Higgs Physics @ LHC
run I, II, and beyond

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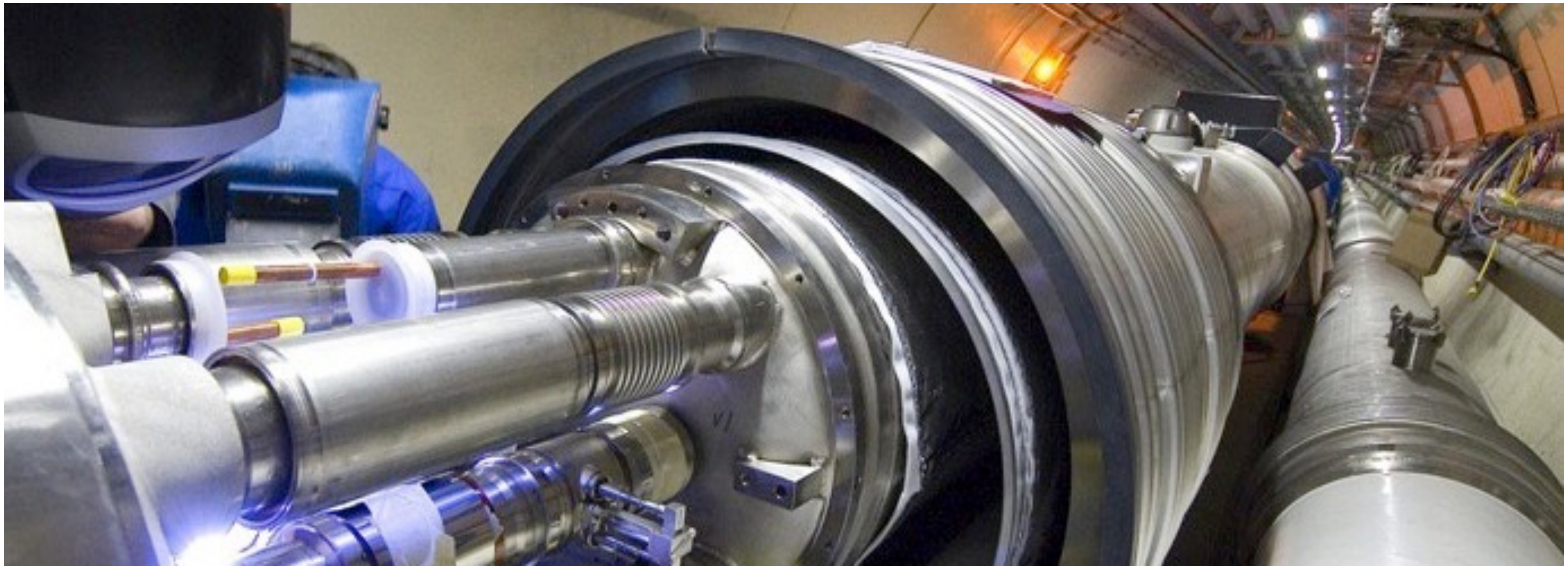
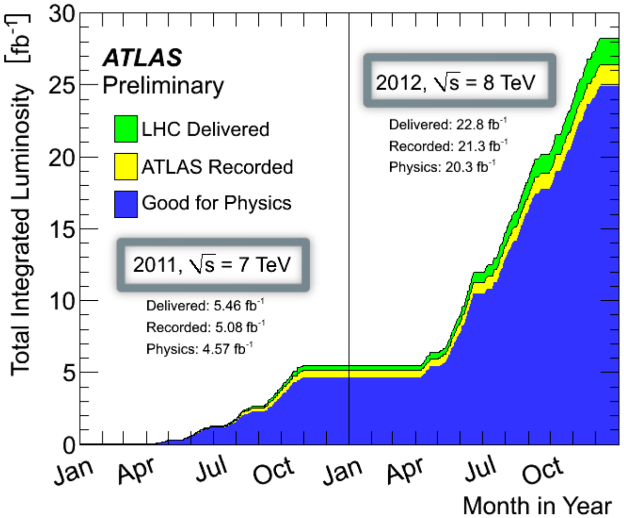


Brief overview of the experimental setup

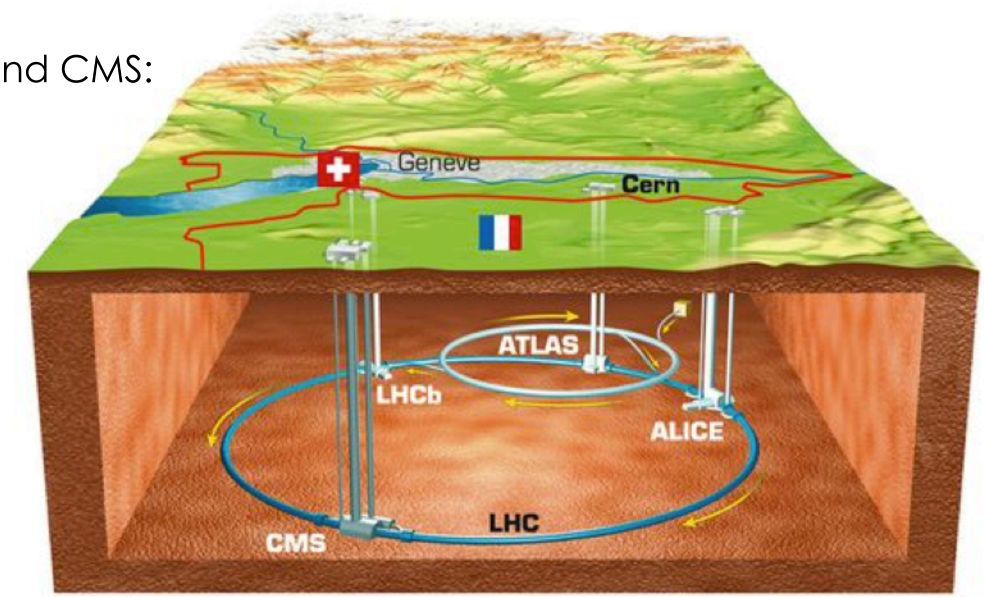
LHC, ATLAS, CMS

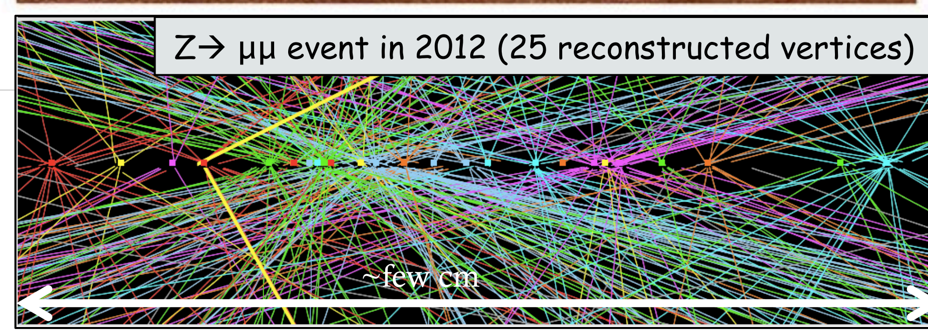
The Large Hadron Collider

LHC is a proton and heavy ion collider.
Run 1 pp collision data recorded by ATLAS and CMS:



$L_{int} \approx 5 fb^{-1}$ $L_{int} \approx 20 fb^{-1}$





- Bunches of 1.5 10^{11} protons cross every 50 ns.
- More than 25 pp interactions per bunch crossing on average.

Comparison with previous generation collider, Tevatron: 2001-2011, ~2 TeV, 10fb^{-1}.

The LHC data taking program

Phase 1 starting soon!

- Run 1 (2010-2012): $\sqrt{s}$ = 7-8 TeV $L_{int} \approx 25\ fb^{-1}$

$L = 7 \times 10^{33}\ cm^2 s^{-1}$ bunch spacing: 50 ns   <PU>~25

Today's lecture

Mostly results from Run 1

Long shutdown 1: LHC upgrade to 13-14 TeV, detector consolidation.

- Run 2 (2015-2018): $\sqrt{s}$ = 13-14 TeV $L_{int} \approx 100\ fb^{-1}$

$L = 10^{34}\ cm^2 s^{-1}$ bunch spacing: 25 ns   <PU>~25

Some Run 2 prospectives

Long shutdown 2: luminosity upgrade, detector upgrade.

- Run 3 (2020-2022): $\sqrt{s}$ = 14 TeV $L_{int} \approx 200\text{-}300\ fb^{-1}$

$L = 2 \times 10^{34}\ cm^2 s^{-1}$ bunch spacing: 25 ns

A few words about physics beyond Run 2

Long shutdown 3: major LHC upgrade. New injection complex (linac, PS 26→50 GeV), magnets 8→13 T, crab crossing, etc. Detector upgrade.

High luminosity LHC (HL-LHC) highest priority of European strategy for particle physics

- Run 4, run 5 (2025-2032+): $\sqrt{s}$ = 14 TeV $L_{int} \approx 3000\ fb^{-1}$

$L = 5 \times 10^{34}\ cm^2 s^{-1}$ bunch spacing: 25 ns   <PU>~140

Particle detection

How can a particle detector distinguish the hundreds of particles that we know now?

http://pdg.lbl.gov ~ 180 Selected Particles

$\gamma, W^{\pm}, Z^0, g, e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, \pi^{\pm}, \pi^0, \eta, f_0(600), \rho(770)$,
$\omega(782), \eta'(958), f_0(980), a_0(980), \phi(1020), h_1(1170), b_1(1235)$,
$a_1(1260), f_2(1270), f_1(1285), \eta(1295), \pi(1300), a_2(1320)$,
$f_0(1370), f_1(1420), \omega(1420), \eta(1440), a_0(1450), \rho(1450)$,
$f_0(1500), f_2'(1525), \omega(1650), \omega_3(1670), \pi_2(1670), \phi(1680)$,
$\rho_3(1690), \rho(1700), f_0(1710), \pi(1800), \phi_3(1850), f_2(2010)$,
$a_4(2040), f_4(2050), f_2(2300), f_2(2340), K^{\pm}, K^0, K^0_S, K^0_L, K^*(892)$,
$K_1(1270), K_1(1400), K^*(1410), K_0^*(1430), K_2^*(1430), K^*(1680)$,
$K_2(1770), K_3^*(1780), K_2(1820), K_4^*(2045), D^{\pm}, D^0, D^*(2007)^0$,
$D^*(2010)^{\pm}, D_1(2420)^0, D_2^*(2460)^0, D_2^*(2460)^{\pm}, D_s^{\pm}, D_s^{*\pm}$,
$D_{s1}(2536)^{\pm}, D_{sJ}(2573)^{\pm}, B^{\pm}, B^0, B^*, B_s^0, B_c^{\pm}, \eta_c(1S), J/\psi(1S)$,
$\chi_{c0}(1P), \chi_{c1}(1P), \chi_{c2}(1P), \psi(2S), \psi(3770), \psi(4040), \psi(4160)$,
$\psi(4415), \Upsilon(1S), \chi_{b0}(1P), \chi_{b1}(1P), \chi_{b2}(1P), \Upsilon(2S), \chi_{b0}(2P)$,
$\chi_{b2}(2P), \Upsilon(3S), \Upsilon(4S), \Upsilon(10860), \Upsilon(11020), p, n, N(1440)$,
$N(1520), N(1535), N(1650), N(1675), N(1680), N(1700), N(1710)$,
$N(1720), N(2190), N(2220), N(2250), N(2600), \Delta(1232), \Delta(1600)$,
$\Delta(1620), \Delta(1700), \Delta(1905), \Delta(1910), \Delta(1920), \Delta(1930), \Delta(1950)$,
$\Delta(2420), \Lambda, \Lambda(1405), \Lambda(1520), \Lambda(1600), \Lambda(1670), \Lambda(1690)$,
$\Lambda(1800), \Lambda(1810), \Lambda(1820), \Lambda(1830), \Lambda(1890), \Lambda(2100)$,
$\Lambda(2110), \Lambda(2350), \Sigma^+, \Sigma^0, \Sigma^-, \Sigma(1385), \Sigma(1660), \Sigma(1670)$,
$\Sigma(1750), \Sigma(1775), \Sigma(1915), \Sigma(1940), \Sigma(2030), \Sigma(2250), \Xi^0, \Xi^-$,
$\Xi(1530), \Xi(1690), \Xi(1820), \Xi(1950), \Xi(2030), \Omega^-, \Omega(2250)^-$,
$\Lambda_c^+, \Lambda_c^+, \Sigma_c(2455), \Sigma_c(2520), \Xi_c^+, \Xi_c^0, \Xi_c'^+, \Xi_c'^0, \Xi(2645)$
$\Xi_c(2780), \Xi_c(2815), \Omega_c^0, \Lambda_b^0, \Xi_b^0, \Xi_b^-, t\bar{t}$

There are many more

W. Riegler, AEPSHEP12

Particle detection

How can a particle detector distinguish the hundreds of particles that we know now?

- only 27 have a lifetime that is long enough such that at GeV energies they travel more than one micrometer;
  (remember $l = \beta\gamma c\tau = (p_{lab}/m)c\tau$)

- only 14 travel more than half a millimeter;

Particle	Mass (MeV)	Lifetime τ (s)	$c\tau$
γ	0	∞	∞
$\pi^\pm (u\bar{d}, d\bar{u})$	140	$2.6 \cdot 10^{-8}$	7.8 m
$K^\pm (u\bar{s}, \bar{u}s)$	494	$1.2 \cdot 10^{-8}$	3.7 m
$K^0 (d\bar{s}, \bar{d}s)$	497	$5.1 \cdot 10^{-8}$ / $8.9 \cdot 10^{-11}$	15.5 m / 2.7 cm
$D^\pm (c\bar{d}, \bar{c}d)$	1869	$1.0 \cdot 10^{-12}$	315 μm
$D^0 (c\bar{u}, u\bar{c})$	1864	$4.1 \cdot 10^{-13}$	123 μm
$D_s^\pm (c\bar{s}, \bar{c}s)$	1969	$4.9 \cdot 10^{-13}$	147 μm
$B^\pm (u\bar{b}, \bar{b}u)$	5279	$1.7 \cdot 10^{-12}$	502 μm
$B^0 (b\bar{d}, d\bar{b})$	5279	$1.5 \cdot 10^{-12}$	462 μm
$B_s^0 (s\bar{b}, \bar{s}b)$	5370	$1.5 \cdot 10^{-12}$	438 μm
$B_c^\pm (c\bar{b}, \bar{c}b)$	~6400	$\sim 5 \cdot 10^{-13}$	150 μm
$p (uud)$	938.3	$> 10^{33}$ y	∞
$n (udd)$	939.6	885.7 s	$2.655 \cdot 10^{8}$ km
$\Lambda^0 (uds)$	1115.7	$2.6 \cdot 10^{-10}$	7.89 cm
$\Sigma^+ (uus)$	1189.4	$8.0 \cdot 10^{-11}$	2.404 cm
$\Sigma^- (dds)$	1197.4	$1.5 \cdot 10^{-10}$	4.434 cm
$\Xi^0 (uss)$	1315	$2.9 \cdot 10^{-10}$	8.71 cm
$\Xi^- (dss)$	1321	$1.6 \cdot 10^{-10}$	4.91 cm
$\Omega^- (sss)$	1672	$8.2 \cdot 10^{-11}$	2.461 cm
$\Lambda_c^+ (udc)$	2285	$\sim 2 \cdot 10^{-13}$	60 μm
$\Xi_c^+ (usc)$	2466	$4.4 \cdot 10^{-13}$	132 μm
$\Xi_c^0 (dcs)$	2472	$\sim 1 \cdot 10^{-13}$	29 μm
$\Omega_c^0 (ssc)$	2698	$6.0 \cdot 10^{-14}$	19 μm
$\Lambda_b (udb)$	5620	$1.2 \cdot 10^{-12}$	368 μm

"Secondary Vertices" ($D^\pm$ through $B_c^\pm$)

W. Riegler, AEPSHEP12

Particle detection

How can a particle detector distinguish the hundreds of particles that we know now?

- only 27 have a lifetime that is long enough such that at GeV energies they travel more than one micrometer;
  (remember $l = \beta\gamma c\tau = (p_{lab}/m)c\tau$)

- only 14 travel more than half a millimeter;

- among those 14 particules, 8 are by far the most frequent ones:
  $\mathbf{e^{\pm}, \mu^{\pm}, \gamma, \pi^{\pm}, K^{\pm}, K^{0}, p^{\pm}, n}$

W. Riegler, AEPSHEP12

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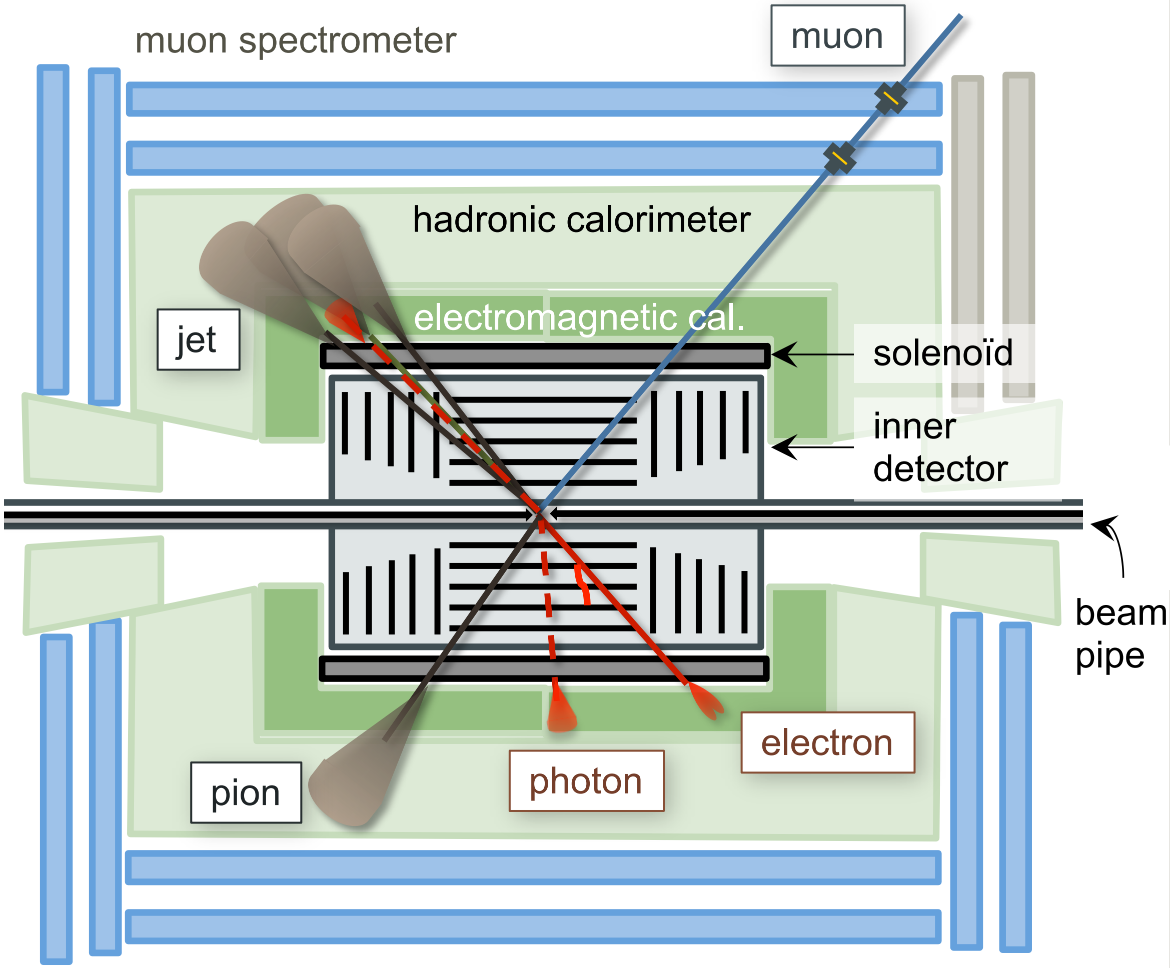
A particle detector must be able to **identify** and measure **energy** and **momenta** of these 8 particles.

