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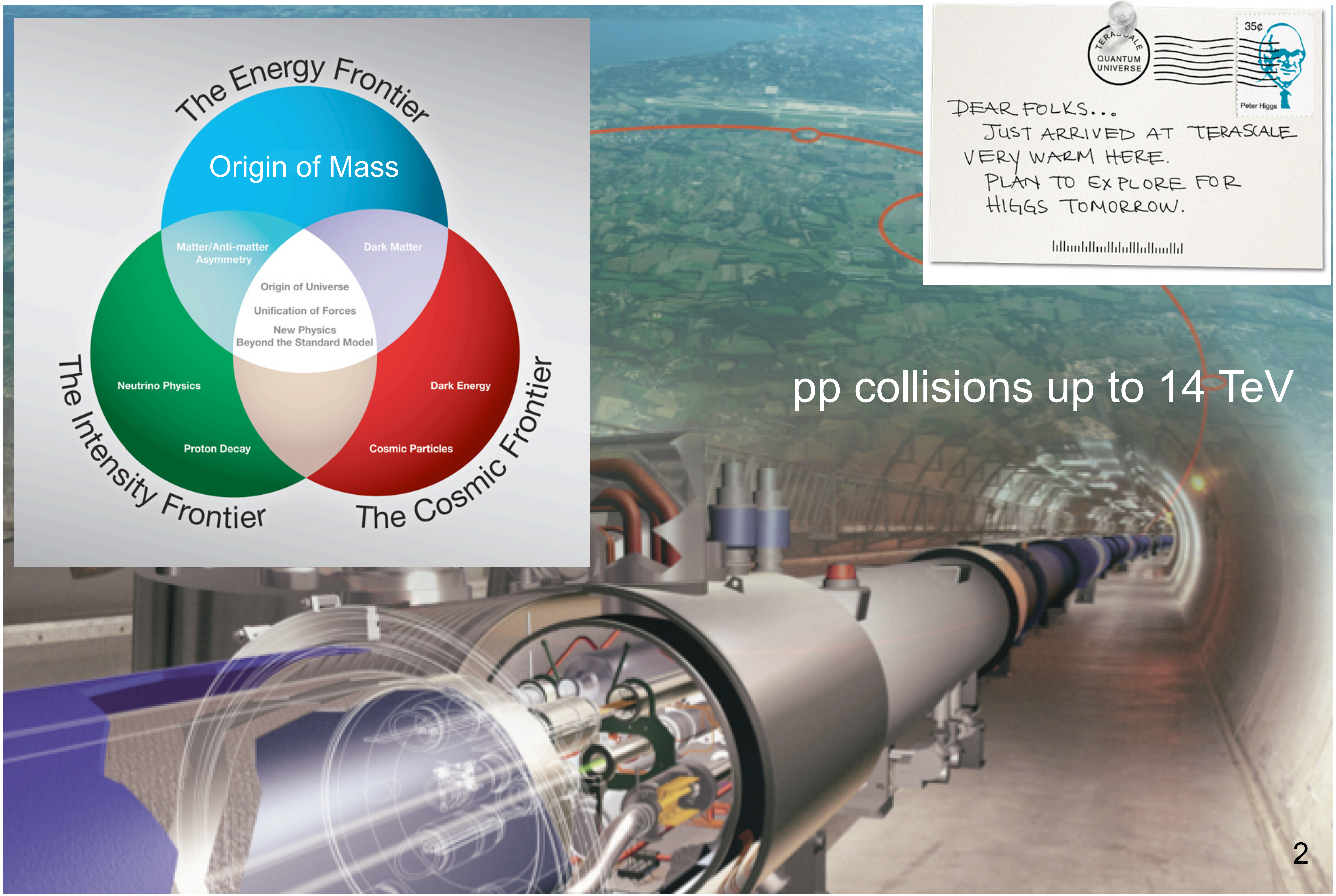
Standard Model Higgs Boson Studies at the LHC

Aurelio Juste
(ICREA/IFAE, Barcelona)

On behalf of the ATLAS and CMS Collaborations

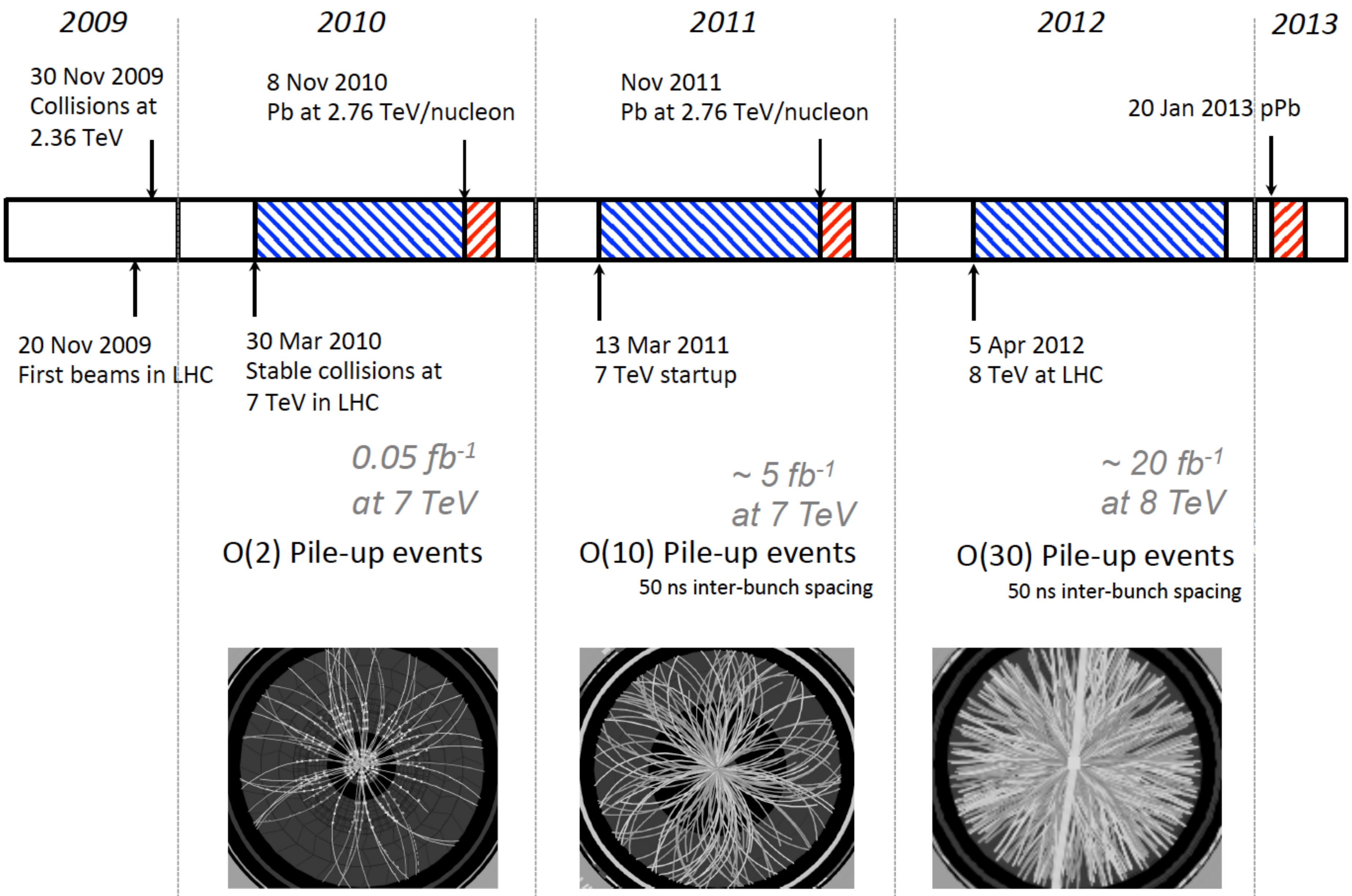
The LHC and the Energy Frontier



Outline

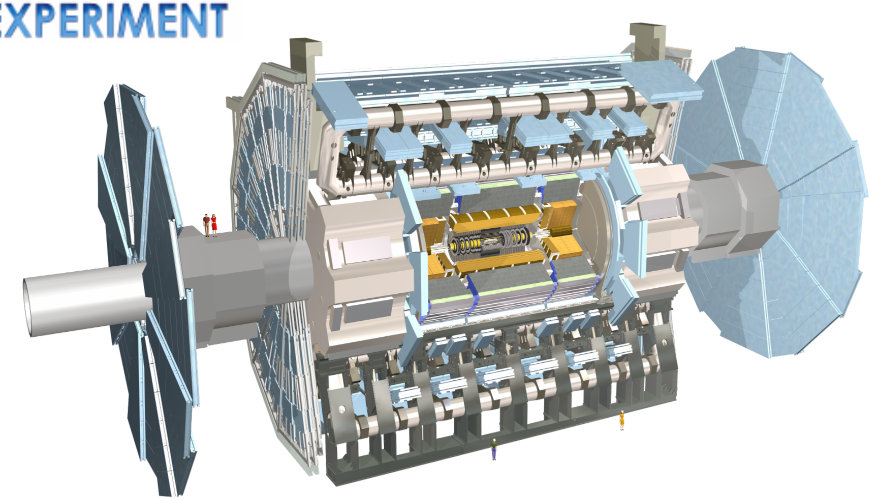
- Introduction
  - LHC Run 1 program
  - Higgs boson production and decay
  - Overview of main analysis channels
- Higgs boson properties measurements
- First Run 2 results
- Future prospects
- Summary and outlook

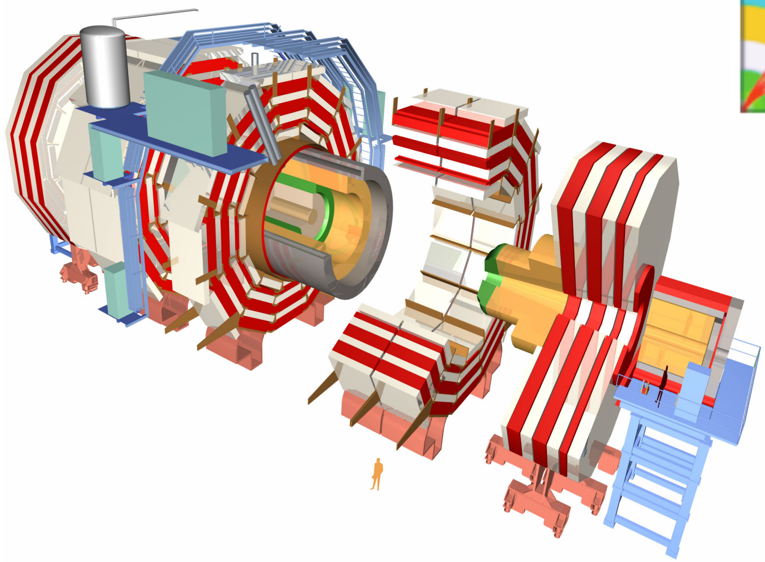
The LHC Run 1



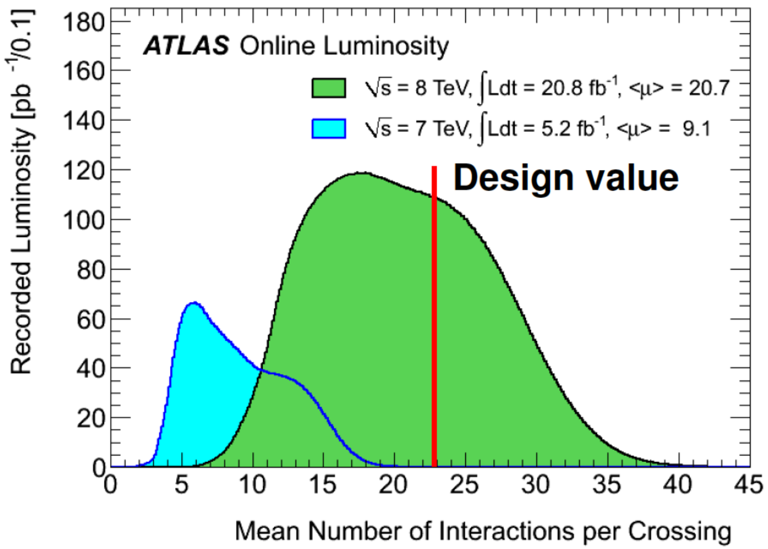
2009
2010
2011
2012
2013
30 Nov 2009
Collisions at
2.36 TeV
8 Nov 2010
Pb at 2.76 TeV/nucleon
Nov 2011
Pb at 2.76 TeV/nucleon
20 Jan 2013 pPb
20 Nov 2009
First beams in LHC
30 Mar 2010
Stable collisions at
7 TeV in LHC
13 Mar 2011
7 TeV startup
5 Apr 2012
8 TeV at LHC
0.05 fb-1
at 7 TeV
~ 5 fb-1
at 7 TeV
~ 20 fb-1
at 8 TeV
O(2) Pile-up events
O(10) Pile-up events
50 ns inter-bunch spacing
O(30) Pile-up events
50 ns inter-bunch spacing

ATLAS and CMS Experiments





- Multipurpose detectors:
  - Central tracking in solenoidal B field
  - Electromagnetic and hadronic calorimeters
  - Muon detectors
- Excellent performance up to the highest instantaneous luminosities delivered by the LHC. ~93% data-taking efficiency during Run 1.
- Run 1 results based on 2011+2012 data:
  - 2011: ~5 fb^{-1} at $\sqrt{s}$=7 TeV
  - 2012: ~20 fb^{-1} at $\sqrt{s}$=8 TeV



The LHC Run 1

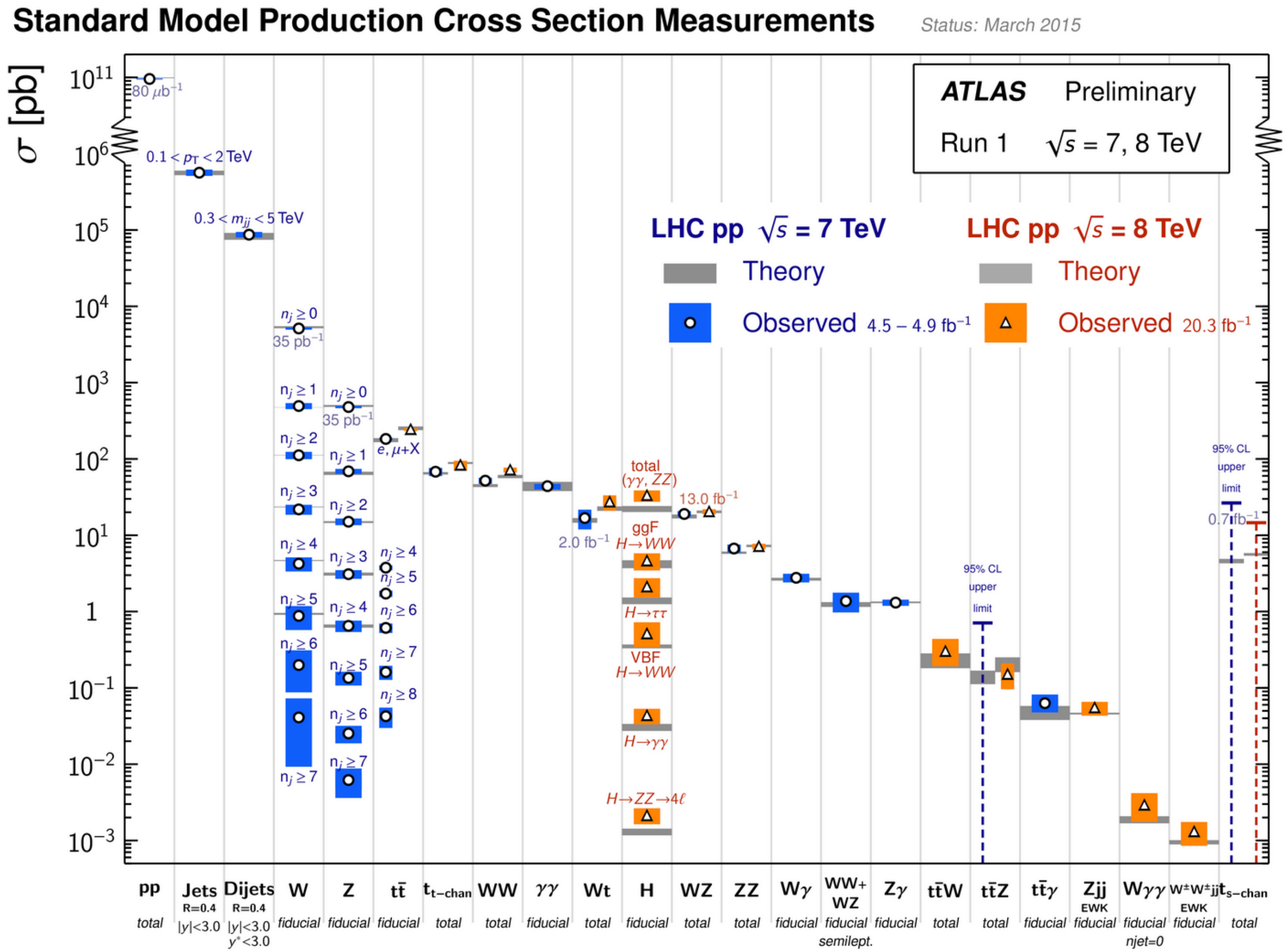
2009 | 2010 | 2011 | 2012 | 2013

Rediscovering the Standard Model

Stunning achievement, both from experiment and theory.

A necessary step to confidently search for the Higgs boson and New Physics in general!

See Alberto Belloni's talk



The LHC Run 1

2009 | 2010 | 2011 | 2012 | 2013

30 Nov 2009
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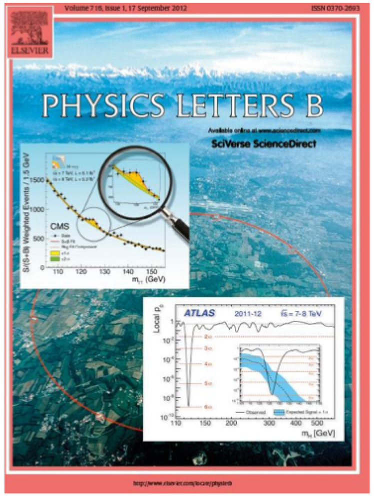
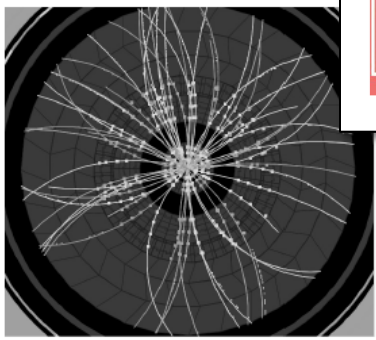
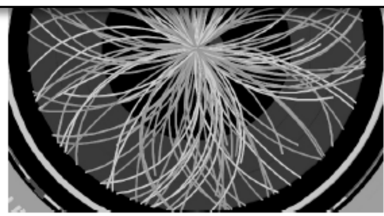
0.05 fb⁻¹
at 7 TeV

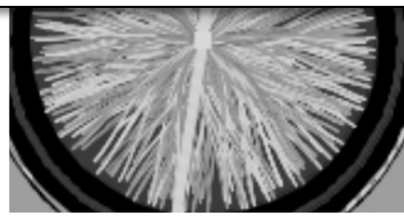
O(2) Pile-up event



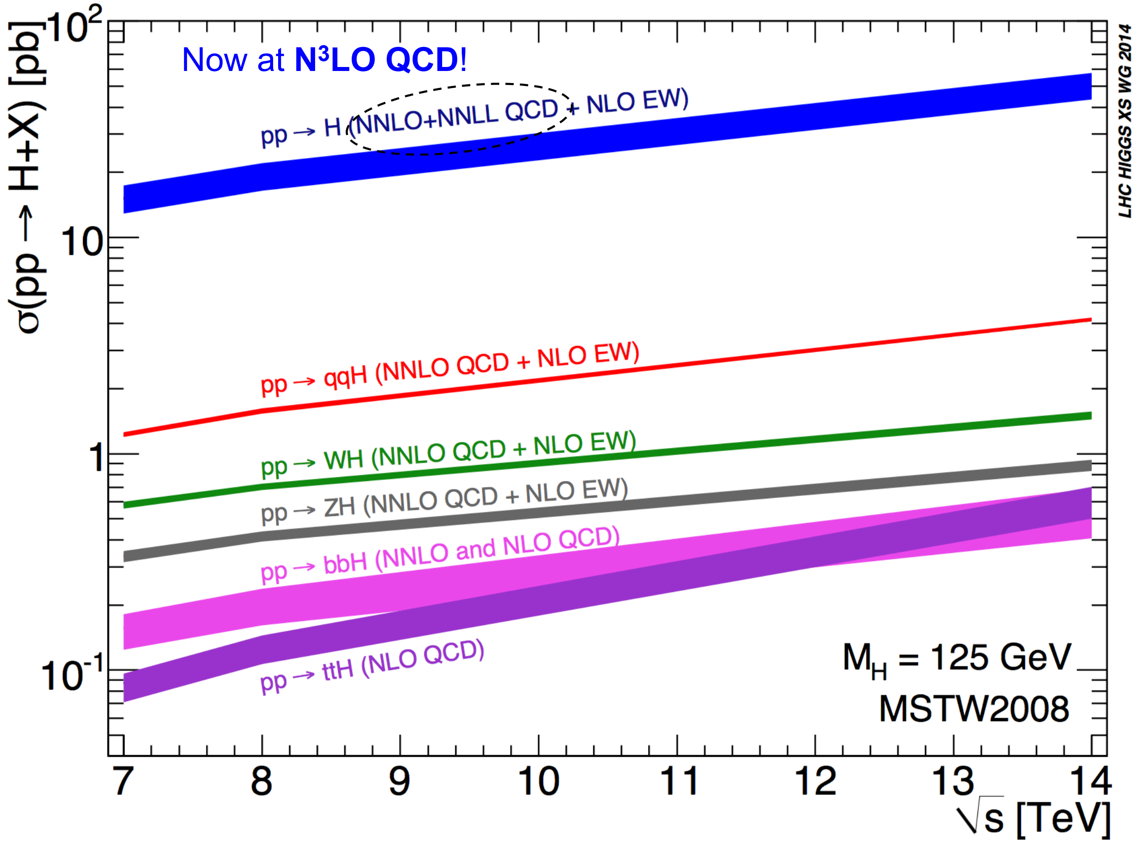
4 July 2012: Higgs boson discovery

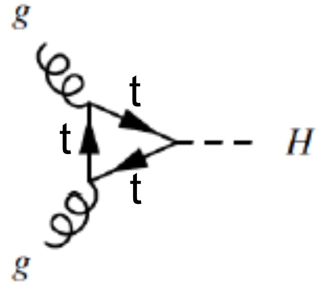






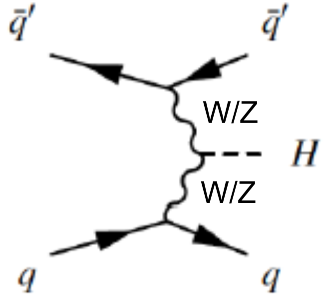
SM Higgs Boson Production at the LHC





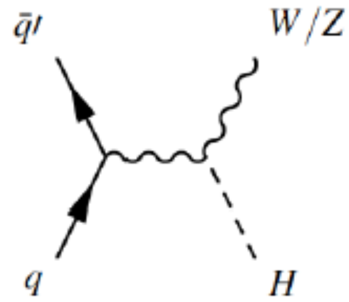
Gluon fusion

(~87%)



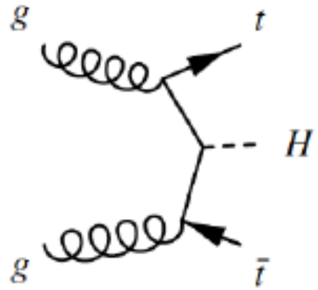
Vector-boson fusion

(~7%)



VH production

(~5%)



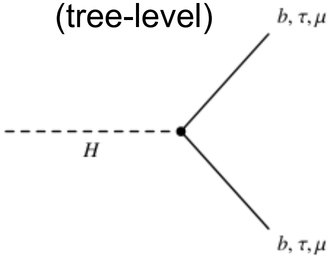
$t\bar{t}H$ production

(~1%)

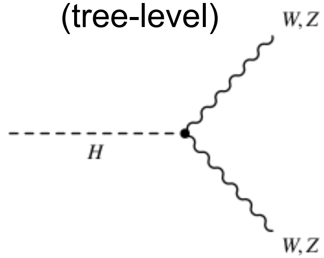
- σ_H(8 TeV)~22 pb. About 450k Higgs events produced at each experiment in 2012!
- Sizeable increase in production cross section from 8 TeV to 13 TeV (~x3.8 for $t\bar{t}H$; ~x2.3 for other modes).
- Impressive progress on theoretical predictions critical for Higgs Physics program. Major role of the LHC Higgs Cross Section Working Group!

