Overview of Higgs boson properties measurements in ATLAS

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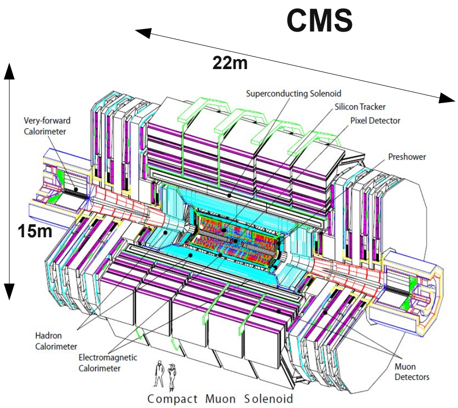
Outline

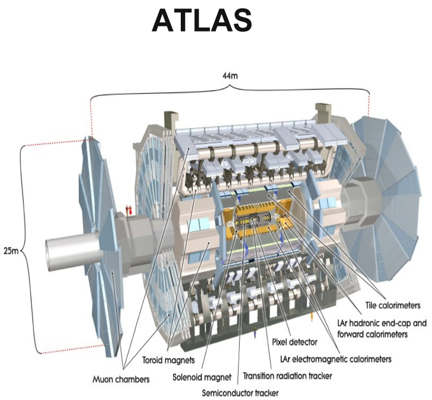
1. Introduction to ATLAS detector
2. Introduction to Higgs physics
3. Coupling measurement
4. Spin/CP measurement
5. Summary

Self introduction

- Name : Haifeng Li (李海峰) , haifeng.li@cern.ch
- Current : Postdoc at Stony Brook University since July of 2012, ATLAS
- **Research interest** : Higgs physics at WW and di-muon channels
- Education
  - Ph.D (2005/09-2008/09) : Shandong University, Pheno
  - Ph.D (2008/10-2012/06) : Joint training Ph.D between University of Wisconsin-Madison and SDU
    Thesis : Search for Standard Model Higgs boson in $H \to WW^* \to l\nu l\nu$ decay mode with ATLAS detector at $\sqrt{s} = 7$ TeV
    Advisors : 梁作堂(SDU), 吴秀兰 (UW, Madison)

ATLAS detector (and comparison with CMS)



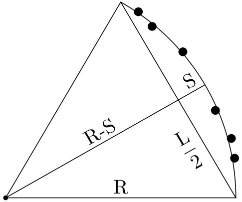


- Why ATLAS is 2 times bigger?

Size of detectors

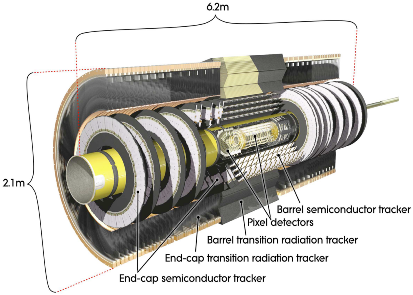
- Size difference mainly due to ATLAS muon toroid system
- ATLAS wants to measure 1 TeV muon at 10% level

- Calorimetry : particle deceleration by absorption (the larger, the better)
- Tracker : $\frac{\sigma_{p_T}}{p_T} = \frac{8p_T}{0.3BL^2}\sigma_s$

