An EFT interpretation of STXS measurements at CMS

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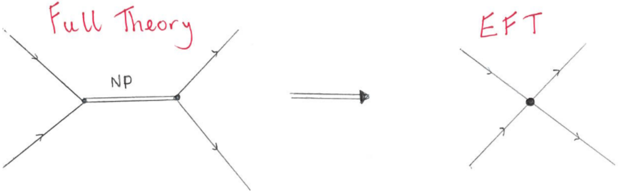
Pushing the Boundaries Workshop
19 Sept 2019

Introduction

- **Theory**: EFT increasingly popular tool to investigate BSM physics
  - large interest in Higgs sector $\Rightarrow$ substantial developments in recent years
  - in-light of no NP @ TeV scale, assume exists at $\Lambda \gg m_H$

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

  - dynamics: described through higher dim operators featuring SM fields



- **Experiment**: Simplified Template Cross Section (STXS) framework
  - natural progression of per-production mode signal strengths, μ_i
  - measure XS: increasingly granular regions of Higgs phase space

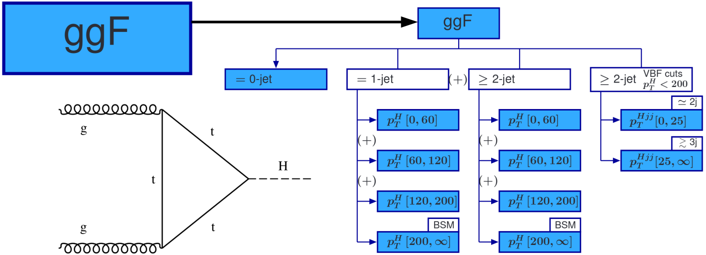
- **Bridging the gap**: EFT interpretation of STXS measurements
  - re-parametrize STXS bins in terms of EFT Wilson coefficients

Overview

1. Simplified Template Cross Sections (STXS)
   - Introduction
   - Stages
   - Status of STXS measurements @ CMS
2. Re-interpretation in an EFT framework
   - Higgs Effective Lagrangain
   - Deriving an EFT parametrization for STXS measurements
   - Examples: EFT parametrization
3. Constraining EFT parameters: χ^2 analysis
   - Results

STXS: introduction

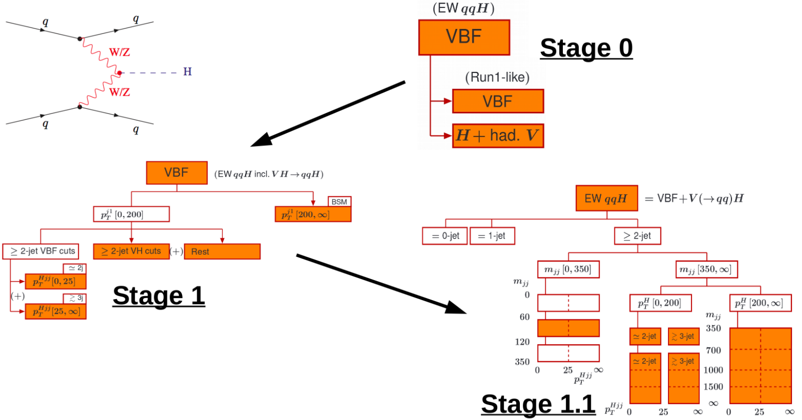
- Coherent framework for increasingly granular Higgs measurements
  - isolate mutually exclusive regions of Higgs phase space (bins)
  - split by production mode + kinematics



- Aims: maximise experimental sensitivity whilst systematically reducing theory dependence folded into measurements
  - design bins to have constant theory unc.
  - + isolate possible BSM physics
  - coherence permits **combinations across decay channels**

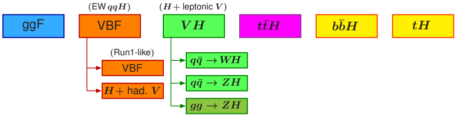
Stages

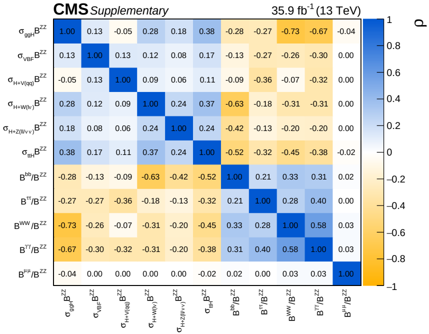
- Evolution of framework (with increasing stats) defined in **stages**:
  - 0: SM production modes
  - 1: splitting by kinematic properties (p_T^H, $N_{\rm jets}$,...)
  - 1.1: revision based on expected sensitivity of full Run 2 dataset

