Higgs physics at FCC

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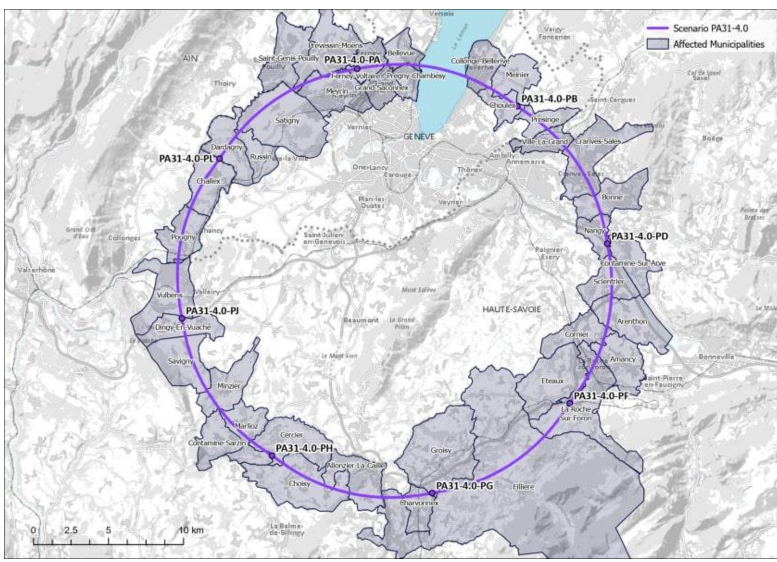
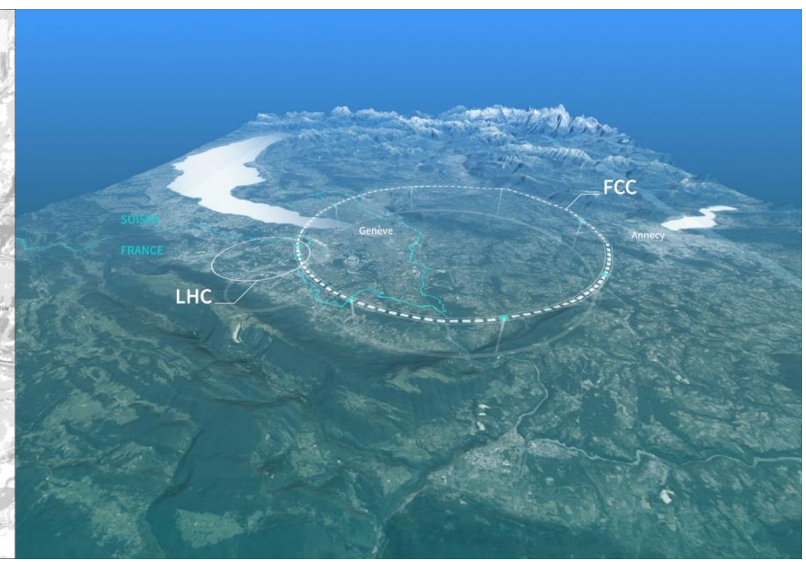




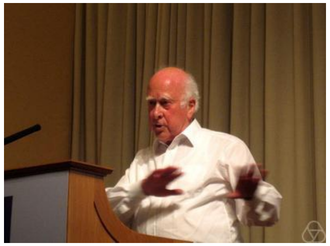
The “Standard Model” of particle physics

- In 1961, S. Glashow discovered a way to combine electromagnetic and weak interactions. In this way, the two forces were unified, and we speak of electroweak interactions.
- In 1964, the Higgs mechanism was developed, by Robert Brout, Francois Englert, Peter Higgs, Gerald Guralnik, Carl Hagen and Tom Kibble. This was a way to incorporate mass into a theory with gauge symmetry.

- In 1967, Steven Weinberg and Abdus Salam incorporated the Higgs mechanism into the electroweak theory. The resulting model is called the Glashow-Weinberg-Salam (GWS) model.

- We define the Standard Model as the combination of the GWS theory (which includes quantum electrodynamics) with QCD.

Kibble, Hagen, Guralnik, Englert, Brout



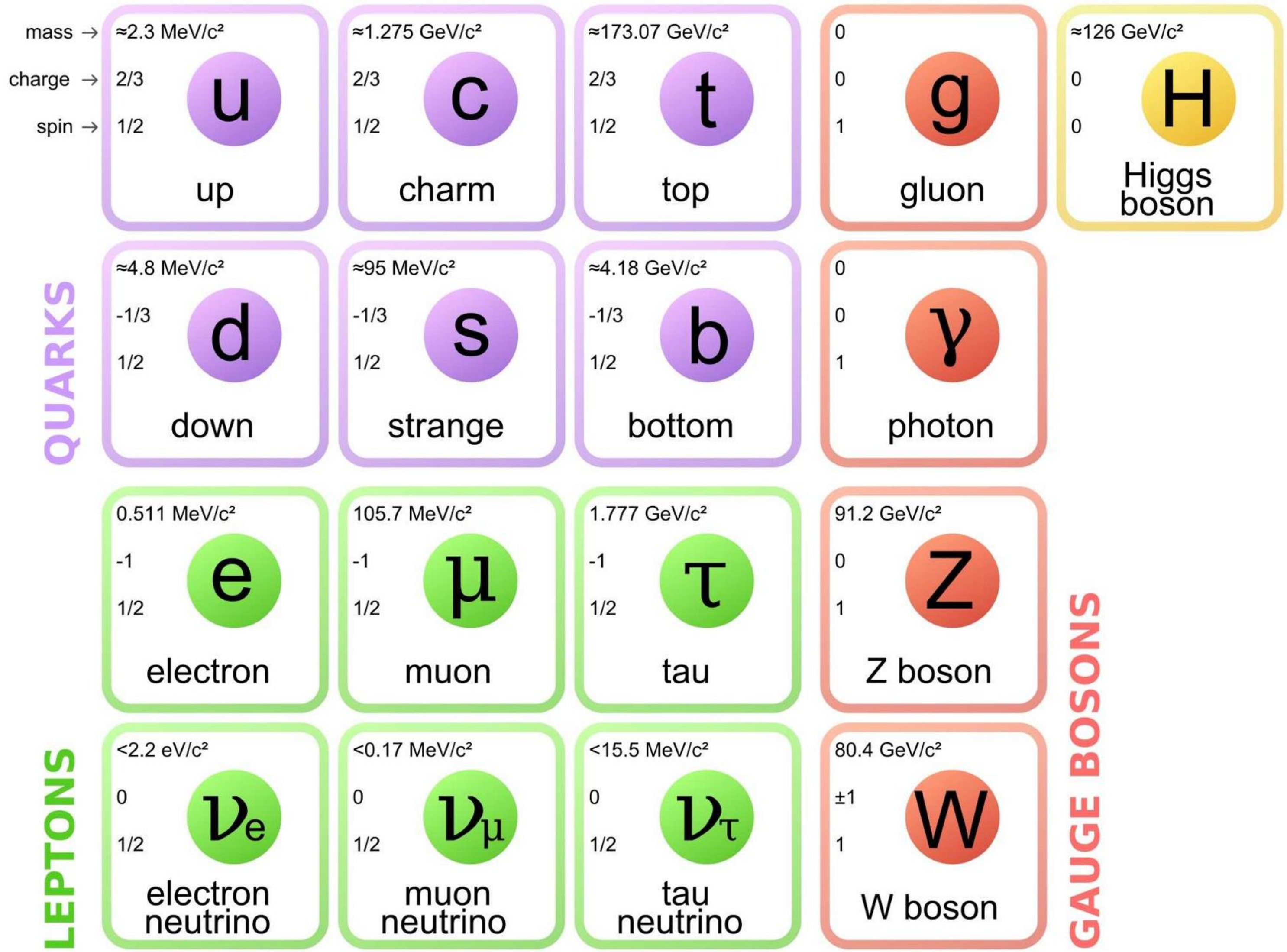
P. Higgs

Sheldon Lee Glashow

Abdus Salam
Prize share: 1/3

Steven Weinberg
Prize share: 1/3

Standard Model of elementary particles

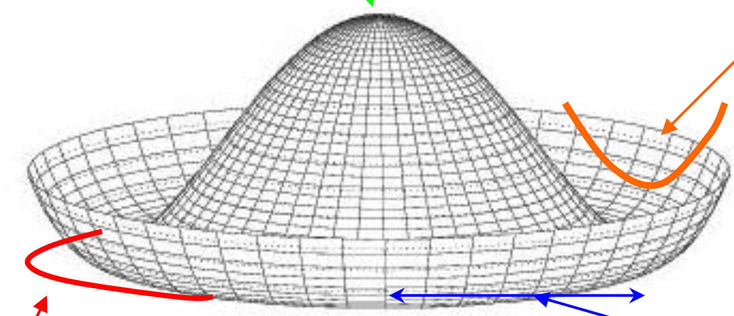


The beginning of Higgs boson story

	Article	Reception date	Publication date
1	F. Englert and R. Brout Phys. Rev. Letters **13-[9]** (1964) 321	26/06/1964	31/08/1964
2	P.W. Higgs Phys. Letters **12** (1964) 132	27/07/1964	15/09/1964
3	P.W. Higgs Phys. Rev. Letters **13-[16]** (1964) 508	31/08/1964	19/10/1964
4	G.S. Guralnik, C.R. Hagen and T.W.B. Kibble Phys. Rev. Letters **13-[20]** (1964) 585	12/10/1964	16/11/1964

The Higgs potential

$m_W, m_Z = 0$



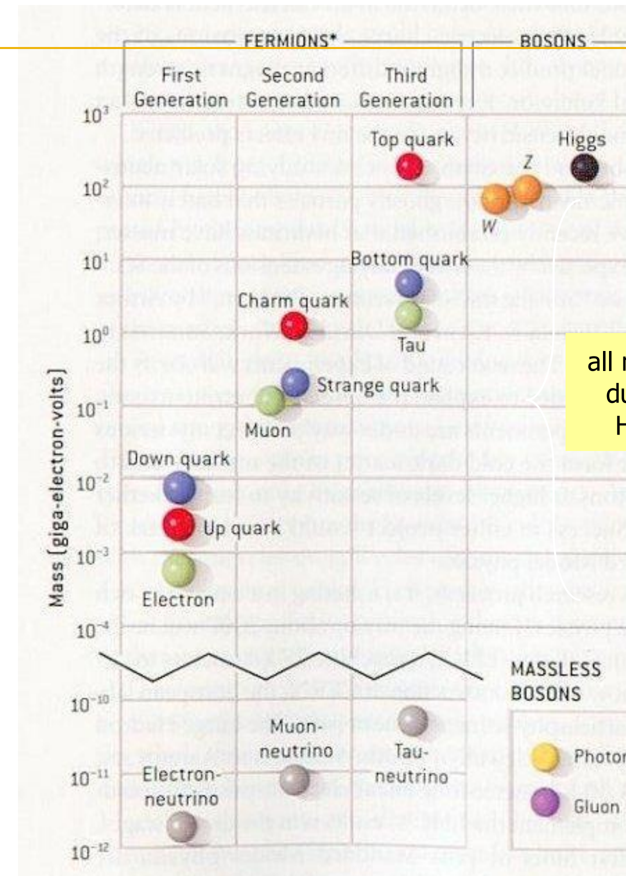
physical Higgs boson

mass[2] of Higgs ~ curvature of potential at minimum

v

$m_W, m_Z \neq 0$

modes "eaten" by W,Z



all masses due to Higgs

- Breaks symmetry while maintaining local gauge invariance (→renormalizability)
- Add complex weak isospin SU(2) doublet with "mexican hat" potential $V = \mu^2|\Phi|^2 + \lambda|\Phi|^4$

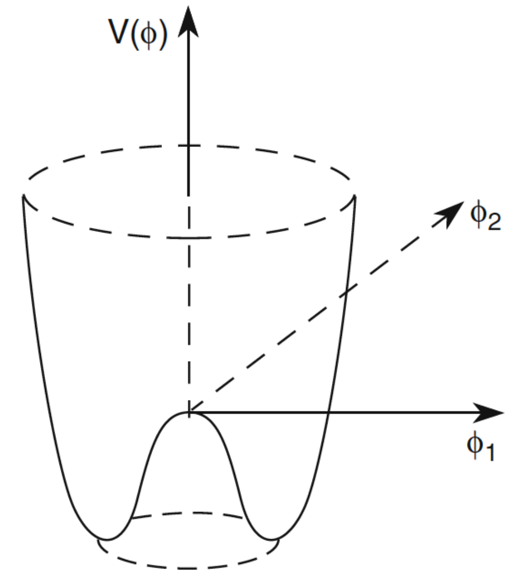
$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

- 3 components of Φ form longitudinal components of $W^\pm$ and Z (→massive)
- 1 component → real scalar particle: Higgs boson
- Couple fermion fields to Φ → fermion mass terms

The Higgs mechanism

$$V(\varphi^+\varphi) = \mu^2\varphi^+\varphi + \lambda(\varphi^+\varphi)^2$$

$$\mu^2 < 0 \qquad \lambda > 0$$



circle of degenerate minima
→ choice of the minimum gives spontaneous simmetry breaking:

$$\varphi_0 = \sqrt{\tfrac{1}{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \text{with} \;\; v = \sqrt{\frac{-\mu^2}{\lambda}}$$

$$\begin{aligned}\mathcal{L}_H =& \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \frac{1}{2}(-2\mu^2)h^2 \\ & -\frac{1}{4}A^1_{\mu\nu}A^{1\mu\nu} + \frac{1}{2}\left(\frac{g^2v^2}{4}\right)A^1_\mu A^{1\mu} \\ & -\frac{1}{4}A^2_{\mu\nu}A^{2\mu\nu} + \frac{1}{2}\left(\frac{g^2v^2}{4}\right)A^2_\mu A^{2\mu} \\ & -\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + \frac{1}{2}\left(\frac{g^2v^2}{4cos^2\theta_w}\right)\mathcal{Z}_\mu\mathcal{Z}^\mu \\ & -\frac{1}{4}A_{\mu\nu}A^{\mu\nu} + 0\mathcal{A}_\mu\mathcal{A}^\mu \\ & +\mathcal{L}_{VVH}.\end{aligned}$$

$$m_W^2 = \frac{g^2v^2}{4} \qquad \text{for } A^1_\mu \text{ and } A^2_\mu$$

$$m_Z^2 = \frac{g^2v^2}{4\cos^2\theta_w} = \frac{m_W^2}{\cos^2\theta_w} \qquad \text{for } \mathcal{Z}_\mu$$

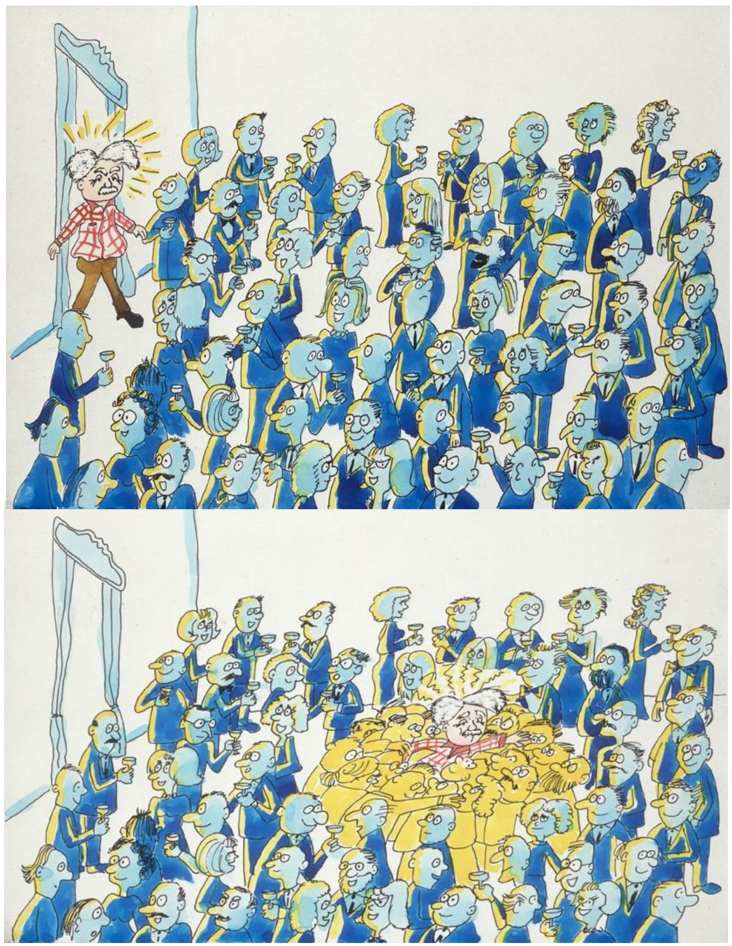
$$m_A^2 = 0 \qquad \text{for } \mathcal{A}_\mu.$$

$$m_{H^0} = \sqrt{-2\mu^2} = \sqrt{2\lambda}v$$

Masses and couplings

From Gauge Invariance :

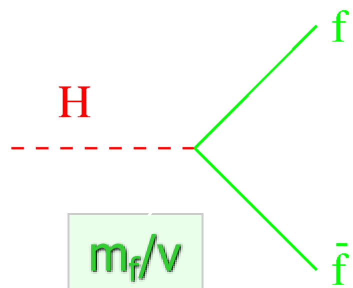
$$m_W = m_Z \cos\theta_w, \quad \sin^2\theta_w = 1 - \frac{m_W^2}{m_Z^2}.$$



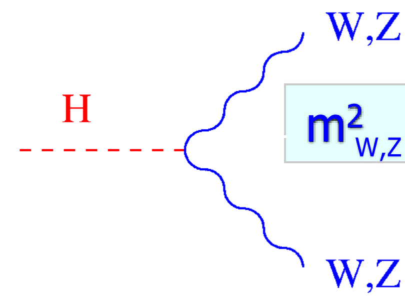
and from the Higgs Mechanism …

$m_W = gv/2$ ($\rightarrow$ v ~ 250 GeV)

vacuum expectation value

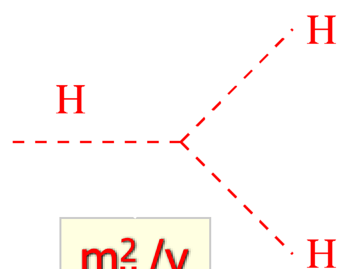


m_f/v

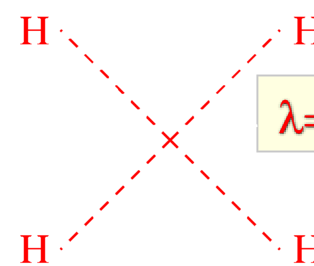


$m^2_{W,Z}/v$

All couplings predicted



m^2_H/v



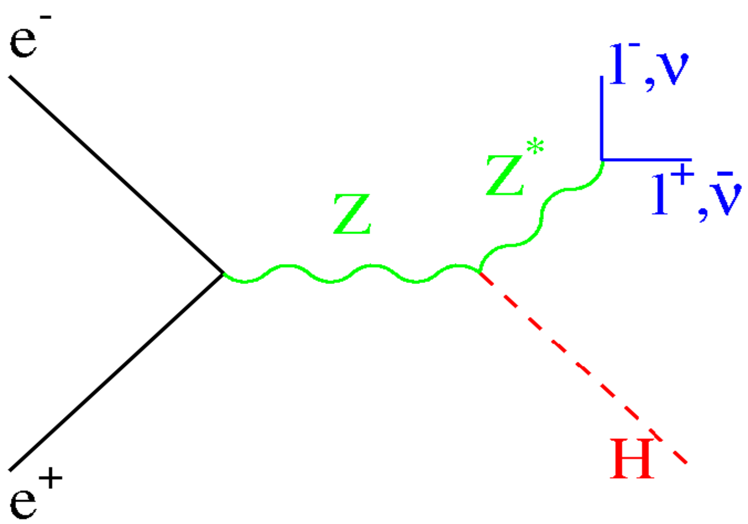
$\lambda = m^2_H/v^2$

SM Higgs production at LEP

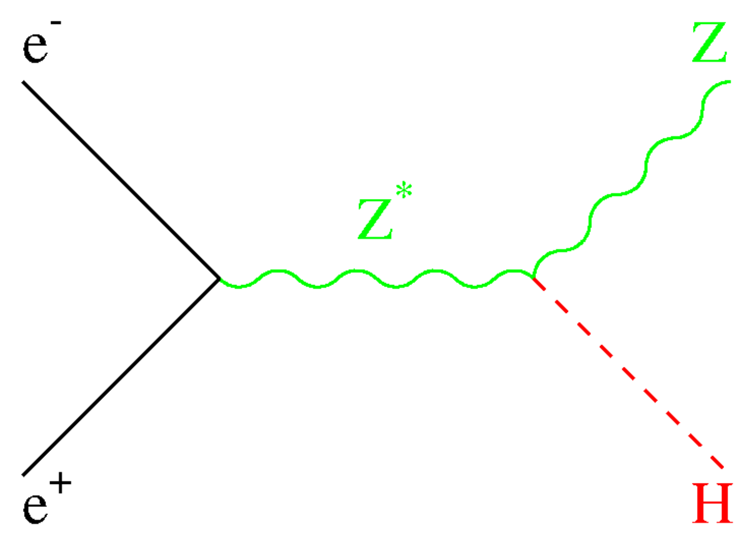
Dominant at LEP: The Higgs-strahlung process

(The production cross section depends only on m_H)

LEP 1: $\sqrt{s} \sim m_Z$



LEP 2: $\sqrt{s} \geq m_Z + m_H$

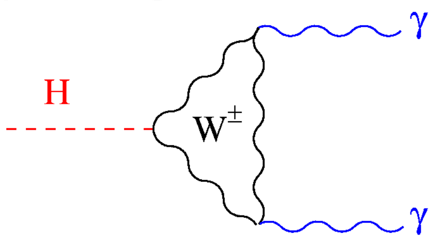


(Large coupling to the Z ⇒ Only sizeable cross section)

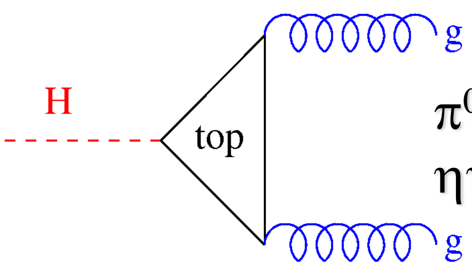
SM Higgs decay at LEP

The decay branching ratios depend only on m_H:

- $m_H < 2m_e$: $H \to \gamma\gamma$ + large lifetime;



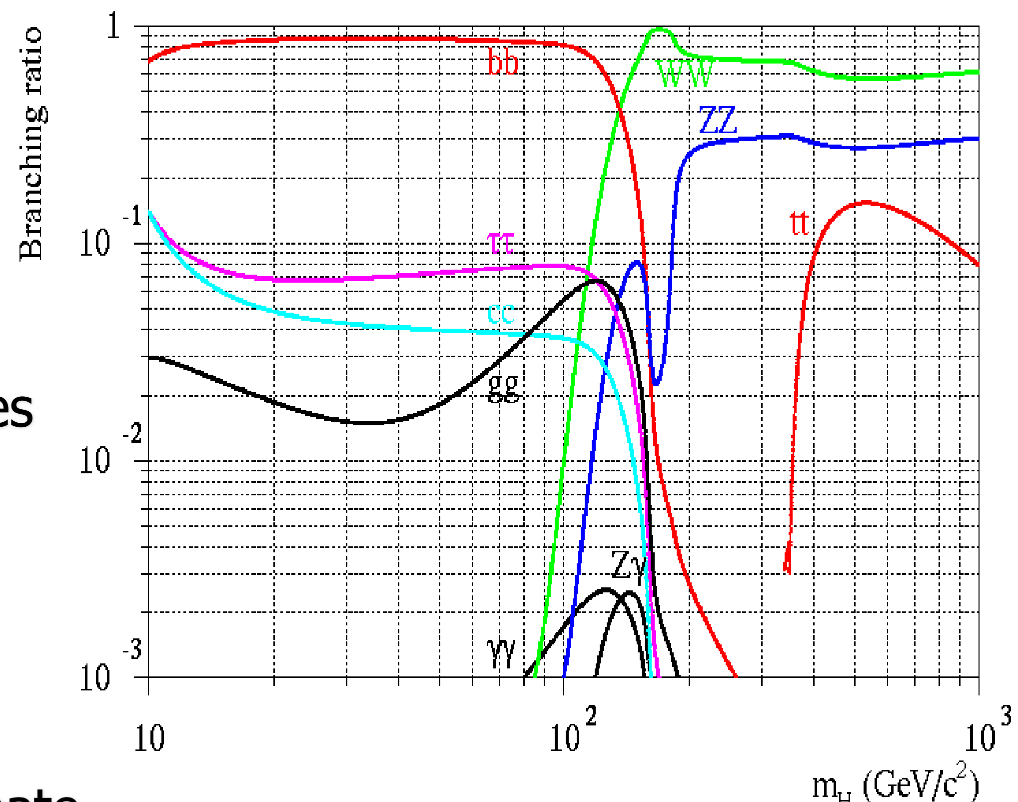
- $m_H < 2m_\mu$: $H \to e^+e^-$ dominates
- $m_H < 2m_\pi$: $H \to \mu^+\mu^-$ dominates
- $m_H < 3 - 4$ GeV: $H \to gg$ dominates



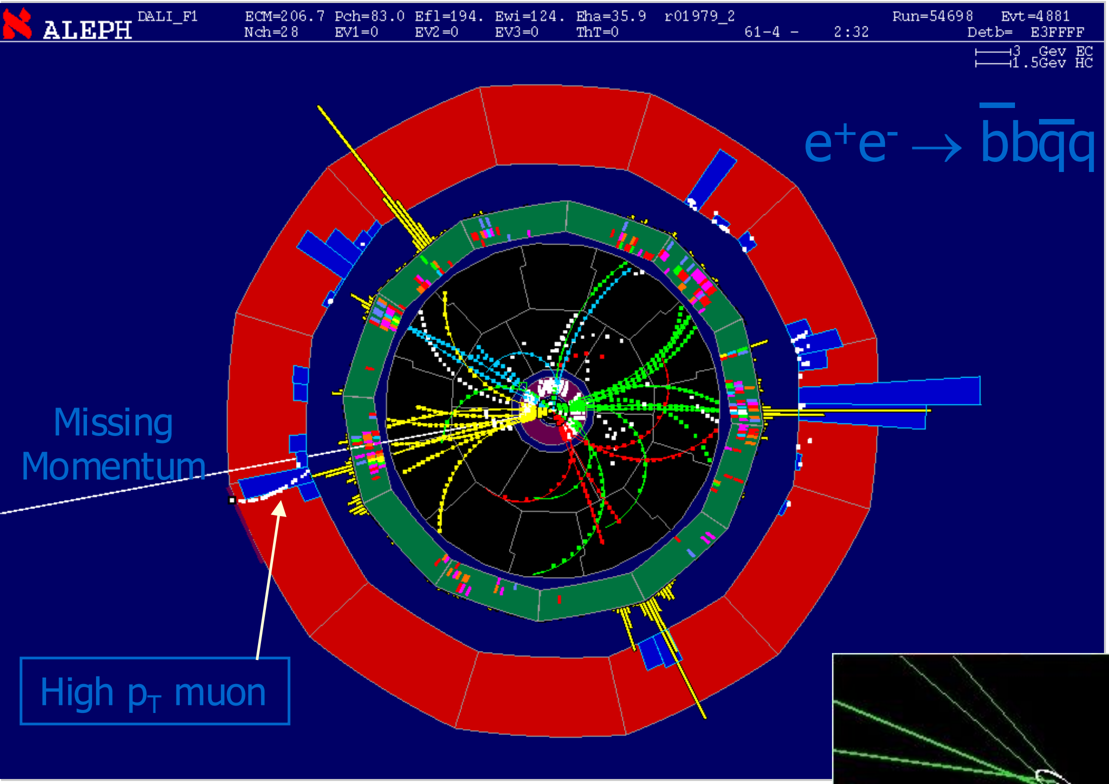
$\pi^0\pi^0$, $\pi^+\pi^-$, KK, $\eta\eta$, ... etc

- $m_H < 2m_b$: $H \to \tau^+\tau^-$ and $c\bar{c}$ dominate

- $m_H > 2m_b$ up to 1000 GeV/c²: $H \to bb$



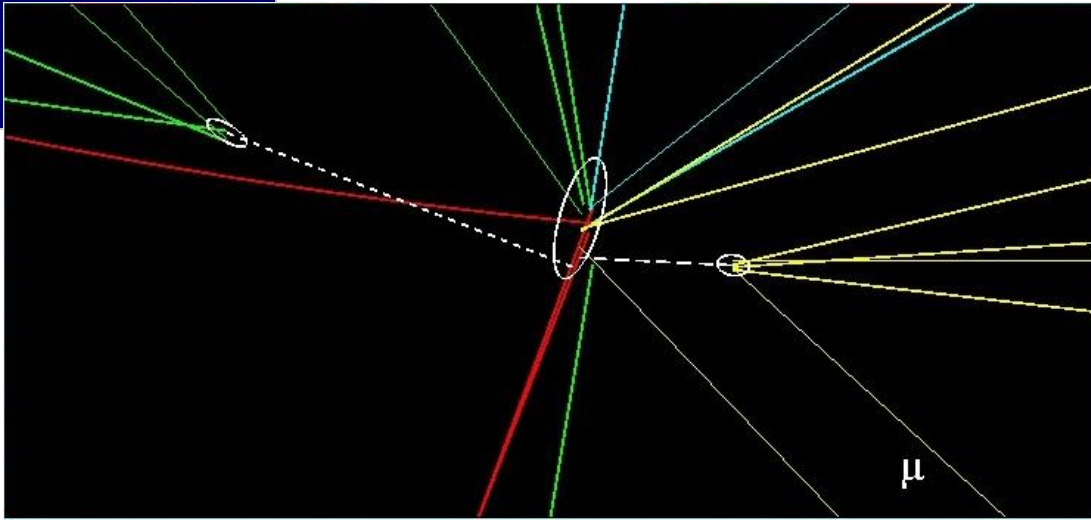
First pb^{-1}'s above 206 GeV, first thrills at 115 GeV



First Candidate Event
(14-Jun-2000, 206.7 GeV)

- Mass 114.3 GeV/c2;
- Good HZ fit;
- Poor WW and ZZ fits;
- P(Background) : 2%
- s/b(115) = 4.7

The purest candidate event ever!



b-tagging
(0 = light quarks, 1 = b quarks)

- Higgs jets: 0.99 and 0.99
- Z jets: 0.14 and 0.01.

