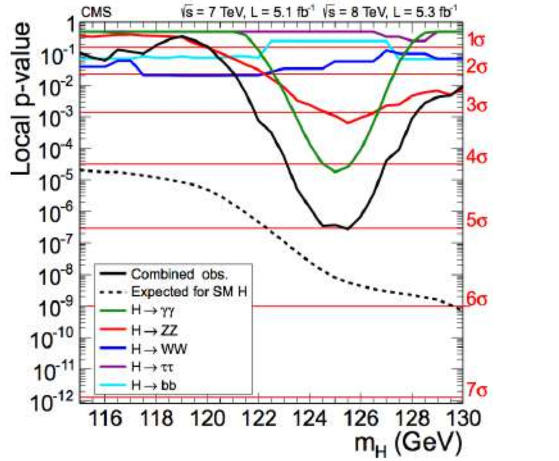
Discovery of the Higgs boson and most recent measurements at the LHC

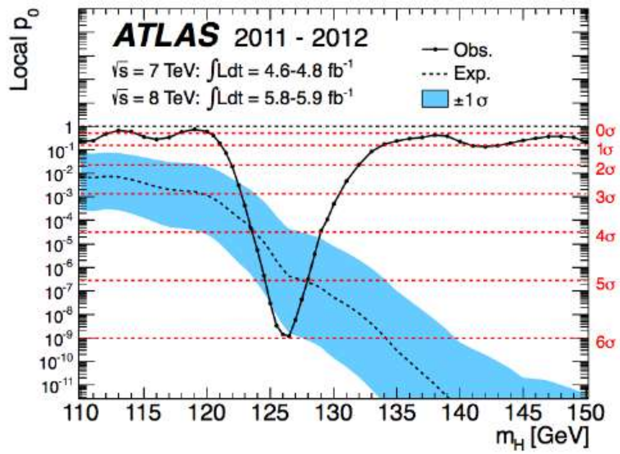
Marcello Fanti

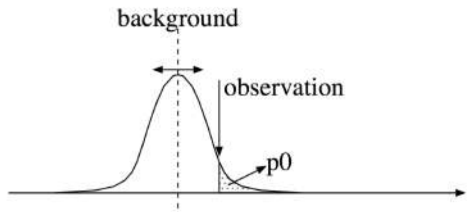
(on behalf of the ATLAS-Mi group)

University of Milano and INFN

July 4th, 2012 – the discovery!







ATLAS and CMS observed a "new signal":
incompatibility with background-only hypothesis was 5σ (CMS) and 6σ (ATLAS)

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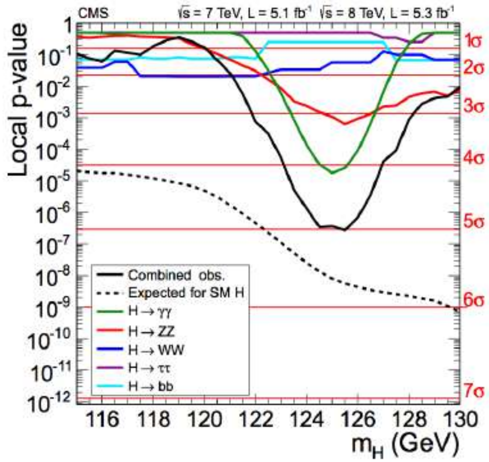
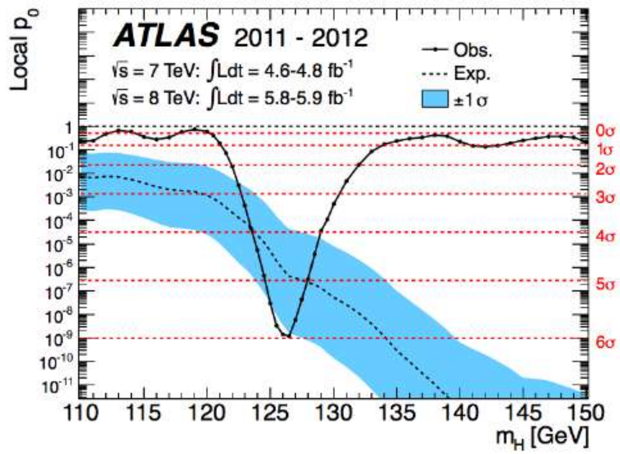
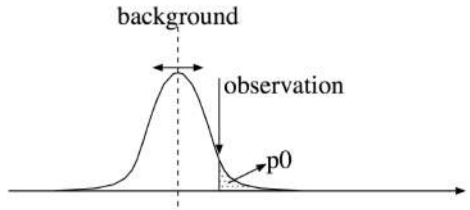






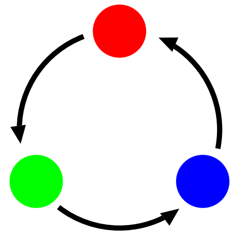
What is this? Is it indeed the Higgs boson?

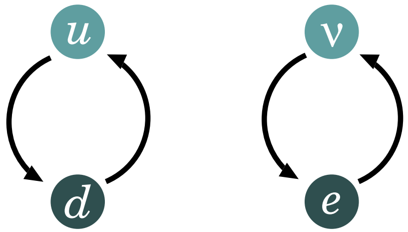
. . . and if so, **why is it so important?**

Symmetries, gauge theories (just a glance. . .)

All interactions (strong, electroweak) are driven by symmetry principles:

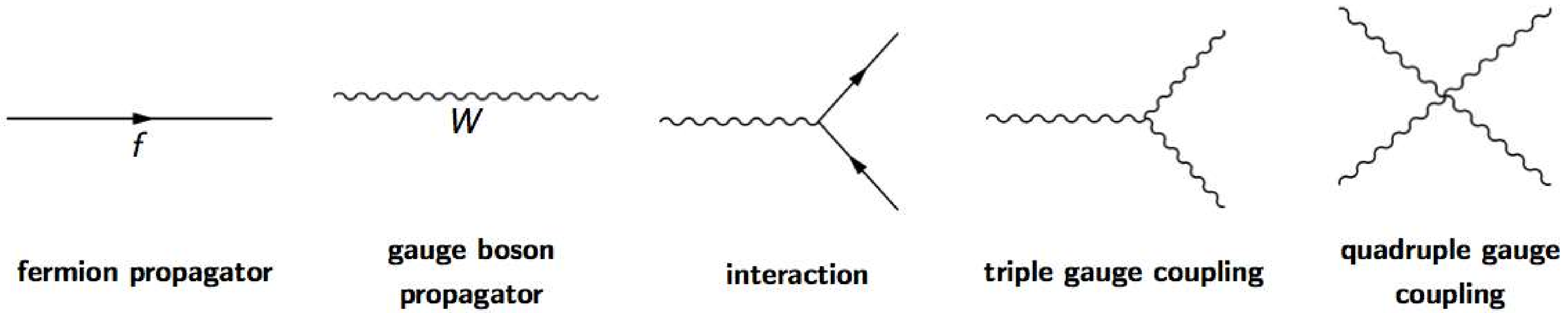
strong interaction $\Longleftrightarrow$ "color" symmetry
electroweak interaction $\Longleftrightarrow$ "isospin" symmetry





$\Rightarrow$ very predictive, only few assumptions

All interactions are reducible to combinations of few elementary processes:



$\Rightarrow$ renormalizable at all perturbative orders, UV-safe, all desirable theory properties . . .

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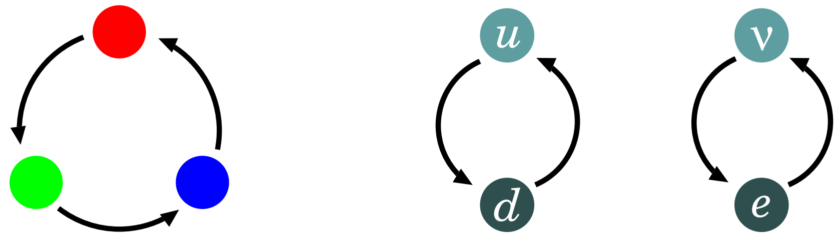

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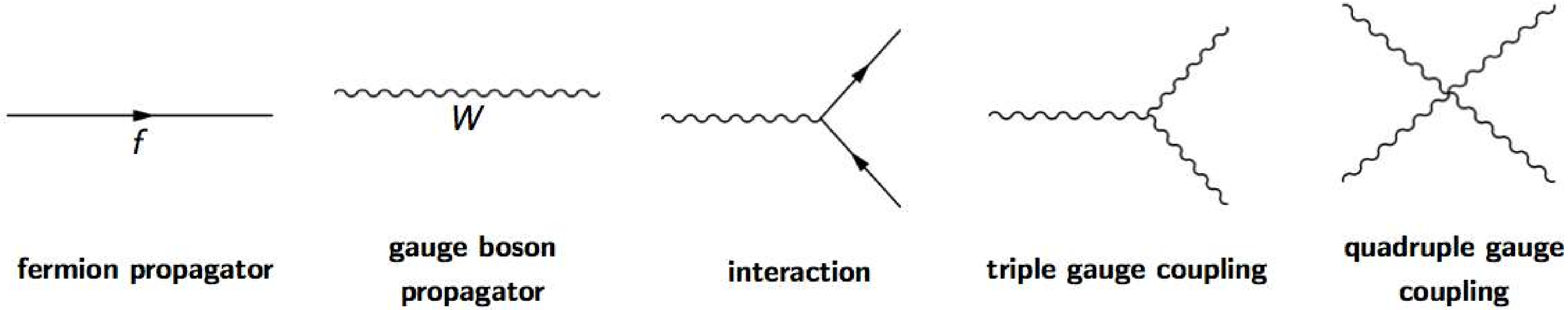


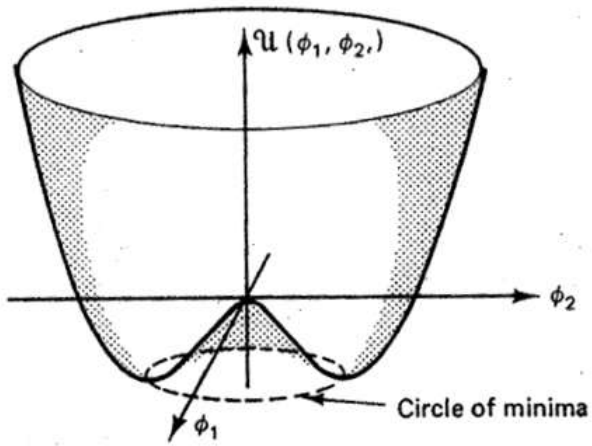
$\Rightarrow$ renormalizable at all perturbative orders, UV-safe, all desirable theory properties ...

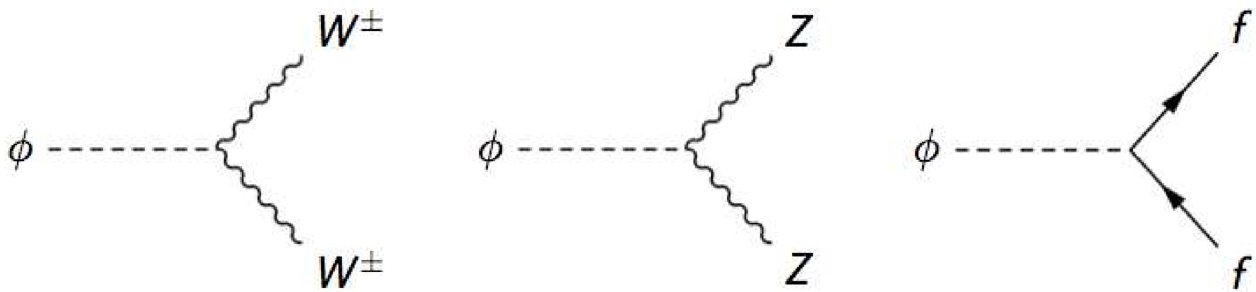
BUT: all this works only if all masses are = 0 — masses break gauge symmetries!

The Higgs mechanism and the Higgs boson

A new quantum field ϕ, with $\mathrm{charge} = 0$ and $\mathrm{spin} = 0$, is postulated, whose potential $\mathcal{U}(\phi)$ has a minimum at $\phi \neq 0$

$\Rightarrow$ the vacuum is characterized by a non-vanishing field, interacting with other particles





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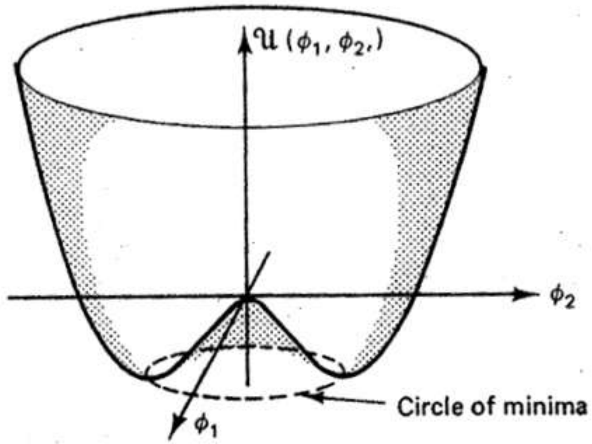

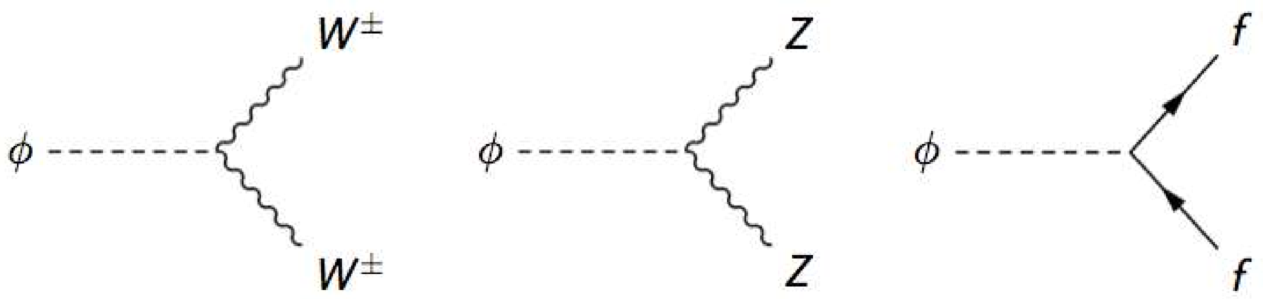

Such interactions modify particles' energies and momenta such to provide a mass (recall: $m = \sqrt{E^2 - p^2}$)

$\Rightarrow$ particles acquire mass dynamically (gauge symmetry is preserved!)

$\Rightarrow$ particles can excite the Higgs field, thus producing an observable quantum: the Higgs particle

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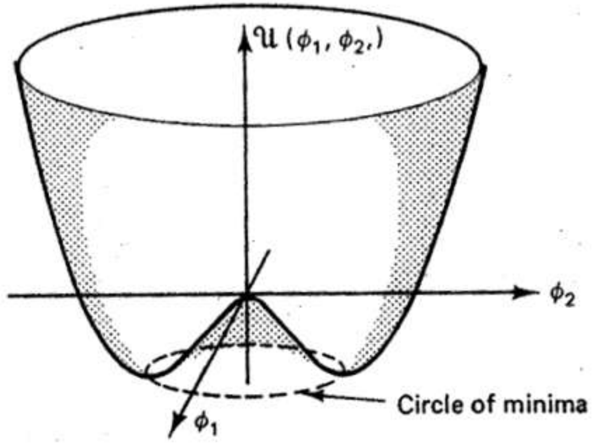

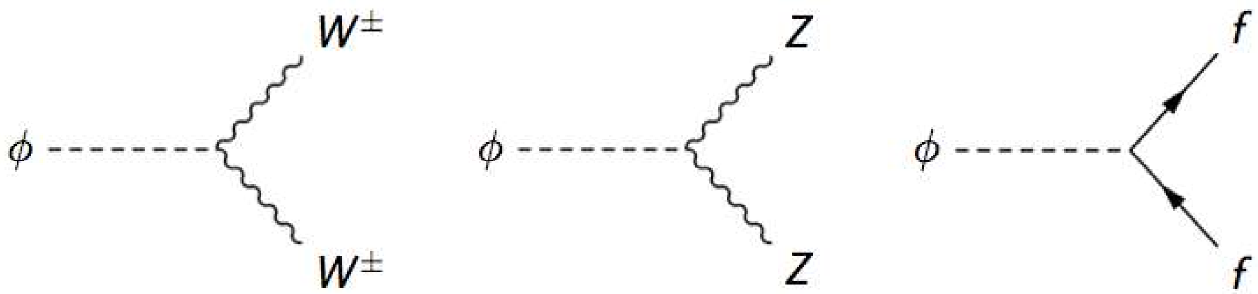

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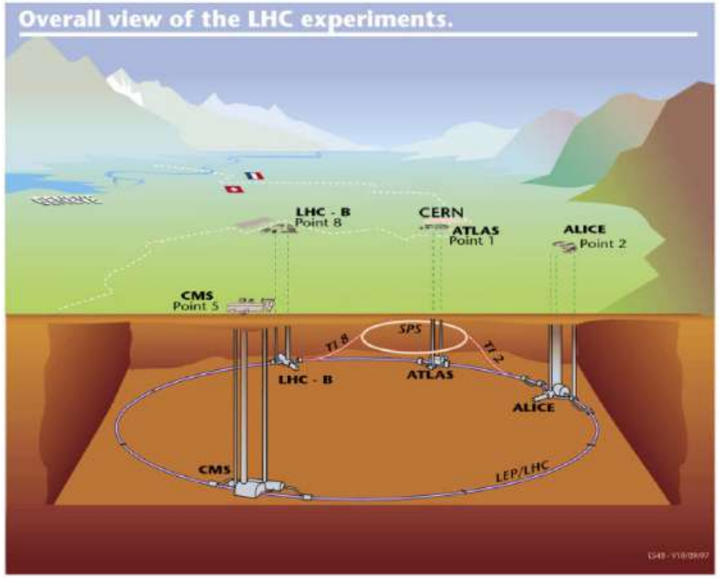
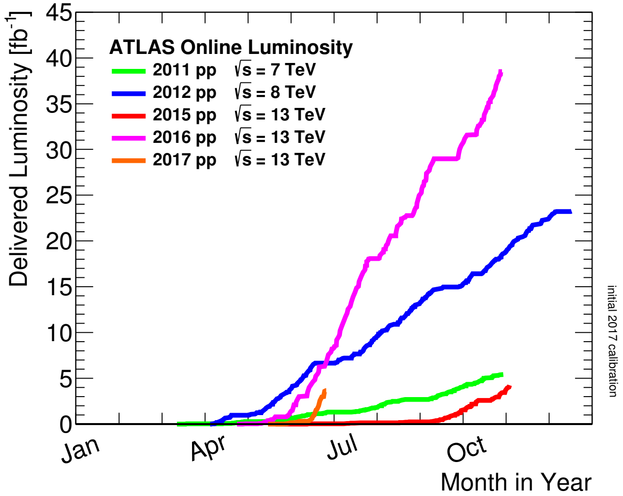
The observation of such a particle is the experimental proof of the Higgs mechanism

Observation of the Higgs boson

The LHC





Located near Geneva,
27 km long, 100 m underground

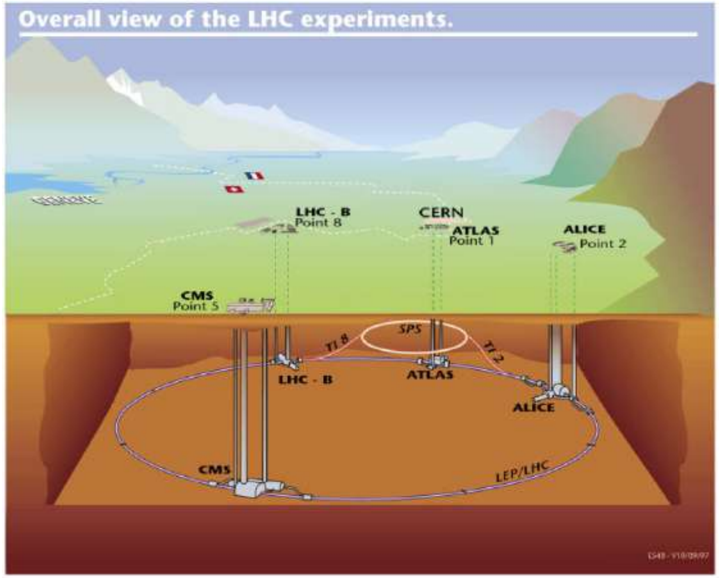
Proton beams accelerated to 6.5 TeV
$\Rightarrow$ colliding at 13 TeV

$\approx 10^{14}$ protons / beam ($\approx 10^{11}$ protons / bunch)

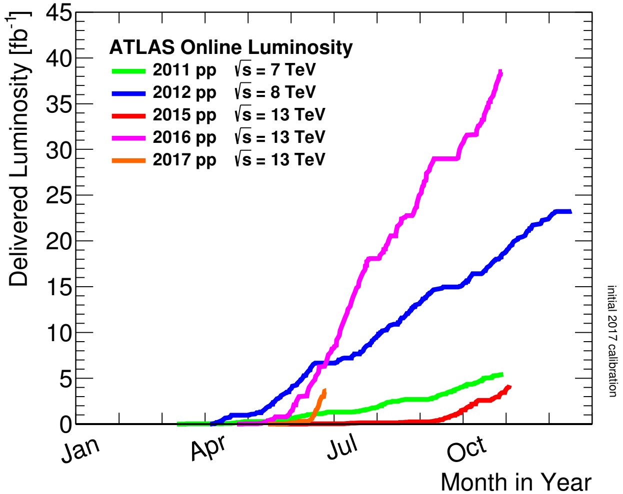
bunches collide every 25 ns
$\Rightarrow$ 40 millions collisions/s

