ATLAS & CMS Standard Model measurements and re-use for constraining BSM

Darren Price (on behalf of the ATLAS and CMS collaborations)
(Re)interpreting results of new physics searches at the LHC
CERN, December 12th '16
Standard Model measurements provide:

- precise understanding and modelling of SM processes
- direct test of anomalies / indirect presence of high scale physics
- incredibly powerful place to search for generic BSM physics

Does not assume Standard Model is correct (no model dependence outside of uncertainties)

For existing BSM searches:
- Critical for filling in gaps in direct searches (low sensitivity, less well-motivated search topology at the time, kinematically similar signature to SM...)

For new BSM searches:
- Data ready and waiting to constrain BSM models in novel search modes (ahead of new purpose-built analysis, if needed)

Standard Model measurements offer a wealth of opportunities for constraining BSM, question is how to make this data easiest to use, and more powerful.
Fundamental challenge to re-interpretation:
Theory predictions developed at parton-level, measurements originate at reconstruction-level

Theory

- Need interface to MC, or non-perturbative corrections applied
- Require good understanding of background and signal modelling
- Efficiencies and resolutions
- Cut flows / implementation of exact details of reconstruction-level selection

Experiment

- Non-perturbative effects
- Large extrapolation uncertainties outside measurable regime
- Need to carefully unfold detector resolution and efficiency effects

“Meet in the middle”: Report measurements at particle-level in well-defined fiducial region.
Fiducial measurements

Standard Model cross-sections generally measured in well-defined fiducial region, region of phase space well-understood, high efficiency, minimal extrapolation.

Correct measured data for:
- background contamination,
- migrations in, out, and within fiducial region due to efficiency and resolution effects.

\[ \sigma_{\text{particle-level}} = \sum_j \frac{(N_{\text{data}} - N_{\text{bkg}})_j \cdot \epsilon_{\text{reco-level}}^j M_{ij}}{\mathcal{L} \epsilon_{\text{particle-level}}^i} \]

Resulting measurement independent of prior assumptions; unfolding uncertainties assessed.
What is provided, what is needed?

At the moment ATLAS and CMS provide with SM publications (coverage improving):

- Fully-corrected data measurements (+uncertainties) [http://hepdata.net]
- Bin-to-bin correlations + any useful auxiliary information (Improved constraints)
- Rivet analysis routine [http://rivet.hepforge.org]
  (Handle object definitions to avoid ambiguity in isolation, jet algorithms, MET definition etc., observable definitions, and binning)

What else is needed to allow ease of (re-)interpretation?

- Should we be providing templates for SM prescriptions?
- Correlations between observables not just within individual distributions?
- Anything else?

\[
\chi^2 = (\sigma_{\text{data}} - \sigma_{\text{theory}})^T (C_{\text{stat}}^{-1} + C_{\text{syst}}^{-1}) (\sigma_{\text{data}} - \sigma_{\text{theory}})
\]
What measurements are available?

[Image: Graph showing production cross sections for different processes, with annotations indicating various CMS measurements and data points.]

- 7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
- 8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
- 13 TeV CMS measurement (L ≤ 2.7 fb⁻¹)
- Theory prediction
- CMS 95%CL limit

[Links to CMS and ATLAS public results pages]

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
**EW Standard Model processes good examples of reinterpretation candidates:**

- Direct connection to mechanism of electroweak symmetry breaking
- Sensitivity to New Physics directly possible in the high energy tails
- Constrain anomalous triple (aTGC) and quartic gauge couplings (aQGC)

### EW Standard Model measurements

- **Direct connection to mechanism of electroweak symmetry breaking**
- **Sensitivity to New Physics directly possible in the high energy tails**
- **Constrain anomalous triple (aTGC) and quartic gauge couplings (aQGC)**