Higgs results at LEP

Physics Letters B 565 (2003) 61–75

Search for the Standard Model Higgs boson at LEP

ALEPH Collaboration [1] DELPHI Collaboration [2] L3 Collaboration [3] OPAL Collaboration [4]
The LEP Working Group for Higgs Boson Searches [5]

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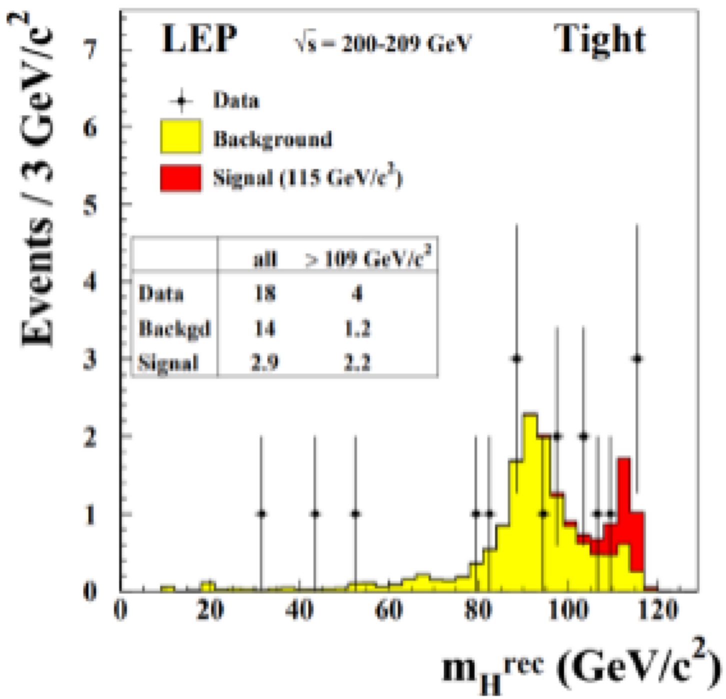
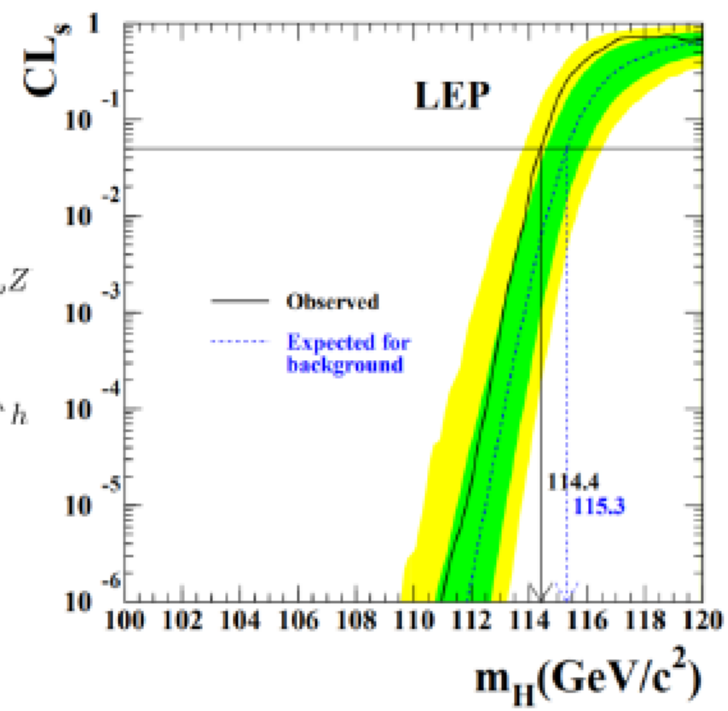
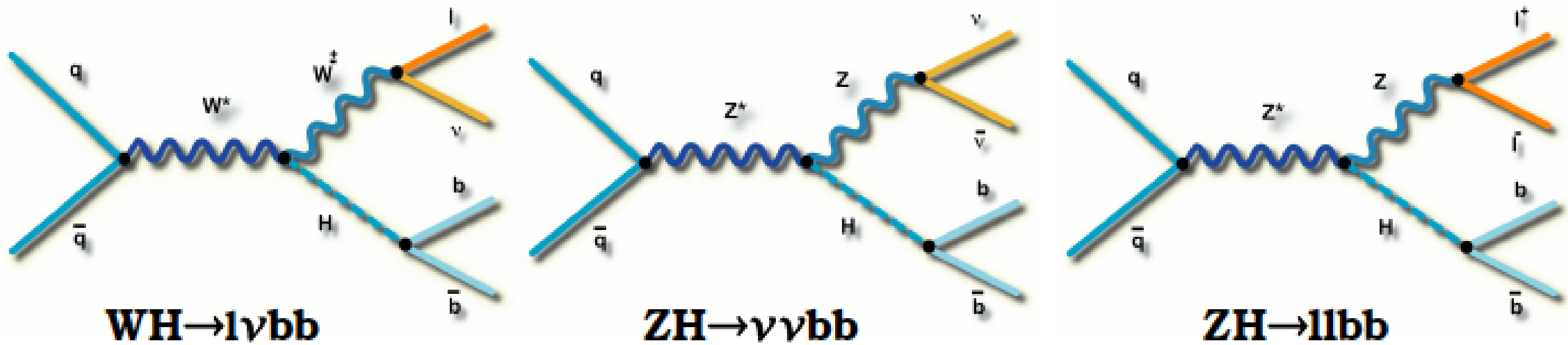
m_H > 114.4 GeV @ 95%CL



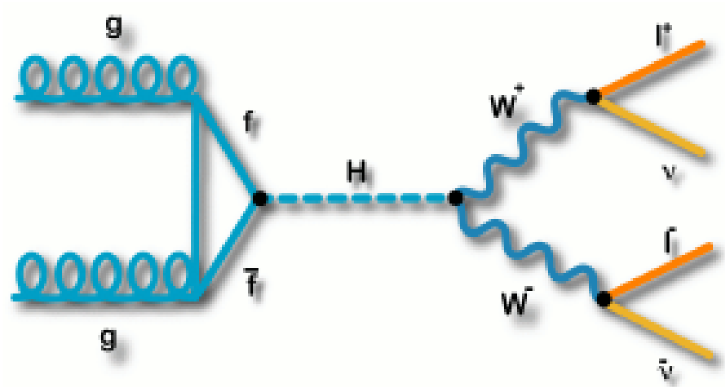


SM Higgs production at Tevatron

Associated Production: Low mass only, 3 dominant final states



Gluon Fusion Production:
Maximum sensitivity at high mass, also useful at low mass

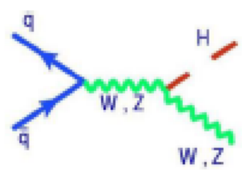


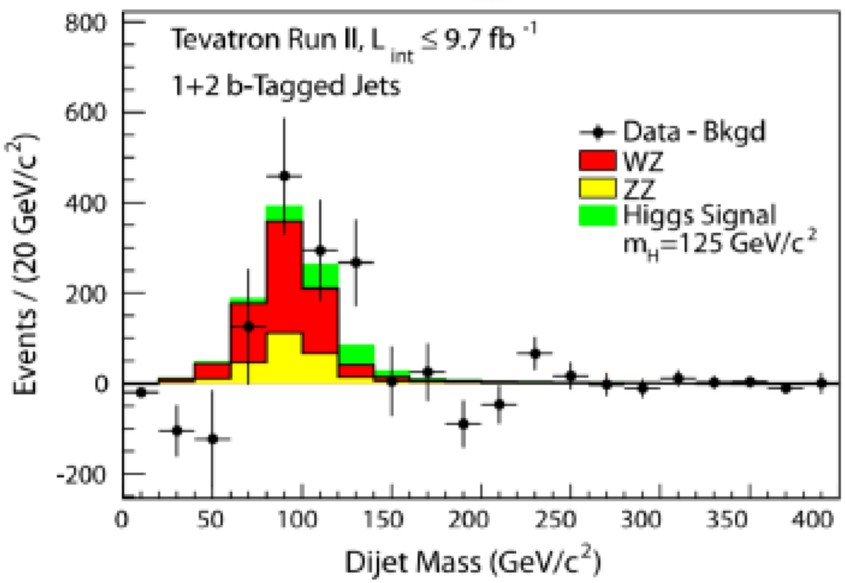
Higgs results at Tevatron

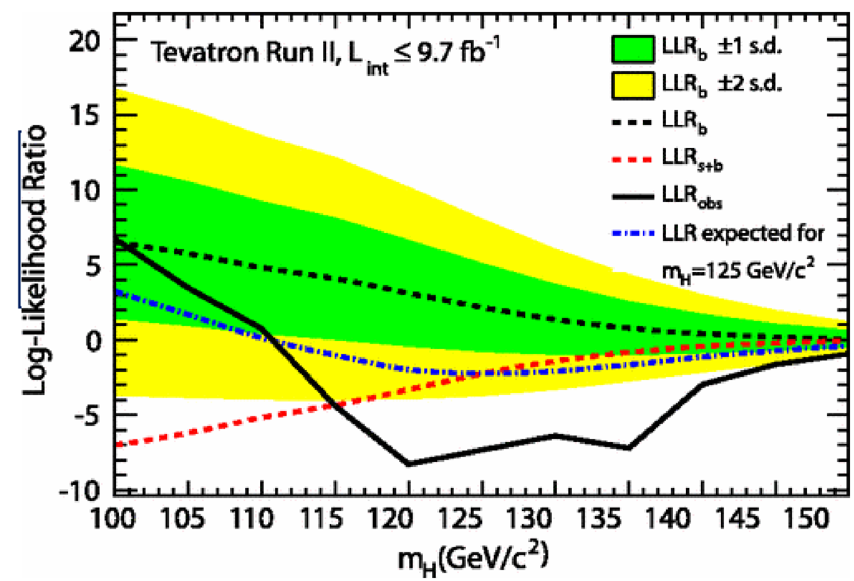
PRL **109**, 071804 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Evidence for a Particle Produced in Association with Weak Bosons and Decaying to a Bottom-Antibottom Quark Pair in Higgs Boson Searches at the Tevatron

(*CDF Collaboration)
(†D0 Collaboration)





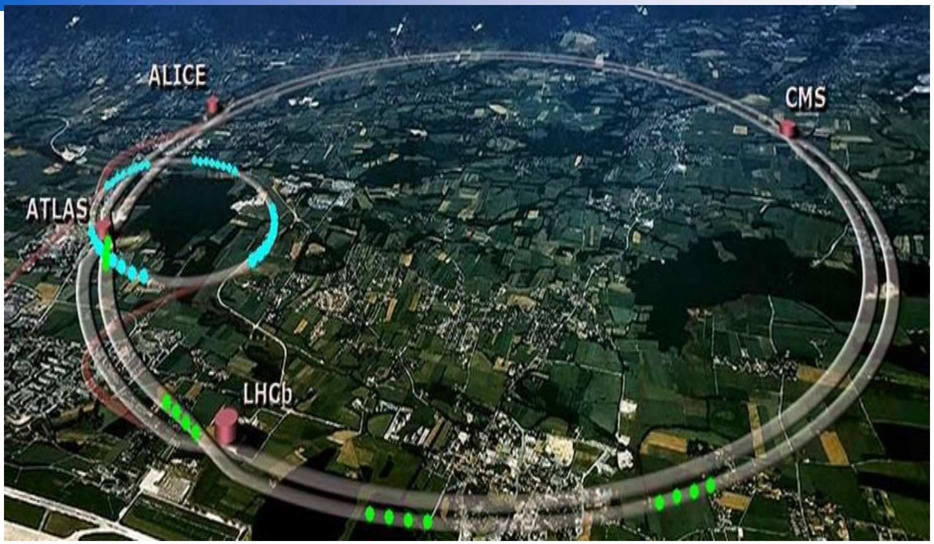


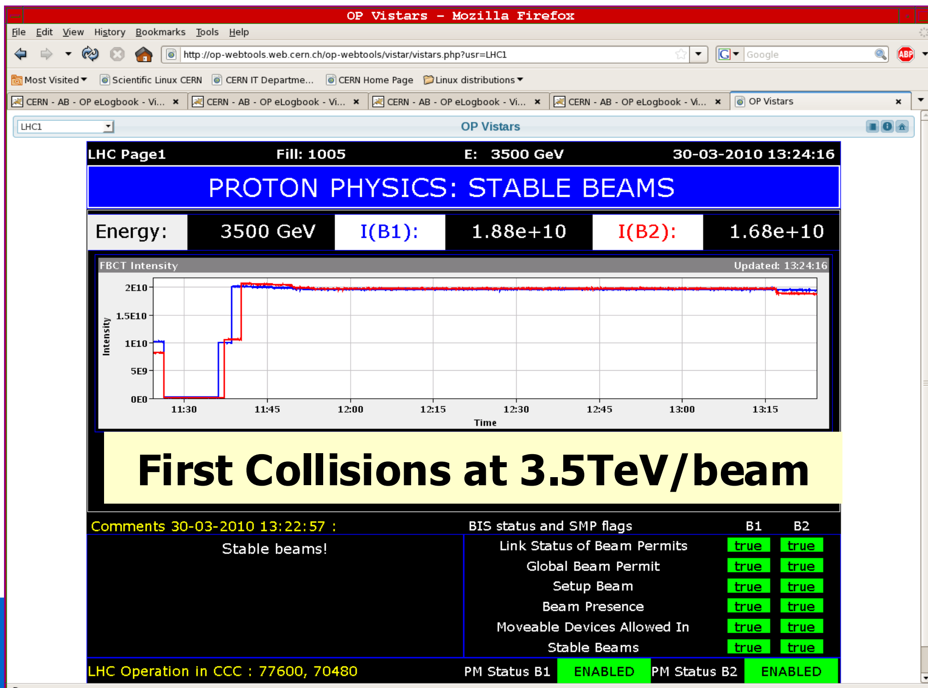
Significance

2.8σ observed @ 125 GeV

N. De Filippis

The LHC machine



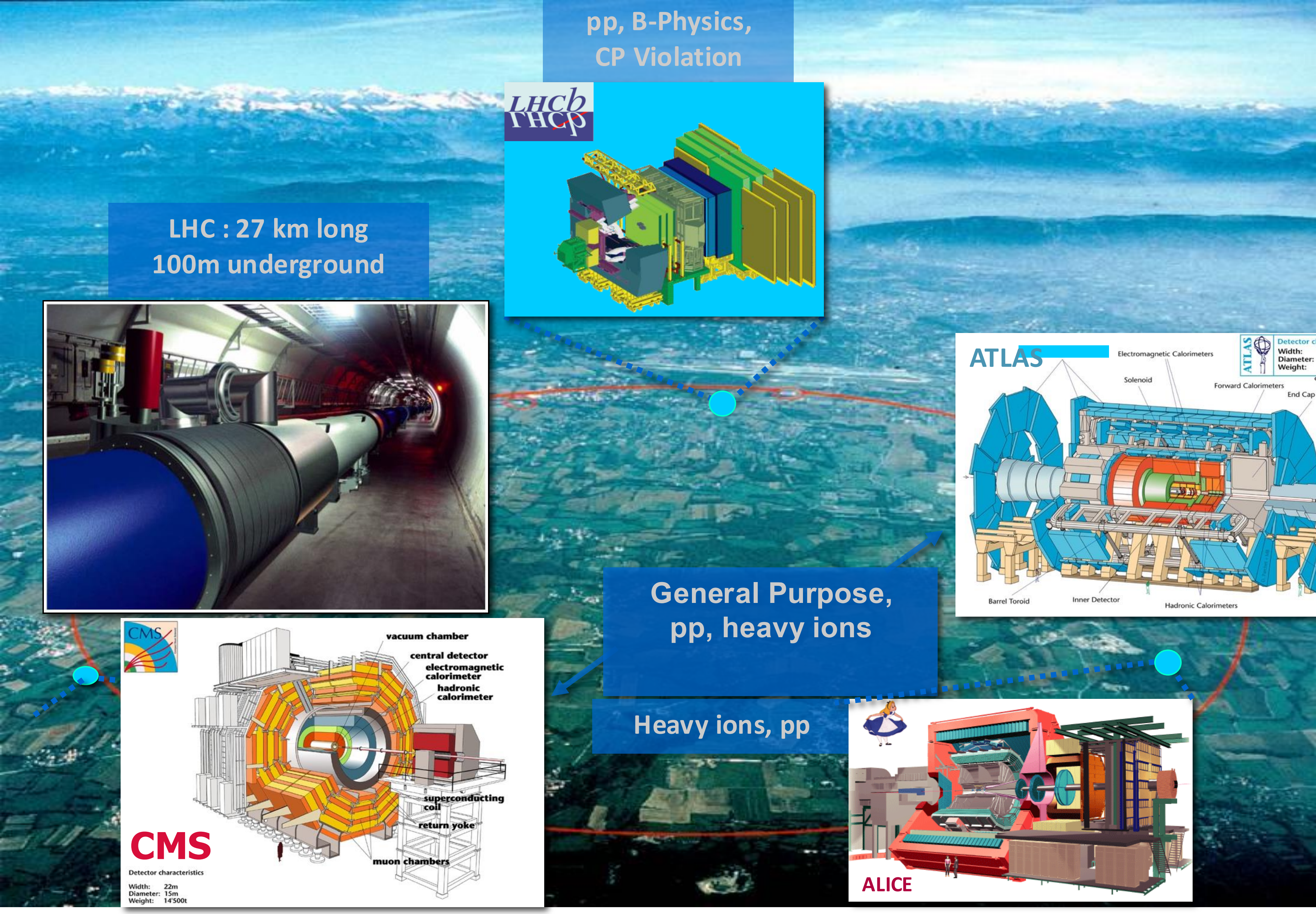


Circumference (km)	26.7
Number of superconducting Dipoles	1232
Length of Dipole (m)	14.3
Dipole Field Strength (Tesla)	8.4
Operating Temperature (K)	1.9
Current in dipole sc coils (A)	13000
Beam Intensity (A)	0.5
Beam Stored Energy (MJoules)	362
Number of particles per bunch	1.15×10^{11}
Number of bunches per beam	2808
Crossing angle (μrad)	285
Bunch length (cm)	7.55
Norm transverse emittance (μm rad)	3.75
Beta function at IP 1,2,5,8 (m)	0.55,10,0.55,10

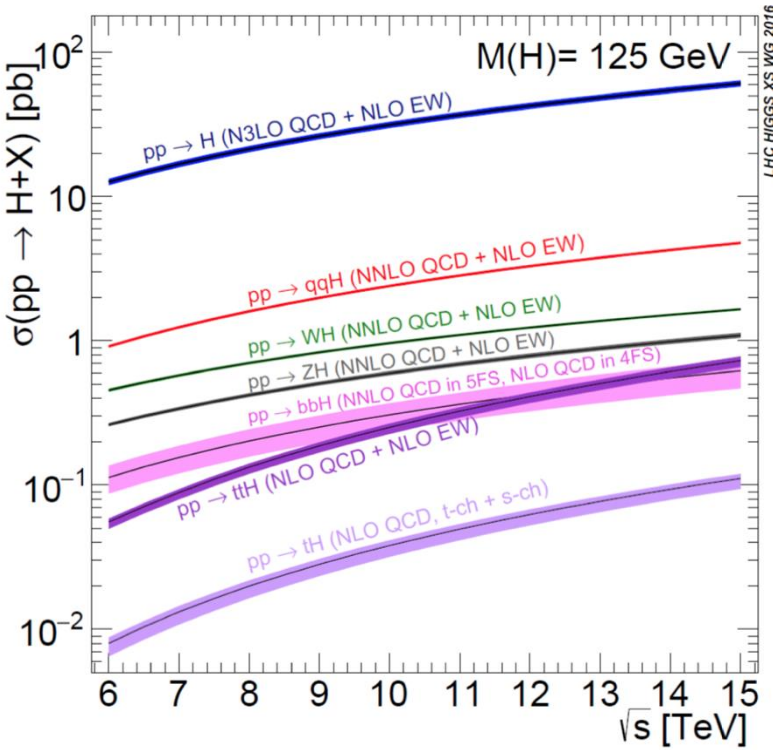
$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \varepsilon_n \beta *} F$$

N_b = number of proton per bunch
n_b = number of bunches
f_{rev} = rotation frequency (~ 11Hz)
F = crossing angle factor

Rms transverse beam size $= \sqrt{\varepsilon \beta / \gamma}$
ε_n = renorm. transverse emittance
$\beta *$ = optics at beam crossing (m)
γ_r = relativistic factor

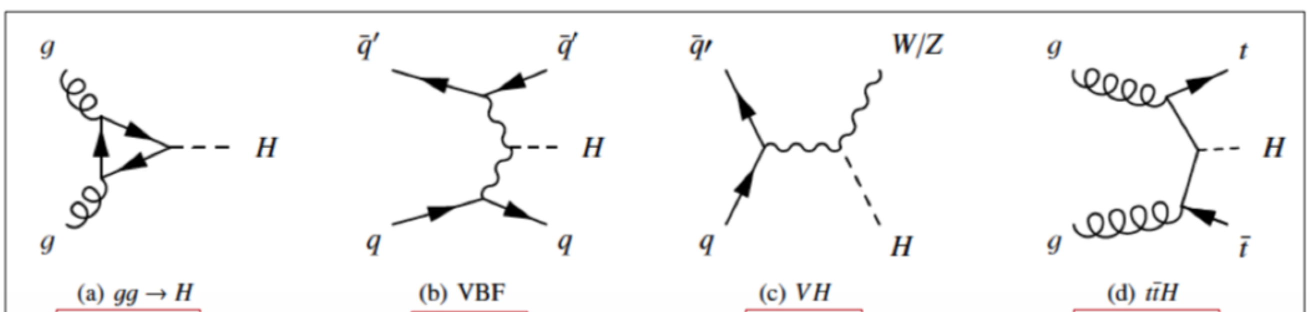

pp, B-Physics,
CP Violation
LHCb
LHC : 27 km long
100m underground
ATLAS
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap
Barrel Toroid
Inner Detector
Hadronic Calorimeters
General Purpose,
pp, heavy ions
vacuum chamber
central detector
electromagnetic calorimeter
hadronic calorimeter
superconducting coil
return yoke
muon chambers
CMS
Detector characteristics
Width: 22m
Diameter: 15m
Weight: 14'500t
Heavy ions, pp
ALICE

Higgs production at the LHC



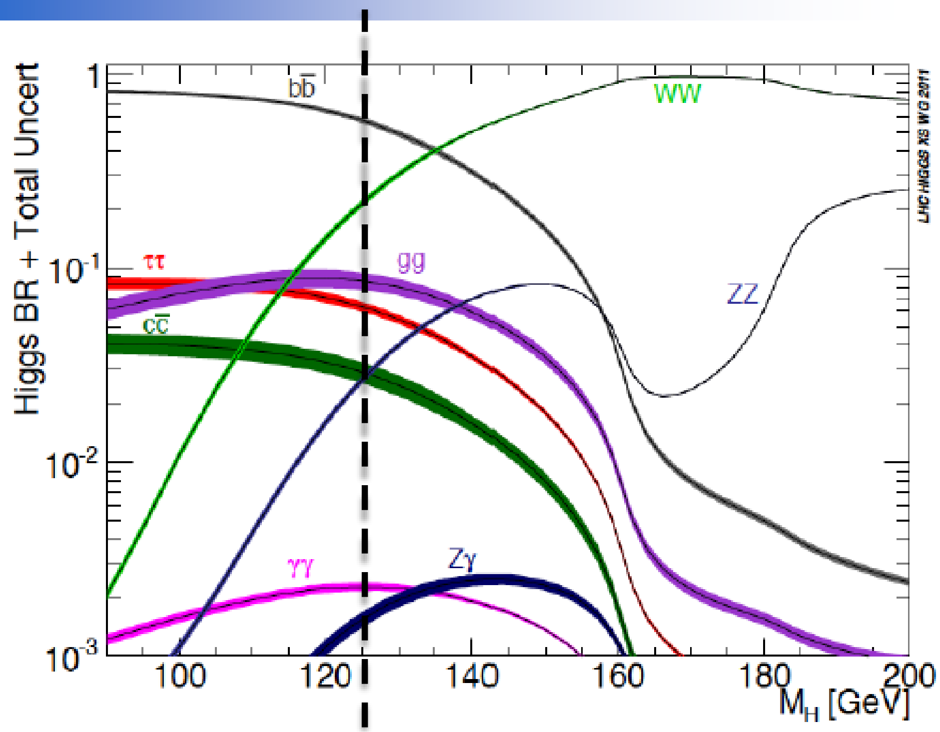
- ggF dominant, larger initial
- VBF: two forward jets with high
- VH vector boson (lν, ll', qq')
- ttH many b-jets, leptons, E_T^{miss}

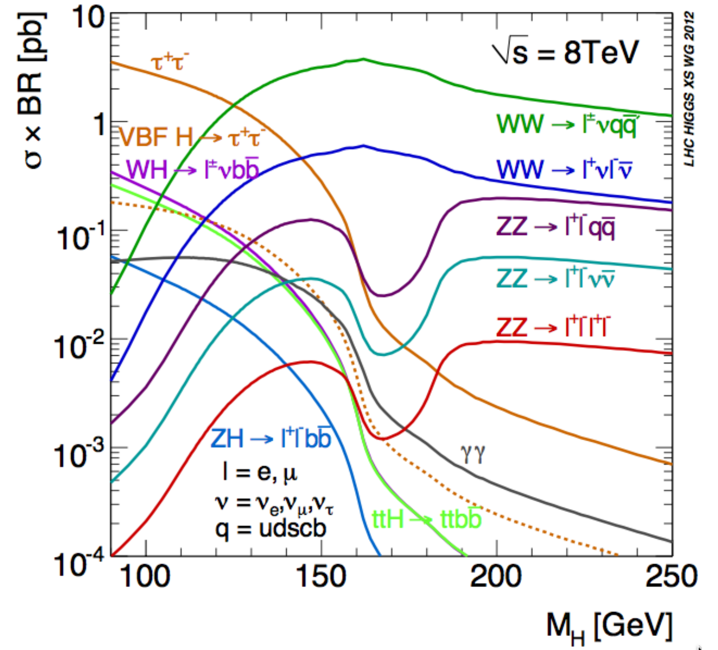
Total cross-section = 56 pb



87%	7%	5%	<1%

Higgs decay channels





Channel	m_H resolution
$H \to \gamma\gamma$	1–2%
$H \to \tau\tau \to e\tau_h/\mu\tau_h/e\mu + X$	20%
$H \to \tau\tau \to \mu\mu + X$	20%
$WH \to e\mu\tau_h/\mu\mu\tau_h + \nu's$	20%
$(W/Z)H \to (e\nu/\mu\nu/ee/\mu\mu/\nu\nu$	10%
$H \to WW^* \to 2\ell 2\nu$	20%
$WH \to W(WW^*) \to 3\ell 3\nu$	20%
$H \to ZZ^{(*)} \to 4\ell$	1–2%
	3%
$H \to ZZ^{(*)} \to 2\ell 2q$	3%
$H \to ZZ \to 2\ell 2\tau$	10–15%
$H \to ZZ \to 2\ell 2\nu$	7%

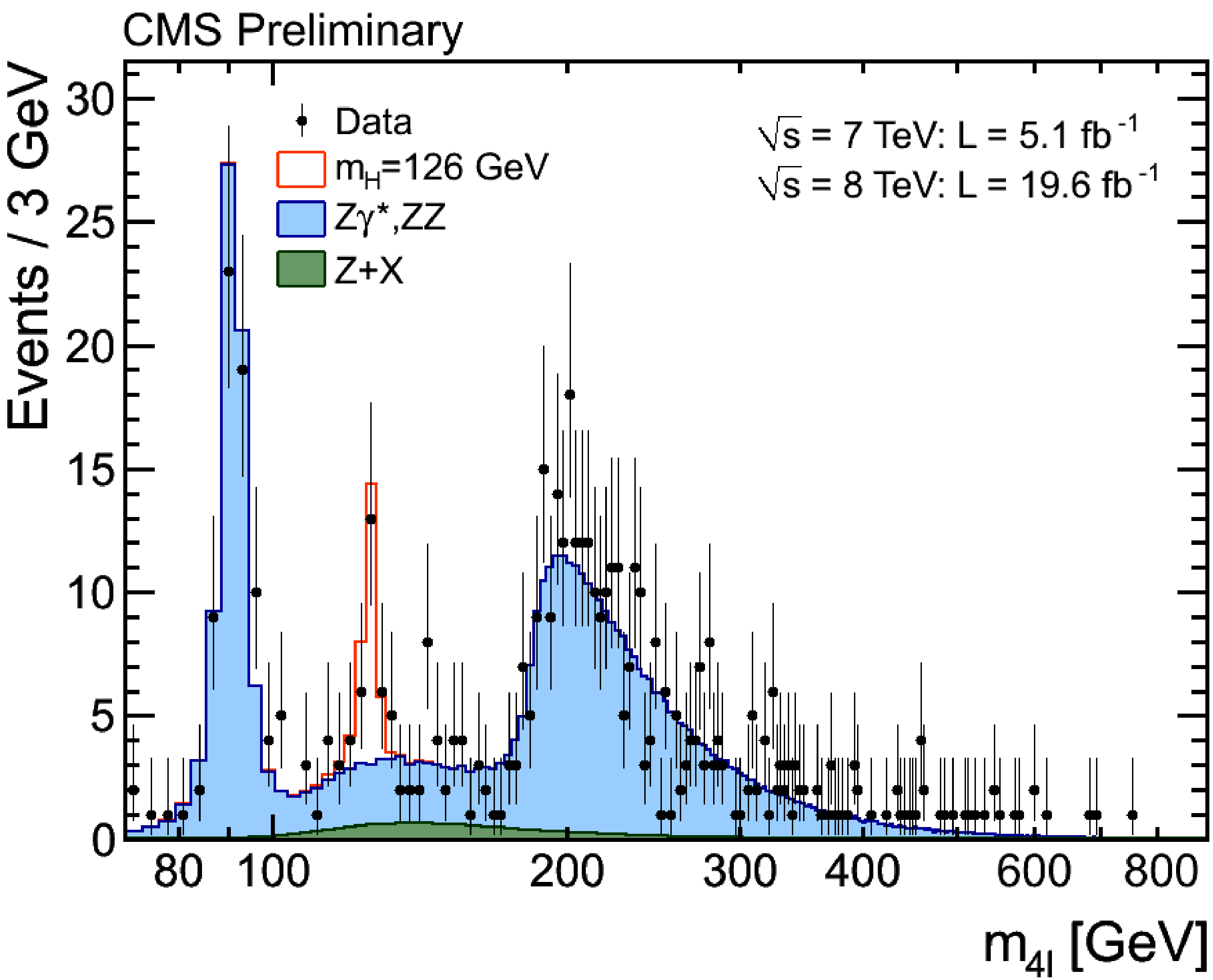
At m_H =125 GeV:

- H(bb) = 57.8%
- H(WW) = 21.4%
- H(gg) = 8.19%
- H(ττ) = 6.27%
- H(ZZ) = 2.62%

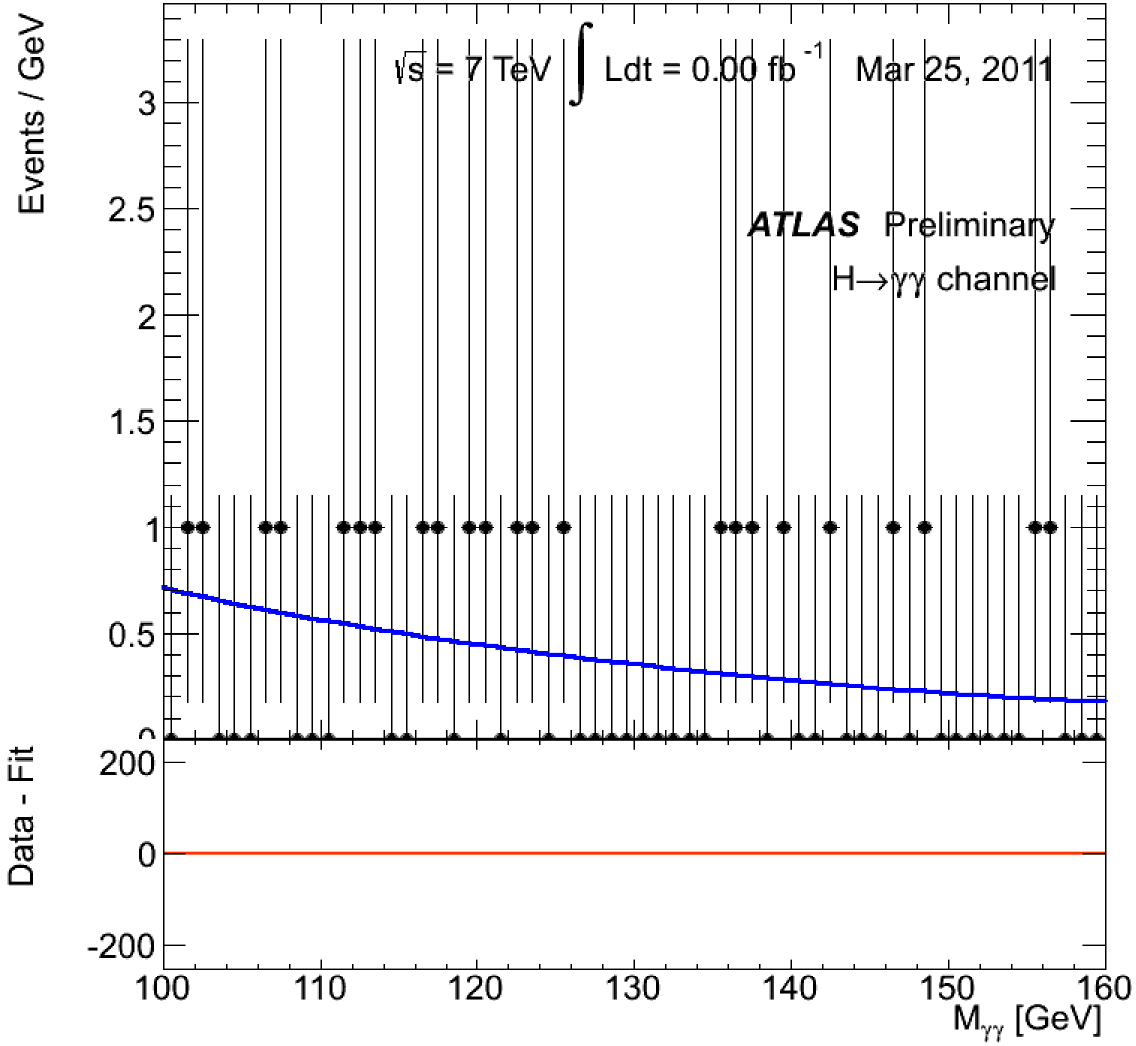
At m_H =125 GeV:

- H(cc) = 2.89%
- H(γγ) = 0.23%
- H(Zγ) = 0.15 %
- H(μμ) = 0.02%

Full 7+8 TeV data: H→ZZ→4l analysis



Full 7+8 TeV data: H→$\gamma\gamma$ analysis



October 8, 2013: Nobel Prize

Nobel Prizes and Laureates

Physics Prizes ‹ 2013 ›

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- Summary
- Prize Announcement
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- Advanced Information
- Popular Information
- Greetings

▶ François Englert

▶ Peter Higgs

All Nobel Prizes in Physics

All Nobel Prizes in 2013

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

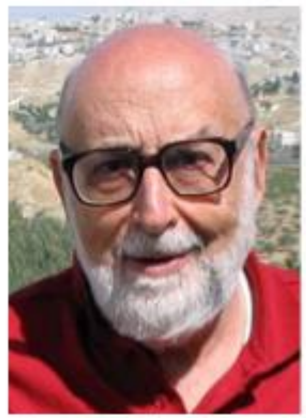


Photo: Pnicolet via Wikimedia Commons

François Englert

Photo: G-M Greuel via Wikimedia Commons

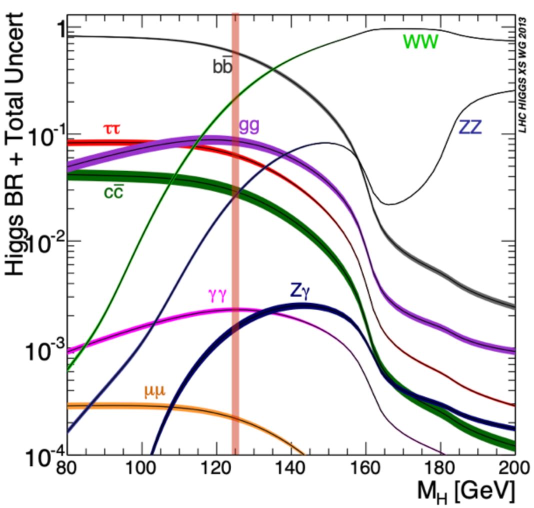
Peter W. Higgs

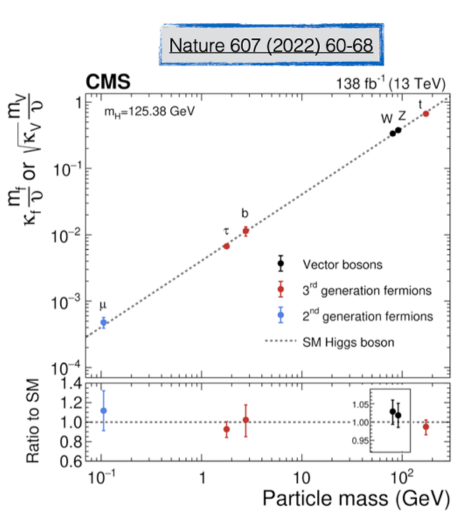
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

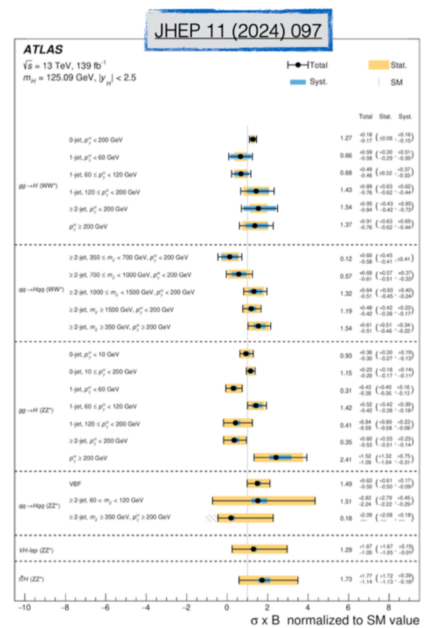
Landscape of the Higgs physics today

So far many questions still open for Higgs physics:

- ✓ How well the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?
- ✓ How do precision electroweak observables provide us information about the Higgs boson properties and/or BSM physics?
- ✓ What progress is needed in theoretical developments in QCD and EWK to fully capitalize on the experimental data?
- ✓ What is the best path towards measuring the Higgs potential ?
- ✓ To what extent can we tell whether the Higgs is fundamental or composite?





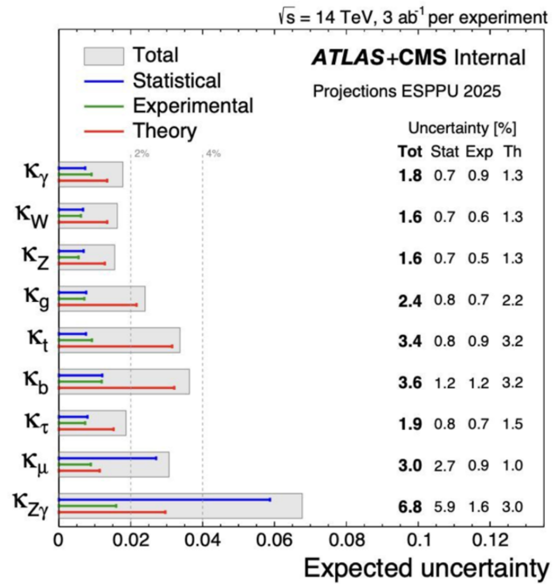


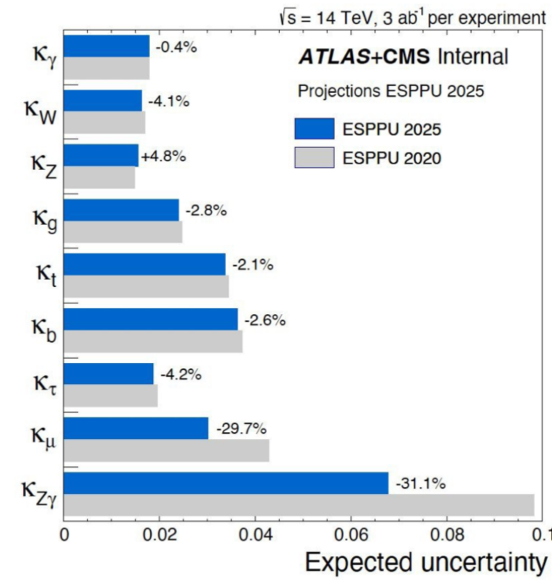
- Couplings to gauge bosons and 3rd generation fermions close to SM expectations (~10% precision), evidence for 2nd generation fermion coupling ($H \rightarrow \mu\mu$), all measurements consistent with CP-even scalar
- LHC experiments entered era of differential cross section measurements (EFT fits, etc.)

Landscape of the Higgs physics today

- **HL-LHC and future colliders would explore in detail the Higgs properties:** understand the deep origin of EWSB

- **Beyond HL-LHC measurements:**
  - ✓ couplings to fermions to %-level, to bosons to per-mil
  - ✓ self-coupling
  - ✓ invisible decays
  - ✓ BSM Higgses





Theory uncertainties are dominating

Non-resonant HH projections: 3000 fb^{-1}

Channel	HH Significance ATLAS	HH Significance CMS
bbττ	3.8	2.7
bbγγ	2.6	2.6
4b resolved	1.0	1.3
4b boosted	-	2.2
Multilepton	1.0	-
bbℓℓ	0.5	-
Combination	**4.5**	**4.5**
ATLAS + CMS	7.60	

Channel	κ_3 precision 68% CL ATLAS	κ_3 precision 68% CL CMS
bbττ	[0.5, 1.6]	[0.3, 2.0]
bbγγ	[0.5, 1.7]	[0.4, 1.9]
4b resolved	[-0.5, 6.1]	[-0.3, 7.2]
4b boosted	-	[-0.4, 8.2]
Multilepton	[-0.1, 4.7]	-
bbℓℓ	[-2.1, 9.1]	-
Combination	[0.6, 1.4]	[0.6, 1.5]
ATLAS + CMS	-26/+29	

Combined evidence >7σ.

Precision on k_λ=1 ~26%

2020 update of European Strategy for Particle Physics

*"**An electron-positron Higgs factory is the highest priority next collider**. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."*

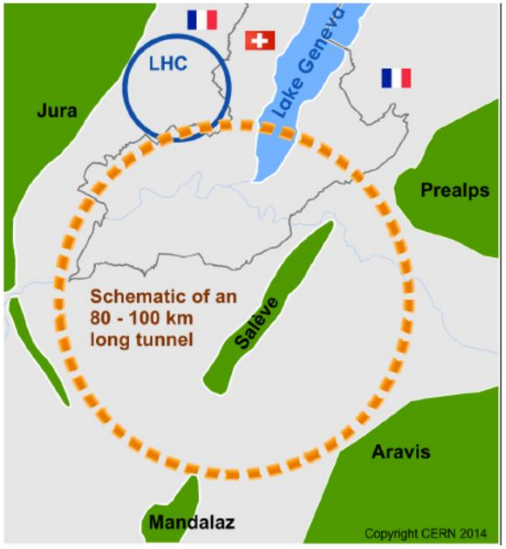
"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

FCC project @ CERN: a new 100 km tunnel in the Geneva region, for two complementary machines covering the largest phase space in the high energy frontier:

- **extreme precision circular e+e-collider (FCC-ee) with** variable collision energy from 90-360 GeV
- **highest energy reach in pp collisions (FCC-hh)**: 100 TeV

FCC Feasibility Study (FS) launched in 2021:

- To be carried out in 2021-2025 ➔ input to the next Strategy update
- Mid-term review in Autumn 2023



Open Symposium on the European Strategy for Particle Physics

23–27 giu 2025
Venice Lido
Europe/Rome fuso orario

European Strategy 2025

FCC Feasibility Study

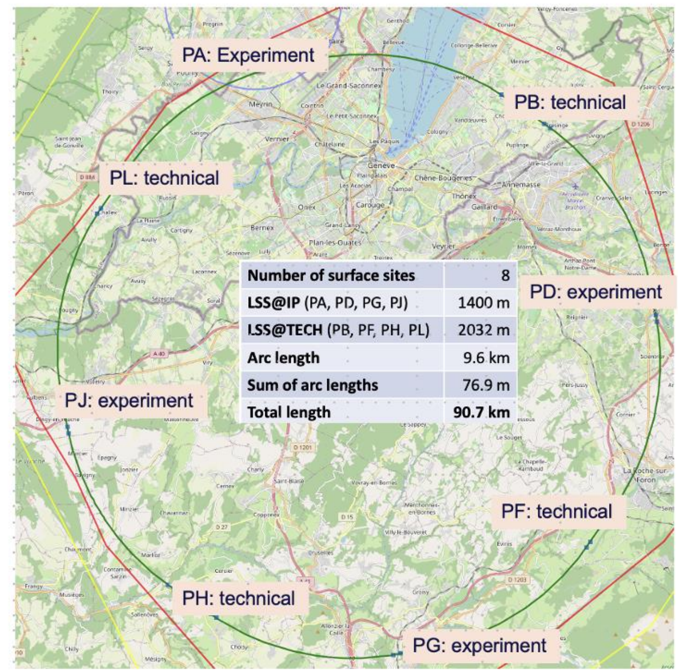
- Started in 2021 → Report completed in March 2025, earlier than initially planned, to align with ESPP input submission deadline
- It covers the geological, technical, environmental and territorial feasibility of a 91-km ring and its infrastructure in the Geneva basin, and scientific potential and required technologies for FCC-ee and FCC-hh.
  Good progress also on financial aspects (→ see later)
- Total cost-to-completion: 83 MCHF

Vol. 1: Physics, Experiments and Detectors (~ 260 pages)
Vol. 2: Accelerators, Technical Infrastructure and Safety (~ 600 pages)
Vol. 3: Civil Engneering, Implementation and Sustainability (~ 330 pages)

An extraordinary collective effort by the FCC community, involving some 1500 contributors from 162 institutions in 38 countries

The **breadth and depth of the results are unprecedented for a project at this stage of development.**

Report being reviewed by expert committee, and then by Council and its subordinate bodies before end of year.



Ring placement selected out of ~ 100 variants taking into account geological, environmental, surface (land availability, access to roads, etc.), infrastructure (water, electricity, transport) constraints, machine performance, etc.

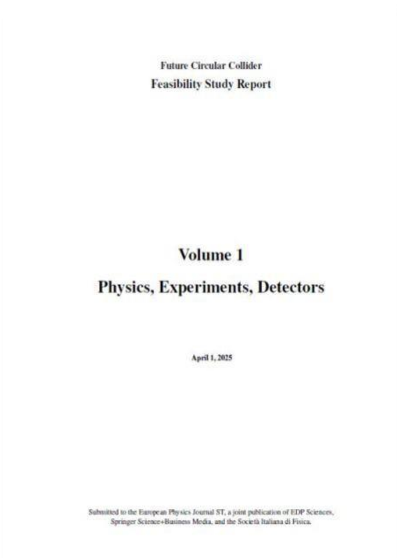
European Strategy 2025

Published! Feasibility Study Reports

INFN Istituto Nazionale di Fisica Nucleare

FUTURE CIRCULAR COLLIDER

And a YellowReport on Future HTE factories

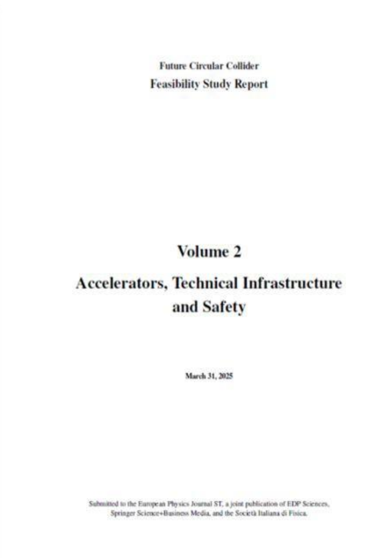


Future Circular Collider
Feasibility Study Report

Volume 1
Physics, Experiments, Detectors

April 1, 2025

Submitted to the European Physics Journal ST, a joint publication of EDP Sciences, Springer Science+Business Media, and the Società Italiana di Fisica.

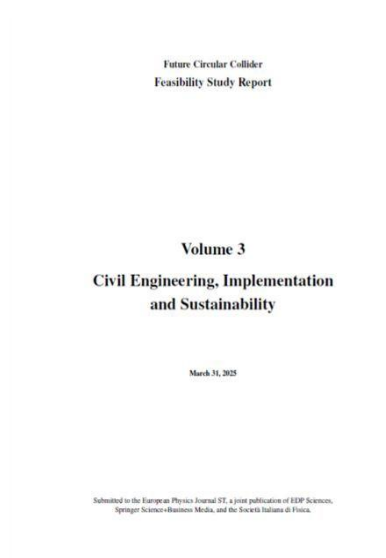


Future Circular Collider
Feasibility Study Report

Volume 2
Accelerators, Technical Infrastructure and Safety

March 31, 2025

Submitted to the European Physics Journal ST, a joint publication of EDP Sciences, Springer Science+Business Media, and the Società Italiana di Fisica.

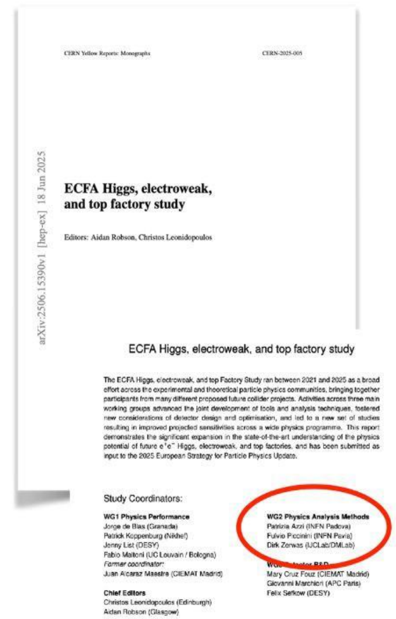


Future Circular Collider
Feasibility Study Report

Volume 3
Civil Engineering, Implementation and Sustainability

March 31, 2025

Submitted to the European Physics Journal ST, a joint publication of EDP Sciences, Springer Science+Business Media, and the Società Italiana di Fisica.



arXiv:2506.15390v1 [hep-ex] 18 Jun 2025

ECFA Higgs, electroweak, and top factory study

ECFA Higgs, electroweak, and top factory study

The ECFA Higgs, electroweak, and top Factory Study ran between 2021 and 2025 as a broad effort across the experimental and theoretical particle physics communities, bringing together participants from many different proposed future collider projects. Activities across three main working groups advanced the joint development of tools and analysis techniques, fostered new considerations of detector design and optimisation, and led to a new set of studies resulting in improved projected sensitivities across a wide physics programme. This report demonstrates the significant expansion in the state-of-the-art understanding of the physics potential of future e^+e^- Higgs, electroweak, and top factories, and has been submitted as input to the 2025 European Strategy for Particle Physics Update.

Study Coordinators:

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Former coordinator:
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Chief Editors
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WG2 Physics Analysis Methods
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Fulvio Piccinini (INFN Pavia)
Dirk Zerwas (IJCLab/DMLab)

Mary Cruz Fouz (CIEMAT Madrid)
Giovanni Marchiori (APC Paris)
Felix Sefkow (DESY)

https://cds.cern.ch/record/2928193

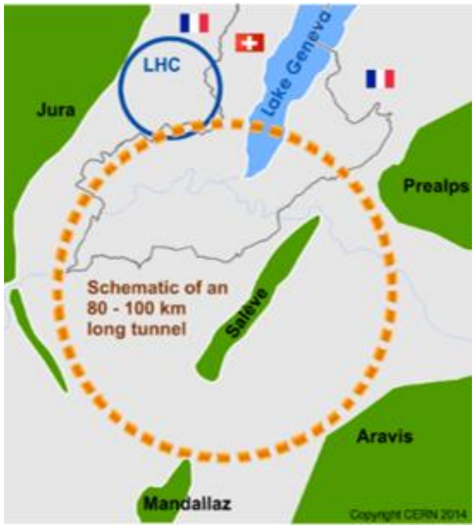
https://cds.cern.ch/record/2928194

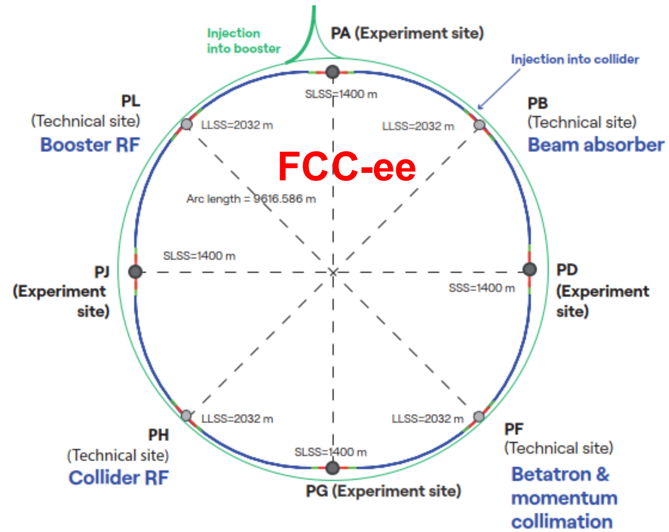
https://cds.cern.ch/record/2928793

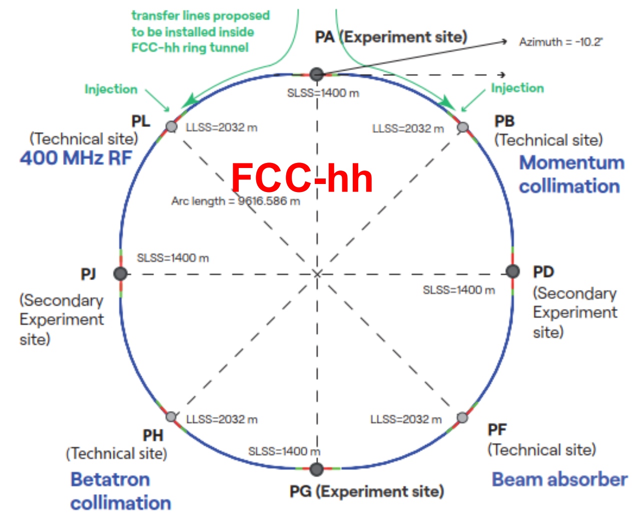
https://arxiv.org/pdf/2506.15390

European Strategy 2025

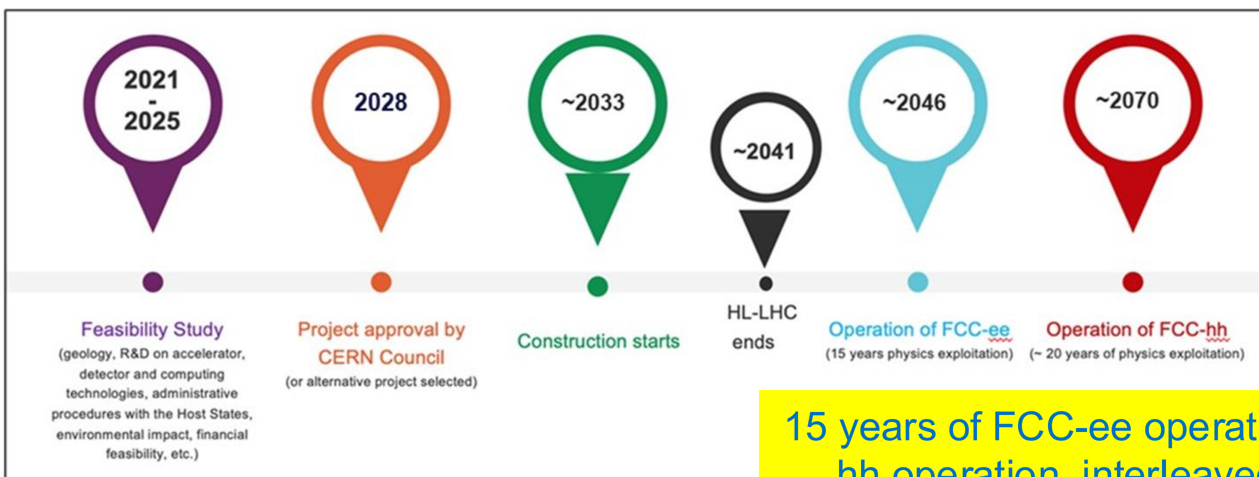
FCC integrated program - timeline







2020 - 2045 | **2046 - 2065** | **2070 - 2100**

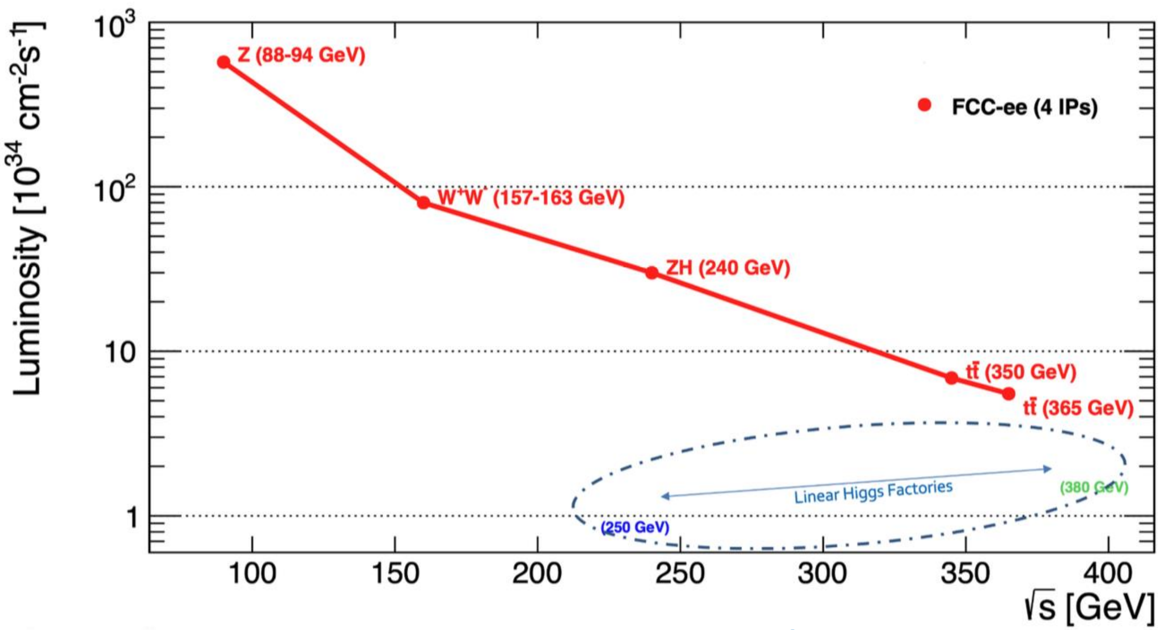


Ambitious schedule taking into account:

- past experience in building colliders at CERN
- approval timeline: ESPP, Council decision
- that HL-LHC will run until 2041
- project preparatory phase with adequate resources immediately after Feasibility Study

15 years of FCC-ee operation followed by 25 years of FCC-hh operation, interleaved with a shutdown of 10 years

Machine luminosity for physics at FCC-ee



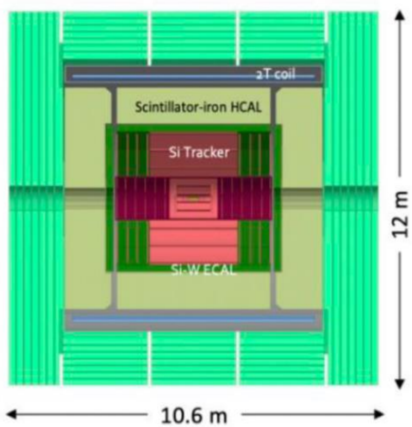
- Higgs factory:
  - 2.2×10^{6} $e^+e^- \rightarrow$ HZ
- EW & Top factory:
  - 6×10^{12} $e^+e^- \rightarrow$ Z (LEPx10^5)
  - 2.4×10^{8} e+$e^- \rightarrow W^+W^-$
  - 2×10^{6} $e^+e^- \rightarrow$ tt
- Flavor factory:
  - 5×10^{12} $e^+e^- \rightarrow$ bb, cc
  - 10^{11} $e^+e^- \rightarrow \tau^+\tau^-$

~100 kHz of physics data at the Z pole

Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^{8} WW	2.2×10^{6} ZH + 65k WW $\rightarrow$ H	2×10^{6} $t\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H	

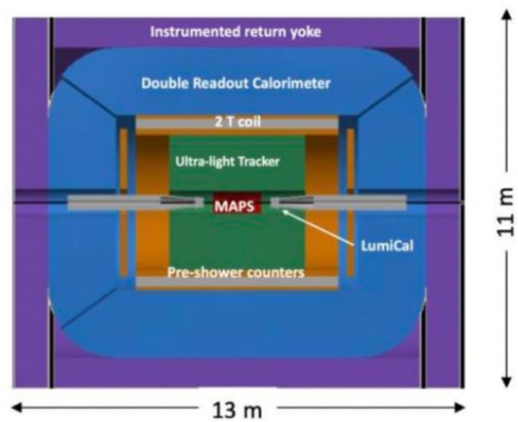
FCC-ee detector benchmarks

CLD

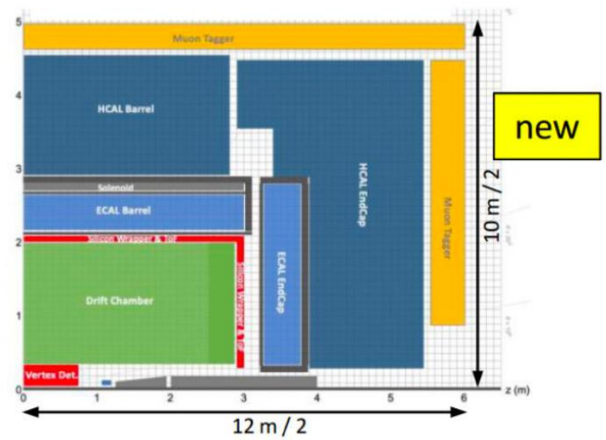


CDR

IDEA



ALLEGRO



Imported from CLIC
- Full Si tracker
- SiW Ecal HG
- SciFe Hcal HG
- Large coil outside

FCCee specific design
- Si Vtx + wrapper (LGAD)
- Large drift chamber (PID)
- DR calorimeter
- Small coil inside

FCCee specific design
- Tracker as IDEA
- LAr EM calorimeter
- Coil integrated
- Hcal not specified

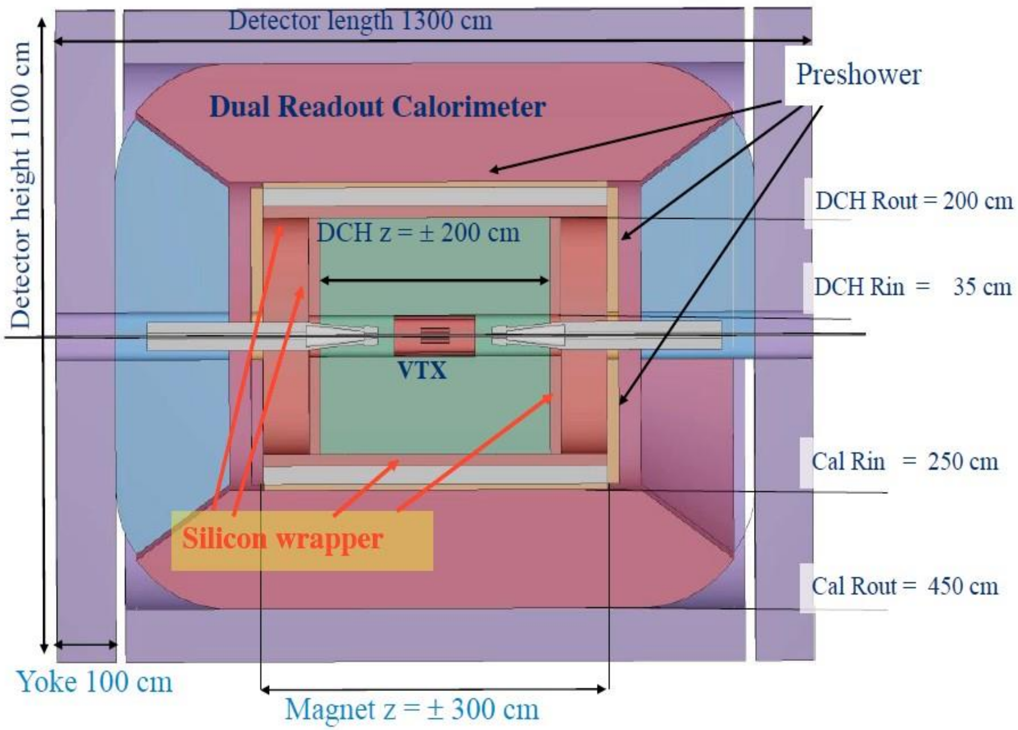
- High luminosity required for the physics → constraints on the design of the detectors close to the machine components, in particular the LumiCal and VTX detectors

