Constraining new physics in the Higgs sector using differential and fiducial cross section measurements from the LHC.

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Two goals for this talk:

i. Tell you about Hype – a statistical tool that makes it easy to perform hypothesis tests with unfolded distributions.

ii. Advertise such tests for fiducial Higgs cross section measurements performed at the LHC.

To that end: show you three results obtained using **LHC Run 1 data**:

1 μ determination

2 κ framework both from $H \to \gamma\gamma$ and $H \to 4\ell$ cross sections

3 Confront LHC $H \to \gamma\gamma$ measurements with Spin 2 models

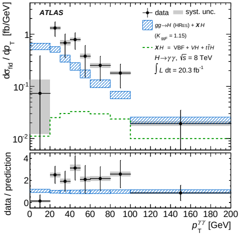
Fiducial measurements of the H(125) Higgs

Fiducial measurements are carried out close to experimental region.

$\longrightarrow$ minimizes extrapolation of regions of phase space that are not actually measured.

Two sets of **fiducial** Higgs Boson cross sections from **ATLAS**.

[JHEP09(2014)112] [Physics Letters B 738 (2014) 234-253] similar results from CMS are in preparation



Higgs $p_T^{\gamma\gamma}$ spectrum

Measured channels: $H \rightarrow \gamma\gamma$ and $H \rightarrow 4\ell$

Assumptions: Existence of narrow resonance at $m_H = 125.4$ GeV.

$\rightarrow$ Measured yields unfolded to **particle level**.

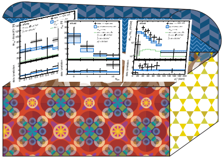
$\rightarrow$ Available on **HepData**:

http://hepdata.cedar.ac.uk/view/ins1306615

1. Minimal *underlying* physics dependence
   unfolding into truth fiducial region closely related to measured fiducial selection
2. Full set of *systematic* bin-by-bin correlations

Ok – so do you want to get hyped?

Treasure chest for *theorists and phenomenologists*:



Do you have a new physics model and it impacts kinematics in the Higgs sector? Why not test it! Do you want to know how well certain dim-6 operator hold up against the measurements? Want to do your own Spin test?

$\rightarrow$ Hype – (Hyp)othesis (e)valuator for unfolded distributions

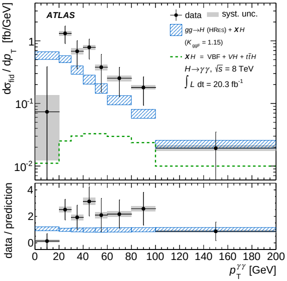
Features:

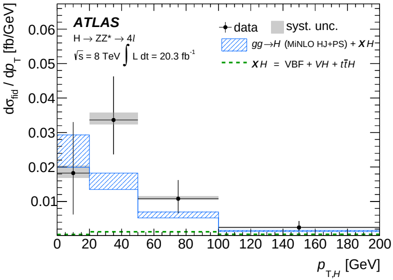
i. **Easily** perform hypothesis tests between two or more hypotheses
ii. Plug-ins: μ and κ-type scans
iii. Direct import of **Hep-Data** measurements
iv. Easy to **interface custom code**
v. For hypothesis tests: automatically determines number of pseudo-experiments needed

Project home: **https://hype.hepforge.org/**

Results with Run 1 data: Higgs signal strength μ fits

Analyze two differential distributions with Hype simultaneously: $p_T^{\gamma\gamma}$ and $p_T^{4\ell}$





