Title: Higgs Physics with the ATLAS experiment

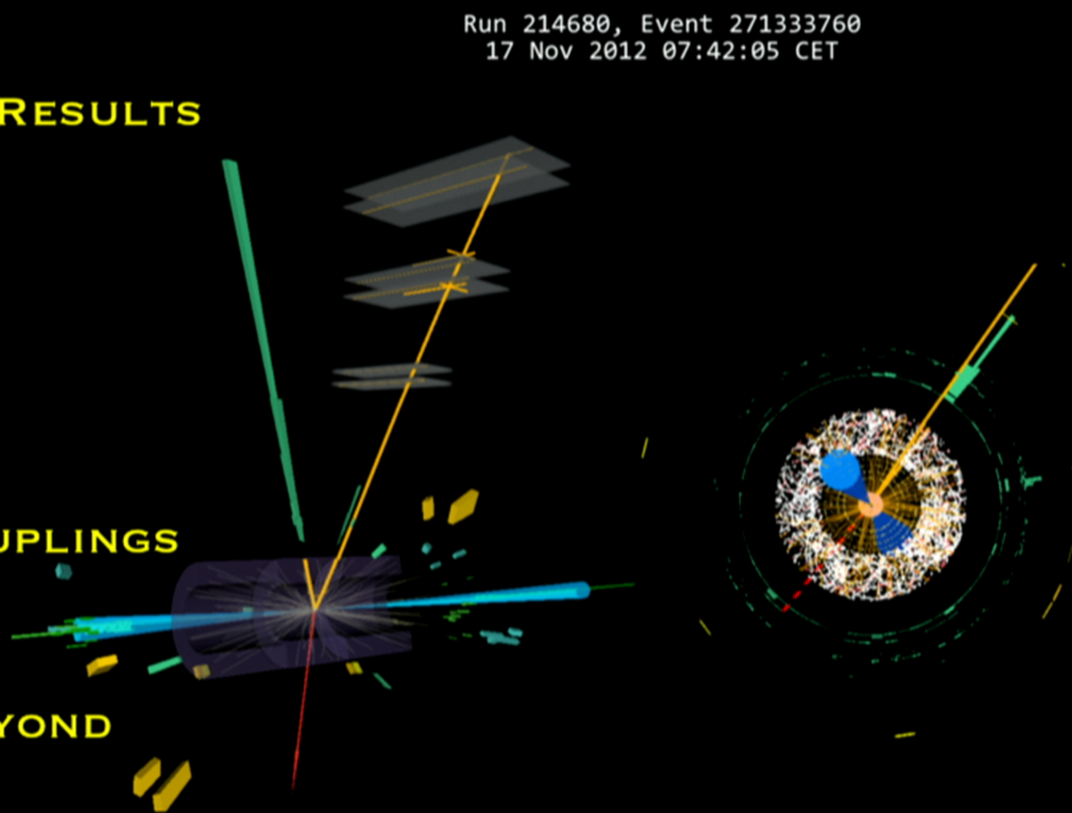
Date: Oct 31, 2014 01:00 PM

URL: http://pirsa.org/14100120

Abstract: An overview of the latest Higgs physics results from the ATLAS collaboration will be presented. Next year, the Large Hadron collider will restart at a higher collision energy after a 2-year shutdown. The Higgs physics programme for this next data taking period will be discussed.

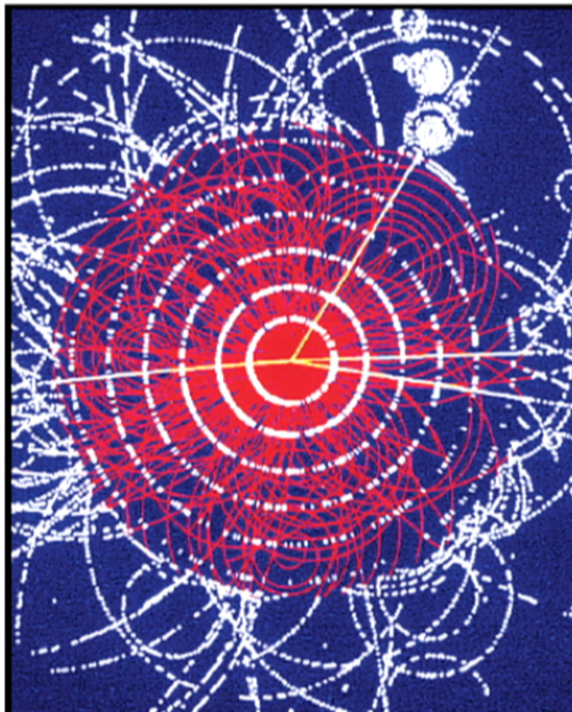
Outline

- Introduction
- Latest Run 1 Results
  - MASS
  - ZZ
  - $\gamma\gamma$
  - WW
  - $\tau\tau$
  - bb
- Off-shell couplings
- Rare decays
- BSM Results
- Run II and Beyond
- Conclusions



INTRODUCTION

•Two years ago: The Discovery (with ~5 fb^{-1} at 8 TeV, and ~5 fb^{-1} at 7 TeV)



SSPL/Getty Images

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

What do you think?

Should **The Higgs Boson** be TIME's Person of the Year 2012?

19.74% **Definitely** 80.26% **No Way**

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Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Courtesy of André David

Introduction

- A lot of progress since we submitted the paper “Observation of a New Particle in the Search for the Standard Model Higgs Boson”

- Results presented in March 2013 prompted CERN to declare that the new particle was “a” Higgs boson (two key ATLAS papers)

- During the shutdown, detector was recalibrated, reconstruction and analysis techniques were improved, and latest results are in general significantly better than results presented in early 2013

- And now, it seems we’ve accepted that the particle we found was not “very exotic” and was SM-like enough that people have started to call the measurements we are doing “SM Higgs physics”
    - Can never conclude that it is the SM Higgs boson, can only demonstrate that it is (in)consistent with that hypothesis
    - Luckily, we have a very predictive theory that has to survive many experimental tests

Higgs Physics Snapshot

Citation: J. Beringer *et al.* (Particle Data Group), PR **D86**, 010001 (2012) and 2013 partial update for the 2014 edition (URL: http://pdg.lbl.gov)

GAUGE AND HIGGS BOSONS

γ

$I(J^{PC}) = 0,1(1^{--})$

Mass $m < 1 \times 10^{-18}$ eV
Charge $q < 1 \times 10^{-35}$ e
Mean life τ = Stable

g or gluon

$I(J^{P}) = 0(1^{-})$

Mass $m = 0$ [a]
SU(3) color octet

W

$J = 1$

Charge = ± 1 e
Mass $m = 80.385 \pm 0.015$ GeV
$m_Z - m_W = 10.4 \pm 1.6$ GeV
$m_{W^+} - m_{W^-} = -0.2 \pm 0.6$ GeV
Full width $\Gamma = 2.085 \pm 0.042$ GeV
$\langle N_{\pi^\pm} \rangle = 15.70 \pm 0.35$
$\langle N_{K^\pm} \rangle = 2.20 \pm 0.19$
$\langle N_p \rangle = 0.92 \pm 0.14$
$\langle N_{\text{charged}} \rangle = 19.39 \pm 0.08$

$$H^0$$

Z

$J = 1$

Charge = 0
Mass $m = 91.1876 \pm 0.0021$ GeV [d]
Full width $\Gamma = 2.4952 \pm 0.0023$ GeV
$\Gamma(\ell^+ \ell^-) = 83.984 \pm 0.086$ MeV [b]
$\Gamma(\text{invisible}) = 499.0 \pm 1.5$ MeV [e]
$\Gamma(\text{hadrons}) = 1744.4 \pm 2.0$ MeV
$\Gamma(\mu^+ \mu^-)/\Gamma(e^+ e^-) = 1.0009 \pm 0.0028$
$\Gamma(\tau^+ \tau^-)/\Gamma(e^+ e^-) = 1.0019 \pm 0.0032$ [f]

Higgs Bosons — H^0 and $H^\pm$

H^0 Mass $m = 125.9 \pm 0.4$ GeV

H^0 signal strengths in different channels [n]

Combined Final States = 1.07 ± 0.26 (S = 1.4)
$W W^*$ Final State = 0.88 ± 0.33 (S = 1.1)
$Z Z^*$ Final State = $0.89^{+0.30}_{-0.25}$
$\gamma\gamma$ Final State = 1.65 ± 0.33
$b\overline{b}$ Final State = $0.5^{+0.8}_{-0.7}$
$\tau^+\tau^-$ Final State = 0.1 ± 0.7

Higgs Physics Snapshot

Characterization of H^0:

Precision Measurements
- Mass
- Coupling properties (incl. off-shell)
- Quantum numbers (Spin, CP)
- Fiducial and differential cross sections
- Width (direct, off-shell couplings, interferometry)

Rare SM decays:
- $Z\gamma$
- $\mu\mu$
- $J/\Psi\gamma$

BSM Searches:

Search for additional scalars
- 2 HDM searches
  - Neutral, charged, CP-odd
- EWK singlet
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

Look for H^0 in decay chains
- New (narrow width) resonance to exploit in cascade decays
- Resonant di-Higgs production

Rare decays:
- LFV $\mu\tau$, $e\tau$
- Top FCNC
- Invisible decays
- Etc.