#### CMS Preliminary

<table>
<thead>
<tr>
<th>CMS measurements vs. NNLO (NLO) theory</th>
<th>7 TeV CMS measurement (stat,stat+sys)</th>
<th>8 TeV CMS measurement (stat,stat+sys)</th>
<th>13 TeV CMS measurement (stat,stat+sys)</th>
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</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>$1.06 \pm 0.01 \pm 0.12$</td>
<td>$5.0 \text{ fb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$W_W$ (NLO th.)</td>
<td>$1.16 \pm 0.03 \pm 0.13$</td>
<td>$5.0 \text{ fb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$Z_Z$ (NLO th.)</td>
<td>$0.98 \pm 0.01 \pm 0.05$</td>
<td>$5.0 \text{ fb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$Z_W$ (NLO th.)</td>
<td>$0.98 \pm 0.01 \pm 0.05$</td>
<td>$19.5 \text{ fb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>WW+WZ</td>
<td>$1.01 \pm 1.3 \pm 1.4$</td>
<td>$4.9 \text{ fb}^{-1}$</td>
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</tr>
<tr>
<td>WW</td>
<td>$1.07 \pm 0.04 \pm 0.09$</td>
<td>$4.9 \text{ fb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>WW</td>
<td>$1.00 \pm 0.02 \pm 0.08$</td>
<td>$19.4 \text{ fb}^{-1}$</td>
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<tr>
<td>WW</td>
<td>$0.96 \pm 0.05 \pm 0.08$</td>
<td>$2.3 \text{ fb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>WZ</td>
<td>$1.08 \pm 0.07 \pm 0.16$</td>
<td>$4.9 \text{ fb}^{-1}$</td>
<td></td>
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<tr>
<td>WZ</td>
<td>$1.04 \pm 0.03 \pm 0.07$</td>
<td>$19.6 \text{ fb}^{-1}$</td>
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<tr>
<td>WZ</td>
<td>$0.80 \pm 0.06 \pm 0.07$</td>
<td>$2.3 \text{ fb}^{-1}$</td>
<td></td>
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<tr>
<td>ZZ</td>
<td>$0.97 \pm 0.13 \pm 0.07$</td>
<td>$4.9 \text{ fb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>ZZ</td>
<td>$0.97 \pm 0.06 \pm 0.08$</td>
<td>$19.6 \text{ fb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>ZZ</td>
<td>$0.90 \pm 0.11 \pm 0.04$</td>
<td>$2.6 \text{ fb}^{-1}$</td>
<td></td>
</tr>
</tbody>
</table>

All results at: [http://cern.ch/go/pNj7](http://cern.ch/go/pNj7)
Di-boson cross-sections / limits good candidates for re-interpretation
Anomalous TGCs modify total production rate + kinematics

EW di-boson production characterised by effective electroweak Lagrangian:

Variety of final states to probe, sensitive to different couplings

$$\Delta \mathcal{L}_{TGV} = -ie \Delta \kappa \gamma W^+_{\mu} W^-_{\nu} \gamma_{\mu\nu} - \frac{ie \lambda \gamma}{2m_W^2} W^+_{\mu\nu} W^{-\nu\rho} \gamma^\rho - \frac{igZ \lambda Z}{2m_W^2} W^+_{\mu\nu} W^{-\nu\rho} Z^\rho$$

$$= -ie \frac{g^2 v_2^2}{8\Delta^2} (f_W + f_B) W^+_{\mu} W^-_{\nu} \gamma_{\mu\nu} - ie \frac{3g^2 f_{WW} W^-_{\mu} W^-_{\nu} \gamma^\rho}{4\Delta^2} W^+_{\mu\nu} W^{-\nu\rho} \gamma^\rho$$

$$- igZ \frac{g^2 v_2^2}{8c_w^2\Delta^2} (c_w^2 f_W - s_w^2 f_B) W^-_{\mu} W^-_{\nu} Z_{\mu\nu} - igZ \frac{3g^2 f_{WW} W^-_{\mu} W^-_{\nu} Z^-_{\nu}}{4\Delta^2} W^+_{\mu\nu} W^{-\nu\rho} Z^\rho$$

$$- igZ \frac{g^2 v_2^2 f_W}{8c_w^2\Delta^2} (W^+_{\mu\nu} W^-_{\nu} Z^-_{\nu} - W^-_{\mu\nu} Z_{\nu} W^{-\nu})$$
ATLAS measurement of $W^\pm Z$ production at 13 TeV
- Fiducial and total (extrapolated) cross-sections
- aTGC limits from high $m_T(WZ)$ behaviour

**Graphs and Figures:***
- ATLAS Preliminary plots showing cross-sections and limits.
- Diagram illustrating the production of $W^\pm Z$ and $q\ell'$ processes.

