Messungen der Higgs-Boson-Eigenschaften mit dem ATLAS Experiment

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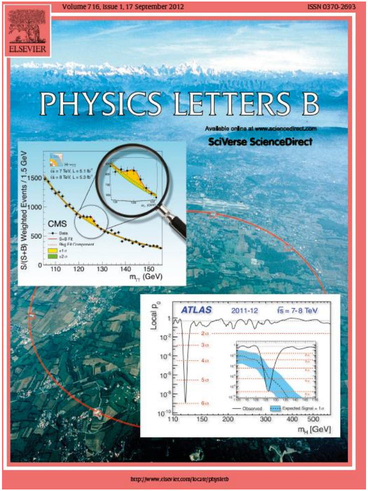
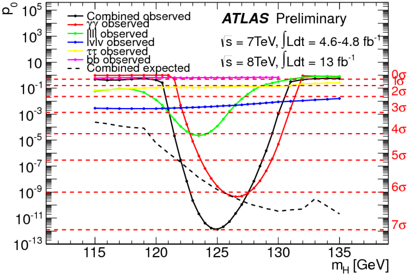
7. März 2013

DPG Tagung 2013, Dresden

LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

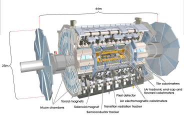
Scalar boson discovery



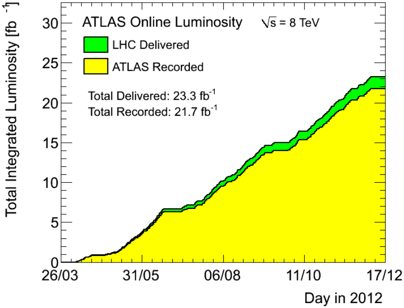


The local probability p0 for a background-only experiment to be more signal-like than the observation as a function of m_H for various individual channels

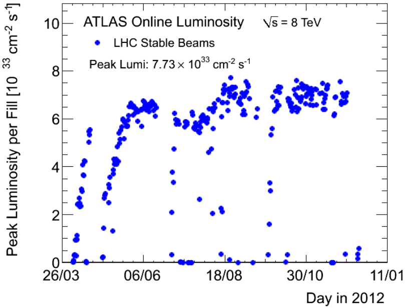
ATLAS DATASETS



2012:



2012:



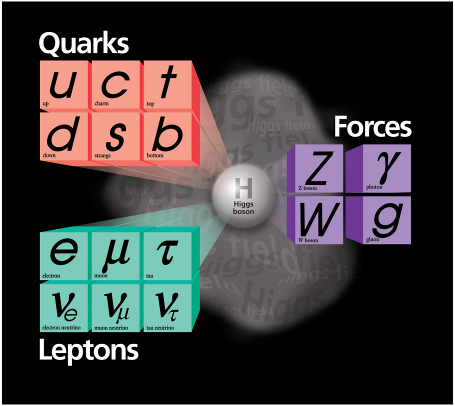
Integrated Luminosity for Analysis:

- $20.7\,\mathrm{fb}^{-1}$ (2012)
- $4.7\ \ \mathrm{fb}^{-1}$ (2011)

Interactions per crossing:

- $<\mu>$=20.7
- With peaks up to 40

The Standard Model and the Higgs boson (I)

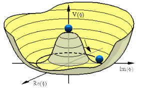


Higgs boson:

- Mass ≈125 GeV
- Charge 0
- Spin 0
- Non-universal couplings

→ supposed to give mass to SM particles

The Standard Model and the Higgs boson (II)

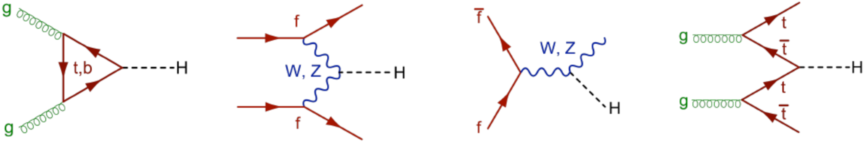


Firm predictions for the SM Higgs boson:

- Fundamental scalar field
- Non-zero vacuum expectation value
- $SU(2)$ gauge interactions generate the W and Z masses
- Yukawa interactions generate fermion masses
  $\rightarrow$ coupling strengths are related to the masses of the related particles
- Quantum excitation of the field: Higgs boson