The difference in mass, charge and iteraction is the key in identification.

W. Riegler, AEPSHEP12

Particle detection

- electrons ionize and show Bremsstrahlung due to small mass → **electromagnetic shower**;
- photons don't ionize but show pair production in material → **electromagnetic shower**;
- charged hadrons ionize and show **hadronic shower** in dense material;
- neutral hadrons don't ionize and show **hadronic shower** in dense material;
- muons ionize and don't shower.
- neutrinos do not interact at all: hermetic detectors to measure missing energy (in the transverse plane)



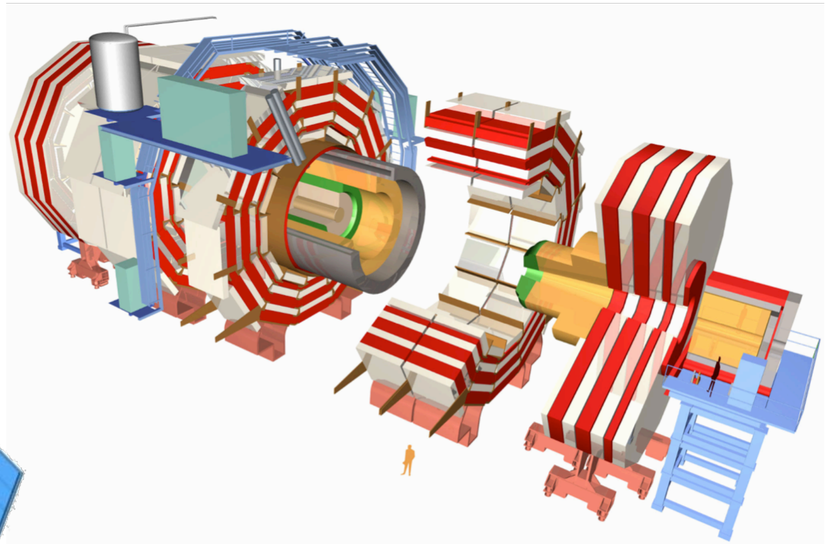
The general-purpose detectors: ATLAS and CMS

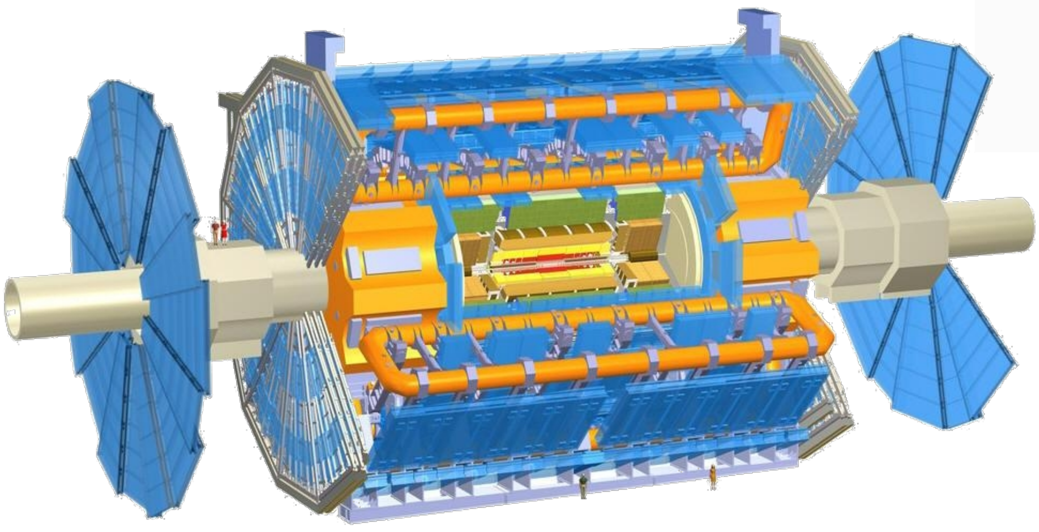
The design of the ATLAS and CMS detectors has been largely driven by what was considered in the 1990's as the most promising channels for the Higgs discovery:

- H→ $\gamma\gamma$ ➔ excellent energy resolution of the electromagnetic calorimeter
- H→Z*Z with Z→e^+e^- ➔ high precision inner tracker, even at low transverse momentum
  or Z→$\mu^+\mu^-$ ➔ high intensity solenoid, precision outer chambers
- H→W*W with W→$l\nu$ (l=e or μ)
  ➔ excellent hermeticity of the detectors in the transverse plane to measure missing energy

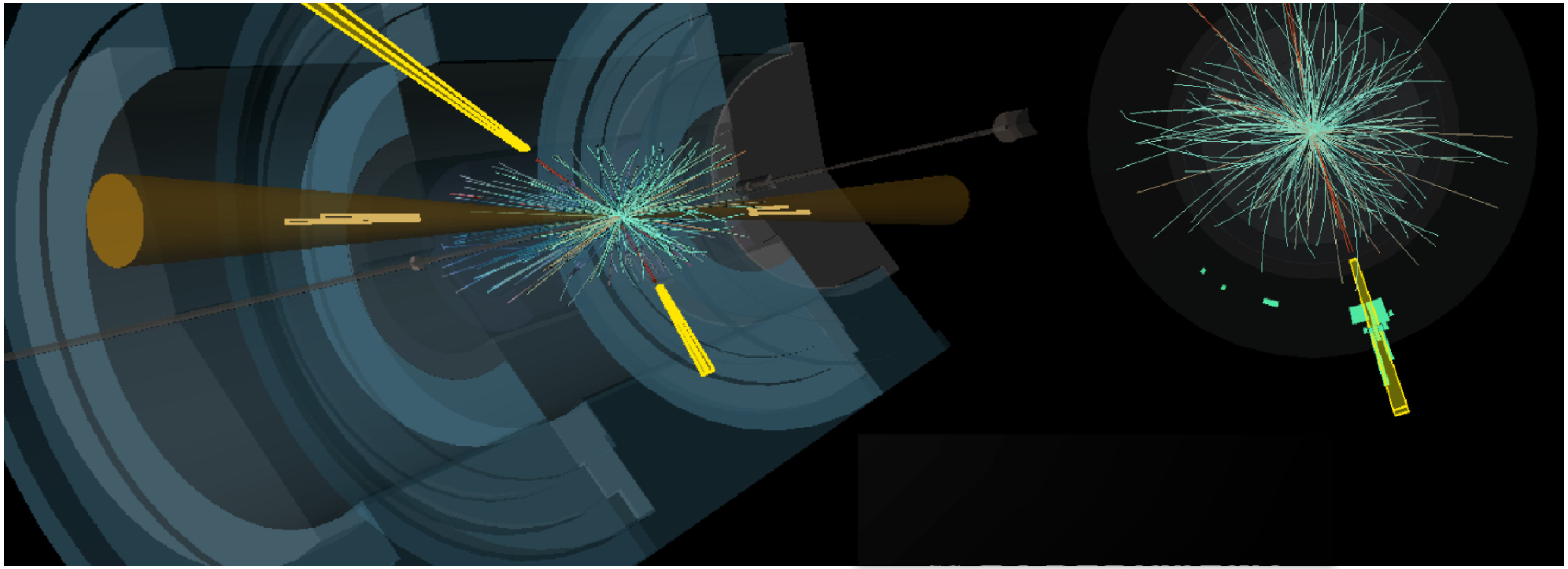
The general-purpose detectors: ATLAS and CMS

CMS (15m x 26m):
- 4T solenoid!
- high resolution EM calo: 1.5-2% on E_{γ}
- full silicon inner detector



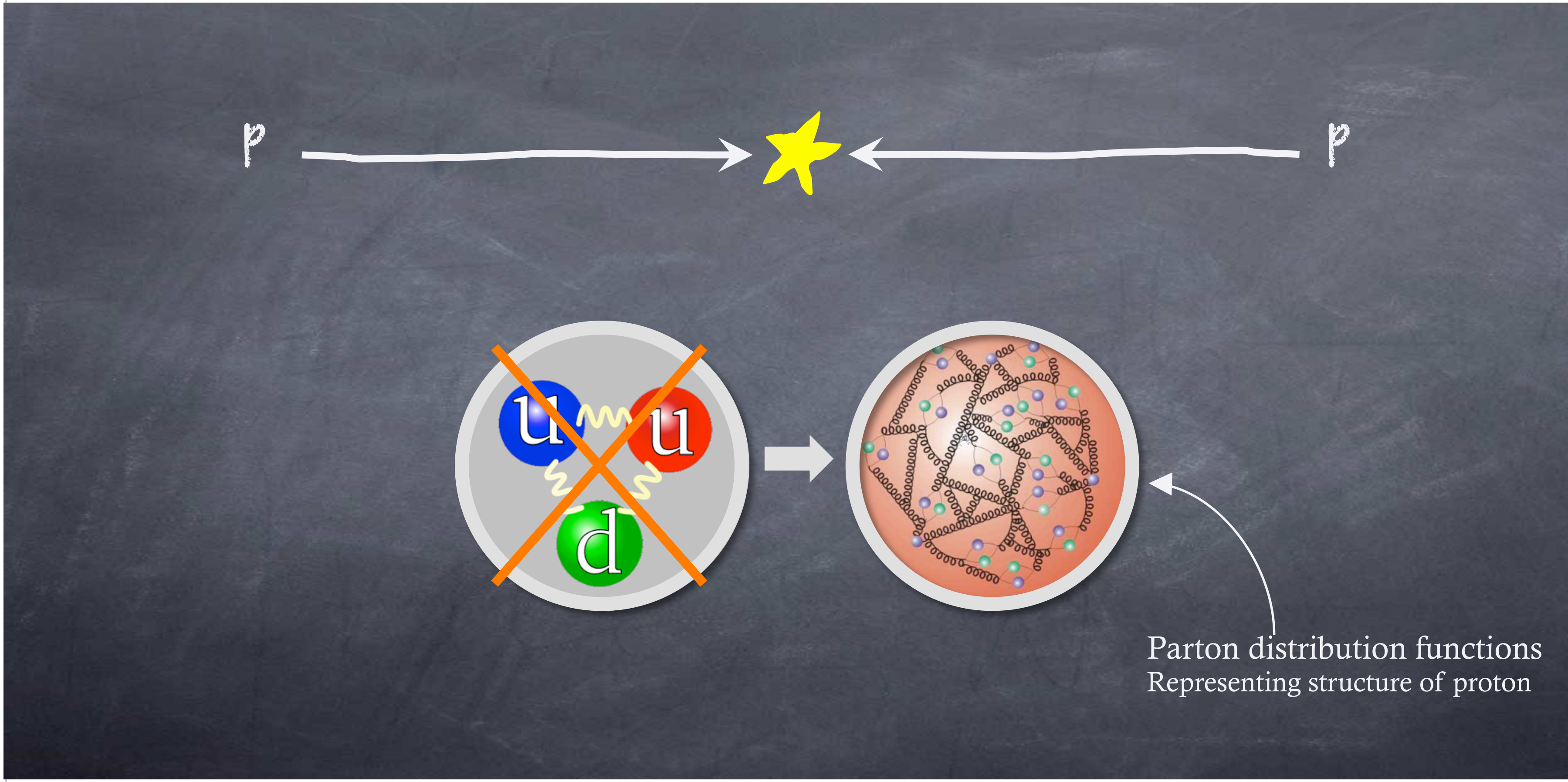


ATLAS (25m x 45m):
- 2T solenoid+ toroid (0.5T & 1T)
- high resolution hadronic calorimeter:
  $\sigma/E \approx 50\%/\sqrt{E} \oplus 0.03$ GeV
- 3 longitudinal layer EM calo + fine transversal segmentation
- ID: silicon + transition radiation



Production and detection of the Higgs boson at LHC

Proton-proton collisions



Higgs production

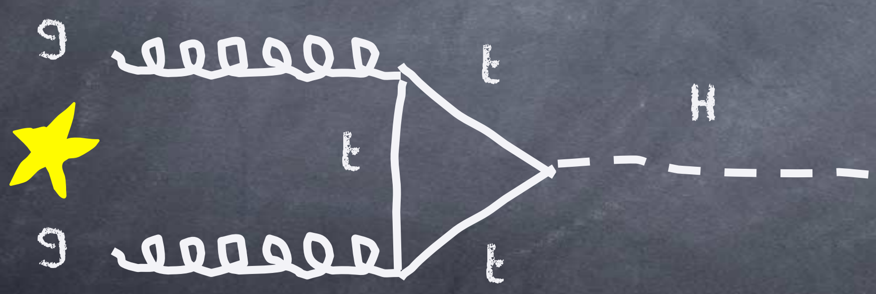
At the LHC, the Higgs is produced dominantly from gluon fusion.

Gluon is massless: coupling through heavy particle loops, mainly top .

coupling to vector bosons: $2m_V^2/v$

coupling to fermions: m_f/v

reminder: vaccum expectation value v=246 GeV



Total production of ~600 thousand Higgs bosons of 125 GeV in 2011 and 2012 in each ATLAS and CMS

Higgs decay

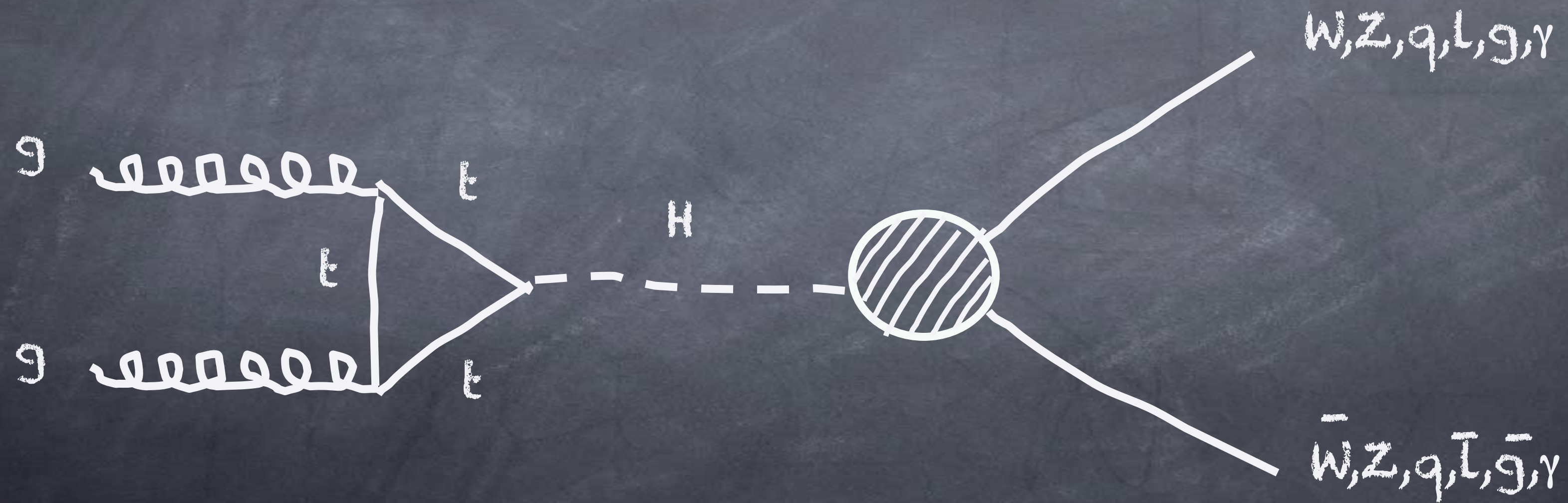
At the LHC, the Higgs is produced dominantly from gluon fusion.

