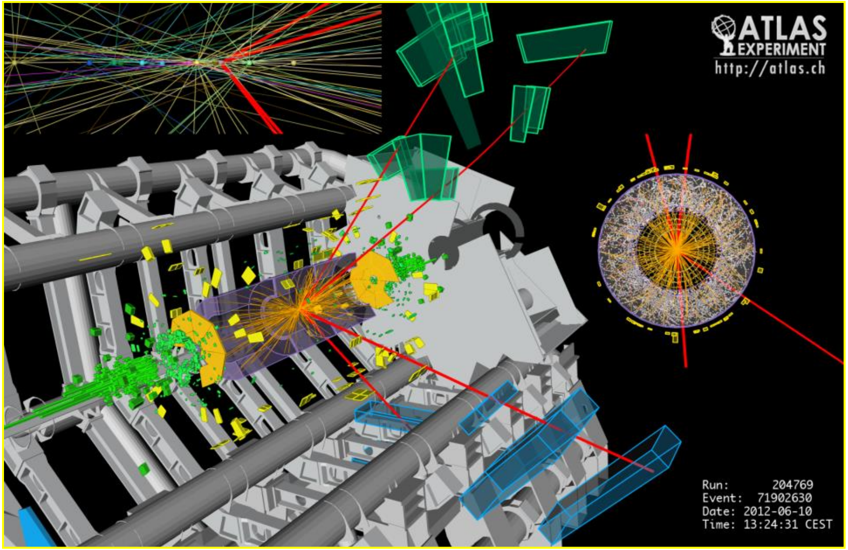
Properties Measurement of H→ZZ*→4l with the ATLAS Detector



Haijun Yang (SJTU)

The First China LHC Physics Workshop

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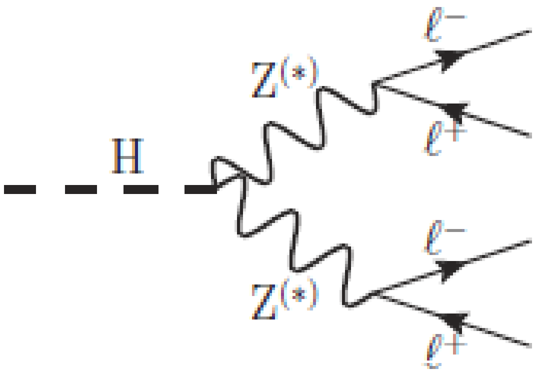
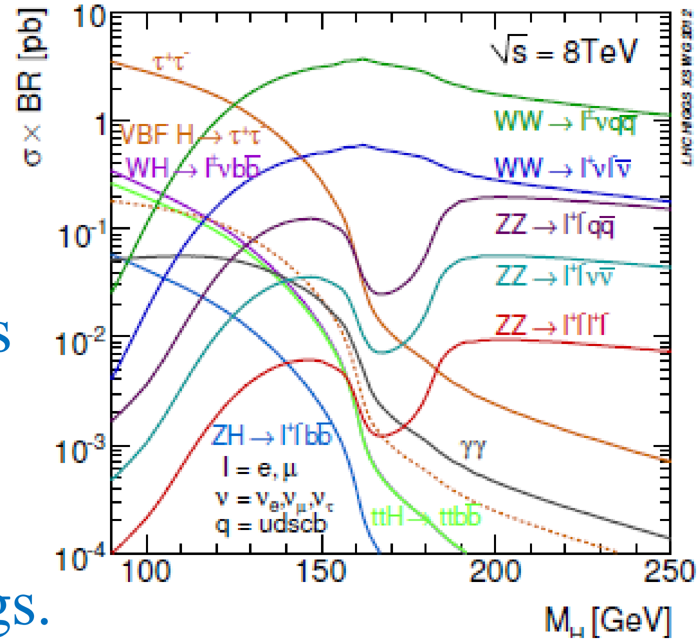
Higgs → ZZ* → 4ℓ Analysis

- ❑ Extremely clean – "Gold-plated" channel
  - o Fully reconstructed final states
  - o Good mass resolution (~ 1.6-2.4 GeV)
  - o High S/B ratio (~ 1.5)
  - o Low decay branching fraction



- ❑ Currently statistically limited
  - o 4.5 fb^{-1} @ 7 TeV + 20.3 fb^{-1} @ 8 TeV
  - o Expect 68 SM H→ZZ*→4ℓ (e,μ) events



- ❑ Properties measurement
  - o Higgs mass, width, spin, parity, couplings.
  - o Critical to determine whether it is fully compatible with the SM Higgs boson

Higgs → ZZ* → 4ℓ Selections

- Trigger match with single and/or di-lepton trigger
- **Four sub-channels: 4e, 2e2μ, 2μ2e, 4μ**

Event Pre-selection	
Electrons	
"MultiLepton" quality GSF electrons with $E_T > 7$ GeV and $\lvert\eta\rvert < 2.47$	
Muons	
combined or segment-tagged muons with $p_T > 6$ GeV and $\lvert\eta\rvert < 2.7$	
Maximum one calo-tagged or standalone muon	
calo-tagged muons with $p_T > 15$ GeV and $\lvert\eta\rvert < 0.1$	
standalone muons with $p_T > 6$ GeV, $2.5 < \lvert\eta\rvert < 2.7$ and $\Delta R > 0.2$ from closest segment-tagged	
Event Selection	
Kinematic Selection	Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-charge leptons fulfilling the following requirements:
	p_T thresholds for three leading leptons in the quadruplet 20, 15 and 10 GeV
	Leading di-lepton mass requirement 50 GeV $< m_{12} <$ 106 GeV
	Sub-leading di-lepton mass requirement $m_{threshold} < m_{34} <$ 115 GeV
	Remove quadruplet if alternative same-flavour opposite-charge di-lepton gives $m_{\ell\ell} < 5$ GeV
	$\Delta R(\ell,\ell') > 0.10(0.20)$ for all same (different) flavour leptons in the quadruplet.
Isolation	Lepton track isolation ($\Delta R = 0.20$): $\Sigma p_T/p_T < 0.15$
	Electron calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T/E_T < 0.20$
	Muon calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T/E_T < 0.30$
	Stand-Alone muons calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T/E_T < 0.15$
Impact Parameter Significance	Apply impact parameter significance cut to all leptons of the quadruplet.
	For electrons : $d_0/\sigma_{d_0} < 6.5$
	For muons : $d_0/\sigma_{d_0} < 3.5$

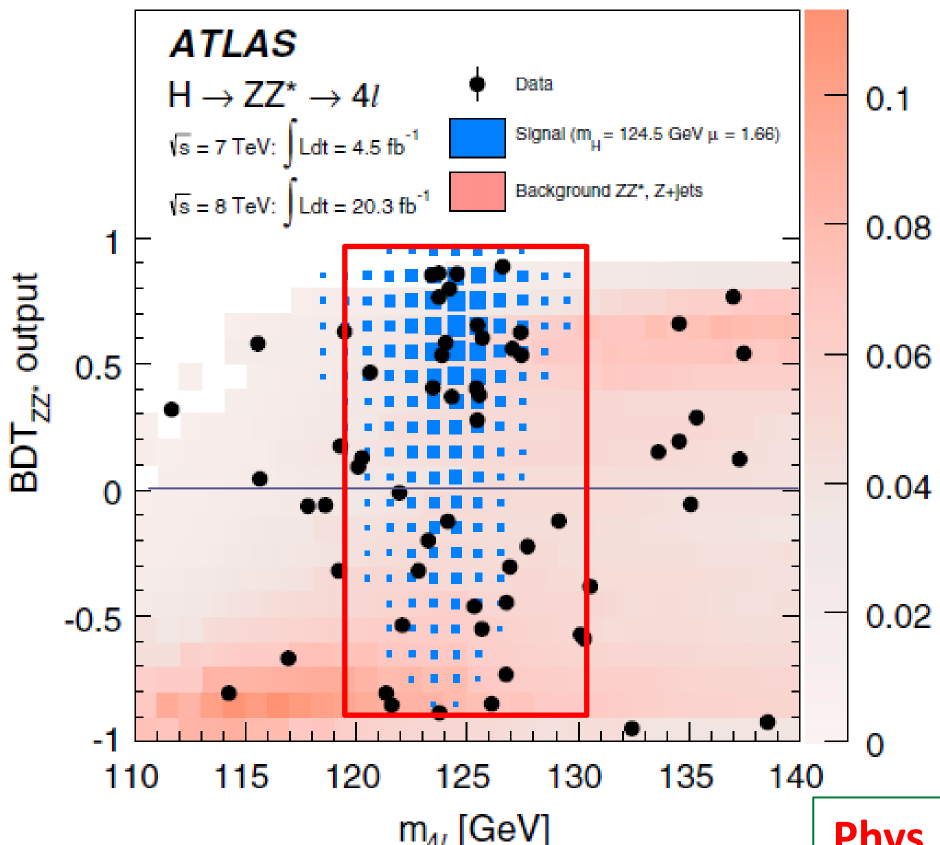
Higgs → ZZ* → 4ℓ Events

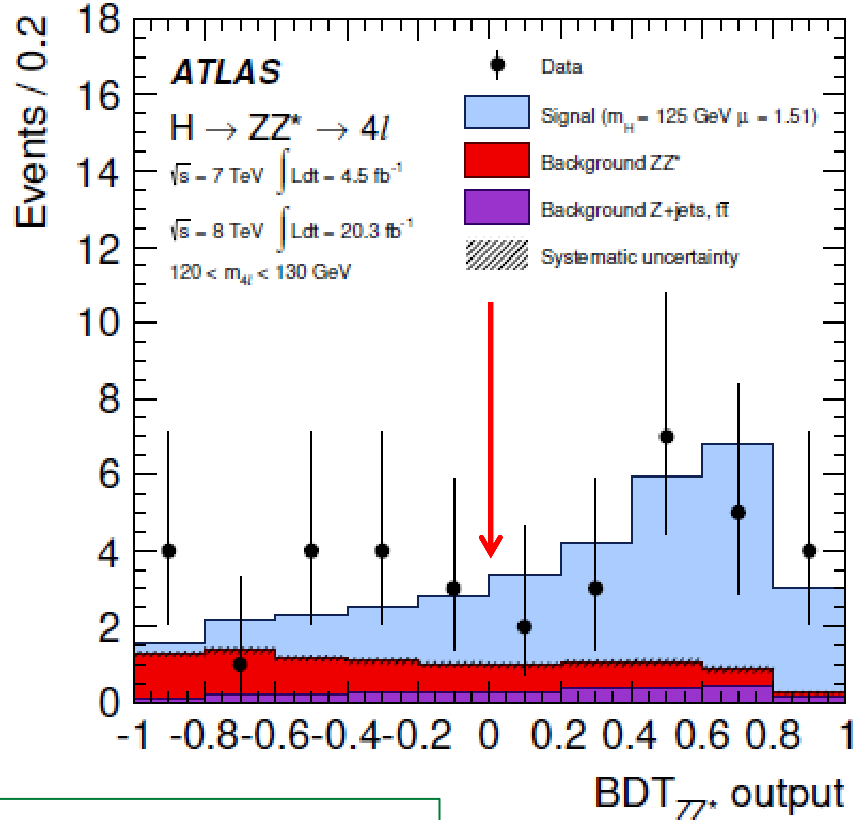
TABLE XI. The number of events expected and observed for a $m_H = 125$ GeV hypothesis for the four-lepton final states in a window of $120 < m_{4\ell} < 130$ GeV. The second column shows the number of expected signal events for the full mass range, without a selection on $m_{4\ell}$. The other columns show for the 120–130 GeV mass range the number of expected signal events, the number of expected ZZ^* and reducible background events, and the signal-to-background ratio (S/B), together with the number of observed events, for 4.5 fb^{-1} at $\sqrt{s} = 7$ TeV and 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV as well as for the combined sample.

Final state	Signal full mass range	Signal	ZZ^*	Z + jets, $t\bar{t}$	S/B	Expected	Observed
			$\sqrt{s} = 7$ TeV				
4μ	1.00 ± 0.10	0.91 ± 0.09	0.46 ± 0.02	0.10 ± 0.04	1.7	1.47 ± 0.10	2
$2e2\mu$	0.66 ± 0.06	0.58 ± 0.06	0.32 ± 0.02	0.09 ± 0.03	1.5	0.99 ± 0.07	2
$2\mu2e$	0.50 ± 0.05	0.44 ± 0.04	0.21 ± 0.01	0.36 ± 0.08	0.8	1.01 ± 0.09	1
$4e$	0.46 ± 0.05	0.39 ± 0.04	0.19 ± 0.01	0.40 ± 0.09	0.7	0.98 ± 0.10	1
Total	2.62 ± 0.26	2.32 ± 0.23	1.17 ± 0.06	0.96 ± 0.18	1.1	4.45 ± 0.30	6
			$\sqrt{s} = 8$ TeV				
4μ	5.80 ± 0.57	5.28 ± 0.52	2.36 ± 0.12	0.69 ± 0.13	1.7	8.33 ± 0.6	12
$2e2\mu$	3.92 ± 0.39	3.45 ± 0.34	1.67 ± 0.08	0.60 ± 0.10	1.5	5.72 ± 0.37	7
$2\mu2e$	3.06 ± 0.31	2.71 ± 0.28	1.17 ± 0.07	0.36 ± 0.08	1.8	4.23 ± 0.30	5
$4e$	2.79 ± 0.29	2.38 ± 0.25	1.03 ± 0.07	0.35 ± 0.07	1.7	3.77 ± 0.27	7
Total	15.6 ± 1.6	13.8 ± 1.4	6.24 ± 0.34	2.00 ± 0.28	1.7	22.1 ± 1.5	31
			$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV				
4μ	6.80 ± 0.67	6.20 ± 0.61	2.82 ± 0.14	0.79 ± 0.13	1.7	9.81 ± 0.64	14
$2e2\mu$	4.58 ± 0.45	4.04 ± 0.40	1.99 ± 0.10	0.69 ± 0.11	1.5	6.72 ± 0.42	9
$2\mu2e$	3.56 ± 0.36	3.15 ± 0.32	1.38 ± 0.08	0.72 ± 0.12	1.5	5.24 ± 0.35	6
$4e$	3.25 ± 0.34	2.77 ± 0.29	1.22 ± 0.08	0.76 ± 0.11	1.4	4.75 ± 0.32	8
Total	18.2 ± 1.8	16.2 ± 1.6	7.41 ± 0.40	2.95 ± 0.33	1.6	26.5 ± 1.7	37

Higgs → ZZ* → 4ℓ

- Very clean signature, with fully Higgs mass reconstruction
- BR(H→ZZ*) = 2.63%, BR(ZZ*→4l, e or μ)=0.45%
- About 68 H→ ZZ*→4l events produced
- Observed 37 candidates with 18 Higgs → ZZ* → 4l signal



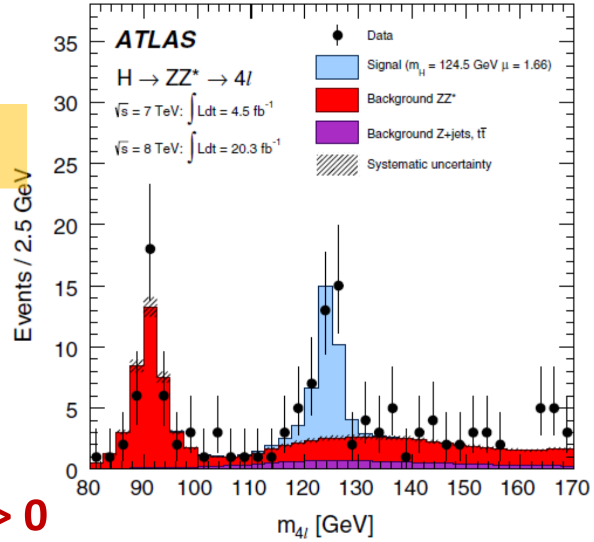


Phys. Rev. D91, 012006 (2015)

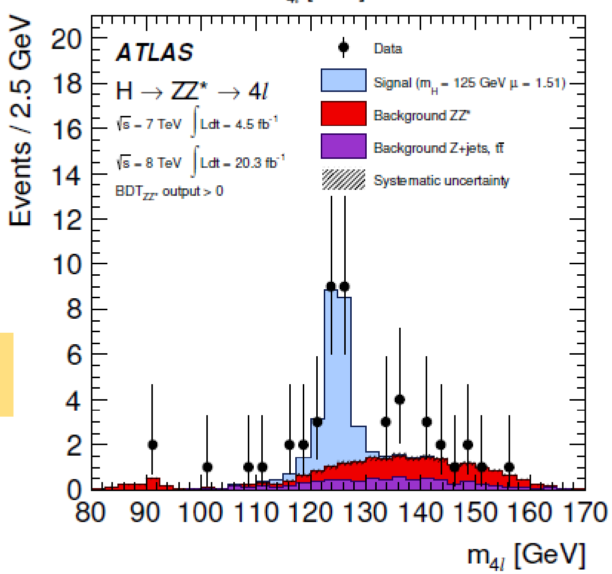
Higgs → ZZ* → 4ℓ

→BDT_{ZZ} helps to increase the Higgs detection sensitivity.