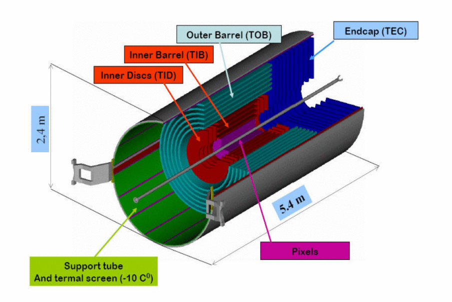


Inner Tracker

ATLAS



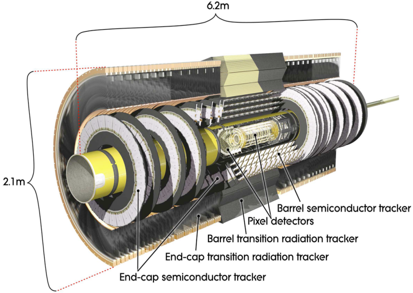
CMS



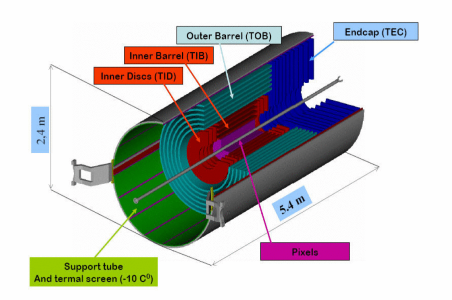
- Size is more or less the same

Inner Tracker

ATLAS



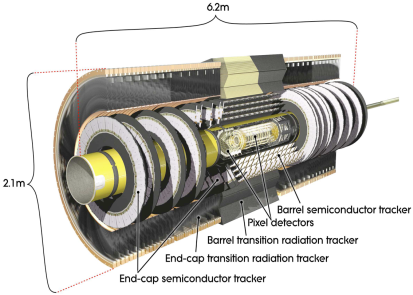
CMS



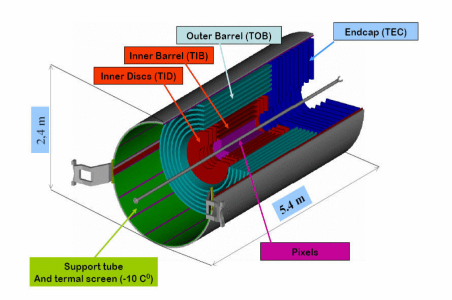
- Size is more or less the same
- But CMS has full silicon strip and pixel detectors - high resolution, high granularity
- ATLAS: silicon (strips and pixels) + Transition Radiation Tracker (TRT)

Inner Tracker

ATLAS



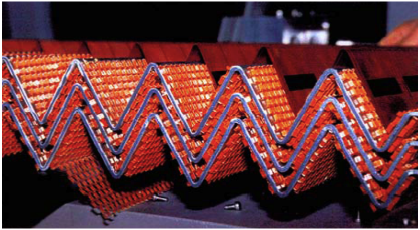
CMS



- Size is more or less the same
- But CMS has full silicon strip and pixel detectors - high resolution, high granularity
- ATLAS: silicon (strips and pixels) + Transition Radiation Tracker (TRT)
- And CMS has 4 Tesla solenoid magnetic fields. ATLAS has 2 Tesla for inner detector

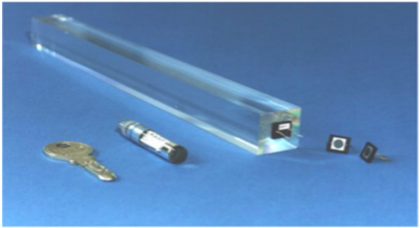
Calorimeter (EM)

ATLAS



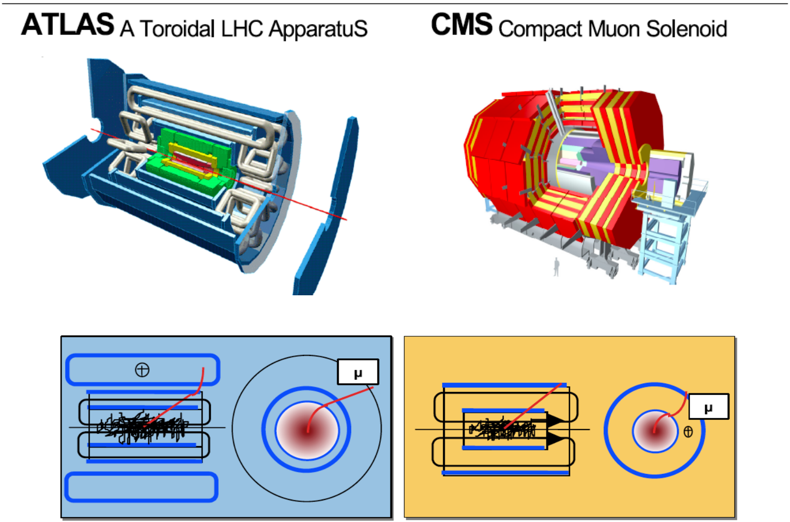
- Liquid Argon（液氩）, Pb
- Good energy resolution
- Not so fast (450 ns)
- Longitudinally segmented
- Angular measurement
- Radiation resistance

CMS



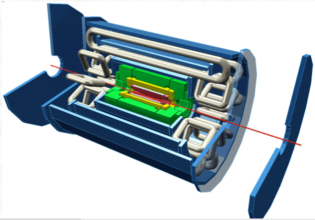
- PbWO4（钨酸铅)
- Excellent energy resolution
- Fast ($\ll$100 ns)
- No longitudinally segmentation
- No angular measurement
- Less radiation tolerance

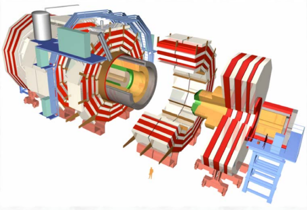
Muon Spectrometer



Performance

	ATLAS	CMS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)	4 T solenoid + return yoke
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$	Silicon pixels and strips (full silicon tracker) $\sigma/p_T \approx 1.5 \cdot 10^{-4} p_T + 0.005$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	$PbWO_4$ crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Brass + scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)	$\sigma/p_T \approx 1\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)	L1 + HLT (L2 + L3)

