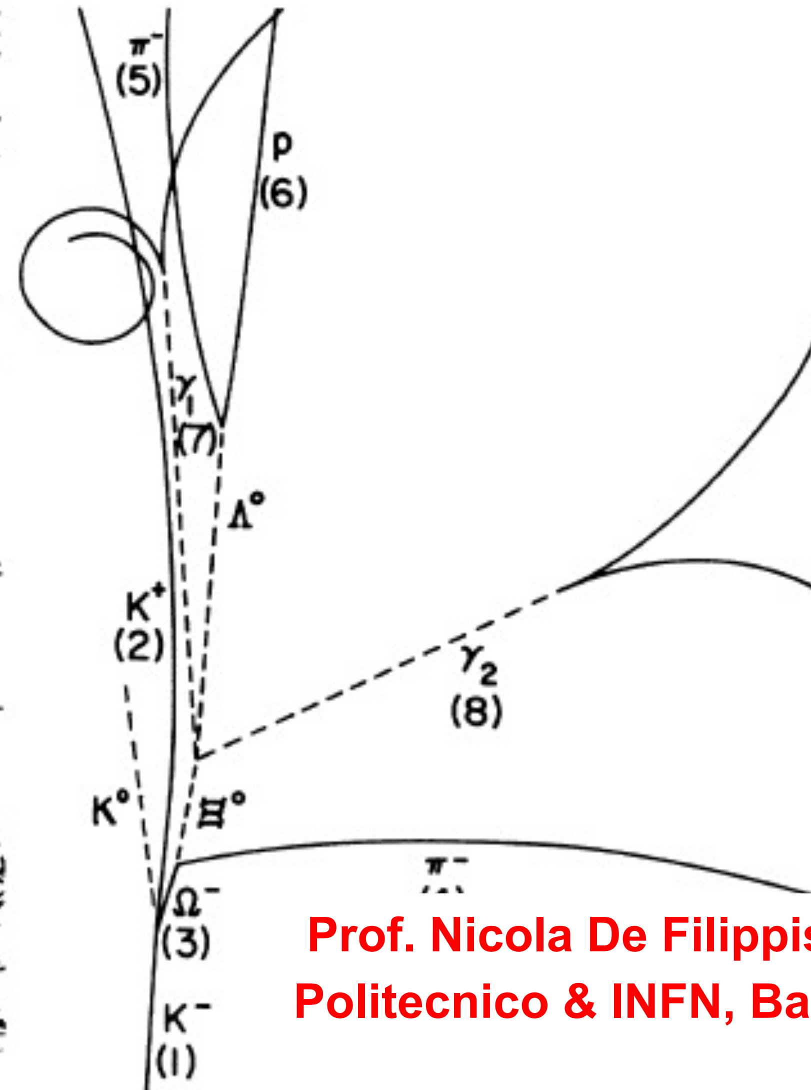
FROM THE DISCOVERY OF THE HIGGS BOSON TO THE MEASUREMENTS OF ITS PROPERTIES AND BEYOND



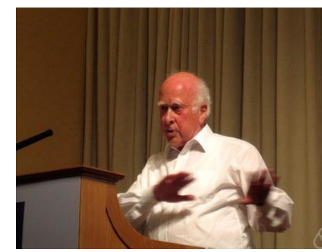
Prof. Nicola De Filippis
Politecnico & INFN, Bari

February 22, 2022, UCLouvain University

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



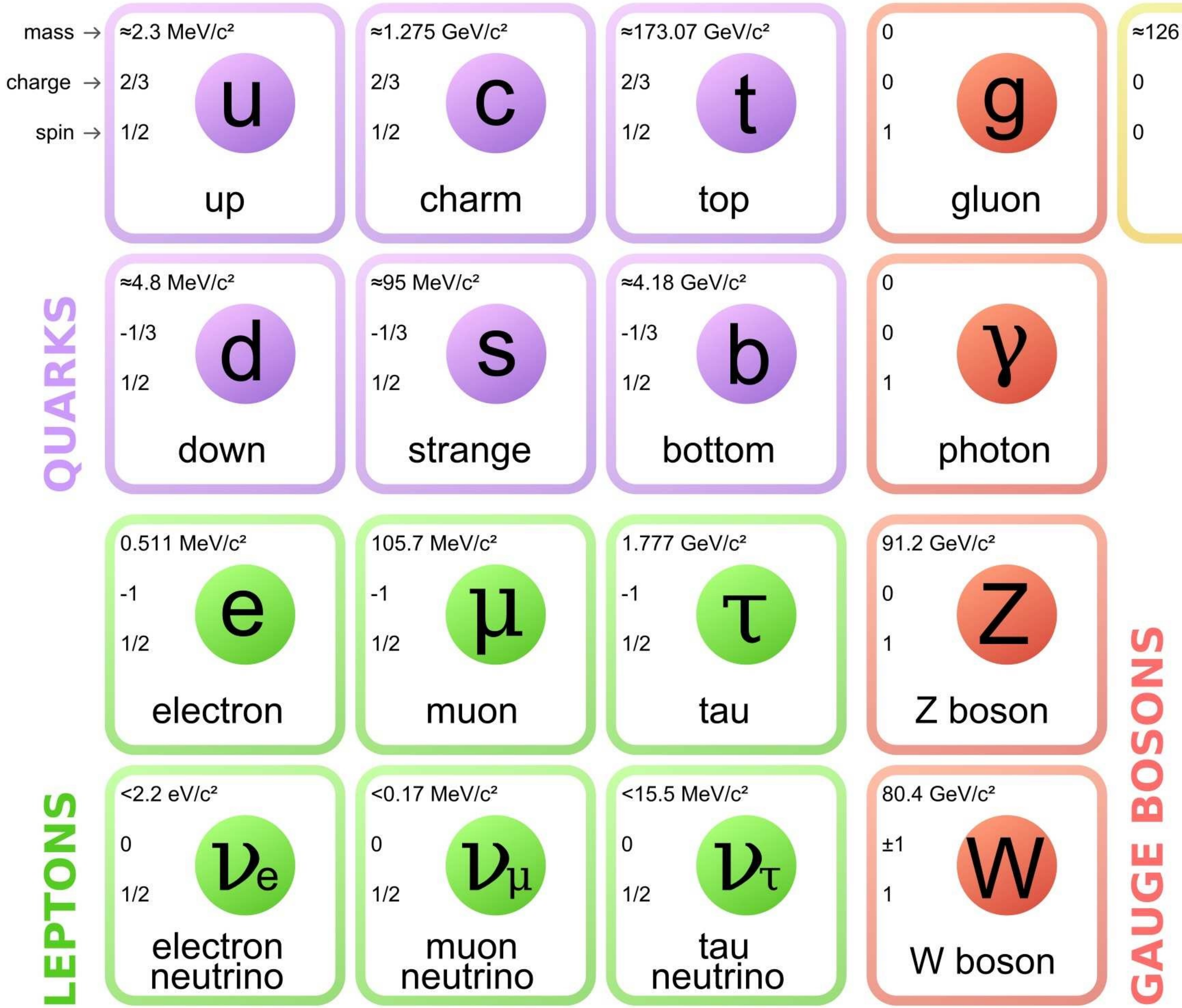
P. Higgs

Sheldon Lee Glashow

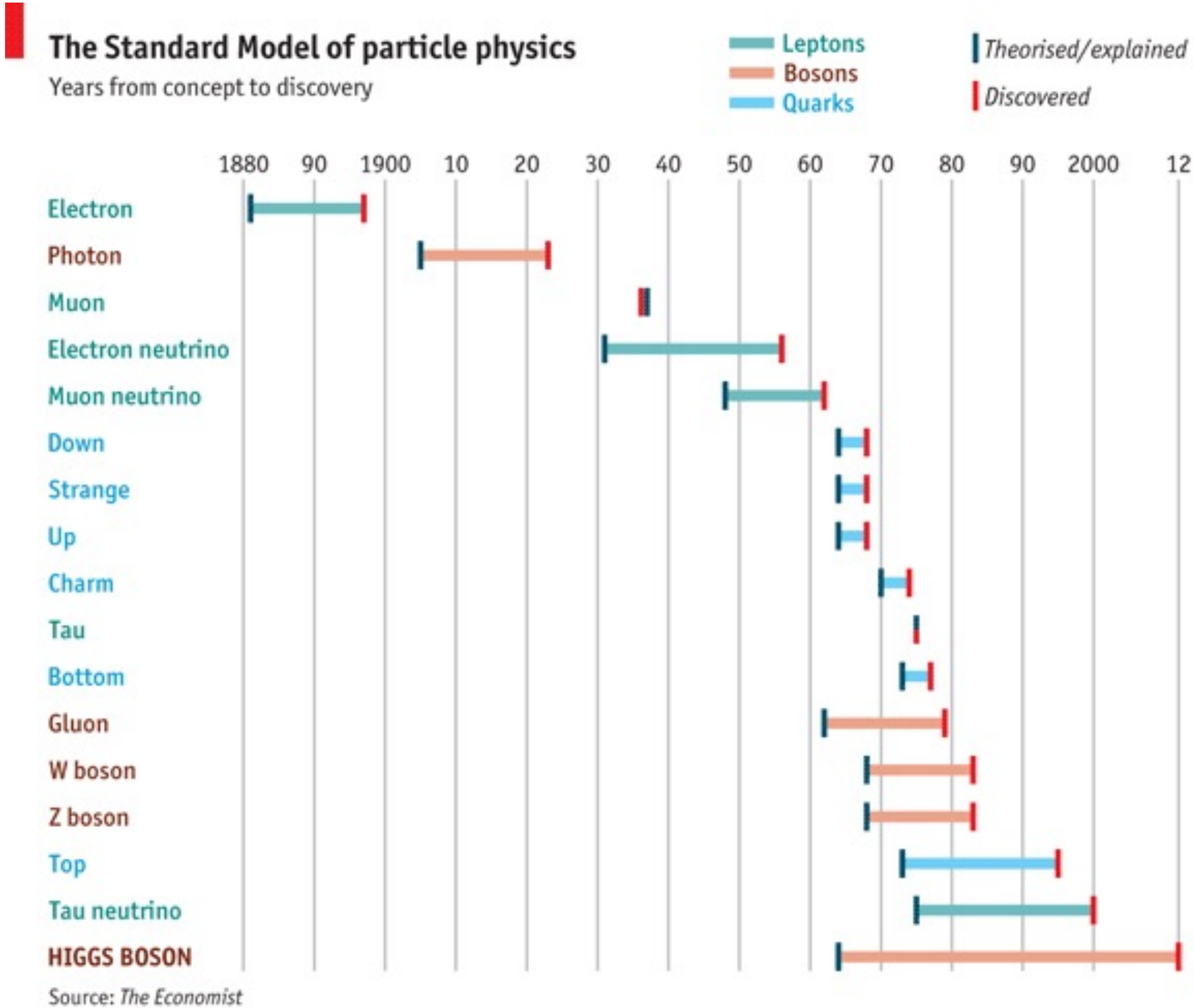
Abdus Salam

Steven Weinberg

Standard Model of elementary particles



Timeline of the discoveries



The beginning of the 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

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

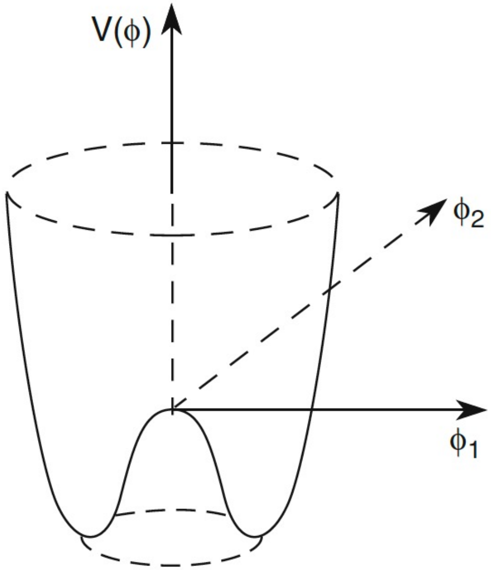
- **Problem:** give mass to gauge files W^+, W^- and Z
  - Explicit mass terms in the Lagrangian break the gauge invariance
- **Solution:** Higgs mechanism
  - **Higgs pointed out a massive scalar boson**

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

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 1964 paper**

The Higgs mechanism



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

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

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

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

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

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

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

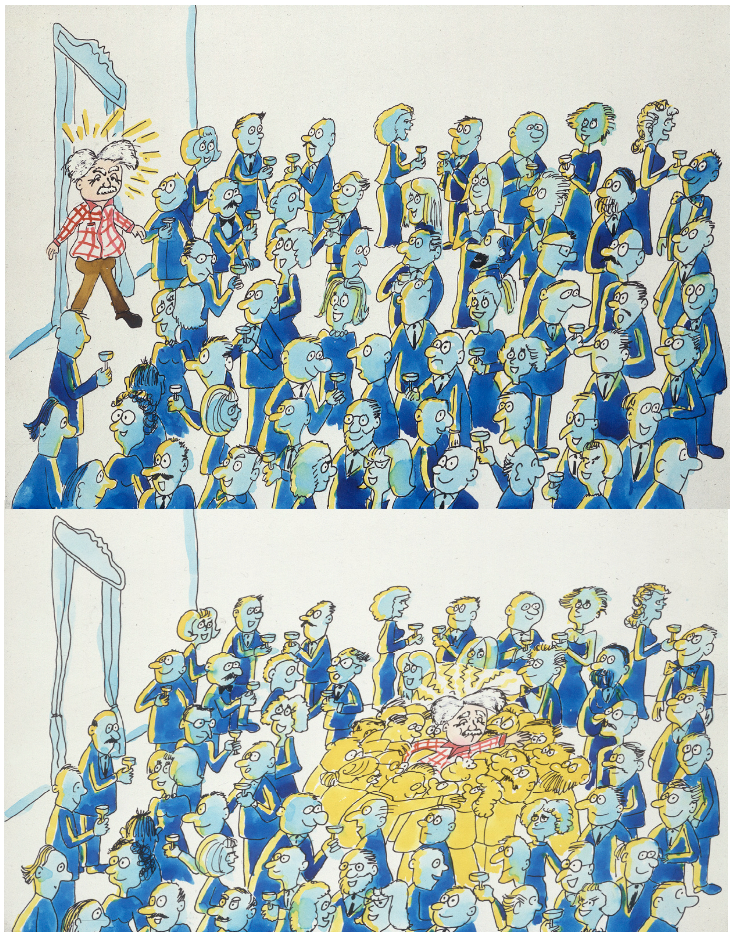
$$m_A^2 = 0 \qquad \text{for } \mathcal{A}_\mu.$$

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

Masses and couplings

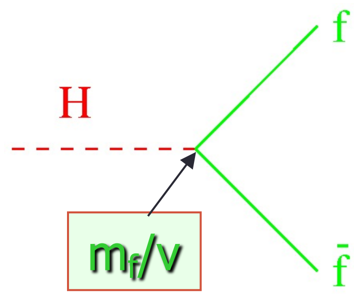
From Gauge Invariance : and from the Higgs Mechanism …

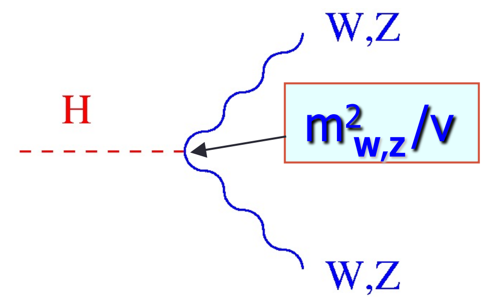
$$m_W = m_Z \cos\theta_w, \qquad \sin^2\theta_w = 1 - \frac{m_W^2}{m_Z^2}.$$



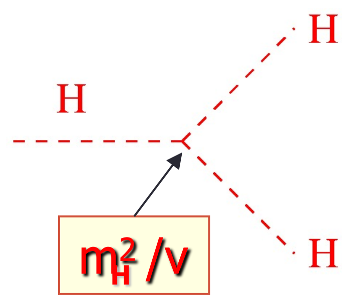
$m_W = gv/2$; (→ v ~ 250 GeV).

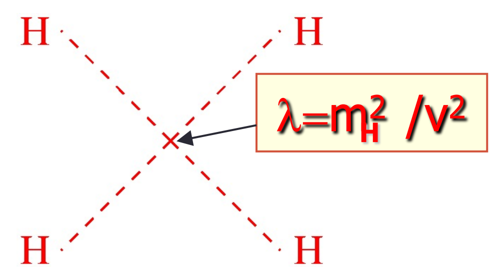
vacuum expectation value





All couplings predicted



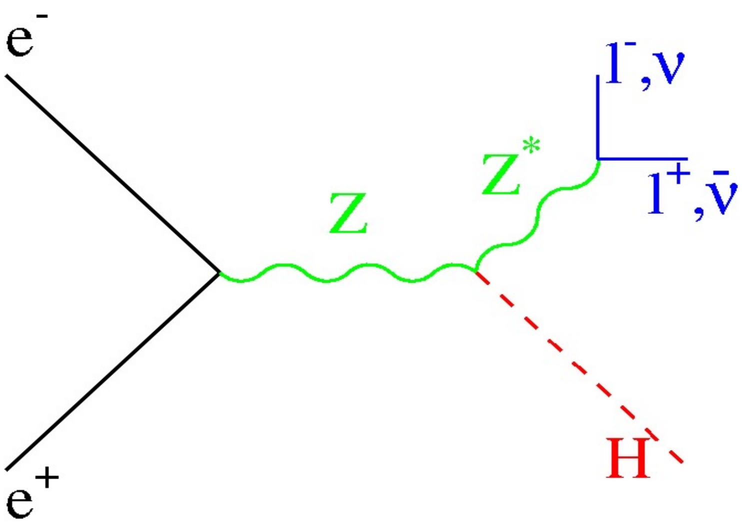


SM Higgs production at LEP

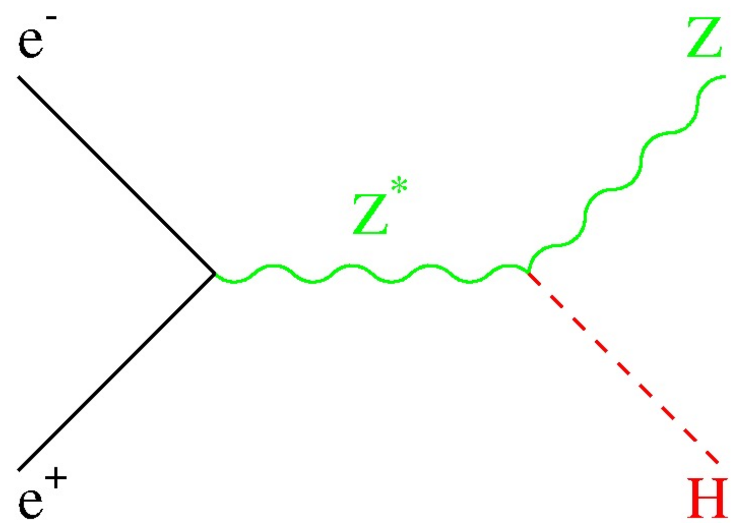
Dominant at LEP: The Higgs-strahlung process

(The production cross section depends only on m_H)

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



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

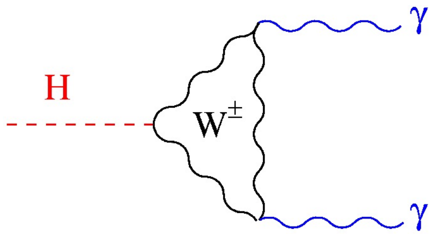


(Large coupling to the Z $\Rightarrow$ Only sizeable cross section)

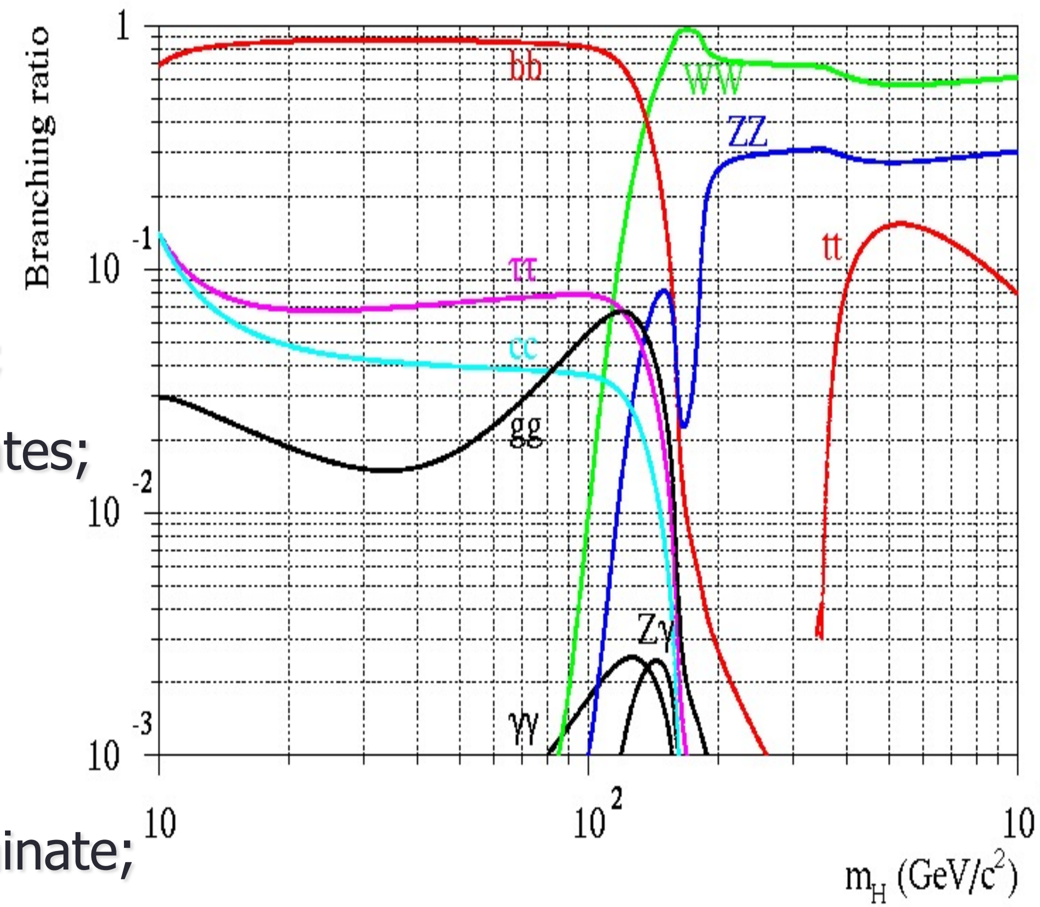
SM Higgs decay at LEP

The decay branching ratios depend only on m_H:

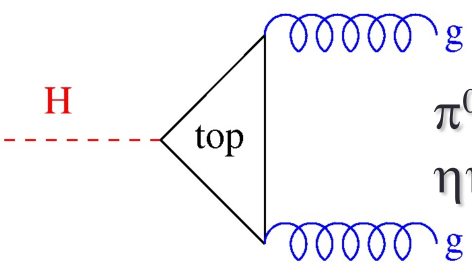
- $m_H < 2m_e$: $H \rightarrow \gamma\gamma$ + large lifetime;



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



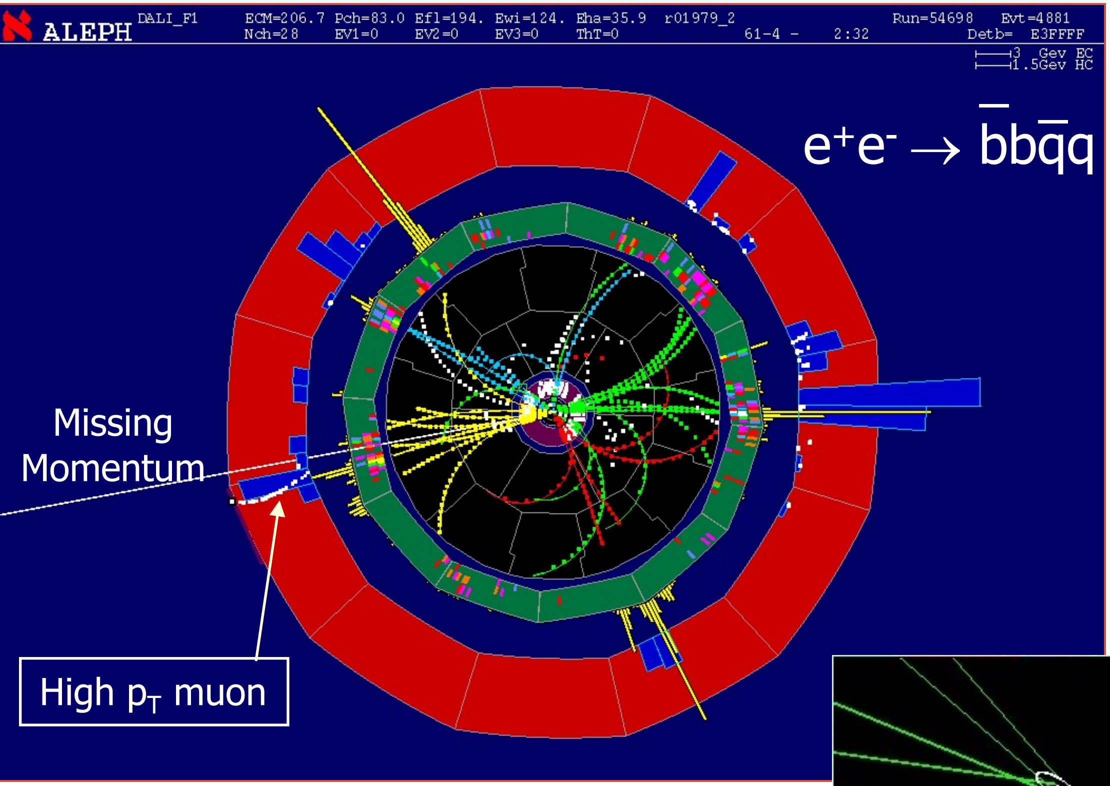
- $m_H < 2m_\mu$: $H \rightarrow e^+e^-$ dominates;
- $m_H < 2m_\pi$: $H \rightarrow \mu^+\mu^-$ dominates;
- $m_H < 3 - 4$ GeV: $H \rightarrow gg$ dominates;



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

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

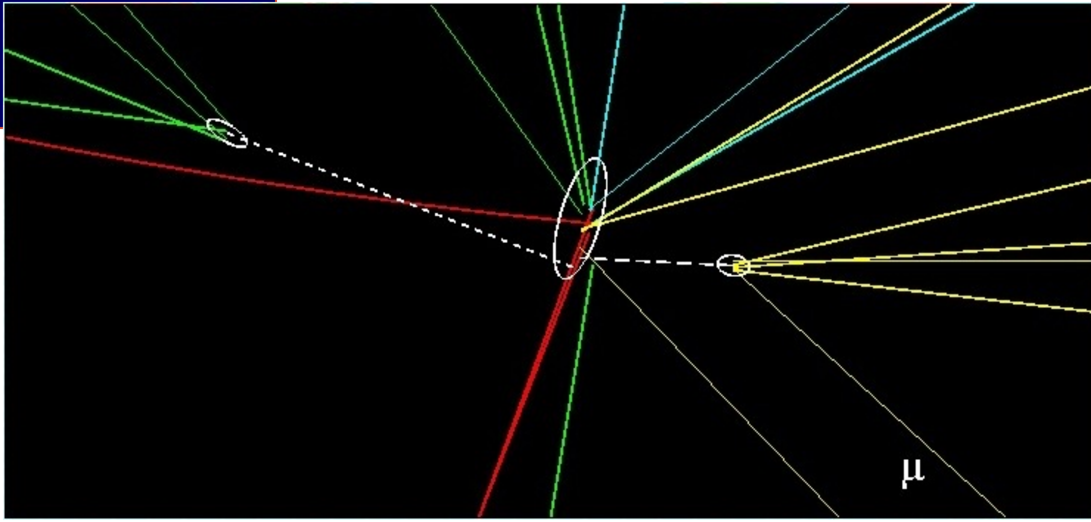
First pb^{-1}'s above 206 GeV, first thrills at 115 GeV/c^2



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

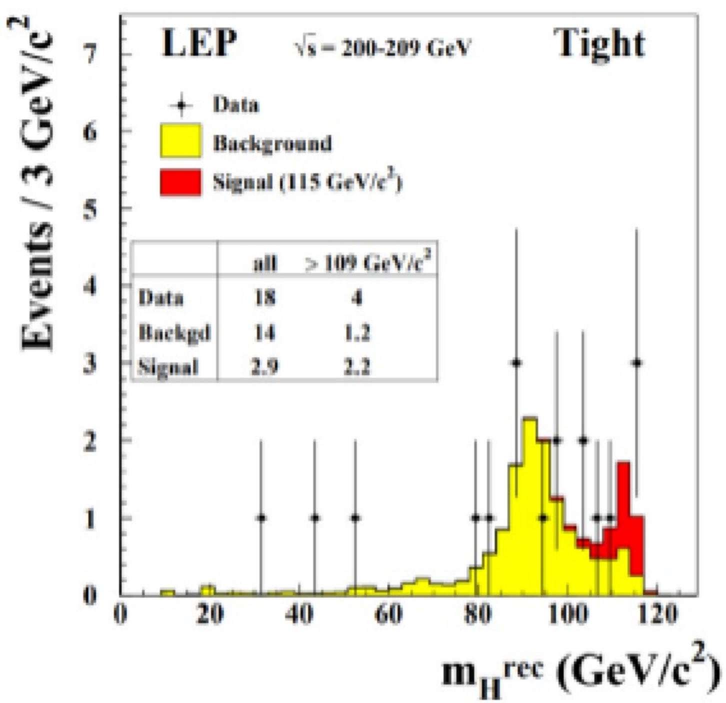
ELSEVIER

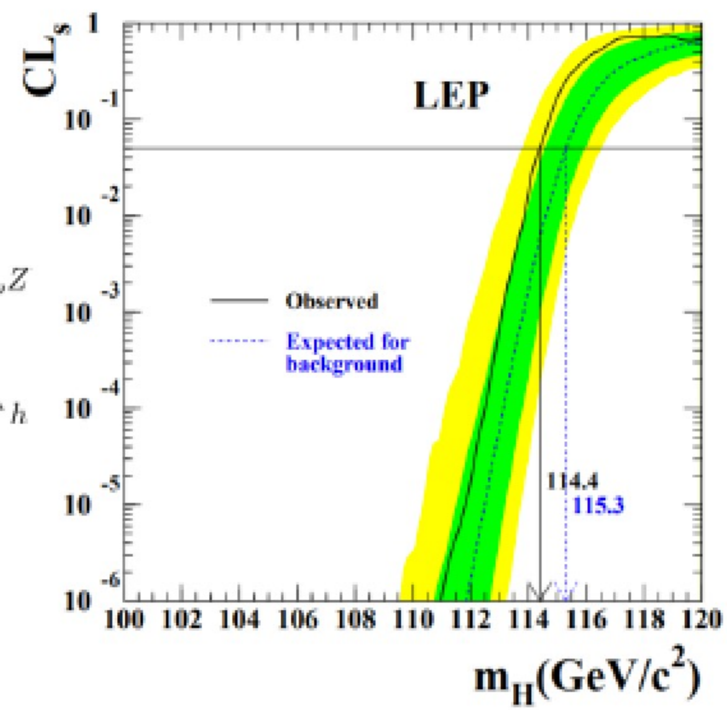
Search for the Standard Model Higgs boson at LEP

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

PHYSICS LETTERS B

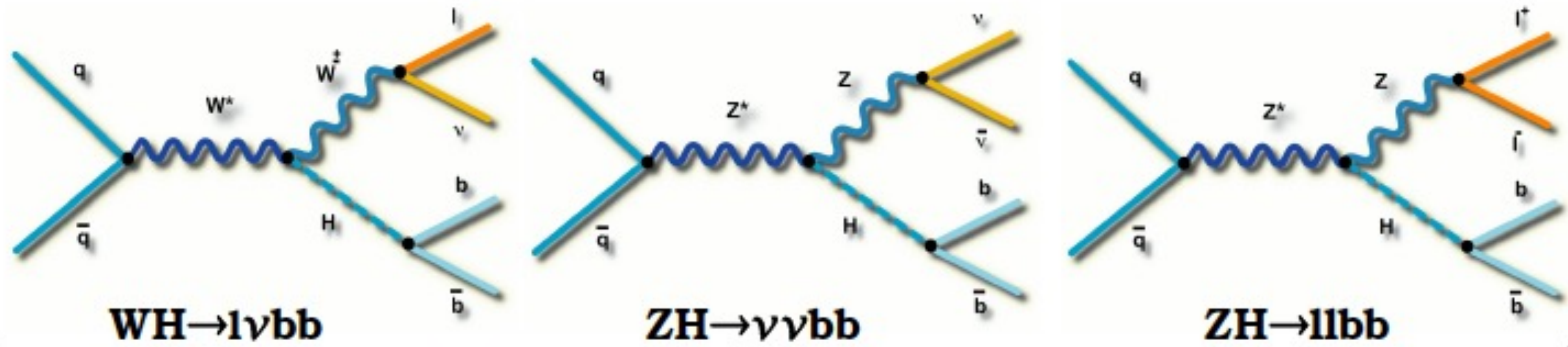
m_H > 114.4 GeV @ 95%CL





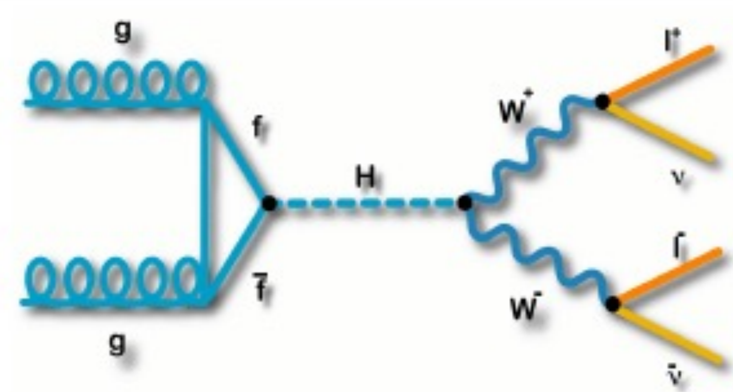
SM Higgs production at Tevatron

Associated Production: Low mass only, 3 dominant final states



Gluon Fusion Production:

Maximum sensitivity at high mass, also useful at low mass

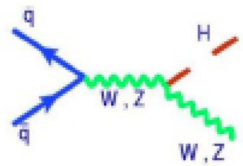


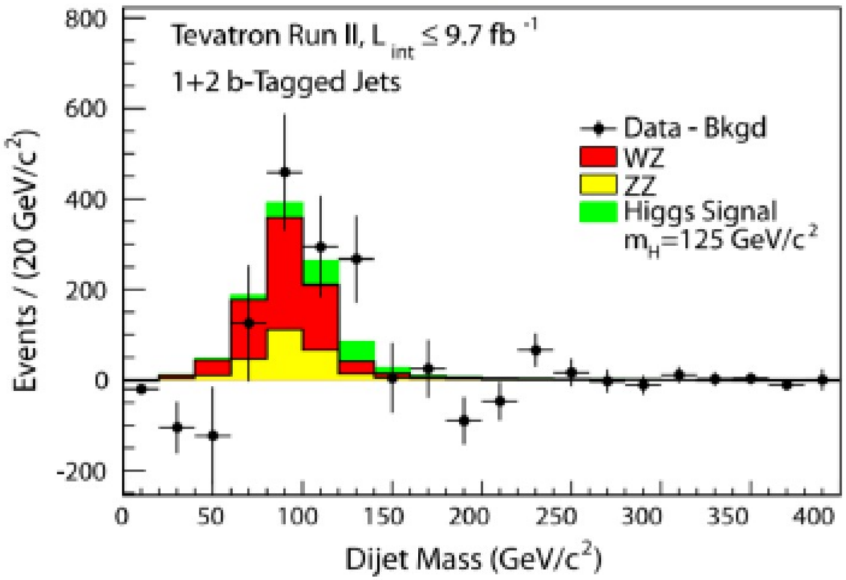
Higgs results at Tevatron

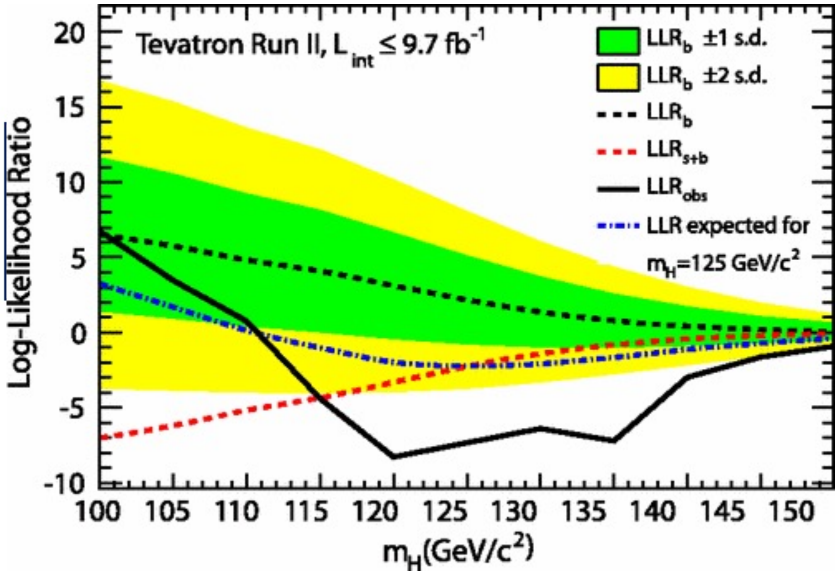
PRL **109**, 071804 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

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)



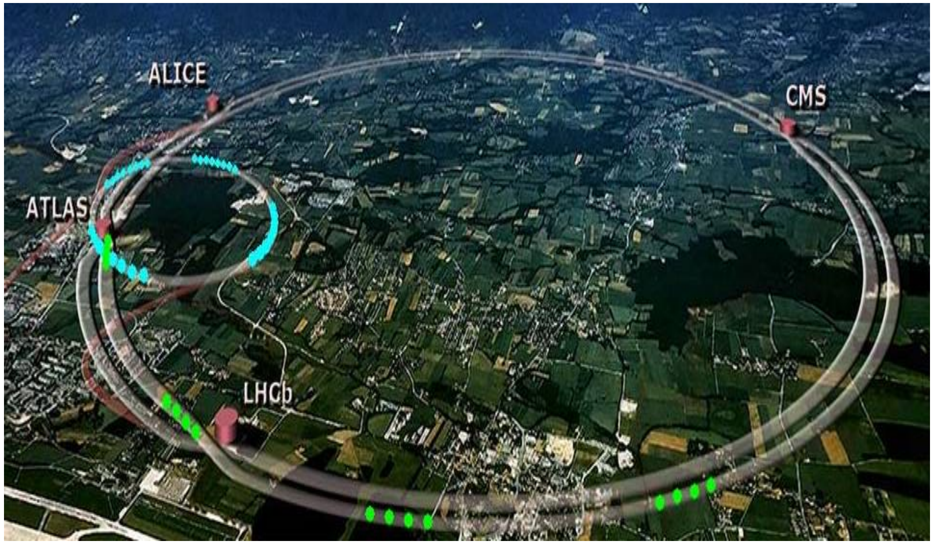


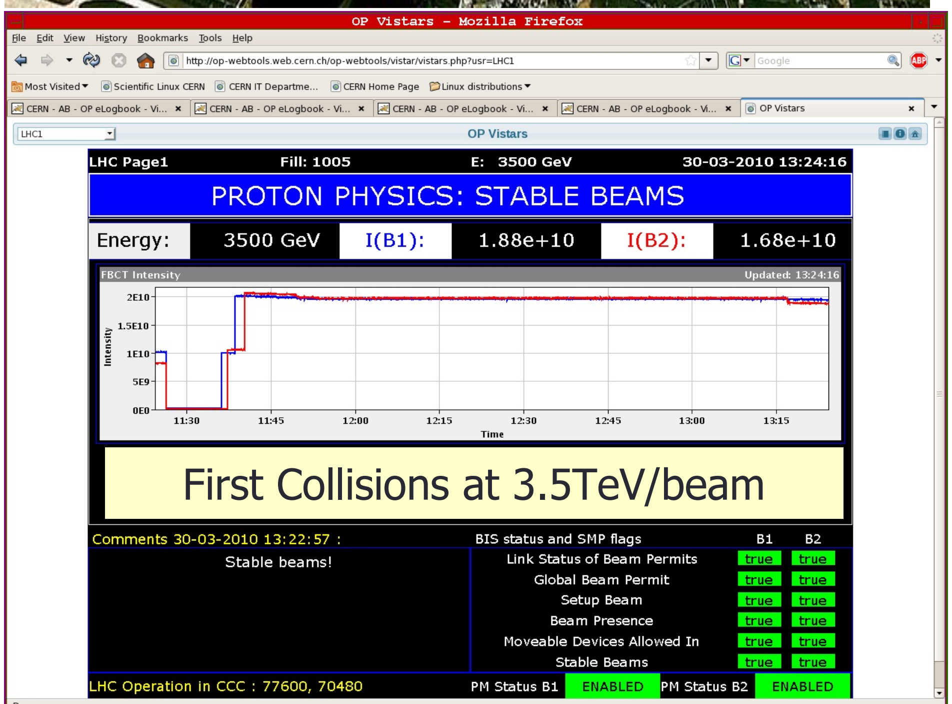


<u>Significance</u>

2.8σ observed @ 125 GeV

The LHC machine





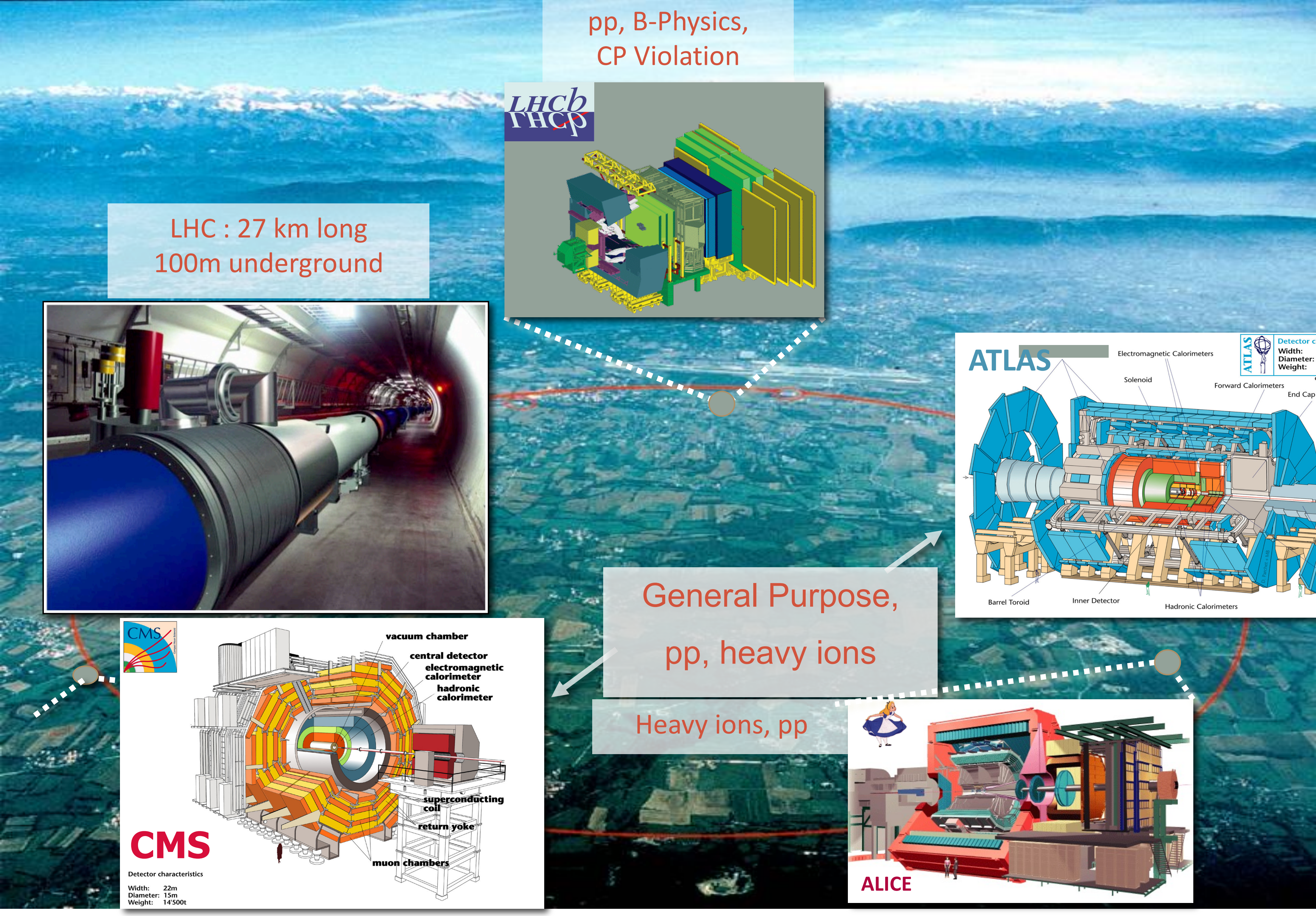
Circumference (km)	26.7
Number of superconducting Dipoles	1232
Length of Dipole (m)	14.3
Dipole Field Strength (Tesla)	8.4
Operating Temperature (K)	1.9
Current in dipole sc coils (A)	13000
Beam Intensity (A)	0.5
Beam Stored Energy (MJoules)	362
Number of particles per bunch	1.15×10^{11}
Number of bunches 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

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

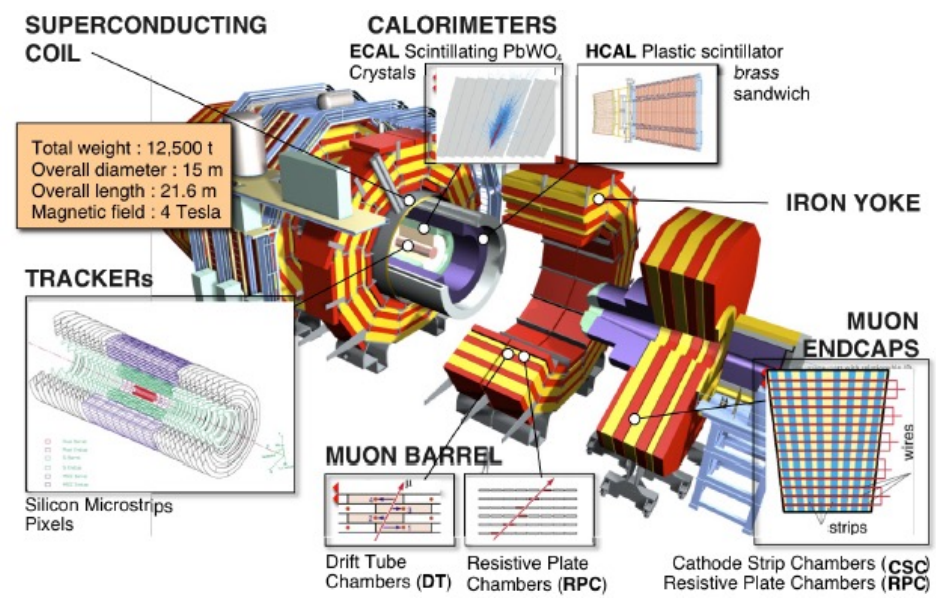
N_b = number of proton per bunch
n_b = number of bunches