6.6σ



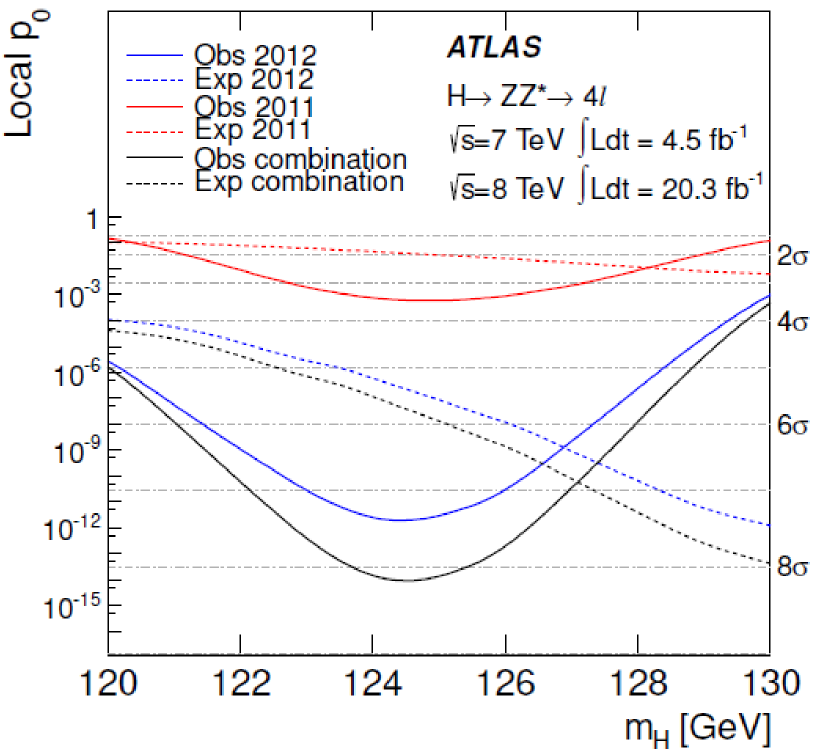
$BDT_{ZZ} > 0$



8.1σ

Expected significances are 6.2σ

Observed significances are 8.1σ



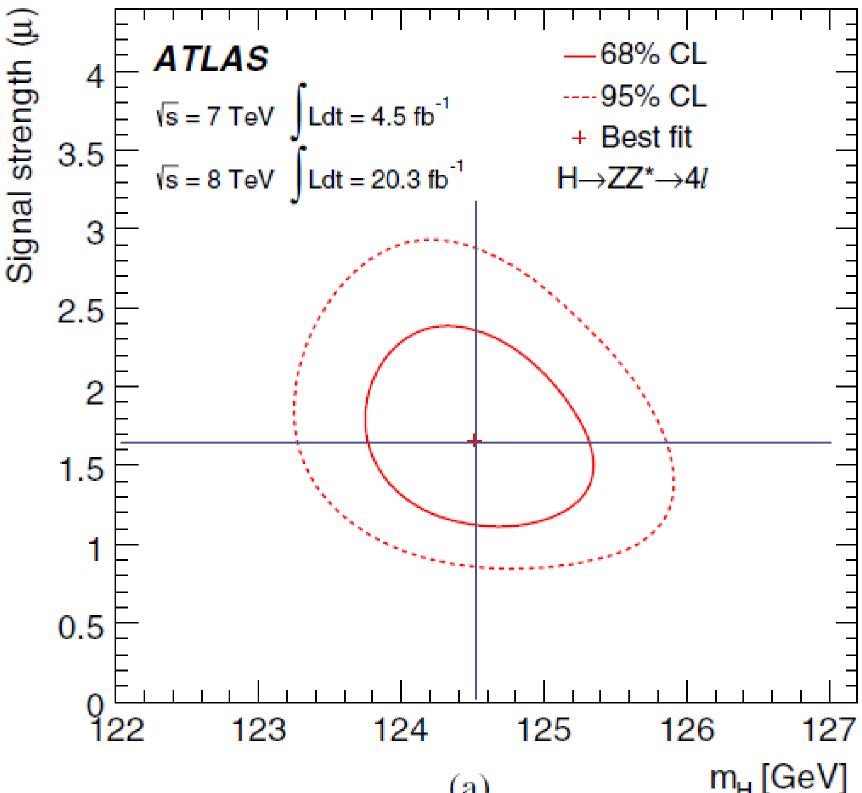
Phys. Rev. D91, 012006 (2015)

Higgs Mass vs Signal Strength

ATLAS H→ZZ*→4ℓ only

$$m_H = 124.51 \pm 0.52 \text{ GeV}$$

$$\mu = 1.66^{+0.39}_{-0.34}\,(\text{stat})\,^{+0.21}_{-0.14}\,(\text{syst})$$

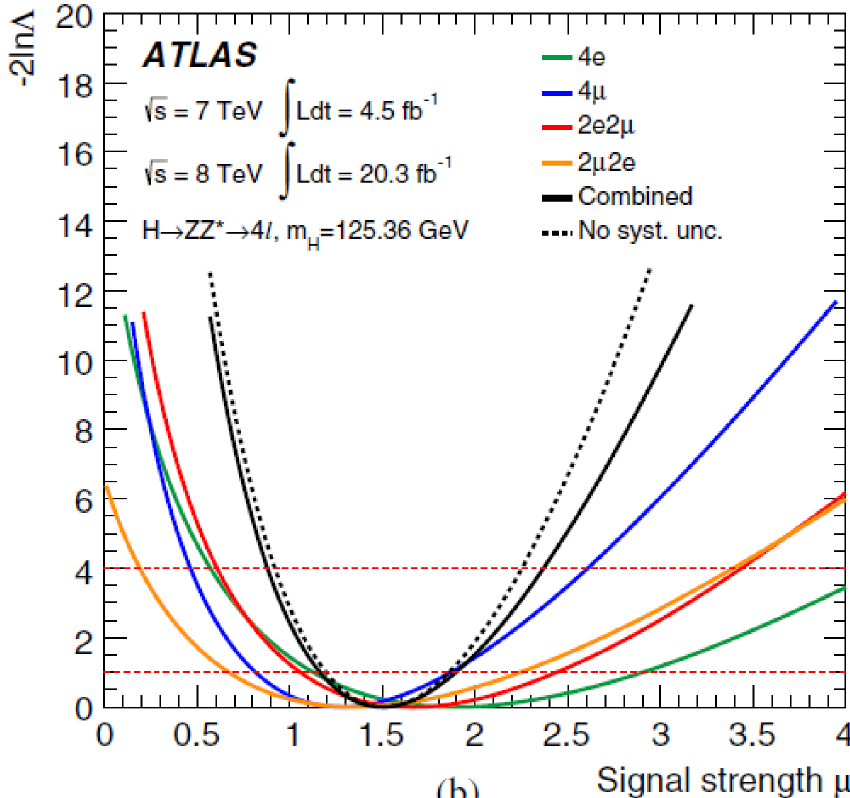


(a)

ATLAS Combined mass

$$m_H = 125.36 \text{ GeV}$$

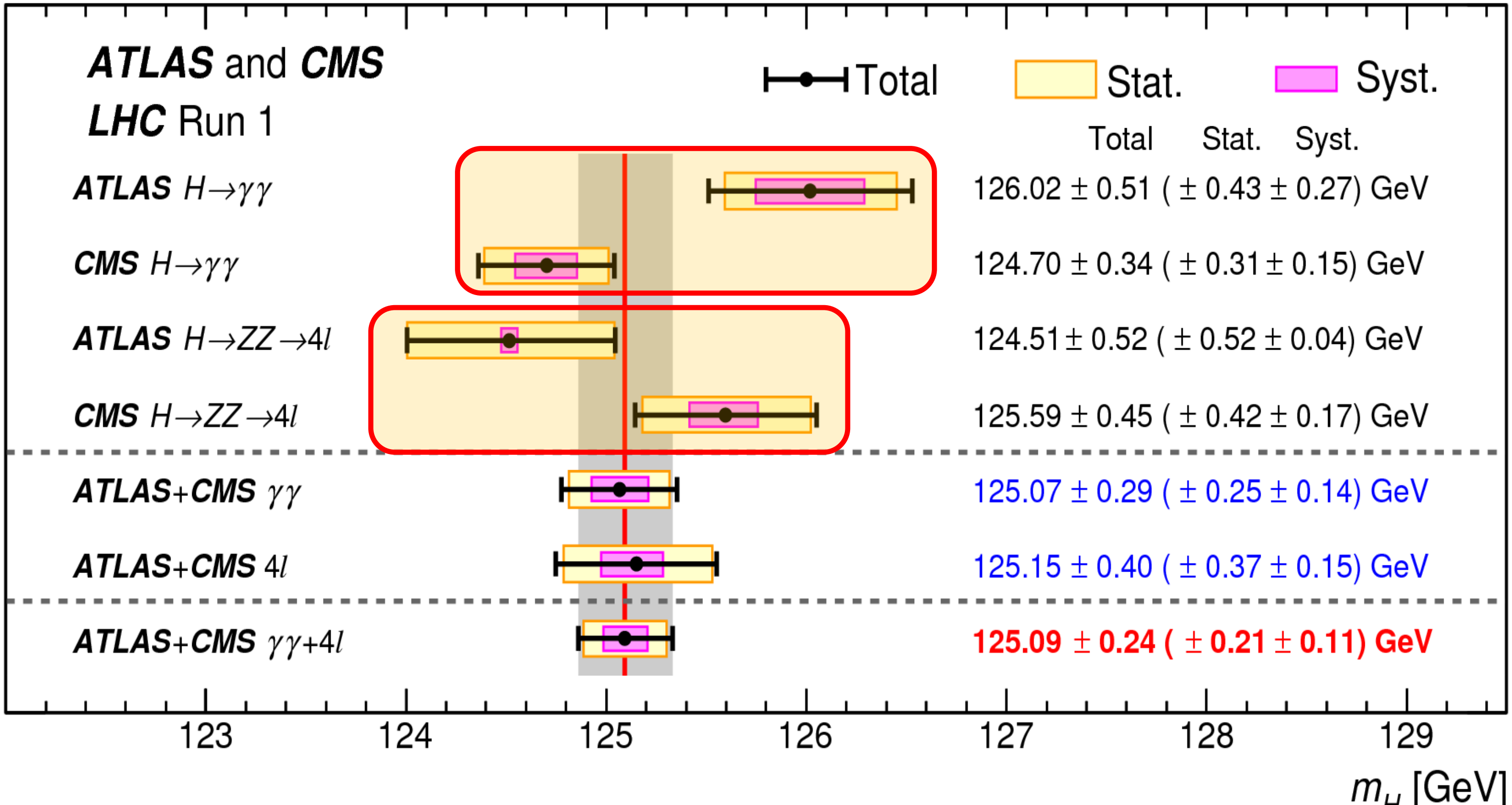
$$\mu = 1.50^{+0.35}_{-0.31}\,(\text{stat})\,^{+0.19}_{-0.13}\,(\text{syst})$$



(b)

Combined Higgs Mass

Higgs mass precision is better than 0.2%.

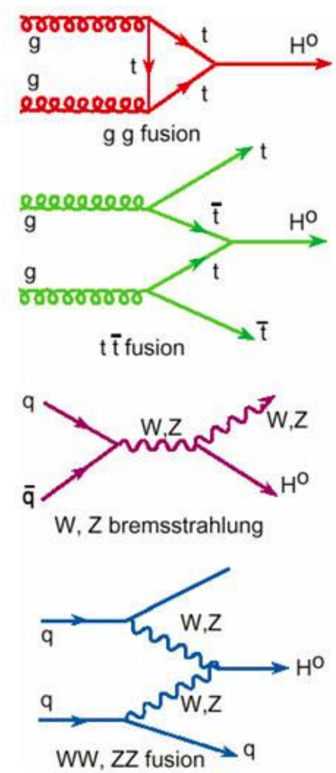


Some tension between the four measurements (p-value ~10%) and opposite in ATLAS and CMS - very good agreement in the central values

ATLAS+CMS: PRL 114 (2015) 191803

Probing Higgs Productions

- using BDT to identify VBF/VH/ggF Higgs
  - M_{jj}, η_{jj} , $\eta_{\text{leading jet}}$, Jet p_T

