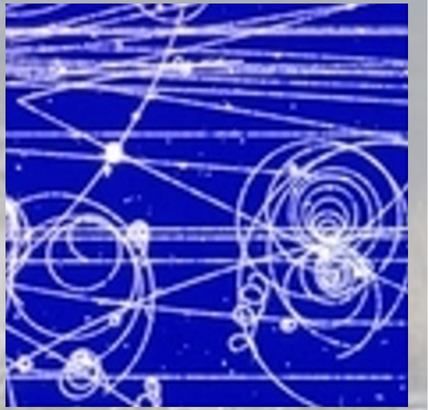
The 10 years of Higgs physics and other major milestones at the LHC

XLIX International Meeting on Fundamental Physics

Benasque

6 – 9 September 2022

Aleandro Nisati



Index

- The Large Hadron Collider, the ATLAS and CMS experiments
- The Standard Model Higgs boson
- Short history of Higgs boson discovery at the LHC
- Higgs boson couplings and properties
- Higgs selfcoupling
- BSM Higgs boson searches
- Higgs Prospects at the High-Luminosity LHC

- Connections to precision top and W mass measurements, searches for Vector Boson Scattering and Dark Matter

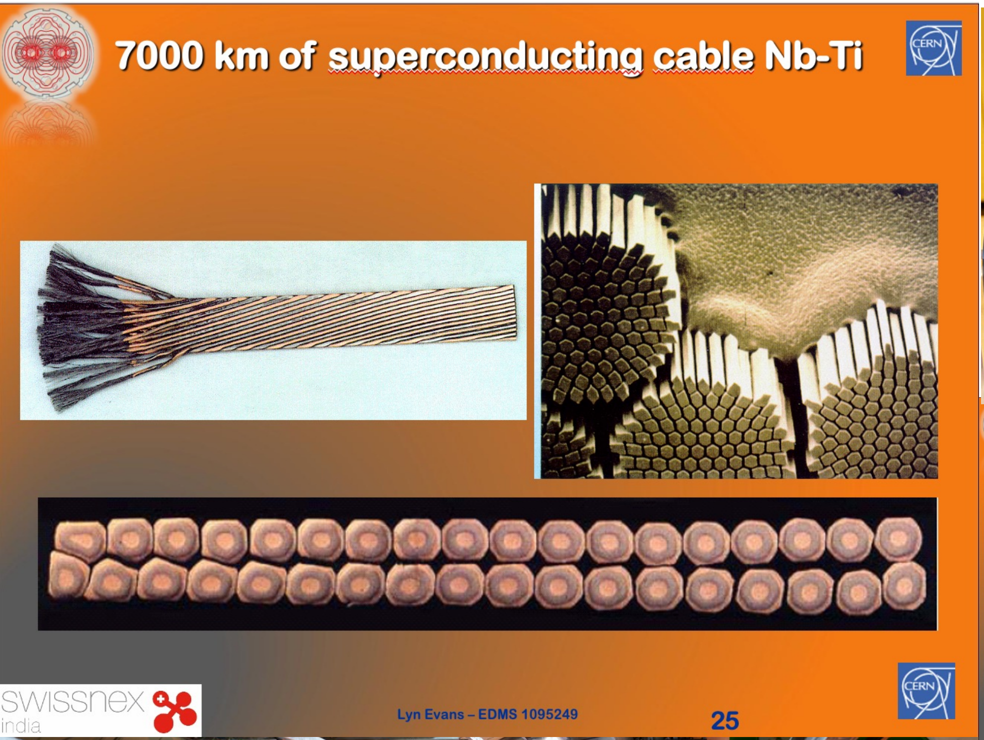
Index

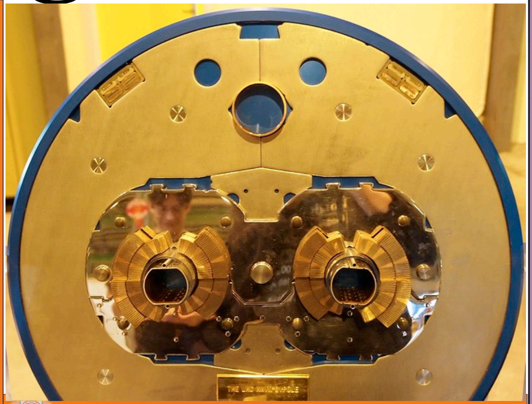
- The Large Hadron Collider, the ATLAS and CMS experiments
- The Standard Model Higgs boson
- Short history of Higgs boson discovery at the LHC
- Higgs boson couplings and properties
- Higgs selfcoupling
- BSM Higgs boson searches
- Higgs Prospects at the High-Luminosity LHC

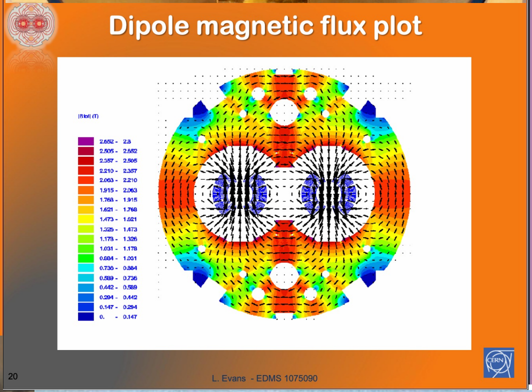
- Connections to precision top and W mass measurements, searches for Vector Boson Scattering and Dark Matter

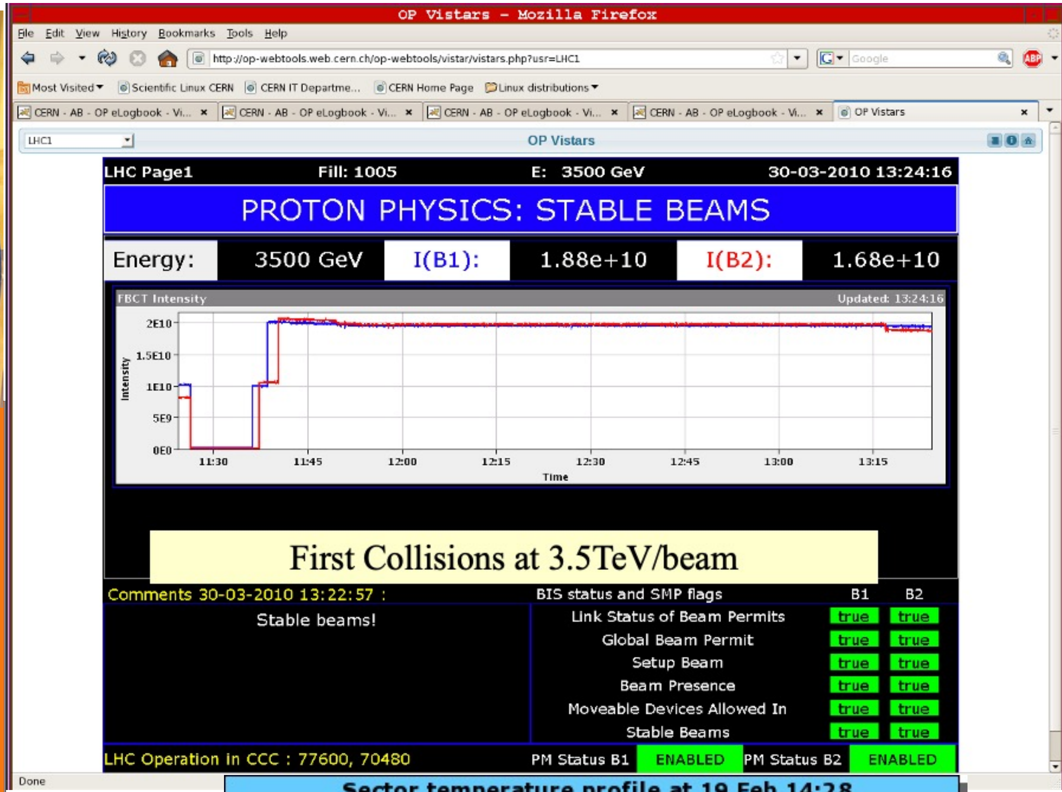
The world's eight marvel…

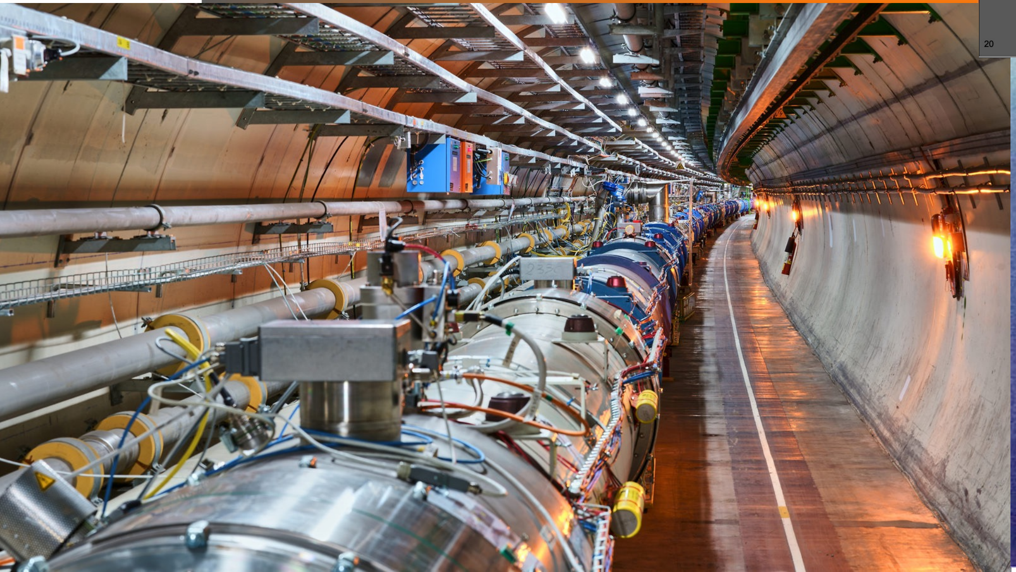
The Large Hadron Collider

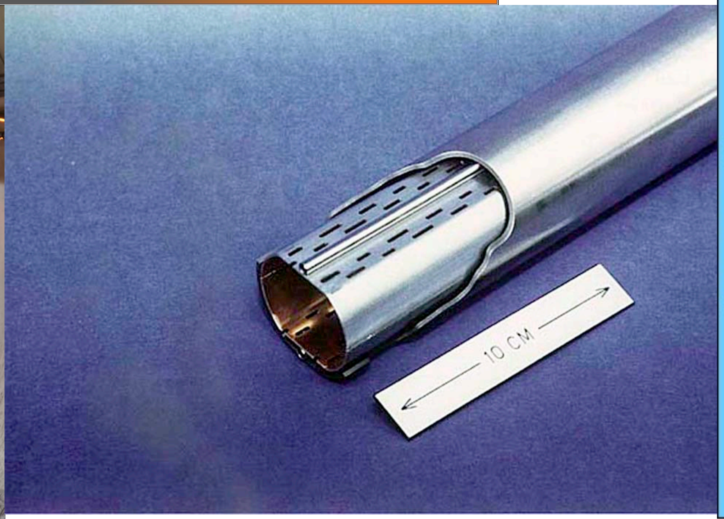


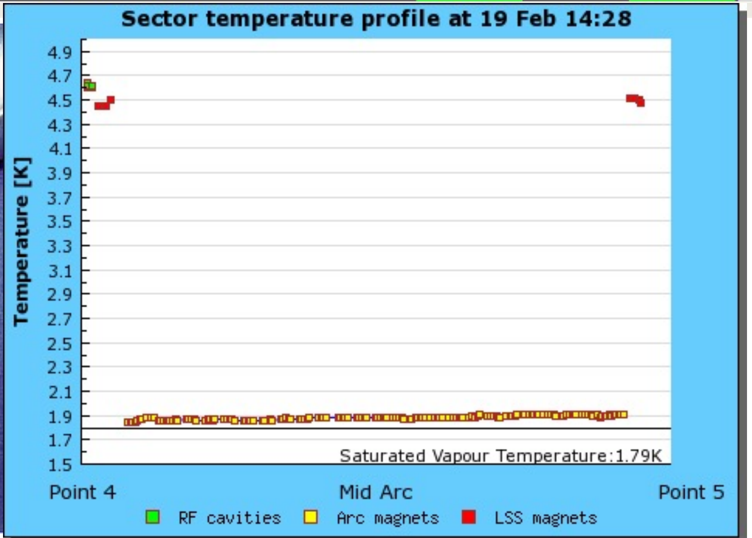












The world's eight marvel

parameter	value
(design) CM energy	**14 TeV**
Luminosity	**10^{34} cm^{-2} s^{-1}**
Bunch crossing spacing	**24.95 ns**
Protons per bunch	**1.15×10^{11}**
Beam radius	**16.7 μm**
Main Dipoles	**1232**
Dipole field	**8.33 T**
Smaller magnets	**7000**
Stored energy	**360 MJ/beam**

LHC: Some of the Technical Challenges

Circumference (km)	26.7	100-150m underground
Number of Dipoles	1232	Cable Nb-Ti, cold mass 37million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K)	1.9	Superconducting magnets needed for the high magnetic field Super-fluid helium
Current in dipole sc coils (A)	13000	Results from the high magnetic field 1ppm resolution
Beam Intensity (A)	0.5	2.2.10^{-6} loss causes quench
Beam Stored Energy (MJoules)	362	Results from high beam energy and high beam current 1MJ melts 2kg Cu
Magnet Stored Energy (MJoules)/octant	1100	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits

June 4, 2012 PLHC Vancouver S. Myers 5

The world's eight marvel

Table 1: Beam and machine parameters for collisions in 2012, 2016, 2017 and 2018 compared to the design.

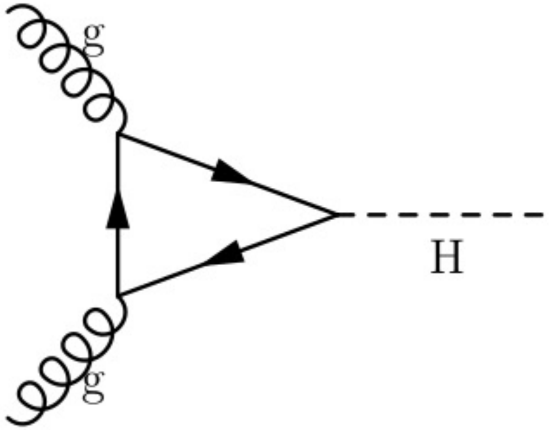
Parameter	Design	2012	2016	2017	2018
beam energy [TeV]	7	4	6.5	6.5	6.5
bunch spacing [ns]	25	50	25	25	25
β^* CMS/ATLAS [cm]	55	60	40	40 / 30	30 - 25
crossing angle [μrad]	285	290	370 / 280	300 - 240	320 - 260
bunch population N [10^{11} ppb]	1.15	1.65	1.1	1.15	1.15
normalized emittance ε [μm]	3.75	2.5	2.2	2.2	2.0
number of bunches per ring k	2808	1374	2220	2556	2556
peak luminosity L [10^{34} cm^{-2}s^{-1}]	1	0.75	1.4	2.05	2.01
peak average event pile-up μ	~ 20	~ 35	~ 50	~ 55	~ 60
peak stored energy [MJ]	360	145	270	320	340

by J. Wenninger **LHC Status and Performance**

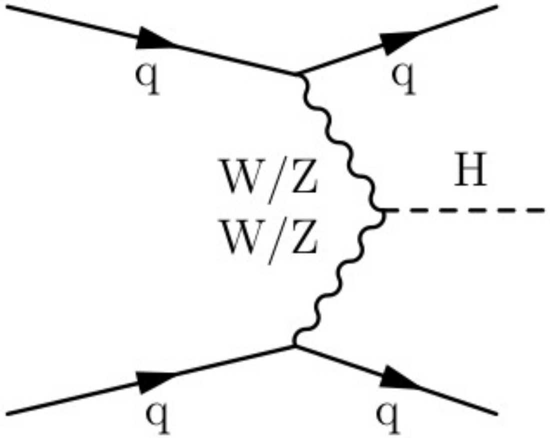
The Standard Model Higgs boson production and decays

Higgs boson production processes at hadron colliders

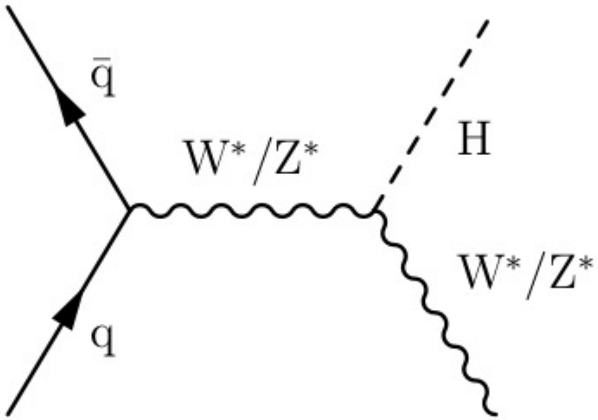
main processes



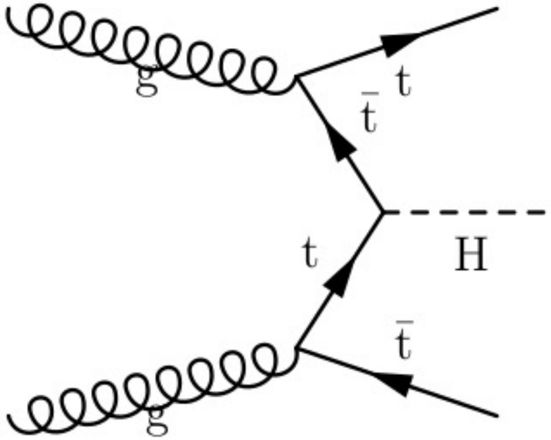
(a) Gluon Fusion



(b) Vector Boson Fusion



(c) Associated Production W/Z



(d) Associated Heavy Quark Production

production cross section in proton-proton collisions

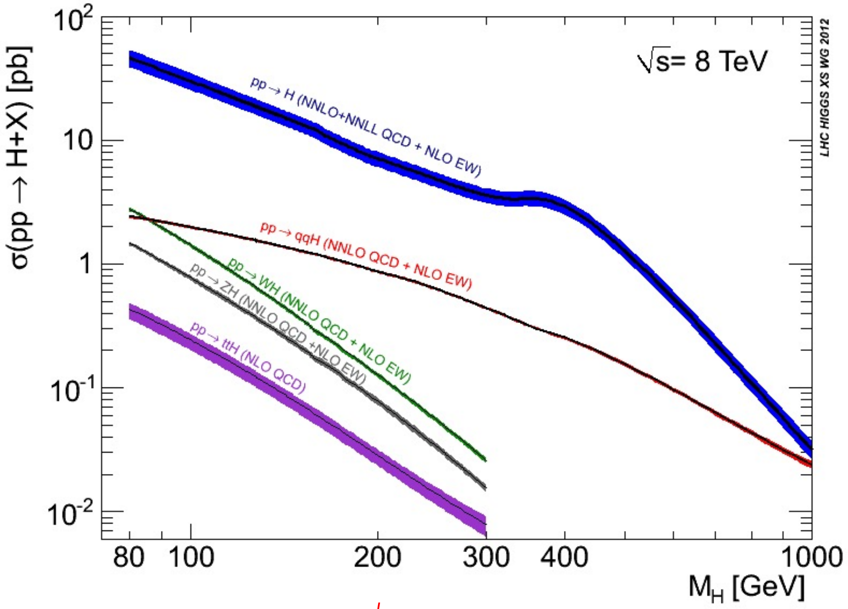
ggF: cross sections are calculated at N^3LO QCD and NLO EW accuracies

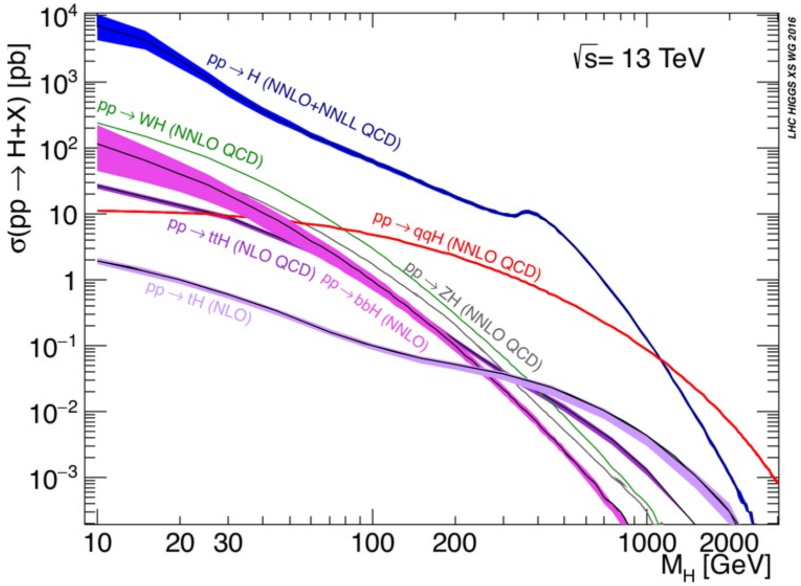
VBF: cross sections are calculated at (approx.) NNLO QCD and NLO EW accuracies

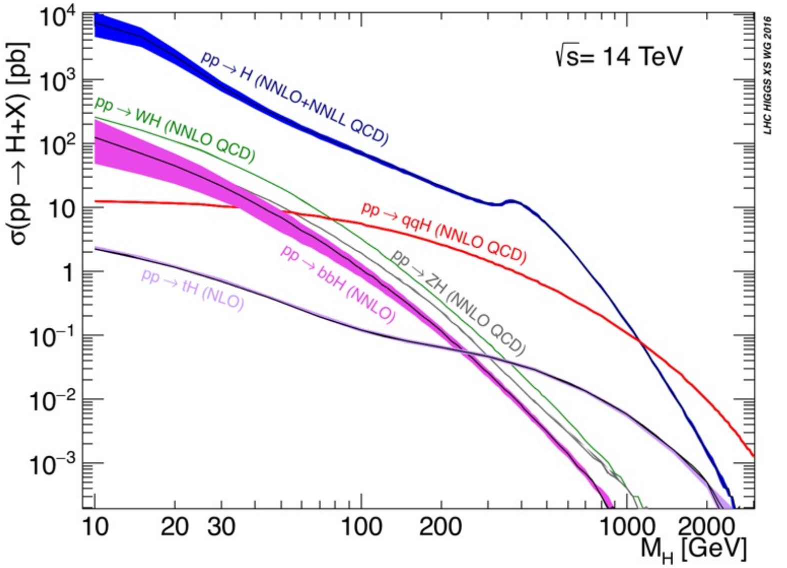
VH: cross sections are calculated at NNLO QCD and NLO EW accuracies

ttH: cross sections are calculated at NLO QCD and NLO EW accuracies

LHC Higgs Cross section WG







√s= 8 TeV **√s= 13 TeV** **√s= 14 TeV**

assuming m_H = 125 GeV and L = 10 fb^{-1}

√s= 8 TeV

σ_{ggF} = 21.42 pb, **214×10³ events**

σ_{VBF} = 1.60 pb, **16×10³ events**

σ_{VH} = 0.064 pb, **0.6×10³ events**

σ_{ttH} = 0.133 pb, **1.3×10³ events**

√s= 13 TeV

σ_{ggF} = 48.58 pb, **486×10³ events**

σ_{VBF} = 3.78 pb, **38×10³ events**

σ_{VH} = 0.124 pb, **1.2×10³ events**

σ_{ttH} = 0.507 pb, **5.1×10³ events**

At √s= 14 TeV cross sections are ~ 10% higher, 20% for ttH

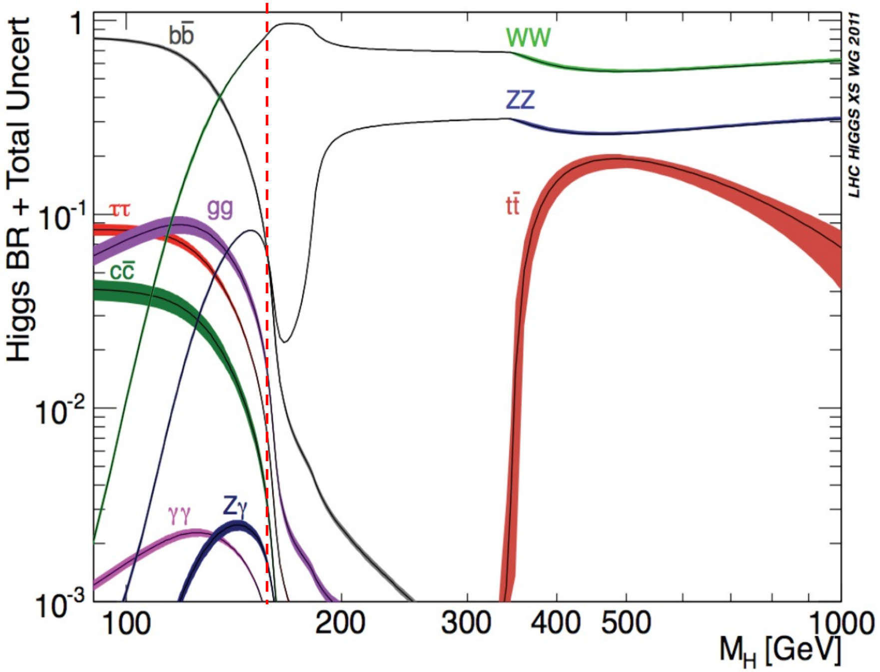
Overall theory uncertainties:

ggF and ttH: ~ +7 −10%

VBF and VH: ~ ±3%

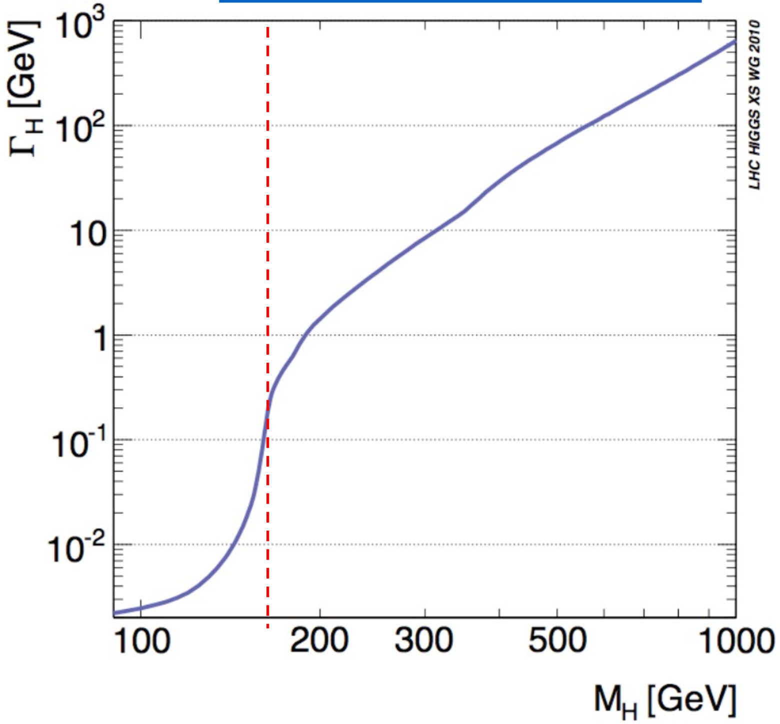
Standard Model Higgs boson decays

LHC Higgs Cross section WG



The Higgs boson branching fractions as a function of the mass

LHC Higgs Cross section WG



The Higgs boson natural width as a function of the mass

125 GeV Higgs Branching fractions:

H→bb: 58.2%
H→$\tau\tau$: 6.27%
H→$\gamma\gamma$: 0.227%
H→WW*: 2.14%
H→ZZ*: 2.62%
H→$\mu\mu$: 0.022%

Remember that:
BR Z→ $\mu\mu$/ee: 3.3632%

BR H→ZZ*→4l(l=e or μ): 0.012%

Total width for m_H = 125 GeV:
4.129 MeV

production cross section in proton-proton collisions

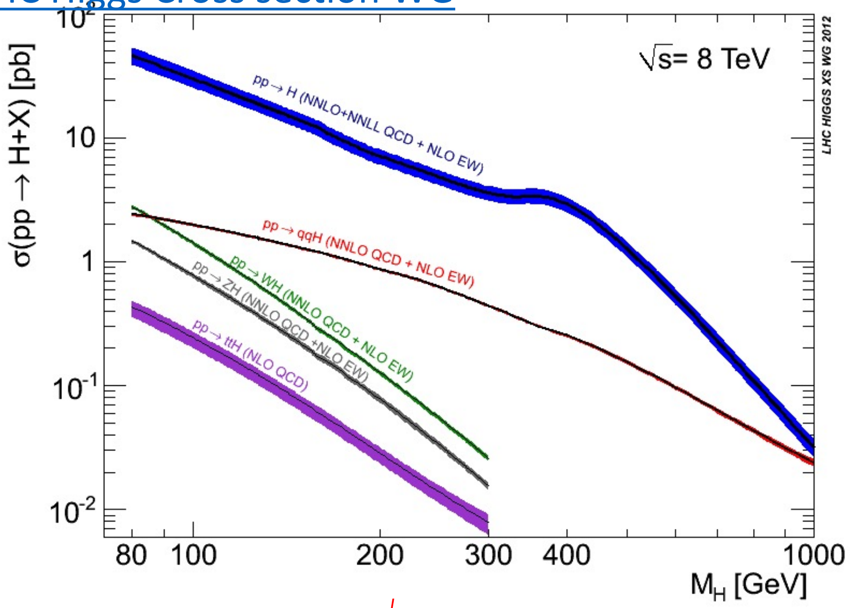
ggF: cross sections are calculated at N^3LO QCD and NLO EW accuracies

VBF: cross sections are calculated at (approx.) NNLO QCD and NLO EW accuracies

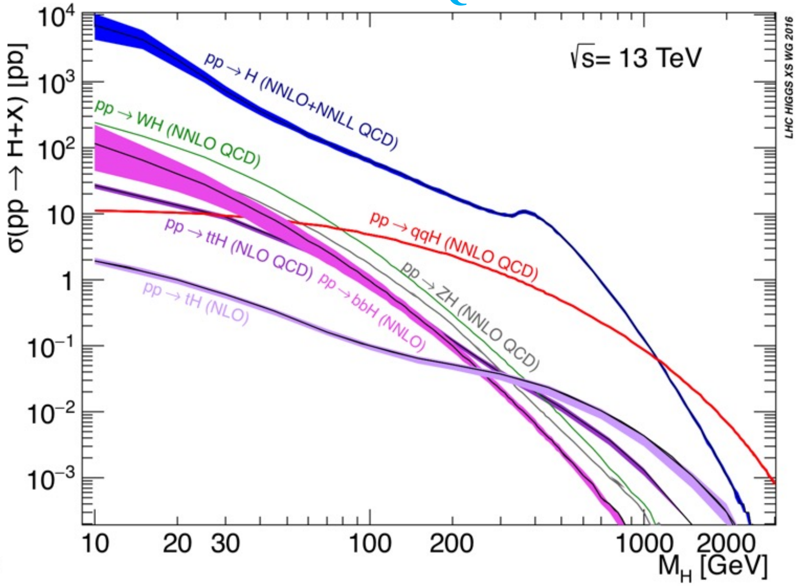
VH: cross sections are calculated at NNLO QCD and NLO EW accuracies

ttH: cross sections are calculated at NLO QCD and NLO EW accuracies

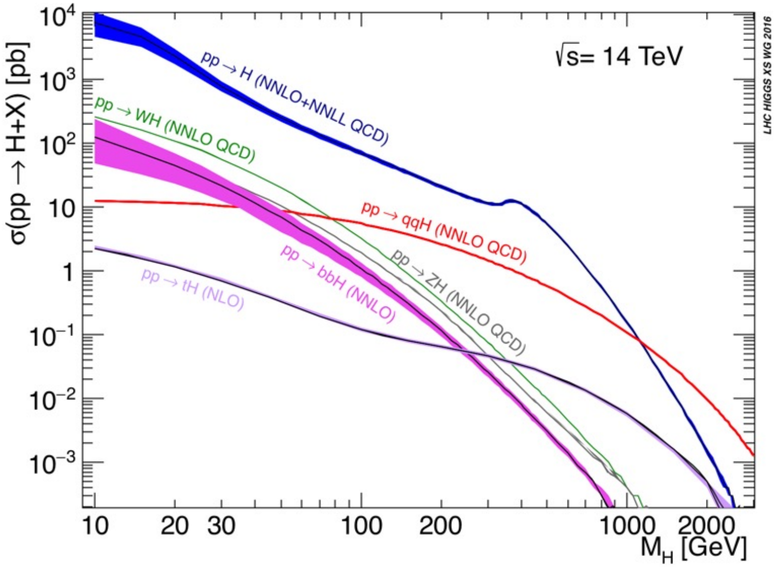
LHC Higgs Cross section WG



√s= 8 TeV



√s= 13 TeV



√s= 14 TeV

L=10 fb^{-1}	$H \rightarrow \gamma\gamma$		$H \rightarrow ZZ^* \rightarrow 4l$		$H \rightarrow \tau\tau$	
	8 TeV	13 TeV	8 TeV	13 TeV	8 TeV	13 TeV
ggF	442	1002	26	58	13400	30500
VBF	36	86	2	5	1000	2380
ttH	3	12	0.2	0.6	82	320

At √s= 14 TeV cross sections are ~ 10% higher, 20% for ttH

Overall theory uncertainties:

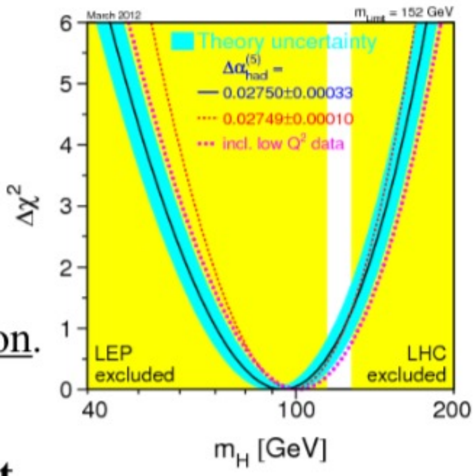
ggF and ttH: ~ +7 −10%

VBF and VH: ~ ±3%

Theory Inputs to Experimental Measurements and the LHC Higgs Working Group

By R. Tanaka, 10 years Higgs Boson Discovery, CERN 4 July 2022

LEP Electroweak Working Group



Preamble

- In late 2000's, a bunch of people had an idea to form TH+ATLAS+CMS forum for Higgs boson precision physics (discussions initiated by G. Passarino).
  - The Higgs boson discovery could happen earlier than expected if light Higgs boson.
  - Many theoretical progresses on Higgs physics before LHC start.
  - **Interactions between TH and EXPs for common language are very important.**
- Access to the most advanced theory predictions for Higgs Cross Sections and Branching Ratios
  - Experiments will coherently use the common XS&BR's based on the interaction with the TH community.
  - This will facilitate the comparison and the combination of the individual results. (LHC Higgs Combination Group was created later.)
  - In case of a deviation from SM prediction, precise theoretical prediction are mandatory.
- The LHC Higgs Cross Section Working Group was created in January 2010.
  - Pre-foundation meeting was held in Torino during 23-24, November, 2009 - the 1st LHC collision day !
  - The first coordinators: S. Dittmaier (TH), C. Mariotti (CMS), G. Passarino (TH), R. Tanaka (ATLAS)

LHC Higgs Cross Section Working Group

WG1: Higgs XS&BR
WG2: Higgs Properties
WG3: BSM Higgs

Annual meetings at Freiburg, Bari, BNL, LAL and CERN

Important interaction with:

- PDF4LHC, MCNet
- LHC Higgs Combination WG
- LHC EW/Top Physics WG
- LHC Effective Field Theory WG

LHC Higgs XS WG CERN Reports

Handbook of LHC Higgs Cross Sections:

1. Inclusive Observables (CERN-2011-002, 151 pp.)
2. Differential Distributions (CERN-2012-002, 275 pp.) ← July 4th 2012 Higgs boson Discovery
3. Higgs Properties (CERN-2013-004, 392 pp.)
4. Deciphering the nature of the Higgs sector (CERN-2017-002-M, 869 pp.)