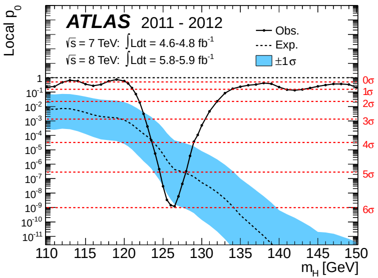




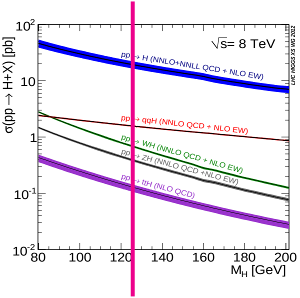
Introduction to Higgs physics

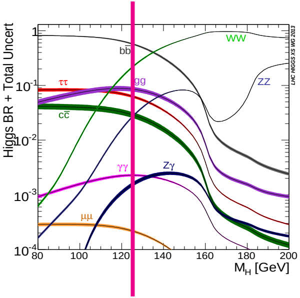
Phys. Lett. B 716 (2012) 1-29 (Submitted: 2012/07/31)

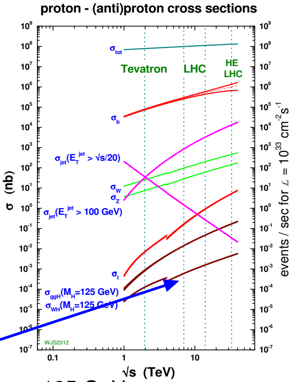
- Higgs discovery has been established with bosonic channels ($H \to \gamma\gamma$, $H \to WW \to \ell\nu\ell\nu$ and $H \to ZZ \to 4\ell$).



- Is the new boson responsible for the electroweak symmetry breaking?
- Have to measure the properties of the Higgs boson (mass, coupling, spin and parity).
- LHC Run I data : 7 TeV and 8 TeV (about 25 fb^{-1})







m_H=125 GeV

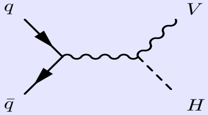
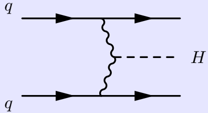
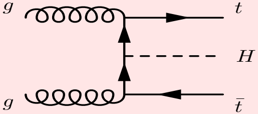
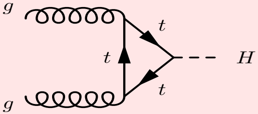
σ (pb)	7 TeV	8 TeV
ggF	15	19
VBF	1.2	1.6
WH	0.57	0.70
ZH	0.33	0.41
ttH	0.09	0.31

m_H=125 GeV

Higgs decay	BR
bb	57%
WW	22%
$\tau\tau$	6.2%
ZZ	2.8%
$\gamma\gamma$	0.23%
$Z\gamma$	0.154%

How to probe different production modes

Higgs candidate events are selected from their decay states. Need to disentangle different production modes to probe Higgs couplings

<table>
<tr><td>VH</td><td>
</td><td>Leptons, missing E_T or low-mass dijets (from W/Z decays) not included in WW or $Z\gamma$ in this talk</td></tr>
<tr><td>VBF</td><td>
</td><td>Two forward jets with high di-jet mass and large rapidity gap</td></tr>
<tr><td>ttH</td><td>
</td><td>Two top quarks : leptons, missing E_T, multi-jets or b-tagged jets not discussed in this talk</td></tr>
<tr><td>ggF</td><td>
</td><td>The rest</td></tr>
</table>

$H \to \gamma\gamma$

It's the first analysis written in ATLAS Technical Design Report (TDR), May 25, 1999

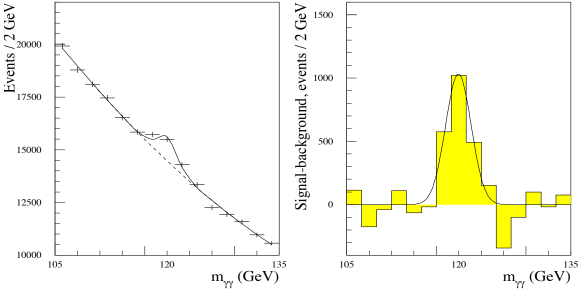
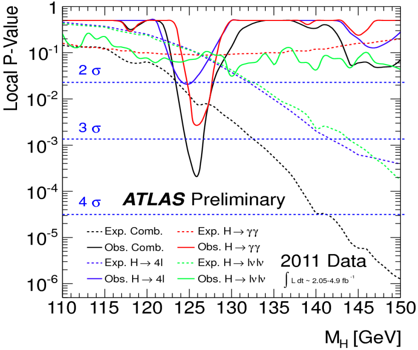
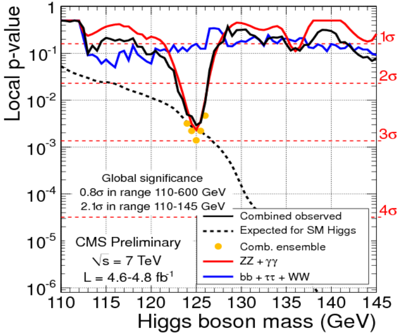