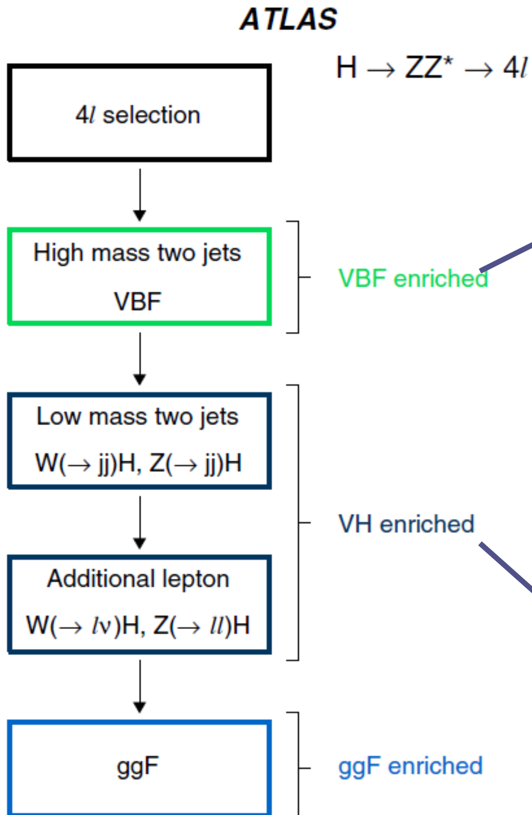


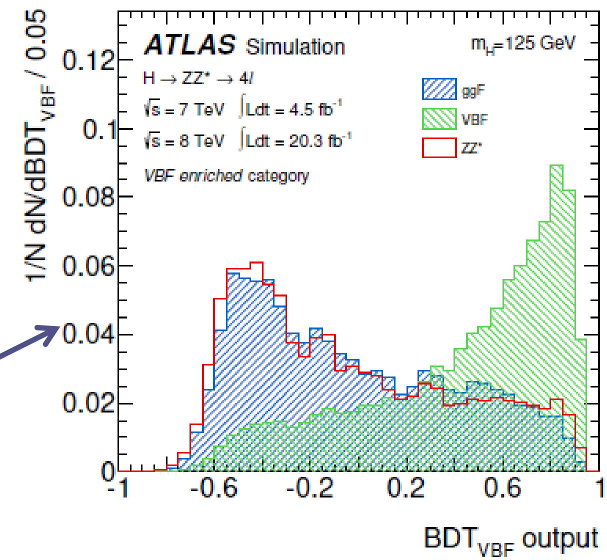
87%

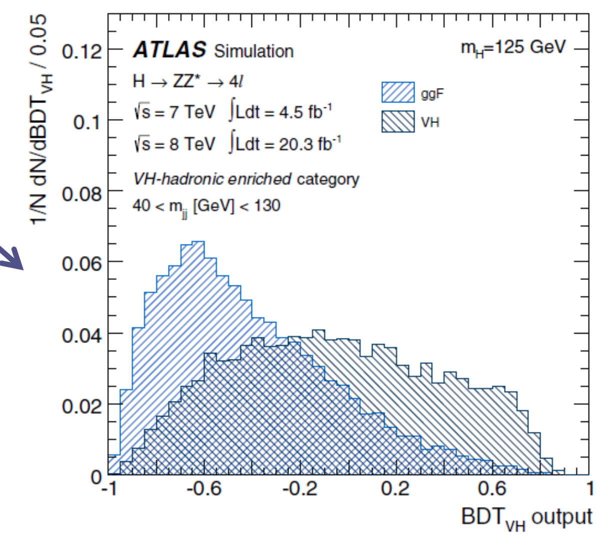
0.5%

5%

7%







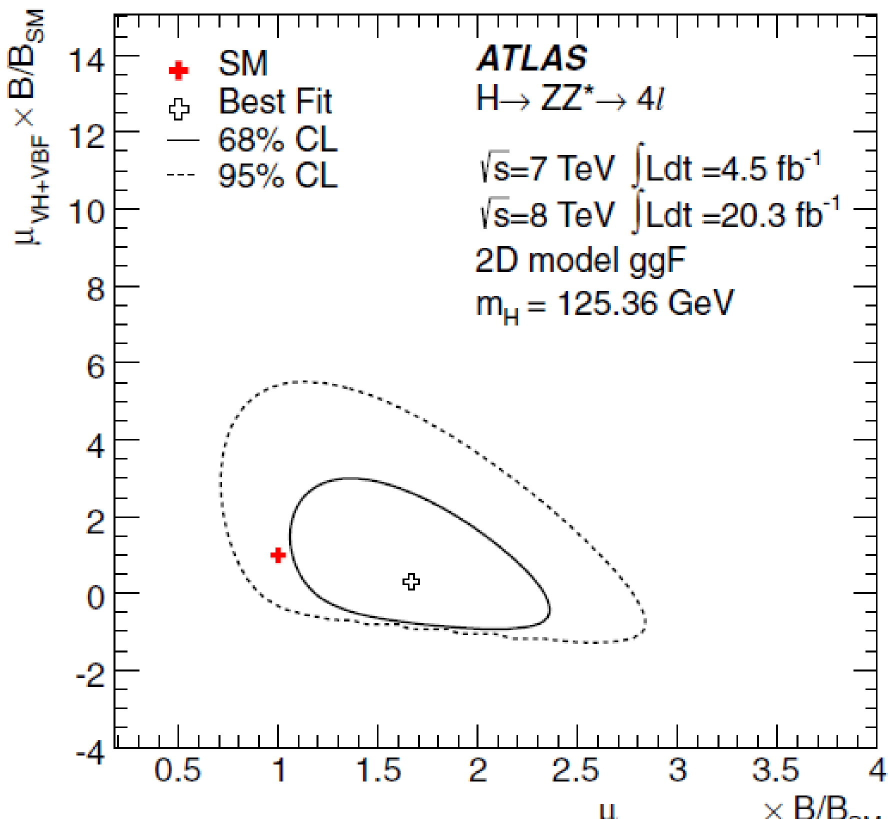
Enriched category	Signal: $ggF + b\bar{b}H + t\bar{t}H$	Signal: VBF	Signal: VH-hadronic	Signal: VH-leptonic	Background: ZZ^*	Background: $Z+\text{jets}, t\bar{t}$	Total expected	Observed
				$120 < m_{4\ell} < 130$ GeV				
VBF	1.18 ± 0.37	0.75 ± 0.04	0.083 ± 0.006	0.013 ± 0.001	0.17 ± 0.03	0.25 ± 0.14	2.4 ± 0.4	3
($BDT_{VBF} > 0$)	0.48 ± 0.15	0.62 ± 0.04	0.023 ± 0.002	0.004 ± 0.001	0.06 ± 0.01	0.10 ± 0.05	1.26 ± 0.15	1
VH-hadronic	0.40 ± 0.12	0.034 ± 0.004	0.20 ± 0.01	0.009 ± 0.001	0.09 ± 0.01	0.09 ± 0.04	0.80 ± 0.12	0
VH-leptonic	0.013 ± 0.002	< 0.001	< 0.001	0.069 ± 0.004	0.015 ± 0.002	0.016 ± 0.019	0.11 ± 0.02	0
ggF	12.8 ± 1.3	0.57 ± 0.02	0.24 ± 0.01	0.11 ± 0.01	7.1 ± 0.2	2.7 ± 0.4	23.5 ± 1.4	34

Phys. Rev. D91, 012006 (2015)

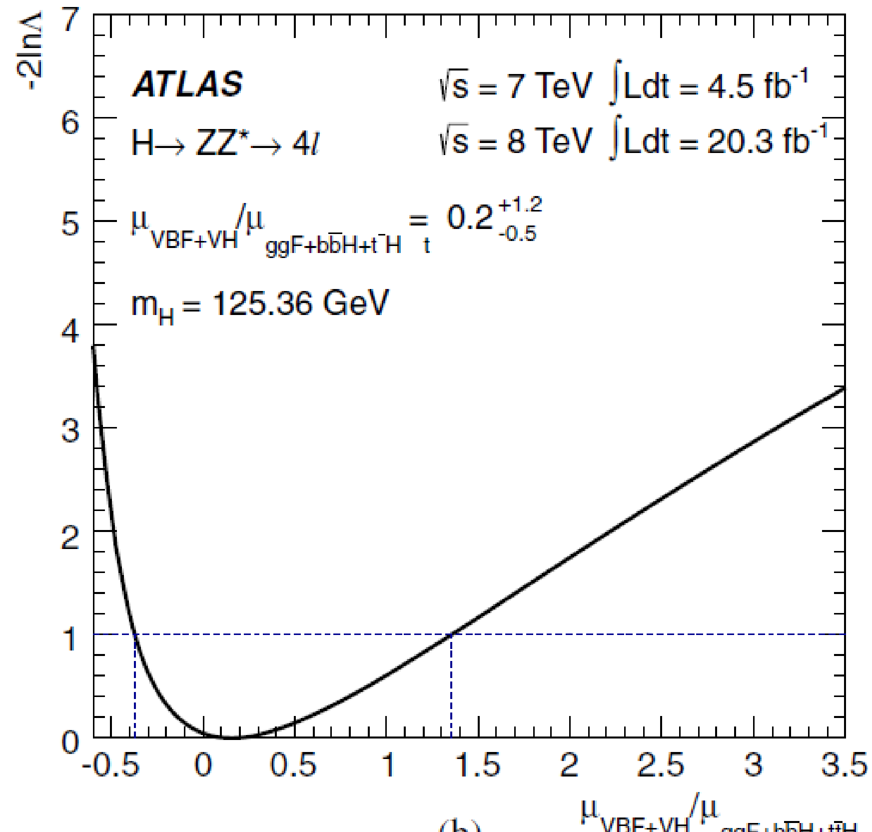
Probing Higgs Productions

$$\mu_{\mathrm{ggF}+b\bar{b}H+t\bar{t}H} \times B/B_{\mathrm{SM}} = 1.66\,^{+0.45}_{-0.41}(\mathrm{stat})^{+0.25}_{-0.15}(\mathrm{syst})$$

$$\mu_{\mathrm{VBF+VH}} \times B/B_{\mathrm{SM}} = 0.26\,^{+1.60}_{-0.91}(\mathrm{stat})^{+0.36}_{-0.23}(\mathrm{syst})$$



(a)

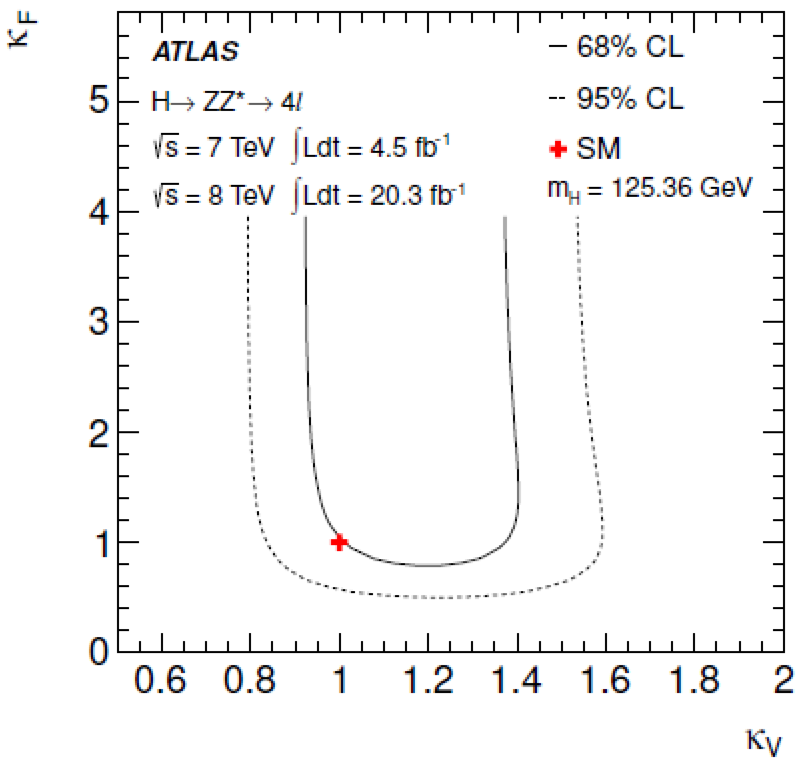


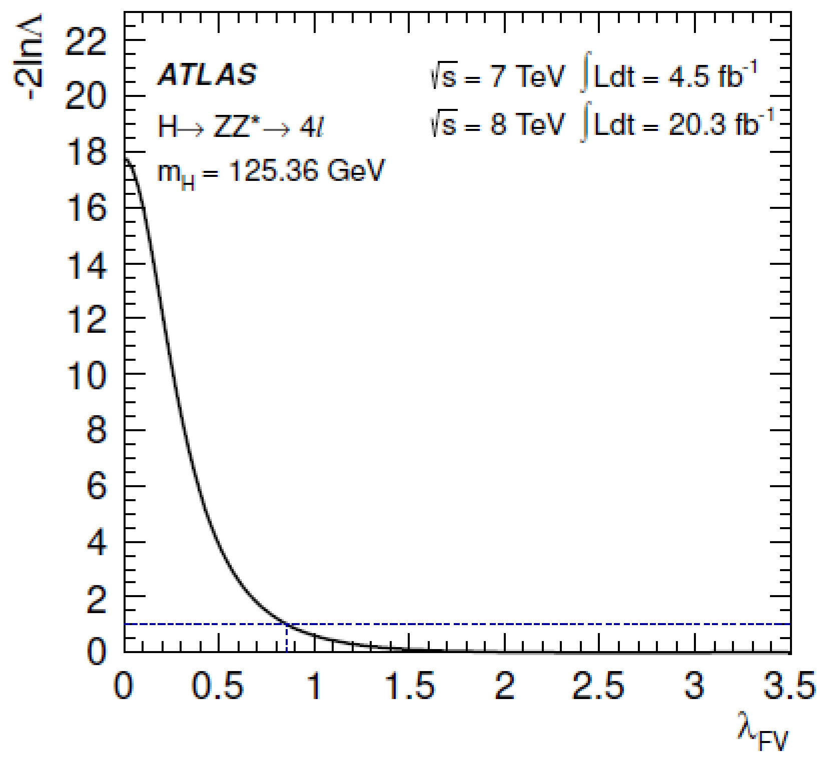
(b)

Phys. Rev. D91, 012006 (2015)

Fermion vs Boson Couplings

- The likelihood scan as a function of the ratio of fermion to vector-boson coupling scale factors, $\lambda_{FV} = \kappa_F / \kappa_V$



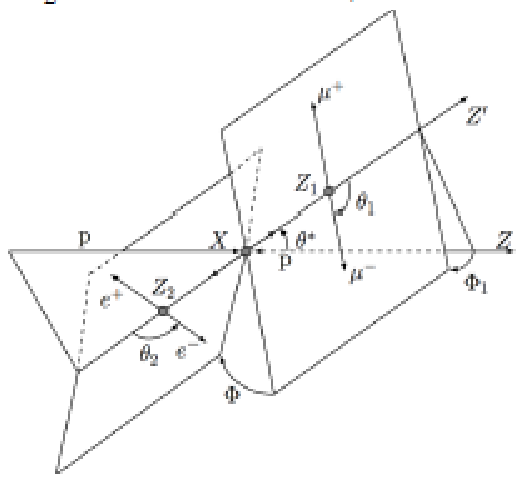


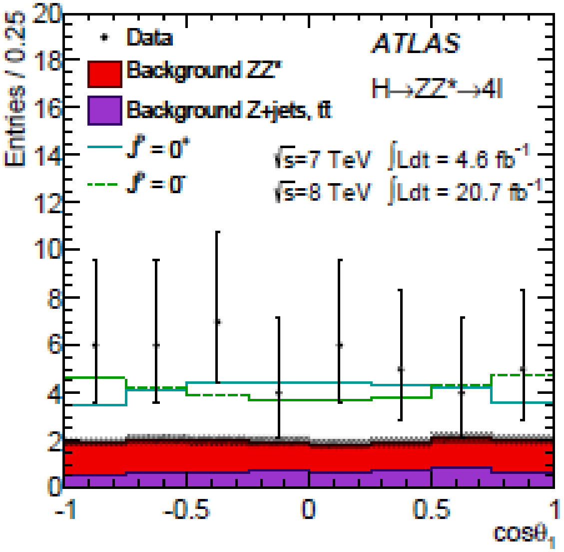
- **The value of $\lambda_{FV} = 0$ is disfavored at the 4σ level.**

Phys. Rev. D91, 012006 (2015)