Detector requirements for an experiment at FCC-ee

Critical Detector	Required Performance
Tracker	$\Delta(1/p_T) \sim 2 \times 10^{-5} \oplus 1 \times 10^{-3}/(p_T \sin\theta)$
Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu m$
ECAL, HCAL	$\sigma_E^{jet}/E \sim 3 - 4\%$
ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

As an example: **IDEA** proposal

- a silicon pixel vertex detector
- a large-volume extremely-light drift wire chamber
- surrounded by a layer of silicon micro-strip detectors
- a thin low-mass superconducting solenoid coil
- a preshower detector
- a dual read-out calorimeter
- muon chambers inside the magnet return yoke



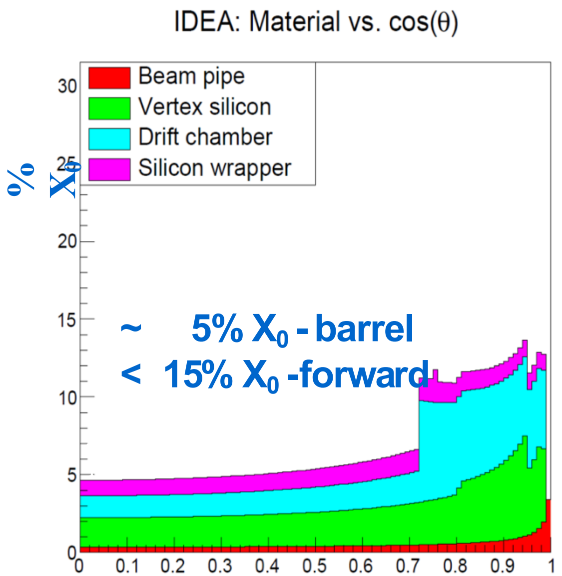
Requirements on track momentum resolution

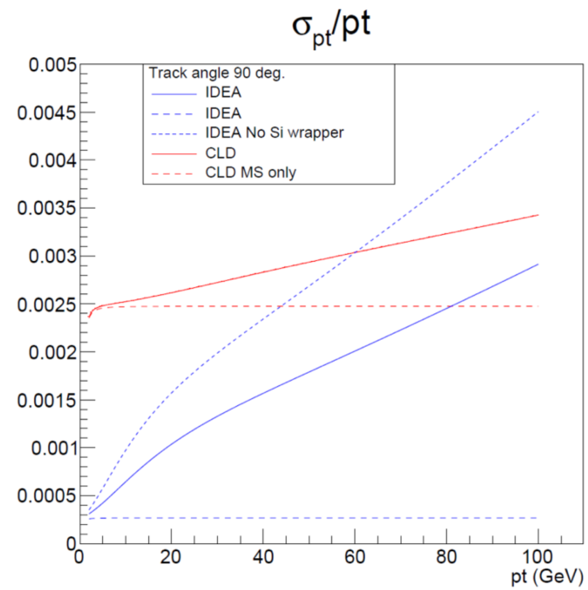
The IDEA Drift Chamber is designed to cope with transparency

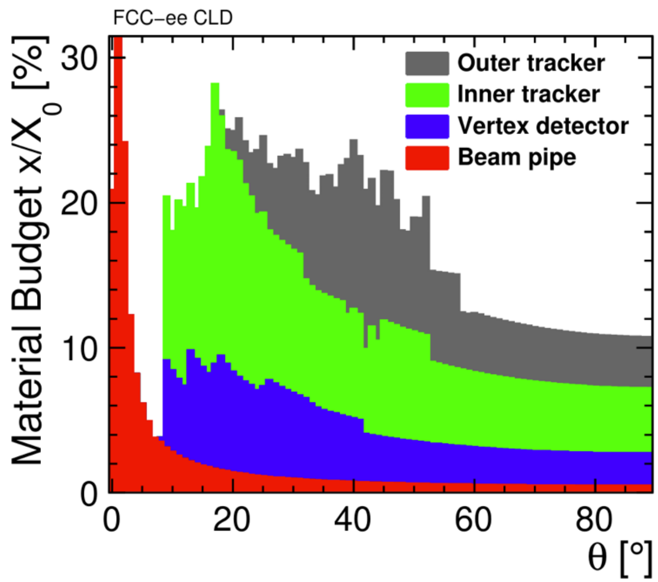
- a unique-volume, high granularity, fully stereo, low-mass cylindrical
- gas: He 90% - iC_4H_{10} 10%
- inner radius 0.35m, outer radius 2m
- length L = 4m

The CLD silicon tracker is made of:

- six barrel layers, at radii ranging between 12.7 cm and 2.1 m, and of eleven disks.
- the material budget for the tracker modules is estimated to be 1.1 − 2.1% of a radiation length per layer





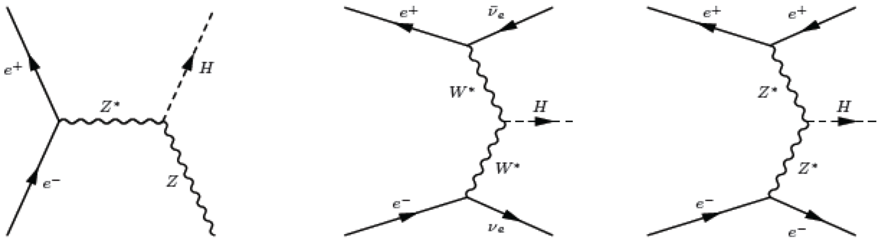


For 10 GeV (50 GeV) μ emitted at an angle of 90° w.r.t the detector axis, the p_T resolution is

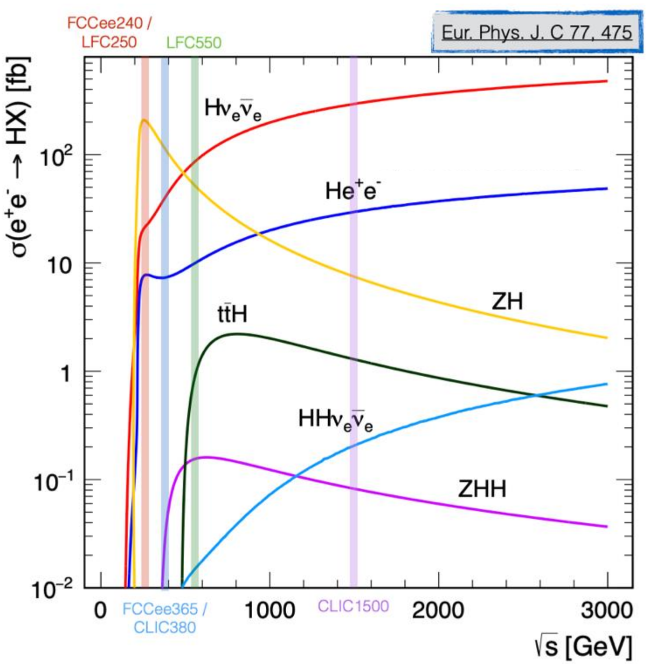
- about 0.05 % (0.15%) with the very light IDEA DCH
- about 0.25% (0.3%) with the CLD full silicon tracker, being dominated by the effect of MS

Higgs production at FCC-ee

Higgs-strahlung or $e^+e^- \rightarrow ZH$



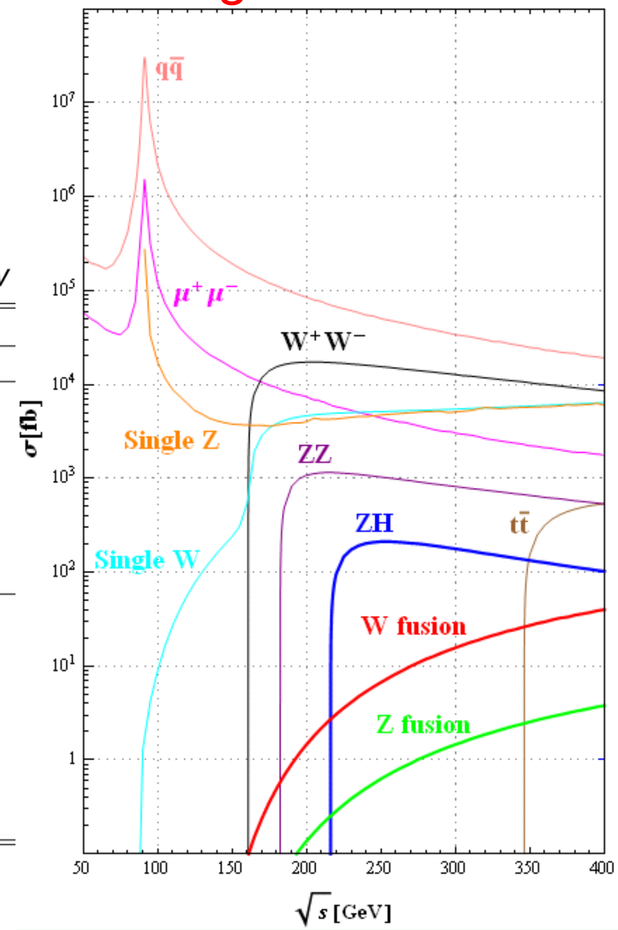
VBF production: $e^+e^- \rightarrow \nu\nu H$ (WW fus.)
$e^+e^- \rightarrow He^+e^-$ (ZZ fus.)



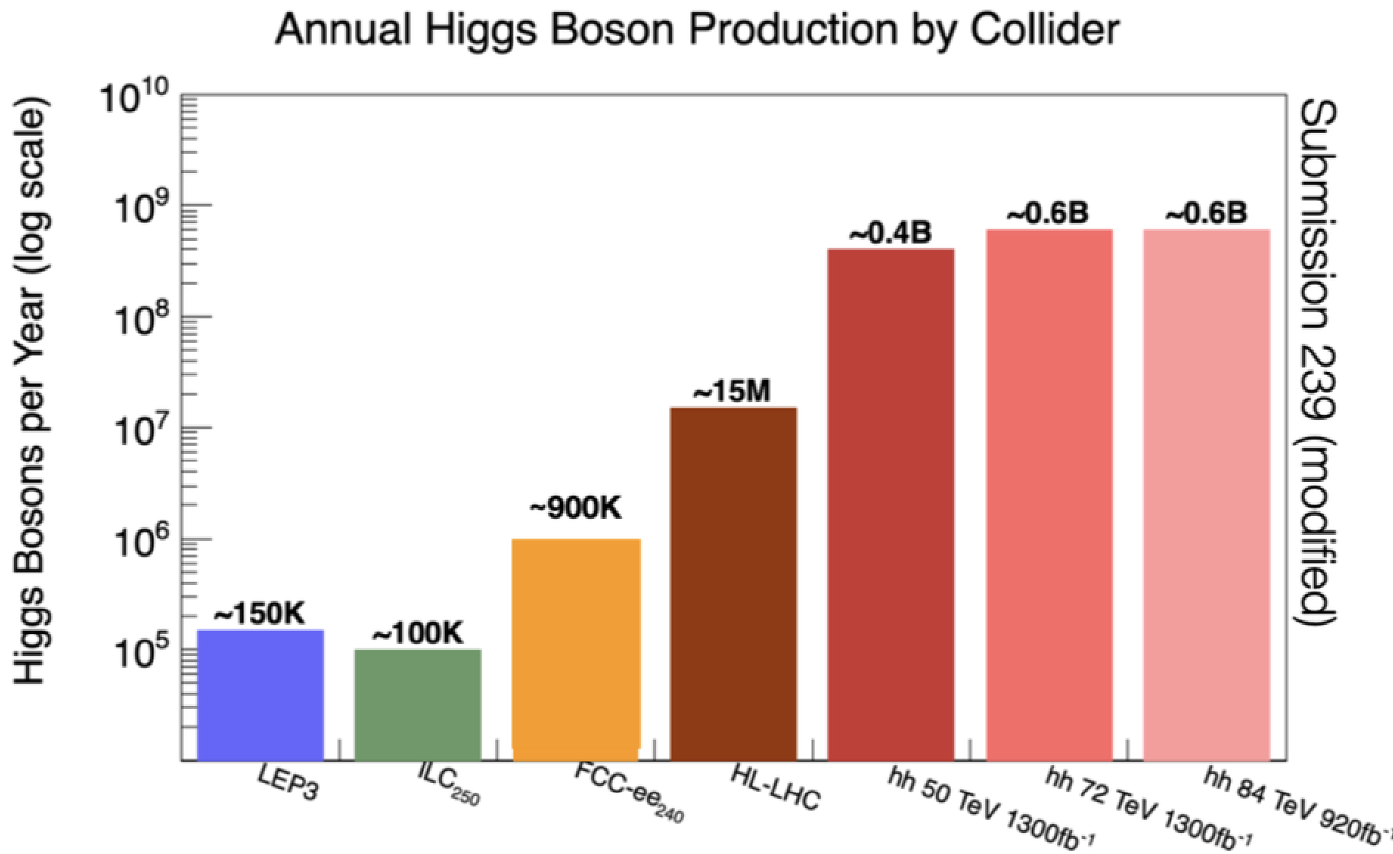
$\sqrt{s}$ = 240.0 GeV

Process	Cross section
Higgs boson production, cross section in fb	
$e^+e^- \rightarrow ZH$	212
$e^+e^- \rightarrow \nu\bar{\nu}H$	6.72
$e^+e^- \rightarrow e^+e^-H$	0.63
Total	219
Background processes, cross section in pb	
$e^+e^- \rightarrow e^+e^-$ (Bhabha)	25.1
$e^+e^- \rightarrow q\bar{q}$	50.2
$e^+e^- \rightarrow \mu\mu$ (or $\tau\tau$)	4.40
$e^+e^- \rightarrow WW$	15.4
$e^+e^- \rightarrow ZZ$	1.03
$e^+e^- \rightarrow eeZ$	4.73
$e^+e^- \rightarrow e\nu W$	5.14

Background sources

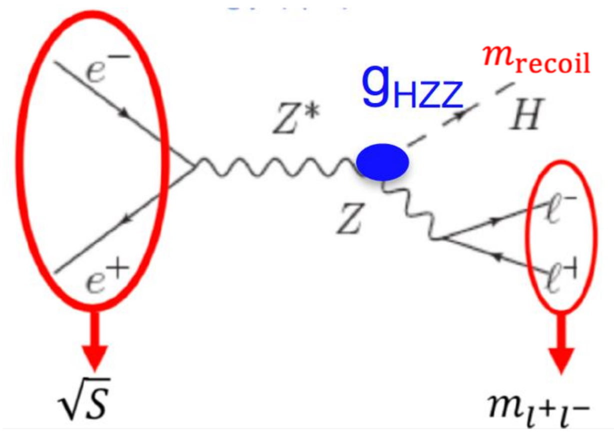


Higgs yield



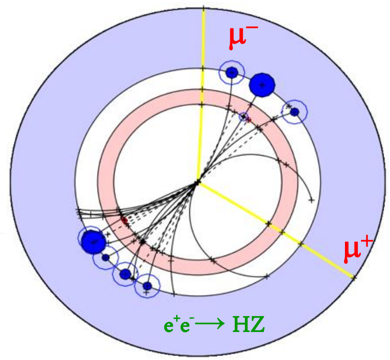
- *e*+*e*− colliders produce less Higgs bosons than the LHC, but they benefit from precise knowledge of initial stage and a "clean" experimental environment.
- *pp* colliders allow measurements of rare decays
- e^+e^- and *pp* colliders are complementary to fully explore the Higgs sector

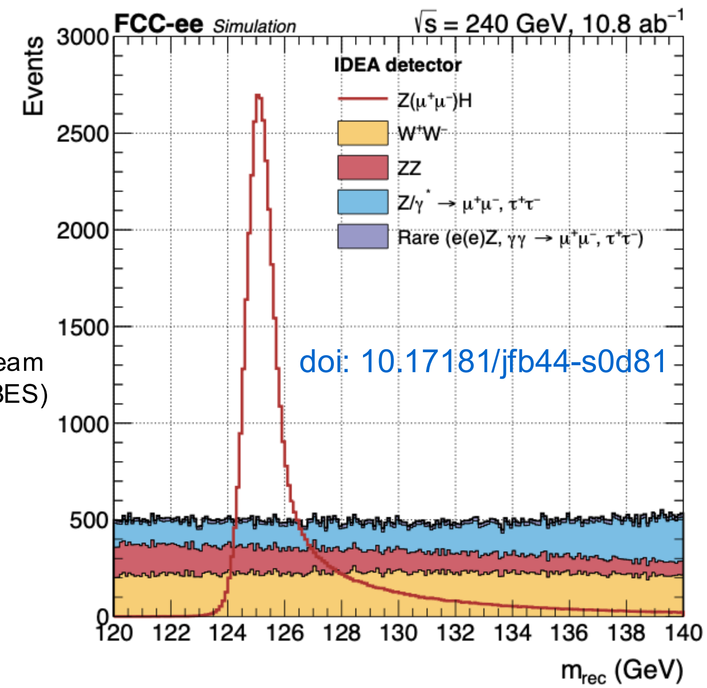
Global strategy for Higgs studies



$\sigma(e^+e^- \rightarrow HZ) \; \alpha \; g^2_{HZZ}$

ZH events tagged by the Z, without reconstructing the Higgs decay. Unique to lepton colliders.





doi: 10.17181/jfb44-s0d81

e.g. when $Z \rightarrow$ leptons :

$$m^2_{\mathrm{recoil}} = s + m^2_{\ell\ell} - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-})$$

affected by the Beam Energy Spread (BES) and Initial State Radiation (ISR)

A fit to the recoil mass distribution allows:

- measurement of σ(ZH) independent of the Higgs decay mode with O(%) uncertainty. Hence an absolute determination on g_{HZZ}

  → **$\delta g_{HZZ}/g_{HZZ}$ ~ 0.1-0.2 %** (also including Z→had)

- a precise meas. of the **Higgs mass → $\delta m_H/m_H$ ~ O(MeV)** (w.r.t 20 MeV for HL-LHC)

Easiest case: $Z \rightarrow$ lep.

• $Z \rightarrow$ had: more careful design of the analysis

Model-independent Higgs couplings measurements

Known g_{HZZ} it is possible to measure σ x BR for specific Higgs decays

$$\sigma_{ZH} \times \mathcal{B}(H \to X\overline{X}) \propto \frac{g^2_{HZZ} \times g^2_{HXX}}{\Gamma_H}$$

- H → ZZ* provides Γ_H
- H → XX provides g_{HXX}

H → ZZ* provides Γ_H :
$$\frac{\sigma(e^+e^- \to ZH)}{BR(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{SM} \times \Gamma_H$$

→ **$\delta\Gamma_H / \Gamma_H$ ~ several %**

Select events with H → bb, cc, gg, WW, tt, γγ, μμ, Zγ, … → **$\delta g_{XX}/g_{XX}$ ~ 1 %**

→ deduce g_{Hbb} , g_{Hcc} , g_{Hgg} , g_{HWW} , g_{Htt} , $g_{H\gamma\gamma}$, $g_{H\mu\mu}$, $g_{HZ\gamma}$, …

Select events with H → “nothing” → deduce Γ(H→invisible)

a model-indep determination of Higgs couplings.

Data at higher energy bring important additional observables:

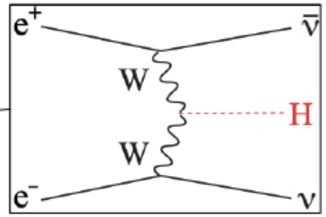
$$\sigma_{H\nu_e\bar{\nu}_e} \times \mathcal{B}(H \to X\overline{X}) \propto \frac{g^2_{HWW} \times g^2_{HXX}}{\Gamma_H}$$

First vvH → vvbb ~ $g_{HWW}^2\, g_{Hbb}^2 / \Gamma_H$

- vvbb / (ZH(bb) ZH(WW)) ~ g_{HZZ}^4 / Γ_H = R → Γ_H precision at 1%

Then do vvH →vvWW ~ g_{HWW}^4 / Γ_H

- R / vvWW ~ g_{HWW}^4 / g_{HZZ}^4
- g_{HWW} precision to few permil



At the end: Higgs couplings and Γ_H extracted from a global fit to all σ x BR (Kappa framework, SMEFT framework)

HZ cross section and mass measurement

MC simulation based on Whizard:

- $\sqrt{s}$ = 240 GeV, L = 10.8 ab^{-1}
- IDEA detector; detector response modelled with Delphes

Analysis workflow based on recoil method using Z(μμ/ee) final state

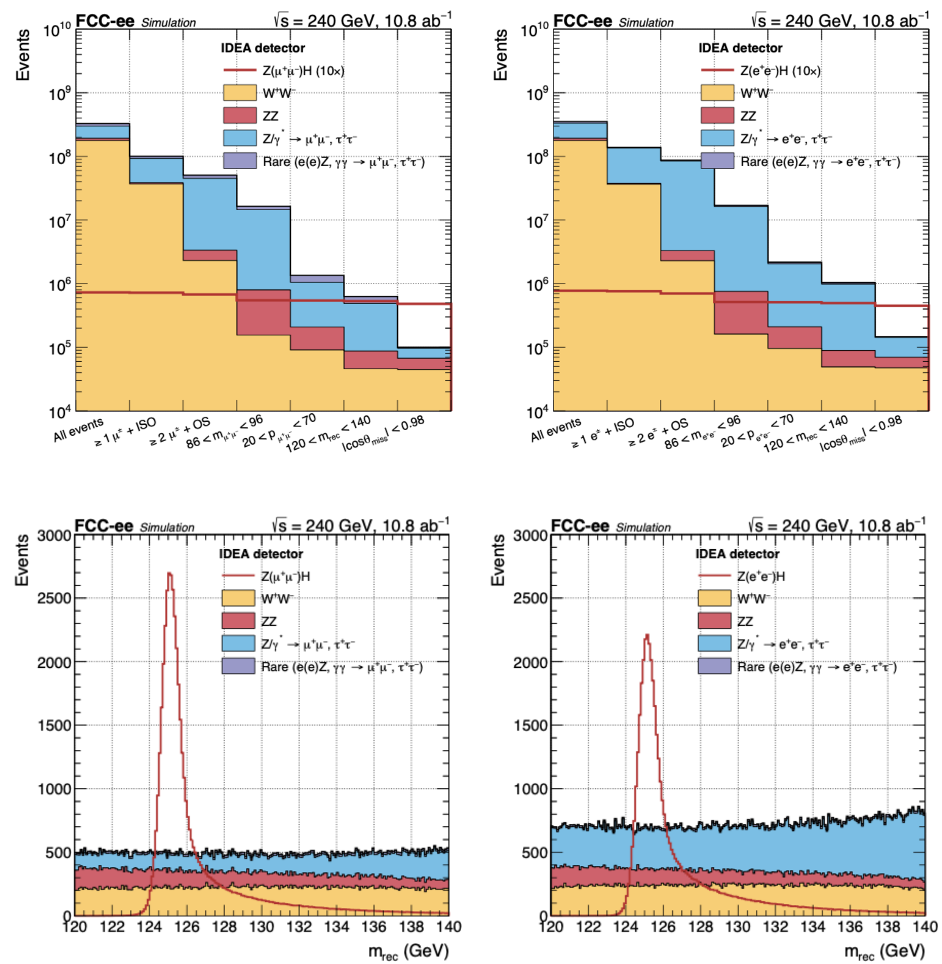
doi:10.17181/jfb44-s0d81

Baseline selection:

- at least 2 OS leptons with p>20 GeV, one isolated
- in case of more than 2 leptons in event, select pair minimizing

$$\chi^2 = 0.6 \times (m_{\ell\ell} - m_Z)^2 + 0.4 \times (m_{recoil} - m_h)^2$$

- tight selection of Z mass between [86, 96] GeV
- Background reduction by cut on Z p_T [20, 70] GeV and $|\cos(\theta_{miss})| < 0.98$
  - the former to suppress Z/γ*, the later for γγ→ee/μμ/ττ event



Parametric fit based on recoil mass distribution:

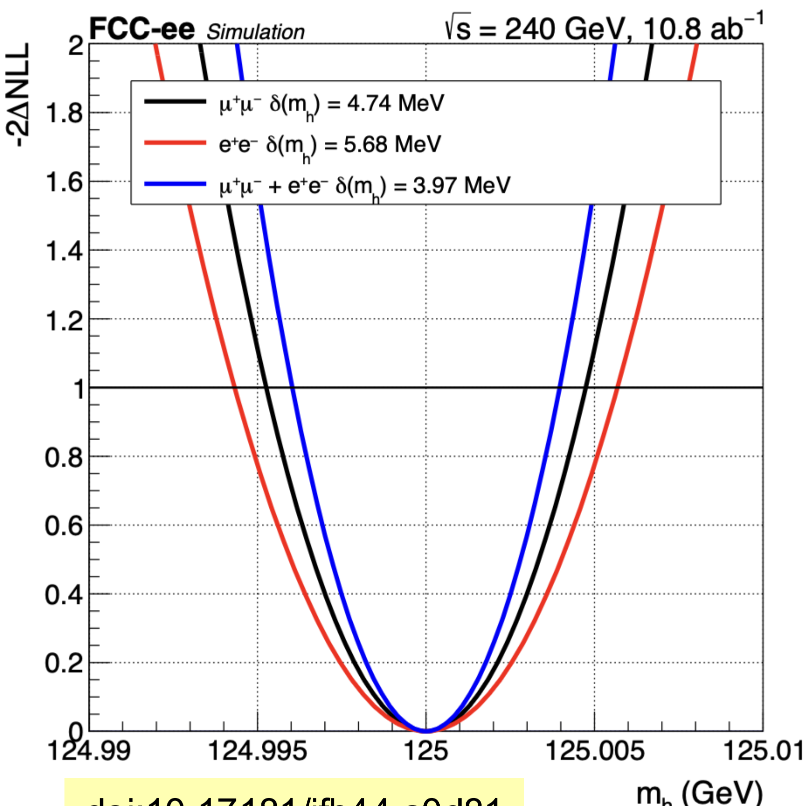
- Fit function: double-sided Crystal-ball + Gaussian core
- Free parameter: H mass, signal and bkg normalization

Higgs mass measurement

Likelihood scans to extract uncertainties on mass

Stat. + syst. uncertainties:

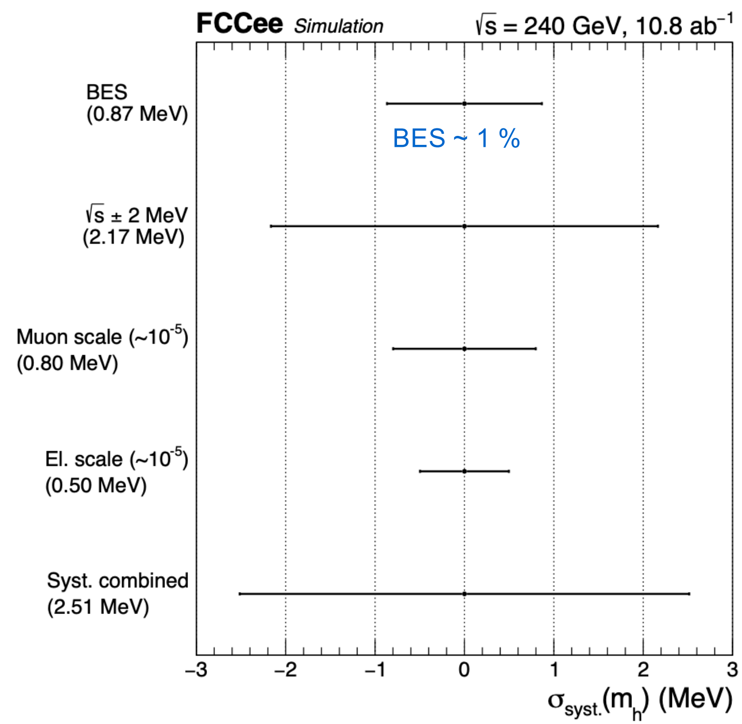
- **Higgs mass: 3.97 MeV at 68% C.L.**



doi:10.17181/jfb44-s0d81

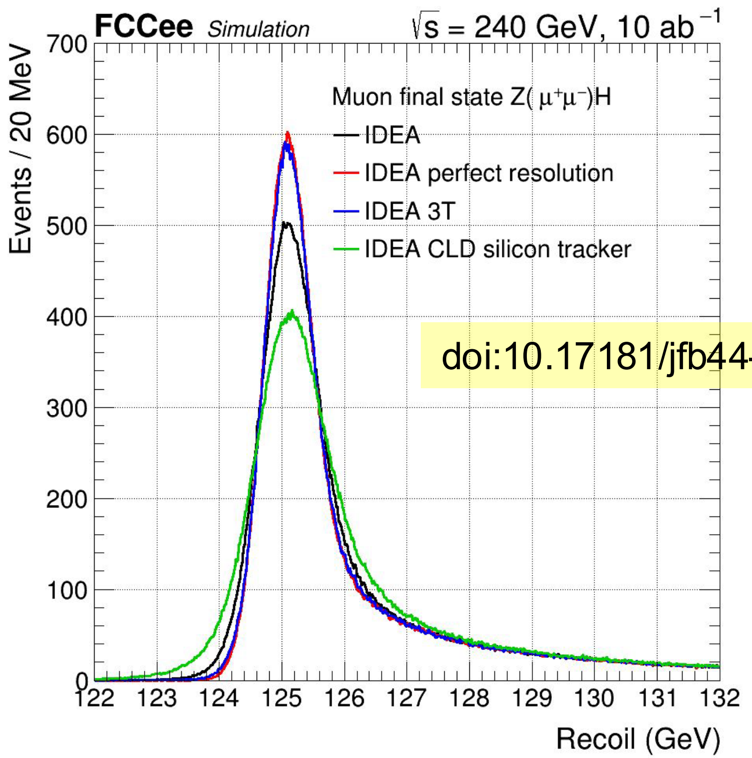
Source of uncertainty:

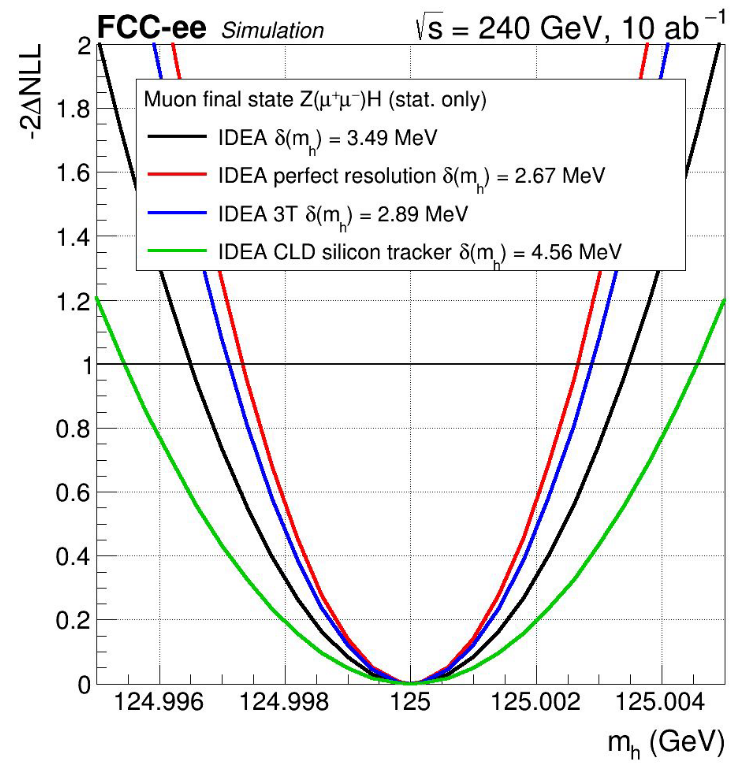
- Beam Energy Spread (BES)
- Initial State Radiation (ISR)
- Muon momentum scale
- Center-of-mass
- FSR uncertainty