Figure 19-4 Expected $H \to \gamma\gamma$ signal for $m_H = 120$ GeV and for an integrated luminosity of 100 fb^{-1}. The signal is shown on top of the irreducible background (left) and after subtraction of this background (right).

$H \to \gamma\gamma$

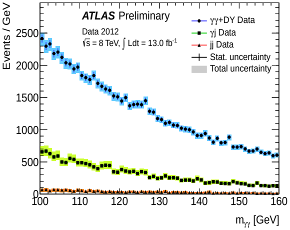
It was the first smoking gun for Higgs at LHC (CERN Council Meeting, December of 2011)





$H \to \gamma\gamma$: analysis overview

- Signal : narrow peak. Good mass resolution (about 1.7 GeV for $m_H = 120$ GeV)
- Background composition : SM di-photon (irreducible, about 75%), γ-jet and jet-jet fake (about 25%)



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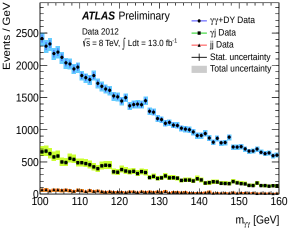
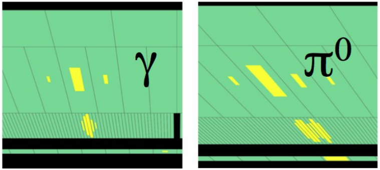
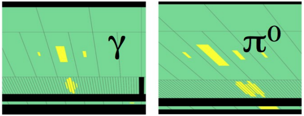


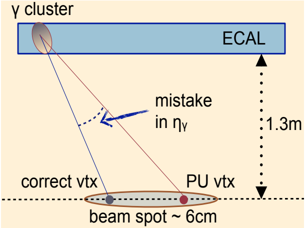


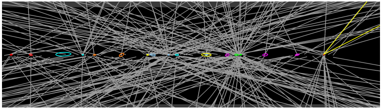
Fine η granularity of first layer can help reject π_0 background

$H \rightarrow \gamma\gamma$: vertex determination

- Di-photon mass resolution is related to angular resolution : $m_{\gamma\gamma} = 2E_1 \times E_2 \times (1 - \cos\theta)$
- Vertex determination becomes more difficult with presence of multiple interactions per bunch crossing (pile-up)
- Thanks to the Longitudinal segmentation of ATLAS EM calorimeter





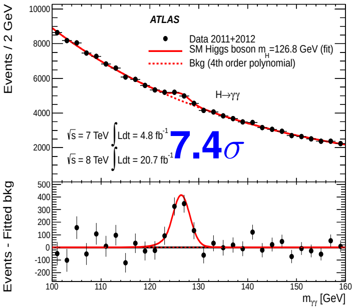


$H \to \gamma\gamma$: mass and coupling

Analysis strategy

- Two isolated photons with large transverse momentum ($p_T > 40, 30$ GeV)
- Fitting background and signal using analytic functions