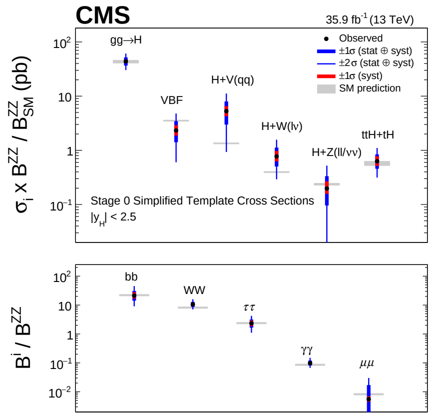


Status of STXS measurements @ CMS

- 2016 combination of **Stage 0** measurements: [Eur. Phys. J. C (2019) 79: 421]

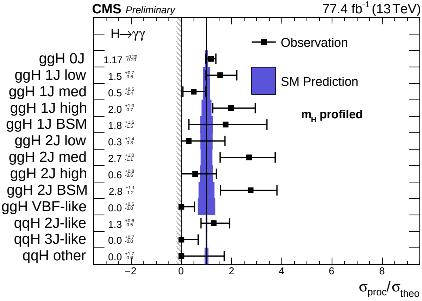




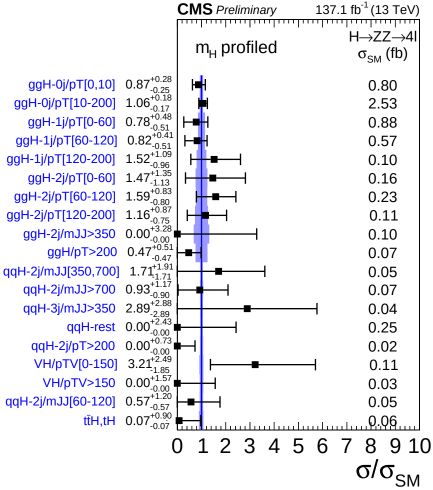


Status of STXS measurements @ CMS

- **Stage 1** measurements in most decay channels: $\gamma\gamma$, VH(bb), $\tau\tau$
- Run 2 Legacy: adhere to **stage 1.1** binning scheme
  - public 1.1 measurements in 4ℓ using full dataset



- Intermediate combination:
  - frankenstein of different stages
  - direct STXS meas. not possible
    $\Rightarrow$ motivates interpretations...

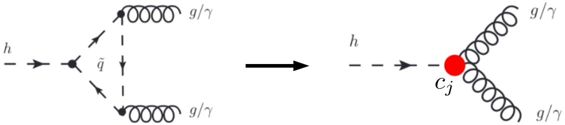


Re-interpretation in an EFT framework

- Goal: parametrize each STXS bin in terms of EFT parameters
- Higgs Effective Lagrangian (HEL): 39 flavour independent dim-6 operators

$$\mathcal{L}_{\mathrm{HEL}} = \mathcal{L}_{\mathrm{SM}} + \sum_j c_j \mathcal{O}_j$$

  - NP: deviations from zero in HEL parameters, c_j



- Require **scaling functions**: $\mu_i(c_j) = \sigma_i^{\mathrm{EFT}}/\sigma_i^{\mathrm{SM}}$
  - for each STXS bin, i

$$\sigma_i^{\mathrm{EFT}} = \sigma_i^{\mathrm{SM}} + \sigma_i^{\mathrm{int}} + \sigma_i^{\mathrm{BSM}}$$

$$\implies \quad \mu_i(c_j) = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$