Constraint on detector requirement from H mass measurement

Higgs boson mass to be measured with a precision better than its natural width (4MeV), in view of a potential run at the Higgs resonance





doi:10.17181/jfb44-s0d81

μ from Z, with momentum of O(50) GeV, to be measured with a p_T resolution smaller than the BES in order for the momentum measurement not to limit the mass resolution

- achieved with the baseline IDEA detector → uncertainty of 4.27 MeV with 10 ab^{-1}
- CLD performs less well because of the larger amount of material → larger effects of MS

If the B increased from 2T to 3T → 50% improvement of the momentum resolution
14% improvement on the total mass uncertainty

HZ cross section measurement

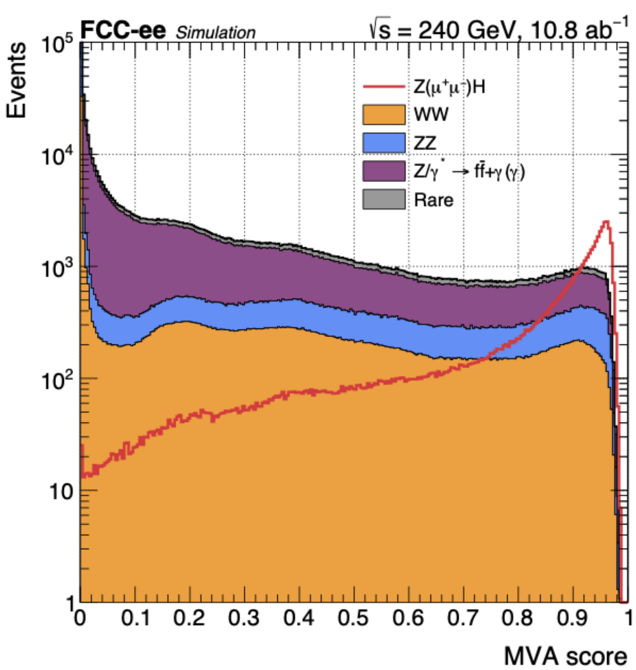
For the ZH cross-section measurement, after applying the basic selection criteria, the $|\cos\theta_{miss}|$ cut is omitted and replaced by a BDT approach to further suppress background.

input variables for BDT

Variable	Description
$p_{\ell^+\ell^-}$	Lepton pair momentum
$\theta_{\ell^+\ell^-}$	Lepton pair polar angle
$m_{\ell^+\ell^-}$	Lepton pair invariant mass
$p_{l_{\text{leading}}}$	Momentum of the leading lepton
$\theta_{l_{\text{leading}}}$	Polar angle of the leading lepton
$p_{l_{\text{subleading}}}$	Momentum of the subleading lepton
$\theta_{l_{\text{subleading}}}$	Polar angle of the subleading lepton
$\pi - \Delta\phi_{\ell^+\ell^-}$	Acoplanarity of the lepton pair
$\Delta\theta_{\ell^+\ell^-}$	Acolinearity of the lepton pair

Stat. uncertainty in %:

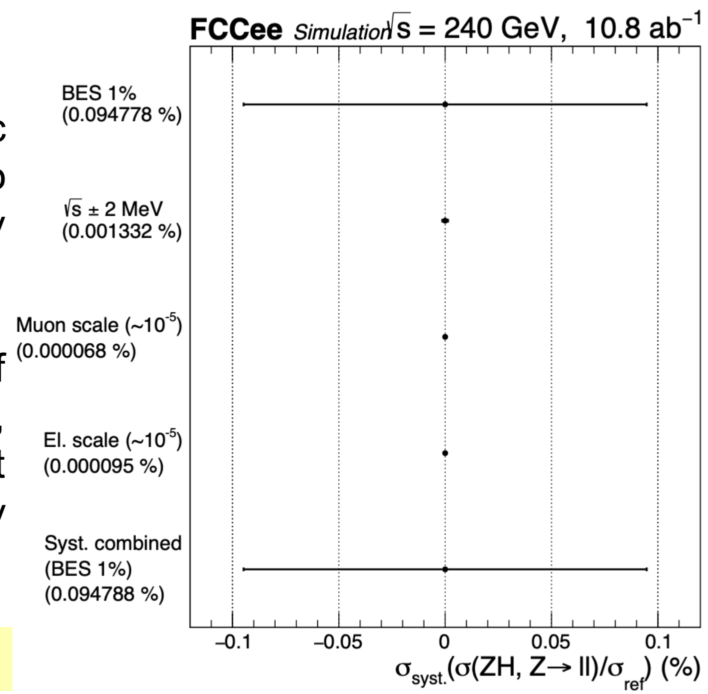
Channel	$\sqrt{s} = 240$ GeV
$Z(e^+e^-)H$	± 0.81
$Z(\mu^+\mu^-)H$	± 0.68
$Z(\ell^+\ell^-)H$	± 0.52



The impact of systematic uncertainties is found to be below 1%, mostly from BES

The overall impact of systematics is minimal, and the measurement remains fully statistically dominated

doi:10.17181/jfb44-s0d81

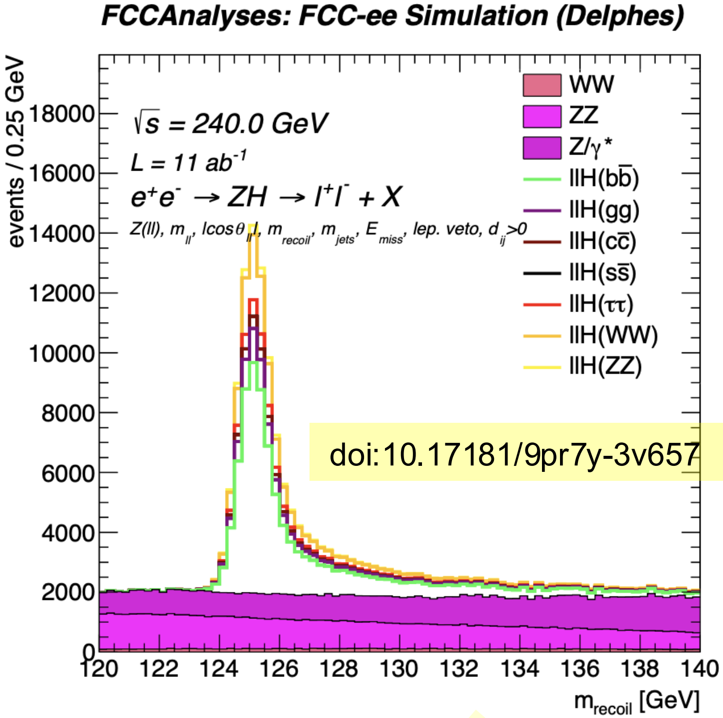


H→qq (hadrons) and progress on jet flavour tagging

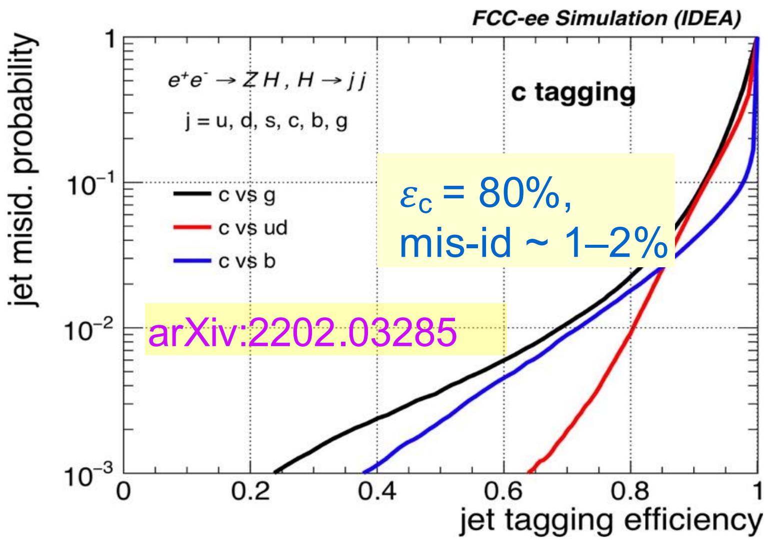
High precision Higgs BRs to hadron measurements:

- Bottom and charm, gluons, probe strange coupling?
- Key ingredients:
  - tagging of b, c and g jets
  - detector requirements (tracking, vertexing, timing)
  - tagging performance from old-ish algorithms
    - large room for improvement for σ x BR(cc)
- State-of-the-art flavour-tagging algorithm developed recently in the context of FCC-ee based on NN

▪ Z(ll)H(qq)
▪ Z(inv)H(qq)
▪ Z(qq)H(qq)



doi:10.17181/9pr7y-3v657



ε_c = 80%, mis-id ~ 1–2%

arXiv:2202.03285

$$\delta(\sigma \times BR_{H\to b\bar{b}}) \approx 0.2\text{-}0.4\ \%$$
$$\delta(\sigma \times BR_{H\to c\bar{c}}) \approx 1.6\text{-}5\ \%$$
$$\delta(\sigma \times BR_{H\to gg}) \approx 0.8\text{-}2.1\ \%$$

@ √s = 240 / 365 GeV

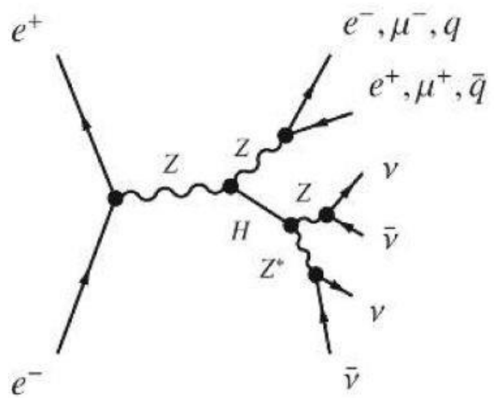
σ(HZ) x BR and σ(WW→H) x BR measurements

Uncertainty on σ * BR in %

$\sqrt{s}$	240 GeV		365 GeV	
channel	**ZH**	**WW → H**	**ZH**	**WW → H**
ZH → any	±0.31		±0.52	
γH → any	±150			
H → bb	±0.21	±1.9	±0.38	±0.66
H → cc	±1.6	±19	±2.9	±3.4
H → ss	±120	±990	±350	±280
H → gg	±0.80	±5.5	±2.1	±2.6
H → $\tau\tau$	±0.58		±1.2	±5.6 $^{(*)}$
H → $\mu\mu$	±11		±25	
H → WW*	±0.80		±1.8 $^{(*)}$	±2.1 $^{(*)}$
H → ZZ*	±2.5		±8.3 $^{(*)}$	±4.6 $^{(*)}$
H → $\gamma\gamma$	±3.6		±13	±15
H → Zγ	±11.8		±22	±23
H → $\nu\nu\nu\nu$	±25		±77	
H → inv.	$< 5.5 \times 10^{-4}$		$< 1.6 \times 10^{-3}$	
H → dd	$< 1.2 \times 10^{-3}$			
H → uu	$< 1.2 \times 10^{-3}$			
H → bs	$< 3.1 \times 10^{-4}$			
H → bu	$< 2.2 \times 10^{-4}$			
H → sd	$< 2.0 \times 10^{-4}$			
H → cu	$< 6.5 \times 10^{-4}$			

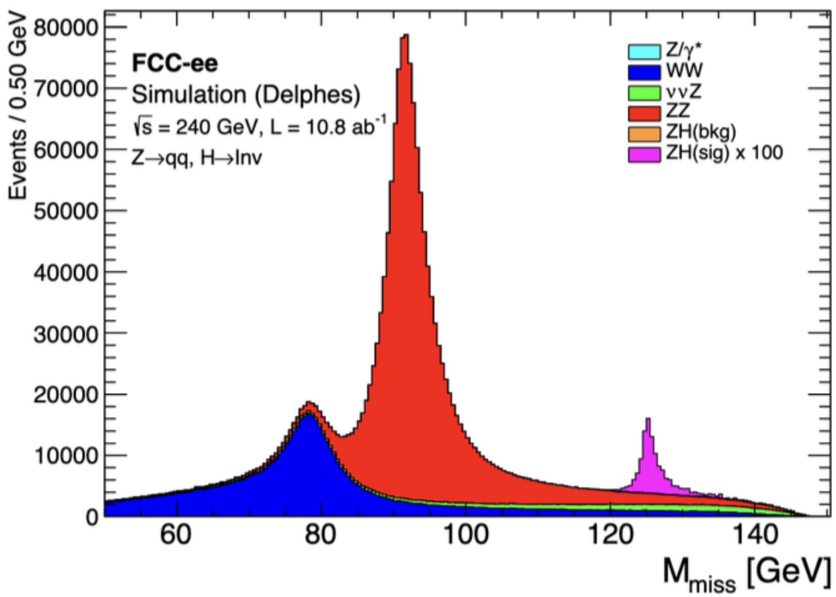
doi: 10.17181/n78xk-qcv56

Higgs to invisible particles analysis

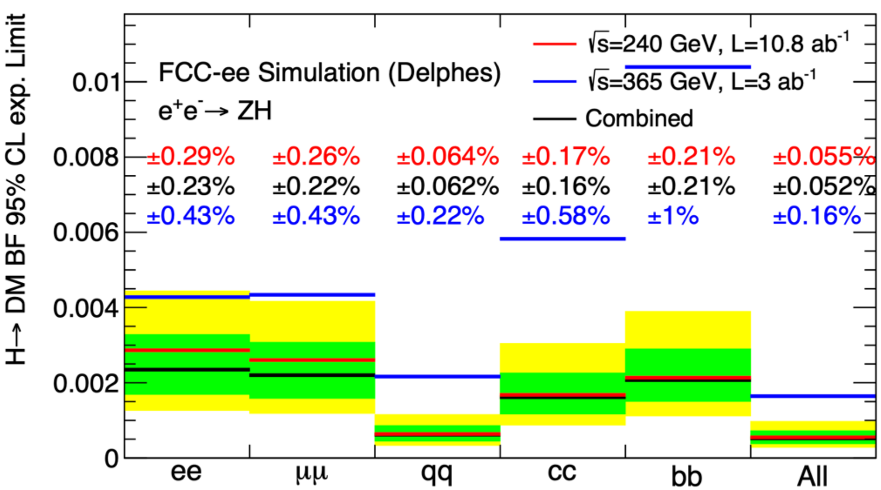


- only invisible decay in the SM: $H \rightarrow ZZ \rightarrow \nu\nu\nu\nu$ (BR = 0.106%)
- best individual measurements from ZH→qq + missing energy using recoil mass or missing mass at the Z peak
  - → requires excellent hadronic energy resolution
- tag the Z using muon, electron and hadron final states (qq and bb), Z peak [87, 96] GeV
- calculate missing mass m_{miss} as 240 GeV minus visible mass m_{vis}

doi: 10.17181/7hbn8-3d233



BR(H → inv) > 0.052 excluded @ 95%CL



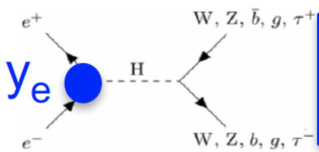
Higgs Yukawa coupling to electron

arXiv:2107.02686

FCC-ee: unique opportunity to study the Higgs Yukawa coupling to electron, $\mathbf{y_e}$, via resonant s-channel production $\mathbf{e^+e^- \to H}$ in a dedicated run at the Higgs pole, $\sqrt{s} = m_H$.

In the SM:

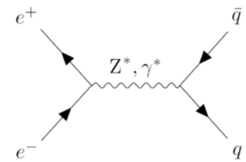
- the Yukawa coupling of the electron is $y_e = \sqrt{2}\, m_e/v = 2.8\cdot10^{-6}$
- $BR(H \to e^+e^-) \approx 5 \times 10^{-9}$



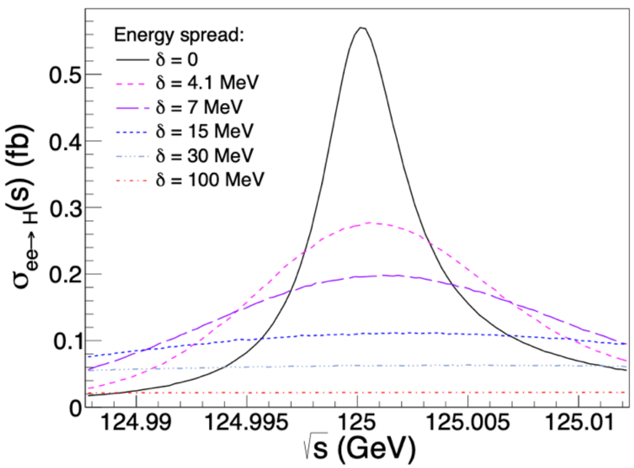
$\sigma(e^+e^-\to H)_{B\text{-}W} = 1.64$ fb

$\sigma(e^+e^-\to H)_{spread} = 280$ ab (ISR + $\sqrt{s}_{spread} = \Gamma_H = 4.2$ MeV)

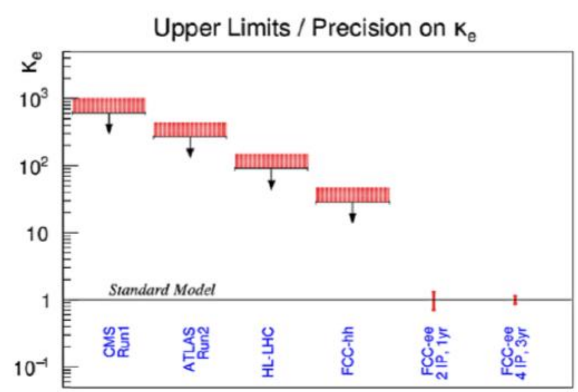
background



- Beams must be monochromatized such that the spread of their center-of-mass energy is commensurate with the narrow width of the SM Higgs boson
- Generator-level study for signal+background for 10 decay channels:
    - most significant channels: H→gg (for light mistag ~ 1%), H→WW* →lν +jets

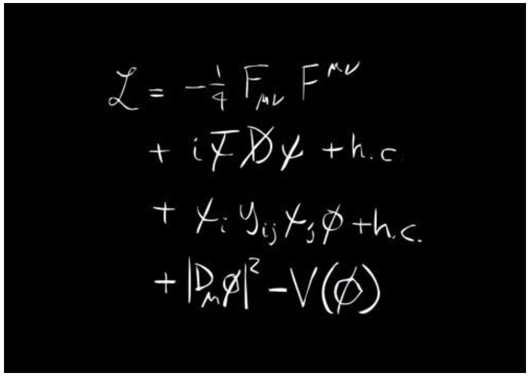


For 10 ab^{-1} & $\sqrt{s}_{spread} = \Gamma_H$: Signif ≈ 1.3σ



upper limit @ 95CL on the electron Yukawa coupling at 1.6 times the SM value for each detector for one year→ **x 100 better than for HL-LHC**

The Higgs self coupling



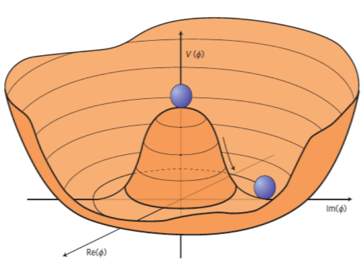
- The Higgs self-couplings λ_i are still largely unconstrained experimentally
- These couplings provide key information on the shape of the Higgs potential V (H) which has important physics implications (e.g. stability of the universe, JHEP08(2012) 098
- known m_H (~125 GeV), SM predicts $\lambda_3 = m_H^2 / 2v^2$ (~0.13)
- $\lambda_3 = \lambda_4$ in SM

$$m_H = \sqrt{2\lambda v^2}$$

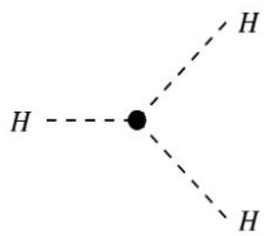
$$v \simeq 246 \text{ GeV.}$$

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

$$\kappa_\lambda = \lambda_3 / \lambda_3^{\text{SM}}$$



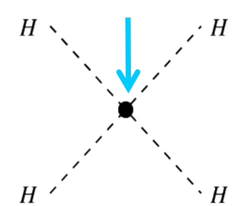
Mass term



Higgs trilinear self-coupling (κλ)
Higgs pair production

Higgs quadratic self-coupling

SM quartic Higgs coupling out of reach even for HL-LHC



PRD 72, 053008

- λ_3 can be directly accessed through the production of Higgs boson pairs (HH)
- contributions also come from single Higgs production (H) via NLO EW corrections

Higgs self coupling at √s < 500 GeV – i.e. ZH & tt thresholds

Probe *indirectly* trilinear Higgs self coupling **λ_3** through higher-order corrections to single-Higgs processes

O(fewv%) NLO correction to SM observable (i.e the cross section) parameterized according to:

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

Z_H: Universal coefficient from wave function

C_1: Process and kinematic dependent coefficient

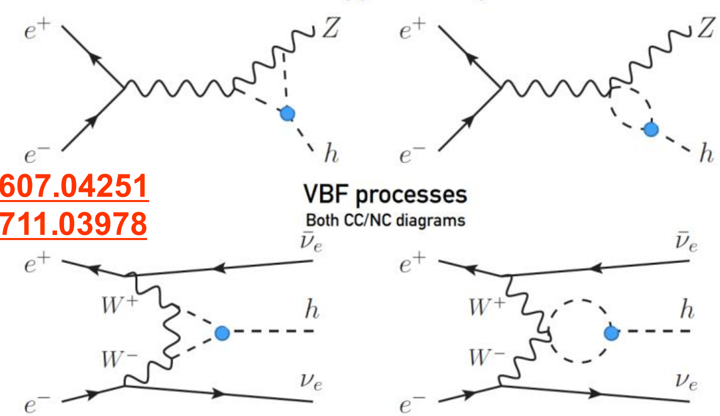
C_1 process-dependent coefficient that encodes the interference between the NLO amplitudes and the LO ones

The total (NLO) cross section can be measured O(1%):

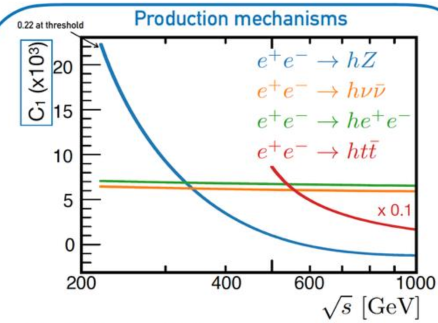
- possible probing NLO deviations from SM: $\delta\kappa_\lambda = \kappa_\lambda - 1$
- parameter C_1 sensitive to √s: exploit different sensitivities at 240 GeV and 365 GeV:
  - ZH @ 240 GeV
  - VBF @ 365 GeV

Vertex corrections (linear in k_λ)

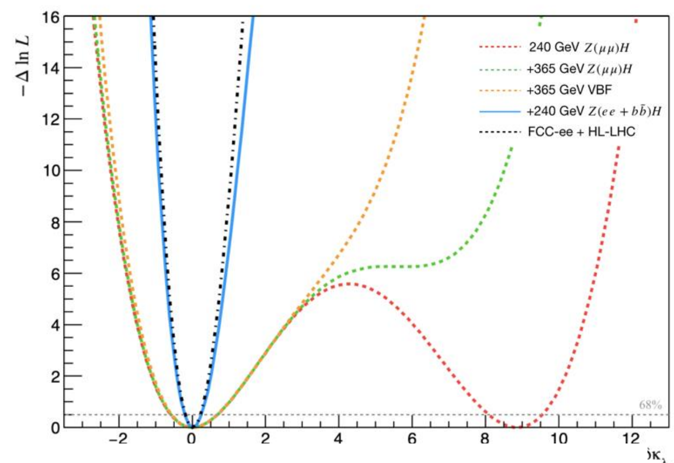
arxiv:1607.04251
arxiv:1711.03978



Production mechanisms



Negligible impact of a modified λ_{HHH} on the angular asymmetries. At 1-loop C_1 for HZ, WW-boson fusion and ZZ-boson fusion are independent of the beam polarization.

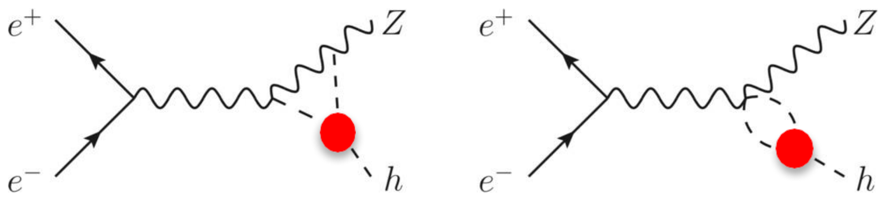


The secondary minimum easily excluded adding a 2nd energy point

Higgs self coupling at √s < 500 GeV – i.e. ZH & tt thresholds

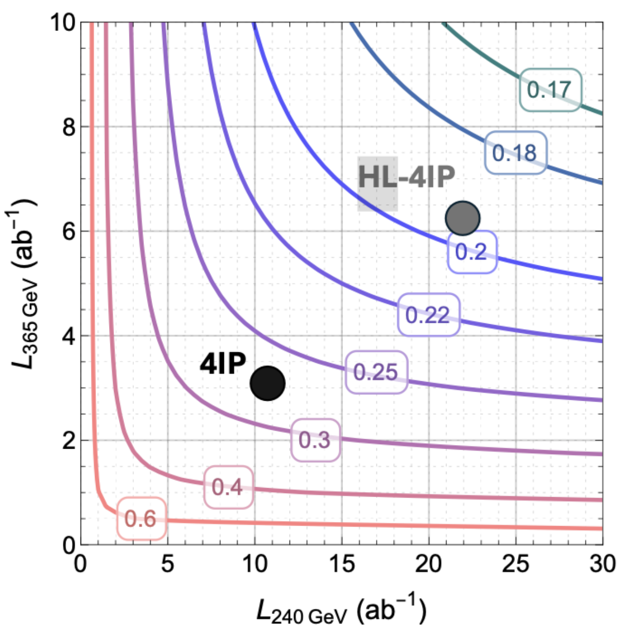
NB: 365 GeV > ZHH threshold, but too low ZHH x-section

λ_3 affects single-Higgs prod at NLO



e.g. 100% variation on λ_3 modifies σ(ZH) by ~ 2% at 240 GeV and ~ 0.5% at 365 GeV.
Larger than / comparable with the exp. precision on σ(ZH)

Precise measurement of σ(ZH) constrains a combination of λ_3 and g_{HZZ}.
Measurements at two values of √s needed to determine separately λ_3 and g_{HZZ}.



- Recent: 4 IPs. Running at √s = 240 and 365 GeV → **$\delta\kappa_\lambda$ ~ 28% for FCC-ee**
  ~ 18% (combining with HL-LHC)

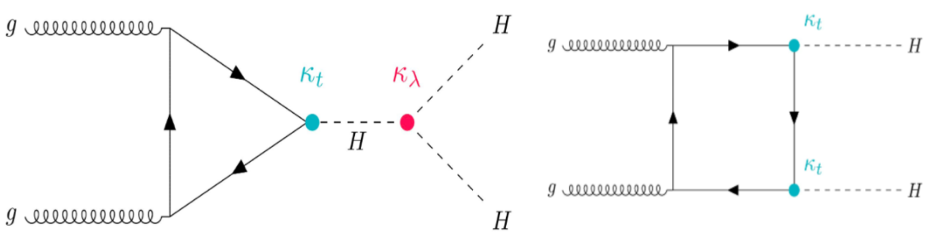
arXiv:2505.00272v1

With 4 IPs: 5σ observation of λ_3 within reach with 15 years of operation at FCC-ee.