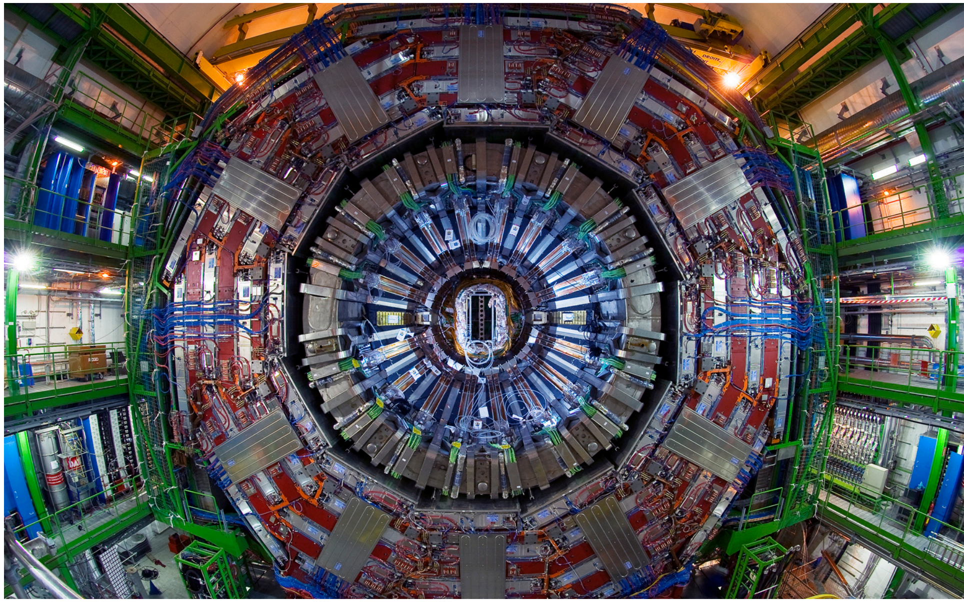
f_{rev} = rotation frequency (~ 11Hz)
F = crossing angle factor

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
Heavy ions, pp
CMS
vacuum chamber
central detector
electromagnetic calorimeter
hadronic calorimeter
superconducting coil
return yoke
muon chambers
CMS
Detector characteristics
Width: 22m
Diameter: 15m
Weight: 14'500t
ALICE

CMS in a nutshell





|η|<2.5 : Tracker

$\sigma / p_T \approx 10^{-4} p_T \oplus 0.005$

|η|<4.9 : EM Calorimeter

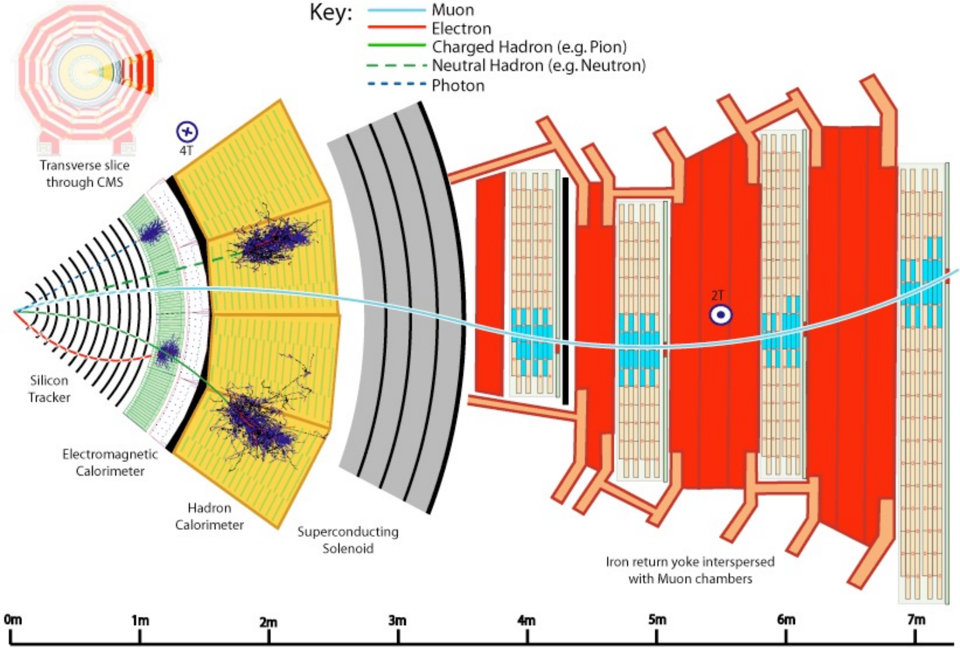
$\sigma / E \approx 0.03/\sqrt{E} + 0.003$

|η|<4.9 : HAD Calorimeter

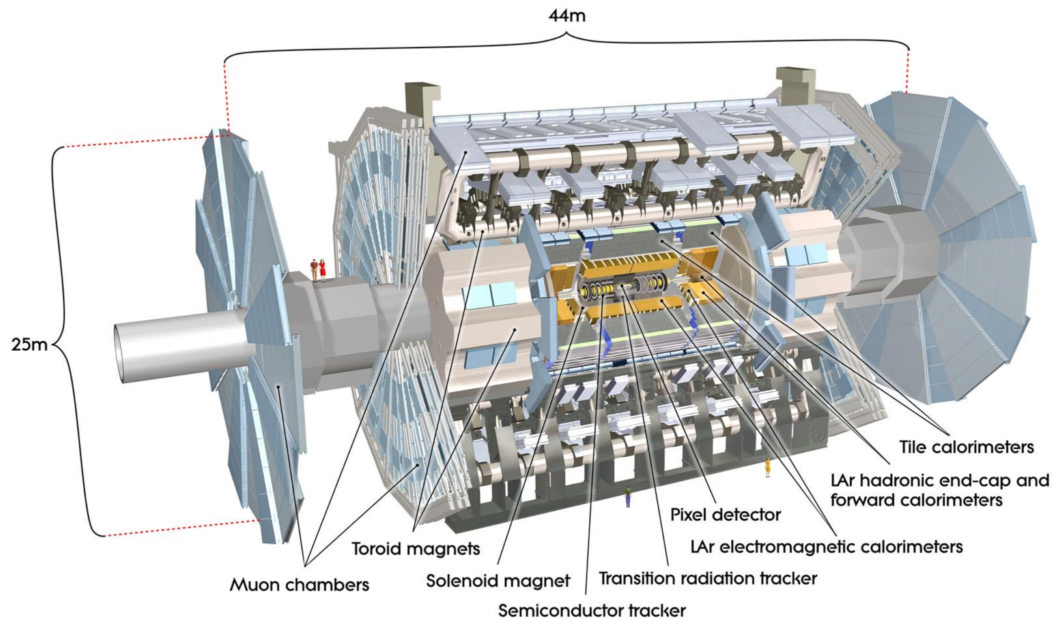
$\sigma / E \approx 1.0/\sqrt{E} + 0.05$

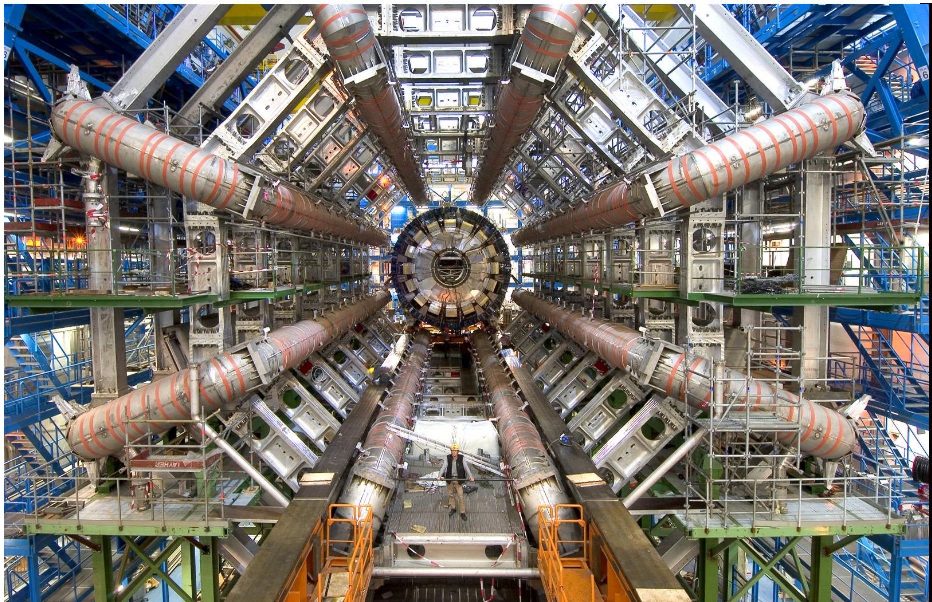
|η|<2.4 : Muon spectrometer

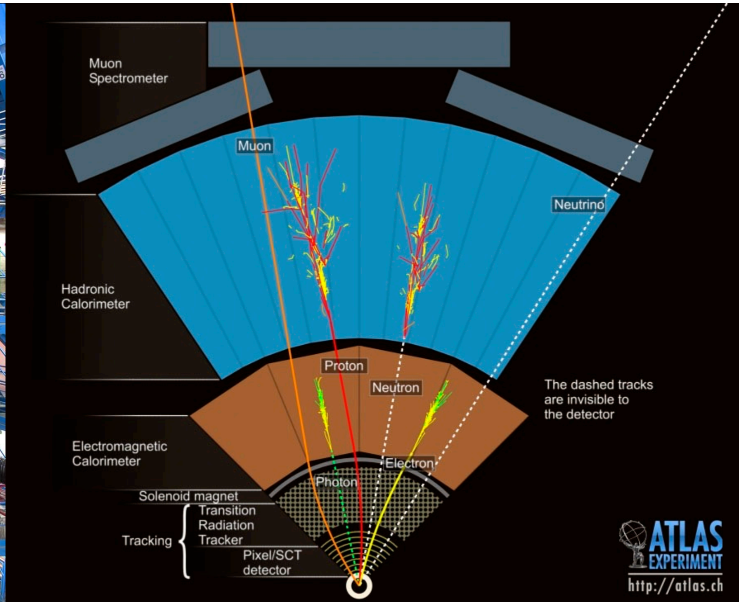
$\sigma / p_T \approx 0.10$ (1TeV muons)



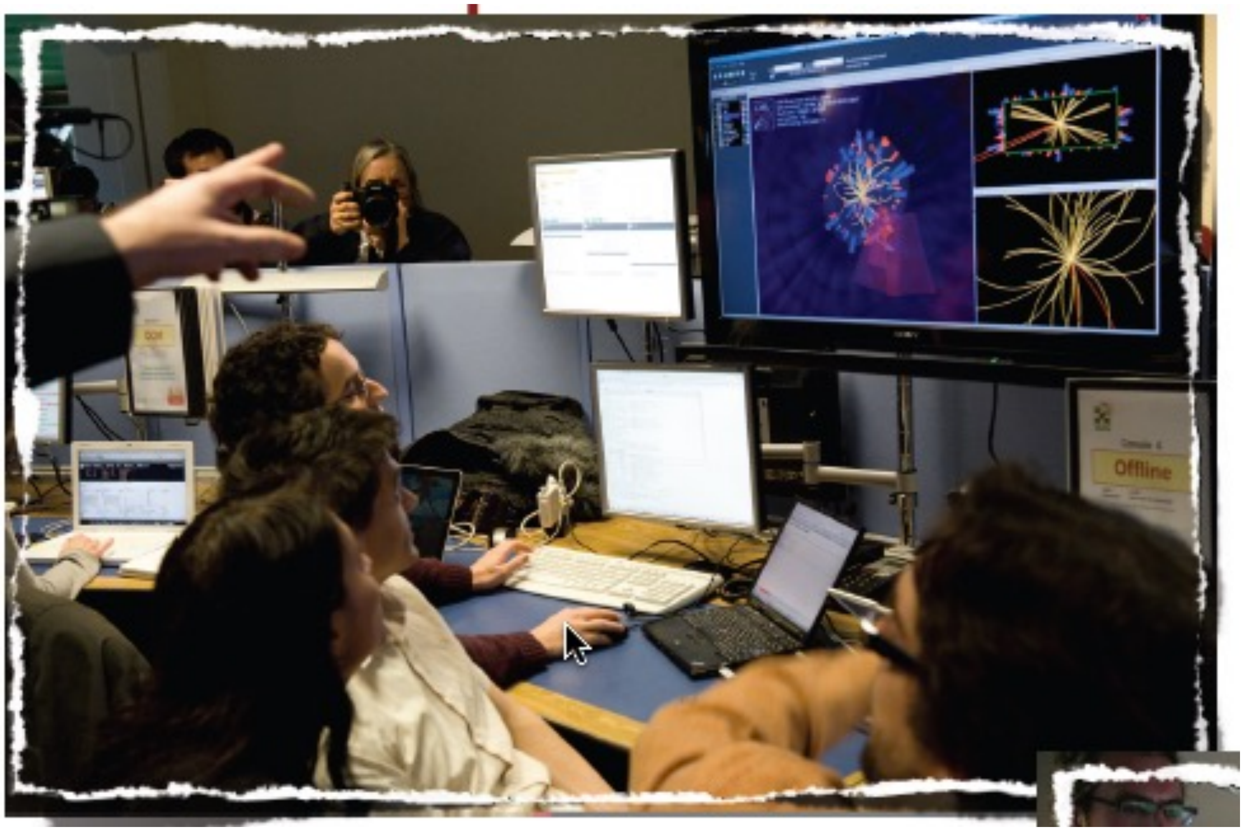
ATLAS in a nutshell



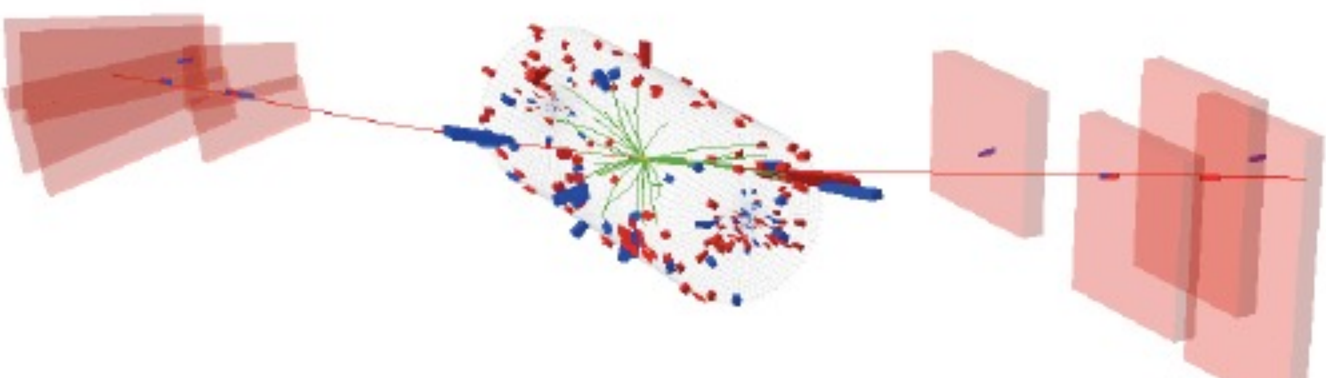




First collisions at 7 TeV

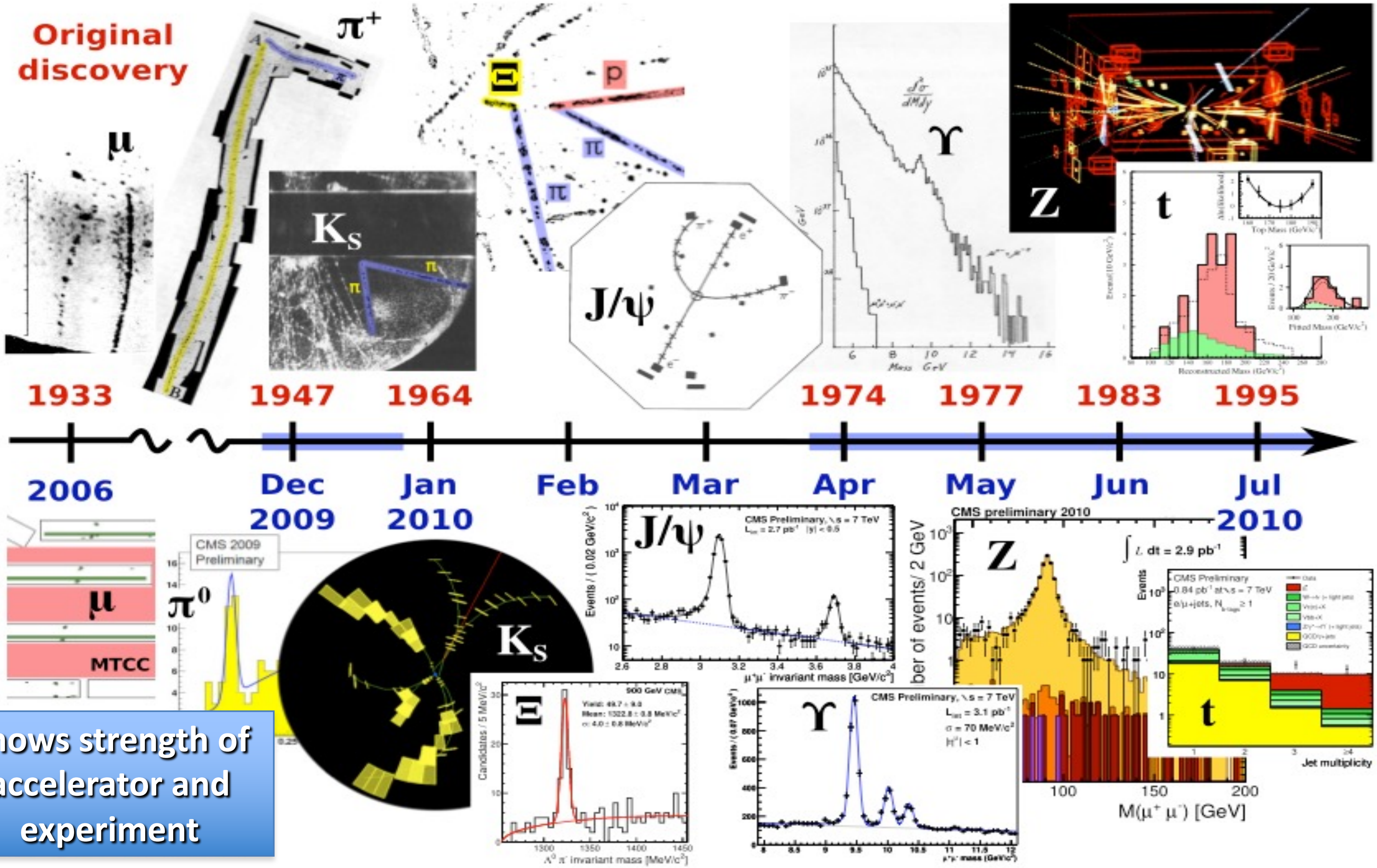


March 2010:
Collisions at 7 TeV.
LHC delivered:
44.22 pb-1
CMS recorded:
40.56 pb-



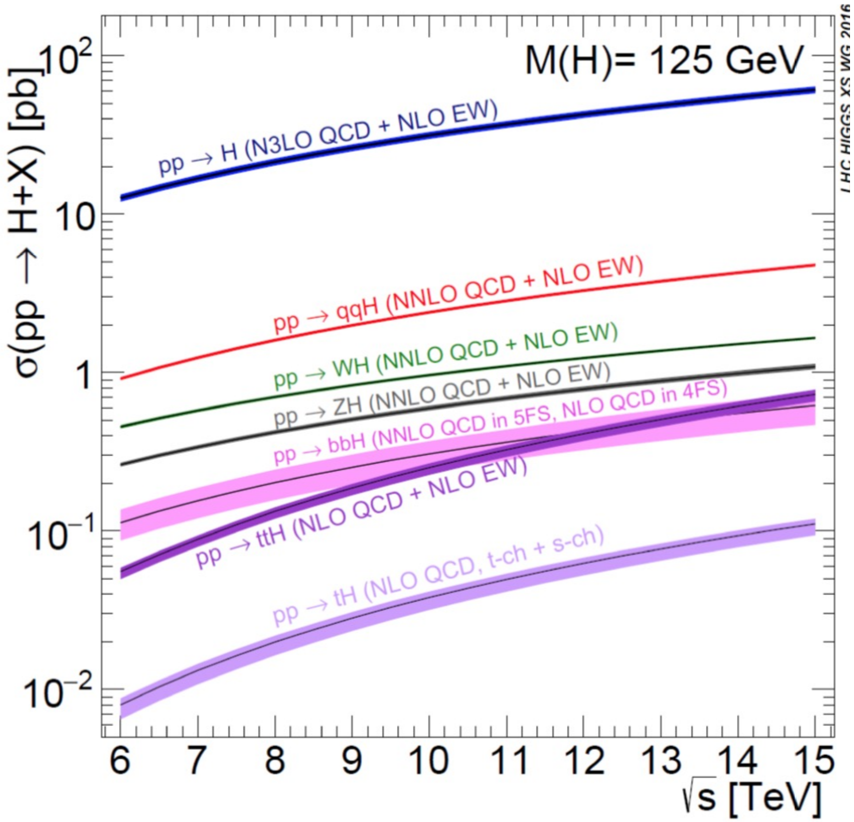
The first Z→μμ Candidate

2010: “Rediscover” the SM



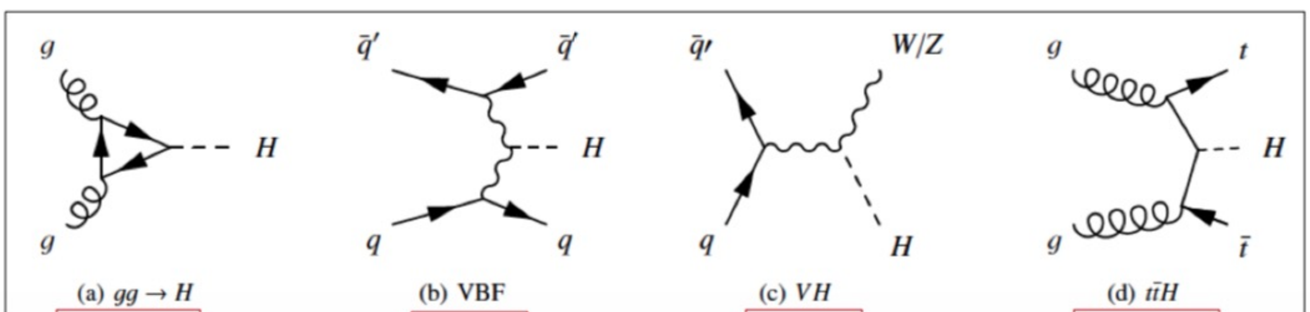
Shows strength of accelerator and experiment

SM Higgs production at the LHC



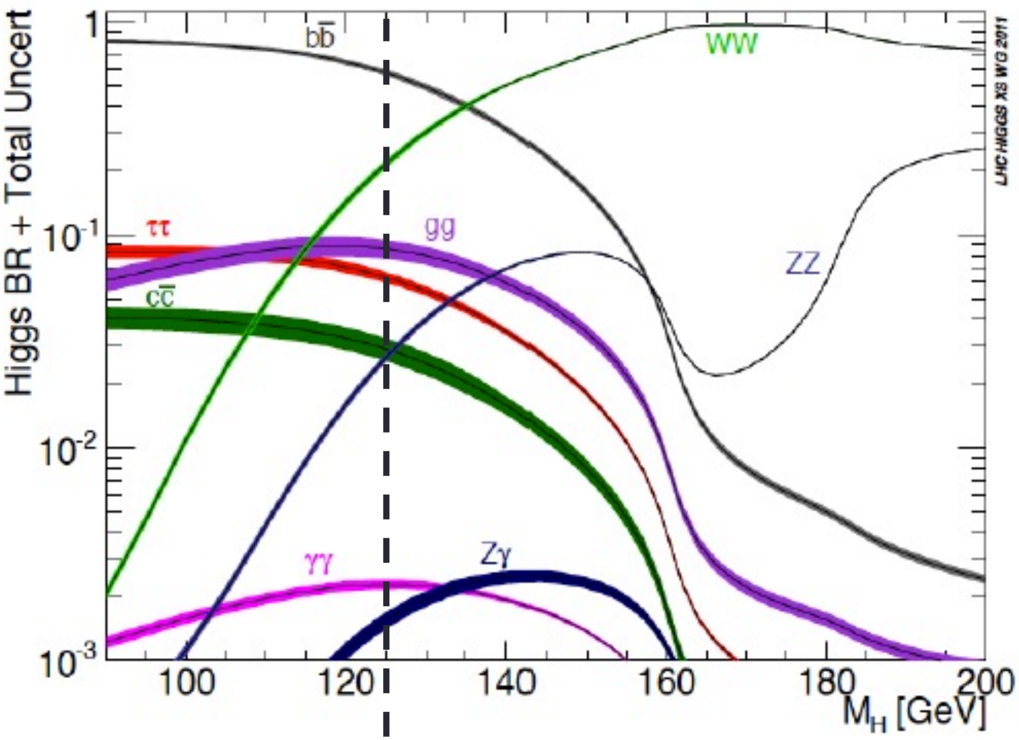
- ggF: dominant, larger initial state radiation from gluons
- VBF: two forward jets with high mass and large rapidity gap
- VH: vector boson (lν, ll', qq')
- ttH: many b-jets, leptons, E_T^{miss}

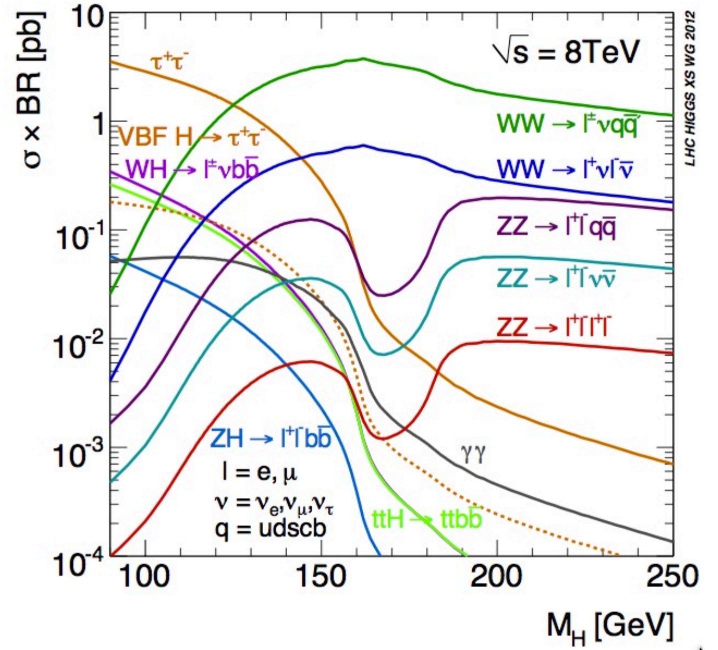
Total cross-section = 56 pb at 13 TeV



87%	7%	5%	<1%

Higgs decay channels





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%

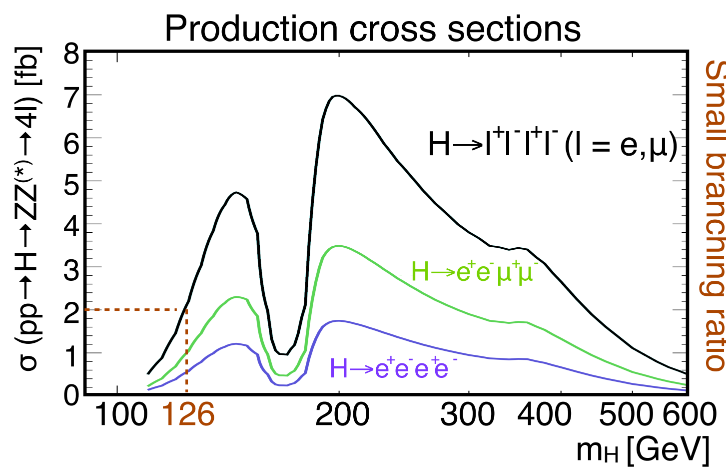
At m_H =125 GeV:

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

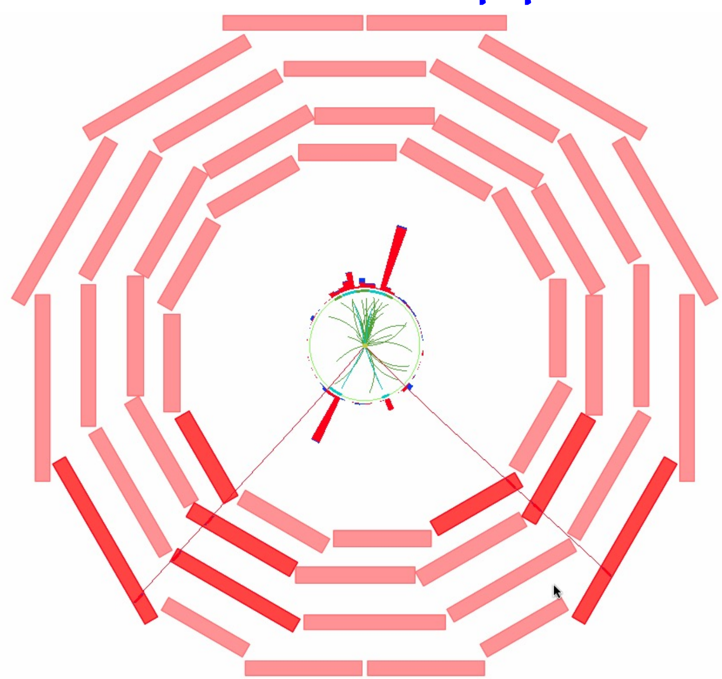
Channel	m_H resolution
$H \to \gamma\gamma$	1–2%
$H \to \tau\tau \to e\tau_h/\mu\tau_h/e\mu + X$	20%
$H \to \tau\tau \to \mu\mu + X$	20%
$WH \to e\mu\tau_h/\mu\mu\tau_h + \nu's$	20%
$(W/Z)H \to (e\nu/\mu\nu/ee/\mu\mu/\nu$	10%
$H \to WW^* \to 2\ell 2\nu$	20%
$WH \to W(WW^*) \to 3\ell 3\nu$	20%
$H \to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

H→ZZ→4l in a nutshell

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



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



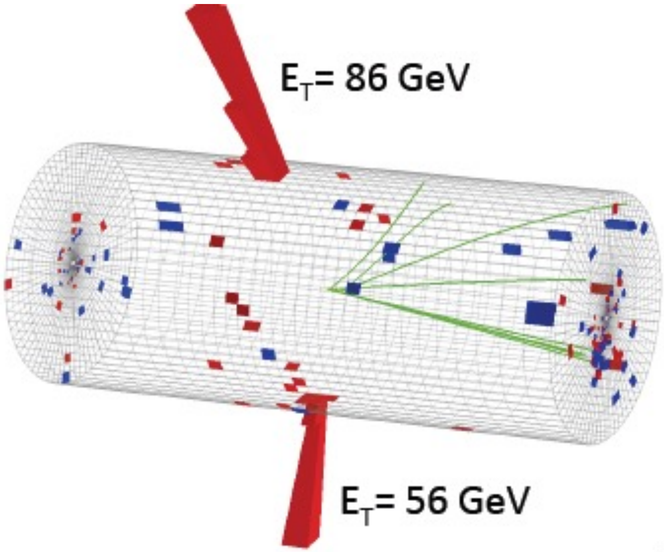
- Sensitivity: 115 < m_H < 600 GeV

- 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→$\gamma\gamma$ 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



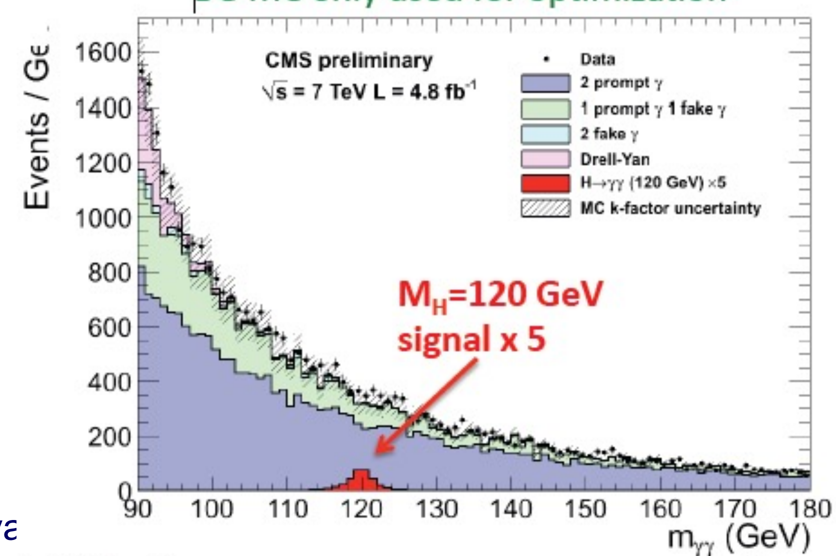
Background:

- irreducible : gg→$\gamma\gamma$, qqbar, q**g**→**g**γ from QCD
- reducible:

  pp → γ+jets (1 prompt γ + 1 fake γ)

  pp → jets (2 fake γ), fake γ from π^0→$\gamma\gamma$

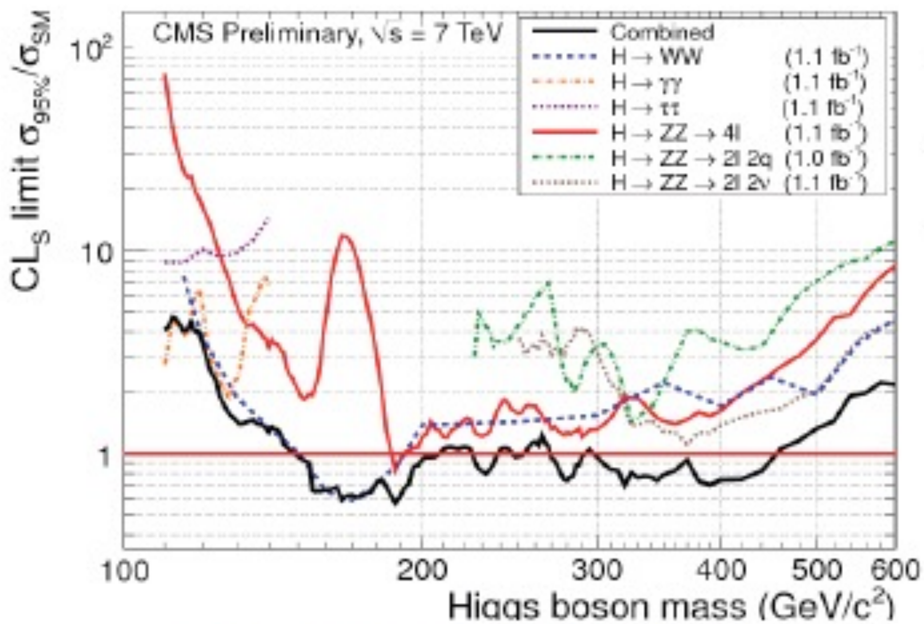
BG MC only used for optimization



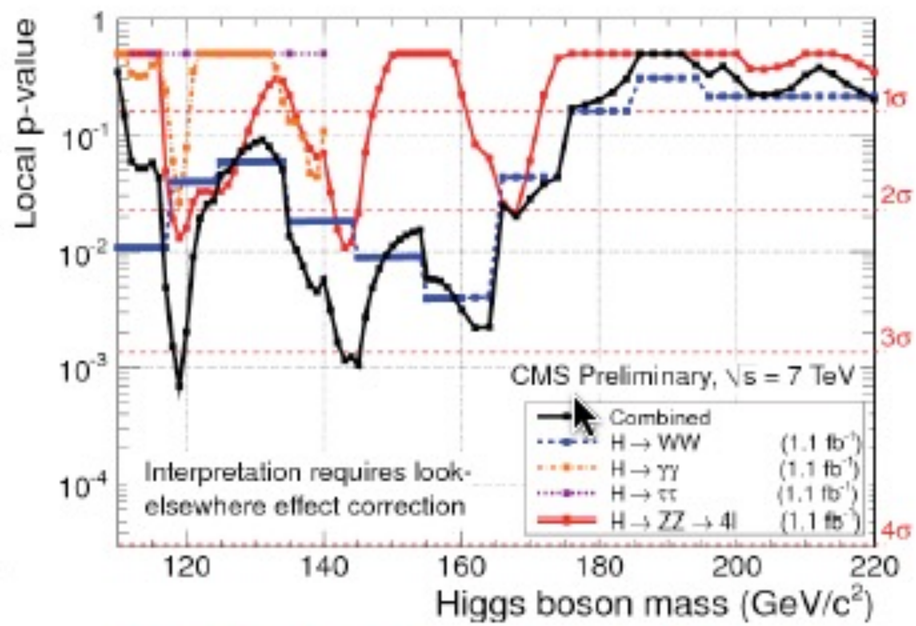
Analysis strategy based on:

- 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



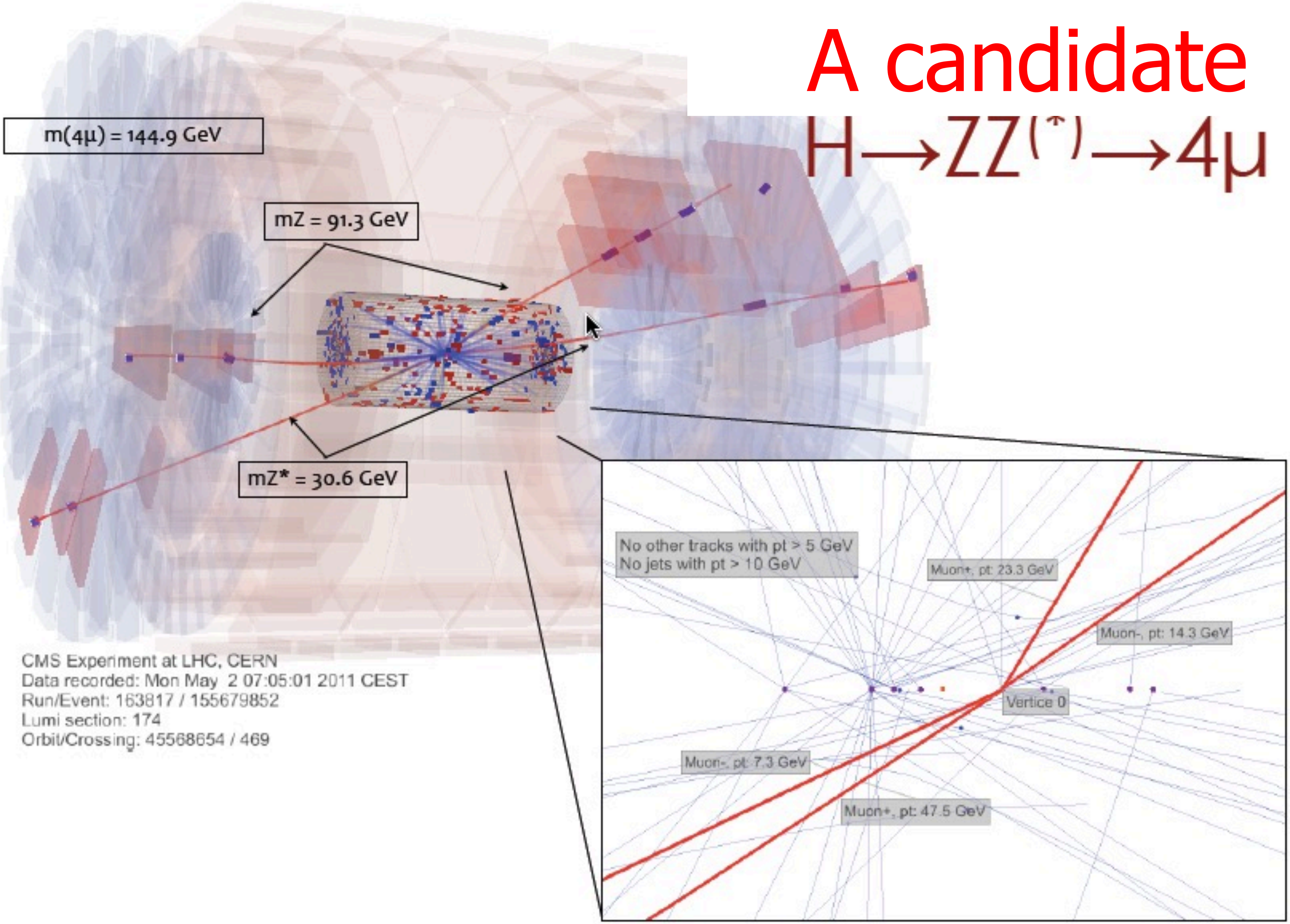
Observed combined upper limit on $\mu=\sigma/\sigma_{SM}$