Peak luminosity $\approx 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

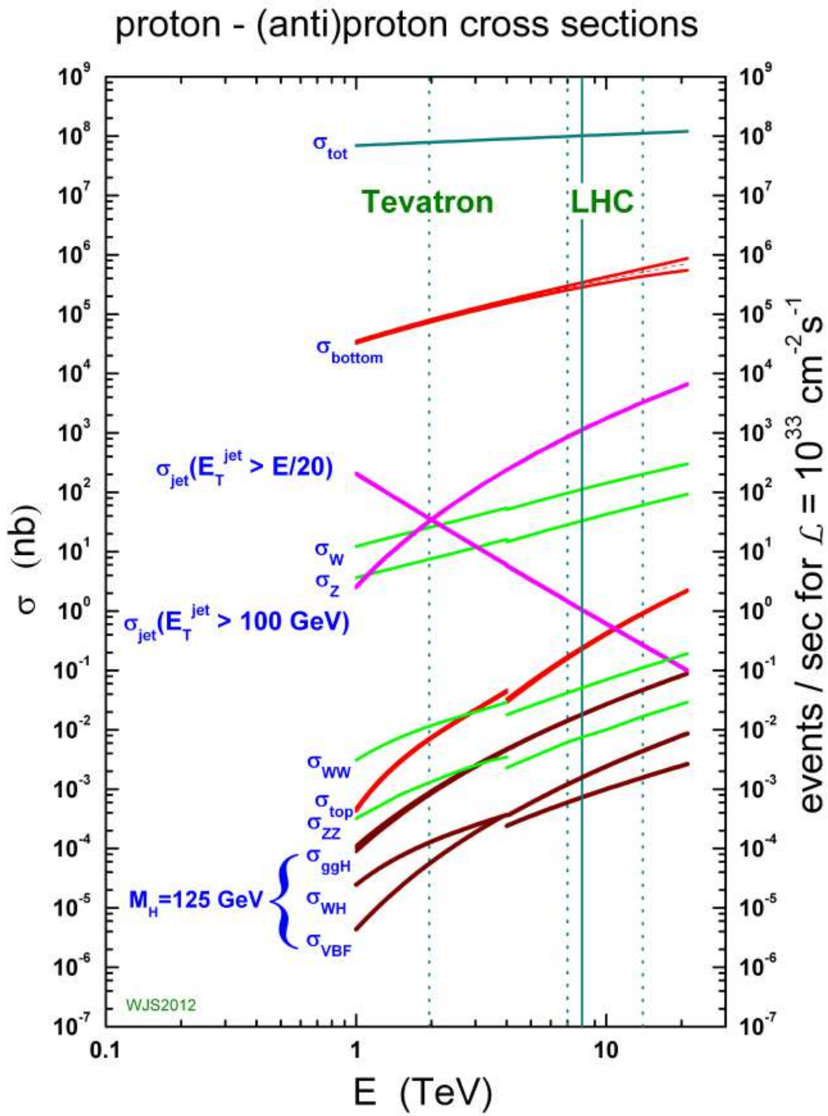
The LHC



Overall view of the LHC experiments.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
LHC - B
ATLAS
ALICE
CMS
LEP/LHC



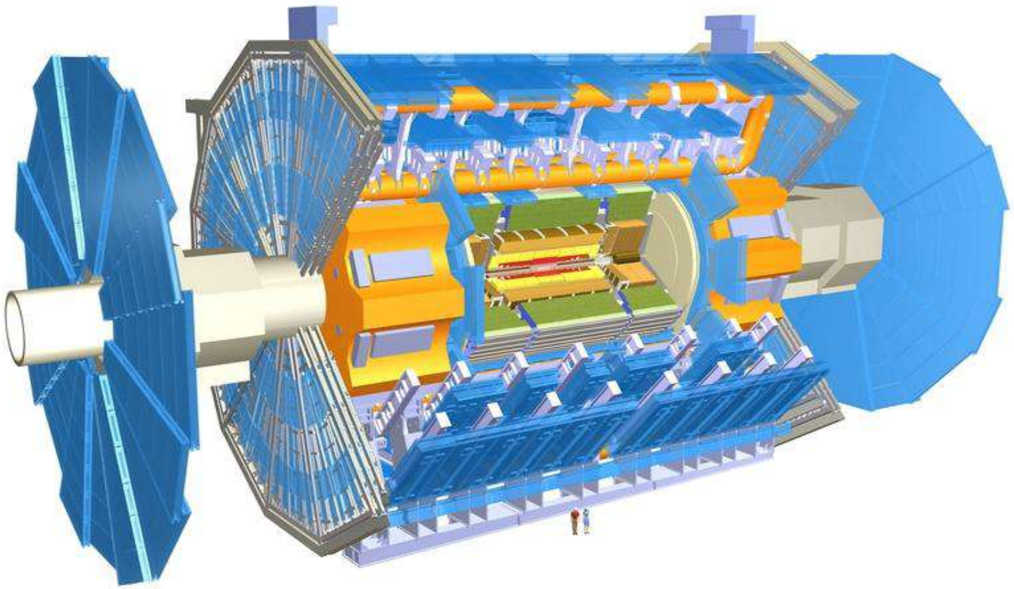
ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
2017 pp √s = 13 TeV
Delivered Luminosity [fb⁻¹]
Jan
Apr
Jul
Oct
Month in Year
initial 2017 calibration



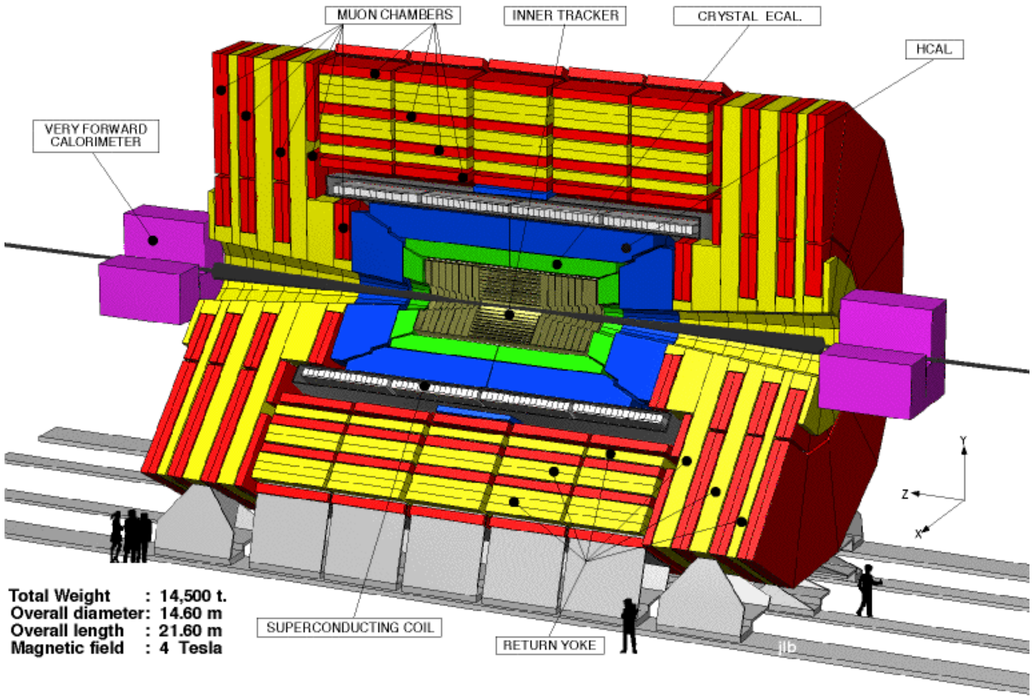
proton - (anti)proton cross sections
Tevatron
LHC
σ (nb)
events / sec for L = 10^33 cm^-2 s^-1
σ_tot
σ_bottom
σ_jet(E_T^jet > E/20)
σ_W
σ_Z
σ_jet(E_T^jet > 100 GeV)
σ_WW
σ_top
σ_ZZ
σ_ggH
σ_WH
σ_VBF
M_H=125 GeV
WJS2012
E (TeV)

ATLAS and CMS

ATLAS



CMS



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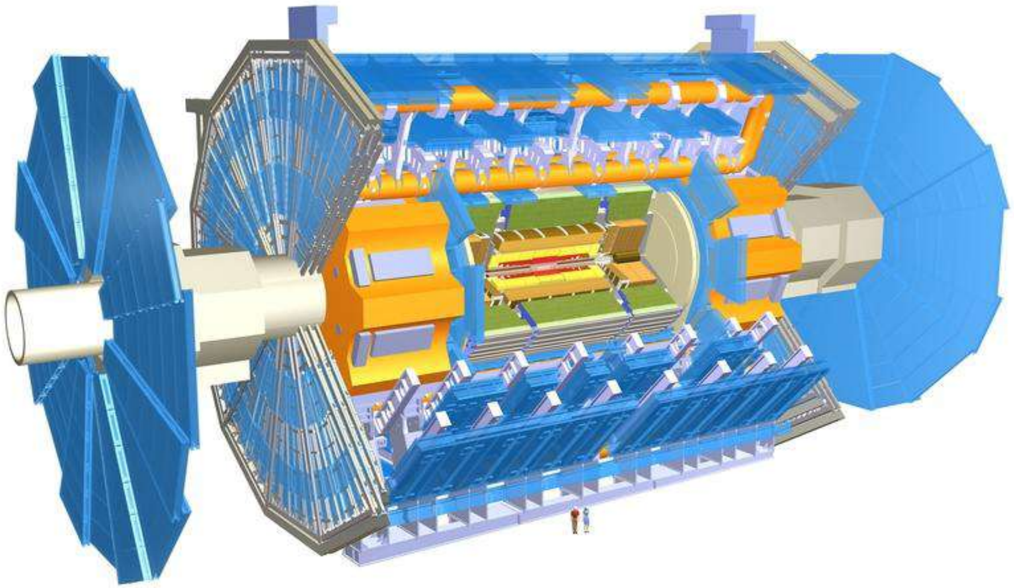

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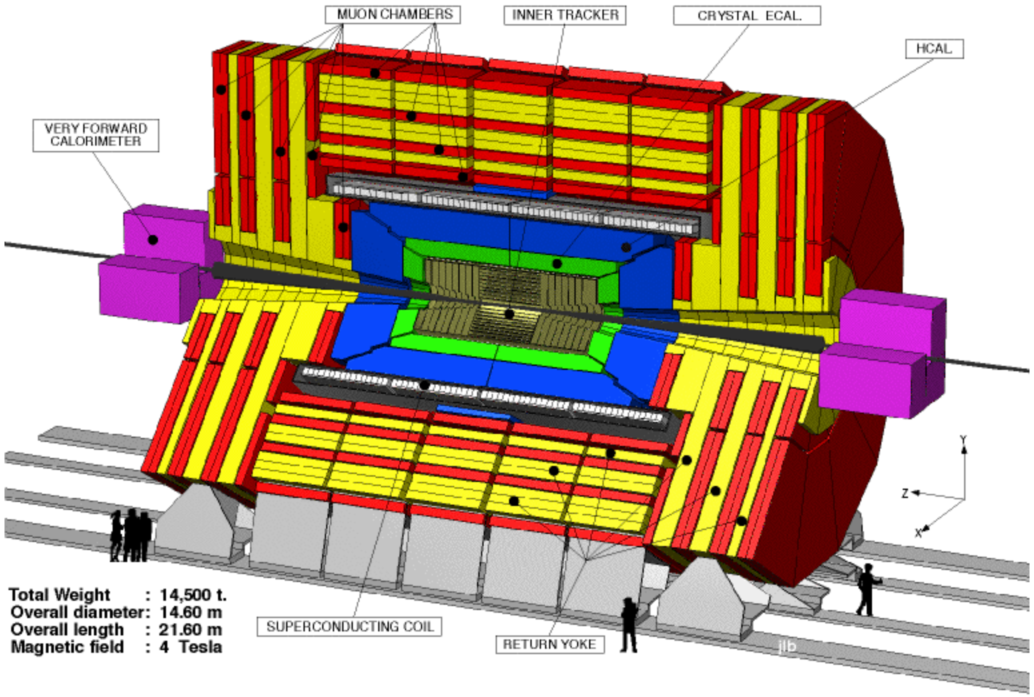
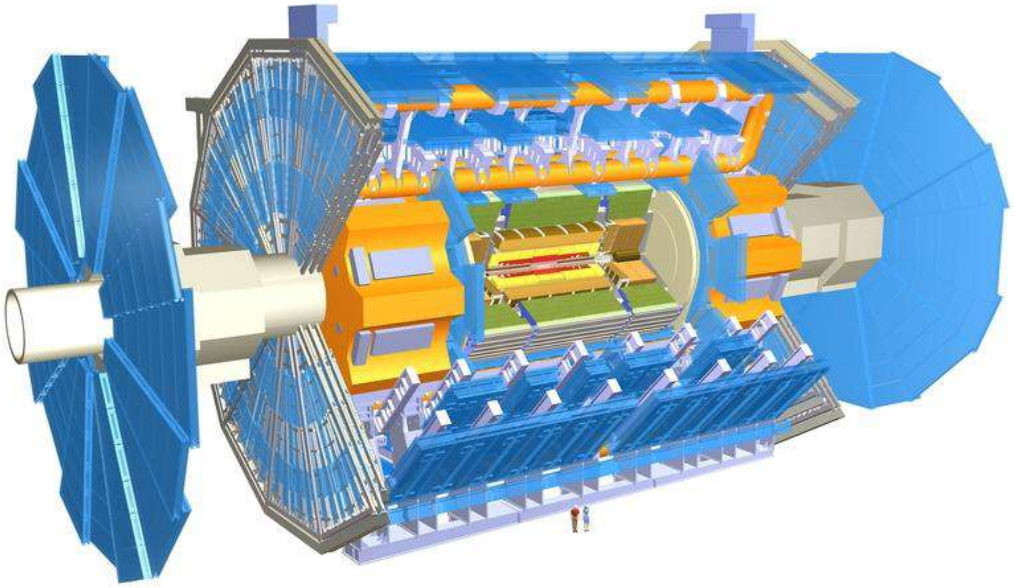


Characteristics

- multi-purpose experiments, made of several nested detectors
- full solid angle coverage, high granularity (millions of electronics channels)
- fast data acquisition (every 25 ns)
- high radiation hardness

ATLAS and CMS

ATLAS



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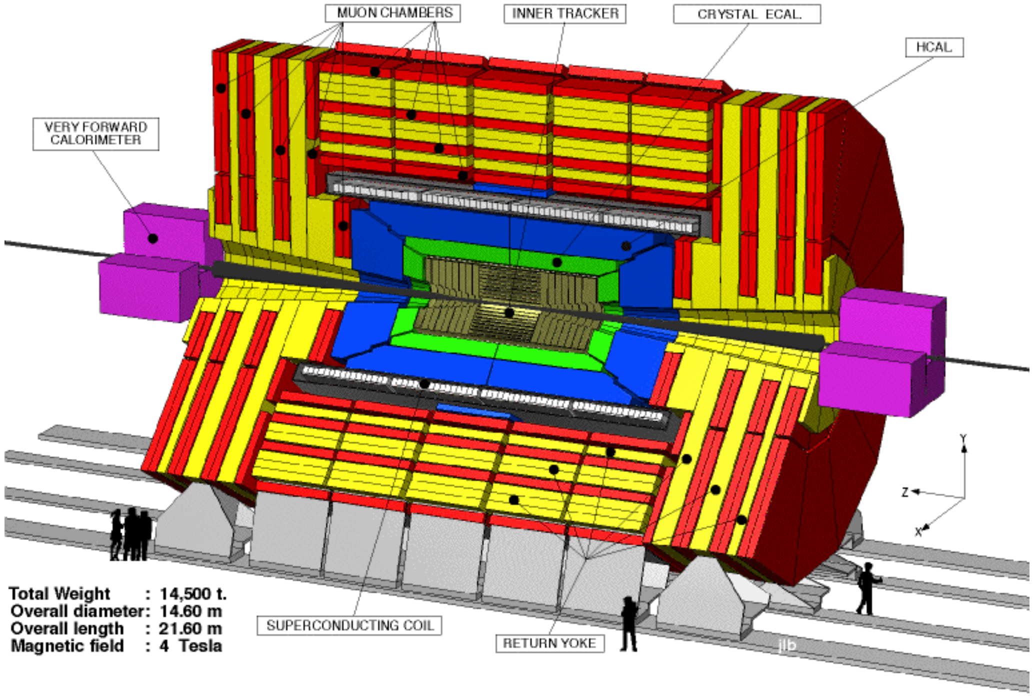

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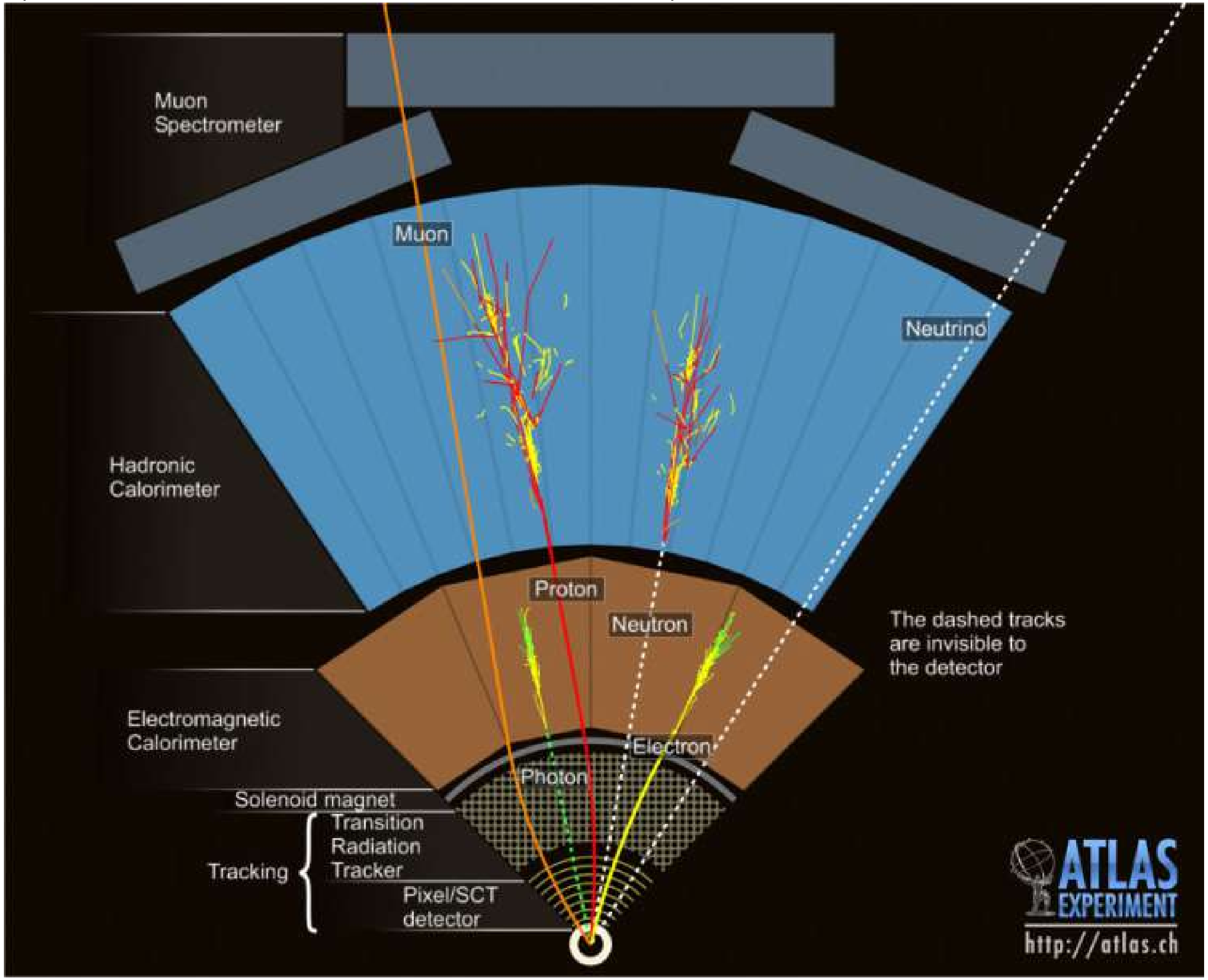
A little of history

- conceived in 1992, approved in 1995
- construction started in 1997
- tests of prototypes at test beams: 1998 – 2004
- assembly and installation: 2003 – 2007
- tests with cosmic rays: 2008 – 2009
- start of operation at LHC: end 2009

Identifying particles

Only few particles are stable, or "quasi-stable" : $e^{\pm}, \gamma, \pi^{\pm}, p, \bar{p}, n, \bar{n}, K_L^0, \mu^{\pm}$
(i.e. living long enough to cross the full detector)



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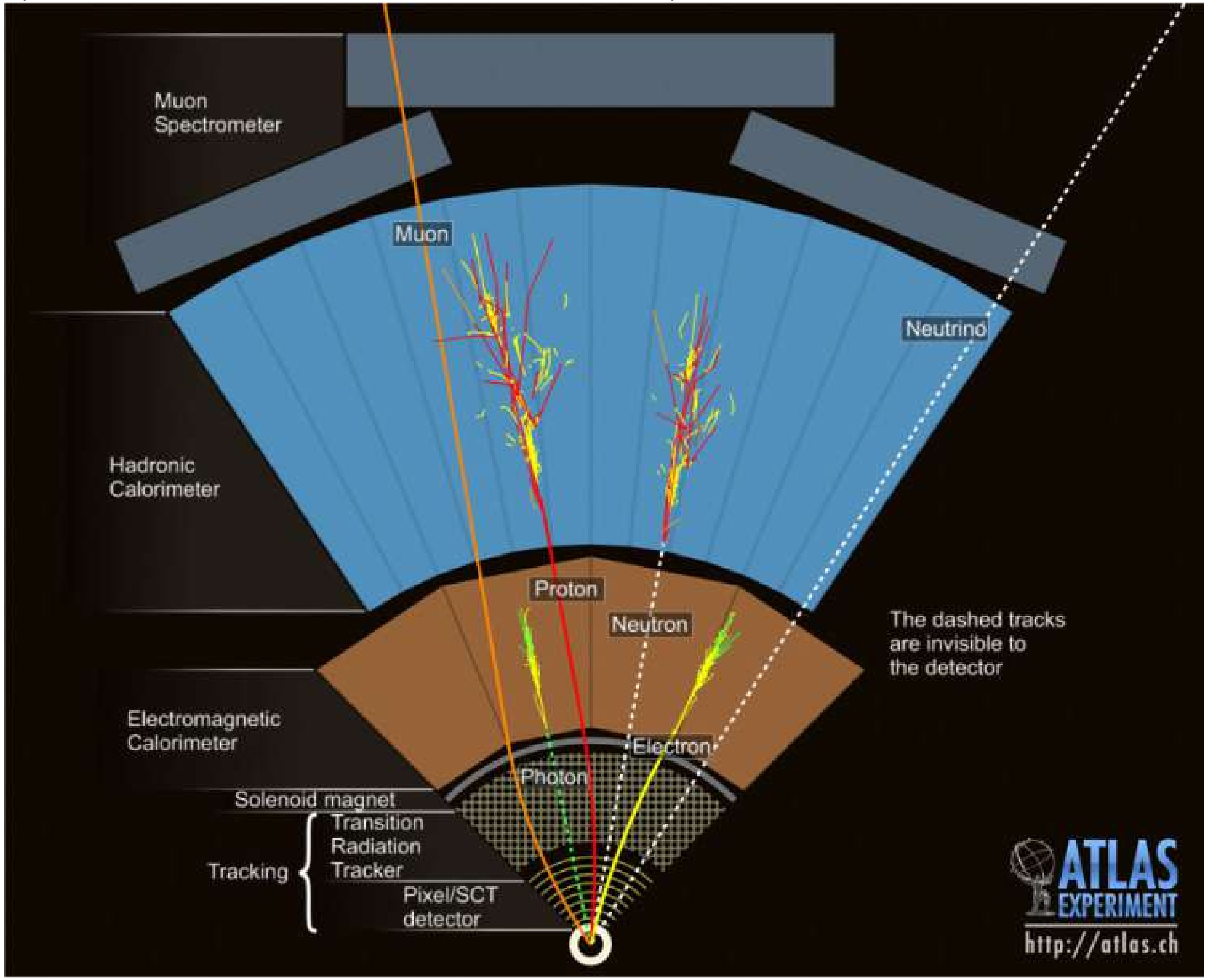
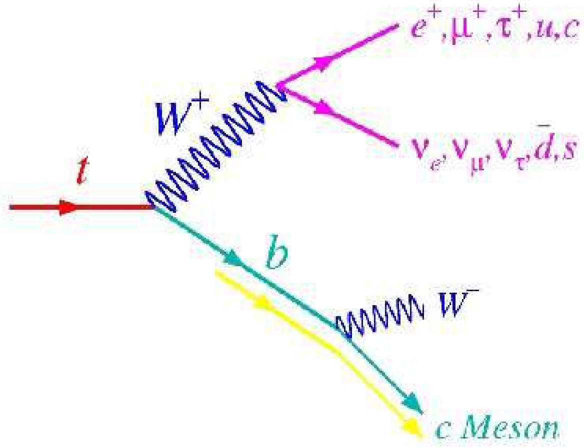


