Higgs J^{CP} Properties From ATLAS & CMS

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BSM Higgs Workshop
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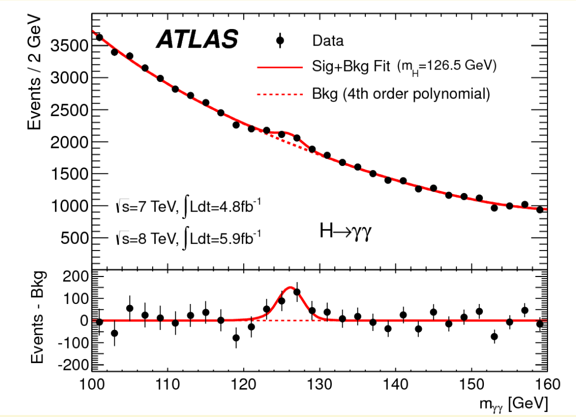
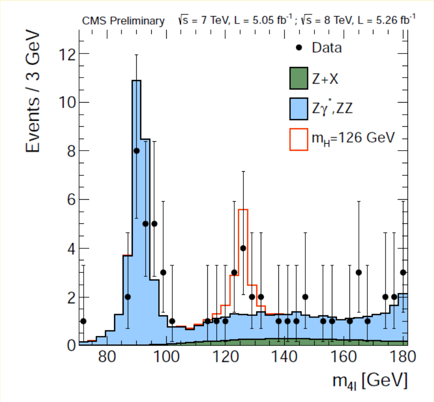
Caltech

Higgs Boson

- First elementary scalar particle observed in nature





- Likely the key to understanding important outstanding questions in particle physics
- Spin & CP quantum numbers are some of the most fundamental properties to study

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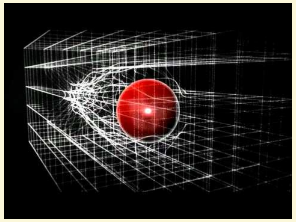

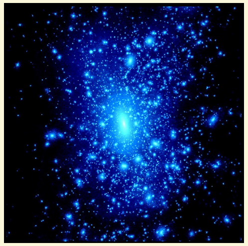

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Spin & CP Measurements

- Spin & CP discrete quantum numbers generally tricky to “measure”
- Many possible interaction terms produce the same spin and CP quantum numbers

An example:
All of these terms produce spin-2 $H \to ZZ \to 4l$ decays

$$\begin{aligned} A(X_{J=2} \to V_1 V_2) \sim \Lambda^{-1} \Big[& 2c_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta} \\ & + c_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha} \right) + c_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta} \\ & + m_V^2 \left(2c_5 t_{\mu\nu} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} + 2c_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon^{*\nu}_{V_1} \epsilon^{*\alpha}_{V_2} - \epsilon^{*\alpha}_{V_1} \epsilon^{*\nu}_{V_2} \right) + c_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon^*_{V_1} \epsilon^*_{V_2} \right) \\ & + c_8 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + c_9 t^{\mu\alpha} \tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon^{*\nu}_{V_1} \epsilon^{*\rho}_{V_2} q^\sigma \\ & + \frac{c_{10} t^{\mu\alpha} \tilde{q}_\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon^{*\nu}_{V_1} (q \epsilon^*_{V_2}) + \epsilon^{*\nu}_{V_2} (q \epsilon^*_{V_1}) \right) \Big] , \end{aligned}$$

- In general, the best we can do is rule out each individual term in favor of the Standard Model term

Spin & CP Measurements

- Higgs spin and CP measurements are performed by using distributions of kinematic variables :
  - Interaction terms producing different spin and CP quantum numbers exhibit different distributions
  - These differences discriminate between different spin and CP hypotheses
  - The number of kinematic variables available differs depending on the Higgs decay channel

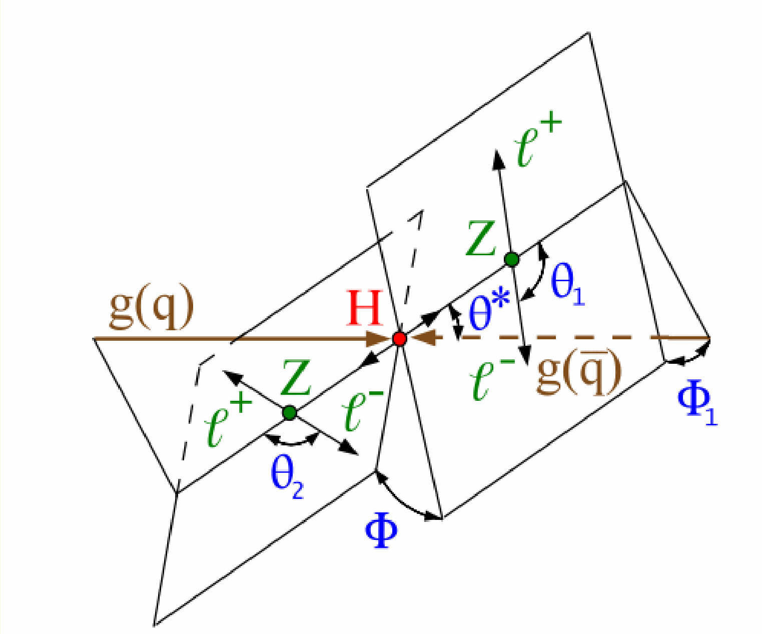
J^{CP} in $H \to ZZ \to 4l$

- Has the most kinematic information available
- 8 kinematic variables :

  5 angles : $\theta^*, \theta_1, \theta_2, \Phi, \Phi_1$

  3 masses: m_{Z1}, m_{Z2}, m_{4l}

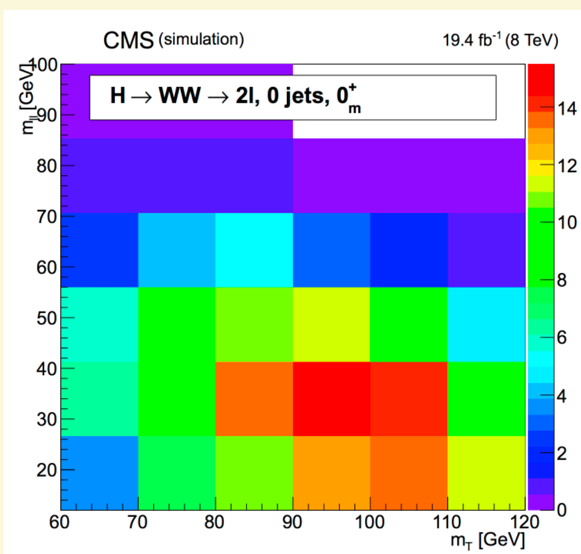
  Collectively denote as **Ω**

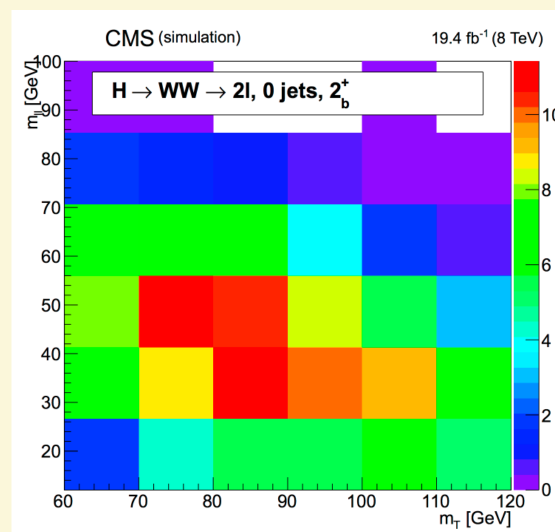


- Can also condense the information into a set of kinematic discriminants
  - Can be based on matrix element calculations (CMS) or simulation trained MVA discriminants (ATLAS)