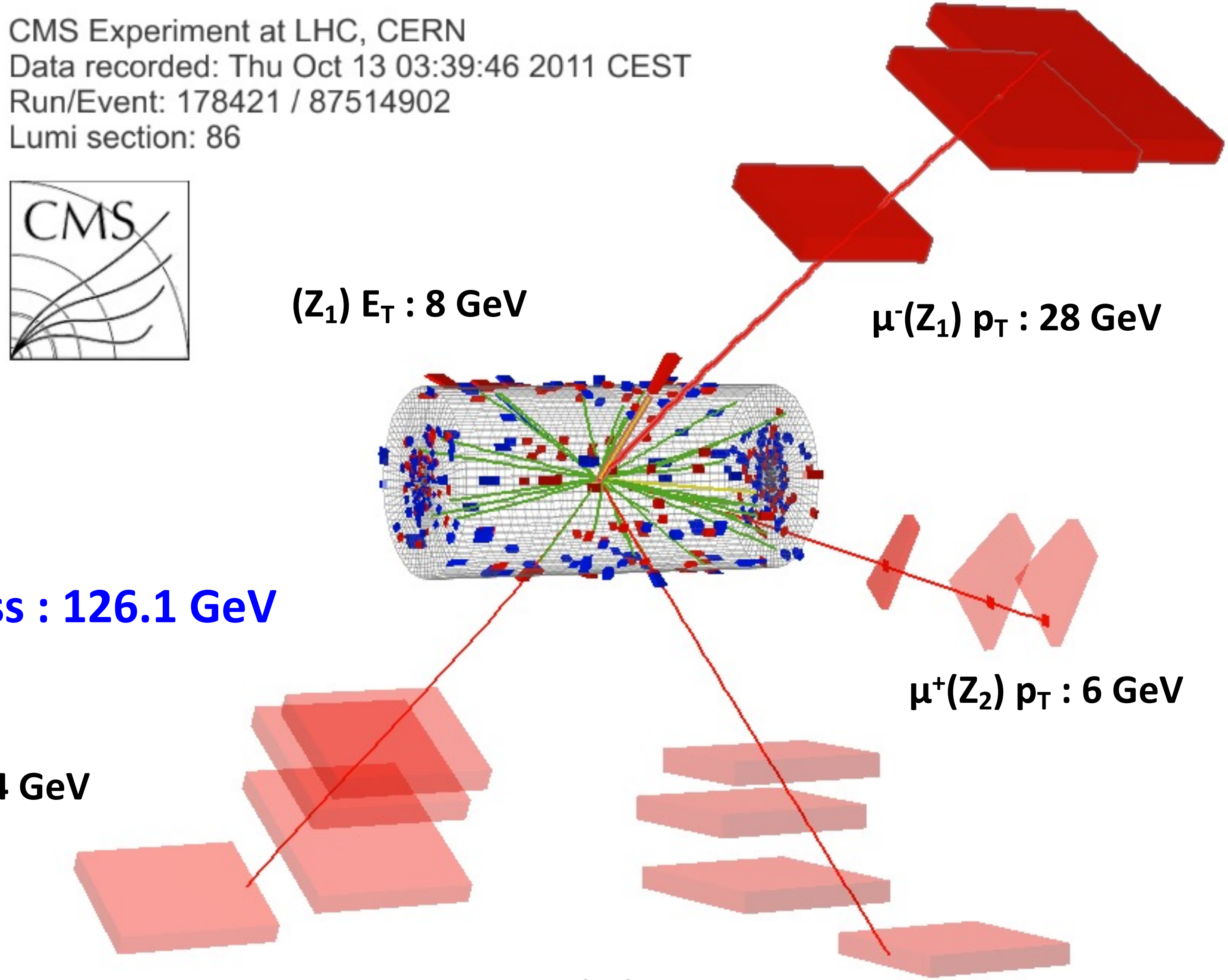
Overall combined local p-values

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

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



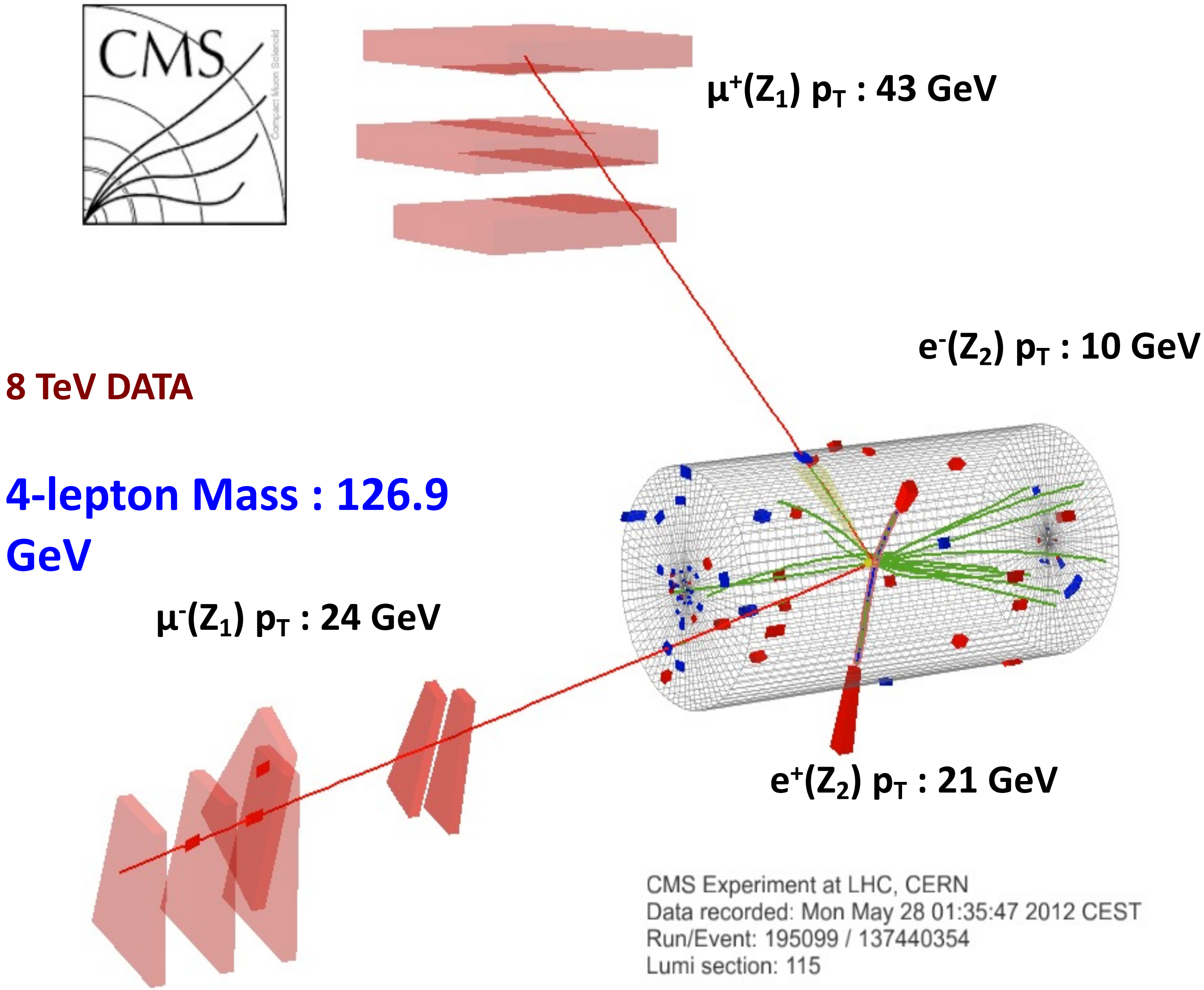
Candidates

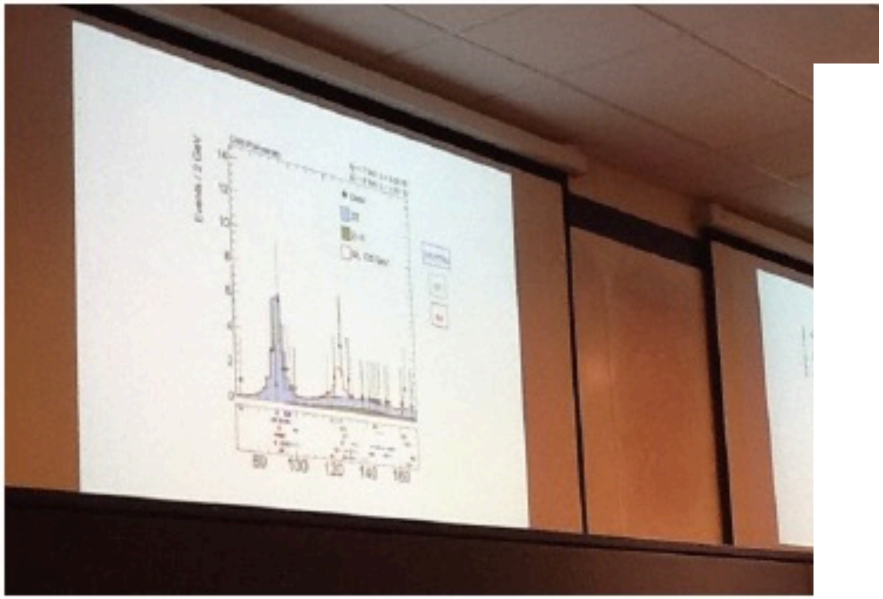


7 TeV DATA

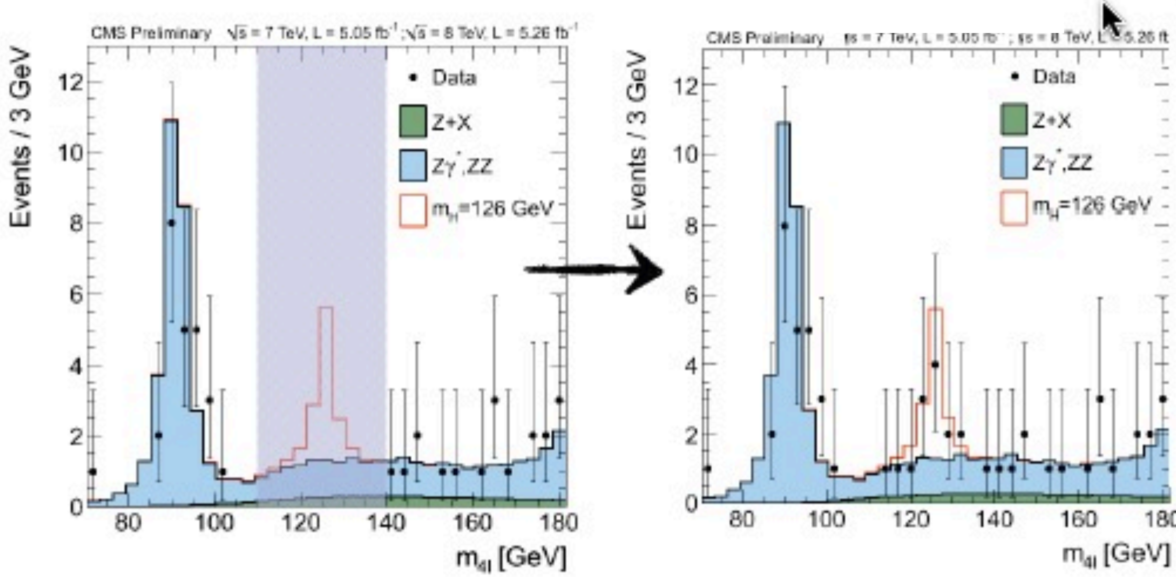
$4\mu+\gamma$ Mass : 126.1 GeV

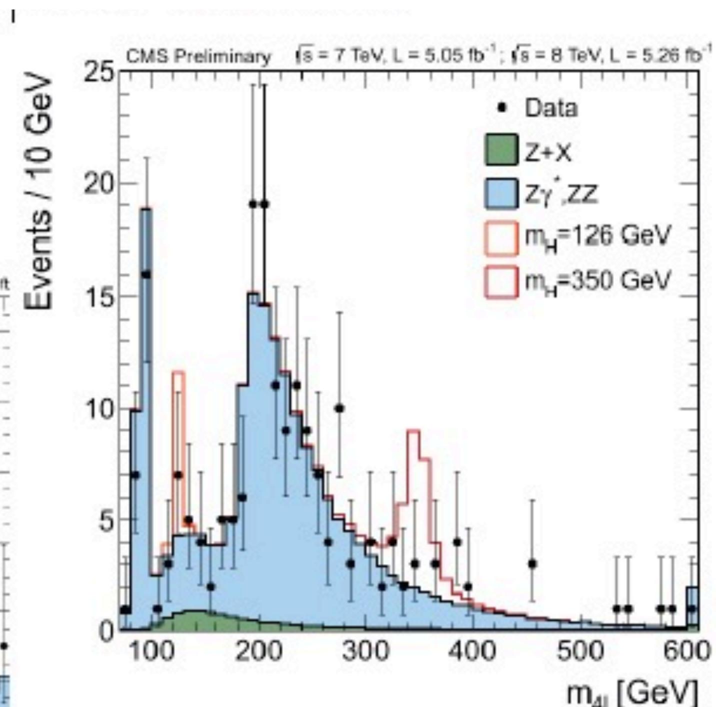
Candidates


CMS
μ+(Z1) pT : 43 GeV
e-(Z2) pT : 10 GeV
8 TeV DATA
4-lepton Mass : 126.9 GeV
μ-(Z1) pT : 24 GeV
e+(Z2) pT : 21 GeV
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115

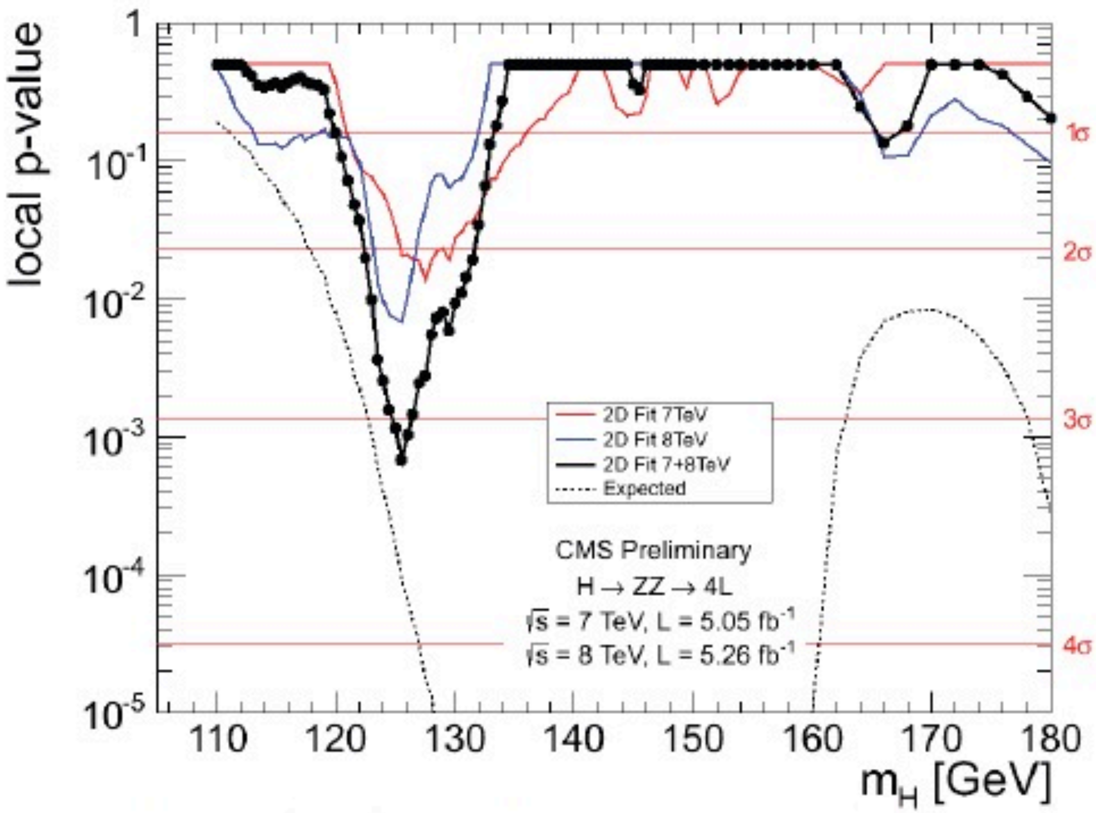


14.6.2012: Approval of **H→ZZ→4l analysis**





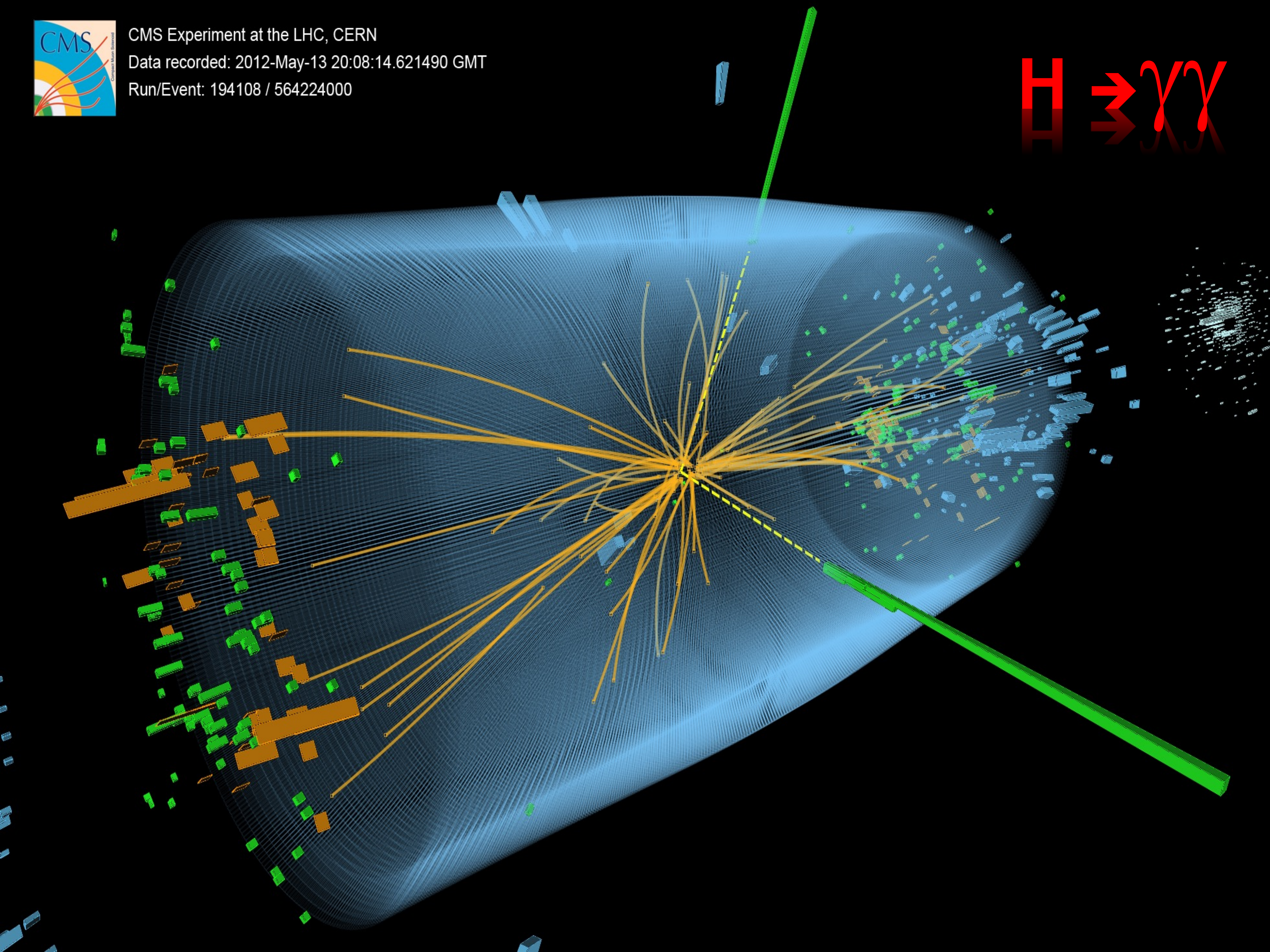
Evidence of a new state



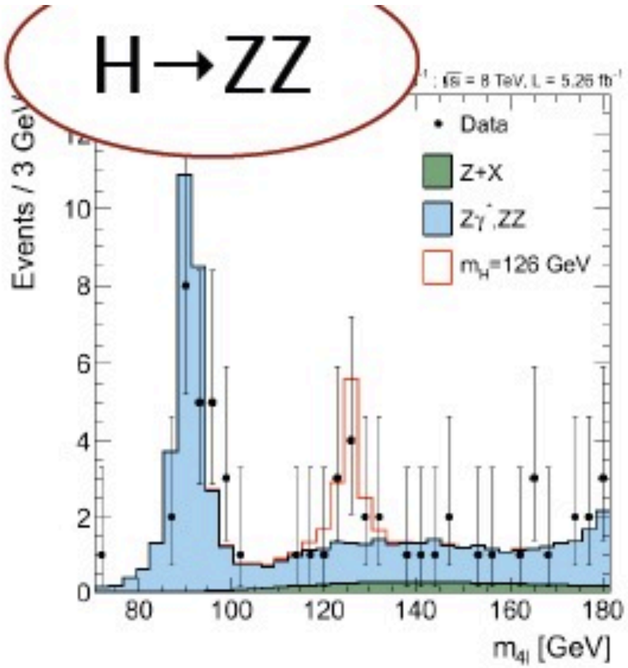
Evidence for a new state in the search for the standard model Higgs boson in the $H \rightarrow ZZ \rightarrow 4\ell$ channel in pp collisions at $\sqrt{s} = 7$ and 8 TeV

The CMS Collaboration

Excess at $m_{4l} \approx 126$ GeV with a p-value of **3.2σ**


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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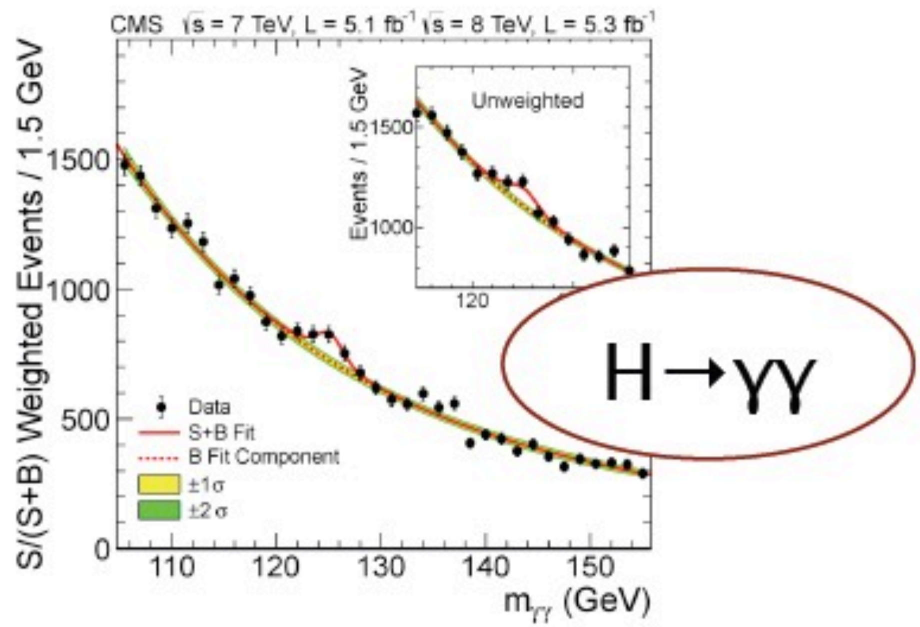

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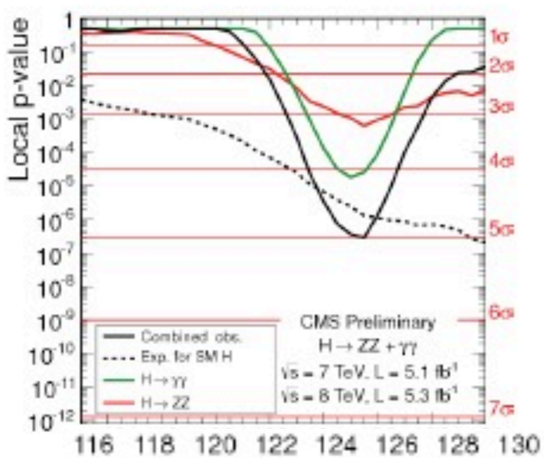
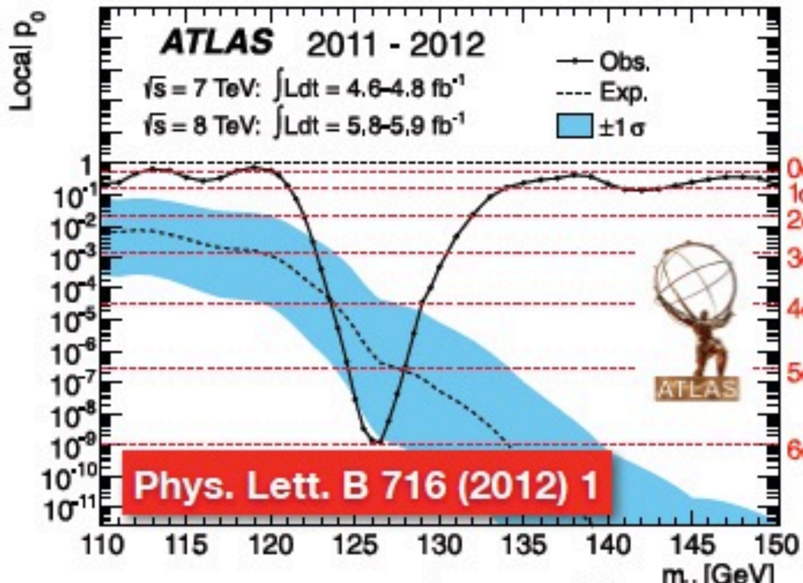
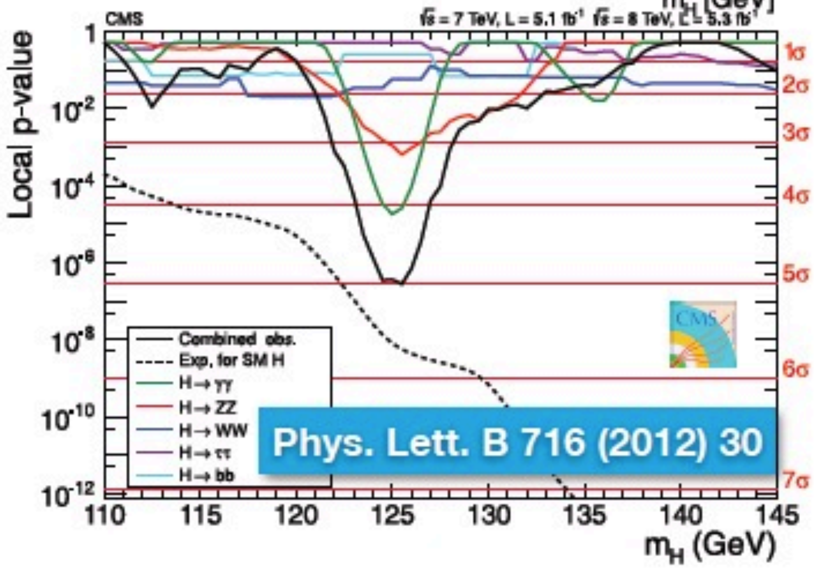
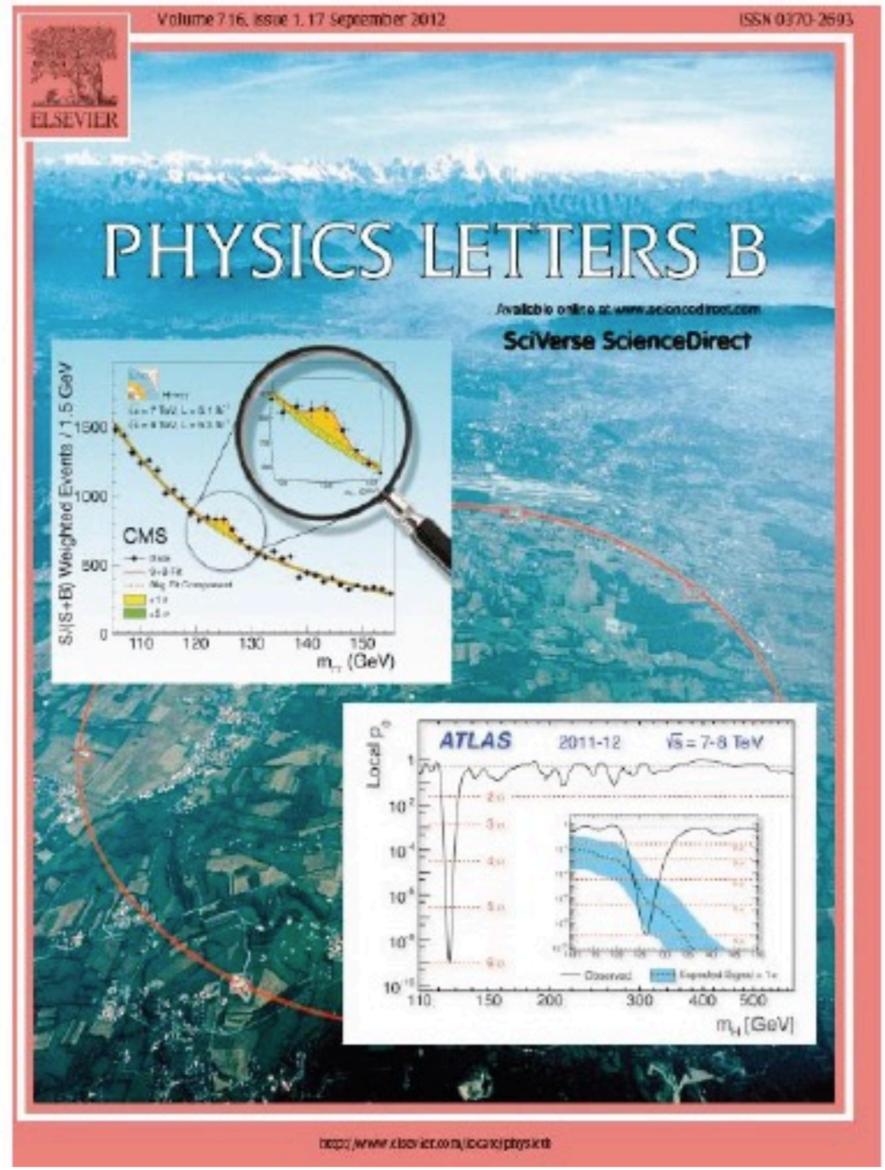


We have observed a new boson with a mass of 125.3 ± 0.6 GeV

A new boson discovery: 4th of July 2012

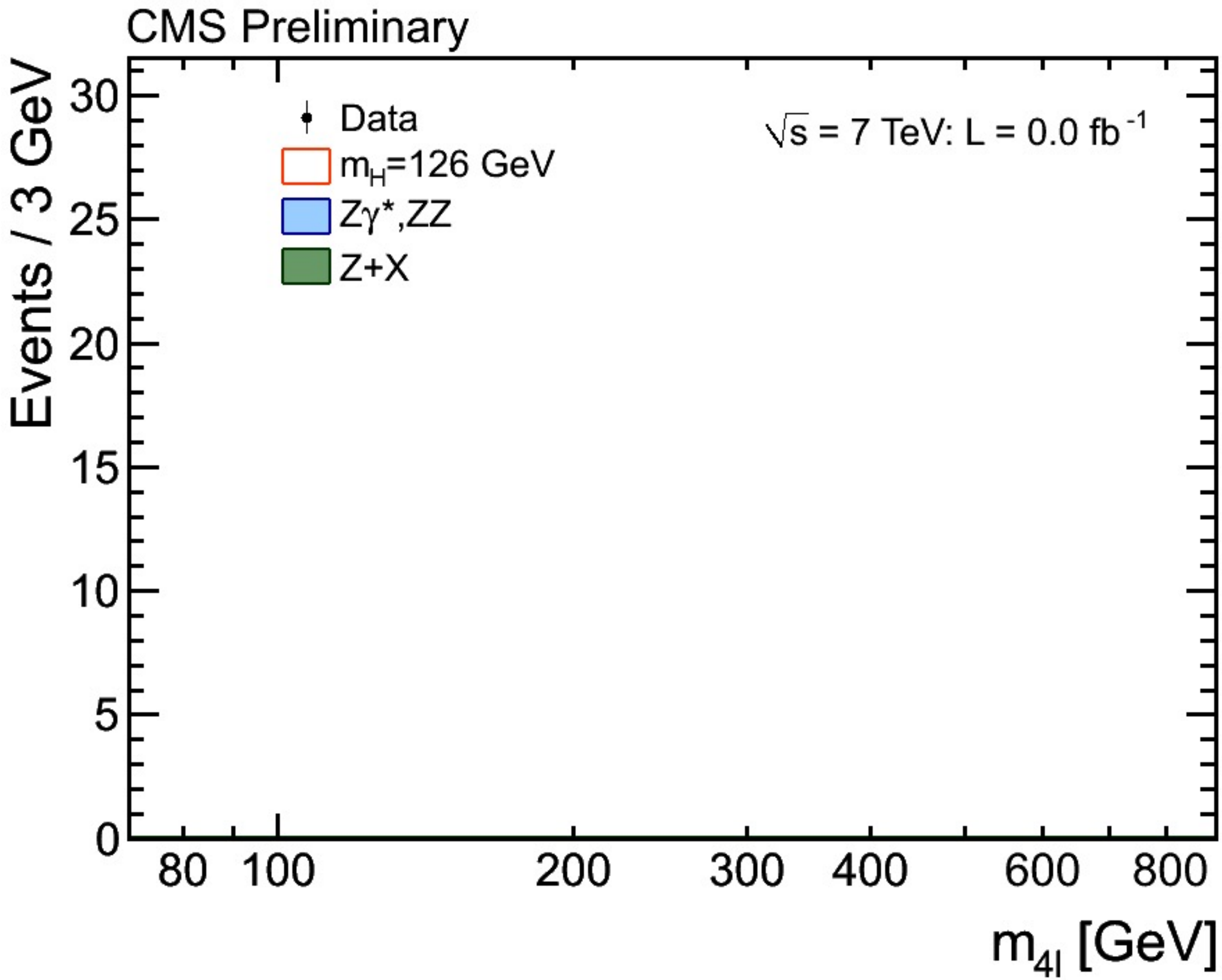




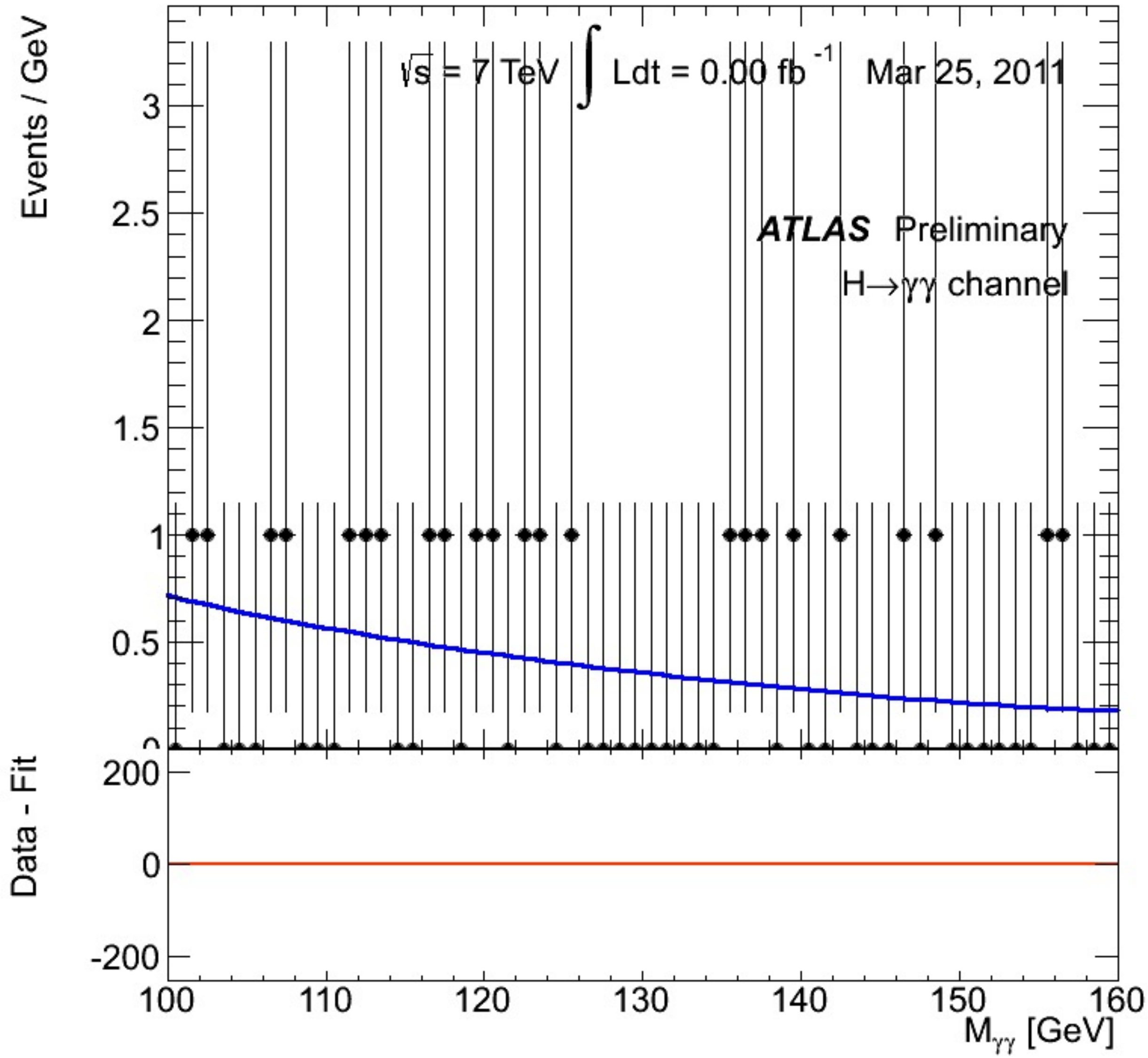


4th of July fireworks

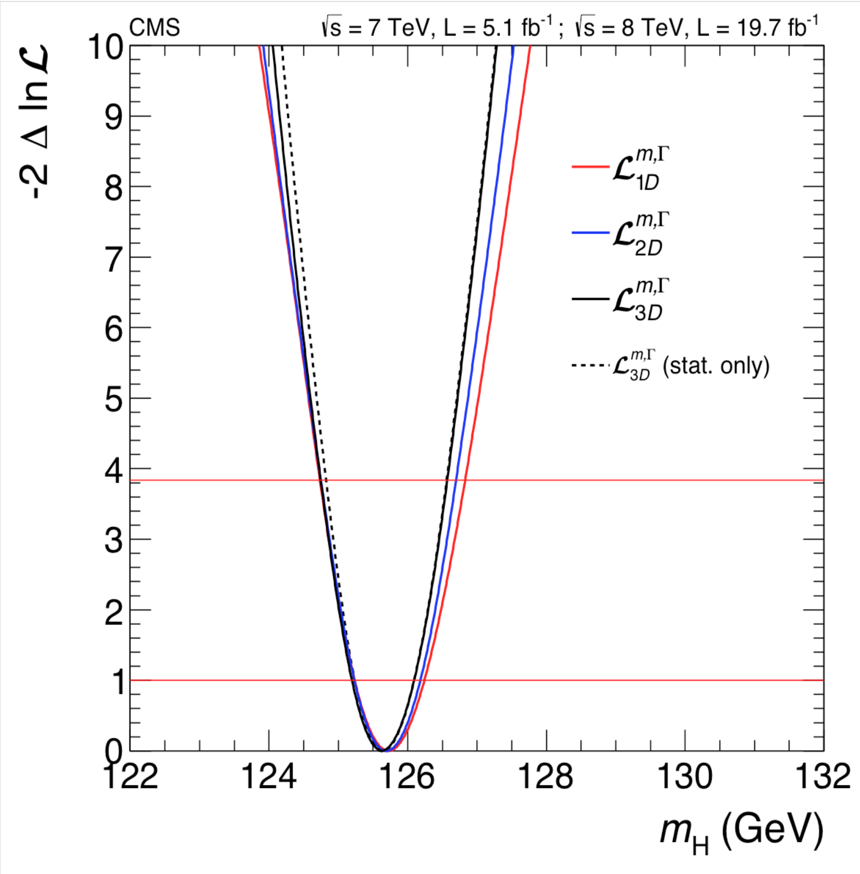
Full 7+8 TeV data: H→ZZ→4l analysis



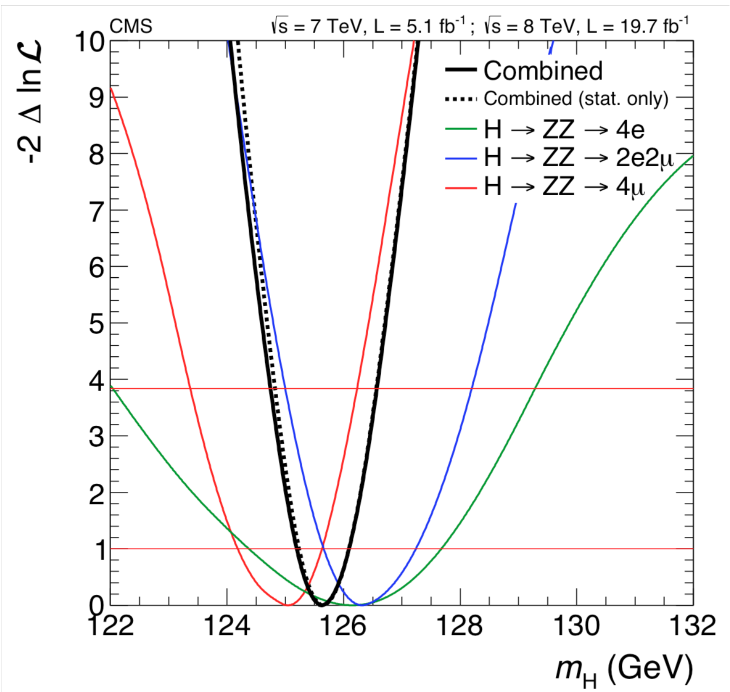
Full 7+8 TeV data: H→$\gamma\gamma$ analysis



Mass measurement



- Event by Event mass error (EBE) included
  - from muon track fit error matrix
  - from electron momentum error
- 3% of better significance
- 10% improvement on error on m_X



The combined best-fit mass is

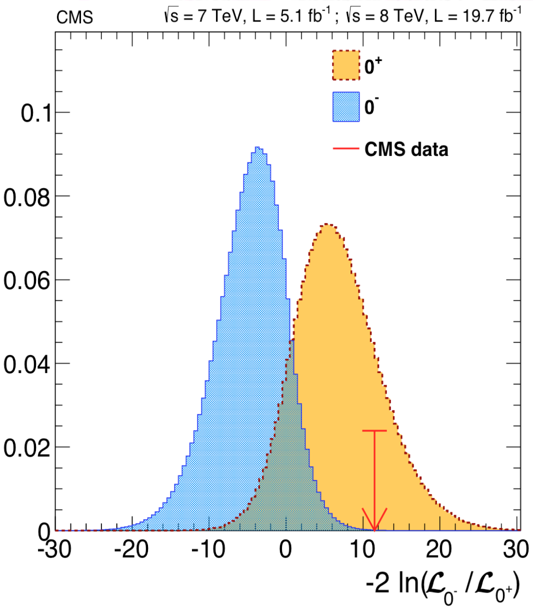
$$m_X = 125.6\ ^{+0.5}_{-0.4}\ (\text{stat})\ ^{+0.1}_{-0.4}\ (\text{syst})\ \text{GeV}$$

CP analysis

- Strong exclusion of a spin-1 resonance (could not decay to $H\rightarrow\gamma\gamma$)
- pseudo-scalar excluded at >3σ level
- graviton-like resonances excluded at >~3σ level

J^P model	J^P production	expected (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	any	2.4σ (2.7σ)	-0.9σ	+3.6σ	0.09%
0_h^+	any	1.7σ (1.9σ)	-0.0σ	+1.8σ	7.1%
1^-	qqbar → X	2.6σ (2.7σ)	-1.4σ	+4.8σ	0.001%
1^-	any	2.6σ (2.6σ)	-1.7σ	+4.9σ	0.001%
1^+	qqbar → X	2.1σ (2.3σ)	-1.5σ	+4.1σ	0.03%
1^+	any	2.0σ (2.1σ)	-1.9σ	+4.5σ	0.01%
2_m^+	gg → X	1.7σ (1.8σ)	-0.8σ	+2.6σ	1.9%
2_m^+	qqbar → X	1.6σ (1.7σ)	-1.6σ	+3.6σ	0.03%
2_m^+	any	1.5σ (1.5σ)	-1.3σ	+3.0σ	1.4%
2_b^+	gg → X	1.6σ (1.8σ)	-1.2σ	+3.1σ	0.9%
2_h^+	gg → X	3.7σ (4.0σ)	+1.8σ	+1.9σ	3.1%
2_h^-	gg → X	4.0σ (4.5σ)	+1.0σ	+3.0σ	1.7%

0^+ vs 0^-



October 8, 2013: Nobel Prize

Nobel Prizes and Laureates

Physics Prizes | 2013

▼ About the Nobel Prize in Physics 2013

- Summary
- Prize Announcement
- Press Release
- 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

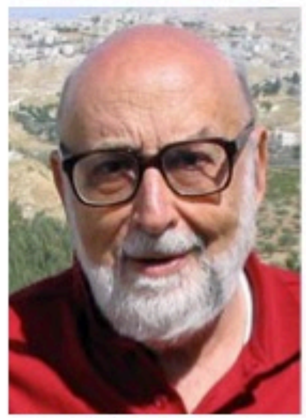


Photo: Pnicolet via Wikimedia Commons

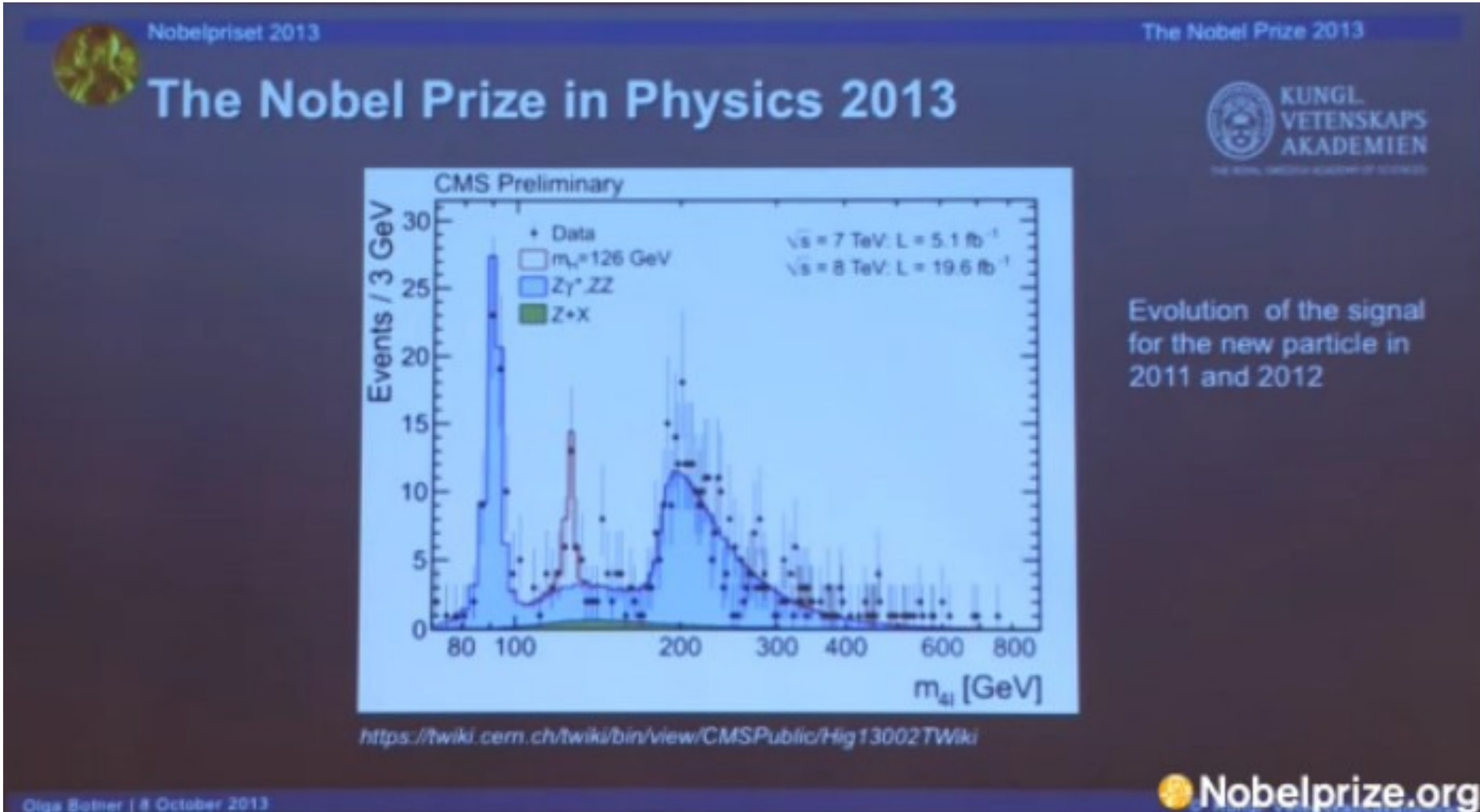
François Englert

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"*

October 8, 2013: Nobel Prize



Physics remarks at Run 1

Consolidated the SM:

- Immense set of measurements at 7-8 TeV
  - Precision measurements in EW and QCD
  - Rare processes, sensitive to new Physics, like $B_s \rightarrow \mu\mu$

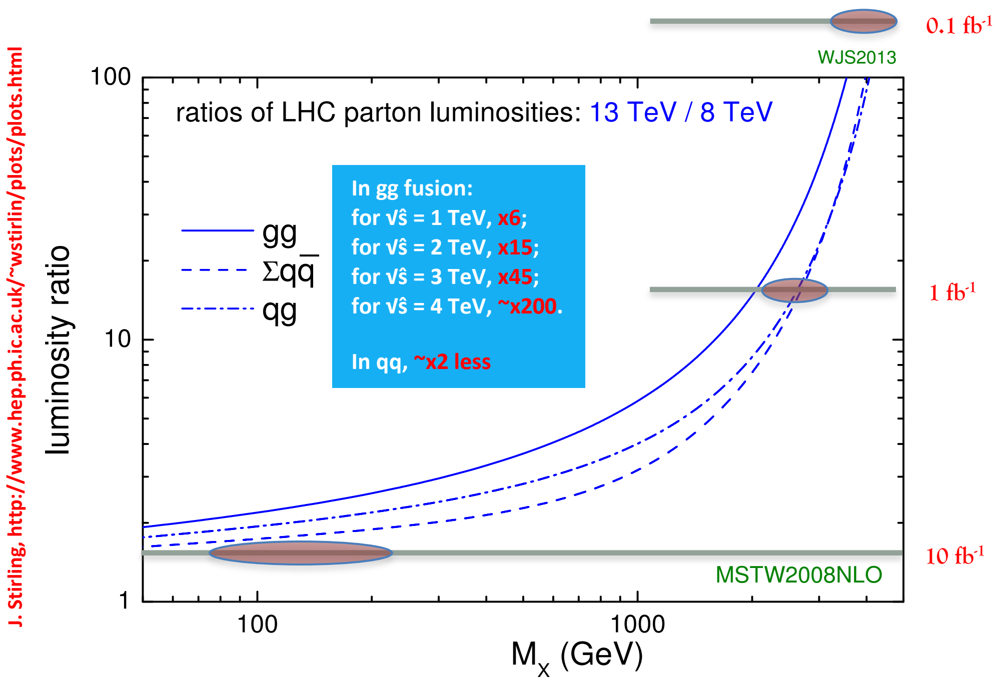
Completed the SM: Higgs boson discovery

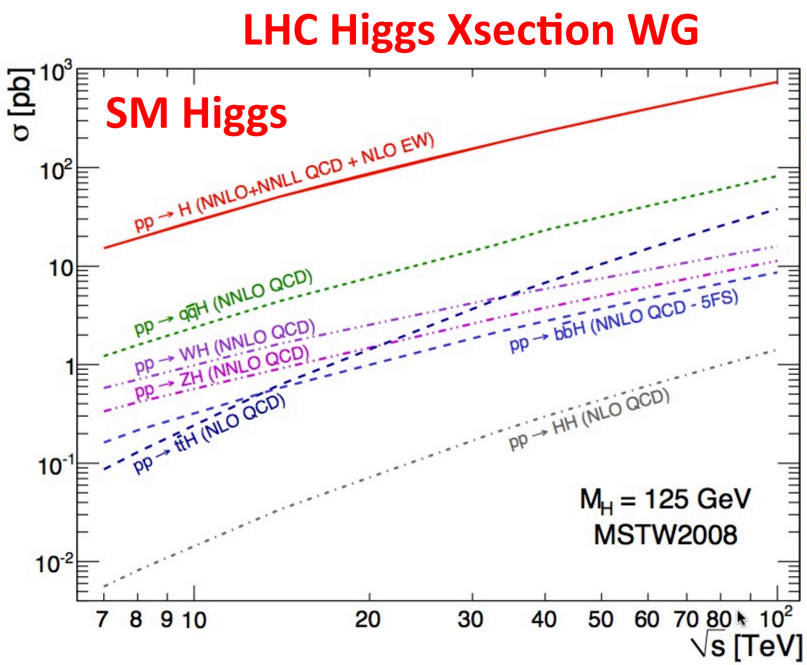
- $\geq 5\ \sigma$ from each of $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$ per experiment
- $\approx 3\ \sigma$ from $H \rightarrow \tau\tau$ per experiment and
- $\approx 2\ \sigma$ from W/ZH, $H \rightarrow bb$ for CMS
- separation $0^+/2^+$ and pure $0^+/0^-$ at $> 3\sigma$ level
- some couplings measured with precision of 20-30 %