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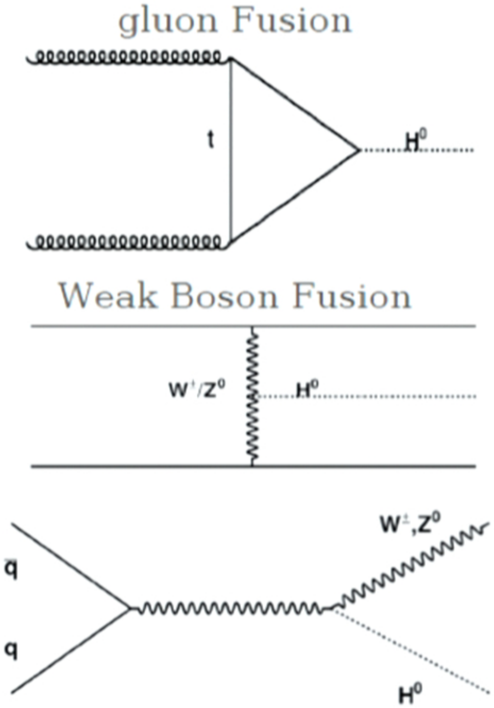
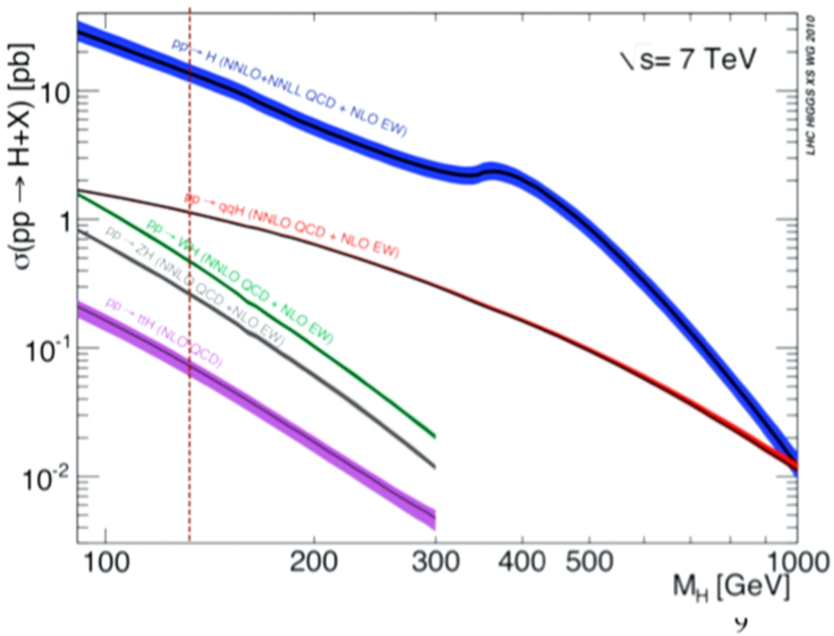
Higgs Production

- Higgs production at LHC dominated by "gluon fusion" process
- "Weak boson fusion" is subdominant but has less background





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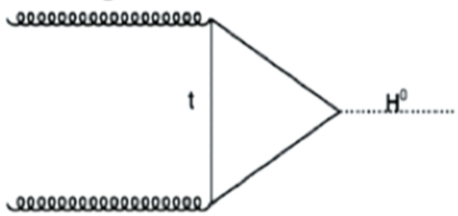
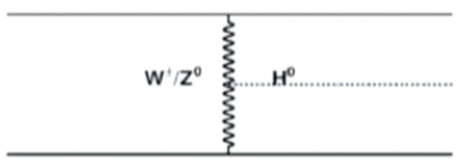
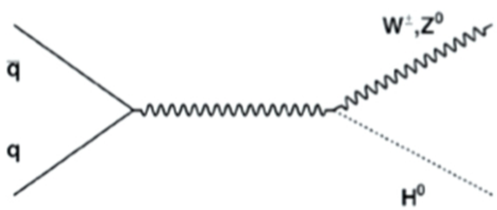
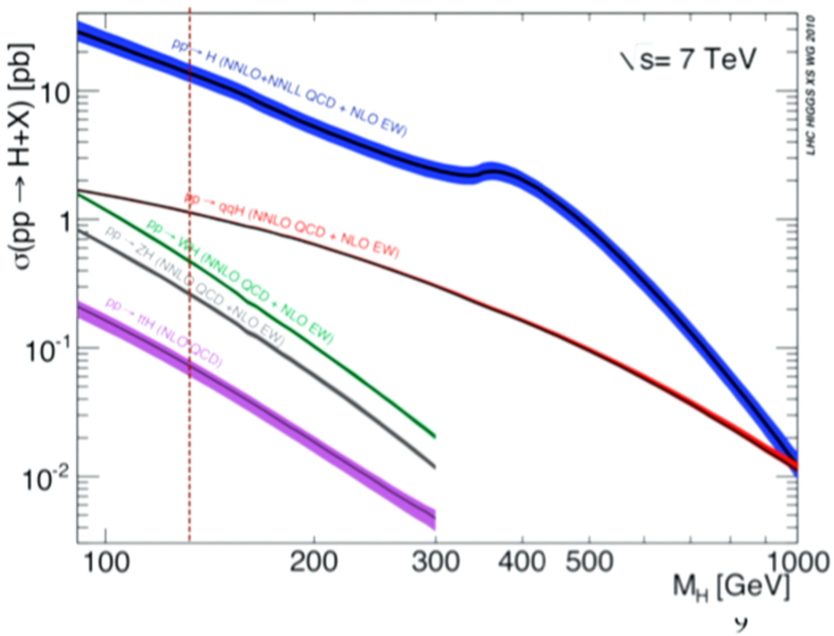
gluon Fusion