J^{CP} in $H \rightarrow WW \rightarrow l\nu l\nu$

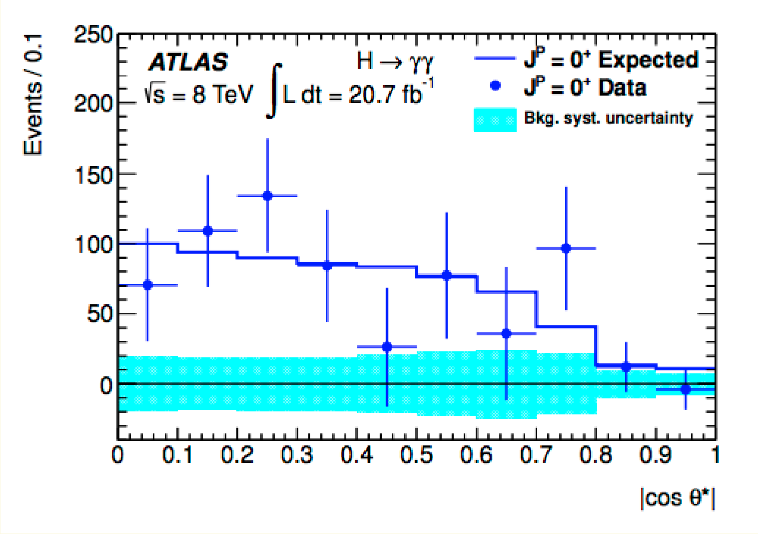
- Due to the presence of two neutrinos, cannot completely determine the decay kinematics
- Rely on a set of possibly correlated kinematic observables:
  - m_{ll} & m_T (CMS)
  - BDT trained using input variables m_{ll} , $\Delta\varphi_{ll}$, $p_{T\,ll}$, m_T (ATLAS)

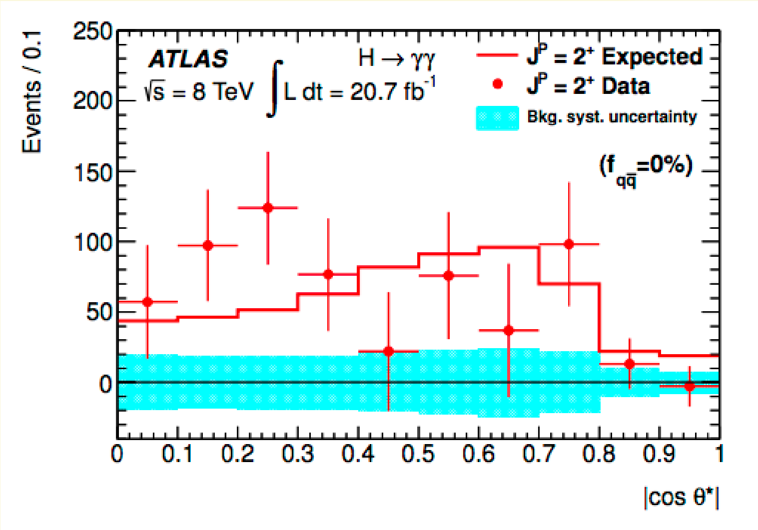




J^{CP} in $H \to \gamma\gamma$

- Only a single kinematic variable encodes the spin information:
  - $\cos\theta^*$: cosine of scattering angle in the Collins-Soper frame





Spin

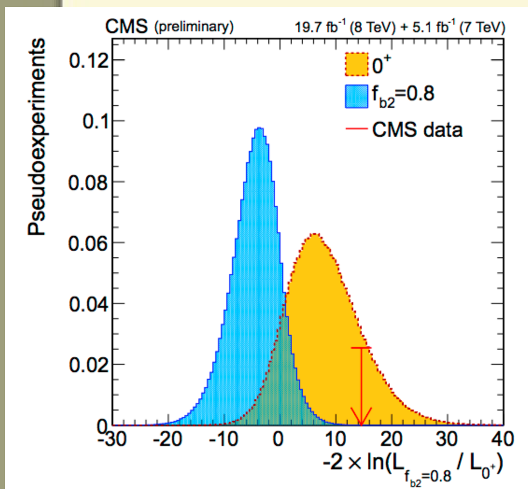
- Main sensitivity from H→ZZ→4l channel
- Hypothesis testing against:
  - all mixtures of spin 1 states
  - each individual spin 2 state