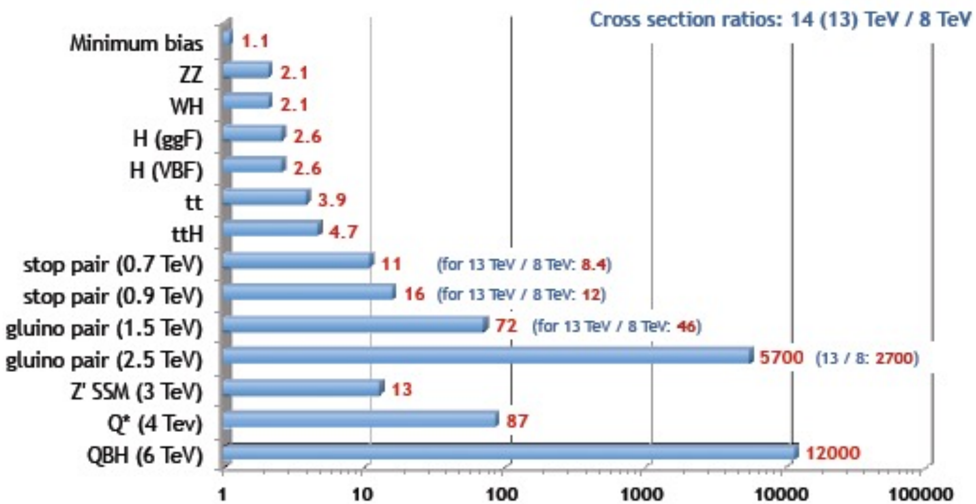
4 July 2014 – ICHEP Happy Birthday Higgs Boson

NO evidence of any new physics

8 TeV→ 13 TeV: what did it change?

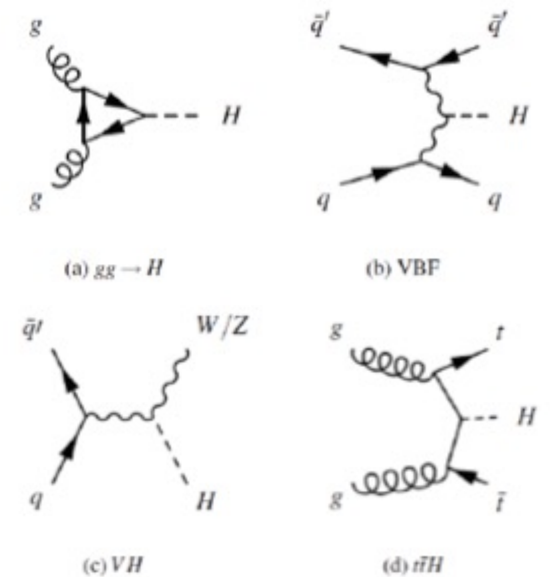






- SM Higgs is light, so the gluon fusion cross section doesn't get that much boost (x2, 19.1 → 43.6 pb)
- **Background cross sections increase too**

SM Higgs production: 8 TeV vs 13 TeV



σ [pb] at m_H=125.5 GeV	8 TeV	13 TeV	Ratio
ggF	19.1	43.62	2.6
VBF	1.6	3.727	2.6
WH	0.7	1.362	2.1
ZH	0.4	0.8594	2.1
ttH	0.1	0.5027	4.7

It's very important to repeat the discovery of SM Higgs at 13 TeV as a part of physics commissioning

- an important exception: **ttH** production, which gets a boost by a factor of 4 (0.13 → 0.50 pb)
  - could potentially see it for the first time during Run 2 @13 TeV
  - But, this is a challenging analysis because of background increase

Uncertainty on σ(13TeV) from theory:
@ NNLO/NNLL QCD + NLO EWK

ggF: 8% scale and 7% PDF
VBF: 0.6% scale and 1.7% PDF

Uncertainty on BRs: 3-5%

Higgs couplings formalism

LHC Higgs Xsection WG - arXiv:1307.1347v2

- Single resonance with mass of 125 GeV.
- Zero-width approximation

$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

- the tensor structure of the lagr. is the SM one → observed 0^+
- coupling scale factors K_i are defined in such a way that:
  - the cross sections σ_i and the partial decay widths Γ_i scale with K^2_i compared to the SM prediction

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$

- deviations of K_i from unity → new physics BSM
- Results from fits to the data using the profile likelihood ratio with κ_i couplings
  - as parameters of interest or as nuisance parameters

Higgs couplings formalism

arXiv:1307.1347v2

Production modes

$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma^{SM}_{VBF}} = \kappa^2_{VBF}(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma^{SM}_{WH}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma^{SM}_{ZH}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{SM}_{Z\gamma}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma^{SM}_{t\bar{t}}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}}$$

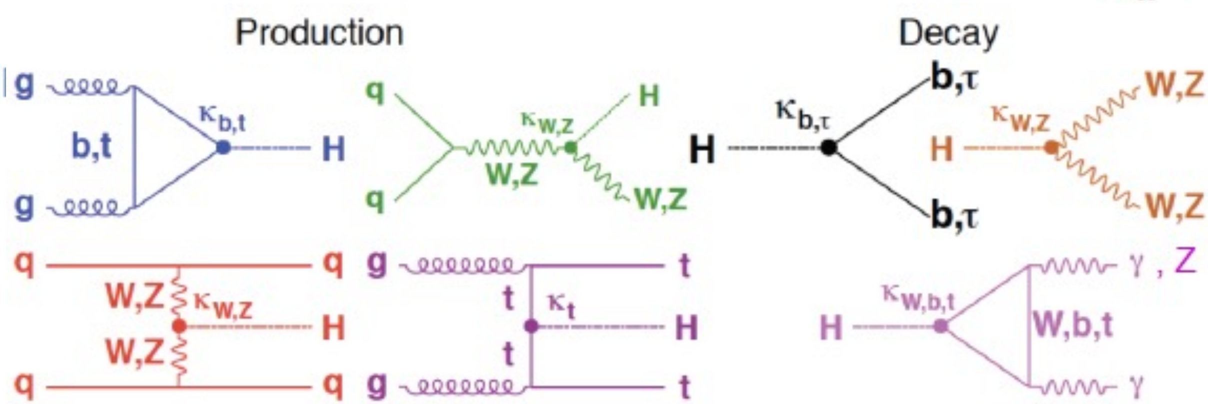
$$\frac{\Gamma_{c\bar{c}}}{\Gamma^{SM}_{c\bar{c}}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{SM}_{s\bar{s}}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{SM}_{\mu^-\mu^+}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_H}{\Gamma^{SM}_H} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

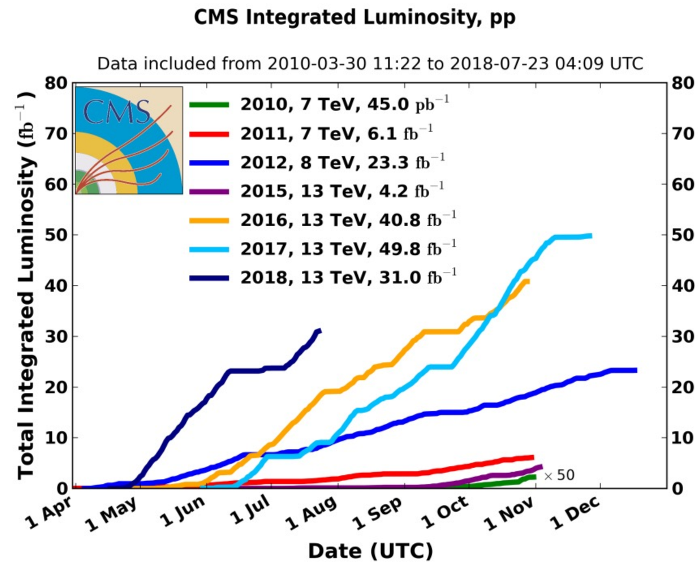


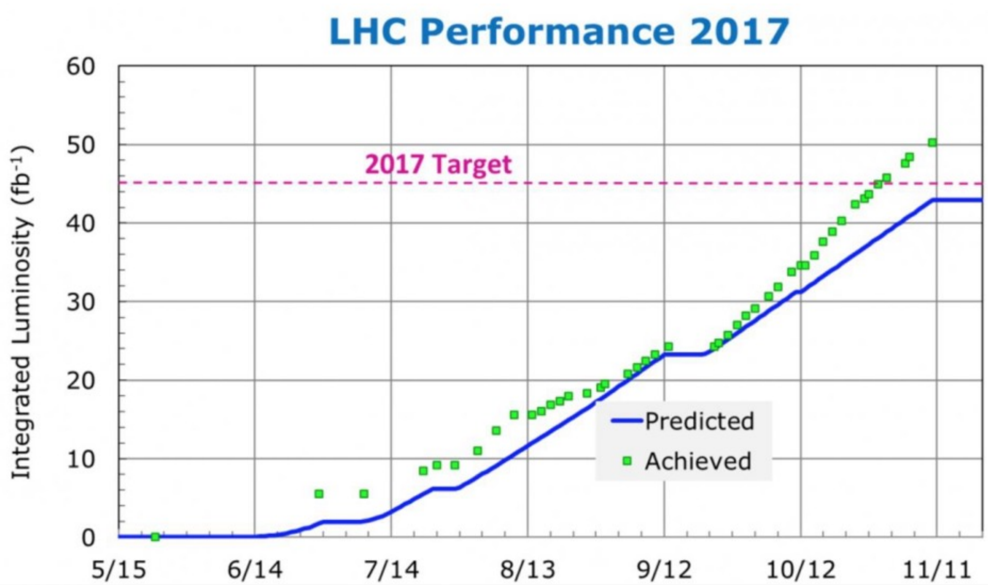
$$\Gamma_H = \Sigma_{SM}\, \Gamma_Y \quad (+\, \Gamma_{BSM})$$

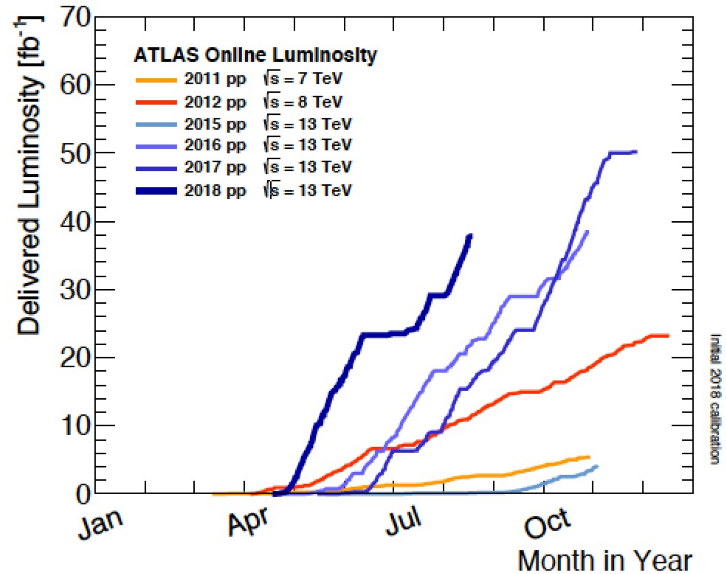
Contributions from **new physics** through Γ_{BSM} and loop processes

LHC Run 2

- LHC has produced > 3 years of 13 TeV data with stunning performance
  - expected to result in >150 fb^{-1} by the end of the 2018 run
  - maximum peak luminosity ~$2x10^{34}$ $cm^{-2}s^{-1}$ with mean pileup ~33 in 2017, ~38 in 2018
  - DESIGN peak Luminosity exceeded by a factor of 2!

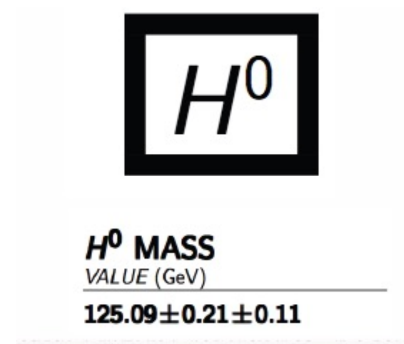






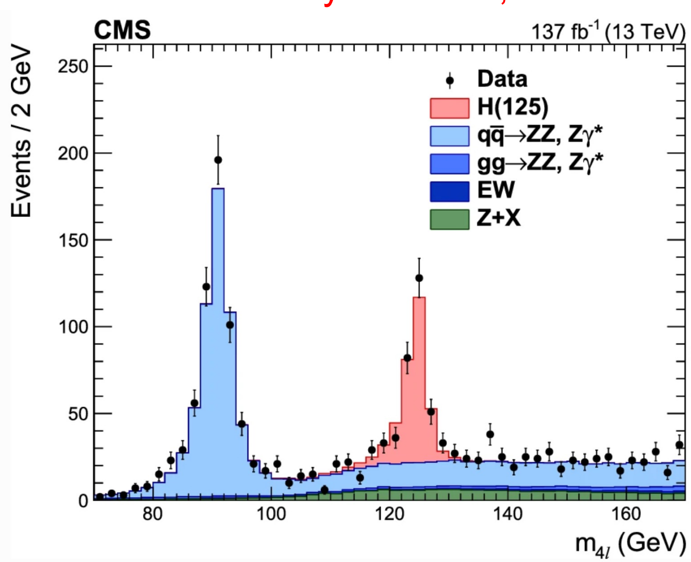
The LHC/Higgs era at Run 2

- Re-discovery of the Higgs
- measur. Higgs properties
  - cross section (also differential)
  - mass & width
  - couplings:
    - to gauge bosons, to fermions
    - tensor structure and effective couplings in the lagrangian
    - ttH couplings
- Searches for HH production and BSM Higgs

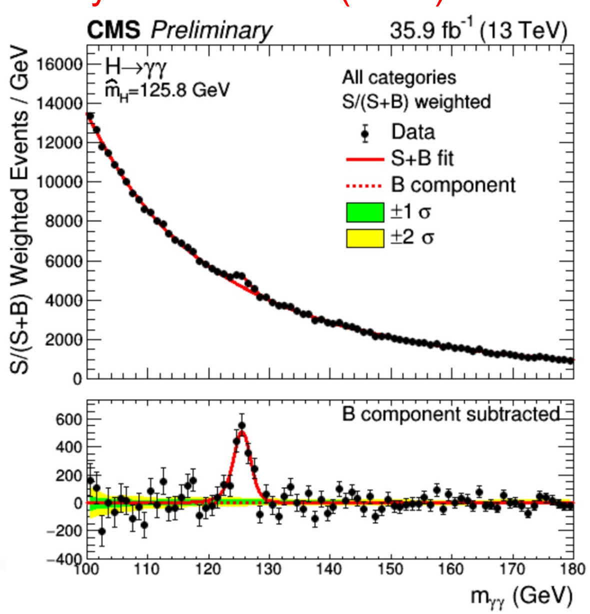


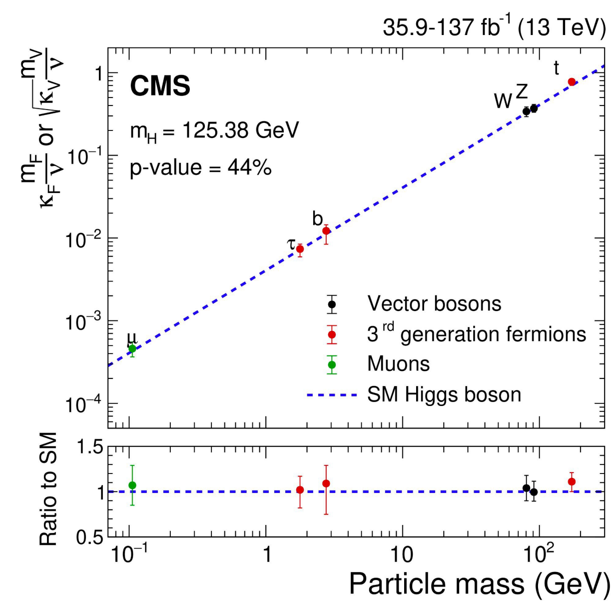
- Mass measured to 0.2%
- Main couplings to ~10%

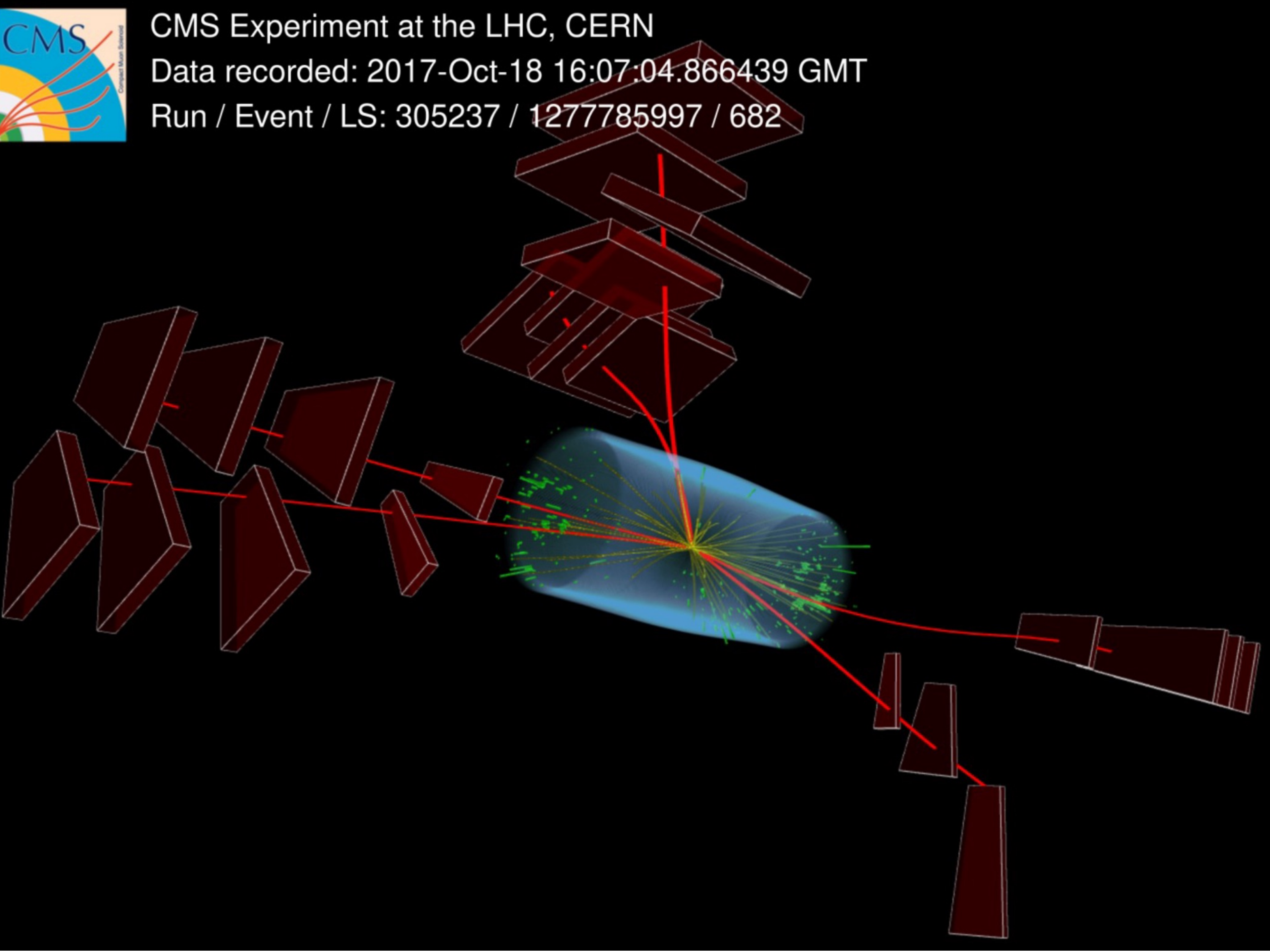
Eur. Phys. J. C 81, 488



Phys. Lett. B 805 (2020)135425






CMS Experiment at the LHC, CERN
Data recorded: 2017-Oct-18 16:07:04.866439 GMT
Run / Event / LS: 305237 / 1277785997 / 682

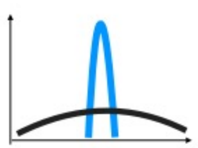
H→bb

Motivation:

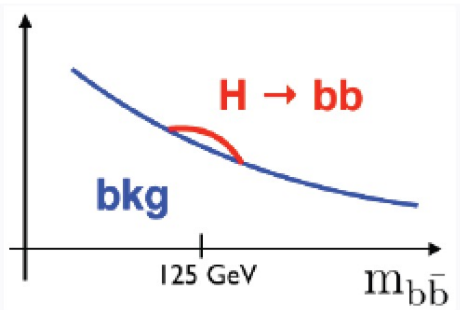
- H→ bb has the largest BR (58%) for m_H=125 GeV
- Unique final state to measure coupling with down-type quarks
- Drives the uncertainty of the total Higgs boson width
- Primary decay mode for searches at LEP and Tevatron
  → a long history of searches

H→bb search challenge:

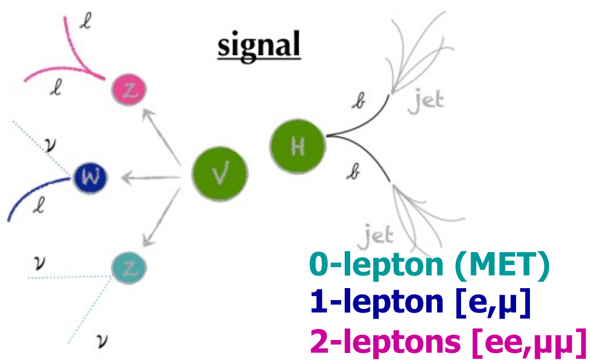
- **Needs:**
  - Good **b-jets identification** performance: 70% efficiency with < 1% q/g mis-identification probability
  - Best possible **resolution on m(bb)**
  - Capability to exploit all possible information from the event to **improve S/B**
- **H(bb) compared with discovery channel**

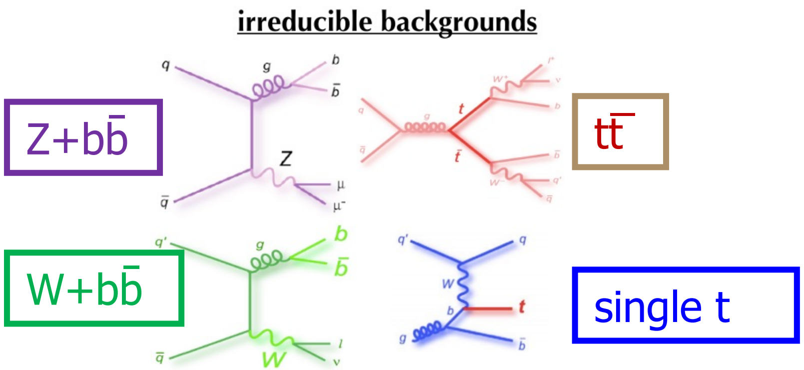


	$H \to 4\ell$	$H \to b\bar{b}$
Branching Ratio	0.03%	58%
mass resolution	1%	10%
S/B	2	0.05



- **Higgs-strahlung - VH (4%) is the most sensitive channel**
  - leptons, E_T^{miss} to trigger and high p_T V to suppress backgrounds



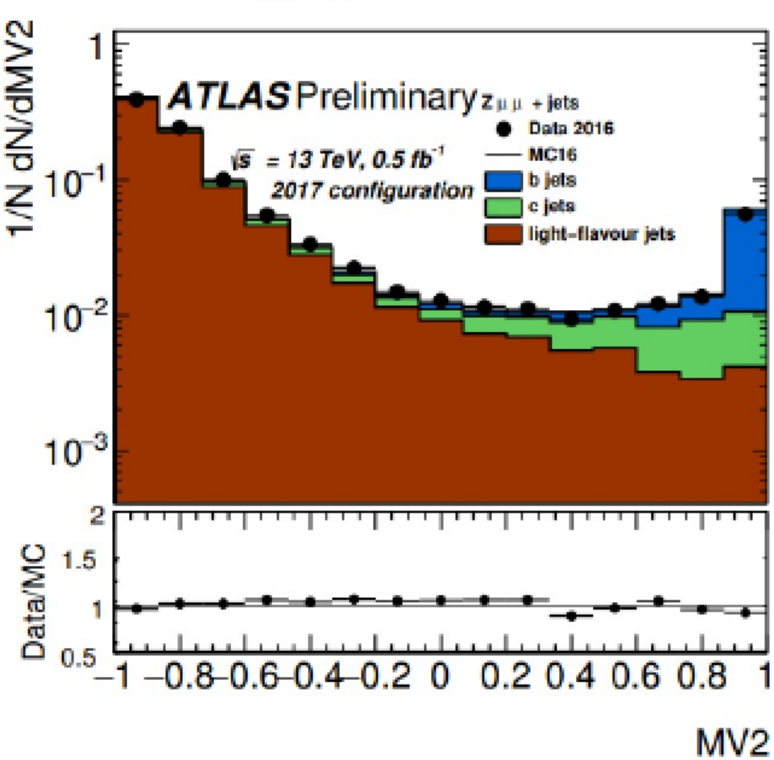


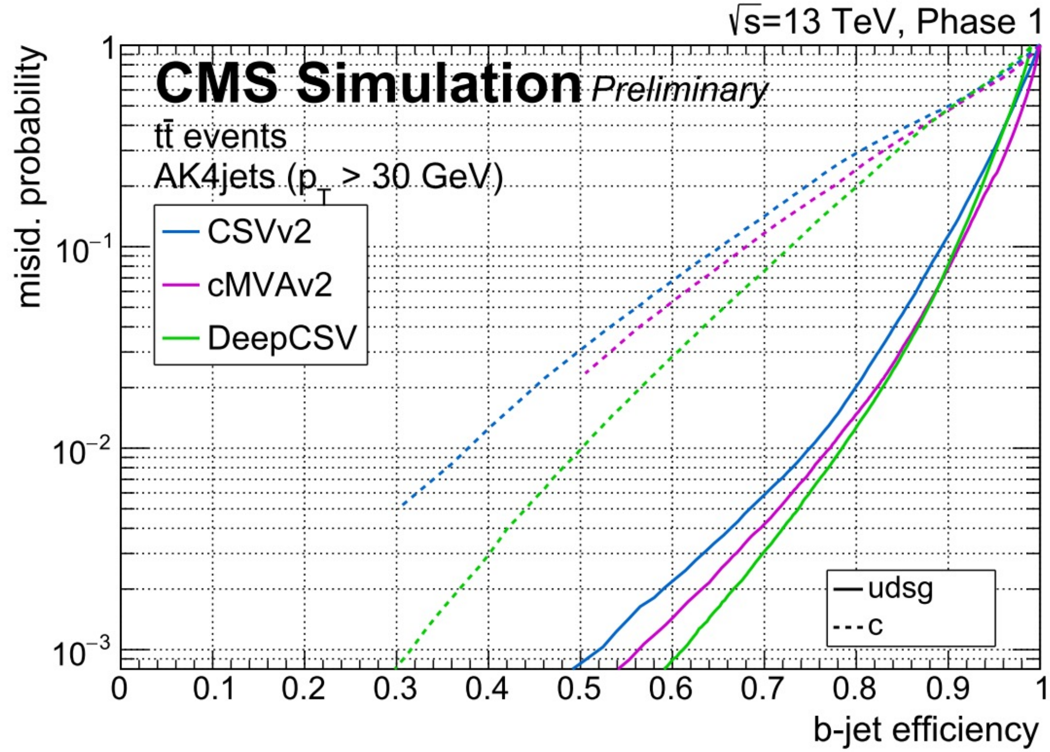
Improvement of b-tagging

CMS: better mis-identification rate and data/MC agreement with Phase 1 pixel detector and DeepCSV algorithm

- Efficiency ~70% per fake rate at < 1%

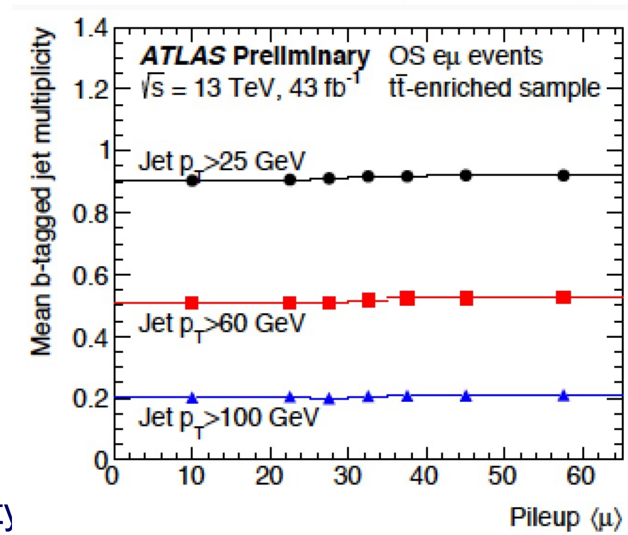
b-tagging discriminant



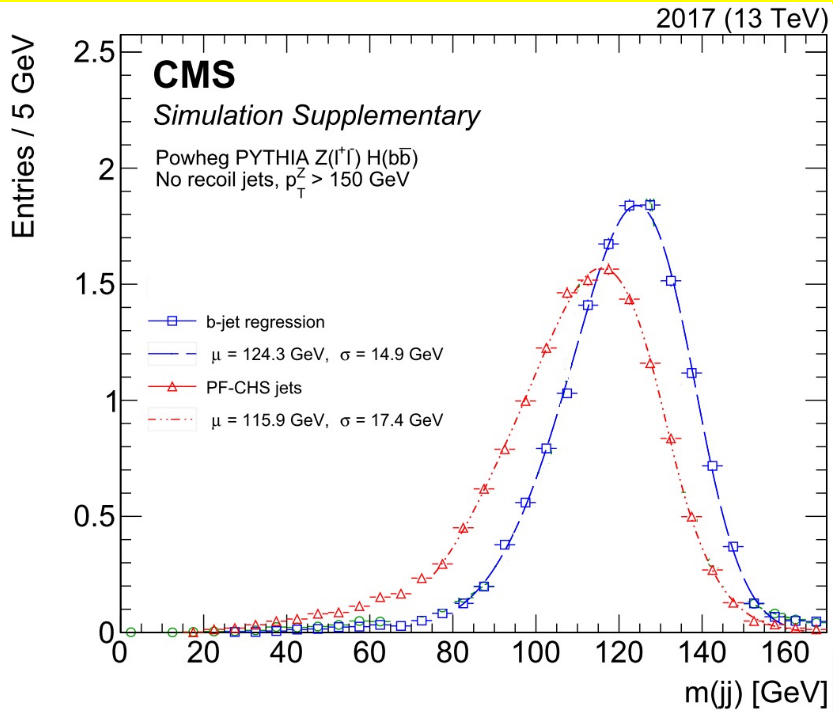


ATLAS:

- rejection of light/c jets 300/8 at 70% b-jet efficiency
- Good performance even at high PU



Improvement of di-jet mass resolution



CMS:

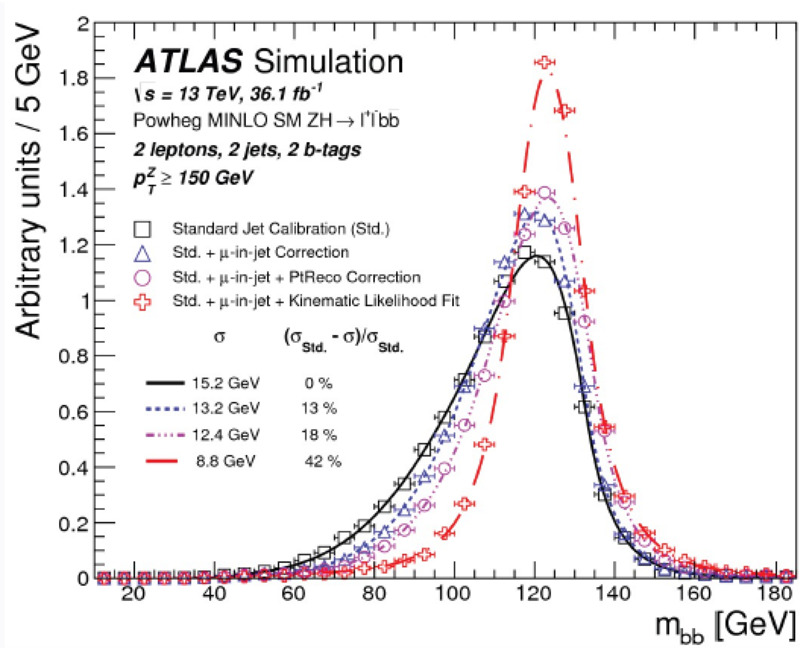
- Regression mainly recovers missing energy in the jet due to neutrino
- Extended set of input variables now including lepton flavour (m/e), jet mass, p_T wrt to lepton axis, energy fractions in DR rings
- Significant m(bb) resolution improvement → s/peak down to 11.9% in 2017 wrt 13.2% in 2016

ATLAS

Mass resolution improvements

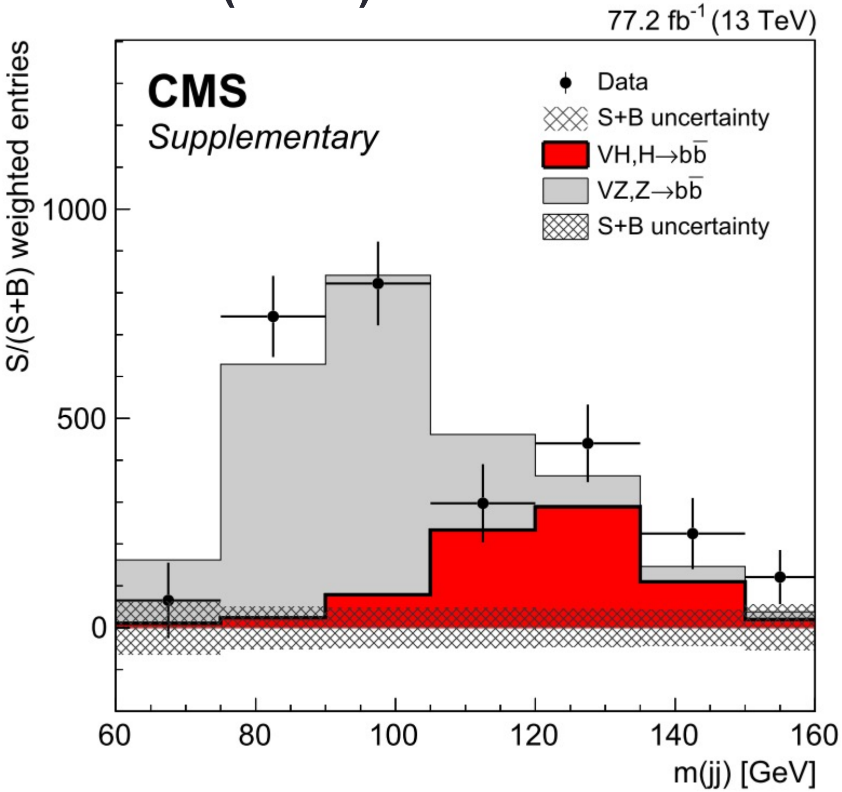
Higgs boson candidate from a pair of *b*-jets

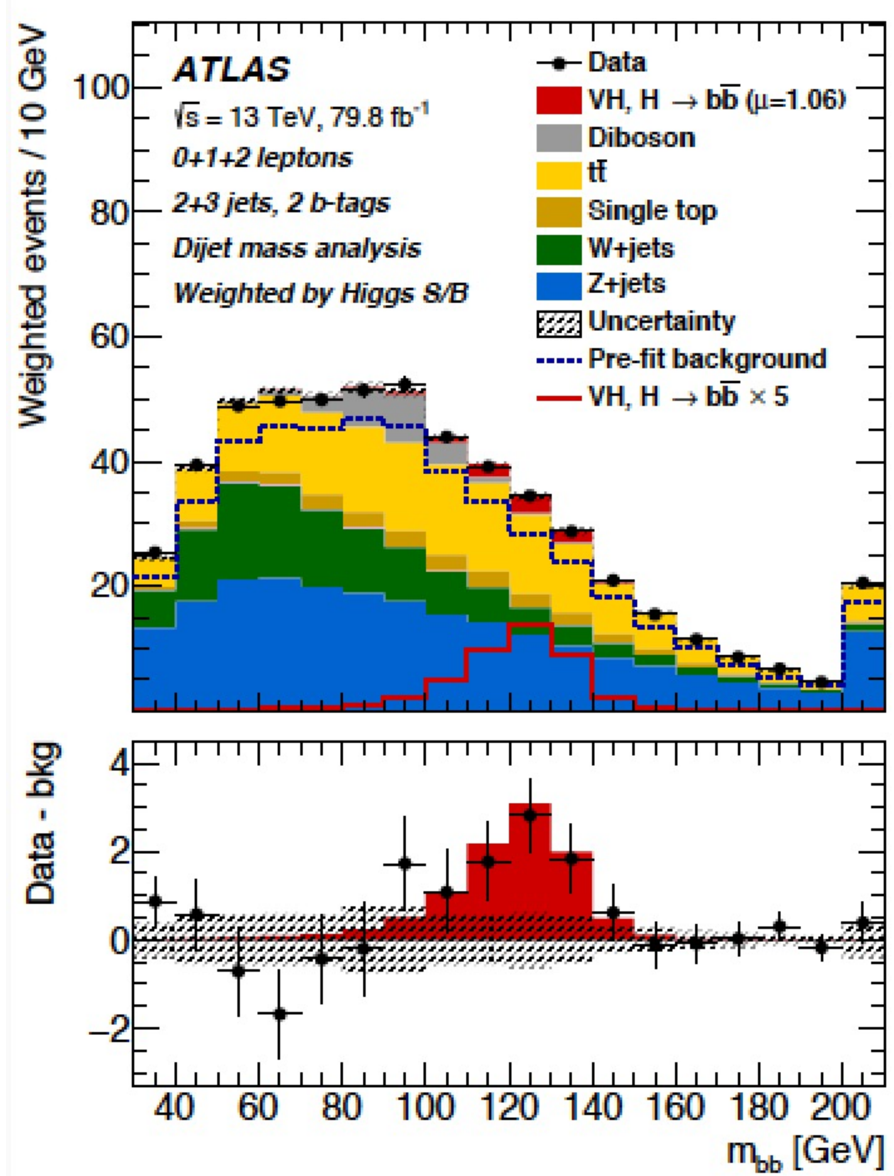
- Add muons in the vicinity (semi-lep. decays)
- Simple average jet p_T correction
  - Accounts for neutrinos, and interplay of resolution and p_T spectrum effects.
- Mass resolution improvement: ∼ 18%



VH(H→bb): m(bb)

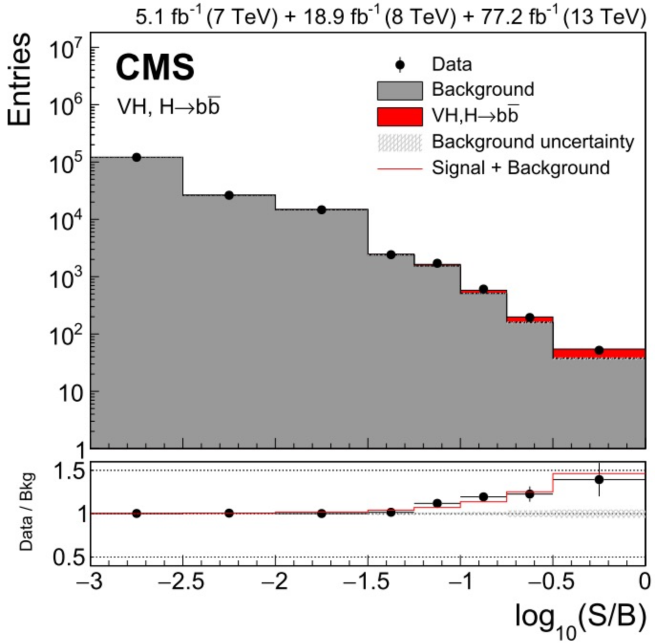
- **Fit to the m(bb)**: lower sensitivity but direct visualization of the Higgs boson signal.
- The fitted **m(bb) distributions are combined and weighted by S/(S + B)**

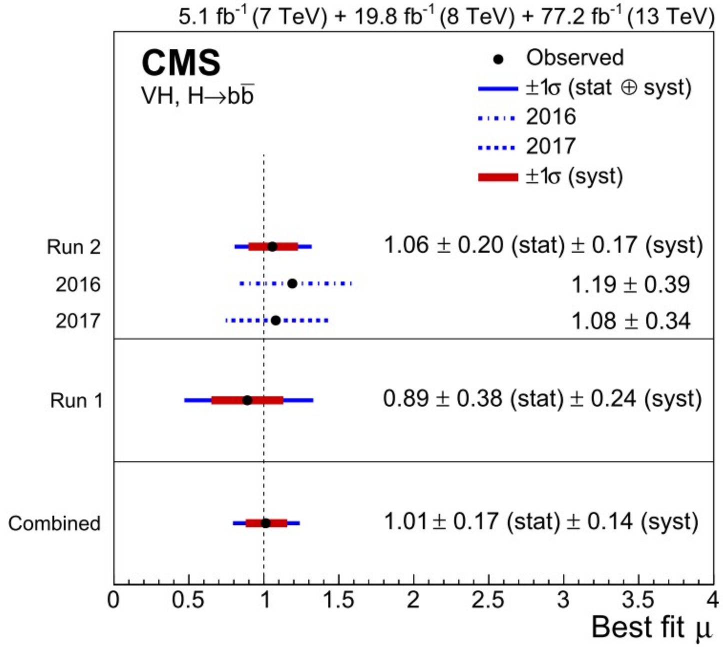




VH(H→bb): Run 1 + Run 2 results (CMS)

Data set	Significance (σ) Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23





H→cc

VH→cc (Full Run2) - ATLAS

ATLAS-CONF-2021-021

Study of the coupling of the Higgs to the c-quark challenging:

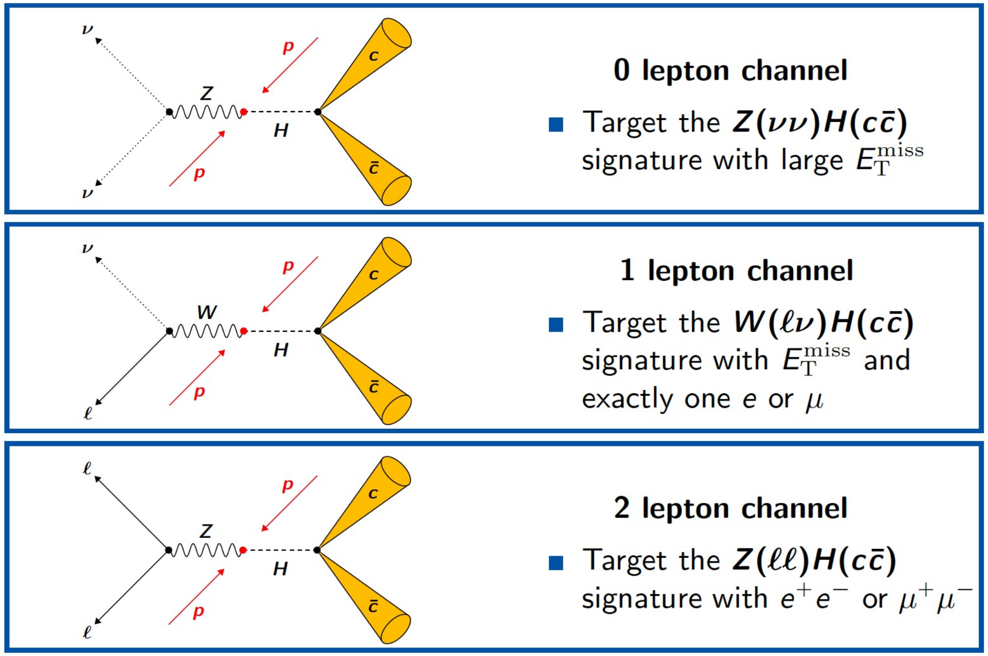
- BR_{SM}~2.9×10^{-2} (20x smaller than H→bb)
- QCD di-jet large background
- c-jets have broader jet energy resolution
  - can have larger fraction of jet energy in neutrinos
  - low Higgs mass resolution
- Large systematics limit the analysis

Charm tagging is a very difficult task:

- c-jets similar to b-jets and $udsg$-jets
- similarities due to properties of the intermediate mesons created during hadronizations

VH production mode:

- can use leptonic Z and W decays to trigger events
- presence of leptons suppresses QCD to negligible levels



