After the Discovery: Hunting for a Non-Standard Higgs Sector

2014, Apr 06 -- Apr 18

Organizers:
C. Grojean (ICREA/IFAE, Barcelona)
A. Juste (ICREA/IFAE, Barcelona)
I. Low (Northwestern/Argonne, Chicago)
F. Moortgat (CERN, Geneva)

Benasque, April 15, 2014

On the presentation of LHC results

José Santiago (CAFPE and U. Granada)

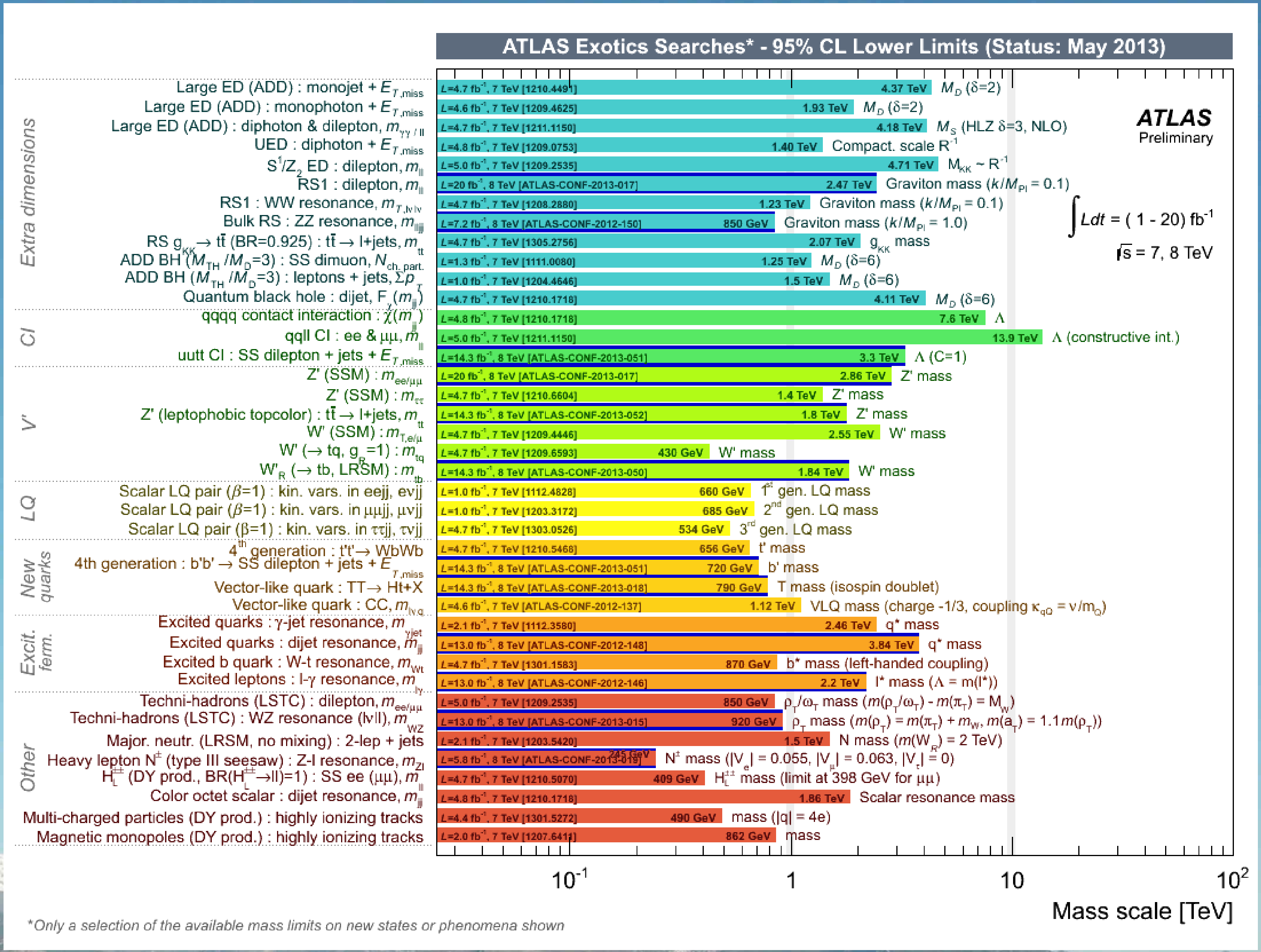
CAFPE

ugr Universidad de Granada

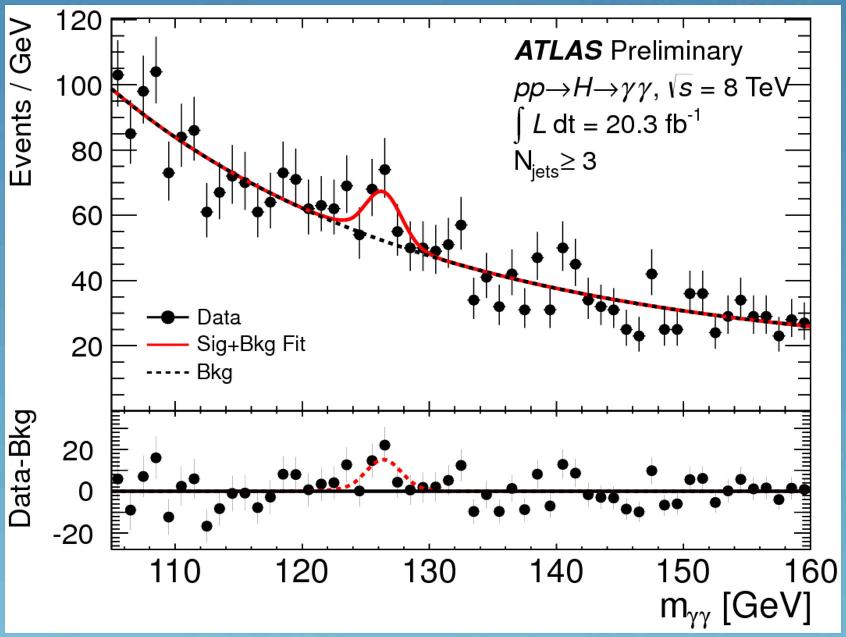
Based on:

J. de Blas, A. Carmona, M. Chala, J.S. (in progress)
and J. de Blas, M. Chala, J.S. PRD88 ('13)

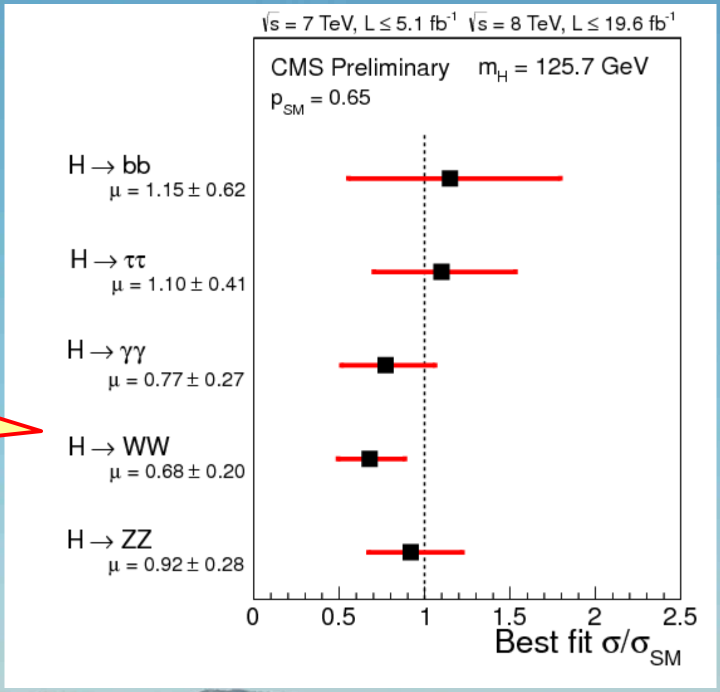
No sign of New Physics at the LHC (yet)



We got the Higgs, of course, but ...



The Higgs mass is where we expected



The Higgs couplings are compatible with the SM ones

Interpretation of null results

- In the absence of any significant excess we would like to interpret the results in the most general possible way
- Effective Lagrangians: model-independent parameterization with minimal assumptions
  - Light degrees of freedom and symmetries identified
  - (Large enough) mass gap between experiment and NP
- Complete-minimal bases only recently proposed

  Grzadkowski, Iskrzynski, Misiak, Rosiek '10
  Contino, Ghezzi, Grojean, Mühlleitner, Spira '13
  Elias-Miró, Espinosa, Masso, Pomarol '13

Eff. Lagrangians and LHC results

- Higgs (and other) LHC data have been comprehensively analyzed in terms of effective Lagrangians (as reviewed in this workshop)
- All these studies have an irreducible source of uncertainty: restricted information from the experimental side
  - Higgs data reported in terms of signal strength

$$\mu = \frac{N - \langle N_{\rm bg} \rangle}{\langle N_{\rm SM} \rangle}$$

Interpretation in terms of new physics requires the assumption of unmodified experimental efficiencies