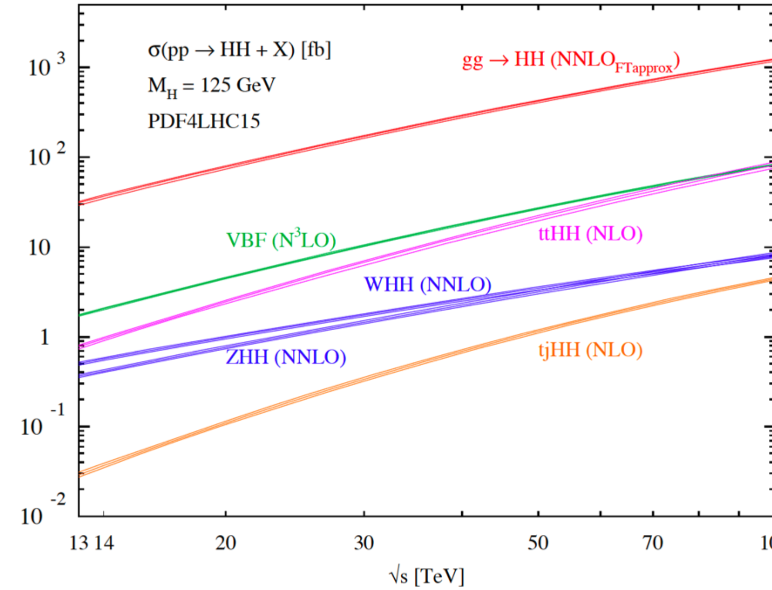
Di-Higgs production at FCC-hh

10.1016/j.revip.2020.100045

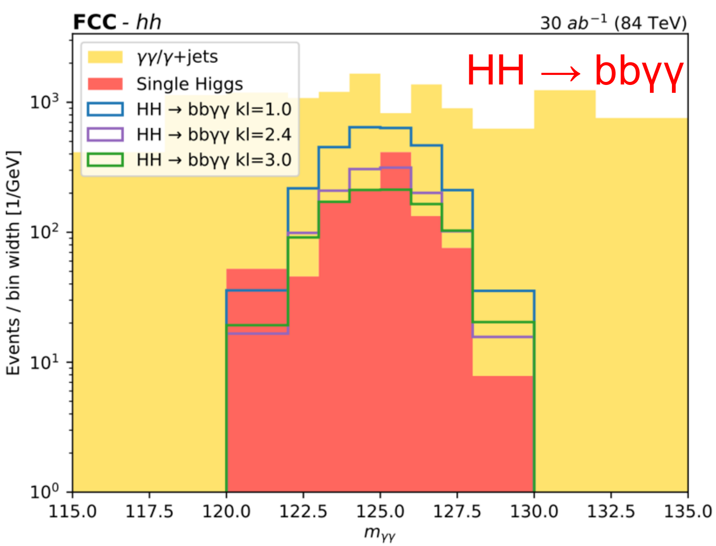
Gluon gluon Fusion (ggF)

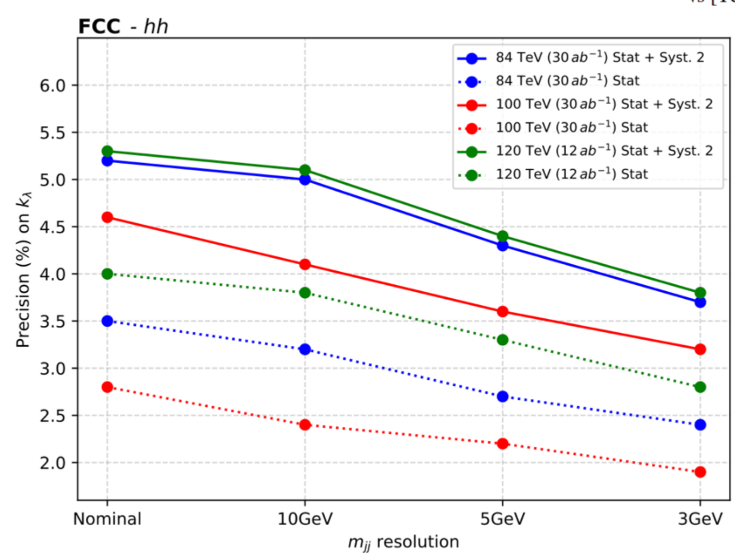


Destructive interference



Most sensitivity in channels that can be cleanly tagged: HH → bbγγ HH → bbbb, HH → bbττ





Depending on the di-jet mass resolution and systematic assumptions →

Expected prec. on κ_λ @ 68% C.L.:

- 3.2% to 5.4% at 84 TeV
- 2.8% to 4.8% at 100 TeV

doi: 10.17181/w6928-gr929

FCChh measurements of Rare Higgs decays

FCChh will produce about 30 billion Higgs bosons in 30 ab^{-1} allowing measurements of $H \rightarrow \gamma\gamma$, $H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$, , with 1-2% uncertainty (systematically limited)

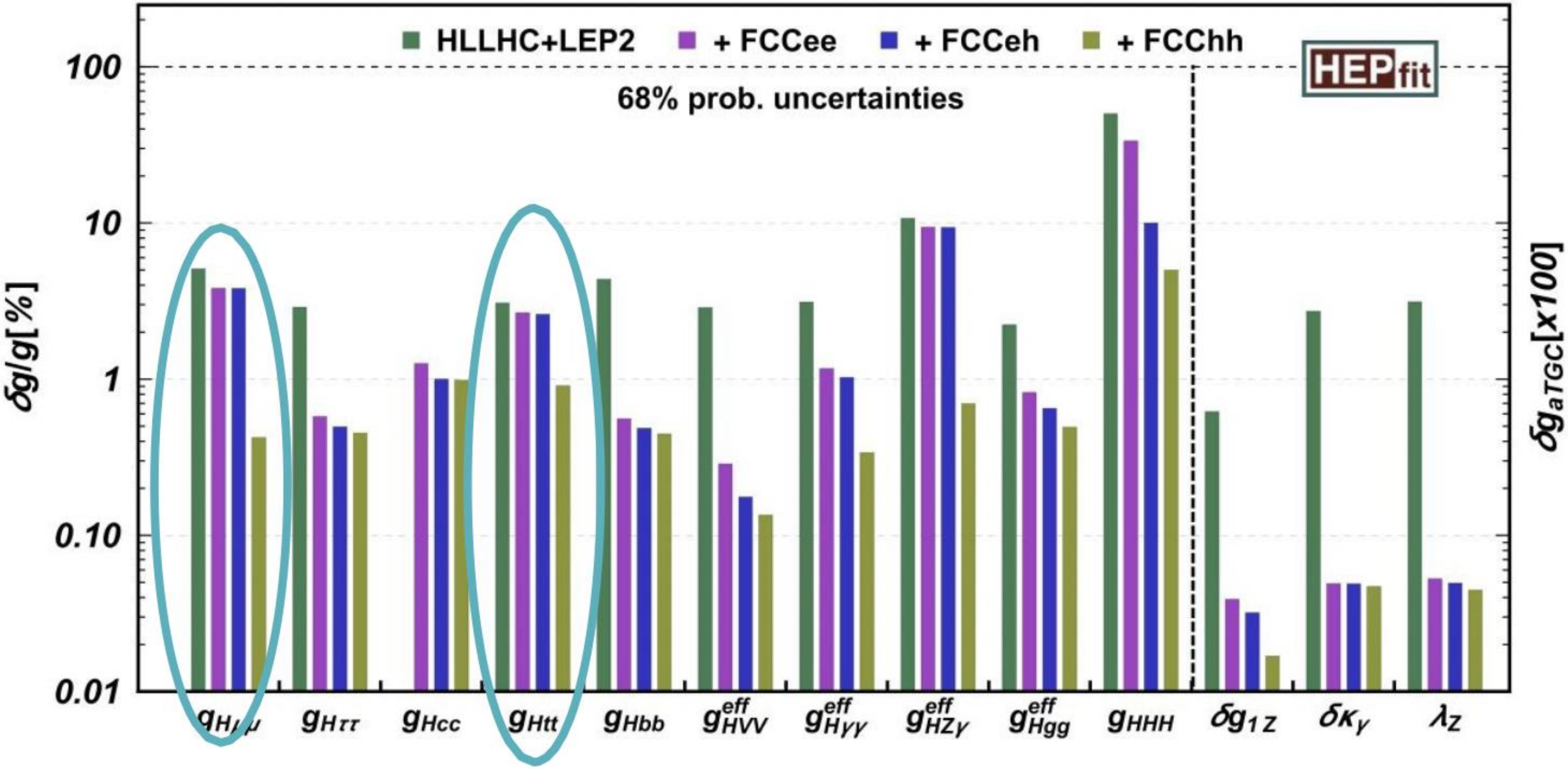
doi: 10.17181/n78xk-qcv56

observable	param	stat.	stat. + syst.	
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \rightarrow \gamma\gamma)$	$\delta\mu$	0.1%	1.4%	(*)
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \rightarrow \mu\mu)$	$\delta\mu$	0.4%	1.2%	
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \rightarrow \ell\ell\ell\ell)$	$\delta\mu$	0.2%	1.8%	(*)
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \rightarrow \gamma\ell\ell)$	$\delta\mu$	1.1%	1.7%	(*)
$\mu = \sigma(\mathrm{ttH})\, \mathcal{B}(\mathrm{H} \rightarrow \gamma\gamma)$	$\delta\mu$	0.4%	2.2%	
$\mathrm{R} = \mathcal{B}(\mathrm{H} \rightarrow \mu\mu)/\mathcal{B}(\mathrm{H} \rightarrow \mu\mu\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	0.5%	1.3%	
$\mathrm{R} = \mathcal{B}(\mathrm{H} \rightarrow \gamma\gamma)/\mathcal{B}(\mathrm{H} \rightarrow \mathrm{ee}\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	0.5%	0.8%	(*)
$\mathrm{R} = \mathcal{B}(\mathrm{H} \rightarrow \gamma\gamma)/\mathcal{B}(\mathrm{H} \rightarrow \mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	0.5%	1.3%	(*)
$\mathrm{R} = \mathcal{B}(\mathrm{H} \rightarrow \mu\mu\gamma)/\mathcal{B}(\mathrm{H} \rightarrow \mu\mu\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	1.6%	2.0%	(*)
$\mathrm{R} = \sigma(\mathrm{ttH})\, \mathcal{B}(\mathrm{H} \rightarrow \mathrm{b\bar{b}})/\sigma(\mathrm{ttZ})\, \mathcal{B}(\mathrm{Z} \rightarrow \mathrm{b\bar{b}})$	$\delta\mathrm{R}/\mathrm{R}$	1.2%	2.0%	(*)
$\mathrm{R} = \sigma(\mathrm{VBF-H}))\, \mathcal{B}(\mathrm{H} \rightarrow \mathrm{e}\mu\nu\nu)/\sigma(\mathrm{VBS-WW}))\, \mathcal{B}(\mathrm{WW} \rightarrow \mathrm{e}\mu\nu\nu)$	$\delta\mathrm{R}/\mathrm{R}$	1.9%	2.0%	
$\mathcal{B}(\mathrm{H} \rightarrow \mathrm{invisible})$	$\mathcal{B}$@95%CL	1.2×10^{-4}	2.6×10^{-4}	(*)
$\sigma(\mathrm{HH})$	$\delta\kappa_\lambda$	3.5%	5.2%	

Complementarity/synergy between HL-LHC, FCC-ee and FCC-hh

Higgs couplings: HL-LHC, FCCee, FCChh

Phys. Rev. Lett. 132 (2024) 221802



- HL-LHC is still going to be the best machine for Zγ, μμ (rare decays) and ttH coupling determination for the next decades years (until FCC-hh)
- HL-LHC has no access to charm Yukawa coupling
- FCC-ee has limited access to top Yukawa coupling (only via loop corrections to $e^+e^- \rightarrow tt$ cross section indirectly)

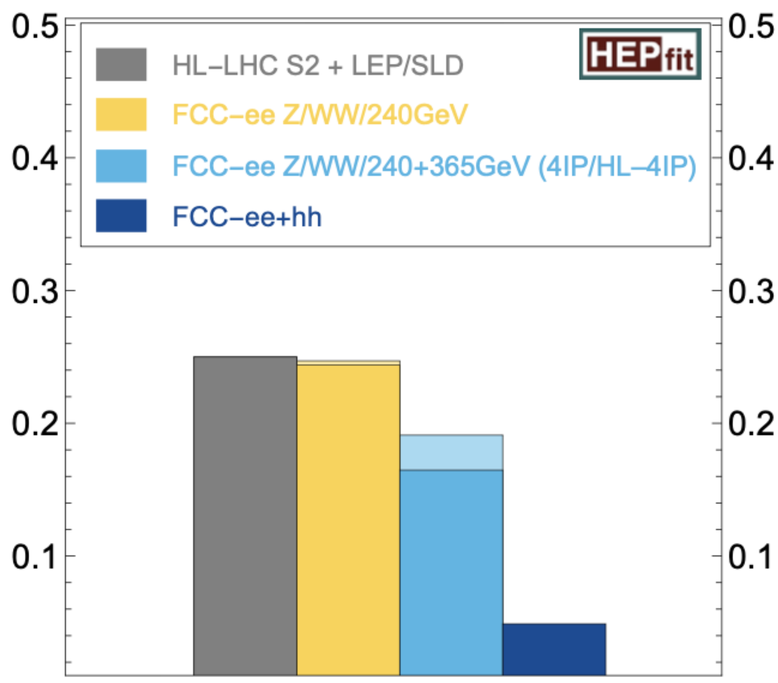
Uncertainty on Higgs couplings: latest

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	–	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$\|\kappa_s\|$ (%)	–	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_H (%)	–	0.78	0.69
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}	6.7×10^{-3}

FCC-ee and FCC-hh Integrated Programme is complementary and provides ~ order of magnitude improvement of all Higgs couplings w.r.t HL-LHC

Precision on Higgs self couplings

HL-LHC	+FCC-ee	+FCC-hh
26–29%	~18%	2–3%



Conclusions

- FCC is a unique project, offering an extremely complete and compelling programme, with synergies and complementarities between the various machines and running scenarios (FCC-ee, FCC-hh) → prospects for 100 years of great physics at energy and intensity frontiers!

- FCC-ee provides ultimate precision in Higgs sector, aimed at starting at CERN in e^+e^- mode, shortly after the end of the HL-LHC.

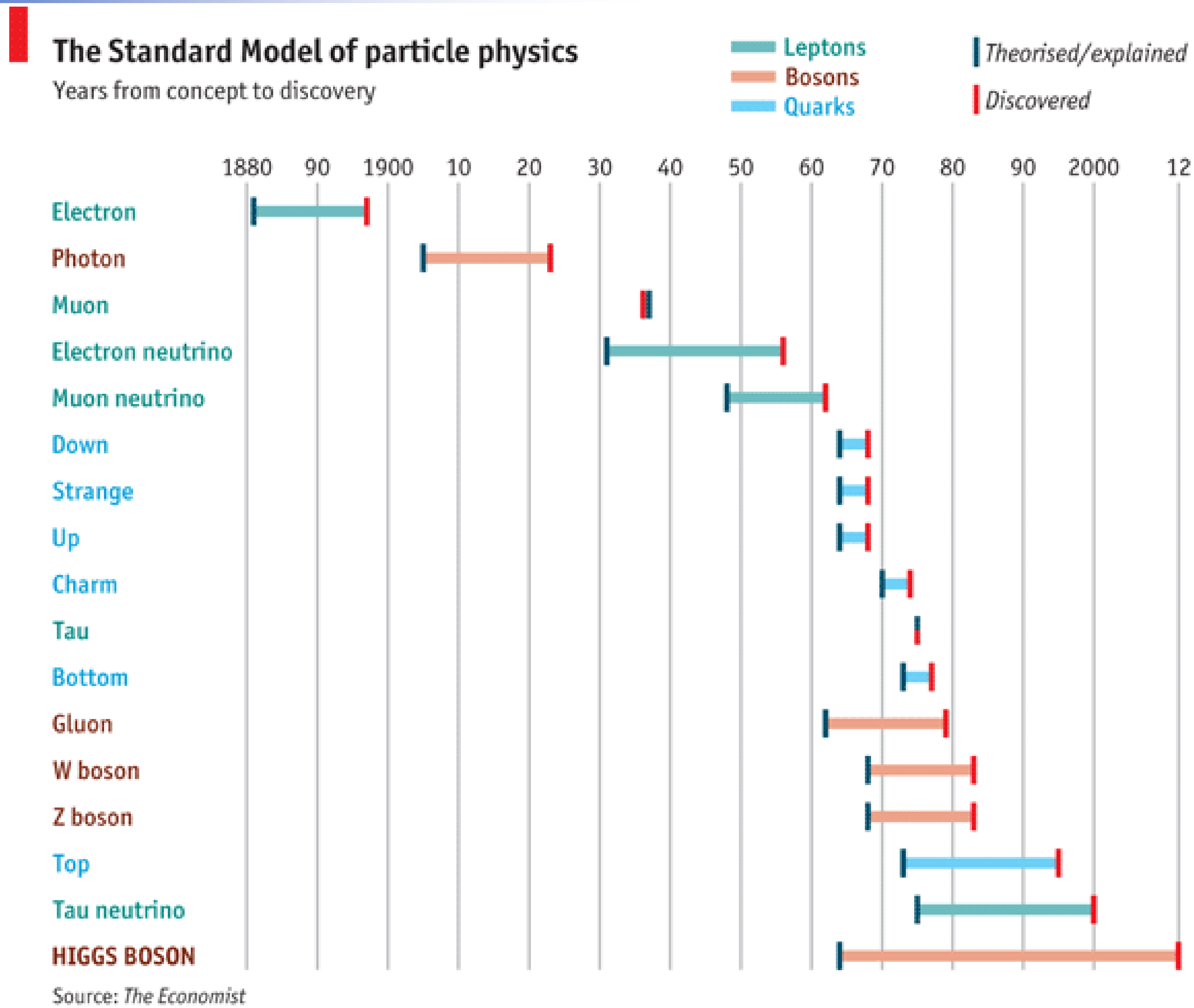
- FCC-ee will produce almost 3 million Higgs in a clean environment:
  - allows for model independent measurement of Higgs properties
  - **an order-of-magnitude** improvement in precision in Higgs decay channels

- FCC-hh will provide precise meaurement of the Higgs tri-linear self coupling, of the top Yukava coupling and inspection of the Higgs rare decays

- New experimental developments coming in: progress on detector R&D, reconstruction algorithms, ML revolution, allow to contemplate more ambitious goals
  - an exciting future for HEP ahead…join the team!

Backup

Timeline of the discoveries



Seminal papers

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

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)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

The Higgs boson

- **Problem:** give mass to gauge files W^+, W^- and Z
  - Explicit mass terms in the Lagrangian break the gauge invariance
- **Solution:** Higgs mechanism
  - **Higgs pointed out a massive scalar boson**

$$\{\partial^2 - 4\varphi_0{}^2 V''(\varphi_0{}^2)\}(\Delta\varphi_2) = 0, \qquad (2b)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0{}^2)\}^{1/2}$

- *"… an essential feature of [this] type of theory … is the prediction of incomplete multiplets of vector and scalar bosons"*
- Englert, Brout, Guralnik, Hagen & Kibble did not comment on its existence
- **Discussed in detail by Higgs in 1966 paper**

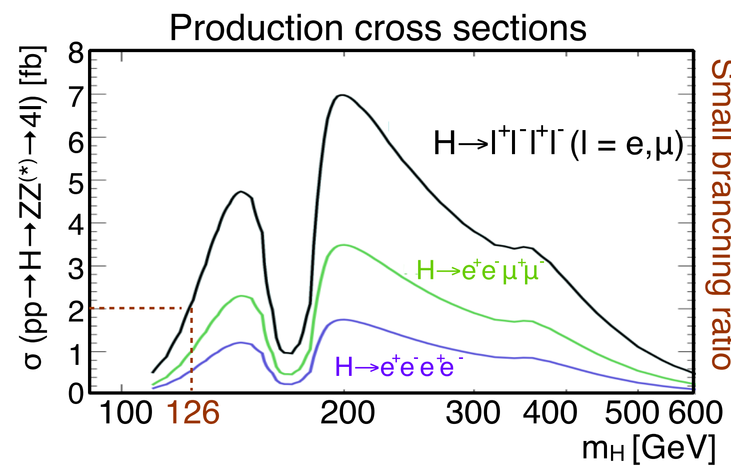
H→ZZ→4l in a nutshell

- Signatures: 4e, 4mu and 2e2mu
  - extremely demanding channel for requiring the highest possible efficiencies (lepton Reco/ID/Isolation).
  - σ x BR small ≈ few fb

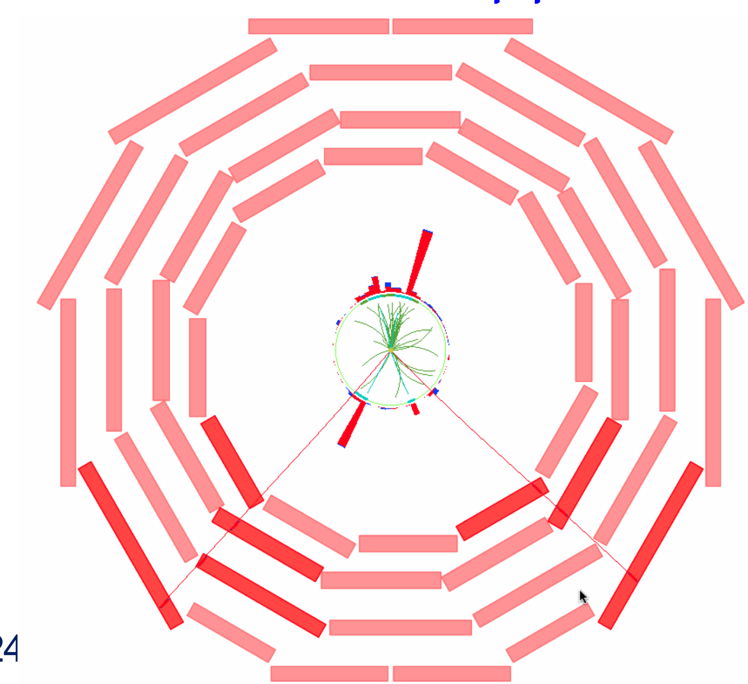
- Backgrounds:
  - Irreducible: ZZ*
  - Reducible: Zbb tt   tt+jets, Z+jets, WZ+jets

- Sensitivity: $115 < m_H < 600$ GeV

- Selection strategy:
  - triggering on double leptons
  - Particle Flow algorithm to build physics objects
  - applying reco, id and isolation of leptons
  - recovery of FSR photons
  - use of impact parameter
  - m_Z and m_{Z*} constraint
  - kinematical discriminant / scalarity of the Higgs



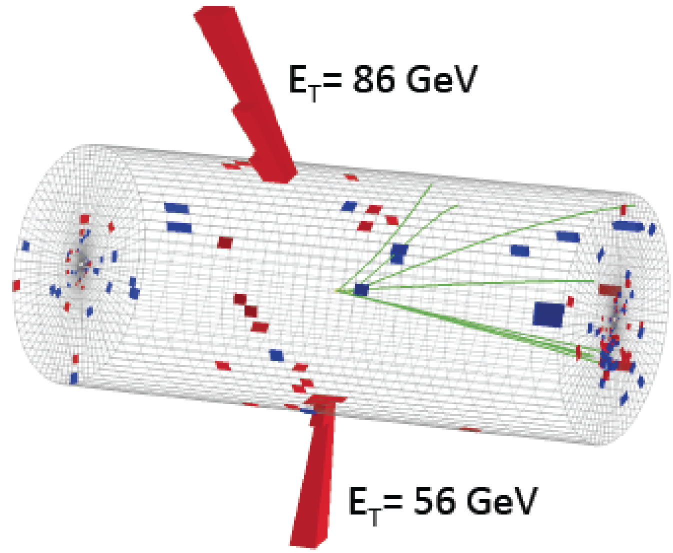
$H \rightarrow ZZ^* \rightarrow e^+e^-\mu^+\mu^-$



$H \rightarrow \gamma\gamma$ in a nutshell

Important channel for Higgs with $110 < m_H < 140$ GeV

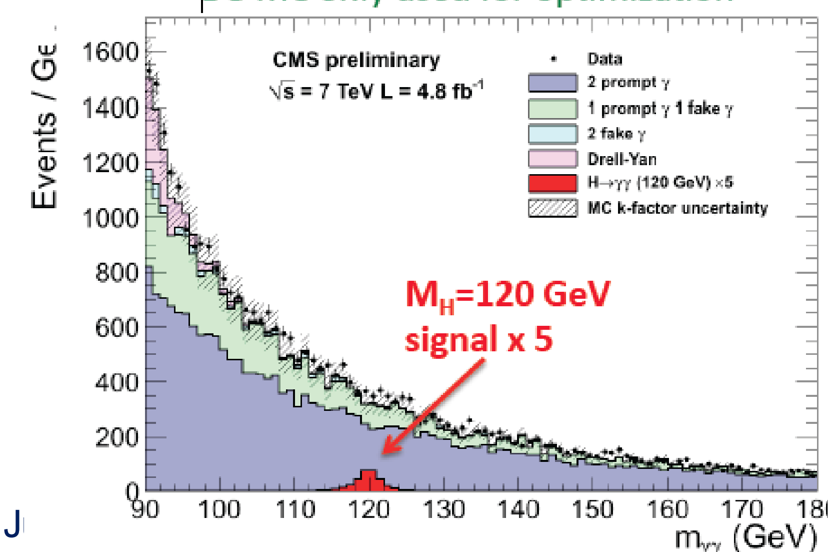
- clear signature of two isolated high E_T photons
- small B.R. (0.2%)
- narrow mass peak with very good mass resolution 1-2%
- VBF channels has two additional jets form outgoing quarks



Background:

- irreducible : $gg \rightarrow \gamma\gamma$, qqbar, $qg \rightarrow g\gamma$ from QCD
- reducible:
  - $pp \rightarrow \gamma$+jets (1 prompt γ + 1 fake γ)
  - $pp \rightarrow$ jets (2 fake γ), fake γ from $\pi^0 \rightarrow \gamma\gamma$

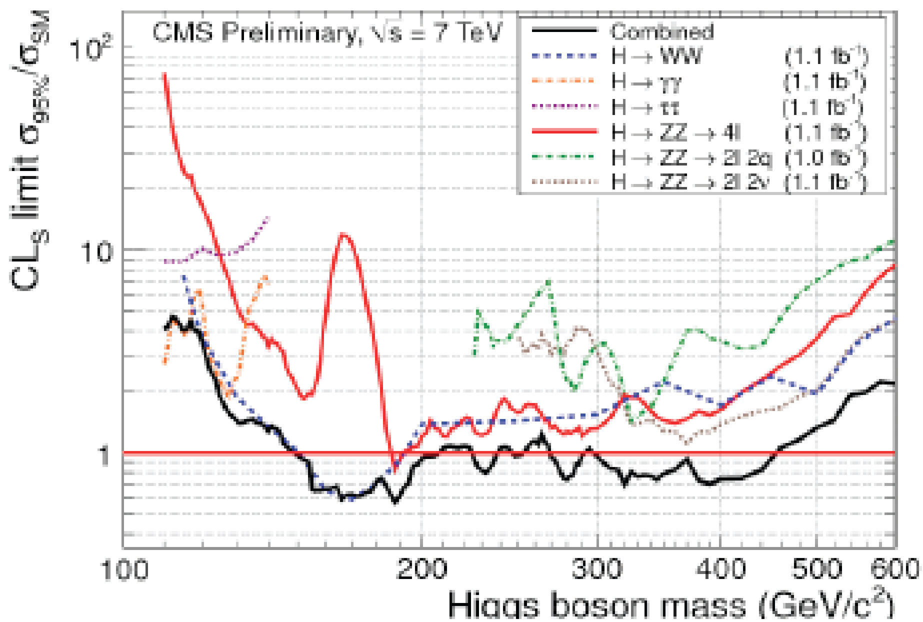
BG MC only used for optimization



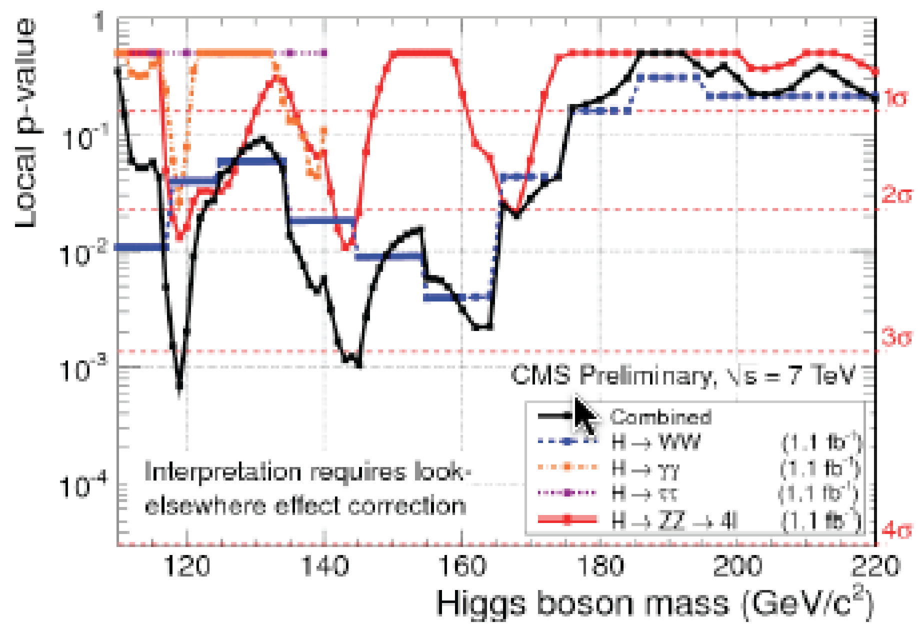
Analysis strategy based on:

- trigger (double photon HLT)
- vertex ID via BDT MVA
- photon reconstruction, ID and isolation via BDT MVA
- categories of events based on the photon h/shower shape (R_9) to optimize s/b
- look for a peak with cut-based and MVA techniques
- use data to evaluate the background

EPS in July 2011 at Grenoble



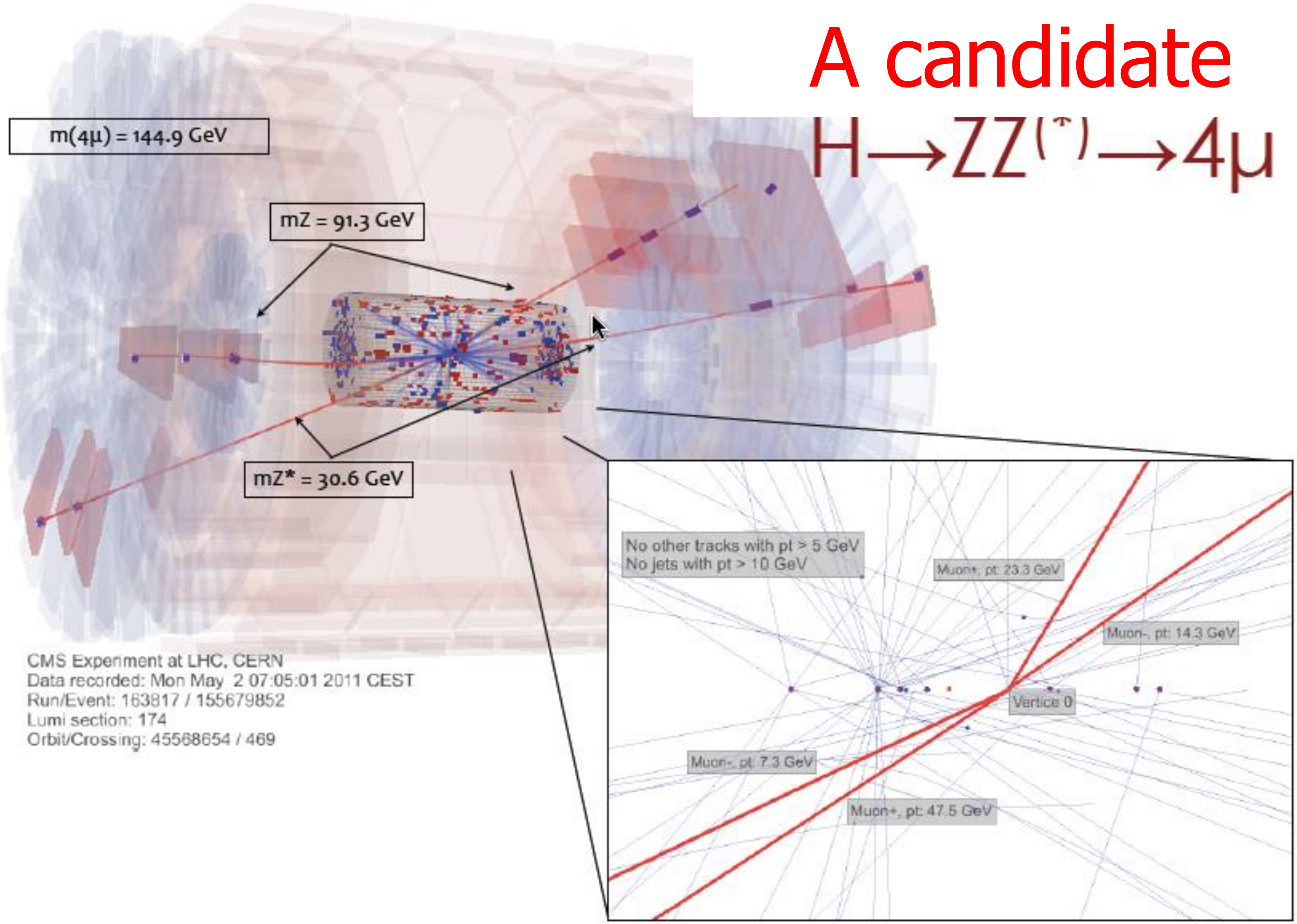
Observed combined upper limit on $\mu=\sigma/\sigma_{SM}$



