PROJECT

RESEARCH AREA

Study of the low mass Higgs boson and search for heavy Higgs boson in the WW channel

French Group			Chinese Group		
Leader Zhiqing Zhang	Dr.	LAL	Leader Shenjian Chen	Prof.	Nanjing Univ.
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Observation of the Higgs Boson and Measuremnt of Its Properties in the $H \to WW^* \to l\nu l\nu$ Channel

Couplings/Spin/Width

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[2]Shenjian Chen, NJU(China)

FCPPL 2015

Outline

1. **Introduction**
2. **Higgs Observation** ⇒ ArXiv 1412.2641 (accepted by PRD)
   - Improvements w.r.t Moridon 2013
   - Latest Results
3. **Higgs Spin** ⇒ ArXiv 1503.03643 (submitted to EPJC)
   - Candidate spin models
   - Details of the analysis
   - Exclusion limits
4. **Higgs Off-shell Couplings** ⇒ ArXiv 1503.01060 (submitted to EPJC)
   - High mass region
   - Analysis Overview
   - Upper limits and Higgs width

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Motivation

Higgs Observation

- Higgs discovery in 2012 [1, 2]
  combination of 3 decay channels: WW^*, ZZ^*, and $\gamma\gamma$
- SM Higgs ? $\Rightarrow$ direct observation in individual channels

Property Measurements

- Properties: mass, couplings, spin, CP, width
- Further confirmation of SM Higgs

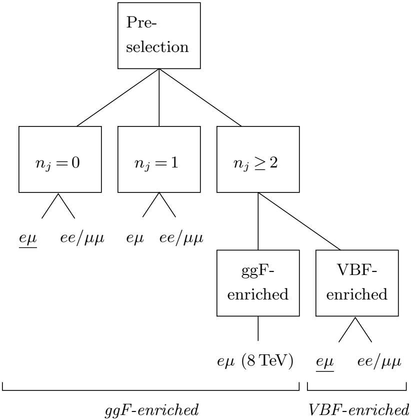
Reminder of the $H \to WW^* \to l\nu l\nu$ Channel

Features

- Large branching ratio
- 2 energetic leptons
- Large missing energy

Event Categorization

- Same/different lepton flavors: SF/DF
- Jet multiplicity: $n_j = 0$, $n_j = 1$, $n_j \geq 2$



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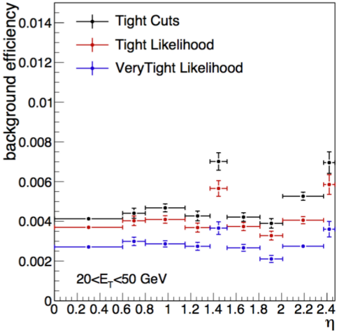
Improved Objects Definition

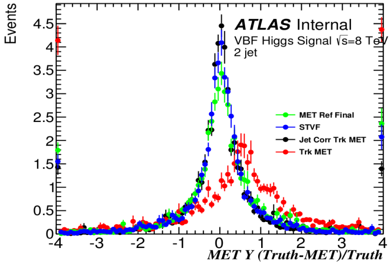
Electron Identification

- Cut-based → Likelihood:
- Same efficiency
- Larger fake rejection

Track-based E_T^{miss}

- Jet energy from calo
- Robust against pile-up
- Better resolution





INCREASED SIGNAL ACCEPTANCE

LOOSENED CUTS

LOWER SUD-LEADING p_T^ℓ

- 15 GeV $\rightarrow$ 10 GeV
- Improved fake suppression in low-p_T region
- Acceptance +75%(50%) in $n_j = 0$ $n_j = 1$

LOWER LEADING p_T^ℓ

- 25 GeV $\rightarrow$ 22 GeV
- Add dilepton trigger
- Final efficiency +~8% in DF

OTHERS

- $m_{\ell\ell}$ upper bound: 50 $\rightarrow$ 55 GeV: +1.5% Z_0
- ggF-enriched $n_j \geq 2$ analysis added: +3.8% Z_0

Overall combined efficiency: 5.3% $\rightarrow$ 10.2%

Reduced Systematics

Methods Improved → Less Uncertainty

Signal

- ggF Jet binning uncertainty: ST-method → JVE method
- 18%→15%, 43→27%, 70%→34% for $n_j = 0$, $n_j = 1$, $n_j \geq 2$

Top Quark

- $n_j = 0$, improved theo. uncert.: 10% → 5%
- $n_j = 1$, improved method: 9.9% → 4.2%