- **Task**: derive A_j and B_{jk} coefficients for STXS bins

$$\mathcal{O}_g = |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
$$\tilde{\mathcal{O}}_g = |H|^2 G^A_{\mu\nu} \tilde{G}^{A\mu\nu}$$
$$\mathcal{O}_\gamma = |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\tilde{\mathcal{O}}_\gamma = |H|^2 B_{\mu\nu} \tilde{B}^{\mu\nu}$$

$$\mathcal{O}_u = y_u |H|^2 \bar{Q}_L H^\dagger u_R + \mathrm{h.c.}$$
$$\mathcal{O}_d = y_d |H|^2 \bar{Q}_L H d_R + \mathrm{h.c.}$$
$$\mathcal{O}_\ell = y_\ell |H|^2 \bar{L}_L H \ell_R + \mathrm{h.c.}$$

$$\mathcal{O}_H = \left(\partial^\mu |H|^2\right)^2$$
$$\mathcal{O}_6 = \left(H^\dagger H\right)^3$$

$$\mathcal{O}_{HW} = i\,(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\tilde{\mathcal{O}}_{HW} = i\,(D^\mu H)^\dagger \sigma^a (D^\nu H) \tilde{W}^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = i\,(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\tilde{\mathcal{O}}_{HB} = i\,(D^\mu H)^\dagger (D^\nu H) \tilde{B}_{\mu\nu}$$

$$\mathcal{O}_W = i\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = i\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

EFT parametrization: derivation

$$\mu_i(c_j) = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$

- Scaling functions for **stage 1** bins calc. previously: [LHCHXSWG-INT-2017-001]
  - use same approach to derive A_j/B_{jk} for stage 0, 1 & 1.1 bins
  - useful for validation: compare stage 1 coefficients
  - also provide decay channel parametrization: $\Gamma^f(c_j)$

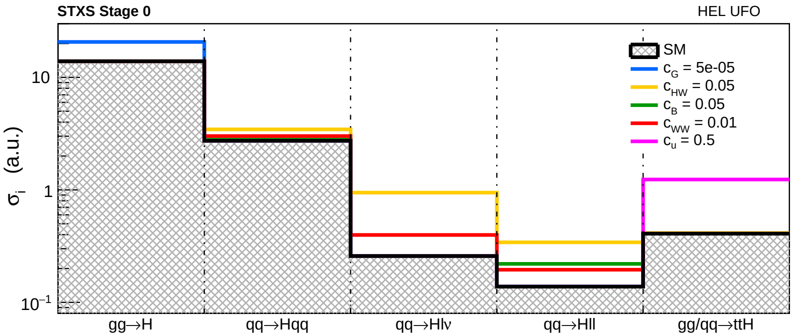
1. Generate events per Higgs prod. mode (LO): MADGRAPH w/ PYTHIA showering
2. Import HEL (UFO): reweight events for different points in HEL param space
   $\Rightarrow$ SM: all $c_j = 0$
   $\Rightarrow$ vary c_j individually: ($c_j =$ w,0,...,0), (0,w,0,...,0), ...
   $\Rightarrow$ pairwise to calc. B_{jk} cross terms ($j \neq k$): (w,w,0,...0), (w,0,w,0,...,0), ...
3. Propagate events through RIVET tool: STXS classification (0, 1 and 1.1)
4. Extract dependence of STXS bin, i, on c_j (or $c_j c_k$): A_j & B_{jk}
   $\Rightarrow$ comparing reweighted cross section to SM

WH Leptonic

$$\boxed{p_T^V\,[0,150]} = 1 + 33\,c_{WW} + 12\,c_{HW} + 320\,c_{WW}^2 + \ldots$$

EFT parametrization: stage 0

- Varying c_j individually...