Experimental verifications and tests needed

Production of a SM Higgs boson at the LHC

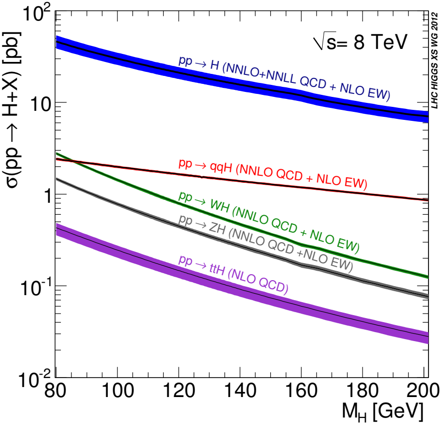


Gluon fusion:

- calculated at NNLO

Vector boson fusion:

- calculated at NNLO
- distinctive experimental signature:
  2 forward jets and rapidity gap



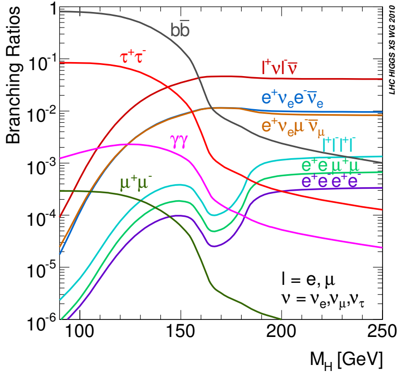
Decays of a SM Higgs boson

Low to intermediate m_H range:

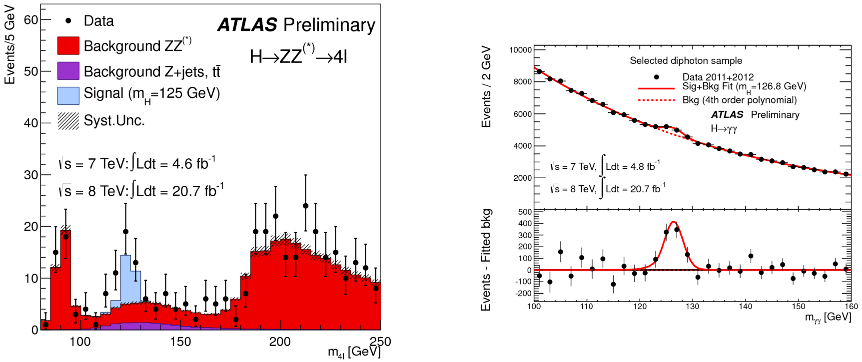
- $\gamma\gamma$: very clean but small BR
- $\tau\tau$: VBF to reduce BG
- bb: huge QCD BG, some potential in assoc. prod.
- $\mu\mu$: very small BR

Intermediate to high m_H range:

- WW and ZZ most sensitive channels



Higgs boson mass m_H, total width, number



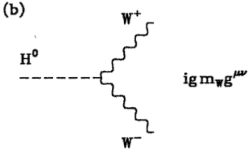
- 2 most sensitive channels for m_H: $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$
- Theoretical true width ≈4 MeV, so we can only confirm that width corresponds to experimental resolution of ≈1-2 GeV
- So far one peak observed with m_H ≈125 GeV, No other SM Higgs-like signal observed for any other mass

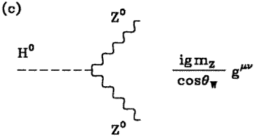
Properties of the SM Higgs boson

- Higgs mass is only free parameter in SM:
    - $m_H \approx$125 GeV
- Coupling strength to W and Z:
    - Fixes W and Z masses
    - $WW \rightarrow WW$ scattering unitary
- Coupling strength to fermions:
    - Fixes fermion masses
- Spin 0 and CP even:
    - $\rightarrow$ SM Higgs boson

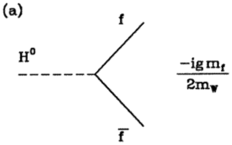
Measurement of Higgs couplings to other particles:

- Coupling to W and Z:



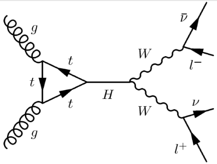


- Coupling to fermions:



Coupling includes strength proportional to mass of particle and structure

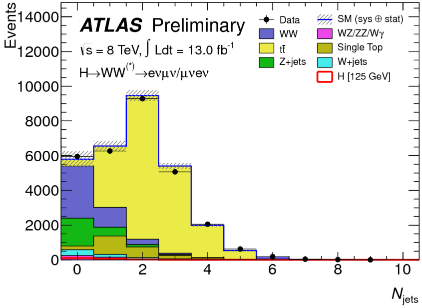
Boson couplings: $H \to WW$



- large event yields and clean signature but lack of mass resolution
- Backgrounds: WW, Z/W+jets, top, WZ/ZZ/Wγ, QCD

Common pre-selection:

- 2 isolated high p_T leptons (e, μ)
- $\not{E}_T$
- $\Delta\phi_{\ell\ell}$ cut in transverse plane

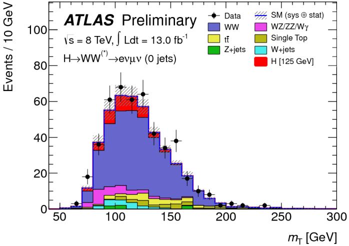


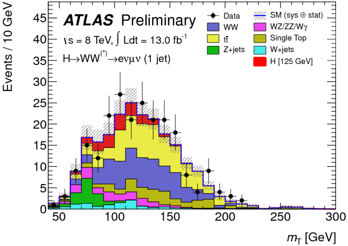
Exclusive analysis in bins of jet multiplicities:

- 0-jets: optimized for gluon-fusion, purest channels, least affected by top BG
- 1-jet: more affected by top BG
- 2-jets: optimized for VBF (tag jets in opposite hemispheres, rapidity gap), small signal expected

Boson couplings: $H \to WW$ Results (I)

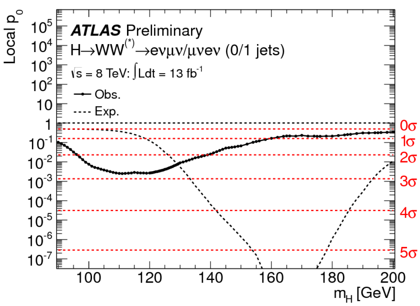
- Data driven techniques to estimate main background contributions
- Main backgrounds estimated in control regions, extrapolated into signal region
- Cross-contamination of different backgrounds in various control regions taken into account
- Analysis optimized in each jet-bin and for each mass hypothesis
- final discriminating observable: transverse mass $m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (P_T^{\ell\ell} + P_T^{miss})^2}$

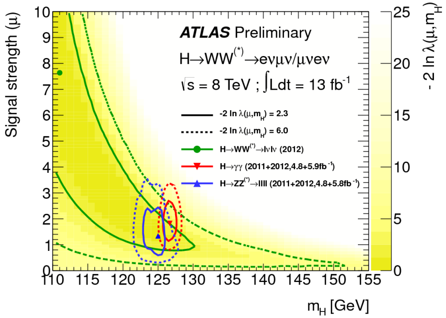




Signal region yield for $e\mu$ and μe channels separately

	0-jet $e\mu$	0-jet μe	1-jet $e\mu$	1-jet μe
Total bkg.	392$\pm$ 7	382$\pm$6	202$\pm$ 6	184 $\pm$ 5
Signal	41.8$\pm$0.6	33.8$\pm$0.5	18.9$\pm$0.4	16.0$\pm$0.4
Observed	469	448	226	207





- Strength: $\mu = 1.48^{+0.35}_{-0.33}$(stat) $^{+0.41}_{-0.36}$(sys th)$^{+0.28}_{-0.27}$(sys exp)± 0.05(lumi)

- At m_H=125 GeV:
  - 2.6 σ (observed)
  - 1.9 σ (expected)

Source	Upward uncertainty (%)	Downward uncertainty (%)
Statistical uncertainty	+23	-22
Signal yield ($\sigma \cdot \mathcal{B}$)	+14	-9
Signal acceptance	+9	-6
WW normalisation, theory	+20	-20
Other backgrounds, theory	+9	-9
W+jets fake rate	+11	-12
Experimental + bkg subtraction	+14	-11
MC statistics	+8	-8
Total uncertainty	+41	-38