Eff. Lagrangians and LHC results

- This is a problem not only for Higgs physics: LHC searches quite comprehensive but interpreted in terms of a small set of models
- Other NP might have different kinematics and therefore different efficiencies
- Several proposals to circumvent this problem:
  - Report full likelihoods, detailed cut efficiencies, fiducial cross sections, use simplified model interpretations, …
- Not a dramatic problem now (in Higgs physics) but it might be in the future

Pomarol, Riva 1308.2803
Banerjee, Mukhopadhyay, Mukhopadhyaya 1308.4860

Eff. Lagrangians and LHC results

- Our suggestion: parameterize observables, at detector level, in a general, yet minimal way with master equations
- The (differential) parton-level x-secs can be always written as a polynomial in the coefficients of the new operators

$$\mathrm{d}\sigma(p_i p_j \to q_{i_1} \dots q_{i_n}) = \mathrm{d}\sigma^{\mathrm{SM}} + \sum_{i=1}^{N_{\mathrm{obs}}} C_i \frac{\alpha_i}{\Lambda^2} + \sum_{i\leq j=1}^{N_{\mathrm{obs}}} C_{ij} \frac{\alpha_i \alpha_j}{\Lambda^4} + \dots$$

$C_i, \; C_{ij}$ are functions of the phase space point. Different operators can have the same functional dependence on phase space and can therefore be combined.

Observables at the LHC: Master Eq.

- Experimental observable: parton-level xsec convoluted with initial parton PDFs and integrated over a region of parameter space (experimental cuts)
- We can write a master equation for each observable

$$\Delta\sigma = \Delta\sigma^{\mathrm{SM}} + \sum_i \frac{1}{\Lambda^2} F_i A_i + \sum_j \frac{1}{\Lambda^4} G_j B_j$$

  - A_i, B_i operator-dependent coefficients (combinations of the coefficients of the higher-dimensional operators)
  - F_i, G_i observable-dependent coefficients (includes the effect of PDFs, experimental cuts, efficiencies, etc.)

Observables at the LHC: Master Eq.

$$\Delta\sigma = \Delta\sigma^{\mathrm{SM}} + \sum_i \frac{1}{\Lambda^2} F_i A_i + \sum_j \frac{1}{\Lambda^4} G_j B_j$$

- This kind of parameterization has been used in the past but typically for inclusive observables (total xsec, decay widths) or for single ops.
- Typically not too many independent operators (easy to compute with MC simulations)
- Dependence of the kinematic distributions on NP automatically incorporated