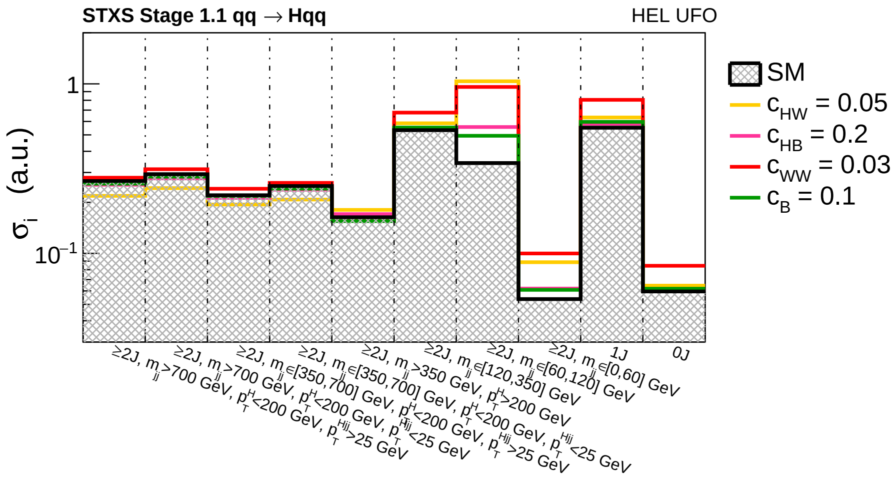


$$\mathcal{O}_G = |H|^2 G^A_{\mu\nu} G^{A,\mu\nu} \qquad \mathcal{O}_{HW} = i(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu} \qquad \mathcal{O}_B = i(H^\dagger \overleftrightarrow{D} H)\partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{WW} = i(H^\dagger \sigma^a \overleftrightarrow{D} H) D^\nu W^a_{\mu\nu} \qquad \mathcal{O}_u = y_u |H^2| \bar{Q}_L H^\dagger u_R + \text{h.c.}$$

EFT parametrization: stage 1.1 qqH

- Beyond stage 0: account for shape effects as well as total rates



Total scaling functions

- Total scaling: product of STXS and decay parametrization
- For signal (i, f):

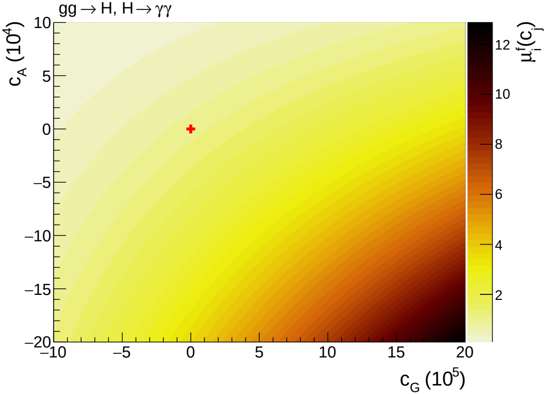
$$\mu_i^f(c_j) = \sigma_i^{\mathrm{EFT}}/\sigma_i^{\mathrm{SM}} \times \mathrm{BR}^{\mathrm{EFT}}(\mathrm{H} \to \mathrm{f})/\mathrm{BR}^{\mathrm{SM}}(\mathrm{H} \to \mathrm{f})$$

  - production: calculated A_j/B_{jk} ourselves
  - decay: taken directly from [LHCHXSWG-INT-2017-001]

- e.g. Stage 0

$$\boxed{gg \to H}$$

$$\times H \to \gamma\gamma$$

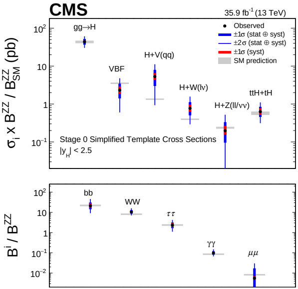


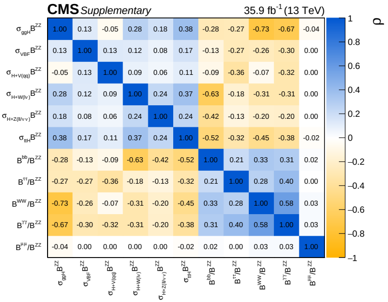
Constraining the EFT parameters: χ^2

- Construct χ^2 function: using 2016 combination stage 0 measurements

$$\chi^2 = (\boldsymbol{x} - \boldsymbol{\mu})^T \boldsymbol{V}^{-1} (\boldsymbol{x} - \boldsymbol{\mu})$$