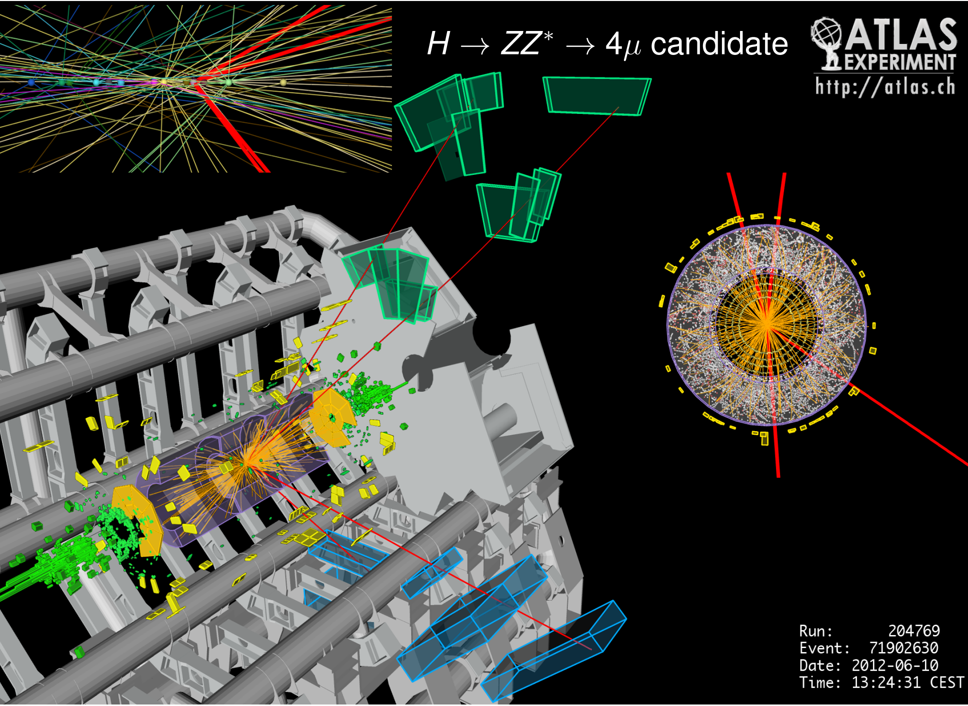
Phys. Lett. B 726 (2013), pp. 88-119



$$m_{\text{Higgs}} = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{syst}) \text{ GeV}$$

$$\text{Signal strength } (\mu \equiv \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{\text{SM exp.}}}) = 1.55^{+0.33}_{-0.28}$$

$H \to ZZ^* \to 4\mu$ candidate



$H \to ZZ^{(*)} \to 4\ell$: Mass and Coupling

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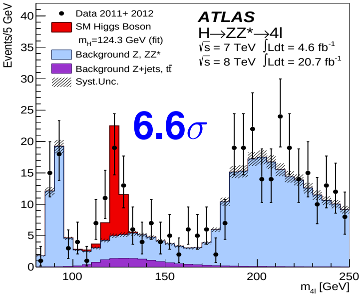

- $p_T^{1,2,3,4} > 20,15,10,(6)7$ GeV $(\mu)e$
- Background : Continuum ZZ^* : normalization, shape both taken from MC simulation. Z+jets, $t\bar{t}$: normalized from data control regions

7+8 TeV; $120 < m_{4l} < 130$ GeV

	Signal	ZZ^*	$Z+$jets, tt	Observed
4μ	6.3±0.8	2.8±0.1	0.55±0.15	13
$2e2\mu/2\mu2e$	7.0±0.6	3.5±0.1	2.11±0.37	13
$4e$	2.6±0.4	1.2±0.1	1.11±0.28	6

- Signal strength $\mu = 1.43^{+0.40}_{-0.35}$
- $m_H = 124.3^{+0.6}_{-0.5}(\text{stat.})^{+0.5}_{-0.3}(\text{sys.})$ GeV

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

- Feature : large production rate but with poor mass resolution
- Observable :

$$m_T = \sqrt{(E_T^{ll} + E_T^{\nu\nu})^2 - |\vec{p}_T^{ll} + \vec{E}_T^{\nu\nu}|^2}$$

- Categories : Same Flavor ($ee/\mu\mu$) and Different Flavor ($e\mu$) with 0, 1

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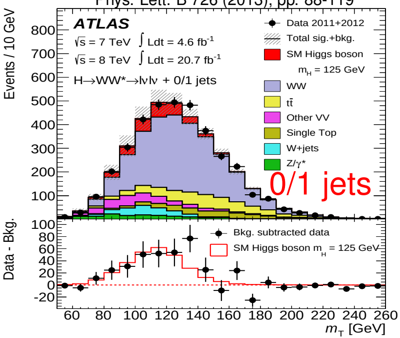
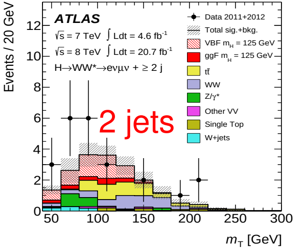




- Observed excess : 3.8σ ($m_H = 125.5$ GeV)
- Signal strength $\mu = 0.99^{+0.31}_{-0.26}$

Coupling Combination

- Take input from previous public individual channels but with new luminosity calibration. So the results is slightly different.
- Also include $H \rightarrow \tau\tau$ and $H \rightarrow bb$ channels

Coupling Combination - ATLAS-CONF-2014-009

Statistical Procedure

Likelihood : Poisson probabilities with parameter of interest (POI) and nuisance parameters.