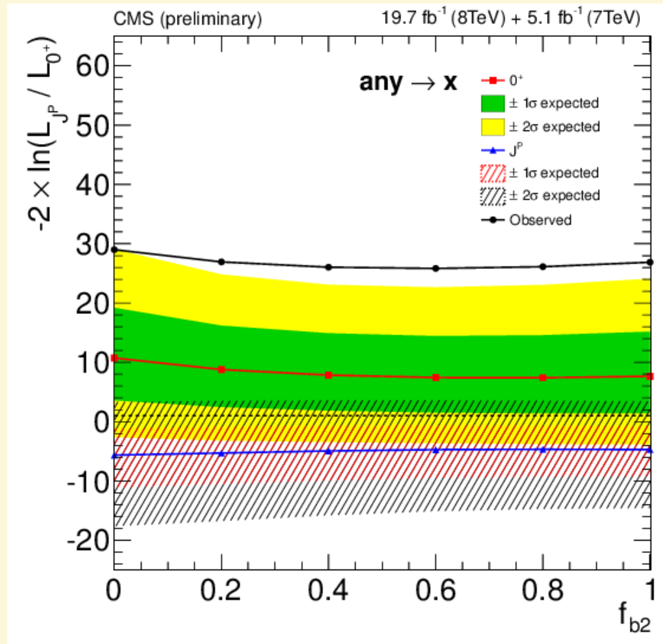
Vector　　　　Pseudo-Vector

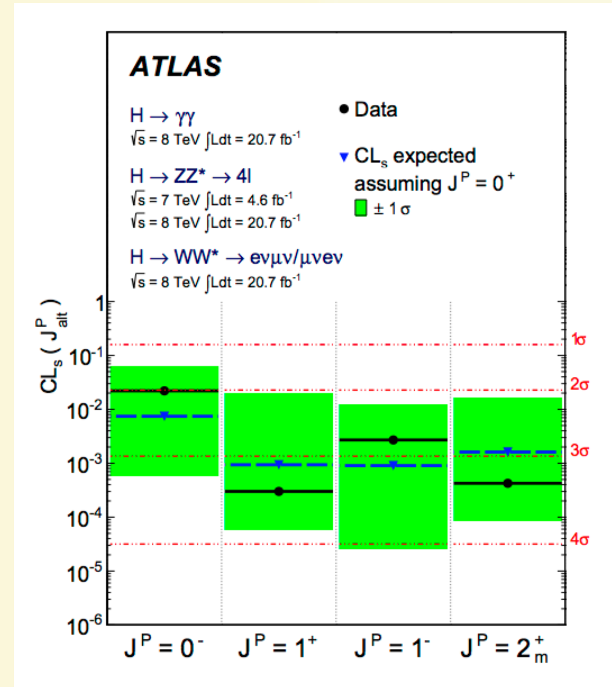
spin-1
$$A(X_{J=1} \to VV) = b_1 \left[(\epsilon_1^* q)\,(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)\,(\epsilon_1^* \epsilon_X) \right] + b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon_X^{\alpha} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \tilde{q}^{\beta}$$

spin-2
$$\begin{aligned} A(X_{J=2} \to V_1V_2) \sim \Lambda^{-1} \Big[& 2c_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta} \\ & + c_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha} \right) + c_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta} \\ & + m_V^2 \left(2c_5 t_{\mu\nu} \epsilon_{V_1}^{*\mu} \epsilon_{V_2}^{*\nu} + 2c_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_{V_1}^{*\nu} \epsilon_{V_2}^{*\alpha} - \epsilon_{V_1}^{*\alpha} \epsilon_{V_2}^{*\nu} \right) + c_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon^*_{V_1} \epsilon^*_{V_2} \right) \\ & + c_8 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + c_9 t^{\mu\alpha} \tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_{V_1}^{*\nu} \epsilon_{V_2}^{*\rho} q^\sigma \\ & + \frac{c_{10} t^{\mu\alpha} \tilde{q}_\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_{V_1}^{*\nu} (q \epsilon^*_{V_2}) + \epsilon_{V_2}^{*\nu} (q \epsilon^*_{V_1}) \right) \Big] , \end{aligned}$$

Spin-1 Results

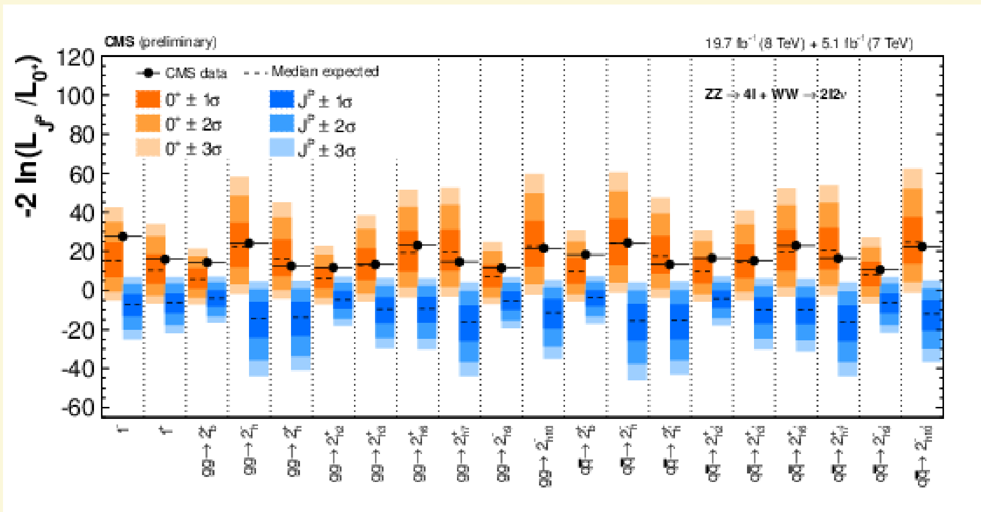




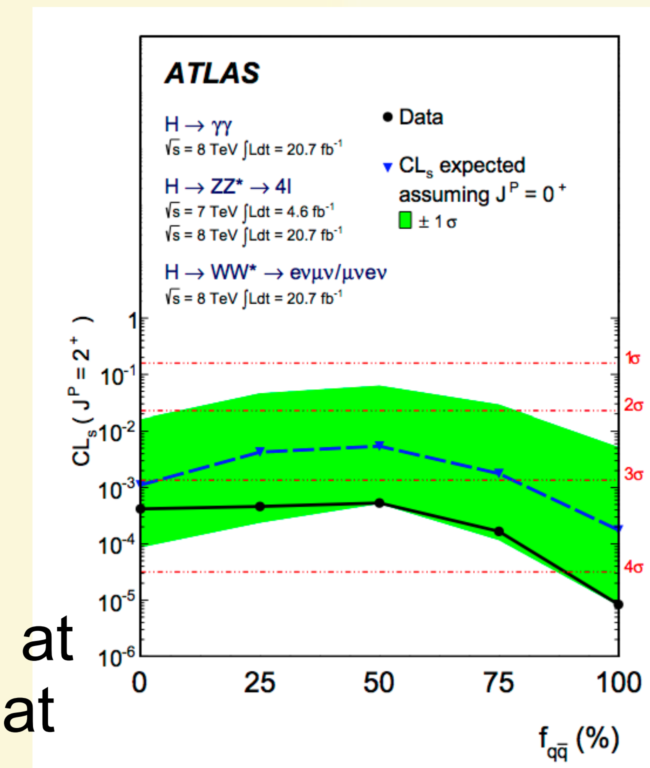


- All spin-1 terms and mixtures excluded at about 4sigma or more
- Similar sensitivity for ATLAS and CMS, where they are comparable