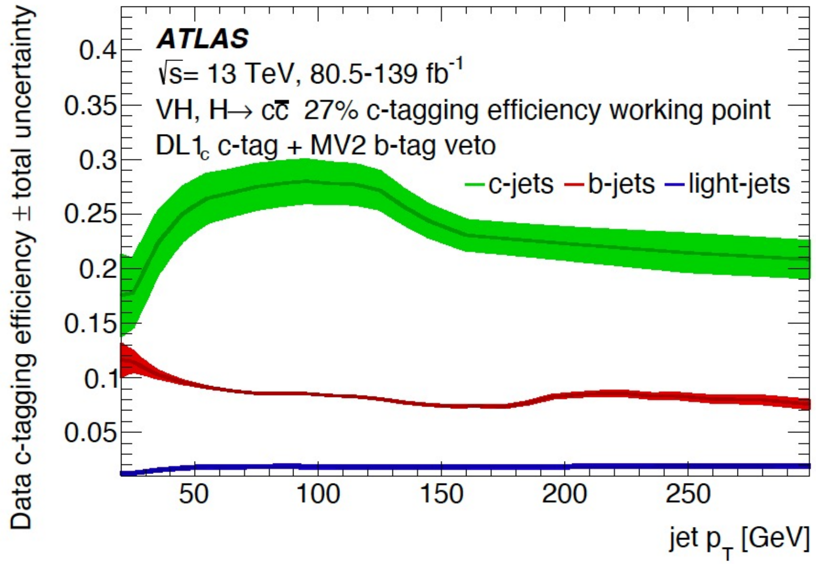
VH→cc (Full Run2) - ATLAS

A dedicated flavour tagging working point, optimised for the VH, $H \to c\bar{c}$ search, is built from two components:

- **1)** - DL1 (Deep NN) algorithm implemented as a *c*-tagger
- **2)** - MV2c10 (BDT) *b*-tagger implemented as a veto at the 70% *b*-jet efficiency working point

Jets are "*c*-tagged" if both conditions are passed

- Together with a *b*-tag veto on non-signal jets, this ensures **orthogonality of the event selection with the VH, $H \to b\bar{b}$ analysis**



Jet Flavour Class	Efficiency (rejection)
c-jets	27% (-)
b-jets	8% (13)
Light flavour jets	1.6% (63)

For more details on ATLAS flavour tagging algorithms, see:

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"Truth-flavour Tagging" - To maximise the statistical power of the main background samples, events are weighted by their probability (parameterised by jet p_T, $|\eta|$ and ΔR_{jj}) of being *c*-tagged, as opposed to accept/reject based on DL1 and MV2c10 discriminants

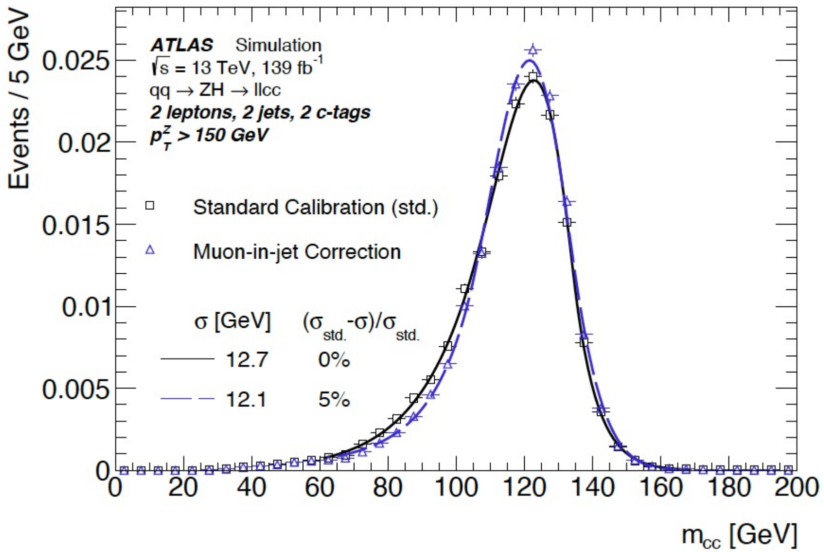
VH→cc (Full Run2) - ATLAS

$H \to c\bar{c}$ candidate selection

- Jets built with anti-k_T ($R = 0.4$) applied to calorimeter clusters
- Any muons within p_T dependent ΔR cone are used to correct the *signal jet* 4-vectors (recover energy in semi-leptonic b/c-hadron decays)
- At least two *central jets* required, one with $p_T > 45$ GeV
- Two highest p_T *central jets* (denoted the *signal jets*) form the $H \to c\bar{c}$ candidate
- p_T^V-dependent $\Delta R(\text{jet }1, \text{jet }2)$ requirement (see table →)
- All non-signal jets must fail 70% b-jet efficiency b-tagging working point

central jets: $|\eta| < 2.5$, $p_T > 20$ GeV

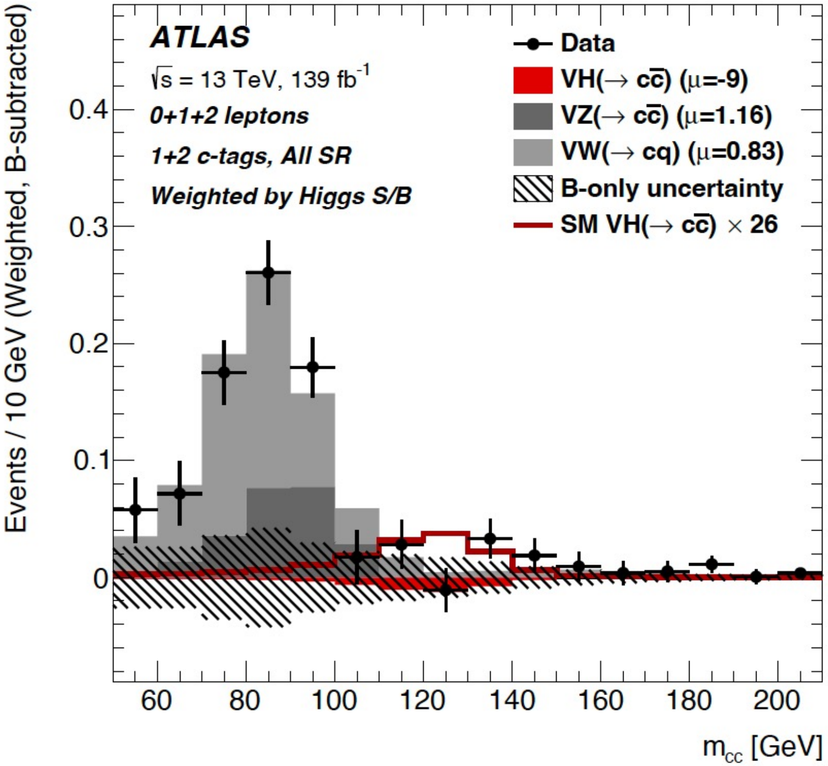
forward jets: $2.5 < |\eta| < 4.5$, $p_T > 30$ GeV

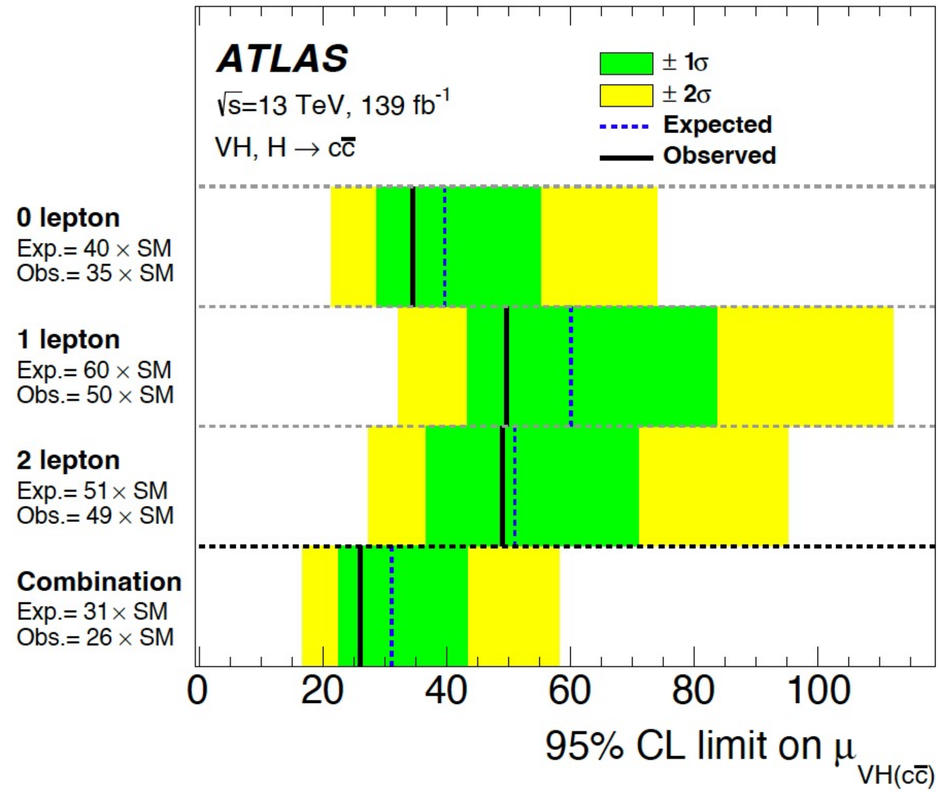


Invariant mass of $H \to c\bar{c}$ candidate, m_{cc}, is primary S/B discriminant

p_T^V	$\Delta R(\text{jet }1, \text{jet }2)$
$75 < p_T^V < 150$ GeV	≤ 2.3
$150 < p_T^V < 250$ GeV	≤ 1.6
$p_T^V > 250$ GeV	≤ 1.2

VH→cc (Full Run2) - ATLAS





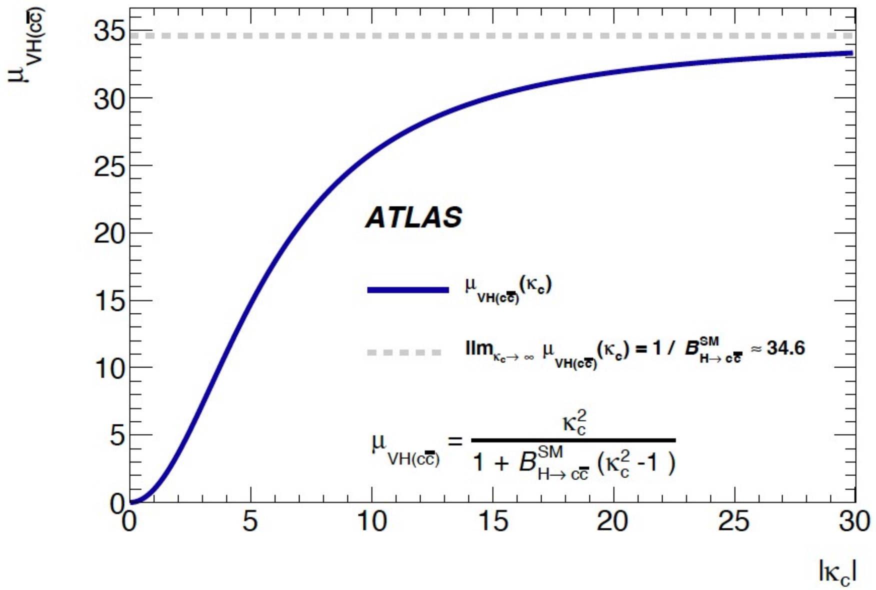
$VW(cq)$ observed (expected) significance 3.8 (4.6)σ

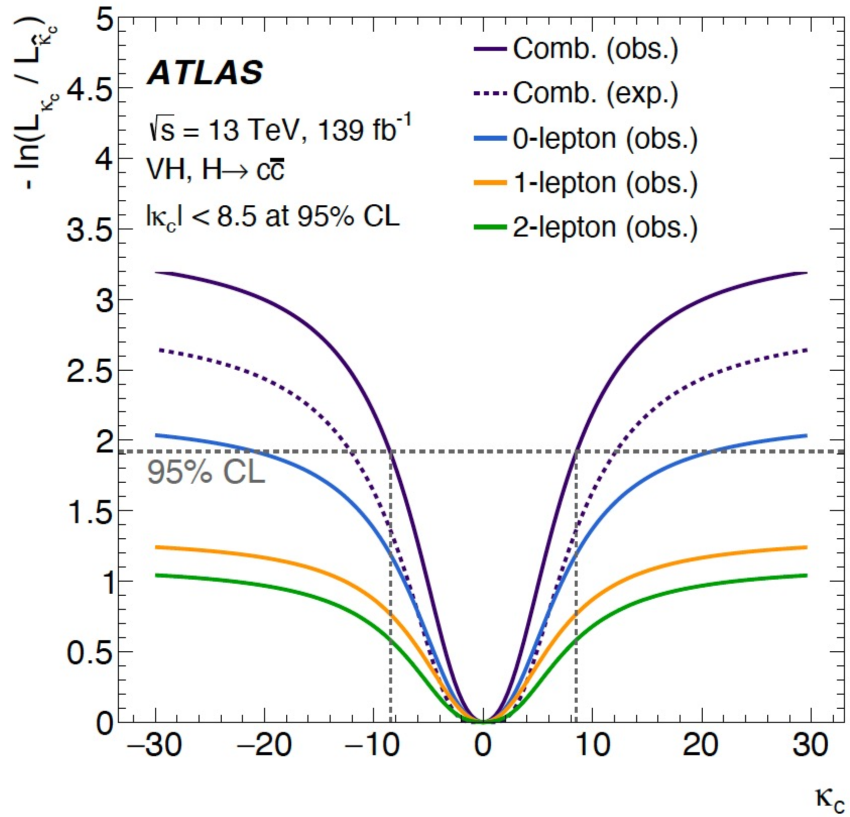
$VZ(c\bar{c})$ observed (expected) significance 2.6 (2.2)σ

Observed (expected) CLs limit on $\mu_{VH(c\bar{c})}$ is 26 (31^{+12}_{-8}) at 95% CL

VH→cc (Full Run2) - ATLAS

The result is interpreted in terms of the $Hc\bar{c}$ coupling based on the κ-framework†, inspired by the leading-order contributions to production and decay processes





- Simple scenario considered where **only Higgs boson decay is parameterised** in terms of $\kappa_c = y_c / y_c^{SM}$
- All other couplings remain fixed to their SM values, no BSM particle contributions to Γ_H considered

Observed (expected) constraint of $|\kappa_c| < 8.5\,(12.4)$ at 95% CL

VH→cc (Full Run2) - ATLAS

VH, H→cc/bb combination

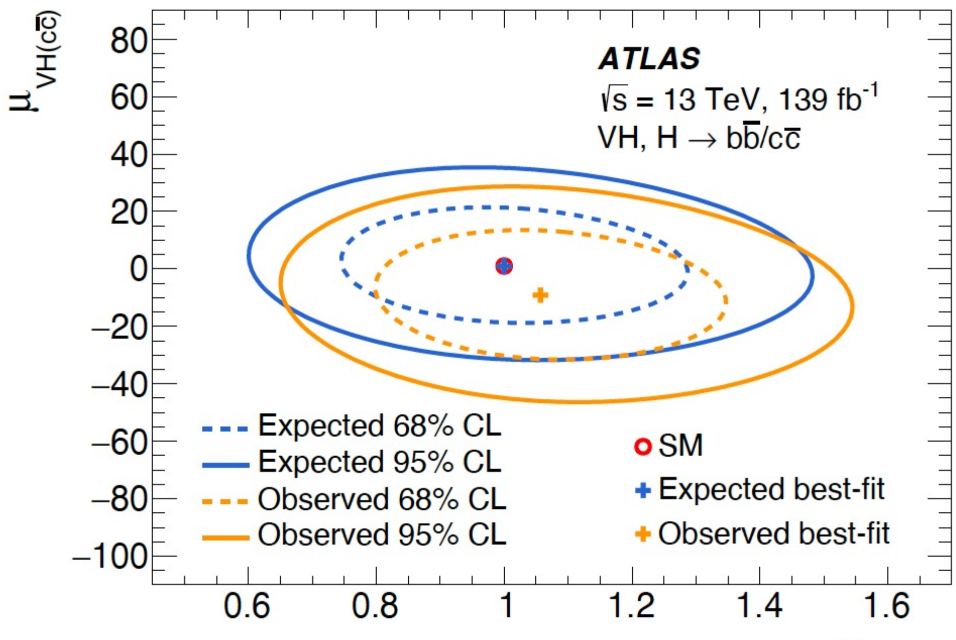
- the signal regions of the two analyses are entirely orthogonal
- a combined analysis allows correlations in the signal strength coupling parameterisations (via G_H and s_{VH}) between the two processes to be exploited
- such a combination has the power to derive more comprehensive and less model-dependent constraints on the Hcc and Hbb couplings

Combined Result

$$\mu_{VH(c\bar{c})} = -9 \pm 10\ (\text{stat.}) \pm 11\ (\text{syst.})$$

$$\mu_{VH(b\bar{b})} = 1.06 \pm 0.12\ (\text{stat.})^{+0.15}_{-0.13}\ (\text{syst.})$$

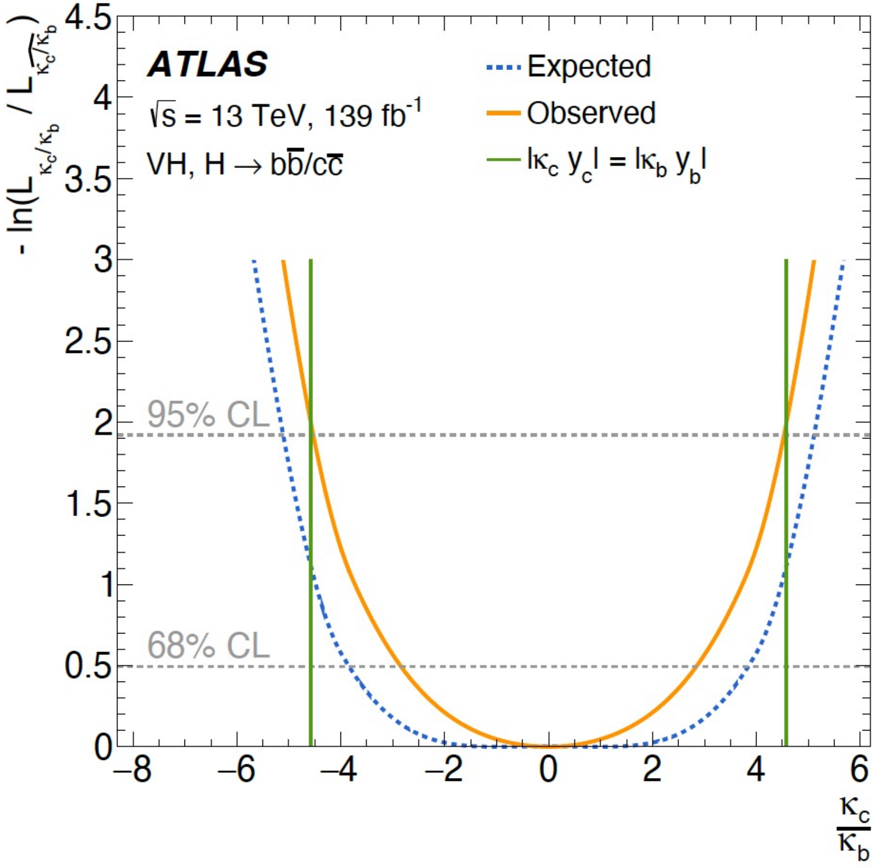
- Consistent with results of the individual analyses
- Correlation coefficient between two parameters is -12%



VH→cc (Full Run2) - ATLAS

The $VH, H \to b\bar{b}/c\bar{c}$ signal strengths can also be parameterised in terms of the ratio of coupling modifiers κ_c/κ_b

- Ratio insensitive to Γ_H, no assumptions on decays to BSM particles required
- Profile likelihood scan of the ratio κ_c/κ_b is performed, with κ_b treated as a free parameter →



Observed (expected) constraint of $|\kappa_c/\kappa_b| < 4.5\,(5.1)$ at 95% CL

Observed constraint is smaller than the ratio of the *b*-quark and *c*-quark masses $m_b/m_c = 4.578 \pm 0.008$ [Phys. Rev. D 98 (2018) 054517 (from lattice QCD)]

Experimental confirmation that the Higgs boson's coupling to the charm quark is weaker than its coupling to the bottom quark!

H→μμ

H→$\mu\mu$ (Full run 2) - CMS

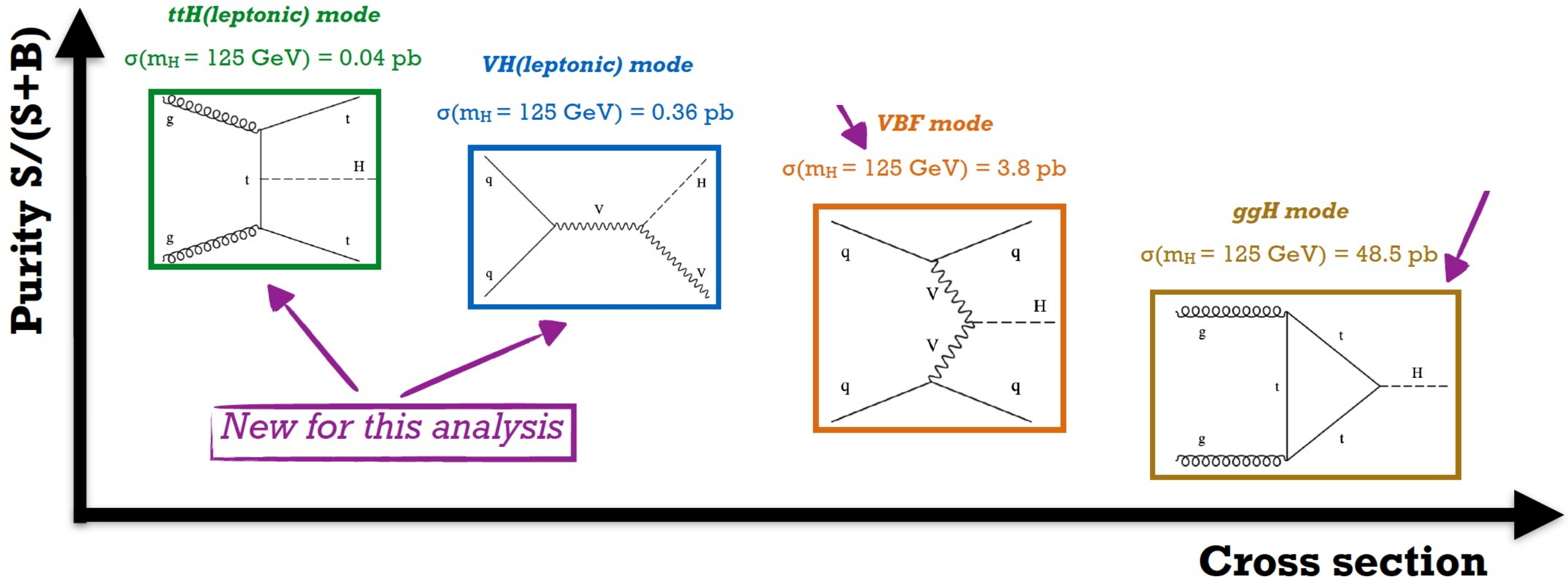
H→$\mu\mu$: very challenging to hunt at the LHC

JHEP01 (2021)148

- Very small BR: 2.2x10^{-4} + large Drell-Yan and leptonic tt+jets backgrounds
- It can rely on the excellent CMS muon energy resolution: $\sigma(Z \to \mu\mu) \sim 1.1\%$-$1.9\%$
- Search for a narrow peak over a falling background in $m_{\mu\mu}$ distribution

Analysis strategy designed to cope with all production modes.

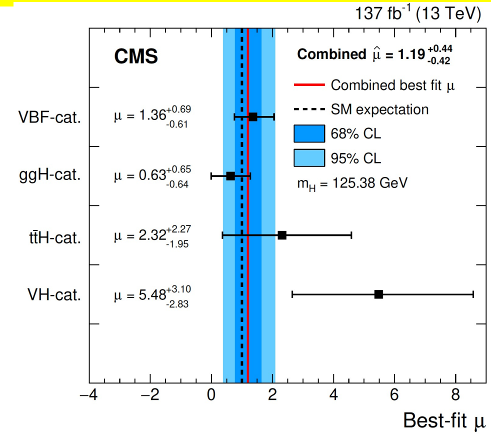
Common selection: single isolated muon trigger, two opposite-sign muons with 110 < m(μμ) < 150 GeV.

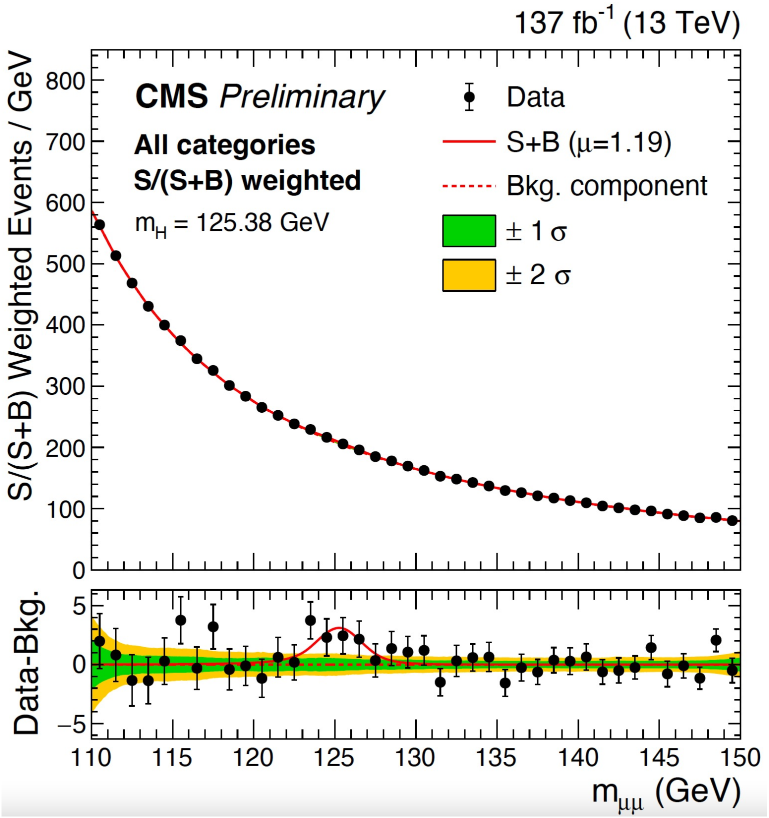


H→$\mu\mu$ (Full run 2) - CMS

Systematics:

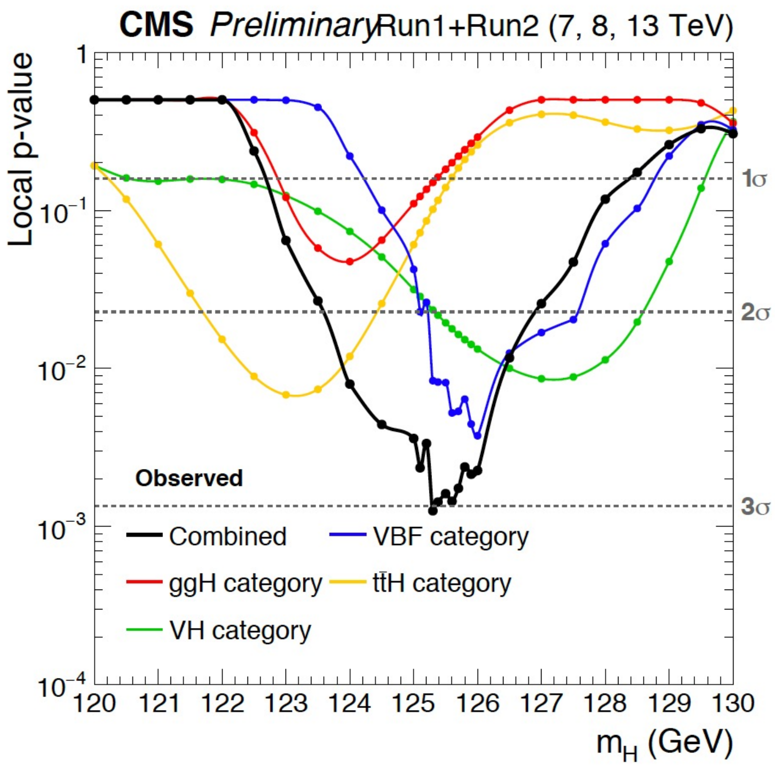
- mismodelling of the signal shape or rate
- calibration of μ momentum scale and resolution propagated to the shape of the signal m_{mm} distribution → variations of up to 0.1% in the peak position and up to 10% in width
- electron and muon selection efficiencies (0.5–1.5% per category)
- μ momentum scale and resolution (0.1–0.8% per category)
- jet energy scale and resolution (2–6% per category)
- efficiency of identifying b quark jets (1–3% per category)
- theoretical uncertainties on Higgs boson production cross sections, decay rate, and acceptance





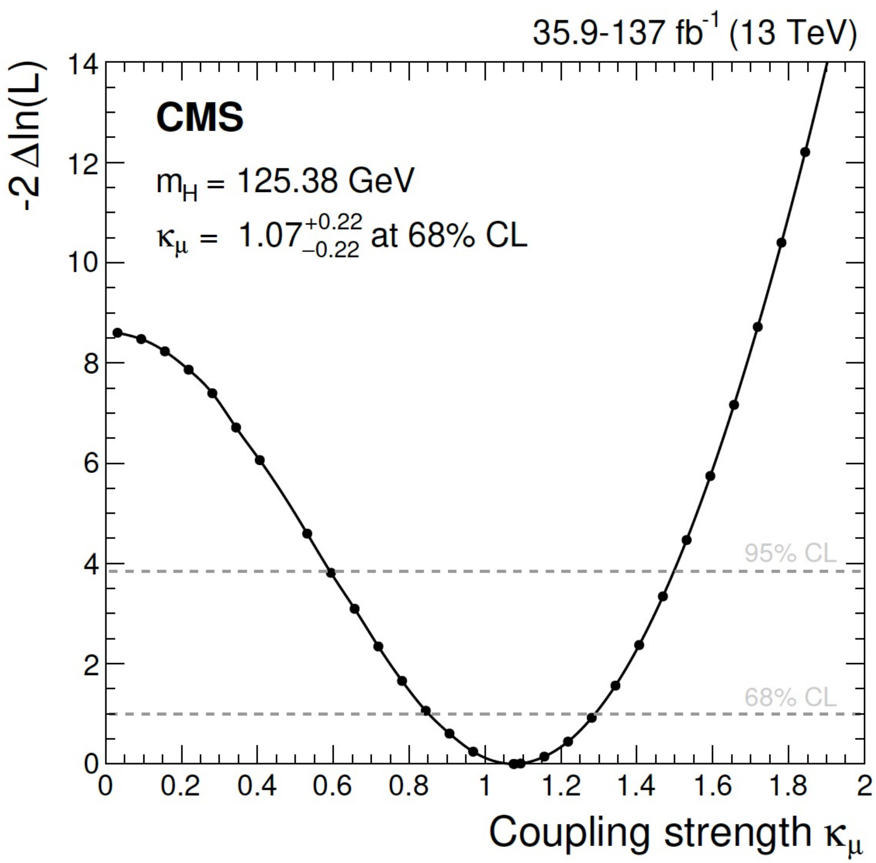
H→$\mu\mu$ (Full run 2) - CMS

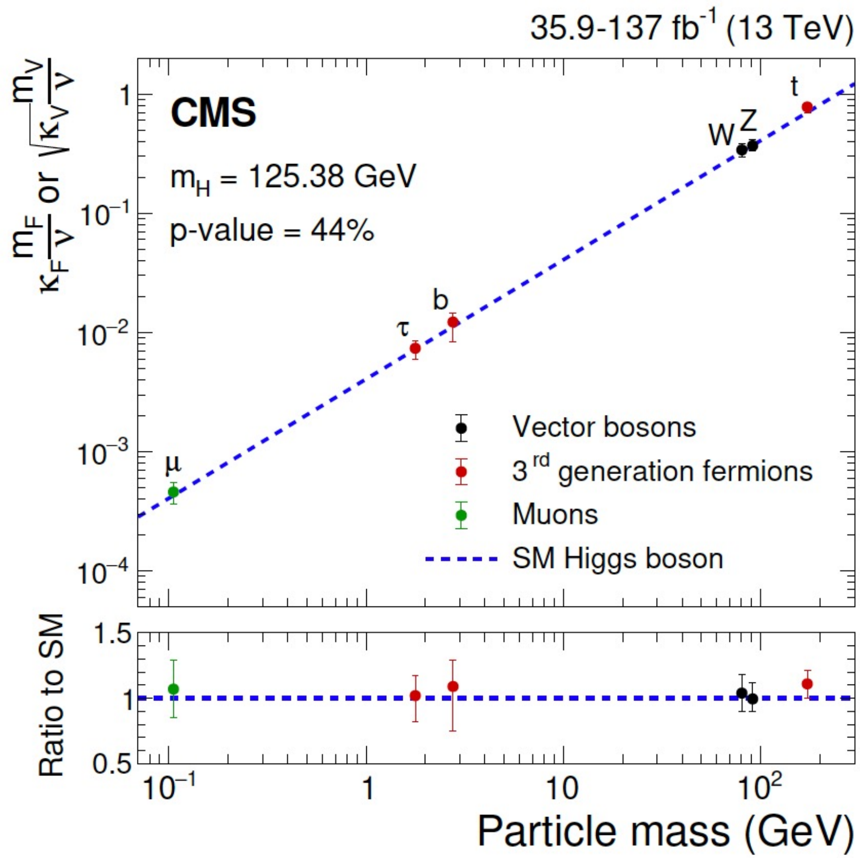
- Combination performed with CMS Run-1 H→μμ search.
  - Full p-value scan vs. m_H.
  - Run-1 cards adjusted to m_H = 125.38 GeV for nominal result.
- **Observed** (expected) **significance 2.98σ** (2.48σ).
- *Local minimum at m_H = 125.3 GeV 3.02σ.*
- *We therefore observe evidence for the Higgs boson decay to muons.*



Production category	Observed (expected) Signif.	Observed (expected) UL on μ
VBF	2.40 (1.77)	2.57 (1.22)
ggH	0.99 (1.56)	1.77 (1.28)
$t\bar{t}H$	1.20 (0.54)	6.48 (4.20)
VH	2.02 (0.42)	10.8 (5.13)
Combined $\sqrt{s} = 13$ TeV	2.95 (2.46)	1.94 (0.82)
Combined $\sqrt{s} = 7, 8, 13$ TeV	2.98 (2.48)	1.93 (0.81)

H→$\mu\mu$ (Full run 2) - CMS

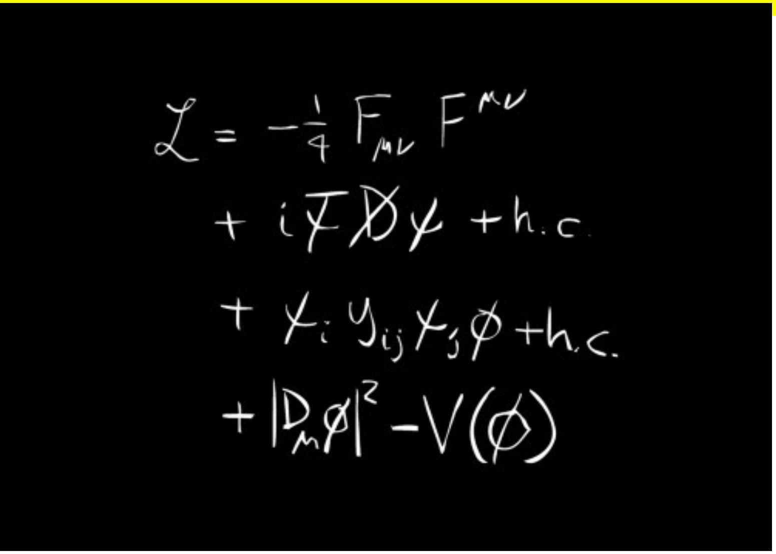




- Best fit value for k_μ is 1.07
- observed 68% CL interval is $0.85 < k_\mu < 1.29$

HH

SM Higgs potential and self-couplings



$$V(\phi^\dagger\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$
$$\supset \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 .$$

$$m_H = \sqrt{2\lambda v^2}$$
$$v \simeq 246 \text{ GeV.}$$
$$\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$$

Known m_H (~125 GeV), SM predicts $\lambda = m_H^2/ 2v^2$ (~0.13)

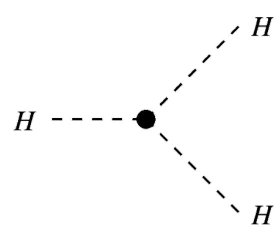
- Higgs field potential:

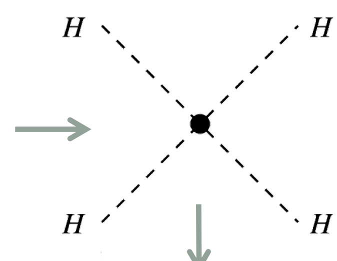
$$V(h) = V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4 + \cdots$$

Mass term

Higgs trilinear self-coupling (κλ) **Higgs pair production**

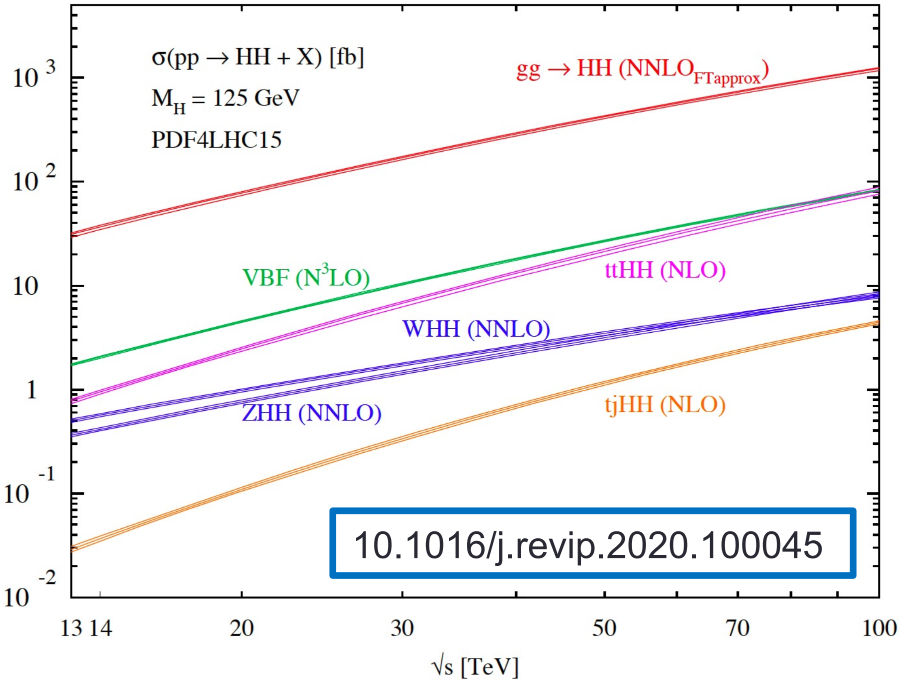
Higgs quadratic self-coupling





Out of reach even for HL-LHC

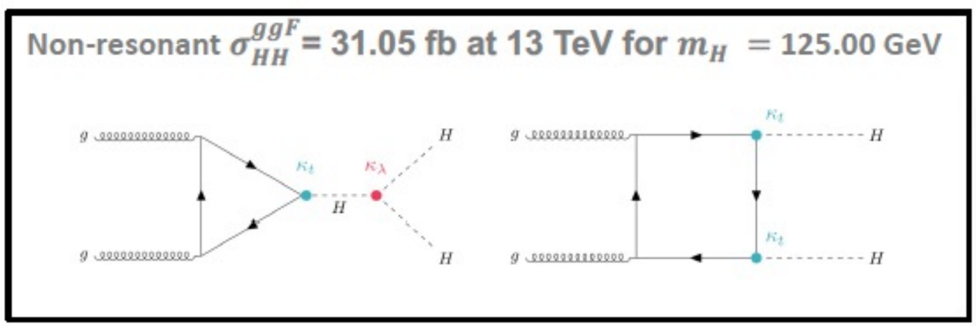
SM HH production at the LHC

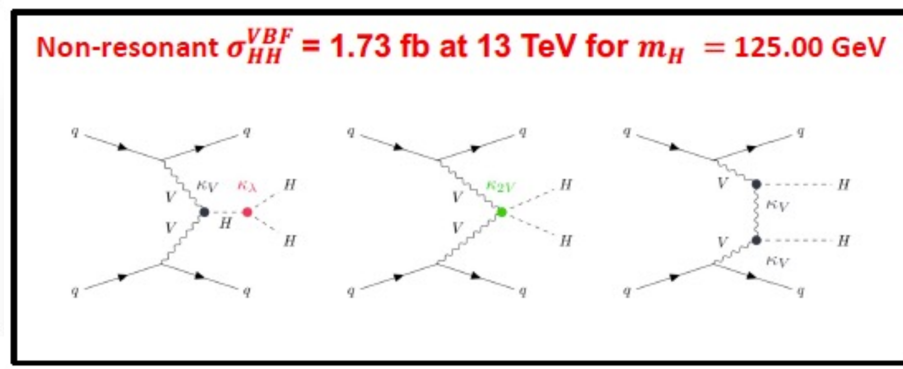


in fb

$\sqrt{s}$	13 TeV
ggF HH	$31.05^{+2.2\%}_{-5.0\%} \pm 3.0\%$
VBF HH	$1.73^{+0.03\%}_{-0.04\%} \pm 2.1\%$
ZHH	$0.363^{+3.4\%}_{-2.7\%} \pm 1.9\%$
W^+HH	$0.329^{+0.32\%}_{-0.41\%} \pm 2.2\%$
W^-HH	$0.173^{+1.2\%}_{-1.3\%} \pm 2.8\%$
$t\bar{t}HH$	$0.775^{+1.5\%}_{-4.3\%} \pm 3.2\%$
$tjHH$	$0.0289^{+5.5\%}_{-3.6\%} \pm 4.7\%$

- ggF HH: dominant, larger initial state radiation from gluons
- VBF HH: two forward jets with high mass and large rapidity gap
- VHH: vector boson (lν, ll', qq')
- ttHH: many b-jets, leptons, E_T^{miss}





σ_{HH} and kinematics depend on k_λ, k_{2V}, k_t, k_V couplings (and existence of new resonances)

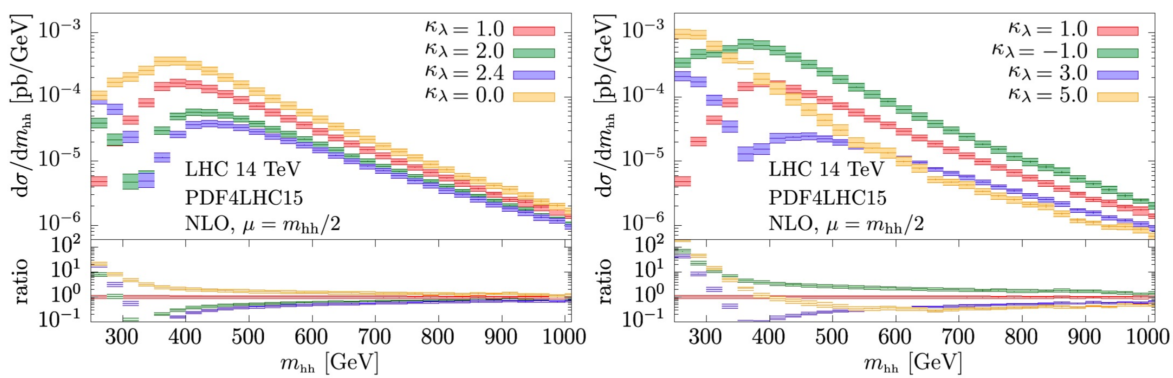
HH cross section as a function of k_λ

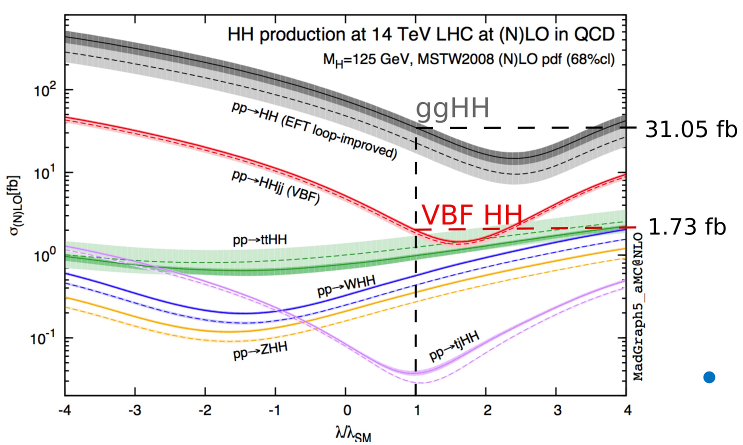
The HH production allows to search for new physics i.e. $k_\lambda \neq 1$

σ(ggF) @ NNLO

$\kappa_\lambda = -10:$	σ_{tot}	$=$	$1680^{+13\%}_{-14\%}$	fb
$\kappa_\lambda = -5:$	σ_{tot}	$=$	$598.9^{+13\%}_{-15\%}$	fb
$\kappa_\lambda = -1:$	σ_{tot}	$=$	$131.9^{+11\%}_{-16\%}$	fb
$\kappa_\lambda = 0:$	σ_{tot}	$=$	$70.38^{+8\%}_{-18\%}$	fb
$\kappa_\lambda = 1:$	σ_{tot}	$=$	$31.05^{+6\%}_{-23\%}$	fb
$\kappa_\lambda = 2:$	σ_{tot}	$=$	$13.81^{+3\%}_{-28\%}$	fb
$\kappa_\lambda = 2.4:$	σ_{tot}	$=$	$13.10^{+6\%}_{-27\%}$	fb
$\kappa_\lambda = 3:$	σ_{tot}	$=$	$18.67^{+12\%}_{-22\%}$	fb
$\kappa_\lambda = 5:$	σ_{tot}	$=$	$94.82^{+18\%}_{-13\%}$	fb
$\kappa_\lambda = 10:$	σ_{tot}	$=$	$672.2^{+16\%}_{-13\%}$	fb

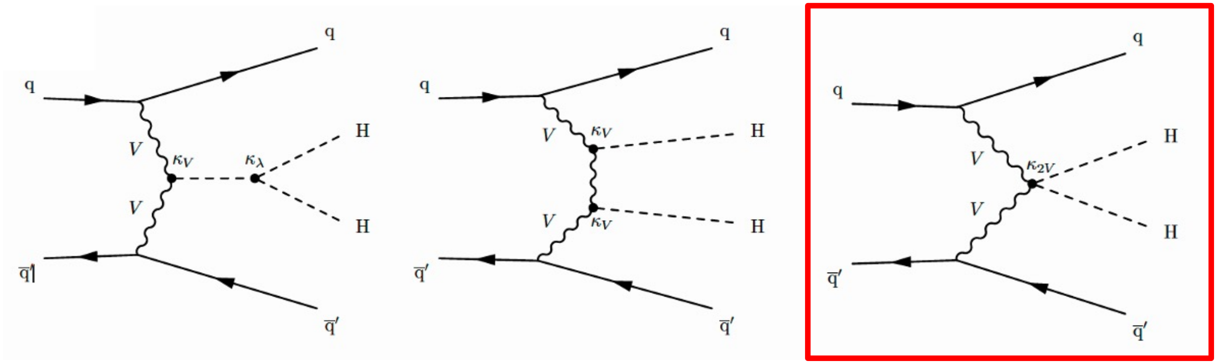
- k_λ = -10 leads to the largest total σ(ggF) in the table.
- dip in the m_{HH} spectrum around k_λ = 2.4, because of maximal destructive interference between diagrams containing the trilinear coupling (triangle-type contr.) and "background " diagrams (box-type contr.).
- at large $|k_\lambda|$: softer m_{HH} spectrum and large cross section
- at medium $|k_\lambda|$: hard m_{HH} spectrum → boosted signatures