Most heavy particles decay quickly to lighter ones:

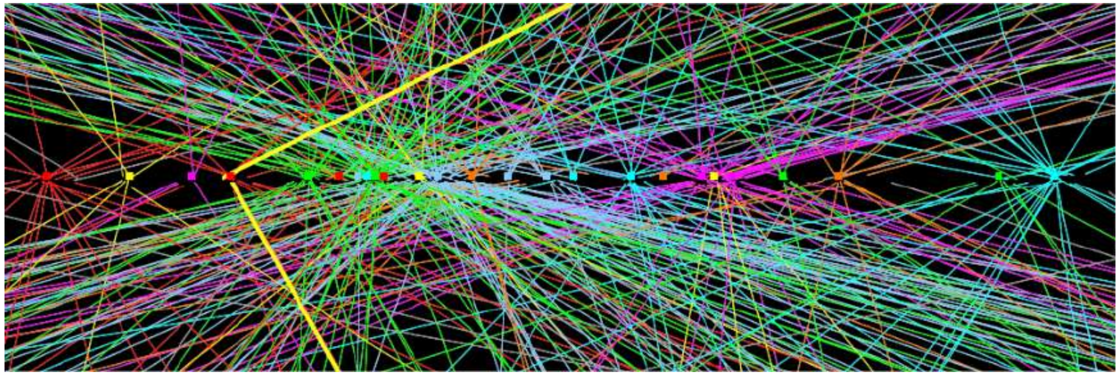


$\Rightarrow$ need to identify decay products and infer the original particle

Typical "events" at LHC

Proton beams collide every 25 ns:

- up to ∼50 proton-proton interactions
- hundreds of particles are produced

$p \longrightarrow$  $\longleftarrow p$

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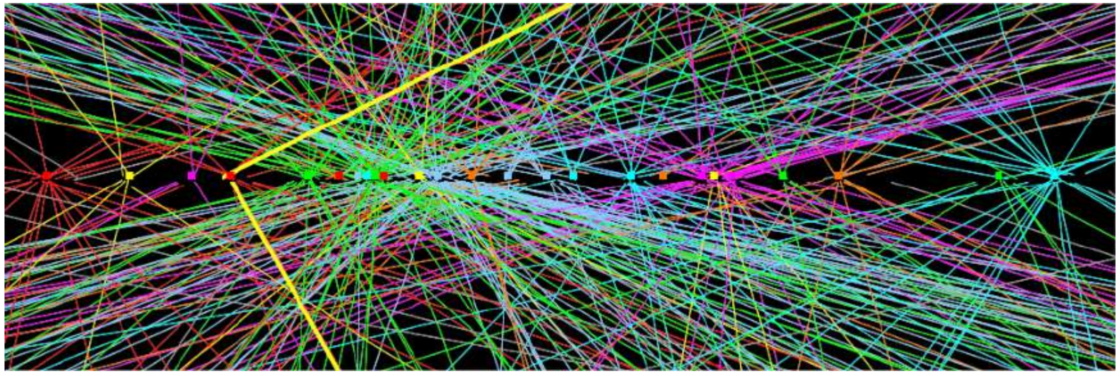
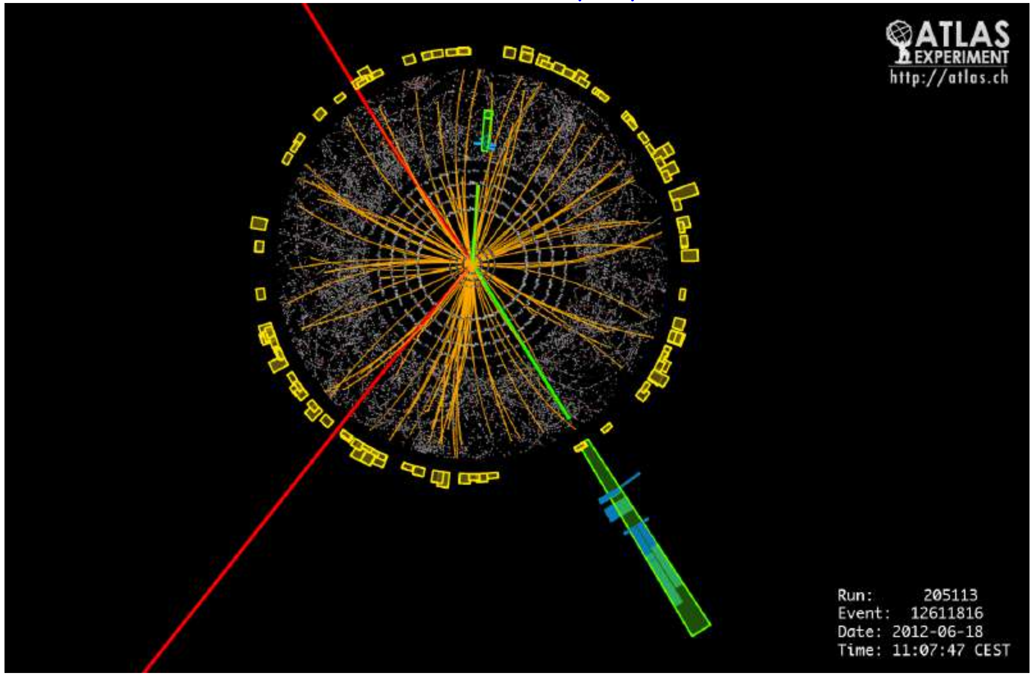
$p \longrightarrow$  $\longleftarrow p$

$ZZ \to e^+e^-\mu^+\mu^-$



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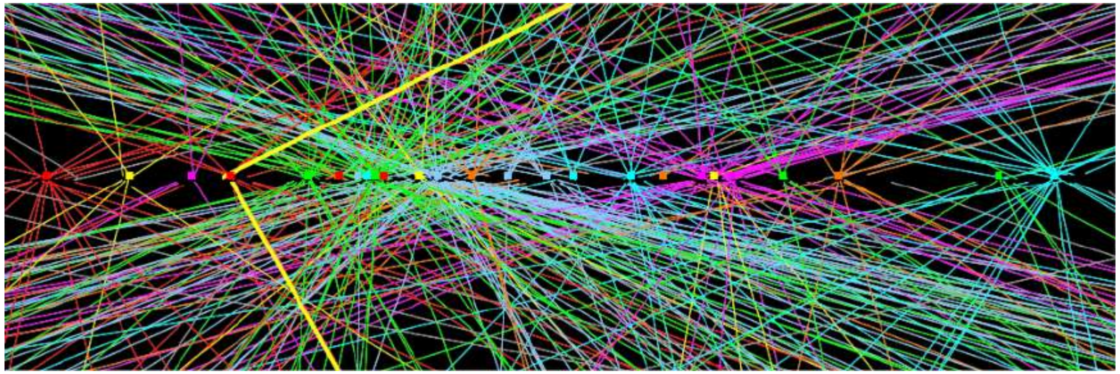
$p \longrightarrow$  $\longleftarrow p$

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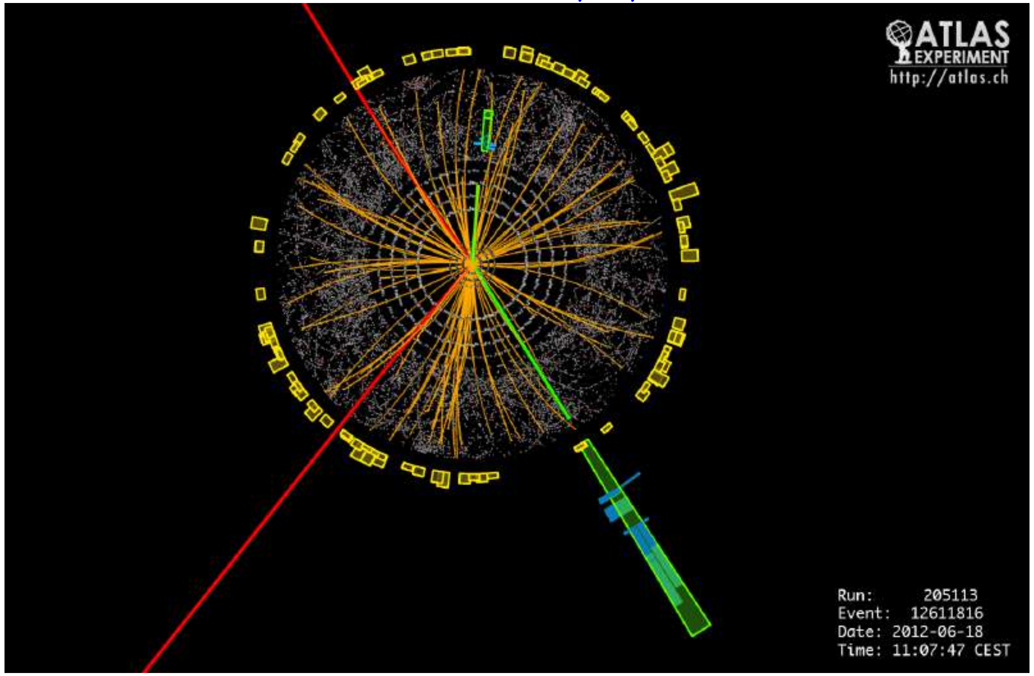
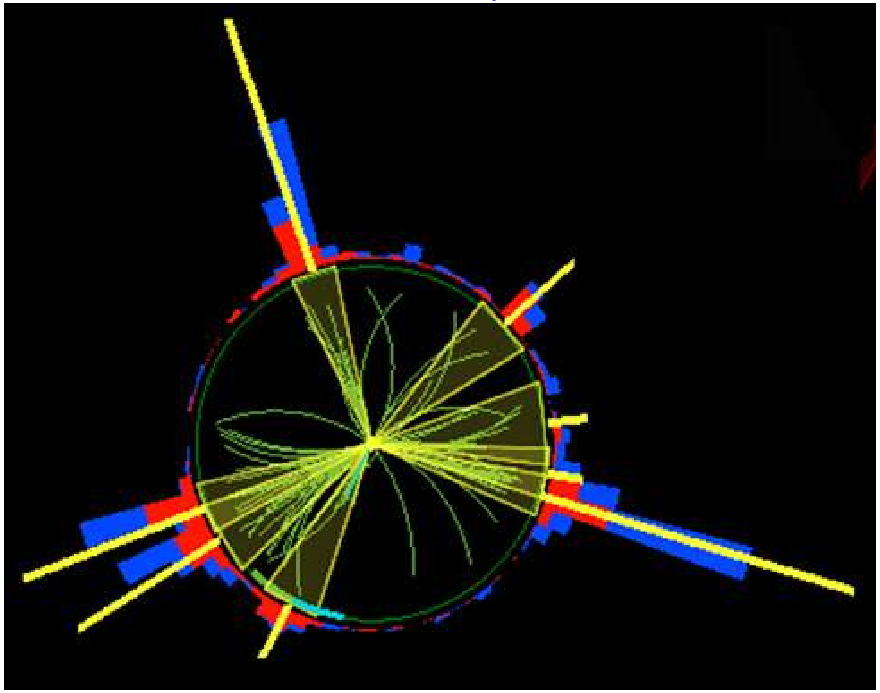


multi-jet event



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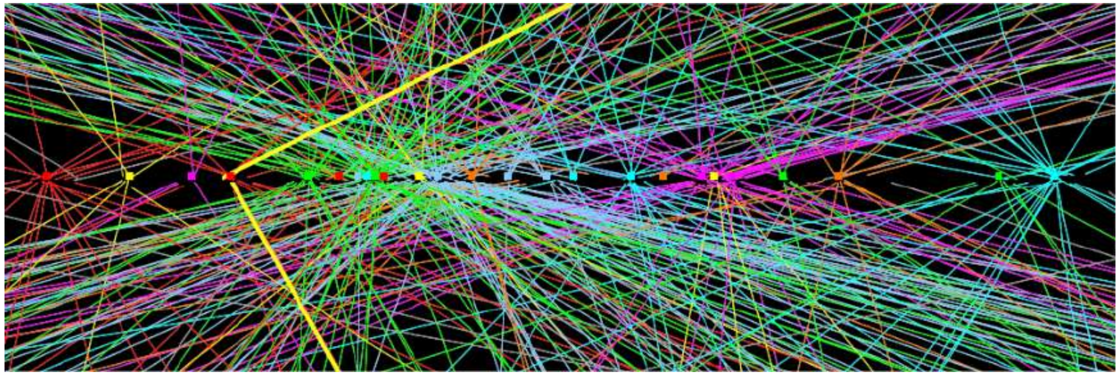
$p \longrightarrow$  $\longleftarrow p$

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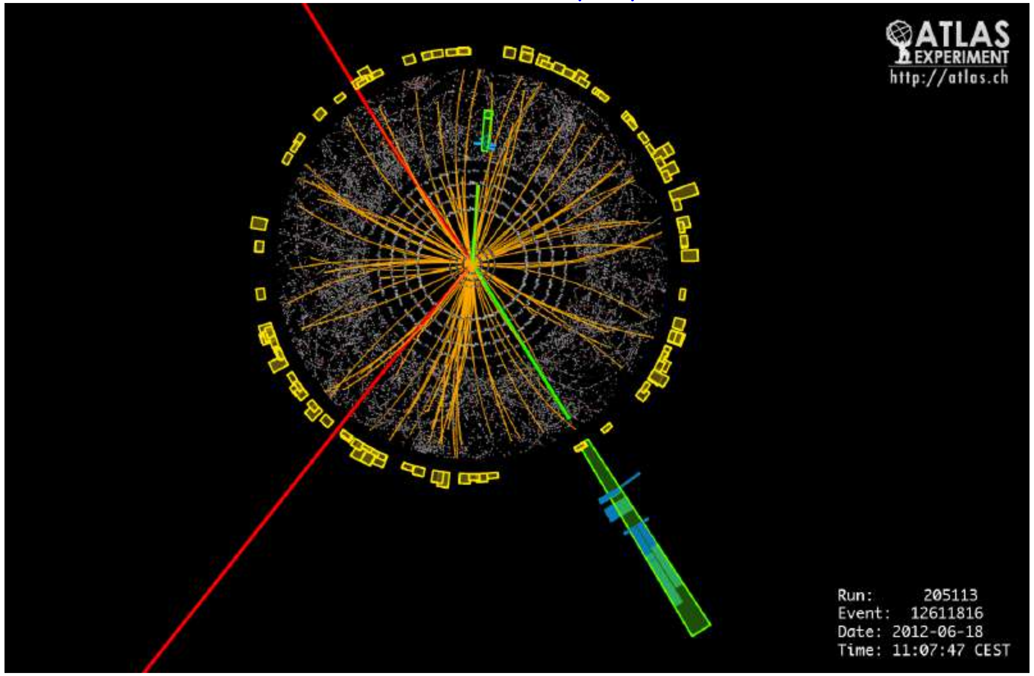

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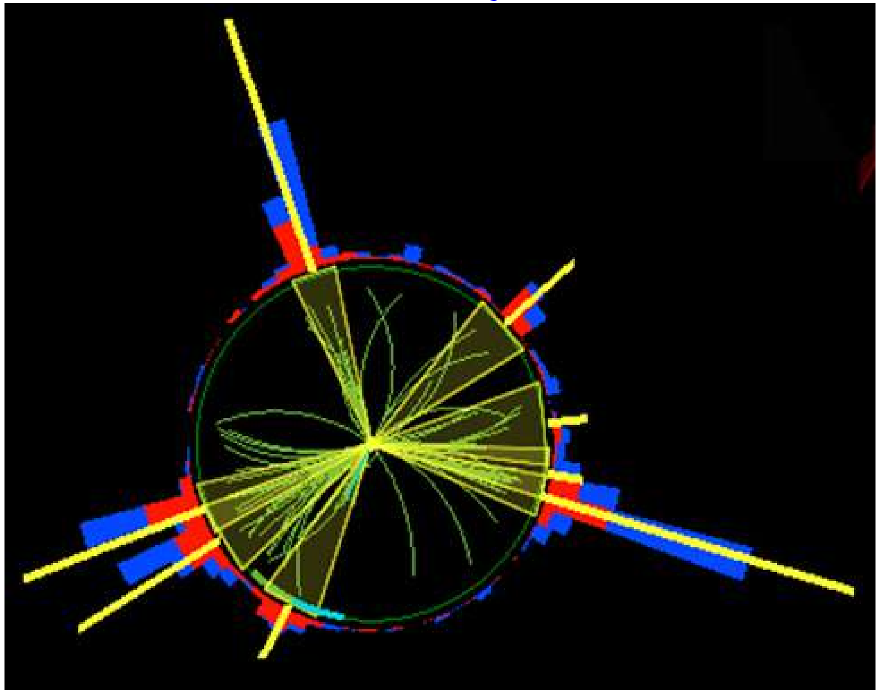
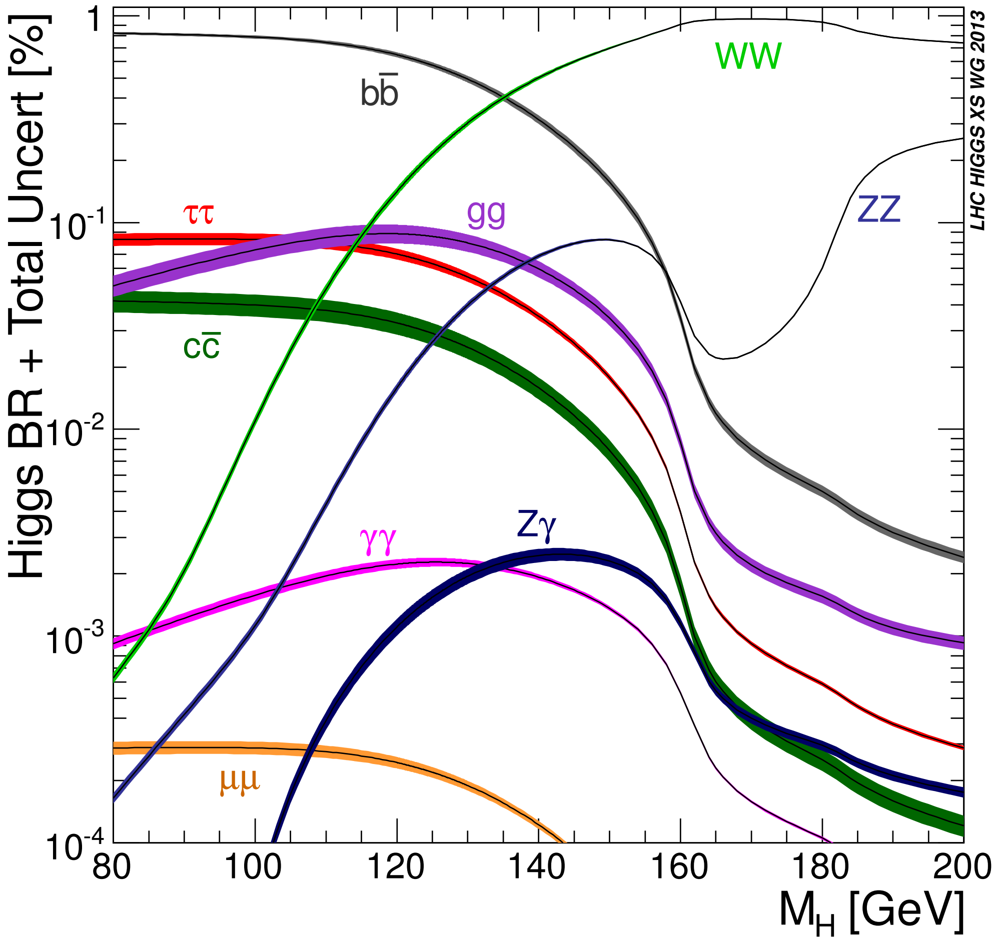


A tiny fraction of such "events" (≈ 1 in 10 billions) is a Higgs boson

How to observe the Higgs boson: decay modes



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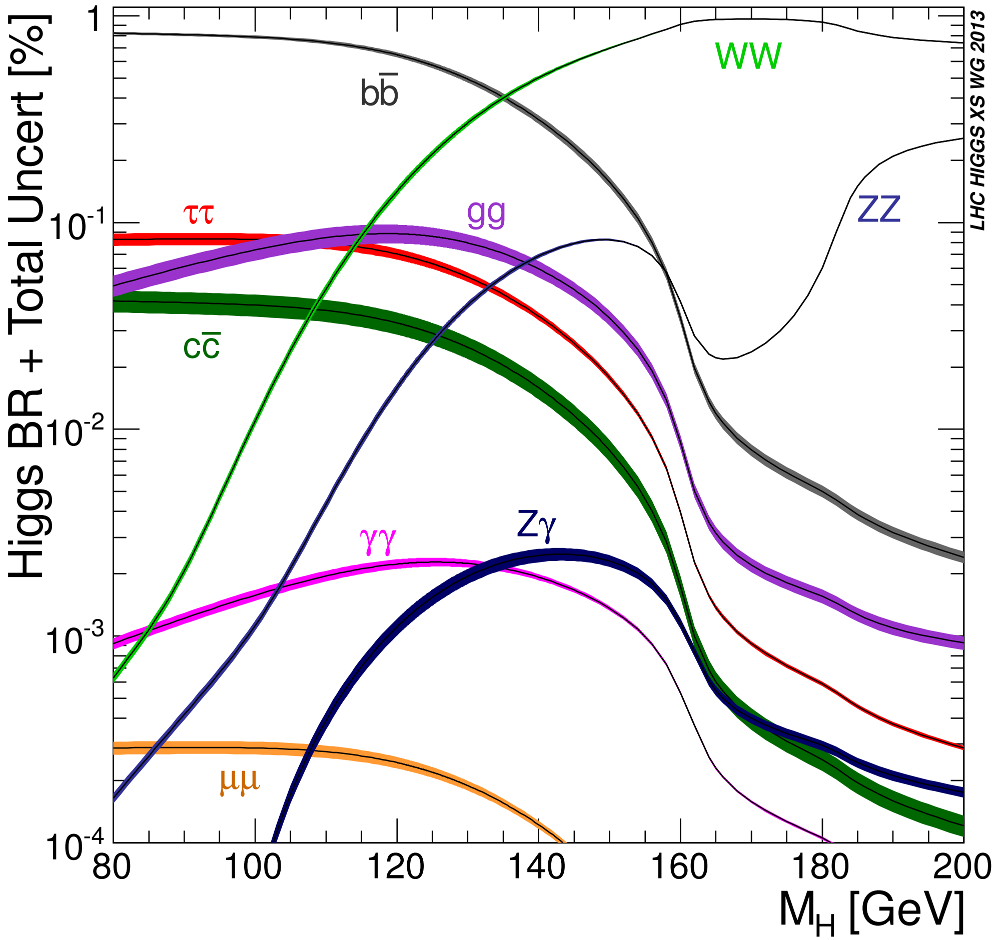

Most common decay modes ($H \to b\bar{b}$, $H \to \tau^+\tau^-$) are very difficult, due to large hadronic background.