$$\mathcal{L}(\text{data}|\mu,\theta) = \text{Poisson}(\text{data}|\mu \times s(\theta) + b(\theta)) \times p(\tilde{\theta}|\theta) \quad (1)$$

Signal strength μ is tested with test statistics

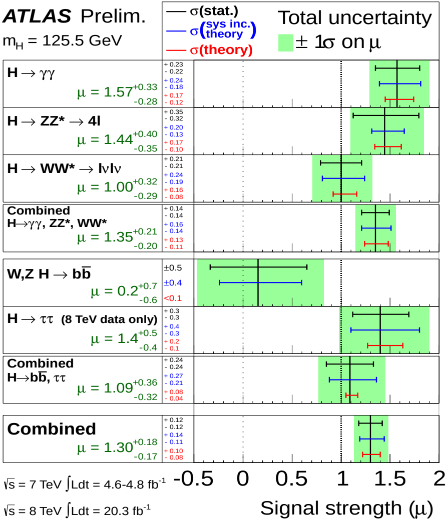
$$q_\mu = -2\ln\Lambda(\mu) = -2\ln\{\frac{\mathcal{L}(\mu,\hat{\hat{\theta}}(\mu))}{\mathcal{L}(\hat{\mu},\hat{\theta})}\} \quad (2)$$

Combined likelihood is the product of likelihoods from different channels,

$$\mathcal{L}(\text{data}|\mu,\theta) = \prod_i \mathcal{L}_i(\text{data}_i|\mu,\theta_i) \quad (3)$$

Global fitting with combined likelihood

Overall Signal Strength - μ

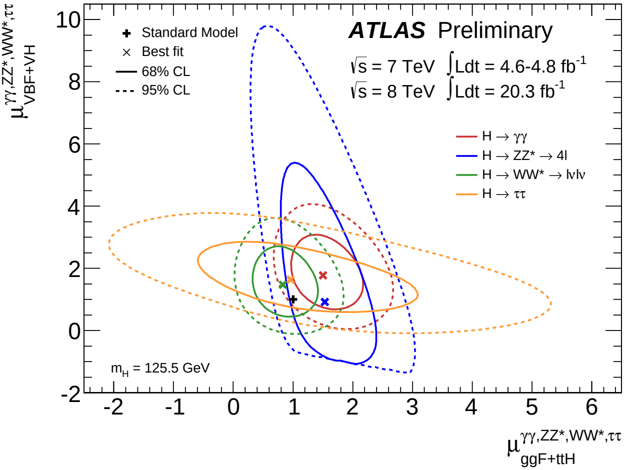


- with $m_H = 125.5$ GeV
- best-fit

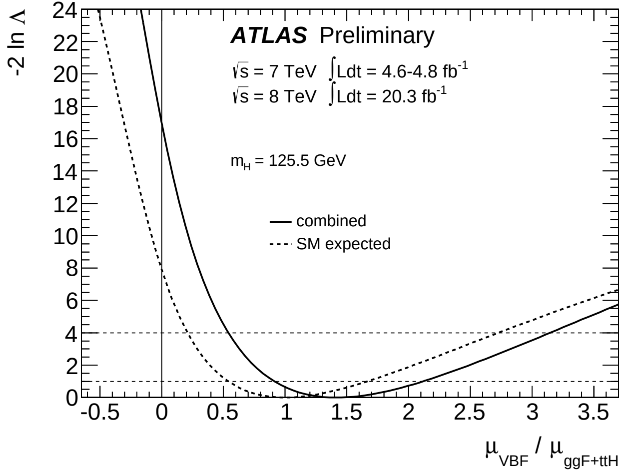
  $\mu =$
  $1.30 \pm 0.12(stat)^{+0.14}_{-0.11}(sys)$

Different Production Modes

ggF and ttH are probing Higgs fermion coupling. VBF and VH are probing coupling between Higgs and vector bosons

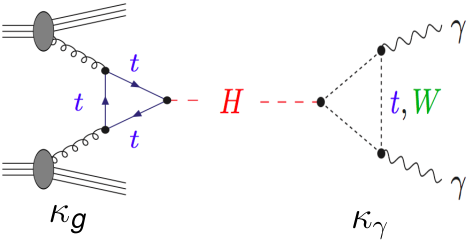


Evidence for VBF Production



$\mu_{VBF}/\mu_{ggF+ttH} = 1.4^{+0.5}_{-0.4}(stat)^{+0.4}_{-0.3}(sys)$. Compatibility with $\mu_{VBF} = 0$ is 4.1 σ