Spin-2 Results



- Combination of HWW and HZZ yields a slight improvement in sensitivity

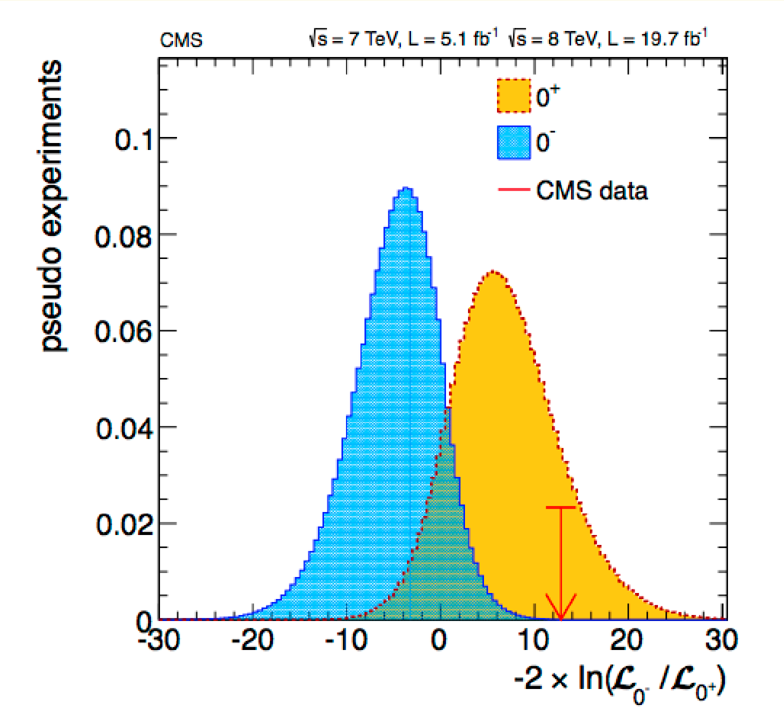


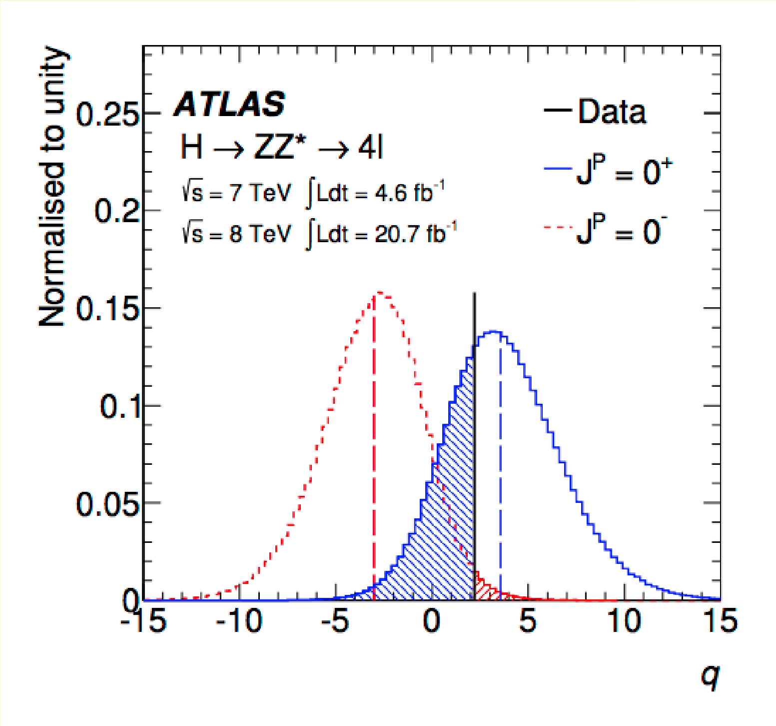
- ATLAS tests minimum coupling spin-2 term for various mixtures of production mechanism
- Similar sensitivity for CMS and ATLAS

- Most spin-2 terms and mixtures excluded at about 4σ or more, with a few exceptions that are excluded at about 3σ

CP

- Pure pseudo-scalar tested against SM Higgs
- Pseudoscalar excluded at 99.9% (CMS) and 98% (ATLAS)





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Spin & CP Summary

(1) Absent complicated conspiracies, we are very sure that the Higgs boson is spin-0

(2) A pure pseudo-scalar is ruled out

Anomalous Couplings

• There remains the possibility that Higgs is some mixture of scalar and pseudoscalar
• To resolve this question, need to move from hypothesis testing to parameter estimation

$$\begin{aligned} A(X_{J=0} \to V_1 V_2) &= v^{-1} \left(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \right. \\ &+ a_2 f_{\mu\nu}^{*(Z)} f^{*(Z),\mu\nu} + a_3 f_{\mu\nu}^{*(Z)} \tilde{f}^{*(Z),\mu\nu} \\ &+ a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\ &+ \left. a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma)} f^{*(\gamma),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma)} \tilde{f}^{*(\gamma),\mu\nu} \right), \end{aligned}$$

Anomalous Couplings

- There remains the possibility that Higgs is some mixture of scalar and pseudoscalar
- To resolve this question, need to move from hypothesis testing to parameter estimation

SM HZZ decay (a1)

Leading momentum dependent correction

$$
\begin{aligned}
A(X_{J=0} \to V_1 V_2) \;=\; & v^{-1}\left(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \right. \\
& + \; a_2 f_{\mu\nu}^{*(Z)} f^{*(Z),\mu\nu} + a_3 f_{\mu\nu}^{*(Z)} \tilde{f}^{*(Z),\mu\nu} \\
& + \; a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\
& + \; \left. a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma)} f^{*(\gamma),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma)} \tilde{f}^{*(\gamma),\mu\nu} \right),
\end{aligned}
$$

non-SM scalar (a2)

SM Z

SM

Pseudo-scalars (a3)

Anomalous Couplings

- In the Standard Model:

(ZZ couplings)

- **a1 = 2**
- a2 is O($10^{-3} - 10^{-2}$)
- a3 is effectively 0

(Z couplings)

- $a_2^Z = 0.0035$
- $a_3^Z = 0$

(couplings)

- $a_2 = -0.004$
- $a_3 = 0$

SM HZZ decay (a1)

Leading momentum dependent correction

$$A(X_{J=0} \to V_1 V_2) = v^{-1} \left(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q^2_{Z_1} + q^2_{Z_2}}{(\Lambda_1)^2} \right] m_Z^2 \epsilon^*_{Z_1} \epsilon^*_{Z_2} \right.$$
$$+ \; a_2 f^{*(Z)}_{\mu\nu} f^{*(Z),\mu\nu} + a_3 f^{*(Z)}_{\mu\nu} \tilde{f}^{*(Z),\mu\nu}$$
$$+ \; a_2^{Z\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f^{*(Z)}_{\mu\nu} \tilde{f}^{*(\gamma),\mu\nu}$$
$$\left. + \; a_2^{\gamma\gamma} f^{*(\gamma)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{\gamma\gamma} f^{*(\gamma)}_{\mu\nu} \tilde{f}^{*(\gamma),\mu\nu} \right),$$

non-SM scalar (a2)