Weak Boson Fusion

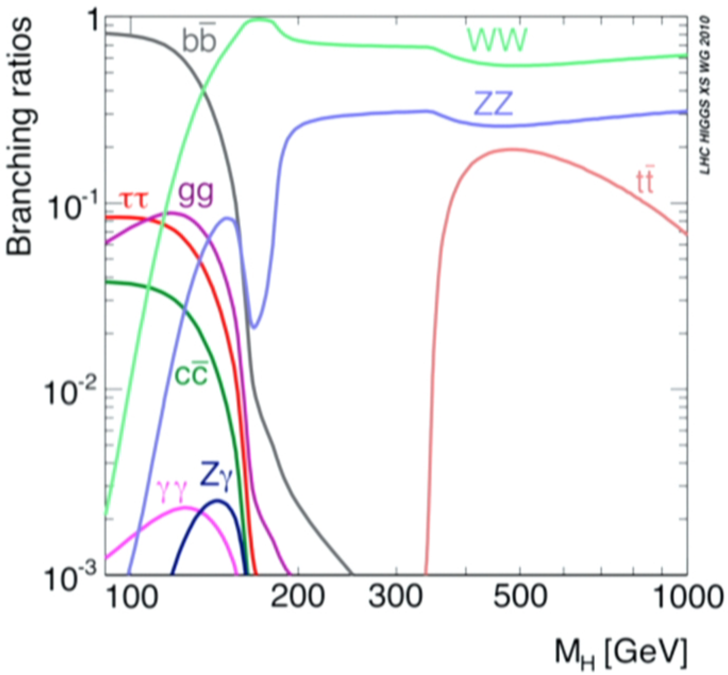


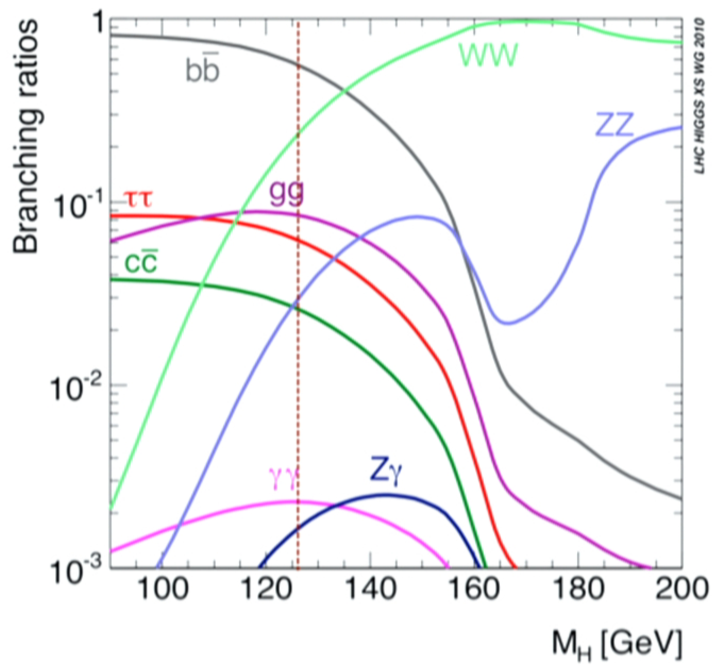




Higgs Decays

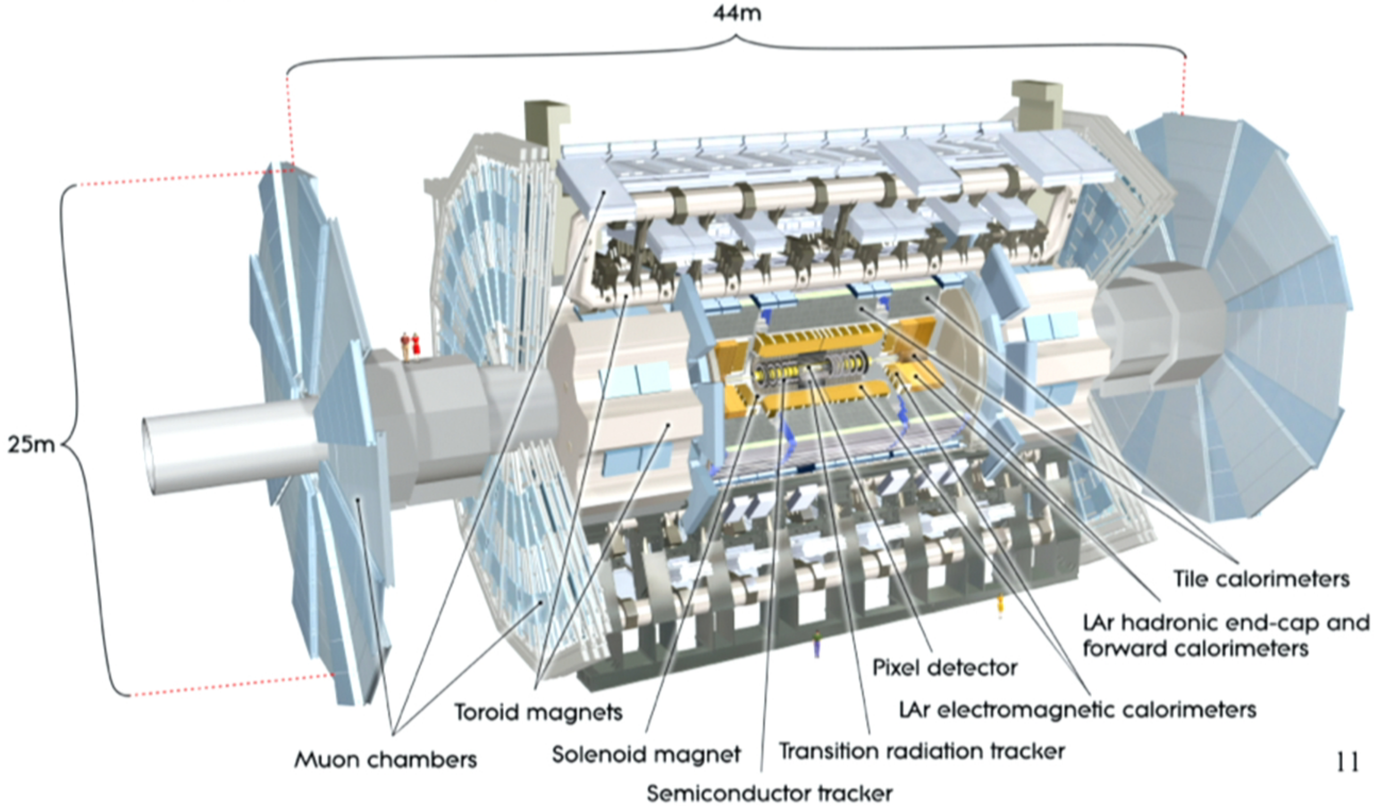
- At a mass of 125 GeV, we can observe many decay modes: Higgs measurements require that we fully exploit the detector capabilities (e, μ, τ, γ, etmiss, jets, tag HF-jets, trigger)





ATLAS Detector

Designed to find or exclude the SM Higgs over full mass range (up to 1 TeV)



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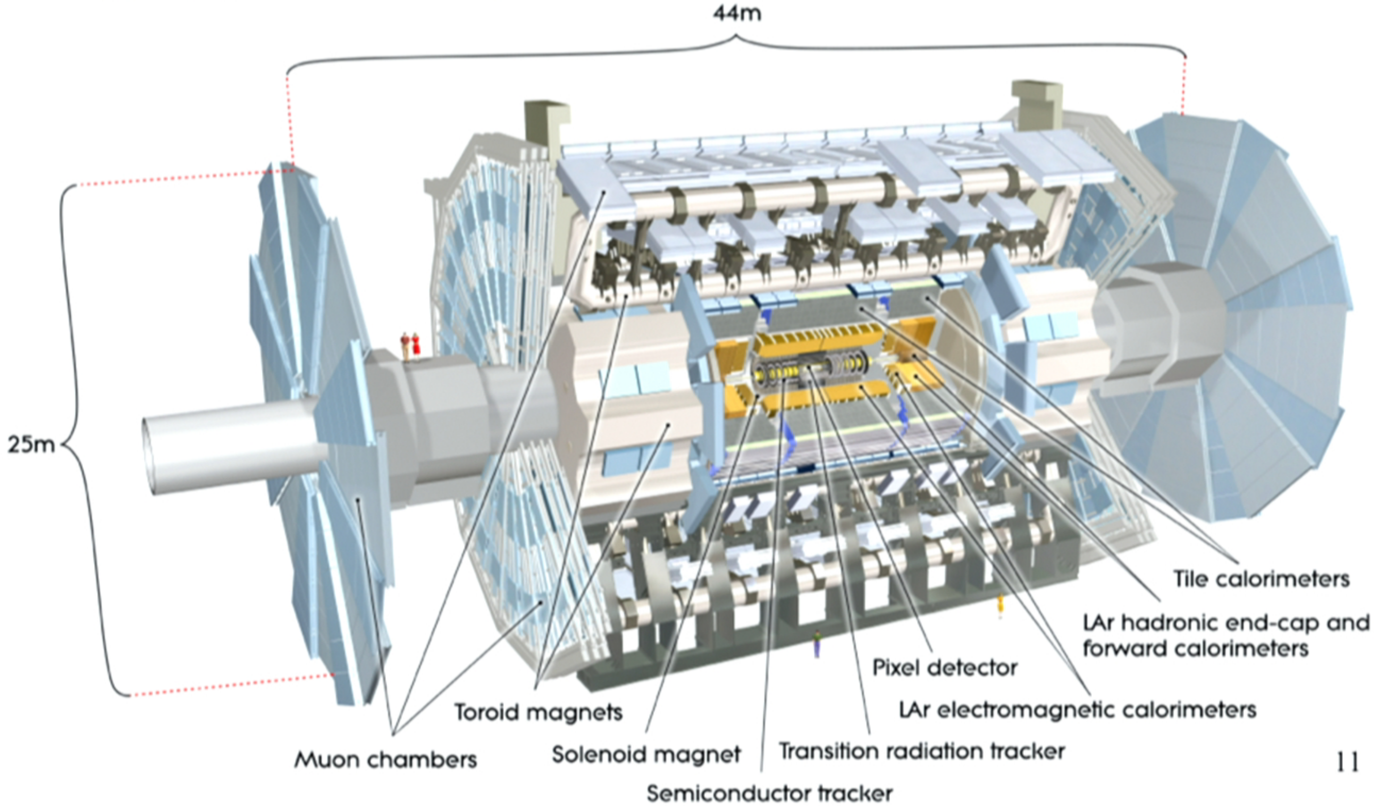

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Trigger, Pileup, Data Acquisition

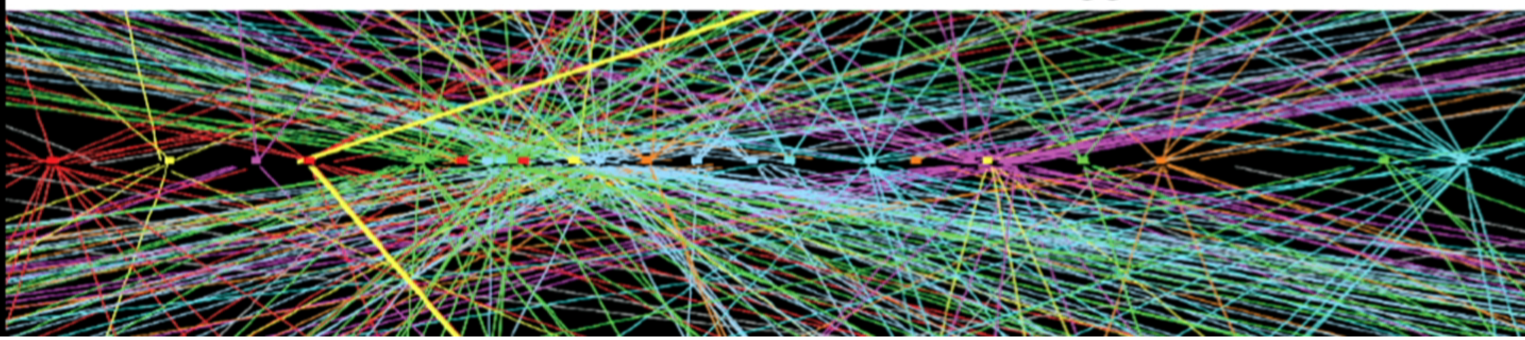
- Data/MC samples: 120 PB
- Over 30 collisions per event at high luminosity: increases event size and processing times for reconstruction
- Maintained good trigger and object reconstruction efficiency in high pileup environment
- Data taking/quality efficiency is 90% (from delivered to physics)

