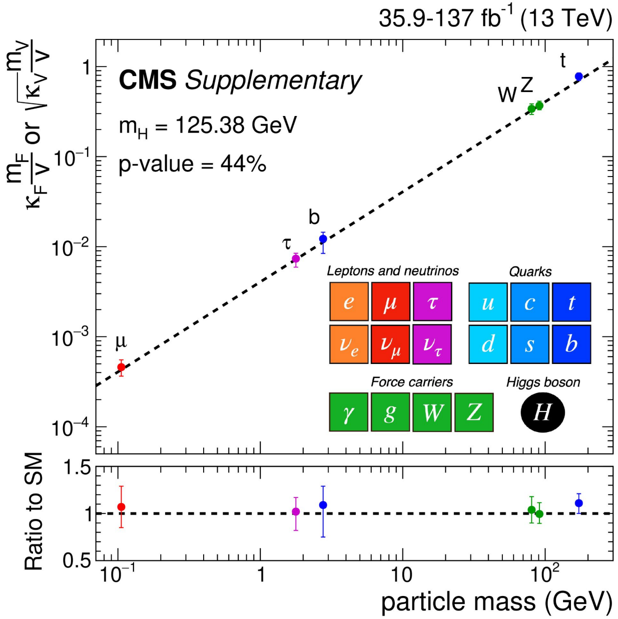
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

Higgs couplings

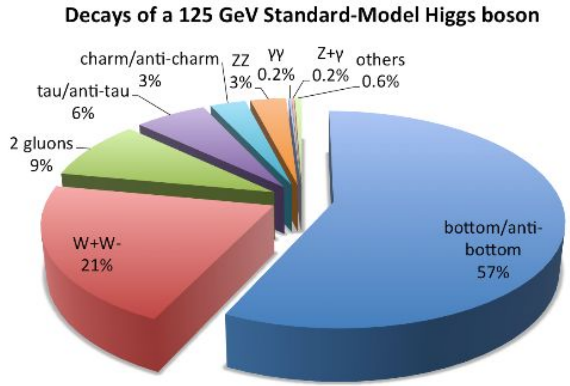
Elementary particles couple to the Higgs field (“Yukawa interaction”)

- Coupling strength κ is linear with the mass of the fermion (or quadratic with vector boson mass)
- Need to measure them accurately → any deviation with theory predictions can be interpreted as new physics





Where does the Higgs decay into



Higgs is not stable; it decays after 1.6 x 10^{-22} seconds

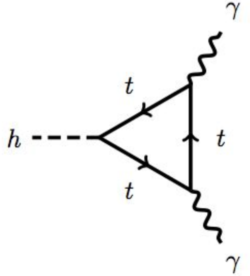
- Higgs coupling linear with the particle’s mass
- Preferentially decays to heavy particles
- Including coupling to the Higgs boson itself (see next slide)

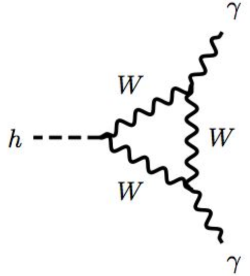
Discovery and properties are measured from most probable decays, i.e. heavy particles): bb, $\tau\tau$, gluons, W^+W^-

Lighter couplings: cc, ZZ, $\gamma\gamma$, Zγ, $\mu\mu$

Very light couplings: u, d, e^+, e^-

- Extremely difficult to measure (not to say impossible)
- These are the building blocks of our universe, so they are important





Higgs to invisible

- In SM only through H→ZZ*→νννν (small probability, 0.1 %)
- Higgs *could* decay to invisible dark matter particles
- Higgs studies important for dark matter and physics beyond SM

Measuring the Higgs potential

Proving its existence, measuring the Higgs potential is important

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4$$

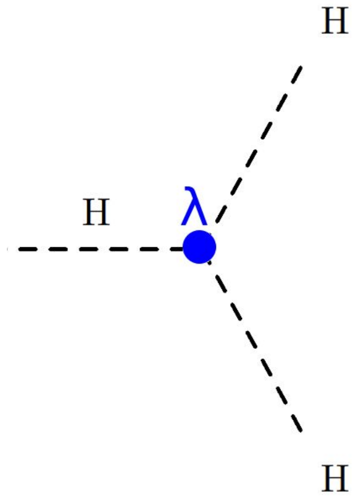
Quadratic term: Higgs mass

Cubic term: self-interaction

Quartic term: Stability + self interaction

The Higgs boson itself is massive and can couple to itself

- To measure the self-coupling at LHC need to produce di-Higgs
- Very rare process → much data needed (HL-LHC)



FCC-ee can probe the self-coupling differently by accurately measure the cross-section (see later)

How do we measure these SM particles?

Muons: track + hits in outer muon detectors

Electrons: track + energy deposit in electromagnetic calorimeter

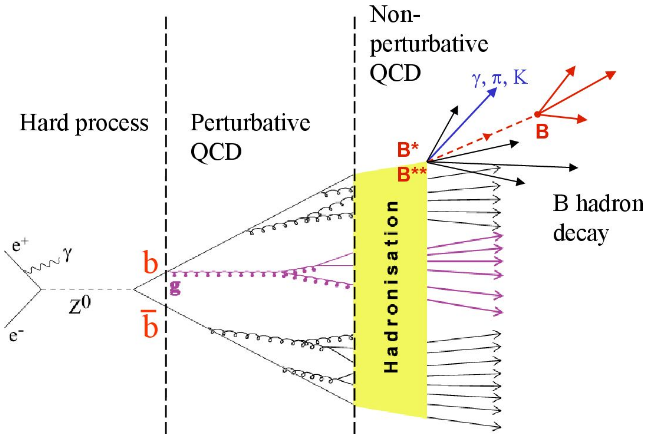
Taus: not stable; decays to electron/muon or hadronically with low particle content (jets)