Blue: SM; green: non-ggF contribution

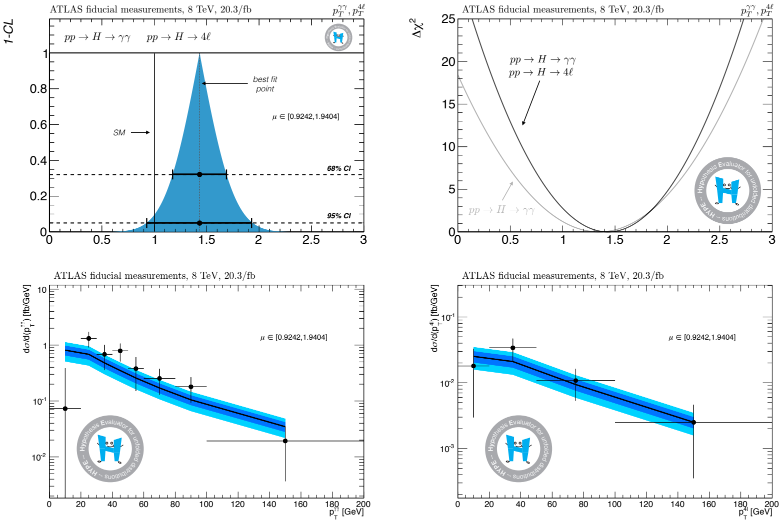
Simplest test:

→ fit 'global' signal strength μ

or

→ production mode dependent coupling strengths $\mu_{\mathrm{ggF}+ttH}$:$\mu_{\mathrm{VBF}+VH}$

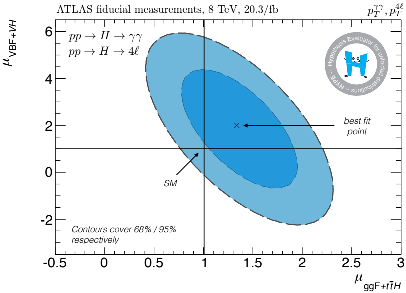
Results with Run 1 data: μ fits

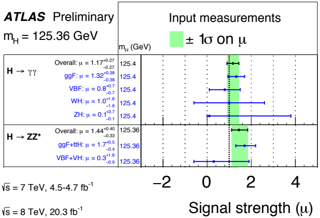


The $\gamma\gamma$ and 4ℓ data favour a larger Higgs boson cross section:

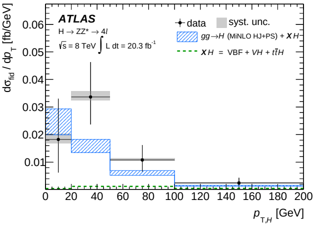
$$\mu = 1.44 \pm 0.26$$

Results with Run 1 data: $\mu_{\mathbf{ggF}+ttH}$ versus $\mu_{\mathbf{VBF}+VH}$





[ATLAS-CONF-2015-007]



Scan result:

$$\mu_{\mathrm{ggF}+ttH} = 1.36 \pm 0.39$$

$$\mu_{\mathrm{VBF}+VH} = 1.85 \pm 1.67$$

Note: The Hype results shown here are based on only on the Higgs pT spectrum. This gives a less precise (and larger) VBF component than that from the official coupling fit that has optimized VBF categories.

Slightly more complicated: κ fits

$\rightarrow$ Leading order tree-level motivated framework

Basic idea simple: allow modifications of prod. and decay of the Higgs

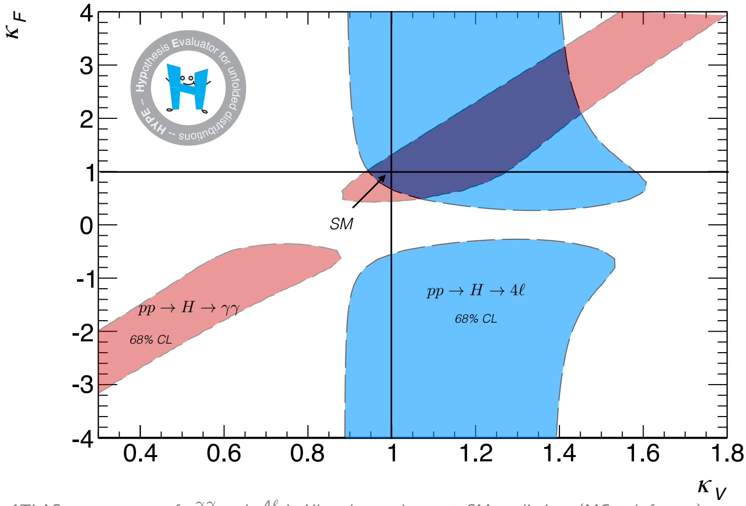
E.g. for $gg \rightarrow H \rightarrow \gamma\gamma$ introduce individual couplings for the top loop:

$$\sigma_{gg\rightarrow H} \backsim a\,\kappa_t^2 + b\,\kappa_b^2 + c\,\kappa_t\kappa_b$$

$$\mathcal{B}(H \rightarrow \gamma\gamma) \backsim \left(a\,\kappa_W^2 + b\,\kappa_t^2 + c\,\kappa_W\kappa_t\right) / \,\Gamma_H(\kappa_i)$$

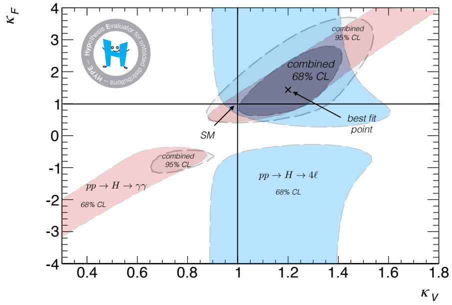
Simplifications possible, e.g. alter couplings to fermions
$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$ and vector bosons $\kappa_V = \kappa_Z = \kappa_W$

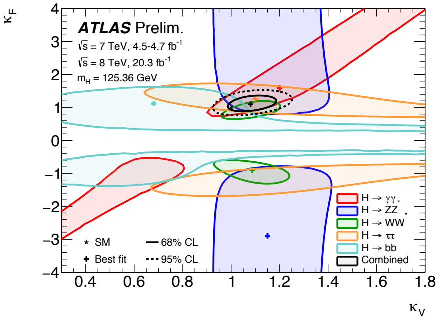
Fit of the Higgs boson's coupling to fermions κ_F and vector bosons κ_V:



Input: ATLAS measurement of $p_T^{\gamma\gamma}$ and $p_T^{4\ell}$ in Higgs boson decays + SM predictions (MC + k-factors)

Results with Run 1 data: κ fits





Fairly good agreement with official ATLAS results!

Results with Run 1 data: Spin 2 tests

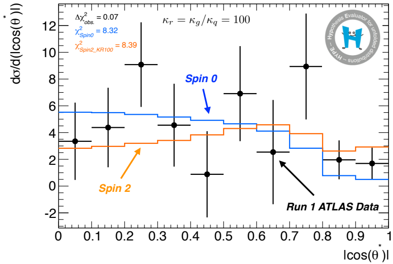
Is the H(125) a Spin 2 imposter? Not a nested Hypothesis as μ and κ

Zero Hypothesis: SM

Alternative Hypothesis: Spin 2^+ with given set of couplings

Effective Lagrangian of alternative hypothesis: *arXiv:1306.6464v3*

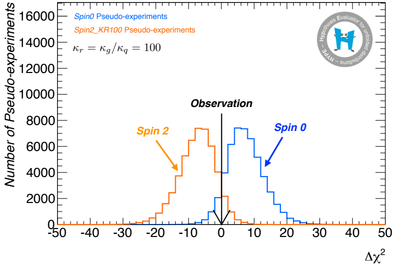
$$\mathcal{L} = -\frac{\kappa}{\Lambda} \sum_{f=q,\ell} \kappa_f \, T^f_{\mu\nu} X_2^{\mu\nu} - \frac{\kappa}{\Lambda} \sum_{V=Z,W,\gamma,g} \kappa_V \, T^V_{\mu\nu} X_2^{\mu\nu}$$

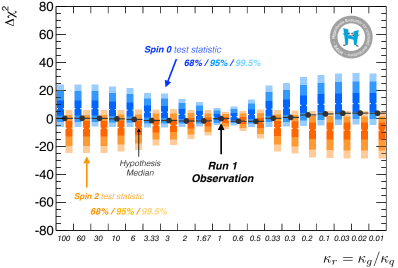


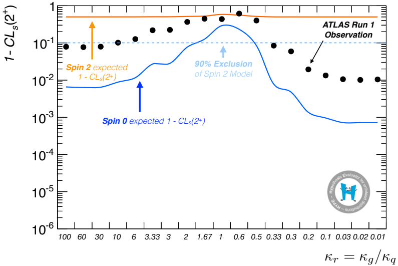
Variable sensitive to spin: $|\cos\theta^*|$

Hype generates pseudo-experiment ensembles to calculates test statistic distributions for CL_s test.