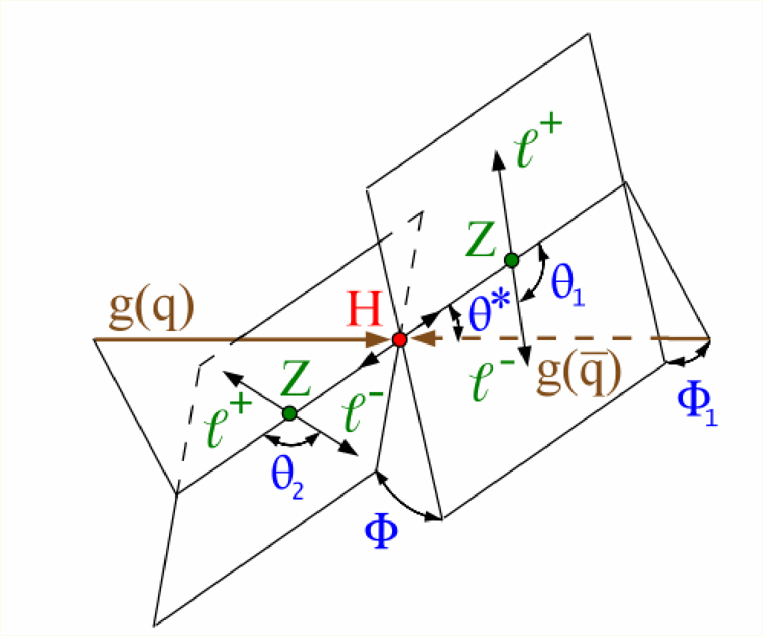
SM Z

SM

Pseudo-scalars (a3)

Maximum Likelihood Fits

- Build probability density functions for these 8 variables as functions of the model parameters :



$P\,(\,\boldsymbol{\Omega}\,|\,\zeta\,)$,

$\zeta = (a_2^{ZZ}, a_3^{ZZ}, a_2^{Z\gamma}, \ldots)$

- Then fit to the data (maximize likelihood) to extract & constrain coupling coefficients ζ

Constructing the PDF

- Two ways to make the PDF:

(1) Write down the analytic expression for the differential cross section in terms of coupling coefficients and convolute with transfer functions : **Multidimensional Fit**

$$P(\vec{p}_T, Y, \phi, m_{4\ell}, m_1, m_2, \vec{\Omega}|\vec{\zeta}) =$$
$$W_{\mathrm{prod}}(\vec{p}_T, Y, \phi, \hat{s}) \times \frac{d\sigma_{4\ell}(m_{4\ell}, m_1, m_2, \vec{\Omega}|\vec{\zeta})}{dm_1^2 dm_2^2 d\vec{\Omega}}$$

Gen-level

Transfer functions: maps generator-level observables to detector-level observables

$$P(\vec{x}^{\mathrm{R}}|\vec{\zeta}) = \int P(\vec{x}^{\mathrm{G}}|\vec{\zeta}) T(\vec{x}^{R}|\vec{x}^{\mathrm{G}}) d\vec{x}^{\mathrm{G}}$$

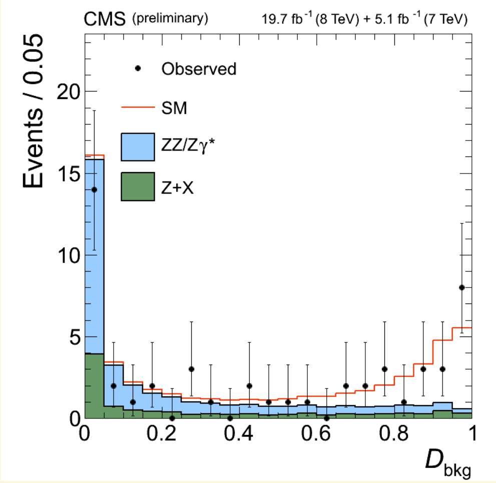
Detector level
(“**R**eco level”)

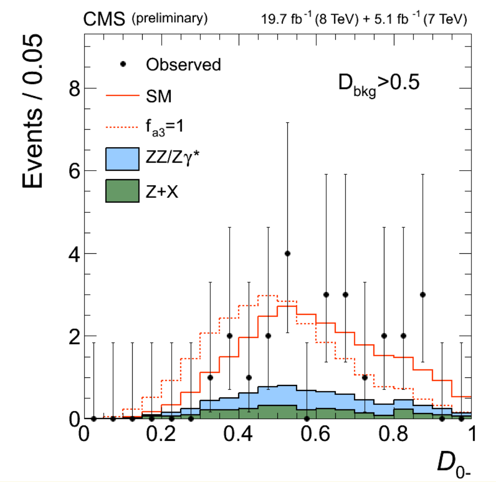
...but extremely computationally challenging

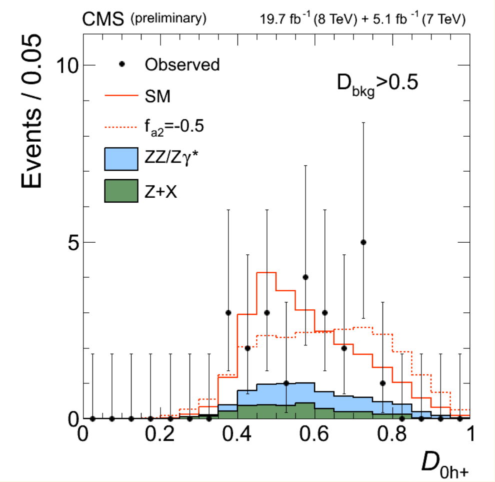
Constructing the PDF

- Two ways to make the PDF:

(2) condense the information from 8 observables to two (or three) Matrix-Element based kinematic discriminants : **KD-method**







...but less flexibility in size of model parameter space that can be simultaneously constrained

Maximum Likelihood Fit

- In practice with only ~25 data events, difficult to constrain the full parameter space
- Restrict the model space to include 2 anomalous couplings at a time (eg. a_2^{ZZ} & a_3^{ZZ})
    - Interpret in context of small deviations from SM

SM HZZ decay (a1)

Leading momentum dependent correction

$$\begin{aligned} A(X_{J=0} \to V_1 V_2) \;=\; v^{-1} \Bigg(& \left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \\ & + a_2 f_{\mu\nu}^{*(Z)} f^{*(Z),\mu\nu} + a_3 f_{\mu\nu}^{*(Z)} \tilde{f}^{*(Z),\mu\nu} \\ & + a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\ & + a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma)} f^{*(\gamma),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma)} \tilde{f}^{*(\gamma),\mu\nu} \Bigg) , \end{aligned}$$

non-SM scalar (a2)