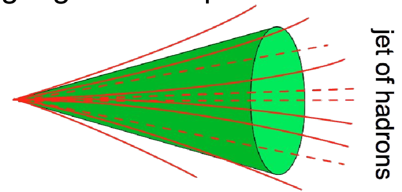
Photons: no track + energy deposit in electromagnetic calorimeter

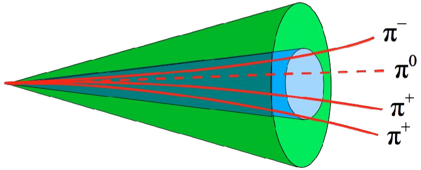
Neutrinos: can’t be detected → missing energy (negative vector sum of all what is visible)

Quarks and gluons: hadronize as hadronic jets

- Quarks are confined and cannot exist freely
- They hadronize to “hadrons“ (hadronic bound states)
- The hadrons are usually short lived and decay to many particles
- Spray of charged and neutral hadrons (e.g. pions, kaons, neutrons, …)
- On average 40 particles per jet
- Requires clustering of many particles into jets
- Clustering algorithm depends on the event topology (how many jets you expect)







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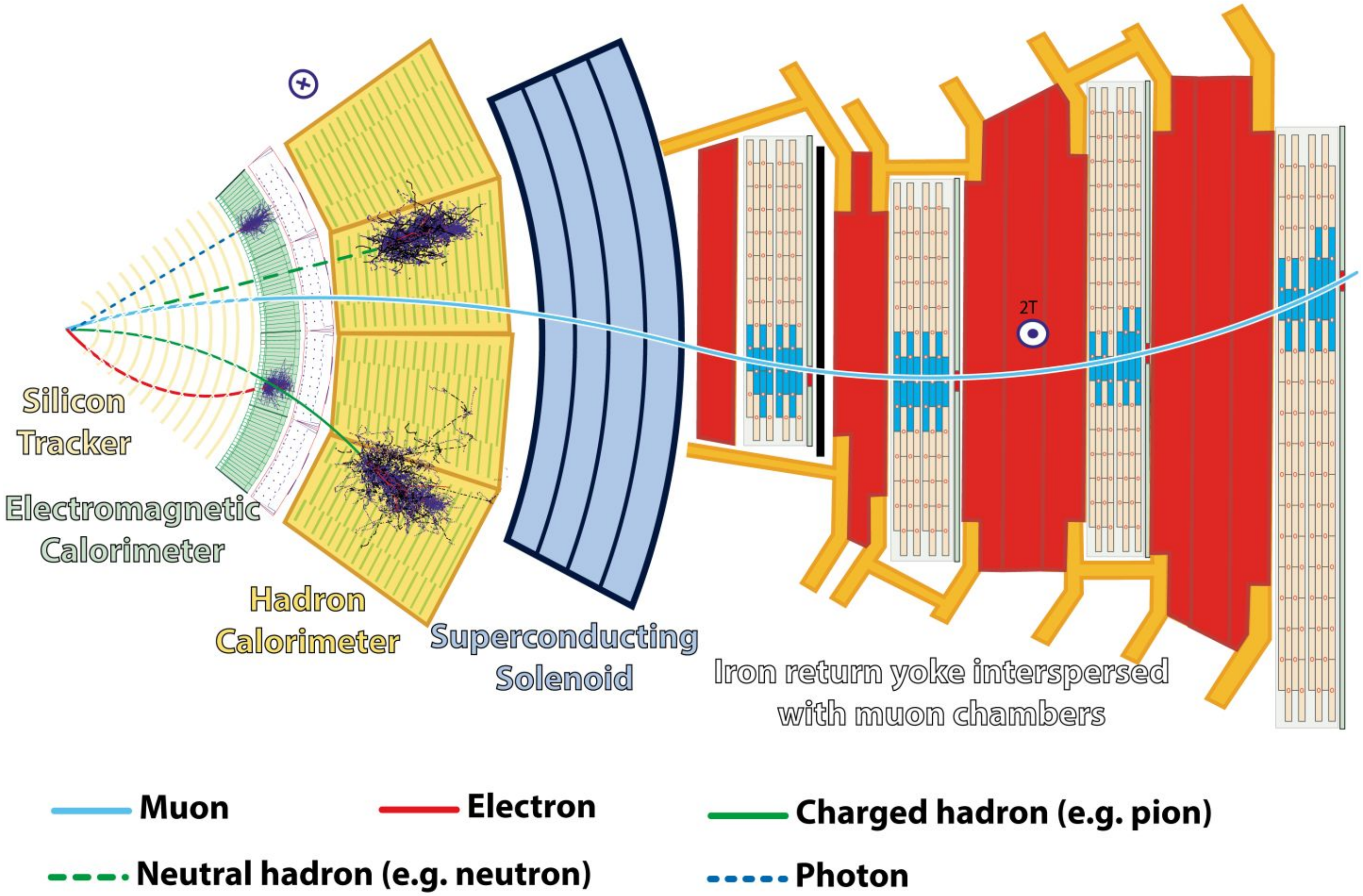


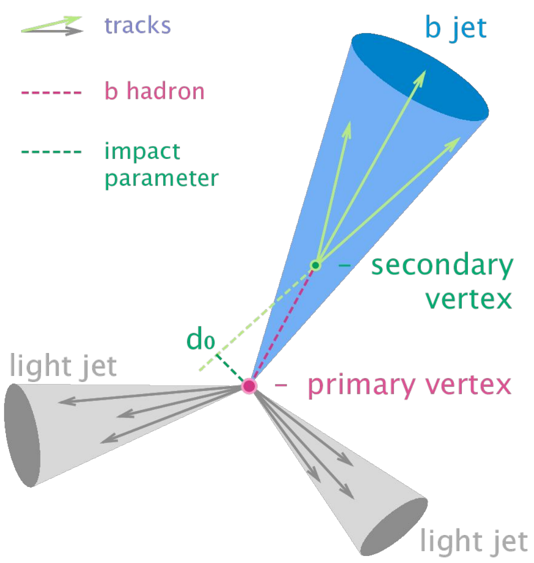
How do we know the flavor of the jet?