SM Higgs Boson Decay

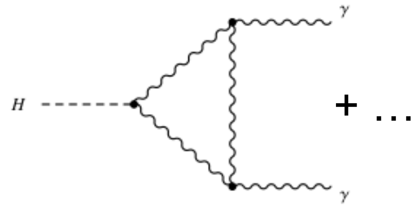
$H \to f\bar{f}$
(tree-level)

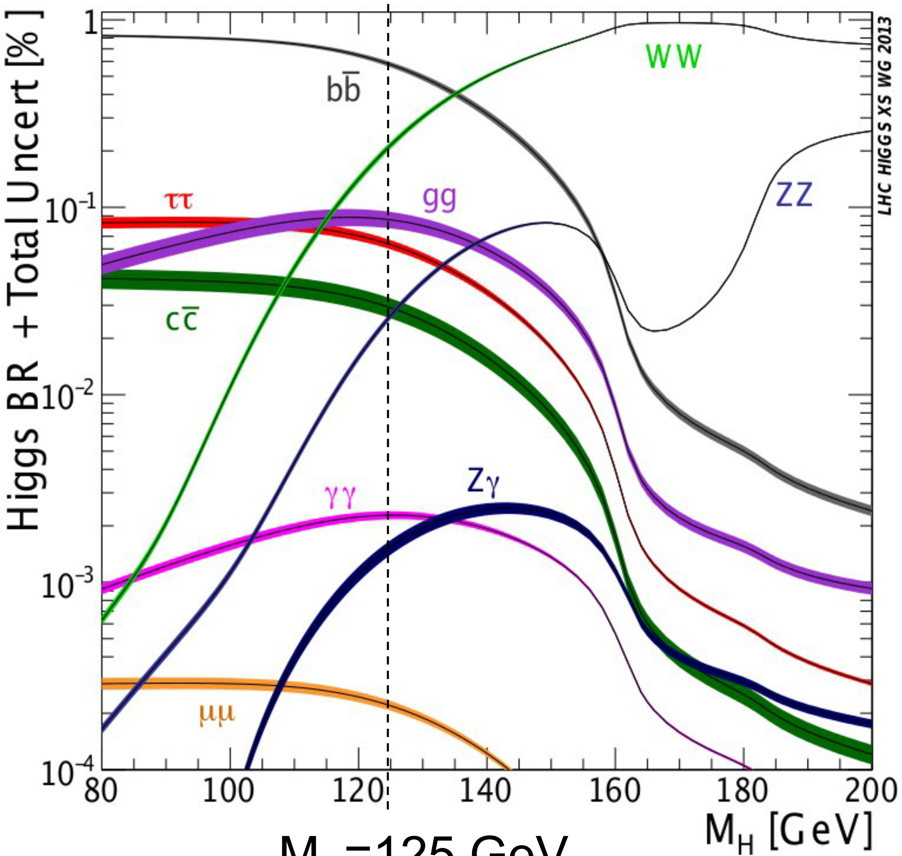


$H \to VV^{(*)}$
(tree-level)



$H \to \gamma\gamma$, γZ, gg
(loop-mediated)





M_H=125 GeV

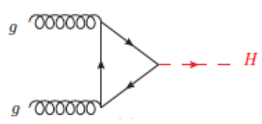
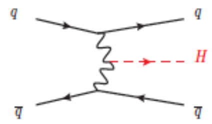
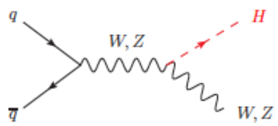
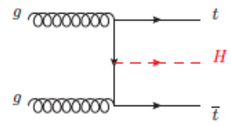
Assuming M_H=125.1 GeV

	Decay mode	Branching fraction [%]
	$H \to bb$	57.5 ± 1.9
	$H \to WW$	21.6 ± 0.9
(*)	$H \to gg$	8.56 ± 0.86
	$H \to \tau\tau$	6.30 ± 0.36
(*)	$H \to cc$	2.90 ± 0.35
	$H \to ZZ$	2.67 ± 0.11
	$H \to \gamma\gamma$	0.228 ± 0.011
	$H \to Z\gamma$	0.155 ± 0.014
	$H \to \mu\mu$	0.022 ± 0.001

(*) Only ~11% of decays not observable

Overview of Main Higgs Analyses

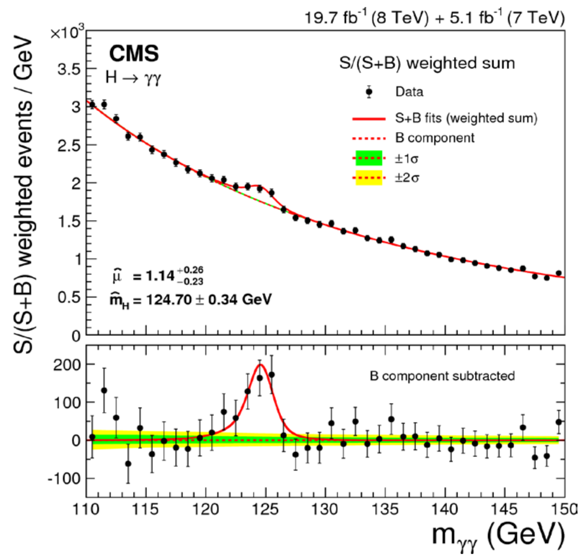
Production modes

Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lνlν)	✓	✓	✓	✓
ττ				
bb				
Zγ				
μμ				
Invisible	✓			

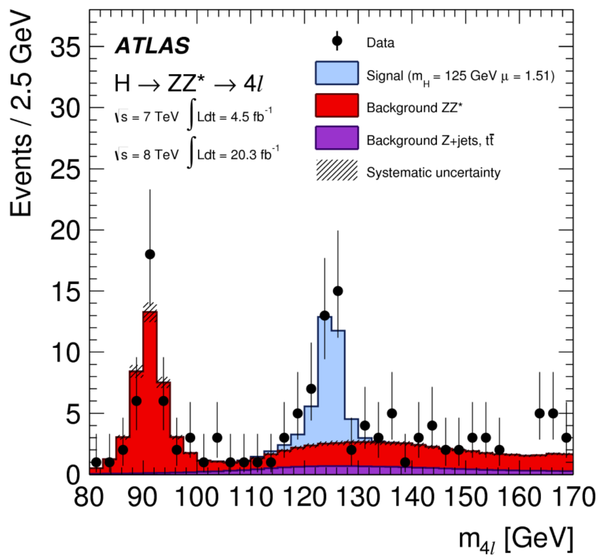
Decay modes

Discovery channels

γγ



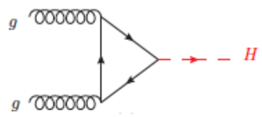
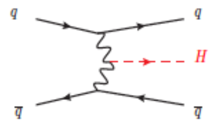
ZZ* → 4l



Overview of Main Higgs Analyses

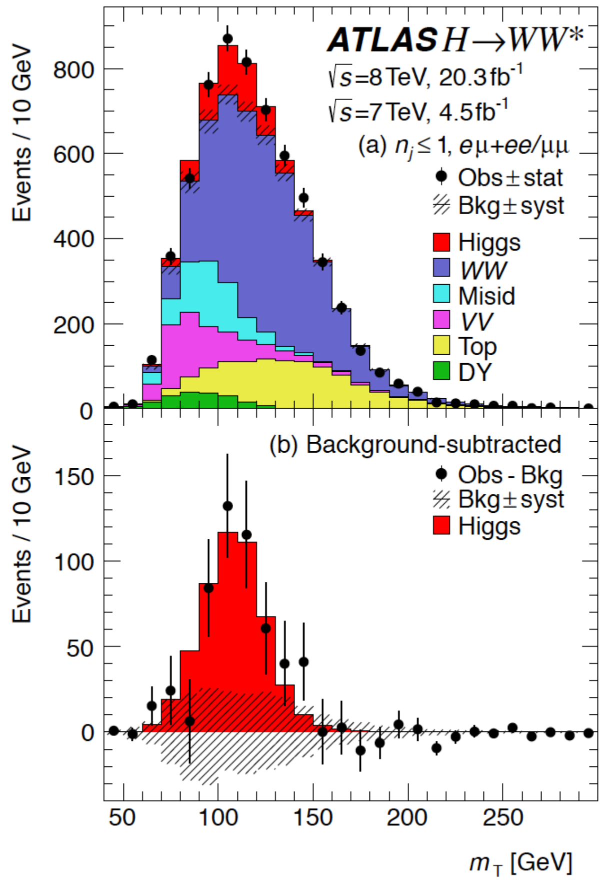
Production modes

Decay modes

Channel categories	ggF 	VBF 
γγ	✓	✓
ZZ (llll)	✓	✓
WW (lνlν)	✓	✓
ττ	✓	✓
bb		✓
Zγ	✓	✓
μμ	✓	✓
Invisible	✓ (monojet)	✓

A different kind of discovery channel

(requires exquisite background understanding)



Overview of Main Higgs Analyses

Production modes

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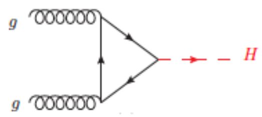
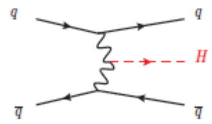
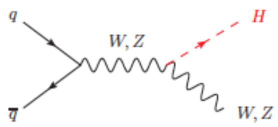
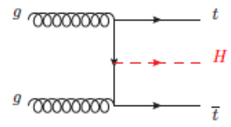
Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
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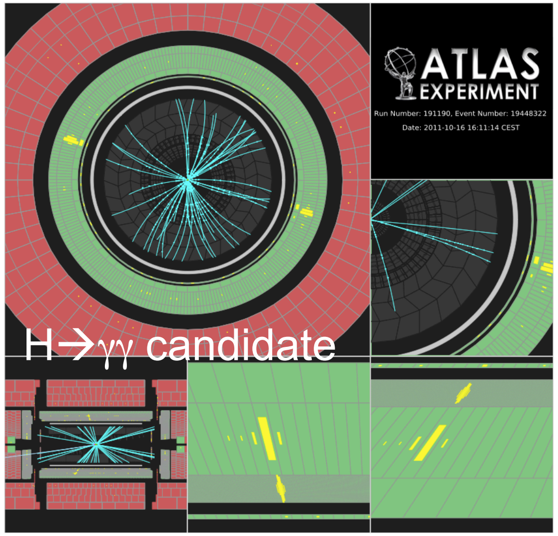
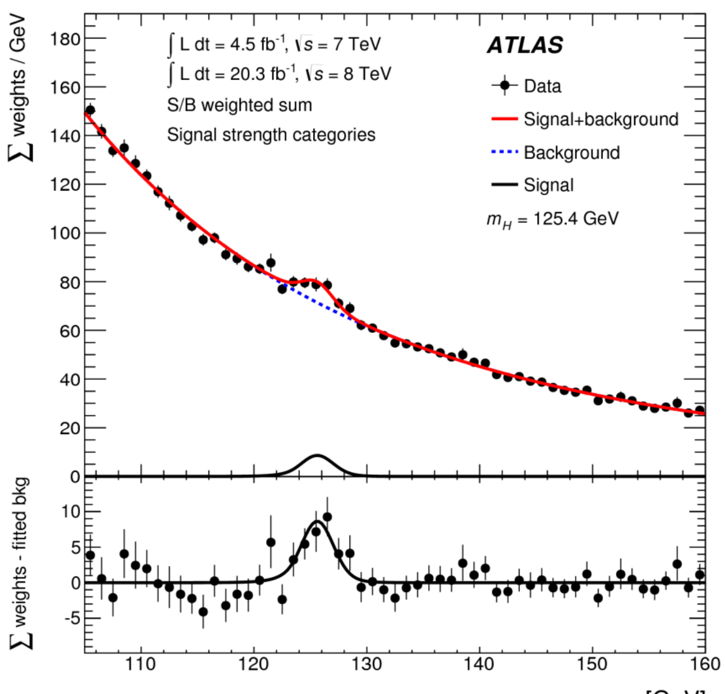
WW (lνlν)	✓	✓	✓	✓
ττ	✓	✓	✓	✓
bb		✓	✓	✓
Zγ	✓	✓		
μμ	✓	✓		
Invisible	✓ (monojet)	✓	✓	

The rest of the channels are crucial to establish the nature of the particle

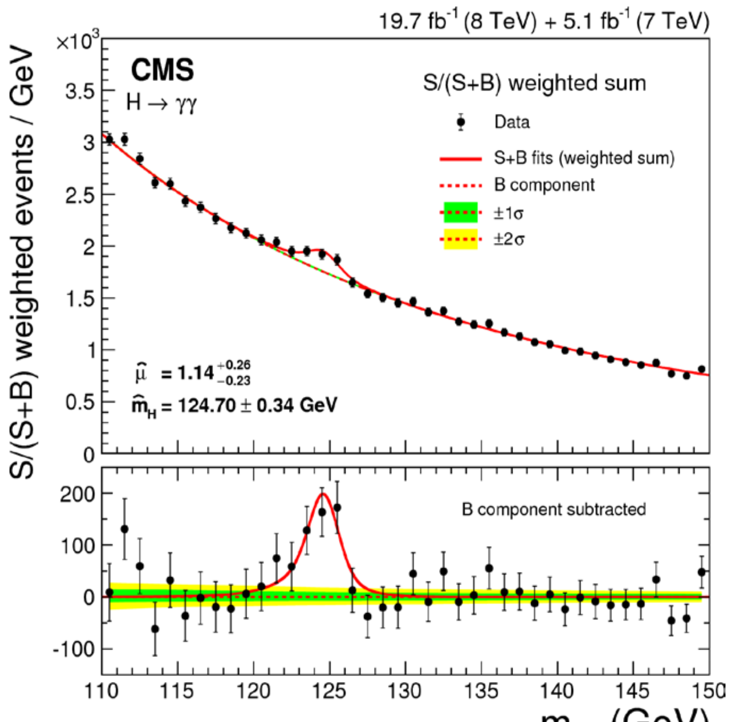
H→γγ

- A rare Higgs decay mode: BR(H→γγ)~0.2%
  But most sensitive search at m_H<125 GeV!
- Narrow diphoton resonance over continuum background (mass resolution of ~1-2%).
- Large background from non-resonant γγ production (irreducible, dominant), and γ+jet and dijet production (reducible). Background determined from data sidebands.
- Event categorization to improve S/B ratios and sensitivity to individual production modes (VH, VBF, $t\bar{t}$H).





arXiv:1408.7084

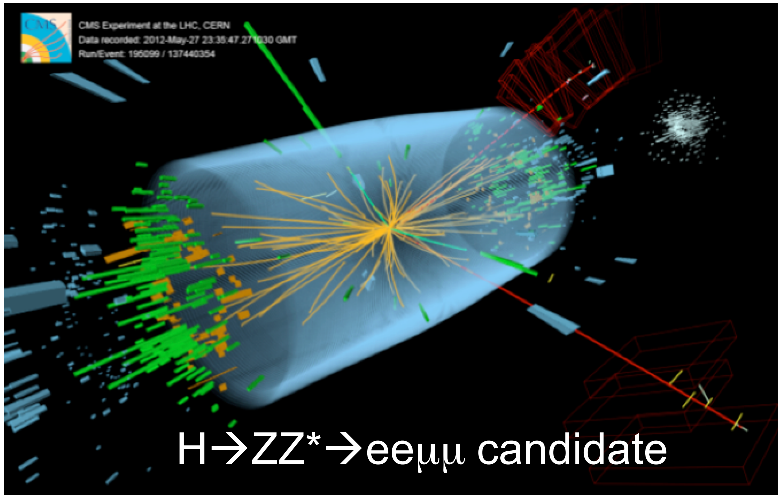


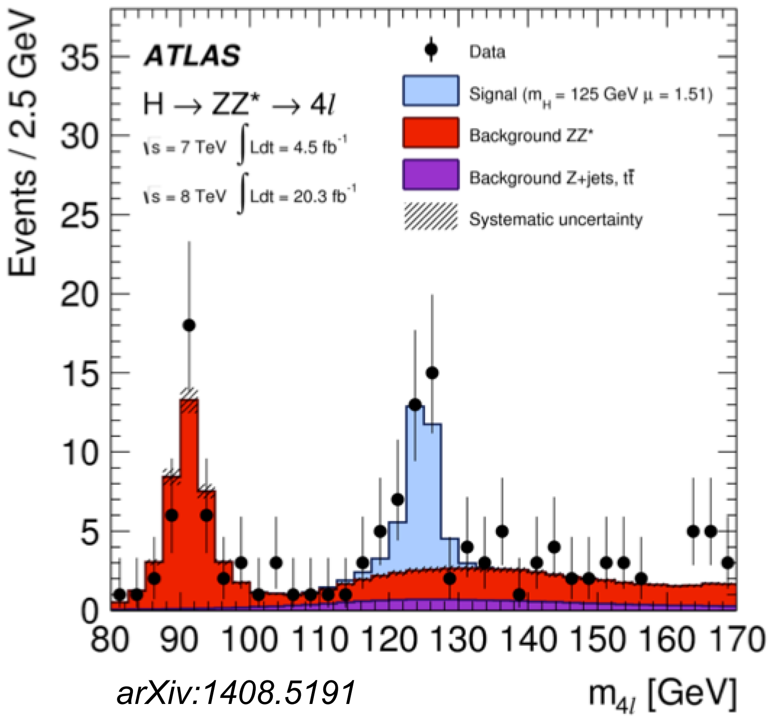
arXiv:1407.0558

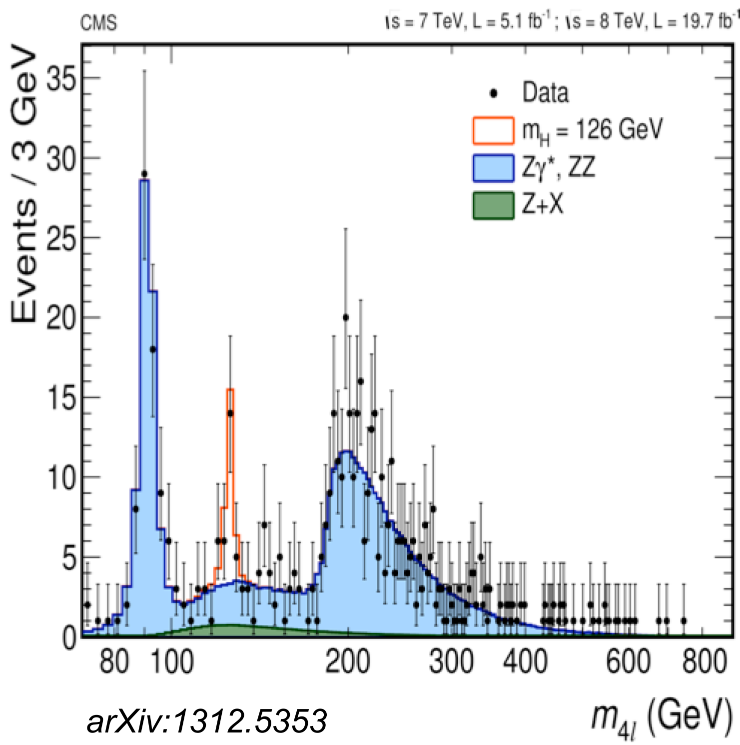
H→ZZ*→4l

- An even rarer Higgs decay mode if both Z bosons are required to decay into ee or μμ!

  BR(H→ZZ*→4e, 4μ or 2e2μ)~0.01%
- Clean signature: four isolated leptons forming a narrow resonance over a small background:
  - Mainly from non-resonant (Z/γ*)(Z/γ*)
  - Small contribution from $t\bar{t}$ and Z+jets
- Good mass resolution ~1-2%
- Event categories also defined.



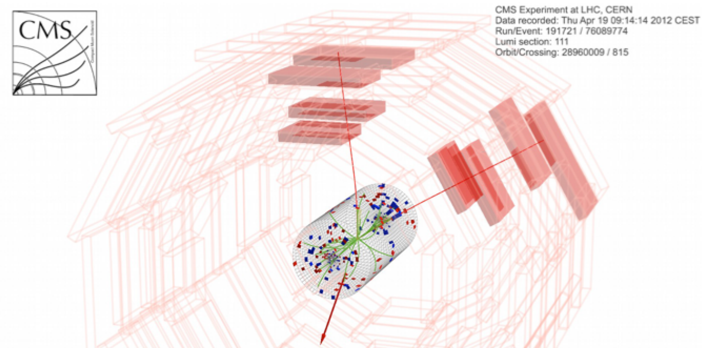




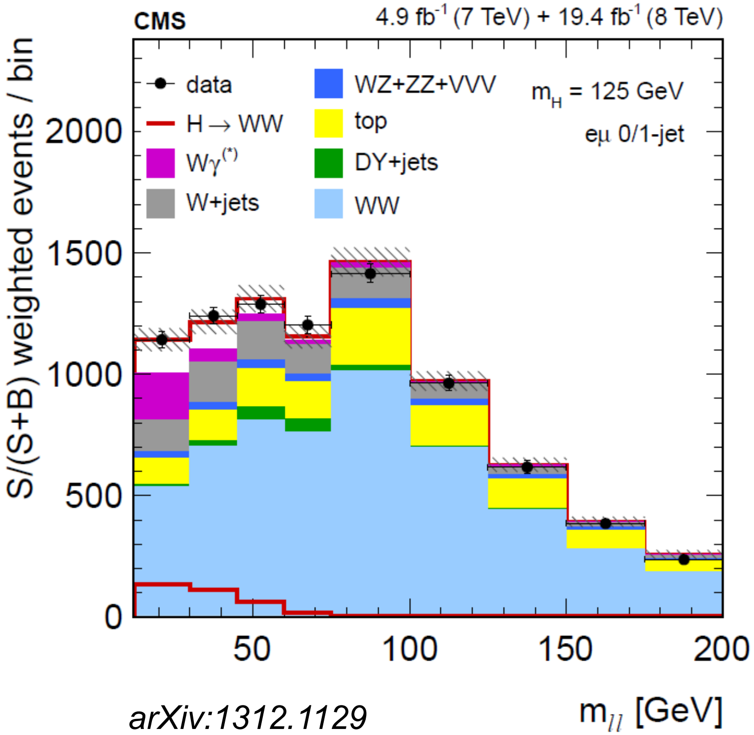
arXiv:1408.5191 *arXiv:1312.5353*

H→WW*→lνlν

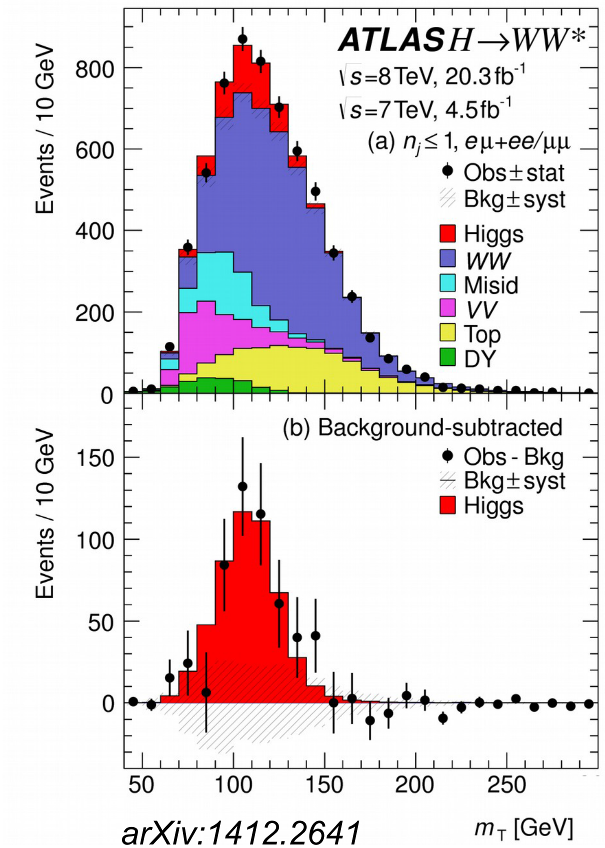
- High-sensitivity channel for 130<m_H<200 GeV.
- Clean dilepton plus E_T^{miss} signature but low S/B.
- Main backgrounds: Z+jets, WW, W+jet/γ, top.
  ➔ normalization in data control regions.
- No direct reconstruction of Higgs mass possible (neutrinos) ➔ use transverse mass variable.
- Exploit spin correlation between W bosons:
  spin 0 ➔ small angular separation between leptons.



H→WW*→μνμν candidate



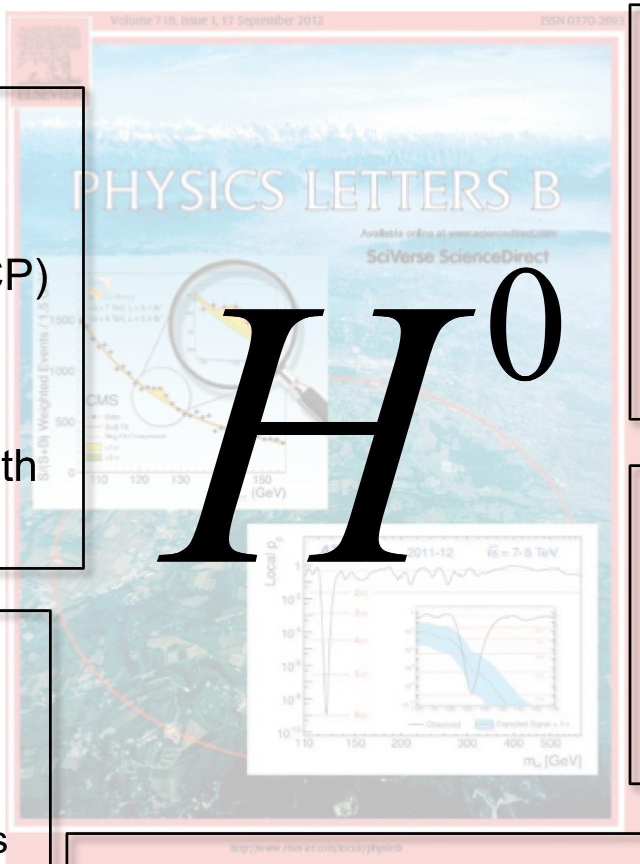
arXiv:1312.1129



arXiv:1412.2641

Explosion of the Higgs Physics Landscape!