Gluon is massless: coupling through heavy particle loops, mainly top .

coupling to vector bosons: $2m_V^2/v$

coupling to fermions: m_f/v

reminder: vaccum expectation value v=246 GeV

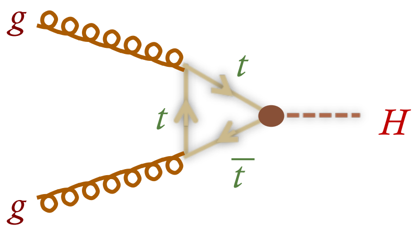


→ Higgs preferably decays to heavy particles

Higgs production

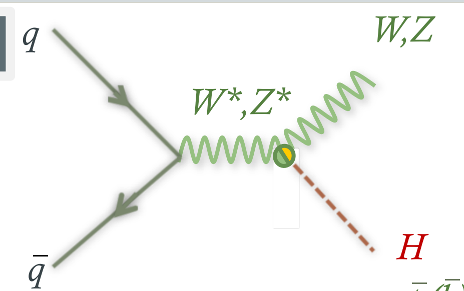
gluon-gluon fusion

86.4%



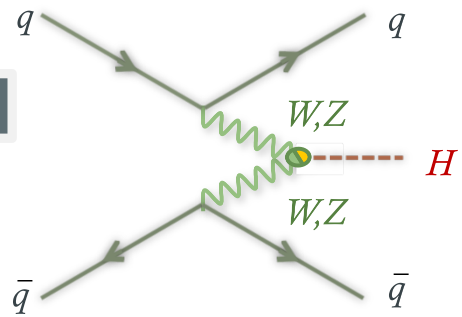
VH (V=Z or W)

5.0%



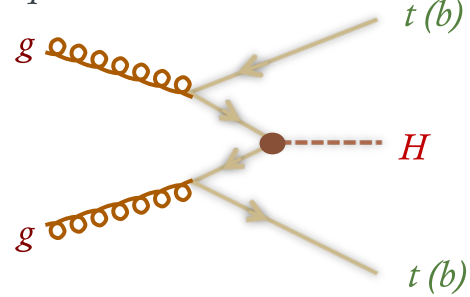
vector boson fusion

7.1%

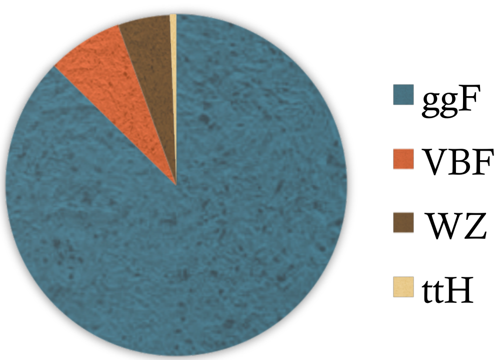


$t\bar{t}$ (bb) fusion

0.6% (0.9%)



Higgs production fractions at E_{cm}=8 TeV



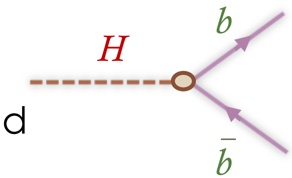
VBF and Higgstrahlung (VH) can be used to fight against background.

ttH important to study the top Yukawa cupling.

Higgs decays

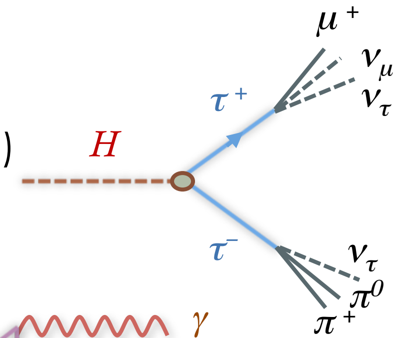
$H \to bb$

- **largest branching ratio** (58%) but high QCD background
- use VH or boosted topologies to fight against background



$H \to \tau^+\tau^-$

- reasonnable BR (6%) but large bkg and poor mass resolution (escaping ν's)
- use VBF or boosted topologies

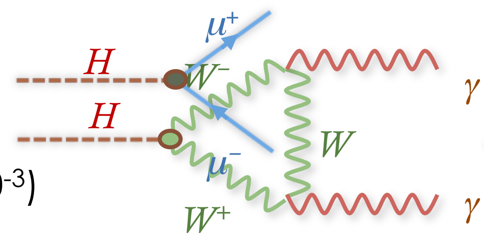


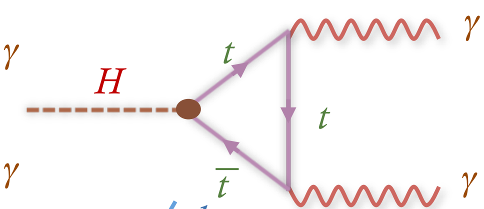
$H \to \mu^+\mu^-$

- **extremely low** BR ($2.\ 10^{-4}$)
- excellent mass resolution

$H \to \gamma\gamma$

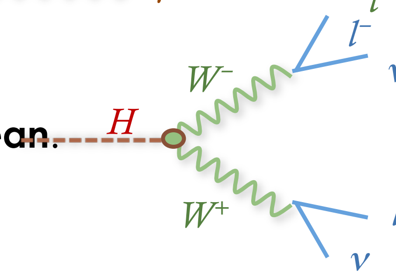
- **very** low branching fraction ($2.\ 10^{-3}$)
- *BUT…* 1-2 GeV mass resolution





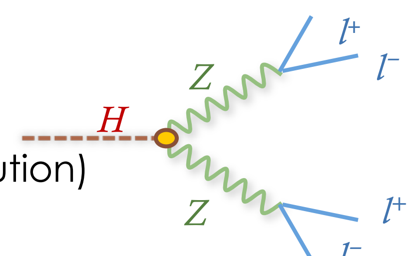
$H \to W^+W^- \to l^+\nu l^-\nu$ (l=e or μ)

- sizeable BR (21% x $(22\%)^2$=1%) and reasonnably **clean**.
- but poor mass resolution (escaping ν's)



$H \to ZZ^* \to l^+l^-l^+l^-$ (l=e or μ)

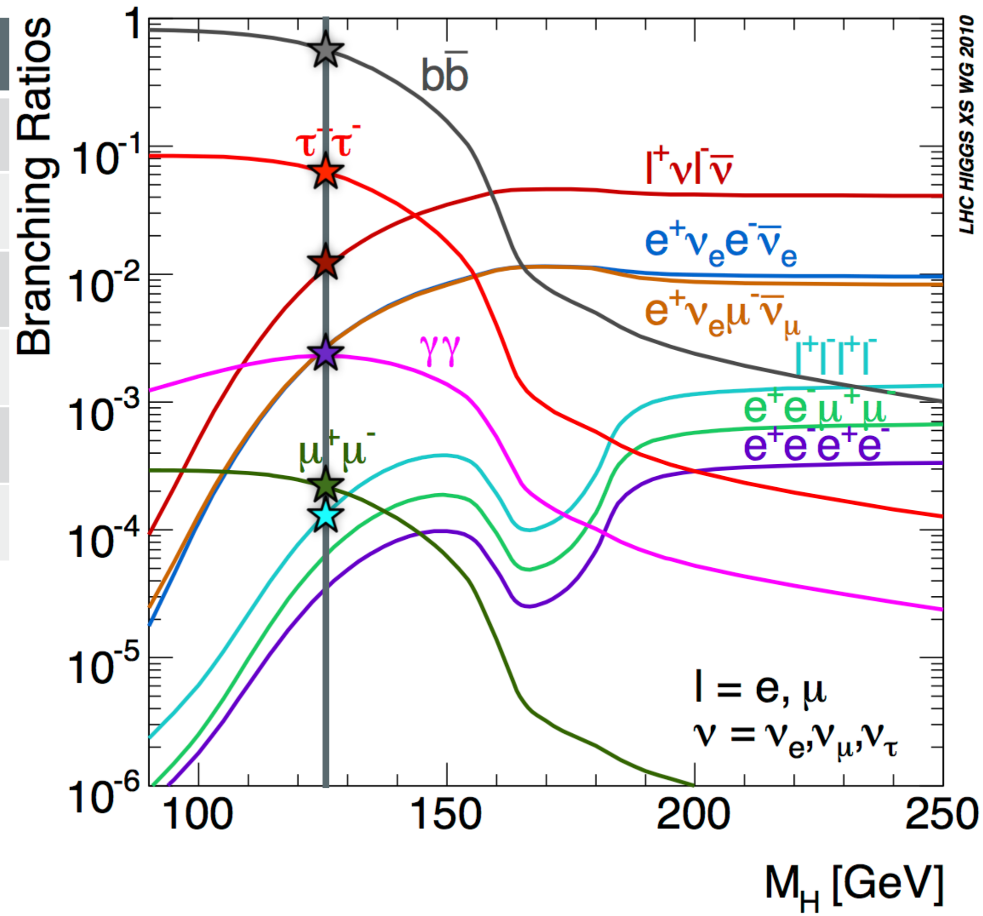
- extremely low BR (0.3%x$(6.7\%)^2$=10^{-4}!) but **very clean** (excellent mass resolution)



$H \to gg, cc, e^+e^-$ are hopeless

SM Higgs event yields at run 1

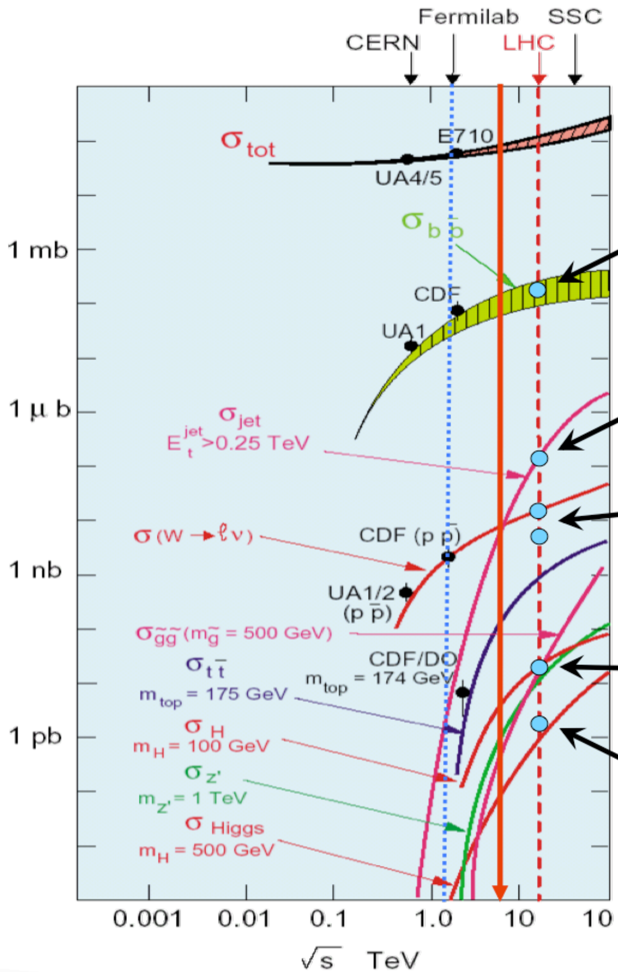
channel	#events
$H \rightarrow bb$	320000 (VH: 16000)
$H \rightarrow \tau^+\tau^-$	35000
$H \rightarrow \mu^+\mu^-$	120
$H \rightarrow \gamma\gamma$	1300
$H \rightarrow W^+W^- \rightarrow l^+\nu l^-\nu$ ($l=e/\mu$)	6100
$H \rightarrow ZZ^* \rightarrow l^+l^-l^+l^-$ ($l=e/\mu$)	72

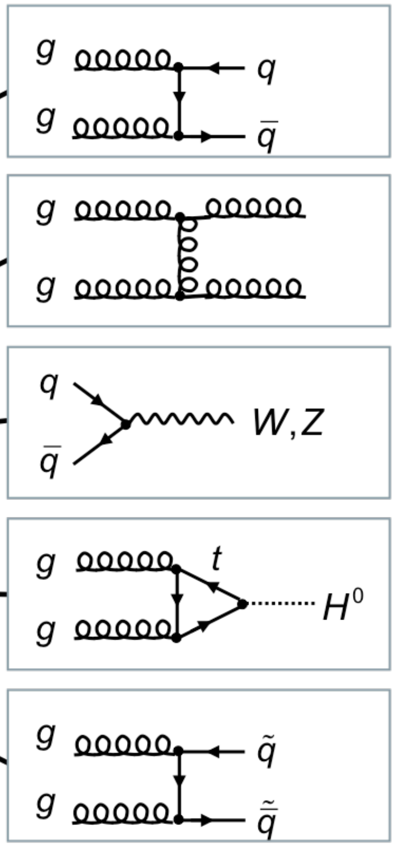


Actual numbers of observed events are further reduced by:

- detector acceptance
- reconstruction efficiency
- event selection efficiency

Cross sections at hadron colliders





Quark-flavour production

High-p_T QCD jets

W, *Z* production

gluon-to-Higgs fusion

squarks, gluinos
(m ~ 1 TeV)

10s at LHC:
~10 billions evts

≈ 100 millions
b quarks

≈ 200 000
W bosons

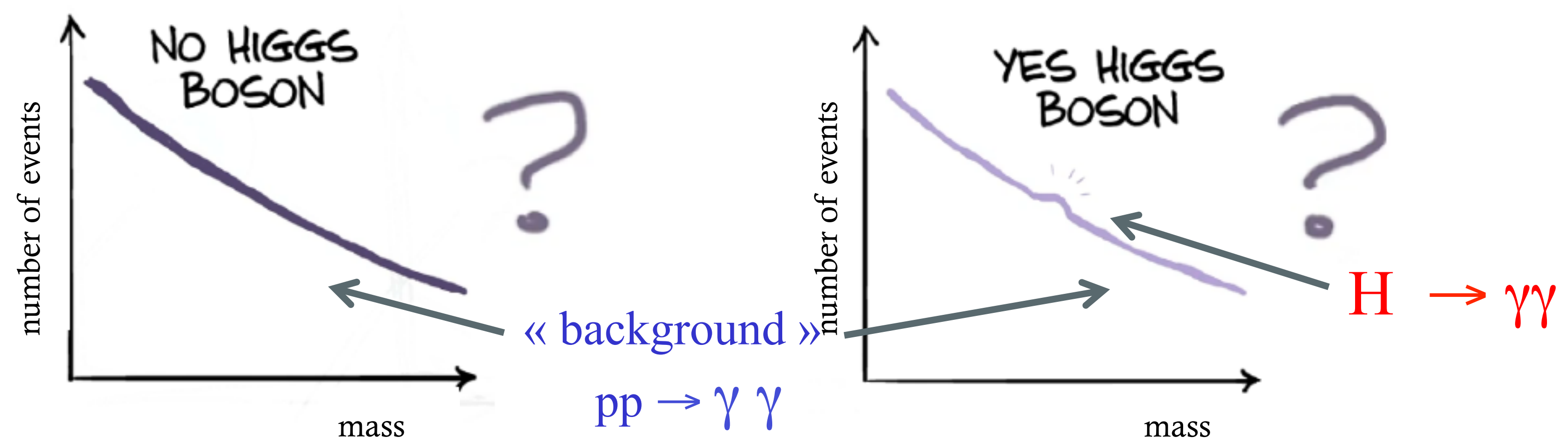
≈ 3 Higgs
bosons

Higgs search basics

Example: search for H $\rightarrow\gamma\gamma$

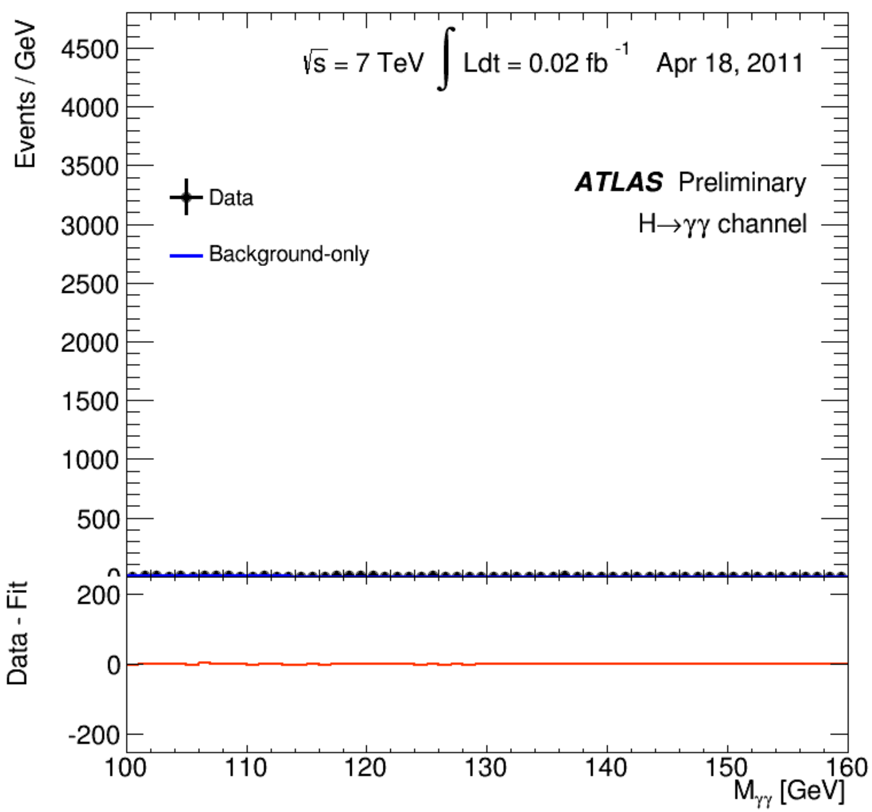
- look for two photons in the detector
- measure their energy (E_i), momentum (p_i), the angle between the two
- calculate the "invariant mass"

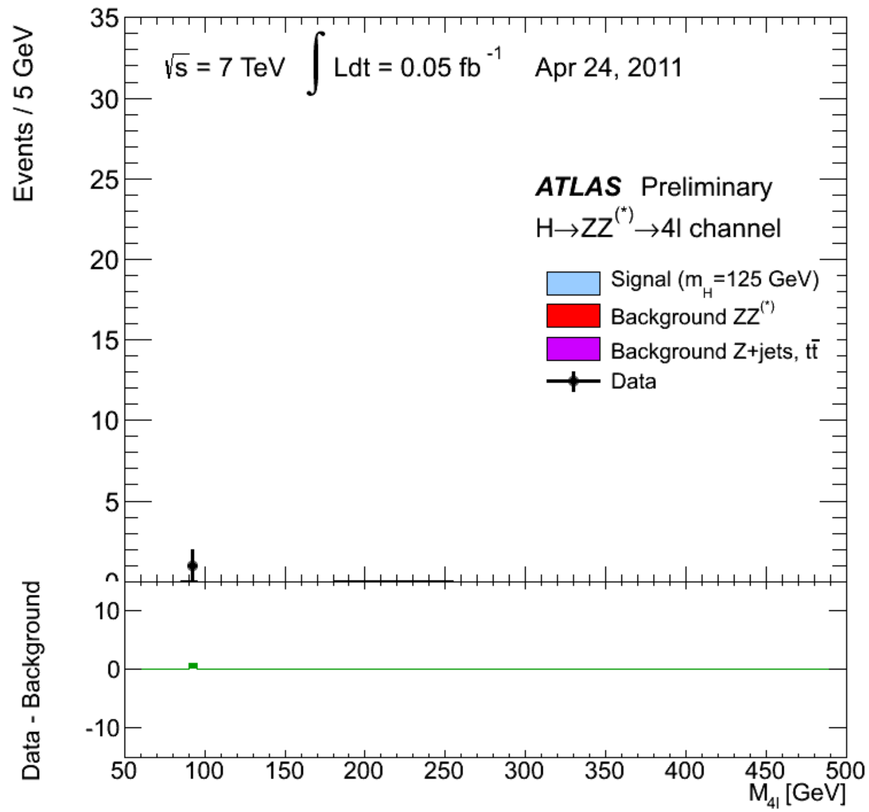
$$m_{\gamma\gamma} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2} = \sqrt{2E_1E_2(1-\cos\theta)}$$



Claim discovery if $N_S / \sqrt{N_B} > 5$ (or use some equivalent but much more complicated criteria). The probability that the number of background fluctuates that much is 10^{-7} (probability to throw a dice and get 21 times the exact same number).