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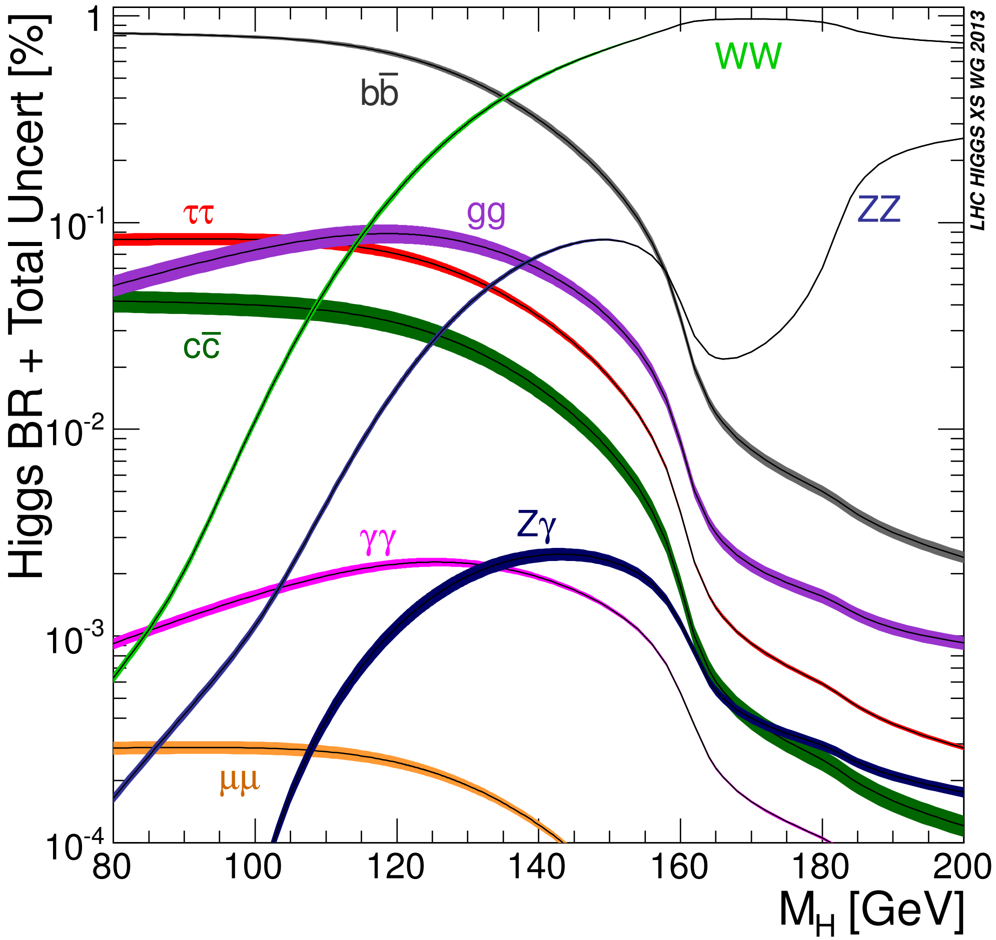

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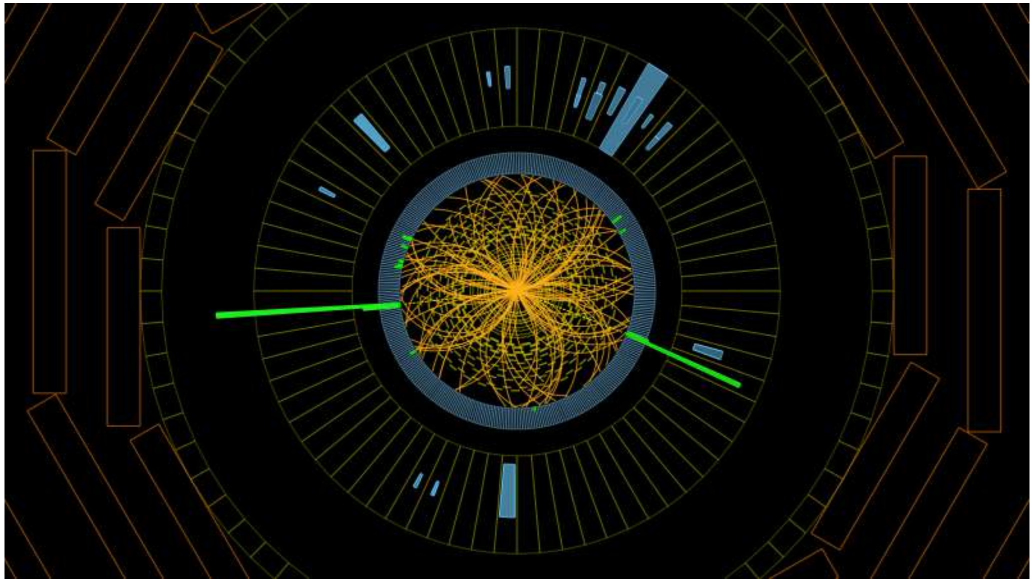
More suitable are:

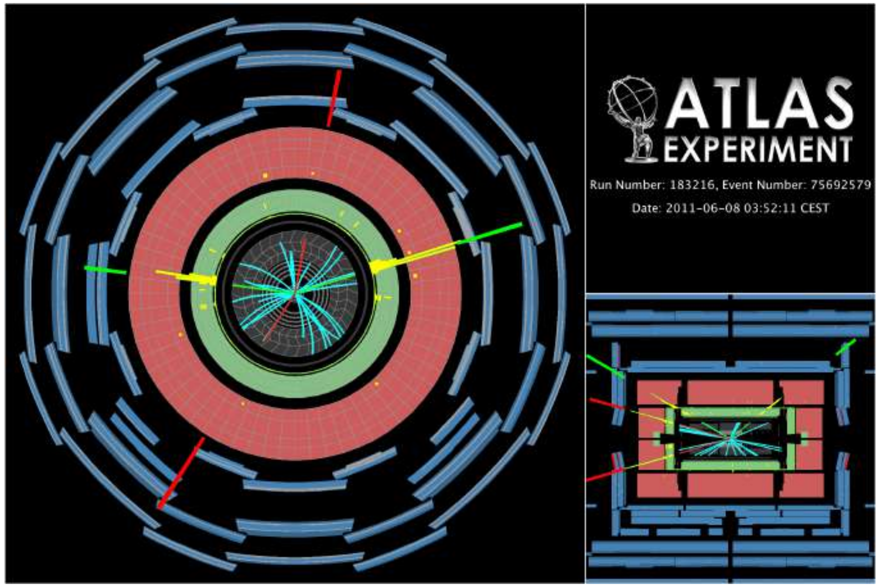
$H \to$	BR	pros/cons
$\gamma\gamma$	0.002	good mass resolution, $S/B \simeq 0.02$
$ZZ \to 4\ell$	0.0001	good mass resolution, $S/B \simeq 1$
$WW \to \ell\nu\ell\nu$	0.009	cannot measure mass

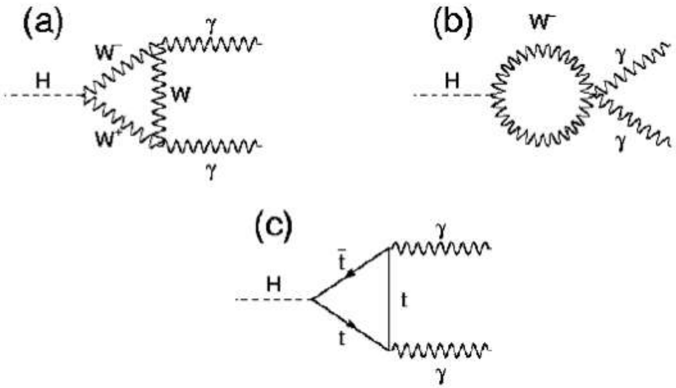
Best discovery channels

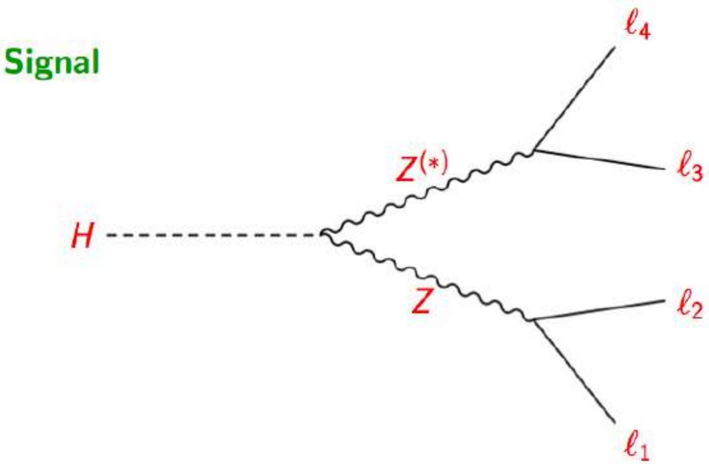
$H \to \gamma\gamma$ candidate at CMS



$H \to ZZ^* \to e^+e^-\mu^+\mu^-$ candidate at ATLAS







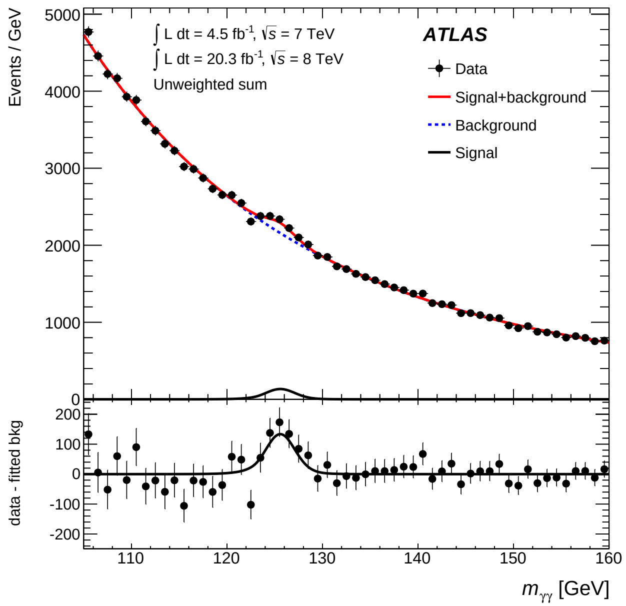
Fully reconstructed final states with good energy resolution

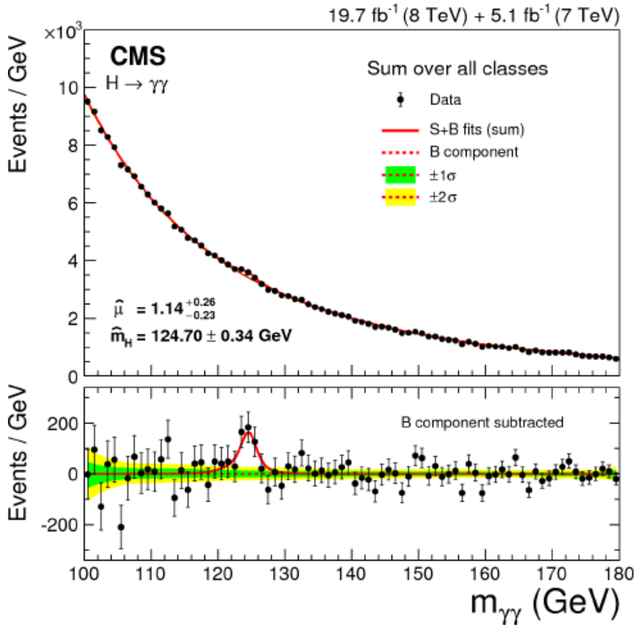
Invariant mass plots

$H \to \gamma\gamma$ decay channel

$$m_{\gamma\gamma} = \sqrt{(E_{\gamma 1} + E_{\gamma 2})^2 - |\vec{p}_{\gamma 1} + \vec{p}_{\gamma 2}|^2}$$

($m_{\gamma\gamma}$ peaks at m_H if $\gamma\gamma$ are from Higgs)

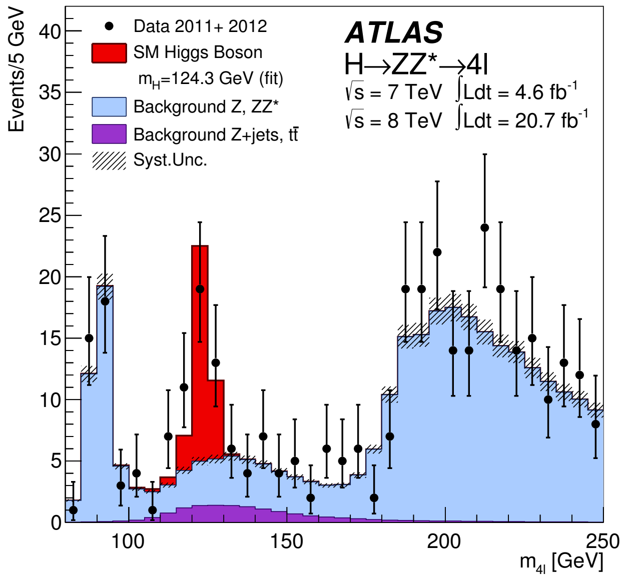


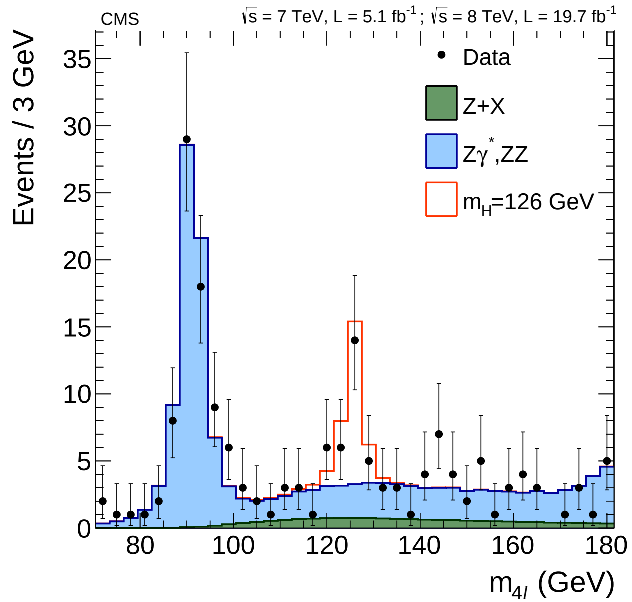


$H \to 4\ell$ decay channel

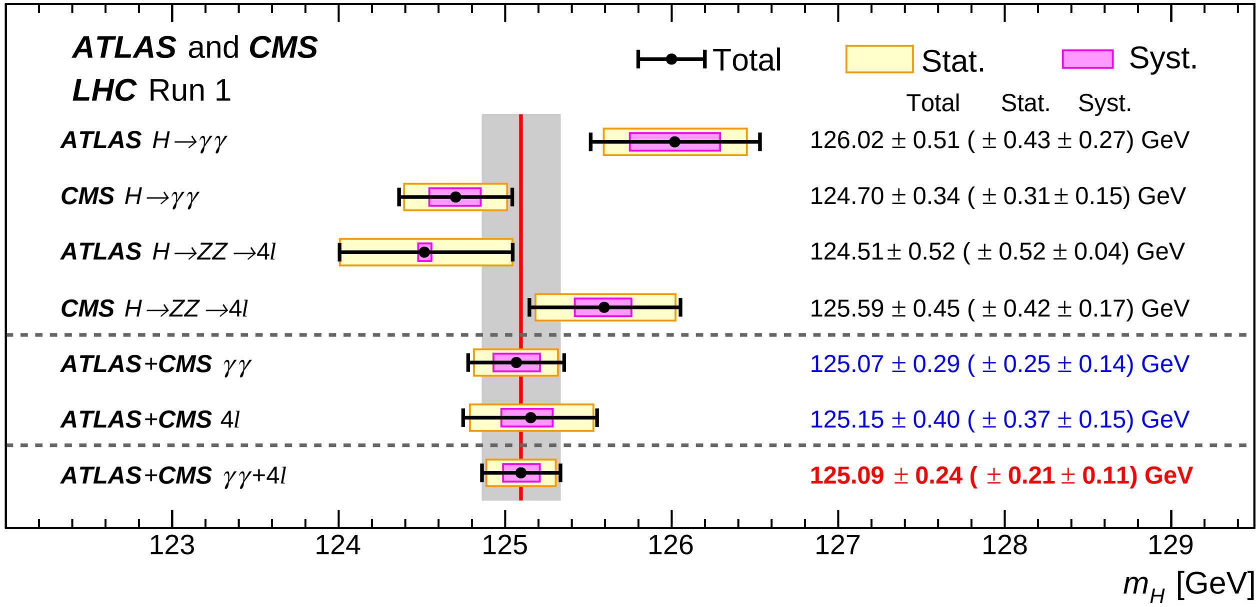
$$m_{4\ell} = \sqrt{\left(\sum_{\ell=1}^{4} E_\ell\right)^2 - \left|\sum_{\ell=1}^{4} \vec{p}_\ell\right|^2}$$

($m_{4\ell}$ peaks at m_H if 4ℓ are from Higgs)





The Higgs mass



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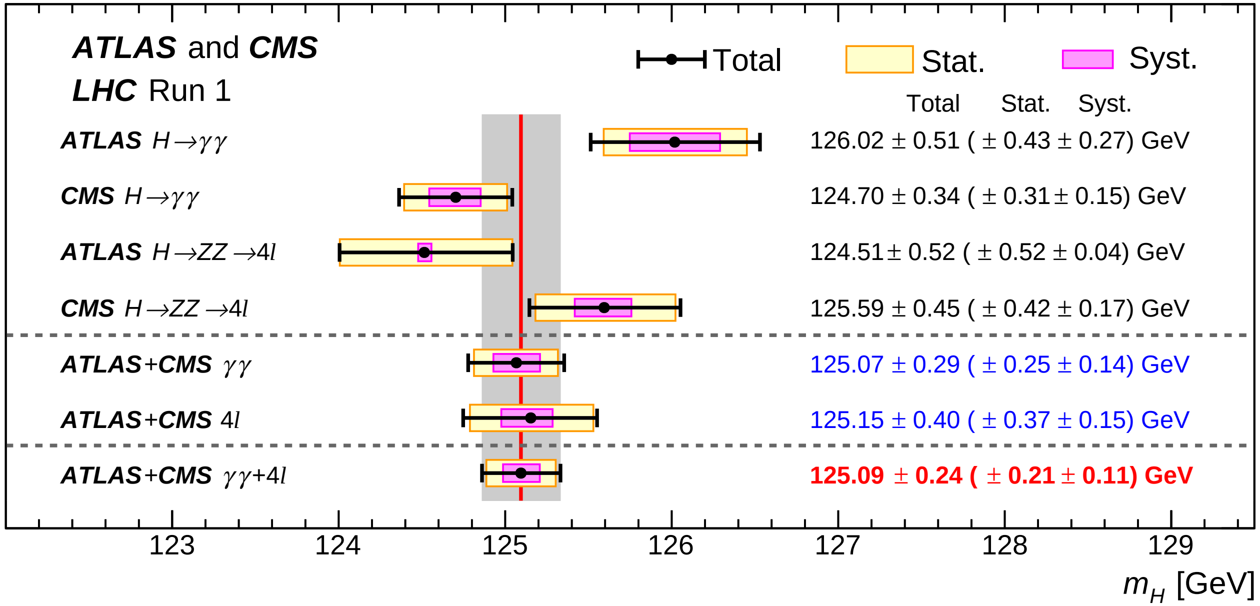
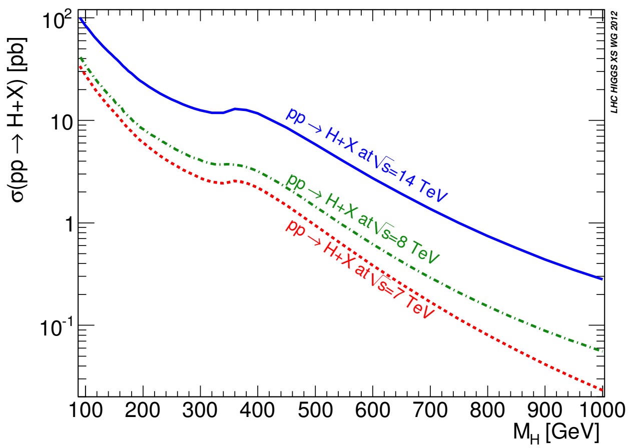