- Since the discovery of the Higgs boson, an entire new field has emerged.



Precision measurements
- Mass and width
- Quantum numbers (spin, CP)
- Coupling properties
- Differential cross sections
- Off-shell couplings and width
- Interferometry

Is the SM minimal?
- 2HDM searches
- MSSM, NMSSM searches
- Doubly-charged Higgs bosons

See Anna Goussiou's talk

Rare / BSM decays
- $H^0 \rightarrow \mu\mu$
- $H^0 \rightarrow Z\gamma$
- $H^0 \rightarrow J/\psi\gamma$, $\Upsilon(ns)\gamma$
- LFV $H^0 \rightarrow \mu\tau$, $e\tau$, $e\mu$
- $H^0 \rightarrow aa$

…and more!
- FCNC $t \rightarrow H^0q$ decays
- Di-Higgs production
- Trilinear coupling
- … etc

Tool for discovery
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (VH^0, H^0H^0)

See Farid Ould-Saada and Bjoern Penning's talks

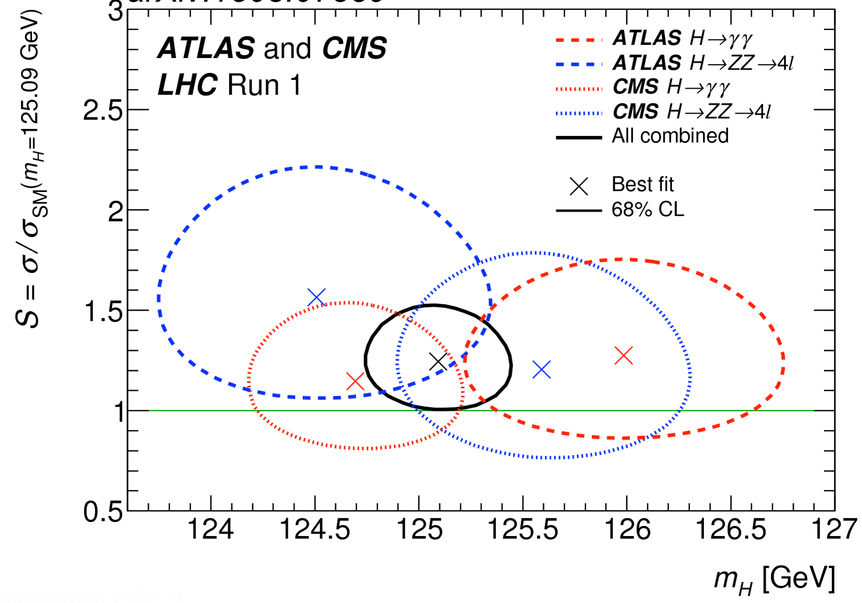
Higgs Boson Mass

- Measurement of the Higgs boson mass performed in the two channels with the best mass resolution: H→γγ and H→ZZ*→4l using final Run 1 calibrations.
- Signal yield left free to avoid biasing mass measurement.

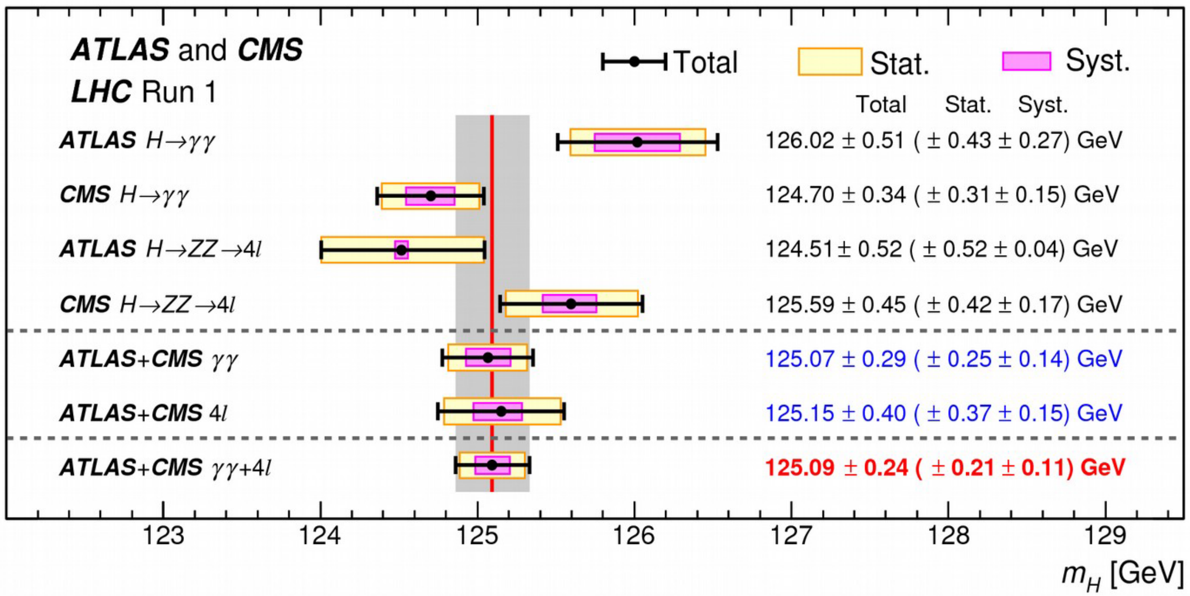
$$\boxed{m_H = 125.09 \pm 0.24 \text{ GeV}}$$

2 per-mille accuracy!

arXiv:1503.07589



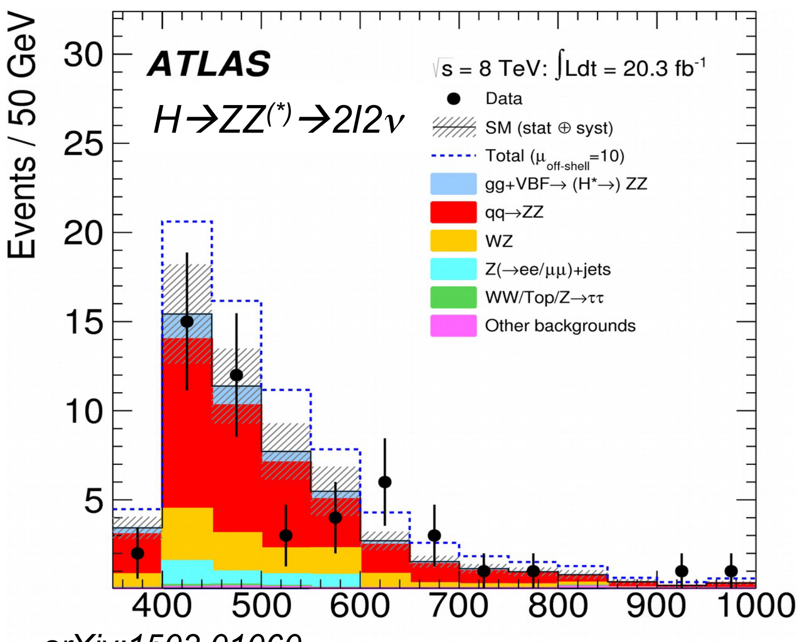
arXiv:1503.07589



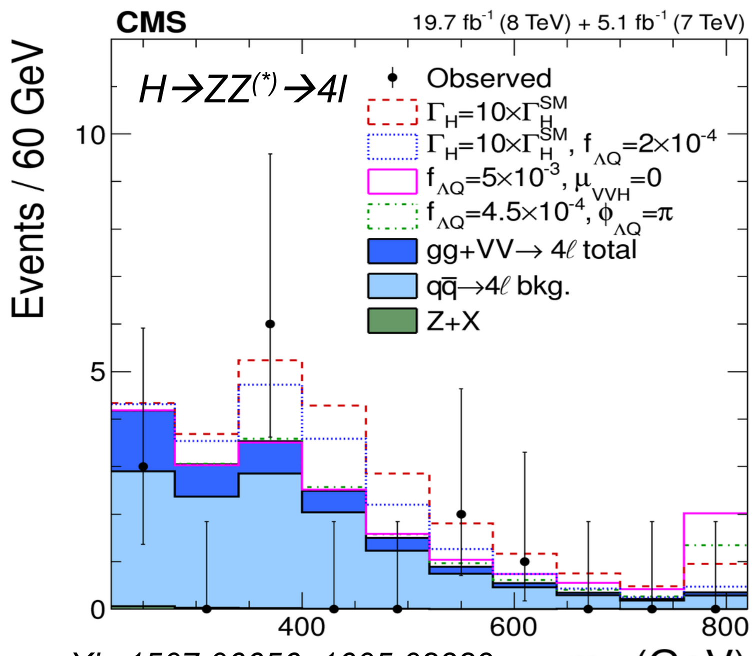
- Compatibility of the four measurements ~10%.
- Measurement still dominated by the statistical uncertainty.
- Main systematic uncertainty related to photon and lepton energy scales.

Higgs Boson Width

- SM prediction: Γ_H(SM)=4.2 MeV (~3 orders of magnitude smaller than $\Gamma_{W,Z}$).
- Existing direct bounds have no sensitivity to the SM width:
  - Γ_H>3.6x10^{-9} MeV (from lifetime in H→ZZ$^{(*)}$→4l)
  - Γ_H<1.7 GeV (from invariant mass distribution)
- Higher sensitivity from indirect measurement comparing cross section for on-shell and off-shell H→VV$^{(*)}$ (V=W,Z) production (and including interference with background).
  - Assumes same couplings on-shell and off-shell and no New Physics at high m_{VV}.



arXiv:1503.01060



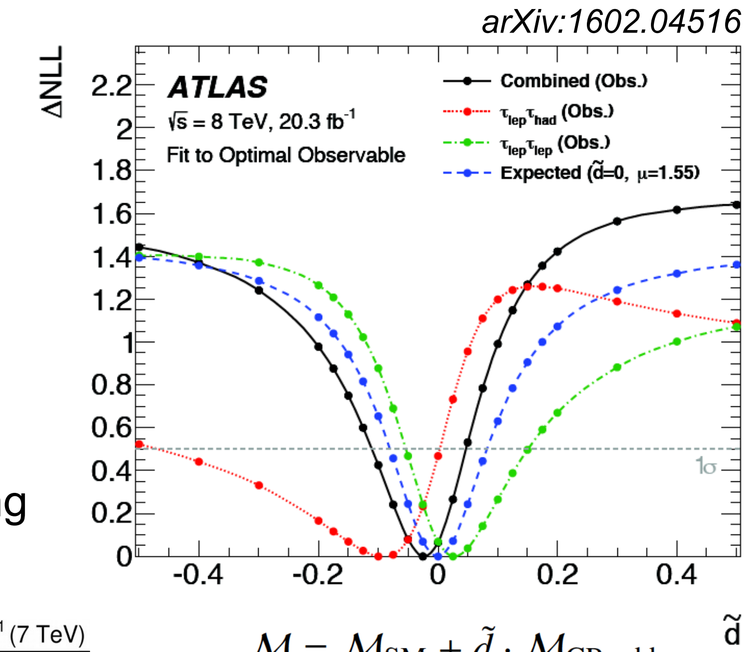
arXiv:1507.06656, 1605.02329

Obs (exp) limit: Γ_H<23 (33) MeV

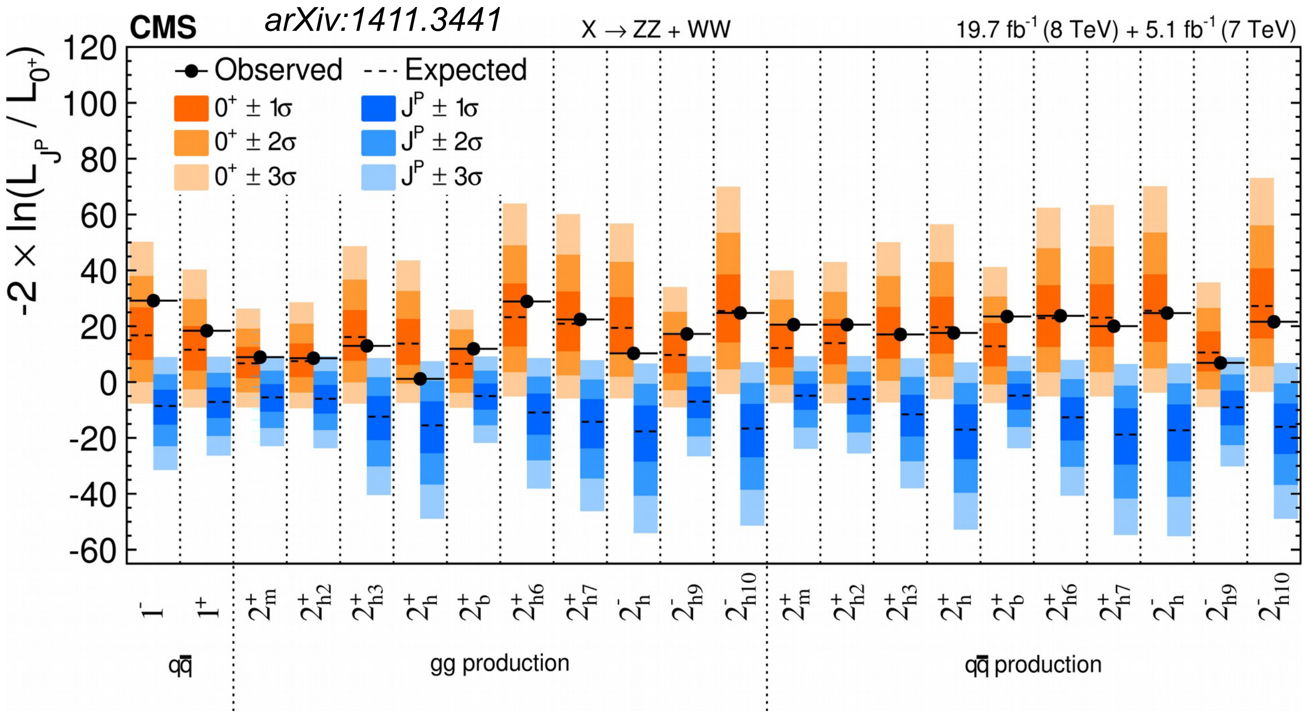
Obs (exp) limit: Γ_H<13 (26) MeV

Spin/CP Properties

- **Goal**: verify scalar and CP-even nature ($J^{CP}=0^+$) of the new boson.
- Use $H\rightarrow\gamma\gamma$, ZZ^* and WW^* analyses re-optimized for spin/CP tests. Different kinematic distributions used.
- Alternative spin hypotheses are disfavored by $>3\sigma$ combining $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ^*$, and $H\rightarrow WW^*$ analyses.
- Tensor structure of the HVV interaction has been tested using $H\rightarrow ZZ^*$ and $H\rightarrow WW^*$ analyses, including CP-odd contributions.



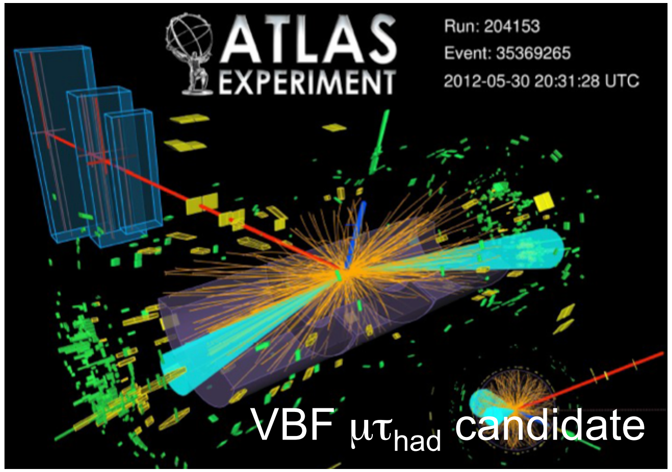
$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \tilde{d} \cdot \mathcal{M}_{\mathrm{CP\text{-}odd}}$$

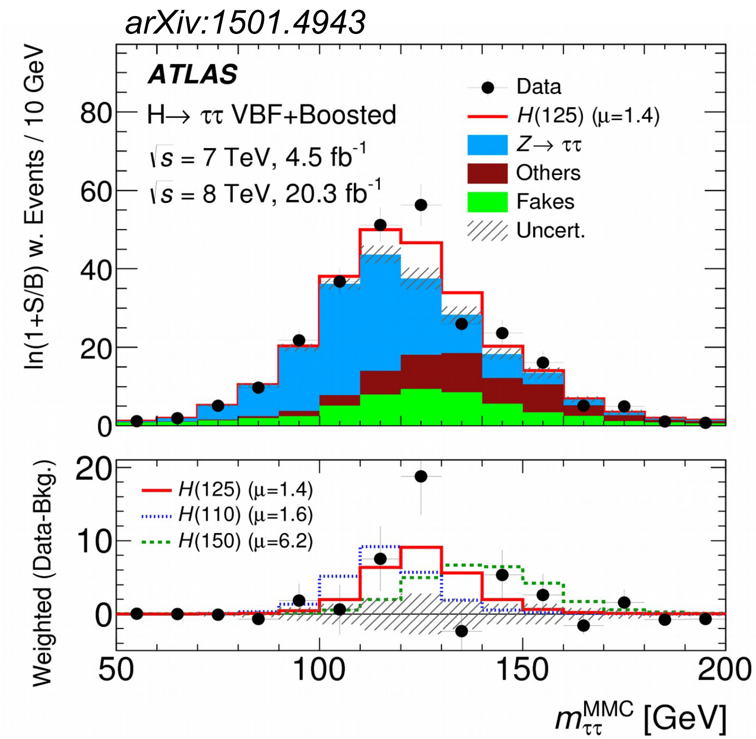


- Additional constraints on CP-odd contributions have been obtained using the VBF, $H\rightarrow\tau\tau$ process.

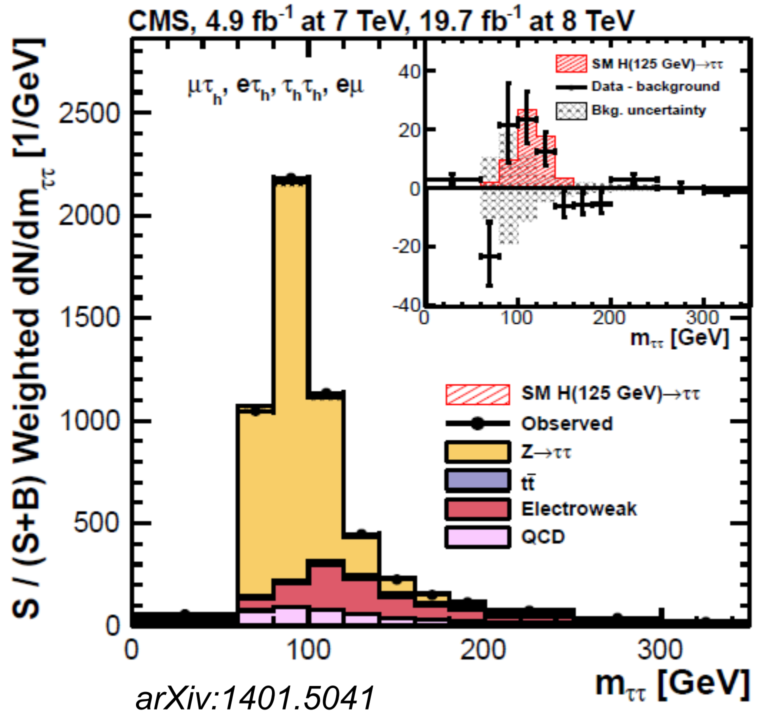
Higgs Couplings to Fermions: H→$\tau^+\tau^-$

- The most sensitive of the fermionic decay modes.
- Events categorized depending on the tau decay modes (leptonic, hadronic) and the jet multiplicity to enhance the sensitivity to VBF and gluon fusion production of highly-boosted Higgs bosons.
- Main background is Z→$\tau\tau$, modeled from Z→$\mu\mu$ data replacing muons by simulated tau decays ("τ embedding").





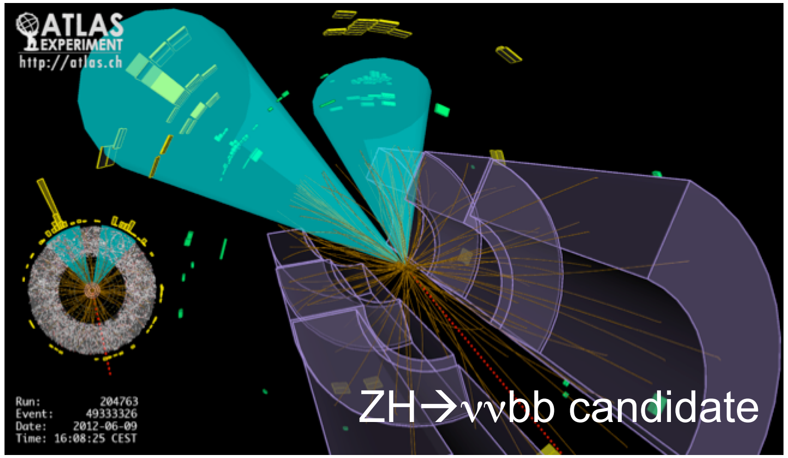
Obs (exp) significance: 4.5σ (3.4σ)



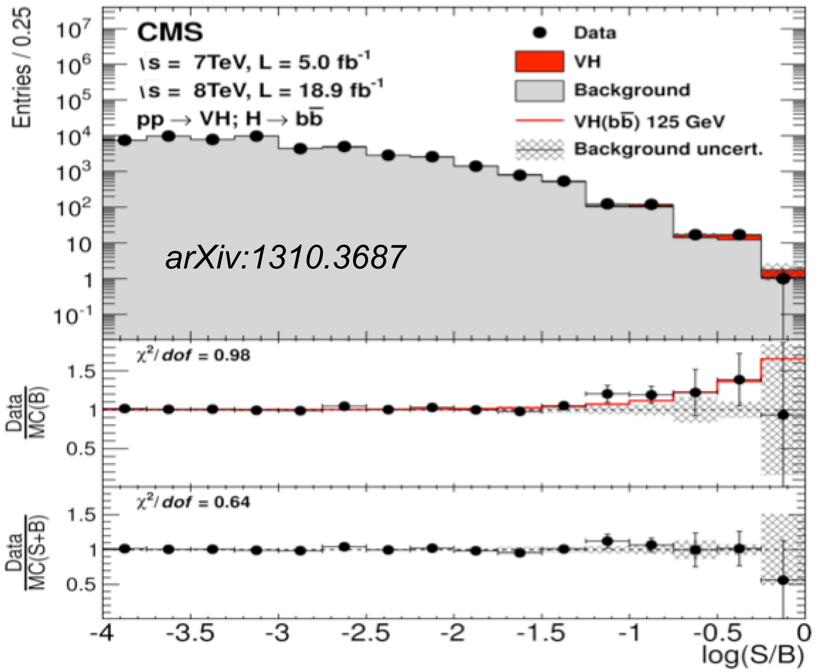
Obs (exp) significance: 3.2σ (3.7σ)

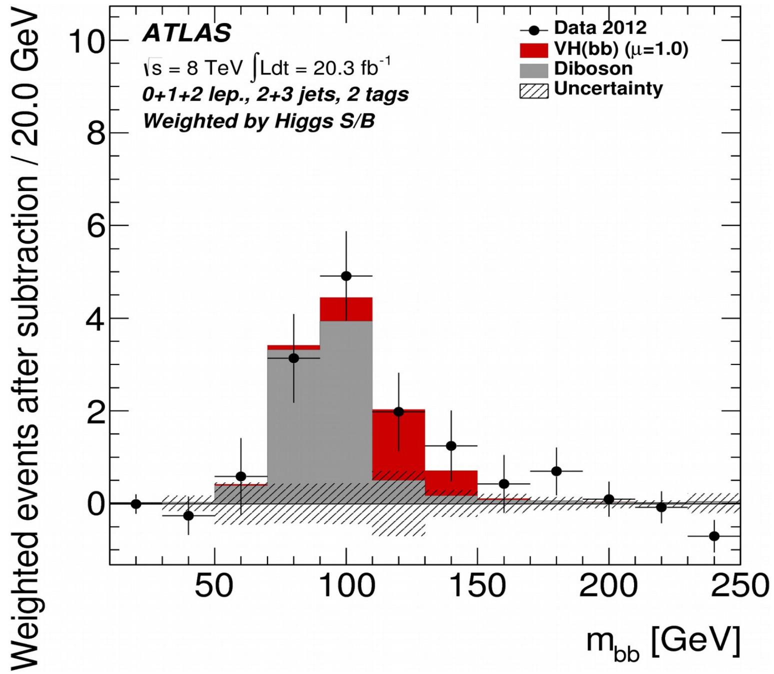
Higgs Couplings to Fermions: H→b$\bar{b}$

- Most abundant decay mode: BR(H→b$\bar{b}$)~58%.
- Exploit three leptonic W/Z decay modes in VH associated production ➔ categorize events by lepton multiplicity (0-lepton, 1-lepton, 2-lepton).
- Broad di-b-jet resonance over large background from W+heavy-flavor and t$\bar{t}$ production.
- Multivariate analyses to increase sensitivity.
- Use VZ(Z→b$\bar{b}$) to validate search strategy.



arXiv:1409.6212





Obs (exp) significance: 2.1σ (2.1σ)

Obs (exp) significance: 1.4σ (2.6σ)

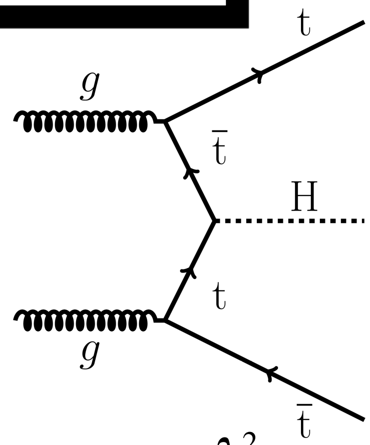
Higgs Couplings to Fermions: $t\bar{t}H$

- Associated $t\bar{t}H$ production allows direct measurement of the top-Higgs Yukawa coupling.
- Very rich experimental signature, depending on the decay of the top quarks and the Higgs boson.