Coupling Fitting Beyond Signal Strengths



- Assume narrow width approximation

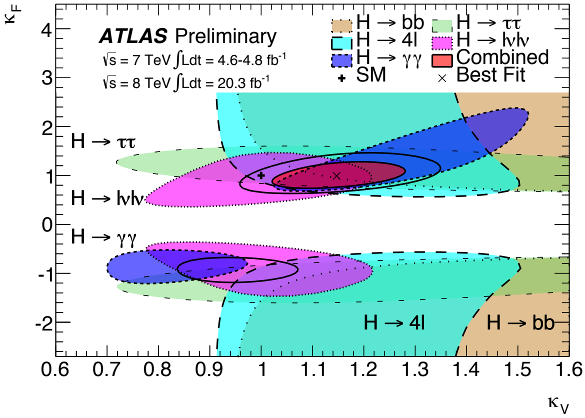
$$\sigma \times BR(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

- $$\kappa_g = \frac{\sigma}{\sigma_{SM}} = \frac{\kappa_t^2 \sigma_{tt} + \kappa_b^2 \sigma_{bb} + \kappa_t \kappa_b \sigma_{tb}}{\sigma_{tt} + \sigma_{bb} + \sigma_{tb}}$$
- $$\kappa_\gamma = \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \frac{\kappa_t^2 \Gamma_\gamma^{tt} + \kappa_W^2 \Gamma_{\gamma\gamma}^{WW} + \kappa_t \kappa_W \Gamma_{\gamma\gamma}^{tW}}{\Gamma_{\gamma\gamma}^{tt} + \Gamma_{\gamma\gamma}^{WW} + \Gamma_{\gamma\gamma}^{tW}}$$

Fermion and Vector Gauge Coupling

Define $\kappa_V = \kappa_W = \kappa_Z$,

$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$



best-fit values : $\kappa_V = 1.15 \pm 0.08$, $\kappa_V = 0.99^{+0.17}_{-0.15}$

Spin/CP Measurement

Higgs Spin/CP Models

- In SM, Higgs is spin-0 and CP even ($J^P = 0^+$)
- Alternative hypothesis can be $J^P = 0^-, 1^+, 1^-, 2^+$.
  Detail can be found in Phys. Rev. D 81 (2010) 075022,

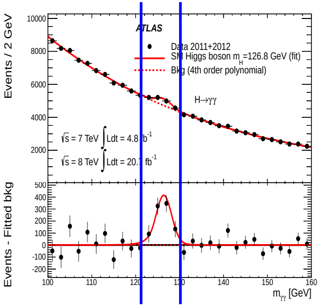
	ZZ^*	WW^*	$\gamma\gamma$
0^-	✔	-	-
$1^-, 1^+$	✔	✔	-
2^+	✔	✔	✔

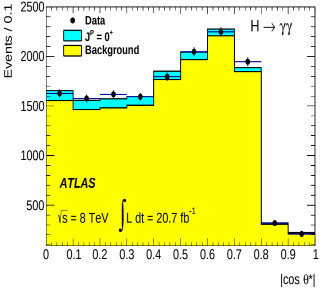
Spin-2 model

- Lots of possibilities for spin-2. A specific one, 2^+_{m}, is chosen. Graviton-inspired tensor with minimal coupling to SM particles (4% qq, 96% gg at LO).
- Fraction of qq ($f_{q\bar{q}}$) can be very different with higher-order QCD corrections.
- Instead of assigning systematics, we perform a scan for $f_{q\bar{q}}$ (0%, 25% , 50% , 70%, 100%)

$H \to \gamma\gamma$: Spin/CP

Separate 0^+ and 2^+ spin hypotheses using angular correlation between the two photons ($\cos\theta^*_{cs} = \frac{\sinh(\eta_{\gamma 1} - \eta_{\gamma 2})}{\sqrt{1 + (p^{\gamma\gamma}/m_{\gamma\gamma})^2}} \cdot \frac{2 p_T^{\gamma 1} p_T^{\gamma 2}}{m^2_{\gamma\gamma}}$)



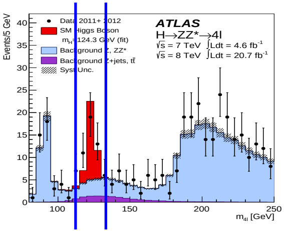


- **Signal region** ($122 < m_{\gamma\gamma} < 130$ GeV): 2-D fit with $m_{\gamma\gamma}$ and $\cos(\theta^*)$
- **Side bands**: 1-D fit with $m_{\gamma\gamma}$

2^+ ($f_{q\bar{q}=0}$) is excluded at 99.3% C.L.