What is the underlying quark flavor of the jet?

- Can be u/d/c/s/b/g; what about the top quark?

How to distinguish → look at the jet constituents!

- b-jets come from b-hadrons and live relatively long (lifetime $\tau \sim 10^{-12}$s)
  - They travel before decay and hadronize
  - Distance $c\tau$ ~ few mm → secondary vertex is detectable
- c-quark similar, but shorter lifetime → shorter distances
- s-quark tend to hadronize to kaons that carries a large fraction of the momentum
- u/d quarks very difficult → jet charge?
- gluons tend to have a higher particle multiplicity



Much more on this by E. Smith!

The jet flavor identification requires excellent detectors (granular, timing, vertexing)

Sophisticated flavor taggers based on neural networks to assign a flavor probability per jet, based on the jet constituents and their properties

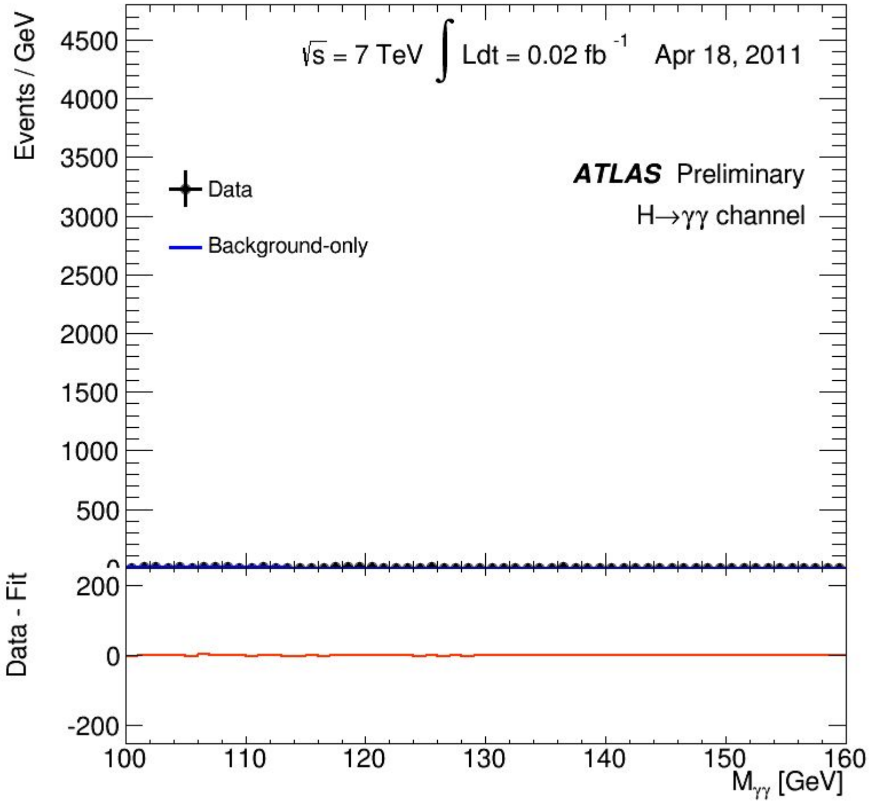
Discovery of the Higgs boson

At the HLC using two “golden” channels

- H→ZZ* → 4 leptons (electrons, muons)
- H→ $\gamma\gamma$

These channels are not the most probable decay channels, but they are powerful in rejecting background events

- bb, $\tau\tau$, gluons are overwhelmingly produced at the LHC



Discovery of the Higgs boson

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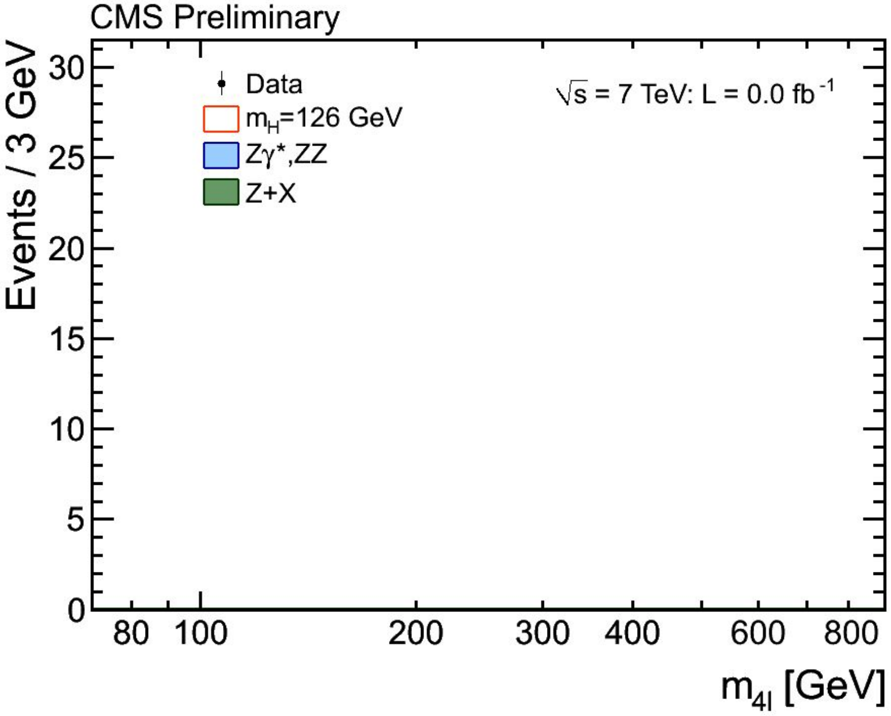