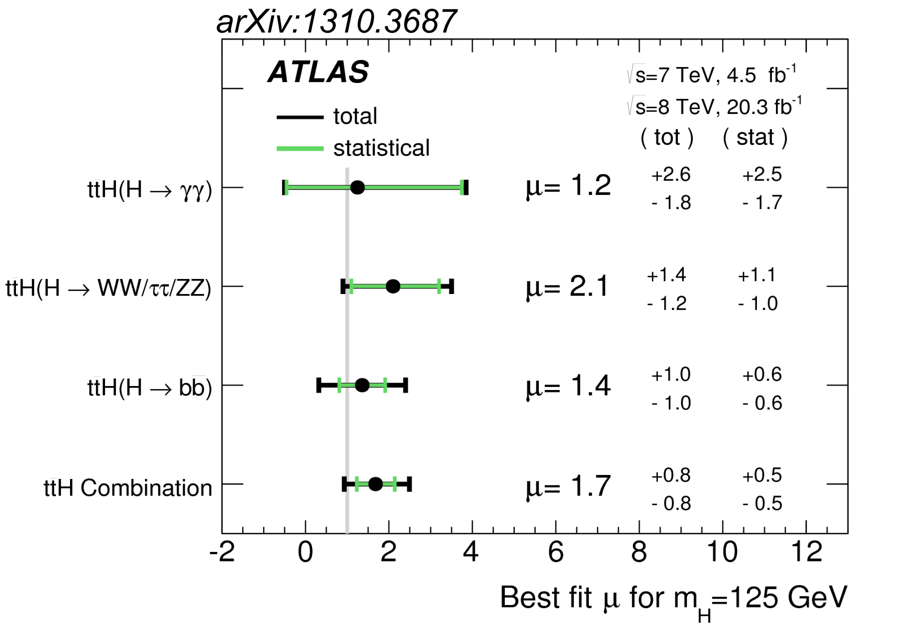
  H→$b\bar{b}$: multi-b final states; large background from $t\bar{t}$+jets

  H→WW, ττ: multi-lepton lepton final states (e.g. SS dileptons, trileptons); better S/B, background from $t\bar{t}V$, $t\bar{t}$+jets

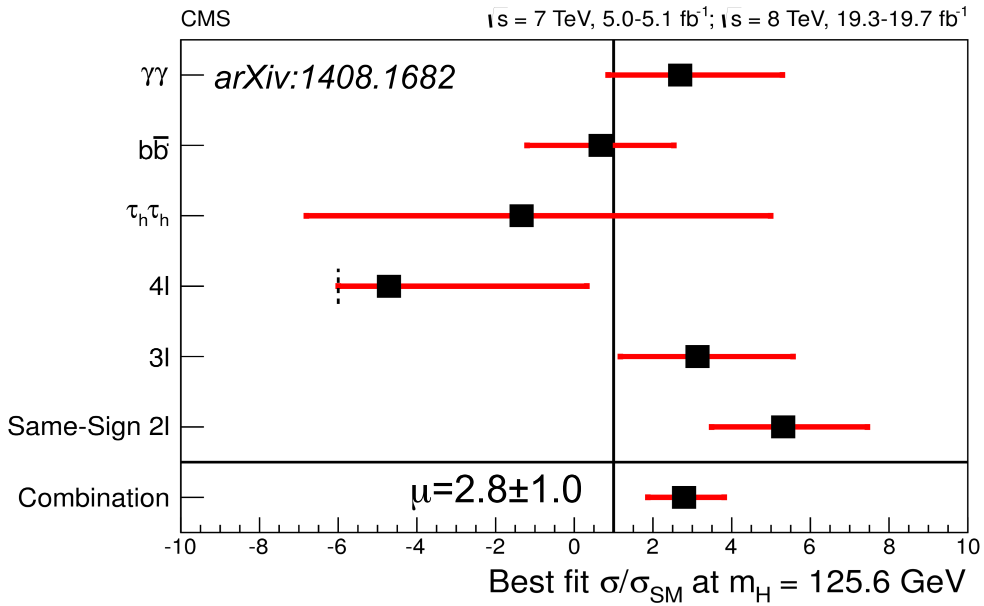
  H→γγ: best S/B but low rate
- Analyses characterized by large number of categories and control regions.



$$\sigma_{t\bar{t}H} \propto \lambda_t^2$$



Obs (exp) significance: 2.5σ (1.5σ)



Obs (exp) significance: 3.4σ (1.2σ)

Total Cross Section

- At the LHC only products of cross section times branching ratios are measured. There is no model-independent way to determine the cross section and the branching ratio separately.

- Combined total cross section (including 7 and 8 TeV measurements) assuming SM kinematics, SM ratios for production cross sections, and SM branching ratios:

$\mu = \sigma / \sigma_{SM}$

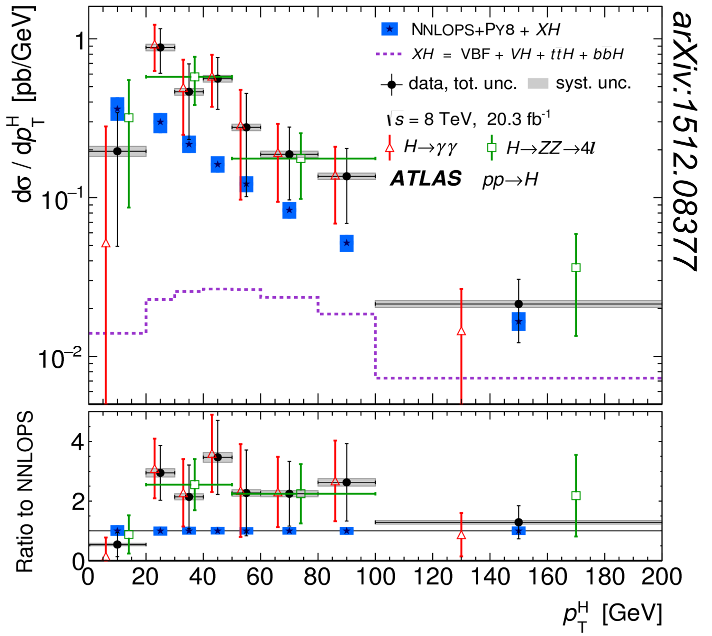
arXiv:1606.02266

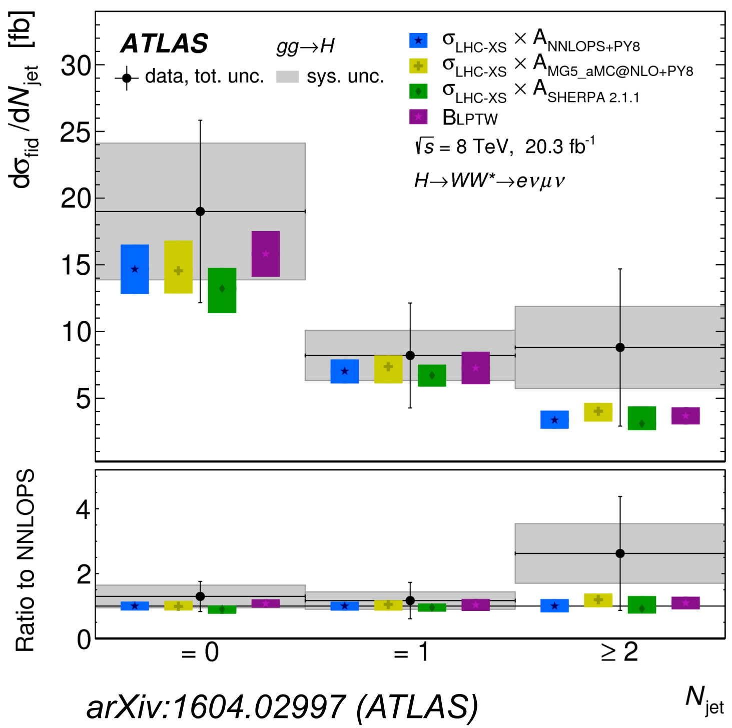
Combined	μ	$=$	$1.09^{+0.11}_{-0.10}$	$=$	$1.09^{+0.07}_{-0.07}\,(\mathrm{stat})\,^{+0.04}_{-0.04}\,(\mathrm{expt})\,^{+0.03}_{-0.03}\,(\mathrm{thbgd})\,^{+0.07}_{-0.06}\,(\mathrm{thsig})$
ATLAS	μ	$=$	$1.20^{+0.15}_{-0.14}$	$=$	$1.20^{+0.10}_{-0.10}\,(\mathrm{stat})\,^{+0.06}_{-0.06}\,(\mathrm{expt})\,^{+0.04}_{-0.04}\,(\mathrm{thbgd})\,^{+0.08}_{-0.07}\,(\mathrm{thsig})$
CMS	μ	$=$	$0.98^{+0.14}_{-0.13}$	$=$	$0.98^{+0.10}_{-0.09}\,(\mathrm{stat})\,^{+0.06}_{-0.05}\,(\mathrm{expt})\,^{+0.04}_{-0.04}\,(\mathrm{thbgd})\,^{+0.08}_{-0.07}\,(\mathrm{thsig})$

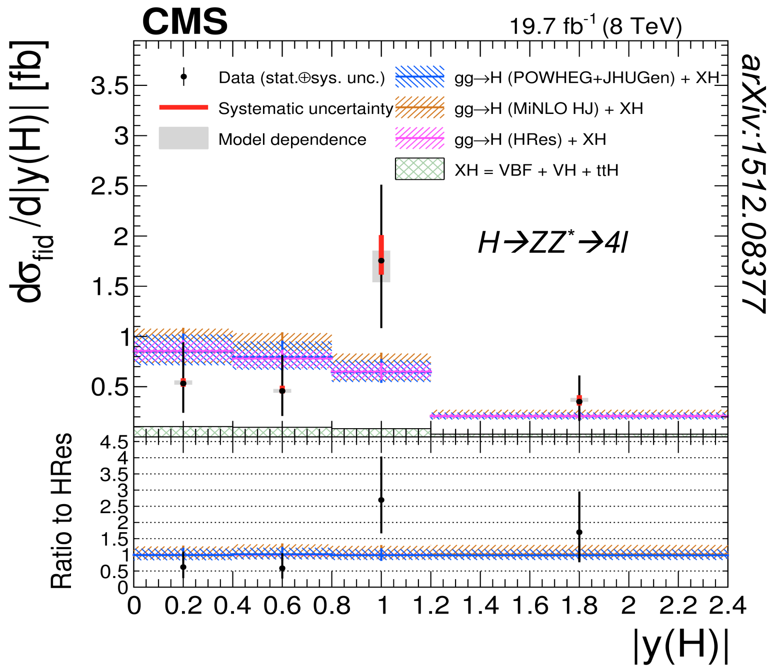
➔ Good agreement with the SM prediction (μ=1)

Differential Cross Sections

- Measurements of differential cross sections using Run 1 data for quantities such as p_T^H, $|y_H|$, or jet multiplicity, unfolded to the particle level.
- Using $H \rightarrow \gamma\gamma$, ZZ^* and even WW^* decay channels.
- Measurements still dominated by the statistical uncertainty.







arXiv:1604.02997 (ATLAS)
arXiv:1606.01522 (CMS)

Signal Strengths by Production and Decay

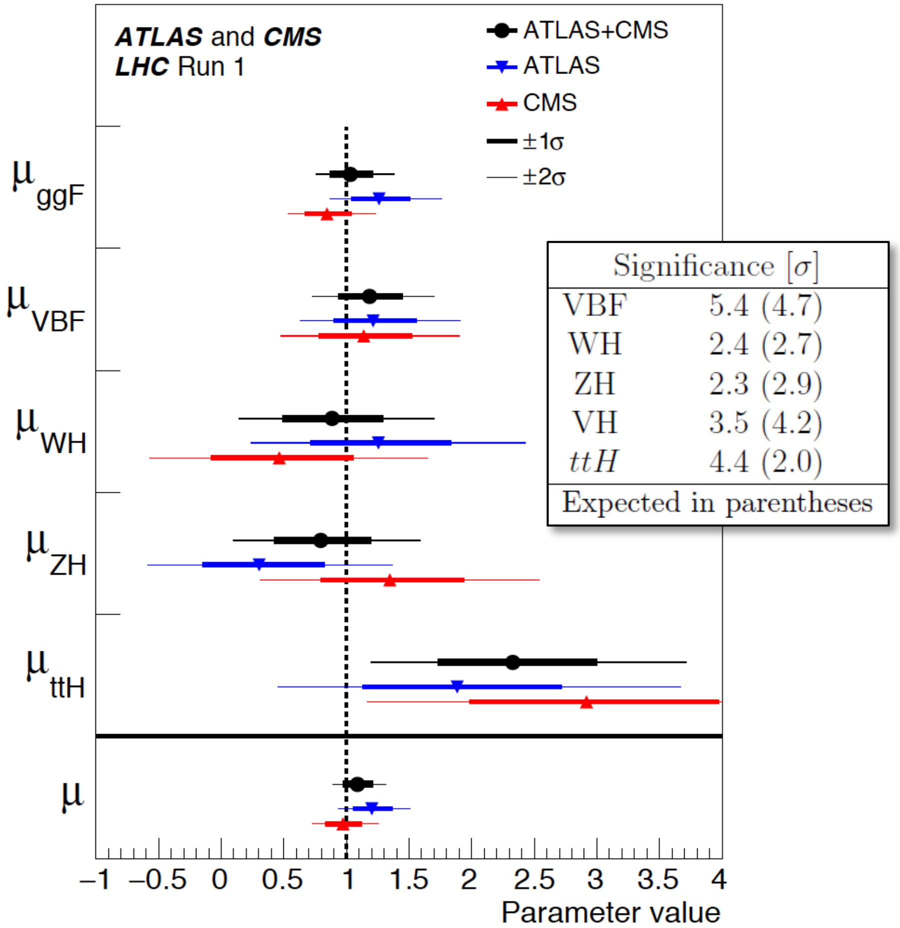
$\sigma_{meas}/\sigma_{SM}$ per production mode

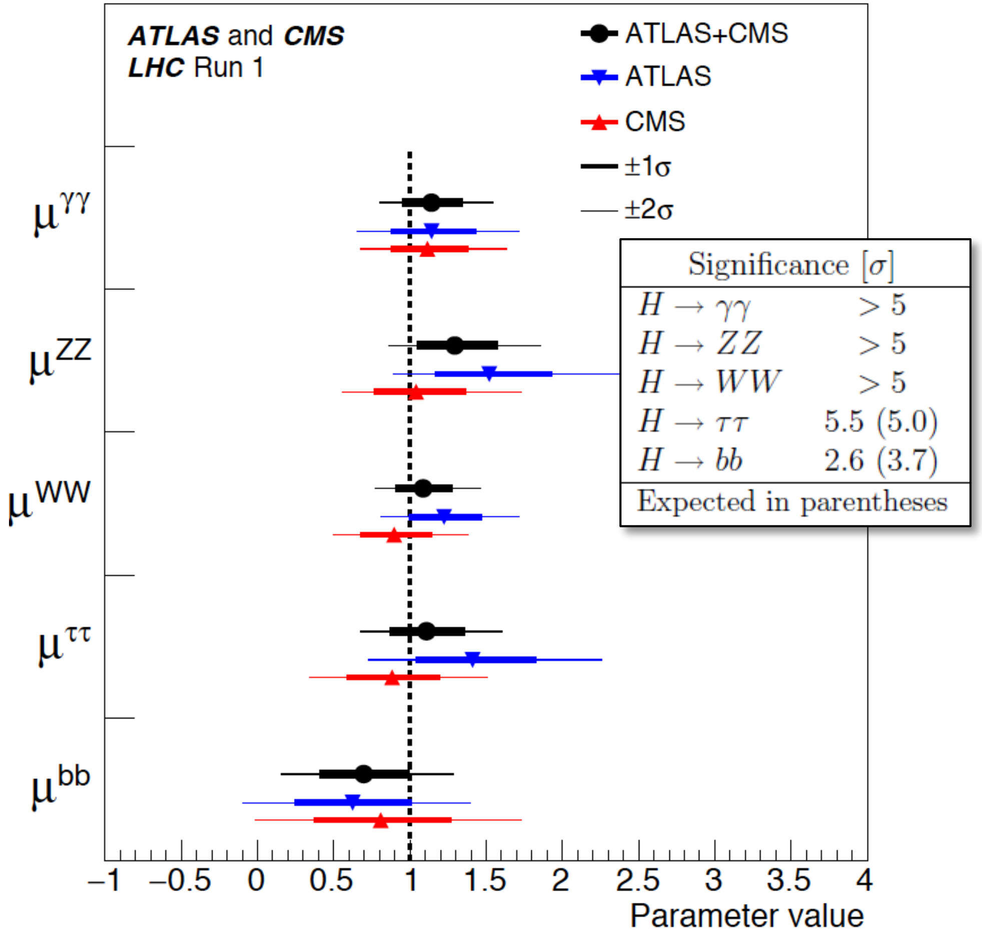
(assuming SM decay)

BR_{meas}/BR_{SM} per decay mode

(assuming SM production)

arXiv:1606.02266





Good agreement with the SM prediction (μ=1)

Probing Higgs Couplings

- Several production and decay mechanisms contribute to signal rates per channel
  ➔ interpretation is difficult
- A better option: measure deviations of couplings from the SM prediction (*arXiv:1209.0040*).
  Basic assumptions:
  - there is only one underlying state with m_H=125.09 GeV,
  - it has negligible width,
  - it is a CP-even scalar (only allow for modification of coupling strengths, leaving the Lorentz structure of the interaction untouched).
- Under these assumptions all production cross sections and branching ratios can be expressed in terms of a few common multiplicative factors to the SM Higgs couplings.
  Examples:

$$\sigma(gg \to H)BR(H \to WW) = \sigma_{SM}(gg \to H)BR_{SM}(H \to WW)\frac{\kappa_g^2 \kappa_W^2}{\kappa_H^2}$$

$$\sigma(WH)BR(H \to bb) = \sigma_{SM}(WH)BR_{SM}(H \to bb)\frac{\kappa_W^2 \kappa_b^2}{\kappa_H^2}$$

$$\kappa_g = f(\kappa_t, \kappa_b, m_H)$$

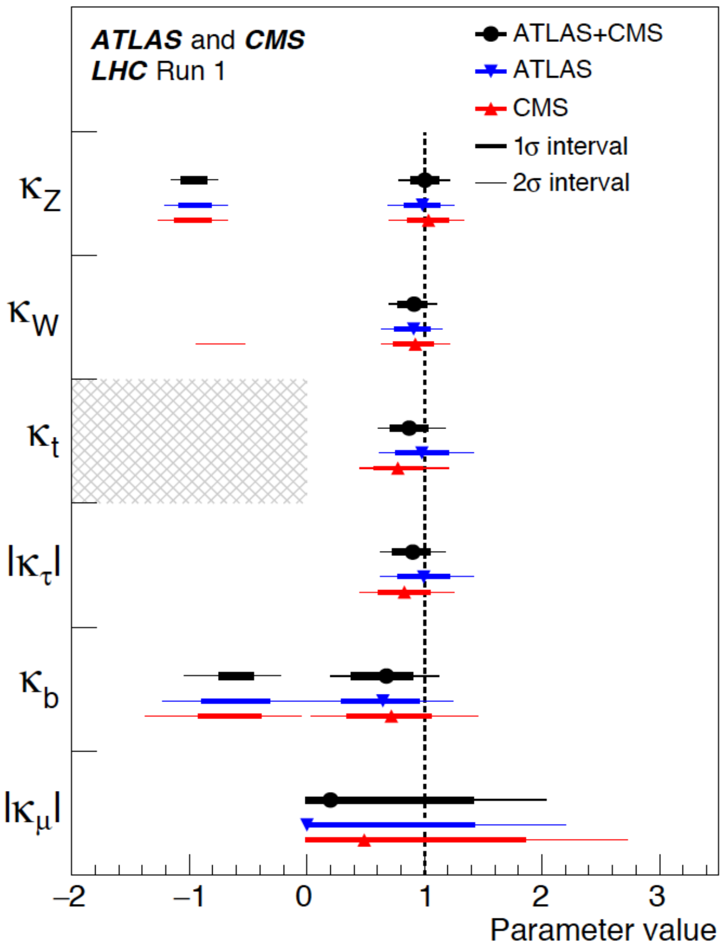
$$\kappa_H = f'(\kappa_t, \kappa_b, \kappa_\tau, \kappa_W, \kappa_Z, m_H)$$

Standard Model Fit

- Resolve all loops.
- One coupling parameters per SM particle.
- No beyond-SM decays.

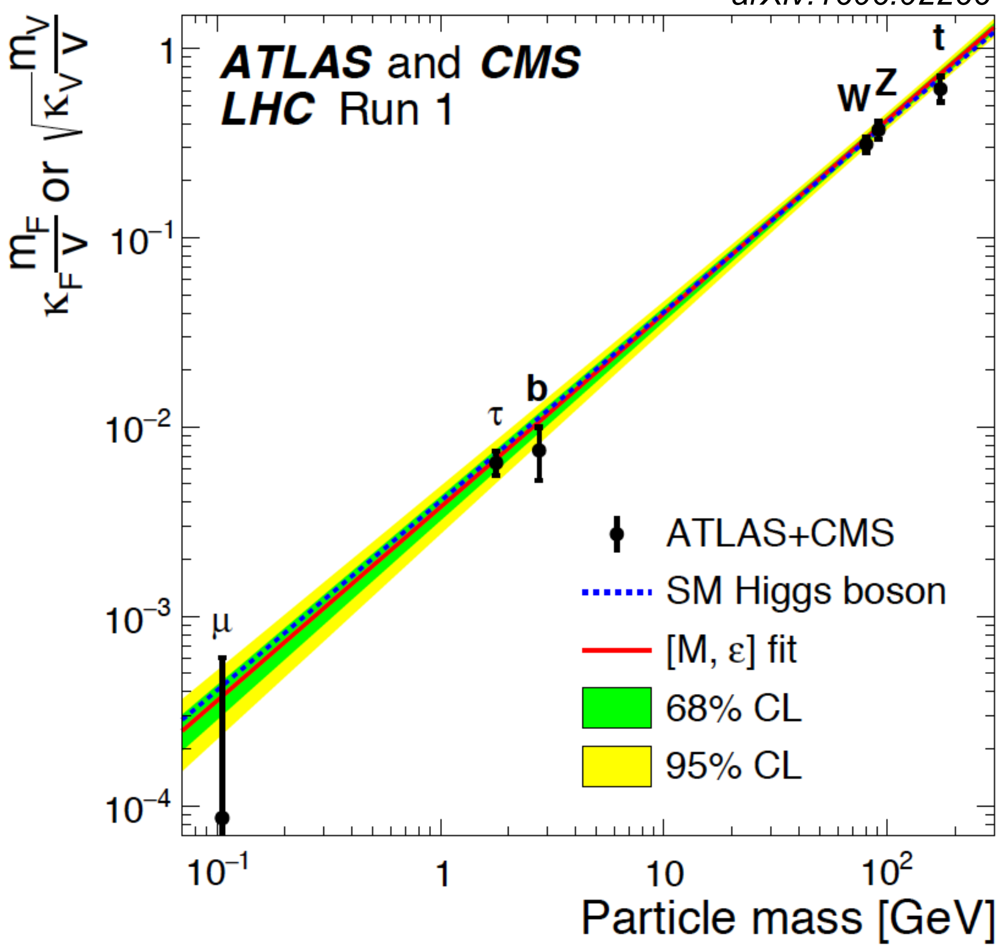
κ_Z, κ_W, κ_t, κ_b, κ_τ, κ_μ

arXiv:1606.02266



Compatibility with the SM: 74%

arXiv:1606.02266



Beyond Standard Model Fit

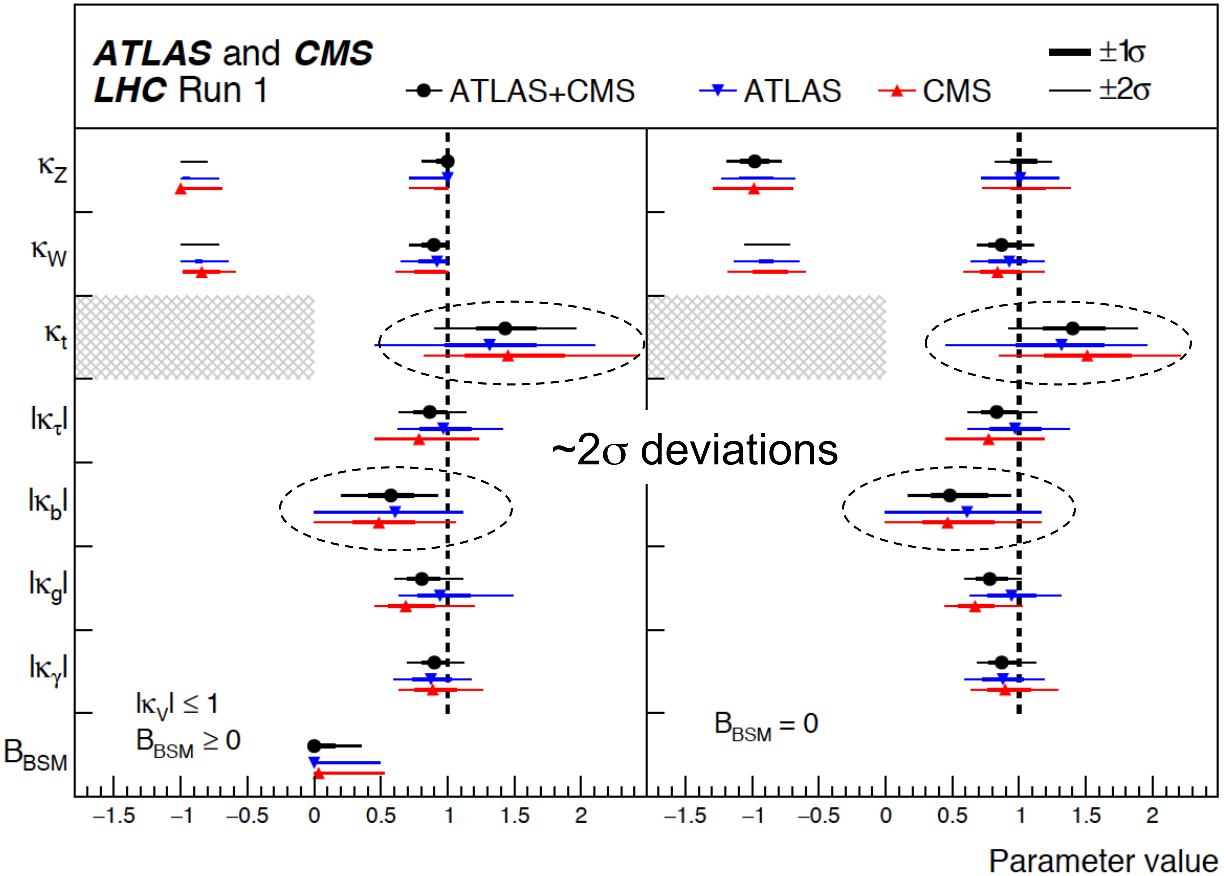
- Allow deviations in all tree-level couplings.
- Allow independent deviations in loop couplings.
- Allow beyond-Standard-Model decays.