H→ γγ and H→Z*Z→4l signals





Similar distributions in CMS.

Higgs decay observation status (2011+2012)

$H \rightarrow bb$	ATLAS: 1.4σ, CMS: 2.1σ	run2 major goal!
$H \rightarrow \tau^+\tau^-$	ATLAS: 4.5σ, CMS: 3.2σ	almost there!
$H \rightarrow \mu^+\mu^-$	ATLAS, CMS upper limit: ~7xSM prediction	

H→fermions
ATLAS: 3.7σ
CMS: 3.8σ

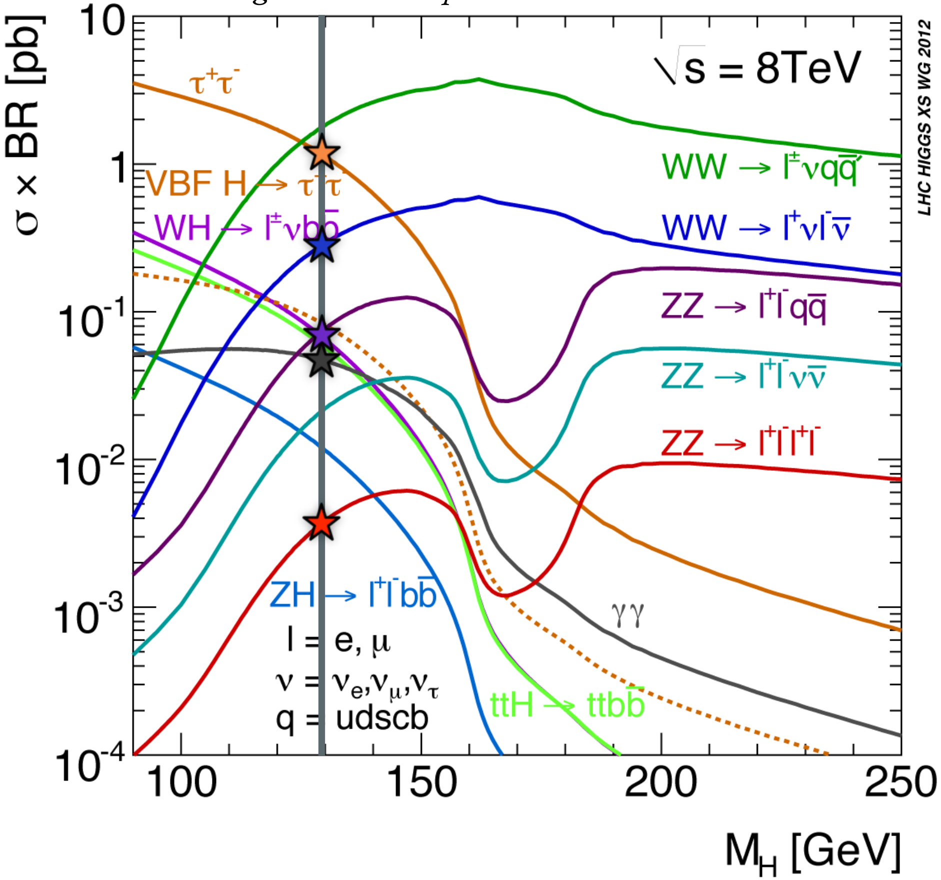
non-universality of lepton couplings!

$H \rightarrow \gamma\gamma$	ATLAS: 5.2σ, CMS: 5.7σ	✓
$H \rightarrow W^+W^- \rightarrow l^+\nu l^-\nu$	ATLAS: 6.1σ, CMS: 4.3σ	✓
$H \rightarrow ZZ^* \rightarrow l^+l^-l^+l^-$	ATLAS: 8.1σ, CMS: 6.8σ	✓

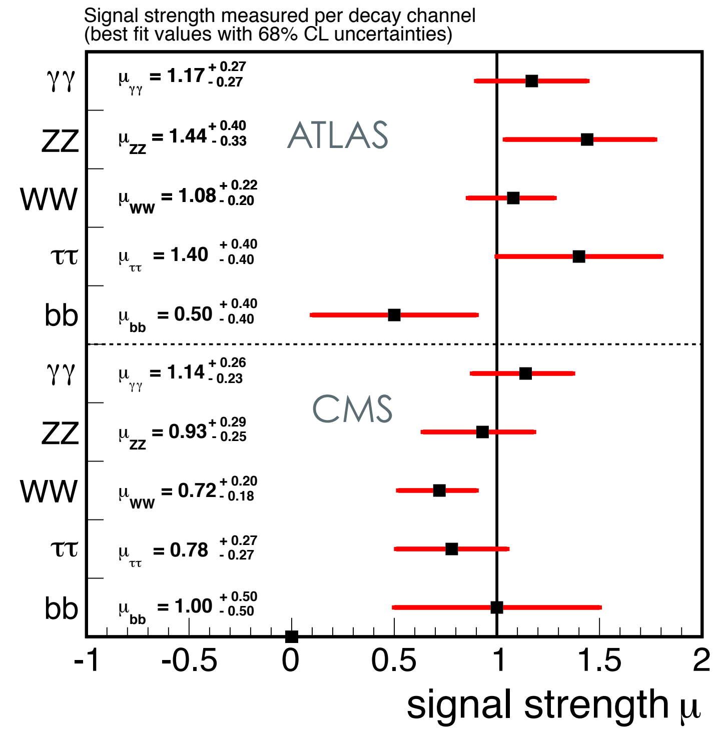
H→bosons clearly established

Higgs decay observation status (2011+2012)

Warning: not the same plot as on slide 18!



$\mu=(\sigma \times BR)_{observed}/(\sigma \times BR)_{predicted\ by\ SM}$



Y. Sirois, http://www.lpt.ens.fr/spip.php?article214

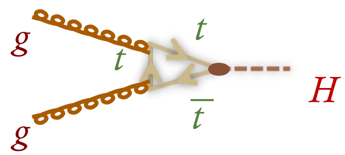
CMS combination of the 5 decay channels:
μ=1.00 ± 0.09 (stat) ± 0.08 (theo) ± 0.07 (syst)

Decay rates so far compatible with SM predictions for a m_H=125 GeV Higgs boson

Higgs production observation status (2011+2012)

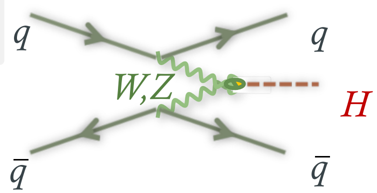
gluon-gluon fusion

86.4% ✓



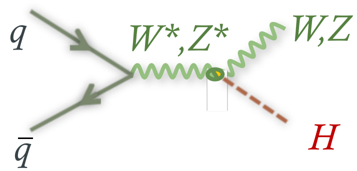
vector boson fusion

7.1% ✓



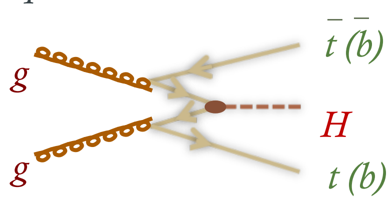
VH (V=Z or W)

5.0%



tt̄ (bb) fusion

0.6% (0.9%)



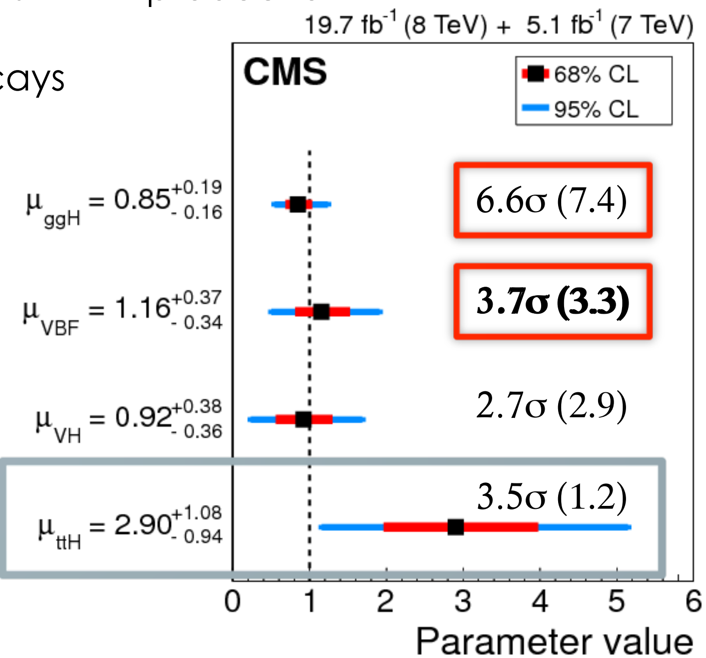
The Higgs is the first particle discovered (mainly) through a loop-level production process!

What about other production channels? In a given decay channel, one can tag the events with:

- forward jets → VBF production
- Z or W bosons → VH production

Combining decays channels:

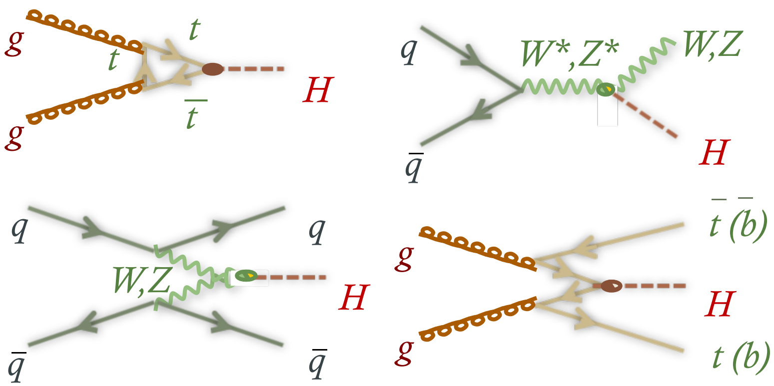
run2 major goals: top Yukawa coupling!



Also in ATLAS: 4.1σ evidence for VBF production.

Higgs couplings

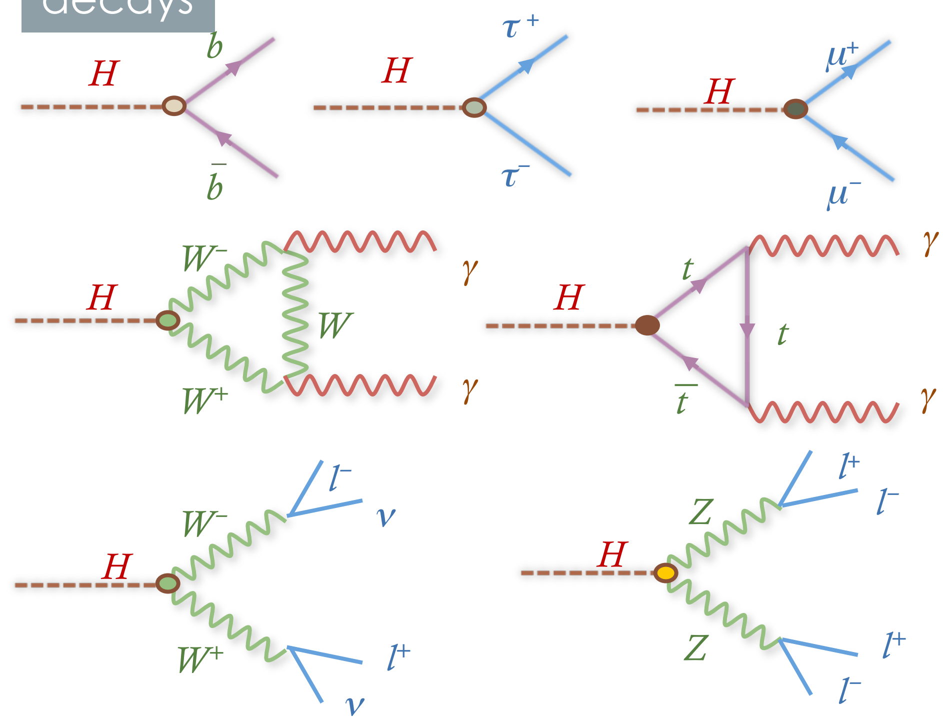
production



Couplings:

- ttH
- bbH
- $\mu^+\mu^-H$
- $\tau^+\tau^-H$
- W^+W^-H
- ZZH

decays



Production and decay processes give access to the same couplings. A global analysis of the Higgs data allows to estimate the value of the couplings and check for possible deviation from SM prediction.

Search for deviations from SM prediction for couplings

Are the measurements in agreement with the predicted couplings of Higgs to SM particles?

- Measure $(\sigma \,.\, BR)(ii \rightarrow H \rightarrow ff)$ and test deviations on σ_{ii}, Γ_{ff} and Γ_H:

$$(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

Assumption: one single, narrow, CP-even scalar resonance near 125 GeV, with the same coupling structure as for the SM Higgs.

- Parametrise possible deviations with individual coupling scale factors κ_i. Examples:

Production:

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2 \qquad \frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2 \qquad \frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma_{\mathrm{t\bar{t}H}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^2$$

Decays:

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma_{\mathrm{WW}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2 \qquad \frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma_{\mathrm{ZZ}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2 \qquad \frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma_{\mathrm{b\bar{b}}}^{\mathrm{SM}}} = \kappa_{\mathrm{b}}^2 \qquad \frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{\mathrm{SM}}} = \kappa_{\tau}^2$$

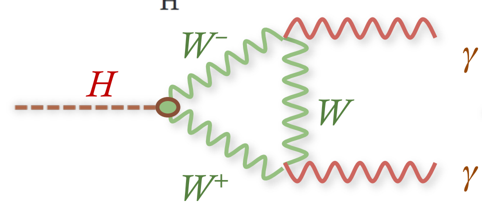
Production x decay:

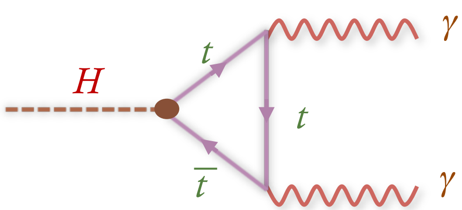
$$(\sigma \cdot \mathrm{BR})\,(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_{\mathrm{g}}^2 \cdot \kappa_{\gamma}^2}{\kappa_{\mathrm{H}}^2}$$

where κ_g and κ_γ are effective scale factors:

$$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_{\mathrm{W}}^2 - 0.66 \cdot \kappa_{\mathrm{W}}\kappa_{\mathrm{t}} + 0.07 \cdot \kappa_{\mathrm{t}}^2$$

$$\kappa_{\mathrm{g}}^2 \sim 1.06 \cdot \kappa_{\mathrm{t}}^2 - 0.07 \cdot \kappa_{\mathrm{t}}\kappa_{\mathrm{b}} + 0.01 \cdot \kappa_{\mathrm{b}}^2$$



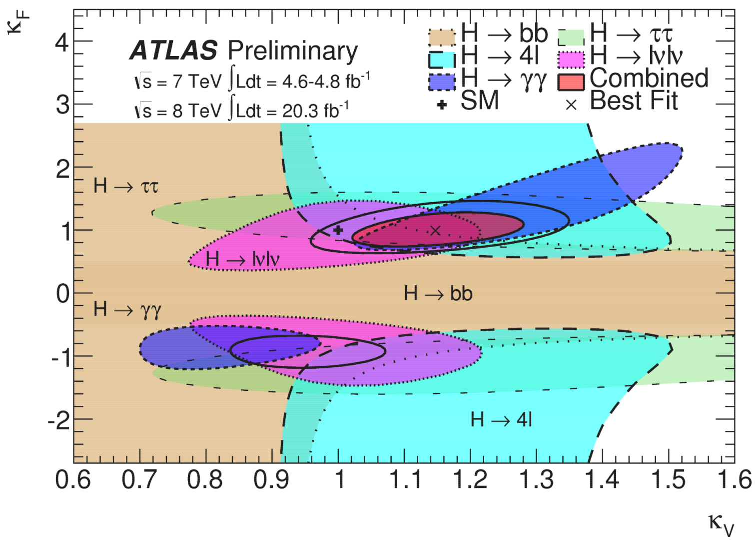


interference term allows to test the sign of κ_i

Search for deviations from SM prediction for couplings

Not enough inputs to constrain all scale factors.
Define benchmark models. For example, assume:

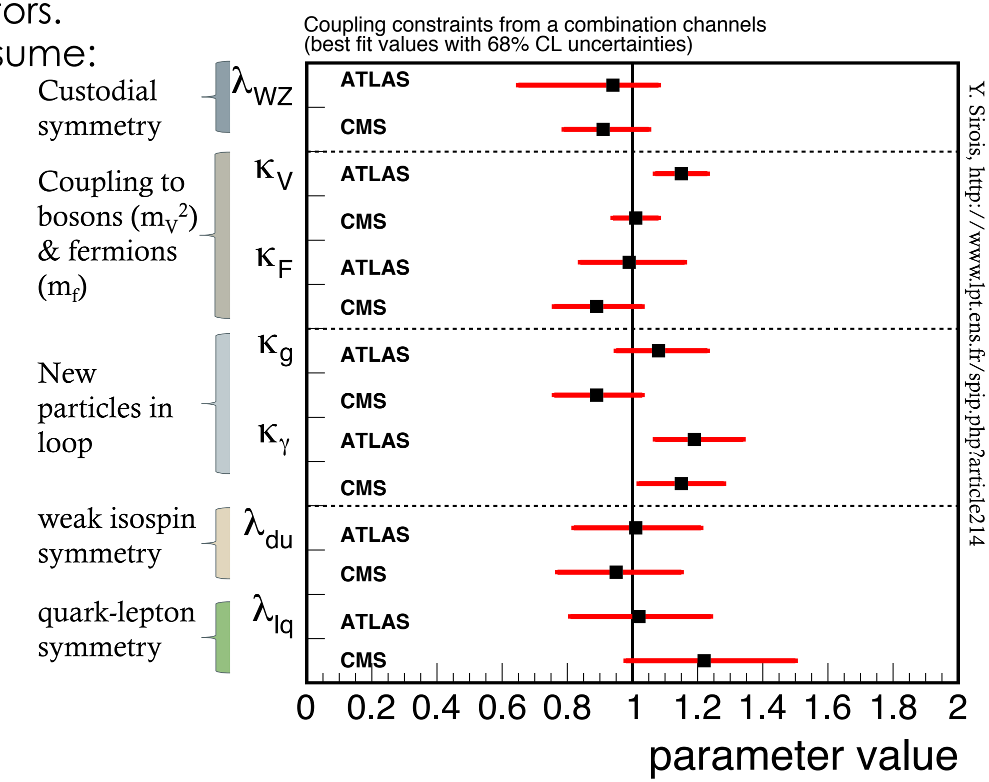
- one scale-factor for fermions: $\kappa_F = \kappa_b = \kappa_t = \kappa_\tau$
- one scale-factor for vector bosons: $\kappa_V = \kappa_W = \kappa_Z$
- no new particles in loops or in decays ($\Gamma_H = \Gamma_H^{SM}$)