Results with Run 1 data: Spin 2 tests







Can convert this into a limit of $\kappa_r \in [0.33, 10]$ 90% CL_s

Much of param. space excluded at 90%

All results shown here are based on only $|\cos\theta^*|$ distribution. Significant improvement in sensitivity if one also would include $p_T^{\gamma\gamma}$ information.

Conclusions

Since fiducial/differential measurements are model independent:

i. Possible to confront with any prediction (data stays the same!)

ii. Easy to do interpretations, e.g. extract μ, κ, or spin as shown in this talk!

Already with Run 1 data, possible to do tests using more advanced theoretical frameworks:

i. General EFT tests (LO or NLO)

ii. Simplified cross-sections

$\rightarrow$ Tests would be even more powerful if statistical correlation between distributions were available: can then do simultaneous fits with several distributions.

Also presented you the **Hype** tool: a statistics code that makes it easy to carry out such tests; close to release version 1.0.

Features:

i. For nested and non-nested Models

ii. Plug-ins: μ, κ-type scans

iii. Hep-Data files can be imported

iv. Easy to interface with custom code

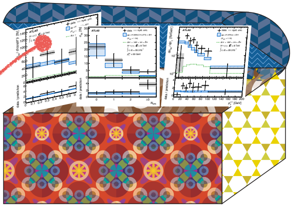
v. **Includes large set of examples; including how to reproduce all results in this talk**

https://hype.hepforge.org/

Backup

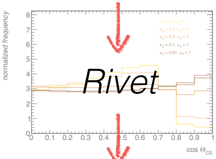
Flow of a typical Hype analysis:

Measurements



Predictions

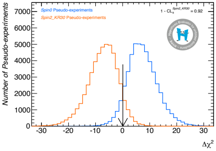
(MG5_)[a]MC@NLO+ PS

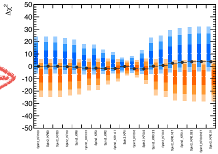


Spin0 hypothesis predictiona and uncertainty covariance
Spin0.XSec: 4.28232 4.25835 ….
Spin0.XSecUncert: 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
Spin0.FullyUncorrelatedUncertainties: 1

Spin2 hypothesis predictiona and uncertainty covariance
Spin2.XSec: 3.04068 3.12015 ….
Spin2.XSecUncert: 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
Spin2.FullyUncorrelatedUncertainties: 1

HypE -- Hypothesis Evaluator for unfolded distributions





Say, you have two hypothesis: SM and alternative theory

Neyman-Pearson Lemma: Likelihood ratio of both Hypothesis

$$\mathcal{L}_{\mathrm{alt}}/\mathcal{L}_{\mathrm{zero}}$$

most powerful discriminator *(called a test statistic)* you can build.

Applied to binned data: $-2\ln\left(\mathcal{L}_{\mathrm{alt}}/\mathcal{L}_{\mathrm{zero}}\right) = \chi^2_{\mathrm{alt}} - \chi^2_{\mathrm{zero}} = \Delta\chi^2$ where