  Impose weak constraint $\kappa_V \leq 1$.

$\kappa_Z, \kappa_W, \kappa_t, \kappa_b, \kappa_\tau, \kappa_g, \kappa_\gamma, BR_{BSM}$

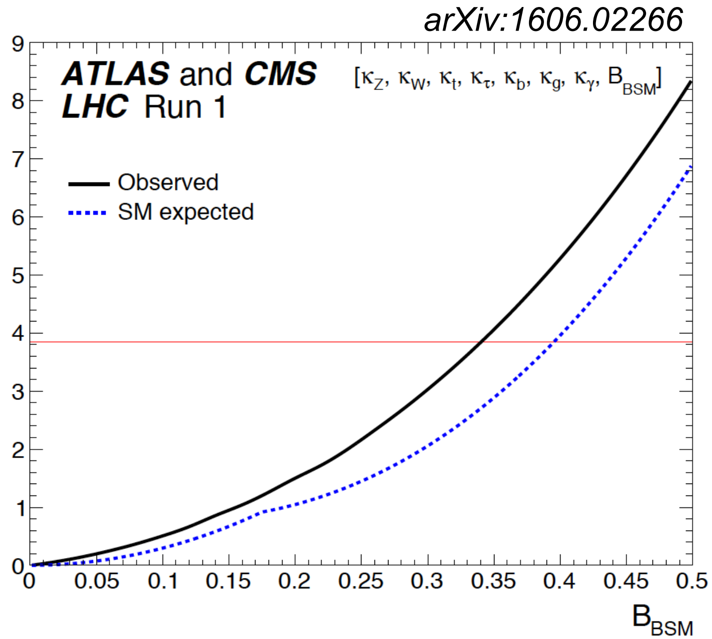
$$\Gamma_H = \Gamma_H^{SM} \times \frac{\kappa_H^2}{1 - BR_{BSM}}, \quad BR(H \to xx) = BR_{SM}(H \to xx) \times (1 - BR_{BSM}) \cdot \frac{\kappa_x^2}{\kappa_H^2}$$

arXiv:1606.02266



Compatibility with the SM: 11%

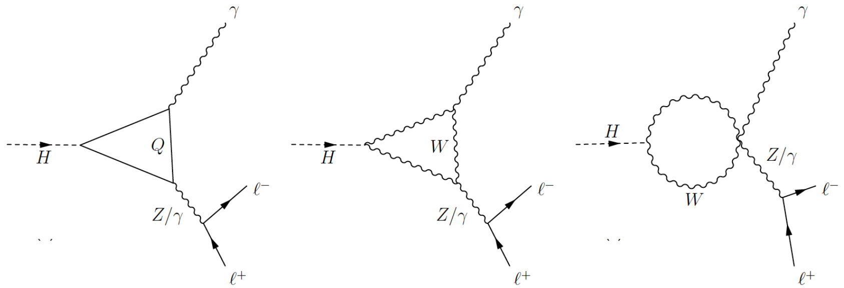
arXiv:1606.02266

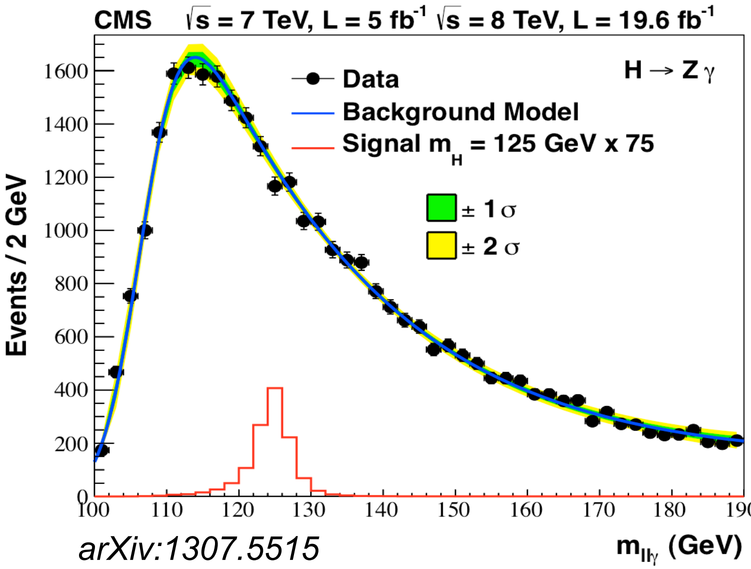


Obs (exp) limit: BR_{BSM}<0.34 (0.39)

Rare Decays: H→Vγ→l⁺l⁻γ (V=γ*, Z, J/ψ, ϒ)

Rare decays H→(Z/γ*)γ provide additional information to probe beyond-SM effects in loop couplings





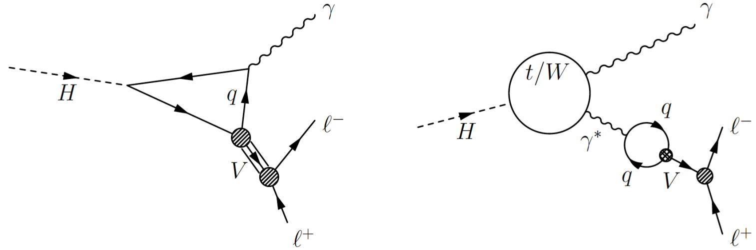
arXiv:1307.5515

Obs (exp) limits on H→Zγ:

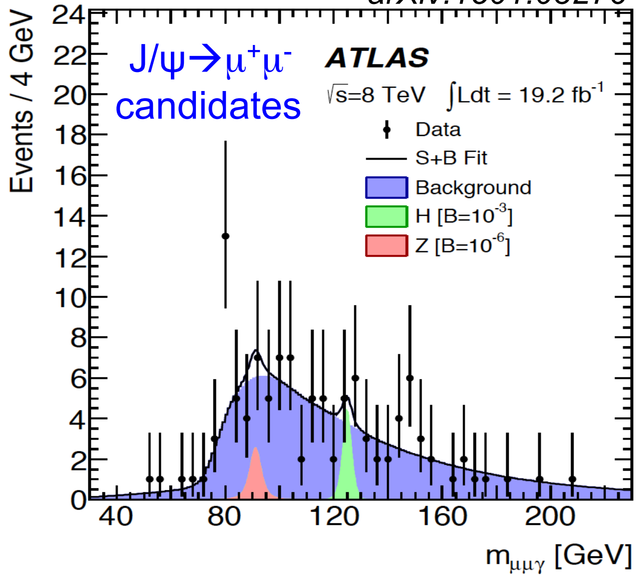
ATLAS: 11xSM (9xSM) at m_H=125.5 GeV

CMS: 10xSM (10xSM) at m_H=125 GeV

Rare decays H→J/ψγ (ϒγ) allow probing H→$c\bar{c}$ ($b\bar{b}$) couplings



arXiv:1501.03276



Obs (exp) limits at m_H=125 GeV:

BR(H→J/ψγ)<1.5x10^{-3} (ATLAS, CMS)

[SM prediction: ~3x10^{-6}]

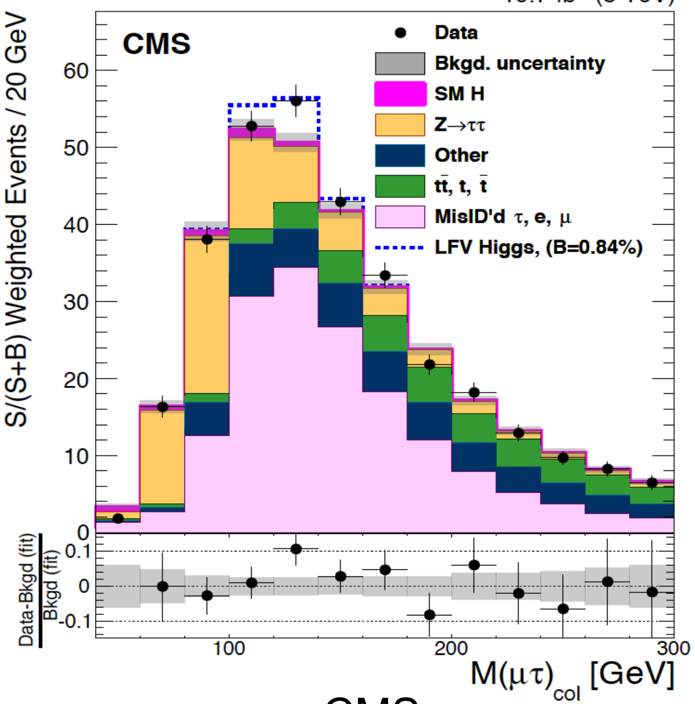
BR(H→ϒ(ns)γ)<2.0x10^{-3} (ATLAS)

[SM prediction: ~10^{-9}]

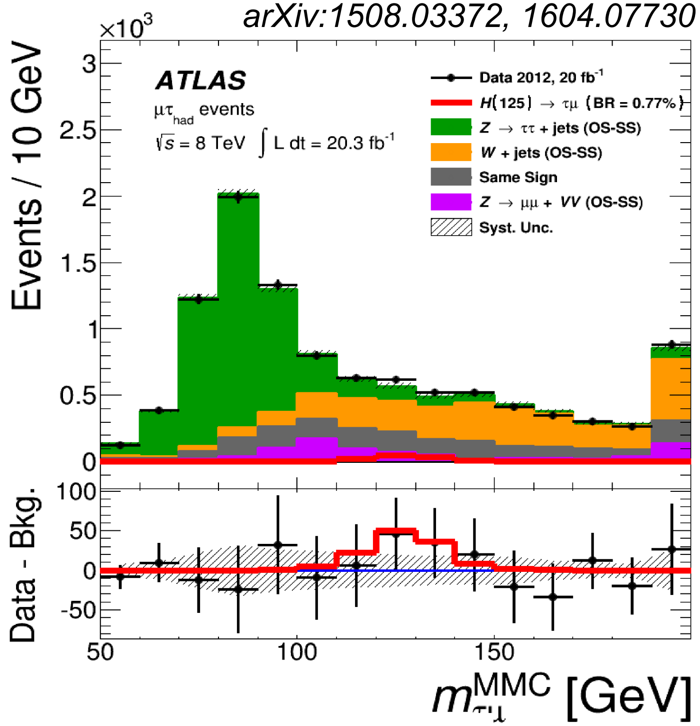
Beyond-SM Decays: H→μτ, eτ, eμ

- The study of Higgs boson couplings still leave plenty of room for BSM decays.
- Lepton-flavor-violating decays are forbidden in the SM but can occur naturally in BSM scenarios with an extended Higgs sector.

arXiv:1502.07400



arXiv:1508.03372, 1604.07730



CMS

Obs (exp) limits: BR(H→μτ)<1.51% (0.75%)

Best-fit BR: $BR(H \rightarrow \mu\tau) = (0.84^{+0.38}_{-0.37})\%$

p-value of BR=0% is 0.01 (2.4σ excess)

Obs (exp) limits: BR(H→eτ)<0.69% (0.75%)

Obs limit: BR(H→eμ)<0.036%

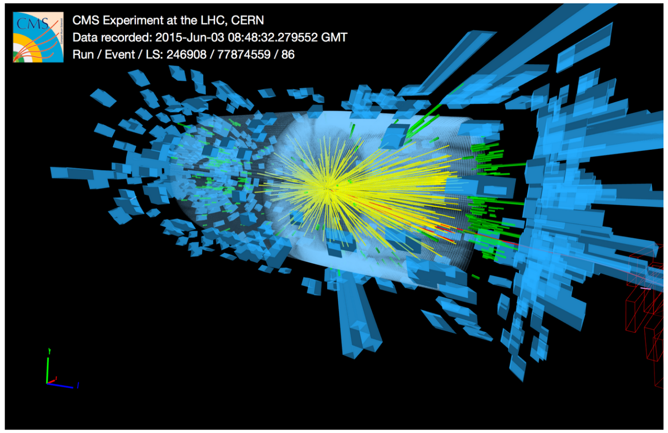
ATLAS

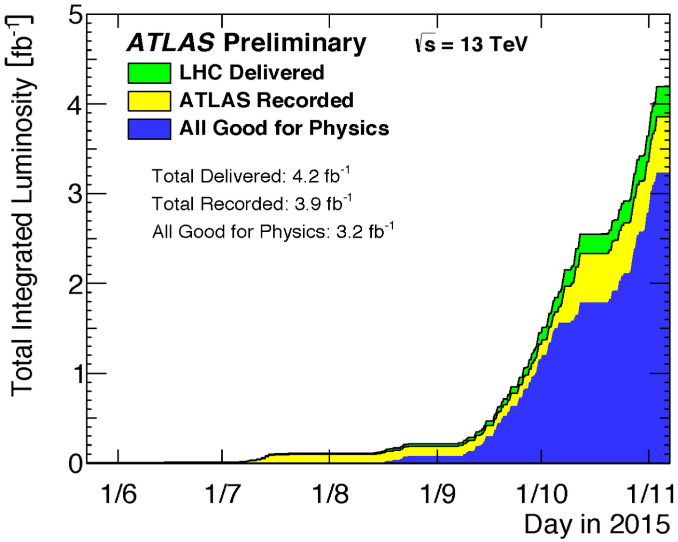
BR(H→μτ)<1.43% (1.01%)

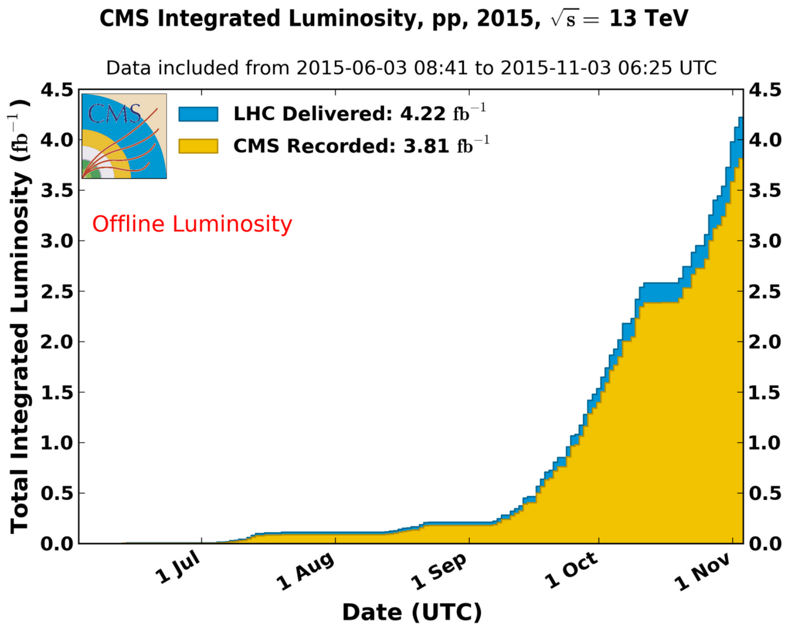
$BR(H \rightarrow \mu\tau) = (0.53 \pm 0.51)\%$

BR(H→eτ)<1.04% (1.21%)

June 3, 2015: Run 2 Starts!







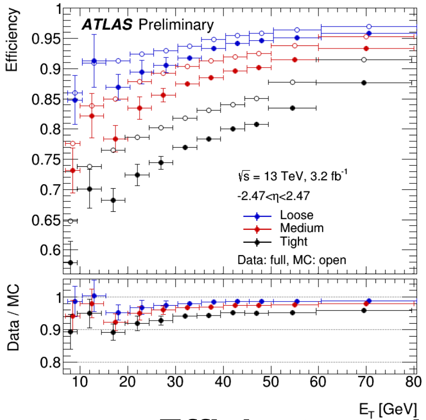
13 TeV pp 2015 dataset (at 25 ns):

- Highest inst. luminosity: 5x10^{33} cm^{-2}s^{-1} (Run 1: 7-8x10^{33} cm^{-2}s^{-1})
- ~3.9 fb^{-1} recorded (<μ>=13). **2.3-3.2 fb^{-1} analyzed.**

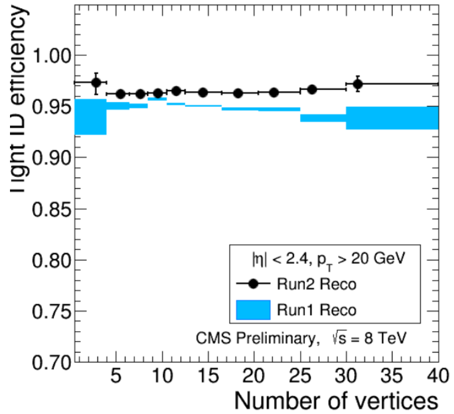
Physics Objects at 13 TeV

- In general performance of object reconstruction comparable or better than in Run 1. Further improvements expected (also on uncertainties) with further studies.