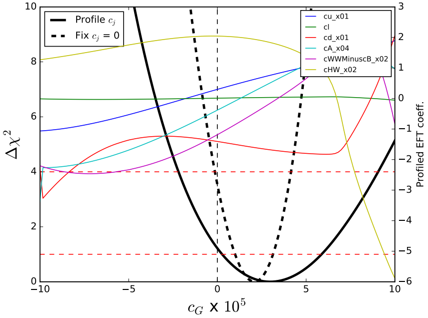
  - $\boldsymbol{x}$: vector of STXS measurements (cross-sections + ratios of BRs)
  - $\boldsymbol{\mu}$: vector of respective EFT parametrizations (functions of c_j)
  - $V_{ij} = \rho_{ij}\sigma_i\sigma_j$: covariance matrix of STXS measurements (symmetrized errors)
- Constraints: vary c_j and extract χ^2

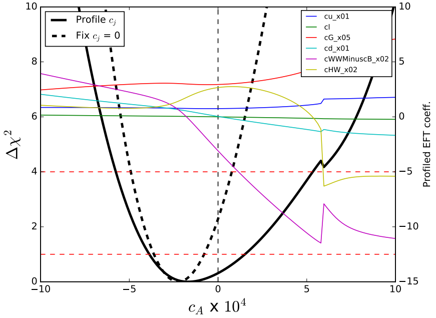




Stage 0 combination: χ^2 results

- Consider variations in subset of HEL params:
  $\Rightarrow c_G,\ c_A,\ c_u,\ c_d,\ c_l,\ c_{HW},\ c_{WW} - c_B$
  - leading terms in measured processes + not tightly constrained by other data
  - not including CP-odd operators: do not enter STXS observables at leading-order
  - $S = c_{WW} + c_B$: precision EWK param, strong exp. constraint
  - fix other $c_j = 0$
- Solid: profile other HEL params. Dashed: fix other HEL params to 0

