Exploring the SM at the LHC

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On behalf of the ATLAS and CMS Collaborations
Why study SM processes at LHC?

• Provide the ability to test a wide range of SM predictions
  - in new kinematic regime
  - and study SM processes observed for the first time at LHC

• Determine fundamental SM parameters.

• Provide constraints on proton PDFs.

• Provide description of background event kinematics for different searches for new physics.
What do we measure?

Measure cross-sections in fiducial volume

\[ \sigma_{fid} = \frac{N_{data} - N_{bkg}}{lumi \times C} \]

Extrapolate to total phase space

\[ \sigma_{tot} = \frac{N_{data} - N_{bkg}}{lumi \times A \times C} \]

Measure differential cross-sections

- Provide additional kinematic information
- Data subtracted from background
- Corrected for detector effects (reported at “particle” level)
Wealth of SM processes studied

$pp \rightarrow \text{jet(s)}$

$pp \rightarrow \gamma + X$

$pp \rightarrow W/Z + X$

$pp \rightarrow \bar{t}t + X$

$pp \rightarrow t$

$pp \rightarrow H$

$pp \rightarrow V V$

$pp \rightarrow V V V$

etc...
LHC Operation

2010, 7 TeV, 48.9 fb$^{-1}$
2011, 7 TeV, 5.6 fb$^{-1}$
2012, 8 TeV, 23.3 fb$^{-1}$
2015, 13 TeV, 4.2 fb$^{-1}$
1. Testing the SM in new kinematic regime
2. Precision tests of SM predictions
3. Determination of fundamental parameters of the SM
   3.1. Strong coupling constant
   3.2. CKM matrix element: $|V_{tb}|$
4. Constraints on Parton Distribution Functions
5. Study of rare processes (accessible for the first time)
   5.1. Higgs
   5.2. Multiboson production
Disclaimer

• Results presented only account for a small fraction of all measurements performed.
  - Doesn’t do justice to all the work done.

• Only results from ATLAS and CMS are presented.
  - SM explored by other LHC experiments (e.g. LHCb, etc.)

• Chose a wide ranging selection of different types of measurements to provide a broad overview of the different ways the SM is explored at the LHC.

• Also aimed to present measurements from different physics processes....

• .....and with a particular emphasis on most recent measurements.
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1. Testing SM in new kinematic regime

- Increase in $\sqrt{s}$ allows study of SM processes in new kinematic regime.
- SM processes are background processes to searches for new physics.
- Theoretical predictions at (N)NLO+(N)NLL compatible with measured total/differential cross-section of different SM processes.
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1. Testing the SM in new kinematic regime

2. Precision tests of SM predictions

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2. Precision tests of SM predictions

Calculations at the NNLO accuracy level available for several different SM processes, and in excellent agreement with measured total cross-sections.
2. Precision tests of SM predictions

$\text{pp} \rightarrow Z/\gamma \rightarrow e^+e^-$

Data much more precise than predictions!

non-perturbative effects and soft-gluon resummation are most important

sensitive to the emission of hard partons

Not quite sensitive to EW corrections.

arXiv:1512.02192

approximate NNLO (QCD ISR) + full NNLL

DYNNLO: Full NLO (QCD ISR)+NLO EWK added (but no multiple soft gluons (i.e. no LL))
2. Precision tests of SM predictions

Impact of missing higher-order terms

- NLO + PS [PWG+PY6] (ok)
- Approximate NNLO and Approximate N^3LO (not much improvement)
- Full NNLO (better agreement)

\[ pp \rightarrow t\bar{t} \rightarrow \ell + \text{jets} \]
Roadmap

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3.1 Determination of $\alpha_s$

- Single free parameter of QCD ($m_q \to 0$)

- $\alpha_s$ determined at a reference scale (e.g. $M_Z$)

- Running of $\alpha_s$ goes as $\sim 1/\ln(Q^2/\Lambda^2)$ with $\Lambda \sim 250$ GeV.

- Least precisely known coupling: $\Delta \alpha_s \sim 1\%$  
  $\Delta \alpha \sim 3 \times 10^{-10}$, $\Delta G_F \sim 5 \times 10^{-7}$, $\Delta G \sim 10^{-5}$

- Impacts all LHC cross-section predictions!
3.1 Determination of $\alpha_s$ (at NLO)

**Inclusive jet production**

$\alpha_s(M_Z) = 0.1185 \pm 0.0019 \text{ (exp)} \pm 0.0028 \text{ (PDF)} 
\pm 0.0004 \text{ (NP)} + 0.0053 \pm 0.0024 \text{ (scale)}$

**3-jet mass**

$\alpha_s(M_Z) = 0.1171 \pm 0.0013 \text{ (exp)} \pm 0.0024 \text{ (PDF)} 
\pm 0.0008 \text{ (NP)} + 0.0049 \pm 0.0040 \text{ (scale)}$

**Dominant uncertainty**

1) Scale uncertainty $\sim$ 4-5% $\rightarrow$ NNLO calculations will provide improved precision
2) PDF uncertainty $\sim$ 2% $\rightarrow$ Need more data to better constrain PDF
3.1 Determination of $\alpha_s$ (at NLO)

$R_{32} = \frac{N \geq 3\text{-jet}}{N \geq 2\text{-jet}}$

- Dominant uncertainty is scale uncertainty.
- Reduce PDF uncertainty from choice of observable 2% → 1%

$\alpha_s(M_Z) = 0.1148 \pm 0.0014 \text{ (exp)} \pm 0.0018 \text{ (PDF)} \pm 0.0050 \text{ (theory)}$

Transverse Energy-Energy correlation function in multi-jet events.