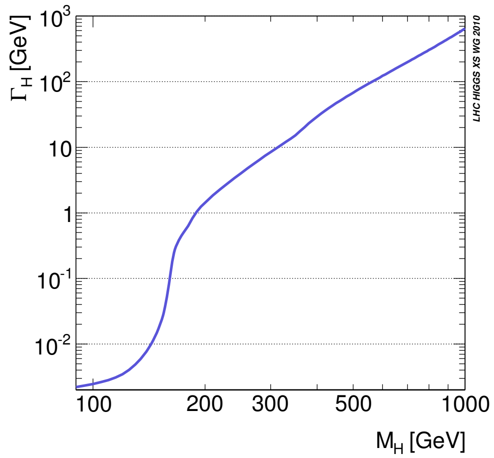
Once m_H is measured, all other properties can be predicted

$\Rightarrow$ can test the Higgs sector

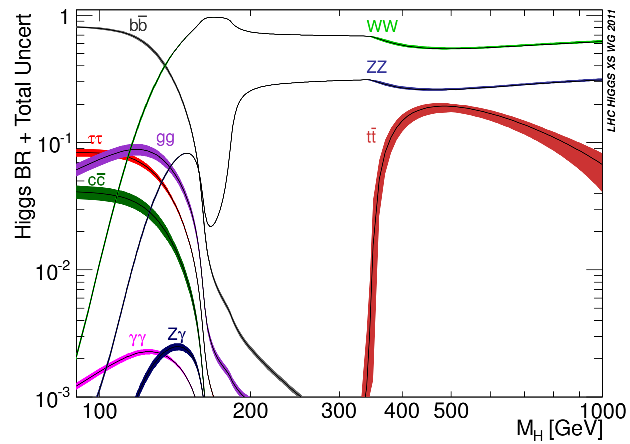
cross-section



decay width



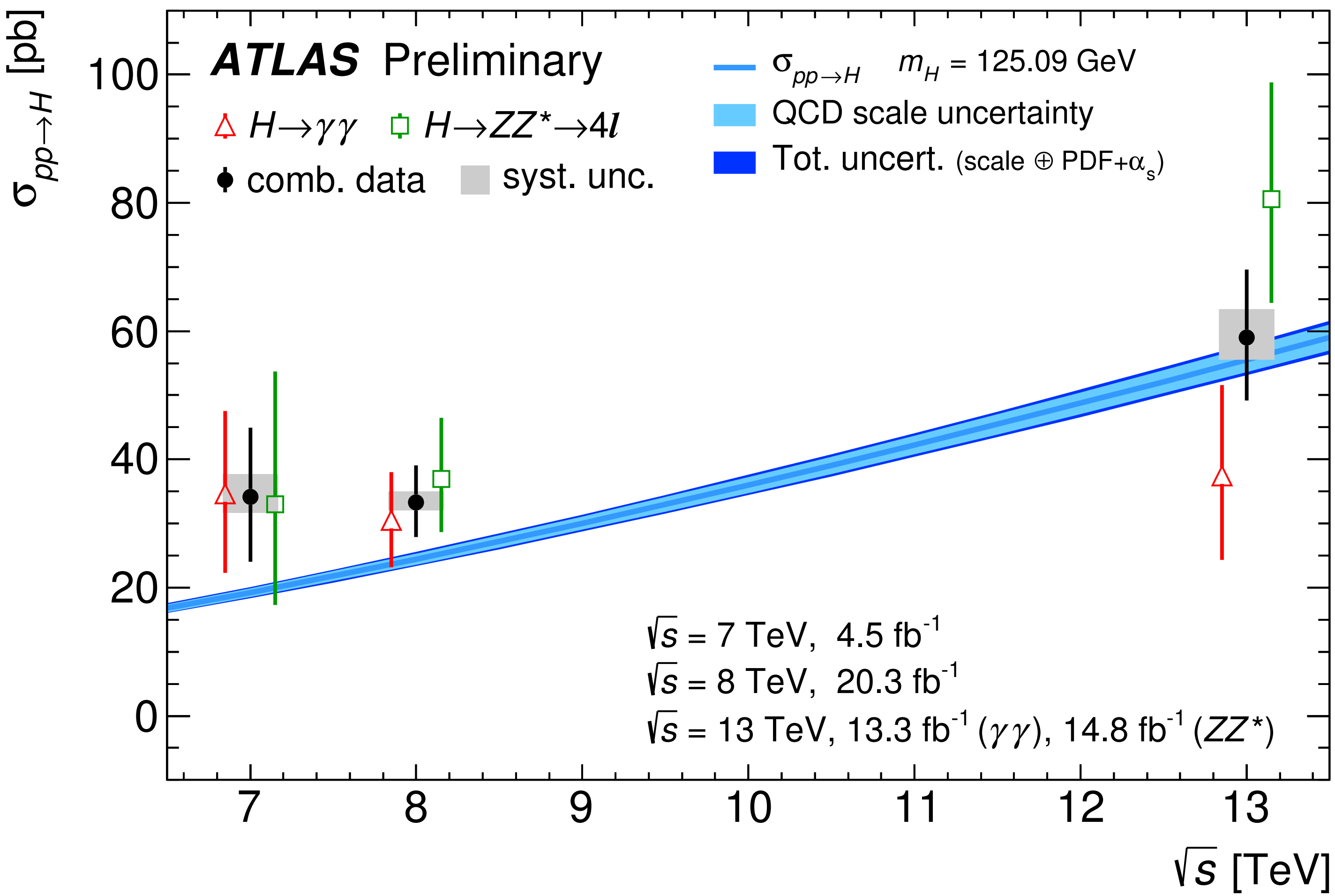
branching ratios



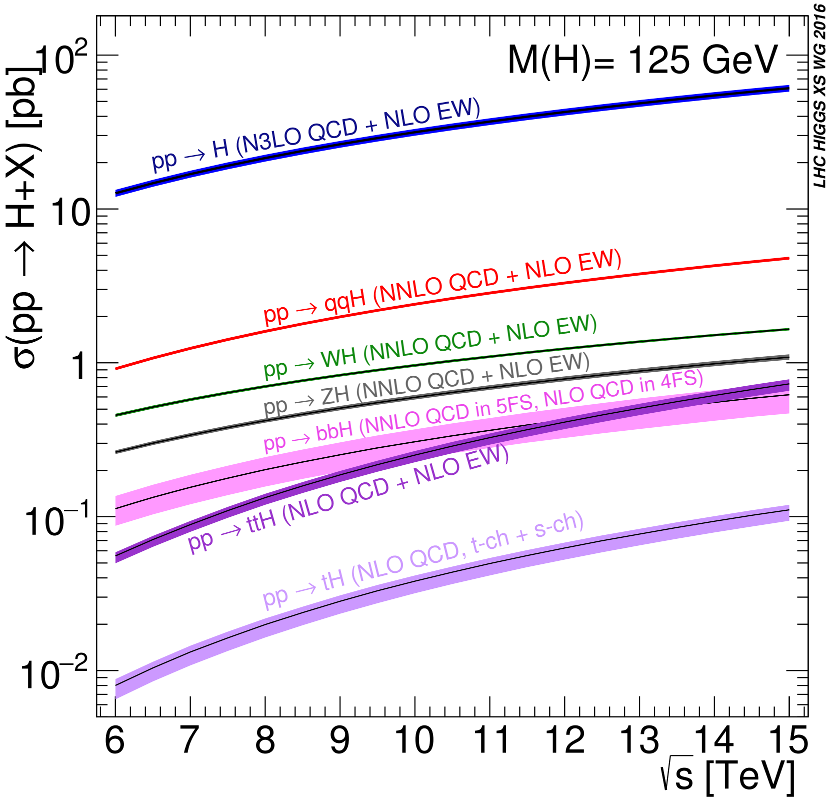
Properties of the Higgs boson

Cross-section measurements

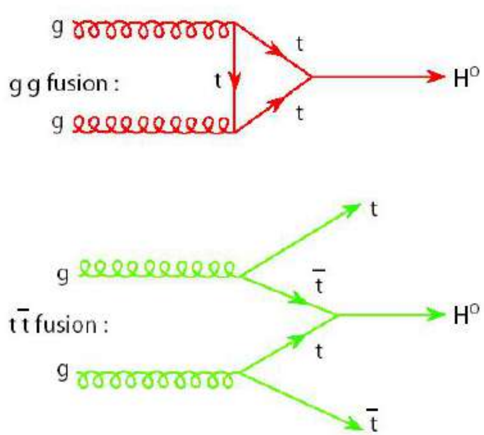
Total cross-section vs $\sqrt{s}$ ($\gamma\gamma$ and 4ℓ combined)



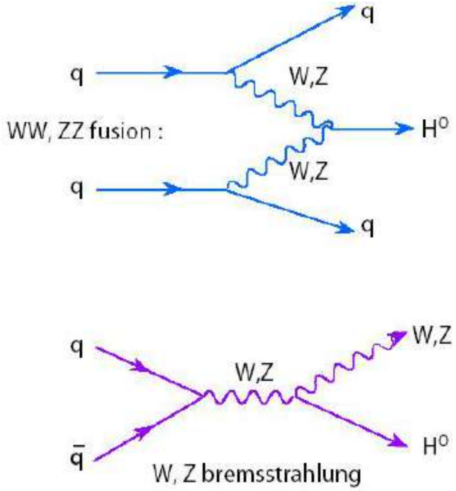
Higgs production modes at the LHC



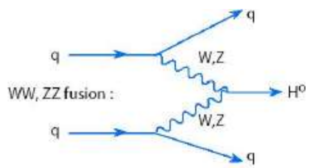
QCD production

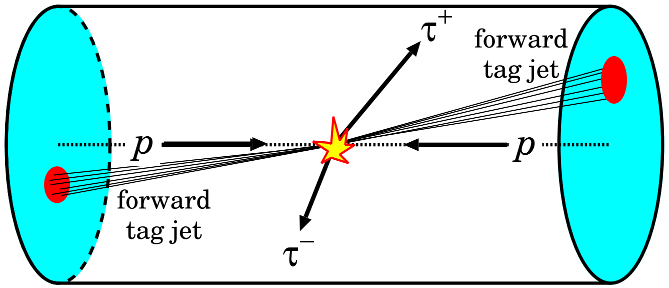


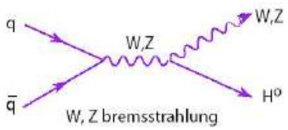
EW production

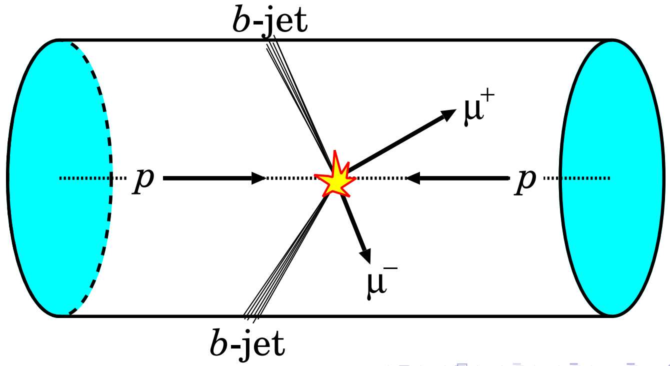


Experimental identification of VBF and VH productions ("tagging"):



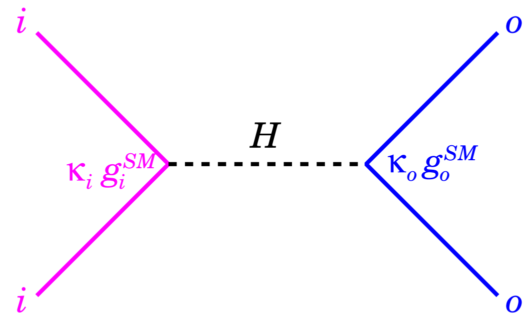






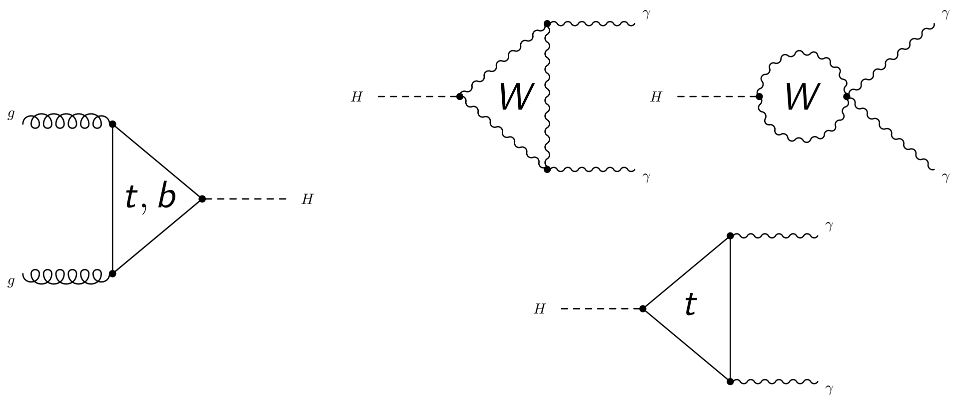
Couplings measurements

According to SM, the Higgs couplings are $g_f^{SM} = \frac{m_f}{v}$ and $g_V^{SM} = 2\frac{m_V^2}{v}$



Couplings are accessible through production ($ii \to H$) and decay ($H \to oo$)

$\Rightarrow$ Several couplings: $g_\mu,\ g_\tau,\ g_b,\ g_W,\ g_Z,\ g_t$



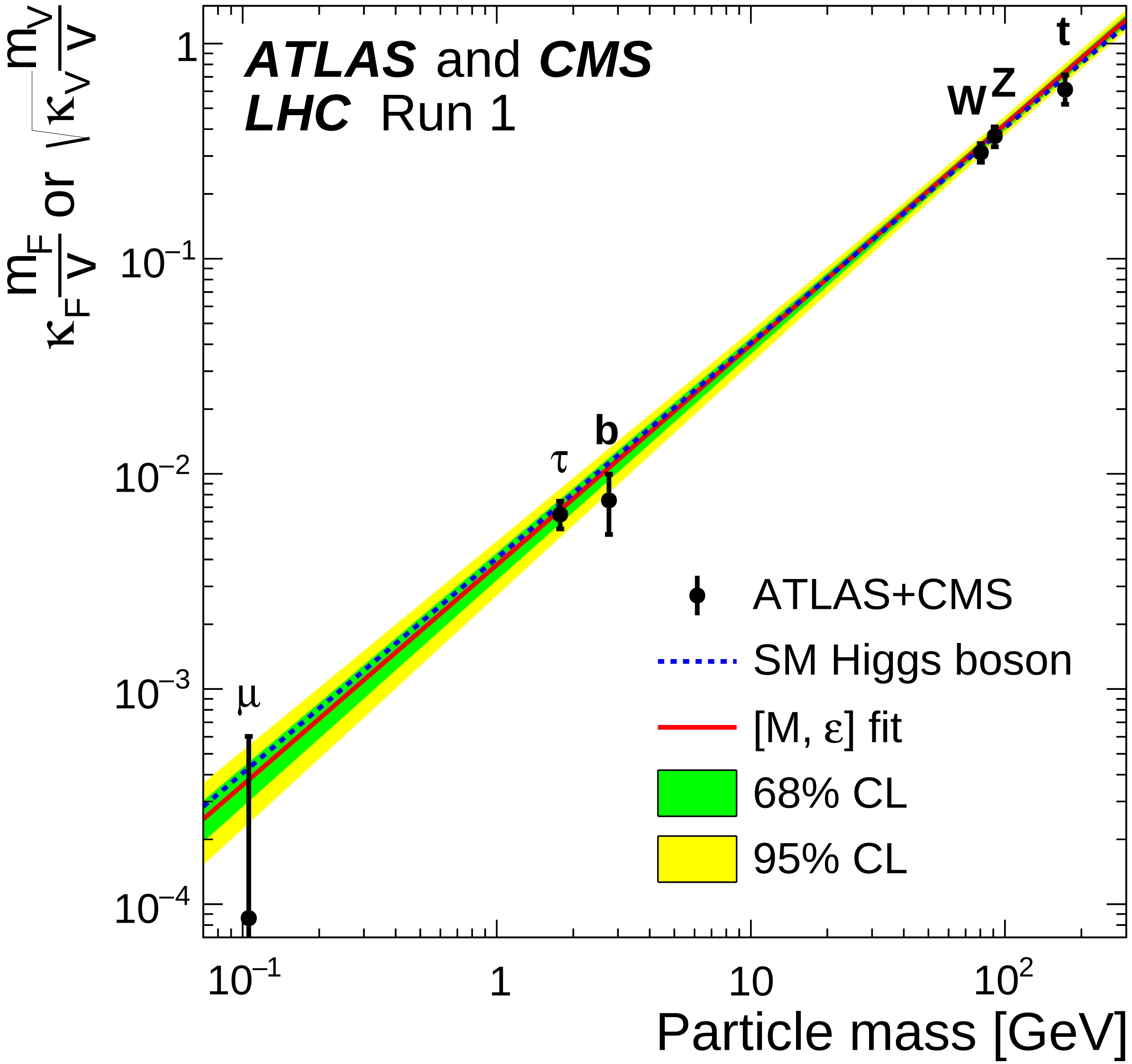
gluons and photons are massless
$\Rightarrow$ no direct ggH, $H\gamma\gamma$ couplings

$gg \to H$ through top/bottom virtual loop
$\Rightarrow$ mainly driven by g_t, g_b

$H \to \gamma\gamma$ through top/bottom and W virtual loops
$\Rightarrow$ mainly driven by g_W, g_t, g_b

Couplings measurements

According to SM, the Higgs couplings are $g_f^{SM} = \frac{m_f}{v}$ and $g_V^{SM} = 2\frac{m_V^2}{v}$



decay	measure	plot
fermions	g_f	g_f
bosons	g_V	$\sqrt{\frac{g_V}{2v}}$

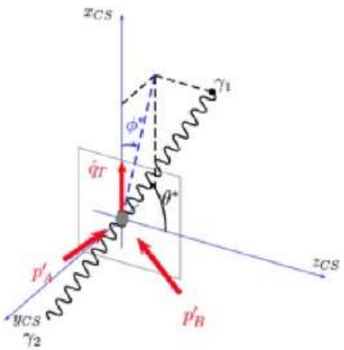
$\Rightarrow$ all scale like $\frac{m}{v}$ as expected,

over $>$ 3 orders of magnitude!