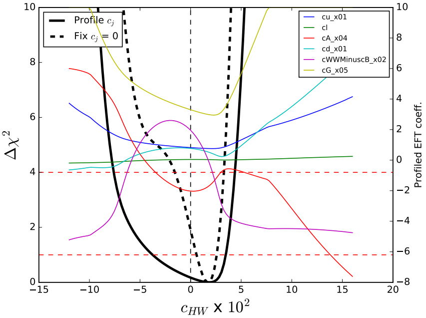


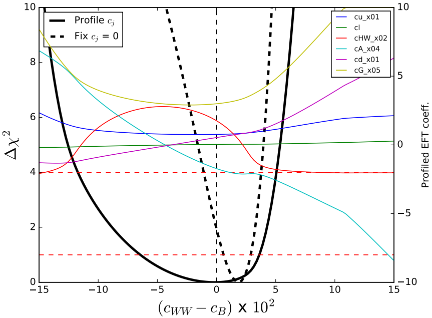


- c_G constraint primarily from ggH, c_A from H$\rightarrow \gamma\gamma$

Stage 0 combination: χ^2 results

- Solid: profile other HEL params. Dashed: fix other HEL params to 0

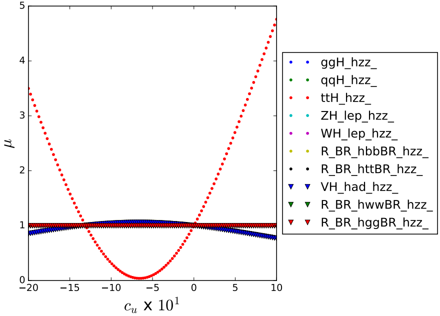


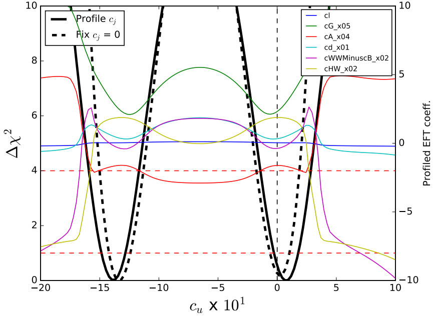


- Both affect HVV vertices $\Rightarrow$ constraints from VBF + VH

Stage 0 combination: χ^2 results

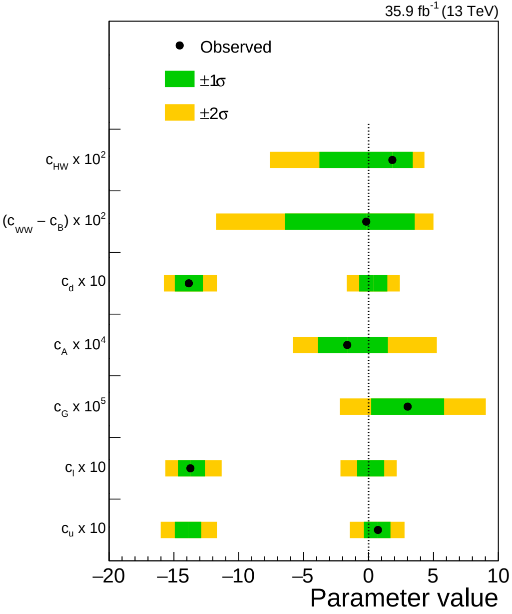
- Solid: profile other HEL params. Dashed: fix other HEL params to 0
- $\mathcal{O}_u$: affects Htt vertex $\Rightarrow$ constraint from ttH





- Turning point in μ for ttH: two values of c_u give $\mu = 1$
- Leads to double minimum in χ^2 distribution
- Rest of χ^2 distributions + scaling functions in Back-up

Stage 0 combination: summary



CMS Higgs Combination: EFT interpretation

- Run 2 Legacy: stage 1.1 combination of major H decay channels
  - direct XS measurements + interpretation

- Intermediate combinations: mixture of stage 0, 1 and 1.1 processes
  - binning schemes **not** backwards compatible: direct XS measurements not possible
  - EFT interpretation is: now have complete set of μ_i^f (HEL)

- For final results: $\chi^2 \Rightarrow$ full maximum-likelihood fit
  - confine signal process (i,f) to scale according to relevant $\mu_i^f(c_j)$
  - likelihood scan over $c_j \Rightarrow$ extract constraints

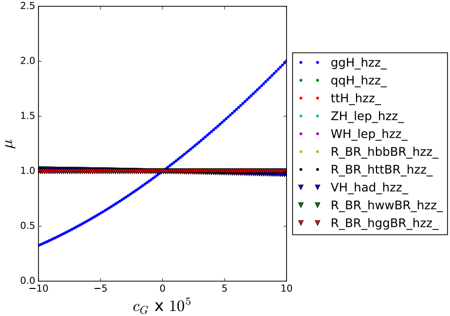
- Transition from HEL to SMEFT interpretation (SMEFTSim model)
  - change of basis (SILH $\rightarrow$ Warsaw)
  - permits combinations with other areas of HEP: VBS, top, SM

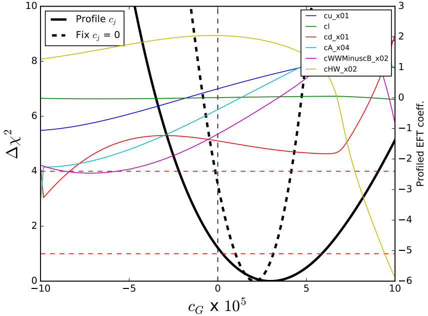
Summary

- Summarised status of STXS measurements in CMS
- EFT interpretation of STXS
  - derived $\mu_i(c_j)$: describe how XS scales as function of HEL parameters
- Presented results based on χ^2 analysis of CMS 2016 Higgs combination