SM Z

SM

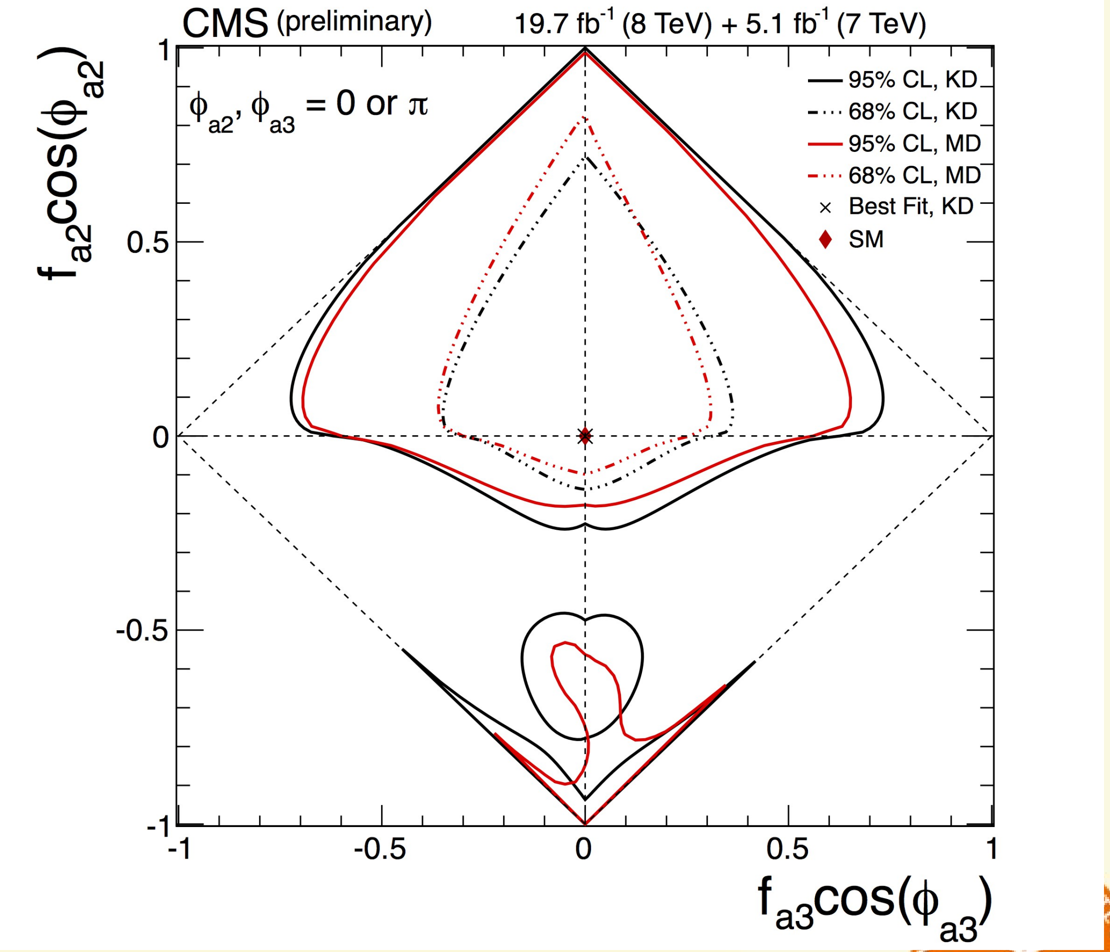
Pseudo-scalars (a3)

Anomalous Coupling Results on (a_2^{ZZ}, a_3^{ZZ})

More accurately, we constrain a_2^{ZZ}/a_1^{ZZ} & a_3^{ZZ}/a_1^{ZZ} , as a_1^{ZZ} is essentially profiled in the fit

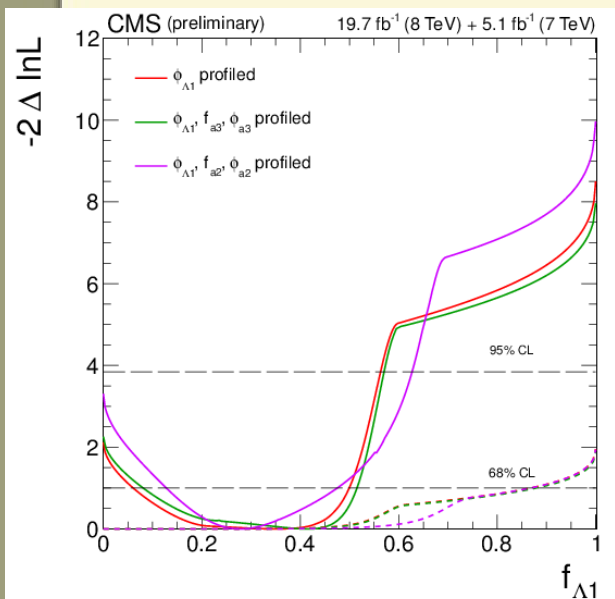
- **No significant deviations from SM**

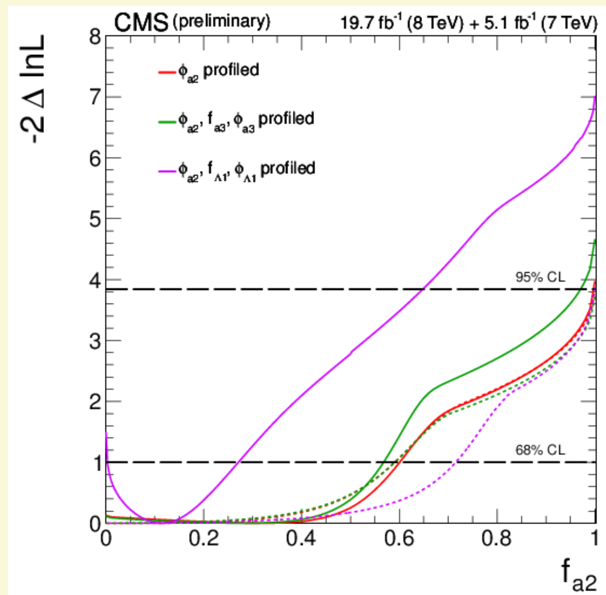
- Two approaches yield very similar constraints
- Potential deviation away from 0 in a_2 and a_3 can produce significant CP violation