Electron ID

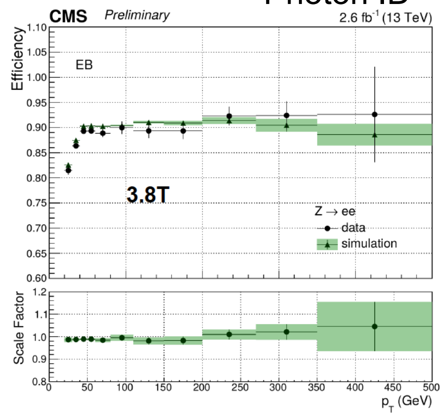


Muon ID

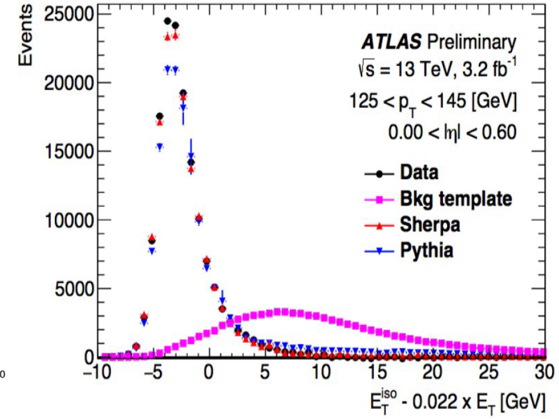


Efficient e and μ identification

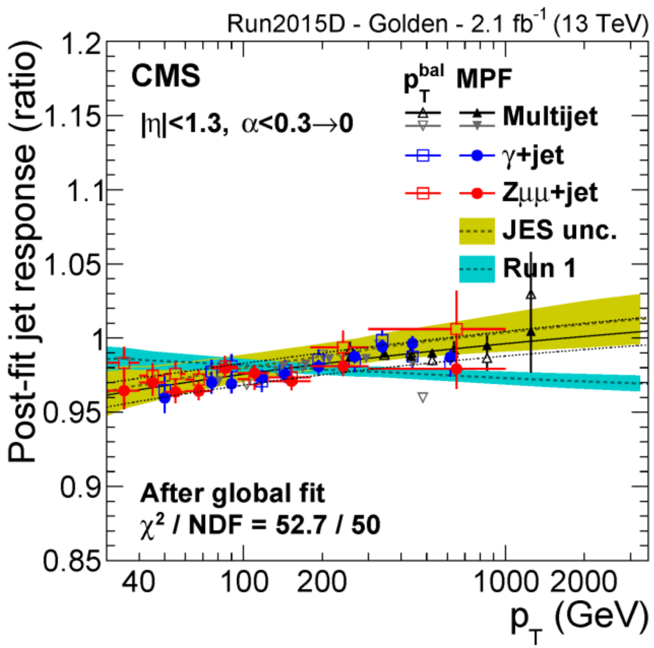
Photon ID



Photon isolation

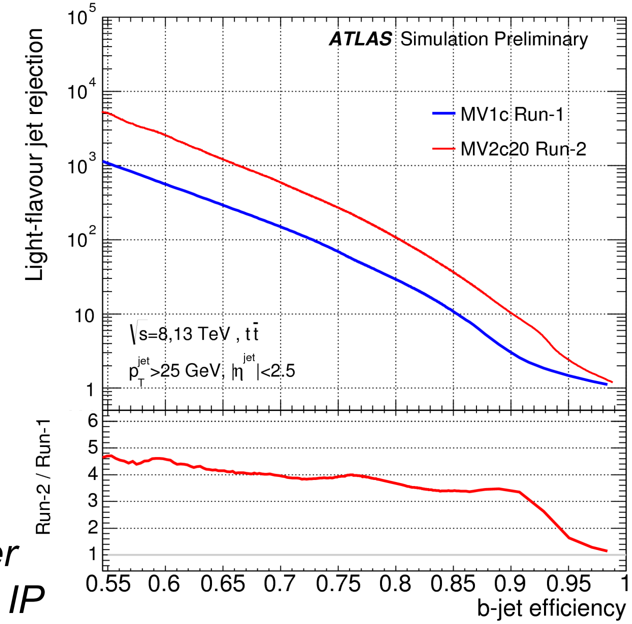


Efficient γ identification



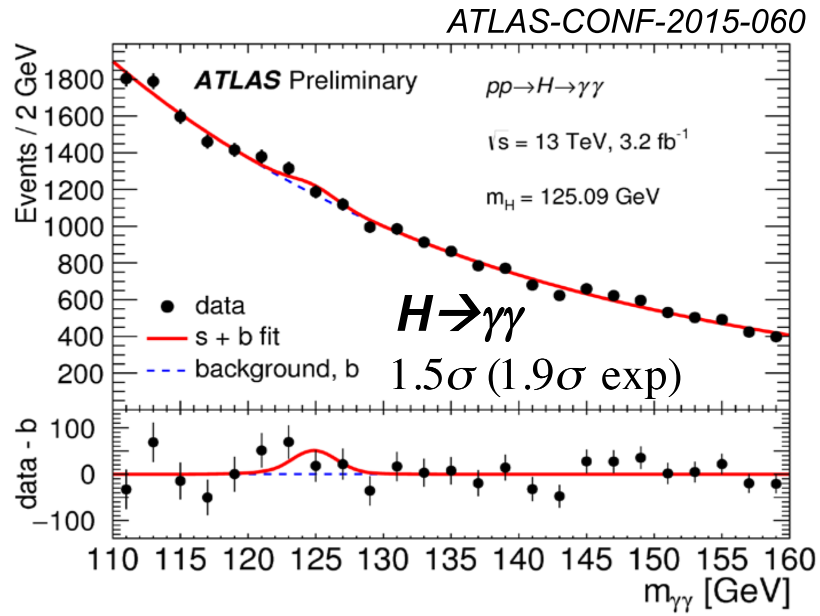
Well-understood jet energy calibration

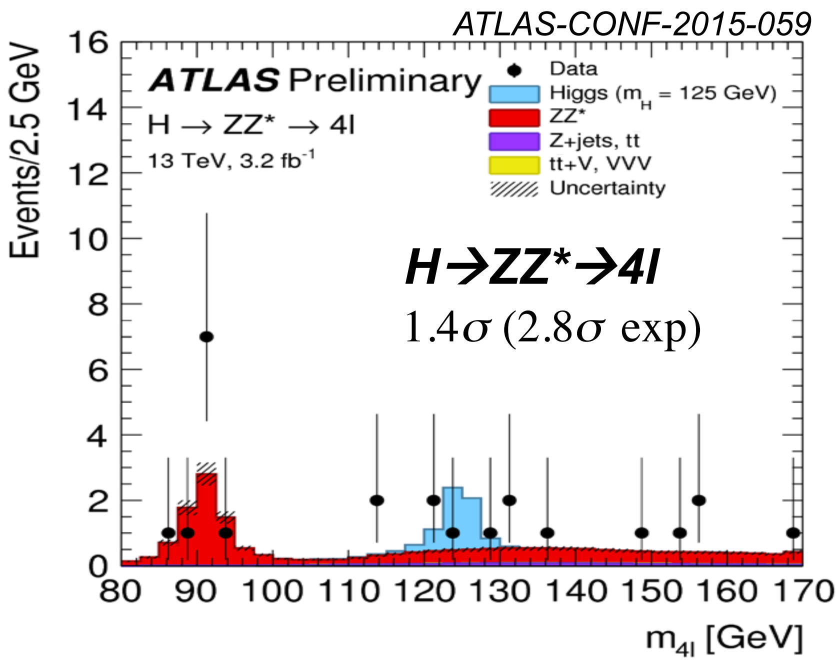
Improved b-jet identification



ATLAS: new pixel layer (IBL) installed closer to IP

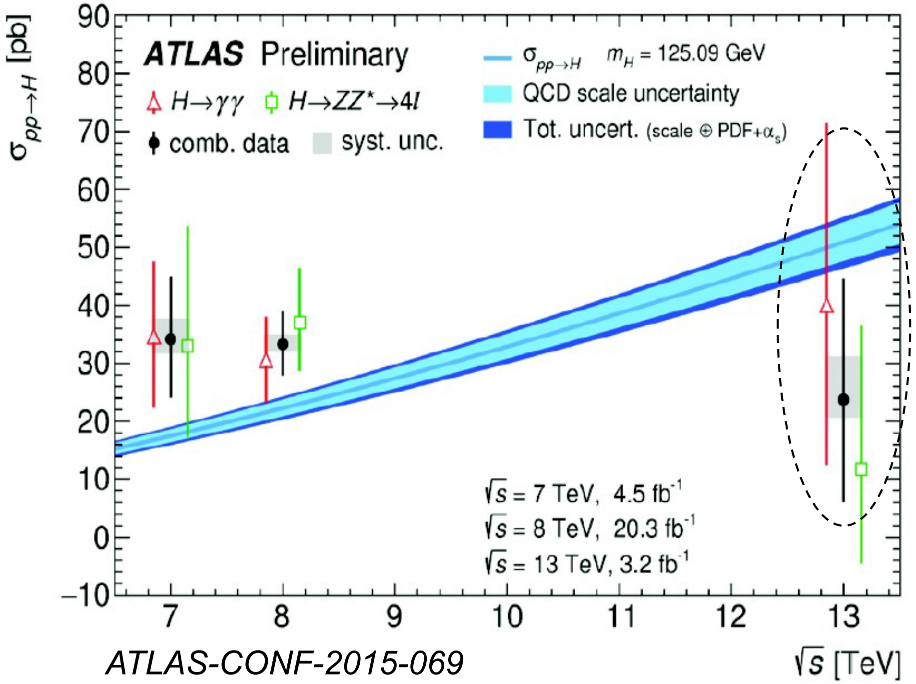
First 13 TeV Results: Discovery Channels





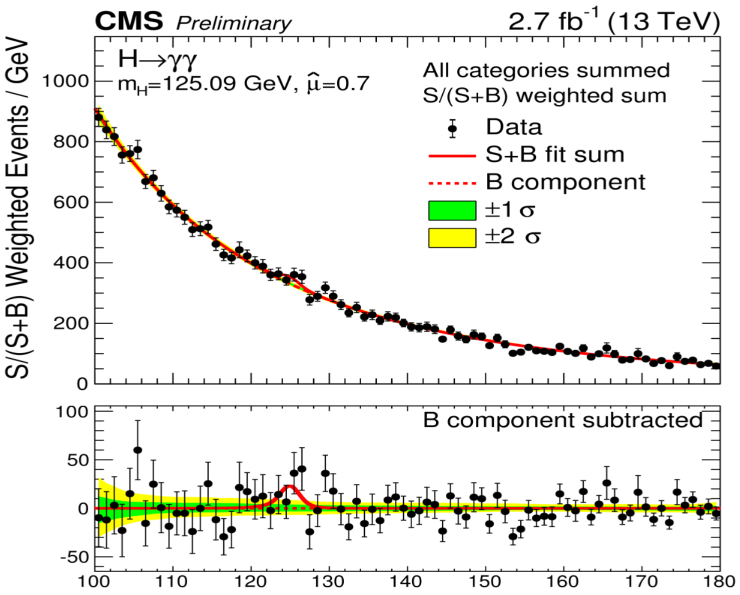
- First Higgs analyses with early 13 TeV data (~3 fb^{-1}) collected in 2015.
- Integrated luminosity used so far still too low to reach Run 1 sensitivity.

Total (and fiducial) cross-section measurements at √s=13 TeV



ATLAS-CONF-2015-069

First 13 TeV Results: Discovery Channels



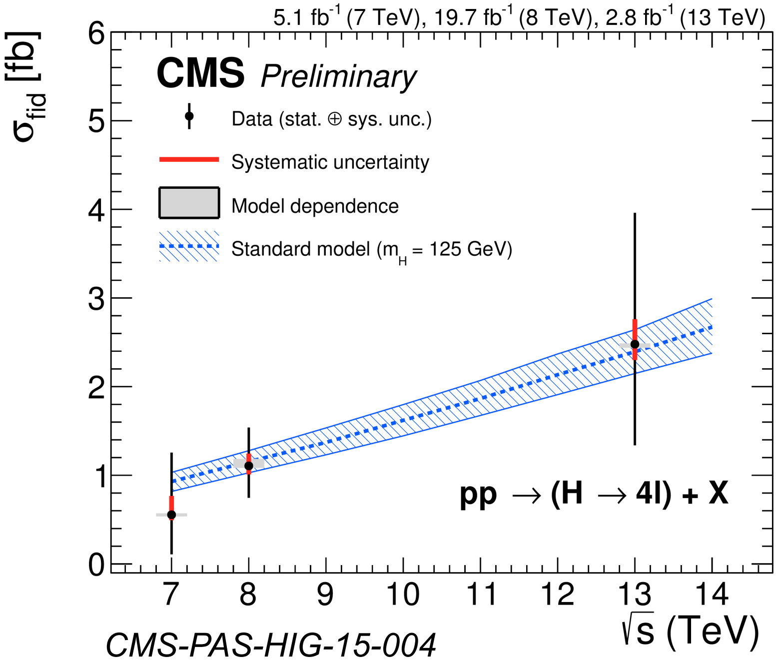
CMS-PAS-HIG-15-005

H→γγ

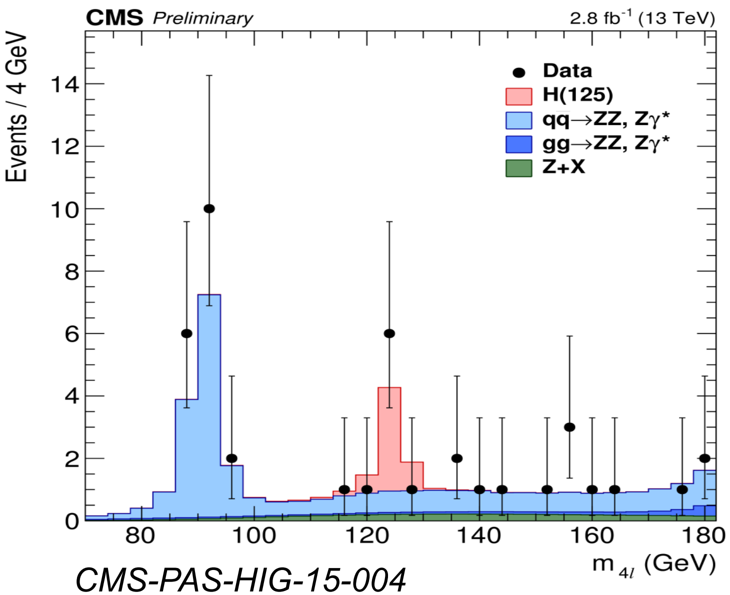
$\mu = 0.69^{+0.47}_{-0.42}$

1.7σ (2.7σ exp)

Fiducial cross-section at √s=13 TeV



CMS-PAS-HIG-15-004



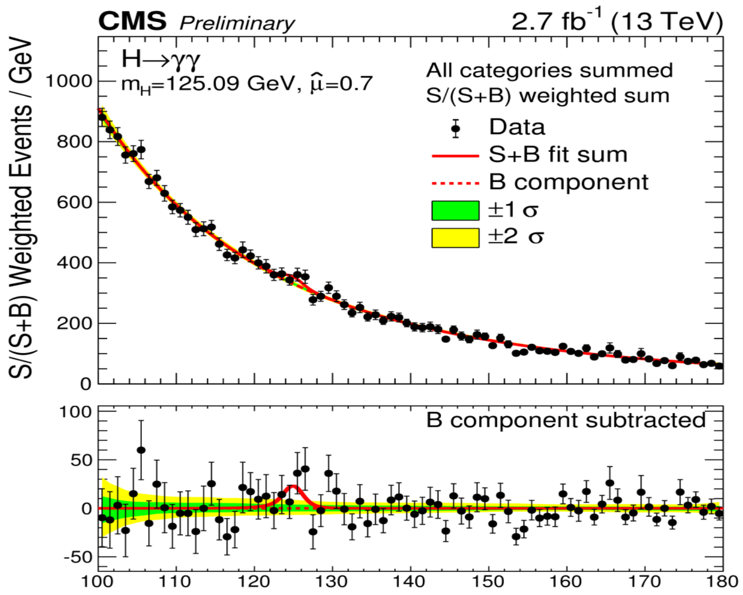
CMS-PAS-HIG-15-004

H→ZZ*→4l

$\mu = 0.82^{+0.57}_{-0.43}$

2.5σ (3.4σ exp)

First 13 TeV Results: Discovery Channels

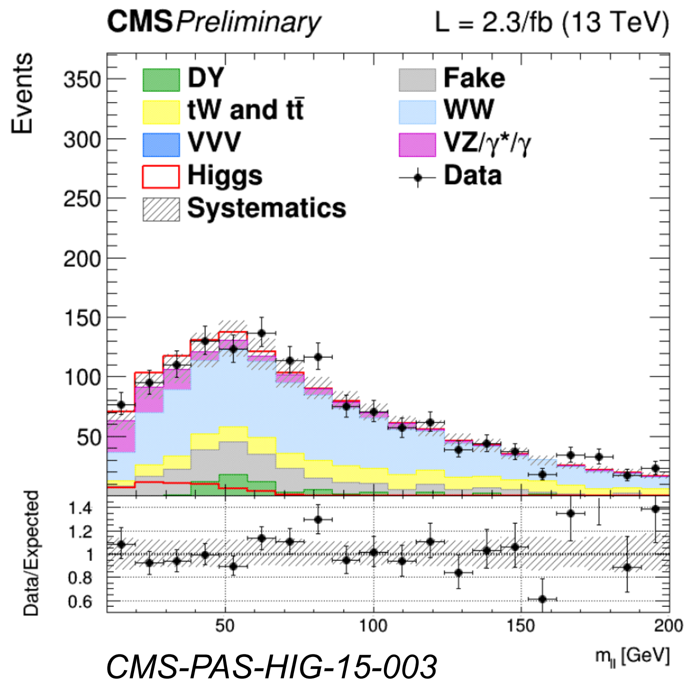


CMS-PAS-HIG-15-005

H→γγ

$\mu = 0.69^{+0.47}_{-0.42}$

1.7σ (2.7σ exp)

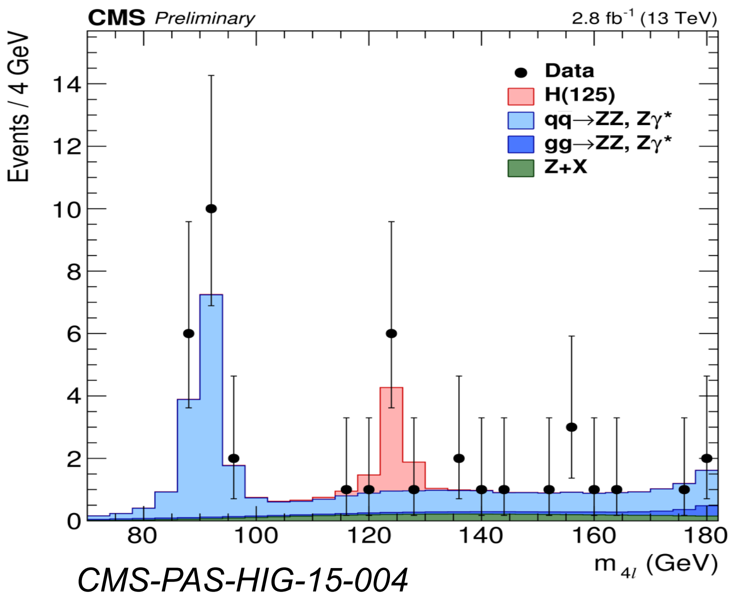


CMS-PAS-HIG-15-003

H→WW*→lνlν

$\mu = 0.3 \pm 0.5$

0.7σ (2.0σ exp)



CMS-PAS-HIG-15-004

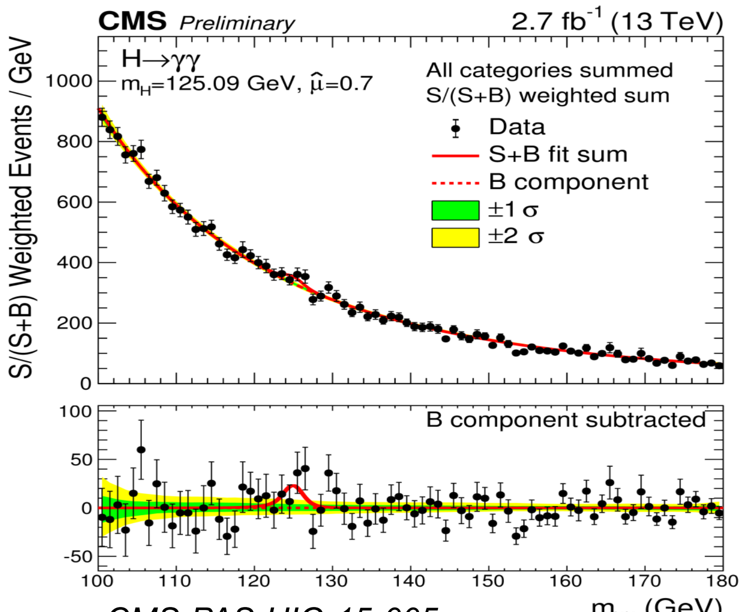
H→ZZ*→4l

$\mu = 0.82^{+0.57}_{-0.43}$

2.5σ (3.4σ exp)

The Higgs signal is yet to be re-established …

First 13 TeV Results: Discovery Channels

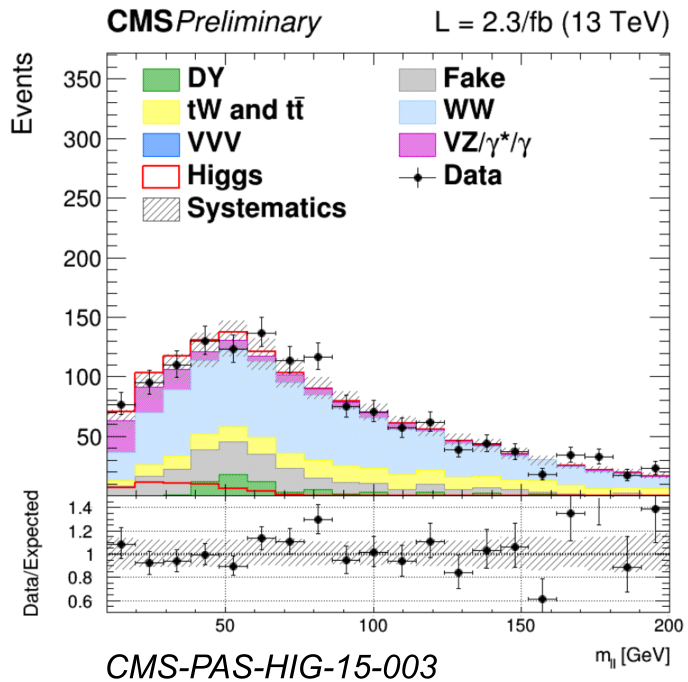


CMS-PAS-HIG-15-005

H→γγ

$\mu = 0.69^{+0.47}_{-0.42}$

1.7σ (2.7σ exp)

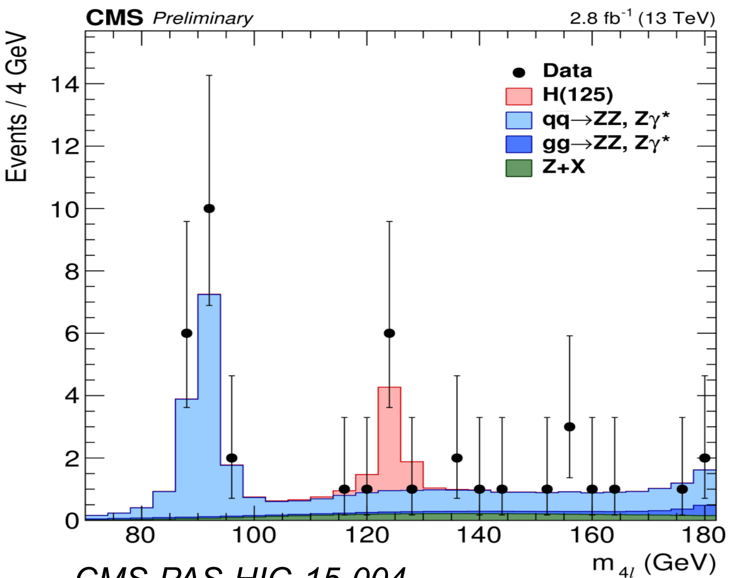


CMS-PAS-HIG-15-003

H→WW*→lνlν

$\mu = 0.3 \pm 0.5$

0.7σ (2.0σ exp)



CMS-PAS-HIG-15-004

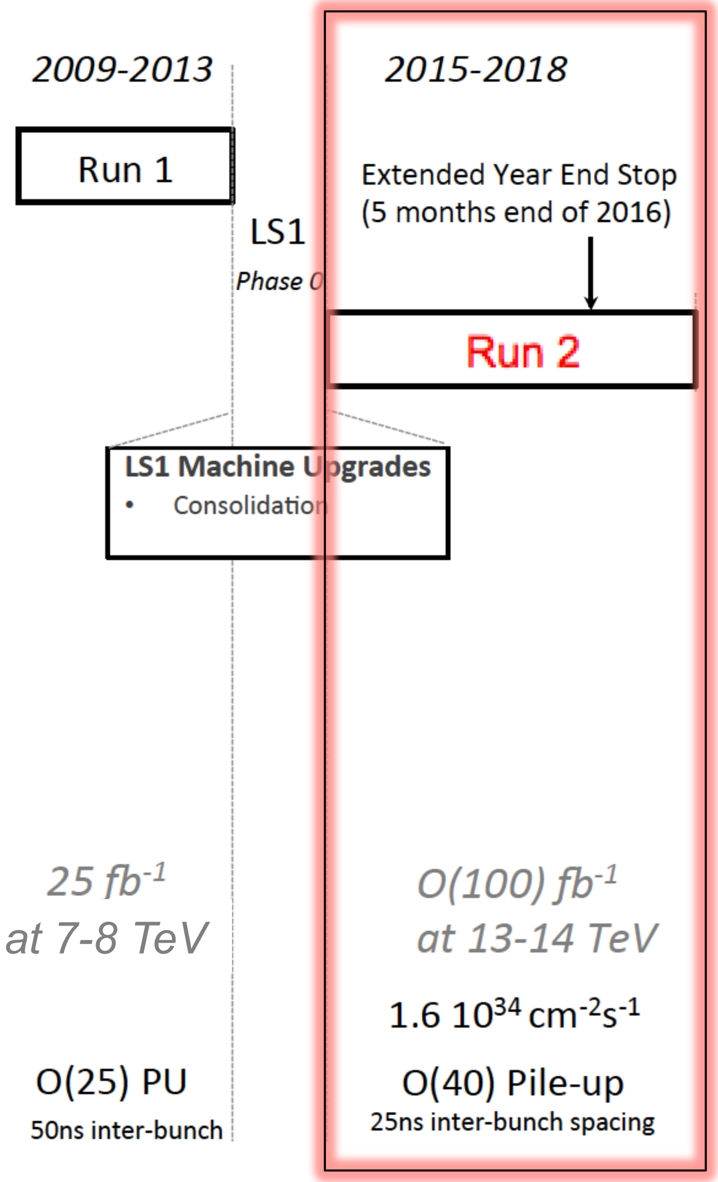
H→ZZ*→4l

$\mu = 0.82^{+0.57}_{-0.43}$

2.5σ (3.4σ exp)

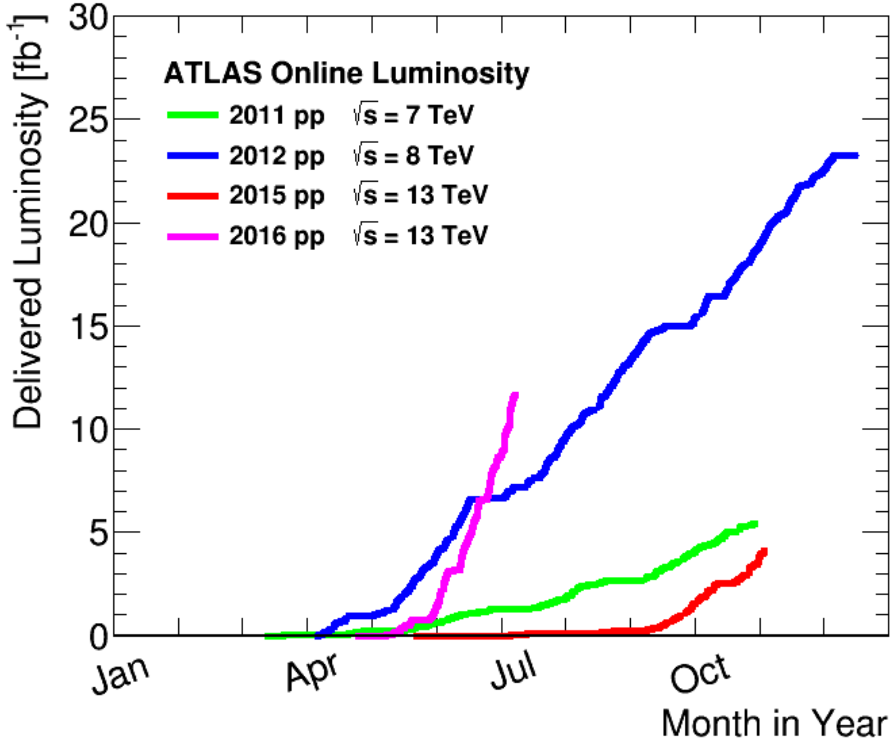
The Higgs signal is yet to be re-established …
but data is coming in FAST!