**References:**
- ATLAS-CONF-2016-043 (aTGC limits)
CMS measurement of $W^\pm Z$ production at 7+8 TeV
- Fiducial differential cross-sections
- aTGC limits from high $p_T(Z)$ behaviour

CMS measurement of $W^\pm Z$ production at 7+8 TeV

Inclusive $W^\pm Z$ production

CMS measurement of $W^\pm Z$ production at 7+8 TeV
Various theory papers reinterpreted original ATLAS+CMS WW cross-section excess in terms of BSM models.

One such re-interpretation closed gap in SUSY models where mass splittings between EW BSM states small, placing bounds on these scenarios

\[ pp \rightarrow \chi^+\chi^- \rightarrow W^+W^-\chi^0\chi^0 \]
Inclusive $W^+W^-$ production

- CMS measurement of $W^+W^-$ production at 8 TeV
  - Fiducial differential cross-sections
  - aTGC limits from high dilepton mass spectrum; competitive sensitivity to $c_{WWW}$

![Graph showing CMS measurement results](image)

- **Events / (75 GeV)**
  - Data
  - WW
  - Top quark
  - DY
  - WZ/ZZ/VVV
  - W+jets
  - $c_W/\Lambda^2 = 20$ TeV$^2$
  - $c_{WWW}/\Lambda^2 = 20$ TeV$^2$
  - $c_B/\Lambda^2 = 55$ TeV$^2$

![Graph showing CMS measurement results](image)

- 19.4 fb$^{-1}$ (8 TeV)
- $d\sigma / d(m_{\ell\ell} + 0 \text{ jets}) / d\ell_\ell$
- Observed 68% CL
- Expected 68% CL
- Observed 95% CL
- Expected 95% CL
- Standard Model
- Best Fit

First observations of weak boson fusion production of W/Z in 8 TeV data

- Sensitive to aTGCs
- Not as stringent numerically as $W^\pm Z$
- Complementary constraints on new phenomena

**VBF**: two bosons with space-like momentum transfer vs. three bosons with time-like momentum transfer in di-boson


- Many differential $Zjj$ cross-sections of use in BSM reinterpretation
- Fiducial cross-section rates for $Wjj$ available

Approaching era of VBS/VBF precision measurements: expect detailed differential measurements of EW boson production soon
Direct relationship between TGVs and Higgs couplings in Effective Field Theories in model-independent fashion

**Higgs Effective Lagrangian:**

\[ \mathcal{L}_{\text{eff}} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2} + \frac{f_{\text{bot}}}{\Lambda^2} \mathcal{O}_{d\Phi,33} + \frac{f_{\tau}}{\Lambda^2} \mathcal{O}_{e\Phi,33} + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_{WWW}}{\Lambda^2} \mathcal{O}_{WWW} \]

*e.g.* **WWV Effective Lagrangian:**

\[ \mathcal{L}_{WWV} = -ig_{WWV} \left\{ g_1^V \left( W_{\mu\nu}^+ W^{-\mu\nu} - W_{\mu}^+ V_{\nu} W^{-\mu\nu} \right) + \kappa V W_{\mu}^+ W_{\nu}^{-\mu\nu} + \frac{\lambda V}{m_W^2} W_{\mu\nu}^+ W^{-\nu\rho} V_{\rho} \right\} \]