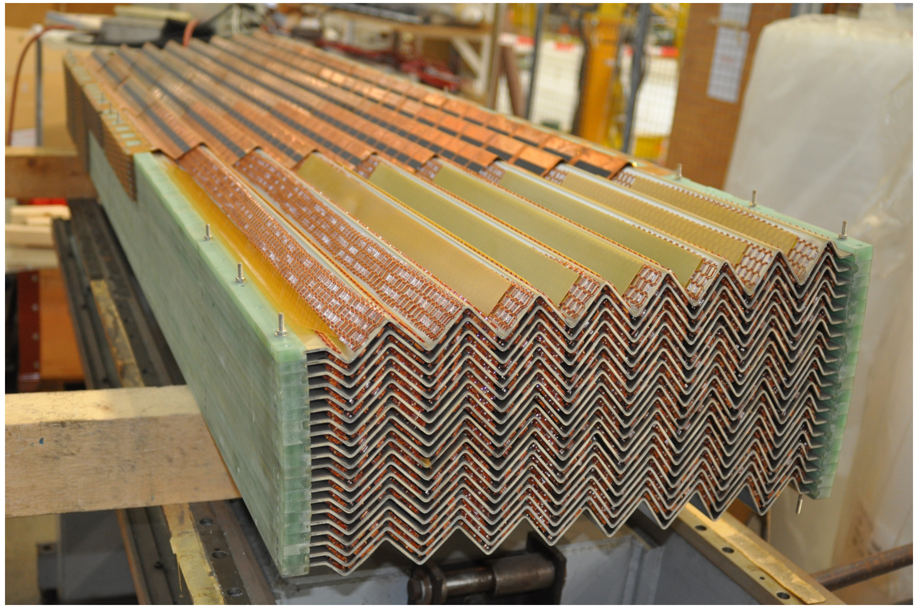
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG

The design of ATLAS and CMS at the LHC

The two gold channels: $H \rightarrow \gamma\gamma$ …

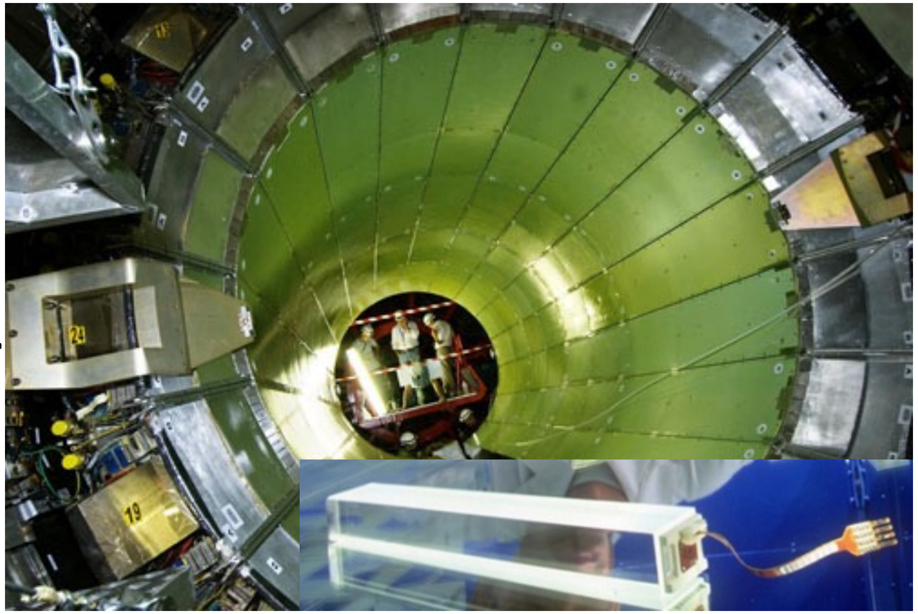
- Two isolated high-p_T photons in the final state
- Large irreducible and reducible background (SM $\gamma\gamma$ production, and fake γ from jets)
- Large event pileup
- Safe $\gamma\gamma$ vertex reconstruction and identification
- Narrow $\gamma\gamma$ invariant mass peak

- High granularity electromagnetic calorimeter
- High enery-resolution electromagnetic calorimeter
- Safe photon identification
- Highly segmented hadron calorimeter
- Possibly measurement of the photon direction of flight
- High precision inner tracking and vertexing



ATLAS: a module of the LAr e.m. calorimeter (the “accordion”)

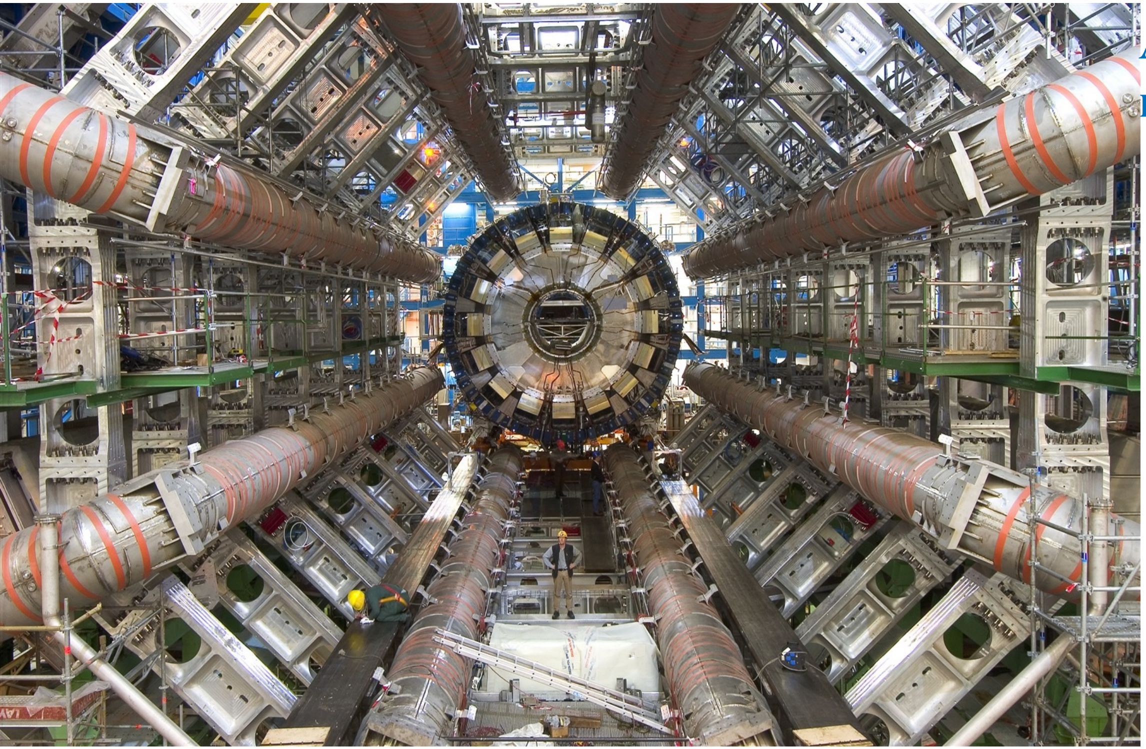
CMS: the barrel e.m. calorimeter and a lead tungstate crystal



The two gold channels: … and the H→ZZ(*)→4 leptons

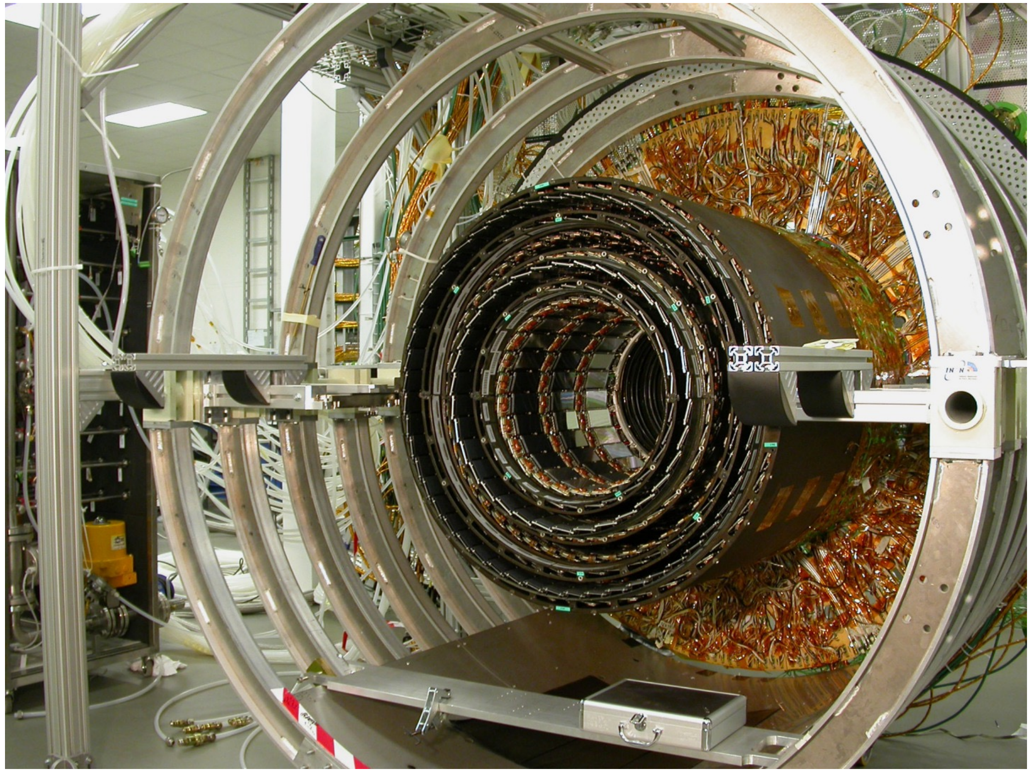
- Four isolated high-p_T leptons (electrons or muons) associated to the pp collision point
- Large event pileup
- Narrow 4-lepton invariant mass peak

- High precision reconstruction of muons electromagnetic calorimeter
- Safe muon and electron identification
- High precision inner tracking and vertexing

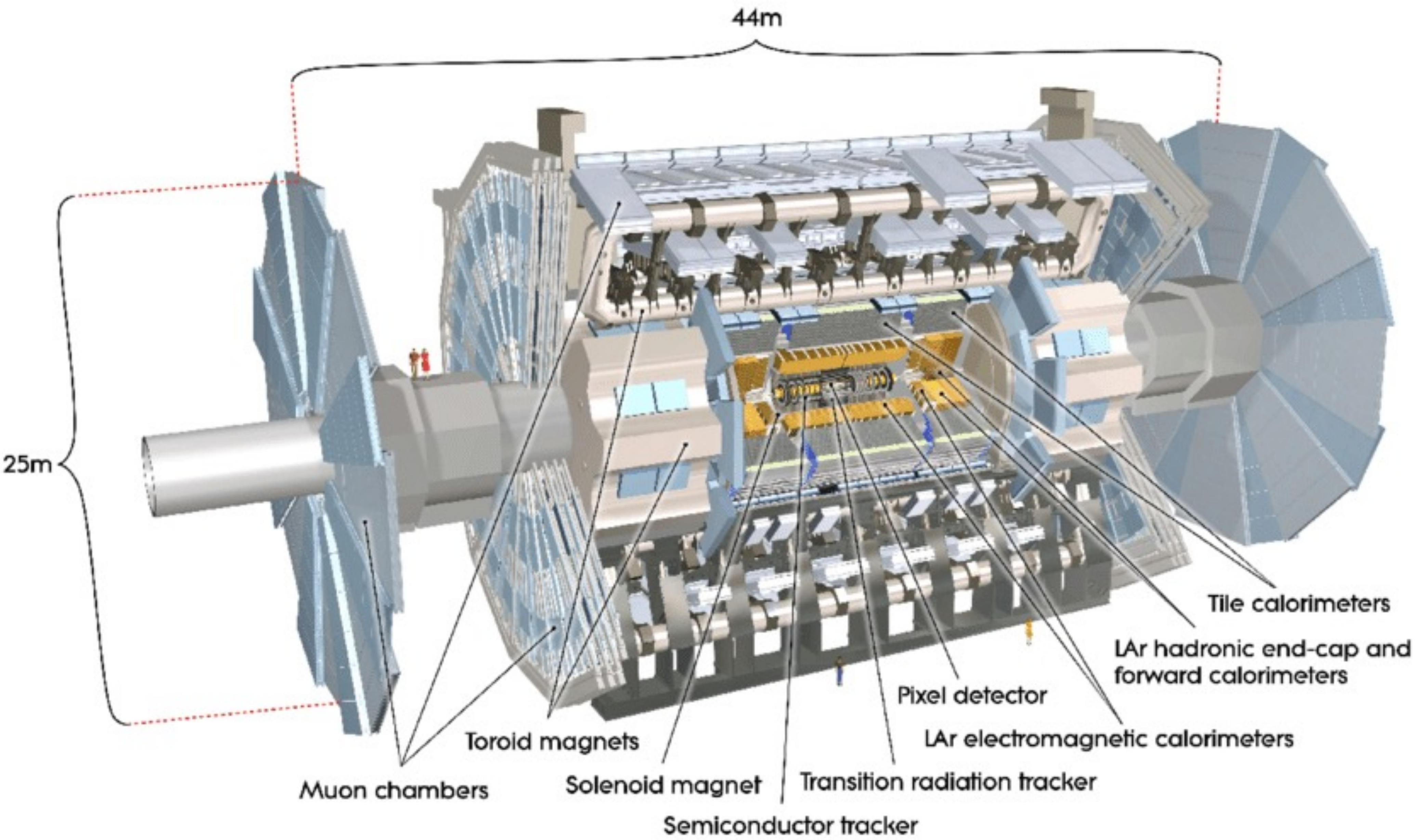


ATLAS: the barrel muon toroid

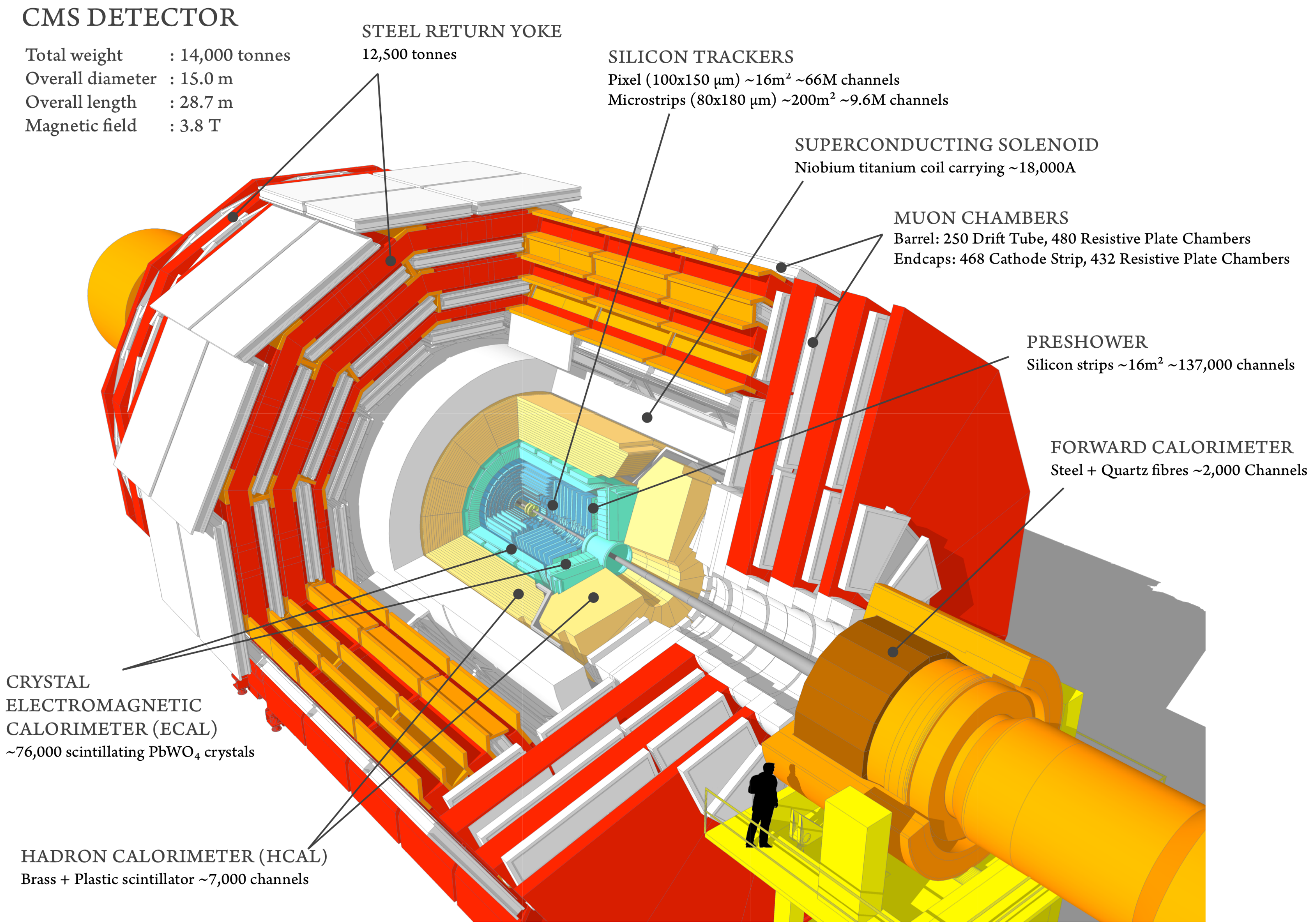
CMS: the barrel Inner Tracker



The ATLAS detector



The CMS detector

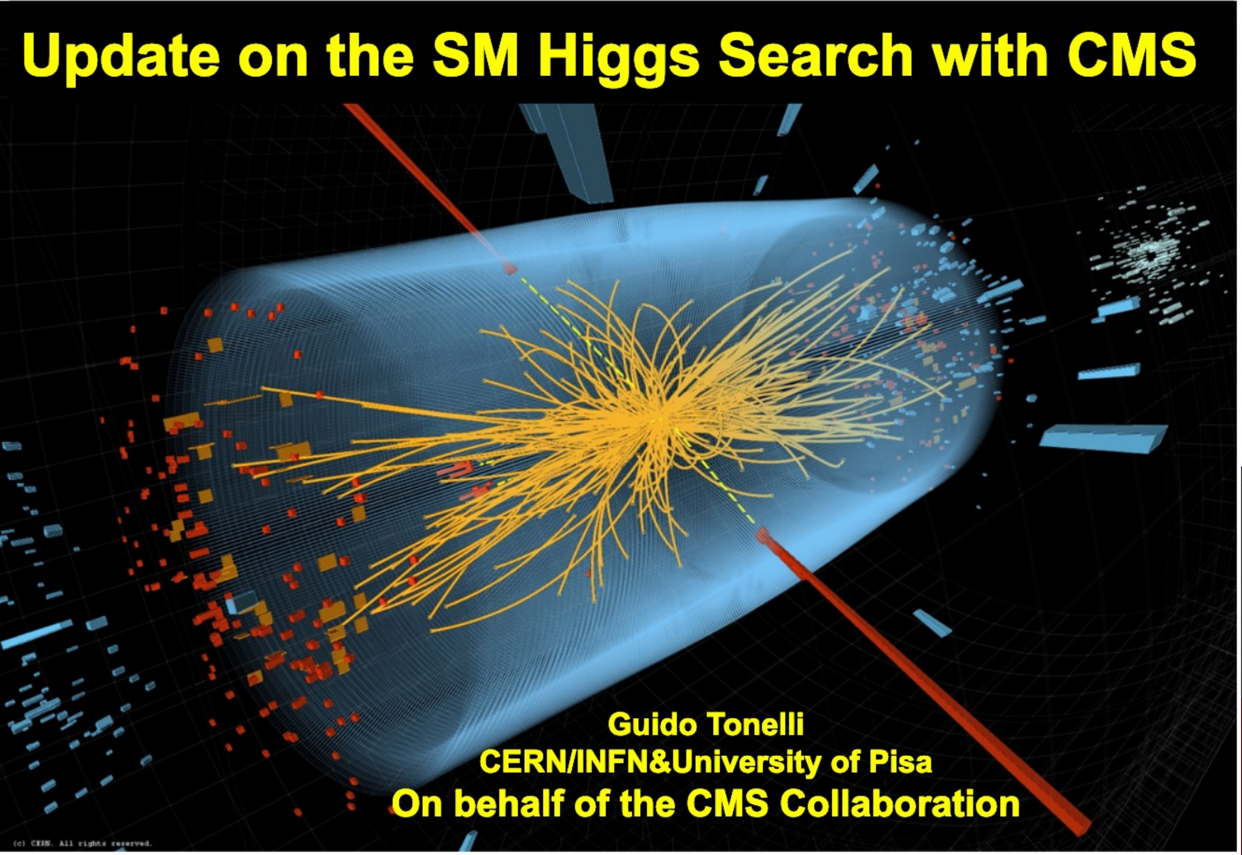


Detector performance

Performance of the main components of the ATLAS and CMS detectors

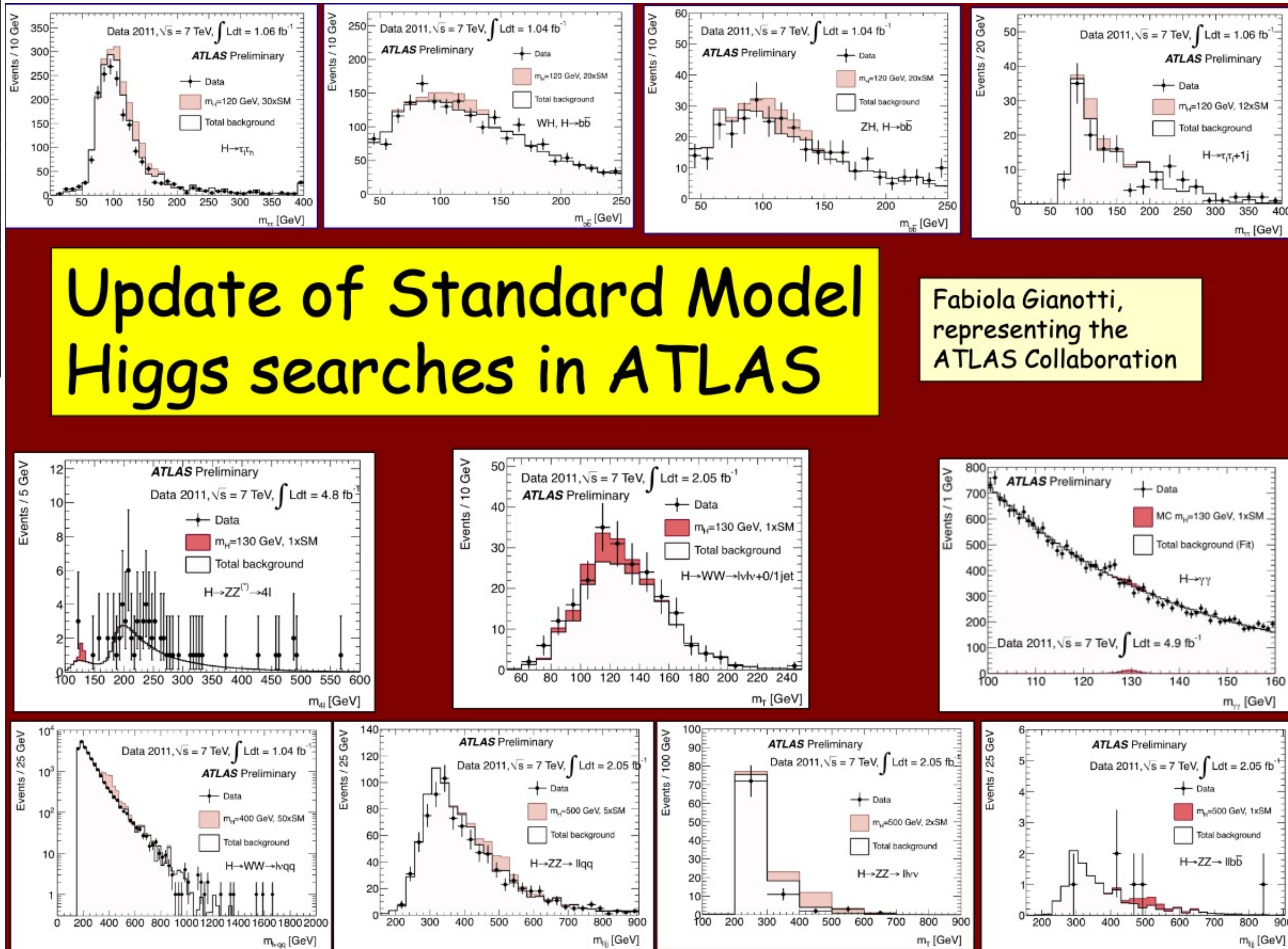
subsystem	ATLAS	CMS
Magnetic field	2T central solenoid; Air-core muon toroids: 0.5T barrel and 1T endcap	3.8T central solenoid + return yoke
central tracking momentum resolution $\sigma(p_T)/p_T$	$5 \times 10^{-4} p_{\mathrm{T}} \oplus 0.01$ (p_{T} in GeV)	$1.5 \times 10^{-4} p_{\mathrm{T}} \oplus 0.005$ (p_{T} in GeV)
muon system momentum resolution $\sigma(p_T)/p_T$	2% for p_{T}=50 GeV 10% for p_{T}=1 TeV	1% for p_{T}=100 GeV 5% for p_{T}=1 TeV
electromagnetic calorimeter $\sigma(E)/E$	$0.10/\sqrt{E} \oplus 0.007$ (E in GeV)	$0.03/\sqrt{E} \oplus 0.005$ (E in GeV)
hadronic calorimeter $\sigma(E)/E$	$0.50/\sqrt{E} \oplus 0.03$ (E in GeV)	$1/\sqrt{E} \oplus 0.05$ (E in GeV)

The Higgs boson @ the end of 2011: towards the discovery



CERN PUBLIC SEMINAR

13 December 2011



$H \to ZZ^{(*)} \to 4l$ (4e, 4μ, 2e2μ)

$110 < m_H < 600$ GeV

- σ ~ 2-5 fb
- However:
  - -- mass can be fully reconstructed → events would cluster in a (narrow) peak
  - -- pure: S/B ~ 1
- 4 leptons: $p_T^{1,2,3,4} > 20,20,7,7$ GeV; $m_{12} = m_Z \pm 15$ GeV; $m_{34} > 15\text{-}60$ GeV (depending on m_H)
- Main backgrounds:
  - -- $ZZ^{(*)}$ (irreducible)
  - -- $m_H < 2m_Z$: Zbb, Z+jets, tt with two leptons from b/q-jets → l

→ Suppressed with isolation and impact parameter cuts on two softest leptons

- Signal acceptance x efficiency: ~ 15 % for m_H~ 125 GeV

Crucial experimental aspects:

- High lepton reconstruction and identification efficiency down to lowest p_T
- Good lepton energy/momentum resolution
- Good control of reducible backgrounds (Zbb, Z+jets, tt) in low-mass region:
  - → cannot rely on MC alone (theoretical uncertainties, b/q-jet → l modeling, ..)
  - → need to compare MC to data in background-enriched control regions (but: low statistics ..)

→ Conservative/stringent p_T and m(ll) cuts used at this stage

ATLAS

$H \rightarrow \gamma\gamma$

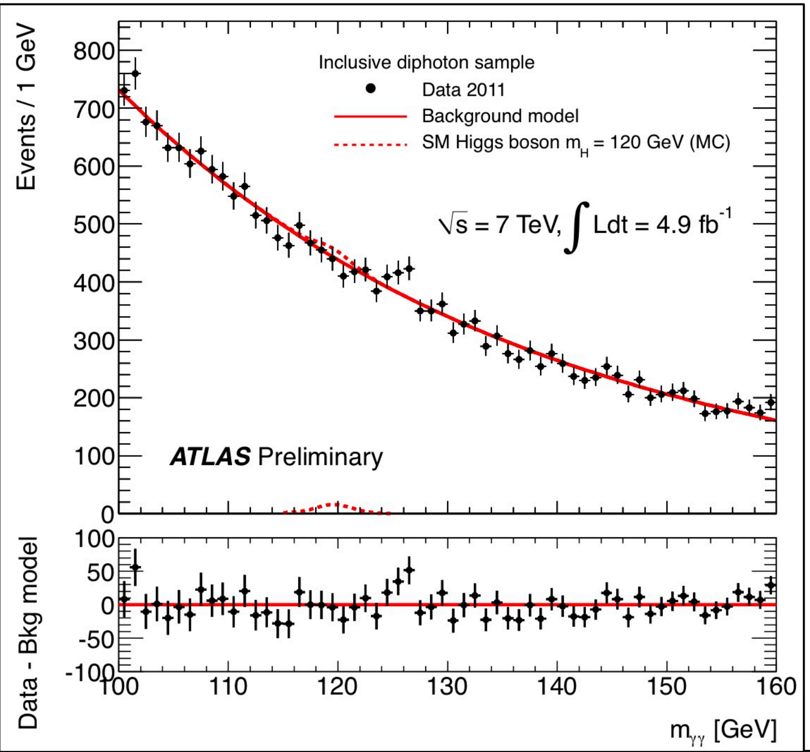
$110 \leq m_H \leq 150$ GeV

$m^2_{\gamma\gamma} = 2 E_1 E_2 (1-\cos\alpha)$

- Calorimeter pointing capability reduces vertex uncertainty from ~ 5.6 cm (LHC beam spot) to ~ 1.5 cm

After all selections: kinematic cuts, γ identification and isolation

- 22489 events with $100 < m_{\gamma\gamma} < 160$ GeV observed in the data
- expected signal efficiency: ~ 35% for m_H=125 GeV



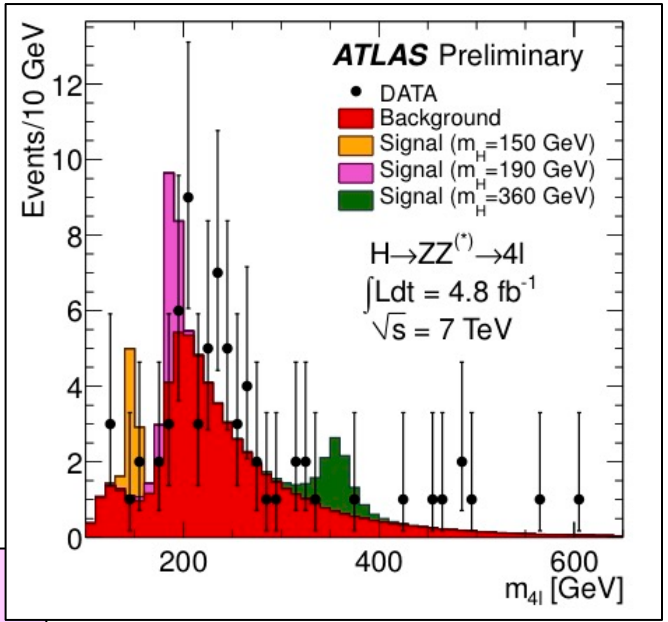
$m_{\gamma\gamma}$ spectrum fit with exponential function for background plus Crystal Ball + Gaussian for signal
→ background determined directly from data

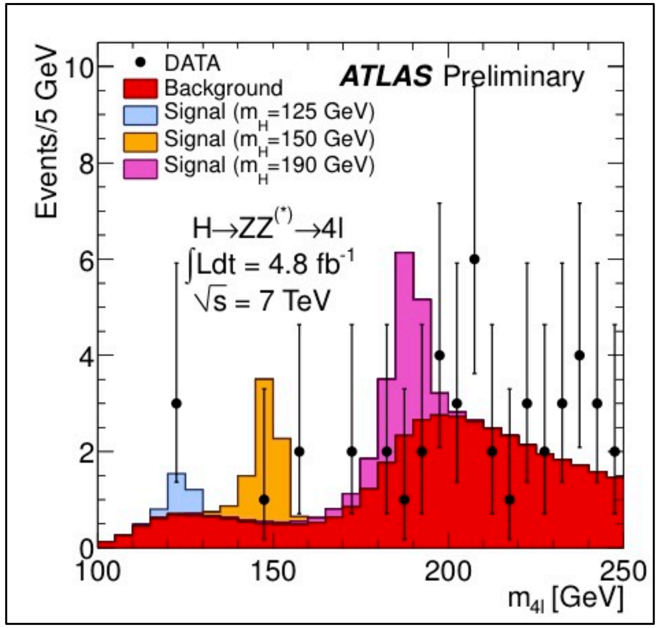
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (4e, 4μ, 2e2μ)

After all selections: kinematic cuts, isolation, impact parameter

Full mass range
Observed: 71 events: 24 4μ + 30 2e2μ + 17 4e
Expected from background: 62±9

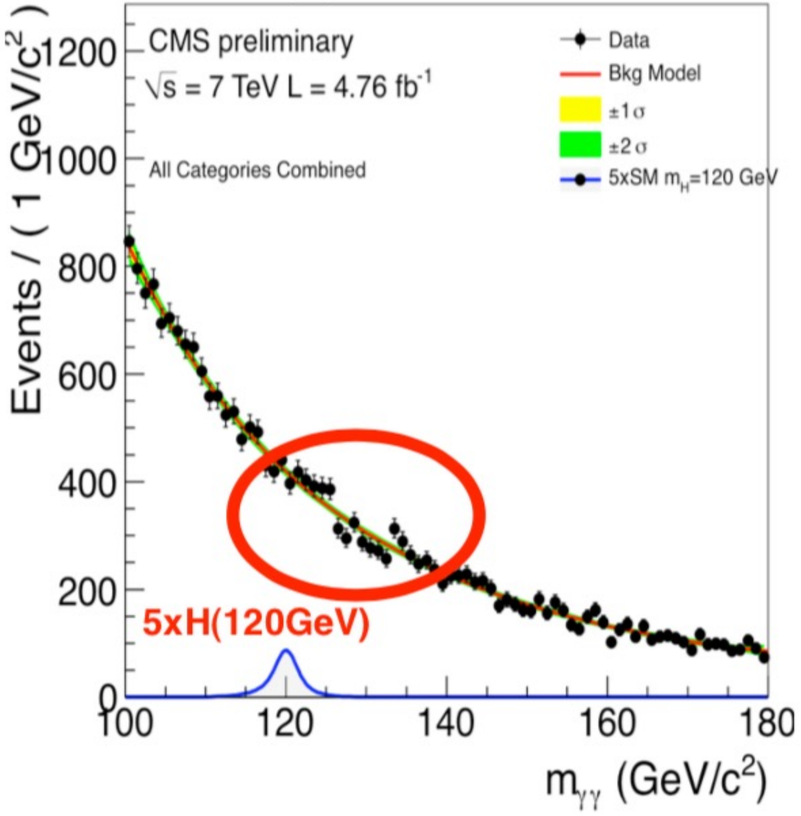
m(4l) < 180 GeV
Observed: 8 events: 3 4μ + 3 2e2μ + 2 4e
Expected from background: 9.3±1.5





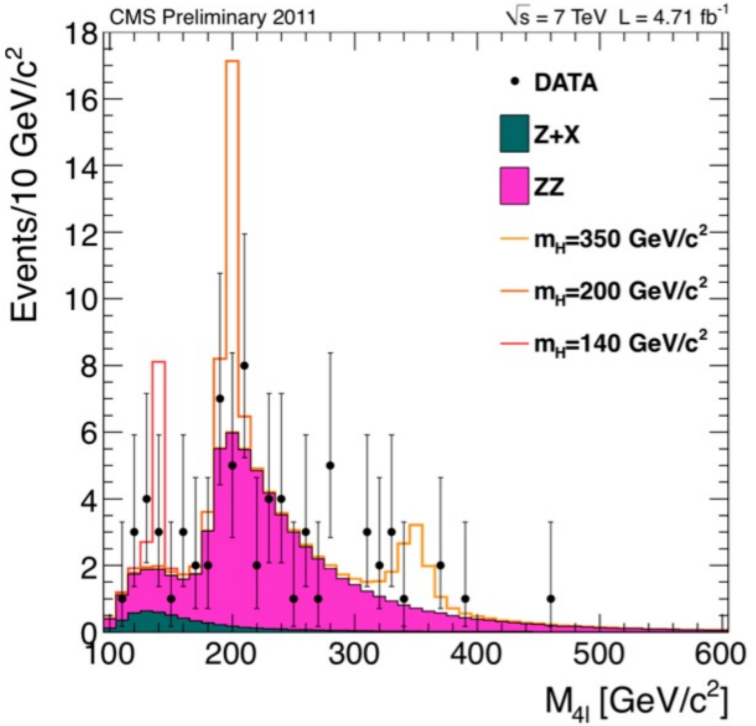
CMS

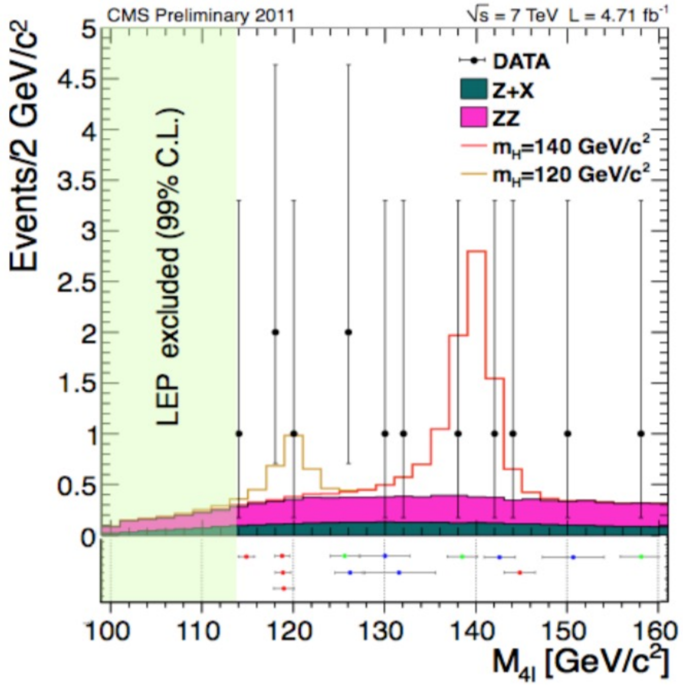
$H \rightarrow \gamma\gamma$



A lot of studies on the background fit model. Is the structure/shape of the observed limit due to the chosen background model? No – this has been shown to not be the case.

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (4e, 4μ, 2e2μ)





$100 < m_{4l} < 160$ GeV/c^2

Observed events: 13

Expected events: 9.5 ± 1.3

Final state:	4e	4μ	2e2μ
Obs. events:	3	5	5
Exp. events:	1.7	3.3	4.5

F. Gianotti

Conclusions

It has been a wonderful year for the LHC and ATLAS → THANKS LHC TEAM !