Example rates

Trigger	p_T Threshold	Rate (Hz) *
Inclusive e	24	70
Inclusive μ	24	45
ee	12	8
μμ	13	5
ττ	29,20	12
γγ	35,25	10
E_T^{mis}	80	18
5-jets	55	8

* At 5 10^{33} $cm^{-2}s^{-1}$

Total trigger rate: 400 Hz



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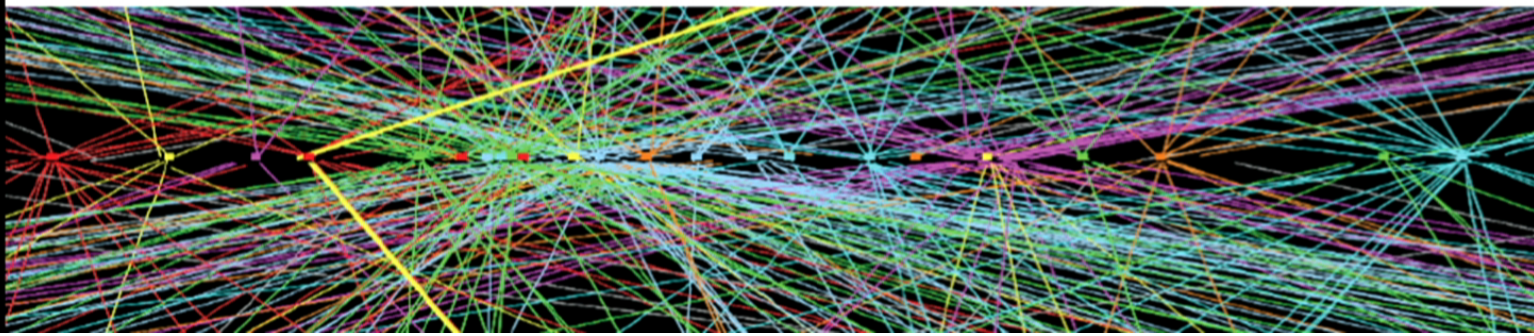

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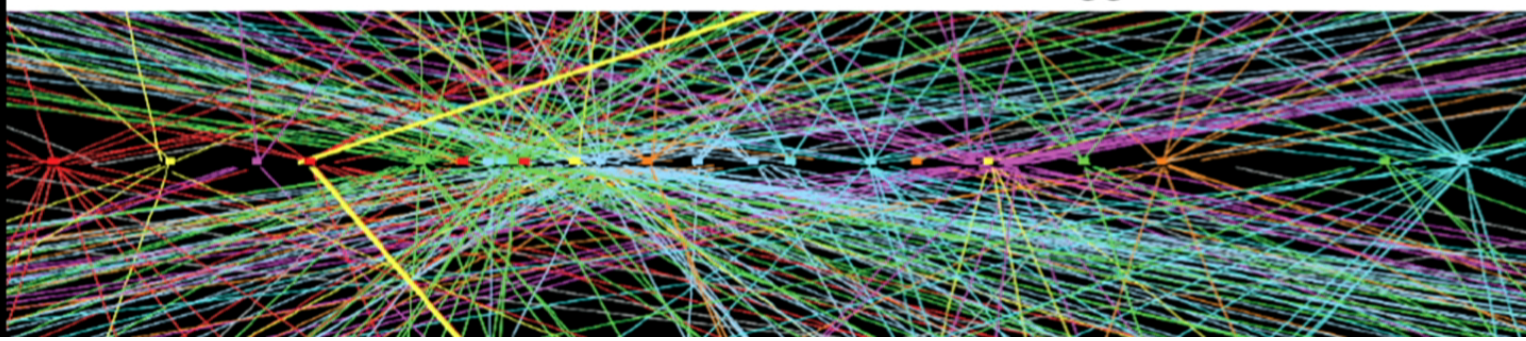
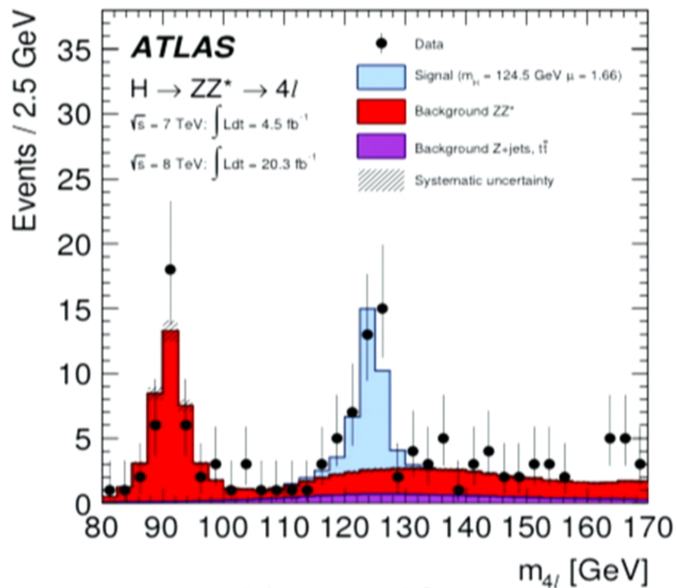
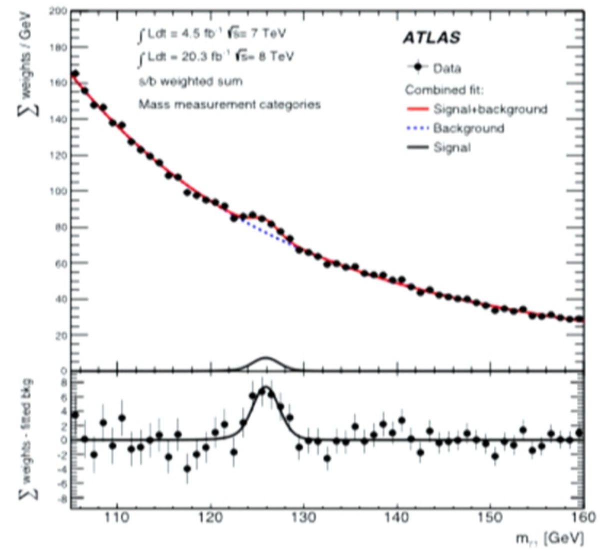


HIGGS MASS MEASUREMENT

Published in PRD arXiv:1406.3827





Old: $124.3\ ^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV

126.8 ± 0.2 (stat) ± 0.7 (syst) GeV

Expected mass shift -450 +/- 350 MeV

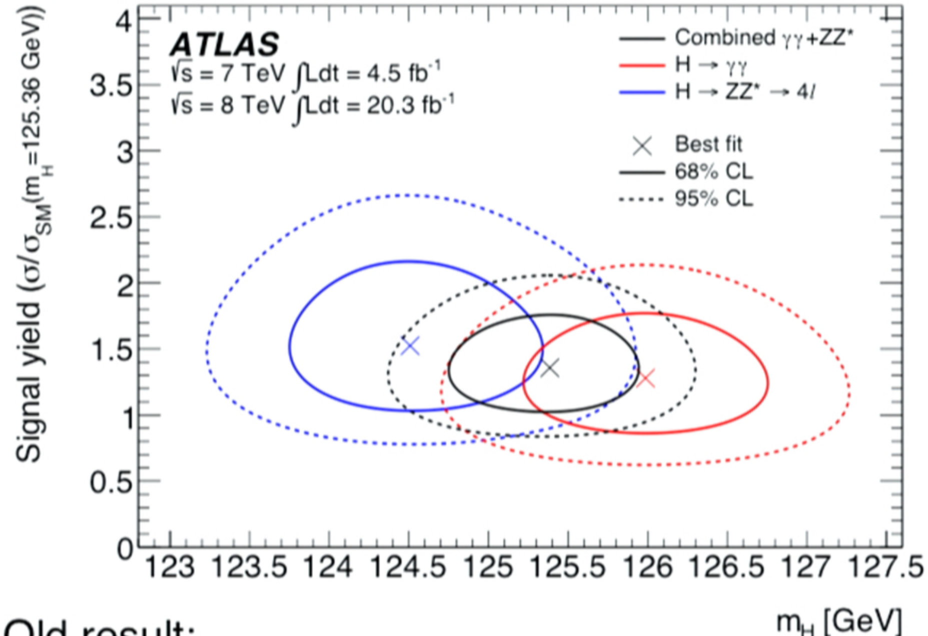
New: 124.51 ± 0.52 (stat) ± 0.06 (syst) GeV