Direct mapping between terms in the two Lagrangians:

\[ \Delta \kappa_\gamma = \frac{g^2 v^2}{8\Lambda^2} \left( f_W + f_B \right), \quad \lambda_\gamma = \lambda_Z = \frac{3g^2 M_W^2}{2\Lambda^2} f_{WWW}, \]

\[ \Delta g_1^Z = \frac{g^2 v^2}{8c^2\Lambda^2} f_W, \quad \Delta \kappa_Z = \frac{g^2 v^2}{8c^2\Lambda^2} \left( c^2 f_W - s^2 f_B \right). \]

*Allows TGV data to test strength/structures of Higgs couplings and vice-versa*
Examples of re-use of di-boson data

LHC Higgs data reinterpreted:
\[ \rightarrow \text{constraints on TGVs} \]

Equivalently:
\[ \text{ATLAS+CMS (WW, WZ, Wγ) production data reinterpreted:} \]
\[ \rightarrow \text{constraints on Higgs coupling parameters} \]


Complementary constraints from both datasets benefit from combination
Examples of re-use of di-boson data

LHC di-boson (reco-level) kinematic yields used to constrain Higgs couplings: TGV data provides important complementarity

Butter et al., JHEP 1607 (2016) 152

Ellis, Sanz, You, JHEP 1503 (2015) 157

Single coefficient fits
VH production data
TGC data
VH+TGC
Examples of re-use of di-boson data

LHC WW+WZ data at particle-level used to constrain BSM coefficients
Looking at high energy tails for anomalous rate

Filled red quadratic terms allowed, dotted linear only

Falkowski et al., arXiv:1609.06312

Some discussion in paper about alternative route, presentation of aTGC likelihoods by experiments for combinations

ATLAS measurement of $Z\gamma(\gamma)$ production at 8TeV

- Probes of both triple and quartic gauge couplings
- Measure cross section in inclusive ($N_{\text{jets}} \geq 0$) and exclusive ($N_{\text{jets}} = 0$) categories

$\sigma(pp\rightarrow Z\gamma)\, [\text{fb}/\text{GeV}]$

$\sigma(pp\rightarrow \gamma\gamma)\, [\text{fb}/\text{GeV}]$

$\sigma(pp\rightarrow \nu\nu\gamma)\, [\text{fb}/\text{GeV}]$
Search for WWW triboson production

- Sensitive to aQGCs

No observation (yet) but able to set 95% CL on cross-section and reinterpret in terms of contact interaction:

**Confidence Intervals**

<table>
<thead>
<tr>
<th><strong>Confidence</strong></th>
<th><strong>Observed Value</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>95% CL</td>
<td>Observed 95% CL</td>
</tr>
<tr>
<td>68% CL</td>
<td>Observed 68% CL</td>
</tr>
</tbody>
</table>

**ATLAS**

1s = 8 TeV, 20.3 fb⁻¹

W⁺W⁻W⁺ → ℓννjj + ℓννℓν

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1s = 8 TeV, 20.3 fb⁻¹

W⁺W⁻W⁺ → ℓννjj + ℓννℓν

Λ_{FF} = ∞

**Benefits of 95% CL limits**

(in addition to EFT interpretations) discussed in Green, Meade, Pleier, arXiv:1610.07572
Measurement of inclusive and EW-only $W^\pm W^\pm$ scattering

- Measure production rates
- Bounds on aQGCs
- Reinterpretation in terms of limits on VBF $H^{\pm\pm}$ production (reconstruction-level yields in di-lepton mass)

**Graphs and Tables**

- **ATLAS**
  - 20.3 fb$^{-1}$, $\sqrt{s} = 8$ TeV
  - $pp \rightarrow W^+ W^-$ (reconstruction-level yields in di-lepton mass)

- **CMS**
  - $19.4$ fb$^{-1}$ (8 TeV)
  - $VBF H^{\pm\pm} \rightarrow W^3W^\pm$
Higgs boson fiducial cross-section measurements as Standard Model probes

- Differential cross-sections versus five kinematic variables
- Corrected for detector effects, no implicit assumptions