Fermion couplings: $H \to \mu^+\mu^-$ analysis

Motivation:

- $H \to \mu^+\mu^-$ directly probes SM Higgs couplings to 2nd generation fermions
- $B(H[125] \to \mu^+\mu^-) = 2.2 \times 10^{-4}$

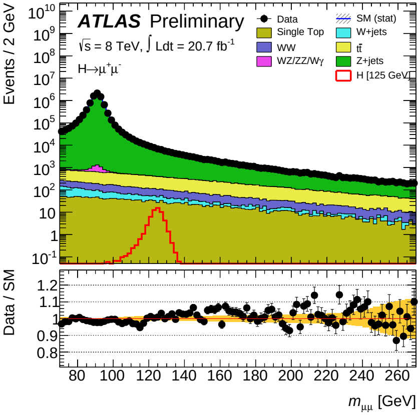
Search strategy:

- Look for a narrow bump on top of continuous $m_{\mu\mu}$ background distribution
- A blinded search for the SM resonance in 110-150 GeV $m_{\mu\mu}$ window
- Use background fit to data shape/yield
- Dominant background is inclusive Z/γ^* (minor di-bosons, $t\bar{t}$)

Challenges:

- Irreducible background from $Z/\gamma^* \to \mu\mu$
- $\Gamma(H[125]) = 4.1$ MeV - signal width is dominated by detector resolution

$H \rightarrow \mu^+\mu^-$: $m_{\mu\mu}$ and Event yields

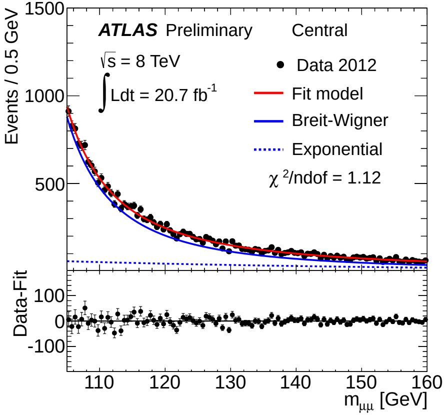


Invariant mass $m_{\mu\mu}$

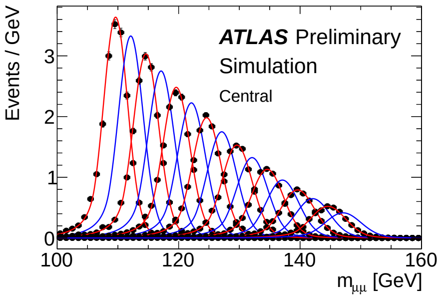
Event yields:

	$\lvert m_H - m_{\mu\mu} \rvert \leq 5$ GeV
Signal [125 GeV]	37.7 ± 0.2
WW	250 ± 4
$WZ/ZZ/W\gamma$	30 ± 1
$t\bar{t}$	1374 ± 13
Single Top	151 ± 5
Z+jets	15810 ± 130
W+jets	88 ± 6
Total Bkg.	17700 ± 130
Observed	17442