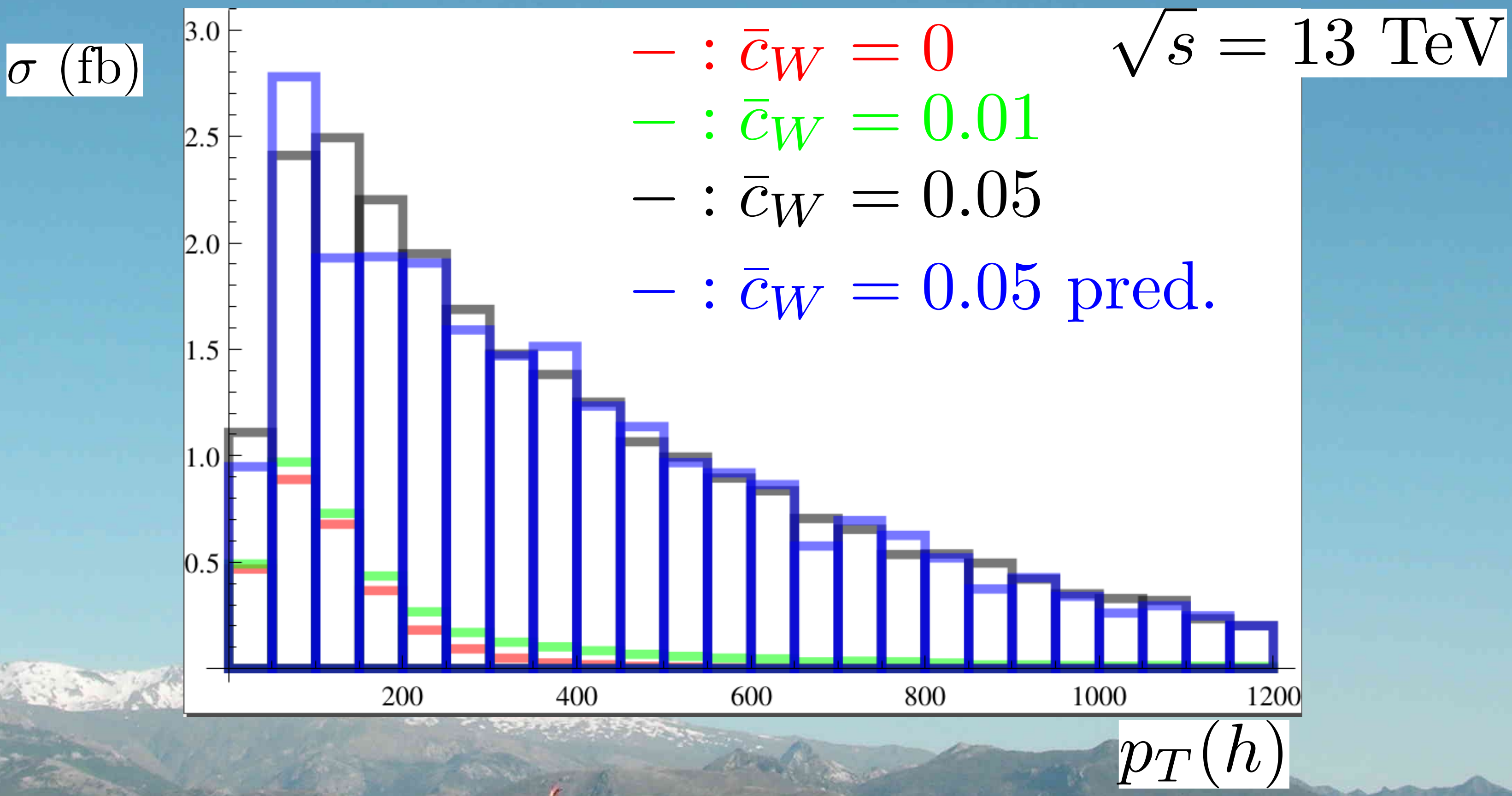
Kinematics parameterization

Double Higgs production mediated by $\frac{ig\bar{c}_W}{2m_W^2}\Phi^\dagger \overleftrightarrow{D}^{k\,\mu}\phi D^\nu W^k_{\mu\nu}$

$pp \to hhjj$

Alloul, Fuks, Sanz 1310.5150

$$N = N_{\rm SM} + F\bar{c}_W + G\bar{c}_W^2$$



Kinematics parameterization

Double Higgs production mediated by

$$\frac{\mathrm{i}g\bar{c}_W}{2m_W^2}\Phi^\dagger \overleftrightarrow{D}^{k\,\mu}\phi D^\nu W^k_{\mu\nu}$$

$$pp \to hhjj$$

Alloul, Fuks, Sanz 1310.5150

$$N = N_{\mathrm{SM}} + F\bar{c}_W + G\bar{c}_W^2$$

$$\begin{pmatrix}
0.467606 + 0.596176\ cW + 180.242\ cW^2 \\
0.888326 + 0.757377\ cW + 741.343\ cW^2 \\
0.677966 + 0.109316\ cW + 498.2\ cW^2 \\
0.366135 + 0.758832\ cW + 612.059\ cW^2 \\
0.180688 + 2.12985\ cW + 646.952\ cW^2 \\
0.0927935 + 2.11187\ cW + 556.891\ cW^2 \\
0.048986 + 2.29611\ cW + 522.08\ cW^2 \\
0.0265924 + 2.00694\ cW + 554.471\ cW^2
\end{pmatrix}$$

J. de Blas, M. Chala, J.S. 1307.5068

Detailed Example:
Drell-Yan from lepton-quark contact interactions

A case study: lq contact interactions

J. de Blas, M. Chala, J.S. 1307.5068

- Classify operators that contribute
  - Ten operators contribute to dilepton production

$$
\begin{aligned}
\mathcal{O}_{lq}^{(1)} &= (\bar{l}\gamma^{\mu}l)(\bar{q}\gamma_{\mu}q), & \mathcal{O}_{lq}^{(3)} &= (\bar{l}\sigma_I\gamma^{\mu}l)(\bar{q}\sigma_I\gamma_{\mu}q),\\
\mathcal{O}_{eu} &= (\bar{e}\gamma^{\mu}e)(\bar{u}\gamma_{\mu}u), & \mathcal{O}_{ed} &= (\bar{e}\gamma^{\mu}e)(\bar{d}\gamma_{\mu}d),\\
\mathcal{O}_{lu} &= (\bar{l}\gamma^{\mu}l)(\bar{u}\gamma_{\mu}u), & \mathcal{O}_{ld} &= (\bar{l}\gamma^{\mu}l)(\bar{d}\gamma_{\mu}d),\\
\mathcal{O}_{qe} &= (\bar{q}\gamma^{\mu}q)(\bar{e}\gamma_{\mu}e), & \mathcal{O}_{qde} &= (\bar{l}e)(\bar{d}q),\\
\mathcal{O}_{lq\epsilon} &= (\bar{l}e)\epsilon(\bar{q}^{T}u), & \mathcal{O}_{ql\epsilon} &= (\bar{q}e)\epsilon(\bar{l}^{T}u),
\end{aligned}
$$