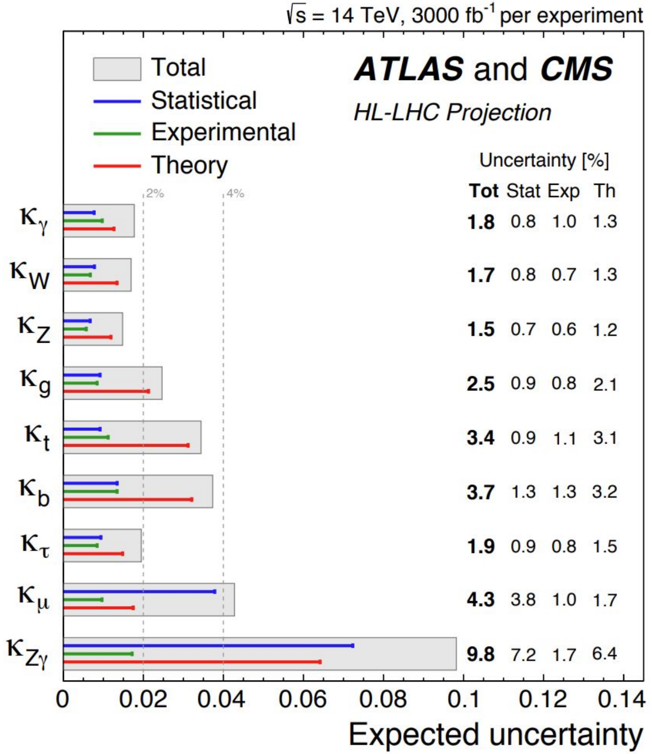
The need for precise Higgs measurements

HL-LHC will deliver about 20 times more data

- Higgs couplings
  - Bosonic Higgs couplings to ~ 1.5–2 %
  - Fermionic Higgs couplings to ~ 2–4%
  - Good share between statistical and experimental uncertainties
  - Theory uncertainties dominant
- Self-coupling ~ 50%
- Fundamental properties mass (~ 20 MeV), width (~ 25%), invisible

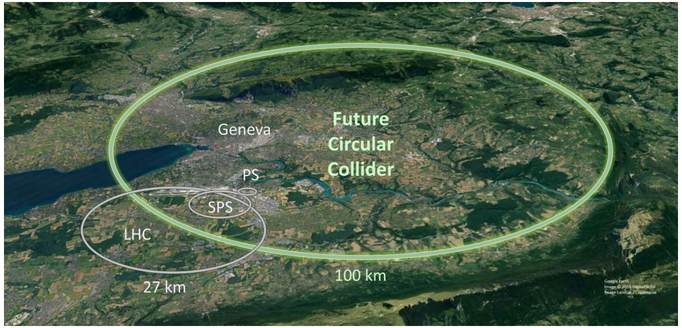
Continue the study of the Higgs properties

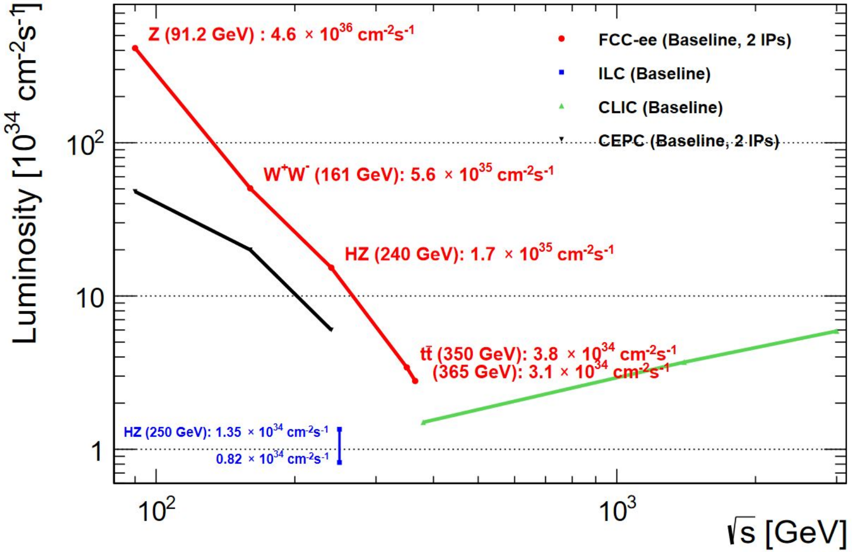
- Diversify the results using non-hadron collider
- Improve all it’s properties: couplings, mass, width, self-coupling
- Absolute determination of the couplings (see later)
  - Only possible at an electron-positron collider
  - Model-independence interpretation for Higgs width
  - Deviations sensitivity to BSM at tree and loop level
- Probe unreachable phase space by hadron-colliders (first-gen, strange)