Run 2 Prospects



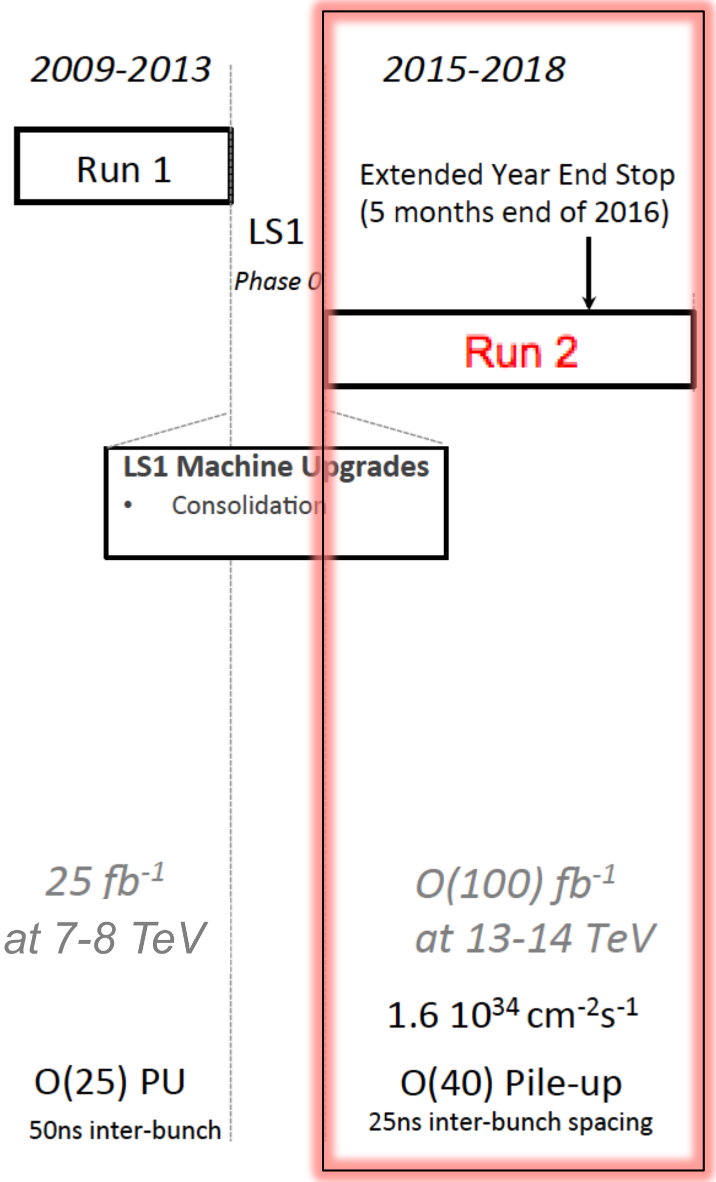
13 TeV pp 2016 dataset:

- Collisions restarted on April 25, 2016.
- Peak luminosity: 1.08×10^{34} $cm^{-2}s^{-1}$
- Daily delivered luminosity: ~0.4-0.5 fb^{-1}.
- As of today: ~13 fb^{-1} delivered!



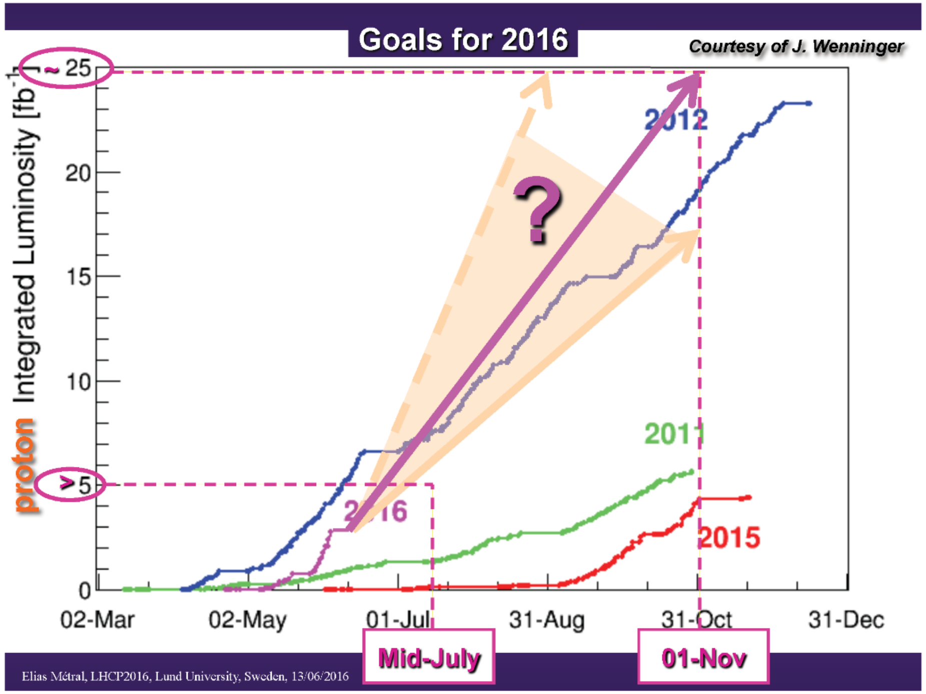
Outstanding performance!

Run 2 Prospects



13 TeV pp 2016 dataset:

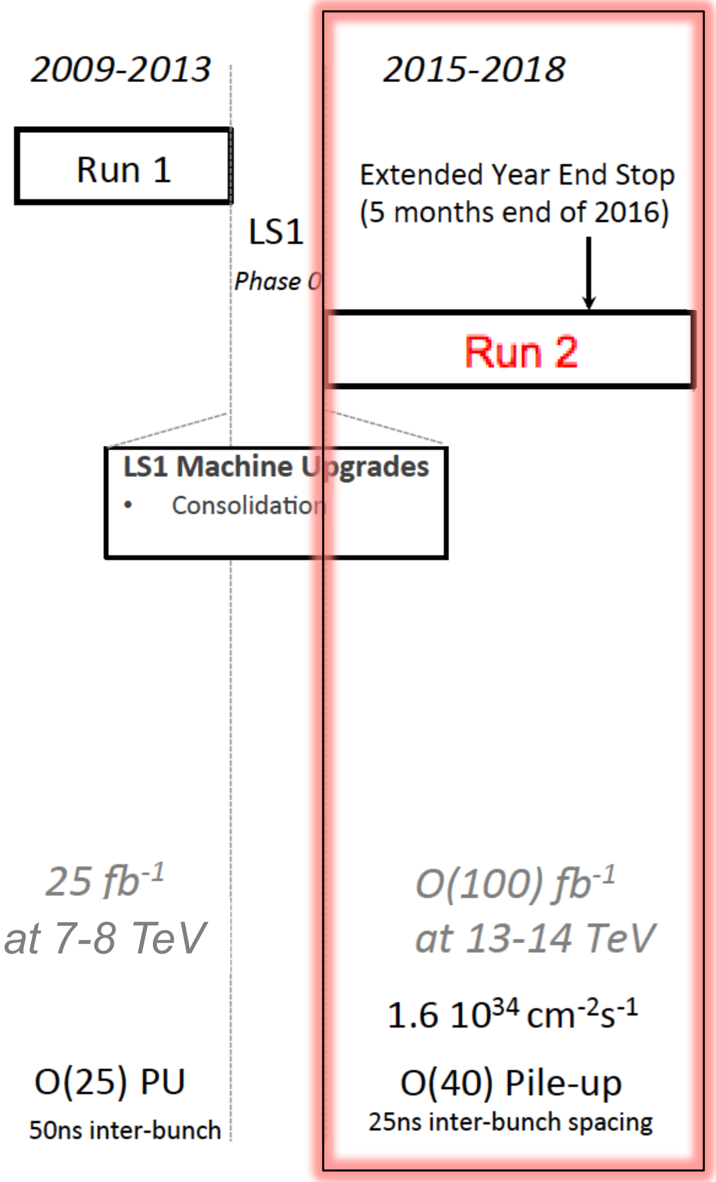
- Collisions restarted on April 25, 2016.
- Peak luminosity: 1.08×10^{34} $cm^{-2}s^{-1}$
- Daily delivered luminosity: ~0.4-0.5 fb^{-1}.
- Expect ~25 fb^{-1} delivered, possibly more!



Full Run 2 (2015-2018):

- Expect ~100 fb^{-1} delivered.

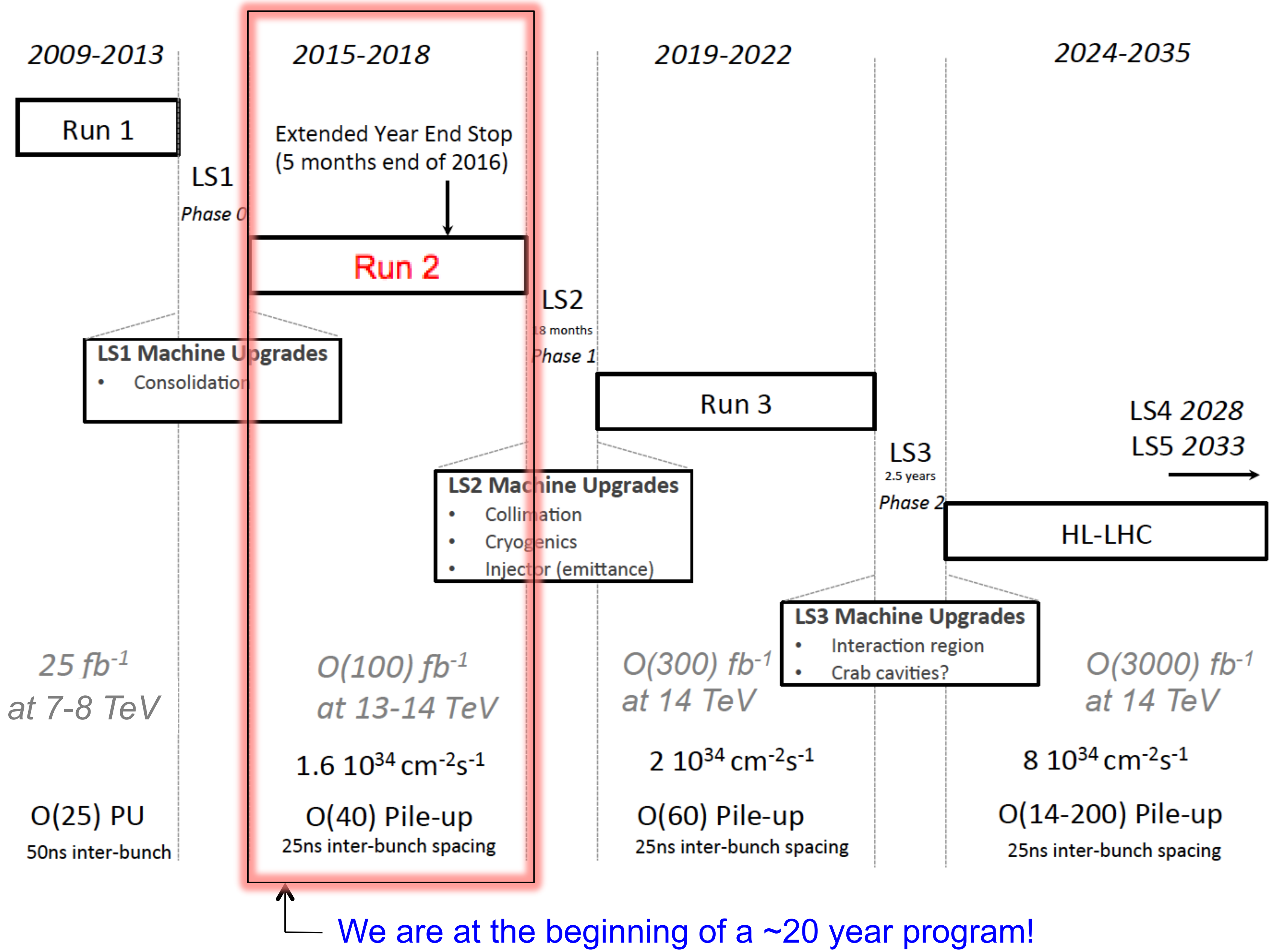
Run 2 Prospects



Run 2 Milestones in Higgs Physics:

- Improved precision in Higgs boson mass.
- Improved precision in Higgs coupling measurements, including observation of couplings to 3rd generation quarks (Hbb and Htt).
- Detailed studies of Higgs boson production via fiducial and differential cross section measurements.
- Detailed studies on production yields and kinematics to search for non-SM interactions (EFT, pseudo-observables, CP-odd admixture, ...)
- Extensive searches for rare and BSM decay modes.

Beyond Run 2



2009-2013
2015-2018
2019-2022
2024-2035
Run 1
LS1
Phase 0
Extended Year End Stop
(5 months end of 2016)
Run 2
LS2
18 months
Phase 1
Run 3
LS3
2.5 years
Phase 2
LS4 2028
LS5 2033
HL-LHC
LS1 Machine Upgrades
• Consolidation
LS2 Machine Upgrades
• Collimation
• Cryogenics
• Injector (emittance)
LS3 Machine Upgrades
• Interaction region
• Crab cavities?
25 fb-1
at 7-8 TeV
O(100) fb-1
at 13-14 TeV
O(300) fb-1
at 14 TeV
O(3000) fb-1
at 14 TeV
1.6 10^34 cm-2s-1
2 10^34 cm-2s-1
8 10^34 cm-2s-1
O(25) PU
50ns inter-bunch
O(40) Pile-up
25ns inter-bunch spacing
O(60) Pile-up
25ns inter-bunch spacing
O(14-200) Pile-up
25ns inter-bunch spacing
We are at the beginning of a ~20 year program!

Beyond Run 2

Beyond-Run 2 Prospects:

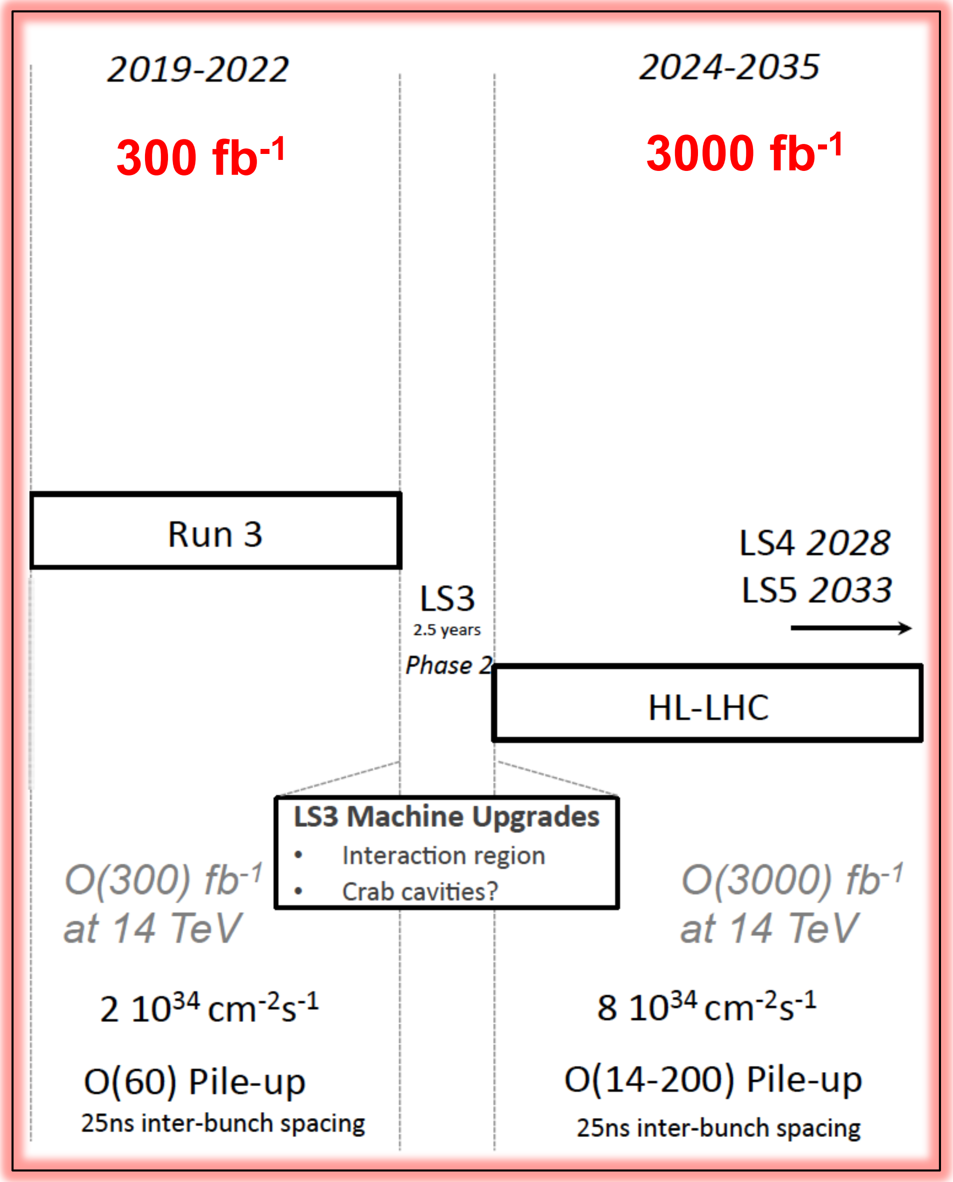
- Precision Higgs couplings:

Projected accuracy per experiment
(arXiv:1307.7135 and ATL-PHYS-PUB-2014-016)

Coupling modifier	300 fb^{-1}	3000 fb^{-1}
$\kappa_{W,Z}$, κ_γ	6%	3%
κ_b	12%	5%
κ_t	15%	7%
κ_τ	10%	5%
κ_μ	22%	7%

(*) Assuming Run 1 experimental uncertainty, theory uncertainty reduced by x2.

- Observation of rare decay modes ($H \rightarrow \mu\mu$, $Z\gamma$).
- Possibly evidence for SM di-Higgs production.

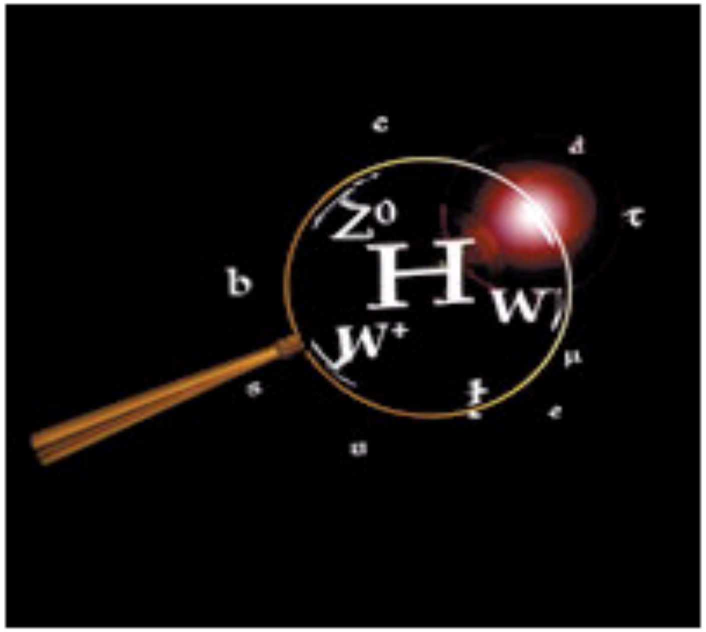


Summary and Outlook

- Since the discovery of the Higgs boson, and entire new field of research has emerged.

- The LHC Run 1 program has allowed outlining the experimental profile of the Higgs boson:
  - Mass measured to 0.2% accuracy.
  - Evidence of CP-even scalar nature.
  - Observation of coupling to W, Z and taus.
  - Evidence for non-universal couplings.
  - First studies on Higgs production.
  - First constraints on Higgs width and rare/BSM decay modes.

  Greatly benefited from strong experiment-theory connection.



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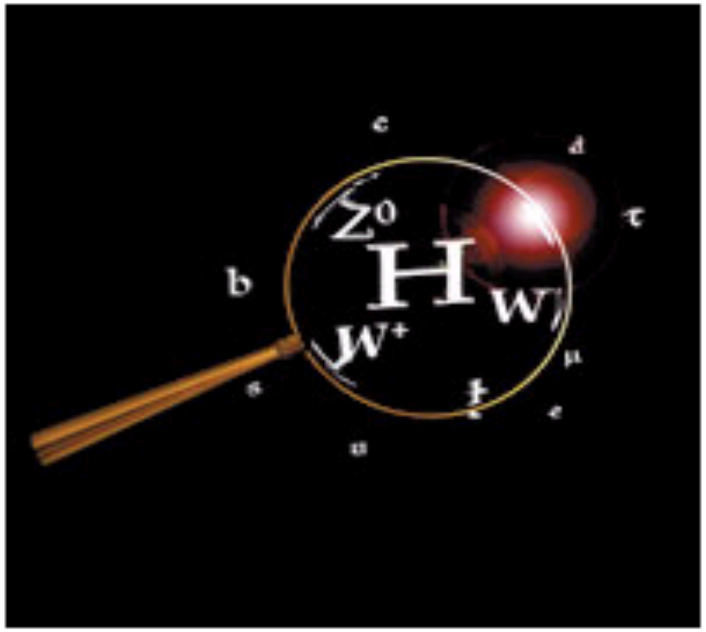


- Establishing with increasing precision the properties of the Higgs boson is a top priority of the LHC Run 2 and beyond.

  Many early Run 2 results already available.

  Record-breaking LHC performance in 2016 shows great promise for the future!

Exciting times ahead!

Backup

Higgs Couplings to Fermions: H→μμ

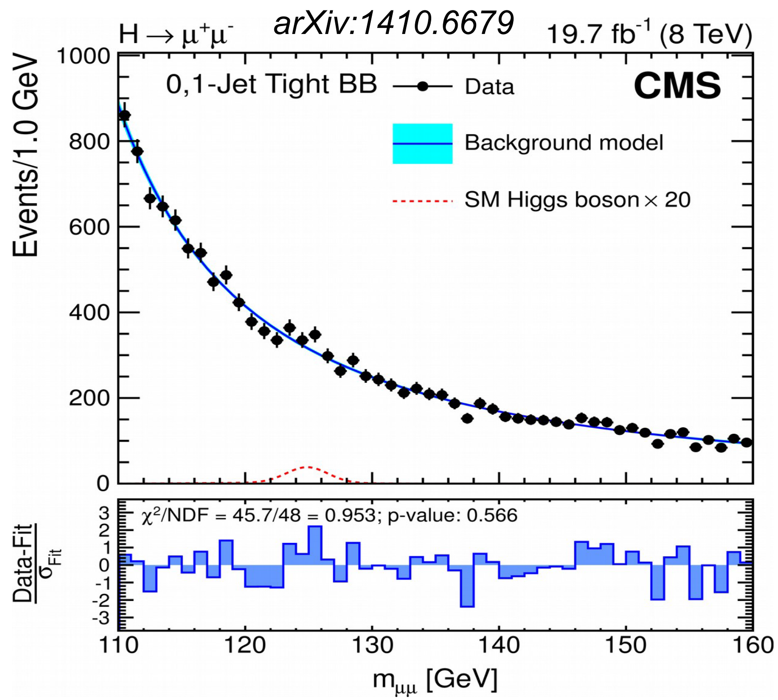
- Very rare decay mode!
  BR(H→μμ)~2.2×10^{-4} at m_H=125 GeV

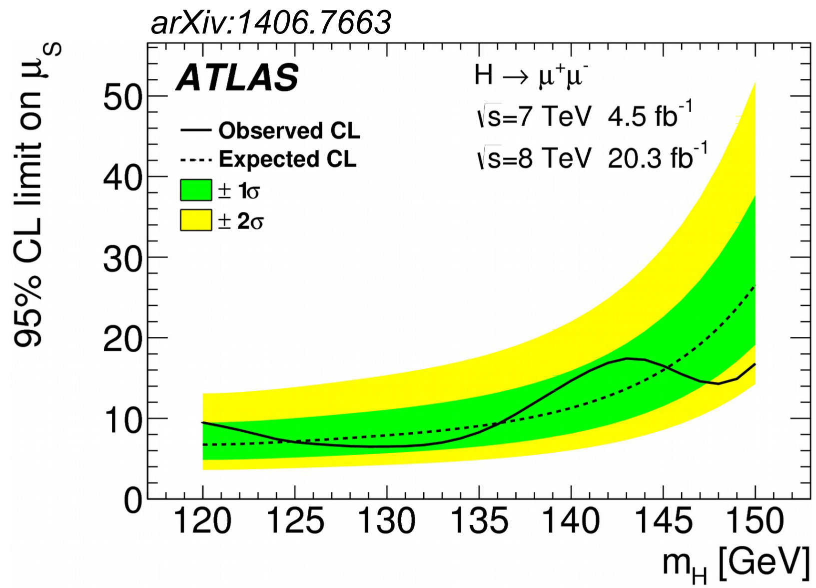
- Dimuon resonance over huge continuum background from Z/γ*→μμ.

- Categorize events in different channels to isolate contributions from different production modes (e.g. by jet multiplicity, dimuon p_T), as well as depending on muon pseudorapidity (different invariant mass resolution).
  A total of 7 (15) channels used by ATLAS (CMS).

- No significant excess observed.
  Need significantly larger statistics to reach SM sensitivity.