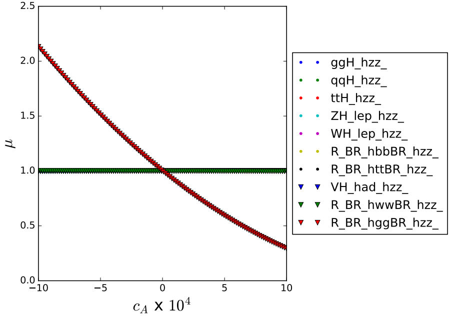
Back-Up Slides

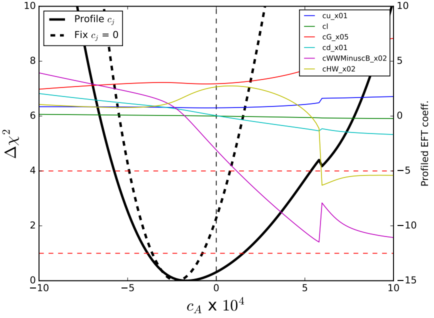
χ^2 results: c_G



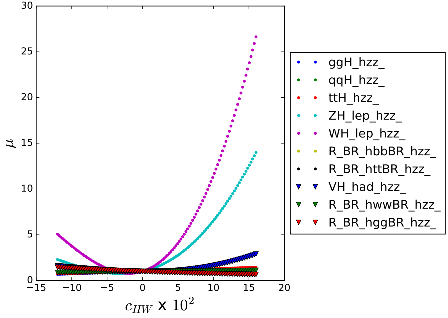


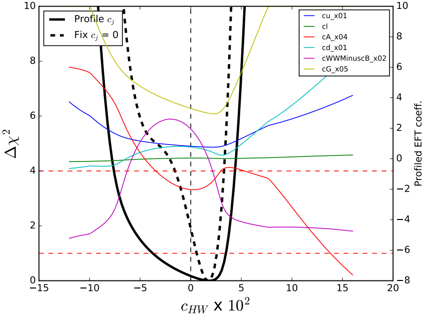
χ^2 results: c_A



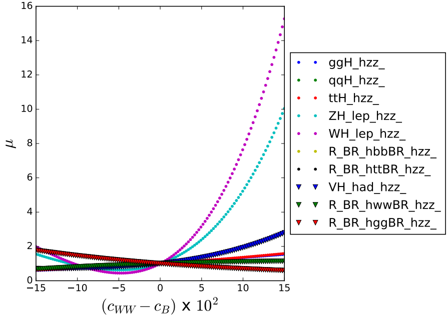


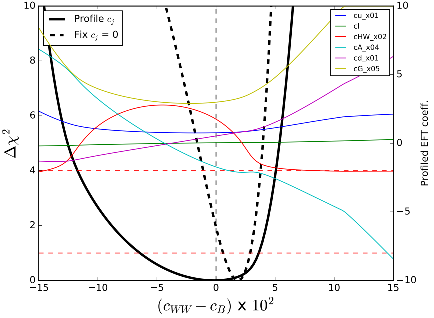
χ^2 results: c_{HW}



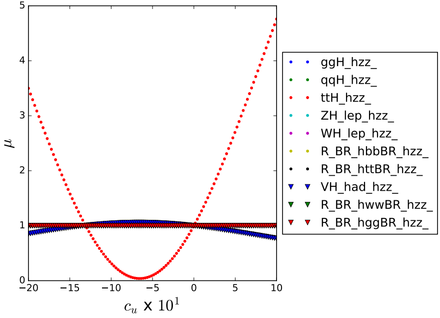


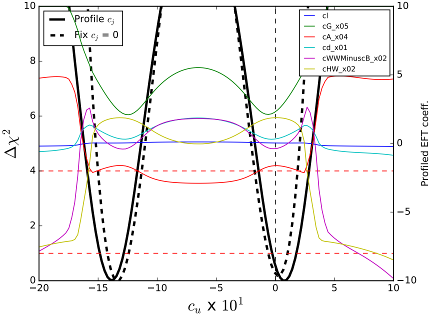
χ^2 results: $c_{WW} - c_B$



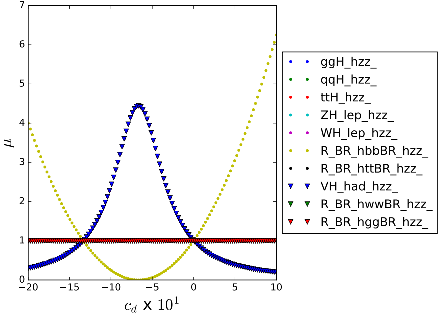


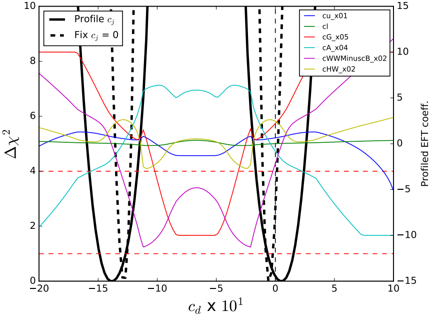
χ^2 results: c_u





χ^2 results: c_d





χ^2 results: c_ℓ