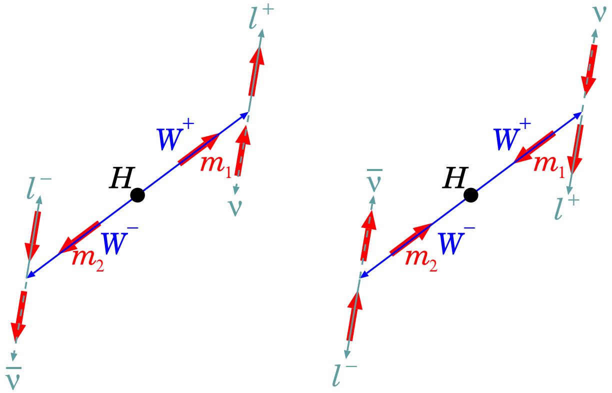
$\Rightarrow$ **distinctive signature of the Higgs mechanism!**

Spin

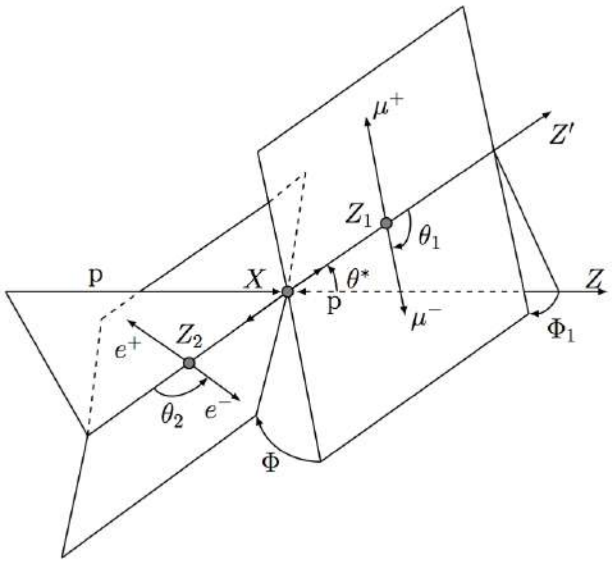
$H \to \gamma\gamma$:



$H \to WW^* \to \ell\nu\ell\nu$:



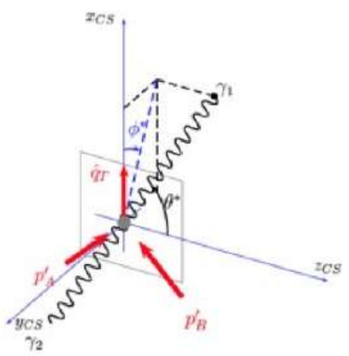
$H \to ZZ^* \to 4\ell$:



Spin can be probed from angular distributions of decay products

Spin

$H \to \gamma\gamma$:



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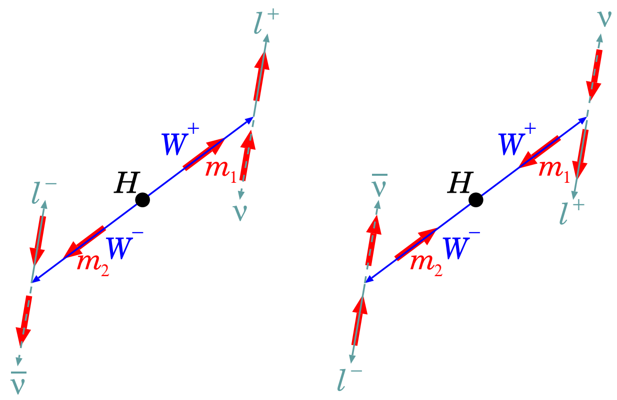
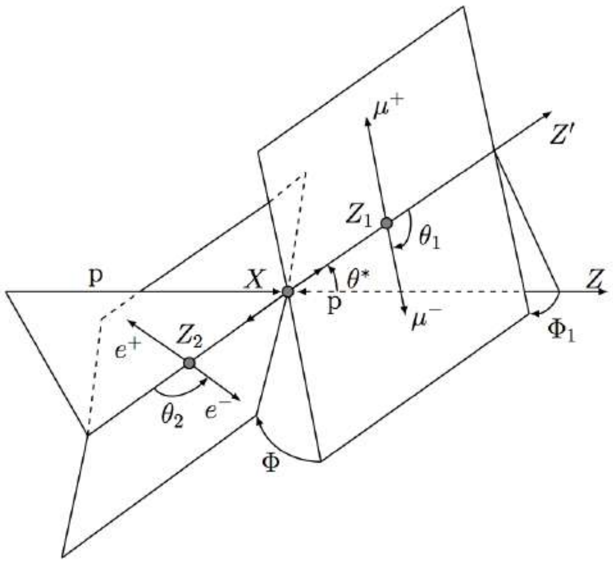


Observation of $H \to \gamma\gamma$ decay excludes spin-1

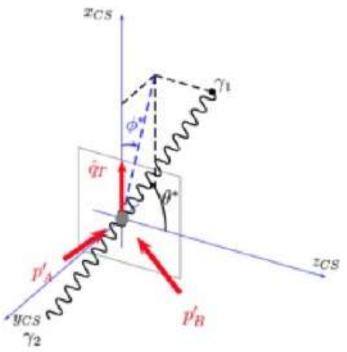
$H \to ZZ^* \to 4\ell$:



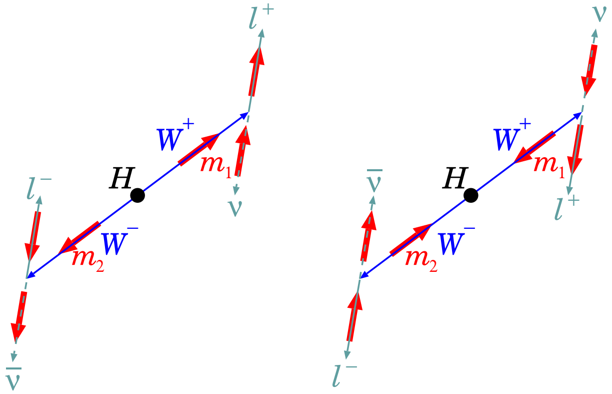
$\Rightarrow$ test spin-0 against spin-2

Spin

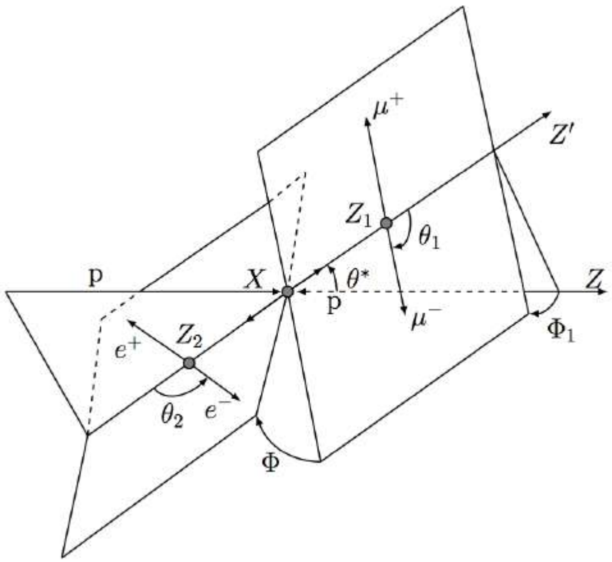
$H \to \gamma\gamma$:



$H \to WW^* \to \ell\nu\ell\nu$:

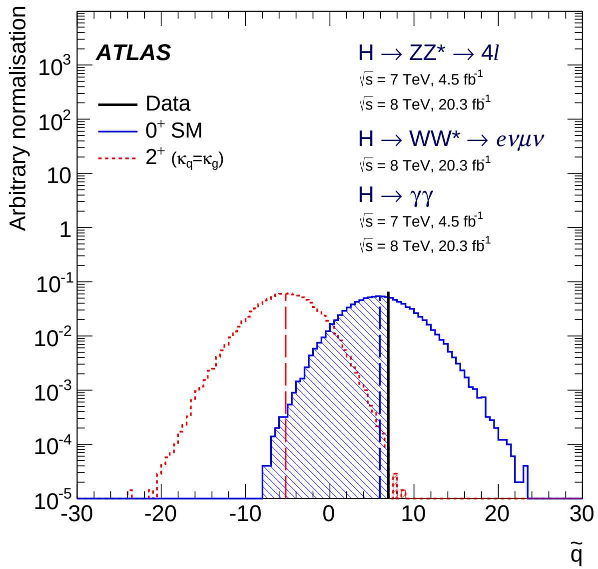


$H \to ZZ^* \to 4\ell$:



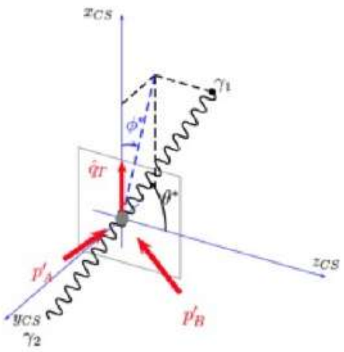
Use likelihood-ratio test statistic

$$\tilde{q} \equiv 2 \ln \left(\frac{\mathcal{L}(\text{spin-0})}{\mathcal{L}(\text{spin-2})} \right)$$

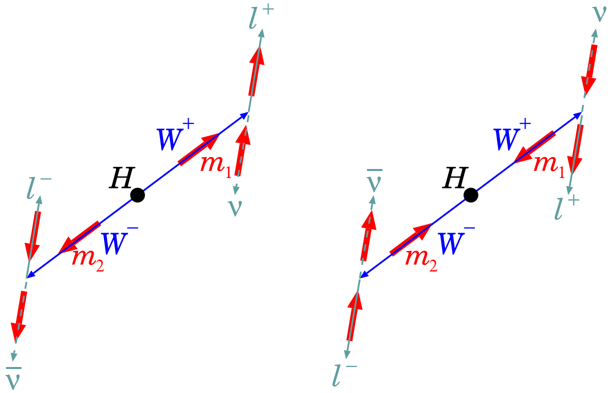


Spin

$H \to \gamma\gamma$:



$H \to WW^* \to \ell\nu\ell\nu$:



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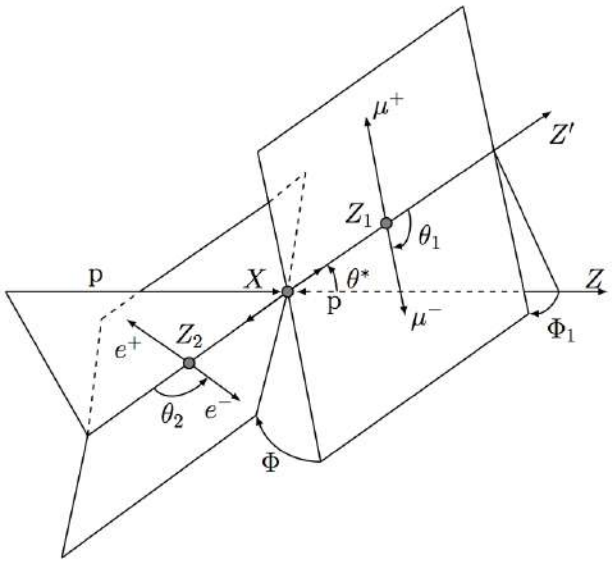

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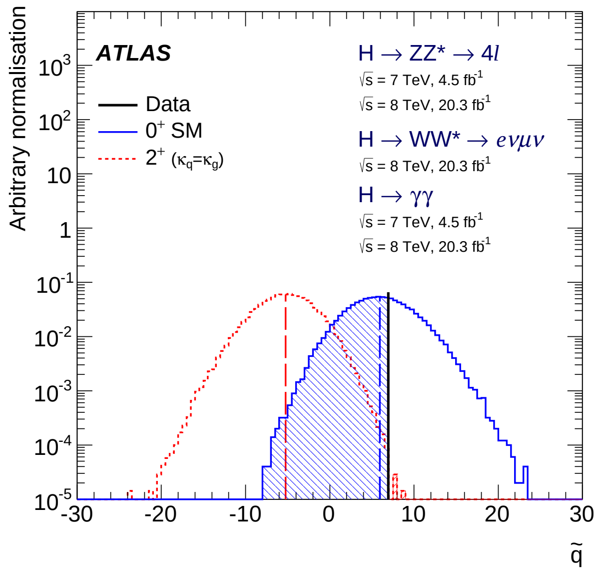
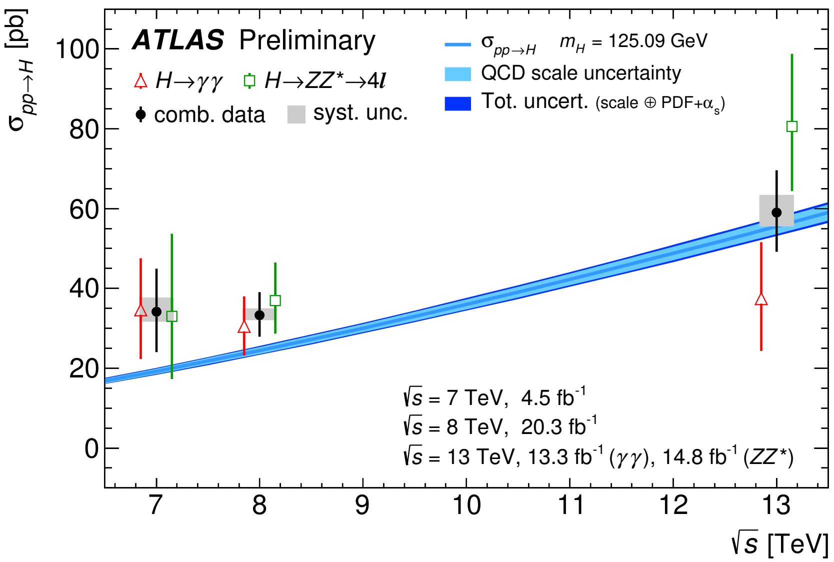


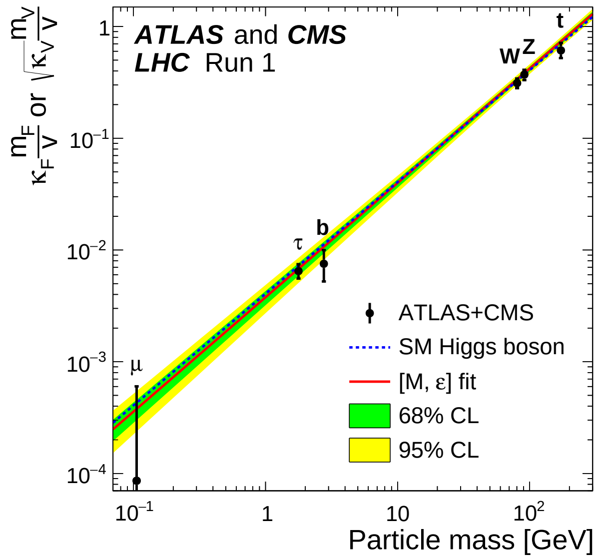
$\Rightarrow$ **data favour spin-0**

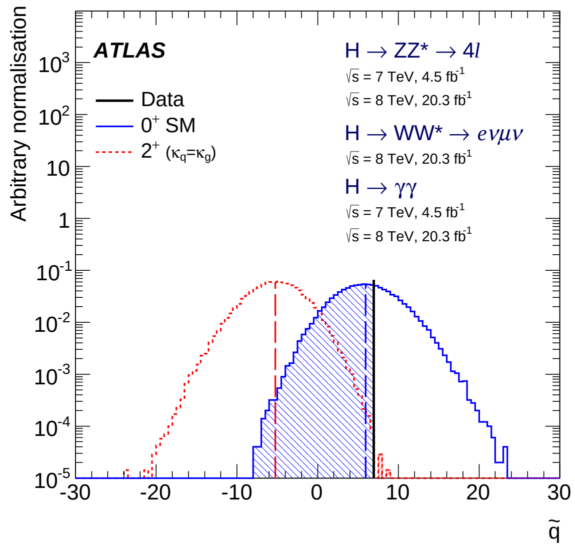
Summary

Present measurements

The Higgs boson was discovered, now we are in the middle of the Higgs measurements era.







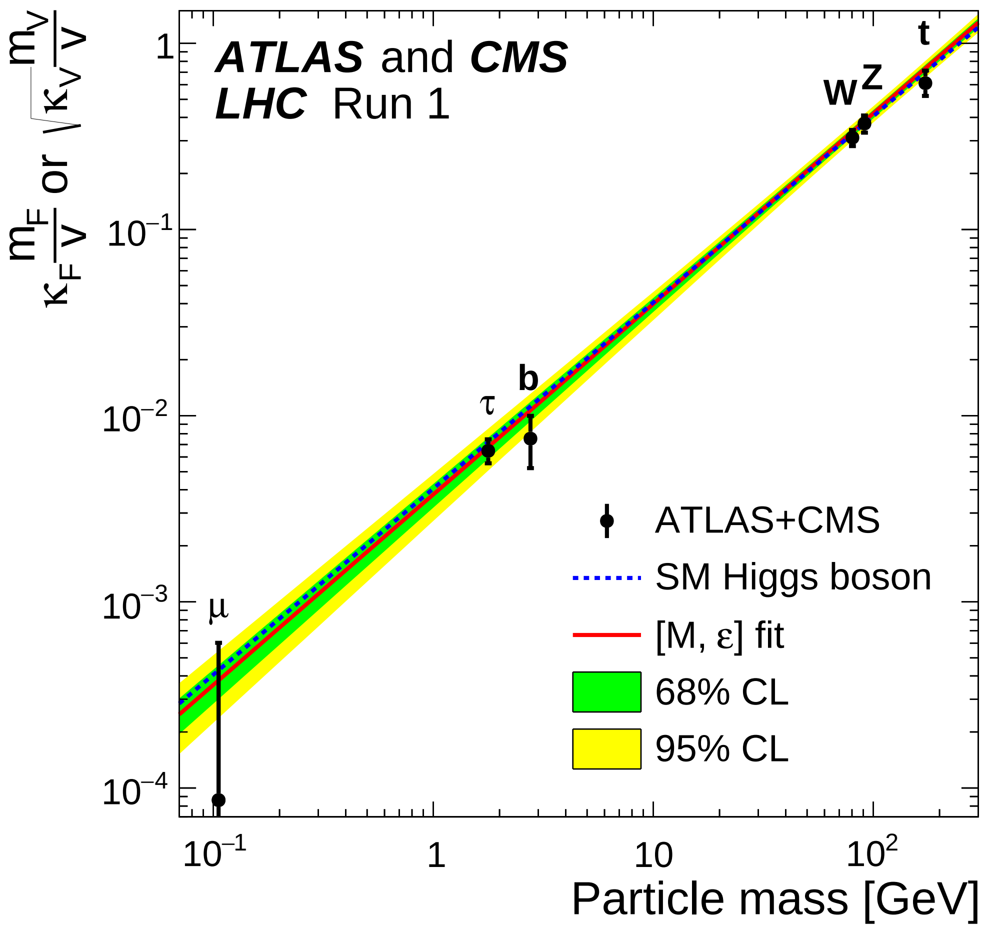
⇒ We are still compatible with Standard Model prediction ... but uncertainties are still large.

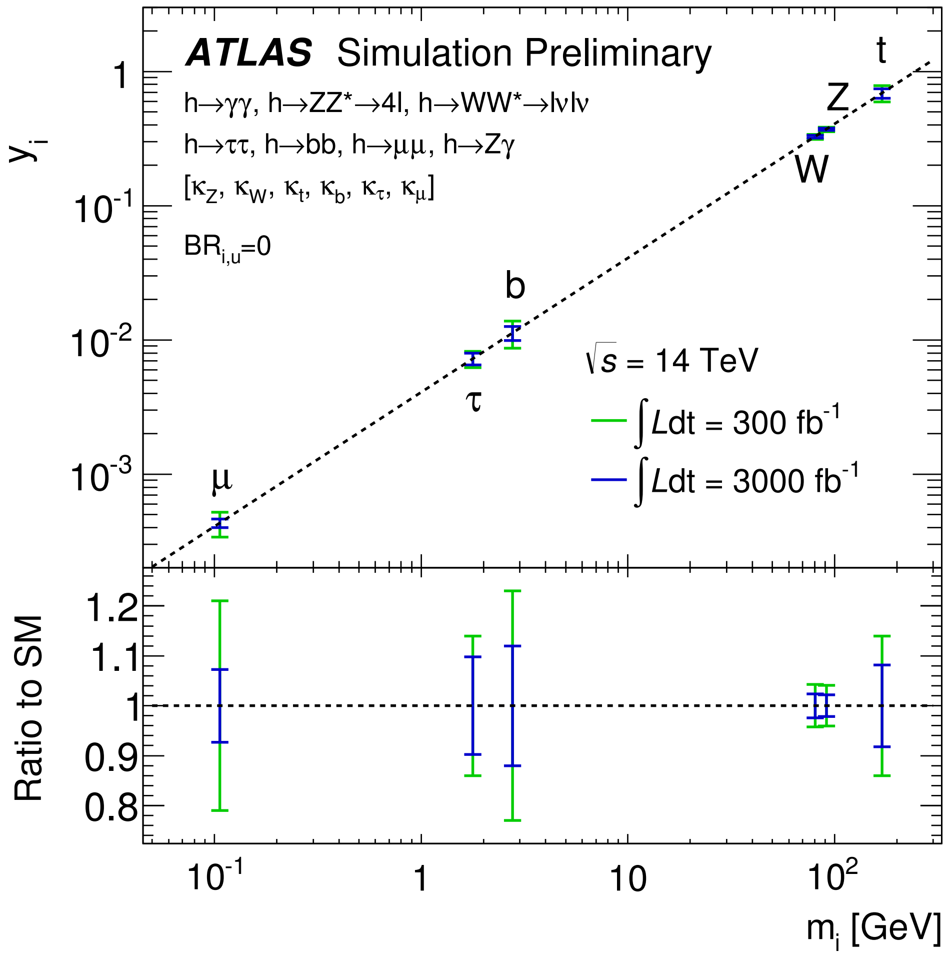
Meanwhile, huge effort from theorists to improve their uncertainties [see talk by G.Ferrera].
Important to pursue precision measurements in the Higgs sector, to investigate possible deviations from SM

Prospects . . .

Results: ATLAS+CMS, 8 TeV

Expected: 13 TeV, 300 fb^{-1} and 3000 fb^{-1}(ATLAS only)





Some "educated guesses" — With 300 fb^{-1}at 13 TeV:

Precise measurements of $H \to \tau^+\tau^-$, observation of $H \to b\bar{b}$, evidence of $t\bar{t}H$ production

Evidence of $H \to \mu^+\mu^-$, precision measurements of all individual κ's to $\lesssim$ 10% accuracy

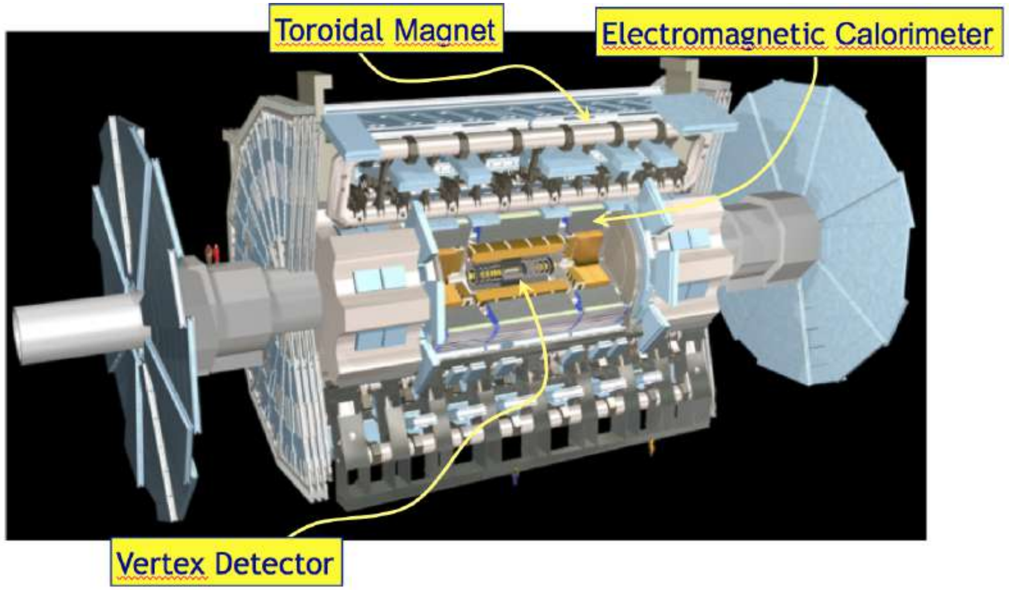
Milano's involvement

Milano's involvements

Detector

Detector construction

- pixel detector (innermost tracking device)
- electromagnetic calorimeter
- magnets for muon chambers