FCC-ee overview

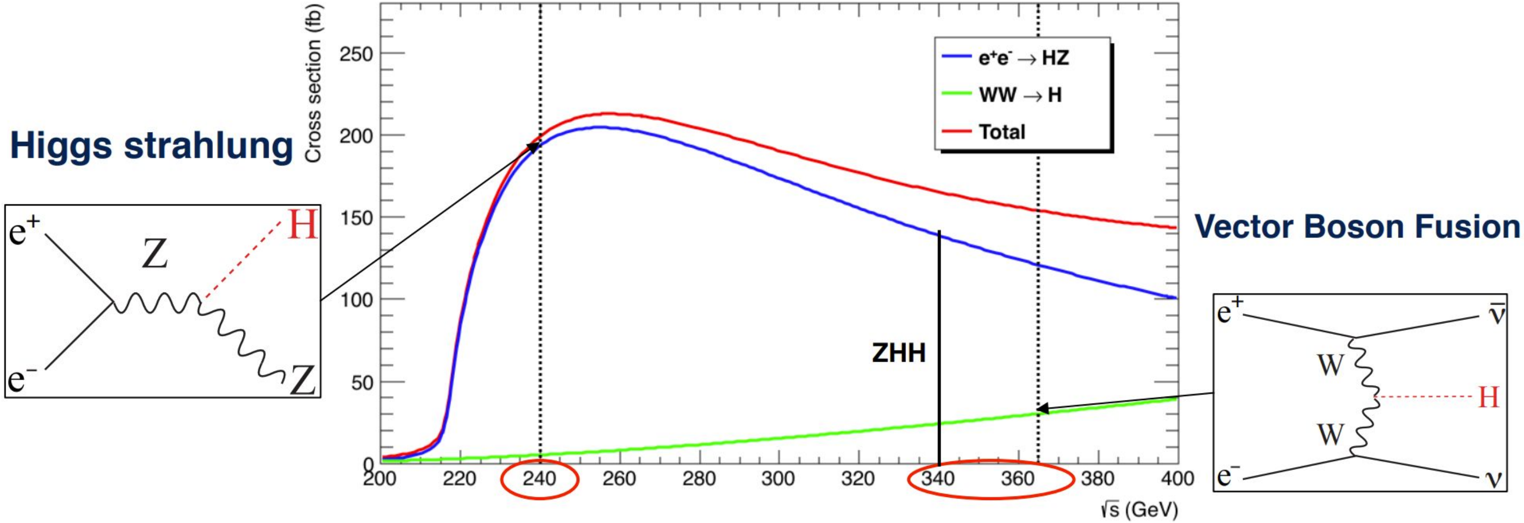
- Proposed circular e+/e- collider with ~ 100 km in circumference
- Colliding at 4 interaction points
- Facility to host hh collider at later stage (cfr. LEP–LHC)
- Foreseen timeline: construction 2030–40, operation 40–55 (15y)





Multiple energy points exploiting large range of physics			
Threshold	Center-of-mass	Luminosity (/ab)	Events
Z-pole	91 GeV	150	5x10^{6}M Z
WW-pole	161 GeV	12	50M WW
H-pole	240 GeV	10.8	2M ZH
tt-pole	365 GeV	3	1M tt

Higgs production at the FCC-ee



Total Higgs production @ FCC-ee		
Threshold	ZH production	VBF production
240 GeV / 10.8 ab^{-1}	2 M	50 k
365 GeV / 3 ab^{-1}	0.4 M	0.1 M

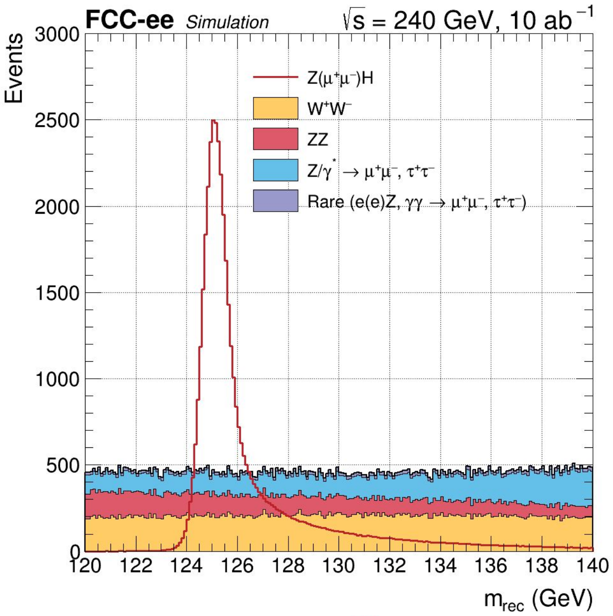
The ZH threshold and recoil method

Main strategy of Higgs analyses based on recoil method

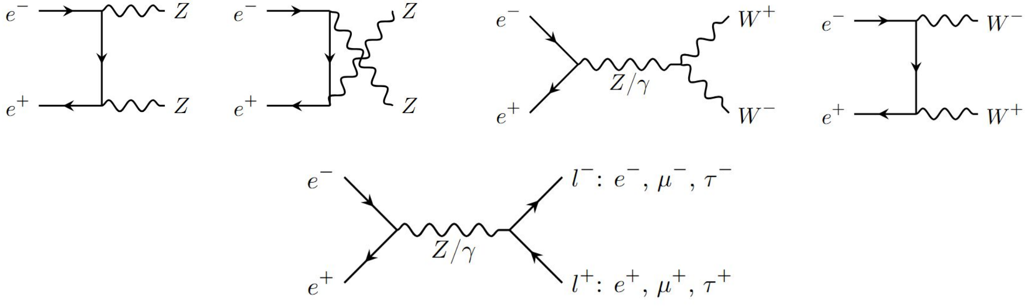
- Tag the Z boson (tight invariant mass constraints) using leptons or jets
- Compute recoil, distribution sharp peaked at Higgs mass, width dominated by detector resolution