Wjets/dijet

- improved fake factor estimation

Others

- MC → data-driven for $WZ/ZZ/W\gamma^*$: +4.5% Z_0

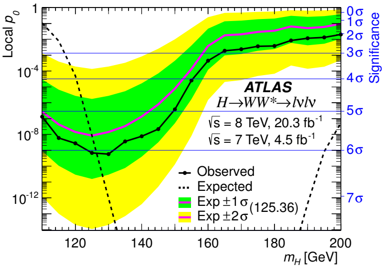
Signal Significances

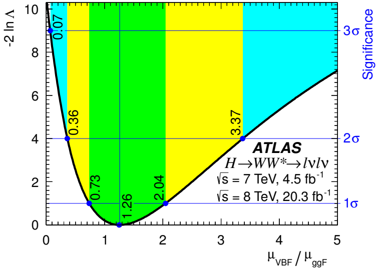
ggF+VBF Signals

- Local p_0 value
- Obs. (exp.) 6.1(5.8) σ
- Moriond: 3.8(3.7) σ

VBF Signal Only

- Likelihood scan
- Obs. (exp.) 3.2(2.7) σ
- Moriond: 2.5(1.6) σ





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Candidate Spin Models

Spin 0

Standard Model

Spin 1

Disfavored

- Observed $H \to \gamma\gamma$ decay (Landau-Yang theorem) [3, 4]
- $>$99% C.L. (previous analysis [5])

Spin 2

Many possibilities $\Rightarrow$ test the simplest in an EFT approach

- Universal couplings, $\kappa_g = \kappa_q$, g (q) for gluon (quark).
- Non-universal, $\kappa_g = 1, \kappa_q = 0$ and $\kappa_g = 0.5, \kappa_q = 1$.
- Each non-universal $\Rightarrow$ Higgs p_T cutoff @125 or 300.

ANALYSIS OVERVIEW

EVENT SELECTION

Follows Higgs Observation

- *Inherited*: high p_T^{ℓ}, large E_T^{miss}, no *b*-jet . . .
- *Loosened*: $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$ . . . (signal topologies)
- *Added*: $p_T^H < 125$ or 300 GeV for non-universals

BACKGROUND (BKG)

- Mainly *WW*, *top*, *Z*jets($Z/\gamma^* \to \tau\tau$), and *W*jets(+dijet)
- Estimated by extrapolation from CRs to SRs

SYSTEMATICS

- Model uncertainties dominate
- BKGs: *WW* ∼3%, *W*jets∼2%, *Z*jets∼1% (limits)

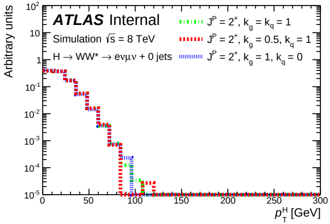
INCLUSION OF 1JET EVENTS

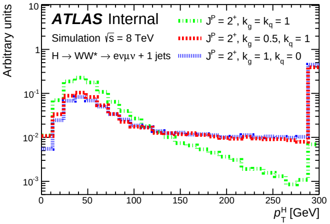
PREVIOUS MEASUREMENT

Only 0jet events with DF used, for they give much more sensitivity to signals than others do

MOTIVATION FOR INCLUDING 1JET EVENTS

- Add more signal sensitivity (naturally)
- Model-dependent Higgs p_T tail only in non-0jet events





ArXiv 1503.03643 Determination of spin and parity of the Higgs boson in the $WW^* \rightarrow e\nu\mu\nu$ decay channel with the ATLAS detector at the LHC.

BDT Technique

Definition

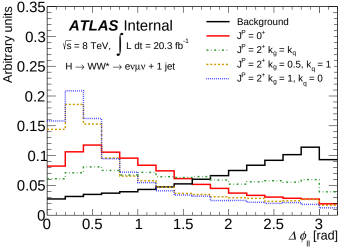
Boosted decision tree $\in$ machine learning: algorithm trained from example inputs to make decision

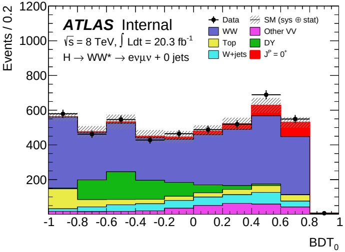
Inputs

- Discriminating power
- $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $p_T^{\ell\ell}$, and m_T

BDTs

- One BDT for one spin model (6)
- High (Low) score $\rightarrow$ signal(BKG)-like