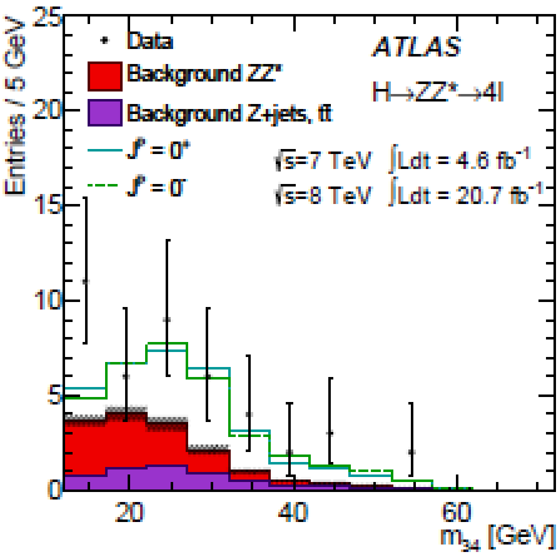
Higgs Spin and Parity

- In $X \to ZZ^{(*)} \to 4\ell$ decays, m_{Z_1}, m_{Z_2} and the production and decay angles are sensitive to $\{m_{4l}, m_{Z_1}, m_{Z_2}, \cos\theta_1, \cos\theta_2, \phi, \cos\theta^*, \phi_1\}$

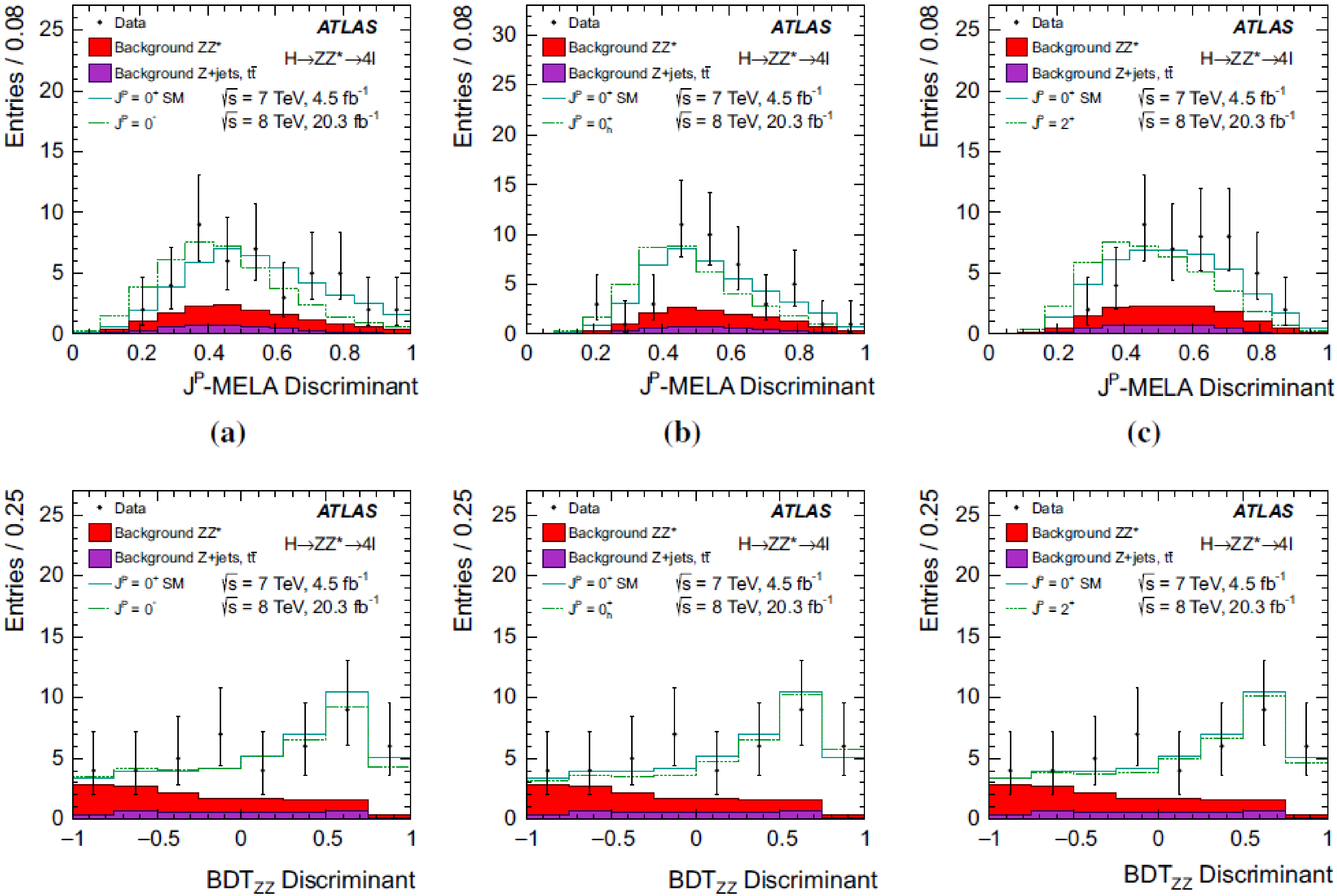




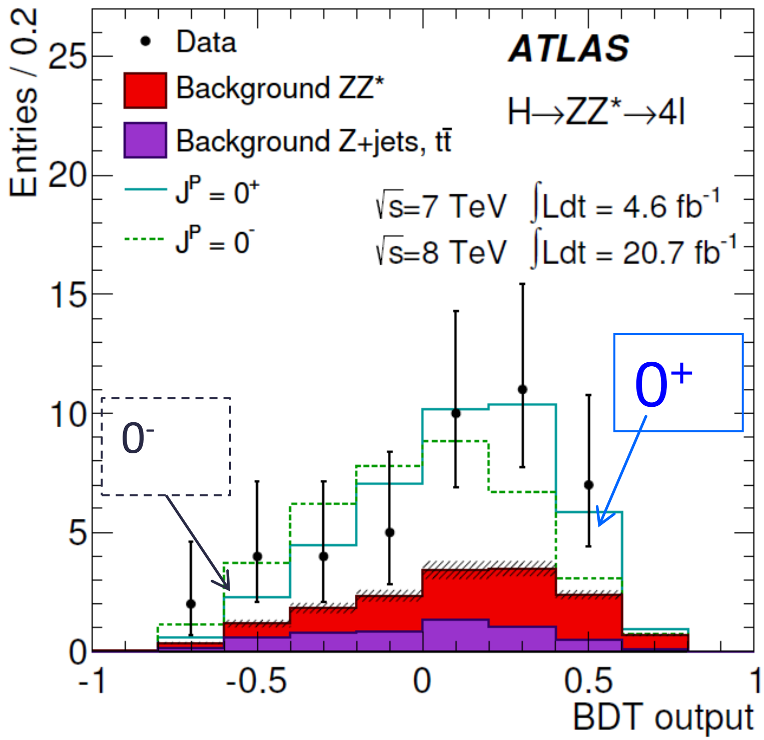
- Construct a discriminant between different hypotheses using two different multivariate techniques:
  - BDT (machine learning)
  - J^P-MELA (use theoretical differential decay rates to construct a matrix element based likelihood ratio)
- Use events in range $115 < m_{4\ell} < 130$ GeV
- Test SM 0^+ hypothesis against alternative hypotheses 0^-, 1^+, 1^-, 2^+_m

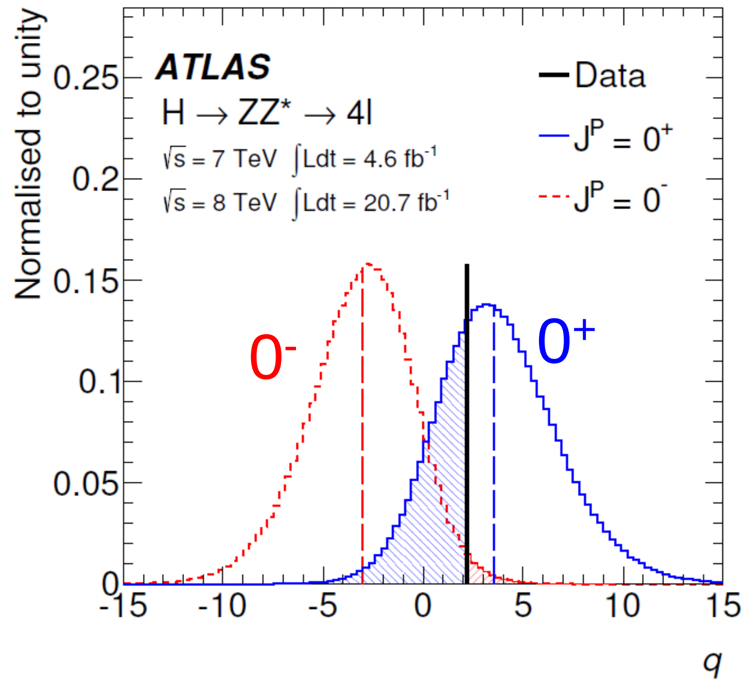


Higgs Spin and Parity



Higgs Spin and Parity





		BDT analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022
1^+	p_0	0.0016	0.001	0.55	0.002
1^-	p_0	0.0038	0.051	0.15	0.060
2^+_m	p_0	0.092	0.079	0.53	0.168
2^-	p_0	0.0053	0.25	0.034	0.258

BDT analysis variables:

m_{Z1}, m_{Z2} from Higgs --> ZZ* →4l
+ production and decay angles

Exclusion (1-CL_s):

Observed 0^- exclusion 97.8%

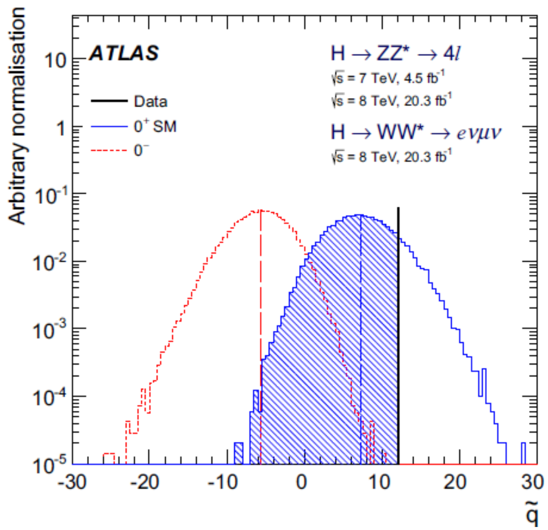
Observed 1^+ exclusion 99.8%

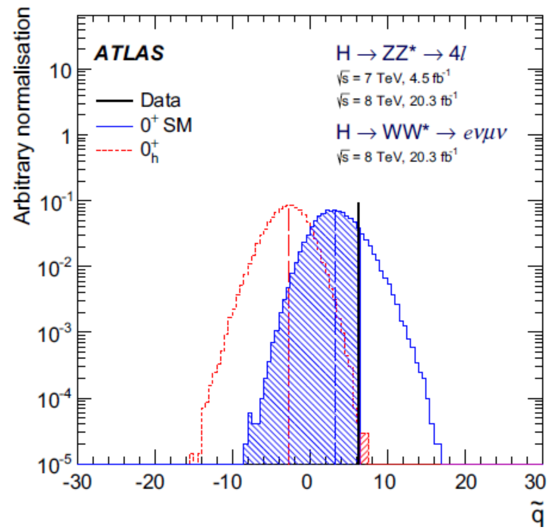
Observed 2^+_m exclusion 83.2%

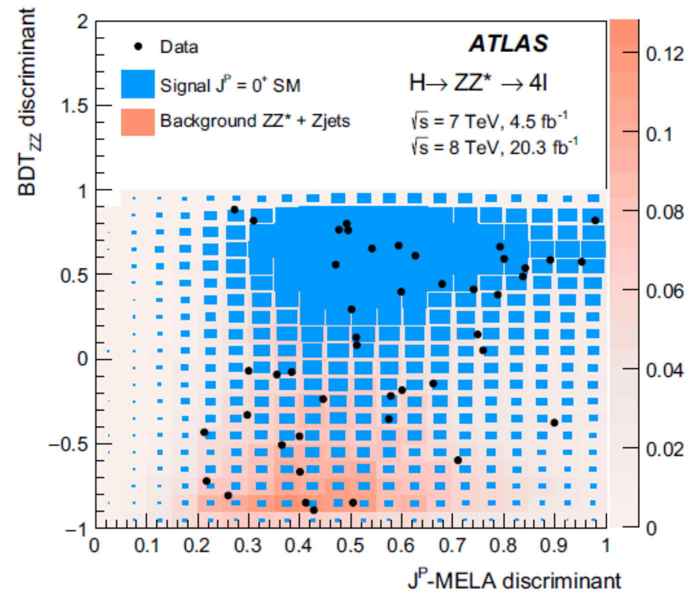
PLB 726, 120-144 (2013)

Higgs Spin and Parity (H→ZZ+WW)

- All tested alternative models are excluded in favour of the SM Higgs boson hypothesis at more than 99.9% CL.







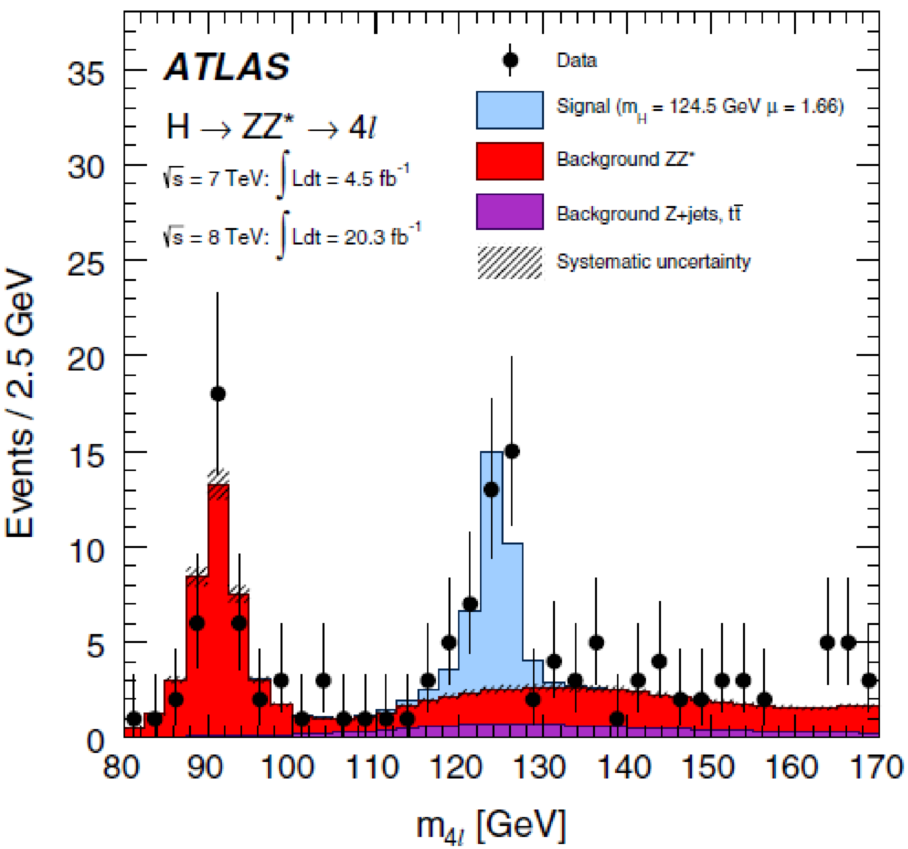
EPJC75, 476 (2015)