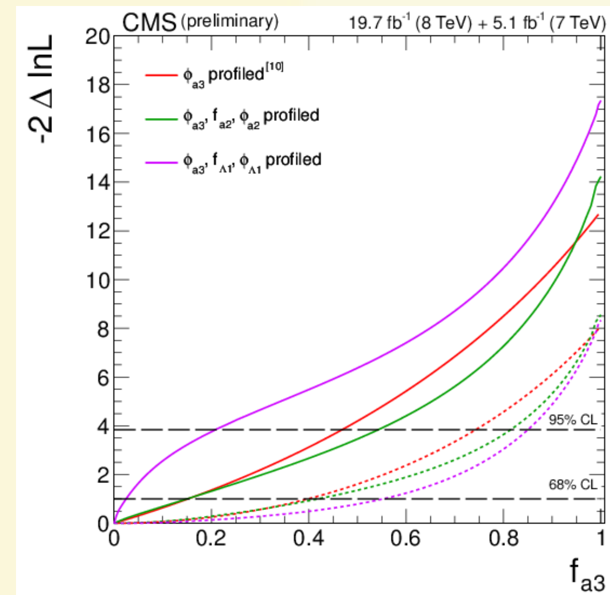


Anomalous Coupling Results

- A full set of constraints on all coupling coefficients mentioned



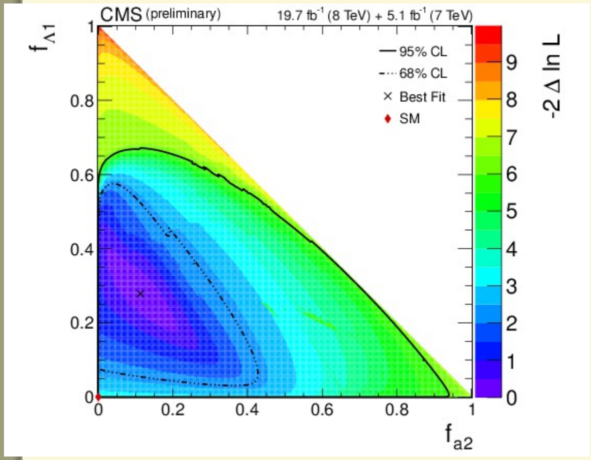


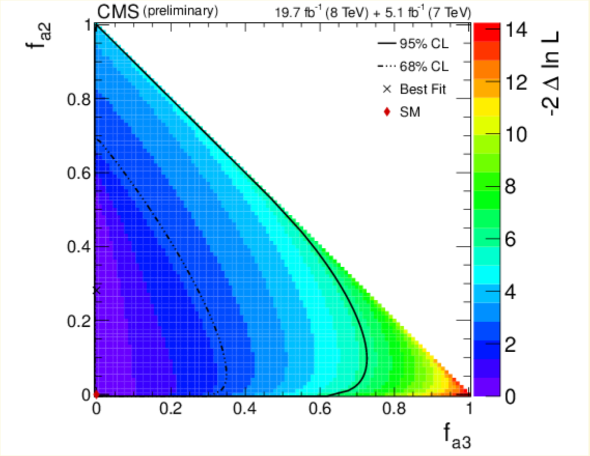


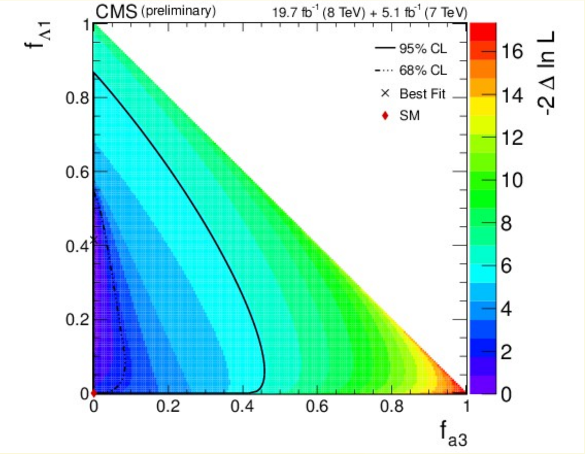
- Including constraints with complex phases of coupling coefficients profiled
- And one other parameter (and its complex phase) profiled
- **No significant deviations from the SM...**

Anomalous Coupling Results

- A full set of constraints on all coupling coefficients mentioned





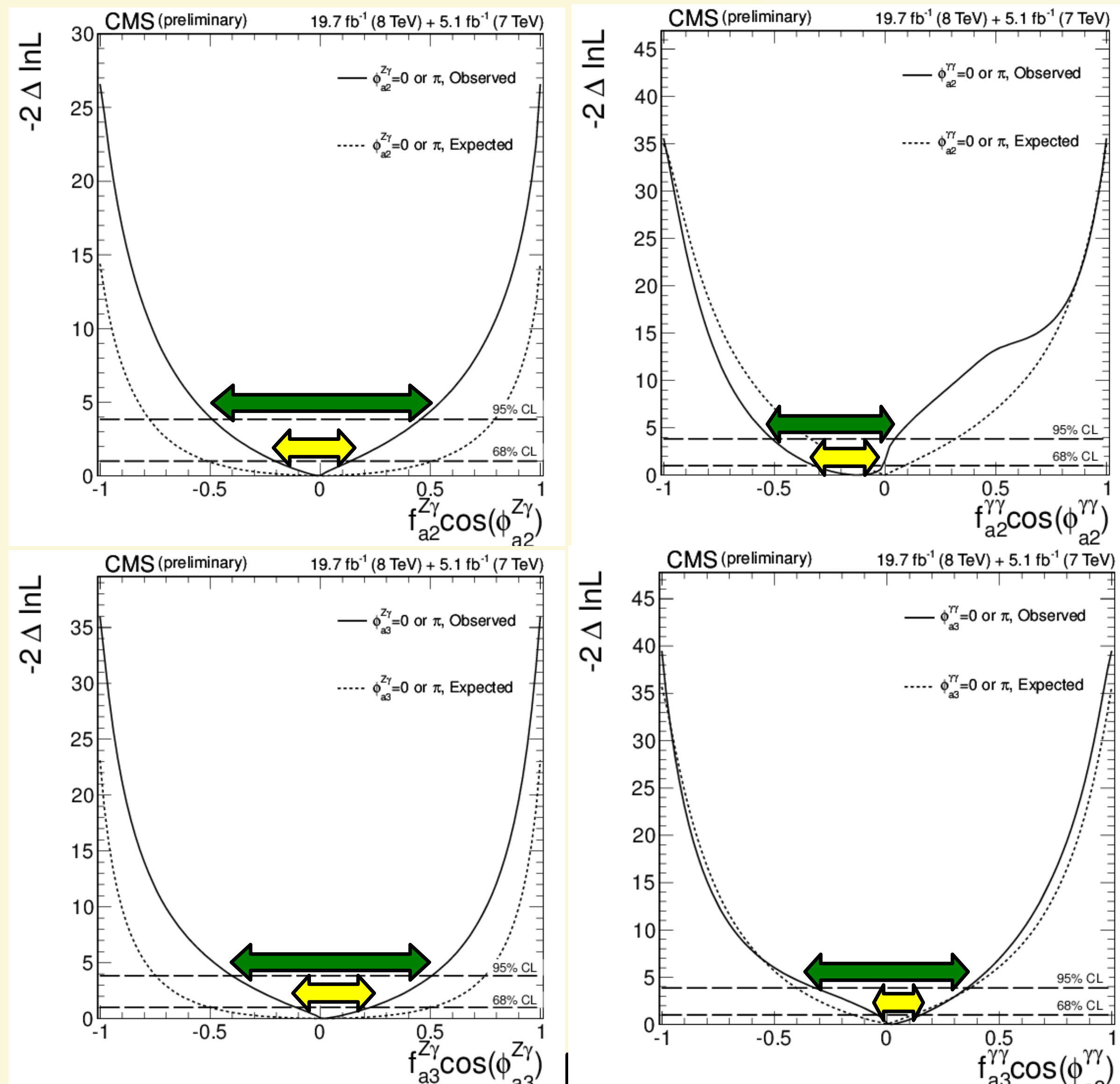


- Including constraints with complex phases of coupling coefficients profiled
- And one other parameter (and its complex phase) profiled
- **No significant deviations from the SM...**

Anomalous Coupling Results: Zγ and γγ couplings

- No deviations from SM
- Currently, sensitivity is limited...