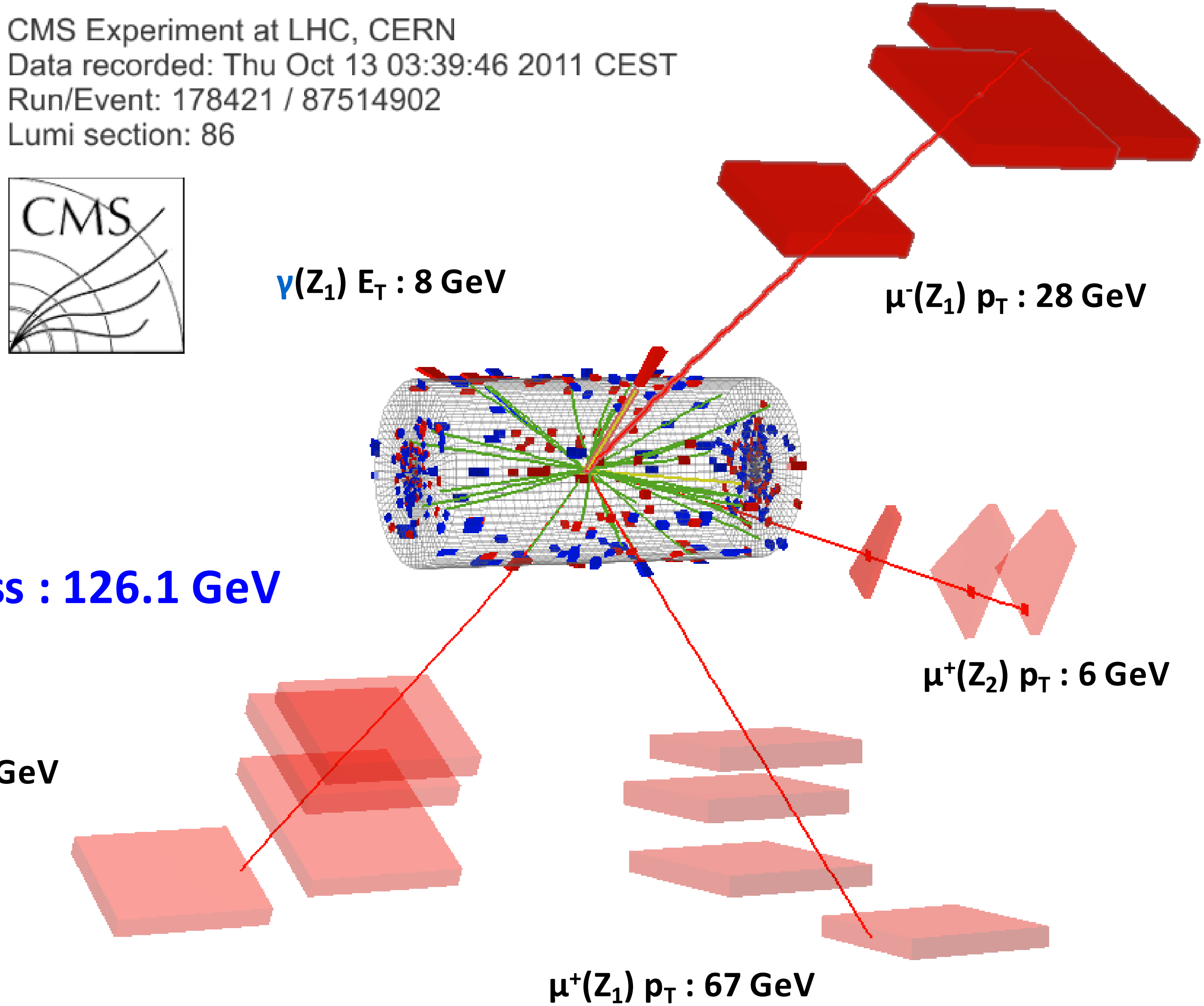
Overall combined local p-values

CMS able to exclude the existence of Higgs in the mass range 149-206 GeV and 300-440 GeV

A candidate $H \rightarrow ZZ^{(*)} \rightarrow 4\mu$



Candidates

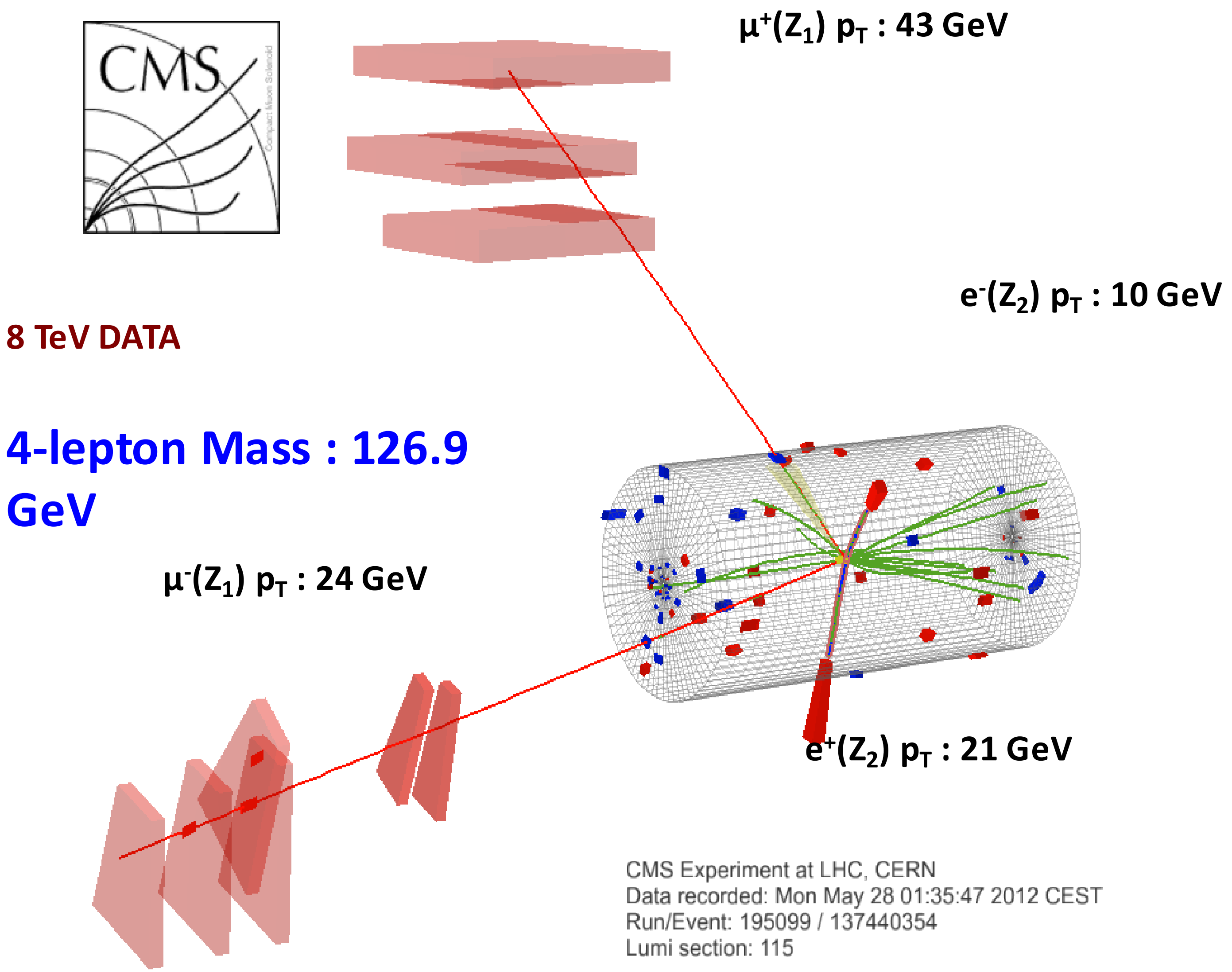


7 TeV DATA

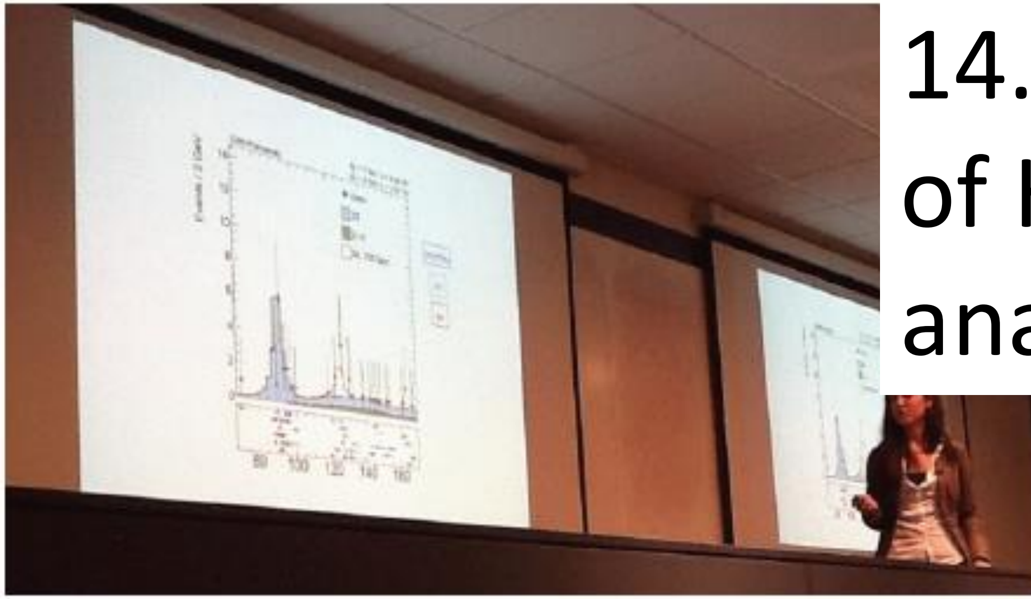
$4\mu+\gamma$ Mass : 126.1 GeV

$\mu^-(Z_2)$ p_T : 14 GeV

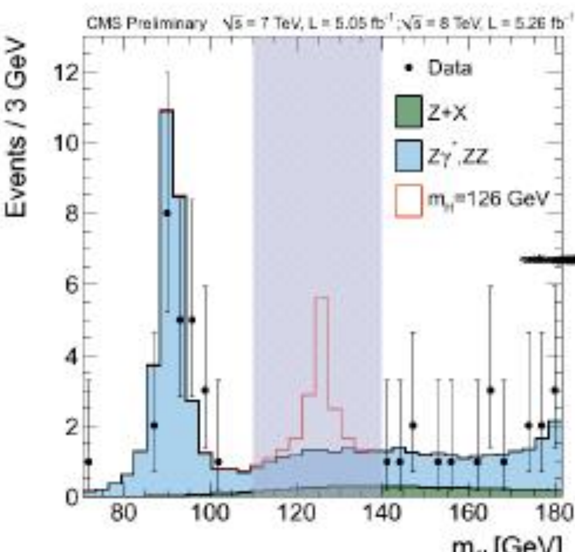
Candidates

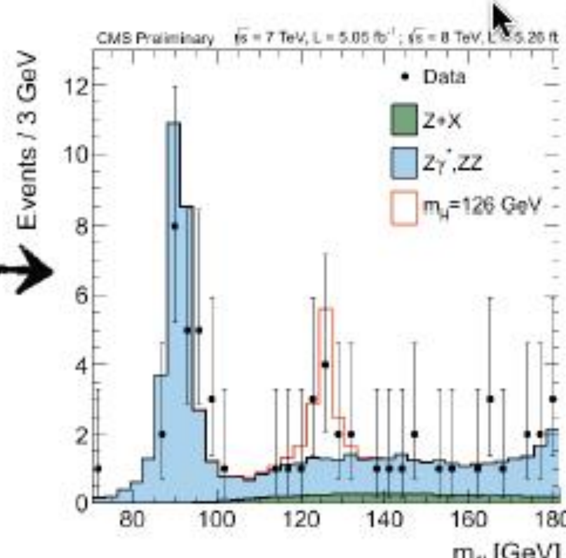

CMS
$\mu^+(Z_1)$ p_T : 43 GeV
$e^-(Z_2)$ p_T : 10 GeV
8 TeV DATA
4-lepton Mass : 126.9 GeV
$\mu^-(Z_1)$ p_T : 24 GeV
$e^+(Z_2)$ p_T : 21 GeV
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115

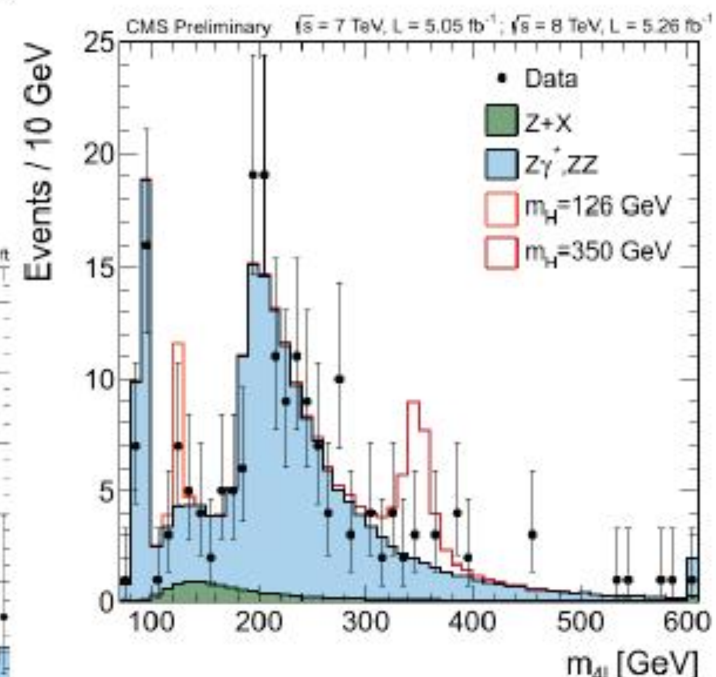
June 2012



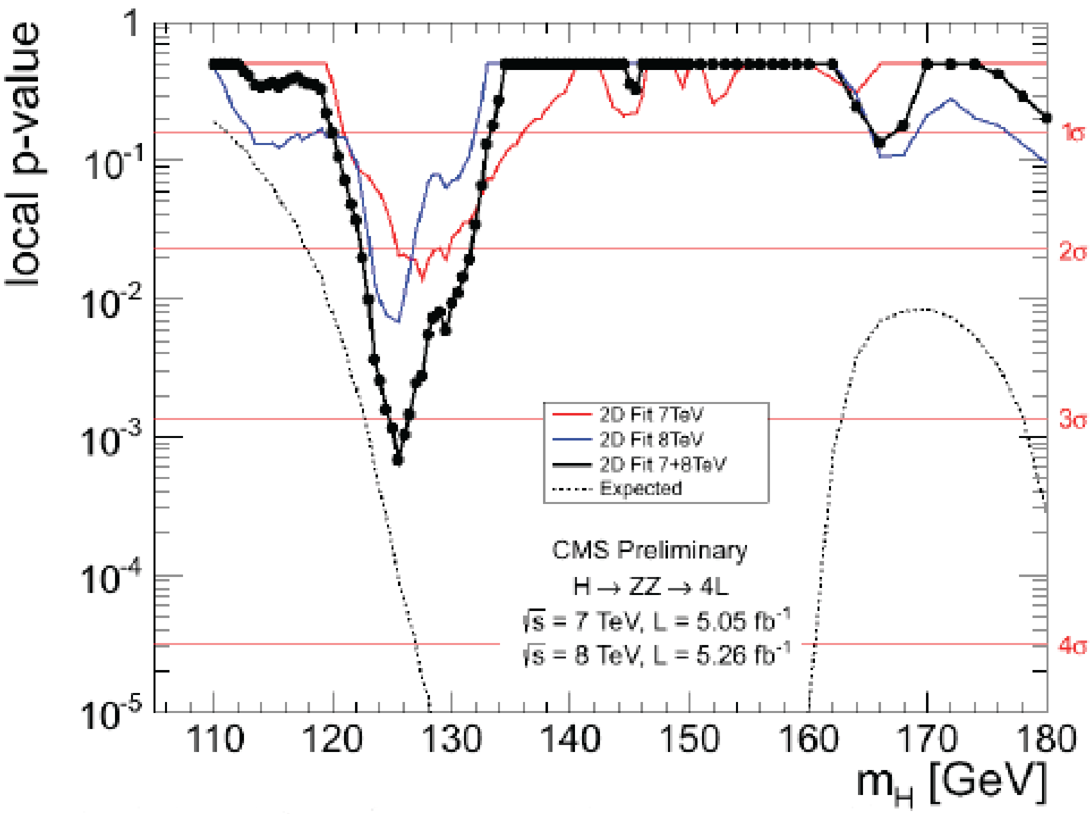
14.6.2012: Approval of H→ZZ→4l analysis

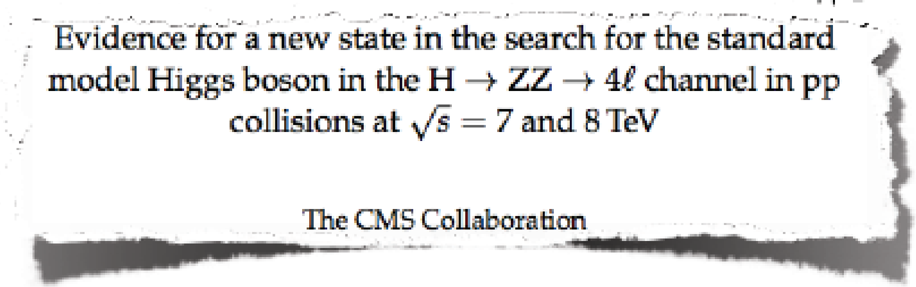






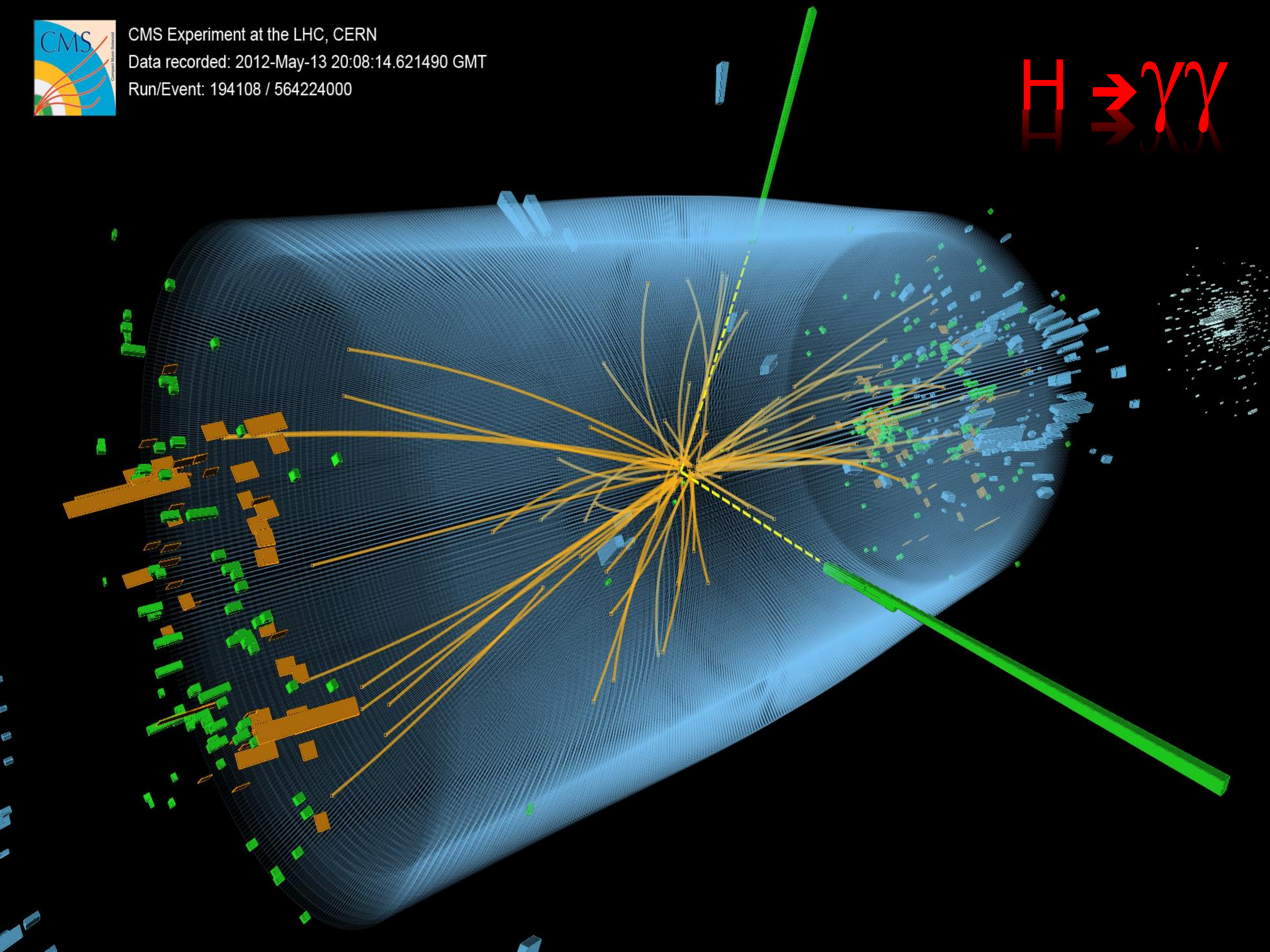
Evidence of a new state



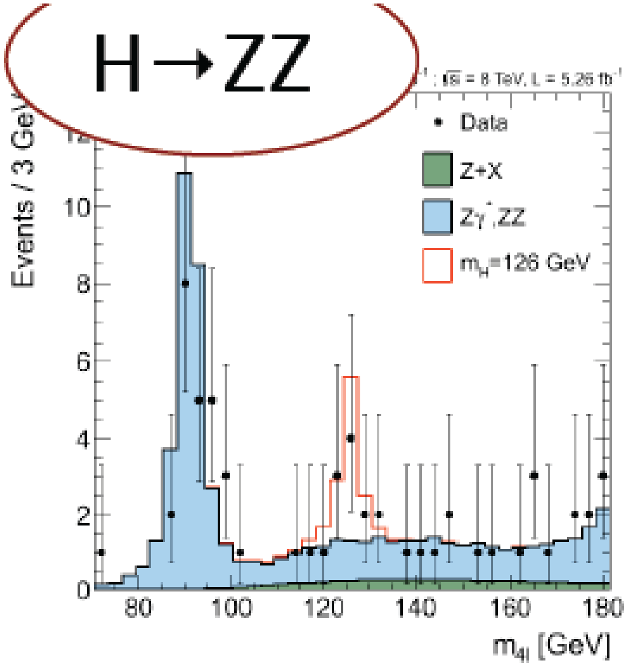


Evidence for a new state in the search for the standard model Higgs boson in the $H \to ZZ \to 4\ell$ channel in pp collisions at $\sqrt{s} = 7$ and 8 TeV

The CMS Collaboration


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H → γγ

July 4: seminar at CERN



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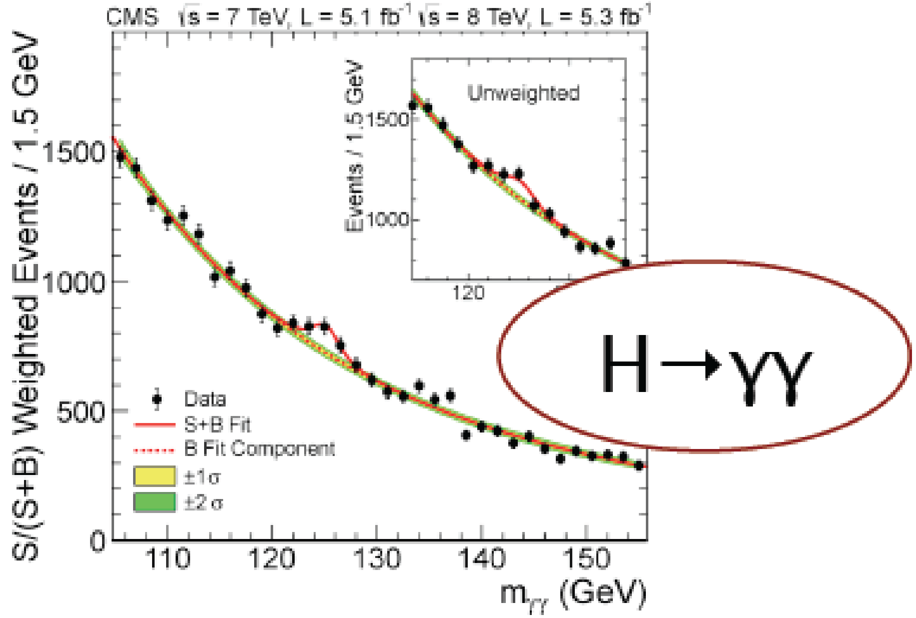

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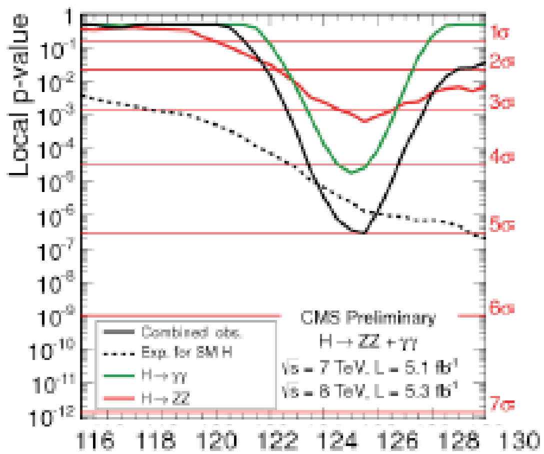
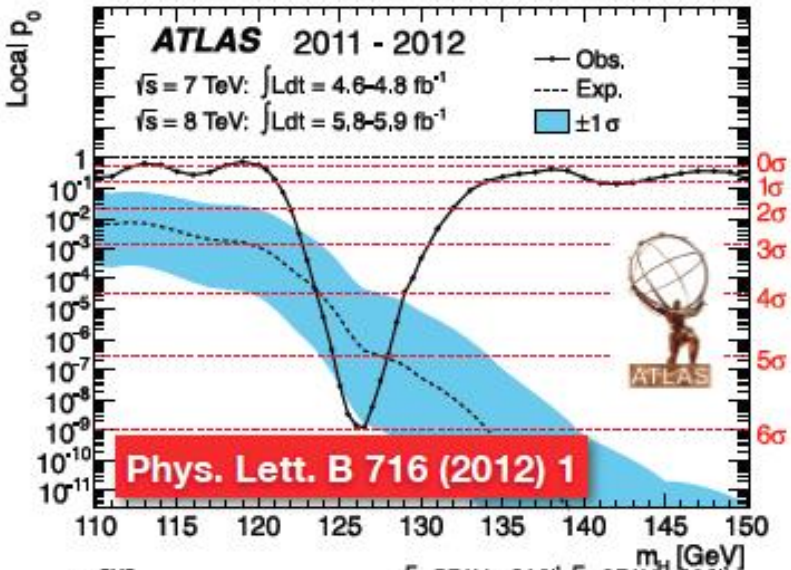
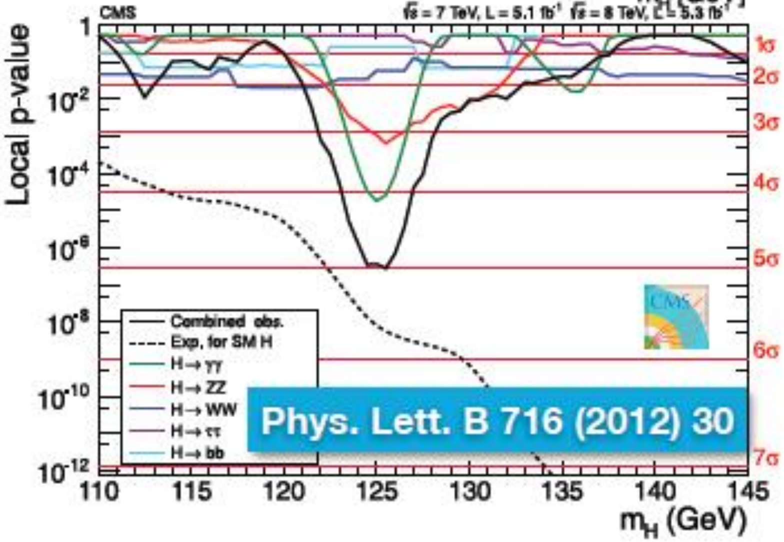
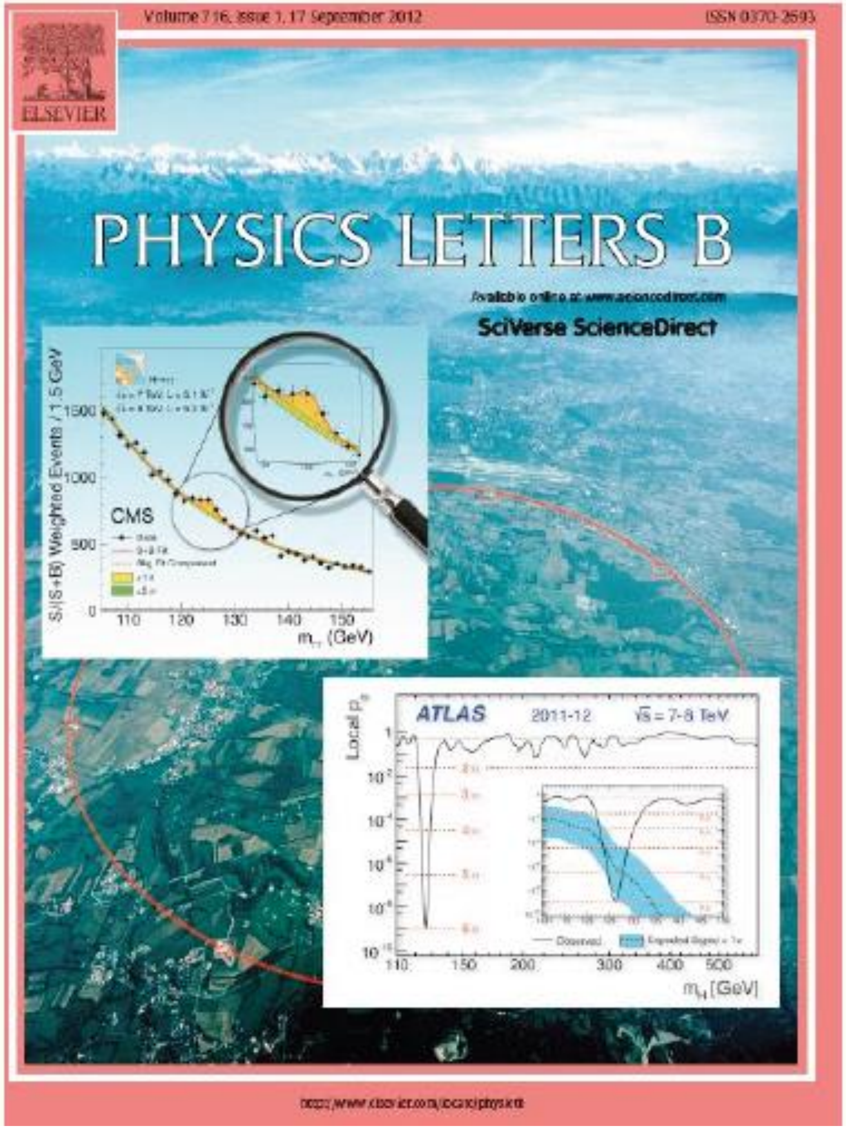