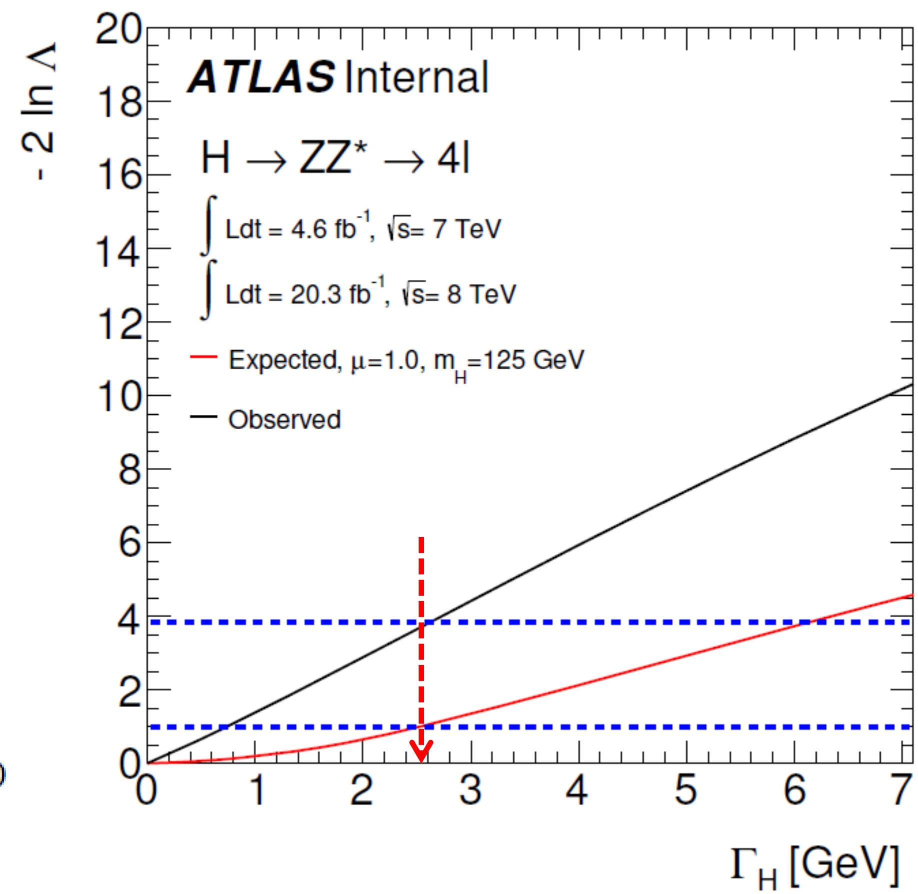
Table 6 Expected and observed p-values for different spin-parity hypotheses, for the combination of the three channels: $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$ and $H \to WW^* \to e\nu\mu\nu$. The observed CL_s for the alternative hypothesis is reported in the last column. The expected and observed p-values and the observed CL_s are defined in Sect. 5.5. The definitions of alternative hypotheses are given in Sect. 3

Tested hypothesis	$p^{\rm alt}_{\exp,\mu=1}$	$p^{\rm alt}_{\exp,\mu=\hat{\mu}}$	$p^{\rm SM}_{\rm obs}$	$p^{\rm alt}_{\rm obs}$	Obs. CL_s (%)
0^+_h	2.5×10^{-2}	4.7×10^{-3}	0.85	7.1×10^{-5}	4.7×10^{-2}
0^-	1.8×10^{-3}	1.3×10^{-4}	0.88	$<3.1 \times 10^{-5}$	$<2.6 \times 10^{-2}$
$2^+(\kappa_q = \kappa_g)$	4.3×10^{-3}	2.9×10^{-4}	0.61	4.3×10^{-5}	1.1×10^{-2}
$2^+(\kappa_q = 0;\ p_T < 300\text{GeV})$	$<3.1 \times 10^{-5}$	$<3.1 \times 10^{-5}$	0.52	$<3.1 \times 10^{-5}$	$<6.5 \times 10^{-3}$
$2^+(\kappa_q = 0;\ p_T < 125\text{GeV})$	3.4×10^{-3}	3.9×10^{-4}	0.71	4.3×10^{-5}	1.5×10^{-2}
$2^+(\kappa_q = 2\kappa_g;\ p_T < 300\text{GeV})$	$<3.1 \times 10^{-5}$	$<3.1 \times 10^{-5}$	0.28	$<3.1 \times 10^{-5}$	$<4.3 \times 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 125\text{GeV})$	7.8×10^{-3}	1.2×10^{-3}	0.80	7.3×10^{-5}	3.7×10^{-2}

Direct Measurement of Higgs Width

- Using per-event-error method, direct limit on the total width of the Higgs boson $\Gamma_H < 2.6$ GeV @ 95% C.L., dominated by the detector resolution.

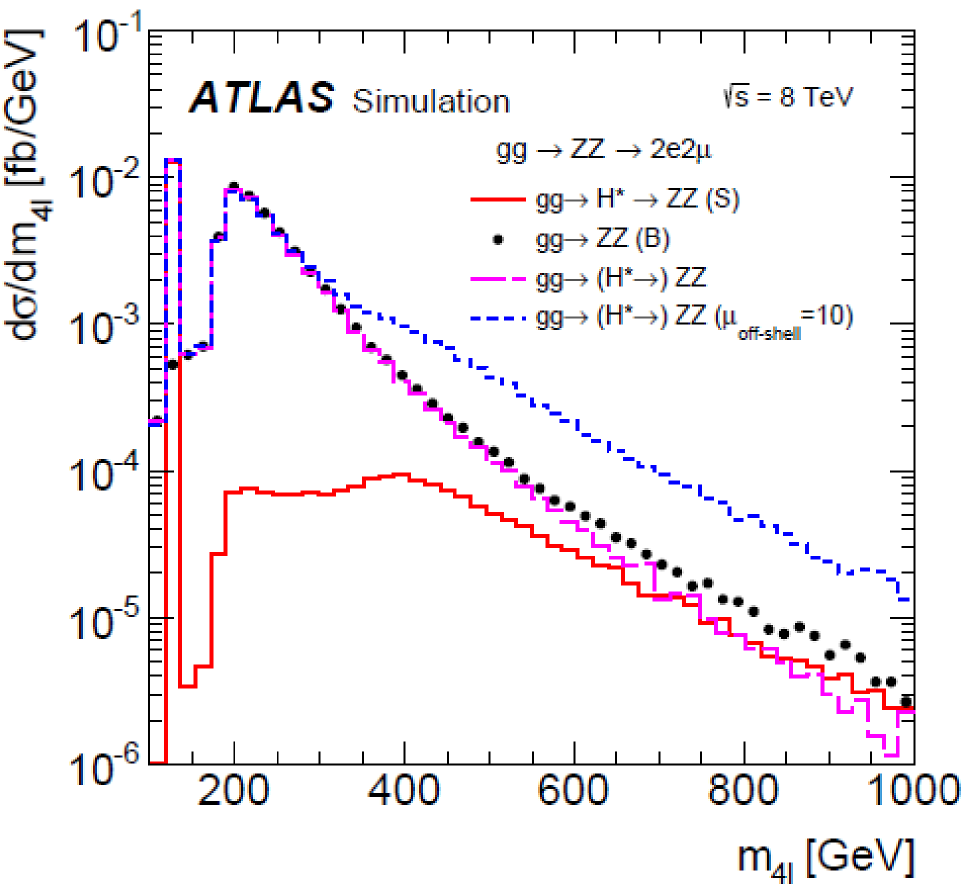




Indirect Measurement of Higgs Width

- High-mass off-peak region of the H→ZZ/WW channel above the $2M_V$ threshold have sensitivity to Higgs production through off-shell and background interference effects.

PRD 88 (2013) 054024, JHEP 04(2014) 060, EPJC (2015) 75:335



$$\frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}} = \mu_{\text{off-shell}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{V,\text{off-shell}}$$

$\mu_{\text{off-shell}}$ is the off-shell signal strength

$$\frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

assumption $\kappa_{i,\text{on-shell}} = \kappa_{i,\text{off-shell}}$

The combination of both on-shell and off-shell measurements of signal strength

$$\mu_{\text{off-shell}} / \mu_{\text{on-shell}} = \Gamma_H / \Gamma_H^{SM}$$

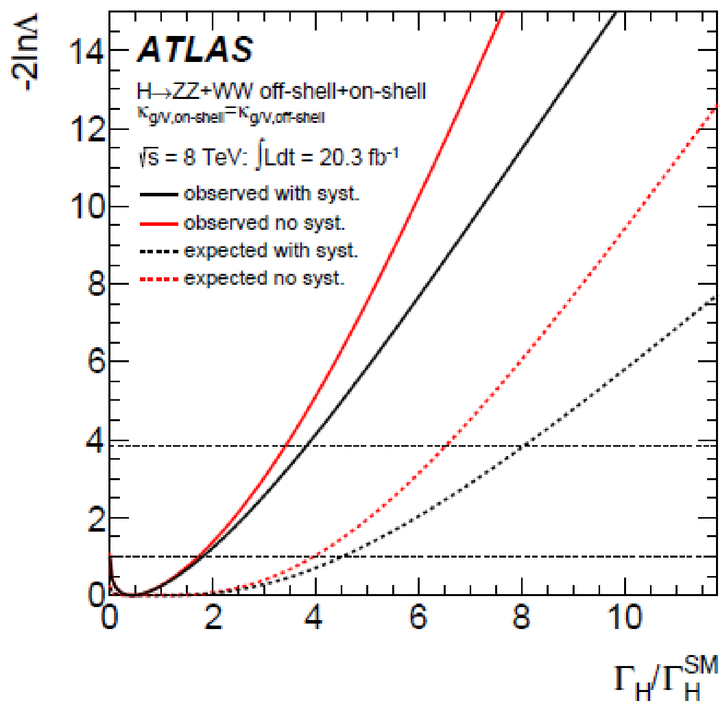
achieve a significantly higher sensitivity to the total width Γ_H.

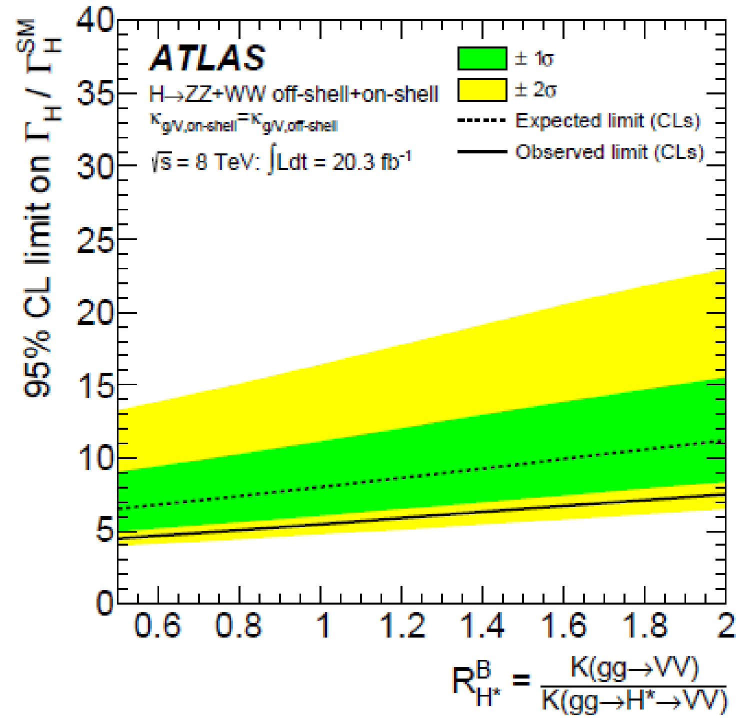
Indirect Measurement of Higgs Width

- ❑ Assuming $R^{B}_{H^*}=1$, the observed (expected) 95% CL upper limit on Γ_H/Γ_H^{SM} is 5.5(8.0), respectively. **It translates into the 95% CL limit on Higgs width of 22.7 (33.0) MeV.**

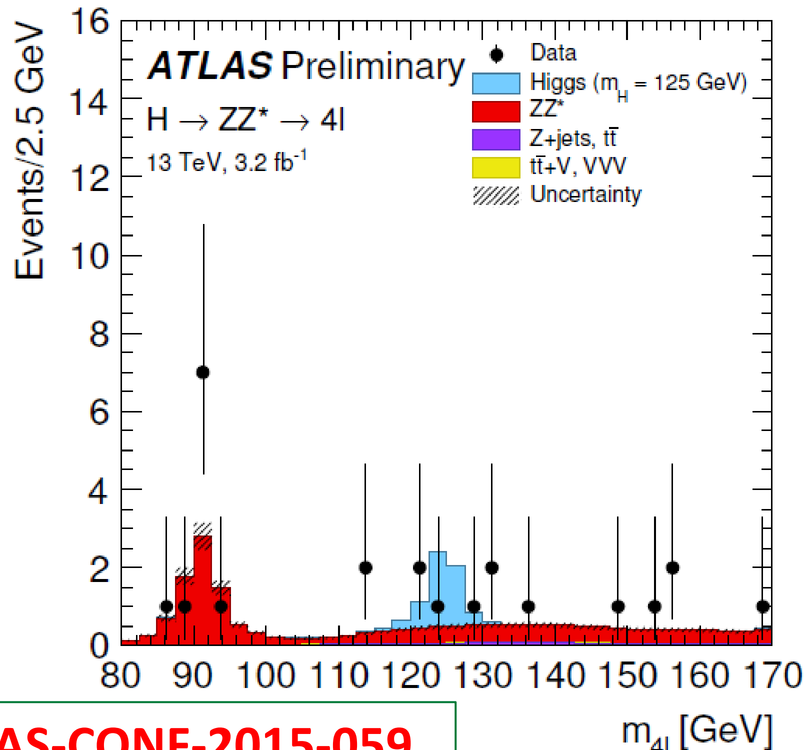
EPJC (2015) 75:335

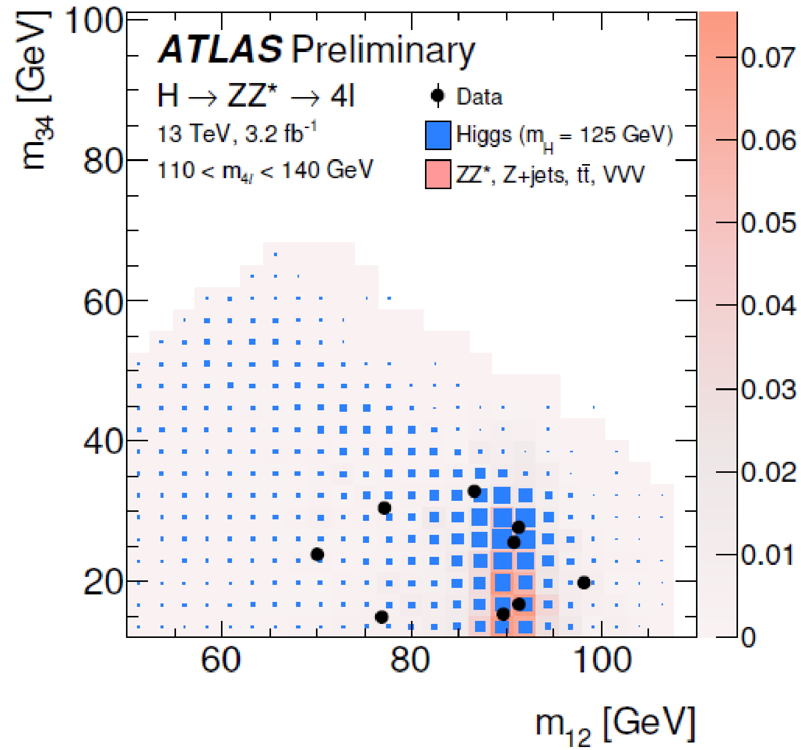
	Observed			Median expected			Assumption
$R^{B}_{H^*}$	0.5	**1.0**	2.0	0.5	**1.0**	2.0	
Γ_H/Γ_H^{SM}	4.5	**5.5**	7.5	6.5	**8.0**	11.2	$\kappa_{i,\text{on-shell}} = \kappa_{i,\text{off-shell}}$
$R_{gg} = \kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}$	4.7	**6.0**	8.6	7.1	**9.0**	13.4	$\kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}, \Gamma_H/\Gamma_H^{SM}=1$