$H \to \mu^+\mu^-$: Signal and BG parametrization

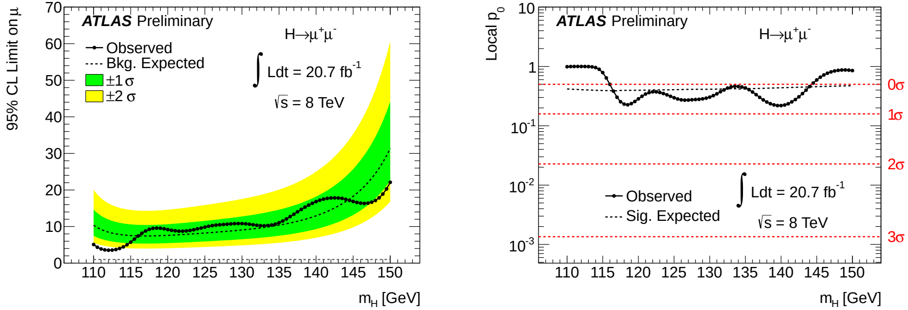


Background model is sum of a Breit-Wigner (BW) and exponential function



Signal described by convolution of Crystal Ball + Gaussian functions

$H \to \mu^+\mu^-$: Results

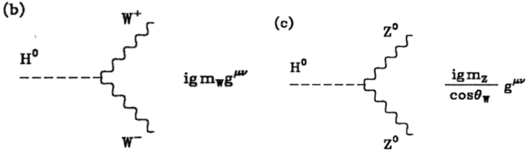


- At m_H=125 GeV:
  - Observed limit: $9.5{\cdot}\sigma_{SM}$
  - Expected limit: $8.2{\cdot}\sigma_{SM}$

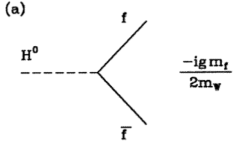
Measurement of Higgs boson properties

SM predicts Higgs boson couplings strength and structure of Higgs couplings:

- Coupling to W and Z:



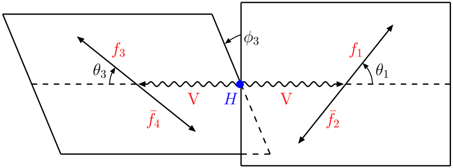
- Coupling to fermions:



If not SM CP even coupling (but still Spin 0): parametrize cross section

CP and Spin observables

If not SM Spin 0 and CP even: no rate prediction
→No rate measurement for Spin and CP
→Need angular variables

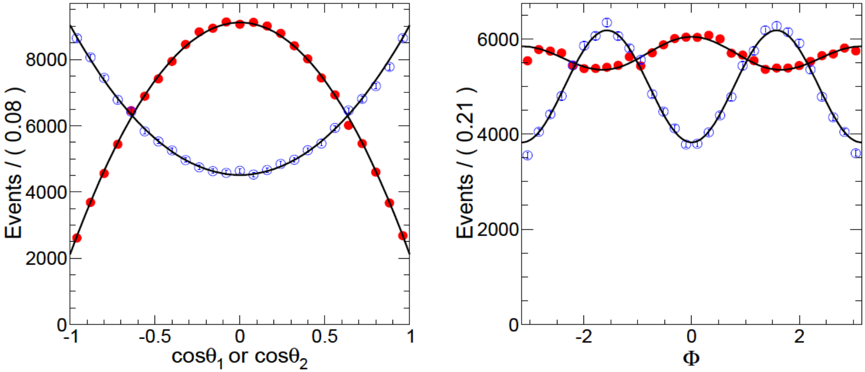


- Best with $H \to ZZ \to 4\ell$
- similar for $H \to WW \to \ell\nu\ell\nu$ but some loss due to neutrinos

Effect of different spin or CP properties parametrized by 5 variables:

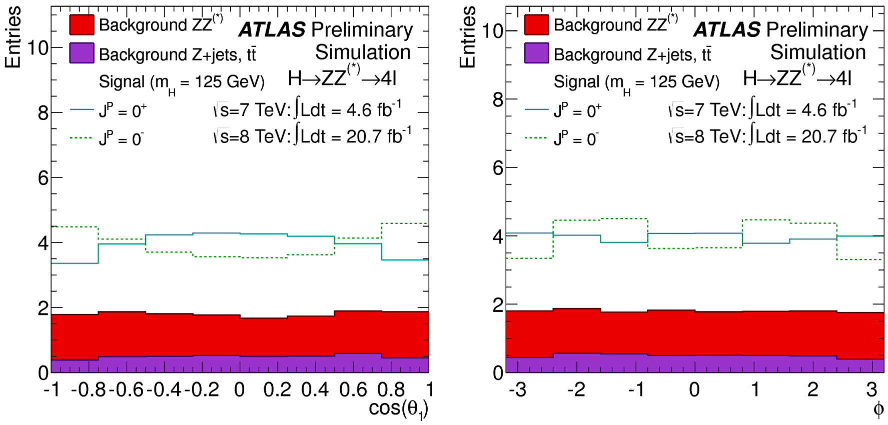
- Invariant mass of each of the two Z / W bosons
- Polar angles θ_1, θ_3 of fermions in corresponding rest frames of Z / W bosons
- Angle Φ_3 between decay planes of 2 Z / W bosons in Higgs rest frame