We have looked for a SM Higgs boson
- over the mass region 110-600 GeV
- in 11 distinct channels
- using up to 4.9 fb^{-1} of integrated luminosity

→

We have restricted the most likely mass region (95% CL) to

115.5-131 GeV

We observe an excess of events around m_H~ 126 GeV:
- local significance 3.6 σ, with contributions from the $H \to \gamma\gamma$ (2.8 σ), $H \to ZZ^* \to 4l$ (2.1 σ), $H \to WW^{(*)} \to l\nu l\nu$ (1.4 σ) analyses
- SM Higgs expectation: 2.4 σ local → observed excess compatible with signal strength within +1σ
- the global significance (taking into account Look-Elsewhere-Effect) is ~2.3σ

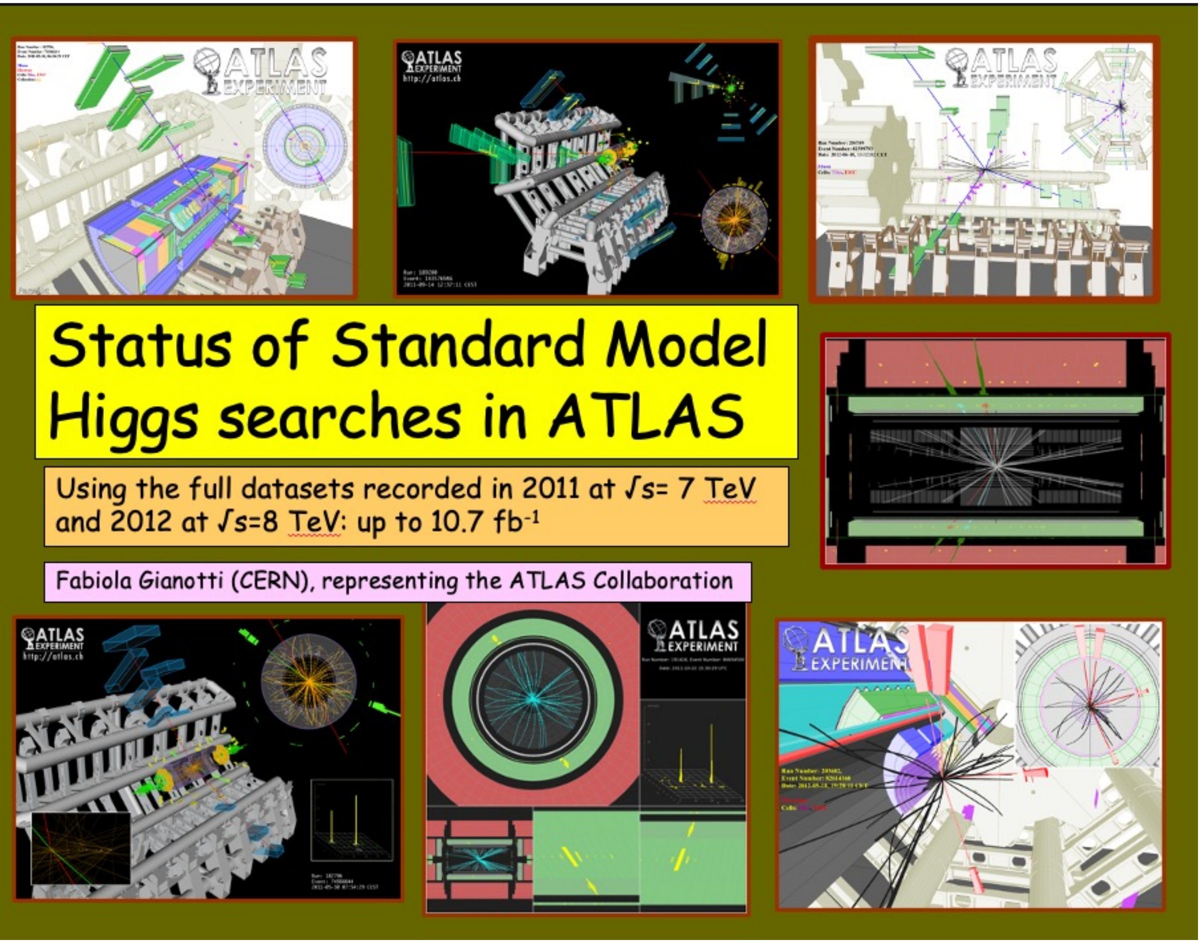
It would be a very nice region for the Higgs to be → accessible at LHC in γγ, 4l, lνlν, bb, ττ

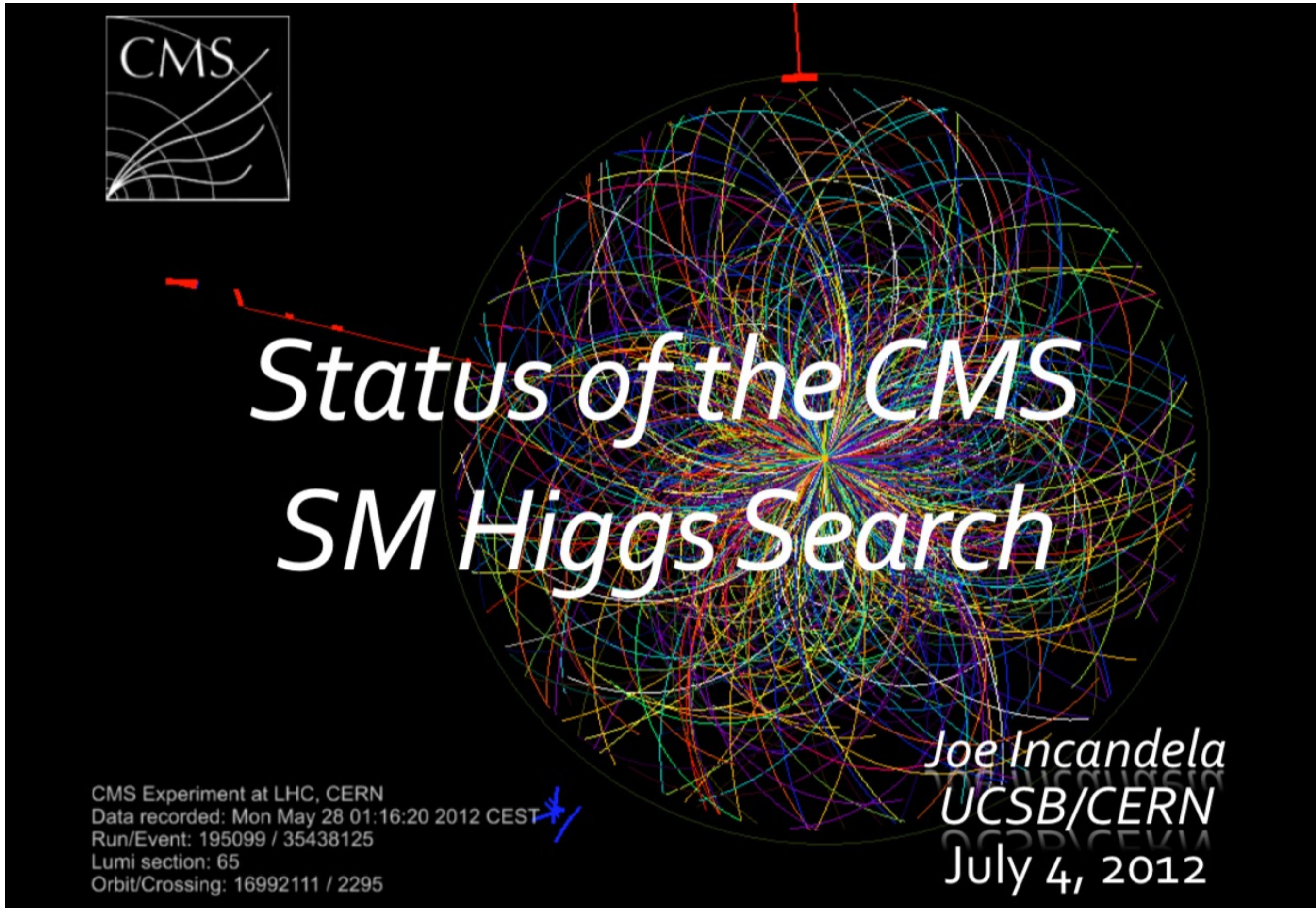
It's too early to draw definite conclusions
More studies and more data are needed
We have built solid foundations for the (exciting !) months to come

Summary.

- We have been able to analyse very quickly the full data set collected in 2011 and to present here a comprehensive set of preliminary results.
- Final results and submission of papers are expected around the end of January (new additional channels, refined analyses).
- **We have reached the expected sensitivity (around or better than 1xSM) in the full mass range of our current exploration (115GeV-600 GeV).**
- We have established **new 95% CL exclusion limits: 127GeV-600GeV.**
- We are not able to exclude the presence of the SM Higgs below 127GeV since we observe in our data **a modest excess of events between 115 and 127GeV that appears, quite consistenly, in five independent channels.**
- **The excess is most compatible with a SM Higgs hypothesis in the vicinity of 124 GeV and below, but the statistical significance (2.6σ local and 1.9σ global after correcting for the LEE in the low mass region) is not large enough to say anything conclusive.**
- As of today what we see is consistent either with a background fluctuation or with the presence of the SM Higgs boson.
- Refined analyses and additional data in 2012 will definitely give an answer.

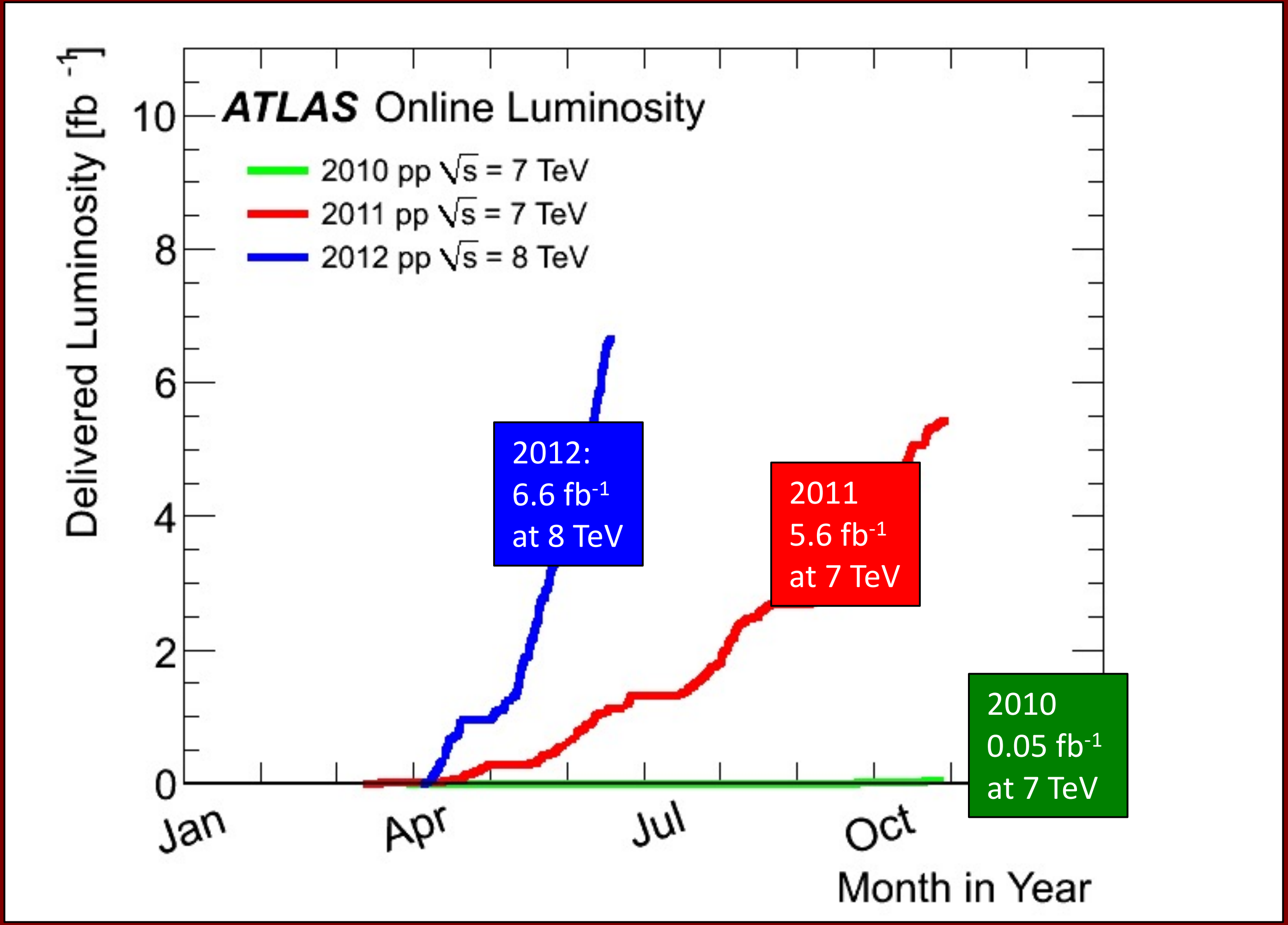
The announcement of the Higgs boson observation: 4 July 2012



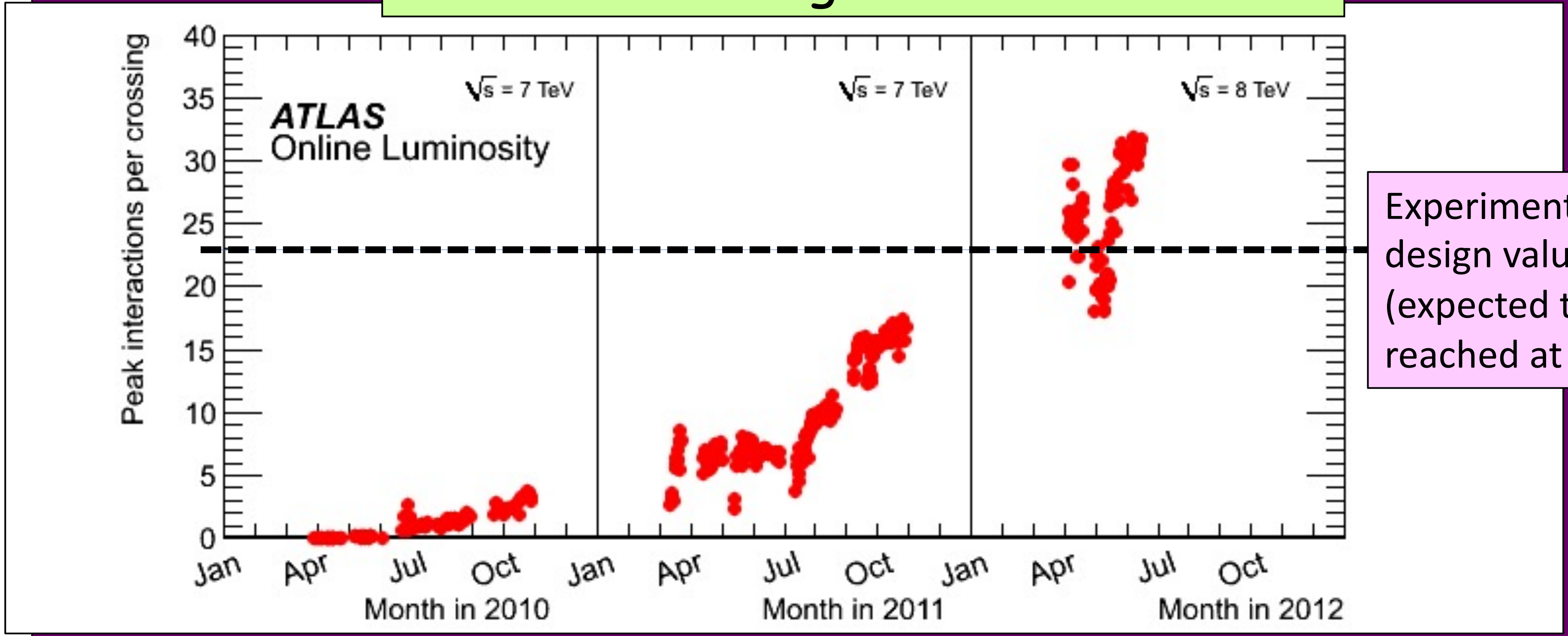


Luminosity delivered to ATLAS since the beginning

Similarly for CMS



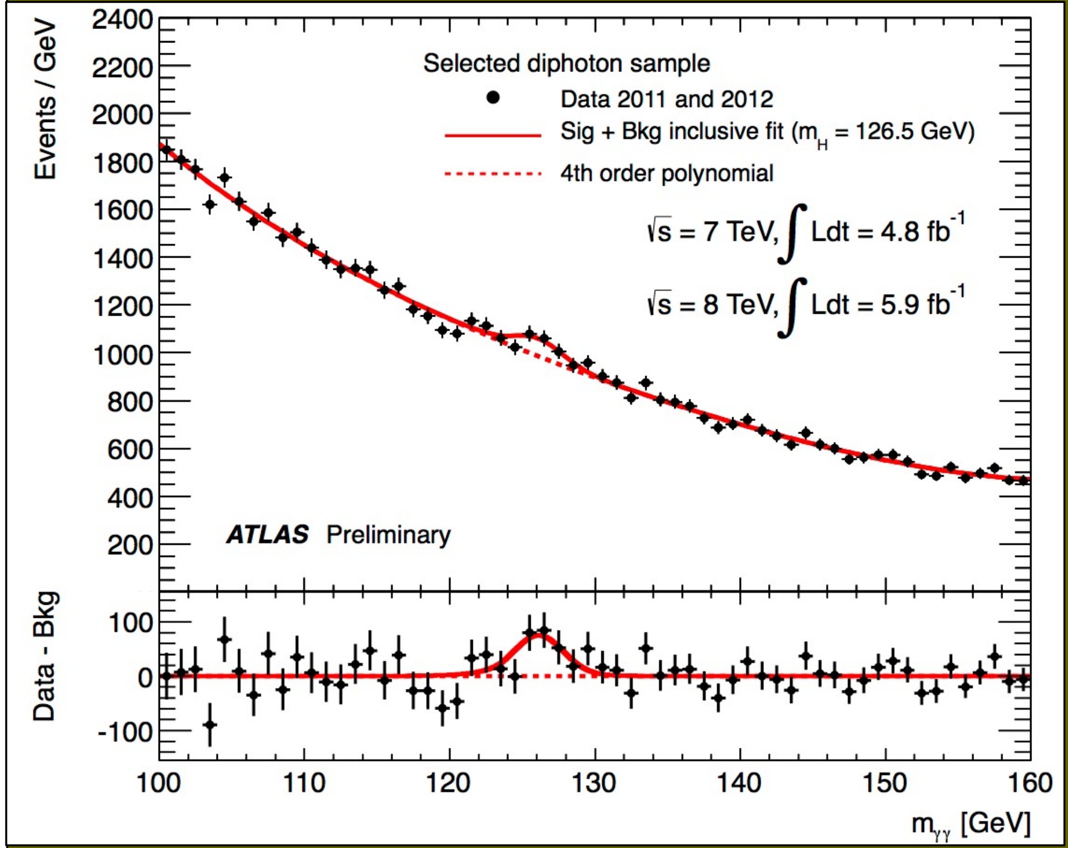
The BIG challenge in 2012: PILE-UP



Experiment's design value (expected to be reached at $L=10^{34}$!)

The data sample and the Higgs boson final states analysed

- **H→ γγ,** and **H→4l**: full 2011 and 2012 datasets (~ 10.7 fb^{-1}) and improved analyses since December 13th, 2011
- all other channels:
  - studied by ATLAS: **H→ WW(*)→ lνlν**, H→ ττ, WH→ lνbb, ZH→ llbb, ZH→ ννbb, ZZ → llνν, H→ ZZ → llqq; H→ WW→lνqq): full 2011 dataset (up to 4.9 fb^{-1})
  - studied by CMS: **H→ WW(*)→ lνlν**,VH H→bb and V= ll, lν, νν; H→ ττ: full 2011 and 2012 datasets;



Total after selections: 59059 events

$m_{\gamma\gamma}$ spectrum fit, for each category, with Crystal Ball + Gaussian for signal plus background model optimised (with MC) to minimize biases
Max deviation of background model from expected background distribution taken as systematic uncertainty

$H \rightarrow \gamma\gamma$

$110 \leq m_H \leq 150$ GeV

Main systematic uncertainties

Signal yield	
Theory	~ 20%
Photon efficiency	~ 10%
Background model	~ 10%
Categories migration	
Higgs p_T modeling	up to ~ 10%
Conv/unconv γ	up to ~ 6%
Jet E-scale	up to 20% (2j/VBF)
Underlying event	up to 30% (2j/VBF)
$H \rightarrow \gamma\gamma$ mass resolution	~ 14%
Photon E-scale	~ 0.6%

H → γγ

Di-jet Tagging: Selection

Analysis improvements in 2012:

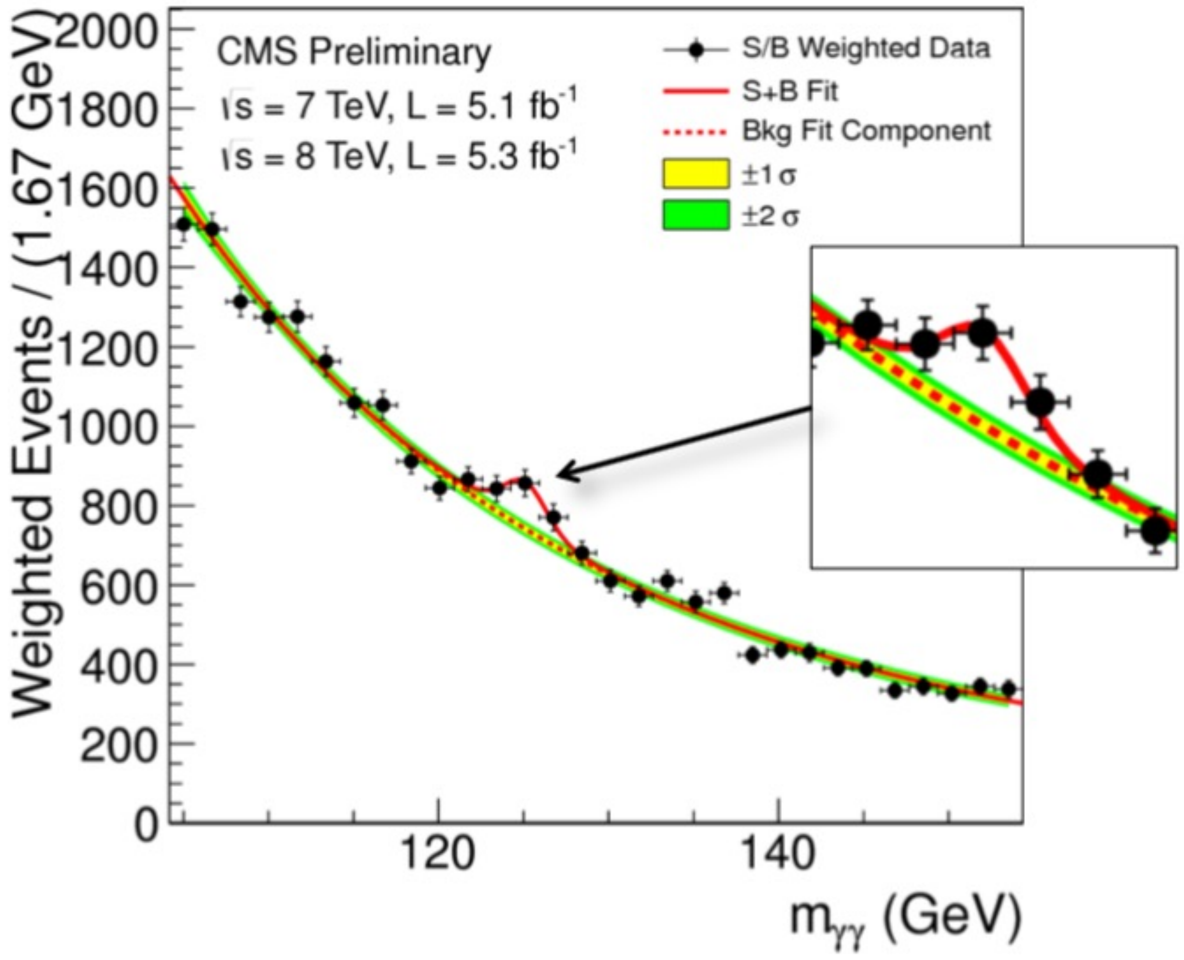
- Split di-jet tagged events in two categories based on M_{jj} and jet p_T
  - ~15% improvement in sensitivity for dijet category
  - better sensitivity to separate different Higgs production modes
- Removal of jets from pileup events
  - Based on the jet shape variables, tracks in jet and vertexing
  - Cross-checked using Z+jet and γ+jet events

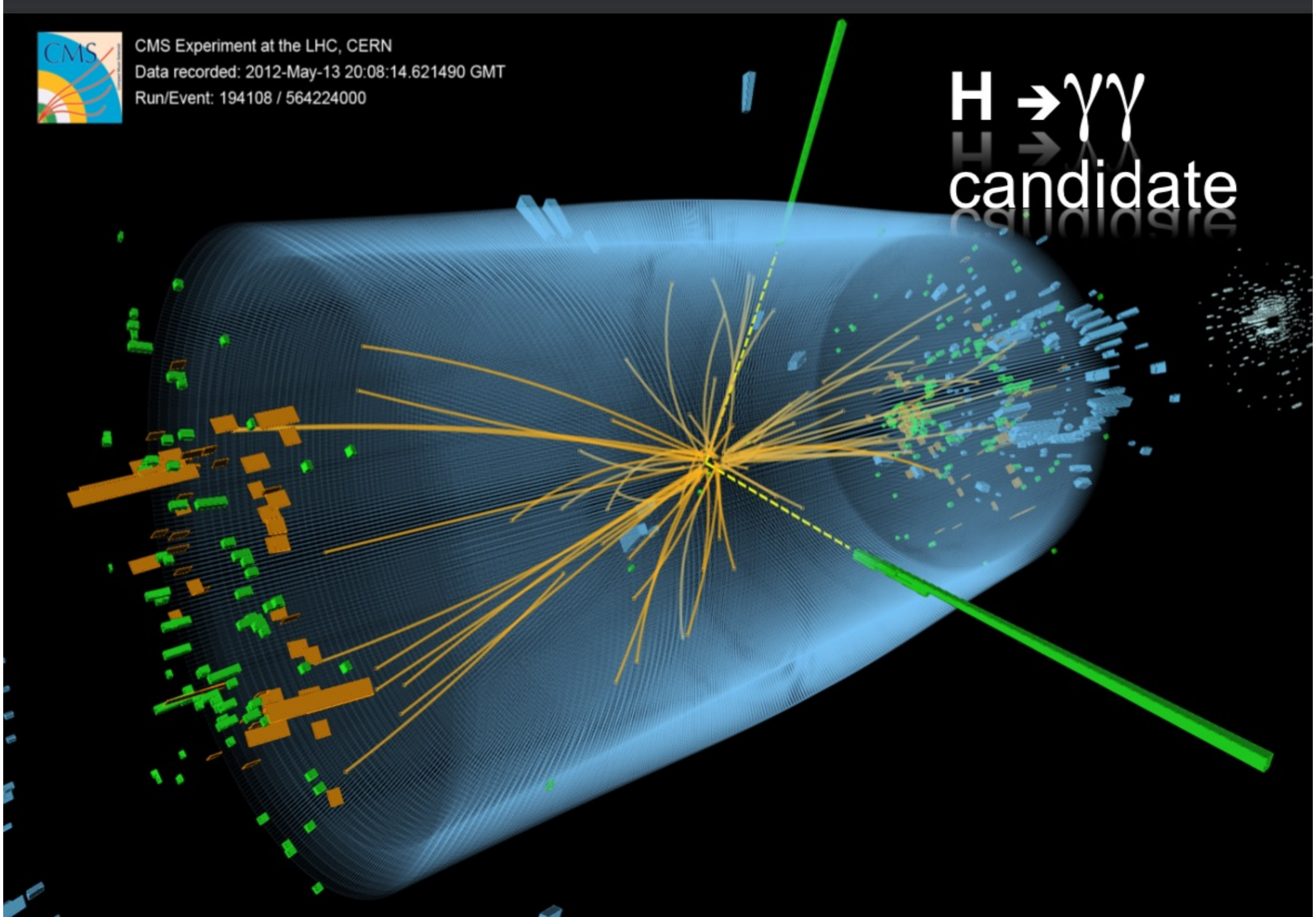
Dijet selection cuts

<table>
<tr><th rowspan="2">Variable</th><th rowspan="2">2011</th><th colspan="2">2012</th></tr>
<tr><th>Loose</th><th>Tight</th></tr>
<tr><td>$p_T(j_1)$</td><td colspan="3">> 30 GeV</td></tr>
<tr><td>$p_T(j_2)$</td><td colspan="2">> 20 GeV</td><td>> 30 GeV</td></tr>
<tr><td>$\Delta\eta(j_1, j_2)$</td><td>> 3.5</td><td colspan="2">> 3.0</td></tr>
<tr><td>$|\eta_{\gamma\gamma} - \frac{1}{2}(\eta_{j1} + \eta_{j2})|$</td><td colspan="3">$< 2.5$</td></tr>
<tr><td>$\Delta\phi(jj, \gamma\gamma)$</td><td colspan="3">$> 2.6$</td></tr>
<tr><td>m_{jj}</td><td>> 350 GeV</td><td>> 250 GeV</td><td>> 500 GeV</td></tr>
</table>

S/B Weighted Mass Distribution

- Sum of mass distributions for each event class, weighted by S/B
  - B is integral of background model over a constant signal fraction interval




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

2012 analysis + improvements

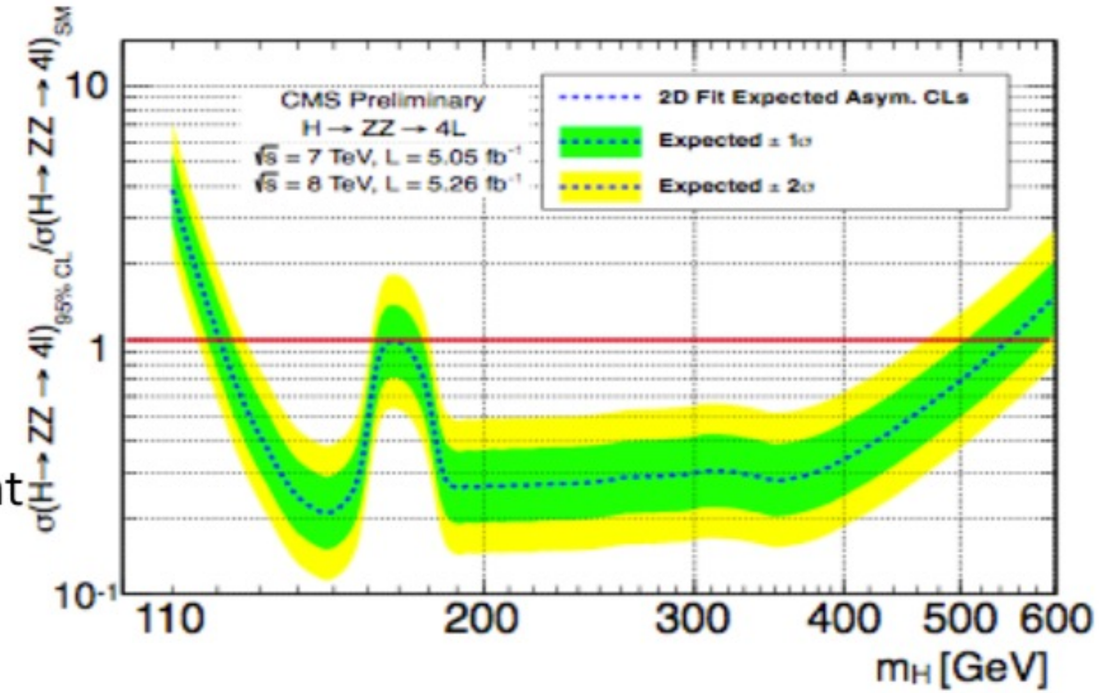
H → ZZ* → 4 leptons

Blinding policy: analysis optimized blindly for 2012, applied to 2011 reoptimization

Do NOT look at 110 < m_{4l} <140 GeV, and m_{4l} > 300 GeV

Main changes:

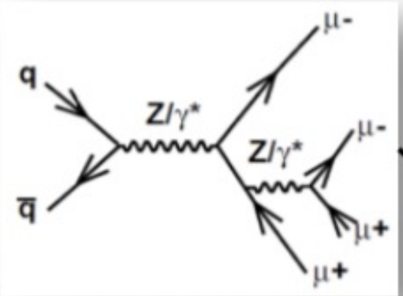
New lepton ID (MVA + PFlow)
New lepton PFlow isolation
Final State Radiation (FSR) recovery
2D analysis: m_{4l} + Kinematic Discriminant

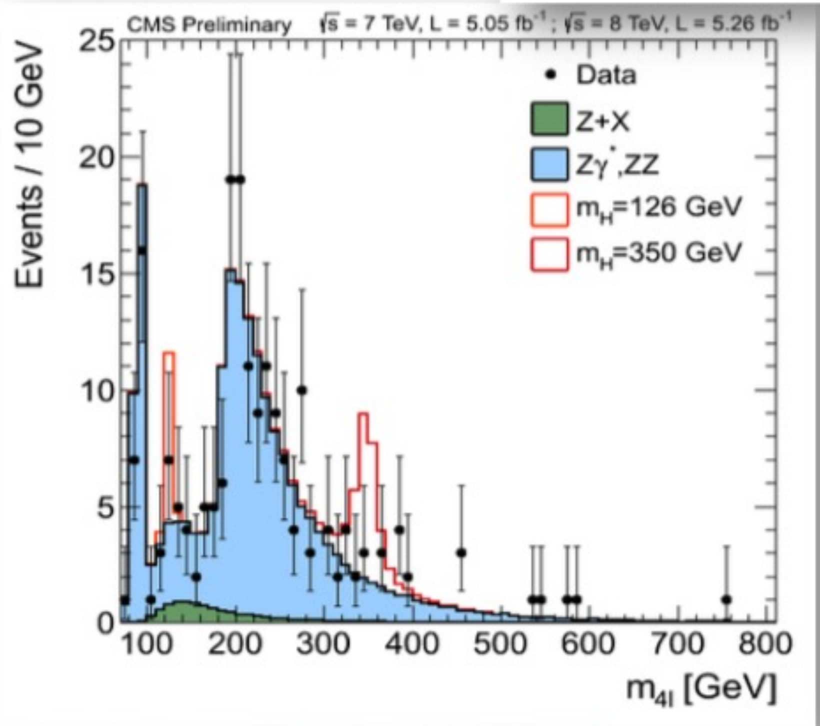


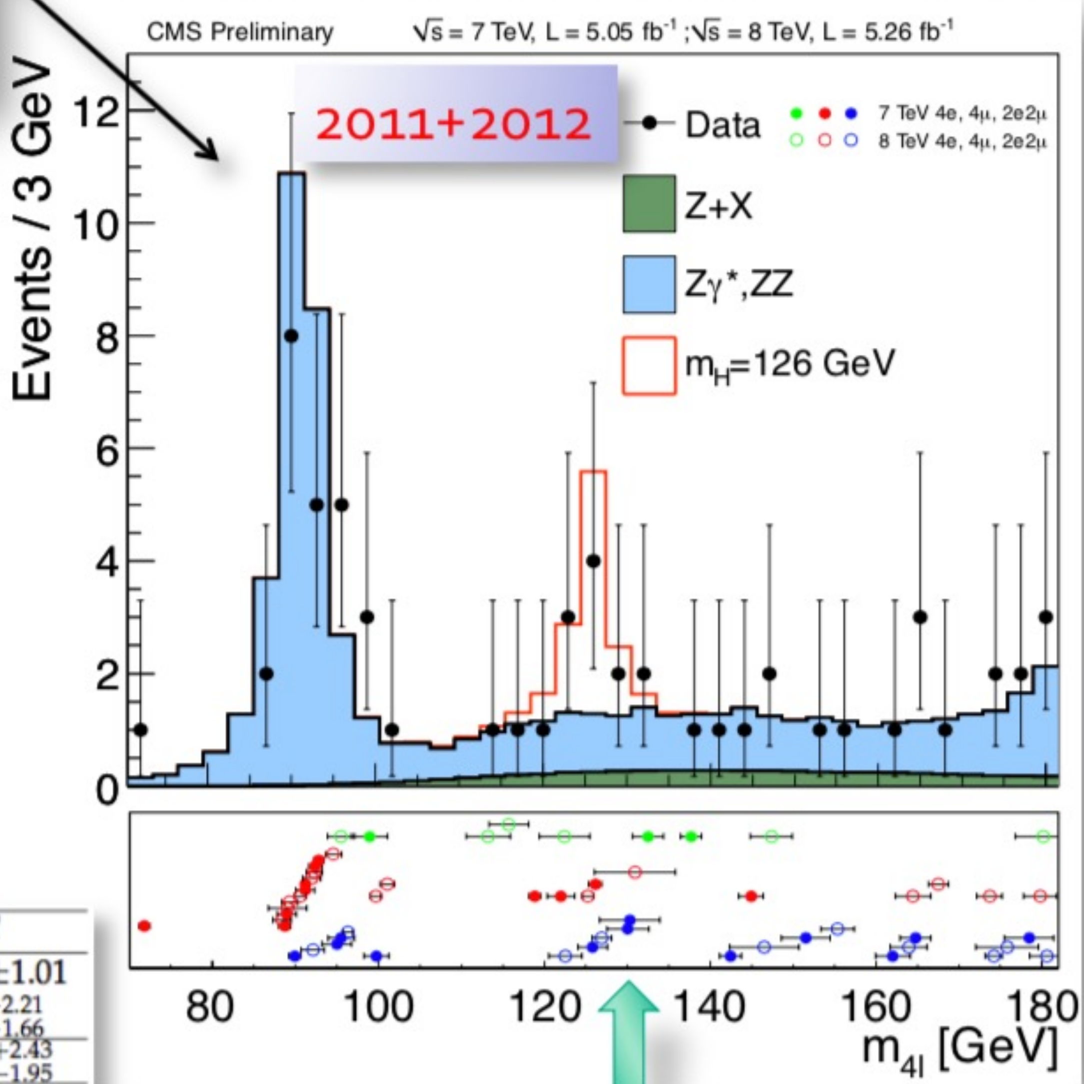
>20% improvement @ m_H = 126 GeV wrt 2011 analysis

Expected exclusion range 121–540 GeV

Results: m(4l) spectrum







Event-by-event errors

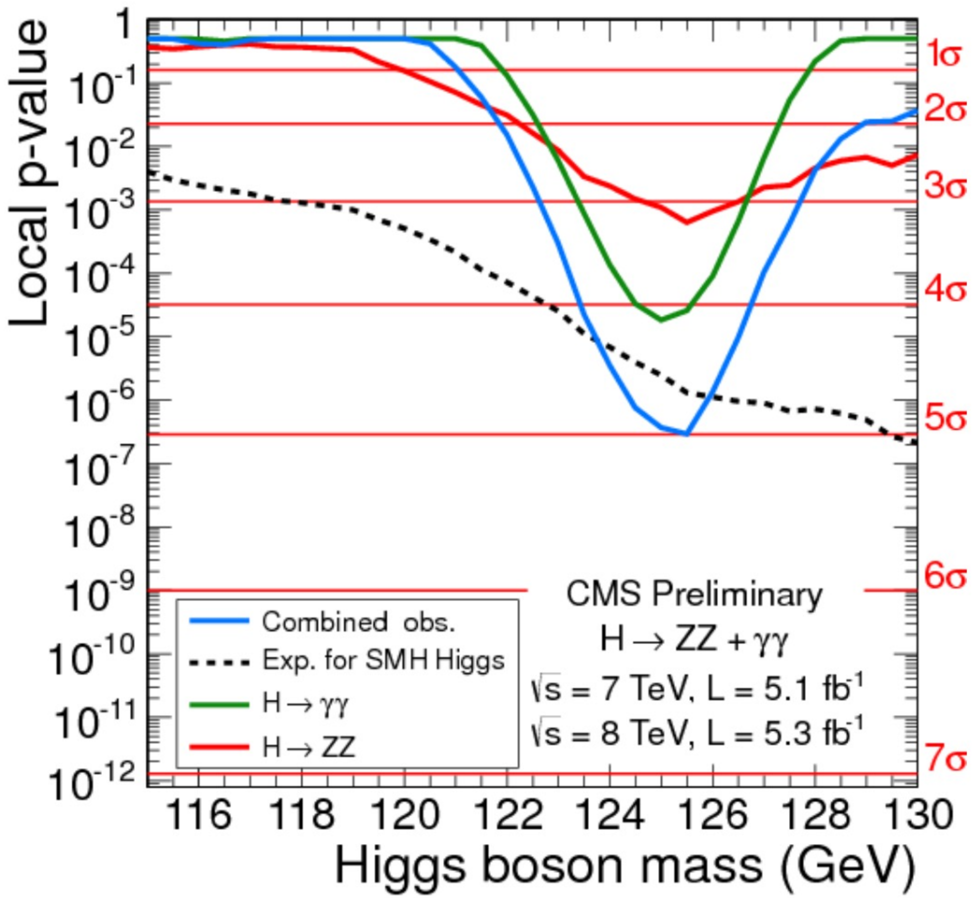
Yields for m(4l)=110..160 GeV

Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.65 ±0.31	5.65 ±0.59	7.17 ±0.76	15.48 ±1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
m_H = 126 GeV	1.51 ±0.48	2.99 ±0.60	3.81 ±0.89	8.31 ±1.18