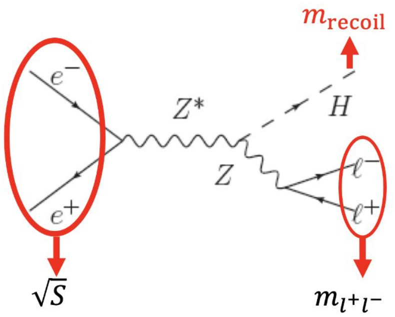
$$m^2_{recoil} = \left(\sqrt{s} - E_{ff}\right)^2 - p^2_{ff}$$
$$= s + m^2_Z - 2E_{ff}\sqrt{s} \approx m^2_H$$

- Tag additional decays of the Higgs – challenging in multijet environment



Backgrounds: dominated by vector boson (pair) production (WW, ZZ) and Z/γ*

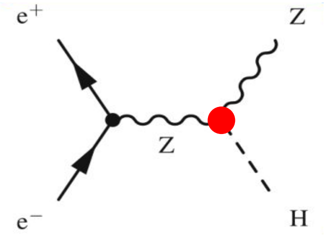


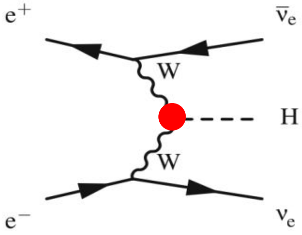


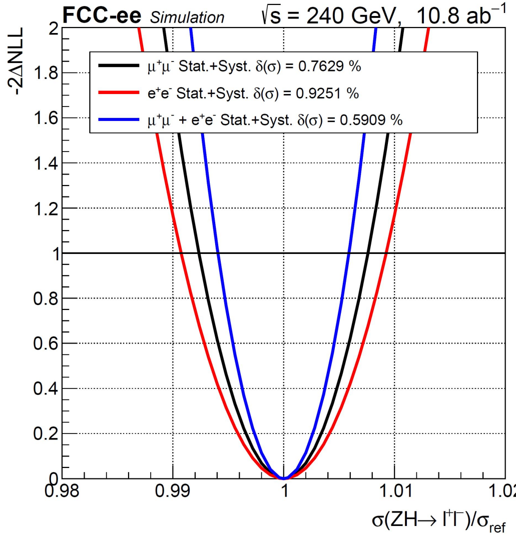
Total Higgs production cross-section

Crucial is to measure the total ZH production cross-section

- Must be done independently of the decay mode, i.e. only look at the associated Z boson (challenging)
- Unique to e^+e^- colliders because of known initial state, not possible at hadron colliders
- Similarly measure the HWW coupling strength at 365 GeV

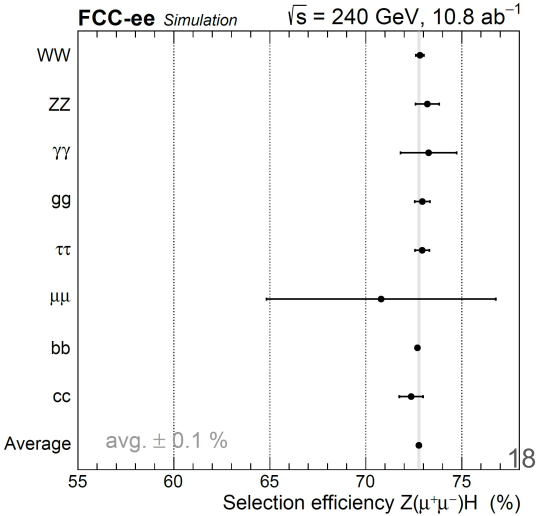






FCC-ee sensitivity prediction to ~ 0.2%

- Analysis in $Z(\mu\mu)H$(any) andZ(ee)H(any) – reaching 0.6%
- Z(qq)H(any) work in progress → very challenging!



Higgs coupling strengths

Start with the knowledge and measurements done at the LHC [2010-2026] and HL-LHC [2028-2040]

- This based on extrapolated measurements of the two experiments CMS and ATLAS
- Assume 20 years of running till 2040

FCC-ee will significantly improve many Higgs couplings

- Just only for 2-3 years running!
- Especially W/Z/gluon/quarks
- Less in rare decays ($\mu\mu$, Zγ) → need more statistics

Uncertainty on coupling (%)			
Ch.	**HL-LHC**	**+ 240 GeV**	**+ 240+365 GeV**
κ_W	0.99	0.88	0.41
κ_Z	0.99	0.20	0.17
κ_g	2.00	1.20	0.90
κ_γ	1.60	1.3	1.3
$\kappa_{Z\gamma}$	10.0	10.0	10.0
κ_c	–	1.50	1.30
κ_t	3.20	3.10	3.10
κ_b	2.50	1.00	0.64
κ_μ	4.40	4.00	3.90
κ_τ	1.60	0.94	0.66
Inv.	1.9	0.22	0.19

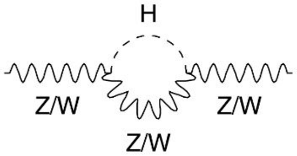
Higgs boson mass

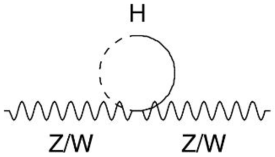
Higgs mass enters SM parameters via radiative corrections

- Depends logarithmically on m_H

$$\sin^2\theta_W = \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{A^2}{1-\Delta r}$$

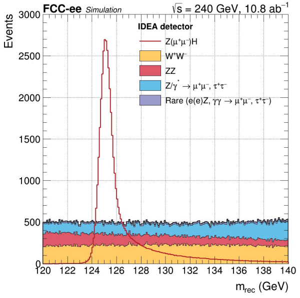
$\Delta r \sim \ln(m_H)$
$\Delta r \sim m_t^2$
$\Delta r \sim$ new physics?