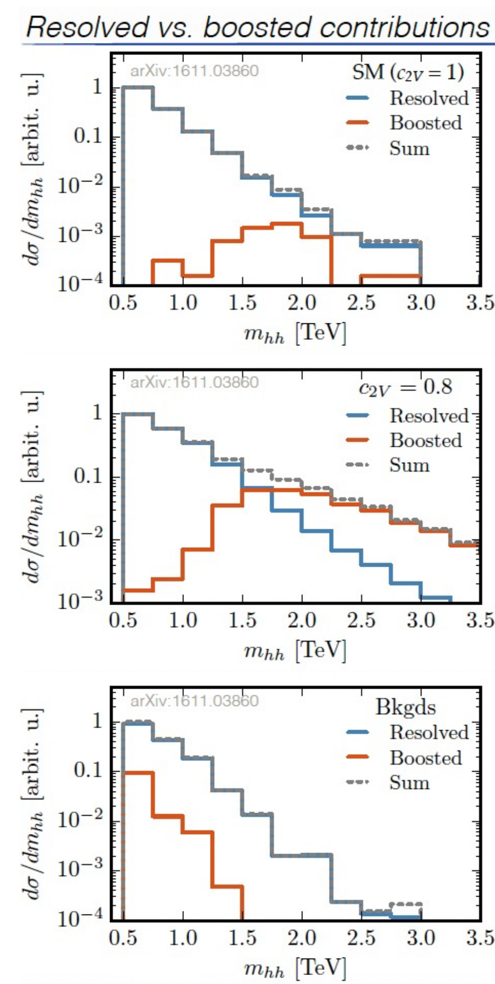
- σ(VBF) has a minimum at around $k_\lambda \approx 1.65$

VBF HH cross section as a function of k_λ

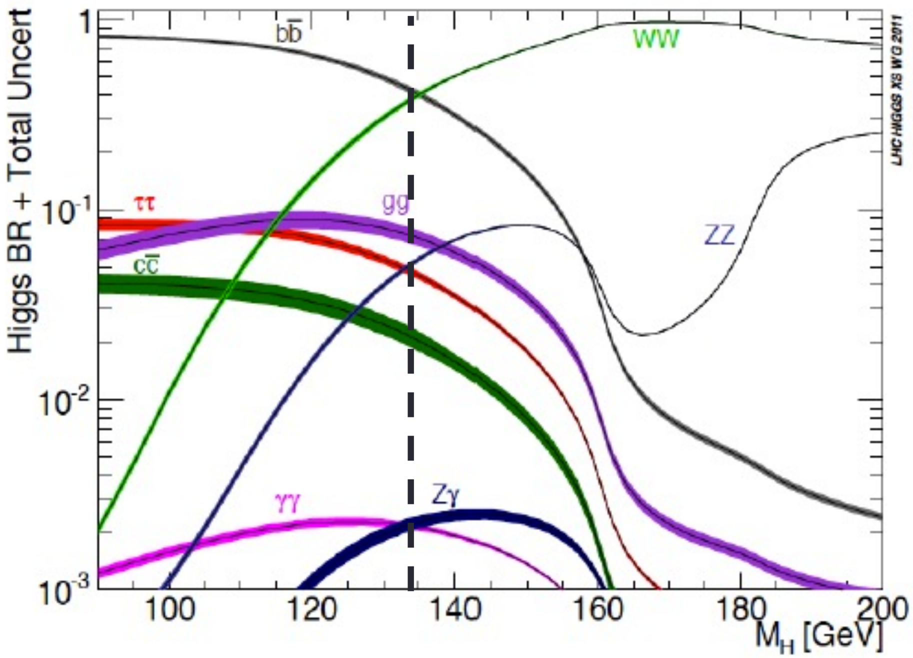


3 couplings for the VBF production:

- the Higgs self-coupling (HHH) probed also via the ggF mode
- the Higgs-vector-boson coupling (VVH) constrained by Higgs boson measurements
- the quartic coupling between two vector bosons and two Higgs bosons (**VVHH**)
  - the VBF HH mode provides a unique handle to probe the quartic VVHH coupling
  - k_{2V} defined to parametrize the strength of these couplings w.r.t. their SM values (k_{2V} =1 in the SM)
  - If the VVhh coupling deviates from the SM ($k_{2V} \neq 1$), the cross section can be enhanced
  - In BSM scenarios with **modified couplings** ($k_{2V} \neq 1$, $k_V \neq 1$), **a significant fraction of signal becomes boosted**, i.e. with decay products merged into large-R jets (arXiv:1611.03860)



HH decay channels



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%

Most sensitive channels:

- $HH \to$ bb $\gamma\gamma$
- $HH \to$ bb $\tau\tau$
- $HH \to$ bbbb

Most final states rely on bb reconstruction

BR HH→xxyy

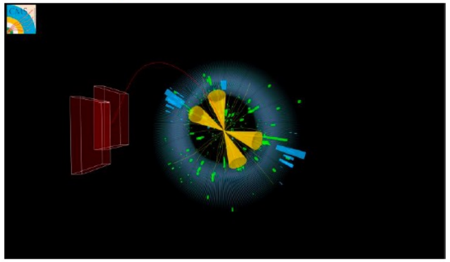
(m_H = 125 GeV)

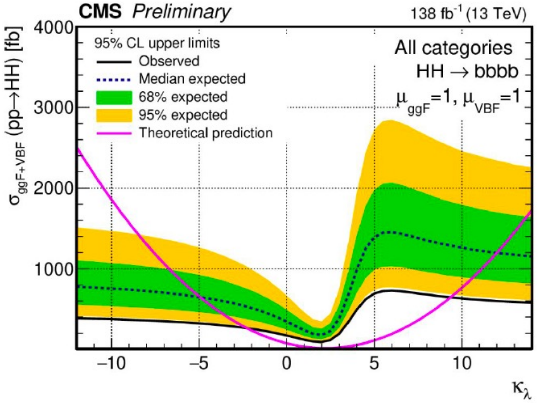
Branching Ratio	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

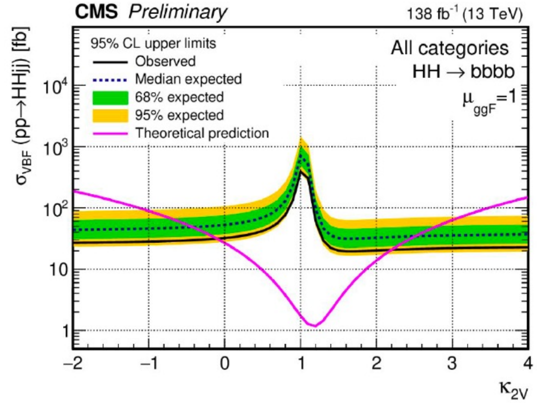
CMS: HH→bbbb (resolved)

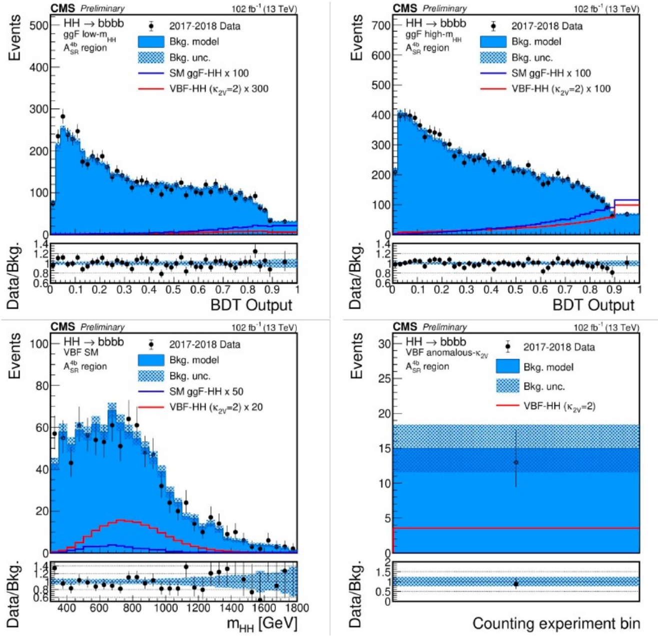
CMS PAS HIG-20-005

- Di-Higgs production exploring several couplings: HHH, HVV, HHVV
  - Dedicated HLT triggers with 3 b-jet
  - Targets both ggF and VBF production
- New multivariate analysis strategy
  - New background estimation from multiple control regions
- B-tagging improvements
  - Phase-1 pixel detector upgrade
  - Latest tagger from BTV (DeepFlavour)





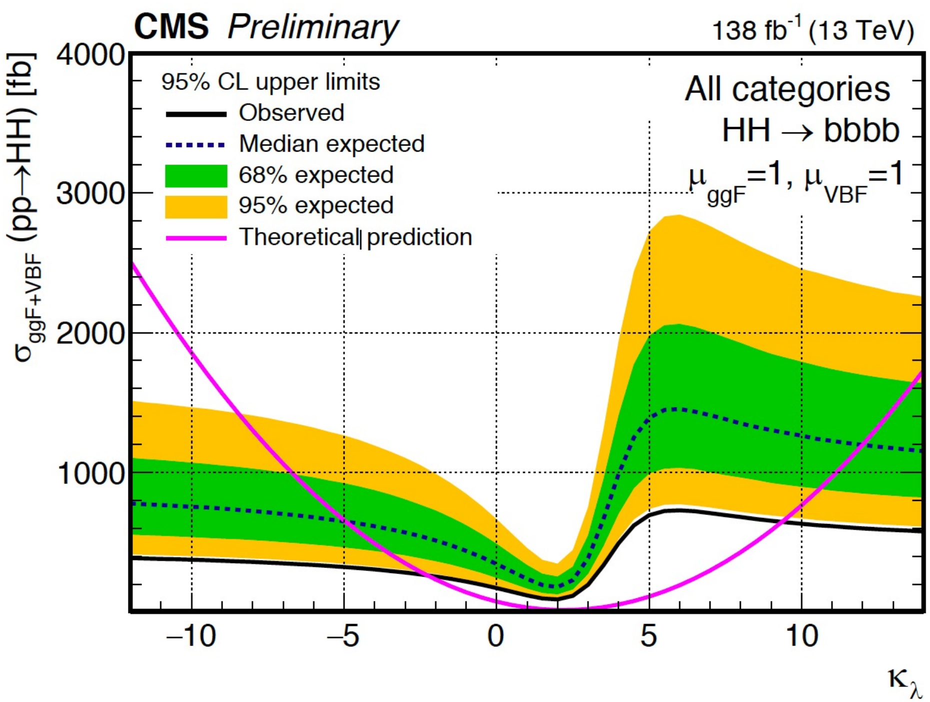




CMS: HH→bbbb (resolved)

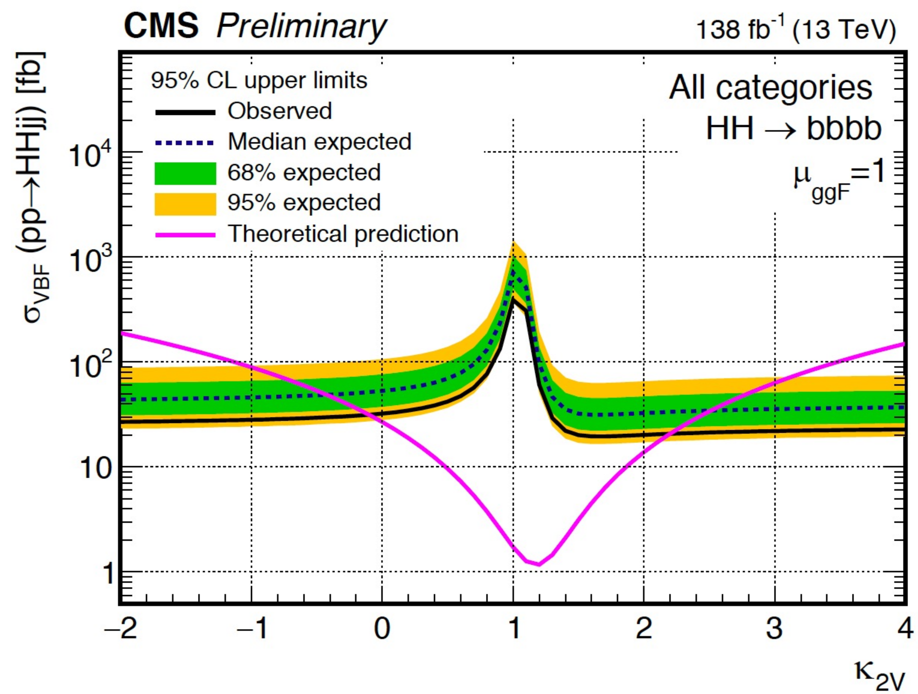
Observed (expected) $\sigma/\sigma_{SM} < 3.7(7.3)$ at 95% CL

Floating ggF+VBF signal strength



Observed: $-2.5 < \kappa_\lambda < 9.5$
Expected: $-5.0 < \kappa_\lambda < 12.0$

Floating VBF and fixing ggF to SM



Observed: $-0.1 < \kappa_{VV} < 2.2$
Expected: $-0.4 < \kappa_{VV} < 2.5$

CMS: HH→bbbb (VBF boosted)

Analysis strategy

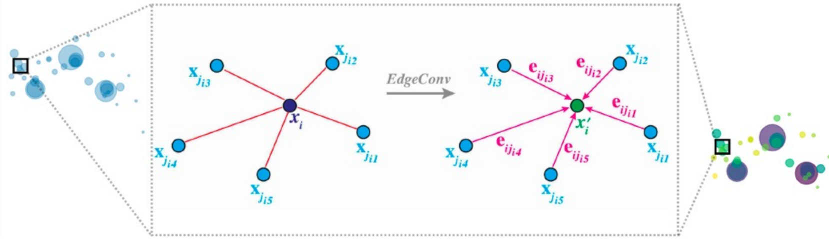
- We target the **HH→4b final state**, with the largest branching fraction (**34%**)
  - Reconstruct the H→bb decay products as AK8 jets, considering the **two highest-p_T AK8 jets** in the event as Higgs candidates
  - Use AK8 jet substructure to identify H→bb decays with **ParticleNet** algorithm
  - Reconstruct Higgs candidate mass with ParticleNet-based **regression** algorithm
  - Selection of **VBF** topology: **two AK4 jets** with large dijet mass and $\Delta\eta$ separation
- **Benefits of the boosted strategy**
  - Enhanced sensitivity for anomalous couplings
  - H→bb decay products in a single jet → exploit correlations for Higgs identification
  - Less combinatorics than in the resolved topology (with four AK4 jets + VBF jets)
  - Only small backgrounds from the tails of SM processes
- **Background estimation**
  - **TTbar** background from simulation, with corrections from a top-enriched region
  - **QCD multijet** background estimated with a data-driven method (ABCD)
- **Signal extraction** using **HH invariant mass** (m_{HH}), reconstructed from the two AK8 j

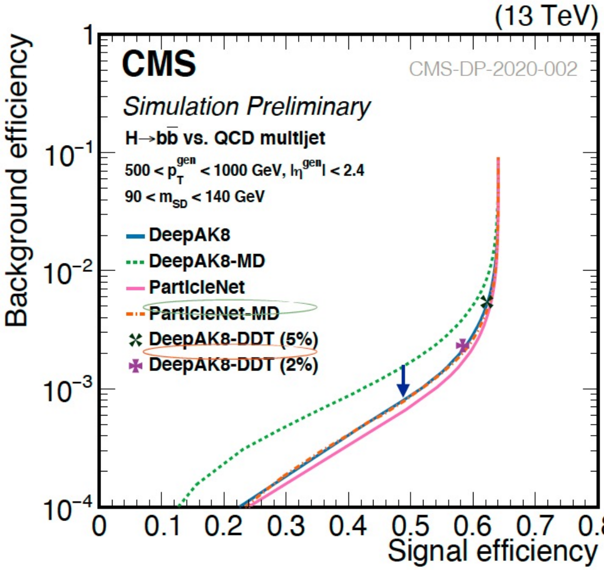
CMS: HH→bbbb (VBF boosted)

Jet classification

CMS-DP-2020-002

- **ParticleNet** jet classifier [arXiv:1902.08570]
  - Permutation-invariant **graph neural network**, based on dynamic graph convolutional neural networks
  - Jets treated as unordered sets of particles in space
  - Inputs: PF candidates & secondary vertices
  - **Multiclassifier** with several output nodes P; **bb-discriminant D_{bb} =** P[X->bb] / (P[X->bb]+P[QCD])

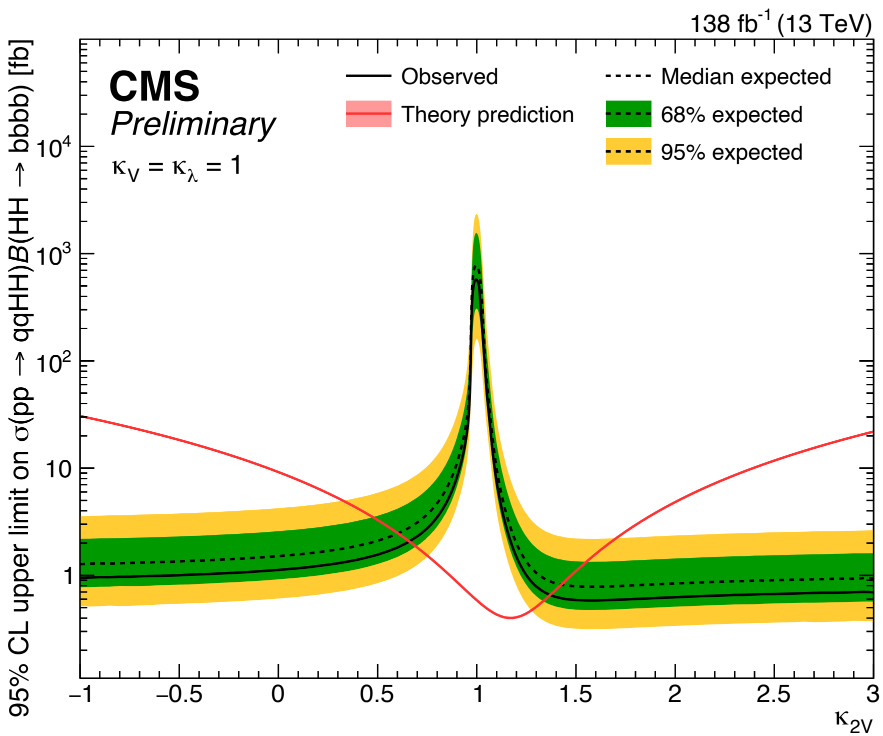


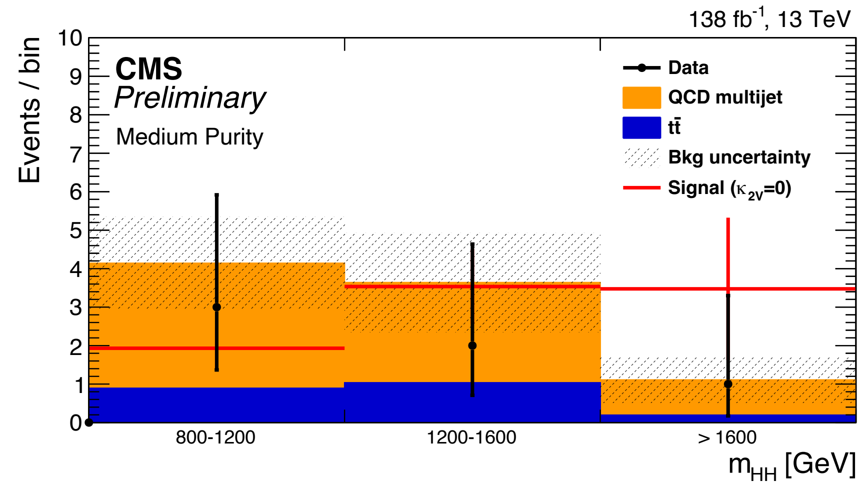


- **Mass decorrelated** (MD) version is used in this analysis
  - Trained using a sample of spin-0 particles with a flat mass spectrum from 15 to 250 GeV (signal) and QCD multijet sample (background)
  - Events reweighted to obtain flat distributions in jet p_T and m_{SD}
- Significant **performance improvement** compared to DeepAK8
  - Background rejection improved by a factor of ~2 per jet → factor of ~4 for HH
- The **calibration** of the ParticleNet tagger performed using g→bb jets
  - Scale factors approved by BTV,
  - The **SFs are consistent with 1**, with uncertainties typically around 20%

CMS: HH→bbbb (VBF boosted)

Post-fit HH invariant mass and exclusion limits



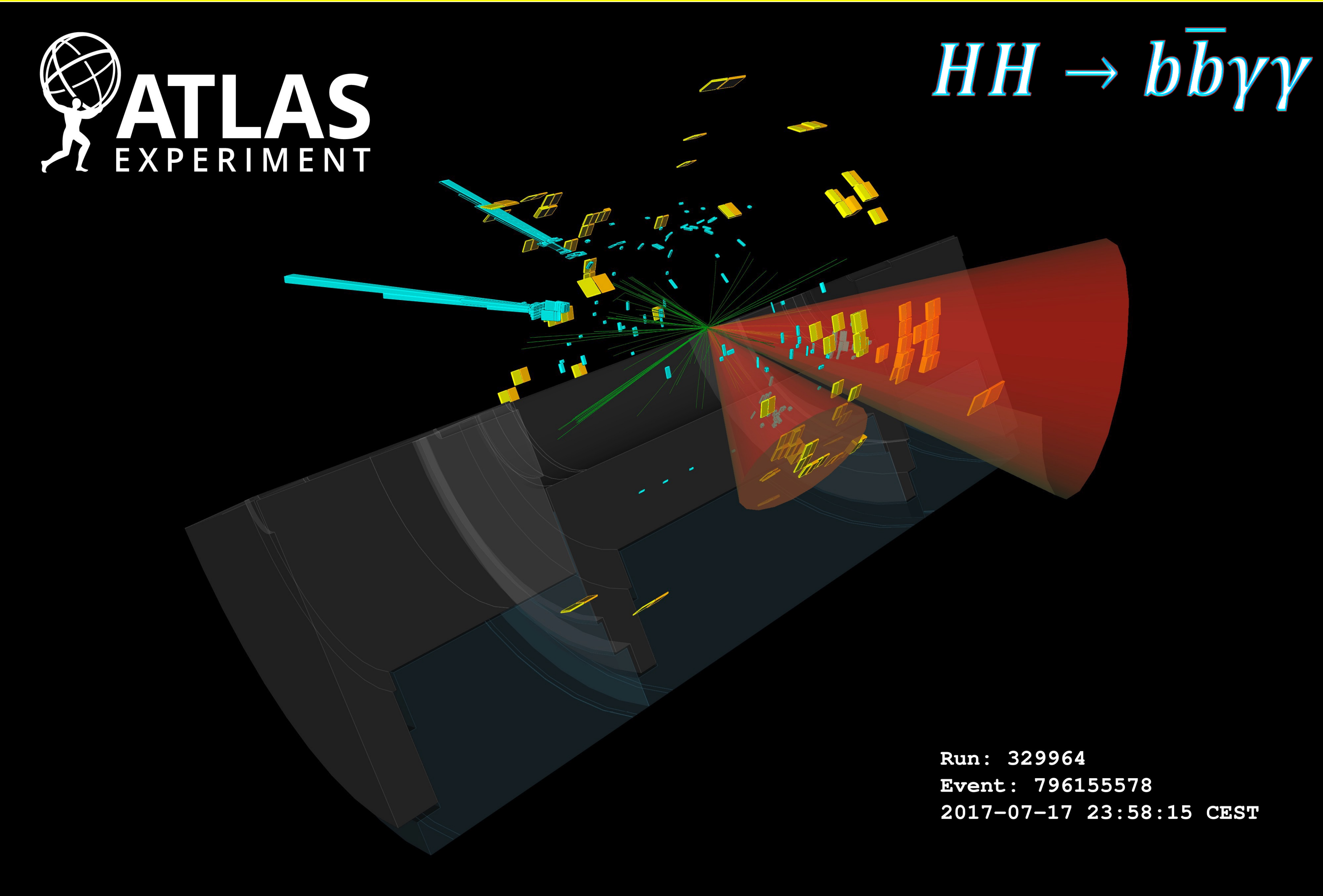


Comparison to previous results:

- CMS HH→4b resolved analysis (HIG-20-005) reports $-0.1 < \kappa_{2V} < 2.2$
- ATLAS VBF HH→4b resolved analysis (arXiv:2001.05178) reports $-0.6 < \kappa_{2V} < 2.9$

Assuming that all other Higgs boson couplings are equal 1, i.e. equal to their SM values, the observed (expected) limit excludes all coupling values outside the range **$0.6 < \kappa_{2V} < 1.4$** ($0.6 < \kappa_{2V} < 1.4$) at 95% CL, which is **the strongest constraint on κ_{2V} achieved so far.**
A hypothesis of vanishing κ_{2V} coupling, namely $\kappa_{2V}=0$ with other couplings equal to 1, is excluded at a CL higher than 99.99%."

ATLAS: HH→bbγγ

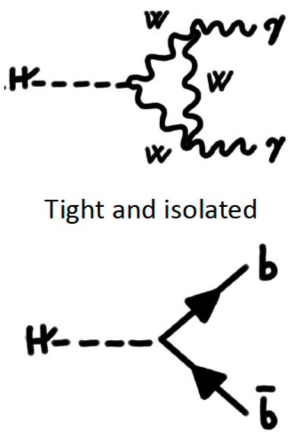


ATLAS: HH→bbγγ

ATLAS-CONF-2021-016

Small BR, but fully **reconstructable** final state, **clean signal extraction**

Di-photon triggers with **E_T > 35, 25 GeV** (82.9% efficiency for non-resonant signal, 69.5% for m_X = 300 GeV)



Tight and isolated

B-jet energy corrections

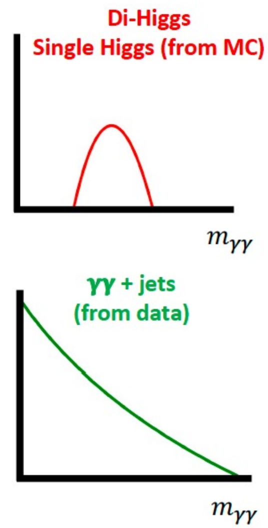
Object selection

Event categorization

MVA approach

4 categories for non-resonant analysis

1 category per m_X for resonant analysis



Modeling of discriminant variable

Simultaneous likelihood fit to all categories

SM σ limits and

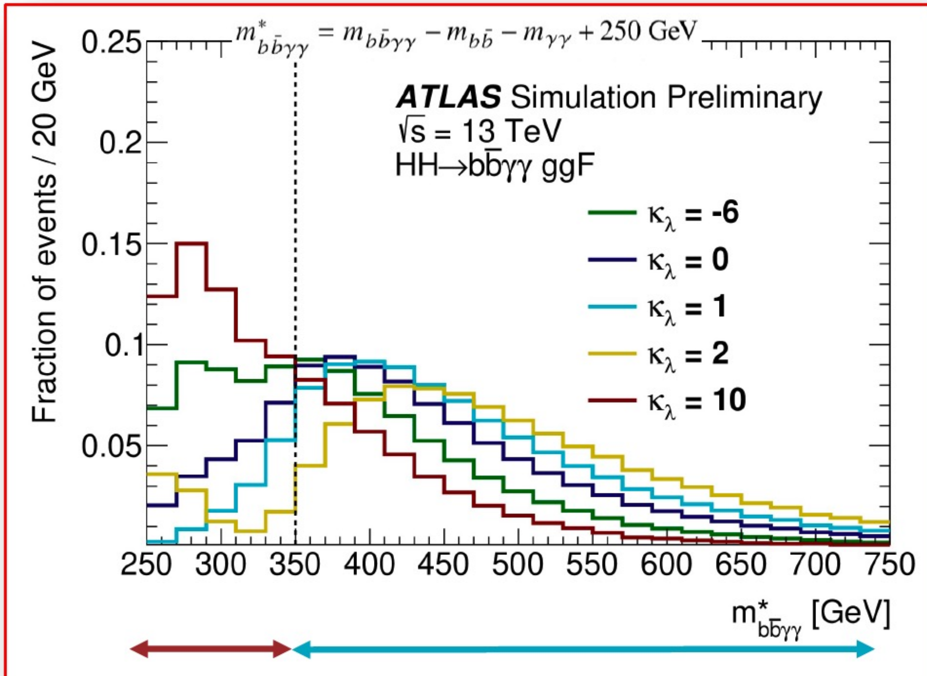
σ vs k_λ

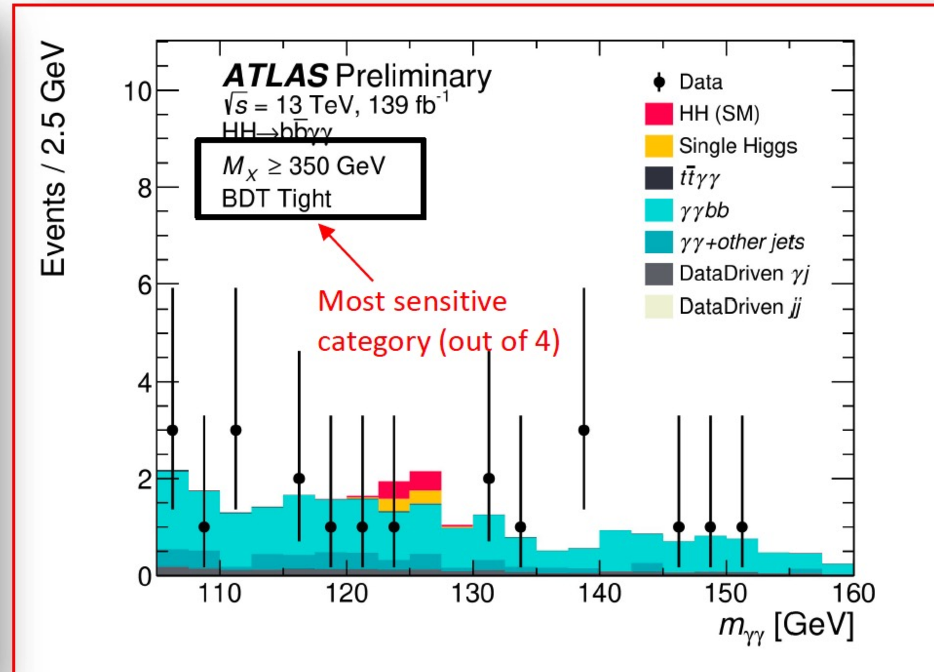
for **non resonant** analysis

σ vs m_X

for **resonant** analysis

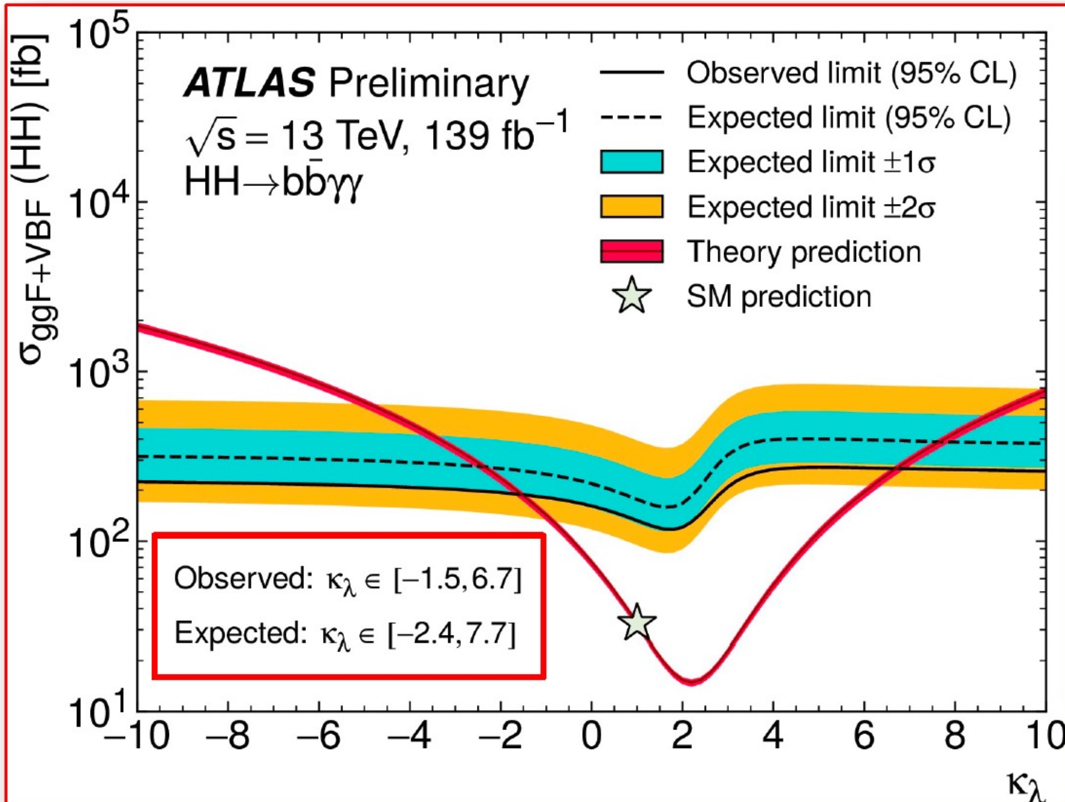
ATLAS: HH→bb$\gamma\gamma$



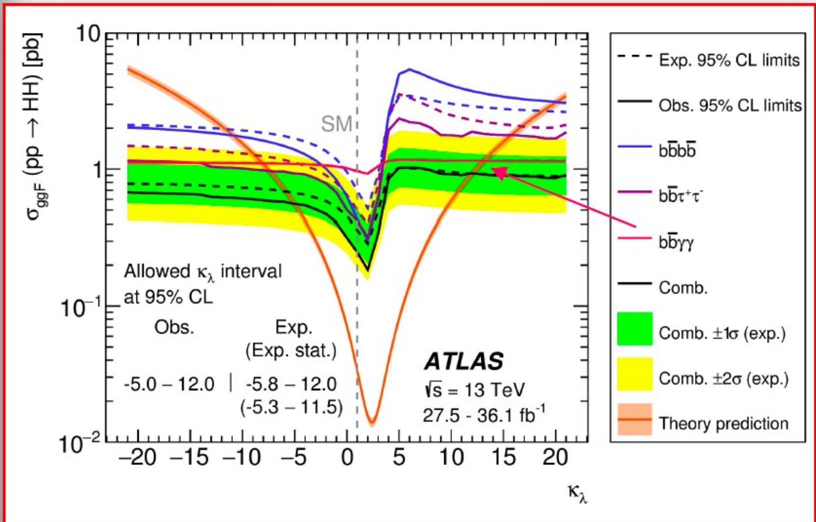


- Low and High $m^*_{b\bar{b}\gamma\gamma}$
  - < 350 GeV for BSM, > 350 GeV for SM
- BDT to discriminate signal ($k_\lambda = 1, 10$) from backgrounds
  - m_{bb} very powerful (b-jet energy corrections improve resolution by ~ **20%**)
- Loose and Tight **BDT**
  - Boundaries chosen to maximize combined expected significance

ATLAS: HH→bbγγ



Earlier ATLAS results



4.1 (5.5) x SM σ_{HH}

5x improvement wrt previous result (~ 26 x SM), ~3x due to analysis techniques

driven by m_{HH} categorization & MVA as well as b-jet corrections

Statistically dominated, few % impact from systematics

World's best constraints to date on Higgs boson's self coupling!

CMS: HH→bbγγ

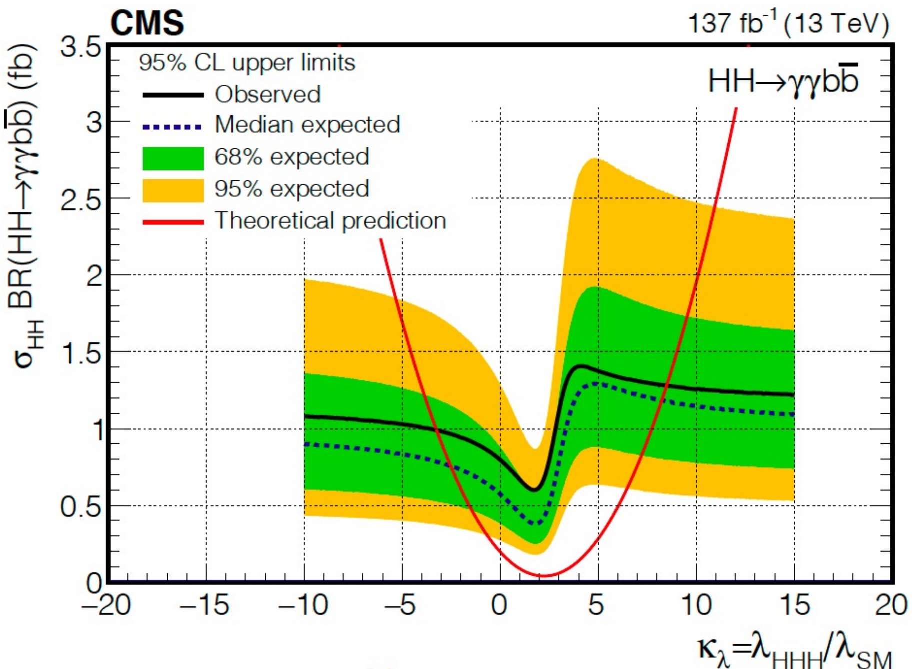
Floating common signal strength for ggHH + VBFHH

PAS HIG-19-018

95% U.L., result on SM for full Run II, 136.8 fb^{-1}

	Observed	Expected
μ_{HH} (incl.)	7.7	5.17

κ_λ scan for the full RunII



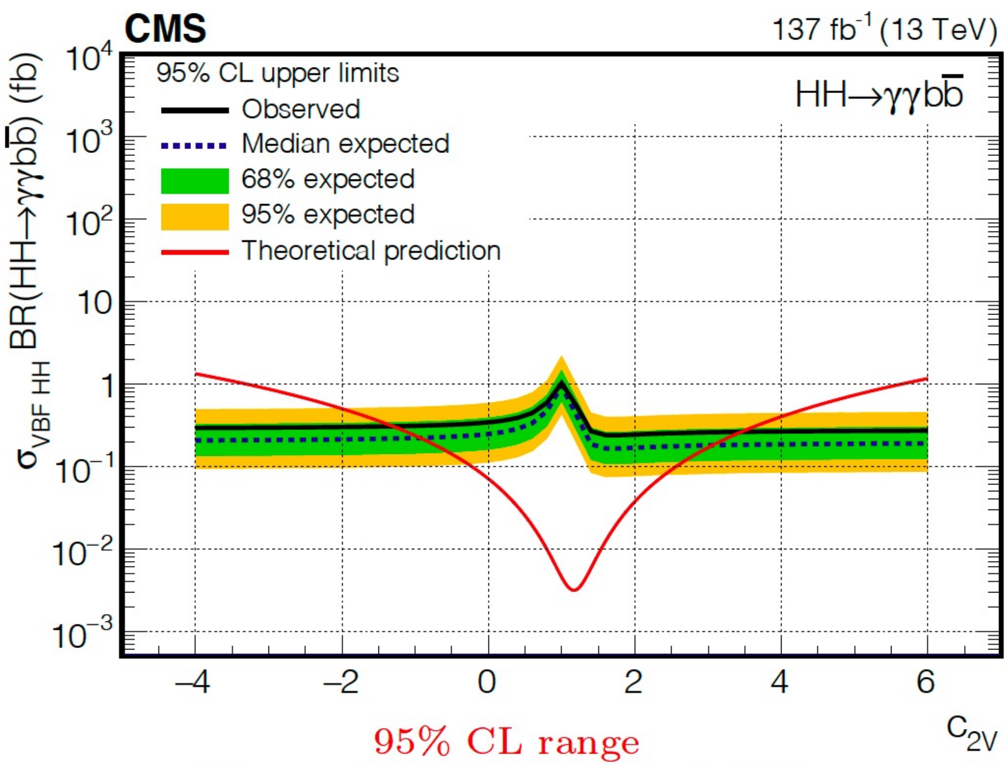
95% CL range

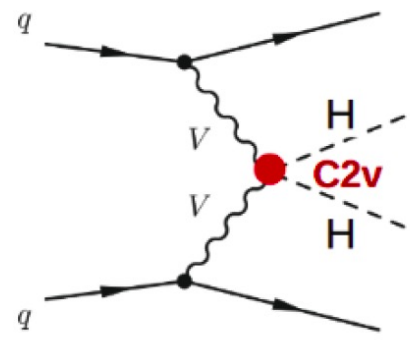
Observed: **-3.26** $< \kappa_\lambda <$ **8.48**

Expected: **-2.54** $< \kappa_\lambda <$ **8.23**

CMS: HH→bbγγ

C_{2V} scan for the full RunII





95% CL range

Observed: **-1.31** $< C_{2V} <$ **3.45**

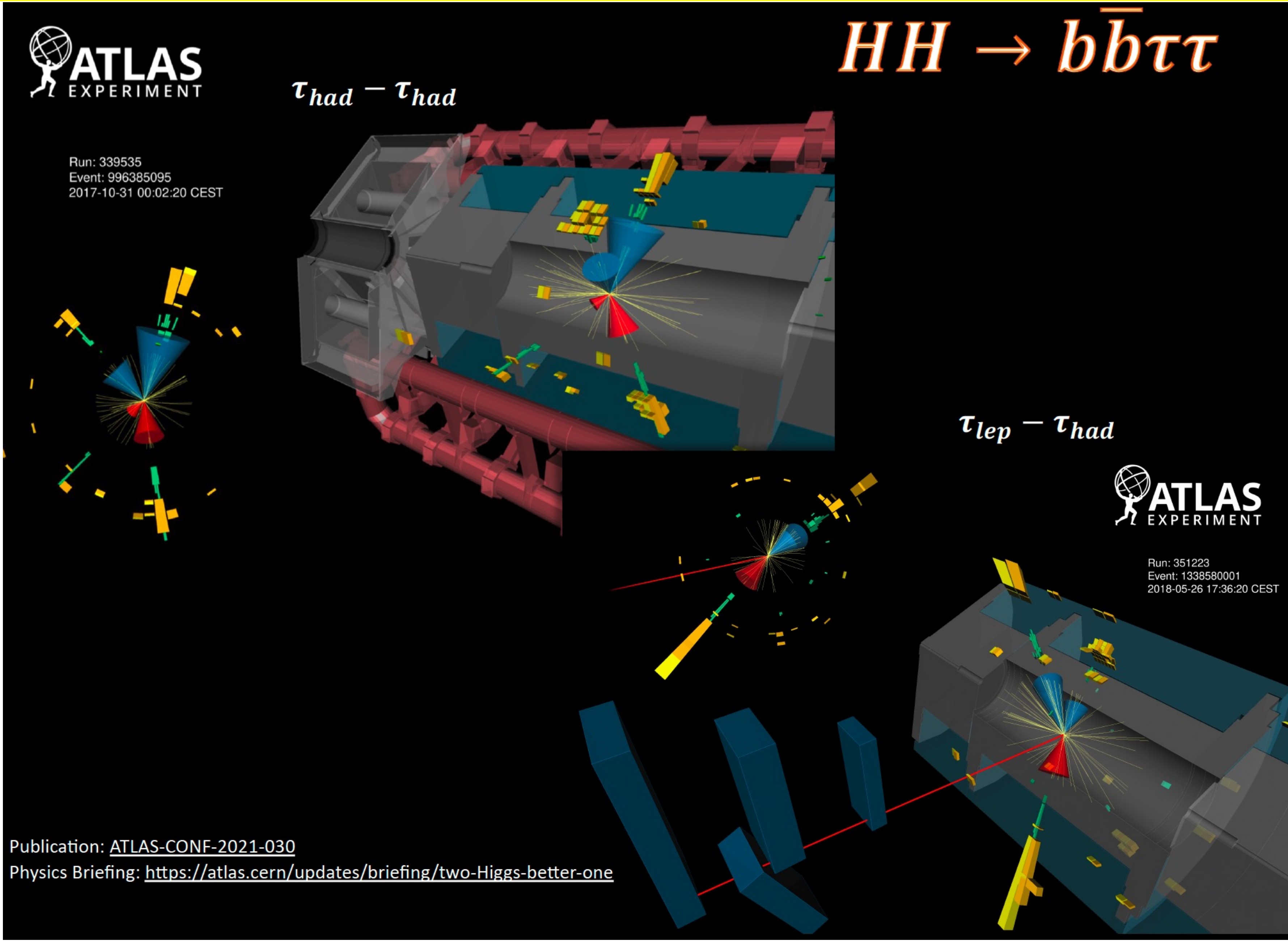
Expected: **-0.93** $< C_{2V} <$ **3.05**

Floating **VBFHH** signal strength only,
ggHH constrained to SM within uncertainties, $C_V = 1$, $\kappa_\lambda = 1$

95% U.L., result on SM for full Run II, 136.8 fb^{-1}

	Observed	Expected
μ_{VBFHH}	225	208

ATLAS: HH→bbττ



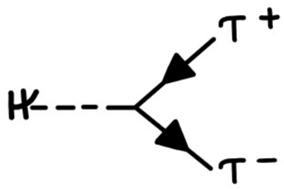
ATLAS: HH→bb$\tau\tau$

ATLAS-CONF-2021-030

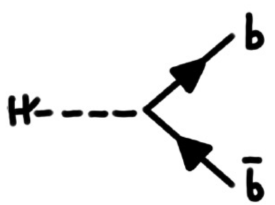
Relatively large BR and **relatively clean final state**

Single Tau Trigger & **Di-Tau** Trigger **for** $\tau_{had}\,\tau_{had}$

Single Lepton Trigger (SLT) and **Lepton+Tau Trigger** (LTT) **in** $\tau_{lep}\,\tau_{had}$

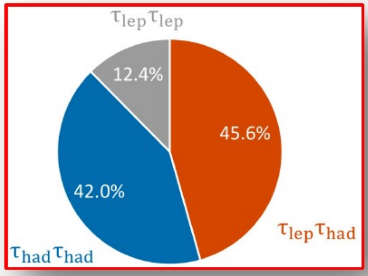


Hadronic & Leptonic



B-jet energy corrections

Object selection



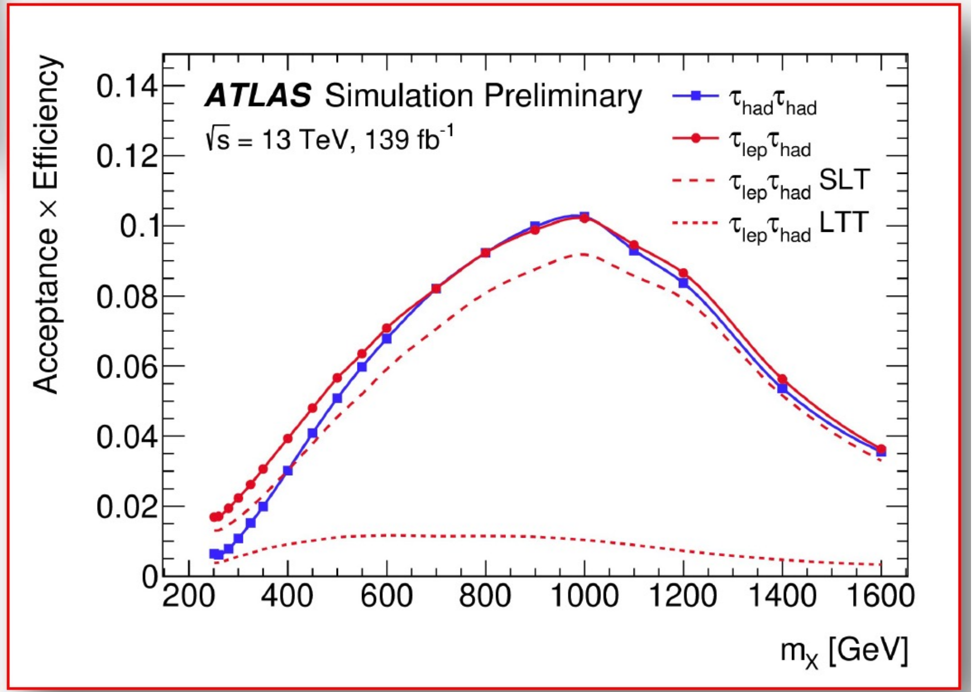
Event categorization

MVA in 3 categories:

$\tau_{had}\,\tau_{had}$ (opp. charged)

$\tau_{lep}\,\tau_{had}$ (e/μ & opp. charged τ) **LTT** **SLT**

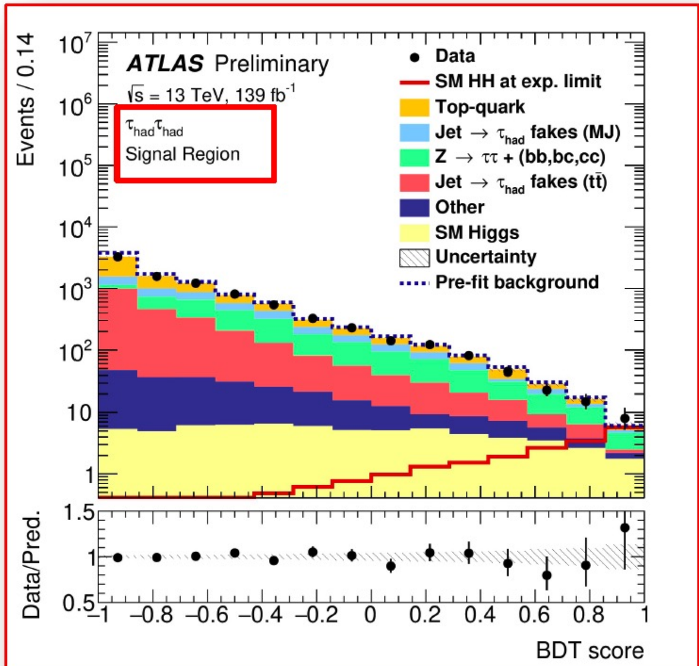
Control region for Z+HF (m_{ll})



ATLAS: HH→bbττ

Binned maximum-likelihood fit of the MVA score to data
(simultaneous in all categories)

Non-resonant analysis thoroughly optimized for SM cross-section limit!