$H \to ZZ^{(*)} \to 4\ell$: Spin/CP

Only select events within $m_{4\ell}$ [115, 130] GeV



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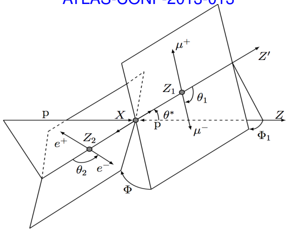

BDT input variables

- Production and decay angles : θ^*, Φ_1, Φ, θ_1, θ_2
- m_{12} (the lepton pair close to Z mass) and m_{34}

- 0^- and 1^+ are excluded above 97.8% C.L.
- 2^+ ($f_{q\bar{q}} \geq 25\%$) : excluded with a C.L. above 96%

Measurements with $H \to WW^{(*)} \to \ell\nu\ell\nu$

- Spin measurement uses **different flavor** channels only.
- BDT method is used. The four variables used for training are m_{ll}, $p_{T,ll}$, $\Delta\phi_{ll}$ and m_T (main analysis is cutting on $\Delta\phi_{ll} < 1.8$)

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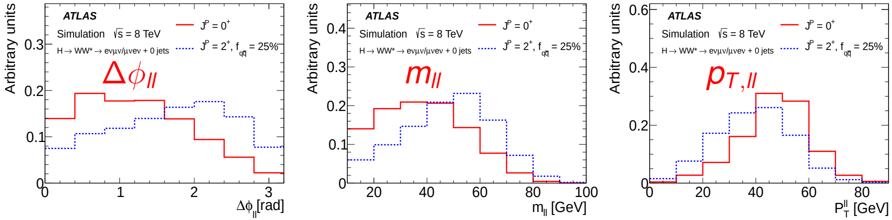


- 1^+ : excluded at 92% C.L.
- 1^- : excluded at 98% C.L.
- 2^+ (all $f_{q\bar{q}}$) : excluded with a C.L. above 95%

Summary for Higgs Spin/CP Measurements

J^P	**Channels**	**Exclusion [C.L.]**
0^-	ZZ	excluded at 97.8%
1^+	ZZ/WW	excluded at 99.9%
1^-	ZZ/WW	excluded at 99.7%
2^+	ZZ/WW/$\gamma\gamma$	excluded $>$ 99%

Conclusion

- Have measured the Higgs properties using full LHC Run I data with ATLAS detector
- All measurements are consistent with SM expectation
- Strong evidence for spin-0 nature of the Higgs boson
- Higgs boson does not universally couple to fermions (which is different from gauge bosons)

Outlook for LHC Run II

Basic facts about Run II

- Time interval between two bunches : 25 ns
- CME of p-p : 13 TeV and 14 TeV
- μ (average interaction per bunch crossing) about 40
- Integrated luminosity : 100 fb^{-1}

Higgs physics priority for Run II

- Fermion coupling
  - ttH (promising)
  - $H \to bb$ (will benefit from the newly installed IBL, but will suffer from higher single lepton trigger threshold)
- Search for a ’second Higgs’ at higher mass
- VBF production
- VBS

backup

Statistical method for spin/parity

Likelihood function for spin/parity measurement

$$\mathcal{L}(J^P, \mu, \theta) = \prod_{j}^{N_{\text{chann.}}} \prod_{i}^{N_{\text{bins}}} P(N_{i,j} \mid \mu_j \cdot S_{i,j}^{(J^P)}(\theta) + B_{i,j}(\theta)) \times \mathcal{A}_j(\theta) \,,$$

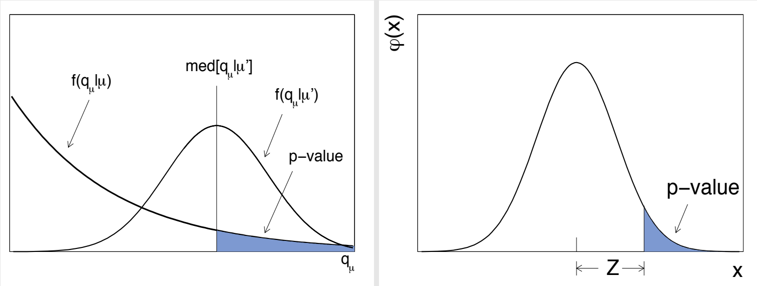
Test statistics : q

$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\text{alt}}, \hat{\hat{\mu}}_{J^P_{\text{alt}}}, \hat{\hat{\theta}}_{J^P_{\text{alt}}})}$$

$CL_s(J^P_{\text{alt}})$

$$\text{CL}_s(J^P_{\text{alt}}) = \frac{p_0(J^P_{\text{alt}})}{1 - p_0(0^+)}$$

p0



(a) **(b)**

$H \to \gamma\gamma$ Spin/CP : $\cos(\theta^*)$

θ^* is defined in Collins-Soper frame : the center of mass frame of di-photon