CP odd expectation: $H \to ZZ \to 4\ell$



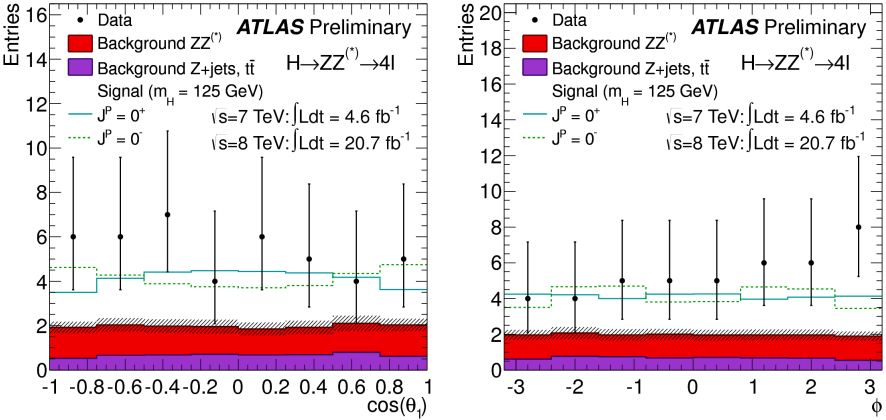
- from arXiv:hep-ph/1208.4018 (JHU generator)
- 0^+ (red) vs. 0^- (blue)

CP odd: $H \to ZZ \to 4\ell$ measurements (I)



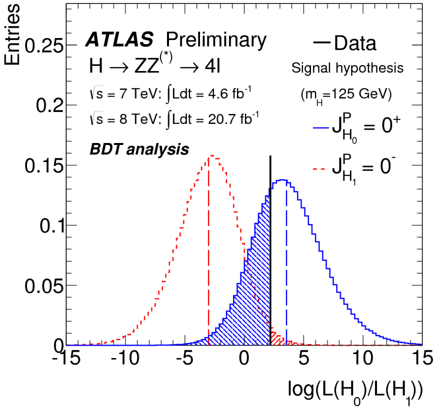
- $H \to ZZ \to 4\ell$ has very low rate
- Use multi variate analysis to enhance sensitivity

CP odd: $H \to ZZ \to 4\ell$ measurements (II)



- $H \to ZZ \to 4\ell$ has very low rate
- Use multi variate analysis to enhance sensitivity

CP odd: $H \to ZZ \to 4\ell$ measurements (III)



- Data disfavors pure CP odd *HZ* coupling
- 0^- disfavored at 97.8 % CL.

Spin prediction

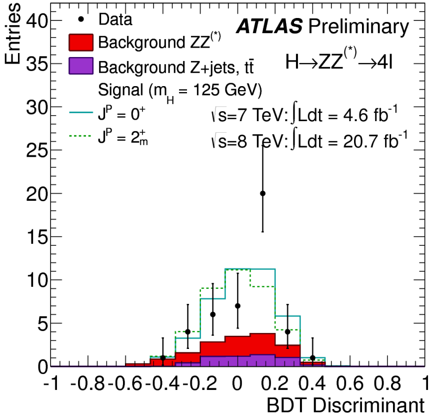
- Has to be a boson, since it decays to $\gamma\gamma$, WW, ZZ (and predicted to decay into bb, $\tau\tau$, $\mu\mu$)
- Spin 0:
  SM prediction
- Spin 1:
  excluded because of mass-less decay $H \rightarrow \gamma\gamma$
  Landau-Yang theorem
- Spin 2:
  possible, but not a SM Higgs boson
- Higher Spin:
  ?