ATLAS-CONF-2021-030

		Observed	−2 σ	−1 σ	Expected	+1 σ	+2 σ
$\tau_{had}\tau_{had}$	$\sigma_{ggF+VBF}$ [fb]	145	70.5	94.6	131	183	245
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	4.95	2.38	3.19	4.43	6.17	8.27
$\tau_{lep}\tau_{had}$	$\sigma_{ggF+VBF}$ [fb]	265	124	167	231	322	432
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	9.16	4.22	5.66	7.86	10.9	14.7
Combined	$\sigma_{ggF+VBF}$ [fb]	135	61.3	82.3	114	159	213
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	4.65	2.08	2.79	3.87	5.39	7.22

4x improvement wrt to previous results! (12.7 x SM),

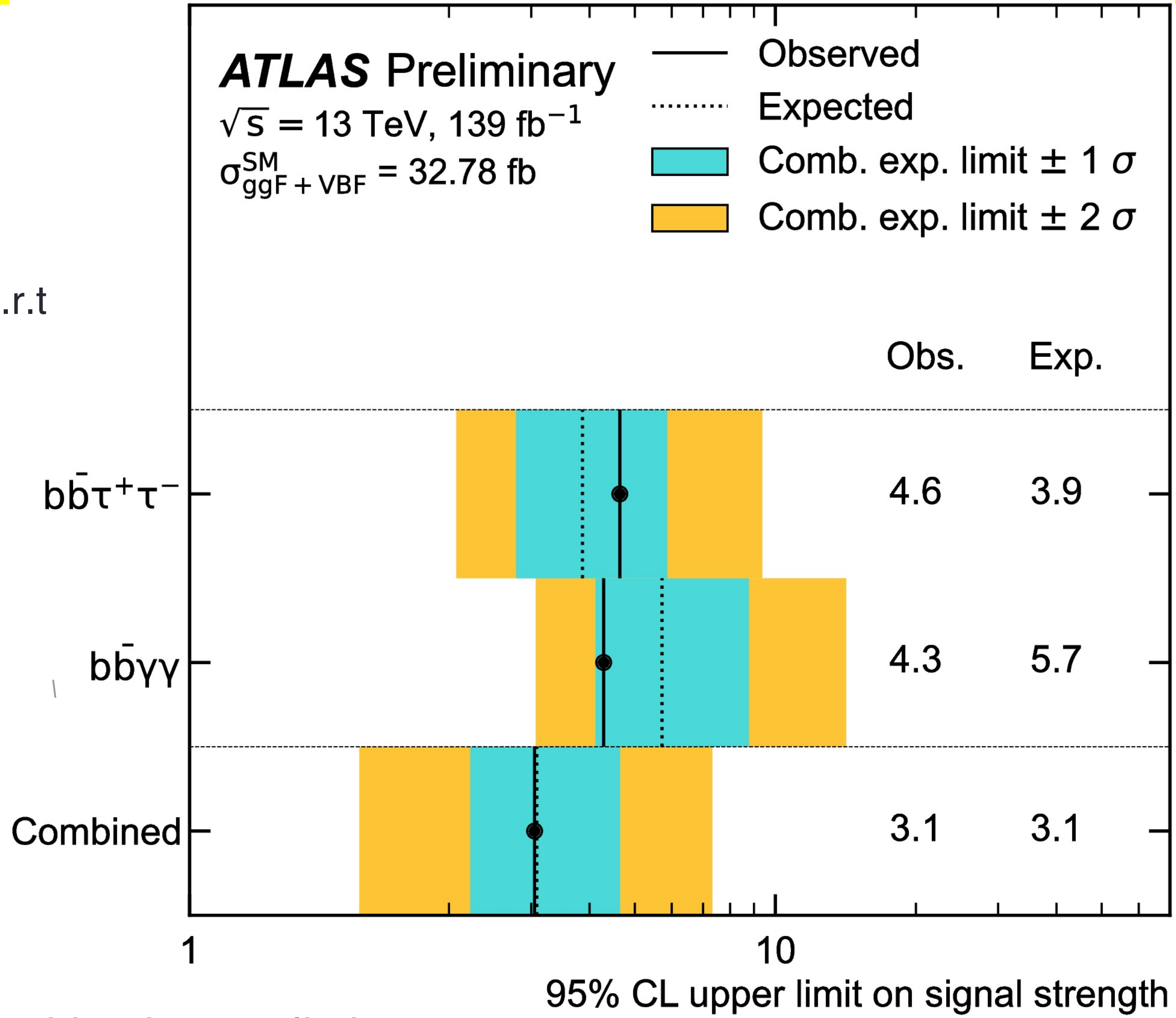
2x due to the τ and *b*-jet reconstruction and identification improvements and to analysis techniques (MVA & fake-τ estimation methods).

- Statistically dominated, largest systematics from background modeling

HH current public results by ATLAS

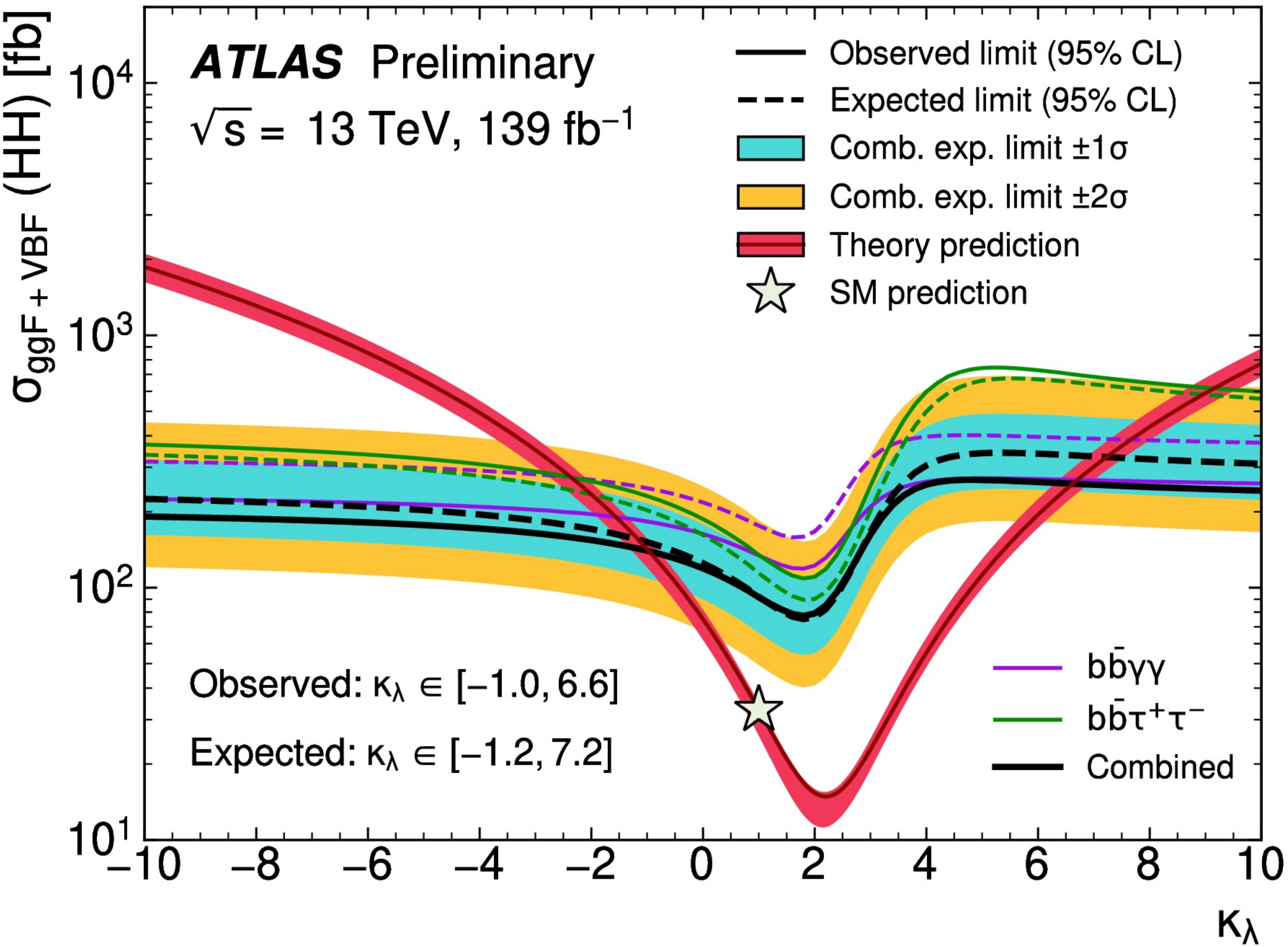
bb$\tau\tau$: a factor 4 improvement w.r.t previous result to 36fb^{-1} (PRL 121(2018)191801):

bb$\gamma\gamma$: a factor 4 improvement w.r.t previous result JHEP(2018)040 due to improved luminosity, b-jet reconstruction and analysis optimizations

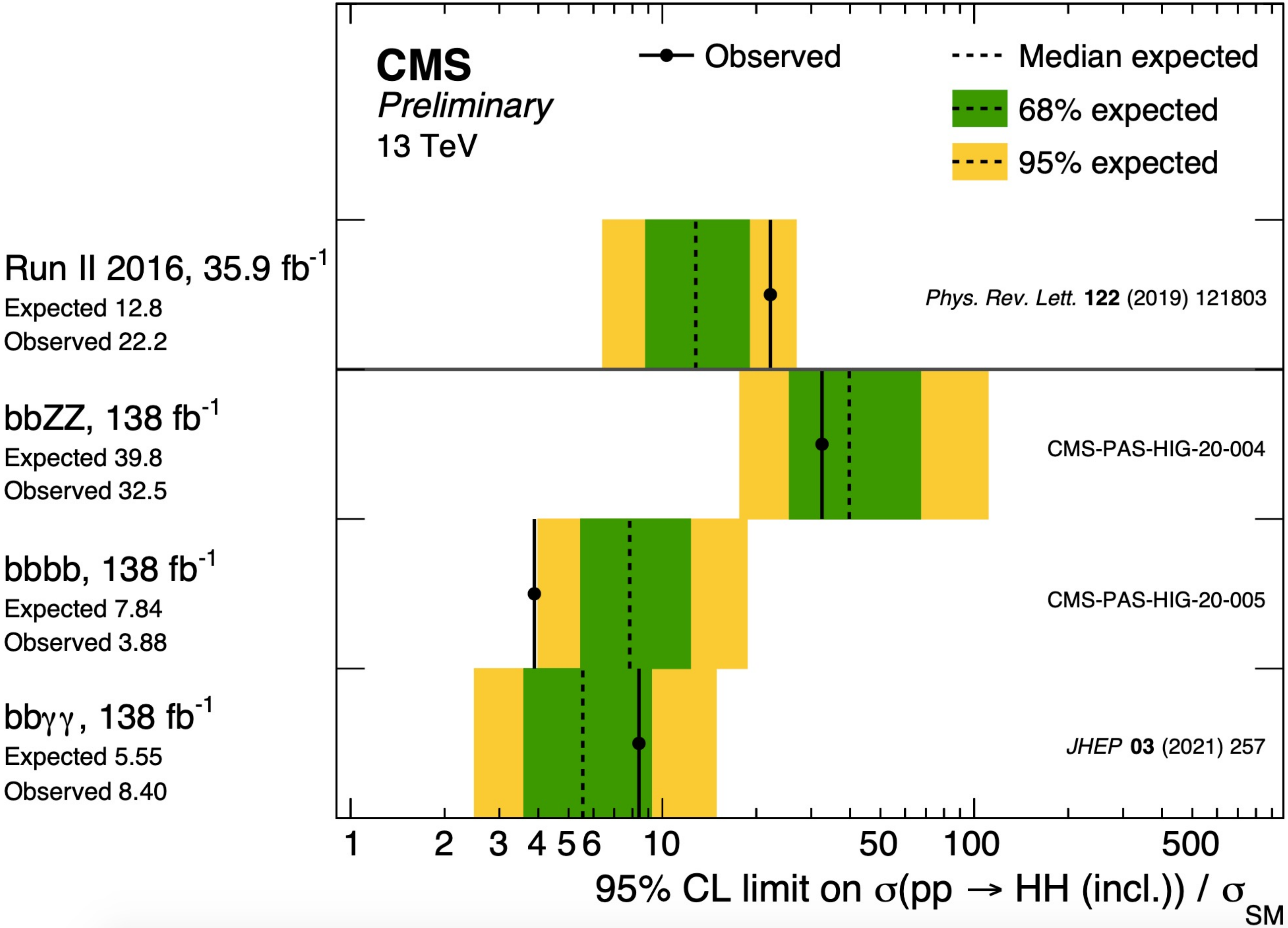


The observed (expected) combined upper limit is found to be 3.1 (3.1) times the SM prediction.

HH current public results by ATLAS



HH current public results by CMS



Physics landscape at the end of Run 2

LHC experiments confirm that the SM is robust but it should not be the ultimate theory of particle physics, because of many questions:

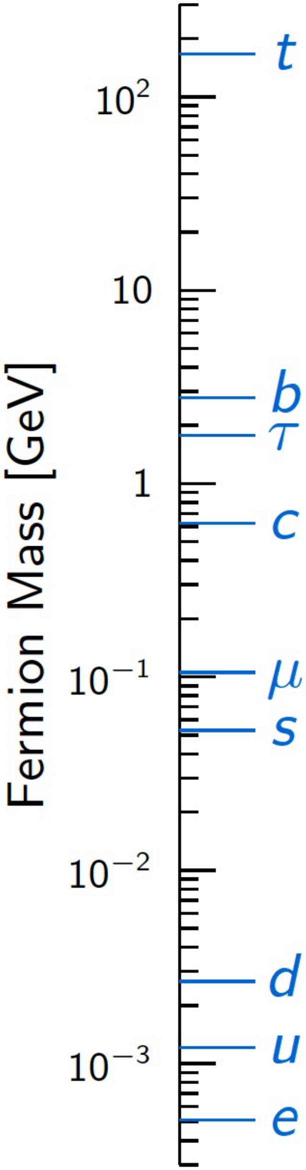
- *why is the Higgs boson so light ("naturalness"/fine-tuning/hierarchy problem) ?*
- *what is the the nature of the dark part (96% !) of the universe ?*
- *what is the origin of the matter-antimatter asymmetry ?*
- *why is gravity so weak ?*
- *Is supersymmetry realized in Nature?*
- *Inflation*

No excess in data for direct signs of new physics:

- Supersymmetry
- Long-lived particles
- New heavy resonances
- Dark Matter and its nature

Doing Precision measurements (Couplings, Cross Sections, Width, Differential Distributions,…) which might be an indirect sign of BSM physics

Almost 10 years from the Higgs discovery



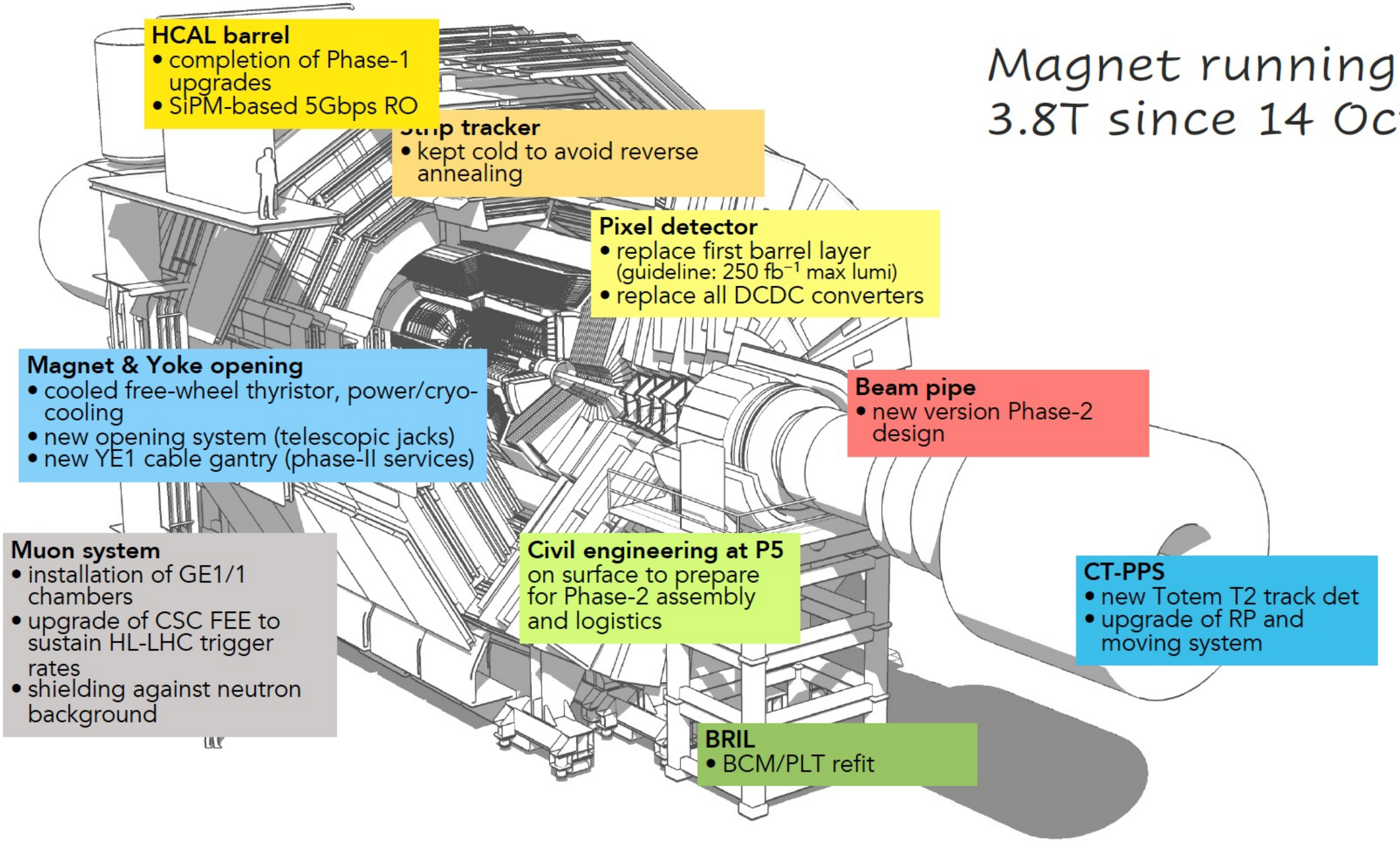
The masses of the charged fermions appear randomly chosen and span several orders of magnitude...

What is the origin of this pattern?

Almost ten years since the discovery of the Higgs boson and verification of the Brout-Englert-Higgs mechanism, are we any closer to <u>fundamentally</u> understanding fermion mass generation?

CMS at the end of Long Shutdown 2 (LS2)

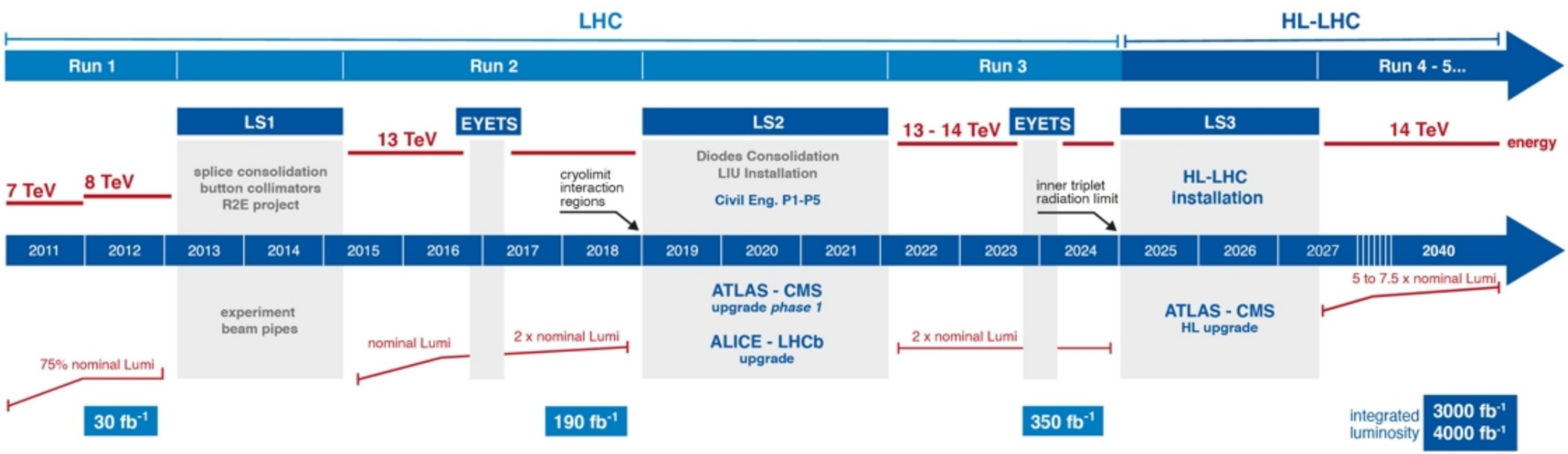
All major LS2 projects are completed



Magnet running at 3.8T since 14 October

Take full advantage of splashes, pilot beams

LHC and HL-LHC schedule



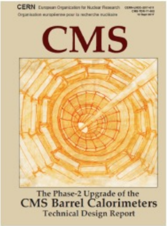
Luminosity

Nominal scenario: $\mathcal{L} = 5\times10^{34}\ \mathrm{cm^{-1}s^{-1}}$
for 3000/fb; Pile-up = 140

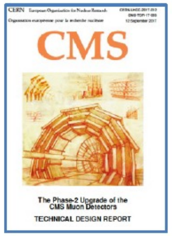
Ultimate Scenario: $\mathcal{L} = 7.5\times10^{34}\ \mathrm{cm^{-1}s^{-1}}$
for 4000/fb; Pile-up = 200
$\Rightarrow$25% increase in integrated lum.

CMS Phase 2 upgrade

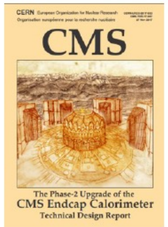
L1-Trigger HLT/DAQ
https://cds.cern.ch/record/2714892
https://cds.cern.ch/record/2759072
- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting



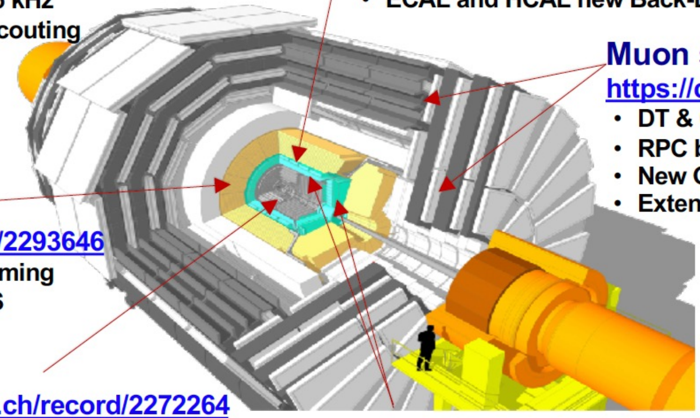
Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



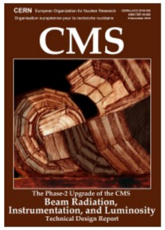
Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



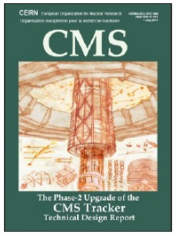
Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS



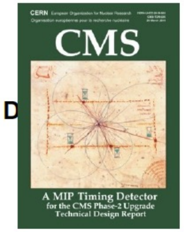
Beam Radiation Instr. and Luminosity
http://cds.cern.ch/record/2759074
- Bunch-by-bunch luminosity measurement: 1% offline, 2% online



Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$



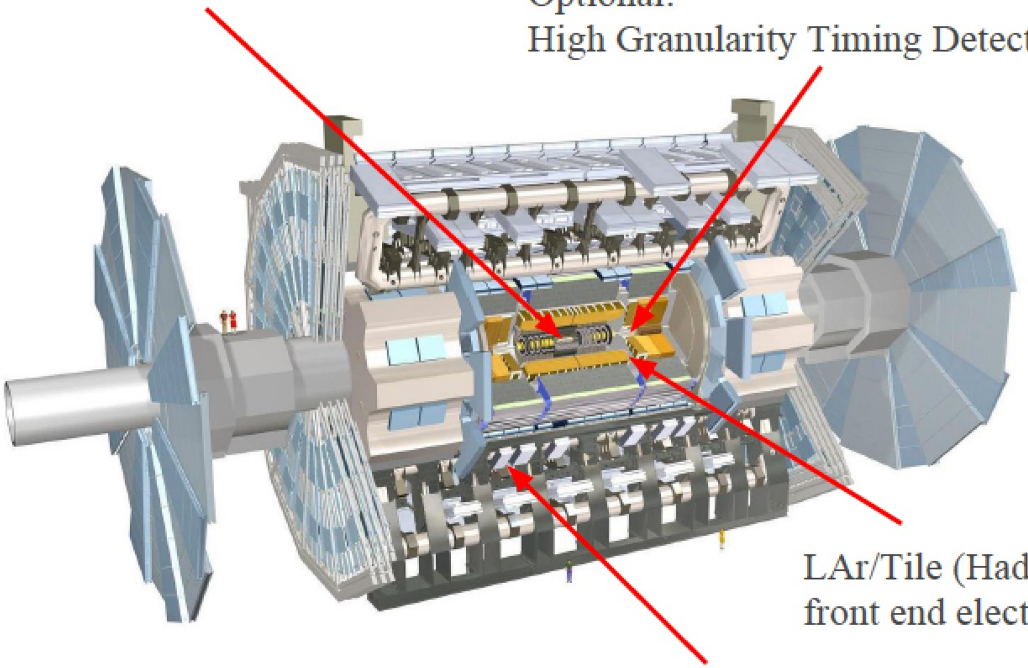
MIP Timing Detector
https://cds.cern.ch/record/2667167
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche D



ATLAS Phase 2 upgrade

New silicon Inner Tracker (ITk)

Optional:
High Granularity Timing Detector (HGTD)



LAr/Tile (Hadronic cal.)
front end electronics

New muon chambers and front
end readout electronics

DAQ off detector electronics:

- L0 hardware triggers will provide trigger decisions within a latency of 10 μs.
  - Based on muon and calorimeter data + their combinations in the topological processors.
- The L1Track trigger processes L0 RoIs to search for ITk tracks with high transverse momentum.
- The L1Global uses full-granularity calorimeter information and improved granularity for the entire detector.

Itk: All-silicon tracker which provides **coverage for tracking for up to |η| < 4.0.**
Optional: A new **High Granularity Timing Detector (HGTD)** instrumenting the gap region between the two LAr cryostats
Muon: new RPCs and sTGCs which are able to cope with the high rate trigger

Strategy for Higgs physics @ HL-LHC

Phase II Detector Upgrades:

- Radiation hardness
- Mitigate physics impact of high pileup
- → Object reconstruction efficiencies, resolutions and fake rates are assumed to be similar in the Run-2 and HL-LHC environments

Higgs@HL-LHC:

- Precision Measurements (Couplings, Cross Sections, Width, differential Distributions,…) → looking for deviations from the SM
- BSM Higgs direct searches: extra scalars, BSM Higgs resonances, exotic decays, anomalous couplings
- VBS scattering
- Rare decays and couplings ($H \rightarrow \mu\mu$)
- Di-Higgs production ➜ Higgs self coupling

Analysis approaches for HL-LHC

- **Method 1: Full simulation (CMS)**: use of the most advanced geometry, algorithms and tuning, PU simulation

- **Method 2: Full analysis with parameterized detector performance (CMS)**: use DELPHES with up-to-date phase-2 detector performance (tracking, vertexing, timing, dedicated PUPPI jet algorithms, increased acceptance, performance of new detectors)

- **Method 3: truth + smearing (ATLAS)**: truth-level events overlaid with jets (full sim) from pileup library, reconstruct particles (electrons, muons, jets, MET) from MC truth+overlay and smear their energy and p_T using appropriate smearing functions → cross checked with some of the 'real' data analyses

- **Method 4: projections (mostly CMS and LHCb)**
  - Existing signal and background samples (simulated at 13 TeV) scaled to higher lumi and $\sqrt{s}$ luminosity and 14 TeV. Analysis steps (cuts) from present analyses
  - 2 scenarios for uncertainties:
    - Scenario 1: all systematic uncertainties are kept unchanged with respect to those in current data analyses + PU/detector upgrades (S1+)
    - Scenario 2: the theoretical uncertainties are scaled by a factor of 1/2, while other systematical uncertainties are scaled by $1/\sqrt{L}$ + PU/detector upgrades (S2+)

Modeling the projections for HL-LHC

Experimental uncertainties:

- Estimates of **ultimately achievable accuracy** based on the upgraded Phase-2 detectors studies (TDRs).
- Assumption that **sufficiently large simulation samples** will be available

Table 1: The sources of systematic uncertainty for which minimum values are applied in S2.

Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%

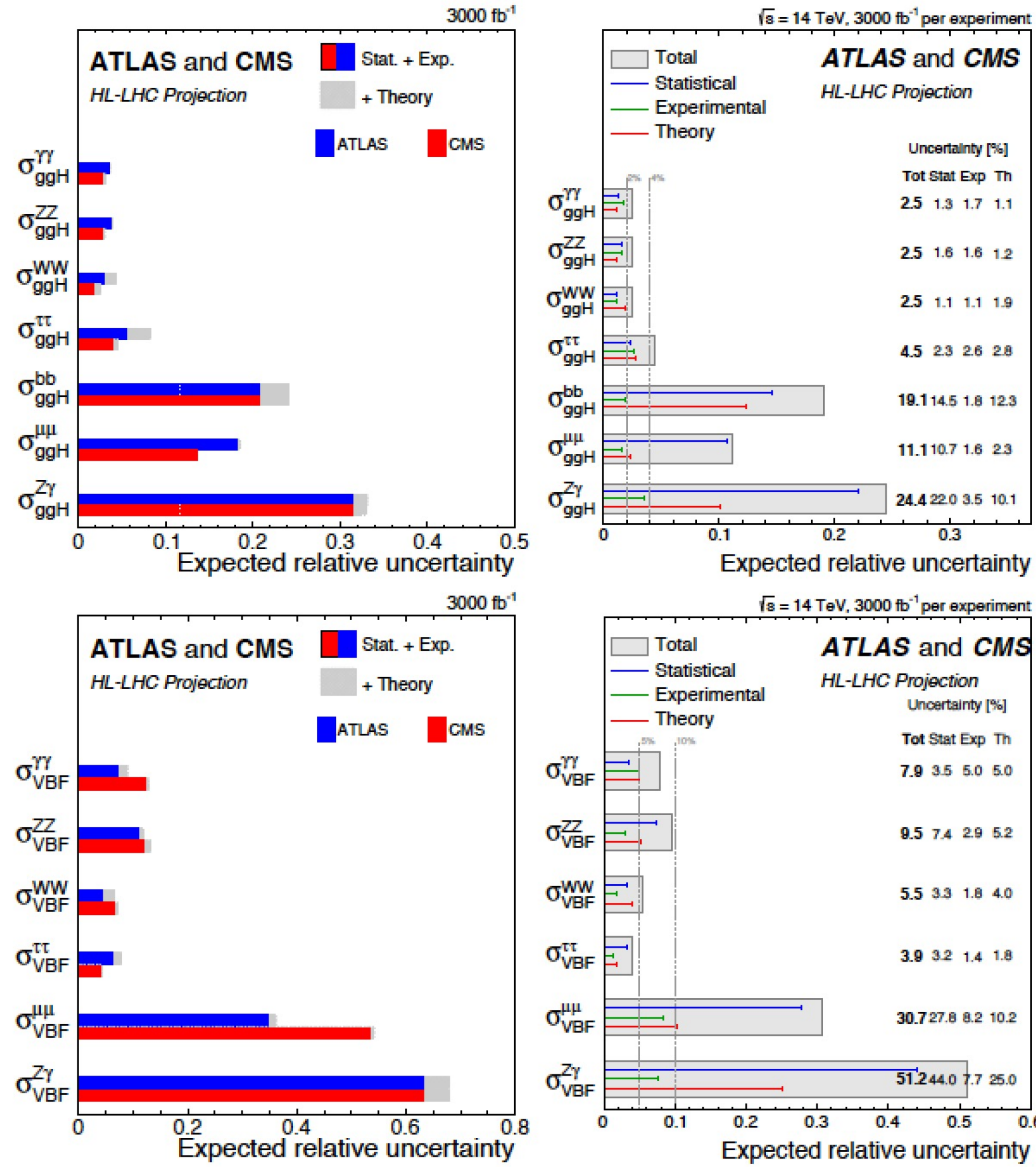
Theoretical uncertainties:

- Build upon existing/recent TH progress/studies
- Assume a scaling down by a constant factor
- **QCD calculations (1/2), understanding of PDFs (1/3), top pT (1/2), etc.**

Higgs boson cross section

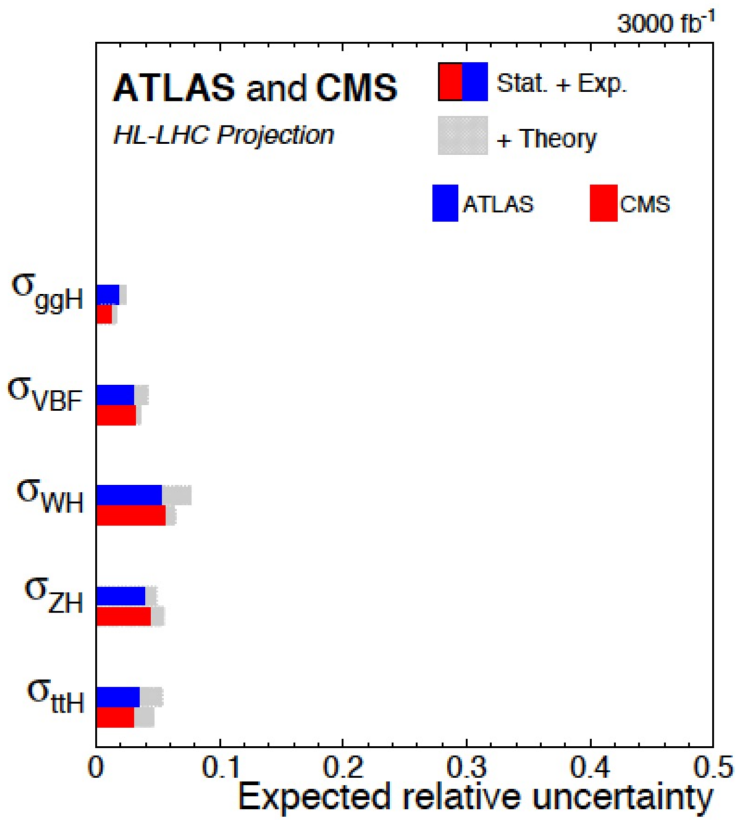
Projections for:

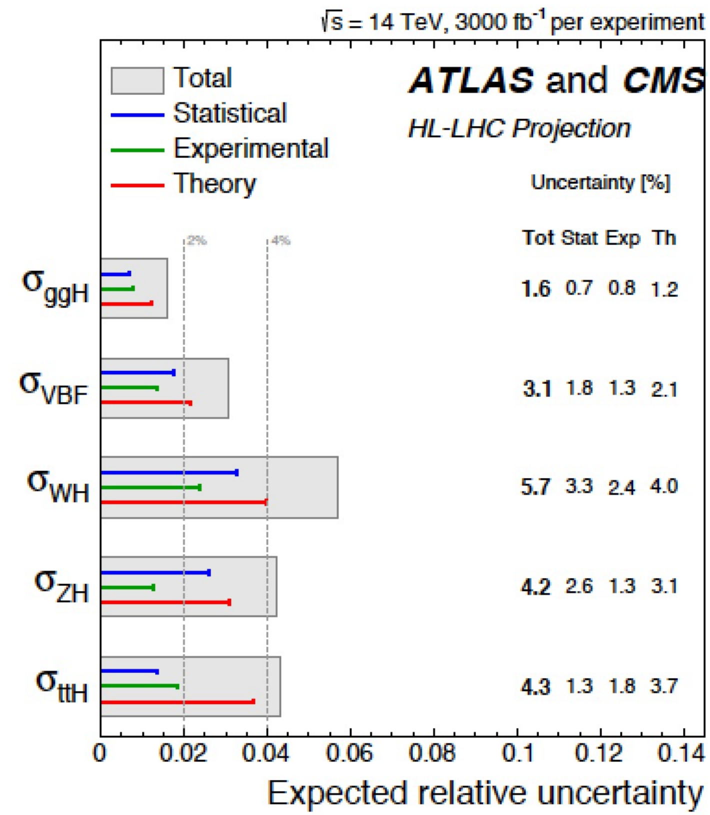
- H→ZZ→4l (ggH, VBF, VH, ttH)
- H→WW→2l2ν (ggH, VBF, VH)
- H→γγ (ggH, VBF, VH, ttH)
- H→ττ (ggH, VBF)
- VH, H→bb and boosted H→bb
- H→μμ (ggH and VBF)
- ttH, H→leptons, H→bb
  + studies about tH



Systematic uncertainties will dominate, in particular theoretical uncertainties on signal and background are the main component for S2 scenario

Higgs boson cross section



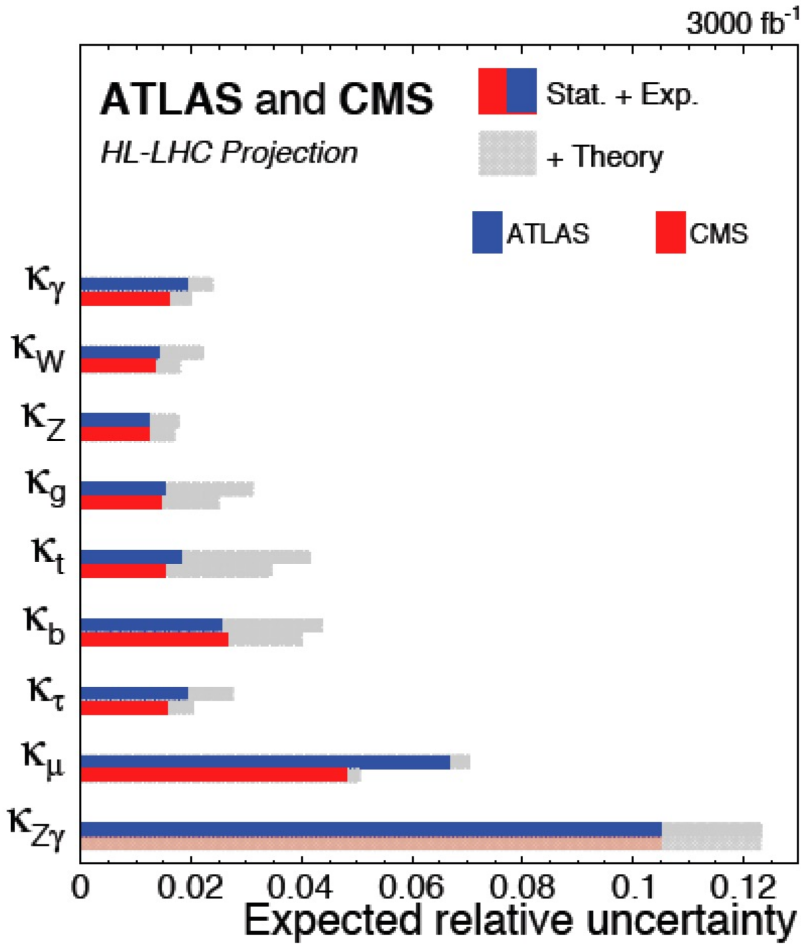


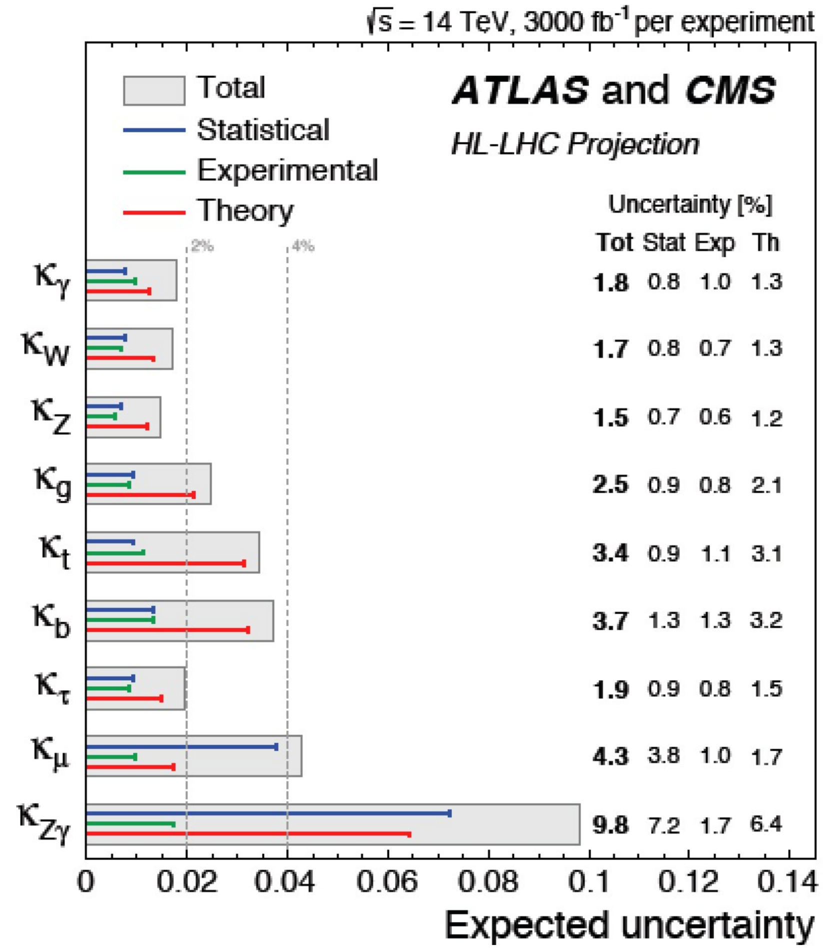
ATLAS							
		3000 fb^{-1} uncertainty [%]					
		Total	Stat	Exp	SigTh	BkgTh
σ_{ggH}	S1	3.5	0.8	2.1	2.1	1.6
	S2	2.4	0.8	1.7	1.2	1.0
σ_{VBF}	S1	5.5	2.0	2.7	3.7	2.1
	S2	4.2	2.0	2.3	2.2	1.7
σ_{WH}	S1	9.3	4.0	4.0	5.1	5.4
	S2	7.7	4.0	3.4	3.3	4.5
σ_{ZH}	S1	6.2	3.4	2.4	3.4	3.0
	S2	4.8	3.4	1.8	2.0	2.1
σ_{ttH}	S1	6.7	1.9	3.1	3.7	4.3
	S2	5.3	1.9	2.8	2.4	3.3