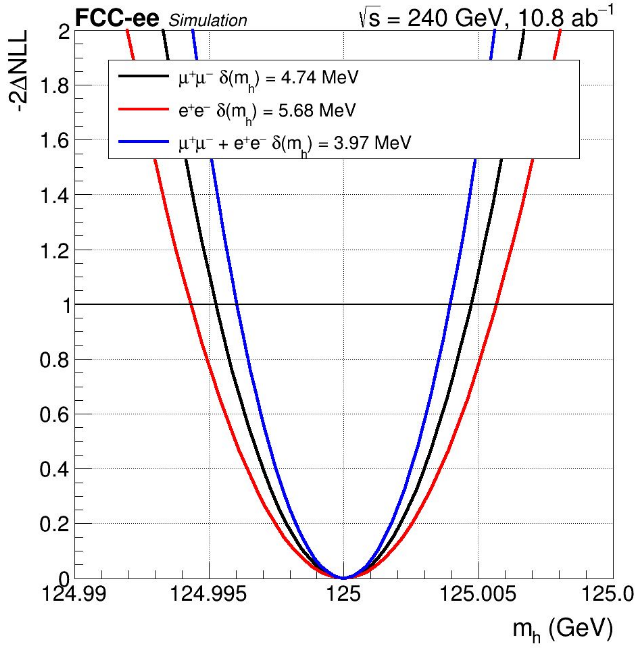




Needs for FCC-ee in context of radiative corrections

- Very high precision on cross-sections, sub-percent level
- Translates to a Higgs mass requirement < O(10) MeV to control radiative corrections for the cross-sections and branching fractions





Measure Higgs mass at FCC-ee (240 GeV)

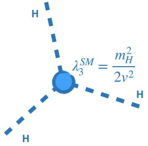
- Recoil mass method using Z($\mu\mu$)H and Z(ee) events
- Total uncertainty of 4 MeV

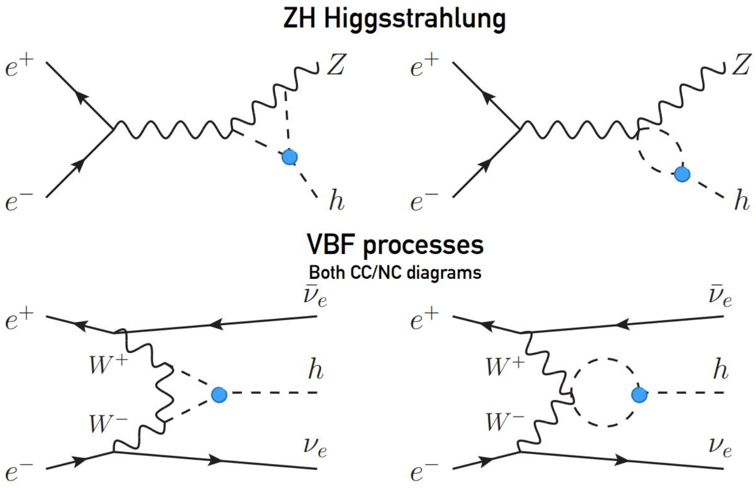
TODAY	HL-LHC	FCC-ee
~ 150 MeV	~ 20 MeV	4 MeV

Higgs self coupling

Probe *indirectly* trilinear Higgs self coupling λ_3 through single Higgs boson cross section

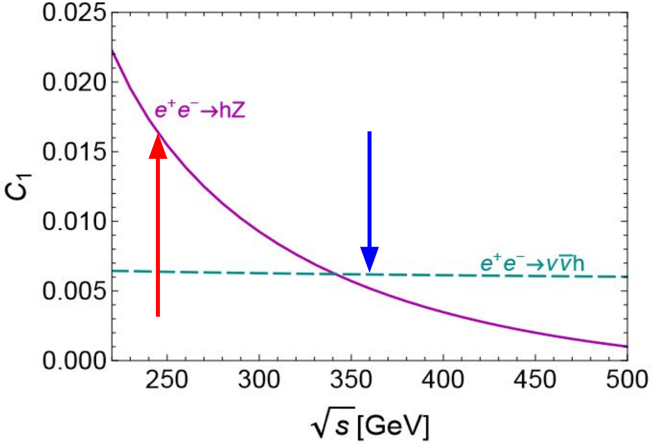
$$\Sigma_{\rm NLO} = Z_H \Sigma_{\rm LO}(1+\kappa_\lambda C_1) \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}$$