ATLAS: κ_V : [1.07,1.23]; κ_F: [0.84,1.16] @ 68% CL

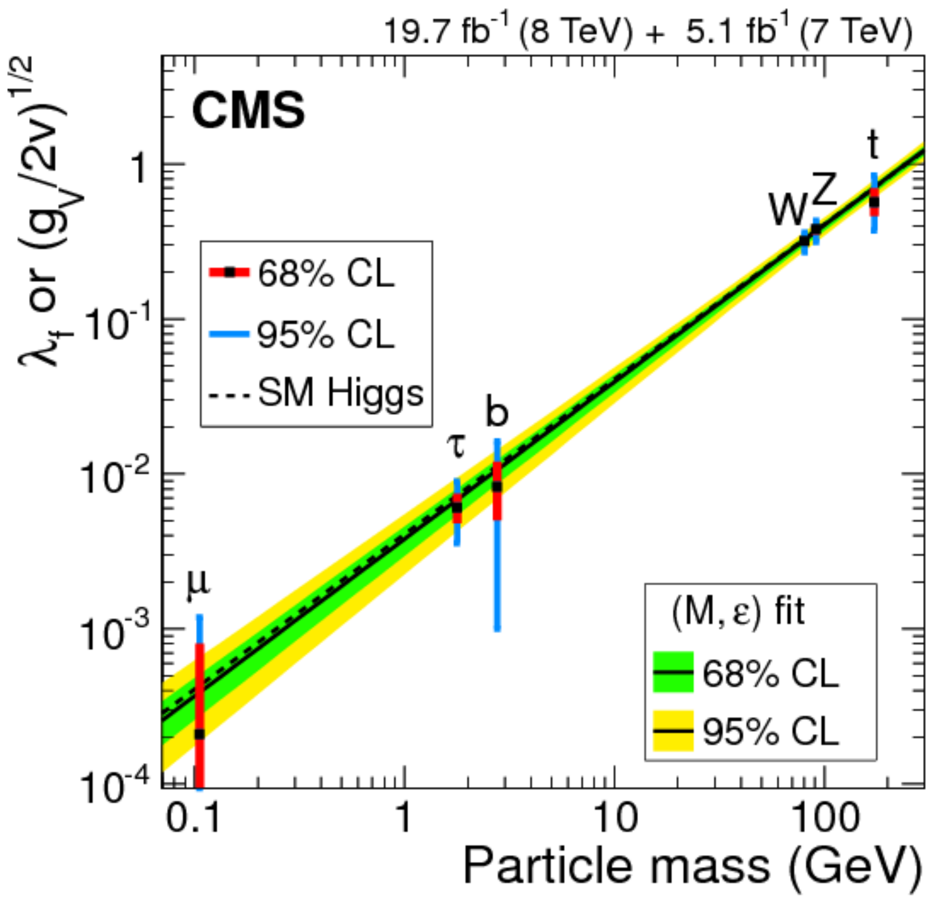
CMS: κ_V : [0.94,1.08]; κ_f: [0.75,1.03] @ 68% CL

Relative negative sign disfavoured at ~2-3σ level

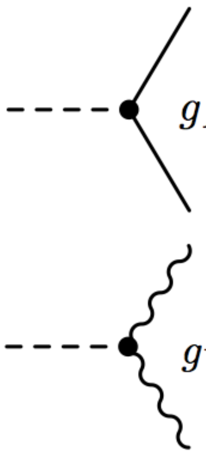


All tested configurations are consistent with SM, with a precision of ~15% (λ_{WZ},κ_V) to 20-30% (λ_{du},κ_F).

Higgs couplings

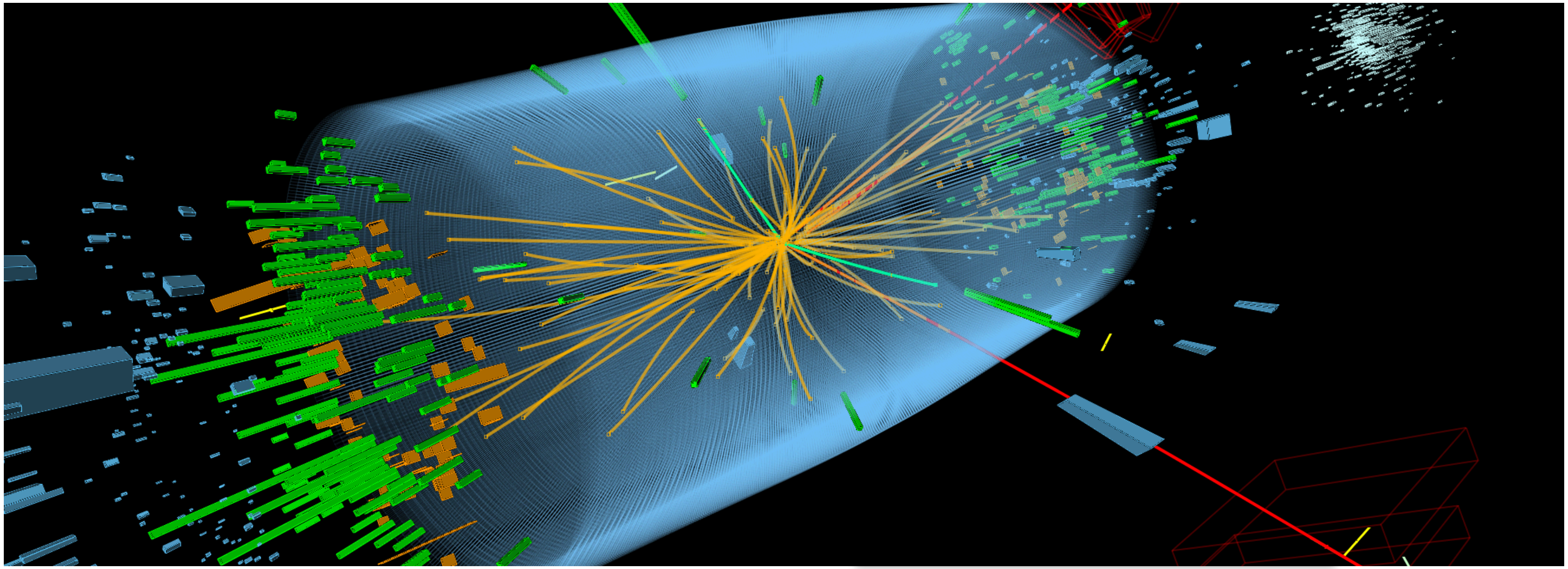


Reminder from slide14:



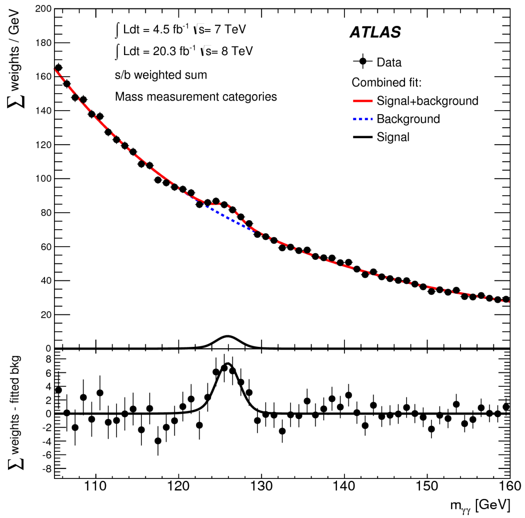
$$g_F = \frac{m_f}{v}$$

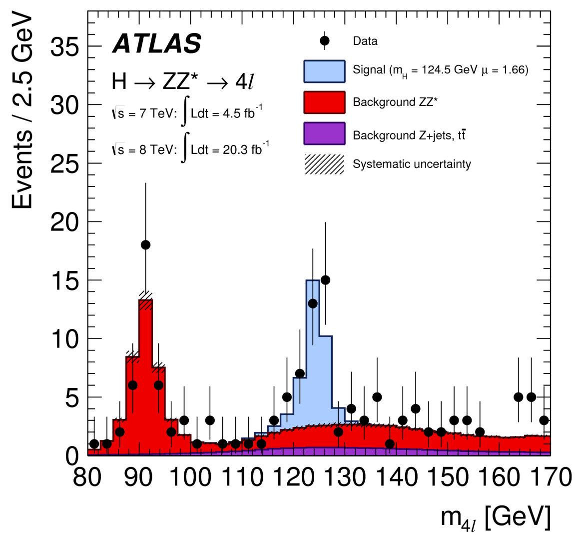
$$g_V = 2\frac{m_V^2}{v}$$



Measuring the Higgs properties at LHC

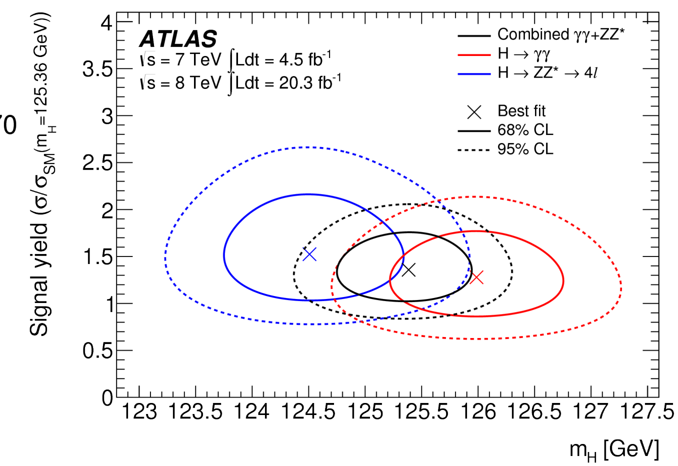
Measuring the mass





Performed using

- $H \rightarrow ZZ^* \rightarrow 4\mu$, $2e2\mu$, $4e$
- $H \rightarrow \gamma\gamma$

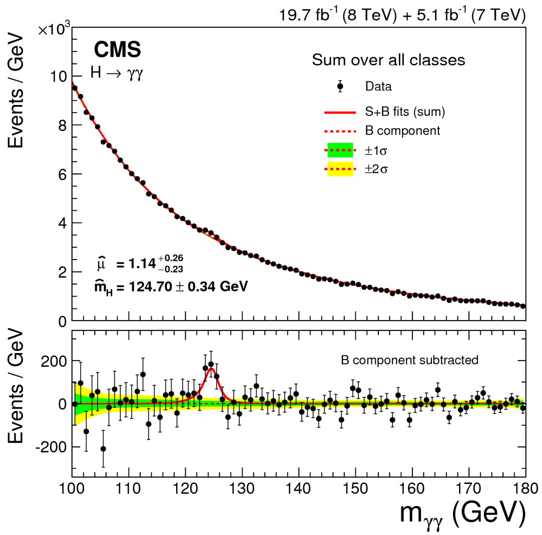


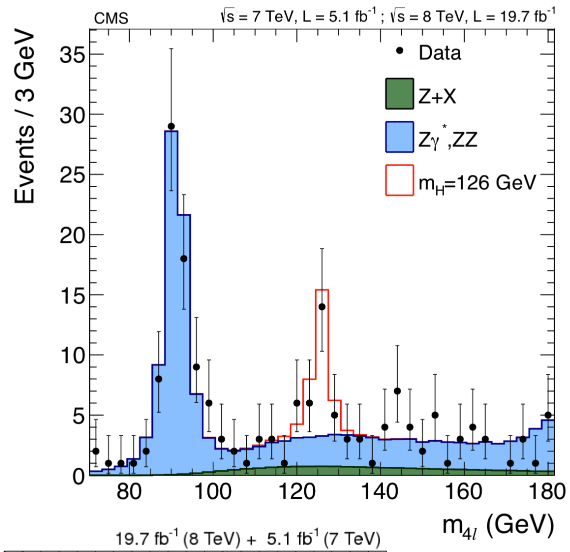
ATLAS arXiv:1406.3827

$H \rightarrow \gamma\gamma$	125.98±0.42±0.28 GeV
$H \rightarrow 4l$	124.51±0.52±0.06 GeV
combined	**125.36±0.37±0.18 GeV**

Mass difference between the 2 channels: Δm_H=1.47±0.67±0.28 GeV. Compatibility at the 2.0σ level.

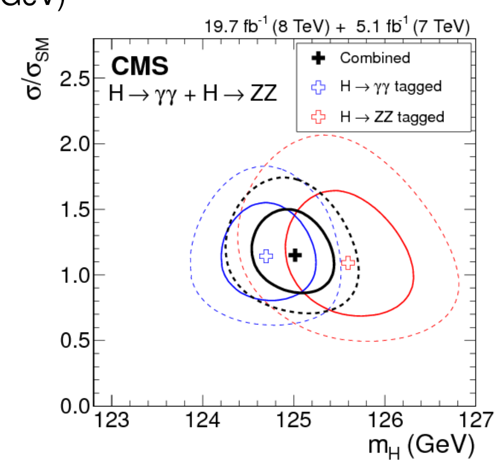
Measuring the mass





Performed using

- H→ZZ*→4μ, 2e2μ, 4e
- H→γγ



CMS arXiv:1412.8662

H→γγ	124.70±0.31±0.15 GeV
H→4l	125.59±0.43±0.18 GeV
combined	**125.02±0.27±0.15 GeV**

Δm_H=-0.89±0.57GeV.
Compatibility at the 1.6σ level.

Measuring the mass

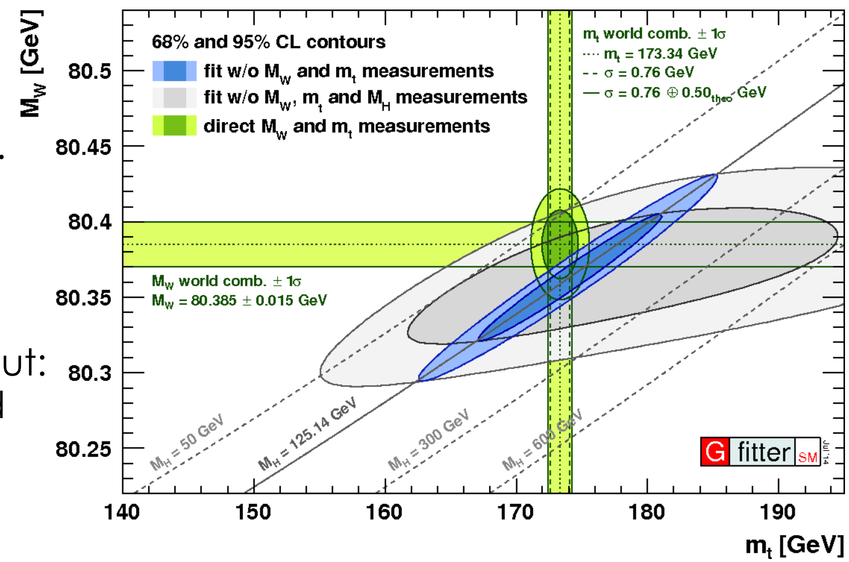
The Higgs mass is already known at the ~2‰ level! (ATLAS+CMS combination to be published soon)

Twice as well as the top mass (discovered in 1995).
but still:

- 10 times less well than the W mass
- 100 times less well than the Z mass

The mass of the Higgs is not predicted by the SM but:

- σ & BR (see previous slides) predictions depend on m_H
- important to test the consistency of the SM (radiative corrections)



ATLAS arXiv:1406.3827

H→γγ	125.98±0.42±0.28 GeV
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combined	**125.36±0.37±0.18 GeV**

CMS arXiv:1412.8662

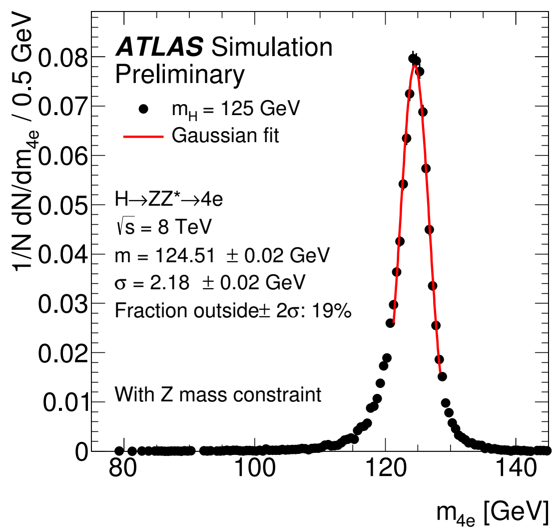
H→γγ	124.70±0.31±0.15 GeV
H→4l	125.59±0.43±0.18 GeV
combined	**125.02±0.27±0.15 GeV**

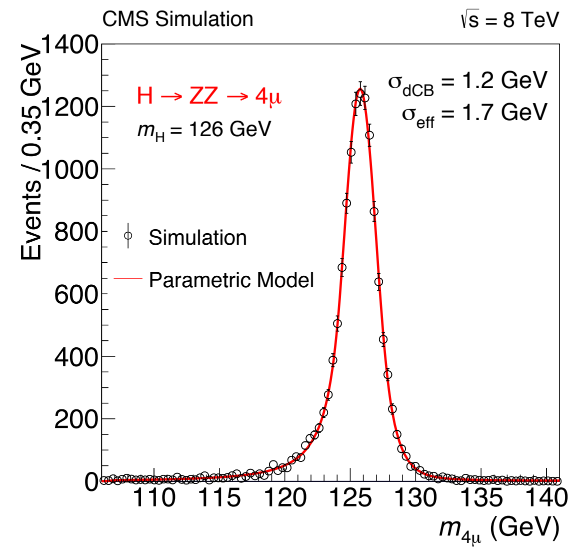
Direct constraints on the width

The width of the Higgs is predicted by the Standard Model. For m_H~125 GeV, Γ_H**~4 MeV**.