H →ZZ* → 4ℓ @ LHC Run2





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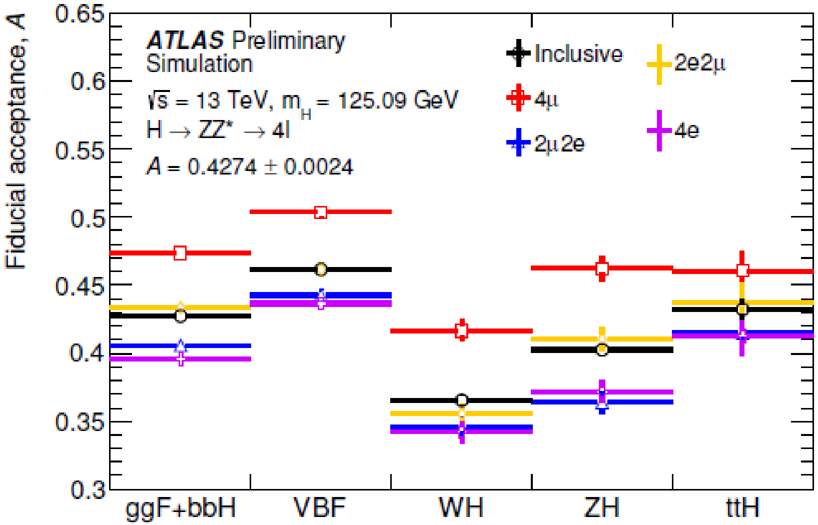
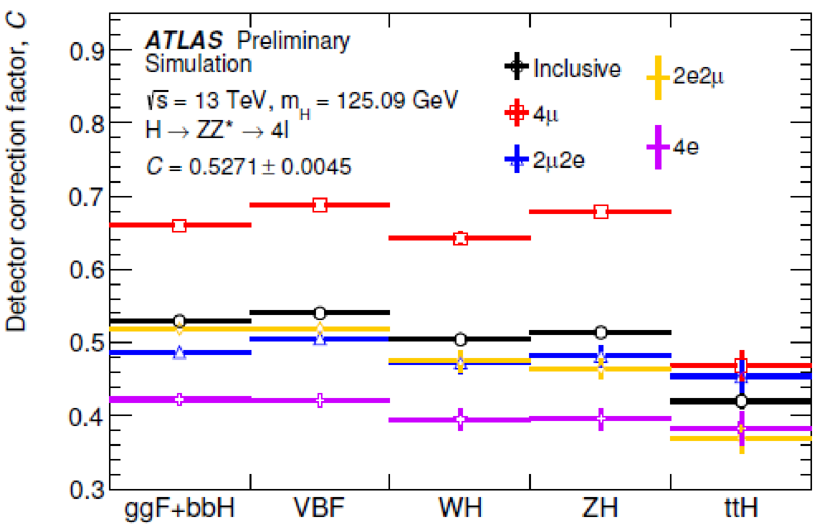
Final state	Signal full mass range	Signal	ZZ^*	$Z + jets, t\bar{t}$ $t\bar{t}V, VVV, WZ$	S/B	Expected	Observed
4μ	1.79 ± 0.21	1.67 ± 0.20	0.64 ± 0.06	0.08 ± 0.03	2.3	2.39 ± 0.21	1
$2e2\mu$	1.19 ± 0.14	1.06 ± 0.13	0.44 ± 0.04	0.07 ± 0.03	2.1	1.57 ± 0.14	1
$2\mu 2e$	1.07 ± 0.16	0.96 ± 0.15	0.34 ± 0.05	0.09 ± 0.02	2.2	1.40 ± 0.16	2
$4e$	1.01 ± 0.15	0.88 ± 0.13	0.32 ± 0.05	0.09 ± 0.02	2.1	1.30 ± 0.14	0
Total	5.06 ± 0.60	4.57 ± 0.54	1.74 ± 0.19	0.34 ± 0.06	2.2	6.65 ± 0.58	4

Higgs→ZZ*→4ℓ Fiducial Cuts

Lepton definition	
Muons: $p_T > 6$ GeV, $|\eta| < 2.7$	Electrons: $p_T > 7$ GeV, $|\eta| < 2.47$
Pairing	
Leading pair:	SFOS lepton pair with smallest $|m_Z - m_{\ell\ell}|$
Sub-leading pair:	Remaining SFOS lepton pair with smallest $|m_Z - m_{\ell\ell}|$
Event selection	
Lepton kinematics:	Leading lepton $p_T > 20, 15, 10$ GeV
Mass requirements:	$50 < m_{12} < 106$ GeV; $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1(0.2)$ for same (opposite) flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$118 < m_{4\ell} < 129$ GeV



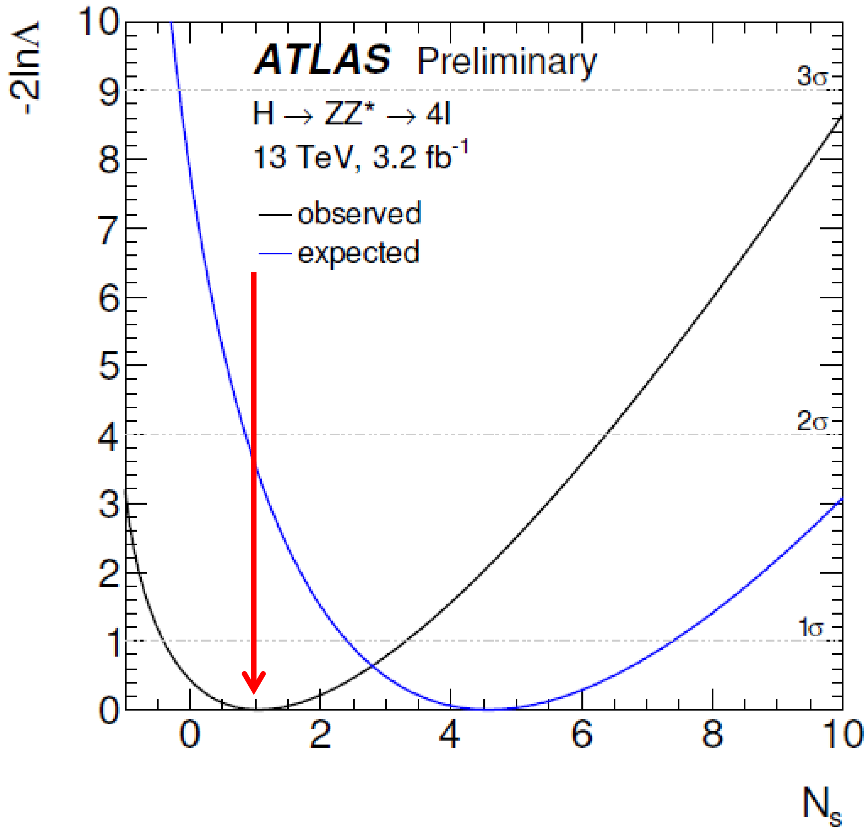


Higgs Fiducial and Total Cross Section

❑ Total and fiducial cross section measurement.

$$\sigma^{\mathrm{tot}} = \frac{N_{\mathrm{s}}}{\mathcal{A} \cdot C \cdot \mathcal{B} \cdot \mathcal{L}_{\mathrm{int}}}.$$

$$\sigma^{\mathrm{fid}}_{4\ell} = \frac{N_{\mathrm{s}}}{C \cdot \mathcal{L}_{\mathrm{int}}}$$



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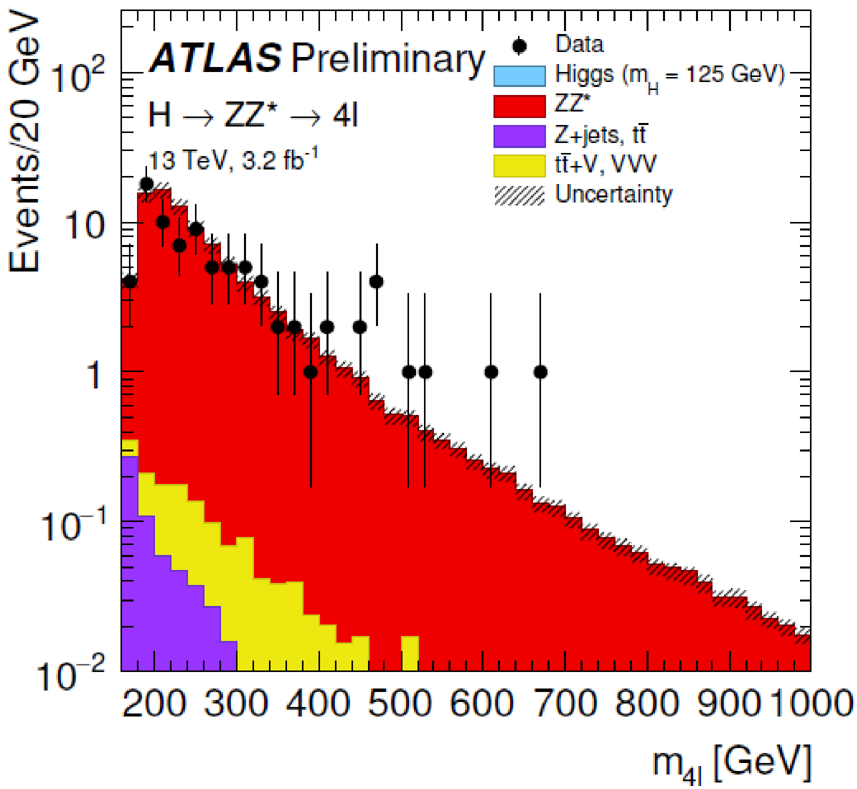
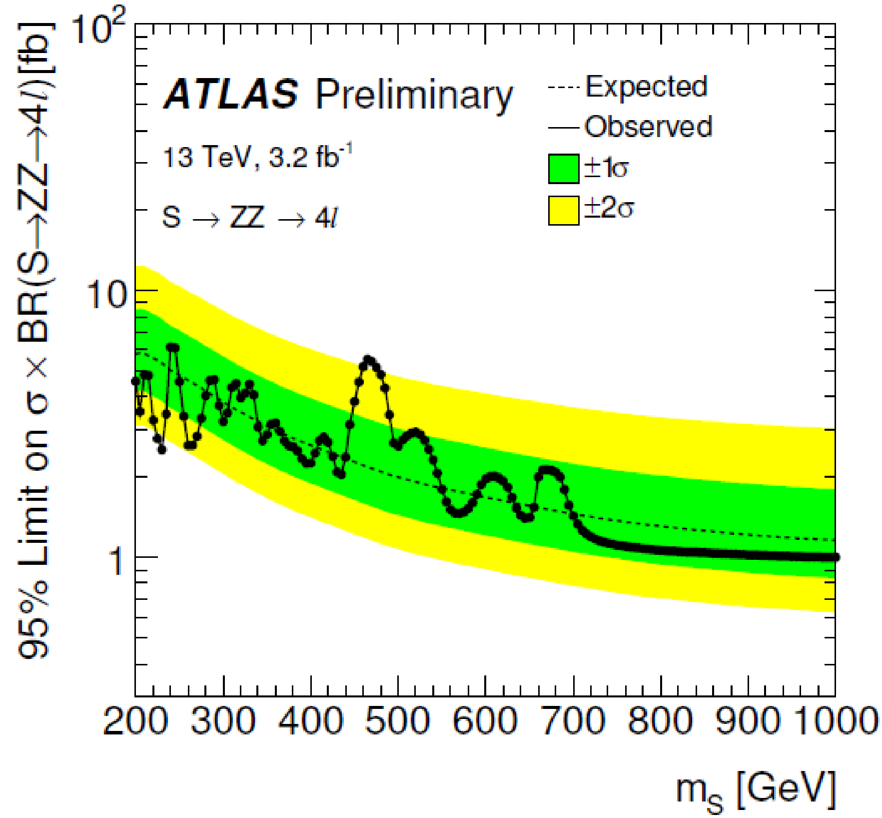
Data set [TeV]	N_{s}	$\sigma^{\mathrm{fid}}_{4\ell}$ [fb]	$\sigma^{\mathrm{fid}}_{\mathrm{theory}}$ [fb]	σ^{tot} [pb]	$\sigma^{\mathrm{tot}}_{\mathrm{theory}}$ [pb]
7	$4.5^{+2.8}_{-2.2}$	$1.9^{+1.2}_{-0.9}$	1.03 ± 0.11	33^{+21}_{-16}	17.5 ± 1.6
8	$24.0^{+6.0}_{-5.3}$	2.1 ± 0.5	1.29 ± 0.13	37^{+9}_{-8}	22.3 ± 2.0
13	$1.0^{+2.3}_{-1.5}$	$0.6^{+1.3}_{-0.9}$	2.74 ± 0.28	12^{+25}_{-16}	$50.9^{+4.5}_{-4.4}$

Search for Heavy Higgs





Final state	ZZ^*	$Z+\text{jets}, t\bar{t}, WZ$	$t\bar{t}V, VVV$	Expected	Observed
4μ	22.1 ± 2.2	0.05 ± 0.02	0.23 ± 0.01	22.4 ± 2.2	20
$2e2\mu$	16.9 ± 1.6	0.05 ± 0.02	0.21 ± 0.01	17.2 ± 1.6	17
$2\mu 2e$	18.1 ± 2.6	0.06 ± 0.02	0.19 ± 0.01	18.3 ± 2.6	13
$4e$	13.9 ± 2.1	0.06 ± 0.02	0.18 ± 0.01	14.1 ± 2.1	12
Total	71 ± 8	0.23 ± 0.04	0.81 ± 0.04	72 ± 8	62

Search for Higgs + Dark Matter

- ❑ To search for dark matter (MET) associated with a Higgs boson.

Process	High-E_T^{miss} category ($E_T^{miss} > 100$ GeV)	Low-E_T^{miss} category ($E_T^{miss} < 100$ GeV)
$H \to ZZ^* \to 4\ell$	$(2.1 \pm 0.6) \cdot 10^{-2}$	4.9 ± 0.5
ZZ^*	$(0.7 \pm 0.4) \cdot 10^{-2}$	4.4 ± 0.4
Z+jets and $t\bar{t}$	$(3.1 \pm 1.2) \cdot 10^{-2}$	0.8 ± 0.5
$ZH(\ell\nu\ell\nu)$	$(1.2 \pm 0.6) \cdot 10^{-5}$	$(5.8 \pm 0.8) \cdot 10^{-4}$
$ZH(\ell\ell\nu\nu)$	$(1.3 \pm 0.8) \cdot 10^{-7}$	$(8.2 \pm 1.5) \cdot 10^{-7}$
Total background	$(5.9 \pm 1.6) \cdot 10^{-2}$	10.1 ± 1.0
Vector mediator signal $m_\chi = 1$ GeV, $m_{med} = 200$ GeV	$(9.7 \pm 3.3) \cdot 10^{-2}$	$(1.3 \pm 0.6) \cdot 10^{-1}$
Scalar mediator signal $m_\chi = 1$ GeV, $m_{med} = 300$ GeV	0.41 ± 0.14	0.44 ± 0.09
Data	0	9

No significant excess is found in search for Higgs boson with large MET.