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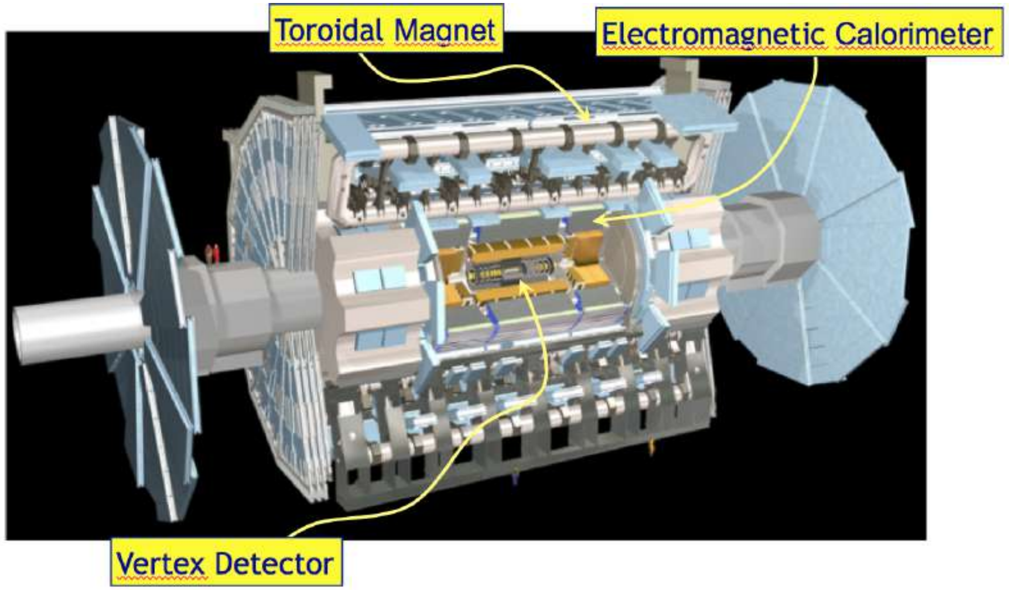

R & D

Electronics: upgrade for high-luminosity phase [talk by A.Stabile]

Pixel detector: radiation damage studies [poster by L.Rossini]

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In Higgs analyses

$H \to \gamma\gamma$:

- photon energy calibration
- photon identification and background treatment
- m_H and couplings measurement
- spin measurement

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

- measurement of the missing transverse momentum (recall, τ decays to ν_τ (invisible!) + other particles)
- τ reconstruction
- CP measurement [poster by A.Murrone]

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- τ reconstruction
- CP measurement [poster by A.Murrone]

More analyses in ATLAS where Milano is involved:

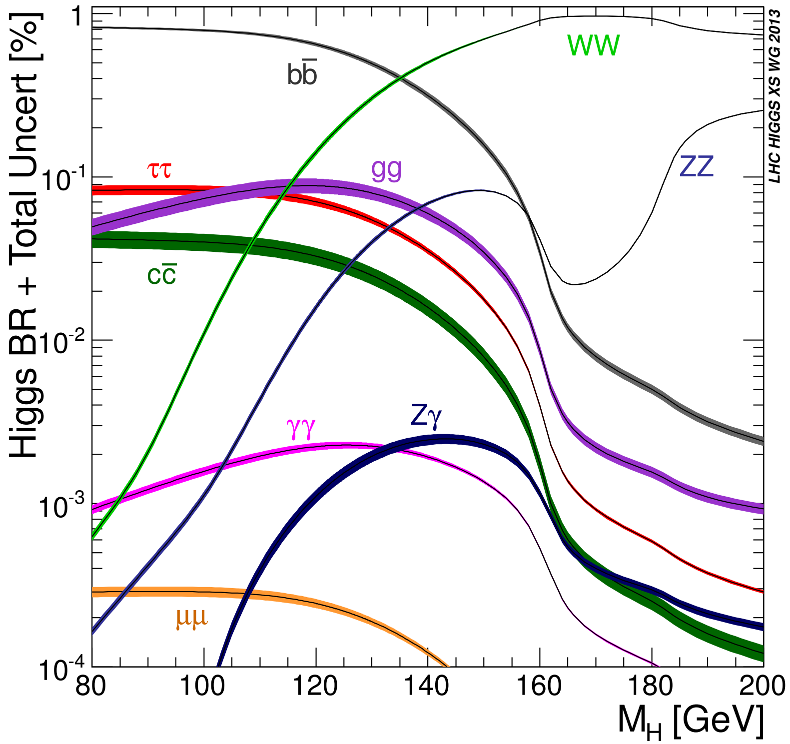
- searches for SUSY [poster by S.Carrà]
- other exotic searches, including Dark Matter [talk by D.D'Angelo]

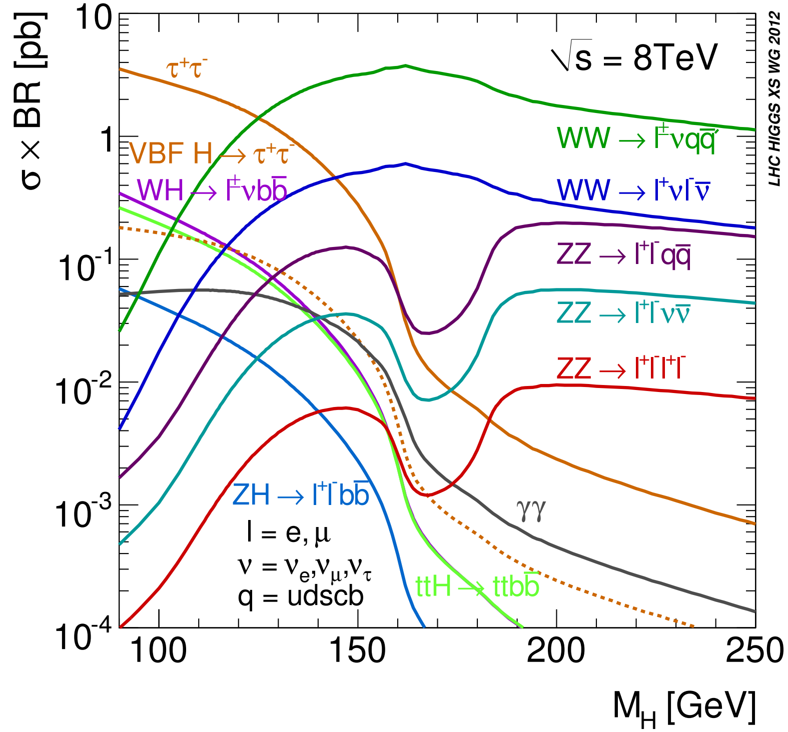
THANKS FOR YOUR ATTENTION

More Material

Decay modes of the Higgs boson

All hadronic decay modes ($H \to b\bar{b}$ and $H \to ZZ, W^+W^- \to q\bar{q}q\bar{q}$) are dominant, but overwhelmed by the QCD backgrounds! $\Rightarrow$ final states with isolated leptons, photons, missing transverse energy are the only viable



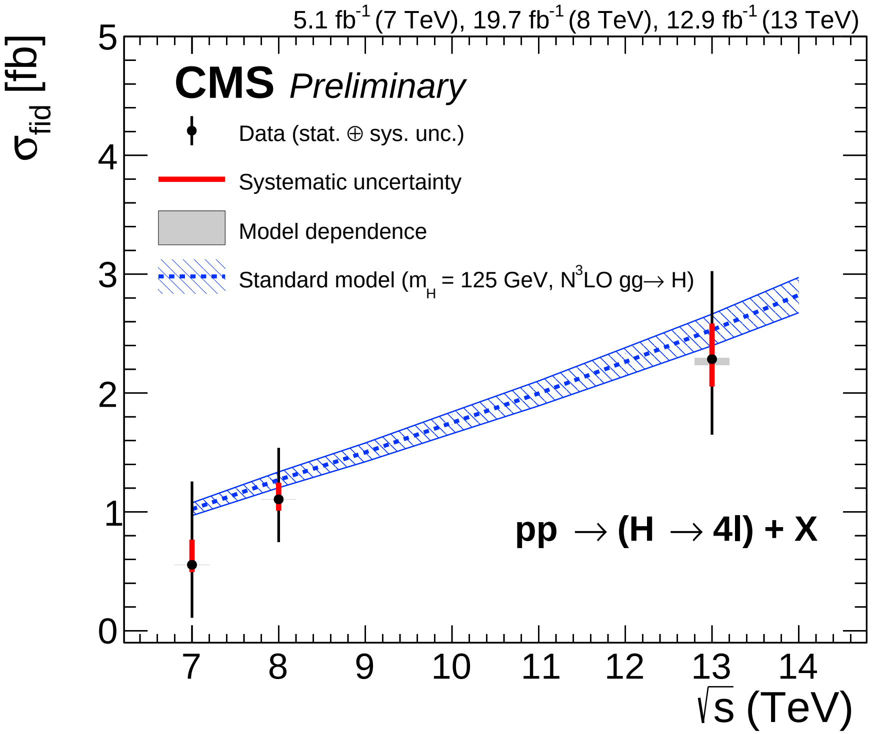


$H \to$	BR (@ $m_H = 125$ GeV)	$\sigma \cdot BR$ (fb)	events produced with 25 fb^{-1}	mass resolution	m_H range	background
$\gamma\gamma$	$2.28 \cdot 10^{-3}$	50	1250	☺☺	$\lesssim 150$ GeV	☹
$ZZ^* \to 4\ell$	$1.25 \cdot 10^{-4}$	2.7	67	☺☺	$\gtrsim 130$ GeV	☺
$WW^* \to \ell\nu\ell\nu$	$1.06 \cdot 10^{-2}$	230	5700	☹☹☹	anywhere	☹
$\tau^+\tau^-$ (VBF)	$6.32 \cdot 10^{-2}$	100	2500	☹	$\lesssim 150$ GeV	☹☹
$b\bar{b}$ (VH, $Z \to \ell^+\ell^- + W \to \ell\nu$)	$5.77 \cdot 10^{-1}$	106	2600	☹	$\lesssim 150$ GeV	☹☹

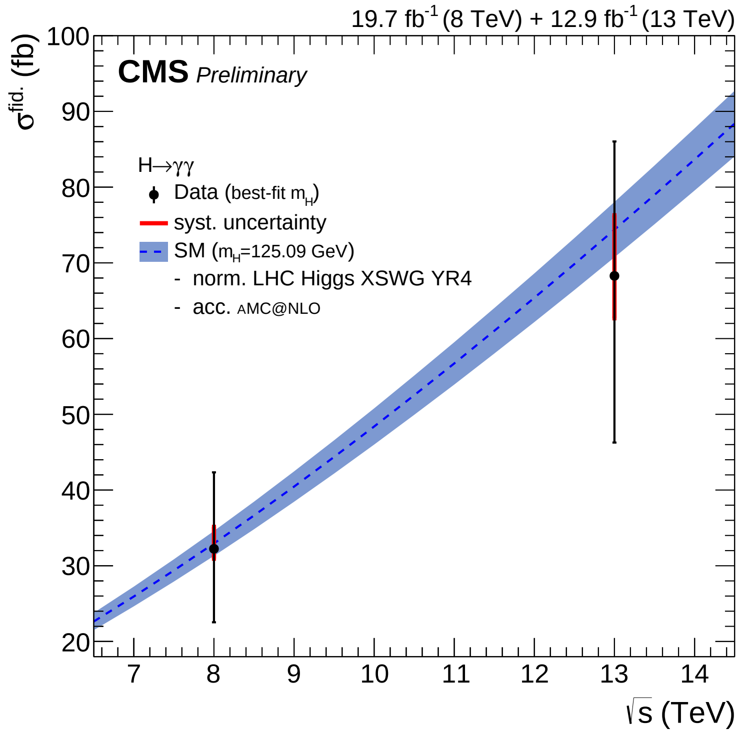
Cross-section by CMS

Fiducial cross-section vs $\sqrt{s}$

$H \to 4\ell$

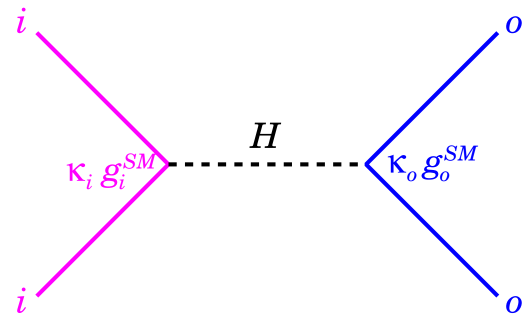


$H \to \gamma\gamma$



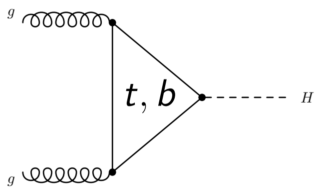
Couplings: the κ-framework

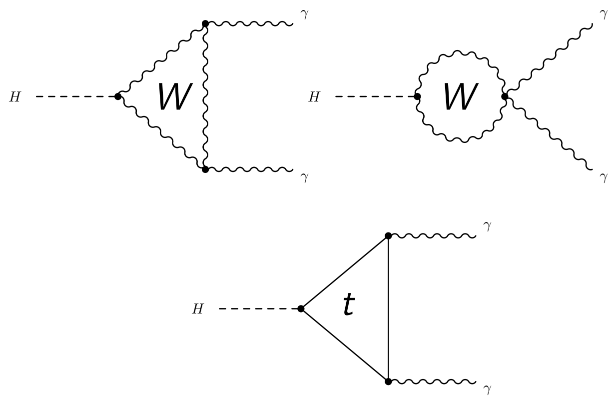
Reminder: in SM Higgs couplings are $g_f^{SM} = \frac{m_f}{v}$ and $g_V^{SM} = 2\frac{m_V^2}{v}$



Couplings are accessible through production ($ii \to H$) and decay ($H \to oo$)
Define "couplings modifiers" $\kappa_x = \frac{g_x}{g_x^{SM}}$
(compatibility with SM $\Longleftrightarrow \kappa \approx 1$)

$\Rightarrow$ Several couplings: $\kappa_\mu,\ \kappa_\tau,\ \kappa_b,\ \kappa_W,\ \kappa_Z,\ \kappa_t$ and two effective couplings: $\kappa_g,\ \kappa_\gamma$



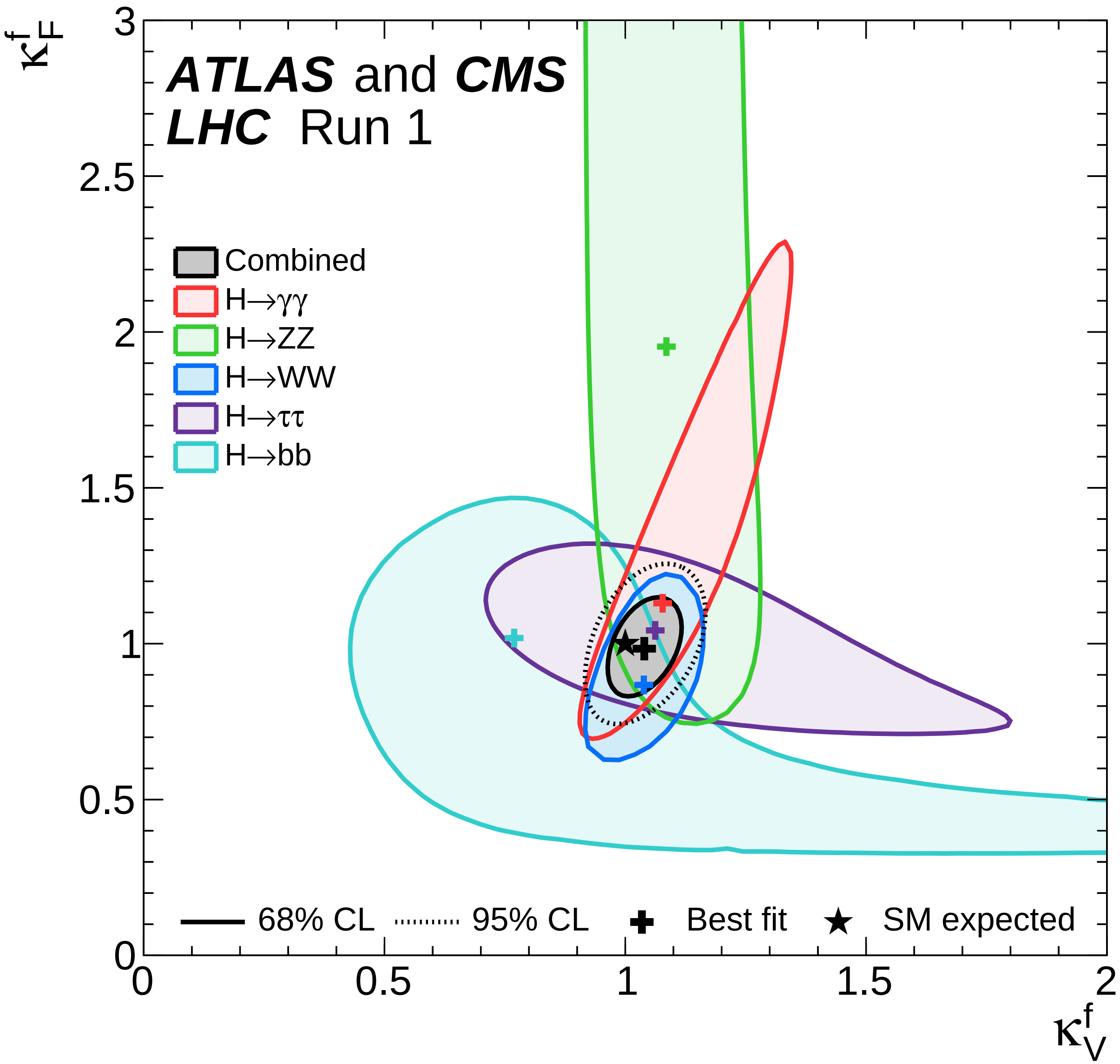


$gg \to H$ (mainly) through top/bottom virtual loop
$\Rightarrow \kappa_g$ depends on $\kappa_t,\ \kappa_b$

$H \to \gamma\gamma$ through top/bottom and W virtual loops
$\Rightarrow \kappa_\gamma$ depends on $\kappa_t,\ \kappa_b,\ \kappa_W$

(Universal) couplings to fermions and weak bosons

Assume weak gauge boson universality: $\kappa_W, \kappa_Z = \kappa_V$ and fermion universality: $\kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu = \kappa_f$



Exploit final state topologies (e.g. VBF, VH)

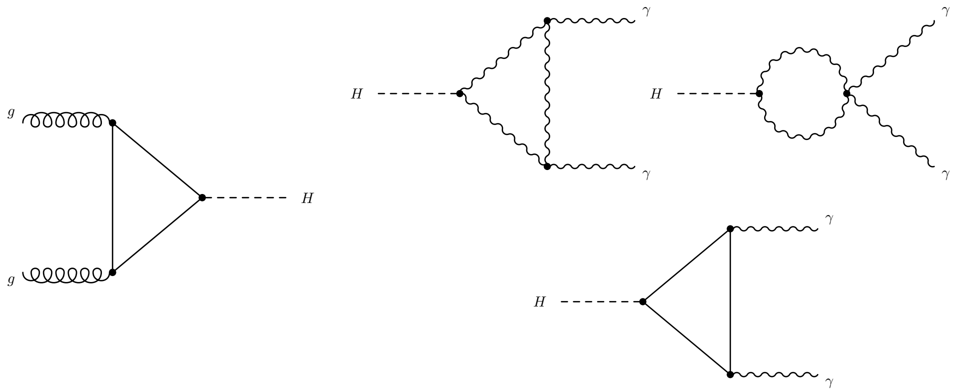
⇒ measure κ_V, κ_f for each decay channel

⇒ then combine decay channels

⇒ all measurements compatible with SM prediction (★)

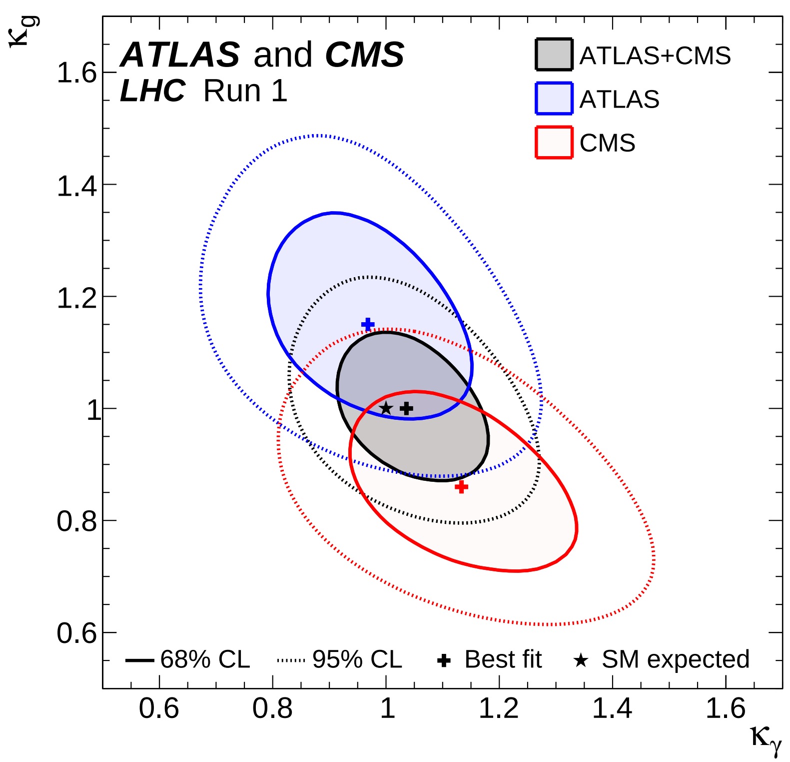
$$(\kappa_V = 1, \ \kappa_f = 1)$$

Testing the ggH and $H\gamma\gamma$ interactions



ggH and $H\gamma\gamma$ interactions in SM are mediated by loops

$\Rightarrow$ particularly sensitive to new particles in the loops

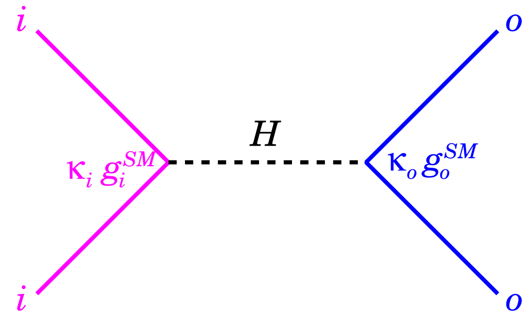


$\Rightarrow$ consider κ_g, κ_γ as free and profile others

$\Rightarrow$ again, compatibility with SM (★)

Couplings: the κ-framework

Reminder: in SM Higgs couplings are $g_f^{SM} = \frac{m_f}{v}$ and $g_V^{SM} = 2\frac{m_V^2}{v}$ and $\sigma^{SM}_{ii\to H\to oo} \propto \frac{\Gamma_{ii}\Gamma_{oo}}{\Gamma_H}$



Couplings are accessible through production ($ii \to H$) and decay ($H \to oo$)