Higgs boson fiducial cross-sections

- $\sigma_{\text{fid}}(\Phi)$
- Corrected for detector effects, no implicit assumptions

**ATLAS**

$pp \rightarrow H$

19.7 $fb^{-1}$ (8 TeV)

**CMS**

$H \rightarrow \gamma\gamma, \ s = 8 \ TeV$

- $L \ dt = 20.3 \ fb^{-1}$
- $N_{jets} \geq 2, \ p_T^H > 30 \ GeV$

- Data
- Syst. unc.
- $gg \rightarrow H (\text{MNLO} \ HJ + p\bar{p}) = XH$
- ($\ell_H = 1.10$)
- $XH = VBF + VH + ttH$

**ATLAS**

$H \rightarrow \gamma\gamma, \ s = 8 \ TeV$

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Reinterpretation of published data as constraint on EFT Wilson coefficients

Ratio of differential cross-section to theory with varied coefficients, CLs limits

**ATLAS**

$p p \rightarrow H \rightarrow \gamma\gamma$, \(\sqrt{s} = 8\) TeV, \(20.3\) fb$^{-1}$

<table>
<thead>
<tr>
<th>(N_{\text{jets}})</th>
<th>(\sigma_{\text{obs}}) (pb)</th>
<th>(\sigma_{\text{SM}}) (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\geq 3)</td>
<td>2.8 \pm 1.0</td>
<td>5.2 \pm 1.0</td>
</tr>
<tr>
<td>(= 2)</td>
<td>4.7 \pm 1.1</td>
<td>9.0 \pm 1.0</td>
</tr>
<tr>
<td>(= 1)</td>
<td>7.7 \pm 1.0</td>
<td>23.0 \pm 1.0</td>
</tr>
<tr>
<td>(= 0)</td>
<td>74.8 \pm 0.5</td>
<td></td>
</tr>
</tbody>
</table>

Impact on gluon fusion
- \(\sigma_g = 0.0001\)
- \(\sigma_g = 0.0002\)

Impact on VBF+VH
- \(\sigma_{HW} = 0.05\)
- \(\sigma_{HW} = 0.1\)

**Higgs production**

Impact on \(H \rightarrow \gamma\gamma\), \(\sqrt{s} = 8\) TeV

**ATLAS** Simulation

**ATLAS**

Ratio to SM

Impact on gluon fusion
- \(\sigma_g = 0.0001\)
- \(\sigma_g = 0.0002\)

Impact on VBF+VH
- \(\sigma_{HW} = 0.05\)
- \(\sigma_{HW} = 0.1\)
Higgs fiducial differential cross-sections have also been reinterpreted in terms of specific models e.g. Buddenbrock et al., arXiv:1506.00612 (scalar + DM candidate model)

And been proposed to directly probe other fundamental parameters of SM: Higgs width via $m_T(WW)$ fiducial differential cross-section in $H \rightarrow WW$

Campbell, Ellis, JHEP 1504 (2015) 030
Potential to benefit from reinterpretation of SM measurements even where dedicated search topologies exist

**Fully unfolded double-differential dijet measurements**

- Set 95% CL on compositeness scale for model of contact interactions using unfolded data
- Compositeness scale limits (>7.3 TeV; PDF dependent), of comparable sensitivity to dedicated reco-level search at time (>7.6 TeV)
- Easily reinterpretable, potential for combination with additional datasets
Conclusions

ATLAS and CMS already producing a huge variety of SM measurements that are reinterpretable and *reinterpreted* for BSM, small subset mentioned today.

- SM reinterpretations can add complementary constraints to existing searches
- Limits derived from unfolded data can equal or beat existing search constraints (*not true that unfolding necessitates reduced sensitivity*)
- Unfolded results in HEPDATA (with auxiliary information: correlations, Rivet routine) ready to be reinterpreted
- Enables easy combination with other data in fits: potential for even greater discriminating power in future

What other information / tools would be useful to facilitate reinterpretation?

- Additional measurements in fiducial regions matching searches?
- Publish corresponding reco-level cross-sections?
Backup