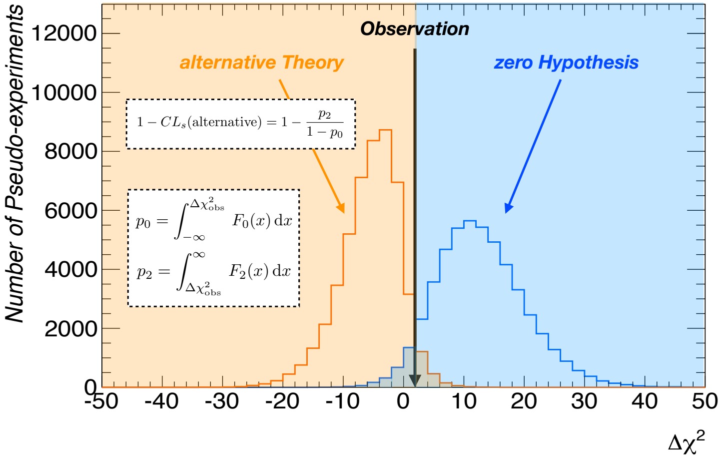
$$\chi^2_{hypo} = \left(\vec{x}_{\mathrm{data}} - \vec{x}_{\mathrm{hypo}}\right) C^{-1}_{\mathrm{hypo}} \left(\vec{x}_{\mathrm{data}} - \vec{x}_{\mathrm{hypo}}\right) .$$

To interpret an observed value of $\Delta\chi^2$ in data:

* Need to know how test statistic is distributed given either zero or alternative theory is the true underlying theory.
* Can be done using Monte Carlo Method with **pseudo-experiments**

Used Test Statistic and CL_s(alternative)

Example test statistic distribution for zero and alternative hypothesis:



Hype automatically determines needed number of pseudo-experiments

to achieve numerical accuracy depending on the observation.

The Hype Approach to Pseudo-Experiments

Besides this normal implementation, Hype has a fast toy option:

$$\chi^2_{hypo} = (\vec{x}_{\rm data} - \vec{x}_{\rm hypo})\, C^{-1}\, (\vec{x}_{\rm data} - \vec{x}_{\rm hypo})\ .$$

This option makes use of the asymptotic behaviour of $\Delta\chi^2$

* Reduces the problem of generating pseudo-experiments with N bins to the *two* or *more* relevant degrees of freedom

→ Cross terms cancelation in $\Delta\chi^2$; given fixed normalization test statistic normal distributed.

* Breaks down when floating normalization: $\vec{x}_{\rm hypo} \rightarrow \mu_{\rm hypo} \cdot \vec{x}_{\rm hypo}$

→ Problem now non-linear, normalization depends on pseudo-experiment.

→ Can be diagonalized in a new set of variables and solved for each pseudo-experiment; leaves only 2 effective degrees of freedom

Reduces toy-generation effort from $2\, N_{\rm bins}$ to 4 random numbers.

Can also be generalized for cases where $C \rightarrow C_{\rm hypo}$.

With this options it takes **3s** to produce 1M pseudo-experiments.

It is activated automatically when the covariances are identical, and it's accuracy checked on the fly with normal pseudo-experiments.

Partial expressions for κ_F and κ_V:

$$\sigma^{\text{SM}}_{gg\to H\to\gamma\gamma} \times \frac{\kappa_F^2\ \left(1.59\,\kappa_V^2 + 0.07\,\kappa_F^2 - 0.66\,\kappa_V\kappa_F\right)}{0.25\,\kappa_V^2 + 0.75\,\kappa_F^2}$$

$$\sigma^{\text{SM}}_{\text{VBF},H\to\gamma\gamma} \times \frac{\kappa_V^2\ \left(1.59\,\kappa_V^2 + 0.07\,\kappa_F^2 - 0.66\,\kappa_V\kappa_F\right)}{0.25\,\kappa_V^2 + 0.75\,\kappa_F^2}$$

$$\sigma^{\text{SM}}_{gg\to H\to 4\ell} \times \frac{\kappa_F^2\ \kappa_V^2}{0.25\,\kappa_V^2 + 0.75\,\kappa_F^2}$$

$$\sigma^{\text{SM}}_{\text{VBF},H\to 4\ell} \times \frac{\kappa_V^4}{0.25\,\kappa_V^2 + 0.75\,\kappa_F^2}$$

See [ATLAS-CONF-2015-007] for more information