125.98 ± 0.42 (stat) ± 0.28 (syst) GeV

125.36 ± 0.37 (stat) ± 0.18 (syst) GeV

Systematics greatly reduced

Higgs Mass Measurement



signal strengths for fitted channel mass:

$$\mu^{\gamma\gamma}_{(m_H=125.98\,GeV)} = 1.29 \pm 0.30$$

$$\mu^{ZZ}_{(m_H=124.51\,GeV)} = 1.66 \,^{+0.45}_{-0.38}$$

Old result:

$$125.5 \pm 0.2\,(\text{stat})\,^{+0.5}_{-0.6}\,(\text{syst})\ \text{GeV}$$

New:

$$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst})\ \text{GeV}$$

0.3% Precision measurement (statistical uncertainty dominant)

ZZ and γγ compatibility

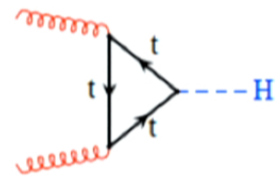
Old $\left\{ \Delta m = 2.3 \pm 0.9 \right.$ Compatibility 2.4σ

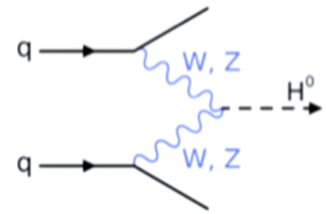
$$\Delta m = 1.47 \pm 0.72$$

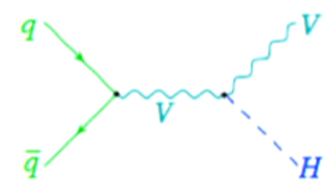
Compatibility 2.0σ

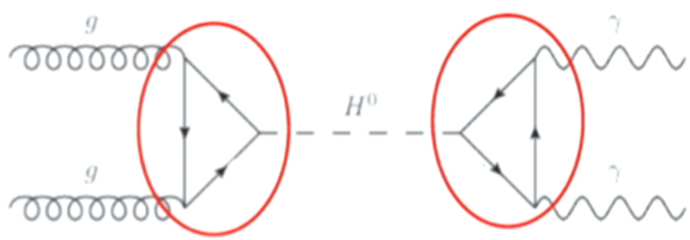
H ➡ γγ

- Main production depends on coupling to top quark (in SM), with smaller contribution from VBF (and VH) which depends on coupling to W/Z bosons
- Decay depends on coupling to top and W boson (in SM)
- Large backgrounds: need good photon identification
  – ATLAS EM calorimeter designed with this signal in mind
- Small branching ratio, need integrated luminosity
- A good discovery final state:
  – Excellent Higgs mass resolution
  – Looking for a resonance on top of smooth background
  – Probes new physics in loops:









H → γγ

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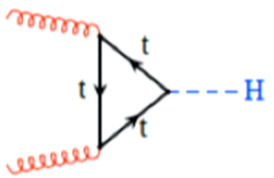

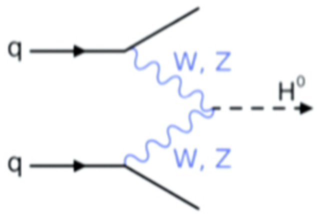

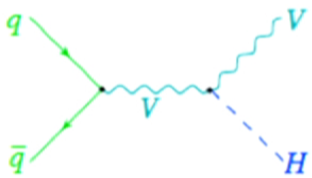

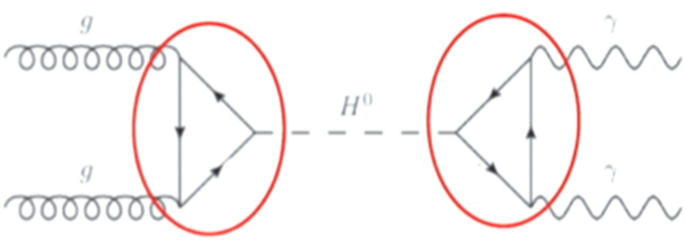

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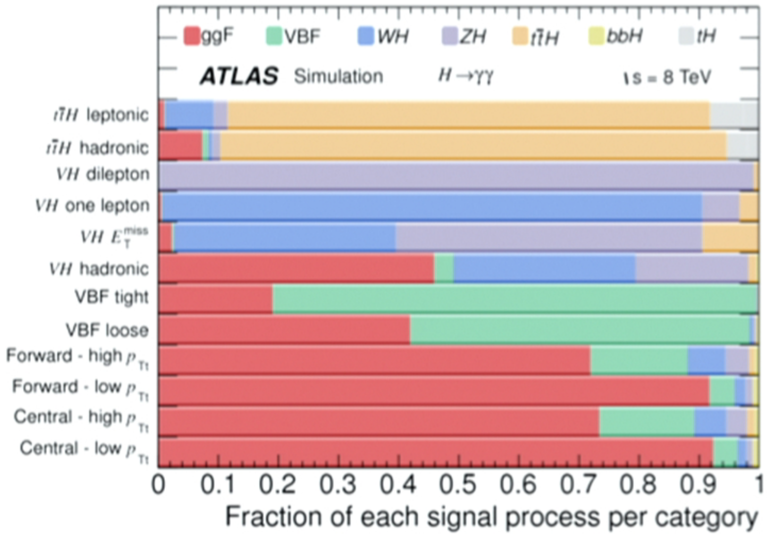
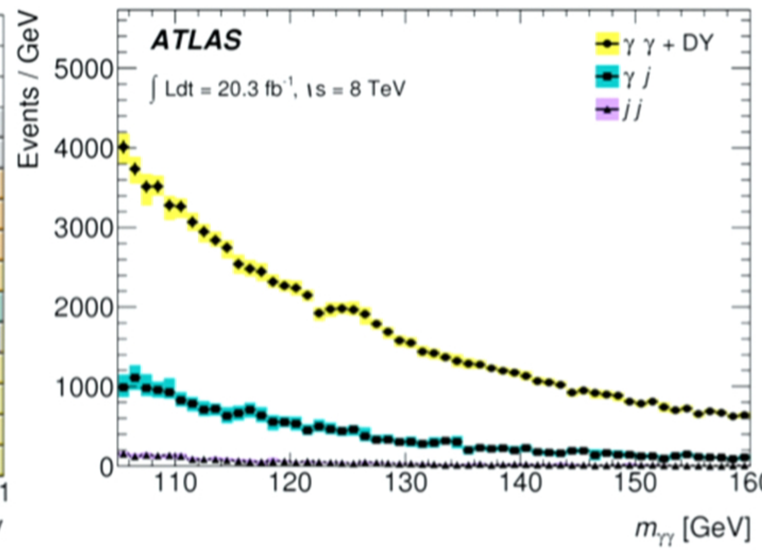
H → γγ

Estimated signal composition in various categories

Estimated background composition (not used in fit)





Combined signal strength at M_H= 125.36:

$$\mu = 1.17 \pm 0.23\ (\text{stat})\ ^{+0.10}_{-0.08}\ (\text{syst})\ ^{+0.12}_{-0.08}\ (\text{theory})$$
$$= 1.17 \pm 0.27,$$

19

H → γγ

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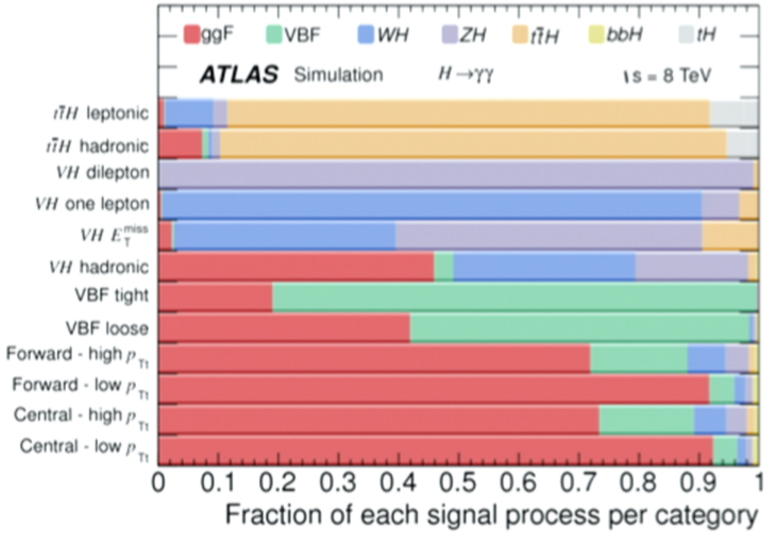