Do not interfere with SM (and are very strongly constrained by pion decay)

A case study: lq contact interactions

J. de Blas, M. Chala, J.S. 1307.5068

- Compute contribution to observable
  - Dilepton production at partonic level

$$
\begin{aligned}
48\pi \frac{d\sigma}{d\hat{t}}(\bar{u}u \to \ell^+\ell^-) &= \left[\left| \mathcal{A}^{\rm SM}_{u_L\ell_R} + \frac{\alpha_{qe}}{\Lambda^2} \right|^2 + \left| \mathcal{A}^{\rm SM}_{u_R\ell_L} + \frac{\alpha_{lu}}{\Lambda^2} \right|^2 + \frac{1}{2\Lambda^4} \left[|\alpha_{ql\epsilon}|^2 + {\rm Re}(\alpha_{lq\epsilon}\alpha^*_{ql\epsilon}) \right] \right] \frac{\hat{t}^2}{\hat{s}^2} \\
&+ \left[\left| \mathcal{A}^{\rm SM}_{u_L\ell_L} + \frac{\alpha^{(1)}_{lq} - \alpha^{(3)}_{lq}}{\Lambda^2} \right|^2 + \left| \mathcal{A}^{\rm SM}_{u_R\ell_R} + \frac{\alpha_{eu}}{\Lambda^2} \right|^2 - \frac{1}{2\Lambda^4} {\rm Re}(\alpha_{lq\epsilon}\alpha^*_{ql\epsilon}) \right] \frac{\hat{u}^2}{\hat{s}^2} \\
&+ \frac{1}{2\Lambda^4} \left[|\alpha_{lq\epsilon}|^2 + {\rm Re}(\alpha_{lq\epsilon}\alpha^*_{ql\epsilon}) \right], \\
48\pi \frac{d\sigma}{d\hat{t}}(\bar{d}d \to \ell^+\ell^-) &= \left[\left| \mathcal{A}^{\rm SM}_{d_L\ell_R} + \frac{\alpha_{qe}}{\Lambda^2} \right|^2 + \left| \mathcal{A}^{\rm SM}_{d_R\ell_L} + \frac{\alpha_{ld}}{\Lambda^2} \right|^2 \right] \frac{\hat{t}^2}{\hat{s}^2} \\
&+ \left[\left| \mathcal{A}^{\rm SM}_{d_L\ell_L} + \frac{\alpha^{(1)}_{lq} + \alpha^{(3)}_{lq}}{\Lambda^2} \right|^2 + \left| \mathcal{A}^{\rm SM}_{d_R\ell_R} + \frac{\alpha_{ed}}{\Lambda^2} \right|^2 \right] \frac{\hat{u}^2}{\hat{s}^2} + \frac{|\alpha_{qde}|^2}{2\Lambda^4},
\end{aligned}
$$

$$
\mathcal{A}^{\rm SM}_{\psi\phi} = \frac{e^2 Q_\psi Q_\phi}{\hat{s}} + \frac{g_\psi g_\phi}{\hat{s} - m_Z^2 + i m_Z \Gamma_Z}
$$

A case study: lq contact interactions

J. de Blas, M. Chala, J.S. 1307.5068

- Master Equation: general parameterization at <u>detector level</u>

$$\sigma = \sigma^{\rm SM} + \frac{1}{\Lambda^2}\sum_{q=u,d}[F_1^q A_1^q + F_2^q A_2^q] + \frac{1}{\Lambda^4}\sum_{q=u,d}[G_1^q B_1^q + G_2^q B_2^q + G_3^q B_3^q]$$