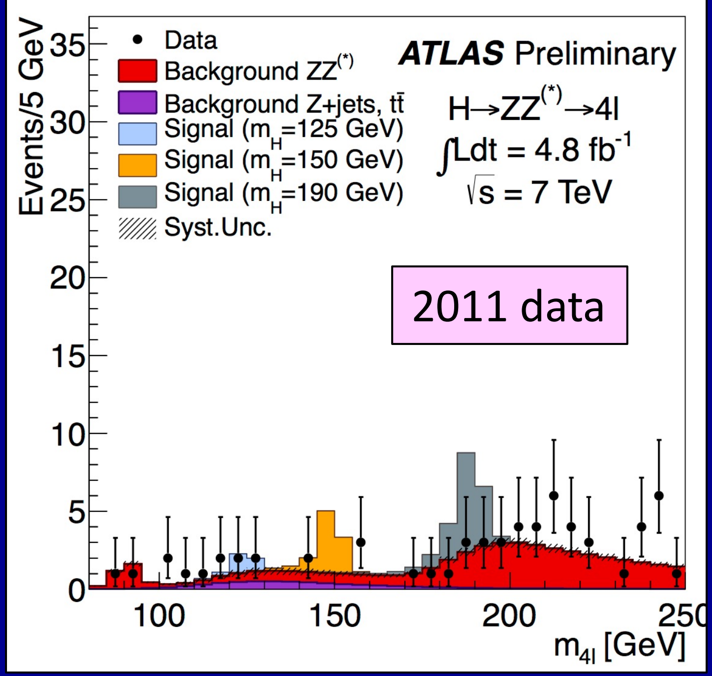
164 events expected in [100, 800 GeV]

172 events observed in [100, 800 GeV]

Characterization of excess near 125 GeV

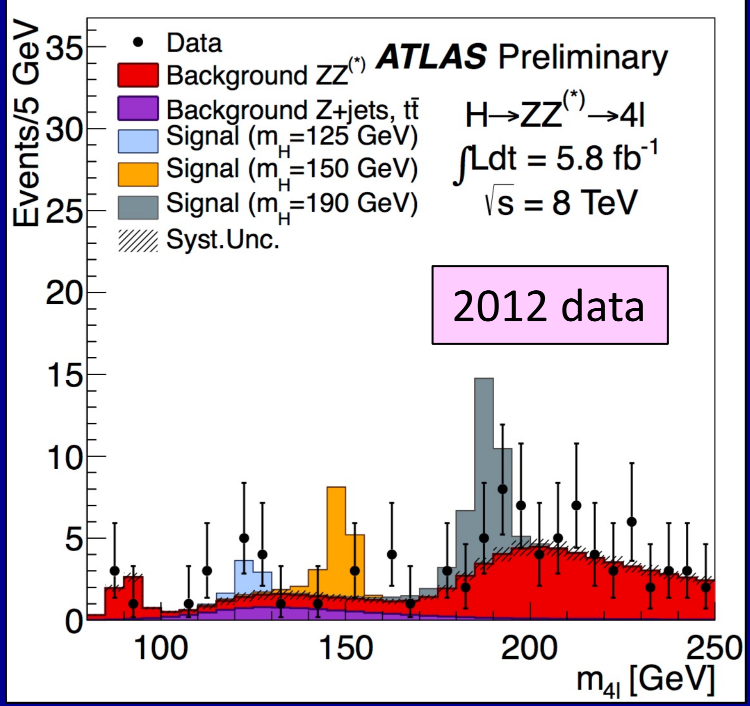


- **high sensitivity, high mass resolution channels: γγ+4l**
  - **γγ: 4.1 σ excess**
  - **4 leptons: 3.2 σ excess**
  - **near the same mass 125 GeV**
- **comb. significance: 5.0 σ**
- **expected significance for SM Higgs: 4.7 σ**

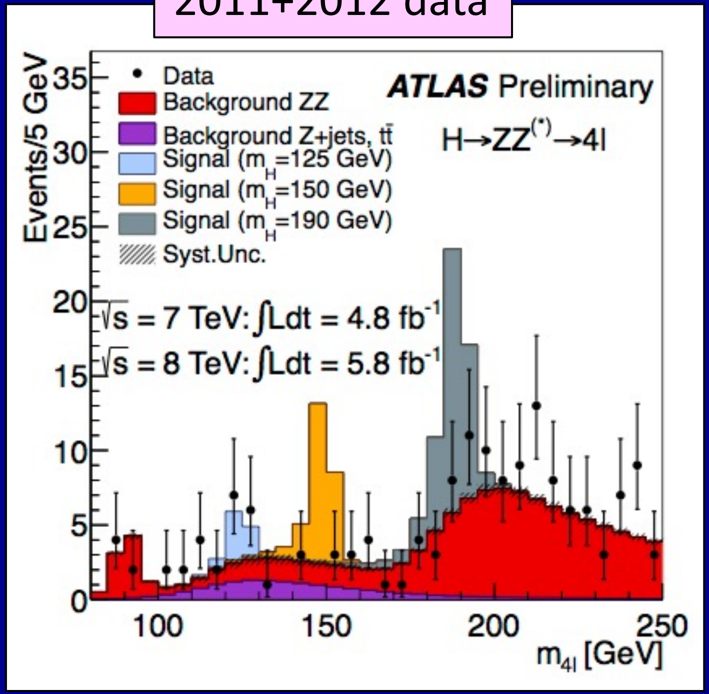


The low-mass region

m4l <160 GeV:
Observed: 39
Expected: 34± 3



2011+2012 data



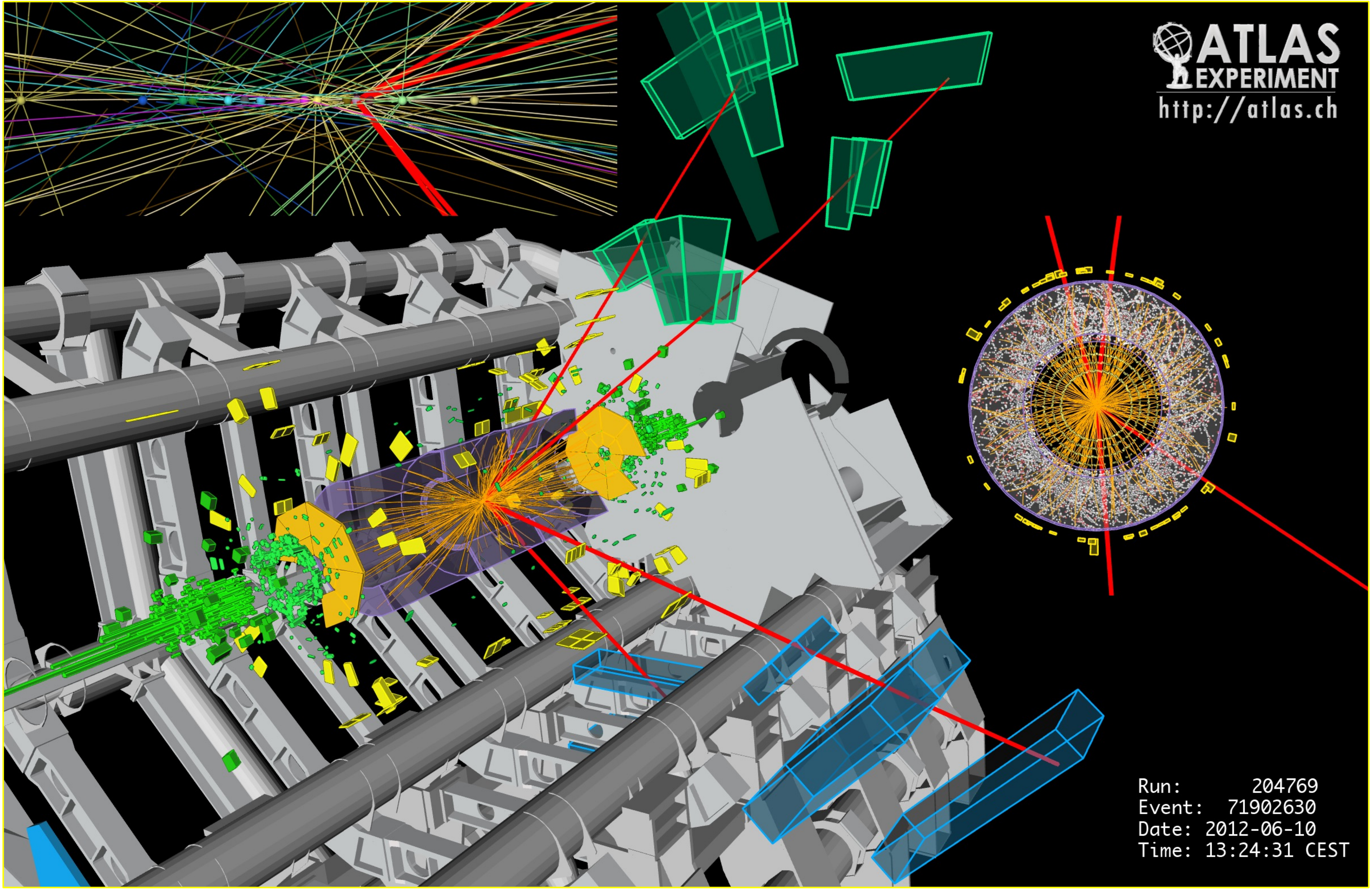
In the region 125 ± 5 GeV

Dataset	2011	2012	2011+2012
Expected B only	2±0.3	3±0.4	5.1±0.8
Expected S m_H=125 GeV	2±0.3	3±0.5	5.3±0.8
Observed in the data	4	9	13

2011+ 2012	4μ	2e2μ	4e
Data	6	5	2
Expected S/B	1.6	1	0.5
Reducible/total background	5%	45%	55%

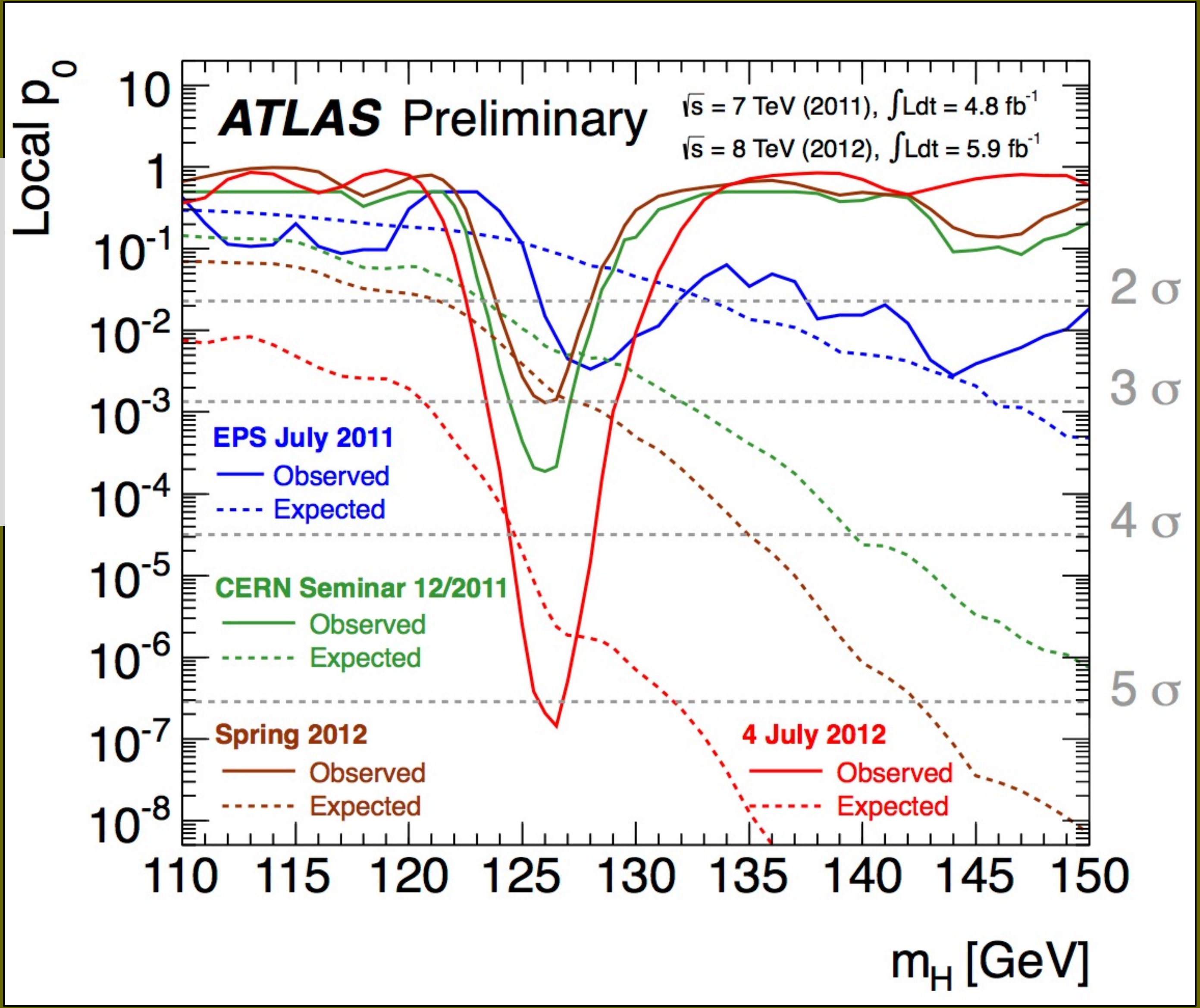
4μ candidate with $m_{4\mu}$= 125.1 GeV

p_T (muons)= 36.1, 47.5, 26.4, 71 .7GeV m_{12}= 86.3 GeV, m_{34}= 31.6 GeV
15 reconstructed vertices



Evolution of the excess with time

p_0: the probability that the background can produce a fluctuation greater than or equal to the excess observed in data



Energy-scale systematics not included

In summary

We have observed a new boson with a mass of

125.3 ± 0.6 GeV

at

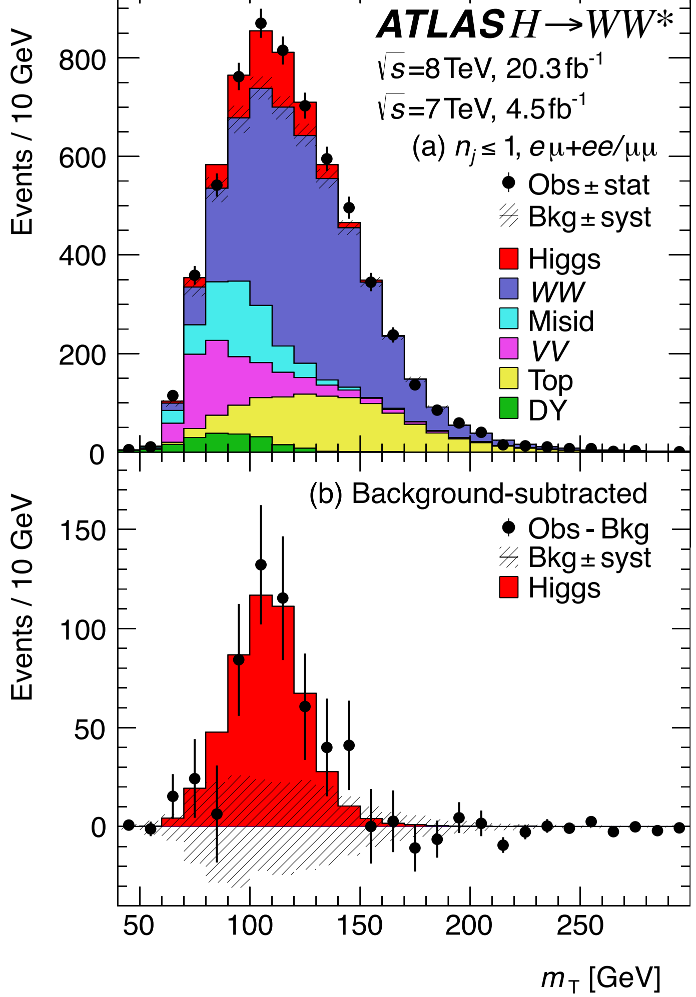
4.9 σ significance !

CMS: https://doi.org/10.1007/JHEP01(2014)096
ATLAS: https://doi.org/10.1103/PhysRevD.92.012006

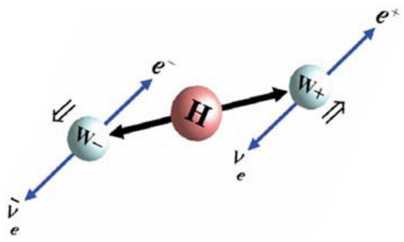
$H \to WW^{(*)} \to l\nu l\nu$

- The most sensitive process for $130 < m_H < 200$ GeV
- But also one of the most challenging channels: complete reconstruction of the invariant mass of this final system **is not possible** because the **production of neutrinos**
- Largest background is the irreducible WW SM production
  – In addition, Drell-Yan and top process when looking to final states associated to one jet
- Select events with two high-p_T opposite sign leptons and large transverse missing energy (E_T^{miss}), produced in association of 0, 1 and 2 jets

Dataset:
25 fb^{-1} of data at $\sqrt{s}$ = 7 and 8 TeV

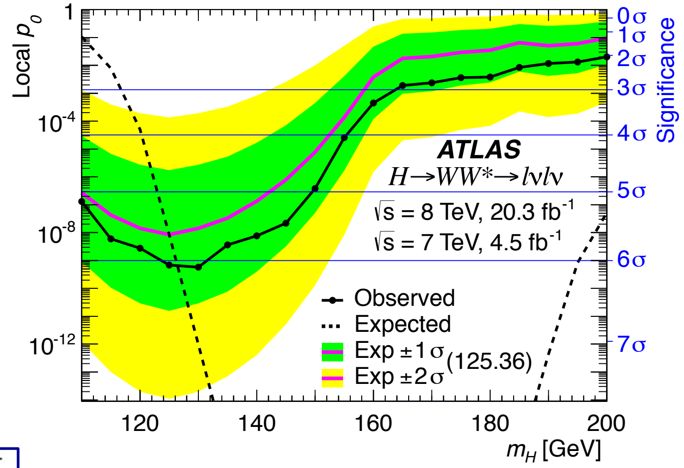


$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$



The spin-0 Higgs boson decays to W bosons with opposite spins, and the spin-1 W bosons decay into leptons with aligned spins. Because of the V − A decay of the W bosons, the charged leptons have a small opening angle in the laboratory frame. This feature is also present when one W boson is off shell.

Transverse mass distributions for $n_j \leq 1$ for all lepton-flavor samples. Plot (b): residuals of the data with respect to the estimated background compared to the expected distribution for a SM Higgs boson with m_H = 125 GeV; the error bars on the data are statistical ($\sqrt{Nobs}$).



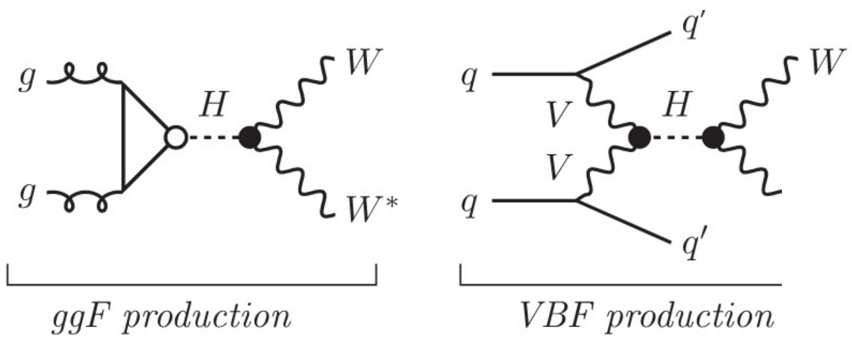
Local p_0 as a function of m_H. Solid line: observed p_0. Dashed line: expected values. Expected values for m_H=125.36 GeV are given as a solid line without points; the inner (outer) band shaded darker (lighter) represents the one (two) standard deviation uncertainty.

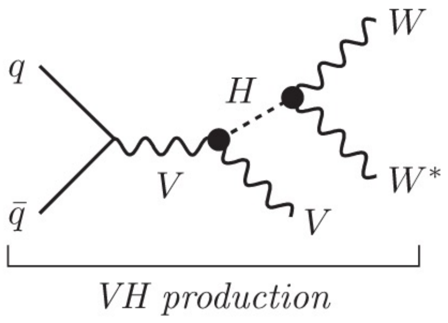
Signal significance of 6.1 standard deviations
Evidence for the vector-boson fusion (VBF) 3.2 standard deviations

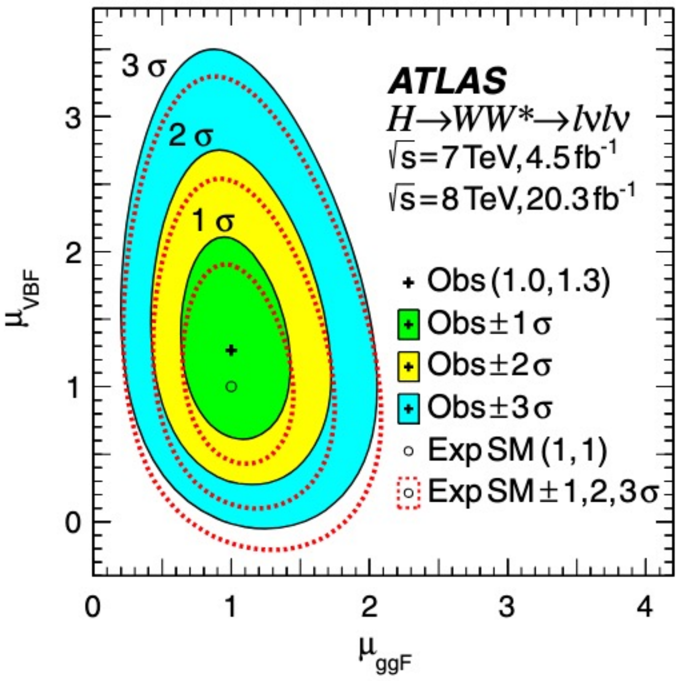
Vector Boson Fusion

- The next most abundant production mechanism, with a factor of ~12 reduction in rate, is the fusion of Vector Bosons radiated by the interacting quarks into a Higgs boson (vector-boson fusion, VBF).
- This process offers, with respect to the ggF process, a stronger signal-to-background ratio

the VBF process directly probes the couplings to *W* and *Z* bosons. direct probe of the couplings to to *W* and *Z* bosons is offered also by the associated production VH (V=W or Z)







Events are selected asking two high-p_T jets at large rapidities.
Example: $p_T^{jet} > 30$ GeV with $2.4 \leq \eta_{jj} < 4.5$
(high p_T threshold to also suppress effects from pile-up)

μ is the signal strength: $\mu = \sigma_{obs}/\sigma_{SM}$

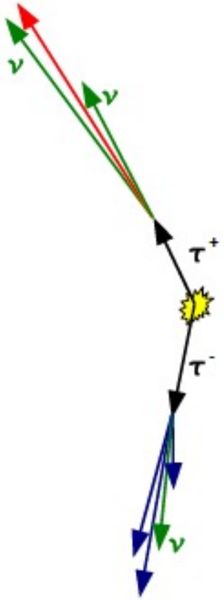
Likelihood scan as a function of μ_{ggF} and μ_{VBF}

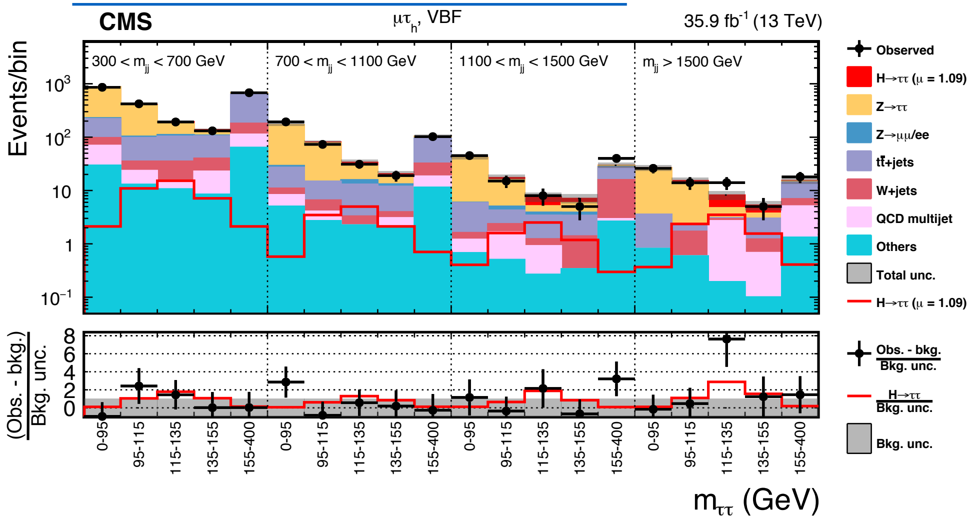
H→ττ

https://link.springer.com/article/10.1007/JHEP04(2015)117

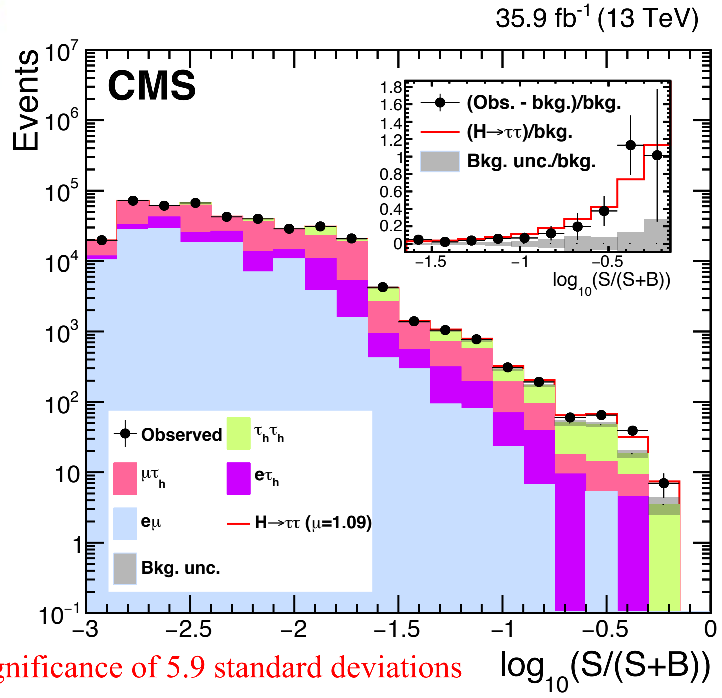
https://www.sciencedirect.com/science/article/pii/S0370269318301035?via%3Dihub

- Important final state to probe the direct coupling of the Higgs boson to elementary fermions, to establish the mass generation mechanism for such particles.
- H→ττ is the most promising decay channel because of the large event rate expected in the SM compared to the μ+μ− decay channel
  - B(H → τ+τ−) = 6.3% for a mass of 125.09 GeV
- ***g-g* fusion and *VBF* main production modes** investigated, three decay final states, depending on the leptonic or hadronic tau decay: *lep-lep*, *lep-had* and *had-had*
- main backgrounds: Drell-Yan Z/ γ*(+jets)→ ττ (irreducible), W+jets, ttbar, multi-jets, …
  - Evaluate background from data control samples
- Select events with high-p_T leptons (e, μ, τ_h), + high-p_T jets for the 2-jet category
- The most important variable studied: the ττ system mass $m_{\tau\tau}$:
  - CMS: the *SVFIT* algorithm combines p_T^{miss} with the four-vectors of both τ candidates to calculate an accurate estimate of the mass of the parent boson
  - ATLAS: use the collinear approximation and the MMC algorithm to estimate the mass of the parent boson





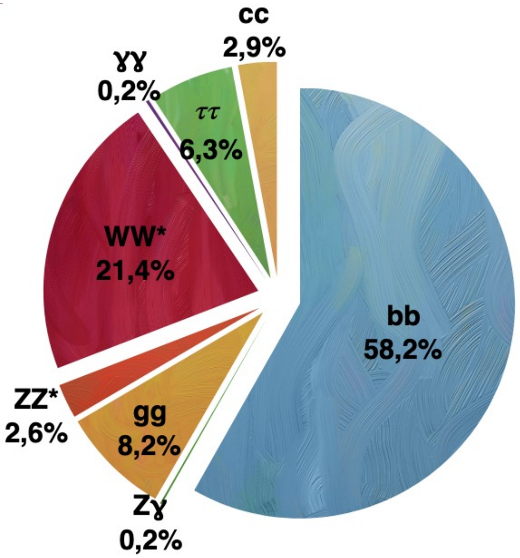
$\tau\tau$ invariant mass distribution, $\mu\tau_h$ decay channel - Observed and predicted 2D distributions in the VBF category



Signal significance of 5.9 standard deviations

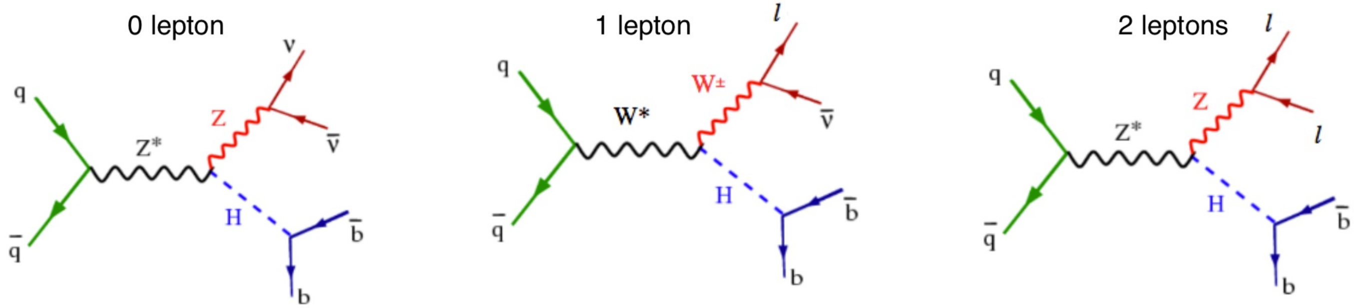
Distribution of the decimal logarithm of the ratio between the expected signal and the sum of expected signal and expected background, in all signal regions.

Observation of H→bb



H→bb: decay channel with the largest BR but with poor signal-to-noise ratio

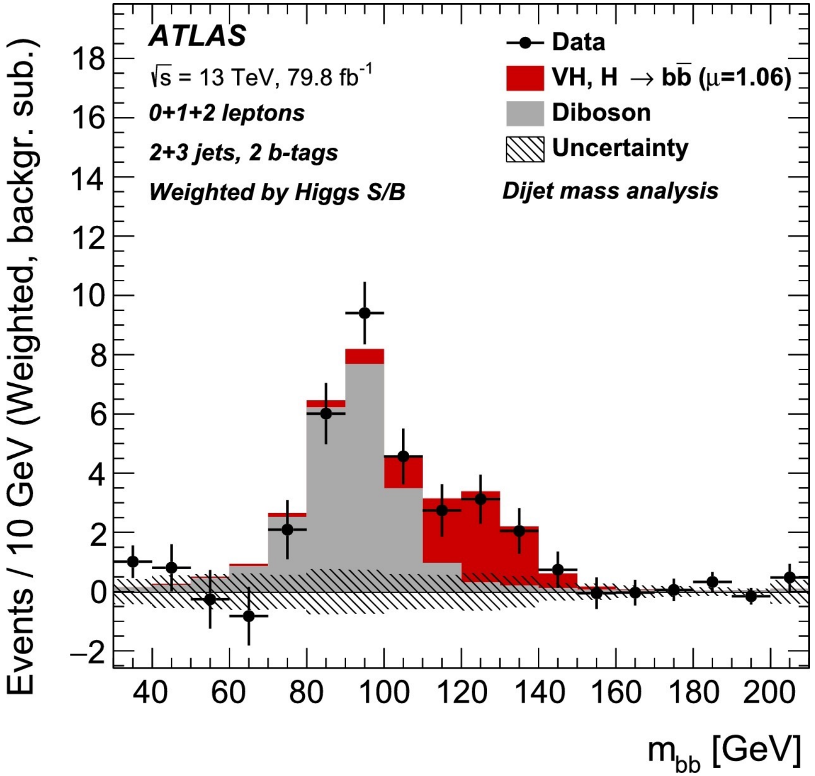
Very important process to test the Higgs Yukawa coupling to (3rd generation) quarks



Consider the VH ($V=W^{\pm},Z$) associate production mode: it offers a good background reduction with respect the gluon-gluon fusion production mode.
Vector boson in the final state are tagged through their decays to neutrinos (E_T^{miss}), and/or charged leptons (electons or muons).
Select events with **b-jets** (apply b-tagging algorithms).

Study the VZ → Vbb ($V=W^{\pm}$,Z) to cross check the data analysis

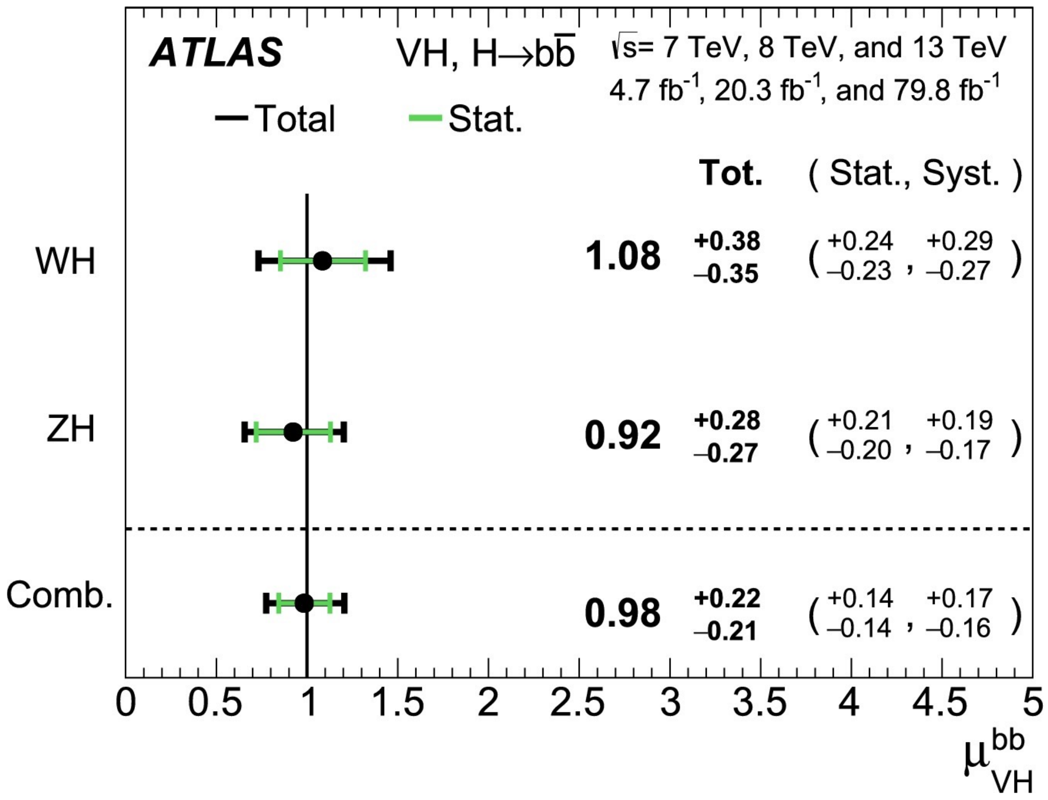
Phys. Lett. B 786 (2018)



distribution of m_{bb} in data after subtraction of all backgrounds except for the WZ and ZZ diboson processes, as obtained with the dijet-mass analysis

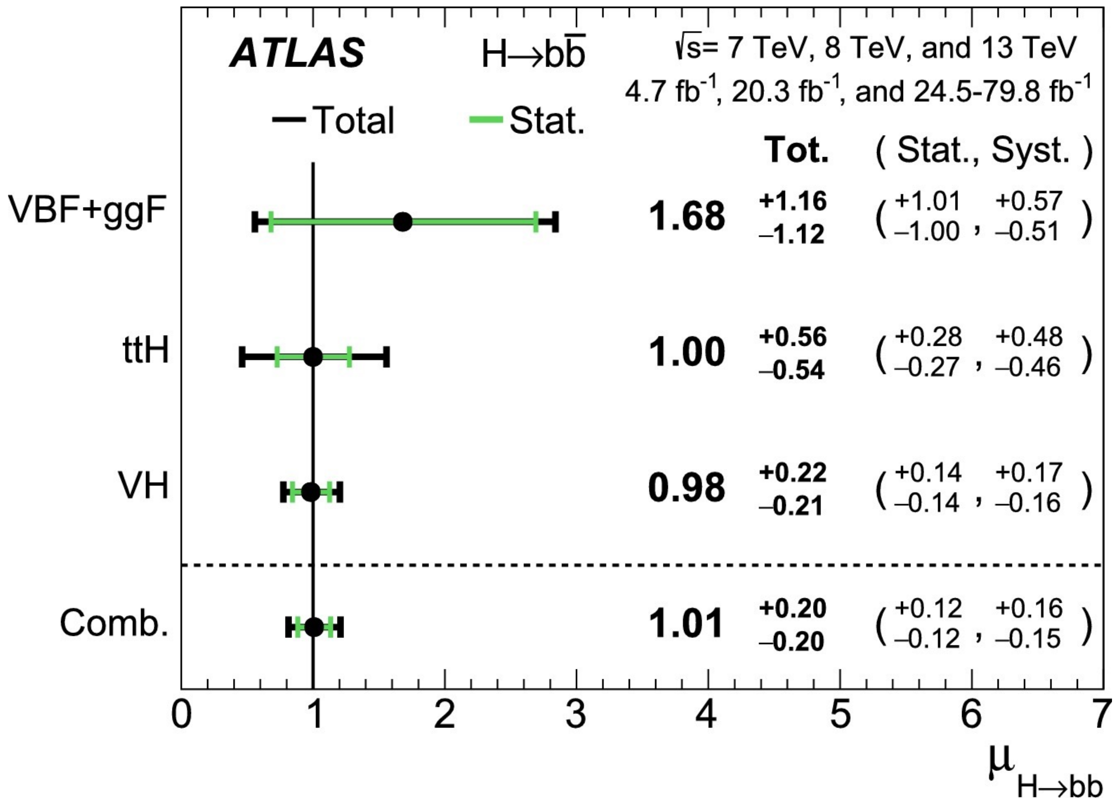
Significance = 4.9 s.d. (4.3 s.d. expected)