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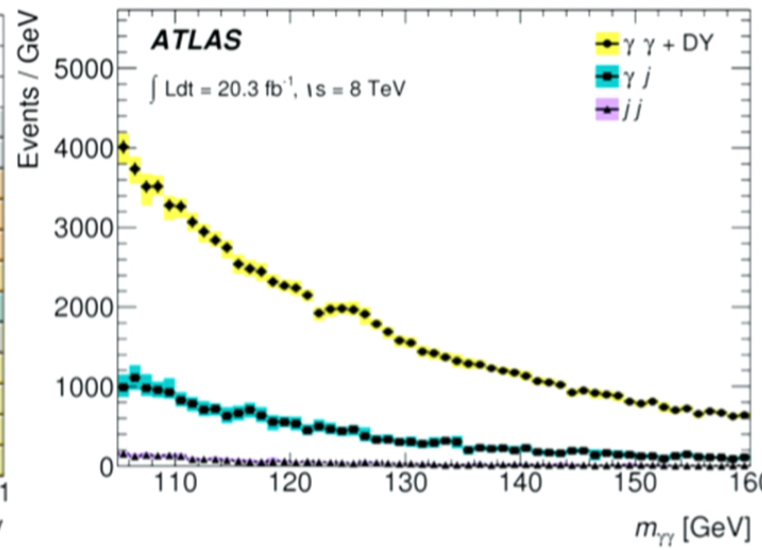

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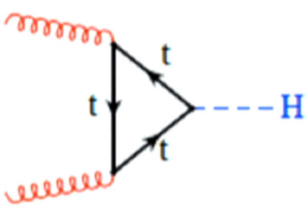
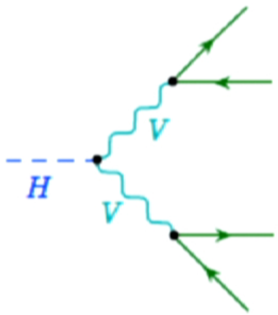
$H \rightarrow ZZ^* \rightarrow llll$

- Production depends on coupling to top quark (in SM), with small contributions from other production modes
- Decay depends on coupling to Z boson
- Small branching fraction to 4-lepton final state (need int. lumi.)
- A good discovery final state:
  - Very low backgrounds
  - Very good Higgs mass resolution
  - Requires good lepton reconstruction efficiencies
    - Can cope with high pileup environment
  - Clear/robust signal of coupling of Higgs to

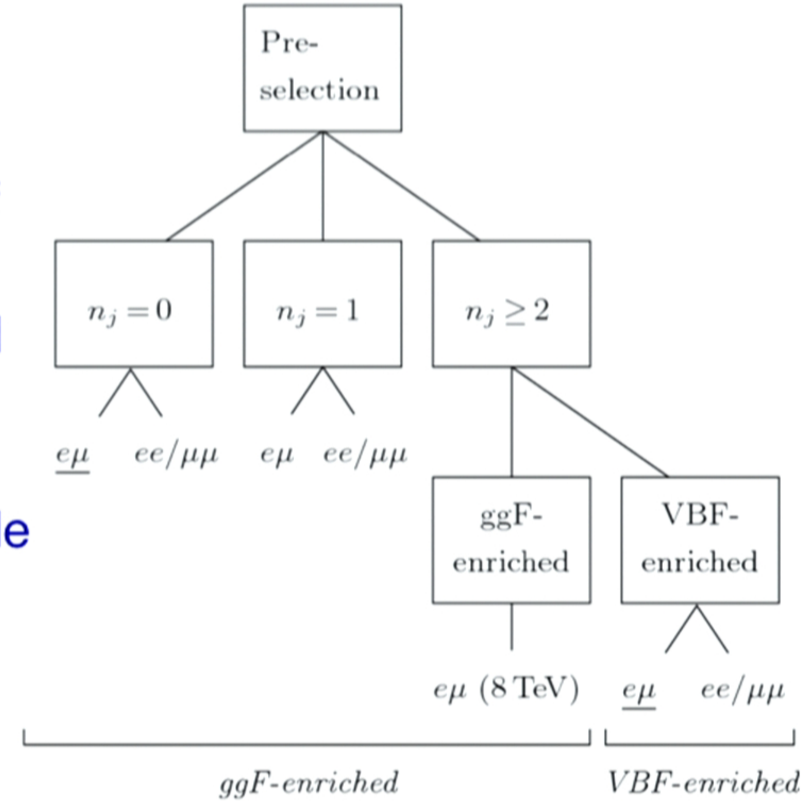




$H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$

Selections (snapshot):

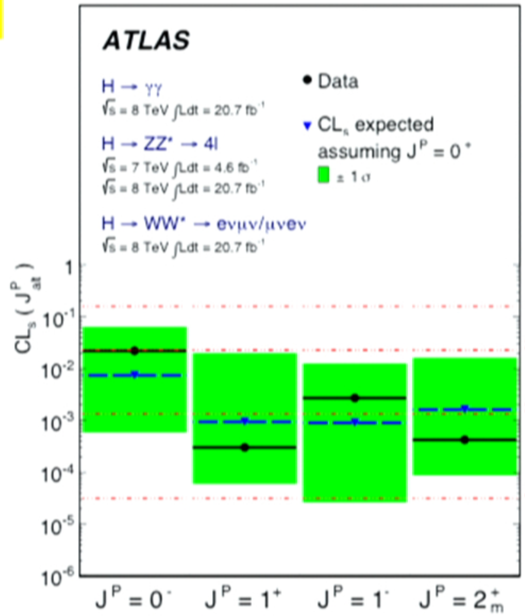
- Leading lepton pt > 22
- Subleading lepton pt > 10
- Sample divided in number of jets above 25 GeV
- Missing Et uses tracking and calorimeter, cut depends on final state
- Topological selections include cuts on m_{ll}, pt_{ll}, $\Delta\phi_{ll}$
- Signal extracted from fit to transverse mass in bins of subleading lepton pt and m_{ll}



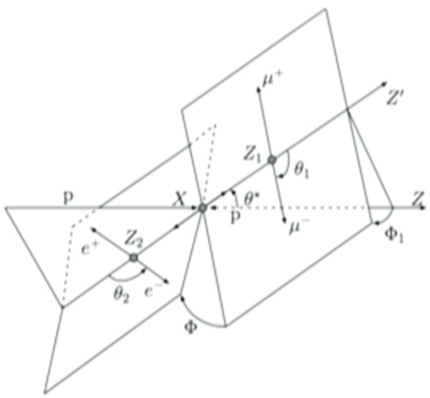
Spin/CP Analyses

Evidence for Spin 0 Nature of the Higgs Boson PLB 726 (2013)

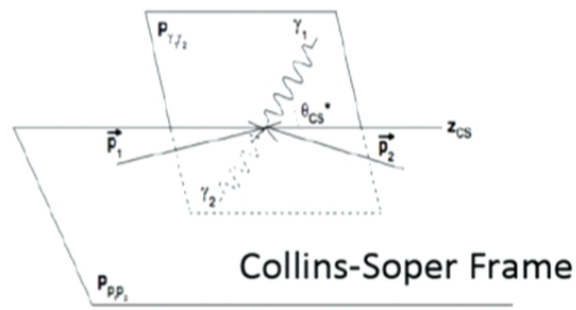
- $\gamma\gamma$:
  - Fit to $\cos(\theta^*)$ distributions
- ZZ: full kinematics of ZZ system
  - Use 5 angles in BDT
- WW:
  - Use m_{ll}, p_{Tll}, $\delta\phi_{ll}$, missing ET in 2D BDT



ZZ



γγ



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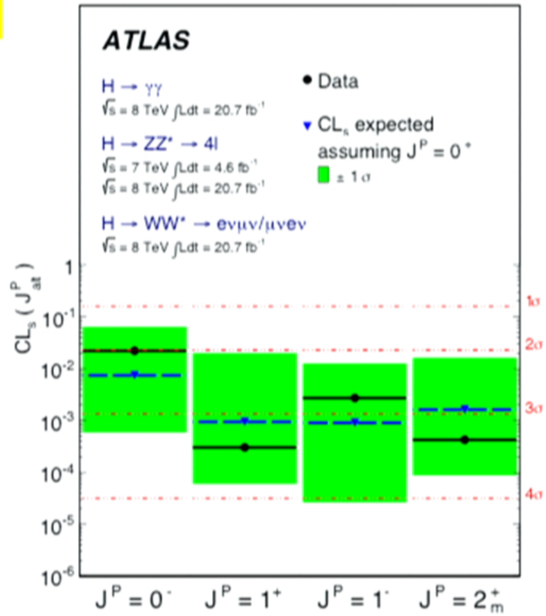
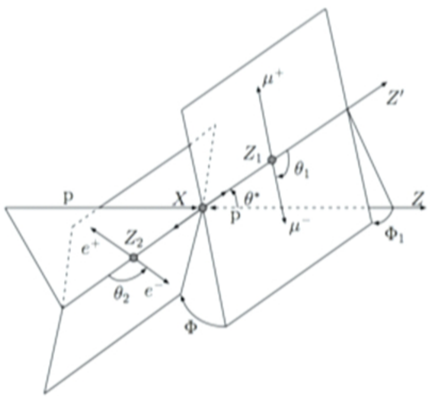
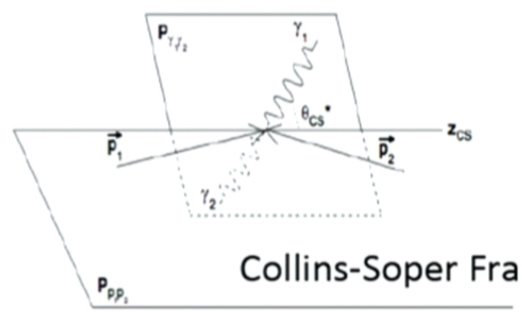