- Obs (exp) limits at m_H=125 GeV:
  ATLAS: 7.0xSM (7.2xSM)
  CMS: 7.4xSM (6.5xSM)

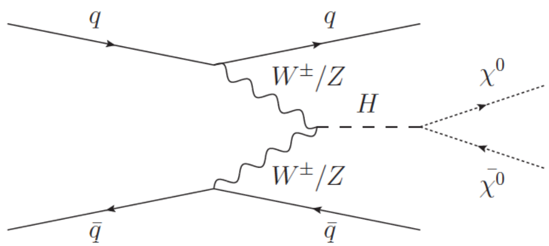


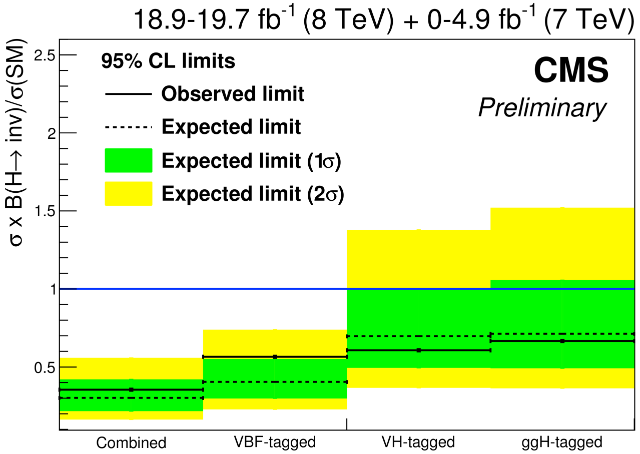


Other Beyond-SM Decays

- In many BSM scenarios the Higgs boson couples to new particles it can decay into if kinematically allowed. Some examples:

H→invisible



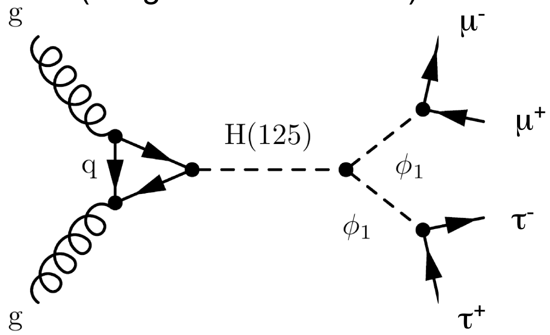


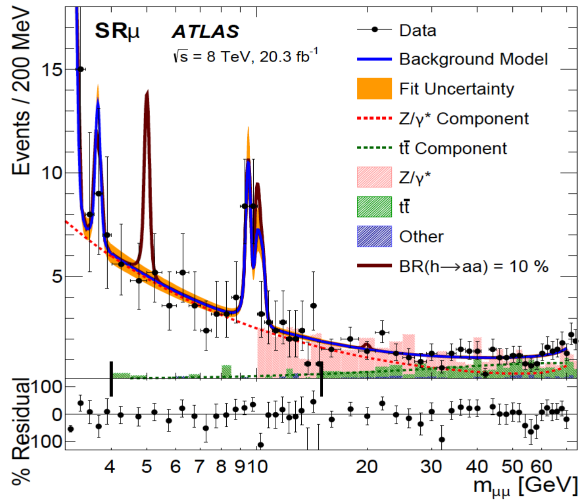
CMS-PAS-HIG-15-012, arXiv:1509.00672

Obs (exp) limits:
ATLAS: BR(H→inv)<0.25 (0.27)
CMS: BR(H→inv)<0.36 (0.30)

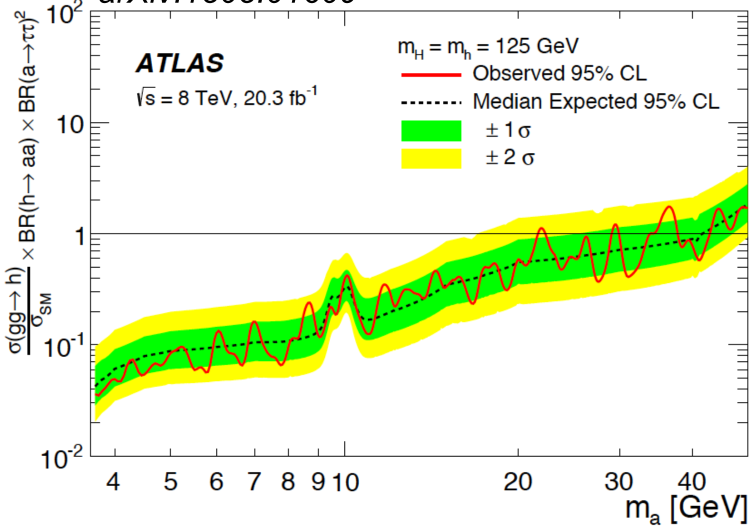
H→aa

(a=light CP-odd scalar)





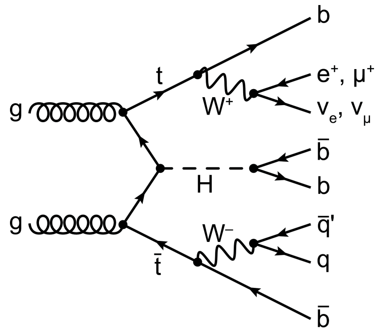
arXiv:1505.01609



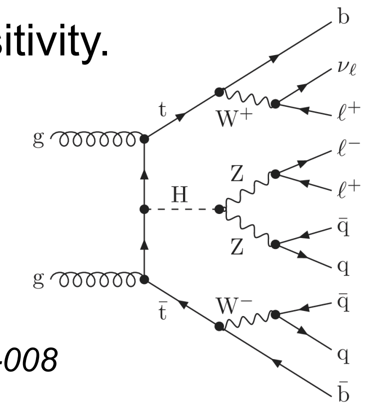
Also, H→aa→$\tau^+\tau^-\tau^+\tau^-$ (CMS) *arXiv:1510.06534*

First 13 TeV Results: $t\bar{t}H$

- Large increase in $t\bar{t}H$ cross section in Run 2: $\sigma_{ttH}(13\text{ TeV})/\sigma_{ttH}(8\text{ TeV})\sim3.8$.
- Broad program of $t\bar{t}H$ searches being re-established.
- Integrated luminosity still too low to reach Run 1 sensitivity.



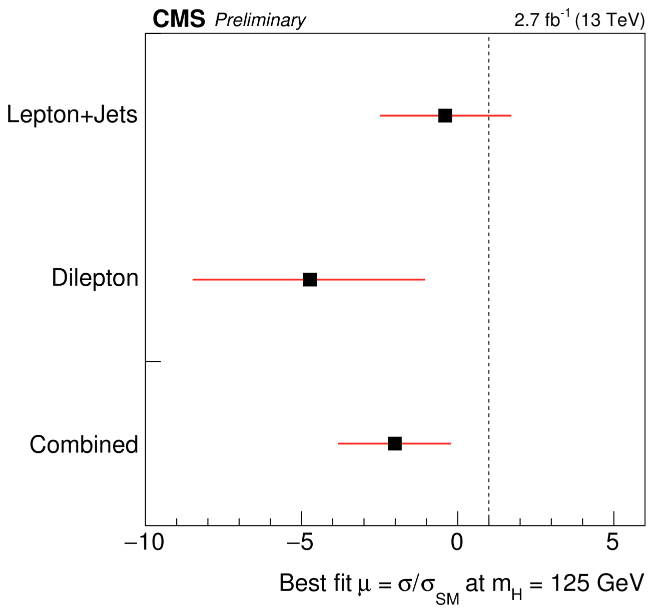
CMS-PAS-HIG-16-004

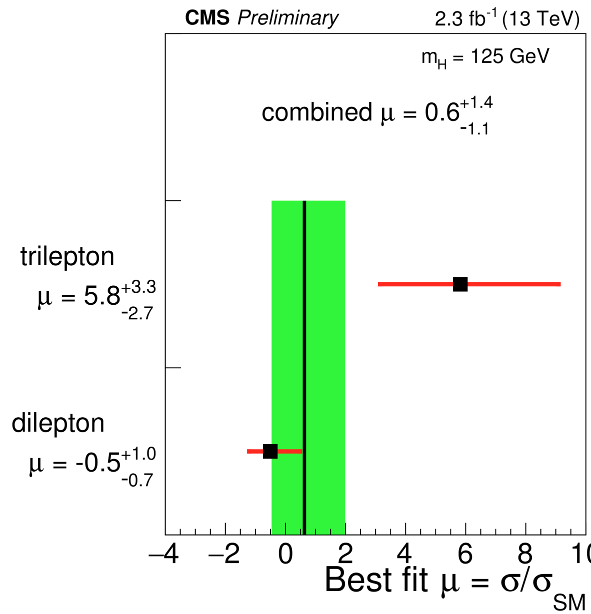


CMS-PAS-HIG-15-008

$H\rightarrow b\bar{b}$ (l+jets, dilepton)

$H\rightarrow WW, \tau\tau, ZZ$ (SS dilepton, trilepton)





$$\boxed{\mu = -2.0 \pm 1.8}$$

$$\boxed{\mu = 0.6^{+1.4}_{-1.1}}$$

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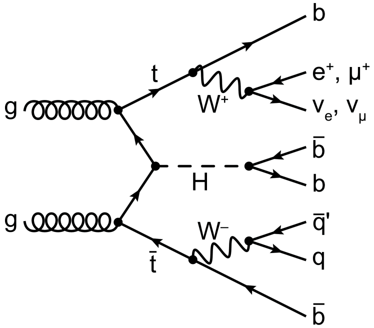
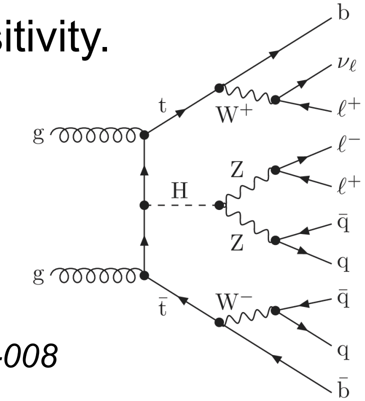


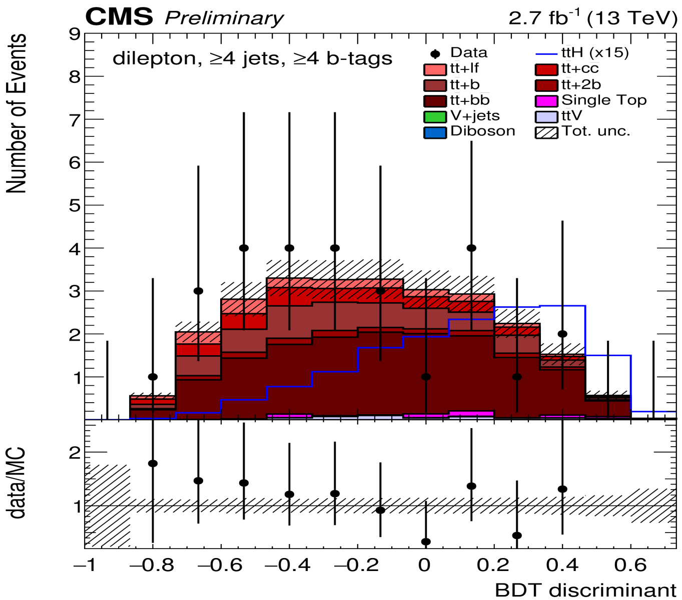
CMS-PAS-HIG-16-004

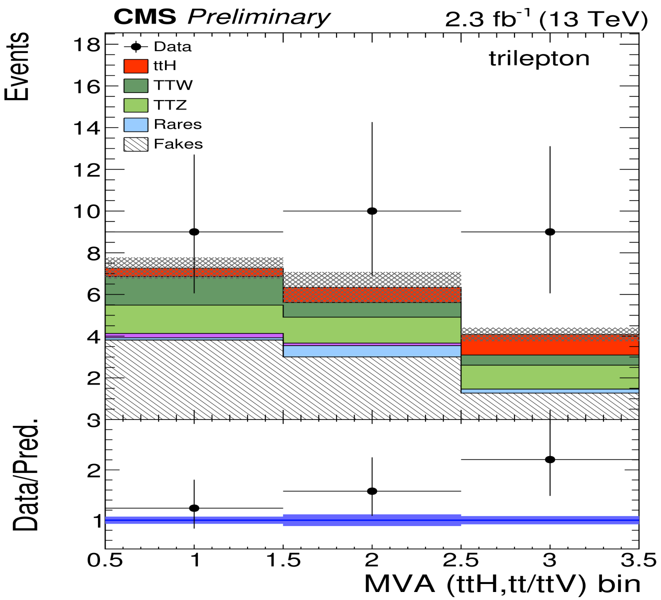


CMS-PAS-HIG-15-008

H→$b\bar{b}$ (l+jets, dilepton)

H→WW, ττ, ZZ (SS dilepton, trilepton)





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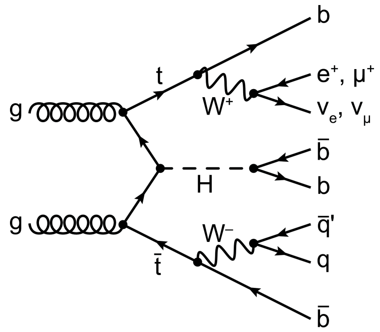

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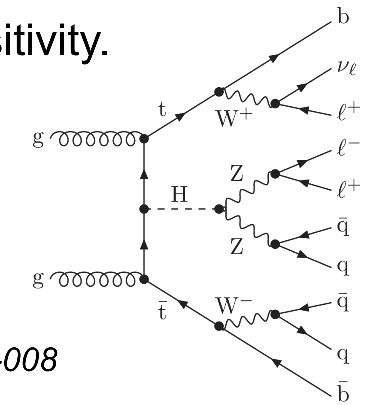
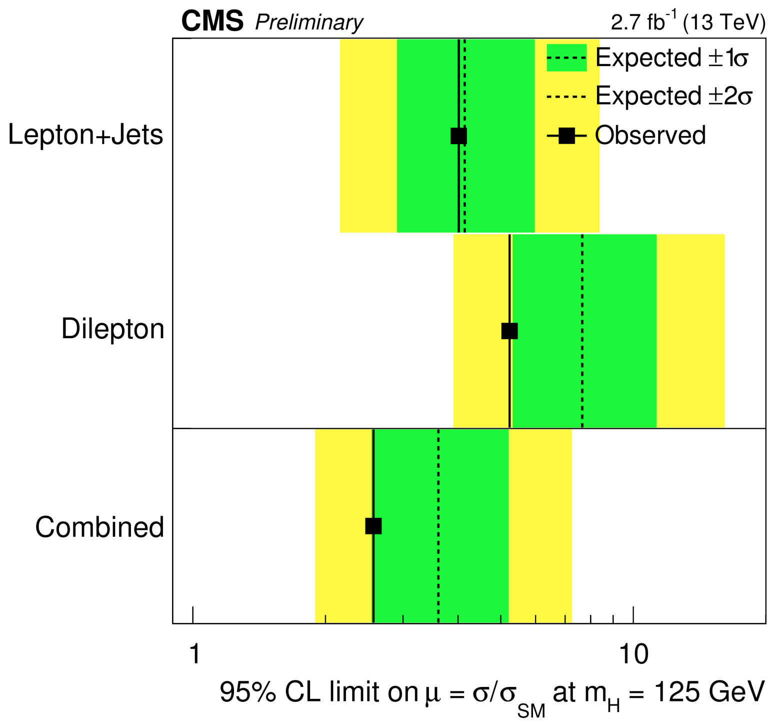
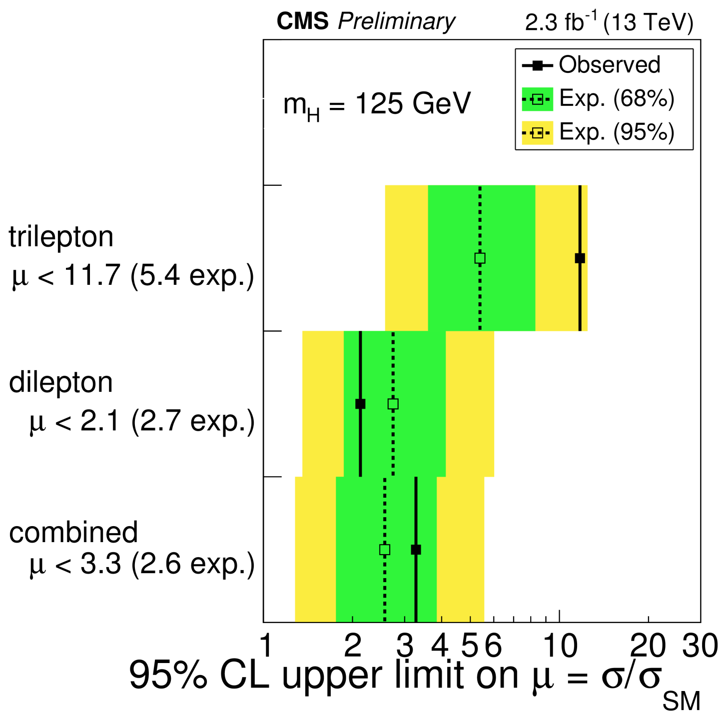


CMS-PAS-HIG-15-008

$H \rightarrow b\bar{b}$ (l+jets, dilepton)

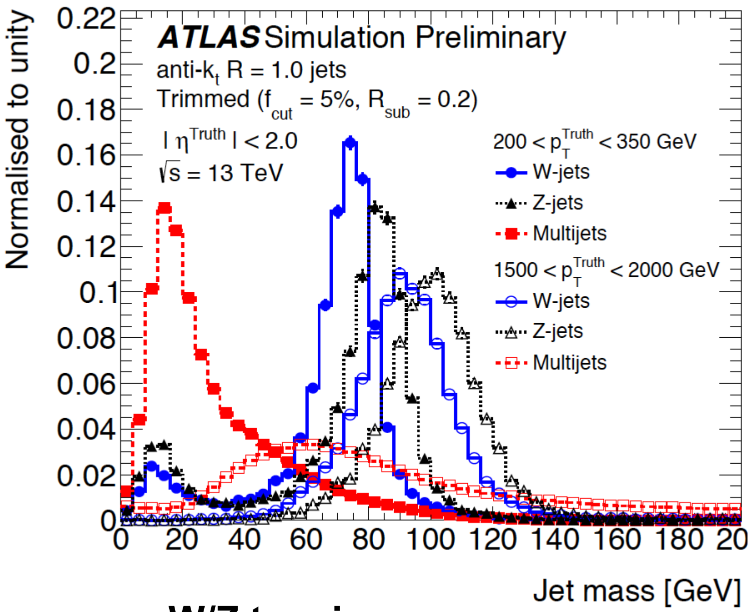


$H \rightarrow WW$, $\tau\tau$, ZZ (SS dilepton, trilepton)



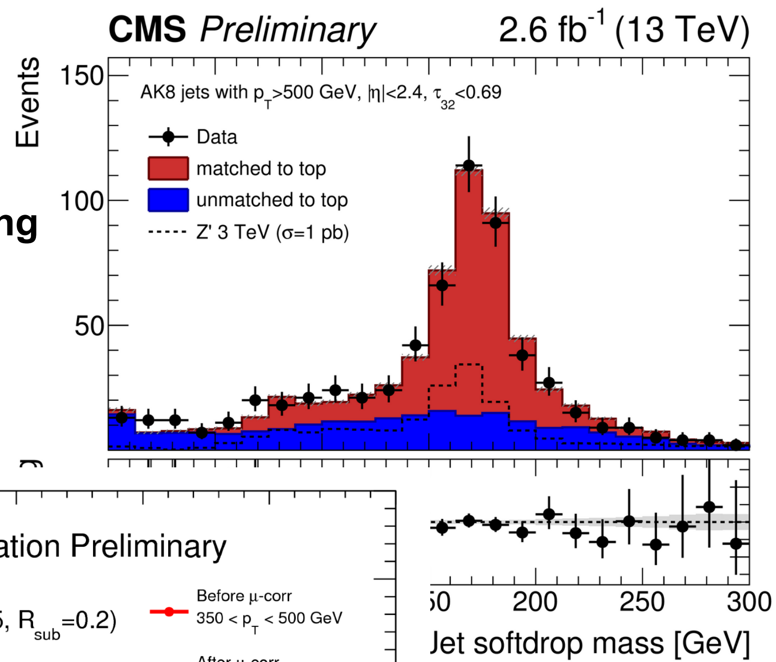
Physics Objects at 13 TeV

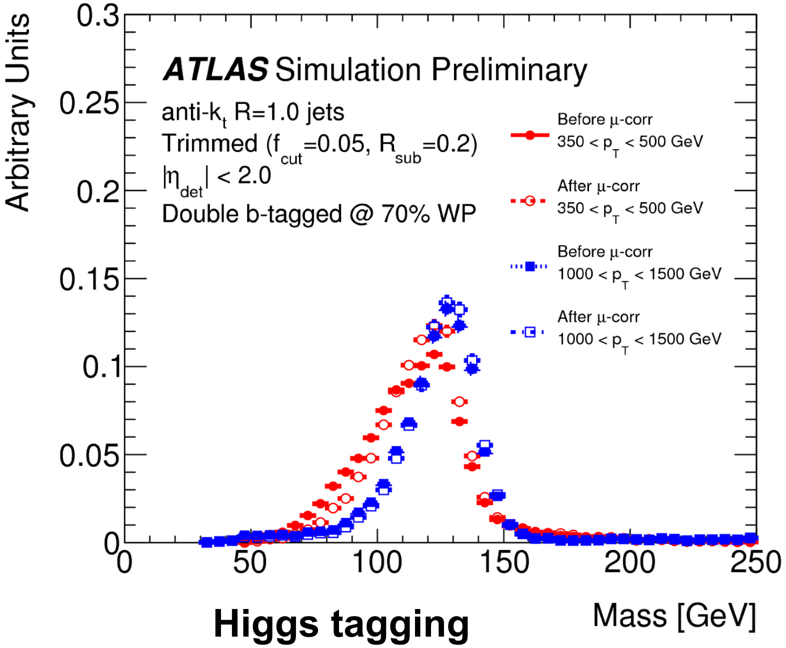
- In general performance of object reconstruction comparable or better than in Run 1. Further improvements expected (also on uncertainties) with further studies.



W/Z tagging

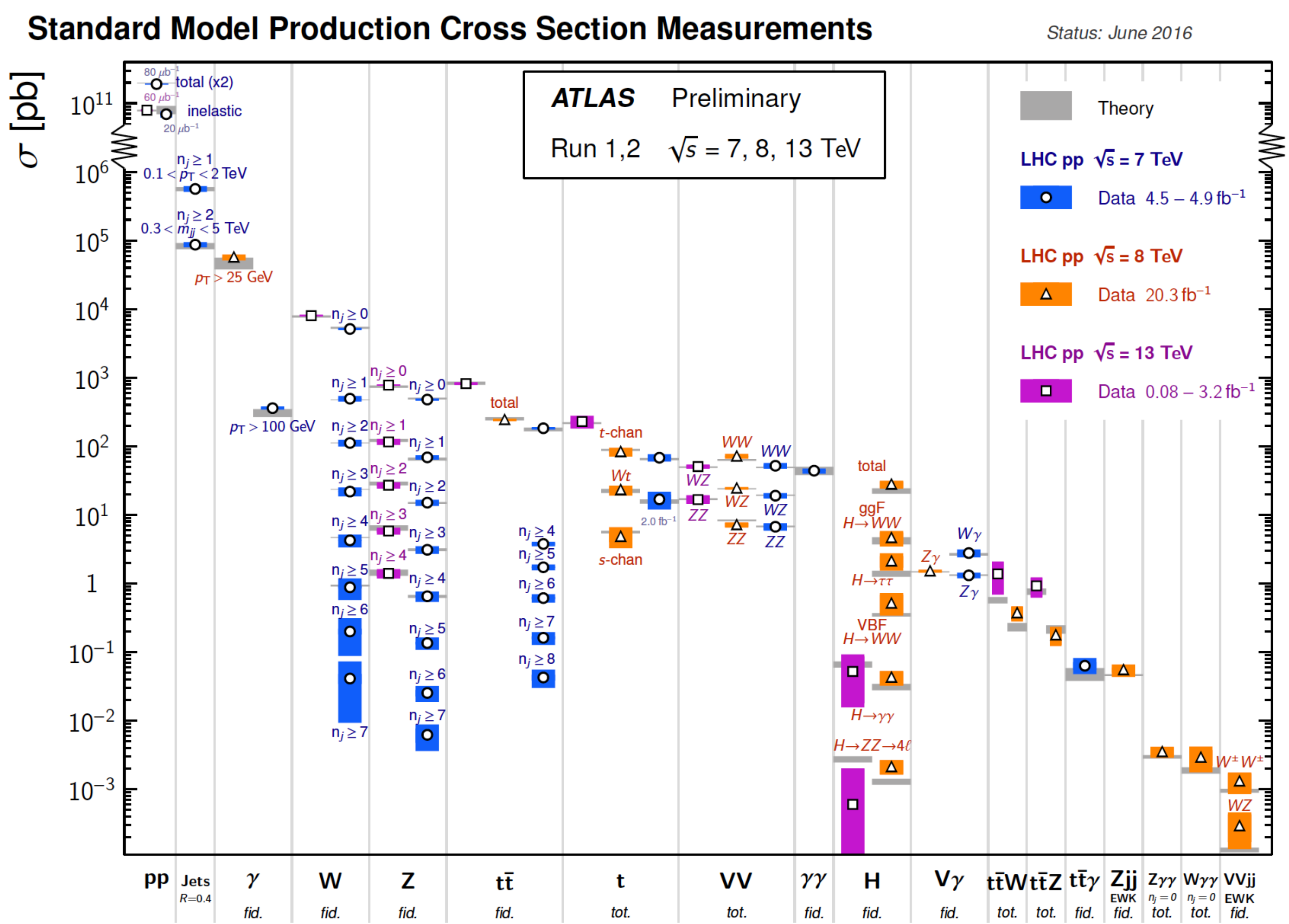
Top tagging





Higgs tagging

Standard Model Measurements



14 orders of magnitude

Stunning achievement, both from experiment and theory.

A necessary step to confidently search for the Higgs boson and New Physics in general!