Beyond SM contributions may increase it significantly.

However, the direct determination is limited by the much larger detector resolution: 1-2 GeV





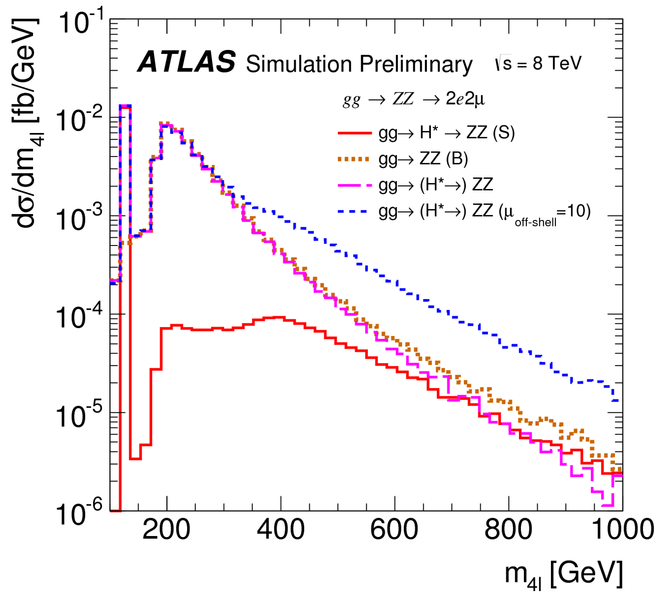
Limits at 95%CL:

	ATLAS	CMS
H→γγ	4.4 GeV	2.4 GeV
H→4l	2.6 GeV	3.4 GeV

Constraints on the width from the $H^{(*)} \rightarrow Z^{(*)}Z^*$ analysis

The H→ZZ decay includes a sizeable off-shell contribution.
Search for deviation from SM:

$$\frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell, SM}}} = \mu_{\text{off-shell}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{V,\text{off-shell}}$$



Similarly:

$$\frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

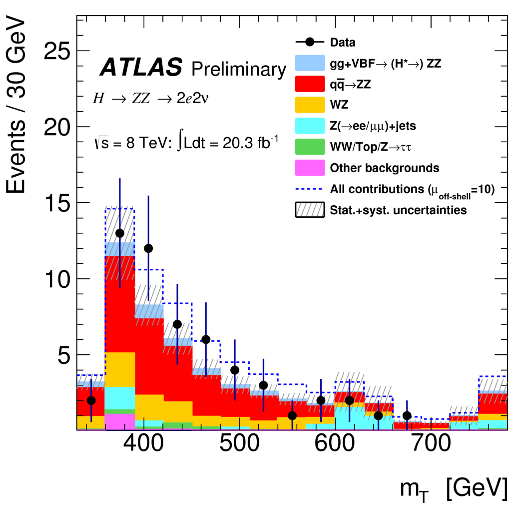
Assuming $\kappa_{i,\text{on-shell}} = \kappa_{i,\text{off-shell}}$, one can set a limit on $\mathbf{\Gamma_H}$.

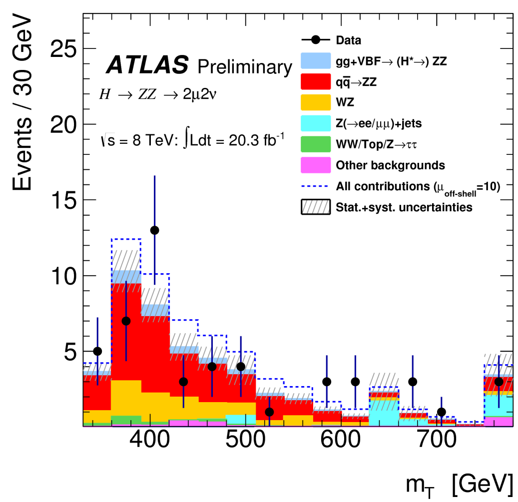
The on-peak cross section is measured in the H→4l channel,
the off-peak cross section is measured both in the H→4l and H→2l2ν channels.

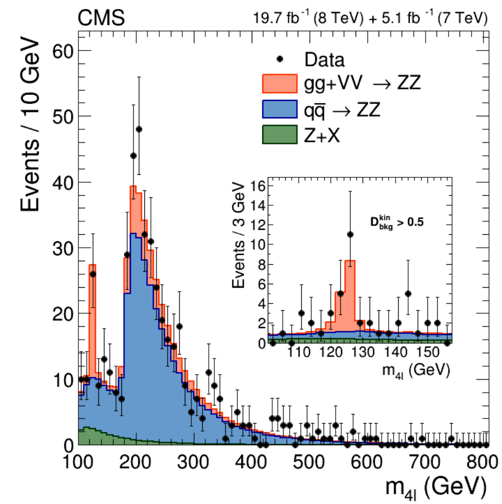
For H→2l2ν, estimate a « transverse mass » m_T from missing transverse energy (E_T^{miss}):

$$m_T^2 = \left[\sqrt{p_{T,\ell\ell}{}^2 + m_{\ell\ell}{}^2} + \sqrt{E_T^{\text{miss}\,2} + m_{\ell\ell}{}^2}\right]^2 - \left[\vec{p}_{T,\ell\ell} + \vec{E}_T^{\text{miss}}\right]^2$$

Constraints on the width from the $H^{(*)} \rightarrow Z^{(*)}Z^{*}$ analysis







ATLAS: $\Gamma_{H}/\Gamma_{H}^{SM}$ ATLAS-CONF-2014-042

channel	Obs. limit @95% CL (expected)
H→4l	7.2 (10.2)
H→2l2ν	11.3 (9.9)
combined	**5.7 (8.5)**

CMS: Γ_{H} arXiv::1405.3455

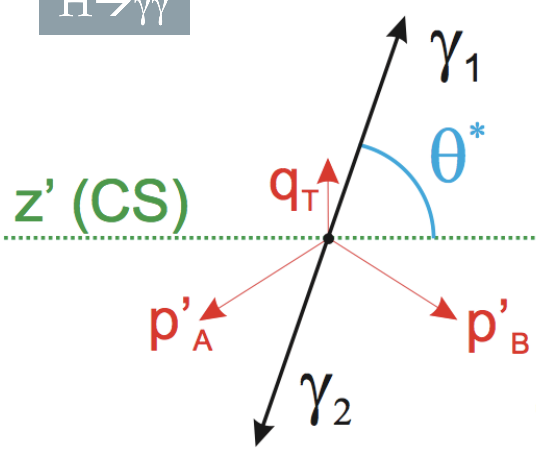
channel	Obs. limit @95% CL (expected)
H→4l	33 MeV (42 MeV)
H→2l2ν	33 MeV (44 MeV)
combined	**22 MeV (33 MeV)**

Measuring spin and parity

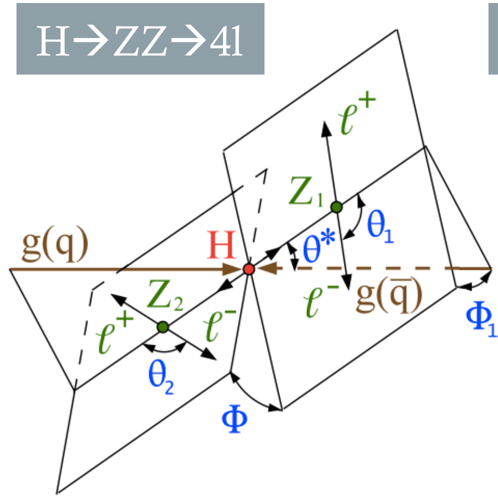
In the Standard Model, the Higgs boson is scalar: $J^P=0^+$

- The observation of the $H \rightarrow \gamma\gamma$ decay excludes a spin-1 state through the Landau-Yang theorem.
- Measure angular distributions to discriminate between different spin-parity hypotheses and check the compatibility with SM expectation.

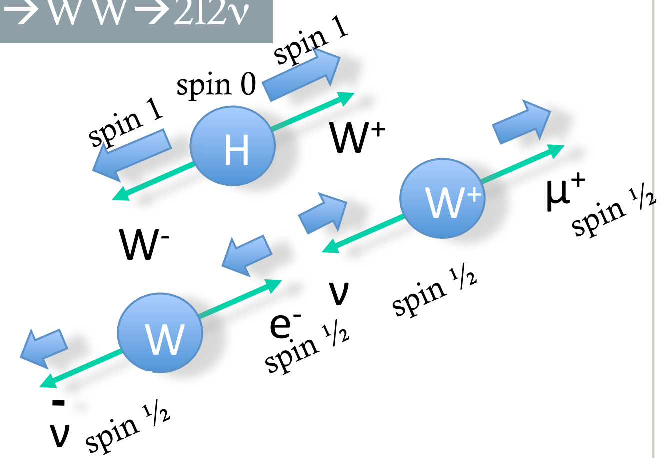
$H \rightarrow \gamma\gamma$



$H \rightarrow ZZ \rightarrow 4l$

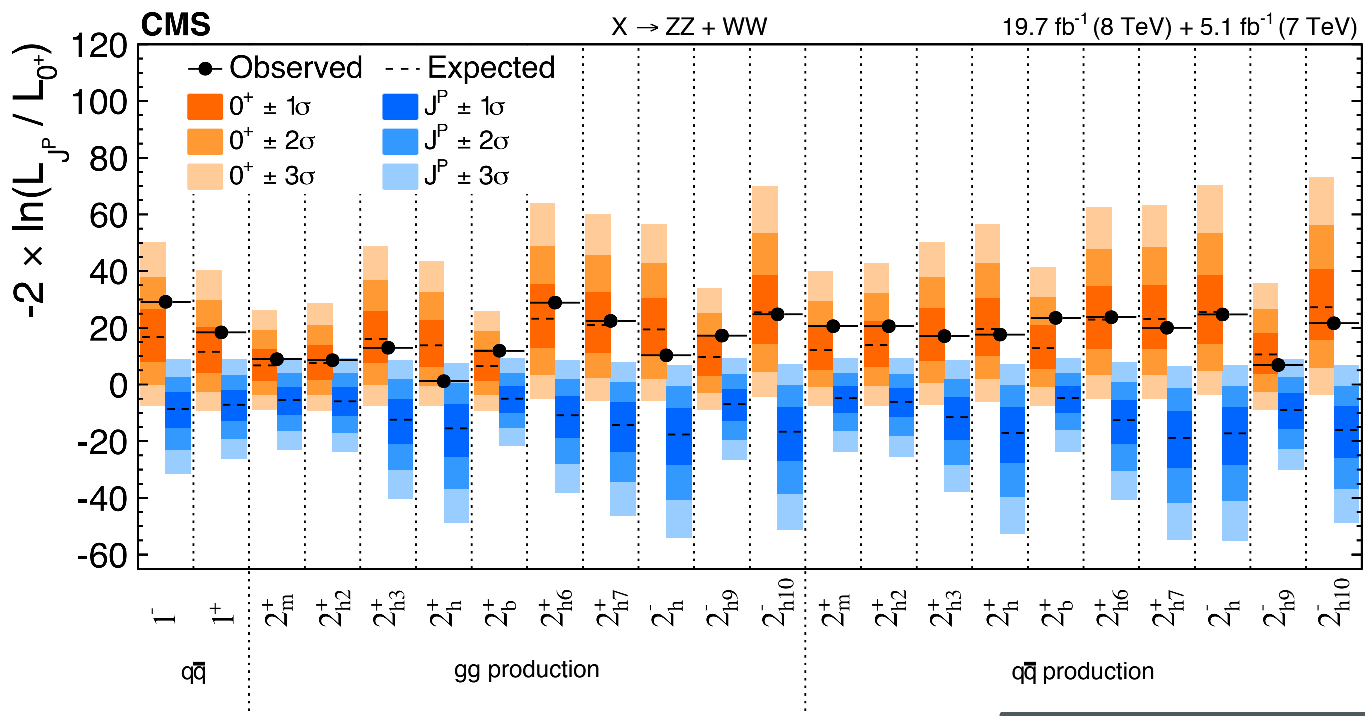


$H \rightarrow WW \rightarrow 2l2\nu$



Measuring spin and CP

CMS tested many spin-1 and spin-2 models using H→ZZ→4l and H→WW→lνlν channels.



spin 1 excluded at 99.999% CL in ZZ and WW (forbidden in γγ)
spin 2 >99% (ZZ, WW, γγ)

$J^P=0^+$ hypothesis strongly favoured

Summary of Higgs properties

Production:
- dominant mode: ggH
- subdominant modes: VBF ~4σ in each experiment; VH, ttH: run 2.

Decay:
- diboson channels: clearly established
- femionic channels: $\tau\tau$ ~3-4σ; bb: early run2.

Coupling analysis: consistency with Standard Model with a precision of 15-30%

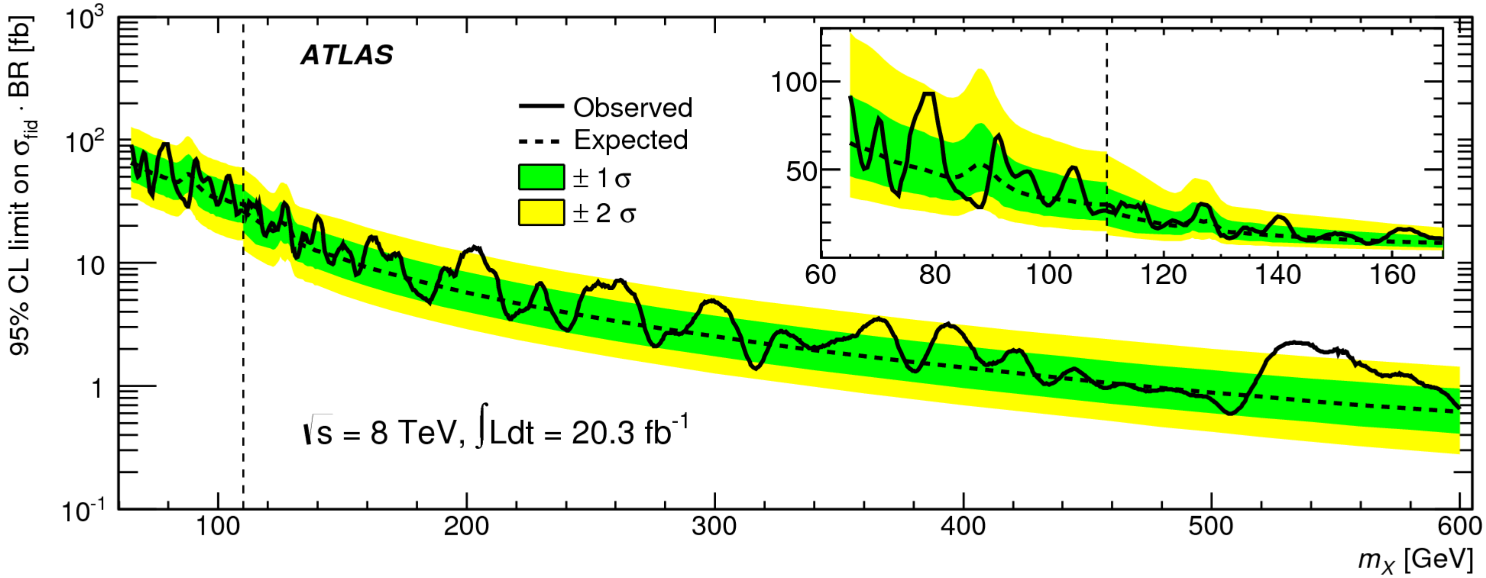
Mass: measured at the 2‰ level

Width:
- direct constraints: 2.4-4.4 GeV (800 x Γ_H^{SM})
- indirect constraints: ~5-6 x Γ_H^{SM}

Spin and CP: $J^P=0^+$

Impressive list of (precision) measurements of the properties of a particle that was unobserved only three years ago!

So far it looks very very very SM-like.



Searching for beyond the Standard Model physics

A SM Higgs rare decay: $H \rightarrow Z\gamma \rightarrow ll\gamma$

Allowed in SM but very rare: expect ~60 events in run 1 data sample.
Could be enhanced in BSM models like those with a composite Higgs.