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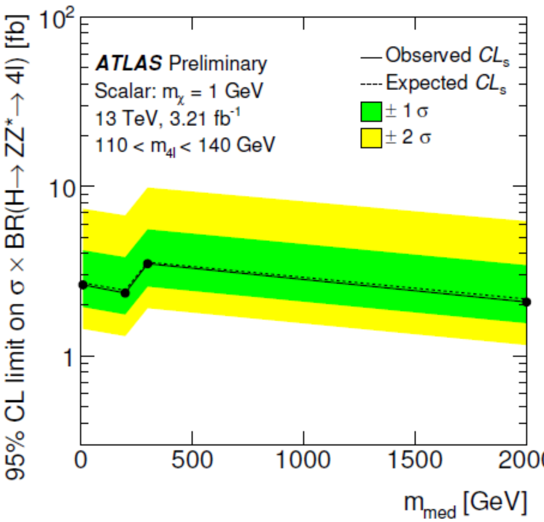
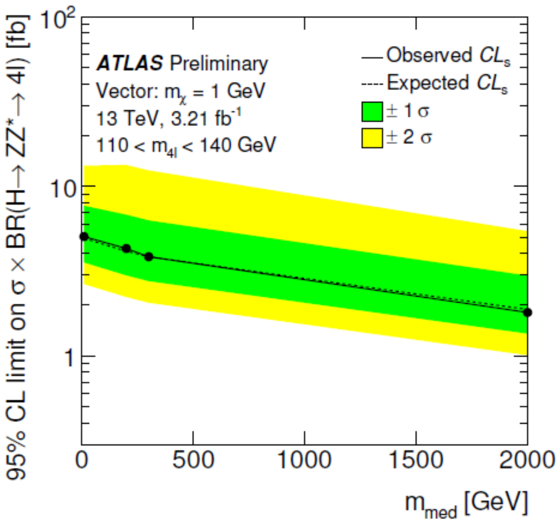
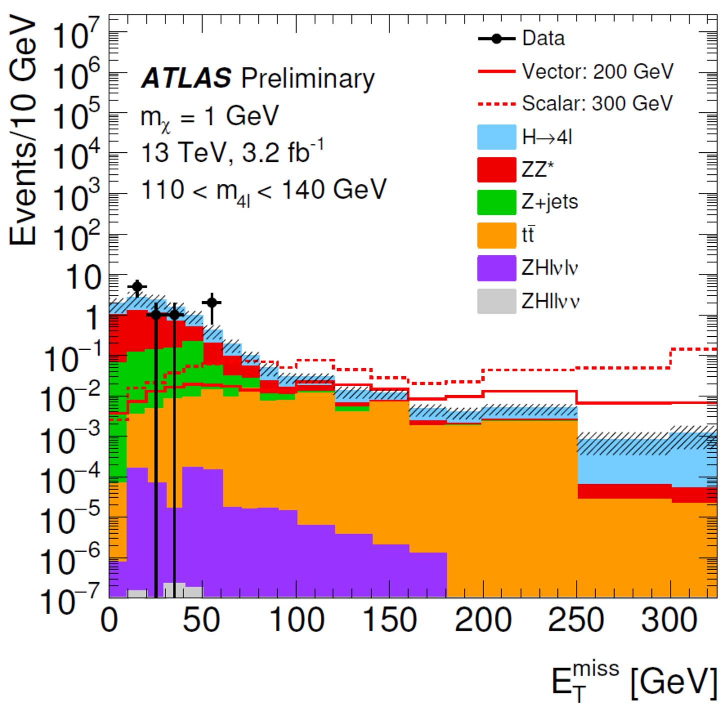


(a) Scalar mediator



(b) Vector mediator



Summary

- ❑ H → ZZ* → 4ℓ is very clean, so called "Gold-plated" channel which has several advantages:
  - o Fully reconstructed final states
  - o Good mass resolution (~ 1.6-2.4 GeV)
  - o High S/B ratio (~ 1.5)
- ❑ H → ZZ* → 4ℓ is sensitive to properties measurements
  - o Higgs mass, width, spin, parity, couplings which are critical to determine whether it is fully compatible with the SM Higgs boson.
- ❑ H → ZZ* → 4ℓ final states is used to search for high mass Higgs or DM with associated production at LHC Run2.

Thank you !

Higgs Cross Section: 8 TeV vs 13 TeV

- Higgs production cross sections for $M_H = 125$ GeV.

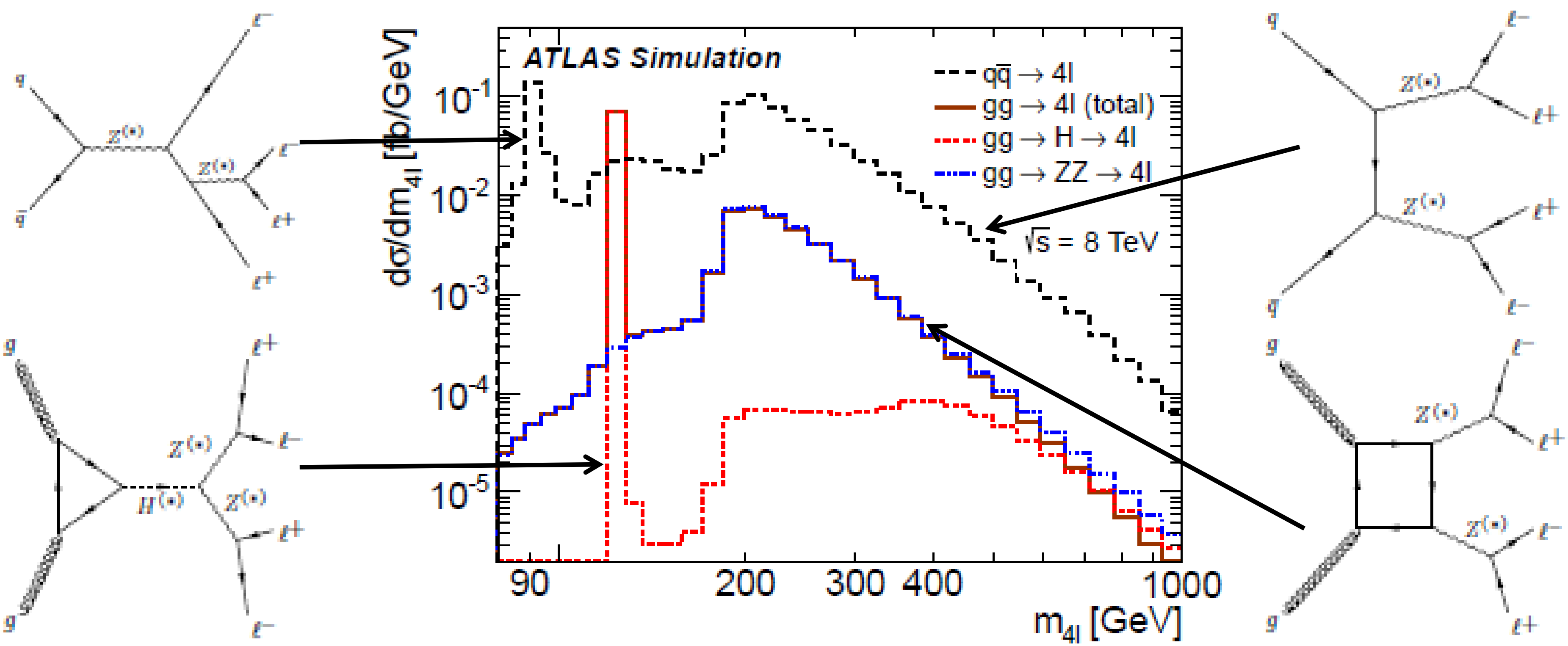
Higgs Production (NNLO QCD and NLO EW) (for M_H = 125 GeV)	Cross section (pb) $\sqrt{s}$ = 8 TeV	Cross section (pb) $\sqrt{s}$ = 13 TeV
ggF	19.27	43.92
VBF	1.58	3.75
WH	0.70	1.38
ZH	0.42	0.87
ttH	0.13	0.51
bbH	0.20	0.51
Total	22.30	50.94

arXiv: 1509.07844

Z/ZZ →4l Productions

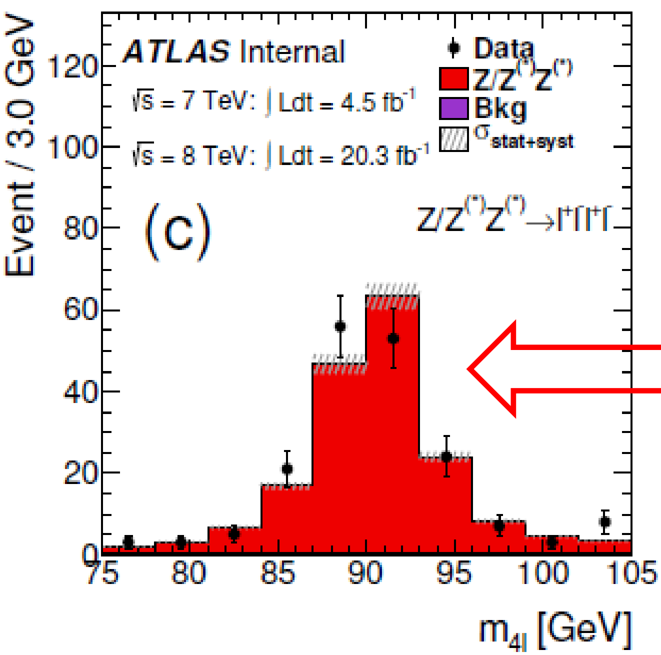
- Very rich physics: resonant Z→4l, H→ZZ*→4l, SM ZZ→4l
- Differential cross section measurements in m_{4l} and P_T for inclusive 4l ($80<m_{4l}<1000$ GeV)
- First try to constraint gg→4l contribution from data
- Theoretical predictions available at different level of corrections

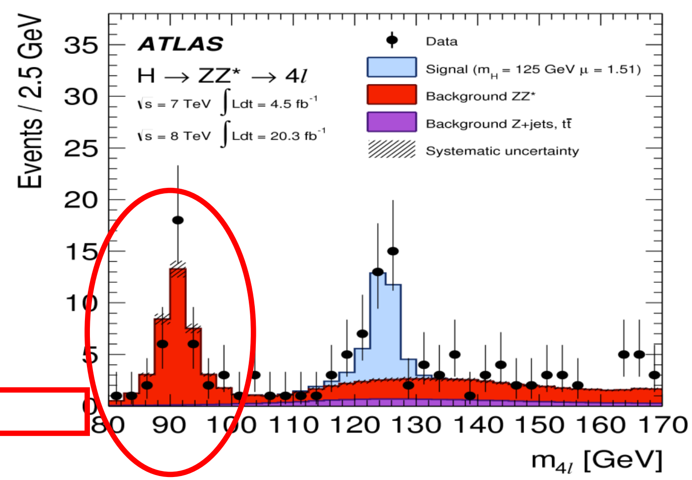
Theoretical Predictions:
qq → ZZ: Powheg (NLO)
on-shell H: Powheg (NLO)
gg → ZZ : MCFM (LO)
H → 4l & on-shell qq → ZZ: NNLO QCD + NLO EWK

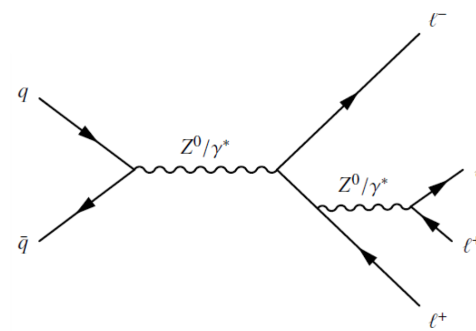


Analysis of Single Resonance Z→4ℓ

- The Z →4l production was first observed at the LHC by ATLAS and CMS. It serves as a standard candle for 4l decay channel along the Higgs discovery.
- Cross section and BR measurement of the Z → 4l production provides
  - A SM test for a rare decay process, measurements of σ(4l) and BR(Z→4l)
  - A complementary test of the detector response for H → 4l detection







$$BR = \frac{\sigma_{4l}^{PS} \cdot (1 - f_t)}{\sigma_{pp \to Z}}$$

BR(meas.)=3.20±0.25±0.13×10^{-6}

BR(SM NLO)=3.33±0.01×10^{-6}

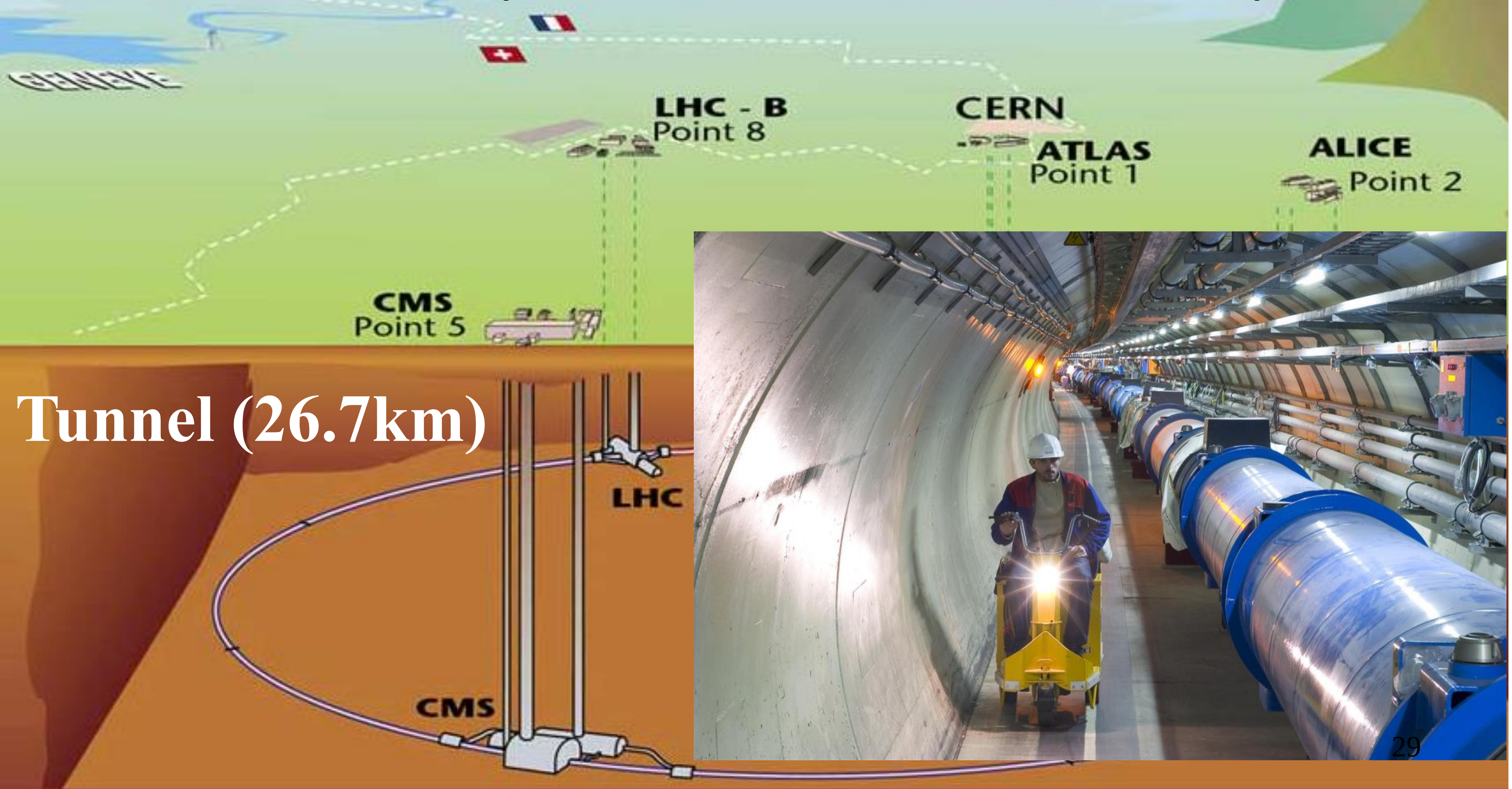
Phys. Rev. Lett. 112, 231806 (2014)