Observation of H→bb



Combination of VH, H→bb

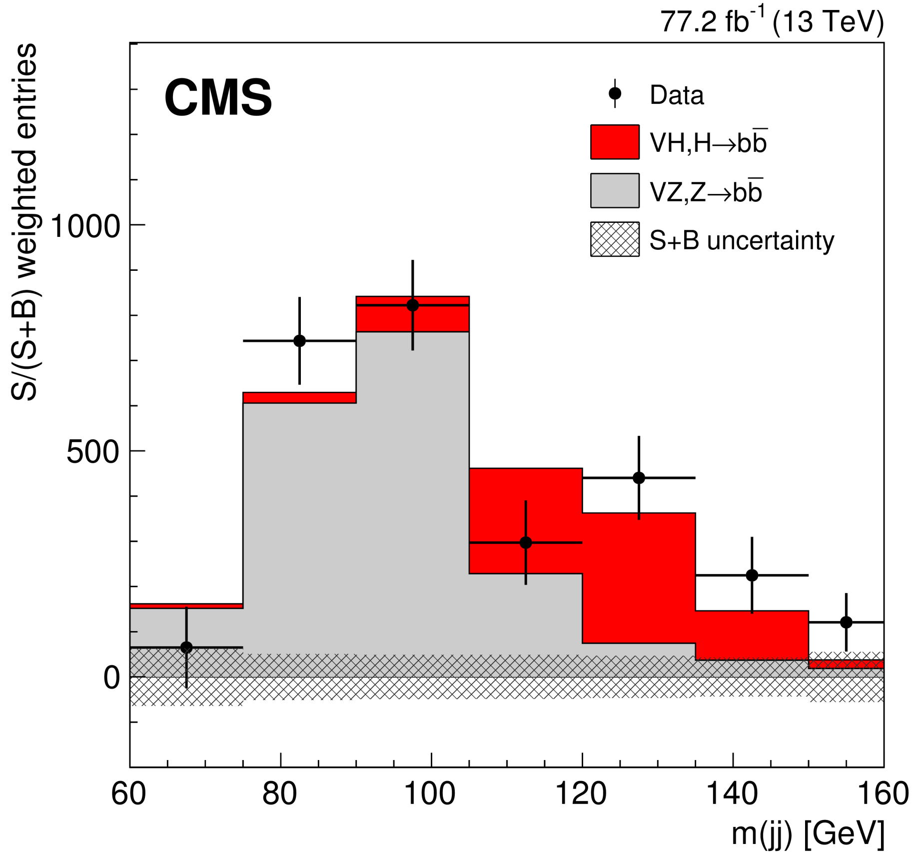
$\mu = 0.98 \pm 0.14\,^{+0.17}_{-0.16}$



Combination of VBF+ggF, VH, and ttH with H→bb

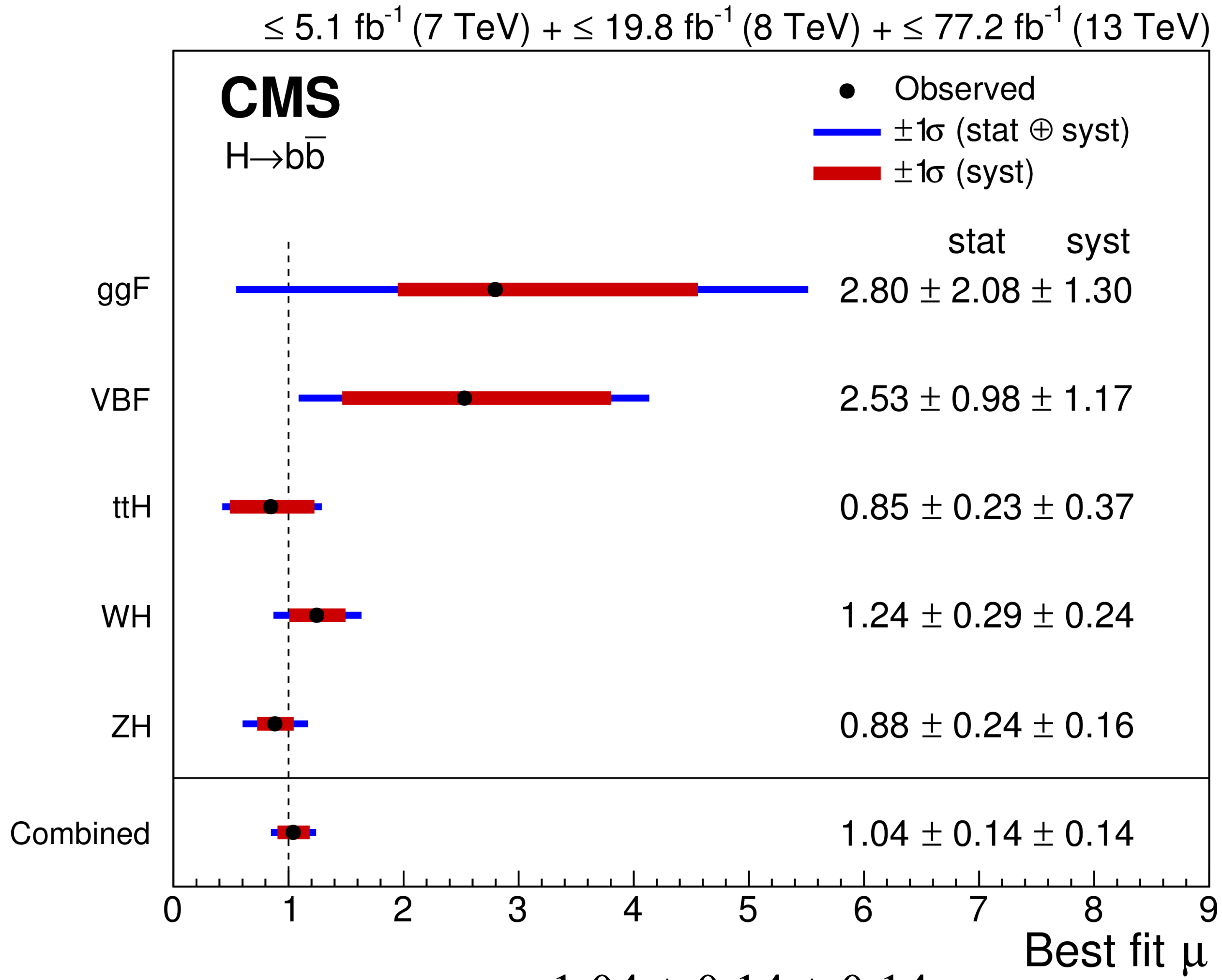
$\mu = 1.01 \pm 0.12\,^{+0.16}_{-0.15}$

Observation of H→bb



Dijet invariant mass distribution for events weighted by $S/(S+B)$. Data (points) and the fitted VH signal (red) and VZ background (grey) distributions, with all other fitted background processes subtracted, are shown.

Phys. Rev. Lett. 121, 121801

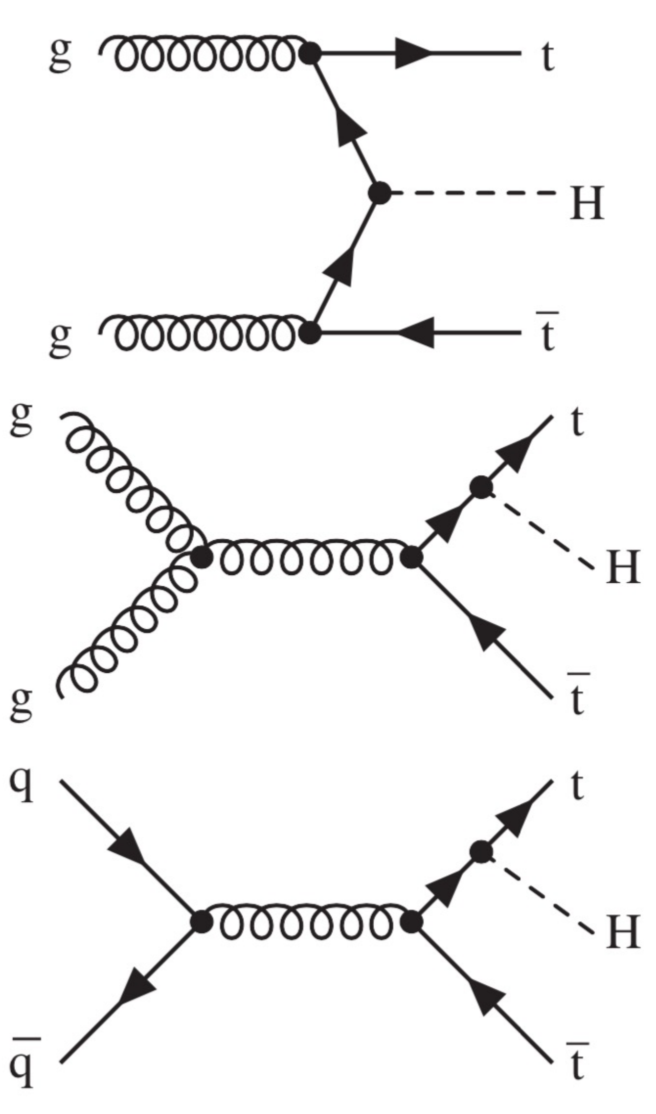


$\mu = 1.04 \pm 0.14 \pm 0.14$

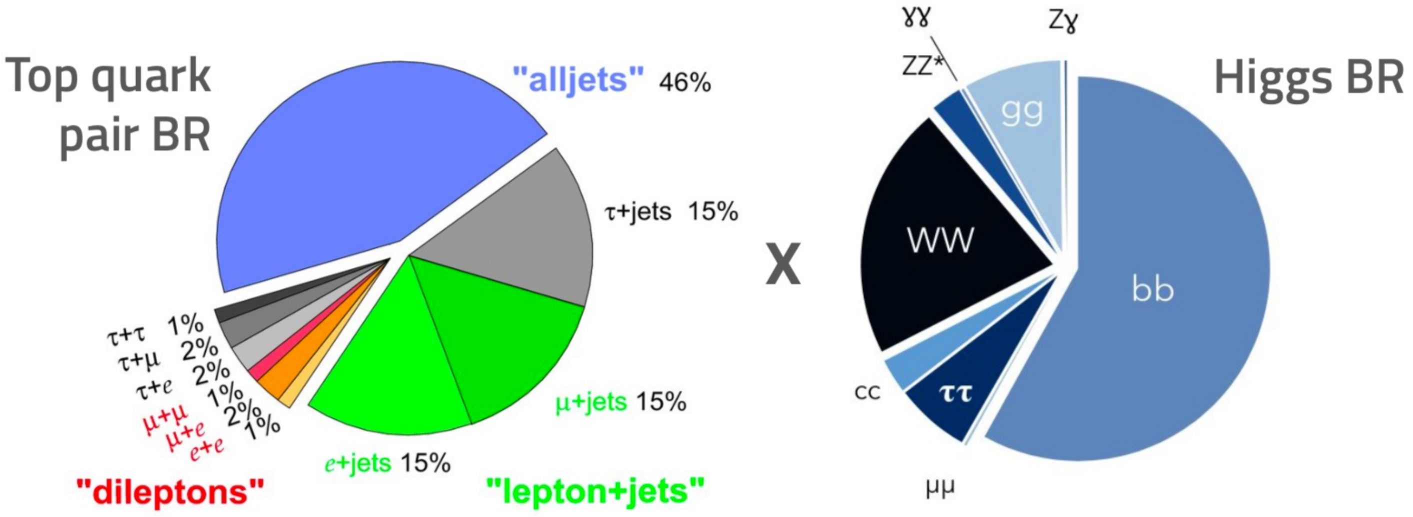
Latest results in Eur. Phys. J. C 81 (2021) 178 : all Run 2 data used $\mu_{\mathrm{Run2}} = \mathbf{1.02}\ ^{+0.12}_{-0.11}\ ^{+0.14}_{-0.13}$

Observation of the ttH production process

- Evidence for the Higgs coupling to fermions is a milestone in the Higgs sector studies
- Top Yukawa coupling is the most important one:
  - Strongest coupling of the Standard Model, ~1
  - Sensitive to New Physics
  - Significant role in ElectroWeak vacuum stability
- Running of Higgs self coupling (λ) sensitive to Top Yukawa coupling (y_t)
- The only Higgs coupling that cannot be observed from direct Higgs decay



ttH process at tree level



ttH system final states

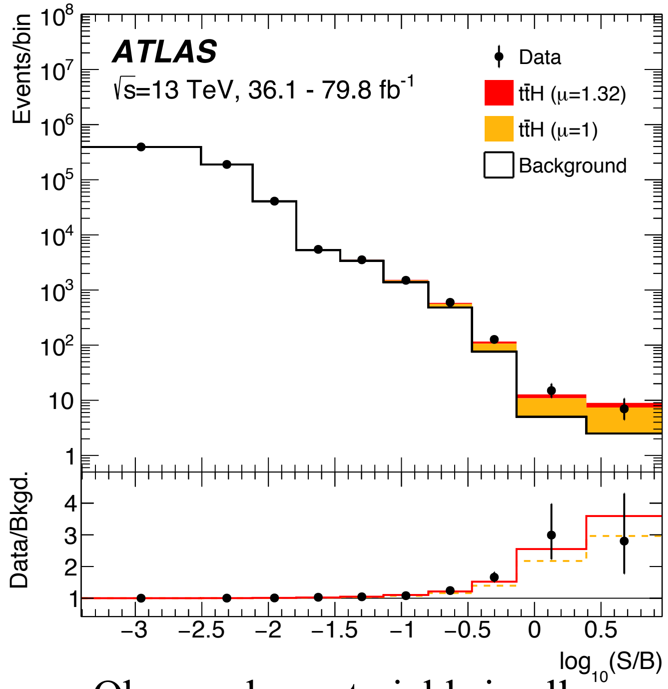
Observation of the ttH production process

- Data sample:

DATA SAMPLE fb $^{-1}$	$\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV	$\sqrt{s}$ = 13 TeV
ATLAS	4.5	20.3	79.8
CMS	5.1	19.7	19.7

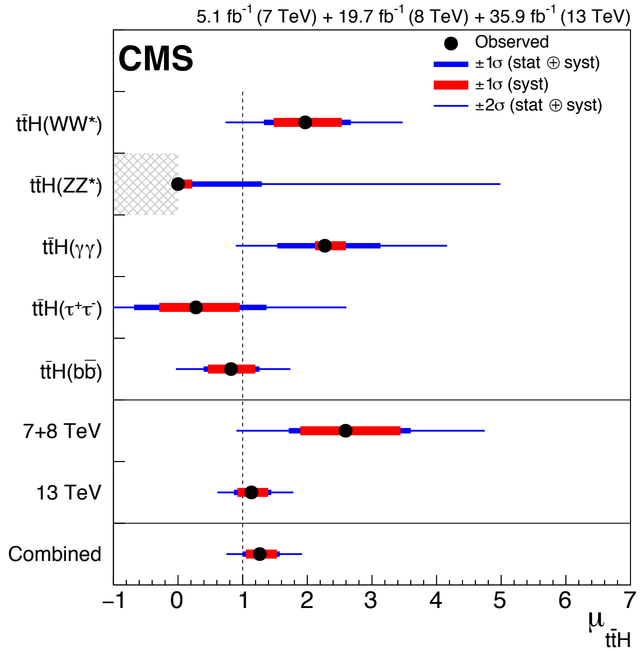
- Event selection:
  - final states with **high-p_T b-jet(s)**, and **leptons** to select ttbar systems.
  - final states **bb**, **WW***, **$\tau^+\tau^-$**, **$\gamma\gamma$** and **ZZ*** are considered to reconstruct the Higgs boson (high-p_T photons, $\tau^{\pm}$ and large E_T^{miss})
  - Event categorisation to enhance signal sensitivity

Phys. Lett. B 784 (2018)

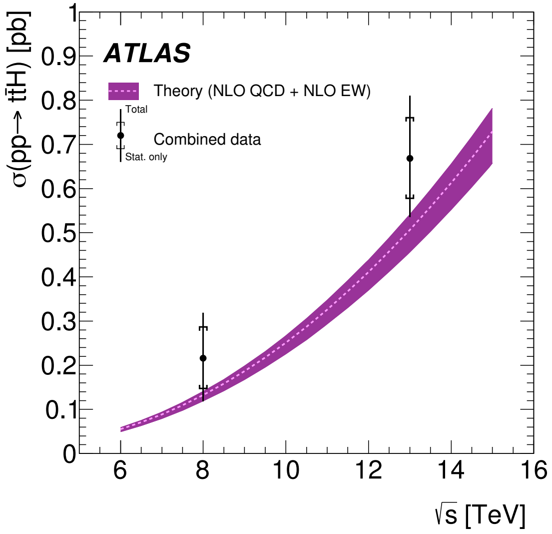


Observed event yields in all analysis categories in up to 79.8 fb^{-1} of 13 TeV data.

Phys. Rev. Lett. 120 (2018) 231801



Best fit value of the ttH signal strength modifier, m_H set to the Higgs 125.09 GeV. Dashed vertical line: SM expectation



Measured $t\bar{t}H$ cross sections in pp collisions at centre-of-mass energies of 8 TeV and 13 TeV

Signal significance: 5.2/6.3 standard deviations from ATLAS/CMS

ttH **production cross section at 13 TeV: 670 ± 90 (stat.) $^{+110}_{-100}$ (syst.) fb (ATLAS)**

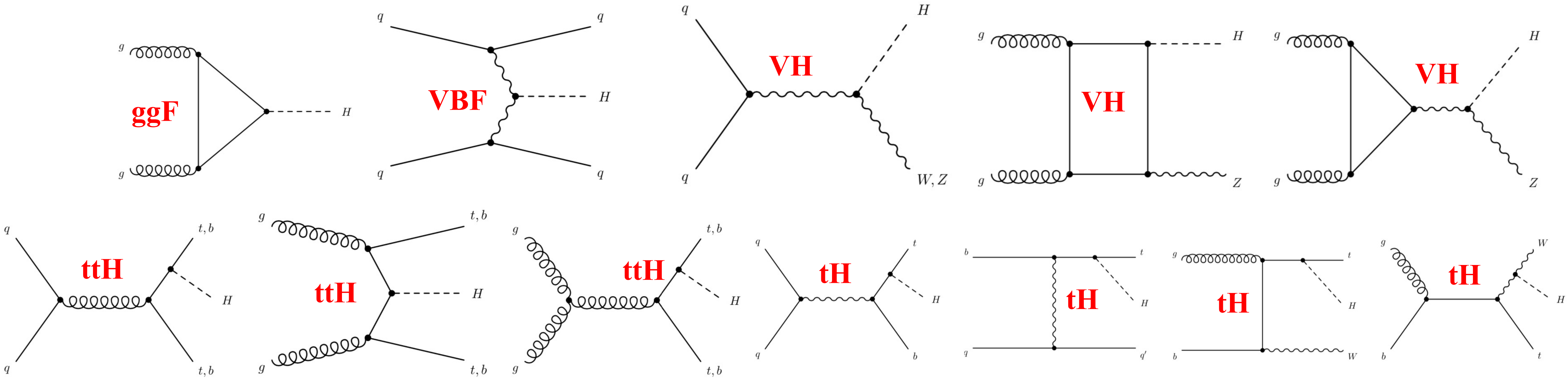
The Higgs Combination

The Higgs Combination - 1

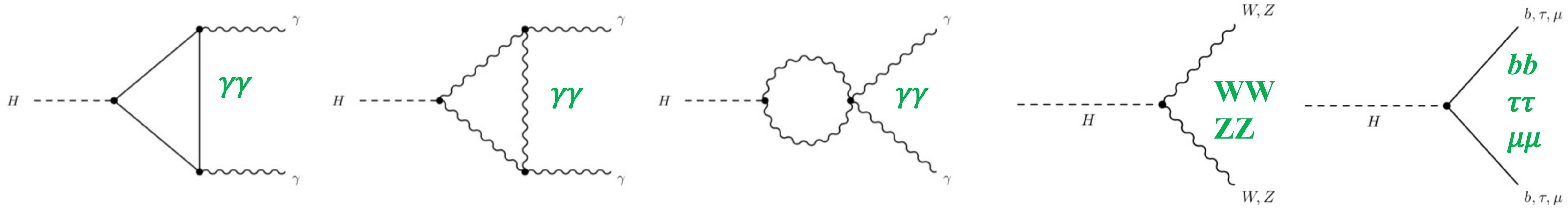
- ATLAS and CMS measured rates from several production processes and decay final states of this new particle
- The combination:
  - of different measurements by the same experiment
  - and the measurements of the two experiments

  is key to verify the consistence of these findings with the predictions of the Standard Model
- Deviations from the SM would inevitably indicate presence of new physics
- ATLAS and CMS made an effort to combine their findings from LHC **Run 1 ($\sqrt{s}$ = 7 and 8 TeV)**
  - data sample: **5 fb^{-1} at $\sqrt{s}$ = 7 TeV and 20 fb^{-1} at $\sqrt{s}$ = 8 TeV**
- The results are available in this paper *JHEP* **2016**, 45 (2016)

The Higgs Combination - 2



Examples of leading-order Feynman diagrams for Higgs boson production



Examples of leading-order Feynman diagrams for the Higgs boson decay final states

The Higgs Combination - 3

- Very detailed and complex studies
- Some example of the most interesting ones follow

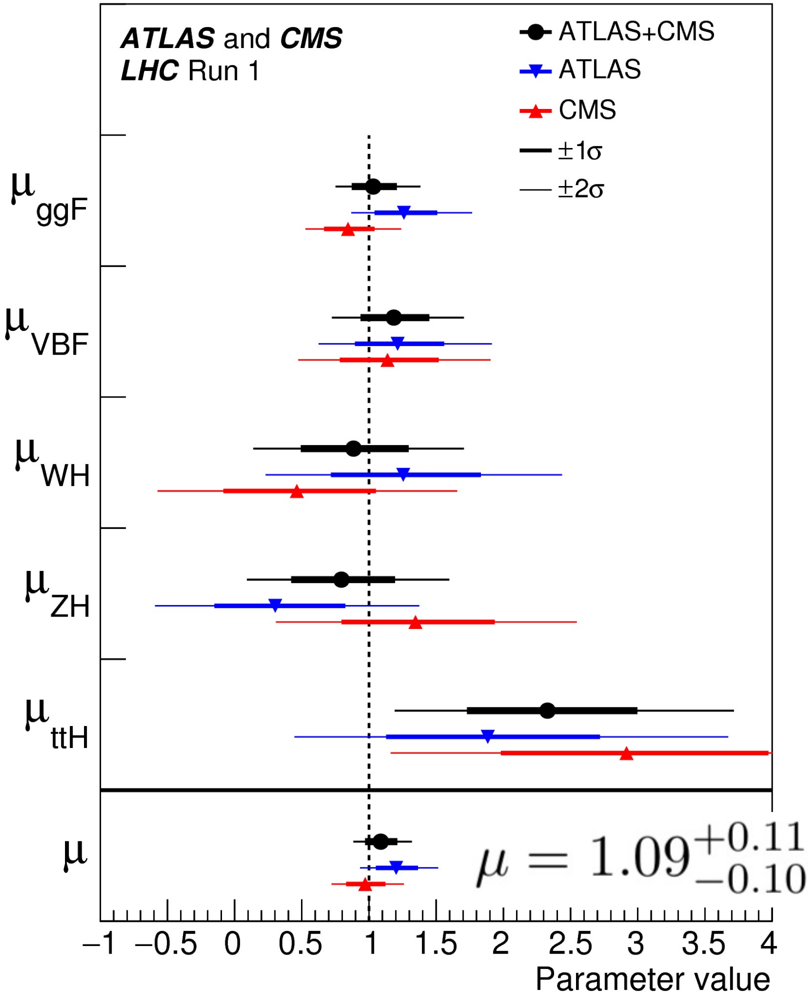
The signal strength:

production signal strength $\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$

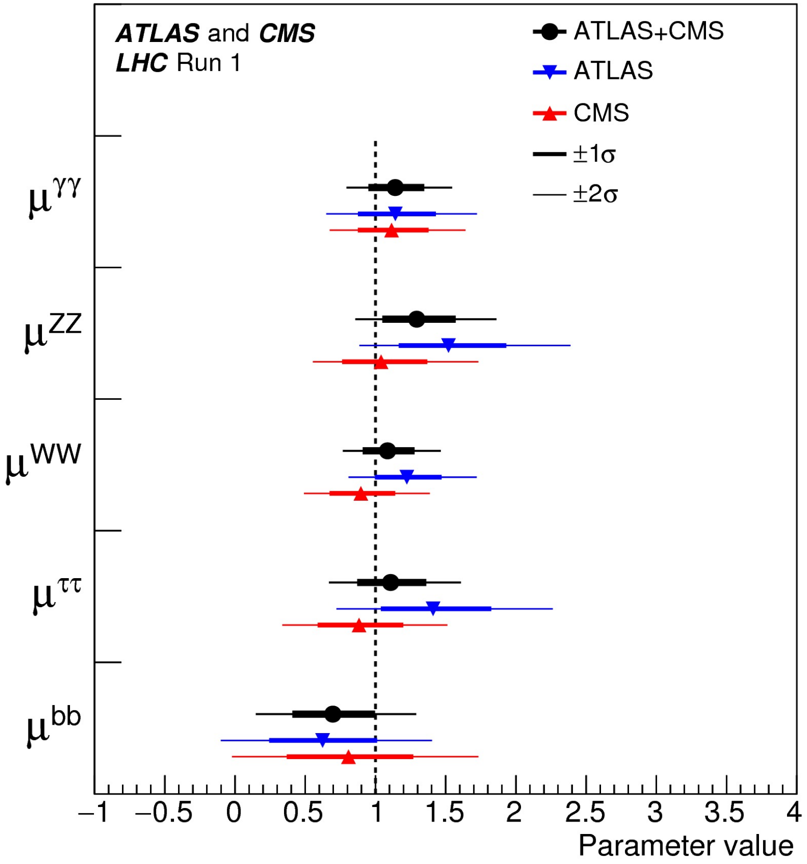
branching fraction signal strength $\mu^f = \frac{B^f}{(B^f)_{SM}}$

$$\mu_i^f = \frac{\sigma_i \cdot B^f}{(\sigma_i)_{SM} \cdot (B^f)_{SM}} = \mu_i \cdot \mu^f.$$

Signal strength consistent with Standard Model predictions



Best fit results for the production signal strengths for the combination of ATLAS and CMS data, assuming the SM values for the Higgs boson branching fractions, $\mu_f = 1$

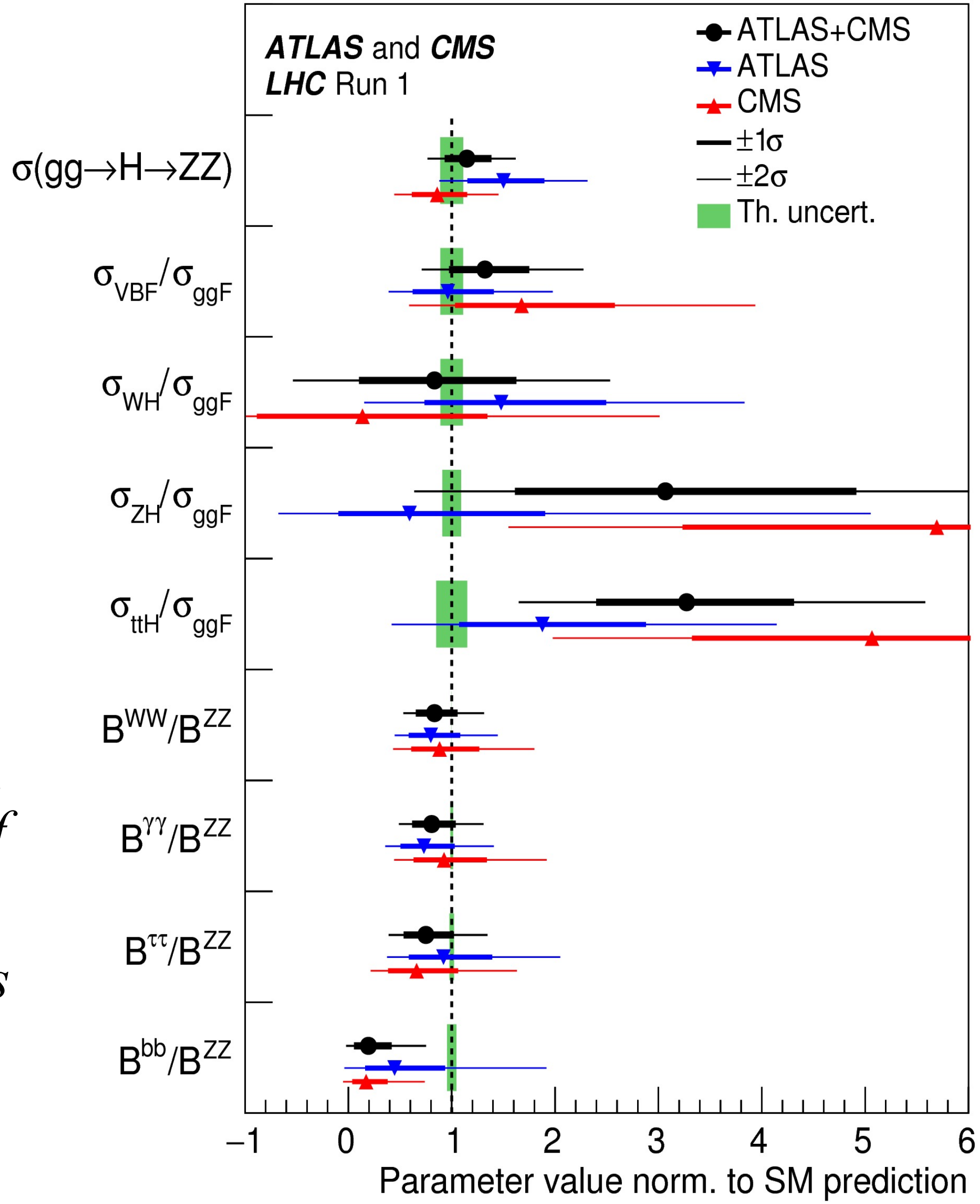


Best fit results for the decay signal strengths for the combination of ATLAS and CMS data, assuming that the Higgs boson production cross sections are the same as in the SM, $\mu_i = 1$

The Higgs Combination - 4

The Higgs boson natural width cannot be measured at LHC. **Model-dependent** assumptions should be made to extract absolute cross sections and/or branching fractions.

A **model independent** assessment can be made by studying ratio of rates from the various processes → gives ratios of production cross sections or ratios of branching fraction



Best fit values of the σ(gg→ H→ ZZ) cross section and of ratios of cross sections and branching fractions. The fit results are normalised to the SM predictions for the various parameters. Shaded bands indicate the theoretical uncertainties in these predictions.

The p-value of the compatibility between the data and the SM predictions is 16%. Most measurements are consistent with the SM predictions within less than 2 standard deviations

Higgs couplings – the *kappa framework* - 1

the production and decay of the Higgs boson can be factorised, such that the cross section times branching fraction of an individual channel σ(i → H → f) can be parameterised as

$$\sigma_i \cdot \mathrm{B}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

Γ_H is the total width of the Higgs boson

Γ_f is the partial width for Higgs boson decay to the final state f

κ is an array of multiplicative parameters that modify the Higgs coupling strength to fermions and bosons

$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}$$

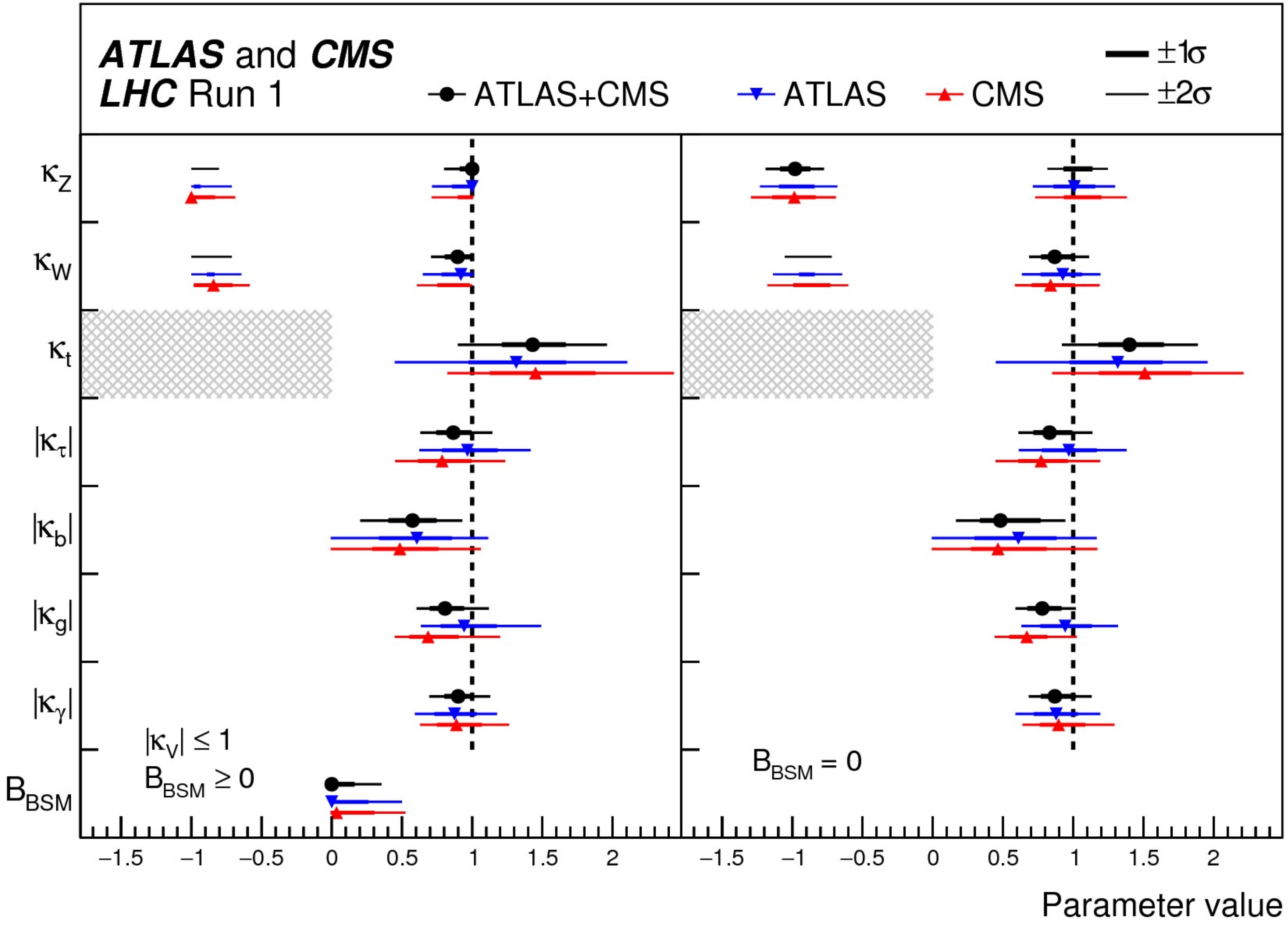
Production — Decay

SM: $\kappa_i = 1$ (for all possible values of *i*)

$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{B}_{\mathrm{BSM}}}$$

Reflects the possibility allow for the possibility of Higgs boson decays to invisible or untagged BSM particles.

Higgs couplings – the *kappa framework* - 2



Coupling fit results

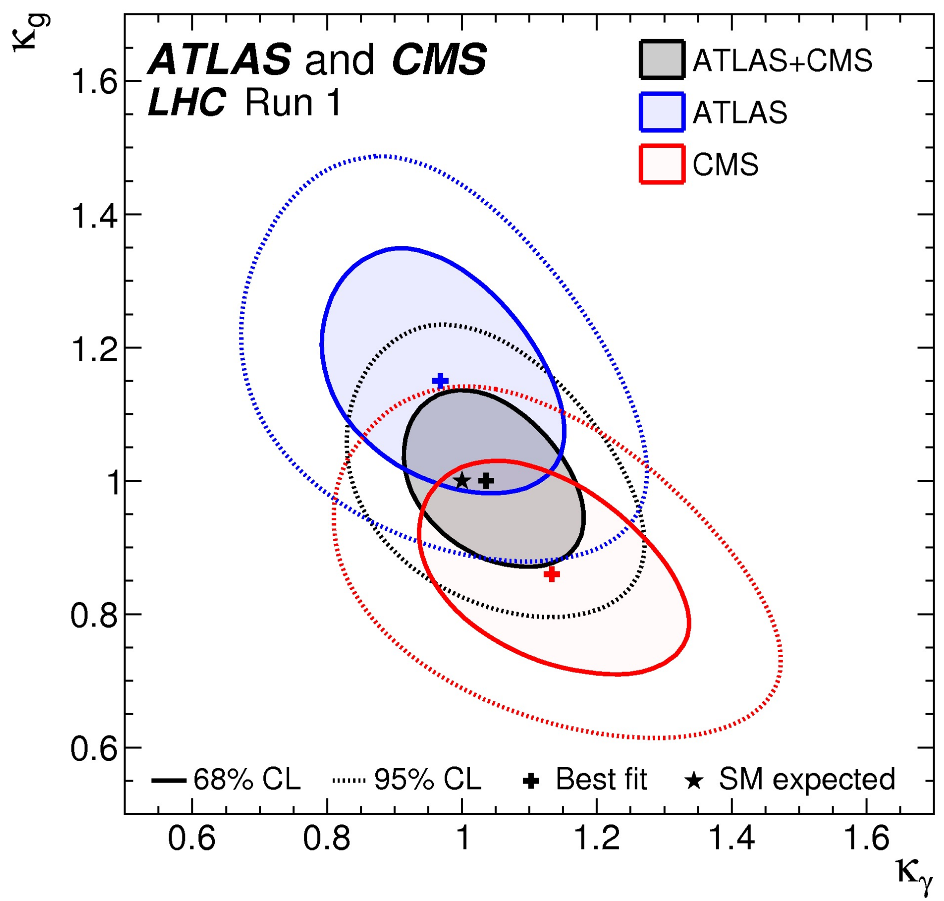
LEFT: B_{BSM} is free, and that $|\kappa_V| \leq 1$, where κ_V denotes κ_Z or κ_W

RIGHT: assumes that there are no additional BSM contributions to the Higgs boson width, i.e. $B_{BSM} = 0$.