ZZ

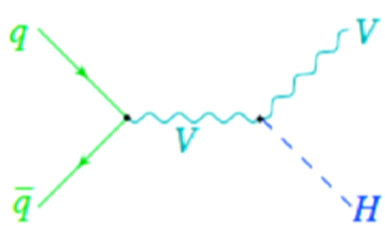


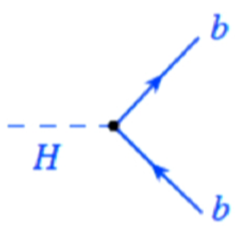
γγ



$H \rightarrow b\bar{b}$

- Production depends (mainly) on coupling to W/Z bosons
- Decay depends on coupling to b quark (down-type quark coupling)
- Small production cross section (but branching ratio is the largest)
- A challenging final state:
  - Very large backgrounds (W/Z+jets)
  - Higgs mass resolution is not that good (two jets compared to two photons)
  - Requires good b-tagging efficiency and fake rejection





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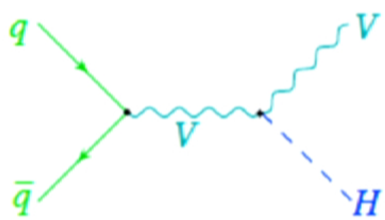
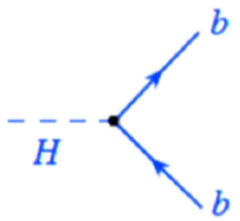
$H \rightarrow b\bar{b}$

- Production depends (mainly) on coupling to W/Z bosons
- Decay depends on coupling to b quark (down-type quark coupling)
- Small production cross section (but branching ratio is the largest)
- A challenging final state:
  - Very large backgrounds (W/Z+jets)
  - Higgs mass resolution is not that good (two jets compared to two photons)
  - Requires good b-tagging efficiency and fake rejection





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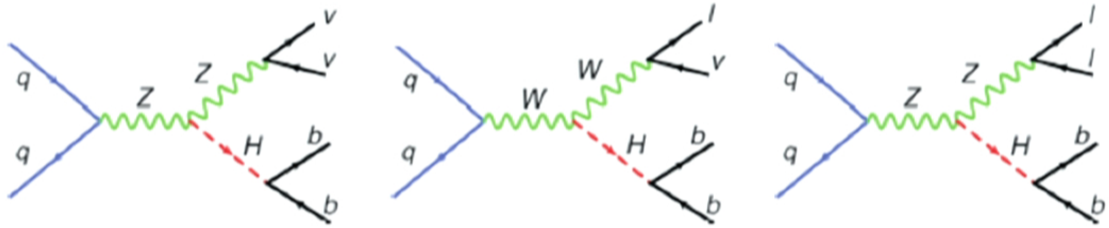
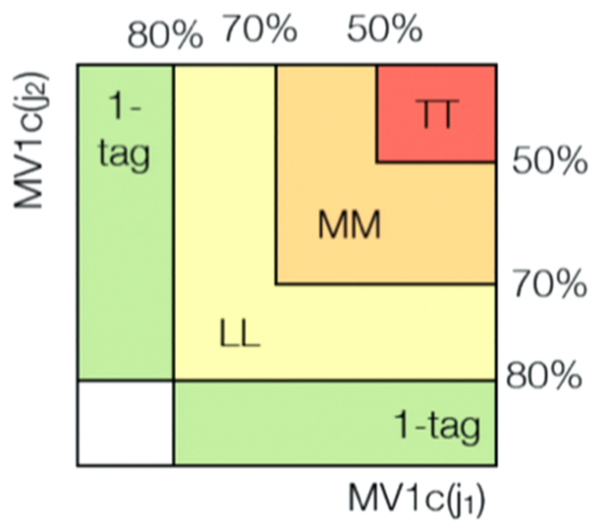
VH (H ➡ bb)



0-lepton **1-lepton** **2-lepton**

- 3 analysis channels
  - 0, 1, 2 leptons
- 2 pT(V) categories
  - < 120 GeV
  - > 120 GeV
- 2 jet bins
  - 2,3 jets
- Discriminating variables
  - Boosted decision tree
  - Multivariate, continuous b-tagging algorithm
- 50% improvement in sensitivity



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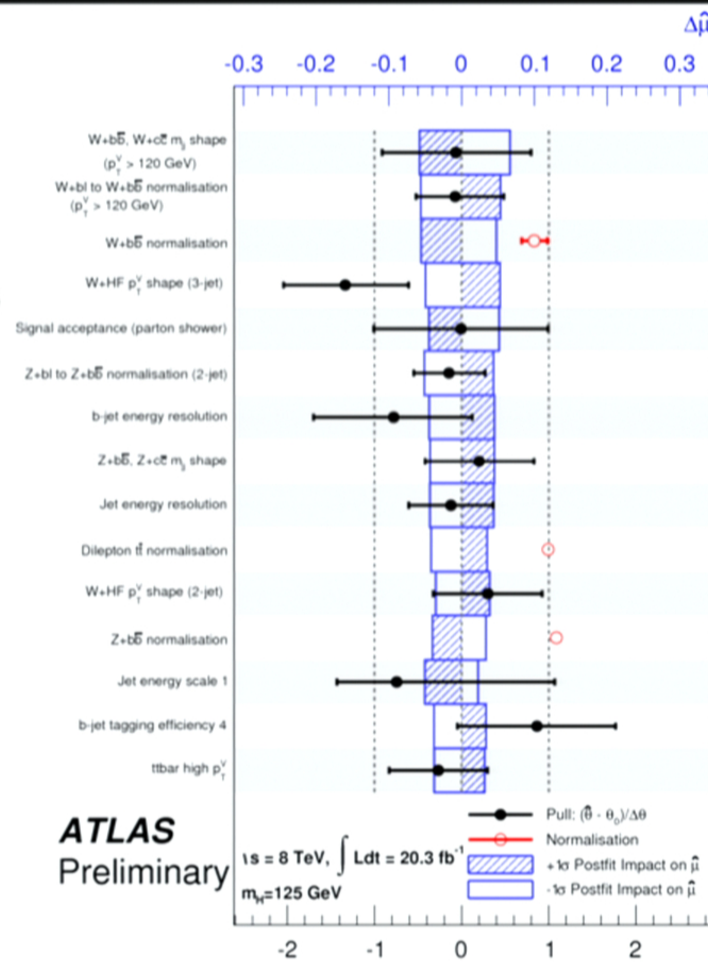
VH (H ➡ bb)

Fit Model:
- 11 control regions (1-tag)
- 27 signal regions (2-tags)
- ~170 nuisance parameters

Main systematic uncertainties
- W+b/c composition and shapes
- Signal acceptance: parton shower
- Jet energy resolution

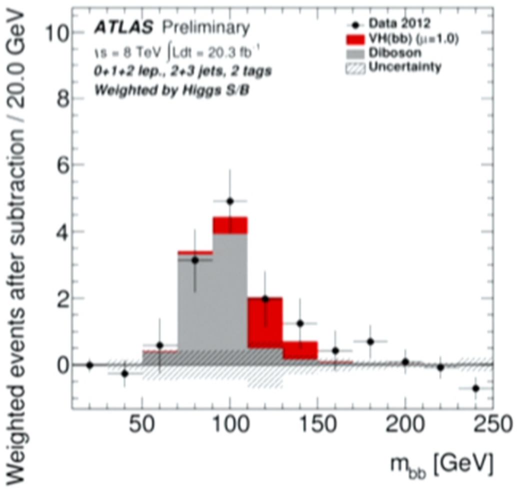
Improving MC modeling is important for Run II