Operator-dependent coefficients

$$\begin{aligned}
A_1^u &= [e^2 Q_u Q_e + g_{u_L} g_{e_L}](\alpha_{lq}^{(1)} - \alpha_{lq}^{(3)}) + [e^2 Q_u Q_e + g_{u_R} g_{e_R}]\alpha_{eu},\\
A_2^u &= [e^2 Q_u Q_e + g_{u_L} g_{e_R}]\alpha_{qe} + [e^2 Q_u Q_e + g_{u_R} g_{e_L}]\alpha_{lu},\\
A_1^d &= [e^2 Q_d Q_e + g_{d_L} g_{e_L}](\alpha_{lq}^{(1)} + \alpha_{lq}^{(3)}) + [e^2 Q_d Q_e + g_{d_R} g_{e_R}]\alpha_{ed},\\
A_2^d &= [e^2 Q_d Q_e + g_{d_L} g_{e_R}]\alpha_{qe} + [e^2 Q_d Q_e + g_{d_R} g_{e_L}]\alpha_{ld},\\
B_1^u &= 4(\alpha_{lq}^{(1)} - \alpha_{lq}^{(3)})^2 + 4\alpha_{eu}^2 - 2{\rm Re}(\alpha_{lq\epsilon}\alpha_{ql\epsilon}^*),\\
B_2^u &= 4\alpha_{qe}^2 + 4\alpha_{lu}^2 + 2|\alpha_{ql\epsilon}|^2 + 2{\rm Re}(\alpha_{lq\epsilon}\alpha_{ql\epsilon}^*),\\
B_3^u &= 2|\alpha_{lq\epsilon}|^2 + 2{\rm Re}(\alpha_{lq\epsilon}\alpha_{ql\epsilon}^*),\\
B_1^d &= 4(\alpha_{lq}^{(1)} + \alpha_{lq}^{(3)})^2 + 4\alpha_{ed}^2,\\
B_2^d &= 4\alpha_{qe}^2 + 4\alpha_{ld}^2,\\
B_3^d &= 2|\alpha_{qde}|^2.
\end{aligned}$$

A case study: lq contact interactions

J. de Blas, M. Chala, J.S. 1307.5068

- Master Equation: general parameterization at <u>detector level</u>

$$\sigma \;=\; \sigma^{\rm SM} + \frac{1}{\Lambda^2}\sum_{q=u,d}\left[F_1^q A_1^q + F_2^q A_2^q\right] + \frac{1}{\Lambda^4}\sum_{q=u,d}\left[G_1^q B_1^q + G_2^q B_2^q + G_3^q B_3^q\right]$$

  - The observable-dependent coefficients, $F_i^q,\ G_i^q,$ can only be computed with detailed MC simulations
  - There are relations for certain observables:
    - Forward-backward symmetric observables $$F_1^u = F_2^u, \quad F_1^d = F_2^d$$ $$G_1^u = G_2^u, \quad G_1^d = G_2^d$$
    - Isotropic observables $$G_3^u = 3G_1^u, \quad G_3^d = 3G_1^d.$$

A case study: lq contact interactions

J. de Blas, M. Chala, J.S. 1307.5068

- Calculation of observable-dependent coeffs.

	$b_1(e)$	$b_2(e)$	$b_3(e)$	$b_4(e)$	$b_1(\mu)$	$b_2(\mu)$	$b_3(\mu)$	$b_4(\mu)$
$N_{\rm SM}$	32.6	4.68	0.60	8.72	37.0	5.38	0.74	9.44
F_1^u	2514	731	202	1324	2746	811	251	1410
F_1^d	1484	359	80.2	677	1590	481	93.6	775
G_1^u	346	203	116	404	376	219	134	415
G_1^d	200	106	46.1	199	219	118	53.0	207
$N_{\rm Obs}$	41	4	0	10	49	11	1	8

- Symmetric and isotropic obs.: only 5 coeffs.
- Relations satisfied better than 3%
- Can experimental collaborations do this? YES!

A case study: lq contact interactions

J. de Blas, M. Chala, J.S. 1307.5068

- Calculation of observable-dependent coeffs.
  - Symmetric and isotropic obs.: only 5 coeffs.

It would suffice that experimental collaborations give the expected number of events in the SM (signal and background separately) and for two different values of the coefficients of two higher-dimensional operators, for instance $(\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$ and $(\bar{e}\gamma^\mu e)(\bar{d}\gamma_\mu d)$

Any extra information (for instance more operators) can be used as cross-check of the approximation

A case study: lq contact interactions

J. de Blas, M. Chala, J.S. 1307.5068

- Include ME into global fit: J. de Blas Ph.D. Thesis (U. Granada)
  - LHC results are competitive and often complementary to EWPT

Universal

	LHC	EWPT
$\mathcal{O}_{lq}^{(1)}$	$[-0.032, 0.073]$	$[-0.012, 0.055]$
$\mathcal{O}_{lq}^{(3)}$	$[-0.106, 0.019]$	$[-0.006, 0.012]$
$\mathcal{O}_{eu}$	$[-0.032, 0.102]$	$[-0.097, 0.017]$
$\mathcal{O}_{ed}$	$[-0.107, 0.068]$	$[-0.077, 0.040]$
$\mathcal{O}_{lu}$	$[-0.043, 0.079]$	$[-0.041, 0.095]$
$\mathcal{O}_{ld}$	$[-0.096, 0.076]$	$[-0.021, 0.106]$
$\mathcal{O}_{qe}$	$[-0.040, 0.058]$	$[-0.055, 0.011]$