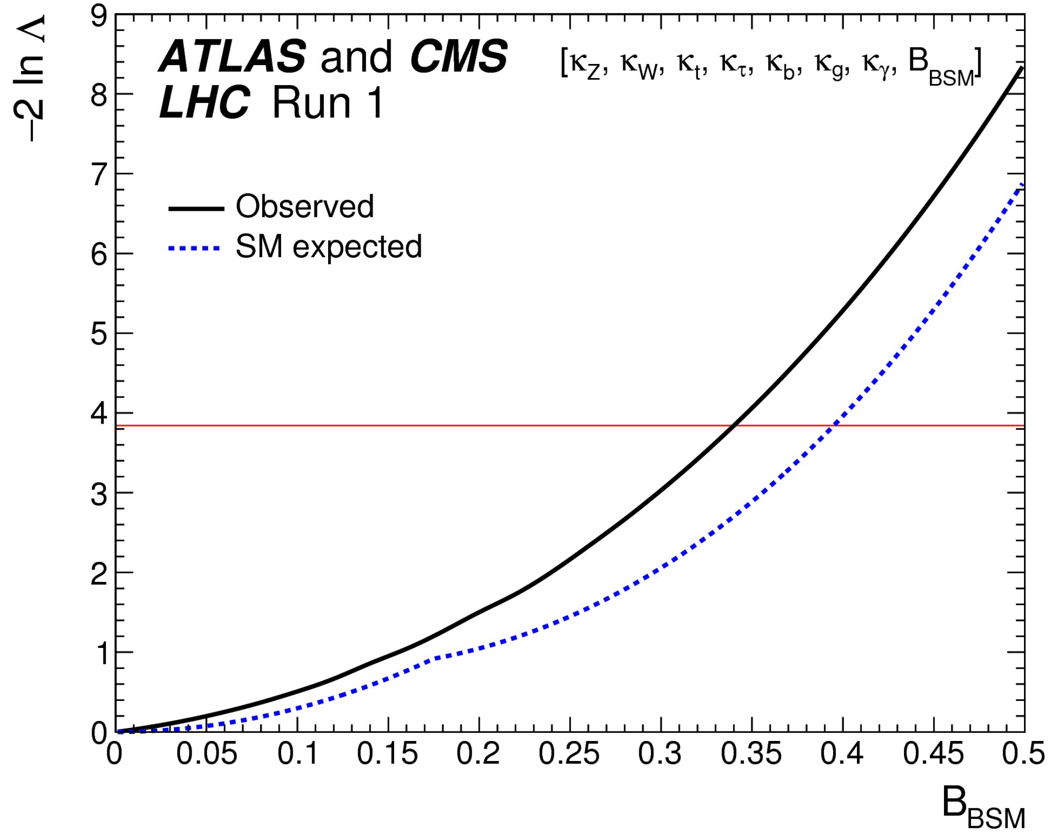
Thick lines: 1σ error bars

Thin lines: 2σ error bars

Higgs couplings – the *kappa framework* - 3

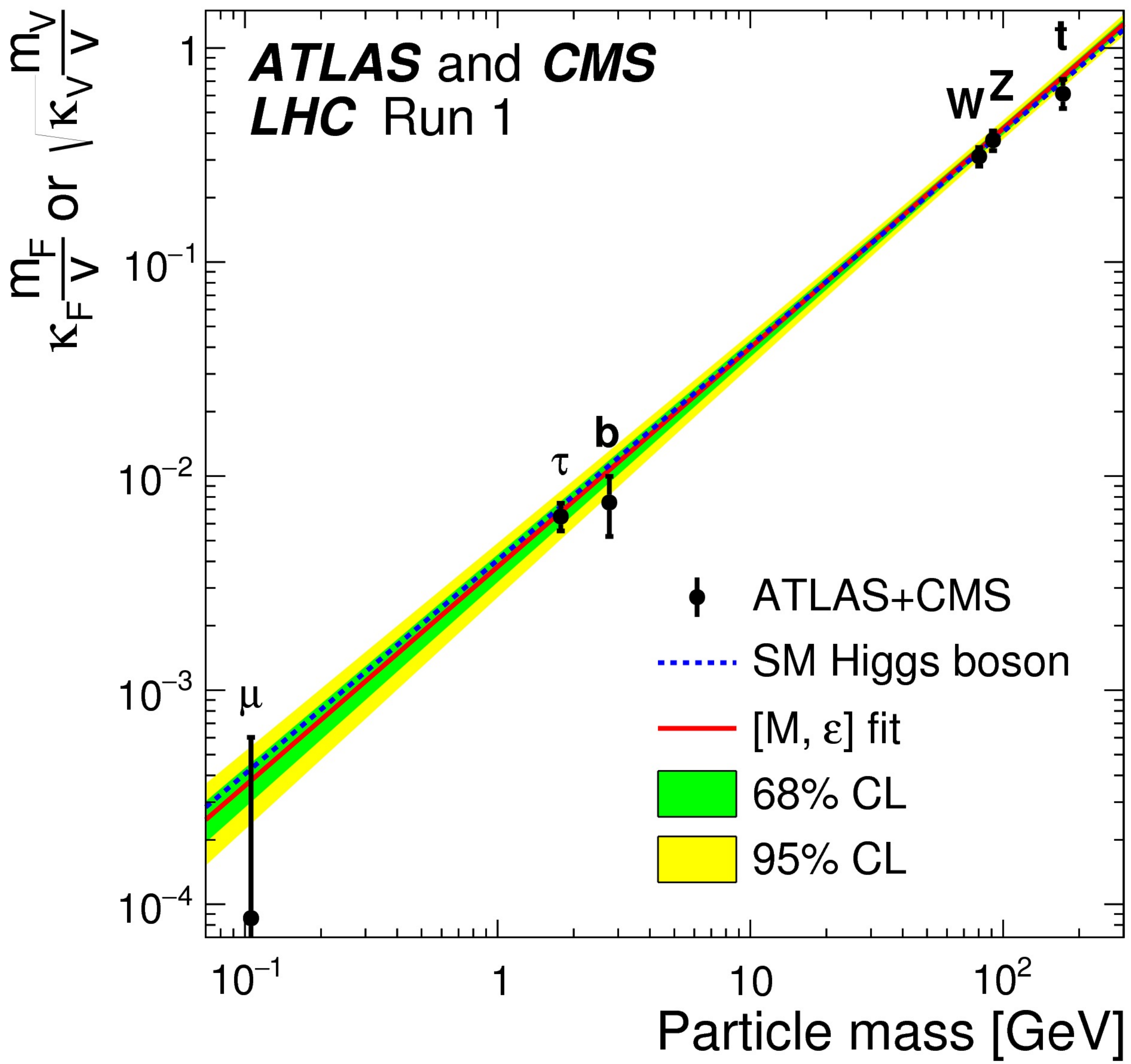


Negative log-likelihood contours at 68% and 95% CL in the (κγ, κ_g) plane for the combination of ATLAS and CMS.
In the fit all the other coupling modifiers are set to their SM values and assuming $B_{BSM} = 0$



Observed (solid line) and expected (dashed line) negative log-likelihood scan of B_{BSM} when allowing additional BSM contributions to the Higgs boson width. Assumptions: $|\kappa_V| \leq 1$ and $B_{BSM} \geq 0$. All other parameters of interest from the list in the legend are also varied in the minimisation procedure. The red horizontal line indicates the log-likelihood variation corresponding to the 95% CL upper limit

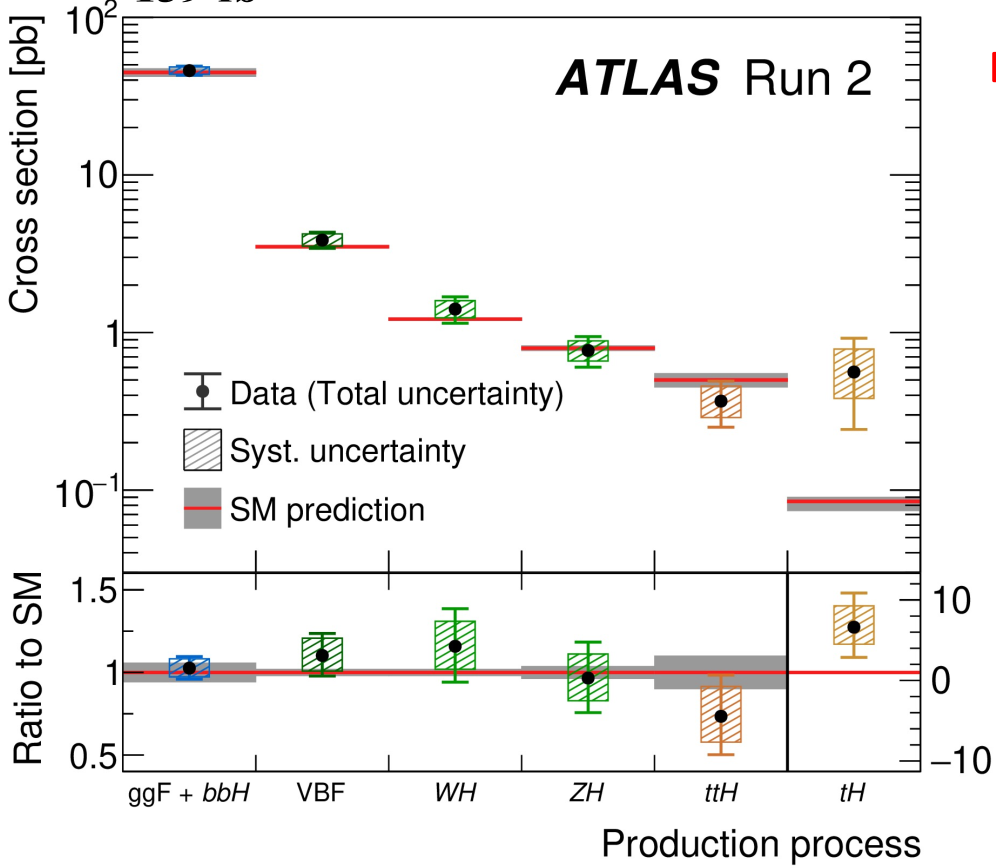
Higgs couplings – the *kappa framework* - 4



- All measurements based on the generic parameterisations are compatible between the two experiments and with the predictions of the SM.
- The potential presence of physics beyond the SM (BSM) is also probed using specific parameterisations.
- With minimal additional assumptions, the overall branching fraction of the Higgs boson into BSM decays is determined to be less than 34% at 95% CL.
- The combined signal yield relative to the SM expectation is measured to be 1.09 ± 0.07 (stat) ±0.08 (syst), where the systematic uncertainty is dominated by the theoretical uncertainty in the inclusive cross sections.

Latest results: signal strengths

139 fb^{-1} [Nature 607 (2022) 52]



Cross sections for different Higgs boson production processes assuming SM decay branching fractions.

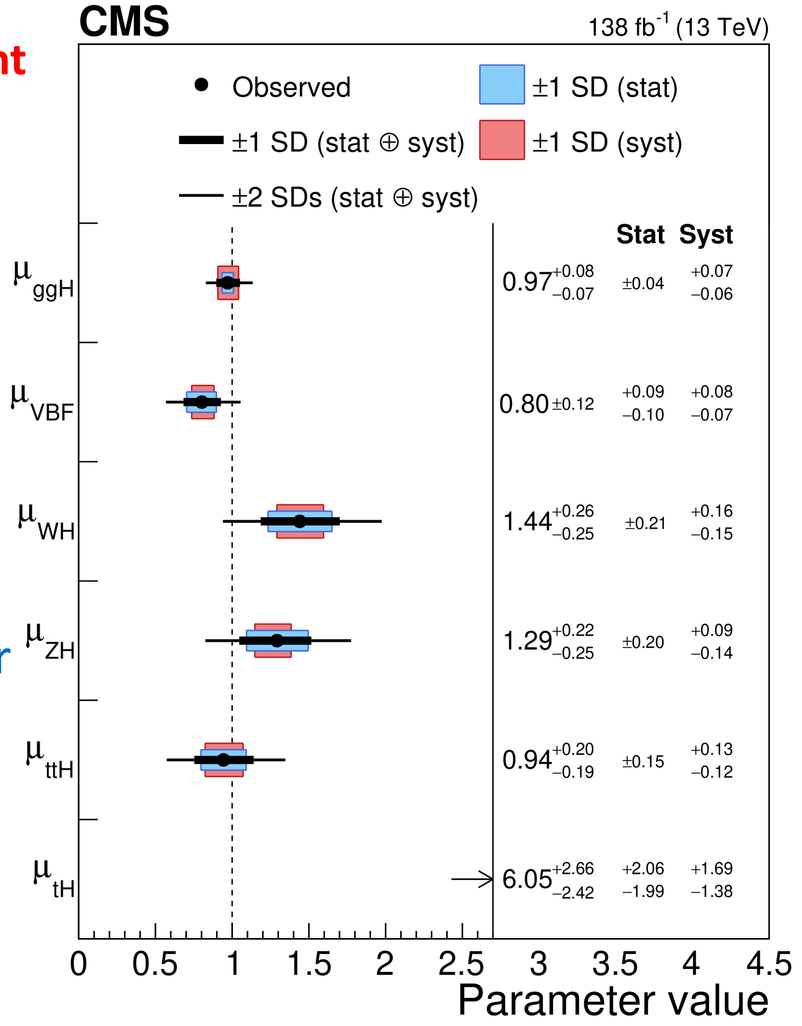
Data sample: 139 fb^{-1} per experiment

Signal strength parameters extracted for various production modes μ_i, assuming SM decay branching fractions

gluon-gluon fusion precision better than 10%!

10-20% precision on other major production modes

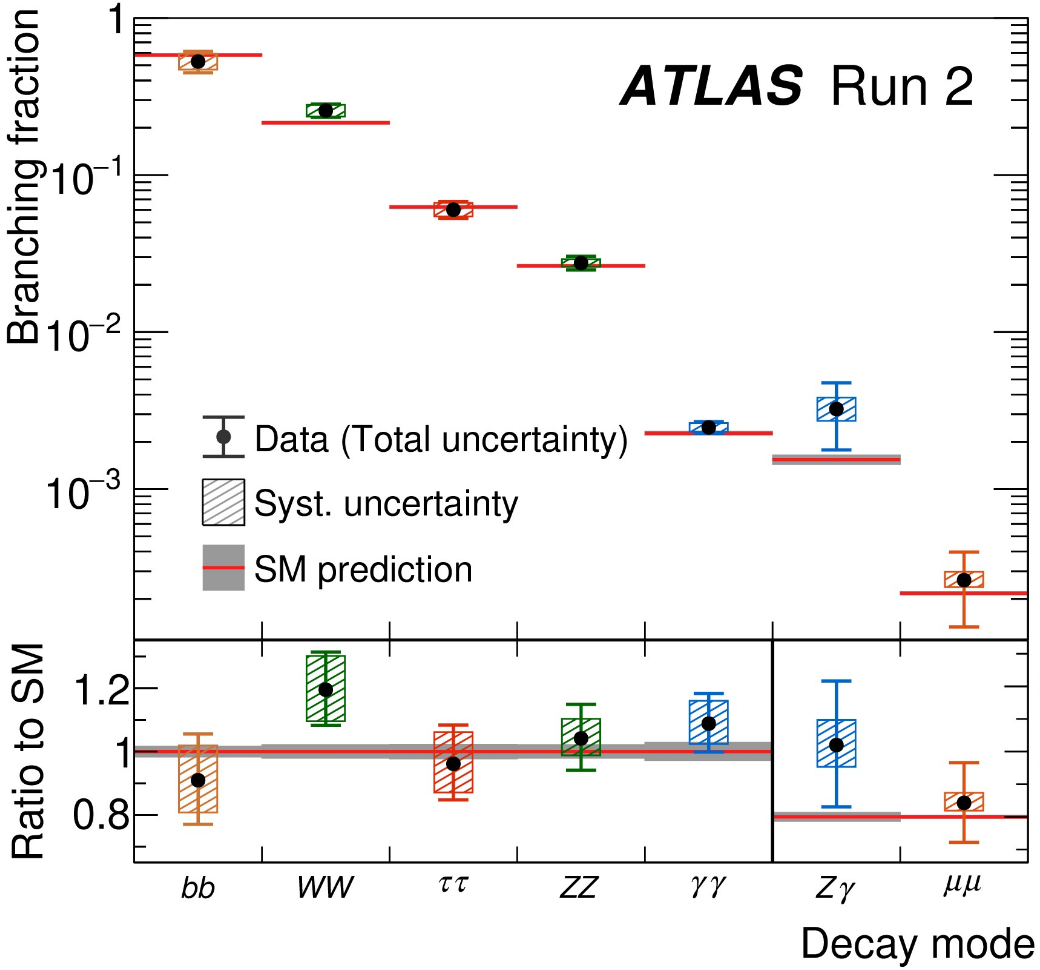
[Nature 607 (2022) 60]



$$\text{ATLAS} \quad \mu = 1.05 \pm 0.06 = 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{sys}) \pm 0.04(\text{th.})$$

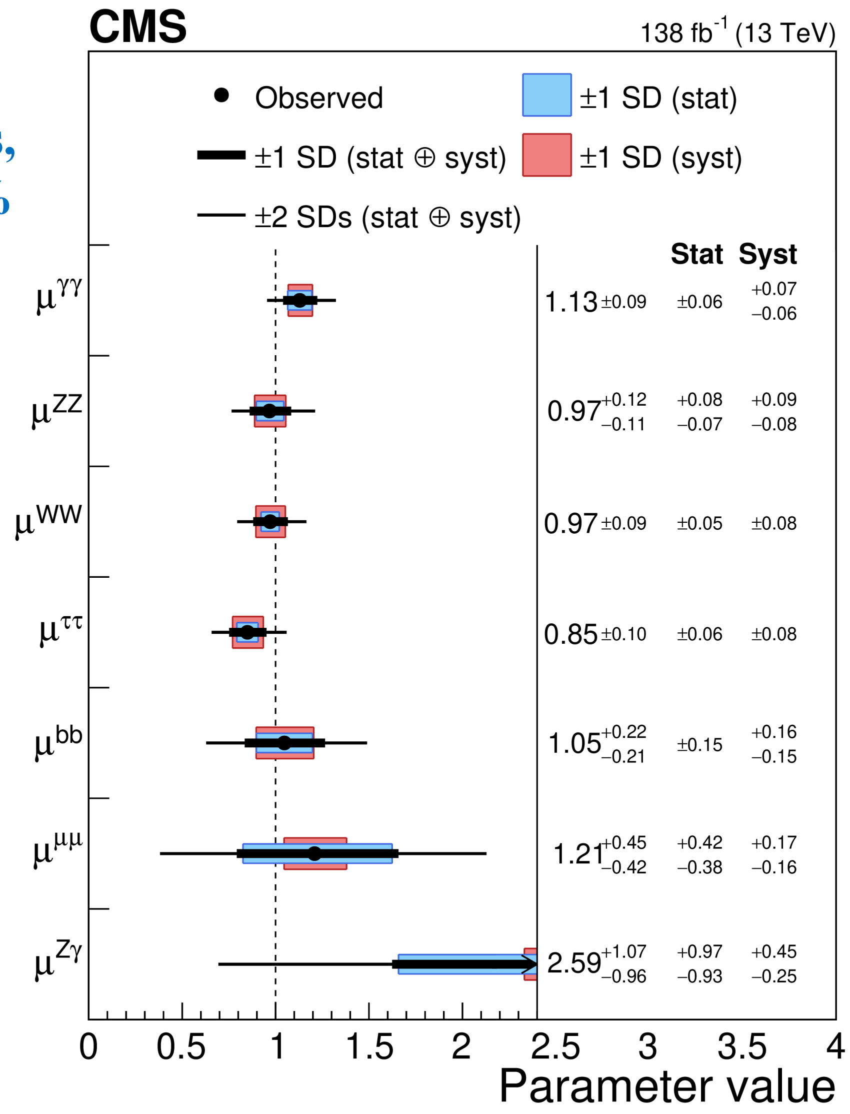
$$\text{CMS} \quad \mu = 1.002 \pm 0.057 = 1.002 \pm 0.029(\text{stat.}) \pm 0.033(\text{sys}) \pm 0.029(\text{th.})$$

Latest results: branching ratios



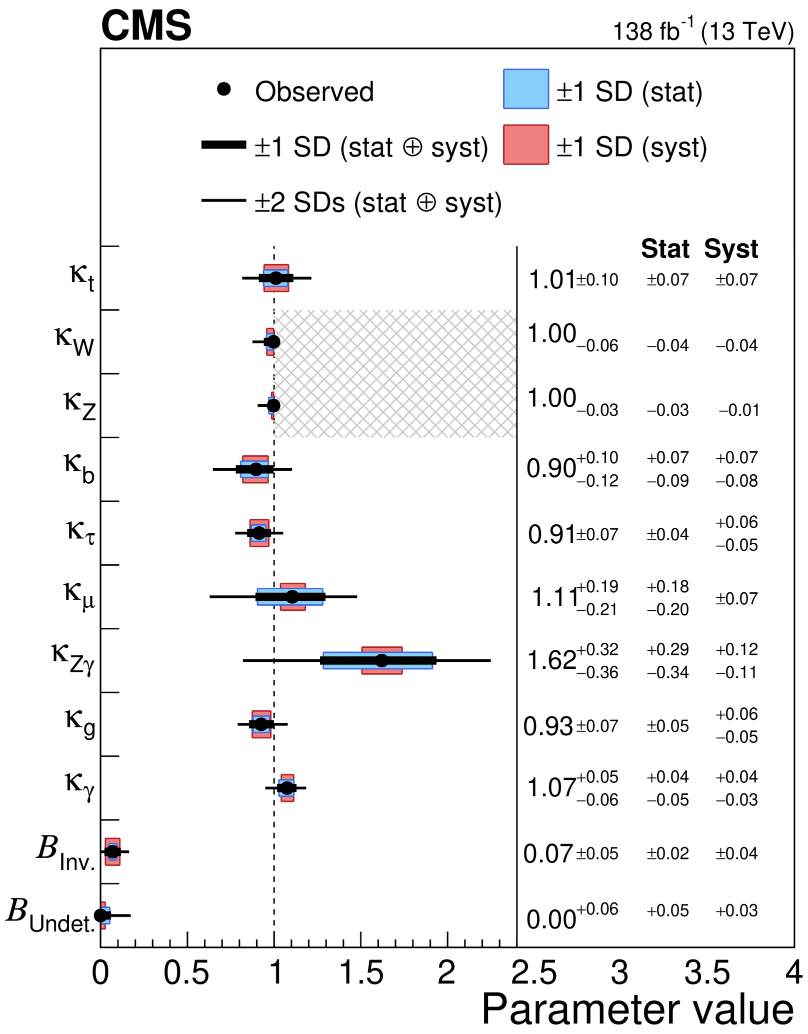
Branching Fractions for different Higgs boson decay modes assuming SM production cross sections.
p-value for compatibility with SM: 65%

Precision on bosonic decays, decays to tau leptons: ~10%



Signal strength parameters assuming SM production cross sections.

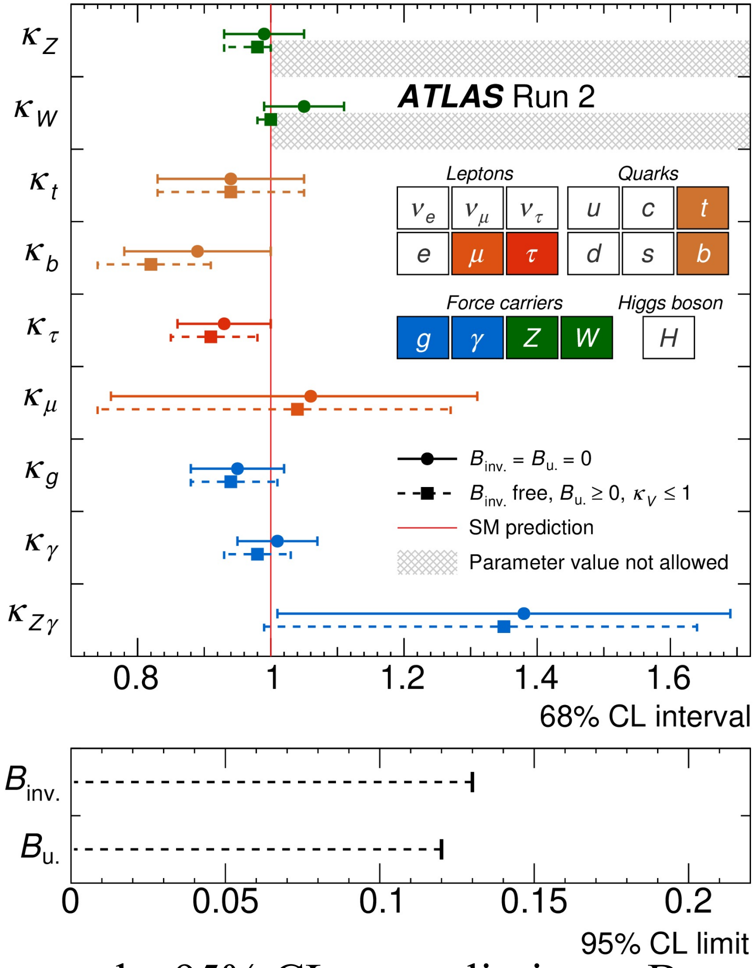
Latest results: couplings - 1



measurements of Higgs boson decays into invisible final states are included and provide a constraint on B_{inv}

To constrain B_{undet}: assume $\kappa_W, \kappa_Z \leq 1$

Compare with the *squares*

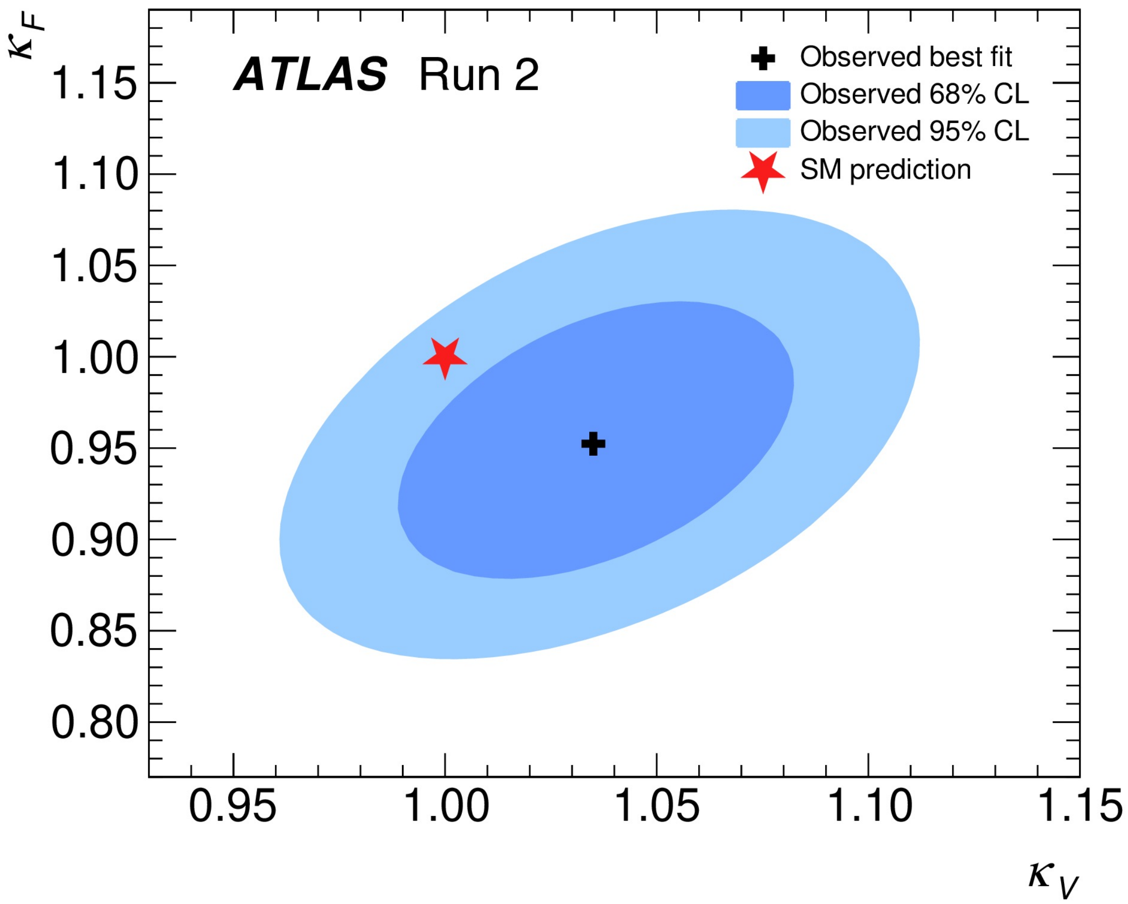


lower panel shows the 95% CL upper limits on $B_{inv.}$ and $B_{u.}$

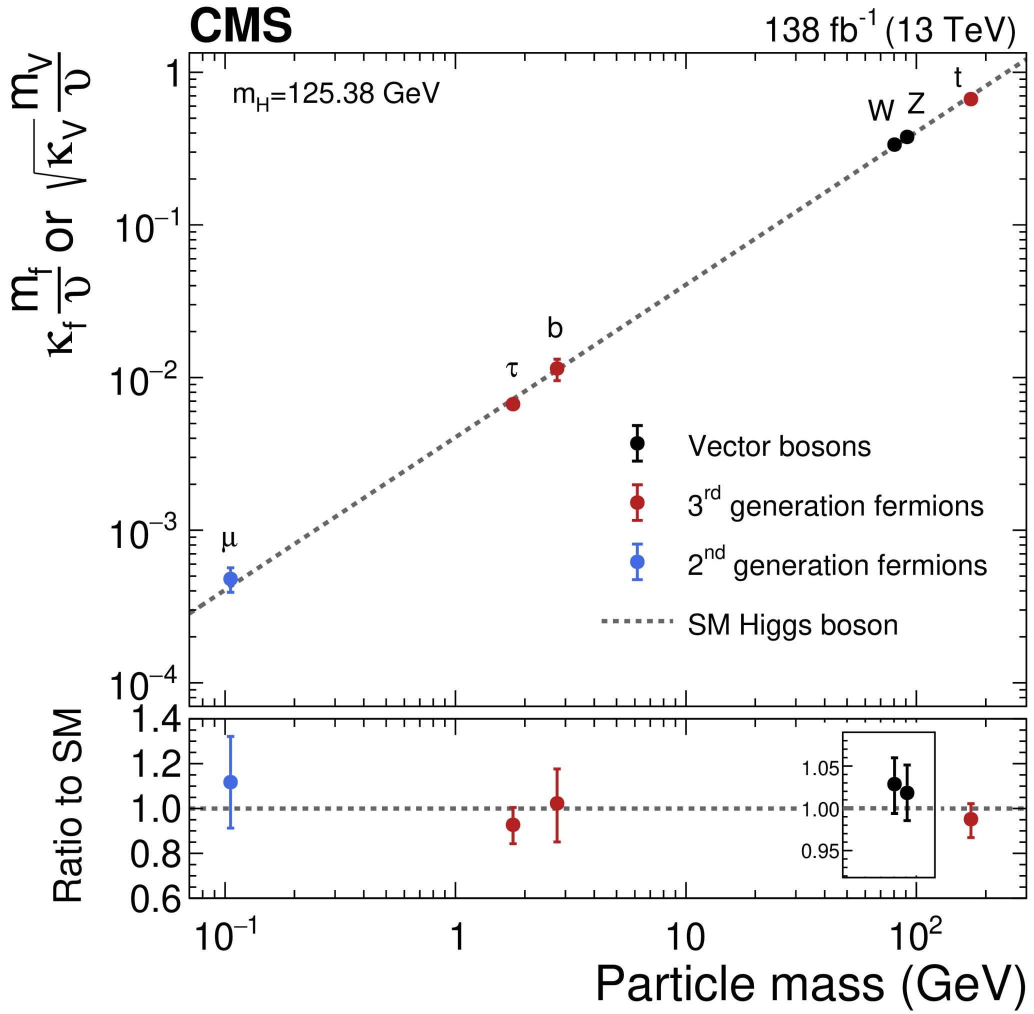
coupling strength modifiers and their uncertainties per particle type with effective photon, $Z\gamma$ and gluon couplings.

Strongest constraints on effective coupling modifiers: **O(5%)**

Latest results: couplings - 2



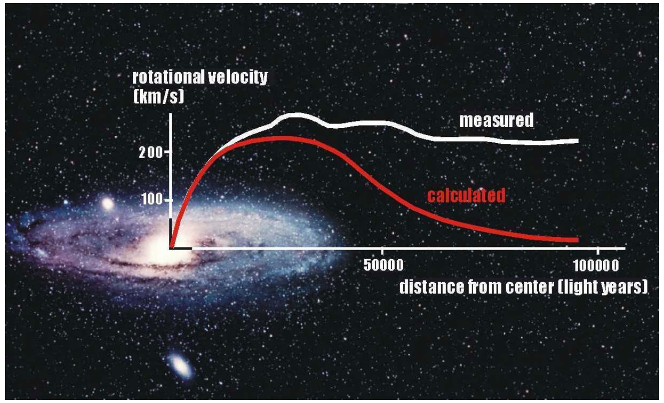
Scale all vector boson couplings with κ_V, all fermion couplings with κ_F



coupling modifiers of the Higgs boson to fermions and heavy gauge bosons, as functions of fermion or gauge boson mass, where υ is the vacuum expectation value of the BEH.

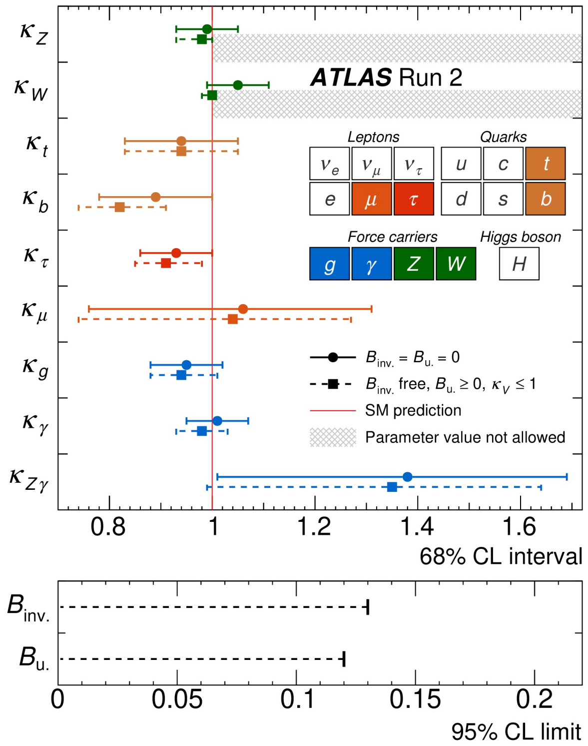
Higgs to invisible decays

- The measurements presented in these slides show consistence of the 125 Higgs boson with the Higgs boson predicted by the Standard Model
- But we have many unanswered questions and open points that cannot be explained by Standard Model and for which the observed Higgs boson could play a role
- Among these open questions we have the existence of Dark Matter and its connection, if any, with this scalar
- Several Beyond Standard Model (BSM) theories predict non-standard 125 GeV Higgs decays
- These final states would consist (also) of "invisible" particles in the final states, so one of the driving channels to search for production of Dark Matter at the LHC is the study of H→invisible decays



galaxy rotation

gravitational lensing



$B_{inv} < 0.13$ @ 95% C.L.

SM BR for H → invisible (4ν) is ~ 0.1%.

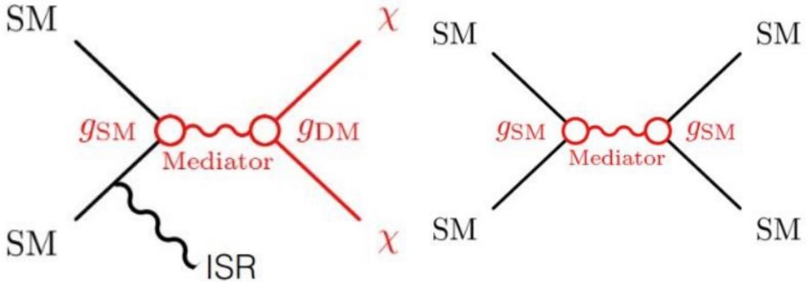
Plenty of room for beyond-SM physics in Higgs boson decays!

Bridge between astrophysics and high-energy physics

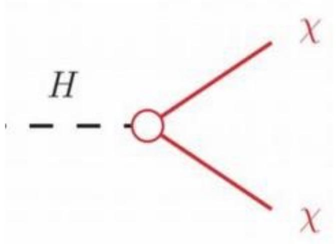
Overview of Dark Matter models

Talk by Zirui Wang at the Lomonosov 21 conference

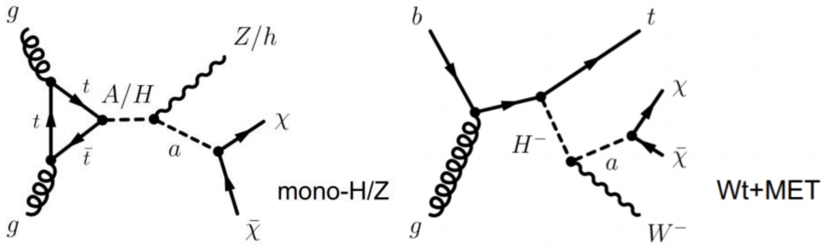
- For Dark Matter searches, **theoretical benchmarks** are necessary to sharpen the regions for the study:
  - to **optimize searches** and characterize a possible discovery
  - to define a theoretical framework for **comparison with results from other (non-collider) experiments**



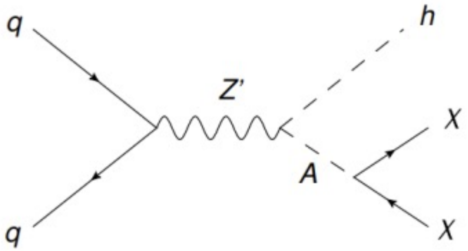
Simplified s-channel mediator model: small set of free parameters. Interesting interplays between Mono-X searches and resonance searches.



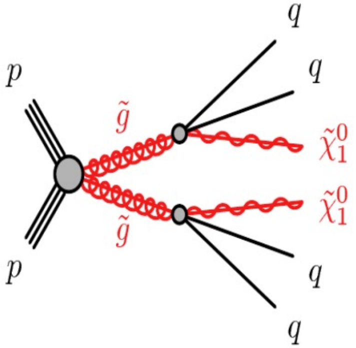
Higgs portal models: Search for enhancement of invisibly decays which increase BR(H→inv) (~0.1% in SM).