CMS						
		3000 fb^{-1} uncertainty [%]				
		Total	Stat	Exp	SigTh	BkgTh
$\sigma_{ggH\|}$	S1	2.4	0.8	1.2	1.6	0.9
	S2	1.7	0.8	0.9	0.9	0.6
σ_{VBF}	S1	4.1	2.6	2.1	2.0	1.3
	S2	3.5	2.6	1.6	1.8	0.3
σ_{WH}	S1	8.1	4.6	5.2	2.6	3.3
	S2	6.4	4.6	3.2	1.5	2.7
σ_{ZH}	S1	6.7	3.9	2.1	4.3	2.5
	S2	5.4	3.9	1.7	2.4	2.3
σ_{ttH}	S1	5.8	1.8	3.1	1.9	4.1
	S2	4.6	1.8	2.4	1.1	3.4

Higgs boson couplings

- Results for couplings in κ-framework
- Six coupling modifiers corresponding to the tree-level Higgs boson couplings are defined: κ_t, κ_b, κ_τ, κ_μ, κ_W, κ_Z (+ κ_g, κ_γ, $\kappa_{Z\gamma}$)



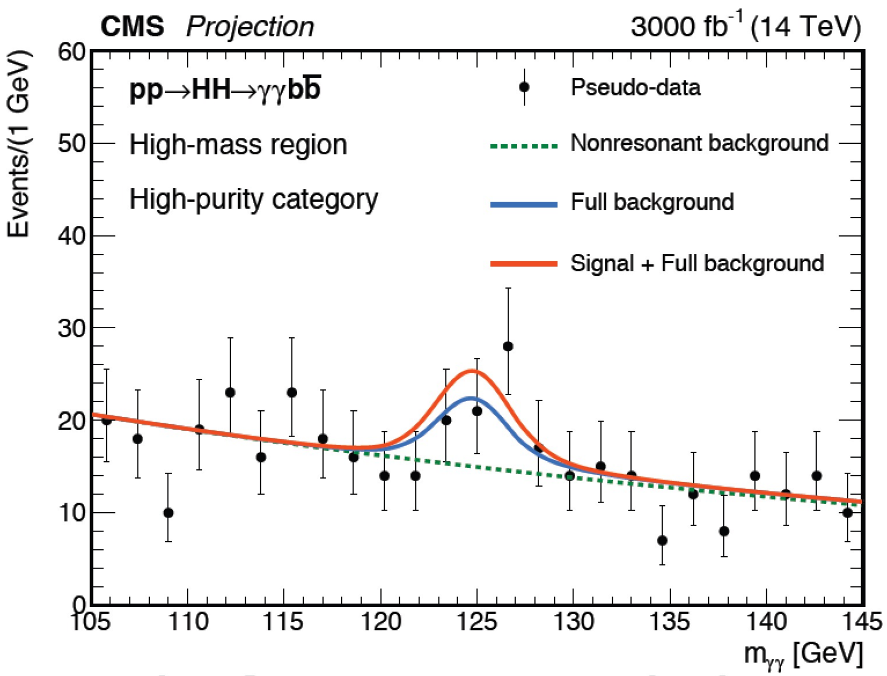


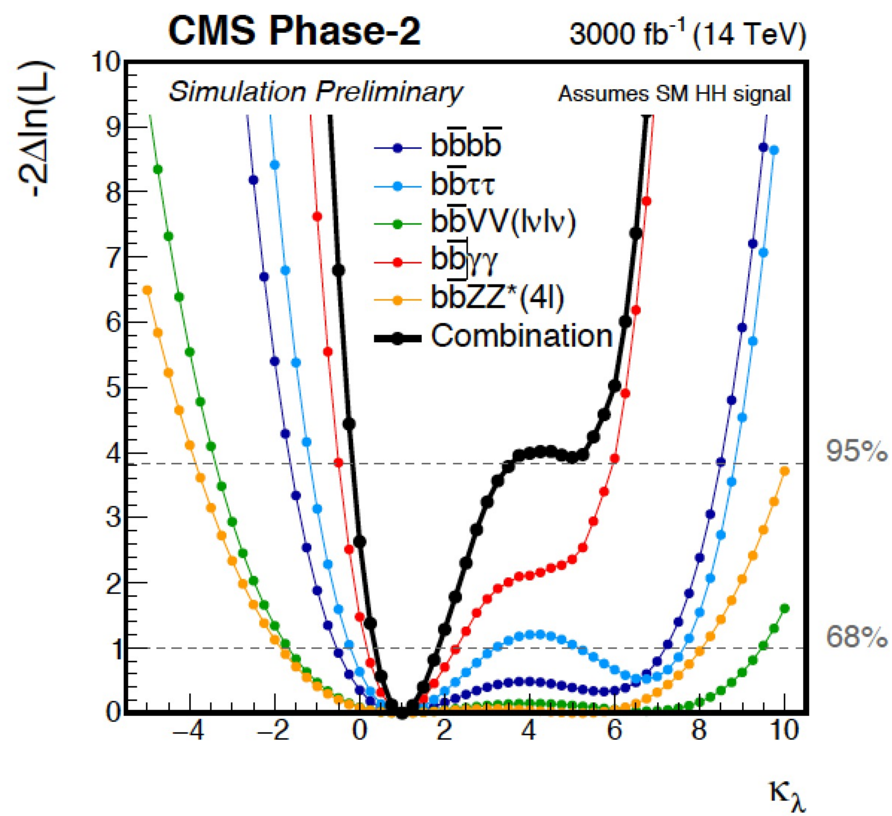
Uncertainties on the κ's 2-5%, apart from Zγ
Mostly limited by theoretical uncertainties

Prospects for HH measurements

Search of Higgs boson pair (HH) production and the measurement of the Higgs boson self-coupling (λ_{HHH})

Decay channels: HH→ bbbb, **bb$\tau\tau$**, bbWW(→ll$\nu\nu$), **bb$\gamma\gamma$ (most sensitive)**, bbZZ(→4l)





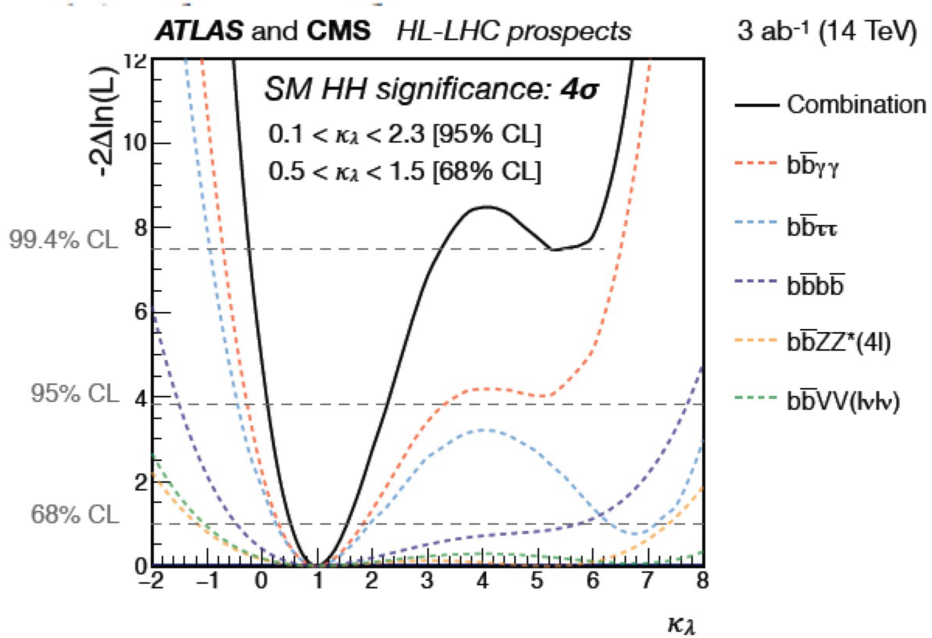
Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma^{SM}_{HH}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
bb$\tau\tau$	1.4	1.6	1.4	1.3
bbWW($\ell\nu\ell\nu$)	0.56	0.59	3.5	3.3
bb$\gamma\gamma$	1.8	1.8	1.1	1.1
bbZZ($\ell\ell\ell\ell$)	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

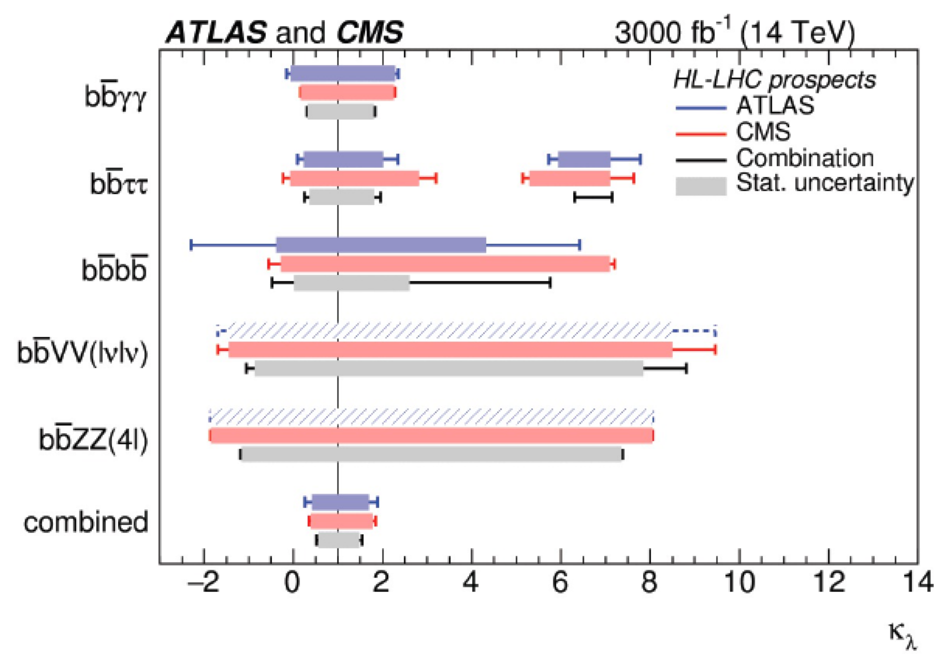
Measurement of the $k_\lambda = \lambda_{HHH} / \lambda^{SM}_{HHH}$ in the range [0.4, 1.9] at the 68% CL

HH: CMS and ATLAS combined

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

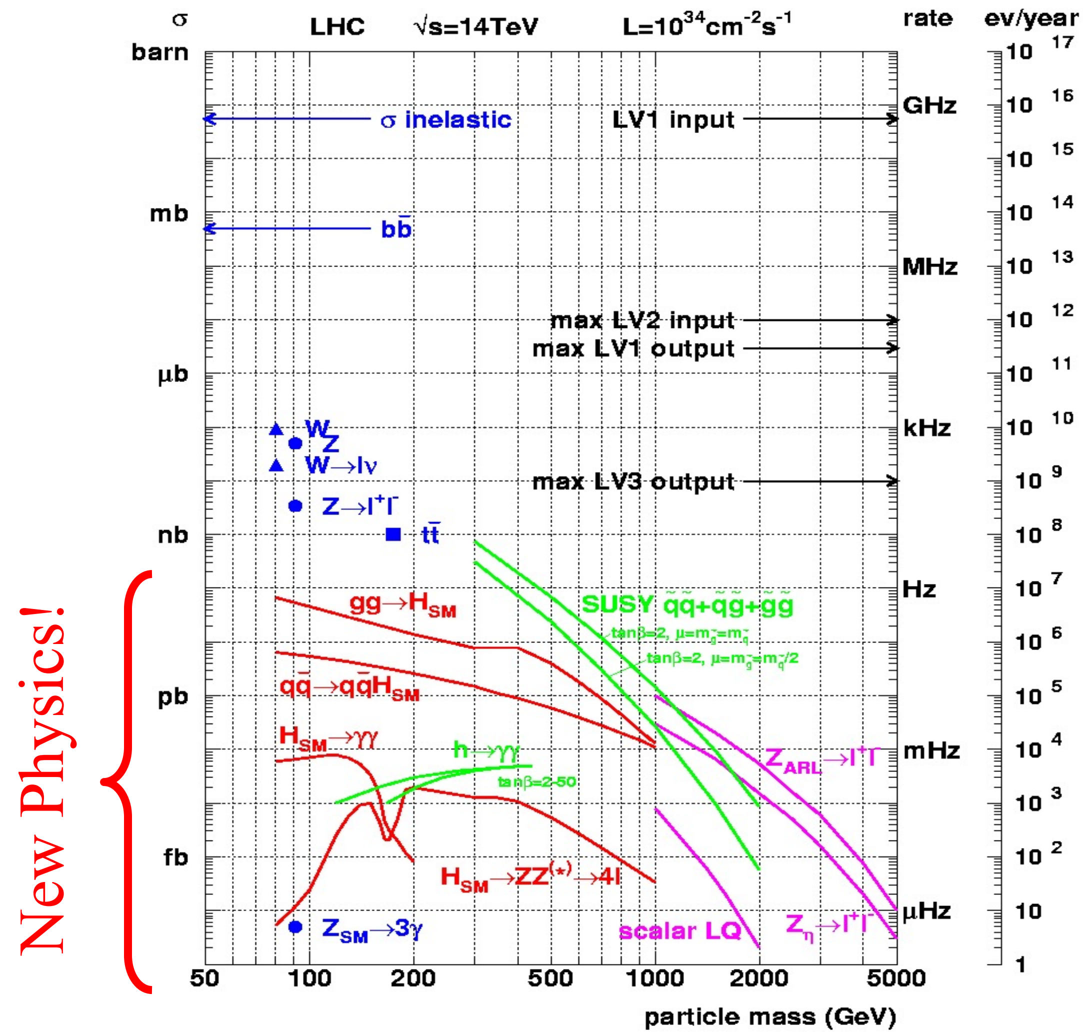
$$\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}.$$





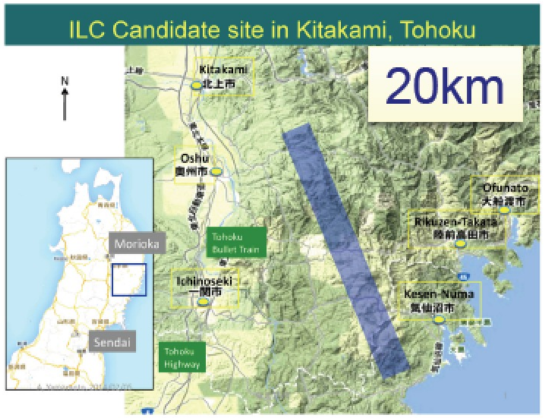
Is the SM enough ? Open questions

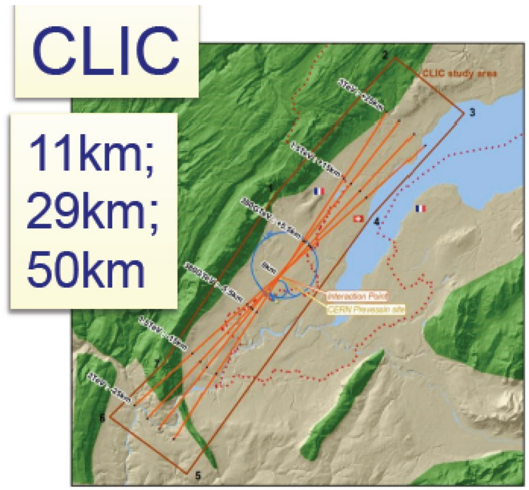
- Is the Higgs mechanism to generate weak boson and fermions masses real ?
- How to solve the problem of the hierarchy between the EWK scale and the GUT or Planck scale ?
- Are the electroweak and strong forces unified at some GUT scale
- Is the SUSY realized in nature ? Do the SUSY particles exist ? Can they explain the dark matter ?
- Do extra dimensions exist?
- ….etc..

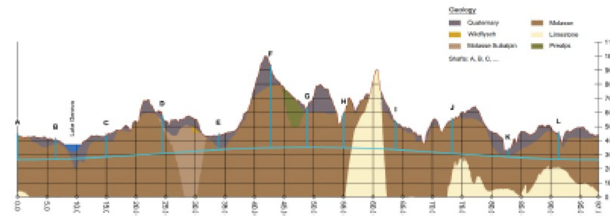


Future colliders can provide some answers

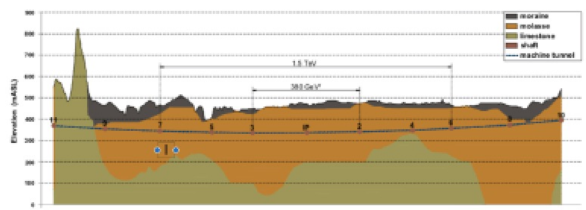
Future colliders: ILC, CLIC, FCC-ee/hh,CepC/SppC

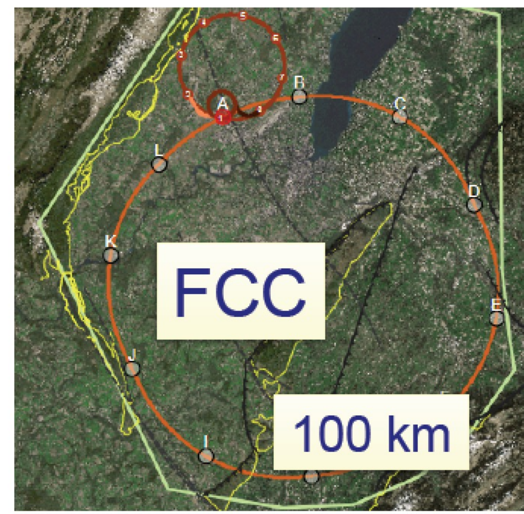






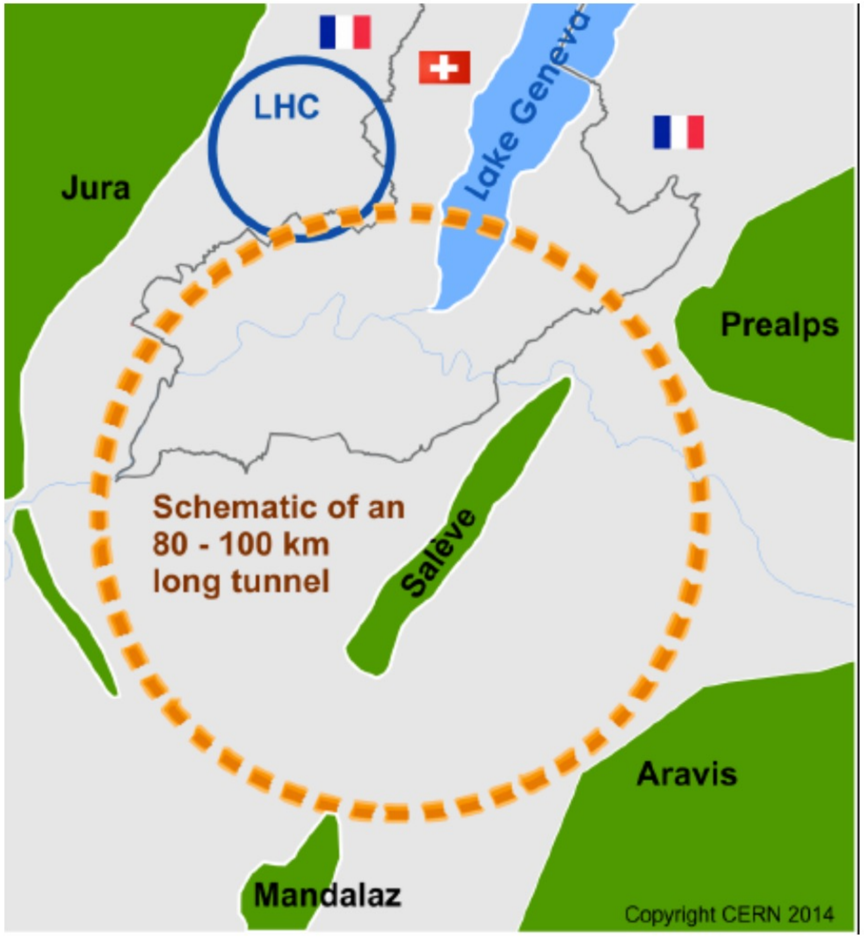
CEPC: multiple candidate sites in China



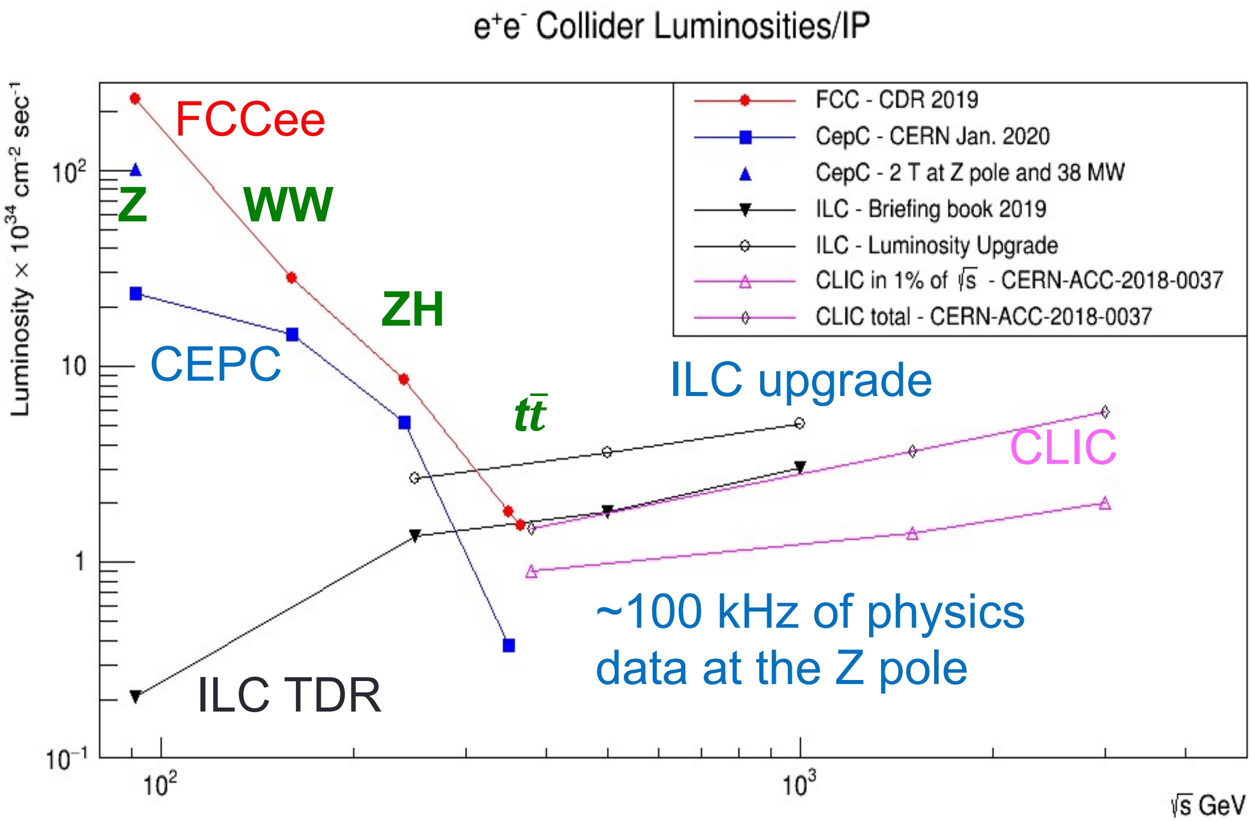


The FCC project at CERN

- Build a new 100 km tunnel in the Geneva region
- Ultimate goal: highest energy reach in pp collisions: 100 TeV
- need time to develop the technology to get there
- First step: extreme precision circular e+e- collider (FCC-ee)
- variable collision energy from 90-360 GeV (beyond top threshold)
- As for the LEP+LHC, one tunnel for two complementary machines covering the largest phase space in the high energy frontier
  - a complete physics program for the next 50 years

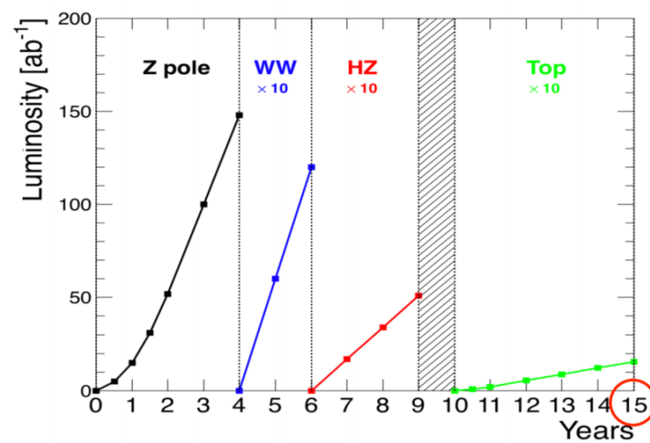


Machine luminosity for physics at e^+e^- colliders



- Higgs factory:
  - 10^6 $e^+e^- \to HZ$
- EW & Top factory:
  - 3×10^{12} $e^+e^- \to Z$
  - 10^8 $e^+e^- \to W^+W^-$
  - 10^6 $e^+e^- \to tt$
- Flavor factory:
  - 5×10^{12} $e^+e^- \to bb, cc$
  - 10^{11} $e^+e^- \to \tau^+\tau^-$

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events



Timeline of the FCC project

European Strategy Update

2020 Strategy Statements

3. High-priority future initiatives

It is essential for particle physics in Europe and for CERN to be able to propose a new facility after the LHC

- There are two clear ways to address the remaining mysteries: Higgs factory and exploration of the energy frontier
- Europe is in the privileged position to be able to propose both: CLIC or FCCee as Higgs factory, CLIC (3 TeV) or FCChh (100 TeV) for the energy frontier
- The dramatic increase in energy possible with FCChh leads to this technology being considered as the most promising for a future facility at the energy frontier.
- It is important therefore to launch a feasibility study for such a collider to be completed in time for the next Strategy update, so that a decision as to whether this project can be implemented can be taken on that timescale.

a) 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. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- *the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*
- *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.*

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

Timeline of the FCC project

The PED Pillar Objectives in 2025

- **Mostly defined by the general (tight) timeline of the FCC project**

Infrastructure and accelerator — **Physics, Experiments, and Detectors**

Milestone / activity	Target date	Possible timeline
First e^+e^- collisions in FCC-ee	Early 2040's	FCC-ee detector commissioning
Start machine installation	2037	Start FCC-ee detector installation
Tunnel completion	2035/36	
Start tunnel construction	2030	Start FCC-ee detector construction
Project approval	2028/29	FCC-ee Detector TDR's and approvals
Next European Strategy Update	2026/27	Next European Strategy Update (ESU)
Key prototypes (feasibility proof)	2026	FCC-ee Proto-collaborations and EoI's
FSR(*) (feasibility proof)	End 2025	PED FSR, includes enough common material and knowledge for FCC-ee proto-collaborations

(*) FSR = Feasibility Study Report

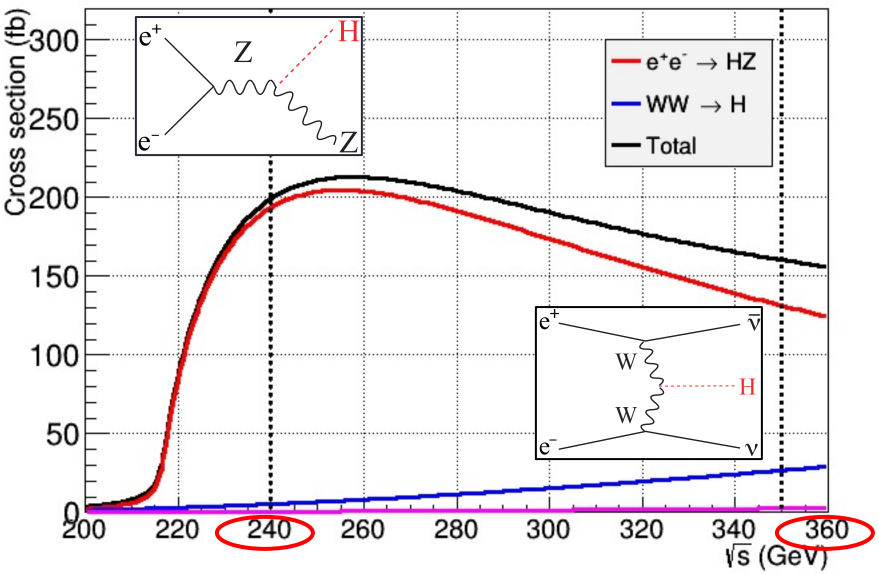
Adapted from schedule in M. Benedikt's presentation

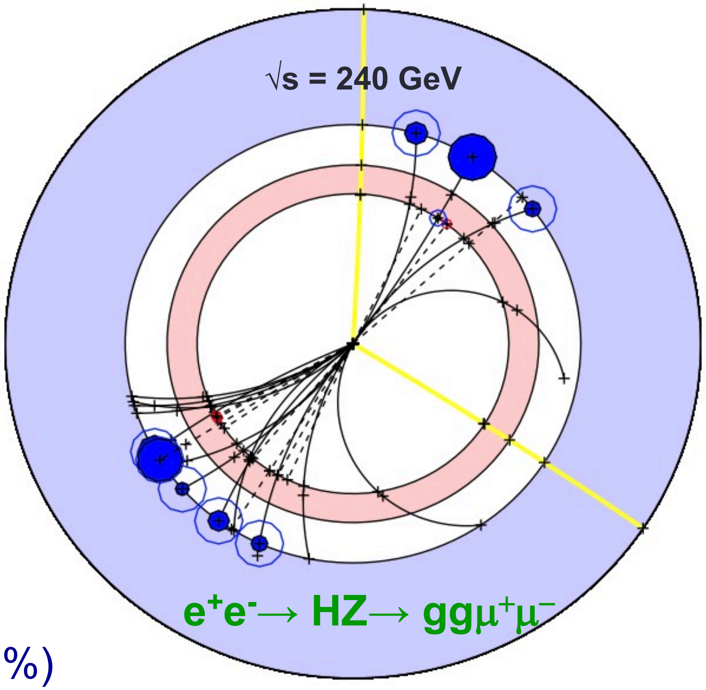
FCC-ee/CepC motivation

e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be

FCC-ee/CepC: focus on a 90-250 GeV e^+e^- machine (100 km circumf.)
5 ab^{-1} integrated luminosity to two detectors over 10 years → 10^6 clean Higgs events
→ FCC-ee/CepC can measure the Higgs boson production cross sections and most of its properties with precisions far beyond achievable at the LHC

- Higgs-strahlung (m_H = 125 GeV)



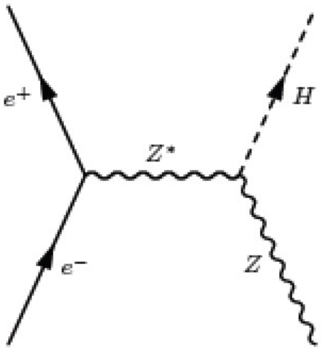


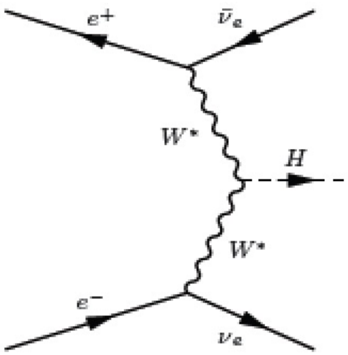
- The gluon can be studied with Higgs decays (BR ~ 10%)

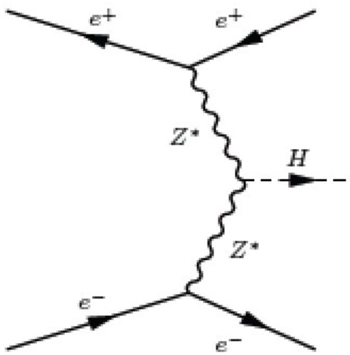
Higgs production at FCC-ee/CepC

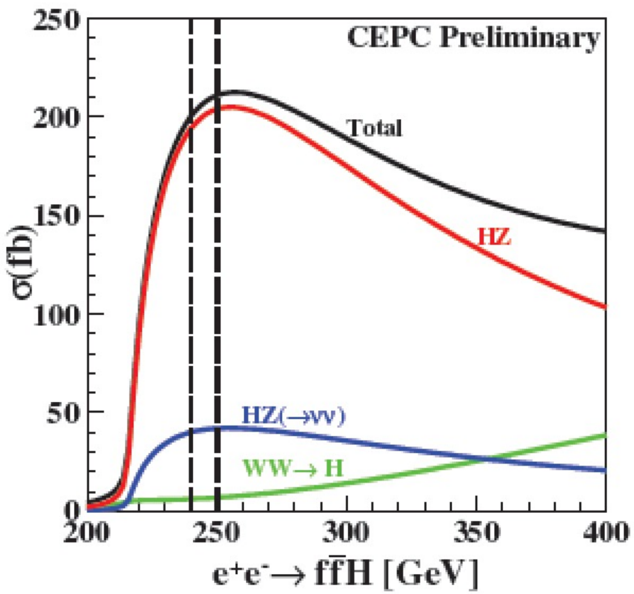
Higgs-strahlung or $e^+e^- \rightarrow ZH$

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

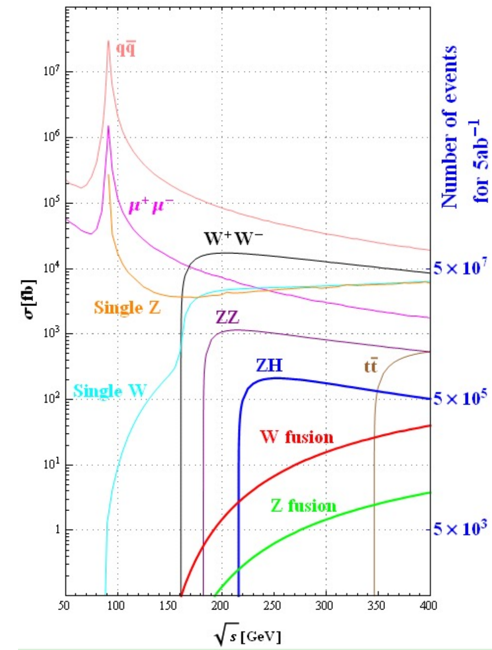








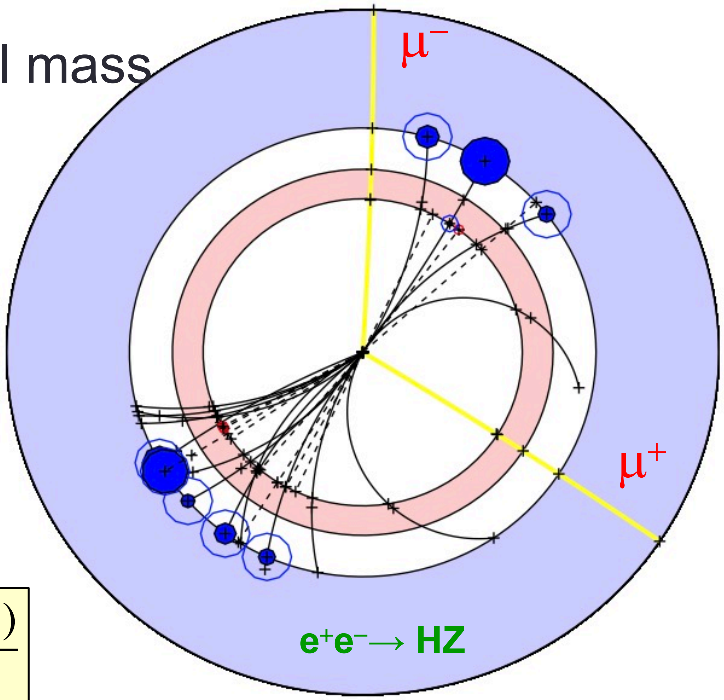
Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6
Background processes, cross section in pb		
$e^+e^- \to e^+e^-$ (Bhabha)	25.1	1.3×10^8
$e^+e^- \to q\bar{q}$	50.2	2.5×10^8
$e^+e^- \to \mu\mu$ (or $\tau\tau$)	4.40	2.2×10^7
$e^+e^- \to WW$	15.4	7.7×10^7
$e^+e^- \to ZZ$	1.03	5.2×10^6
$e^+e^- \to eeZ$	4.73	2.4×10^7
$e^+e^- \to e\nu W$	5.14	2.6×10^7



FCC-ee/CepC Higgs factory: √s = 240 GeV

Model-independent precision measurements

- A Higgs boson is tagged by a Z and the recoil mass

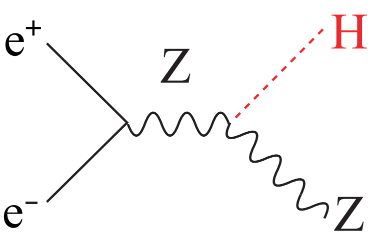


$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$

  - Measure $\sigma(e^+e^- \to HZ)$
  - Deduce g_{HZZ} coupling
  - Infer $\Gamma(H\to ZZ)$
  - Select events with $H\to ZZ^*$
  - Measure $\sigma(e^+e^- \to HZ$, with $H\to ZZ^*)$

$$\sigma(e^+e^- \to HZ \to ZZZ) = \sigma(e^+e^- \to HZ) \times \frac{\Gamma(H \to ZZ)}{\Gamma_H}$$

  - Deduce the total Higgs boson width Γ_H
  - Select events with H → bb, cc, gg, WW, ττ, γγ, μμ, Zγ, …
  - Deduce g_{Hbb} , g_{Hcc} , g_{Hgg} , g_{HWW} , $g_{H\tau\tau}$, $g_{H\gamma\gamma}$, $g_{H\mu\mu}$, $g_{HZ\gamma}$, …
  - Select events with H → "nothing"
  - Deduce $\Gamma(H\to \text{invisible})$



Higgs from recoil mass method

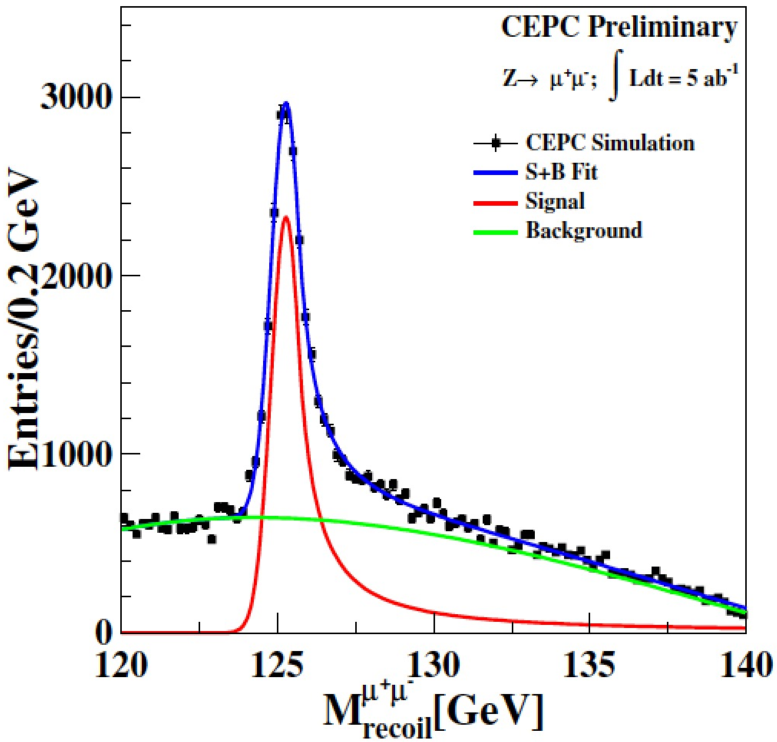
$$m^2_{\text{recoil}} = (\sqrt{s} - E_{f\bar{f}})^2 - p^2_{f\bar{f}} = s - 2E_{f\bar{f}}\sqrt{s} + m^2_{f\bar{f}}$$

- Best mass precision can be achieved with the Z→ll (ee,μμ) decays
- Cross section, ZH and the Higgs-Z boson coupling g(HZZ), can be derived in a model-independent way
- g(HZZ) and Higgs decay branching ratios can be used to derive the total Higgs decay width.

- A relative precision of 0.9% for the inclusive cross section has been achieved with CepC.
- The Higgs mass can be measured with a precision of 6.5 MeV; the precision is limited by the beam energy spread, radiation effect and detector resolution
- A relative precision of 0.51% on σ(ZH) by combining ee,μμ and qq channels
- g(HZZ) can be extracted from σ(ZH) with a relative precision of 0.25%

Z decay mode	ΔM_H (MeV)	$\Delta\sigma(ZH)/\sigma(ZH)$	$\Delta g(HZZ)/g(HZZ)$
ee	14	2.1%	
$\mu\mu$	6.5	0.9%	
$ee+\mu\mu$	5.9	0.8%	0.4%
$q\bar{q}$		0.65%	0.32%
$ee+\mu\mu+q\bar{q}$		0.51%	0.25%

CepC CDR

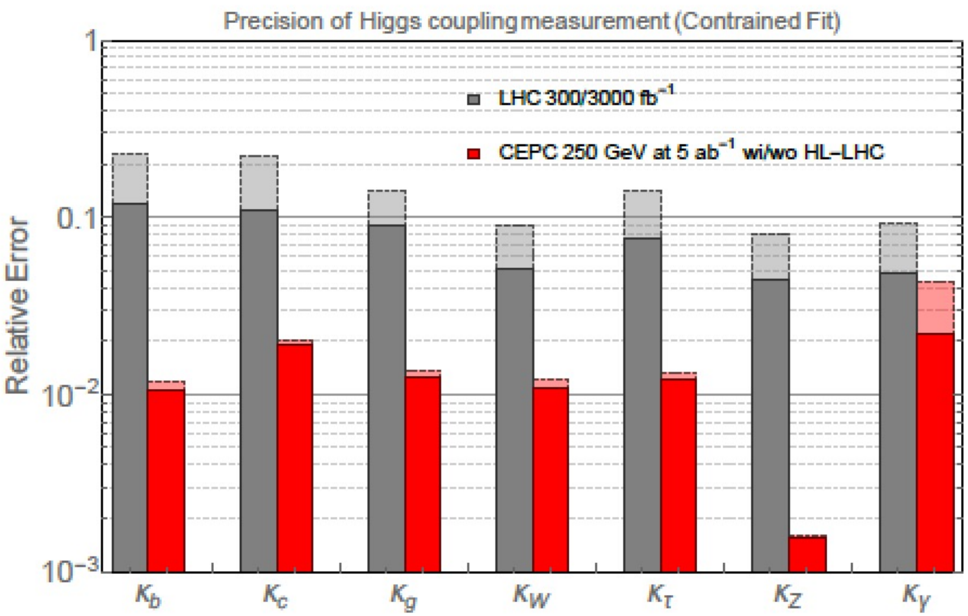


Higgs coupling measurements

- 10 parameters $\kappa_b,\ \kappa_c,\ \kappa_\tau,\ \kappa_\mu,\ \kappa_Z,\ \kappa_W,\ \kappa_\gamma,\ \kappa_g,\ \mathrm{BR}_{\mathrm{inv}},\ \Gamma_h.$
- assuming lepton universality → 9 paramete $\kappa_b,\ \kappa_c,\ \kappa_\tau = \kappa_\mu,\ \kappa_Z,\ \kappa_W,\ \kappa_\gamma,\ \kappa_g,\ \mathrm{BR}_{\mathrm{inv}},\ \Gamma_h.$
- assuming the absence of exotic and invisible decays →7 parameters:

CepC CDR

$$\kappa_b,\ \kappa_c,\ \kappa_\tau = \kappa_\mu,\ \kappa_Z,\ \kappa_W,\ \kappa_\gamma,\ \kappa_g$$



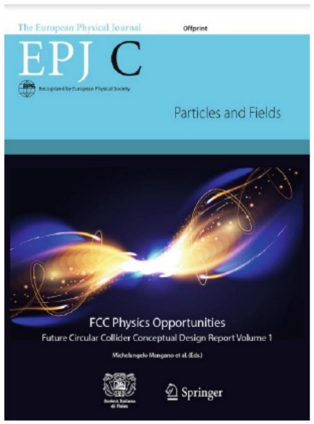
Projections for CEPC at 250 GeV with 5 ab^{-1} integrated luminosity and 7 parameters fit

	CEPC				CEPC+HL-LHC			
Luminosity (ab^{-1})	0.5	2	5	10	0.5	2	5	10
κ_b	3.7	1.9	1.2	0.83	2.3	1.5	1.1	0.78
κ_c	5.1	3.2	1.6	1.2	4.0	2.3	1.5	1.1
κ_g	4.7	2.3	1.5	1.0	2.9	1.9	1.3	0.99
κ_W	3.8	1.9	1.2	0.84	2.3	1.6	1.1	0.80
κ_τ	4.2	2.1	1.3	0.94	2.9	1.8	1.2	0.90
κ_Z	0.51	0.25	0.16	0.11	0.49	0.25	0.16	0.11
κ_γ	15	7.4	4.7	3.3	2.6	2.5	2.3	2.0

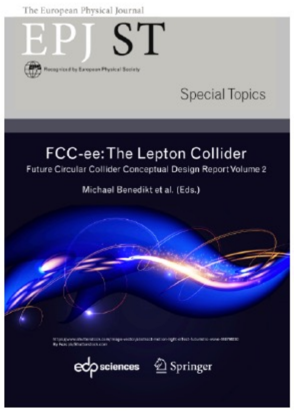
Concerning $\mathrm{BR}_{\mathrm{inv}}$ a high accuracy of 0.25%, while the HL-LHC can only manage a much lower accuracy of 6-17%.

FCC documentation

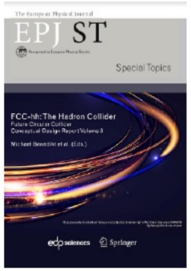
4 CDR volumes published in EPJ



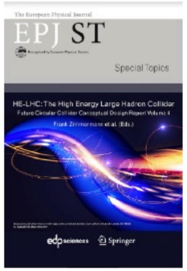
FCC PhysicsOpportunities



FCC-ee: The Lepton Collider



FCC-hh: The Hadron Collider



HE-LHC: The High Energy Large Hadron Collider

- Future Circular Collider - European Strategy Update Documents
  - (FCC-ee), (FCC-hh), (FCC-int)
- FCC-ee: Your Questions Answered
  - arXiv:1906.02693
- Circular and Linear e+e- Colliders: Another Story of Complementarity
  - arXiv:1912.11871
- Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders
  - arXiv:1901.02648
- Polarization and Centre-of-mass Energy Calibration at FCC-ee
  - arXiv:1909.12245

Summary/Conclusions

The story about the Higgs searches and the discovery of it has been exciting

Run 1 and 2 at LHC produced wonderful results and
show good agreement with SM predictions

Searches for double Higgs will shed light on the shape of the Higgs potential through the triple-Higgs self coupling

An exciting journey is anyway ahead!

HL-LHC: potential for new physics discoveries and precision measurements → FCC is the new future of HEP

Backup