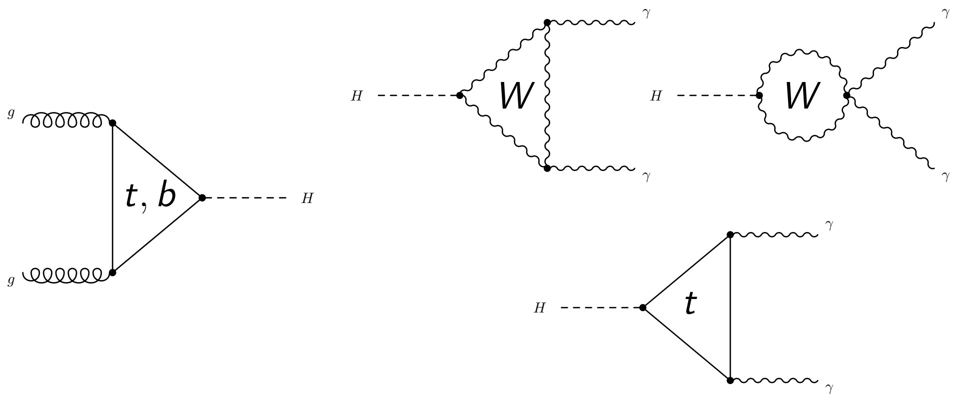
Define "couplings modifiers" $\kappa_x = \frac{g_x}{g_x^{SM}}$ and $\kappa_H^2 \stackrel{\text{def}}{=} \frac{\Gamma_H}{\Gamma_H^{SM}}$

$$\Rightarrow \sigma_{ii\to H\to oo} = \sigma^{SM}_{ii\to H\to oo} \times \frac{\kappa_i^2\,\kappa_o^2}{\kappa_H^2}$$

If no decays beyond Standard Model (BSM), $\Gamma_H = \sum_{o\in\{SM\}} \Gamma_{H\to oo} = \sum_{o\in\{SM\}} \kappa_o^2 \Gamma^{SM}_{H\to oo} \Rightarrow \kappa_H^2 = \sum_{o\in\{SM\}} \kappa_o^2 BR^{SM}_{H\to oo}$

$\Rightarrow$ Several couplings: $\kappa_\mu,\ \kappa_\tau,\ \kappa_b,\ \kappa_W,\ \kappa_Z,\ \kappa_t$ and two effective couplings: $\kappa_g,\ \kappa_\gamma$

Assume weak gauge boson universality: $\kappa_W, \kappa_Z = \kappa_V$ and fermion universality: $\kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu = \kappa_f$



If loop-mediated interactions occur as in SM:

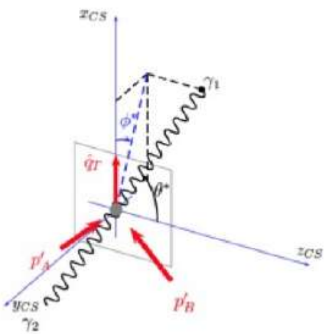
$gg \to H$ (mainly) through top/bottom virtual loop
$\Rightarrow \kappa_g = \kappa_{t,b} = \kappa_f$

$H \to \gamma\gamma$ through top and W virtual loops
$\Rightarrow \kappa_\gamma^2 = (1.26\,\kappa_W - 0.26\,\kappa_t)^2 = (1.26\,\kappa_V - 0.26\,\kappa_f)^2$

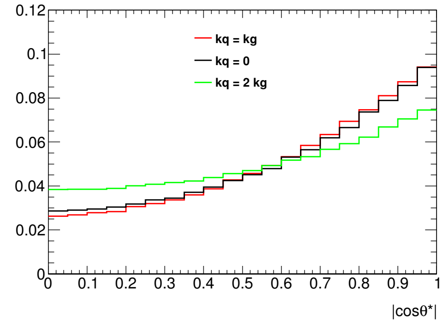
... and $\kappa_H^2 = 0.75\,\kappa_f^2 + 0.25\,\kappa_V^2$ — computed using $BR^{SM}_{H\to oo}$ @ $m_H = 125$ GeV

Spin

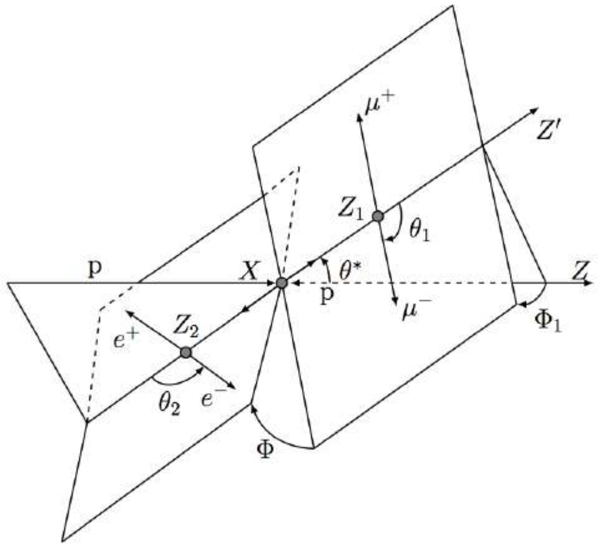
$H \to \gamma\gamma$: flat $|\cos\theta^*|$ for spin-0, sensitive to spin-2



spin 2



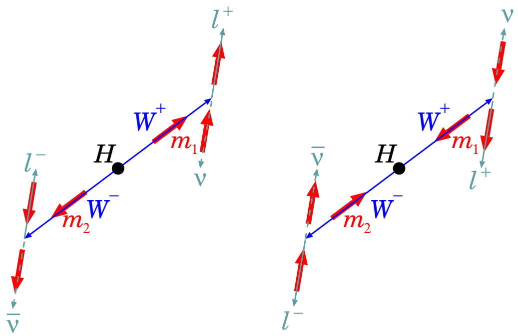
$H \to ZZ^* \to 4\ell$:

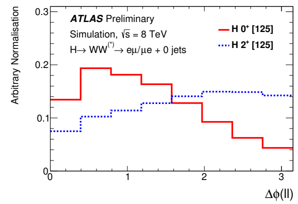


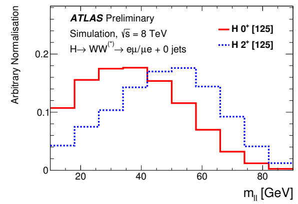
5 angular observables + m_{12}, m_{34}
can probe polarization of both H and Zs
sensitive to spin and parity

$H \to WW^* \to \ell\nu\ell\nu$: W^+/W^- spin correlation

spin 0







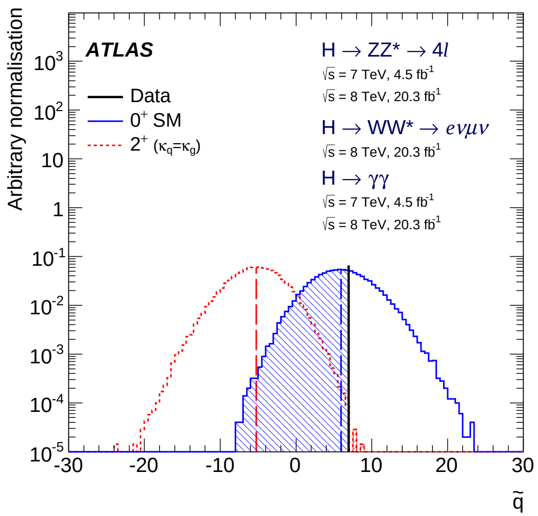
sensitive to spin and parity

Spin-2 tests

effective lagrangian [HiggsCharacterization]

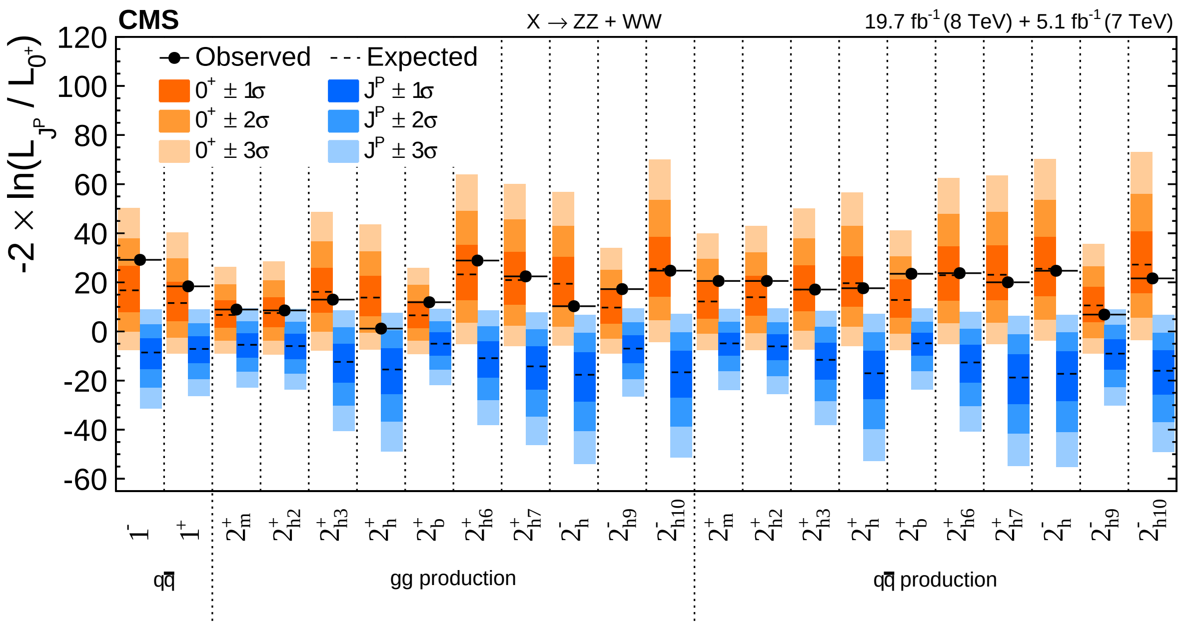
$$\mathcal{L}_2 = \frac{1}{\Lambda}\left[\sum_V \kappa_V X^{\mu\nu} T^V_{\mu\nu} + \sum_f \kappa_f X^{\mu\nu} T^f_{\mu\nu}\right]$$

[below, $\tilde{q} \equiv -2\ln\left(\frac{L_{J^P}}{L_{0+}}\right)$]



effective transition amplitude [JHU]

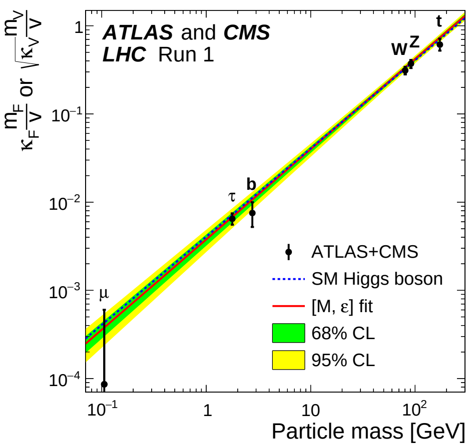
$$A(X_{J=2}VV) \sim \Lambda^{-1}\Big[2c_1^{VV} t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2^{VV} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta}$$
$$+ c_3^{VV} t_{\beta\nu} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2}\left(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}\right) + c_4^{VV} t_{\mu\nu} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} f^{*1,\alpha\beta} f^{*2}_{\alpha\beta}$$
$$+ m_V^2\left(2c_5^{VV} t_{\mu\nu} \epsilon^{*\mu}_{V1}\epsilon^{*\nu}_{V2} + 2c_6^{VV} t_{\mu\nu} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2}\left(\epsilon^{*\nu}_{V1}\epsilon^{*\alpha}_{V2} - \epsilon^{*\alpha}_{V1}\epsilon^{*\nu}_{V2}\right) + c_7^{VV} t_{\mu\nu} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} \epsilon^*_{V1}\epsilon^*_{V2}\right)$$
$$+ c_8^{VV} t_{\mu\nu} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} f^{*1,\alpha\beta} \tilde{f}^{*2}_{\alpha\beta}$$
$$+ m_V^2\left(c_9^{VV} t^{\mu\alpha} \frac{\tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}_{V1}\epsilon^{*\rho}_{V2} q^\sigma}{\Lambda^2} + c_{10}^{VV} t^{\mu\alpha} \frac{\tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon^{*\nu}_{V1}(q\epsilon^*_{V2}) + \epsilon^{*\nu}_{V2}(q\epsilon^*_{V1})\right)}{\Lambda^4}\right)\Big]$$

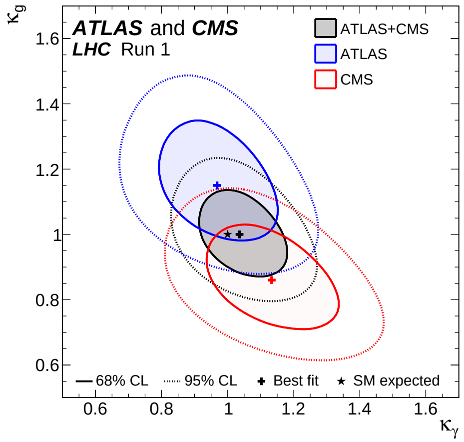


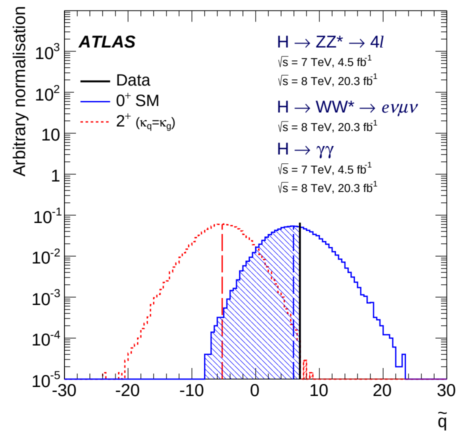
⇒ **data favour spin-0**

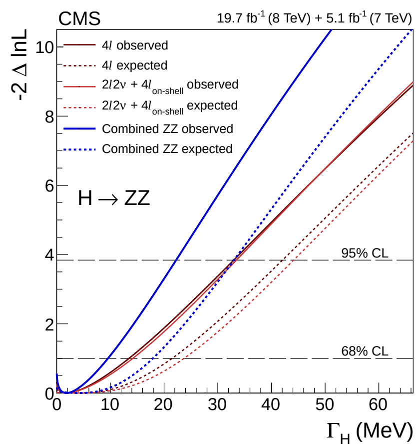
Conclusions

Run-I analyses well mature, ATLAS+CMS combined results available for mass and couplings:

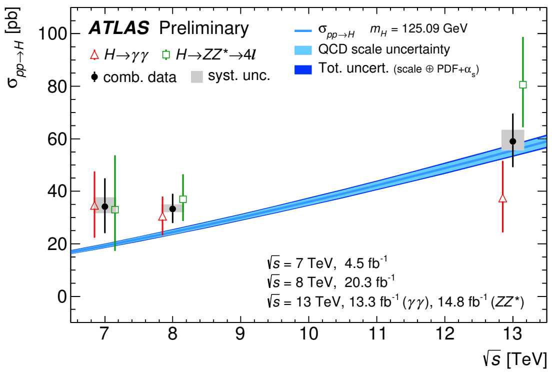


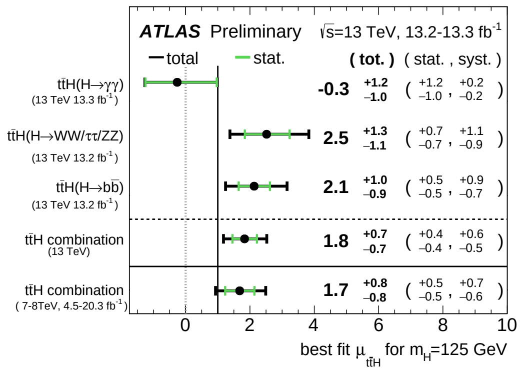


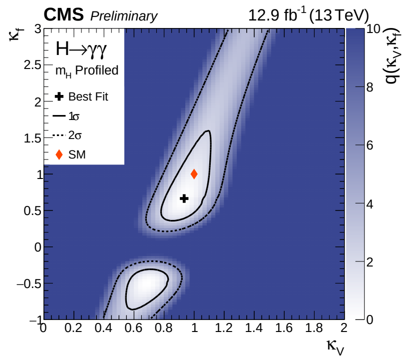


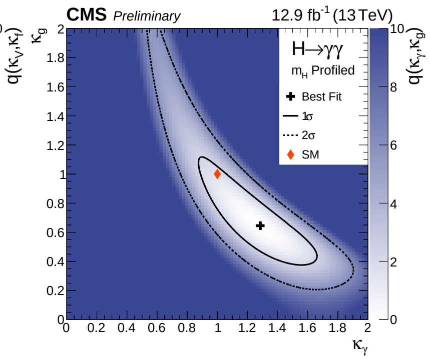


Run-II: efficient data-taking, analyses progressing fast, (cross-section)×(luminosity) already beated Run-I





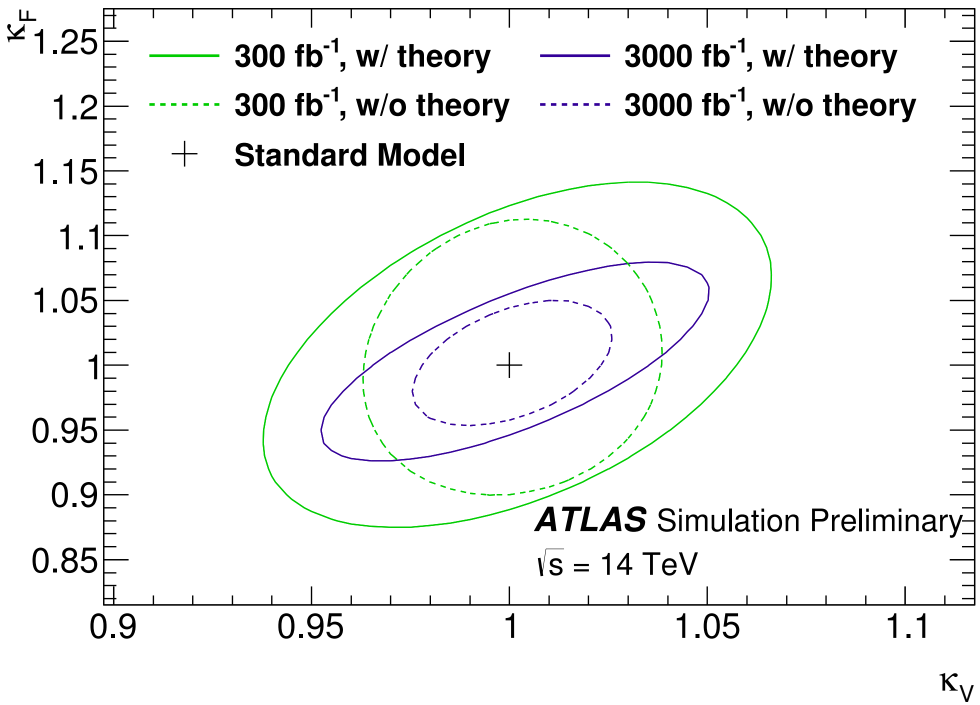


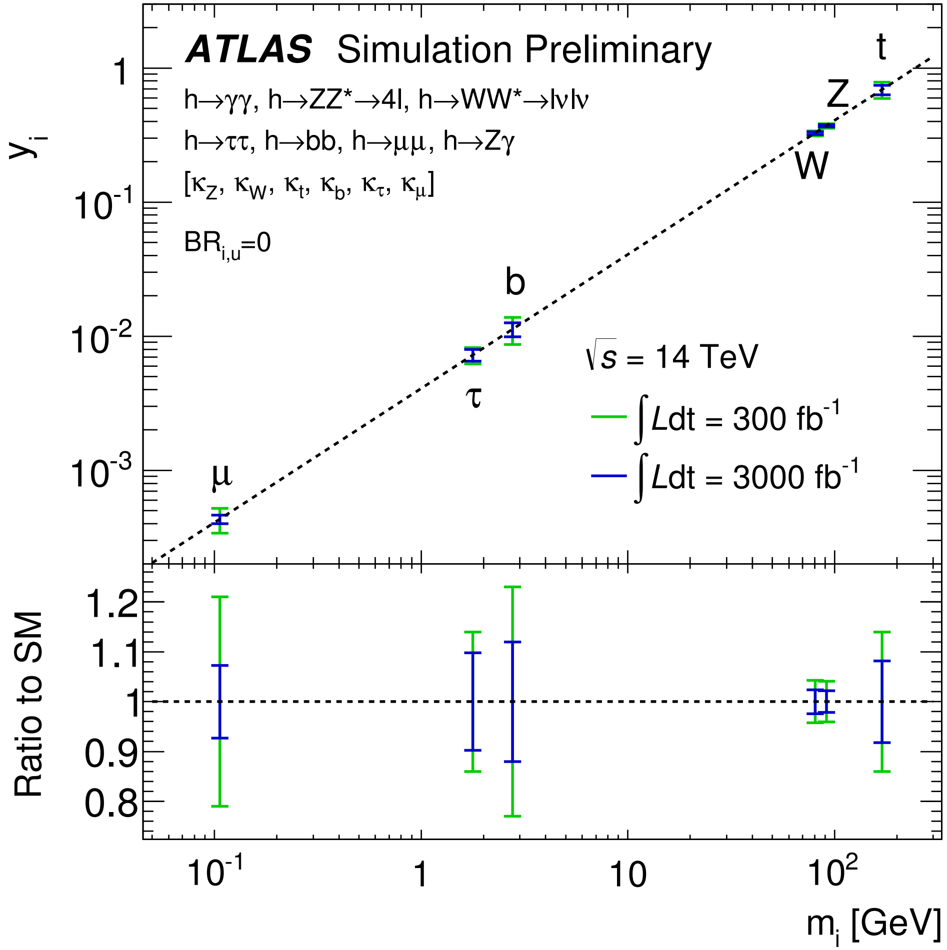


⇒ We are still compatible with Standard Model prediction . . . but uncertainties are still large.

Theory uncertainties improved a lot. Important to pursue precision measurements in the Higgs sector, in Run-II and beyond, to investigate possible deviations from SM

Prospects . . .





Some "educated guesses" — With 300 fb^{-1}at 13 TeV:

Precise measurements of $H \to \tau^+\tau^-$, observation of $H \to b\bar{b}$, evidence of $t\bar{t}H$ production

Evidence of $H \to \mu^+\mu^-$, precision measurements of all individual κ's to $\lesssim$ 10% accuracy