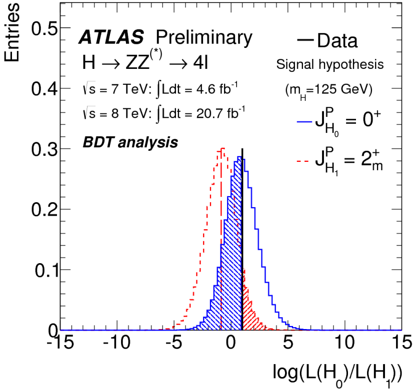
Spin 2 parametrization

$$A(X \to VV) = \Lambda^{-1} \Big[2g_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2g_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\alpha}$$
$$+ g_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + g_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta}$$
$$+ m_V^2 \left(2g_5 t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} (\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}) + g_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right)$$
$$+ g_8 \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + g_9 t_{\mu\alpha} \tilde{q}^\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma$$
$$+ \frac{g_{10} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma (\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*)) \Big] ,$$

- For $J^{CP} = 2_m^+$ signal (graviton-like tensor with minimal couplings, $g_1 = g_5 = 1$), most general amplitude of decay into two identical vector bosons contains 10 different terms and 10 effective coupling constants $g_{1..10}$ which are in general complex numbers
- Test for 2_m^+ as in JHU currently

Spin 2 test in $H \to ZZ \to 4\ell$

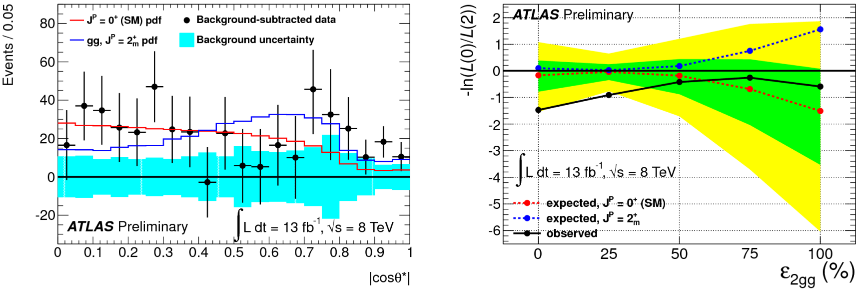




- Similar analysis like for CP

		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

Spin 2 test in $H \to \gamma\gamma$

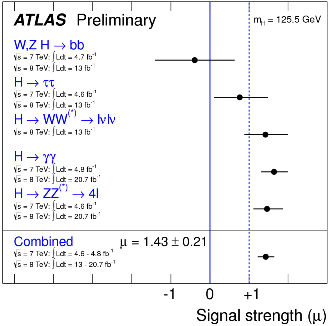


- θ^* polar angle of γs w.r.t. to z-axis of Collins-Soper frame
- For SM-like $gg \to H$ production Spin 2 exclusion at 90% CL (97% expected)

Summary

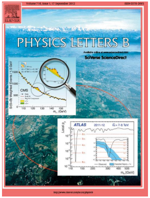
One new boson observed:

- The mass is
  $m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})$ GeV
- Signal strength for $m_H = 125$ GeV:
  $m_H = 125.5$ GeV:
  $\mu = 1.43 \pm 0.16(\text{stat}) \pm 0.14(\text{sys})$
- First Spin/CP measurements are available with SM preference/agreement but still statistically limited



Outlook:

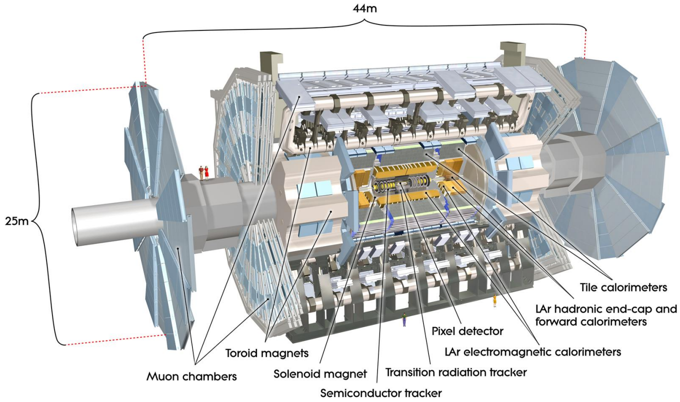
- Determine fermion couplings and production mechanism rates
- Exciting times with remaining LHC Run 1 data and then with LHC Run 2 ahead of us



BACKUP

ATLAS Detector

General purpose detector



Magnets:	2T solenoid 3 air-core toroids	EM Calo.:	sampling LAr technology
Tracking:	silicon + transition radiation tracker	Hadron Calo.:	plastic scintillator (barrel) LAr technology (endcap)
Muon:	independent system		