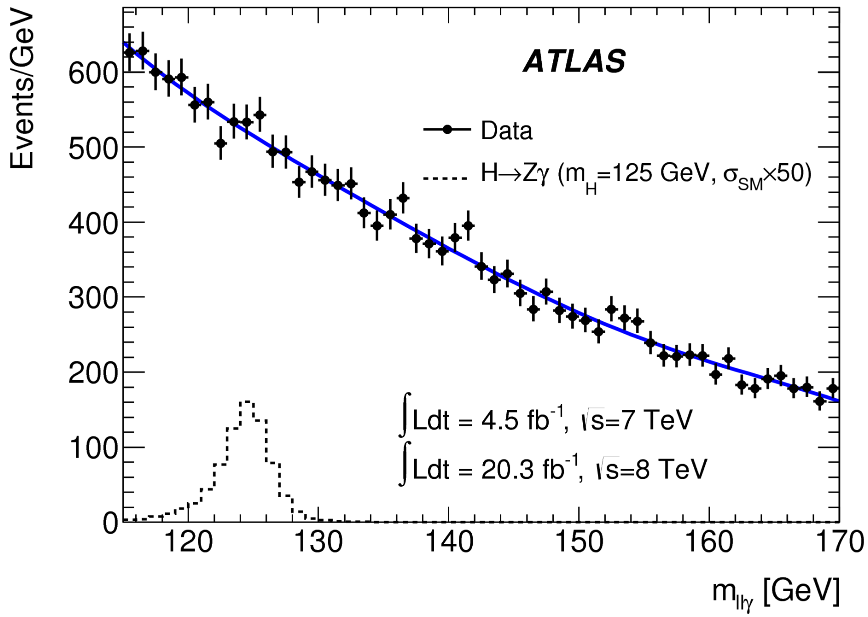
After selection:

- ~15 expected signal (SM) event
- ~5000 background events

Very good mass resolution helps: 1-2%

95% CL limits on $\mu=(\sigma \times BR)/(\sigma \times BR)_{SM}$

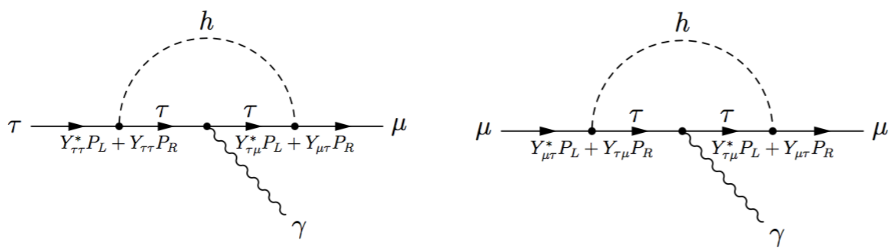
	observed (expected)
ATLAS	11 (9)
CMS	10 (10)



Need ~100 x more data for a 2σ "signal"

A SM Higgs forbidden decay: H→μτ

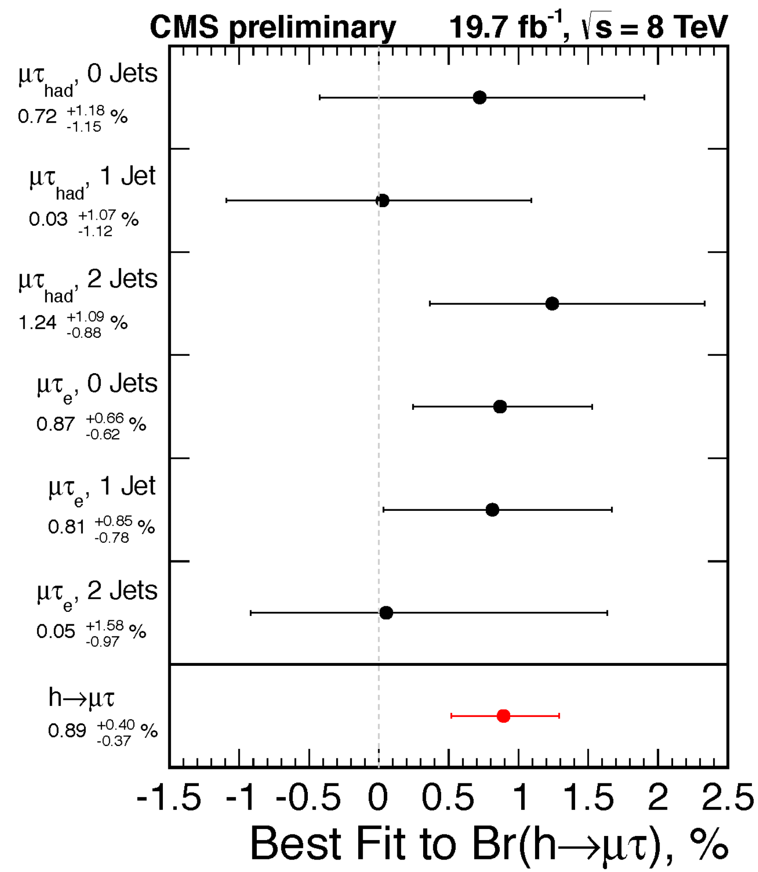
Allowed in composite Higgs models or models with more than one Higgs doublet. Lepton Flavour Violatic could be mediated by the exchange of virtual Higgs.



→ constraints from searches τ→μγ, muon g-2, etc can be translated to a limit on B(H→μτ) < 10%.

CMS direct searches at run 1:

- slight excess at 2.5σ level
- B(H→τμ) = (0.89±0.38)%
- or B(H→τμ) < 1.57% @95% CL

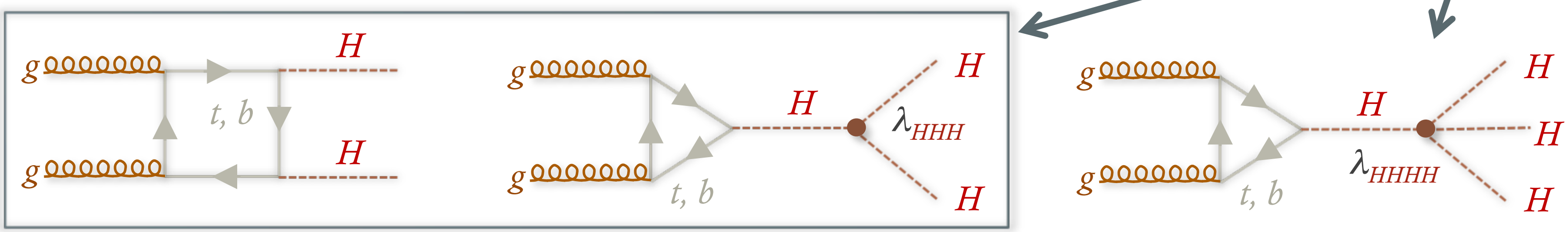


Di-Higgs production

Remember lecture by P. Slavich on Monday:

The ultimate test of the Higgs mechanism: self-couplings

The Higgs potential includes trilinear and quartic self-couplings: $V = \frac{1}{2}(2\lambda v^2)H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$



Di-Higgs production can give access to λ_{HHH} , however:

- need to disentangle the box and the s-channel contributions
- negative interference makes the total cross section tiny: σ(gg→H→HH) ~8 fb @8TeV

Enhanced in some BSM models:

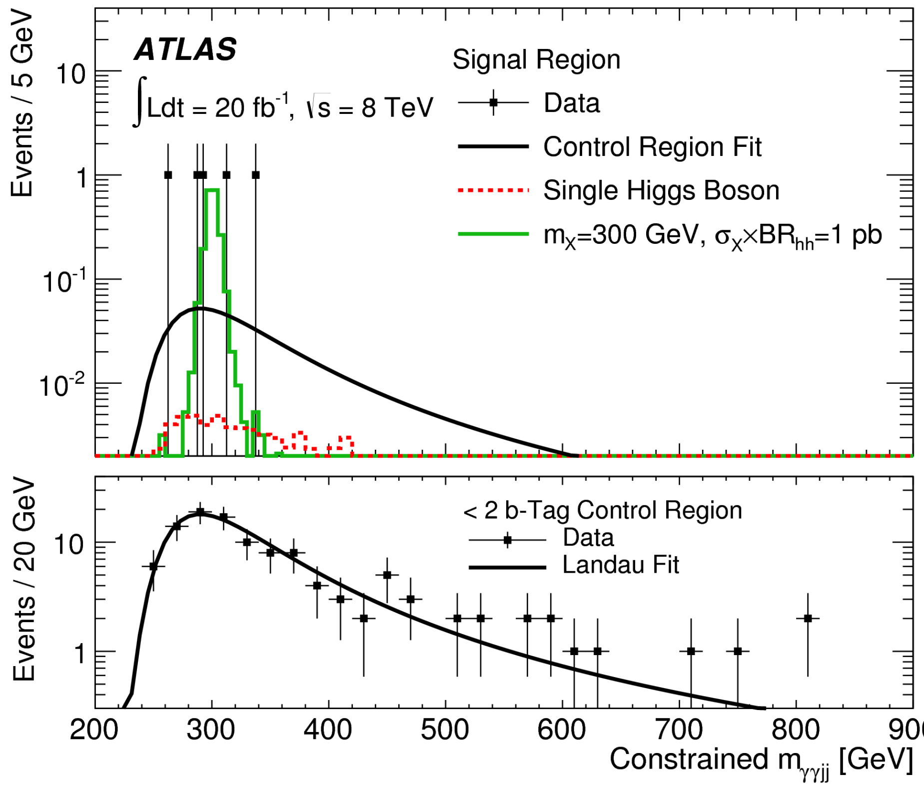
- Resonant production:
  - 2HDM H→hh (up to ~pb)
  - Warped Extra Dimensions: radion (spin-0), KK graviton (spin-2) decays
- Non-resonant production: direct ttHH vertex in composite models, light colored scalars

Search for di-Higgs production in γγbb final state

ATLAS and CMS searched for di-Higgs production in the γγbb final state

large branching fraction

very good mass resolution
to reject background



ATLAS:
Search for X→HH:
σ x Br(HH) < 0.3-3.5pb for 260<m_X<500 GeV

Non-resonant HH:
σ < 2.2pb @95% CL

[*similar results by CMS*]

The Higgs boson as a portal to Dark Matter

New particles coupling very weakly to SM particles are typical candidates for dark matter (e.g. WIMPs). Massive particles: could couple *strongly* to Higgs!

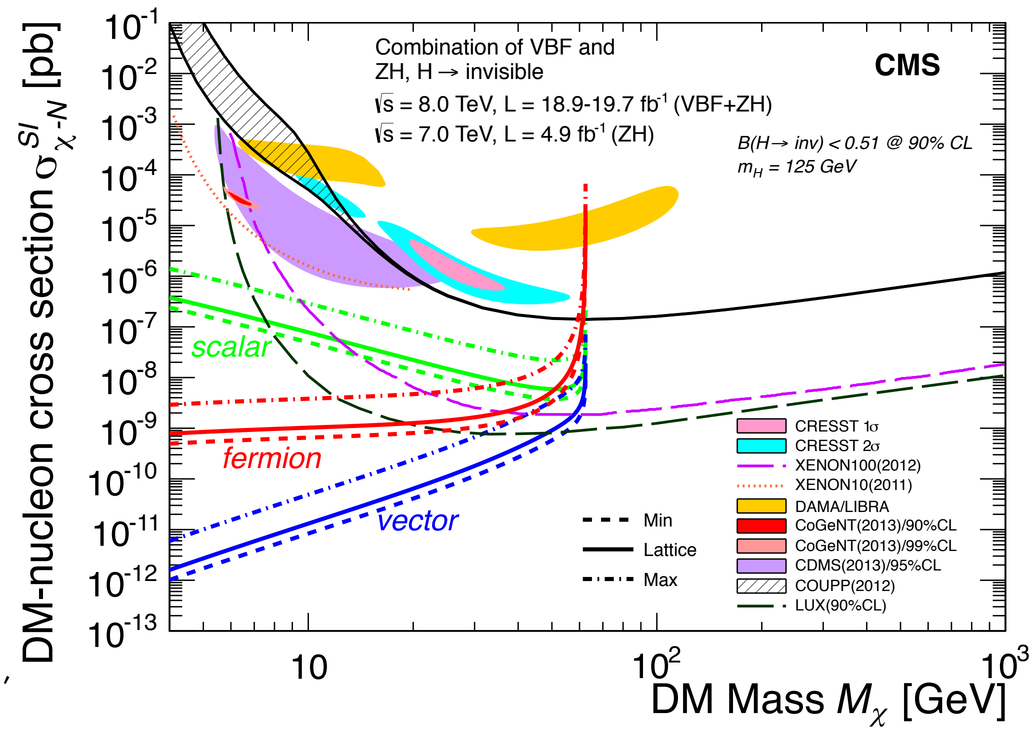
ATLAS and CMS performed a search for H→ invisible decays.

- no (very weak) interaction with the detector → events with large E_T^{miss})
- tag the Higgs:
  - in ZH production, Z→l^+l^- or bb
  - in vector boson fusion (2 forward/backward jets)

CMS limit: B(H→ inv.) <0.58 (0.44) @95%

Interpretation of the results in terms of WIMP-nucleon scattering via Higgs exchange, assuming B(H→ inv.)=B(H→χχ), $m_\chi < m_H/2$.

→Comparison with direct WIMP detection experiments.



Very stringent limits from both ATLAS and CMS up to $m_\chi < m_H/2$

Search for an extended Higgs sector

Two Higgs doublets models (2HDM) provide a simple extension of the Standard Model:

Assuming the existence of an additional SU(2) doublet in the Higgs sector, one gets 5 Higgs bosons:

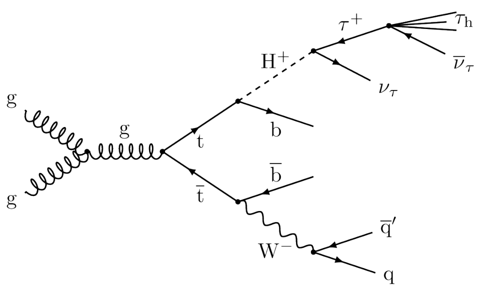
- 2 CP-even states: h and H (with $m_h < m_H$)
- 1 CP-odd state: A
- 2 charged states: H^+ and H^-

MSSM is a 2HDM

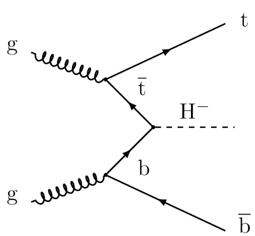
Many searches performed at LHC. Two examples are shown here.

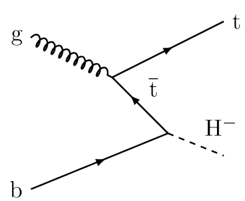
Search for an extended Higgs sector: $H^{\pm} \rightarrow \tau^{\pm}\nu$

low $m_{H^{\pm}}$ ($<m_{top}-m_b$): 80 to 160 GeV

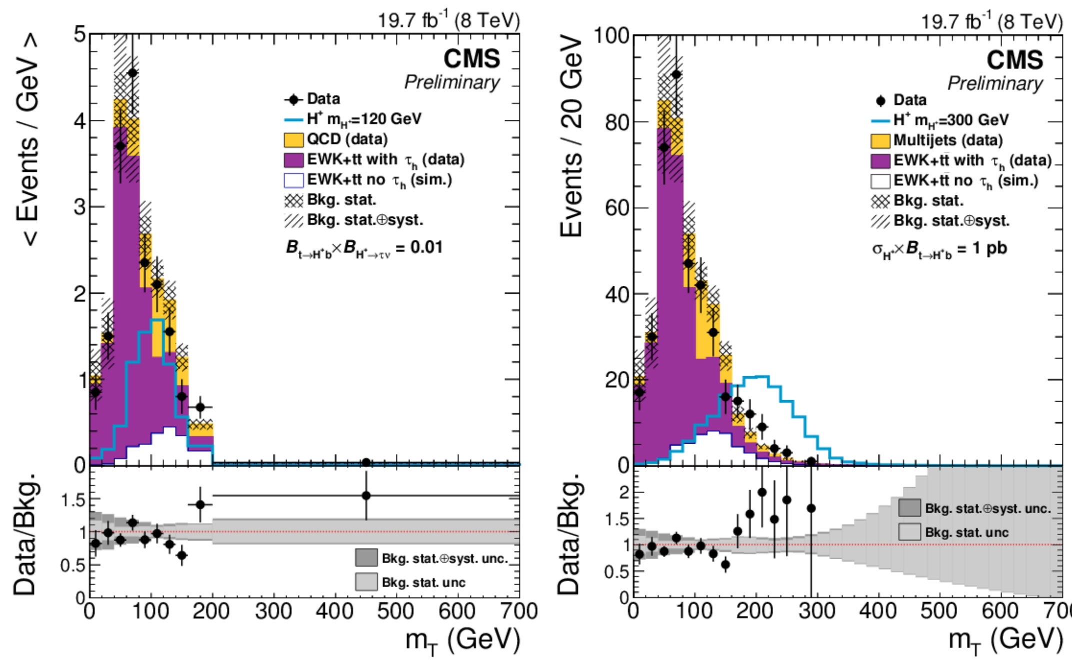


high $m_{H^{\pm}}$ ($>m_{top}-m_b$): 180 to 600 GeV





$$m_T = \sqrt{2 p_T^{\tau_h} E_T^{miss} (1 - \cos\Delta\phi(\vec{p}_T^{\tau_h}, \vec{E}_T^{miss}))}$$



$80 < m_H^+ < 160$ GeV:	$B(t \rightarrow bH^+) \times B(\rightarrow \tau^+\nu) < 1.2$–$0.16$ %
$180 < m_H^+ < 600$ GeV:	$\sigma(pp \rightarrow t(b)H^+) \times B(\rightarrow \tau^+\nu) < 0.38$–$0.026$ pb

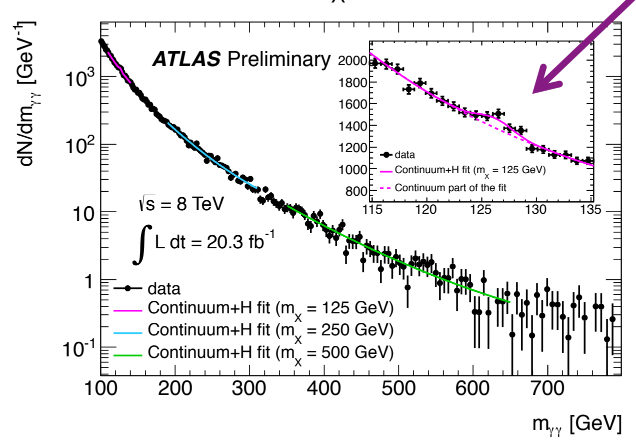
Similar results by ATLAS

Search for X→γγ

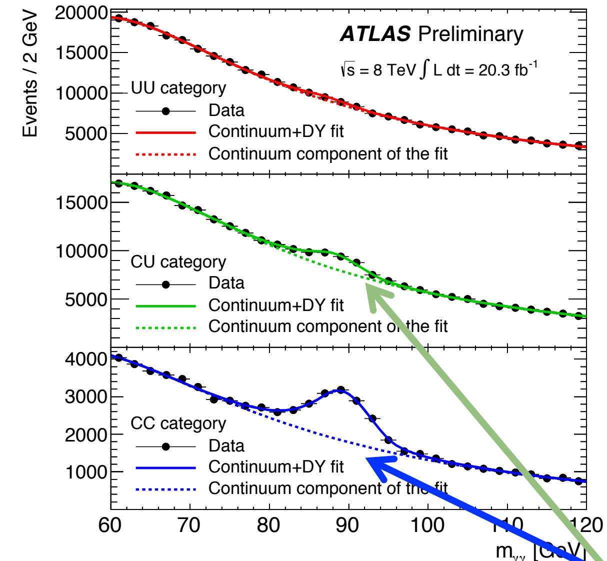
Search for extra Higgs-like state X in an extended mass range: $65<m_X<600$ GeV

$110<m_X<600$ GeV

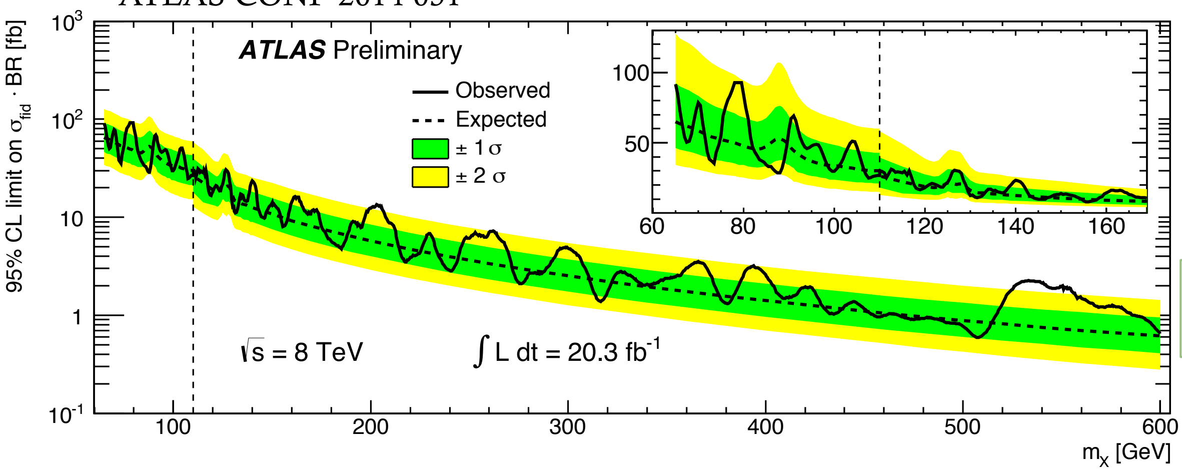
h(125) is a background!