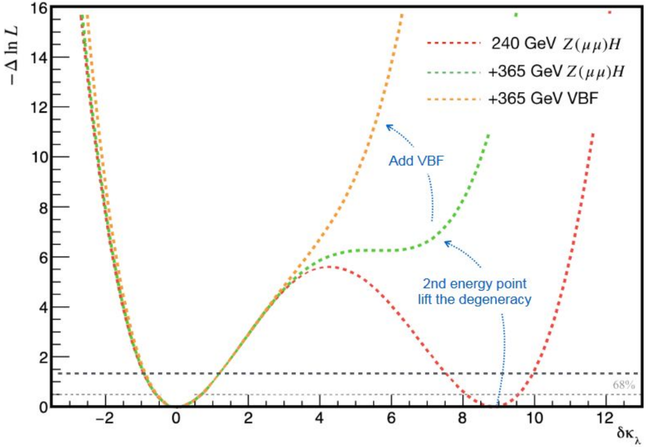




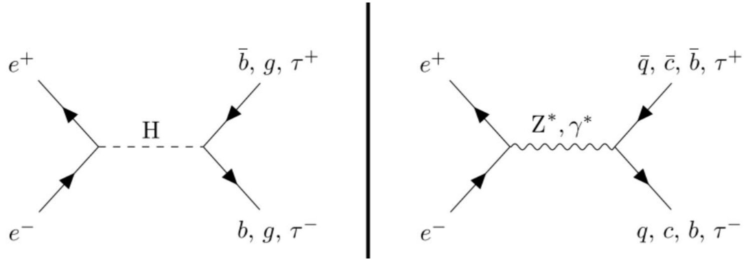
Total cross section can be measured O(1%) at FCC-ee

- Higgs decay-mode independent → challenge for Z(qq)
- Probing NLO deviations from SM: $\delta\kappa_\lambda = \kappa_\lambda - 1$
- C_1 sensitive to $\sqrt{s}$: exploit different sensitivities at both energies





Higgs resonant production



Higgs bosons can be produced at center-of-mass energy equal to the Higgs mass: $e^+e^-\to H$

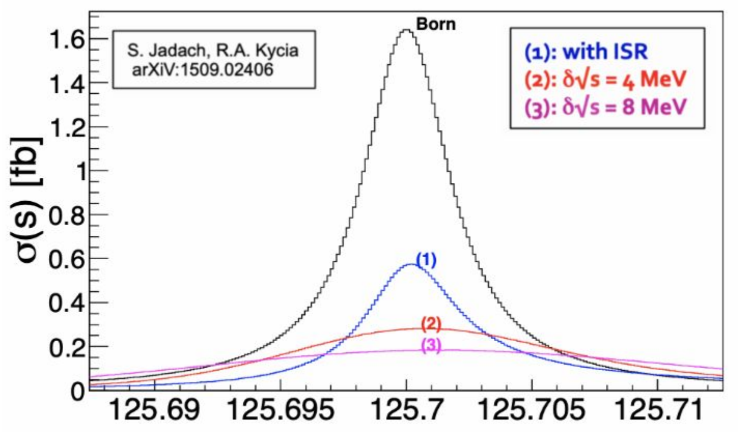
- Similar to $e^+e^-\to Z$, but Z has a width of 2.1 GeV whereas the Higgs has a very small width of only 4 MeV
- It therefore requires to precisely know the instantaneous beam energy: the slightest deviation, and we'll miss the Higgs!

Start already with a small cross-section due to very weak electron Yukawa coupling (electrons are light)

- Initial state radiation → 40 % reduction
- Beam energy spread ~ Γ_H: δE = 4.2 MeV → 45 % reduction
- Potential uncertainty on the Higgs mass
- Total convoluted cross section ~ 280 ab^{-1}: large luminosity needed!

Expectation to produce ~ 6k H bosons per year

- Cope with large Z/γ backgrounds
- Need to run many years to get meaningful uncertainty on κ_e
- Nevertheless maybe the only way to access κ_e?



arXiv:2107.02686

Top physics

Top quark is the heaviest particle in the SM

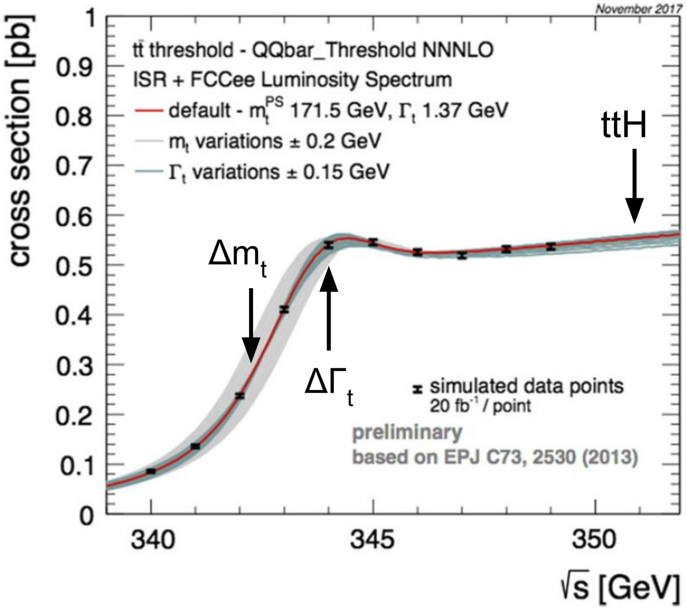
- Unstable, immediately decays to t → b + W
- Extensively studied at Tevatron and LHC
- Top properties inferred by studying b and W decay products

At FCC-ee, top mass and width measured at threshold

- Measure the cross-sections at different center-of-mass energies
- Several energy points needed:
  - Relative large uncertainty on top mass (+/- 0.5 GeV from HL-LHC)
  - Need to constrain shape in optimal way

Example of multipoint scan at FCC-ee

- 5 GeV window [340, 345], each ~ 25 /fb
- Theoretical QCD errors order of 40 MeV for mass and width
- Systematic effects to be studied (but considered to be limited)



$\Delta m_t/\Delta\Gamma_t$ (stat) ~ 8/11 MeV

Conclusions

Higgs and top observed and studied at hadron colliders

Important to study precisely at lepton colliders: clean and different environment

FCC-ee offers unique ways to probe and improve the measurements Higgs couplings and fundamental properties

Detector design and novel analysis techniques are crucial to optimize the physics potential of the FCC-ee → you are part of it with your projects!