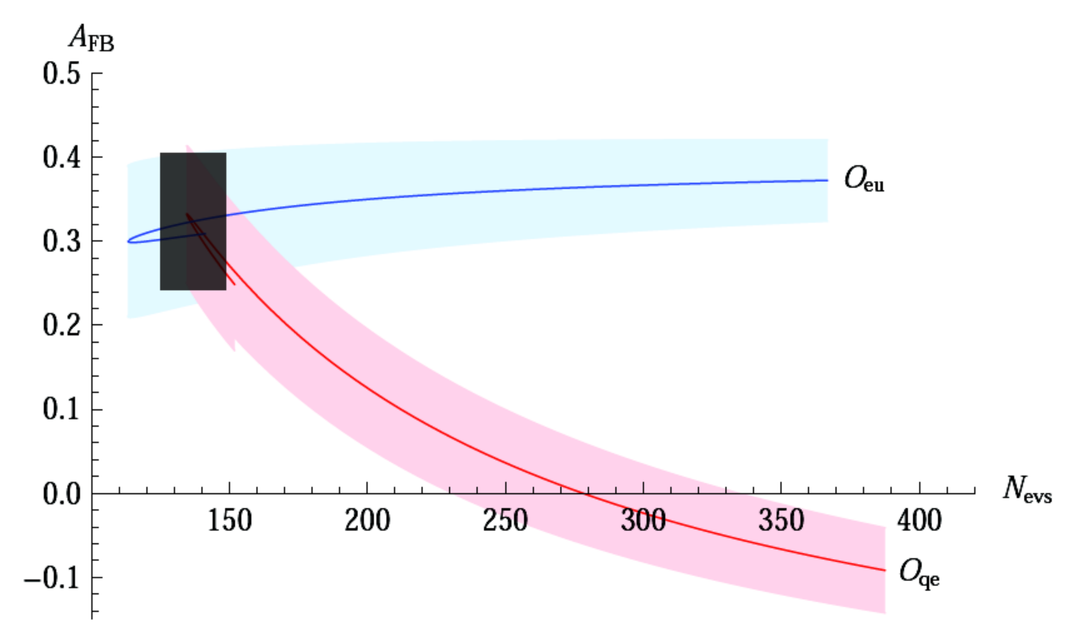
A case study: lq contact interactions

J. de Blas, M. Chala, J.S. 1307.5068

- Can we distinguish different operators?
  - Only classes of operators
  - Sample: forward-backward asymmetry at LHC14

$$A_{FB} = \frac{\sigma(\overline{\Delta\eta} > 0) - \sigma(\overline{\Delta\eta} < 0)}{\sigma(\overline{\Delta\eta} > 0) + \sigma(\overline{\Delta\eta} < 0)}$$

$$\overline{\Delta\eta} \equiv (\eta_{l^-} - \eta_{l^+})/(\eta_{l^-} + \eta_{l^+})$$



$$M_{l^+l^-} \geq 1.8 \text{ TeV}$$

$$\sqrt{s} = 14 \text{ TeV}$$

$$\mathcal{L} = 300 \text{ fb}^{-1}$$

Can be also applied to Higgs physics

J. de Blas, A. Carmona, J.S., to appear

- Sample case: $h \to Z l^+ l^-$
  - Many operators contribute

Preliminary

$$\begin{aligned}
\mathcal{L} \;=\;& \frac{\bar{c}_T}{2v^2}[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi][\Phi^\dagger \overleftrightarrow{D}_\mu \Phi] + \frac{ig\bar{c}_W}{2m_W^2}[\Phi^\dagger \overleftrightarrow{D}^{k\,\mu} \Phi] D^\nu W^k_{\mu\nu} + \frac{ig'\bar{c}_B}{2m_W^2}[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi]\partial^\nu B_{\mu\nu} \\
&+ \frac{ig\bar{c}_{HW}}{m_W^2}[D^\mu \Phi^\dagger \sigma^k D^\nu \Phi] W^k_{\mu\nu} + \frac{ig'\bar{c}_{HB}}{m_W^2}[D^\mu \Phi^\dagger D^\nu \Phi] B_{\mu\nu} + \frac{g'^2\bar{c}_\gamma}{m_W^2}\Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu} \\
&+ \frac{i\bar{c}_{HL}}{v^2}[\bar{l}\gamma^\mu l][\Phi^\dagger \overleftrightarrow{D}_\mu \Phi] + \frac{i\bar{c}'_{HL}}{v^2}[\bar{l}\gamma^\mu \sigma^k l][\Phi^\dagger \overleftrightarrow{D}^k_\mu \Phi] + \frac{i\bar{c}_{He}}{v^2}[\bar{e}\gamma^\mu e][\Phi^\dagger \overleftrightarrow{D}_\mu \Phi] \\
&+ \left[\frac{2g'\bar{c}_{eB}}{m_W^2} y_l \bar{l}\sigma^{\mu\nu} e \Phi B_{\mu\nu} + \frac{2g\bar{c}_{eW}}{m_W^2} y_l \bar{l}\sigma^k \sigma^{\mu\nu} e \Phi W^k_{\mu\nu} + \text{h.c.}\right]
\end{aligned}$$