$65<m_X<110$ GeV

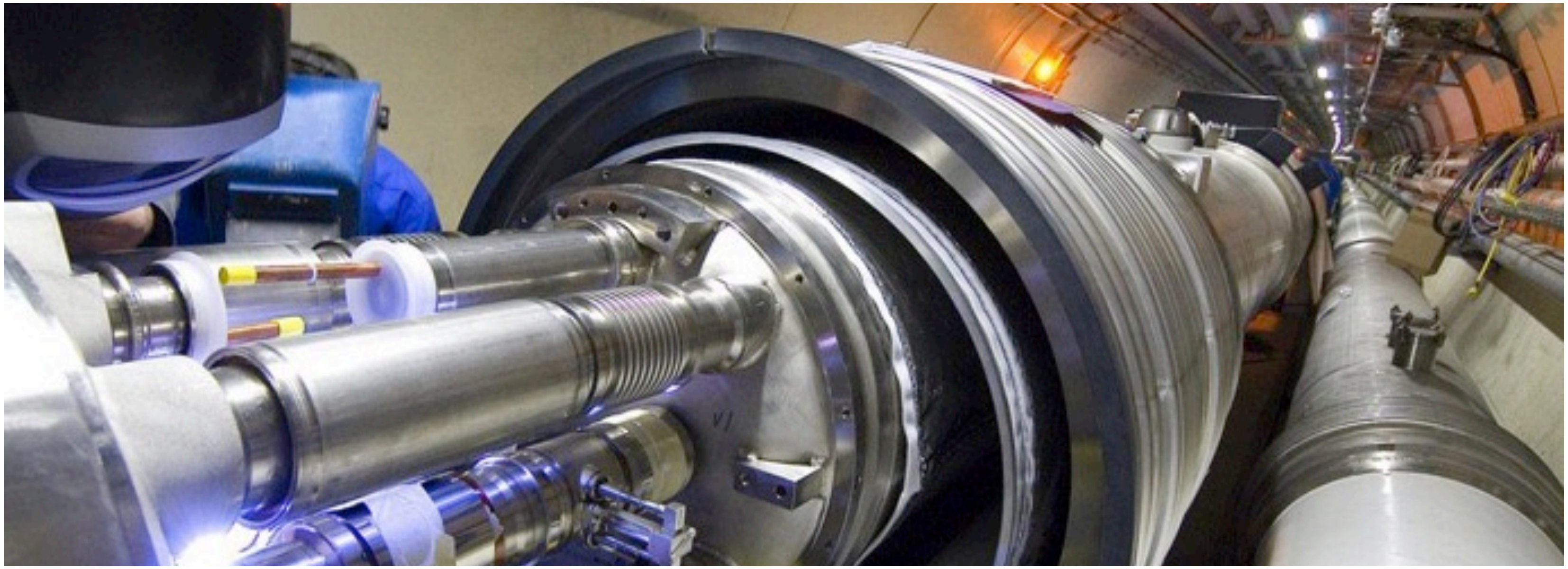


ATLAS-CONF-2014-031



Z→ee background when selecting photon pairs with 1 or 2 converted γ.

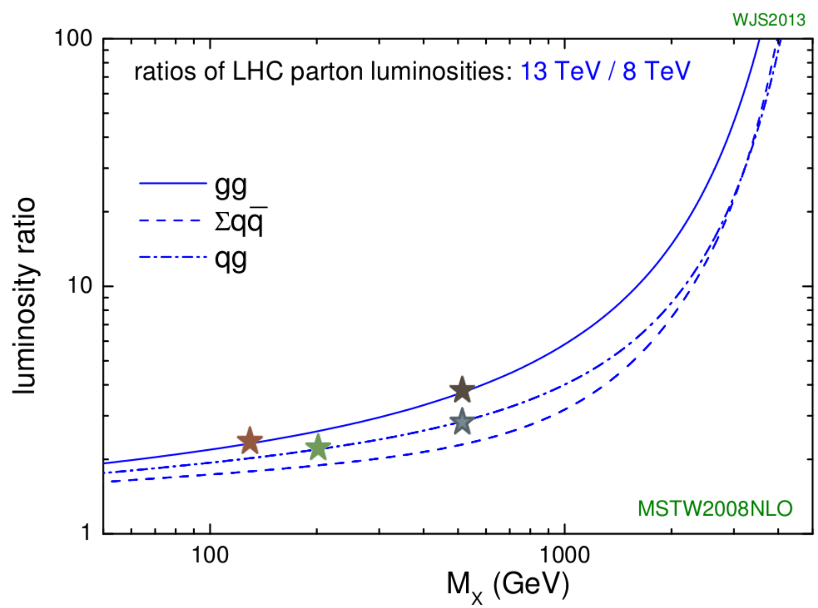
No significant excess



Run 2 prospects

Higgs production cross section at 13TeV

Expected production cross section increase at 13TeV depends on parton luminosities.
It varies according to whether the process is gg or qq induced and to its characteristic mass scale M_X

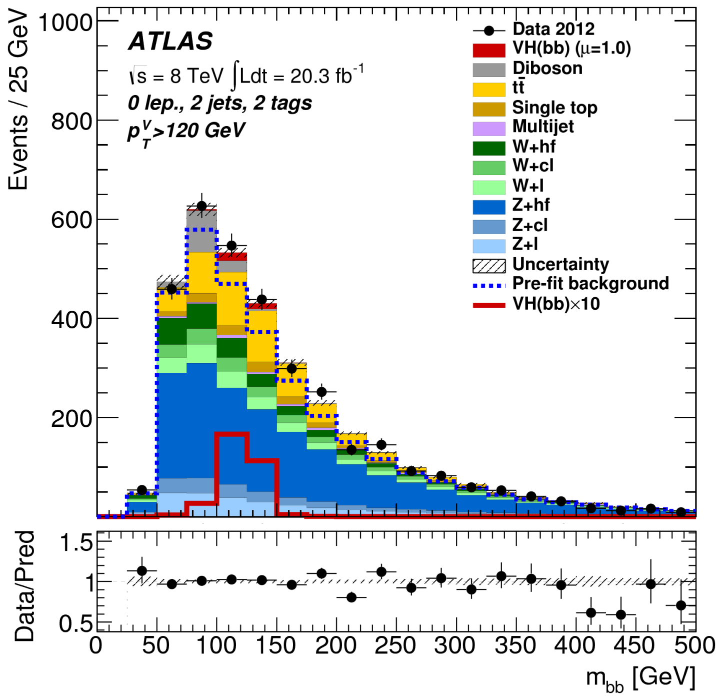


	production process	gg/qq	M_X	σ(13TeV) /σ(8TeV)
★	gg fusion	gg	m_H	2.3
★	VBF	qq	m(H+jets) ~500GeV	2.4
★	VH	qq	$m_V + m_H$	2.0
★	ttH	gg	m(H+2tops) ~500GeV	3.9
★	bbH	gg	m(H+2tops) ~150GeV	2.5

ttH further benefits from a larger opening of phase space at higher collision energy: almost a factor of 4 increase compared to 8 TeV (4.7 at 14 TeV).

Backgrounds increase too!

Run 1 analysis

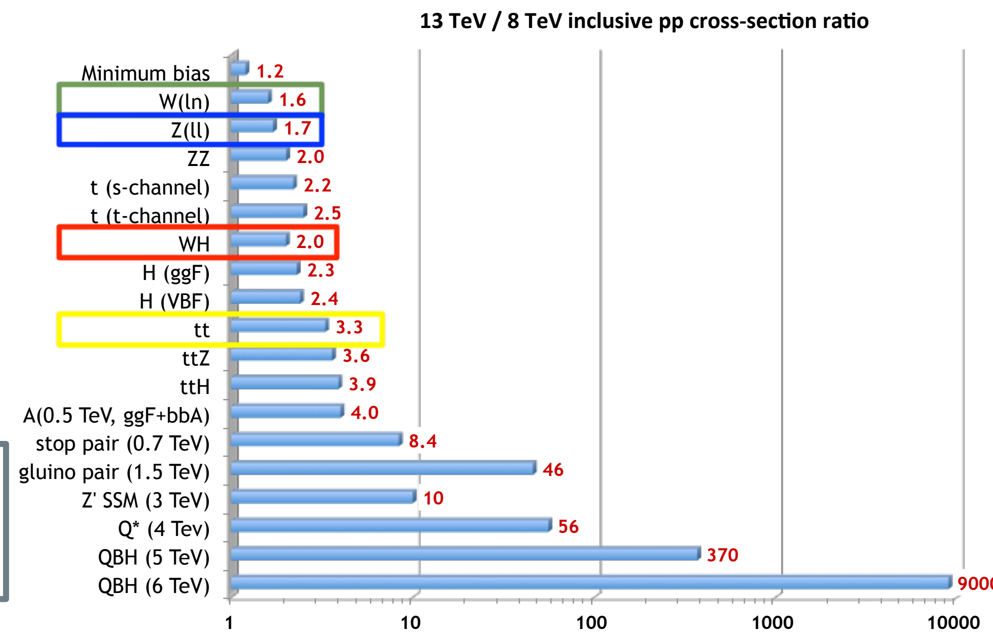


Most Higgs analyses need roughly 10fb^{-1} to reach a sensitivity equivalent to the one achieved at run-1 (ttH~5fb^{-1}).

Example: associated VH production. Most promising channel to observe H→bb at run 2.

- EW backgrounds increase by a factor ~2.
- tt background increases by a factor 3.

5σ observation could be reached with 25-30fb^{-1} (2016 if per experiment).



A. Hoecker

SM Higgs run 2 to do list

- 2015 (10-15 fb^{-1}):
  - "rediscovery" at 13TeV, in H→4l, lνlν, and γγ channels; measurement of inclusive and differential cross-sections, spin & CP studies.
  - Observation of fermionic decay modes H→ττ, H->bb.

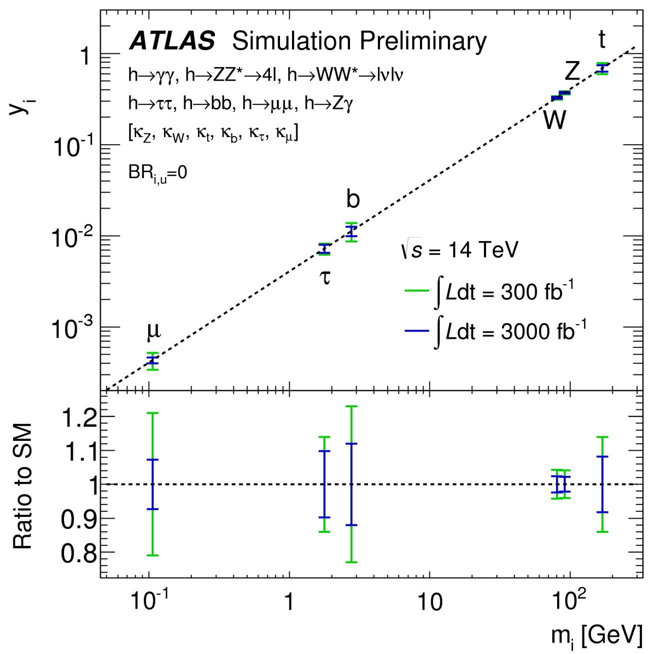
→ combination of run 1 and 2015 data is important!

- Full run 2 dataset (~100 fb^{-1}) :
  - Observation of ttH production!
  - Search for Higgs rare decays: H→Zγ, H→μμ.
  - Detailed study of the Higgs properties including differential cross sections.
  - Work hard to reduce both experimental and theoretical uncertainties! Many measurements are expected to have comparable statistical and systematic uncertainties by the end of run 2. Example 1: mass
    - H→γγ: expect ~100-150 MeV statistical uncertainty. Current systematic uncertainty is 150-280 MeV.
    - H→ZZ: will still be statistically limited, with current systematic down to 60 MeV (ATLAS).
    - Combined measurement (per experiment): ~100MeV (stat), ~200MeV (syst)

Higgs couplings at run 2 and beyond

Example 2: signal strength. Rough estimates of statistical and systematic uncertainties (per experiment):

- H→γγ: 5% stat, 15% syst
- H→ZZ: 5% stat, 10% syst
- H→WW: 15% stat, 15-20% syst
- H→ττ: 10% stat, 20% syst

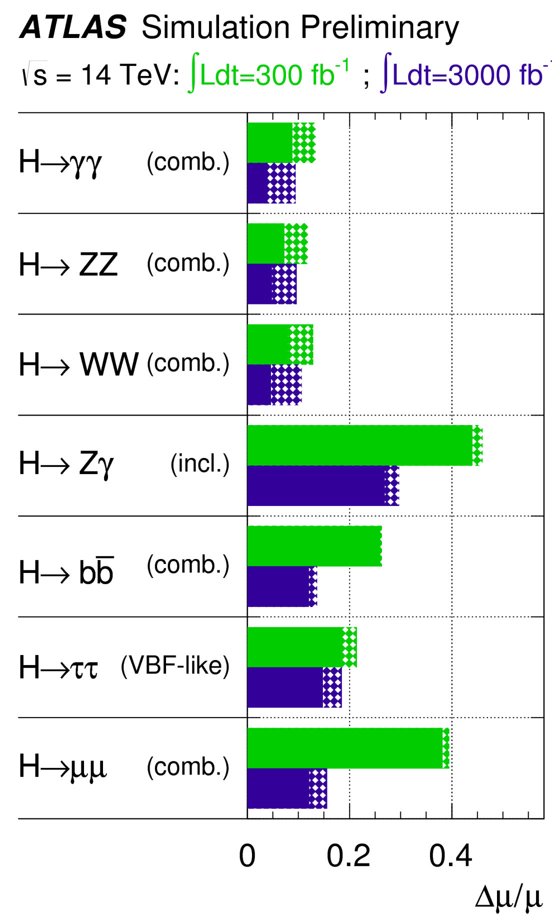


Phase 1: run 2+ run 3

- H→γγ, ZZ, WW: ~10-15% accuracy. Relatively large theo. errors.
- H→fermions still dominated by exp. errors

HL-LHC

Most channels below 15%

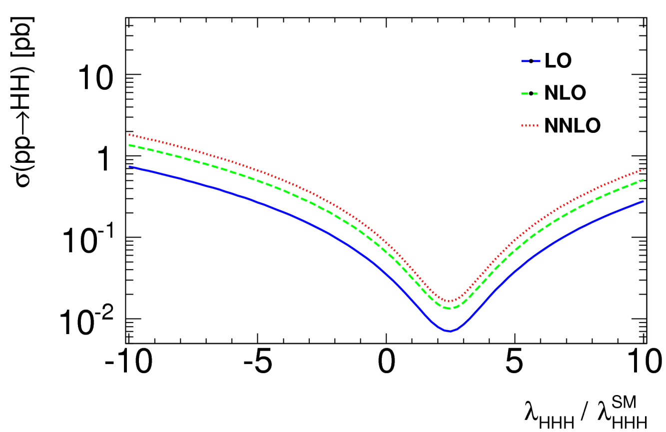


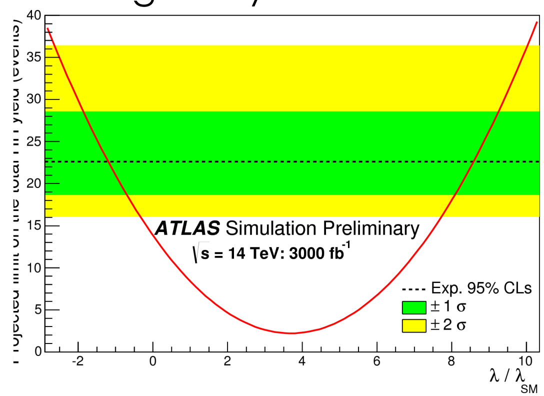
Higgs self-coupling

Destructive interference between the box and s-channel leading to suppression of the event yield.

If no self-coupling, cross section is increased by ~2 compared to SM case. → set constrains on $\lambda_{HHH}/\lambda^{SM}_{HHH}$

However, hopeless at run2+run3. At HL-LHC, expect ~8 bb$\gamma\gamma$ signal events for 47 background events: ~1.2 significance. More channels and ingenuity needed!





$\lambda_{HHH}/\lambda^{SM}_{HHH}<-1.3$
or $\lambda_{HHH}/\lambda^{SM}_{HHH}>8.7$

Estimate of ultimate accuracy at HL-LHC of 50%, down to 30-40% if optimistic.
Future colliders : ILC at 500GeV would reach 83% (21% at 1TeV).
Or with 30 ab^{-1} at a 100 TeV collider, one could reach 5% accuracy!

Summary

- 2.5 years after the Higgs discovery, many measurements have been performed:
  - H→diboson decays clearly established.
  - H→$\tau\tau$ almost here, evidence for H→fermions at the 4σ level.
  - Its mass is known at a 2 permil precision.
  - Indirect limits on its width of 5-6 times the SM prediction.
  - $J^P = 0^+$ is strongly preferred over alternative models.
- Run 2 starting soon. Exciting times ahead of us!
  - 10-15 fb-1 expected in 2015, 100fb-1 by 2018.
  - "Re-discovery" at 13 TeV and detailed studies of properties.
  - H→bb could be observed by next year; ttH also expected at run 2.
  - Higgs physics as a window onto new physics, more discoveries at run 2?
    - rare decay studies
    - Higgs as a portal to a hidden sector
    - direct search for extra Higgs bosons
- Run 3 (300 fb-1) and HL-LHC necessary for further precision studies
  - Observation of rare decays H→$\mu\mu$, H→$Z\gamma$.
  - Precision measurement of the couplings.
  - measurement of the self-coupling could reach 30-50% precision. Future colliders will be crucial.