We have observed a new boson with a mass of **125.3 ± 0.6 GeV**

A new boson discovery: July 4 2012

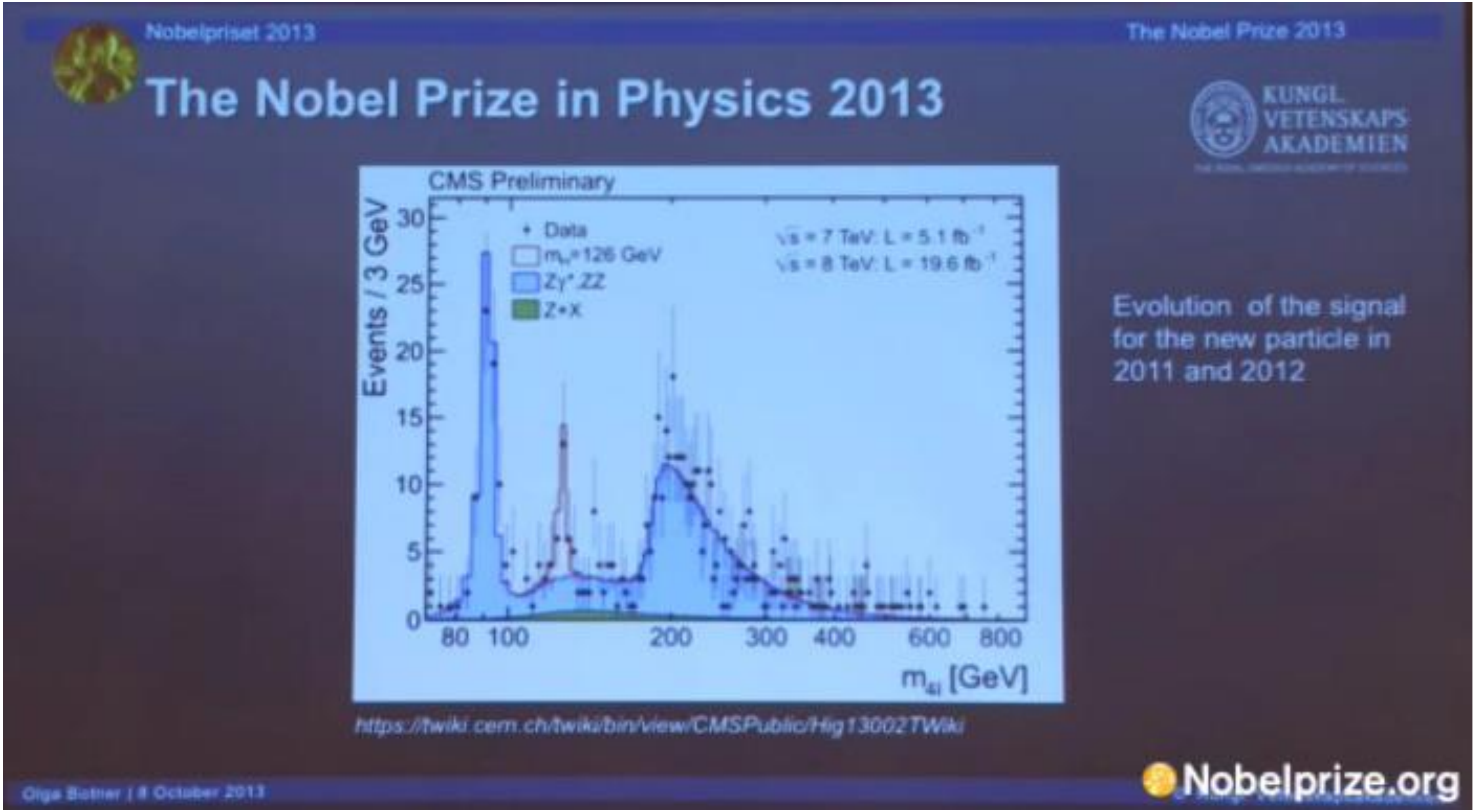




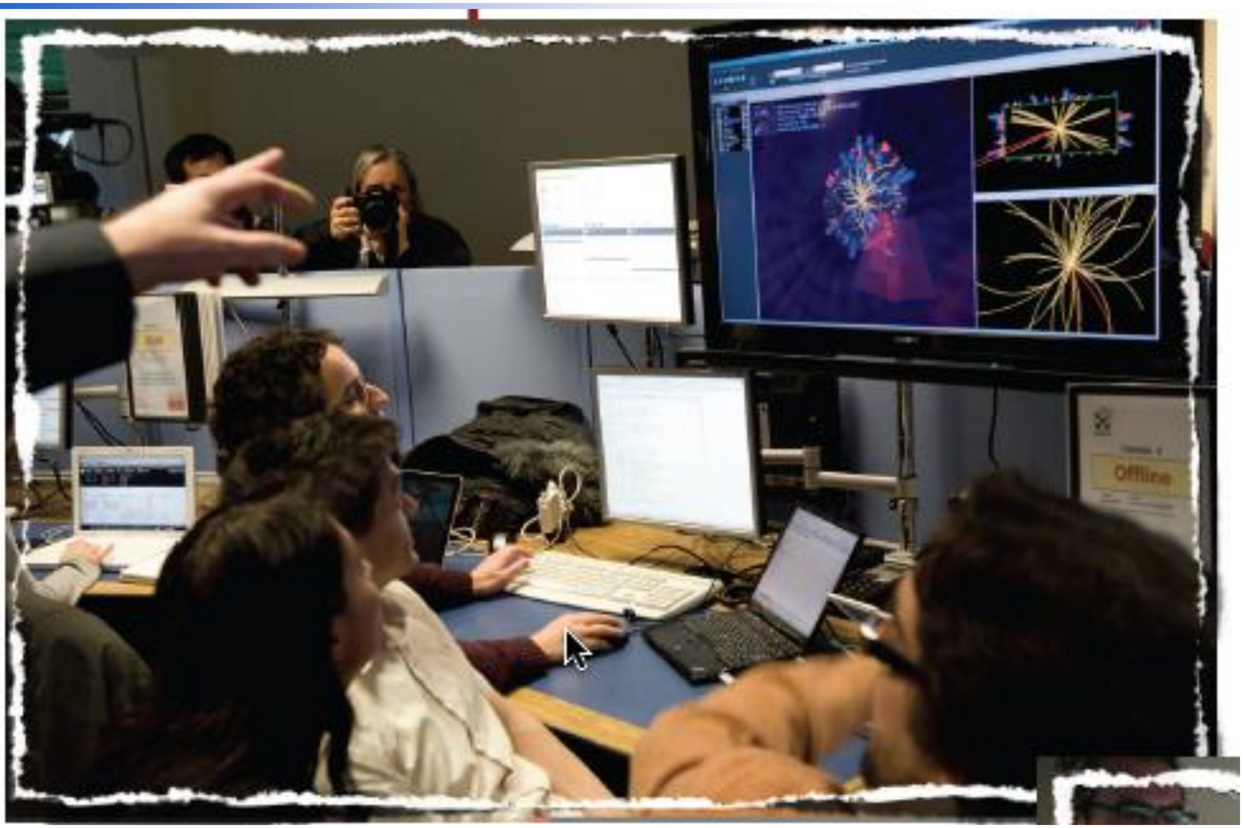


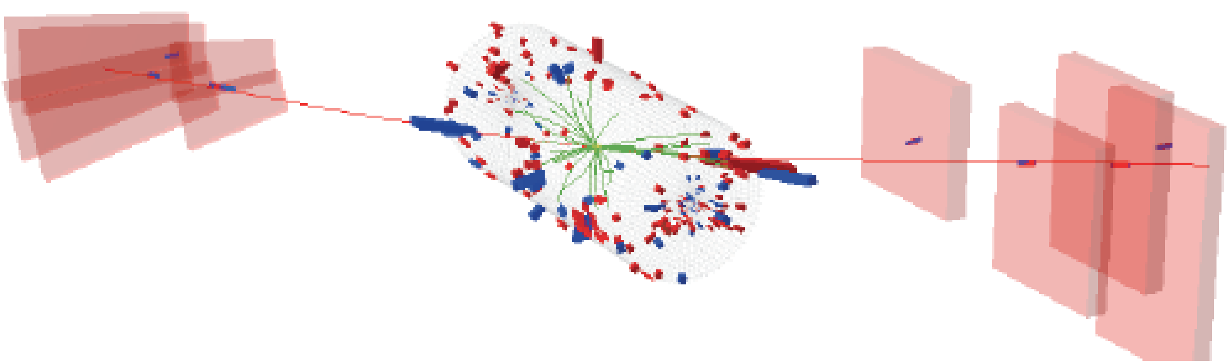
July 4 fireworks

October 8, 2013: Nobel Prize

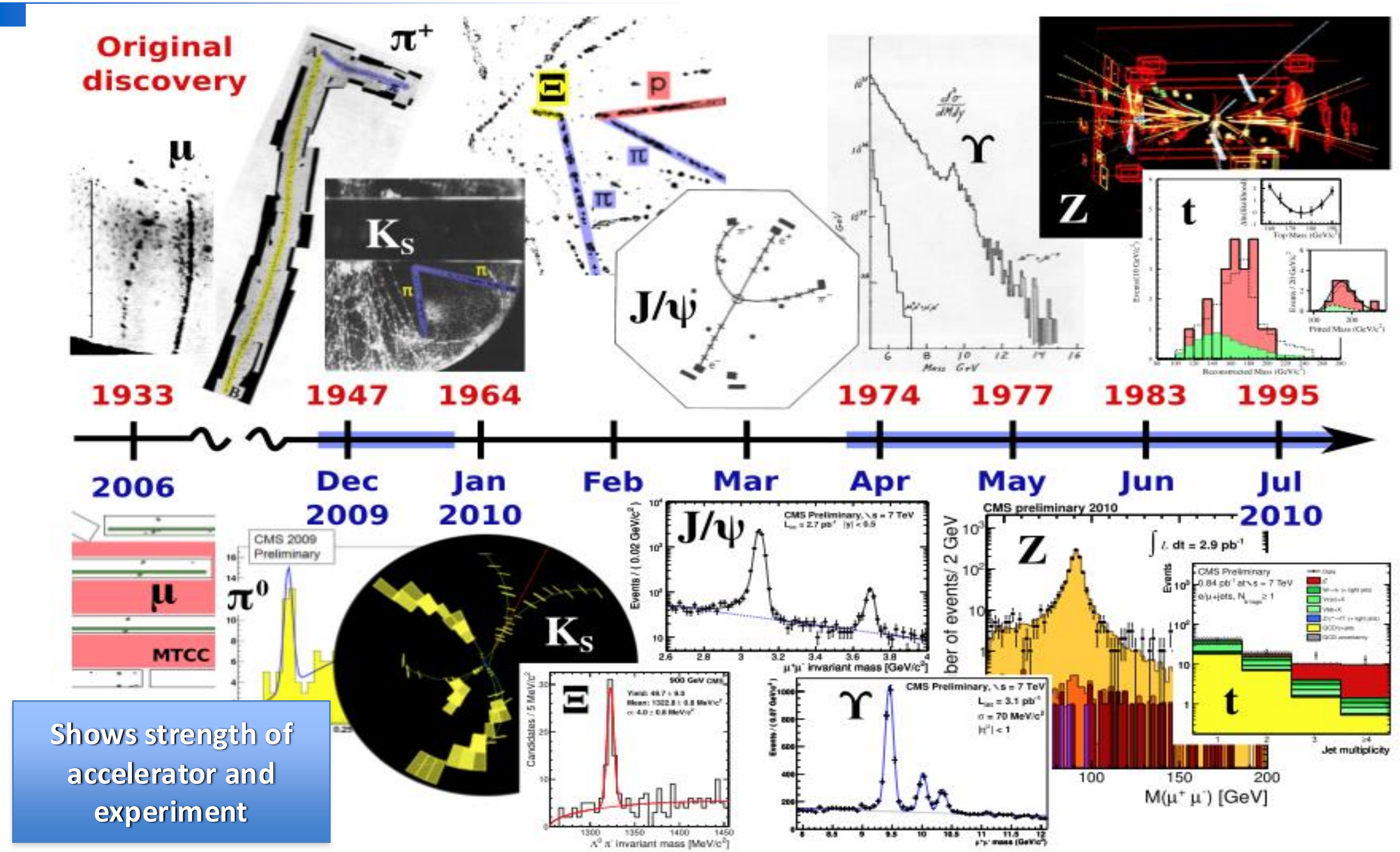


First collisions at 7 TeV



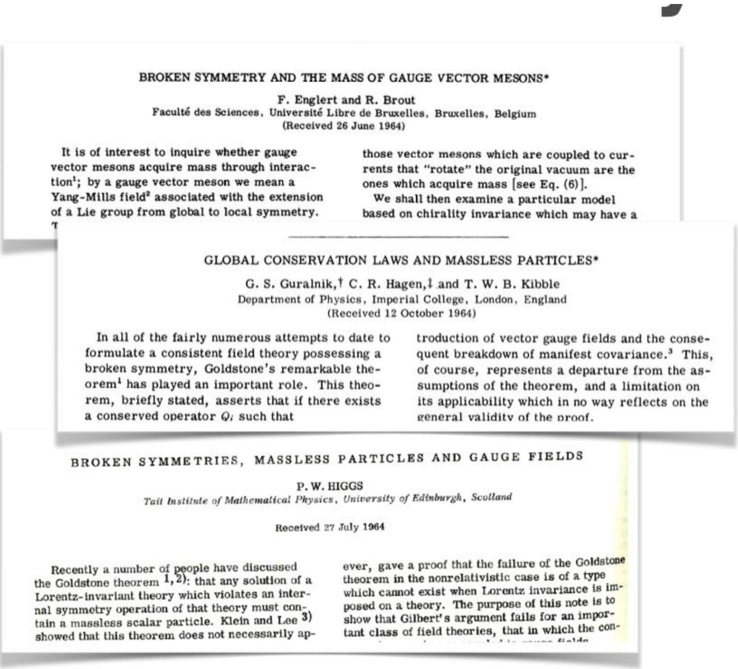


2010: "Rediscover" the SM



Shows strength of accelerator and experiment

History of the Higgs boson


BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

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Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[1]; by a gauge vector meson we mean a Yang-Mills field[2] associated with the extension of a Lie group from global to local symmetry. those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)]. We shall then examine a particular model based on chirality invariance which may have a

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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Department of Physics, Imperial College, London, England

(Received 12 October 1964)

In all of the fairly numerous attempts to date to formulate a consistent field theory possessing a broken symmetry, Goldstone's remarkable theorem[1] has played an important role. This theorem, briefly stated, asserts that if there exists a conserved operator Q_i such that troduction of vector gauge fields and the consequent breakdown of manifest covariance.[3] This, of course, represents a departure from the assumptions of the theorem, and a limitation on its applicability which in no way reflects on the general validity of the proof.

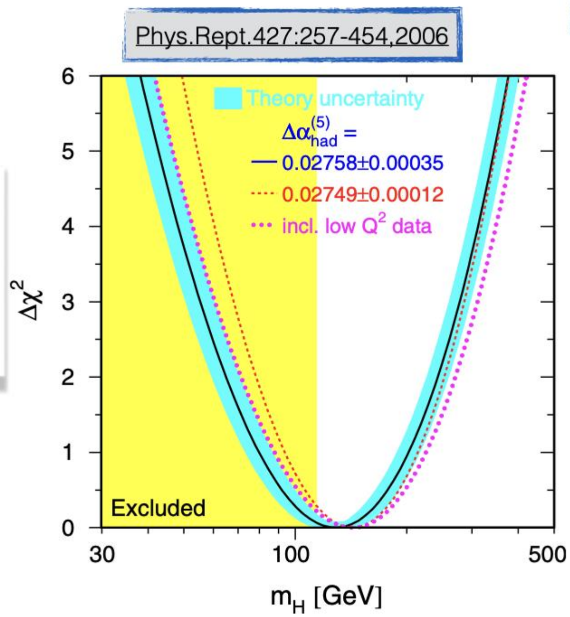
BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

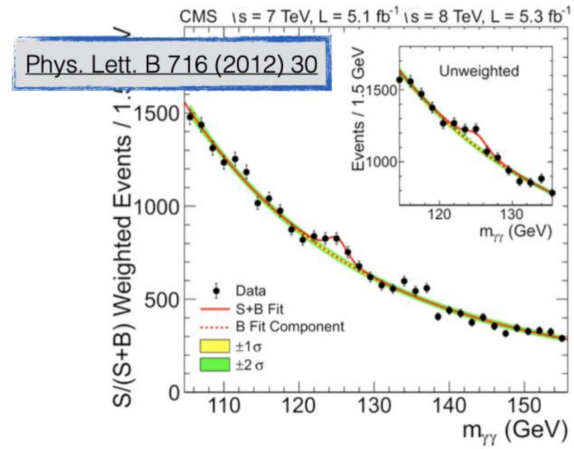
P. W. HIGGS

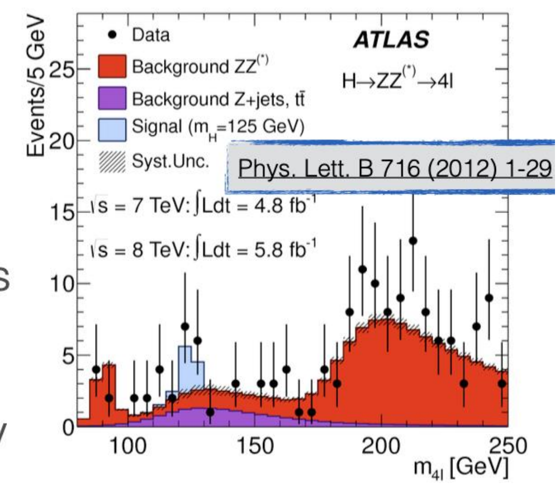
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

Recently a number of people have discussed the Goldstone theorem [1,2]: that any solution of a Lorentz-invariant theory which violates an internal symmetry operation of that theory must contain a massless scalar particle. Klein and Lee [3] showed that this theorem does not necessarily ap- ever, gave a proof that the failure of the Goldstone theorem in the nonrelativistic case is of a type which cannot exist when Lorentz invariance is imposed on a theory. The purpose of this note is to show that Gilbert's argument fails for an important class of field theories, that in which the con-







- Stringent constraints on Higgs sector from electroweak precision fits at LEP
- 50 years between theoretical prediction and experimental discovery

European Strategy

PR07.25
27.06.2025

Venice event brings future of particle physics into focus

Venice, Italy, 27 June 2025. This week, more than 600 scientists met in Venice, Italy, to debate the future direction of European particle physics in the global context. The Open Symposium is an important step in the ongoing update of the European Strategy for Particle Physics (ESPP), providing particle physicists in Europe and beyond with an opportunity to assess scientific priorities and technological approaches for the medium- and long-term future.

The Strategy recommendations, which will reflect the ambitions and priorities of the community, are expected to be submitted to the CERN Council in early 2026. Projects are approved by the Council through a separate decision-making process, taking the Strategy recommendations and other considerations into account.

The previous ESPP update in 2020 emphasised the importance of ensuring Europe's continued scientific and technological leadership. Building on the discovery of the Higgs boson at CERN's Large Hadron Collider (LHC), it recommended an electron-positron "Higgs factory" as the highest-priority next facility after the LHC reaches the end of its operational lifetime in 2041 and that Europe should have the long-term ambition to operate a proton-proton collider at the highest achievable energies.

"The time is ripe to forge a brilliant future for our field in Europe, together with our global partners," said Fabiola Gianotti, CERN Director-General. "The worldwide CERN community's achievements in implementing the 2020 ESPP update prove that we are a strong community, capable of designing, building and operating facilities of astounding complexity that consistently exceed expectations. This is our greatest asset as we prepare for even more ambitious projects."

A total of 266 submissions from the community, spanning all aspects of particle physics, formed the basis for vibrant discussions during the week-long Open Symposium. Participants from almost 40 countries, including many early-career researchers, expressed the need for an ambitious and innovative research programme that will maintain CERN as a world-leading centre for collider physics while also ensuring a diverse programme that maximises physics reach and includes approaches complementary to colliders. Contributions from researchers in neighbouring fields also demonstrated the rich connections between particle physics and nuclear and astroparticle physics.

Identifying the most promising flagship collider to succeed the LHC at CERN is a central aim of the 2026 ESPP update. In direct response to the 2020 Strategy update, a feasibility study for a Future Circular Collider (FCC) facility that could host a 91 km-circumference electron-positron collider followed by an energy-frontier proton-proton collider in the same tunnel was conducted, and the report was released in March 2025. In addition to the FCC, other projects under consideration in the relevant time frame are an electron-positron linear collider at CERN and smaller colliders that would re-use the LHC tunnel. Great progress has also been made towards a muon collider, but several years of R&D work are still needed to demonstrate its feasibility.

National input from members of the high-energy physics communities in CERN's 25 Member States so far indicate broad support for the FCC programme on account of its outstanding scientific potential and long-term strategic value. Underscoring the importance of continued dialogue and assessment, discussions on alternative options will continue. Several important steps remain before the ESPP recommendations are finalised. Expert ESPP panels are working on a comparative evaluation of proposed future colliders in terms of their physics potential, environmental impact and sustainability, technical maturity, cost, required human resources and implementation timelines.

"I am happy to see that the recommendations of the 2020 ESPP update and their implementation via the FCC Feasibility Study enjoy overwhelming support from the vast majority of the high-energy physics community as well as leading experts," said Costas Fountas, President of the CERN Council. "The discovery of the Higgs boson at the LHC in 2012 marked the start of a new journey of discovery that can only be realised by a future collider with the broadest and most powerful research programme, and the CERN Council eagerly awaits the community's final recommendations."

The ESPP conclusions are eagerly awaited, as delays in reaching agreement on which collider should follow the LHC are viewed by the community as a risk to CERN's leadership and its potential to attract interest from scientists across the world.

Following rich dialogue at the Open Symposium, discussions will continue in the coming months. Together with a second round of input from the national communities, which is to be submitted by 14 November, they will provide the basis for the final Strategy recommendations to be drafted in December.

"I am pleased to see so many colleagues from Europe and beyond participating actively in debating the scientific input received from the particle physics community in order to define the next large accelerator project that will allow CERN and Europe to maintain their leading role in our field," said Karl Jakobs, Strategy Secretary. "In addition, the scientific goals and priorities in other areas of physics were discussed. We anticipate further rich input and discussion as the 2026 ESPP update enters its final strait."

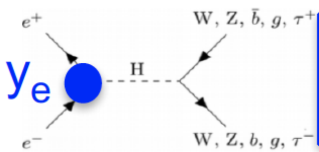
Higgs Yukawa coupling to electron

arXiv:2107.02686

FCC-ee: unique opportunity to study the Higgs Yukawa coupling to electron, $\mathbf{y_e}$, via resonant s-channel production $\mathbf{e^+e^- \rightarrow H}$ in a dedicated run at the Higgs pole, $\sqrt{s} = m_H$.

In the SM:

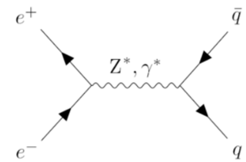
- the Yukawa coupling of the electron is $y_e = \sqrt{2}\, m_e/v = 2.8 \cdot 10^{-6}$
- $BR(H \rightarrow e^+e^-) \approx 5 \times 10^{-9}$



$\sigma(e^+e^- \rightarrow H)_{B\text{-}W} = 1.64$ fb

$\sigma(e^+e^- \rightarrow H)_{spread} = 280$ ab (ISR + $\sqrt{s}_{spread} = \Gamma_H = 4.2$ MeV)

background



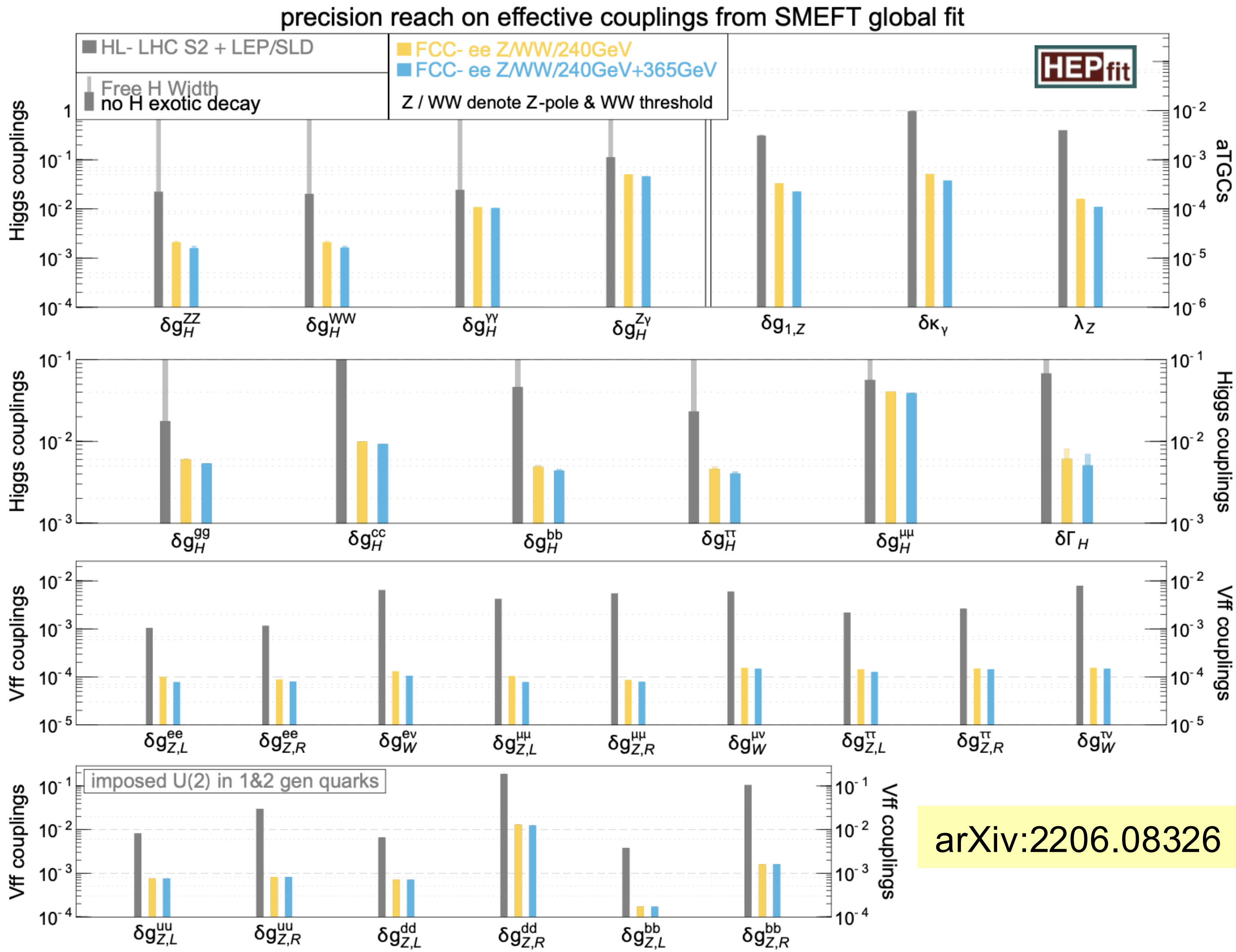
Higgs decay channel	$\mathcal{B}$	$\sigma \times \mathcal{B}$	Irreducible background	σ	S/B
$e^+e^- \rightarrow H \rightarrow b\bar{b}$	58.2%	164 ab	$e^+e^- \rightarrow b\bar{b}$	19 pb	$\mathcal{O}(10^{-5})$
$e^+e^- \rightarrow H \rightarrow gg$	8.2%	23 ab	$e^+e^- \rightarrow q\bar{q}$	61 pb	$\mathcal{O}(10^{-3})$
$e^+e^- \rightarrow H \rightarrow \tau\tau$	6.3%	18 ab	$e^+e^- \rightarrow \tau\tau$	10 pb	$\mathcal{O}(10^{-6})$
$e^+e^- \rightarrow H \rightarrow c\bar{c}$	2.9%	8.2 ab	$e^+e^- \rightarrow c\bar{c}$	22 pb	$\mathcal{O}(10^{-7})$
$e^+e^- \rightarrow H \rightarrow WW^* \rightarrow \ell\nu\, 2j$	21.4%×67.6%×32.4%×2	26.5 ab	$e^+e^- \rightarrow WW^* \rightarrow \ell\nu\, 2j$	23 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \rightarrow H \rightarrow WW^* \rightarrow 2\ell\, 2\nu$	21.4%×32.4%×32.4%	6.4 ab	$e^+e^- \rightarrow WW^* \rightarrow 2\ell\, 2\nu$	5.6 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \rightarrow H \rightarrow WW^* \rightarrow 4j$	21.4%×67.6%×67.6%	27.6 ab	$e^+e^- \rightarrow WW^* \rightarrow 4j$	24 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \rightarrow H \rightarrow ZZ^* \rightarrow 2j\, 2\nu$	2.6%×70%×20%×2	2 ab	$e^+e^- \rightarrow ZZ^* \rightarrow 2j\, 2\nu$	273 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \rightarrow H \rightarrow ZZ^* \rightarrow 2\ell\, 2j$	2.6%×70%×10%×2	1 ab	$e^+e^- \rightarrow ZZ^* \rightarrow 2\ell\, 2j$	136 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \rightarrow H \rightarrow ZZ^* \rightarrow 2\ell\, 2\nu$	2.6%×20%×10%×2	0.3 ab	$e^+e^- \rightarrow ZZ^* \rightarrow 2\ell\, 2\nu$	39 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \rightarrow H \rightarrow \gamma\gamma$	0.23%	0.65 ab	$e^+e^- \rightarrow \gamma\gamma$	79 pb	$\mathcal{O}(10^{-8})$

Higgs couplings from SMEFT fit

Recent example of a global fit in the SMEFT framework

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_j \frac{C_j^{(6)}}{\Lambda^2}\mathcal{O}_j^{(6)}$$

truncated to operators of dimension six



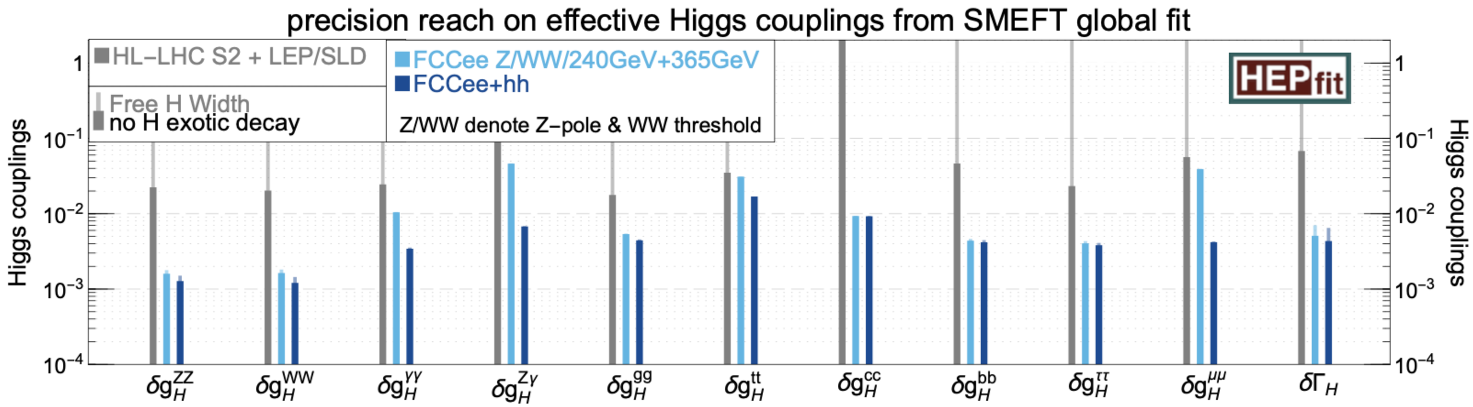
arXiv:2206.08326

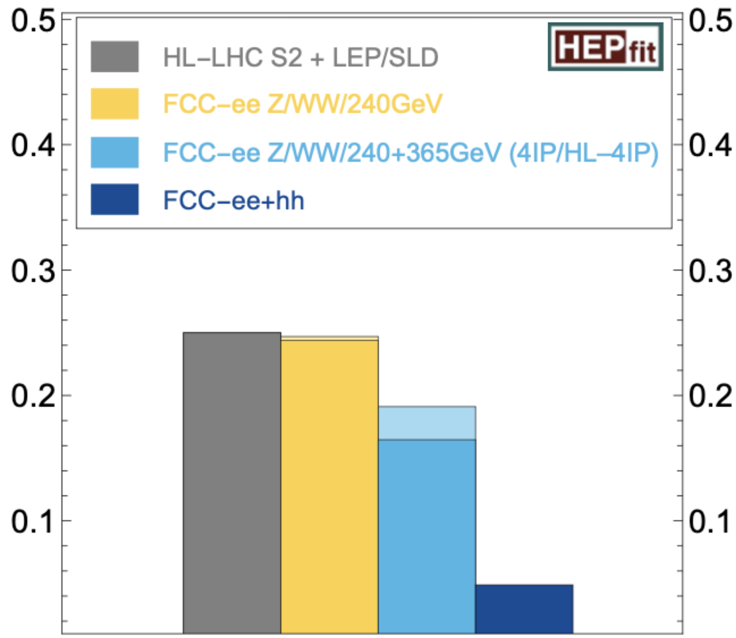
Complementarity and synergy between FCC-ee and FCC-hh

Recent example of a global fit in the SMEFT framework

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_j \frac{C_j^{(6)}}{\Lambda^2}\mathcal{O}_j^{(6)}$$

truncated to operators of dimension six





arXiv:2206.08326

Comparison of accelerators