ArXiv 1503.03643

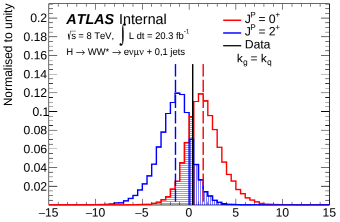
Exclusion Limits

Statistical Test

- Test $q = \ln \frac{\mathcal{L}_{\text{Spin0}}}{\mathcal{L}_{\text{Spin2}}}$, positive (negative) $q \rightarrow$ Spin-0(2)
- 5 spin-2 models $\rightarrow$ 5 tests

Exclusion Limits

- CLs estimator CLs = $\frac{p_{\text{Spin2}}}{1-p_{\text{Spin0}}}$ $\rightarrow$ exclusion C.L. = 1 - CLs
- $p_{\text{Spin0}}(p_{\text{Spin2}})$ = $A_{\text{Red}}(A_{\text{Blue}})$, area left (right) to the black line



ArXiv 1503.03643

Spin-2 Models	1-CLs(%)
$\kappa_g = \kappa_q$	84.5
$\kappa_g = 0.5, \kappa_q = 1, p_T^H < 125$	97.8
$\kappa_g = 0.5, \kappa_q = 1, p_T^H < 300$	99.3
$\kappa_g = 1, \kappa_q = 0, p_T^H < 125$	92.5
$\kappa_g = 1, \kappa_q = 0, p_T^H < 300$	99.4

Outline

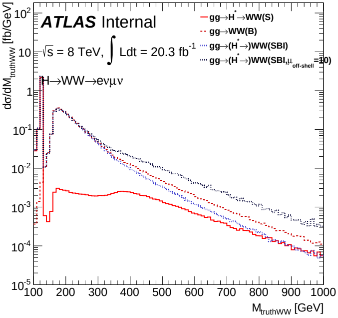
High Mass Region

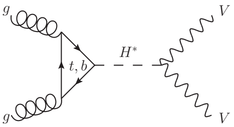
Off-shell Higgs

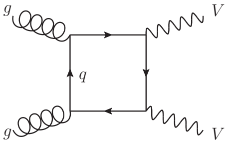
Enhanced xsection after $2m_W(2m_{\text{top}}) \rightarrow$ off-shell measurement

Non-resonant *WW* and Interference

gg(VBF) *WW* $\rightarrow$ negative interfere with *ggF*(VBF) Higgs





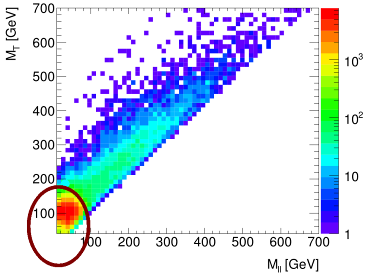


Analysis Overview

Event Selection

Guiding principle: inclusive k-factor $\rightarrow$ inclusive in terms of N_{jet}

- *Inherited*: high p_T^{ℓ}, large E_T^{miss}, no b-jet ...
- *Added*: $\Delta\eta_{\ell\ell} < 1.2$, $R_8 = \sqrt{m_{\ell\ell}^2 + 0.8 \times m_T^2} > 450\,\mathrm{GeV}$ (Opt.)



Backgrounds

Top and WW $\rightarrow$ control regions

Systematics

Mainly on modelling of gg S/B/I

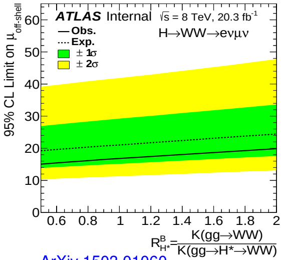
- PDF (20%) and QCD (20%)
- Additional QCD on B and I
- Higgs p_T ...

Upper Limits on Off-shell Couplings

CLs estimator

- Two interpretations: $\mu^{gg}_{\mathrm{off-shell}} = \mu^{\mathrm{VBF}}_{\mathrm{off-shell}}$ and $\mu^{\mathrm{VBF}}_{\mathrm{off-shell}} = 1$
- Scan K^B_{H*} over $[0.5, 2]$ $\rightarrow$ cover possible bias

K^B_{H*}	Obs. Limit			Exp. Limit		
	0.5	**1.0**	2.0	0.5	**1.0**	2.0
$\mu_{\mathrm{off-shell}}$	15.6	**17.2**	20.3	19.6	$\mathbf{21.3}^{+8.6}_{-5.6}$	24.7
$\mu^{gg}_{\mathrm{off-shell}}(\mu^{\mathrm{VBF}}_{\mathrm{off-shell}} = 1)$	18.9	**21.5**	26.2	24.4	$\mathbf{27.2}^{+11.6}_{-7.8}$	32.4