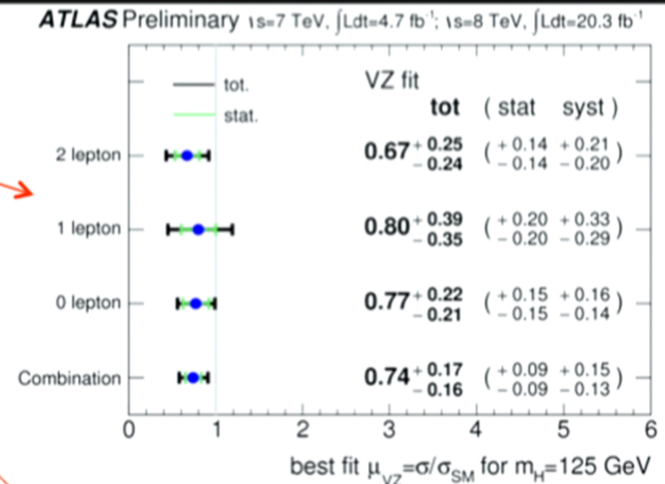


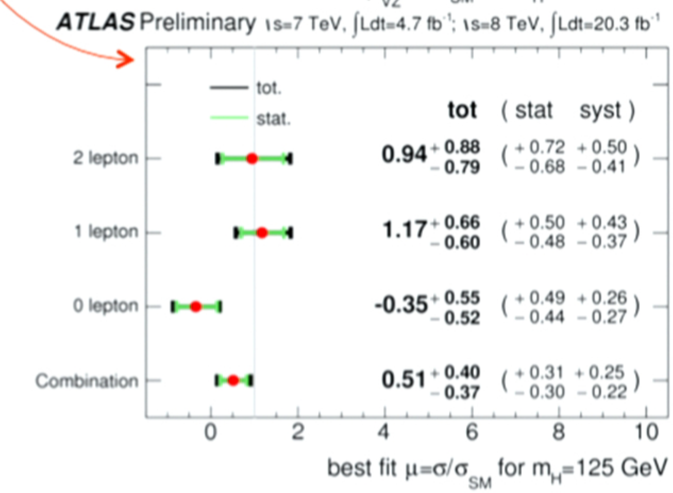
VH (H ➡ bb)

- Test Model with VZ fit
- Results of MVA analysis
- Cut-based analysis cross check with 8 TeV data:

μ = 0.65 ± 0.42 vs. 1.23 ± 0.60
(8% compatibility w/o systematics)

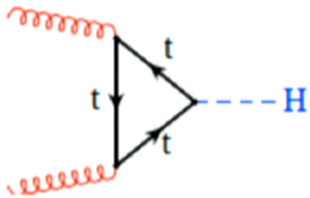


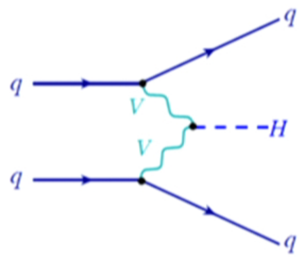


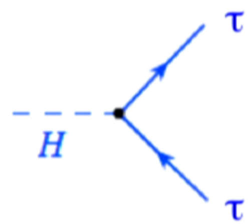


H $\rightarrow \tau\bar{\tau}$

- Production depends on coupling to top quark (in SM) and WBF+ VH production (coupling to Z/W bosons)
- Decay depends on coupling to taus (coupling to leptons)
- Cross section times branching ratio is relatively high
- Challenging final state:
  - Large backgrounds
  - Sensitive to pileup, was an extra challenge in 2012







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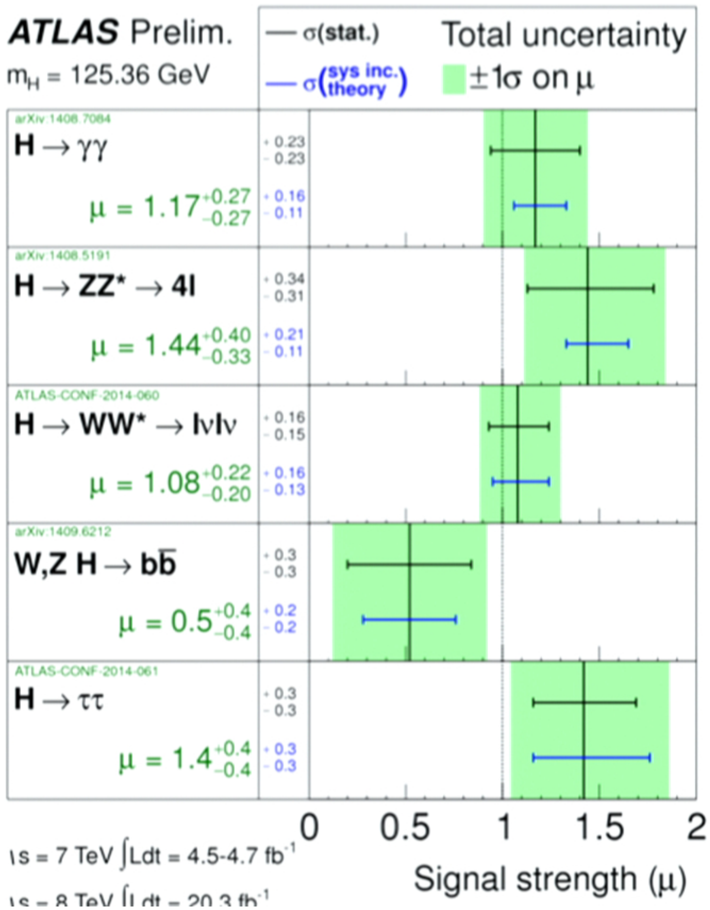
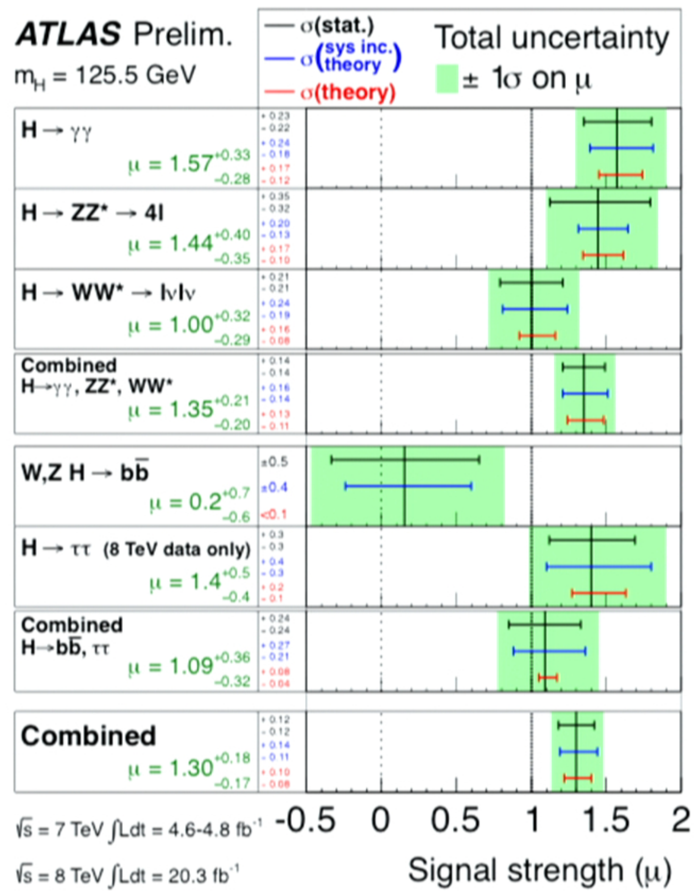
STATUS OF COUPLING ANALYSES

New public combination results



Old public combination results



BSM Physics Program (an incomplete snapshot)

High mass 2HDM· MSSM

- H to yy
- H to WW to lvlv
- H to WW to lvqq
- H to ZZ to 4l
- H to ZZ to llvv
- H to ZZ to llqq
- H to ZZ to vvbb
- (b)tau tau (leplep, lephad, hadhad)
- (b)bb
- (b)mumu
- very high mass tautau

Charged Higgs

- taunu+jets
- taunu+lep
- tb
- cs
- AW
- Wh
- WZ to (lvqq, qqll)
- very high mass tb (allhad, lep+jets)
- H+ to Wgamma

NMSSM

- a to mumu
- 2a to 4y (multiphoton)
- 2a to 4taus
- (bb)a to (bb)tautau to (bb)emu
- 2a to tautaumumu
- H+ to aW

LFV

- tau mu
- tau e
- e mu

Heavy Higgs decays

- Zh to lltautau (leplep, lephad, hadhad)
- Zh to (ll/vv)bb
- hh to yybb
- hh to 4b
- hh to bbtautau
- hh to yyVV to yy4j
- top pair
- Doubly charged Higgs

Other BSM

- mono photon
- mono Higgs
- Cascade decays H to H+W to hWW to bbWW

Invisible Higgs decays

- Mono jet.
- ZH to (ll)inv
- VBF H to inv
- VH to (jj)inv
- Mono-W analysis substructure

Exotic Higgs

- Hidden valley pions
- Dark Z, H to ZdZ(d) to 4l

RUN 2

- •Low intensity commissioning in March/April
- •Physics with a few bunches in May
- •50 ns running in June (<1 fb^{-1})
- •25 ns running in July (<2 fb^{-1})
- •25 ns running plus special runs July-November (~10 fb^{-1})

- •Detector getting back to a fully operational state by end of November
  - •Have added new tracking layer and beampipe
- • New high mass regime can be explored with a few fb^{-1}

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Conclusions

•We are in the process of completing the Run I Higgs physics program that covers a wide array of measurements and searches

- •The 125 GeV Higgs boson measurements are consistent with SM predictions
- •To test the consistency with the SM with higher precision will require substantial effort in improving experimental techniques, MC generators, and theory calculations (for both signal but also many backgrounds)

•We have a very exciting and challenging Higgs physics program for Run II

Run 3 and Beyond

Ongoing studies of Higgs physics potential at high luminosity