2HDM+a . Two-Higgs doublet extensions with a pseudo- scalar a. Gauge-invariant. Richer kinematics + phenomenology



2HDM+Z' : Two-Higgs doublet: extensions with a vector Z'

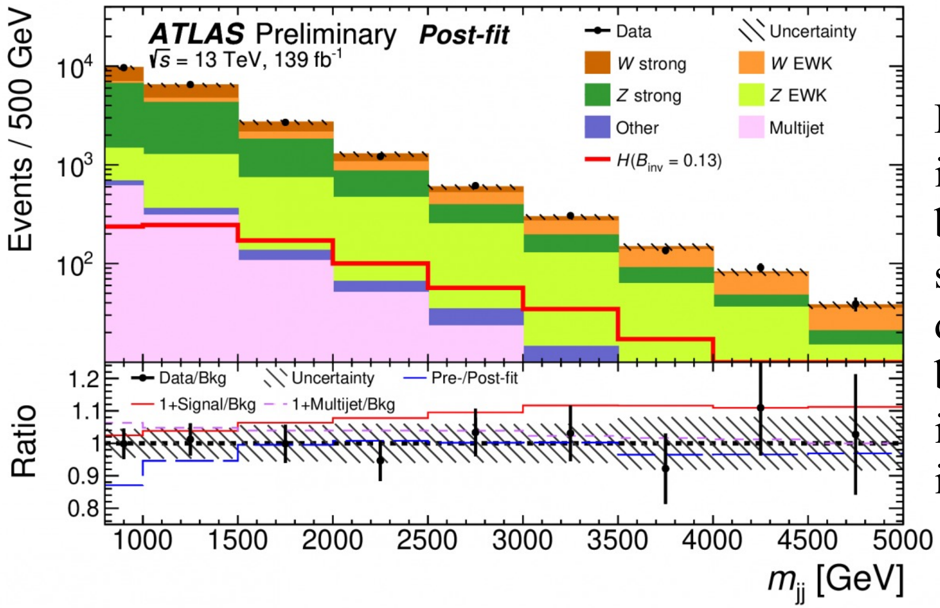


SUSY: Simplified R-parity conserving model

Higgs to invisible decays

- A weakly-interacting, massive dark matter particle could interact with the observed Higgs boson.
- Consider Higgs associate production: VBF+H, ZH and ttH
  - Better background/signal
- select events with
  - VBF: large E_T^{miss} and high-p_T jets, no leptons, no photons
  - ZH: same flavour opposite charge lepton pair consistent with $Z \rightarrow ll$
  - ttH: large E_T^{miss} and 2 b-tagged jets (all hadronic final state)

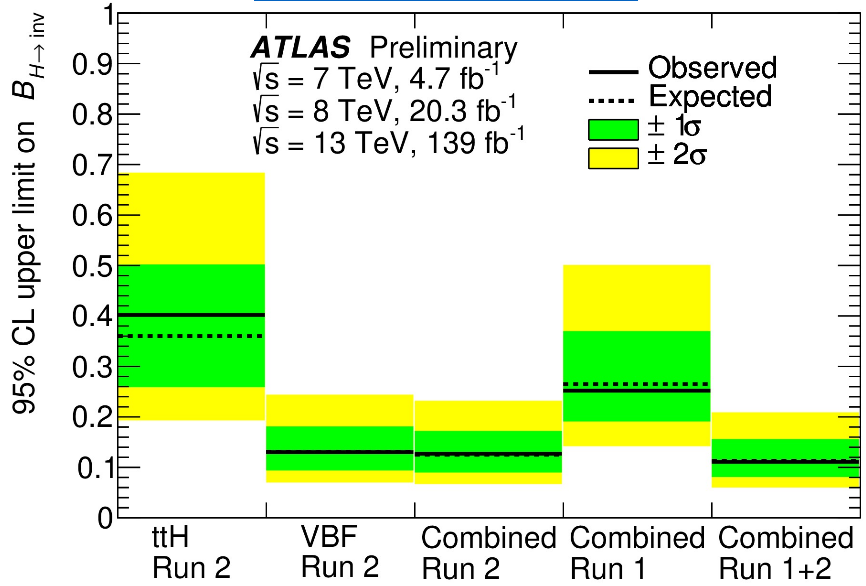
ATLAS-CONF-2020-008



VBF H→invisible

Mass of the leading two jets in the search region with all background processes stacked and compared to data. A hypothetical Higgs boson signal decaying to invisible final states is shown in red.

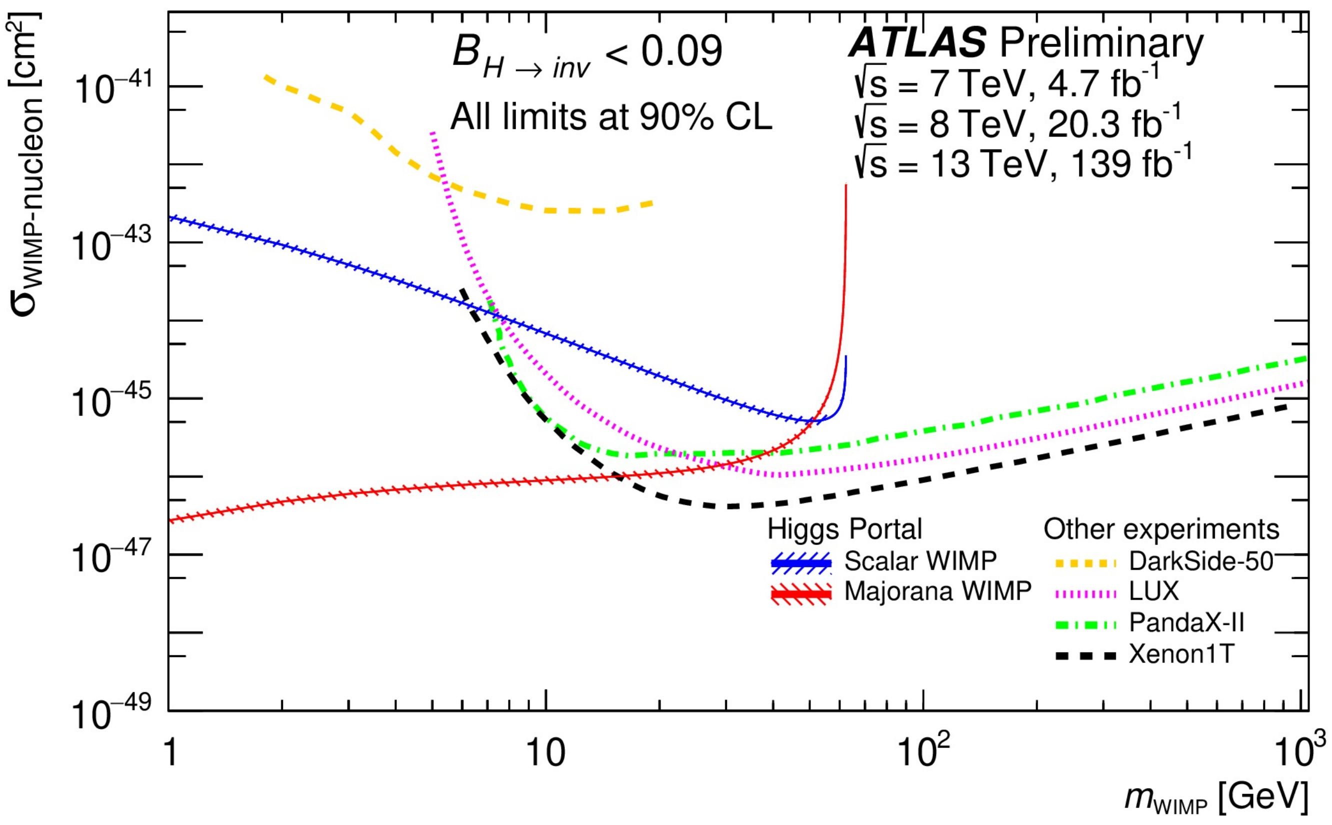
ATLAS-CONF-2020-052



Higgs to invisible decays

Higgs portal: interpret in terms of WIMP mass and nuclear scattering cross section

ATLAS-CONF-2020-052

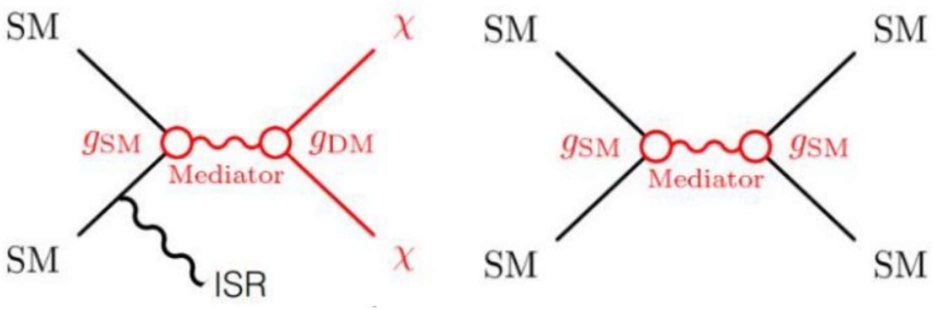


Comparison of the upper limits at 90% C.L. from direct detection experiments on the spin-independent WIMP-nucleon scattering cross-section to the observed exclusion limits from this study, as a function of the WIMP mass. The interpretation of ATLAS results assumes Higgs portal scenarios where the 125 GeV Higgs boson decays to a pair of Dark Matter particles that are either scalars or Majorana fermions.

some examples of other Dark Matter searches at LHC

Dark matter as a new stable neutral particle

Examples:



E_T^{miss} searches
"E_T^{miss}+X"

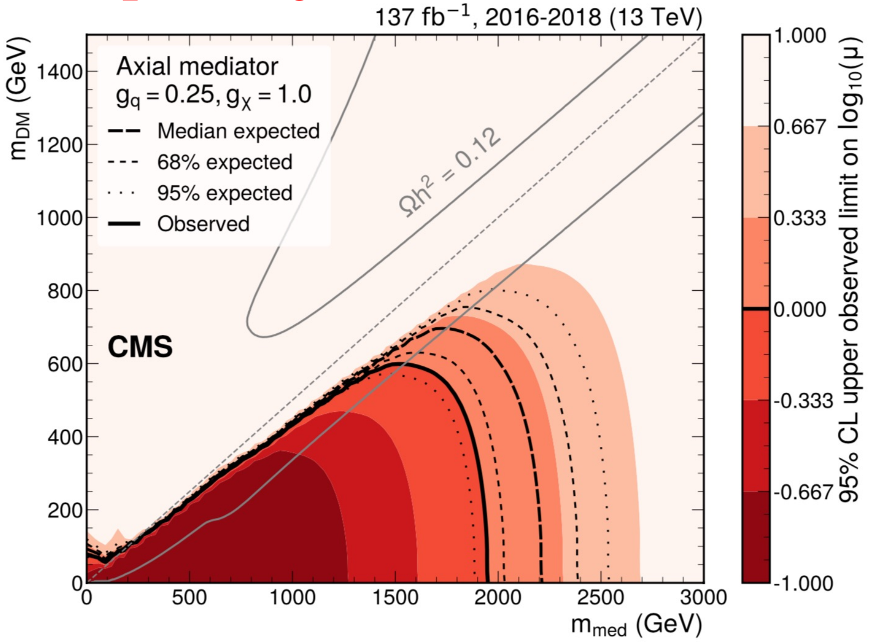
Mediator searches
"Di-X"

E_T^{miss} + jet

Di – X, ex: ZX

Other final analysed final states:
E_T^{miss} + Z→ll, E_T^{miss} + tt, 4t final states, resonances, …

E_T^{miss} + jet JHEP 11 (2021) 153



No signal found, setting limits on various DM and non-DM benchmark models

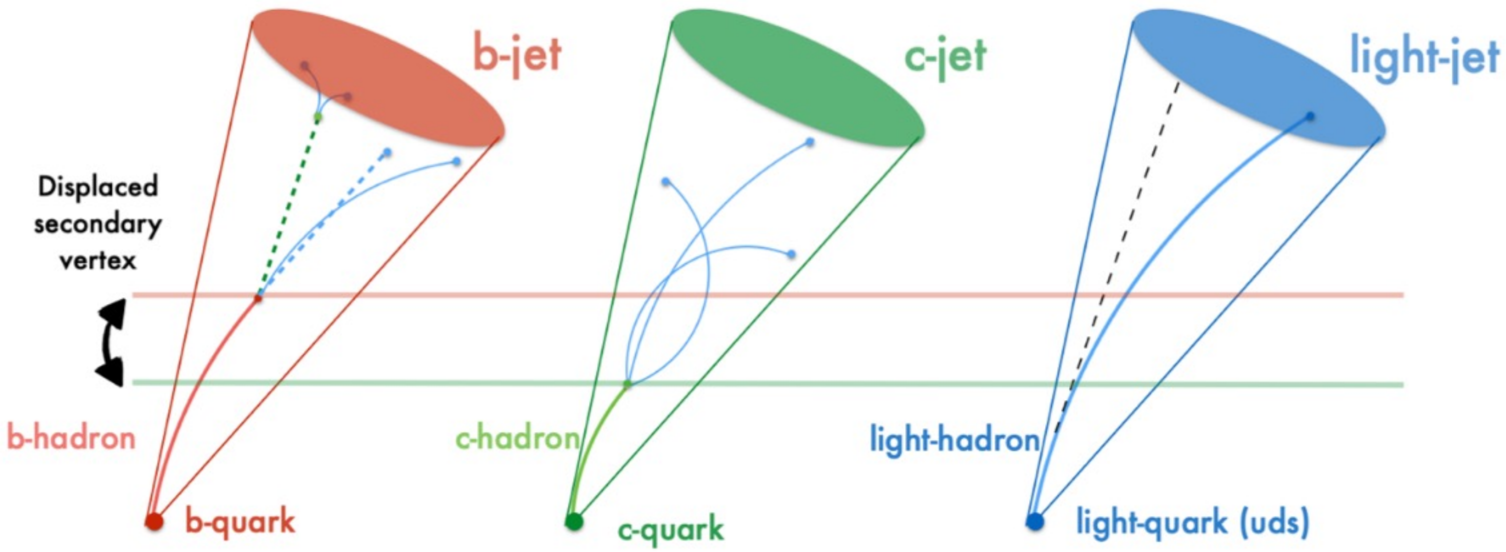
Exclusion limits at 95% CL on the signal strength $\mu = \sigma/\sigma_{th.}$ in the m_{med}-m_{DM} plane for coupling values of $g_q = 0.25$ and $g_\chi = 1.0$ for an axial-vector mediator. The black solid line indicates the observed exclusion boundary $\mu = 1$. The black dashed and dotted lines represent the expected exclusion and the 68 and 95% CL intervals around the expected boundary, respectively

Higgs boson decay to ccbar

- The Higgs boson decay to charm final states represents an important test of the Higgs boson coupling to 2nd generation quarks.
- Search for H→cc follows the approach adopted for the identification and reconstruction of H→bb decays:

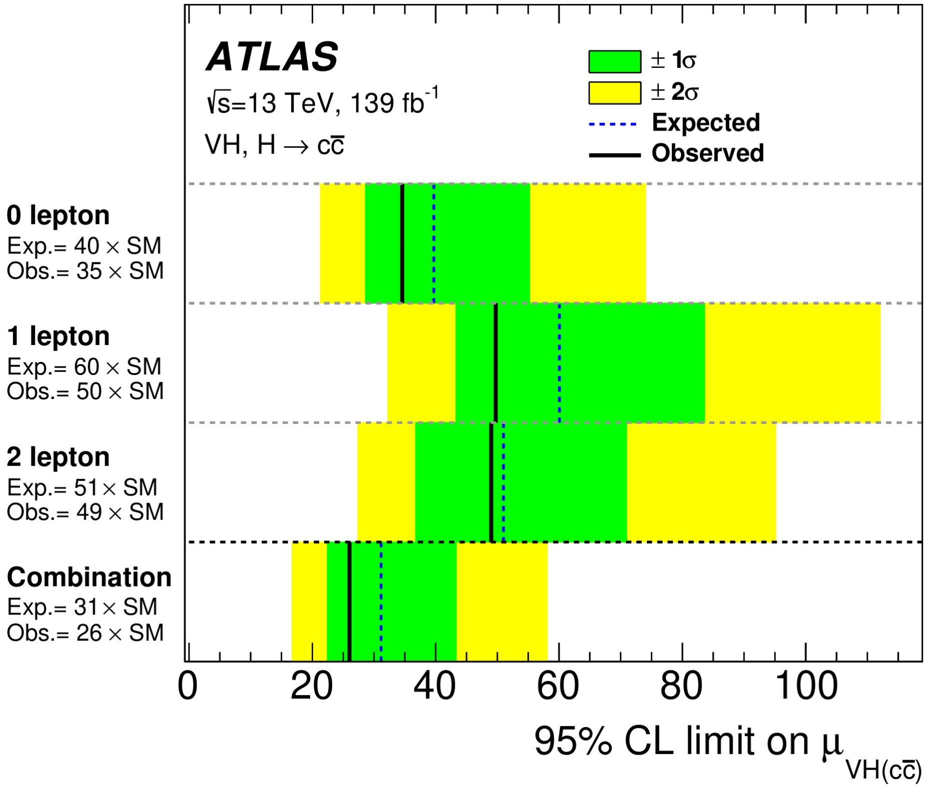
  consider VH production modes (advantageous S/B ratio)

  - Further rejection from jet flavour tagging

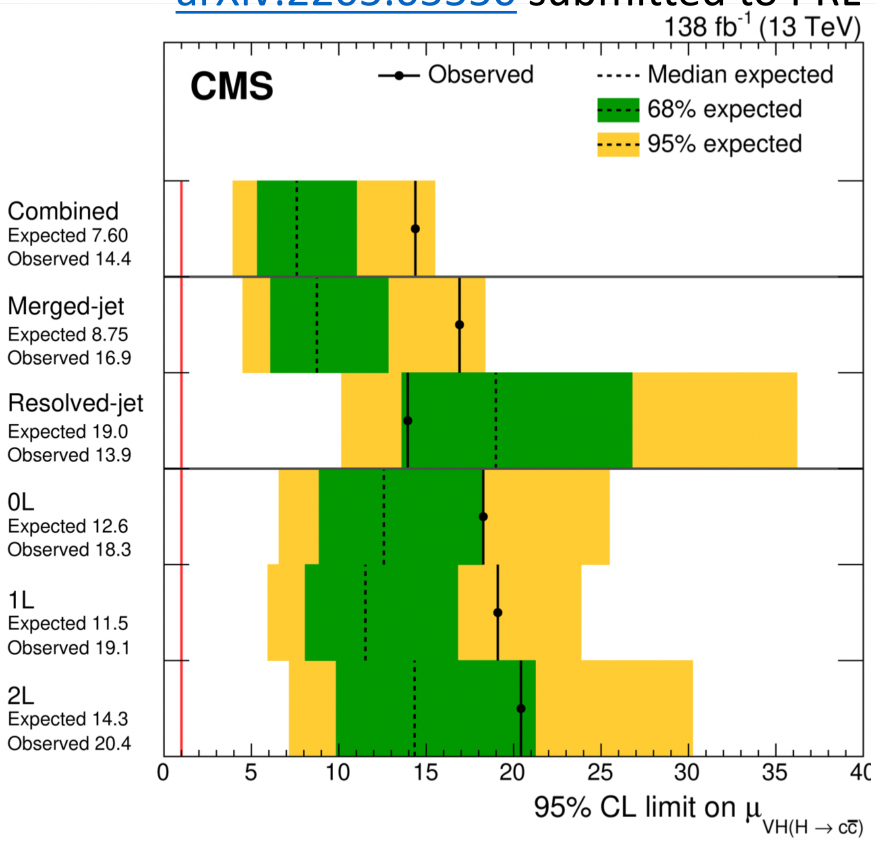


Higgs boson decay to ccbar

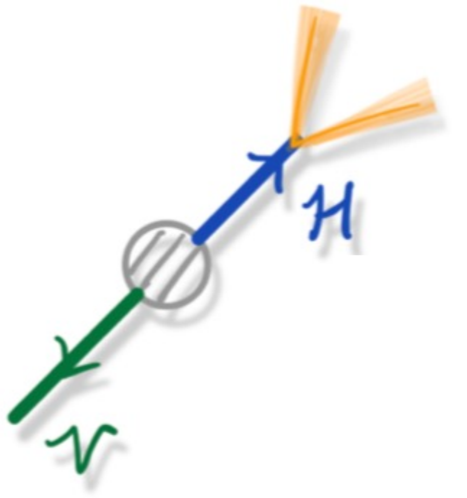
arXiv:2201.11428



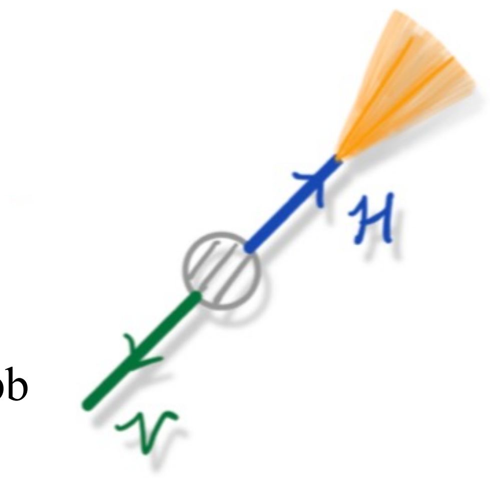
arXiv:2205.05550 submitted to PRL



"Resolved-jet"



"Merged-jet"



- **Full LHC Run-2 dataset**
- **Combined fit of 0+1+2-lepton**
- **16 signal + 28 control regions**

Limit @ 95%CL:

$\mu_{VH(cc)}$ < **26** (31 exp)

Limit @ 95%CL:

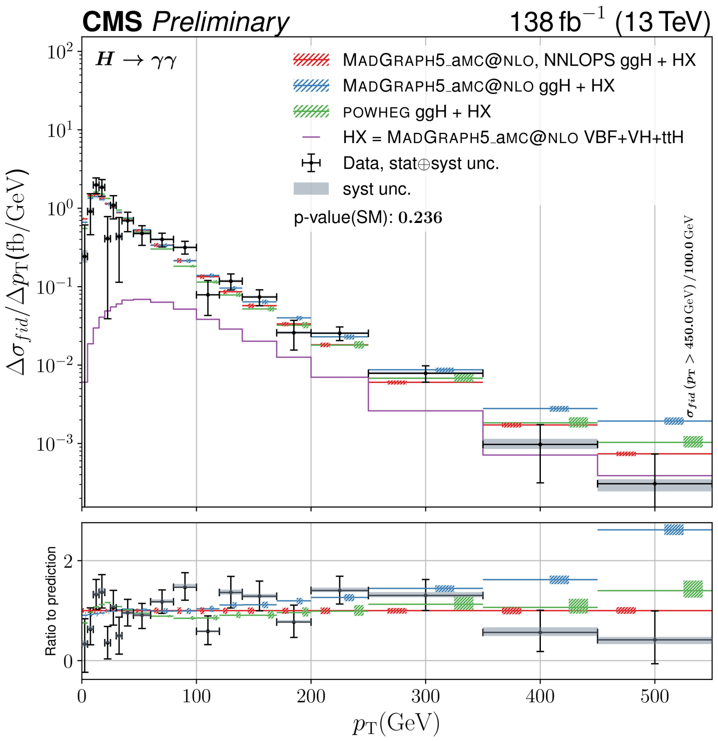
σ (VH) B (H → cc) = 0.94 (exp 50$^{+0.15}_{-0.22}$) pb

$\mu_{VH(cc)}$ < **14** (7.6 exp)

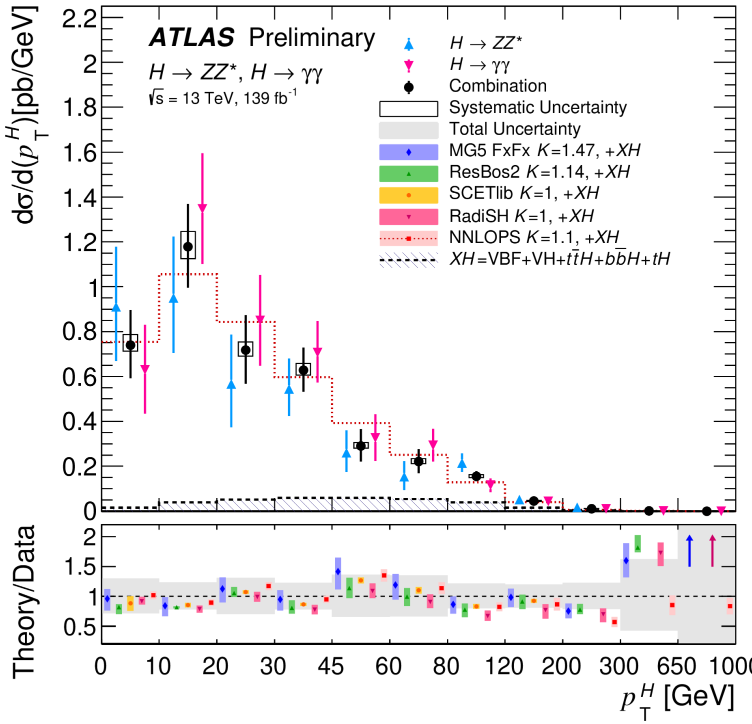
Differential measurements

Compared with inclusive measurements, differential distributions provide extended information on the Higgs boson couplings, which can be extracted by fitting parametrized spectra to a combination of differential cross sections. Distortions of the predicted differential cross section spectra might appear, which are particularly pronounced in the transverse momentum p_T distribution.

CMS HIG-19-016



Differential fiducial cross sections for $p_T^{\gamma\gamma}$. Data: black points with vertical error bars showing full uncertainty. Coloured lines: predictions from different setups of the event generator.



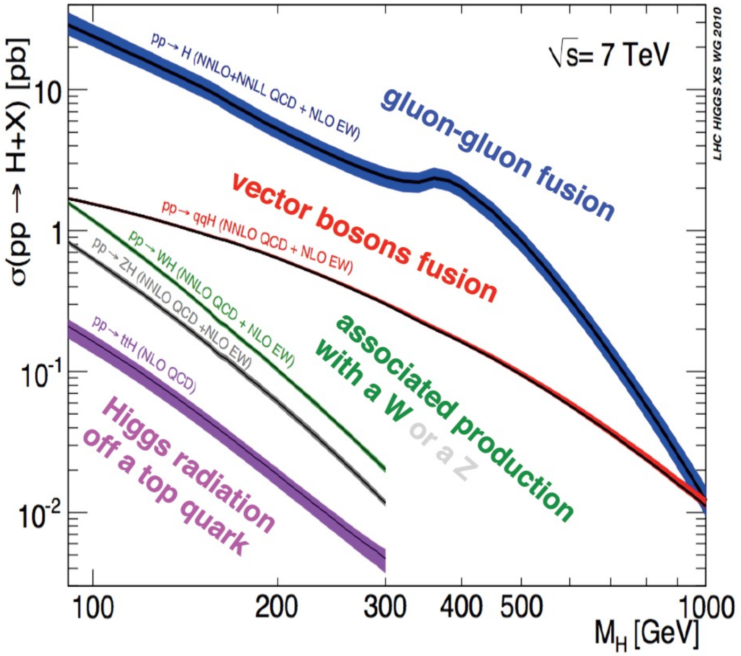
ATLAS-CONF-2022-002

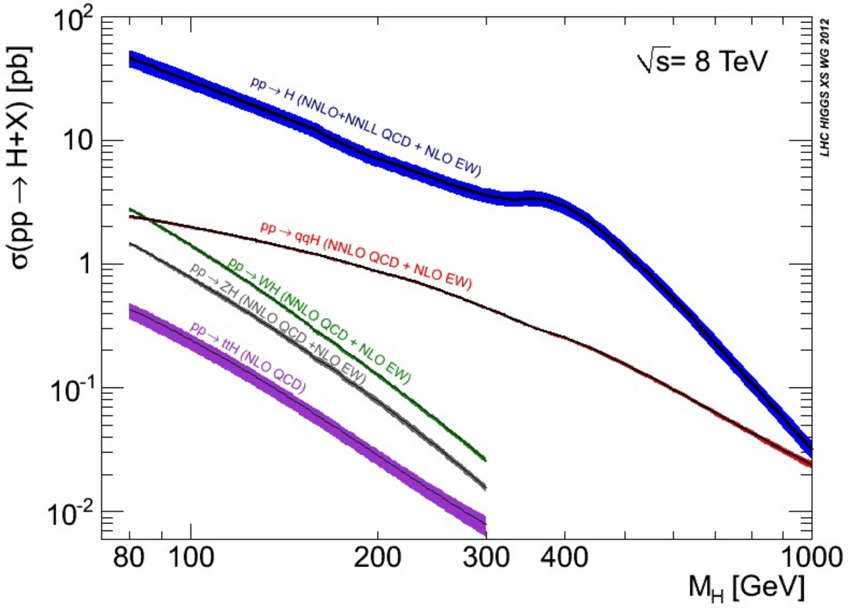
Differential pp → H + X cross-section, along with (b) the corresponding correlation matrix, as a function of Higgs boson transverse momentum p_T^H in the full phase space, compared to Standard Model predictions. The $H \to \gamma\gamma$ (red inverted triangles), $H \to ZZ^* \to 4\ell$ (blue triangles) and combined (black squares) measurements are shown.

backup

The Standard Model Higgs boson

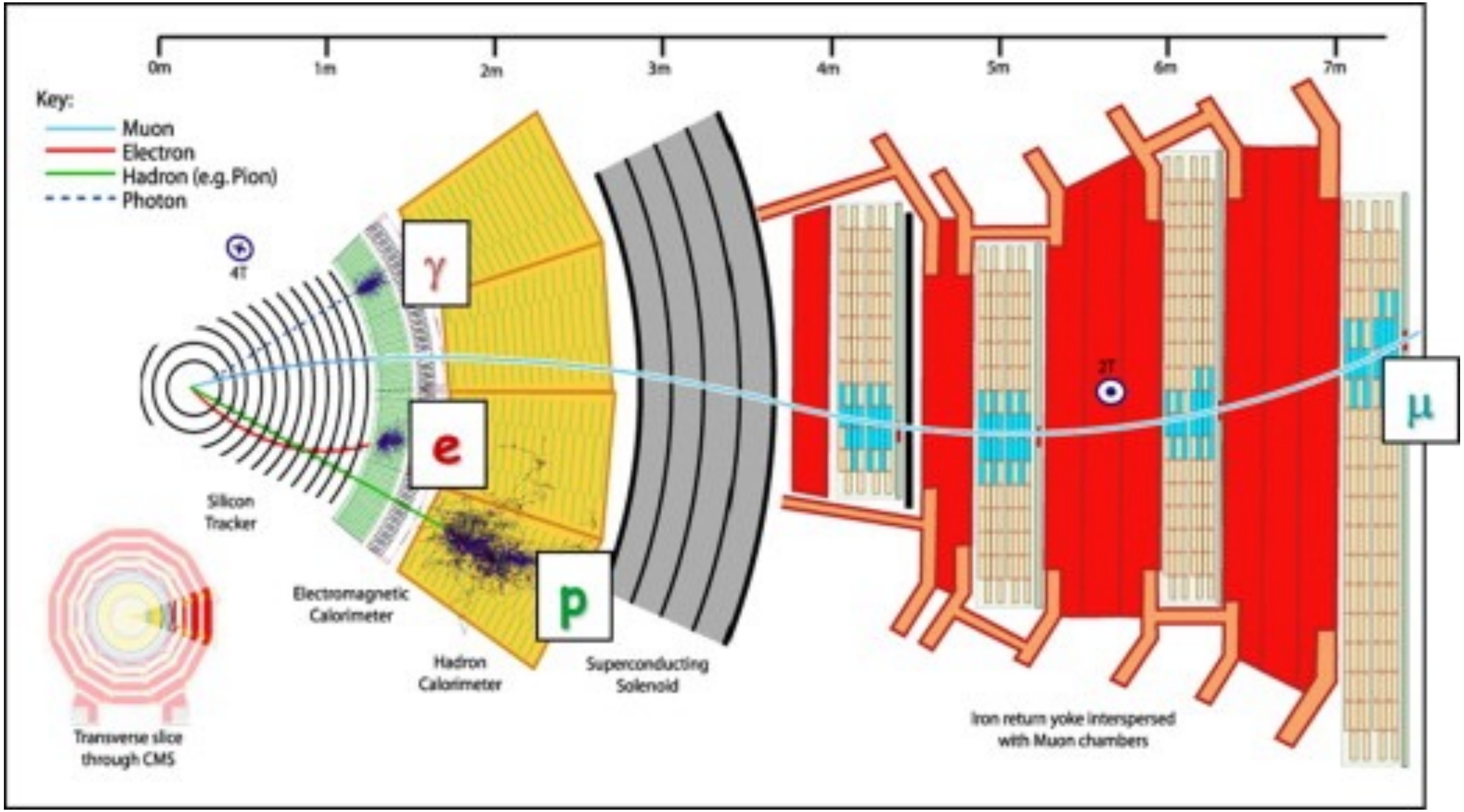
Total production cross section in proton-proton collisions



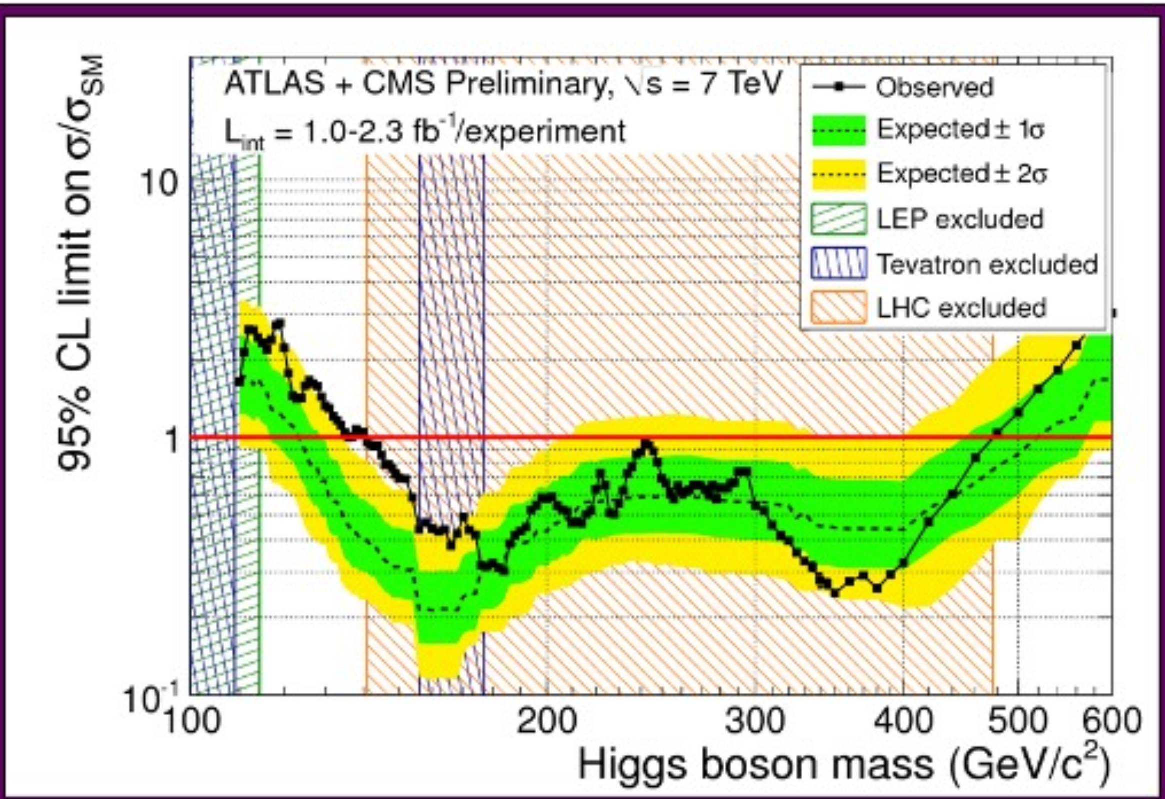


√s= 7 TeV **√s= 8 TeV**

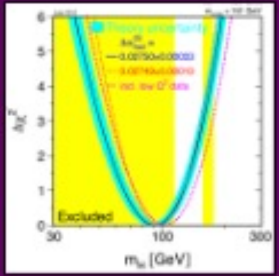
Particle detection



Present status (as of this morning ...)