CERN’s Large Hadron Collider (LHC)

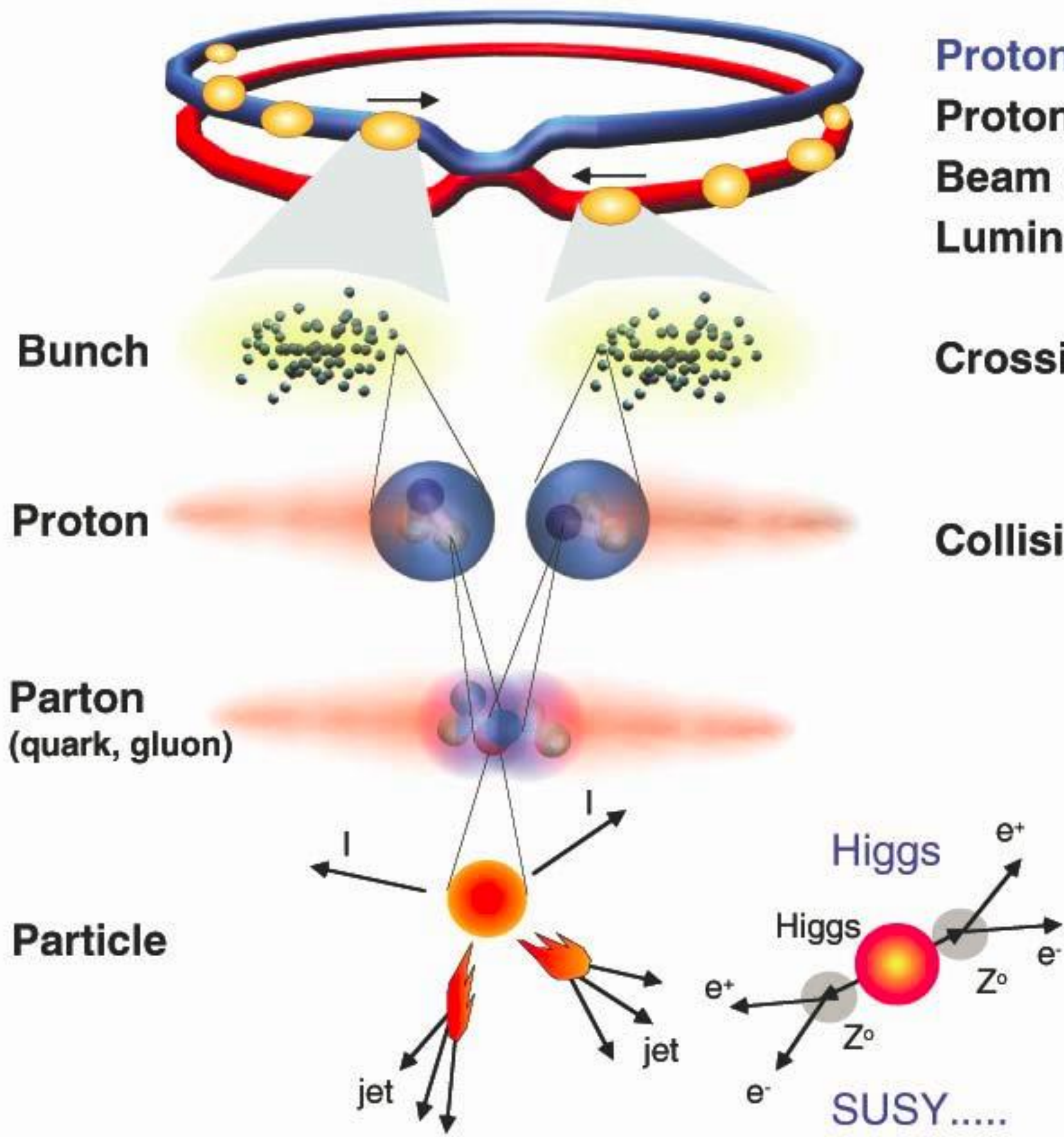
LHC is the world’s largest collider (7-14 TeV)

ATLAS Collaboration (38 countries, 174 institutions, ~ 3000)

CMS Collaboration (41 counties, 179 institutions, ~3300)



LHC：Proton-Proton Collisions



Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^7 - 10^9 Hz

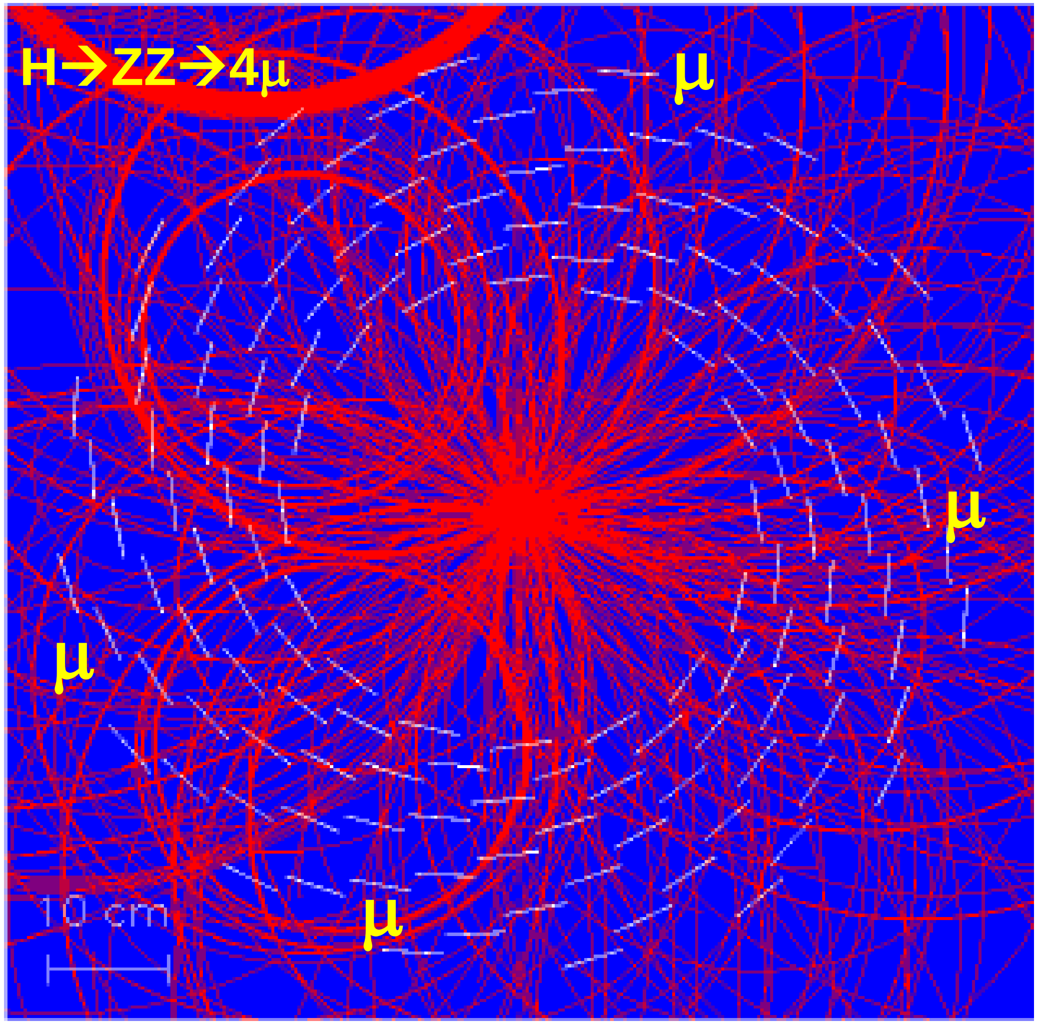
Major challenge：

Higgs → ZZ* → 4l
production rate is very low

Selection of 1 in
10,000,000,000,000

Major Challenge (Large Pileup)

- Large pileup events result in big challenge to the detector, reconstruction and particle identification (**eg. e, μ, γ, τ, b**) !



Boosted Decision Trees (BDT)

BDT was firstly applied for particle identification in MiniBooNE exp. in 2004.

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Boosted decision trees as an alternative to artificial neural networks for particle identification

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Studies of boosted decision trees for MiniBooNE particle identification

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Available online 4 October 2005

Abstract

Boosted decision trees are applied to particle identification in the MiniBooNE experiment operated at Fermi National Accelerator Laboratory (Fermilab) for neutrino oscillations. Numerous attempts are made to tune the boosted decision trees, to compare performance of various boosting algorithms, and to select input variables for optimal performance.

BDT is one of popular analysis tools in CERN TMVA package, it has wide applications in particle physics including the discovery of the Higgs boson and its properties measurement .

Abstract

The efficacy of parti… comparison is perform… oscillations. Based on… algorithms has better performan… the tests in this paper were for … physics.

PACS: 29.85.+c; 02.70.Uu; 07.05.M…

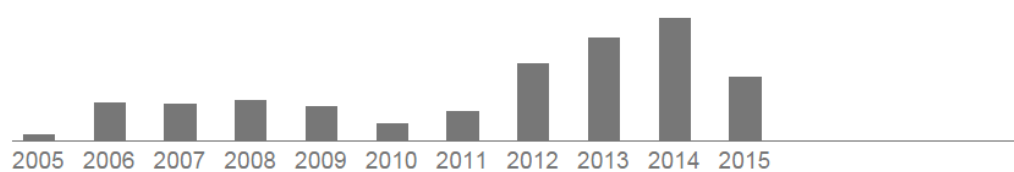
Keywords: Boosted decision trees; A…

1. Introduction

The artificial neural netwo… has been widely used in da… Energy Physics experiments i… use of the ANN technique…

…[6]. This work indicated … trees is superior to the … (PID) using the Mini-… studies show that the … not only better event … also more stable and robust than ANNs … mples with varying input parameters. … o verify that the resultant algorithm is … all biases in the inputs, i.e., that it is … ooNE about two dozen MC data sets, … metrical or physical parameter changed … dard deviation, are generated. It is then … algorithm is trained with a central value … results do not strongly differ when the … is applied to these varied sets. These … but it appears that the boosting method … part due to using many PID variables. … gorithm is one of the most powerful … introduced in the past decade [7–10]. … the boosting algorithm is to design a … ombines many "weak" classifiers to … werful classifier. In the present work … re made to tune the boosted decision … sons are made for various algorithms. … ber of discriminant variables, several

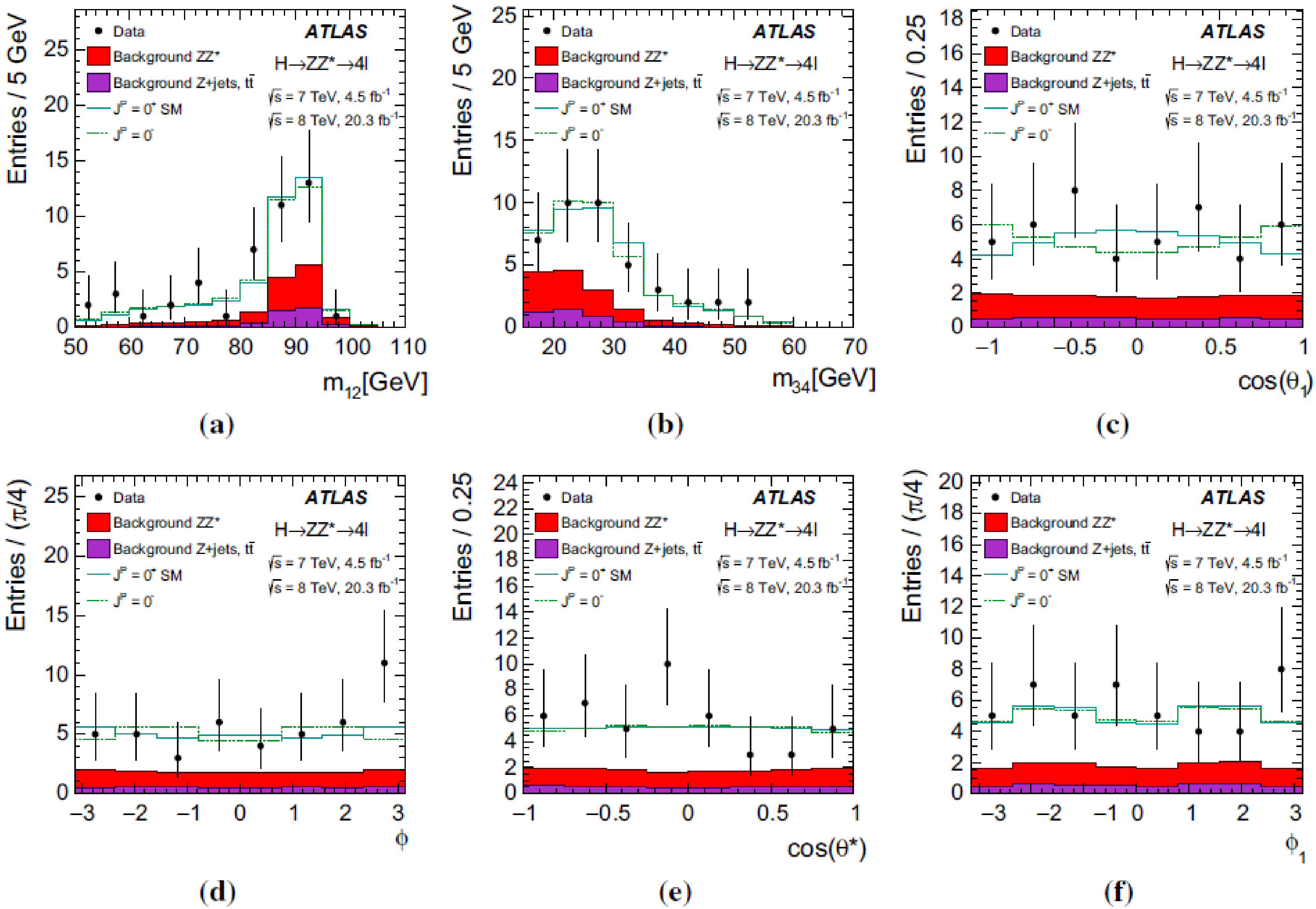
*Corresponding author.
E-mail address: yhj@umich.edu (…



Scholar articles

Boosted decision trees as an alternative to artificial neural networks for particle identification
BP Roe, HJ Yang, J Zhu, Y Liu, I Stancu, G McGregor - Nuclear Instruments and Methods in Physics Research …, 2005
Cited by 284 - Related articles - All 14 versions

Higgs Spin and Parity



Indirect Measurement of Higgs Width

- The expected 95% C.L. upper limits on $\mu_{\text{off-shell}}$。

	Without systematics	With systematics
ME	1.00 (8.85)	1.00 (10.23)
BDT	1.00 (8.52)	1.00 (10.08)