...but in the future, potentially very interesting because signs of new physics may show up in these couplings before the ZZ couplings



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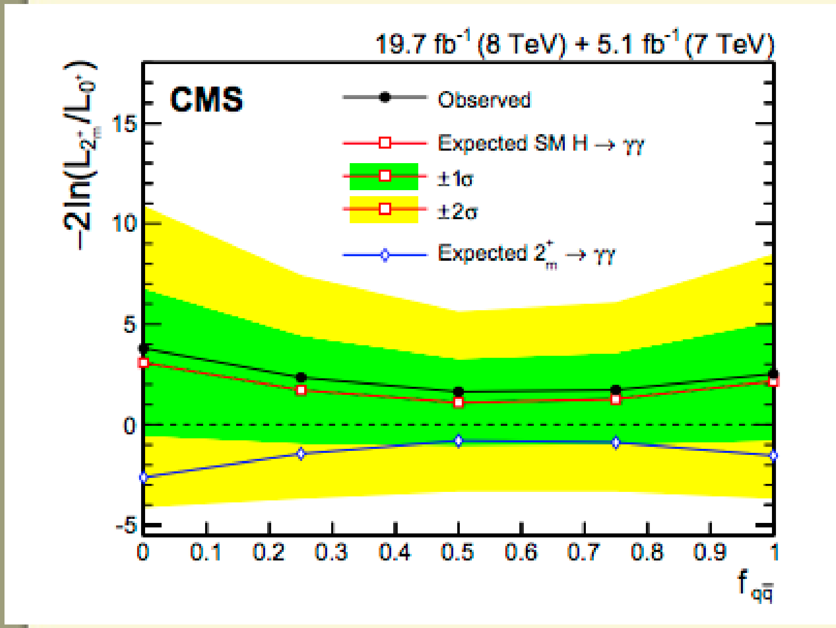
Summary

- Higgs boson is very likely spin-0
- Higgs boson is not a pure pseudoscalar
- No evidence of anomalous couplings – at same order of magnitude as the SM HZZ term

- All J^{CP} properties so far consistent with SM Higgs
- More stringent tests ahead with increased dataset

Backup

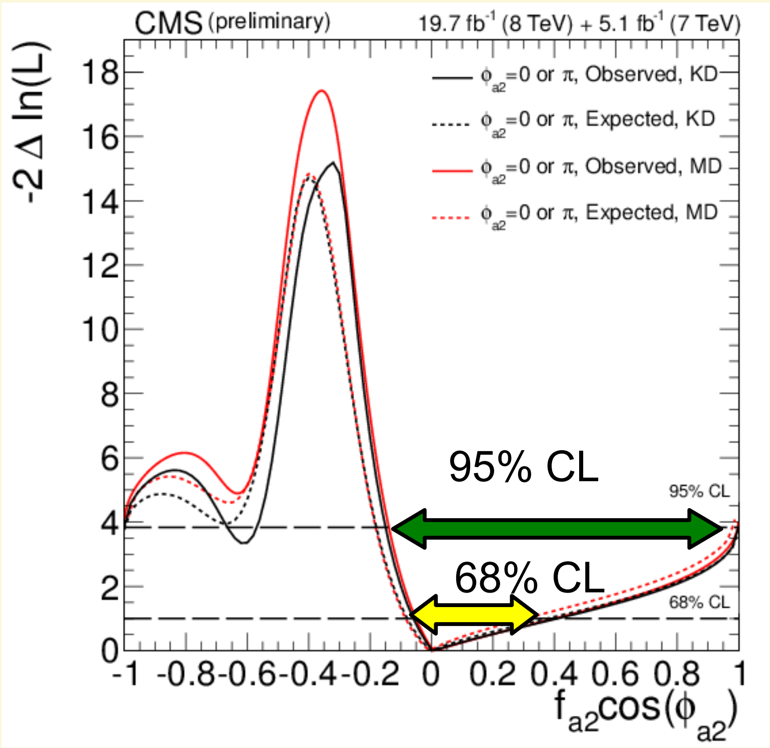
Spin-2 Results Hgg

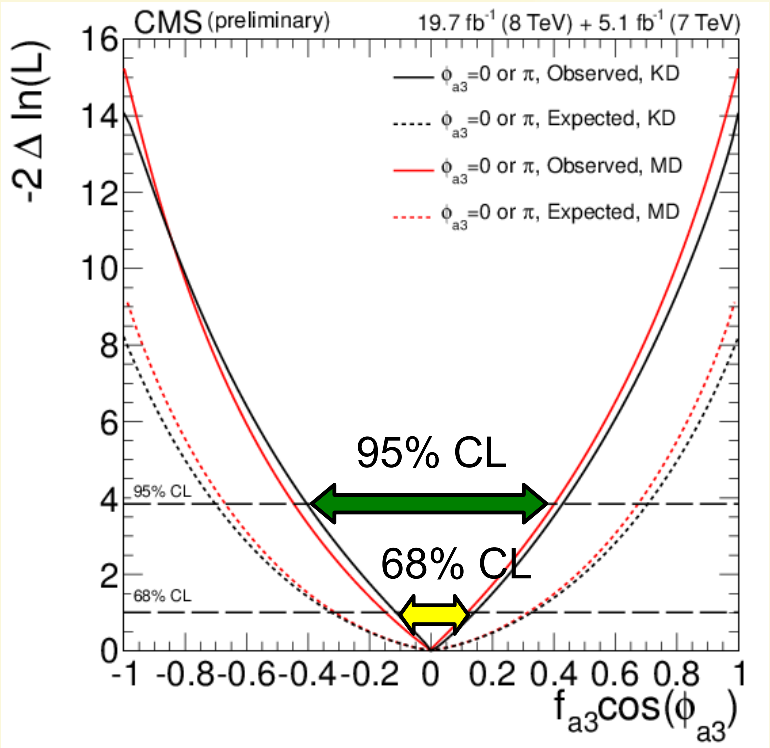


$f_{q\bar{q}}$	$1 - CL_s$ expected	observed
0	0.92	0.94
0.25	0.78	0.83
0.50	0.64	0.71
0.75	0.69	0.75
1	0.83	0.85

Anomalous Coupling Results
on (a_2^{ZZ}, a_3^{ZZ})

• Constraints, assuming no deviation in other couplings





• Constraints can be mapped to parameter space of specific Beyond-SM models → guide for model building

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