November 2011
CMS PAS HIG-11-023,
ATLAS-CONF-201-157



LEP (95%CL)
m_H > 114.4 GeV

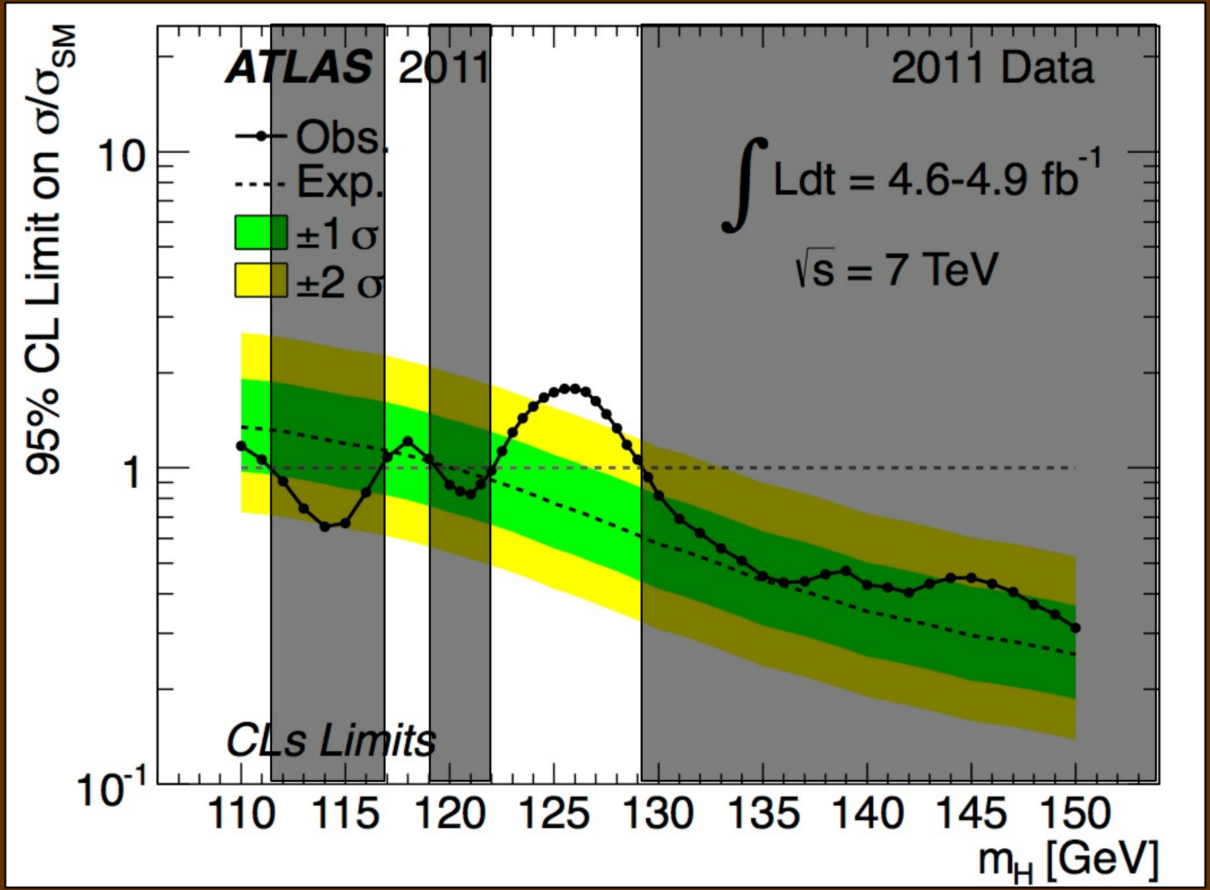
Tevatron exclusion (95%CL):
100 < m_H < 109 GeV
156 < m_H < 177 GeV

First ATLAS+CMS combination: based on data recorded until end August 2011: up to ~2.3 fb^{-1} per experiment

Excluded 95% CL : 141-476 GeV
Excluded 99% CL : 146-443 GeV (except ~222, 238-248, ~295 GeV)
Expected 95% CL : 124-520 GeV → max deviation from background-only: ~ 3σ (m_H~144 GeV)

Status of ATLAS searches … until this morning

Results on the full 7 TeV dataset submitted for publication



Combination of 12 channels:

- H→ γγ
- W/ZH→W/Z bb (3 final states)
- H→ ττ (3 final states)
- H→ ZZ(*) → 4l
- H→ WW(*) → lνlν
- H→ ZZ → llqq
- H→ ZZ → llνν
- H→ WW → lνqq

Excluded at 95% CL

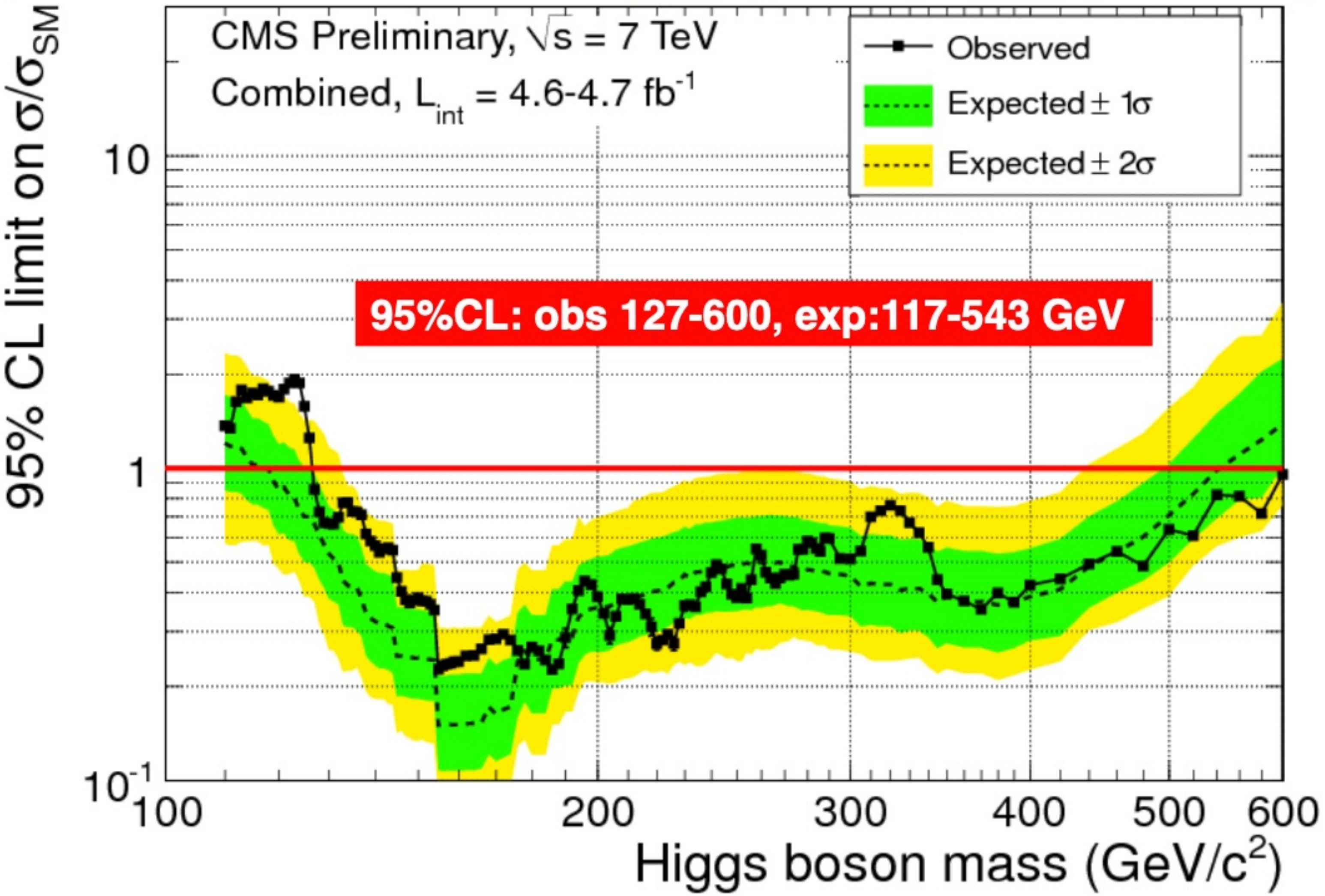
$111.4 < m_H < 122.1$ GeV (except 116.6-119.4)
$129.2 < m_H < 541$ GeV

Expected if no signal:
120-560 GeV

Excluded at 99% CL

$130.7 < m_H < 506$ GeV

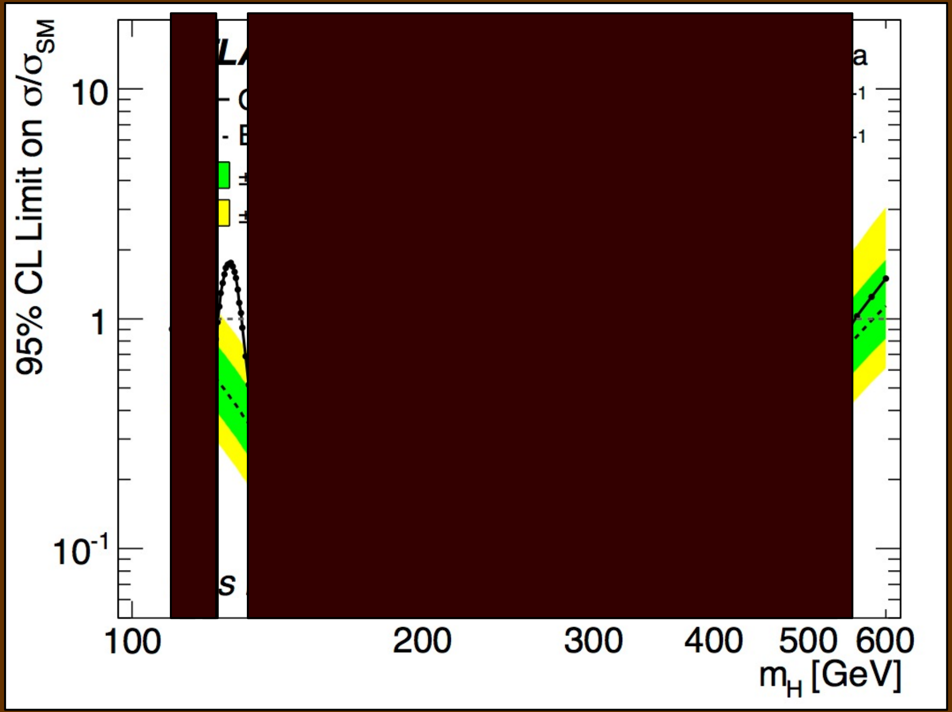
Limits on σ/σ_{sm} (CLs method)

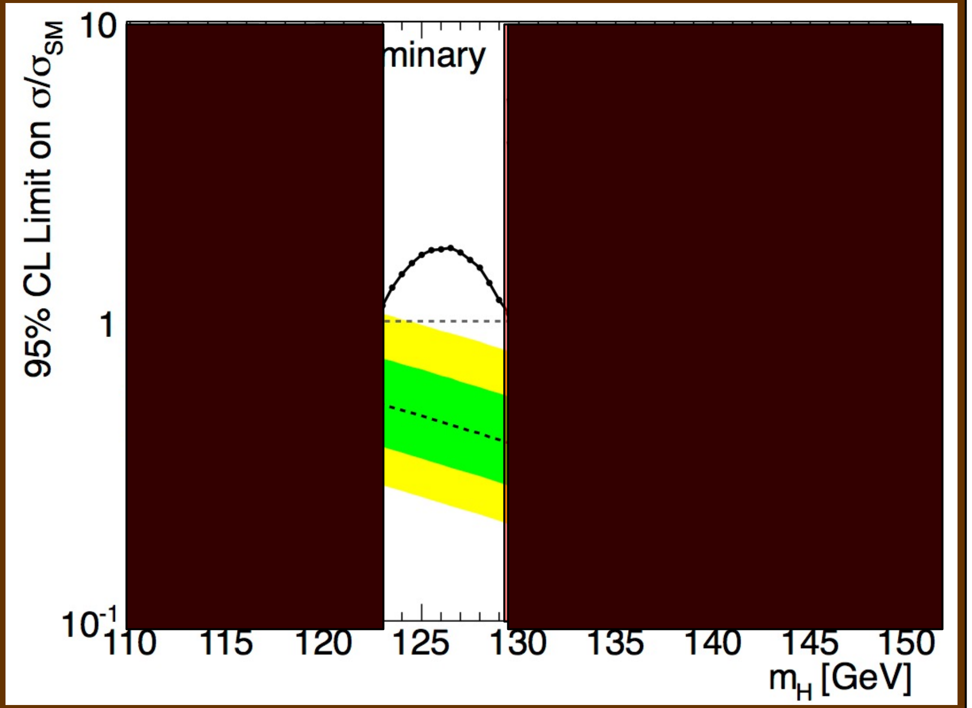


Combined results : exclusion limits

ATLAS today

Previous ATLAS results





Excluded at 95% CL

110-122.6   129.7-558 GeV

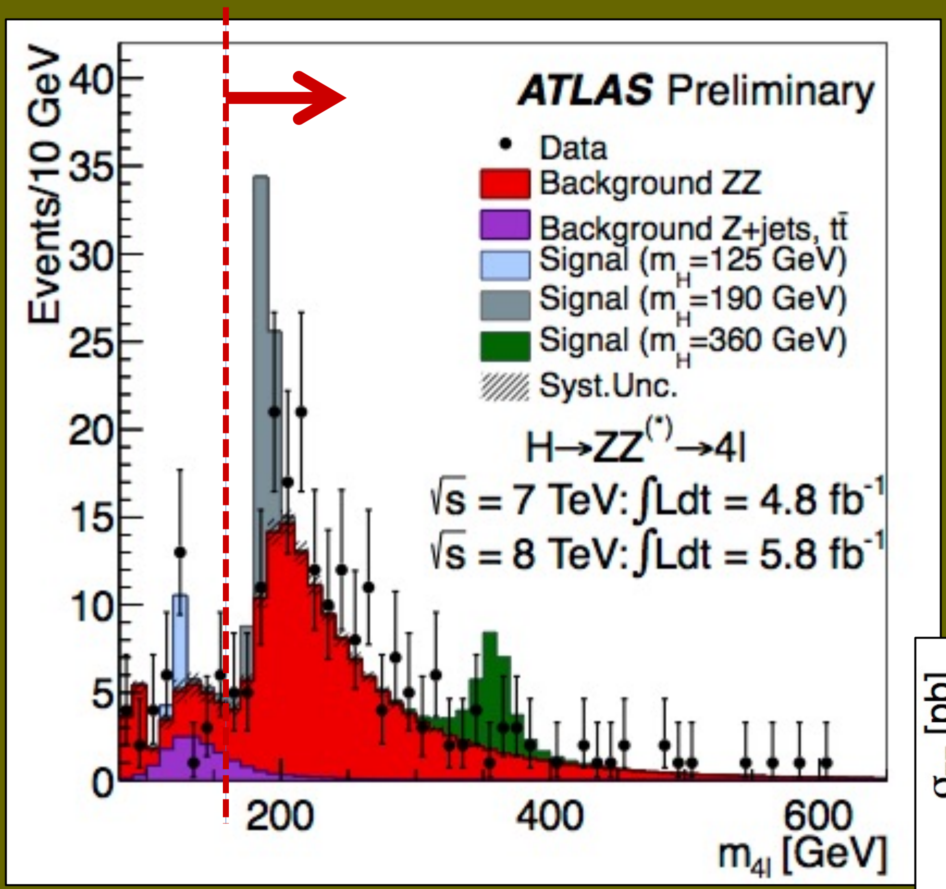
Expected at 95% CL if no signal

110-582 GeV

Excluded at 99% CL

111.7-121.8 GeV 130.7-523 GeV

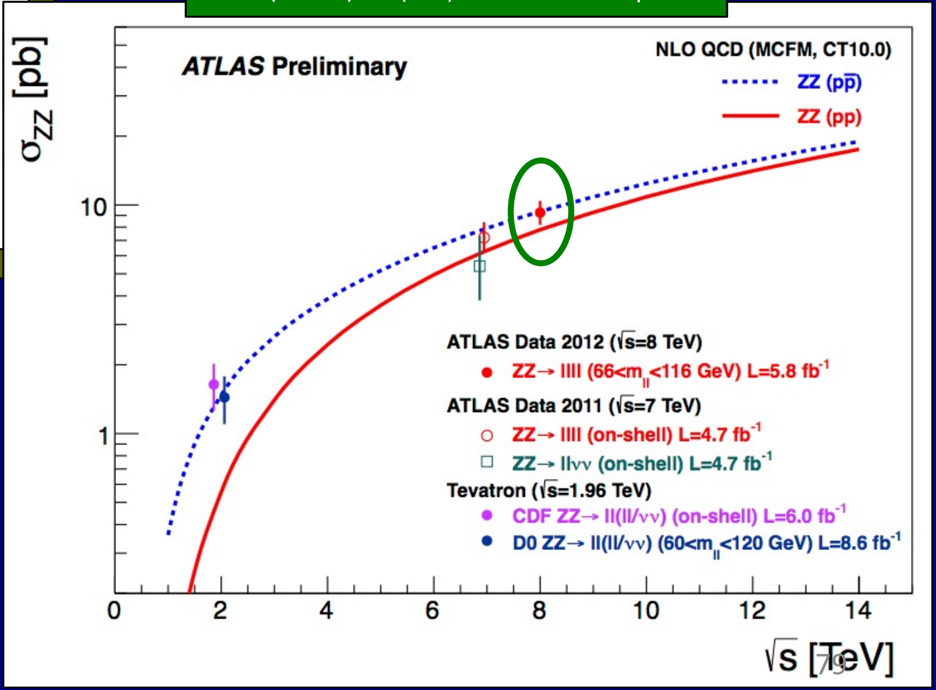
H→ 4l mass spectrum after all selections: 2011+2012 data



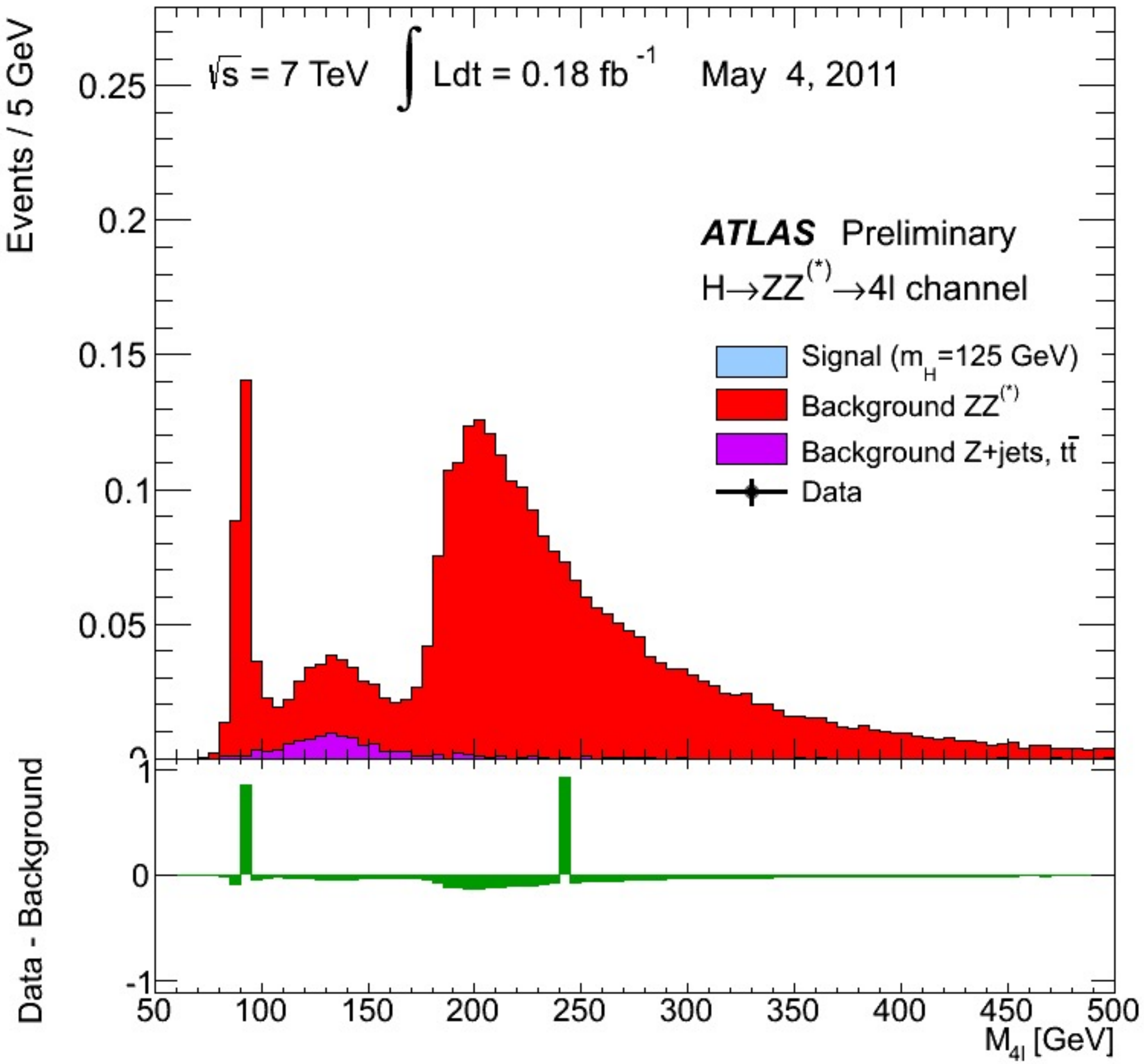
m(4l) > 160 GeV
(dominated by ZZ background):
147 ± 11 events expected
191 observed

~ 1.3 times more ZZ events in data than SM prediction →in agreement with measured ZZ cross-section in 4l final states at √s = 8 TeV

Measured σ (ZZ) = 9.3 ± 1.2 pb
SM (NLO) σ (ZZ) = 7.4± 0.4 pb



Discrepancy has negligible impact on the low-mass region < 160 GeV
(no change in results if in the fit ZZ is constrained to its uncertainty or left free)



√s = 7 TeV ∫Ldt = 0.18 fb-1 May 4, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
0.25
0.2
0.15
0.1
0.05
Data - Background
1
0
-1
50
100
150
200
250
300
350
400
450
500
M4l [GeV]

Global Effort → Global Success

Results today only possible due to extraordinary performance of accelerators – experiments – Grid computing

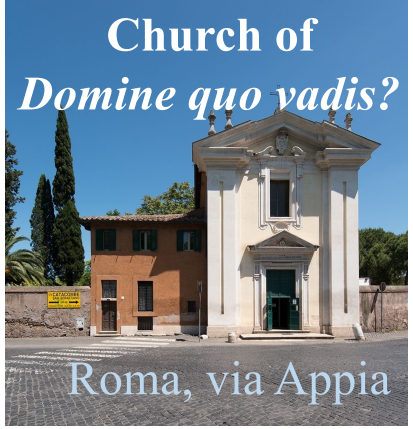
Observation of a new particle consistent with a Higgs Boson (but which one…?)

Historic Milestone but only the beginning

Global Implications for the future

R-D Heuer

Higgs… Quo Vadis?



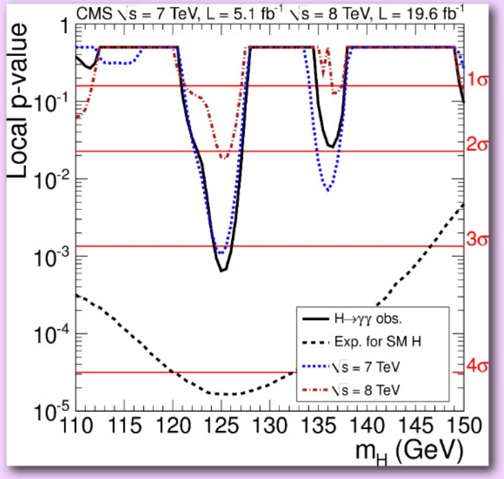
- **Higgs Quo Vadis 2013: very interesting workshop held in 2013 at the *Aaspen Center of Physics***
- **Updated results on Higgs searches were presented and discussed**

Results: P-Values

$H \to \gamma\gamma$

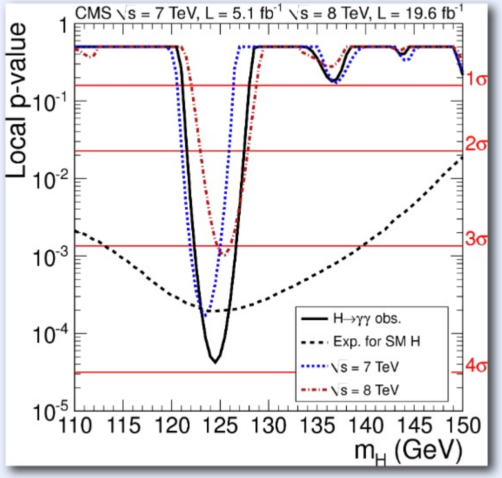
HIG-13-001
public soon

MVA mass-factorized



Local significance: **3.2 σ at 125.0 GeV**

Cut-based



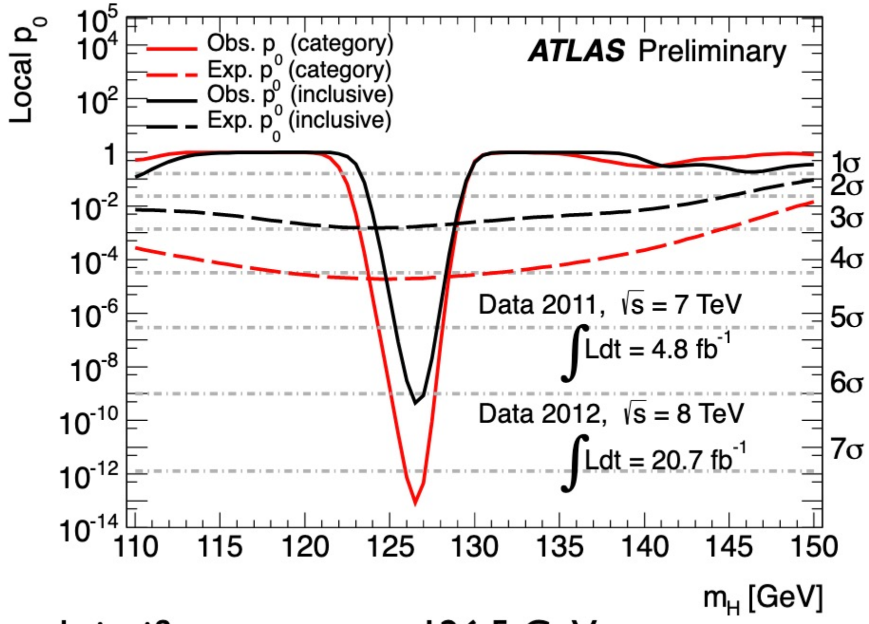
Local significance: **3.9 σ at 124.5 GeV**

Compared to the published results, the significance decreased both because of re-analysis of 8 TeV data and adding new data.

roberta.volpe@cern.ch *Aspen 2013: Higgs Quo Vadis* 19

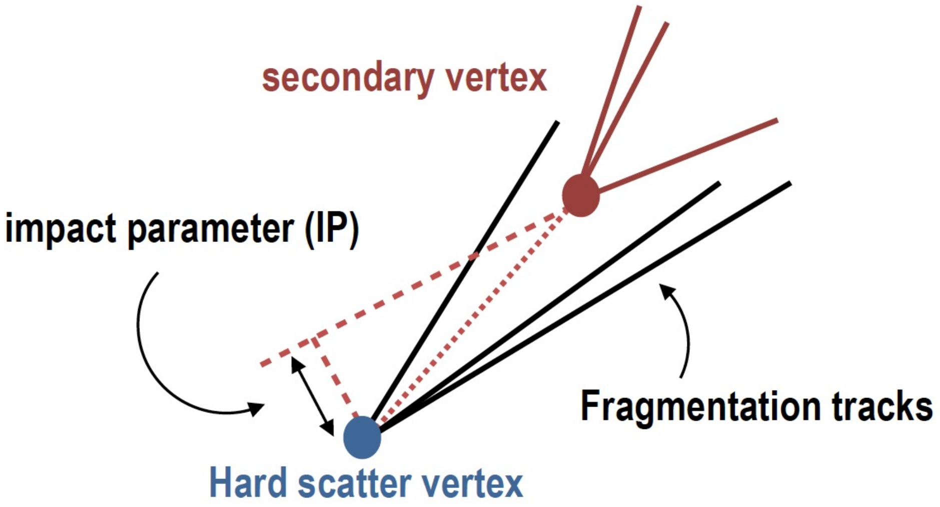
$H \to \gamma\gamma$: status of the excess

ATLAS EXPERIMENT



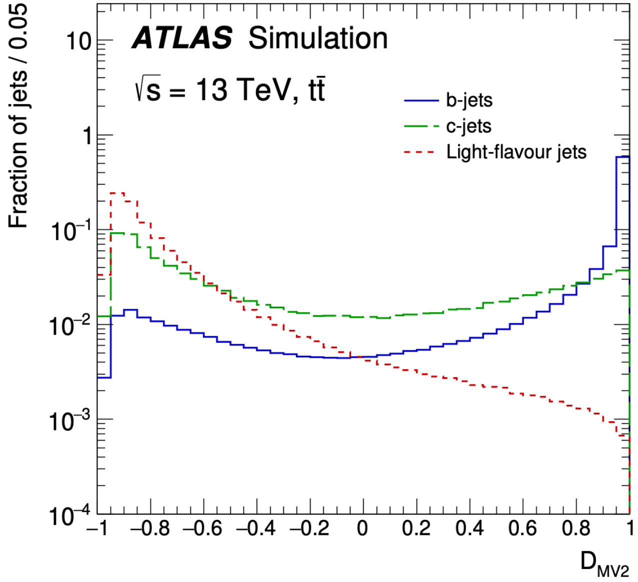
- Largest local significance at m_H = 126.5 GeV
  - ✓ 14 categories: 7.4 σ (expected 4.1 σ)
  - ✓ Inclusive: 6.1 σ (expected 2.9 σ)

b-tagging



Multivariate technique, based upon the secondary vertex information relative to the primary vertex

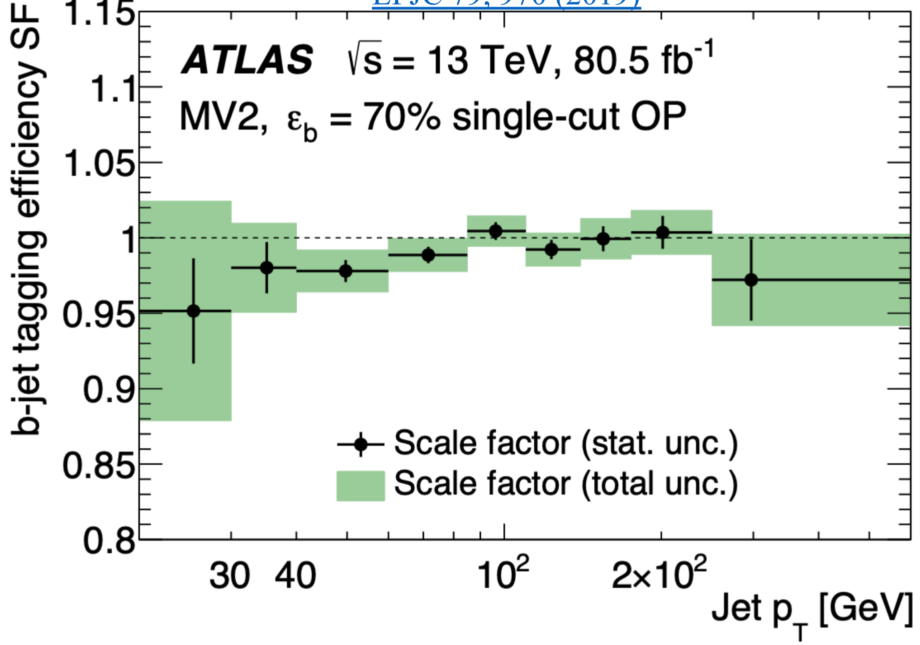
EPJC 79, 970 (2019)



B-tagging discriminant for b-, c- and light jets

- **At a 70 % b-jet efficiency, rejections are ~ 300 (8) for light (c)-jets**

EPJC 79, 970 (2019)



- **Since that time, we have improved by a factor of 2 c-jet rejections and factor of 40% in light jet-rejections:** ATL-PHYS-PUB-2022-027

with state of-the art *machine learning* techniques

Higgs couplings

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t\kappa_b$
$\sigma(VBF)$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z\kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t\kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t\kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{BSM} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Higgs boson production cross sections σ_i, partial decay widths Γ^f, and total decay width (in the absence of BSM decays) parameterised as a function of the κ coupling modifiers as discussed in the text, including higher-order QCD and EW corrections to the inclusive cross sections and decay partial widths.

The coefficients in the expression for Γ_H do not sum exactly to unity because some contributions that are negligible or not relevant to the analyses presented in this paper are not shown.

Announcement at the LHCP2018 Conference

4 June 2018

New ATLAS result establishes production of Higgs boson in association with top quarks

This rare process is one of the most sensitive tests of the Higgs mechanism

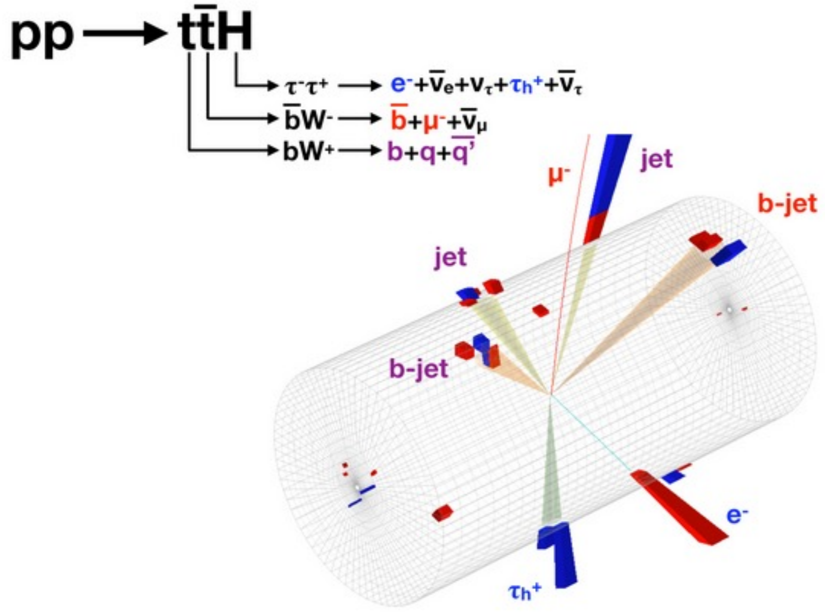
4 June 2018 | By ATLAS Collaboration

According to the Standard Model, quarks, charged leptons, and W and Z bosons obtain their mass through interactions with the Higgs field, a quantum fluctuation of which gives rise to the Higgs boson. To test this theory, ATLAS takes high-precision measurements of the interactions between the Higgs boson and these particles. While the ATLAS and CMS experiments at CERN's Large Hadron Collider (LHC) had observed and measured the Higgs boson decaying to pairs of W or Z bosons, photons or tau leptons, the Higgs coupling to quarks had not – despite evidence – been observed.

In results presented today at the LHCP2018 conference, the ATLAS Collaboration has observed the production of the Higgs boson together with a top-quark pair (known as "ttH" production). Only about 1% of all Higgs bosons are produced through this rare process. This result establishes a direct measurement of the interaction between the top quark and the Higgs boson (known as the "top quark Yukawa coupling"). As the top quark is the heaviest particle in the Standard Model, this measurement is one of the most sensitive tests of the Higgs mechanism.

By CMS

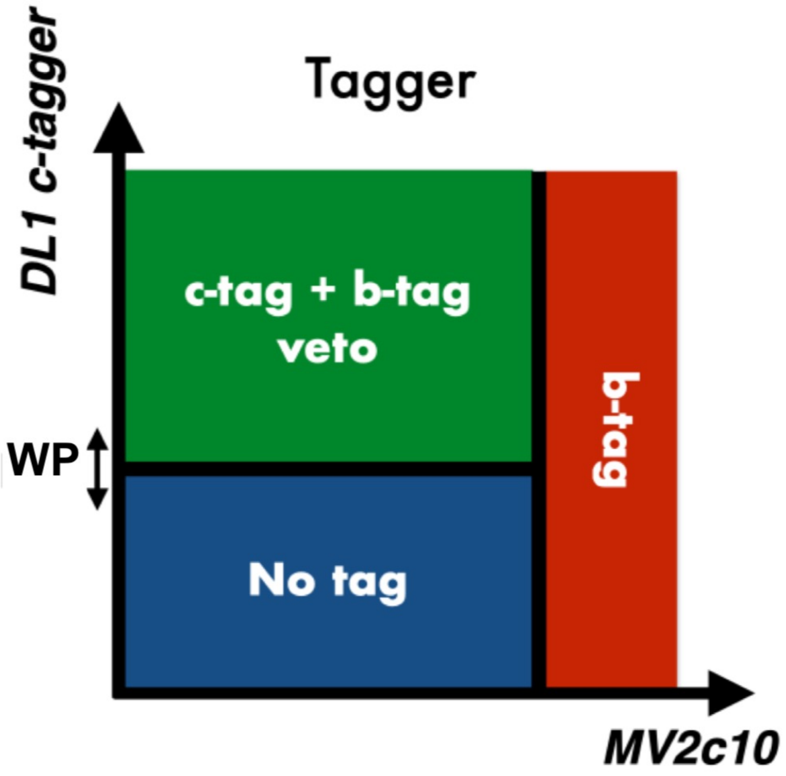
The first observation of the simultaneous production of a Higgs boson with a top quark-antiquark pair is being published today in the journal Physical Review Letters (PRL). This major milestone, first reported by the CMS Collaboration in early April 2018, unambiguously demonstrates the interaction of the Higgs boson and top quarks, which are the heaviest known subatomic particles. It is an important step forward in our understanding of the origin of mass. The paper features as a PRL Editors' Suggestion and also has a Physics Viewpoint article published about it.

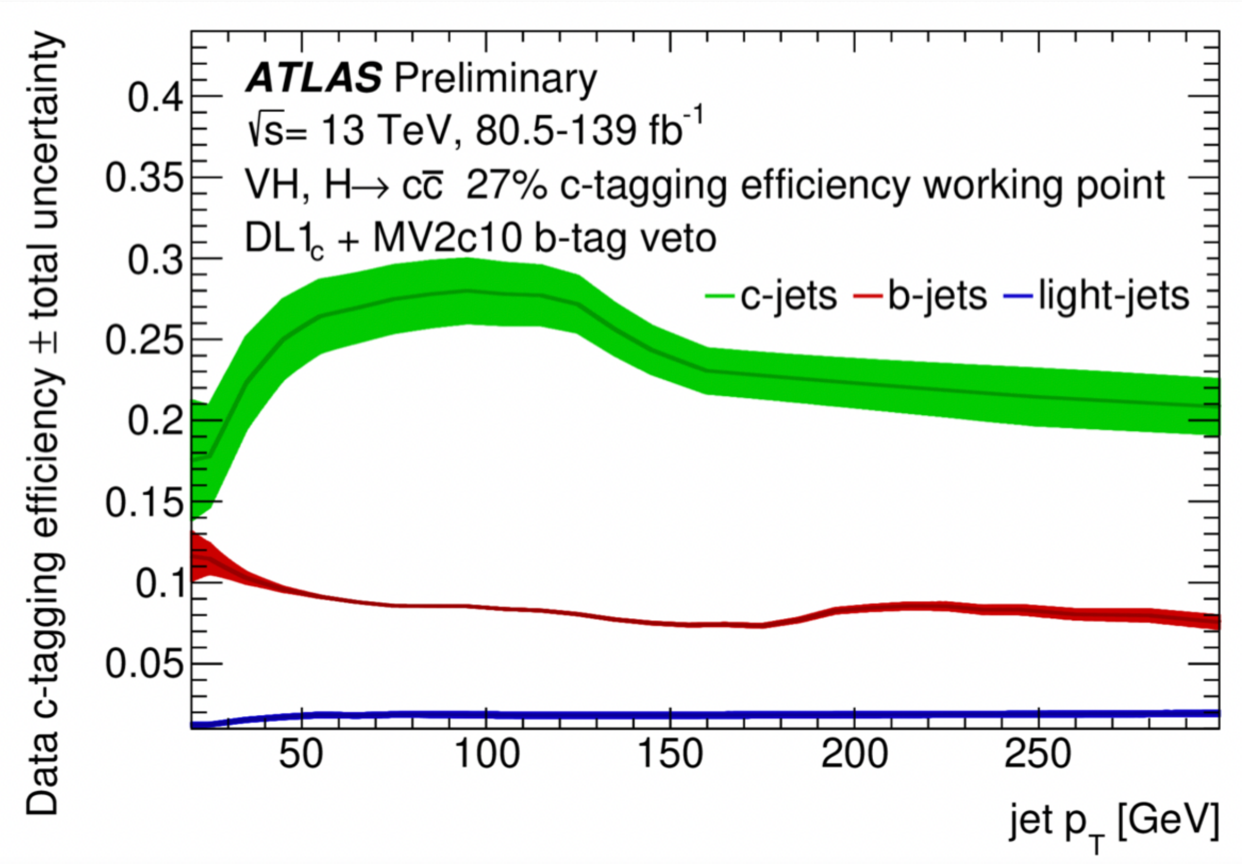


An event candidate for the production of a top quark and top anti-quark pair in conjunction with a Higgs Boson in the CMS detector. The Higgs decays into a tau+ lepton and a tau- lepton; the tau+ in turn decays into hadrons and the tau- decays into an electron. The decay product symbols are in blue. The top quark decays into three jets (sprays of lighter particles) whose names are given in purple. One of these is initiated by a b-quark. The top anti-quark decays into a muon and b-jet, whose names appear in red.

Higgs boson decay to ccbar

Tagging: c-tag + b-tag veto to avoid overlap with Hbb





c-tagging efficiencies:

c-jets: 27%
b-jets: 8%
light jets: 1.6%