Contino, Ghezzi, Grojean, Mühlleitner, Spira '13
Alloul, Fuks, Sanz '13

Can be also applied to Higgs physics

J. de Blas, A. Carmona, J.S., to appear

- Sample case: $h \to Z l^+ l^-$

Preliminary

  - We take as our observable the number of events with $m_{4l} \in [120, 130]\ \mathrm{GeV}$ after the cuts in ATLAS-CONF-2013-013
  - Simplifying assumption (just for the sake of the example, not realistic!): neglect photon exchange and anomalous Z decays
  - Caution: most operators more constrained (currently) by other observables Pomarol, Riva 1308.2803

$$N = N_{\mathrm{SM}} + \sum_{i=1}^{4} A_i F_i + BG + \tilde{B}\tilde{G} + \sum_{i<j=1}^{4} A_i A_j G_{ij} + \sum_{i=2}^{4} A_i^2 G_{ii}$$

Can be also applied to Higgs physics

J. de Blas, A. Carmona, J.S., to appear

- Sample case: $h \to Z l^+ l^-$

Preliminary

$$N = N_{\mathrm{SM}} + \sum_{i=1}^{4} A_i F_i + BG + \tilde{B}\tilde{G} + \sum_{i<j=1}^{4} A_i A_j G_{ij} + \sum_{i=2}^{4} A_i^2 G_{ii}$$

$$\begin{aligned}
A_1 &= g_Z^L g_L + g_Z^R g_R, \\
A_2 &= g_1, \\
A_3 &= g_2, \\
A_4 &= \delta g_3, \\
B &= g_L^2 + g_R^2, \\
\tilde{B} &= |g_4|^2.
\end{aligned}$$

$$\begin{aligned}
g_1 &= \frac{2g}{c_W^2 m_W}[\bar{c}_{HB} s_W^2 - 4\bar{c}_\gamma s_W^4 + \bar{c}_{HW} c_W^2], \\
g_2 &= \frac{g}{c_W^2 m_W}[(\bar{c}_{HW} + \bar{c}_W) c_W^2 + (\bar{c}_B + \bar{c}_{HB}) s_W^2], \\
g_3 &= g_3^{\mathrm{SM}} + \delta g_3 = \frac{g m_Z}{c_w} - 2\frac{g m_Z}{c_w}\bar{c}_T, \\
g_L &= \frac{g}{c_W v}[\bar{c}_{HL} + \bar{c}'_{HL}], \\
g_R &= \frac{g}{c_W v}\frac{\bar{c}_{He}}{2}, \\
g_4 &= \frac{\sqrt{2} g}{c_W m_W^2} y_l [-\bar{c}_{eW} c_W^2 - \bar{c}_{eB} s_W^2].
\end{aligned}$$

Can be also applied to Higgs physics

J. de Blas, A. Carmona, J.S., to appear

- Sample case: $h \to Z l^+ l^-$

Preliminary

$$N = N_{\mathrm{SM}} + \sum_{i=1}^{4} A_i F_i + BG + \tilde{B}\tilde{G} + \sum_{i<j=1}^{4} A_i A_j G_{ij} + \sum_{i=2}^{4} A_i^2 G_{ii}$$

$$\begin{aligned}
A_1 &= g_Z^L g_L + g_Z^R g_R, \\
A_2 &= g_1, \\
A_3 &= g_2, \\
A_4 &= \delta g_3, \\
B &= g_L^2 + g_R^2, \\
\tilde{B} &= |g_4|^2.
\end{aligned}$$

rixForm=

$$\begin{pmatrix}
N_{\mathrm{SM}} = 5.3137 \\
F_1 = 16.509\ \mathrm{TeV} \\
F_2 = 1.01032\ \mathrm{TeV} \\
F_3 = 1.28497\ \mathrm{TeV} \\
F_4 = 155.532\ \mathrm{TeV}^{-1}
\end{pmatrix}$$

Discussion and outlook

- Model independent interpretation of LHC results require further input from experiments
- Master equations provide a simple but general parameterization of new physics:
  - General parameterization of observables at <u>detector level</u>
  - Dependence of kinematic distributions on NP included
  - Easy to combine with EWPT J. de Blas Ph.D. Thesis (U. Granada)
- Easy to implement in LHC searches:
  - Usually small number of simulations needed
  - Cuts can be optimized for different operators