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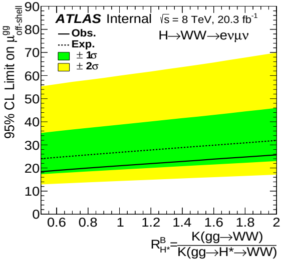


Higgs Width

Methodology

Take *ggH* as example (VBF Higgs similar)

On-shell Xsection

$$\mu^{gg}_{\mathrm{on-shell}} = \frac{\kappa^2_{\mathrm{ggH}} \cdot \kappa^2_{\mathrm{HWW}}}{\Gamma_H/\Gamma_H^{\mathrm{SM}}}$$

Off-shell Xsection

$$\mu^{gg}_{\mathrm{off-shell}} = \kappa^2_{\mathrm{ggH}} \cdot \kappa^2_{\mathrm{HWW}}$$

$R \equiv \Gamma_H/\Gamma_H^{\mathrm{SM}}$: measured width normalized to SM width
$R = \mu^{gg}_{\mathrm{off-shell}}/\mu^{gg}_{\mathrm{on-shell}}$, assuming $\kappa_{\mathrm{on-shell}} = \kappa_{\mathrm{off-shell}}$

$\Rightarrow$ Upper limits on Higgs width: $\sim 20 \times \Gamma_H^{\mathrm{SM}}$, 2 orders of magnitude smaller than direct measurement using ZZ^* and $\gamma\gamma$

SUMMARY

Summary

- Higgs observed alone in $H \to WW^* \to l\nu l\nu$ channel. Evidence for VBF mode also established
- Data supports spin-0 Higgs over spin-2 hypotheses
- Upper limits of Higgs width set to be $\sim 20 \times \Gamma_H^{\mathrm{SM}}$

Future project(RUN II)

- Research interest will shift to high mass Higgs search

French Group			Chinese Group		
Leader Zhiqing Zhang	Dr.	LAL	Leader Shenjian Chen	Prof.	Nanjing Univ.
Yichen Li PhD. LAL-Nanjing Univ.					
Yongke Zhao	PhD	Shandong Univ. London	Lianliang Ma	Prof.	Shandong Univ.
David Rousseau	Dr.	LAL	Yingchun Zhu	Assoc. Prof.	USTC

ATLAS Collaboration
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *arXiv 1207.7214* 2012.

CMS Collaboration
Observation of a new boson at a mass of 125 GeV with theCMS experiment at the LHC. *arXiv 1207.7235* 2012.

Landau, L.D.
On the angular momentum of a two-photon system. *Dokl.Akad.Nauk Ser.Fiz.* **60** (1948) 207-209.

Yang, C.N.
Selection Rules for the Dematerialization of a Particle into Two Photons. *Phys. Rev.* **77** (1950) 242-245.

ATLAS Collaboration
Evidence for the spin-0 nature of the Higgs boson using ATLAS data. *arXiv 1307.1432* 2013.

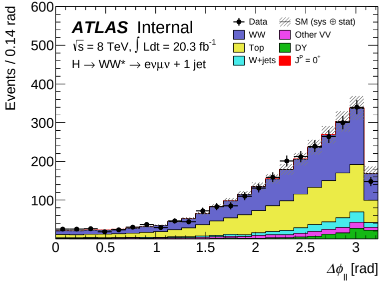
Top Background in 1jet Events

Estimation

- Control region: $N_{bjet} \neq 0$
- Extrapolation: $N^{i}_{top} = N^{CR}_{top} \times \alpha_{i}$
  i = SR or WWCR

Systematics

- Stat.: data population, $\sqrt{N^{CR}_{top}}$
- Exp.: *b*-tagging uncertainty
- Theo.: generator/UEPS, PDF



Sources	SR(%)	WWCR(%)
QCD scale	0.8	0.6
PDF	1.4	0.3
Generator	1.9	2.4
UEPS	2.4	2.0
Total	3.5	3.2

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gg S/B/I QCD SYSTEMATICS

NORMALIZATION

- S/B/I share same k^{H^*} $\rightarrow$ QCD correction (20%)
- only *gg* induced part $k_{\mathrm{gg}}^{H^*}$ applied to B/I ($[-11.8\%, 15.9\%]$)
- Bias of applying k^{H^*} to B/I $\rightarrow K_{H*}^{B} = \frac{k^B}{k_{\mathrm{gg}}^{H*}} \in [0.5, 2]$ (next page)
- Ansatz of interference uncertainty (30%)

SHAPE

- p_T^H reweighting: MCFM(LO) $\rightarrow$ Sherpa(NLO)
- *max*(QCD variation, 50% $\times$ *diff*(MCFM, Sherpa)) $\leq$ 2%