$\alpha_s(M_Z) = 0.1173 \pm 0.0010 \text{ (exp)} \pm 0.0017 \text{ (PDF)} \pm 0.0002 \text{ (NP)} + 0.0063 - 0.0020$
3.1 Determination of $\alpha_s$ (at NNLO)

- $t\bar{t}$ cross-section calculated at NNLO+NNLL.
- Predicted cross-section depends on $\alpha_s$.
- First measurement of $\alpha_s$ using top quarks.
- First measurement of $\alpha_s$ at NNLO.

$$\alpha_s(M_Z) = 0.1151^{+0.0017}_{-0.0018} \text{(exp)} + 0.0013 \text{(PDF)} + 0.0009 \text{(scale)}$$

$$\pm 0.0013 \text{(m}_t^{\text{pole}}) \pm 0.0008 \text{(E}_{LHC})$$

Most precise measurement of $\alpha_s$ at LHC (2.4%)!

Dominant uncertainties
1) Experimental uncertainties $\sim 1.5$
2) Top quark pole mass $\sim 1.1$
3) PDF uncertainty $\sim 1.1$
3.1 Determination of $\alpha_s$

Running of $\alpha_s$ observed up to $\sim 1.5$ TeV at NLO

→ Scope for measuring running to higher energy scale with increase in LHC $\sqrt{s}$

Scope for improvement in precision of $\alpha_s$ determination

→ Jet production at NNLO, increased statistics, improved PDF constraints.
3.2 Determination of $|V_{tb}|$

Single top $t$-channel production

\[ \begin{aligned} &u,c \quad d,s \quad g \quad W \quad t \quad b \quad \bar{b} \\ &g \quad \text{production} \quad t \quad W \quad b \quad \bar{b} \end{aligned} \]

Single top $Wt$ production

Determine $|f_L V_{tb}|$ from cross-section measurement

Assume:

- $|V_{td}|, |V_{ts}| \ll |V_{tb}|$
- $\text{Br}(t \rightarrow Wb) = 1$
- SM-like left-handed weak coupling

\[ f_L V_{tb} \bigg| ^2 = \frac{\sigma_{\text{meas.}}}{\sigma_{\text{theory}}} \]

$|f_L V_{tb}|^2$ measured to $\sim 5\%$
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4. PDF constraints

Extraction of PDF via global fits to fixed-target, collider DIS, collider pp data

- jets, photon, $t\bar{t}$
- W/Z production

Energy scale ($Q^2$)

Parton momentum fraction ($x$)

arXiv:1410.8849
4. PDF constraints from jets

- Inclusive jet $p_T$ distribution measured to $\sim 10\%$ (JES)
- Data described well by NLO pQCD over 11 order of magnitude!

Improved knowledge of gluon PDF at large $x$ (at high $Q^2$).
4. PDF constraints from photons

- Inclusive photon $E_T$ distribution measured to $\sim 10\text{-}20\%$
- Data described well by NLO pQCD over 6 order of magnitude!
- Sensitive to gluon PDF

- Improved knowledge of gluon PDF in medium $x$ region
- However, large scale uncertainty on NLO calculations $\rightarrow$ need NNLO
4. PDF constraints from top quark

Top pair differential cross-section now available at NNLO

Improved knowledge of gluon PDF over wide region of x by up to 20%

\[
\frac{d\sigma}{dt} = 4.6 \text{ fb}^{-1}
\]

\[\sqrt{s} = 7 \text{ TeV}\]
4. PDF constraints from $W$

$W$ produced primarily through annihilation of up/down quark

\[ u \bar{d} \rightarrow W^+ \]
\[ d \bar{u} \rightarrow W^- \]

Muon charge asymmetry:

\[
A(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \rightarrow \mu^+ \nu) - \frac{d\sigma}{d\eta}(W^- \rightarrow \mu^- \bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \rightarrow \mu^+ \nu) + \frac{d\sigma}{d\eta}(W^- \rightarrow \mu^- \bar{\nu})}.
\]

Muon asymmetry measured to $\sim 1\%$

(Uncertainties cancellation in ratio)

Improved knowledge of u/d valence PDF at all $x$. 

CMS Preliminary NLO 13 parameter fit

\[ Q^2 = m_W^2 \]
4. Updated PDF with LHC Run-1

LHC Run-1 data provide useful PDF constraints. Data included in new global fits for LHC Run-2.

arXiv:1410.8849
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5. Study of rare processes

Rare processes measured for the first time at LHC
5.1 Higgs production/decay

For $M_H = 125$ GeV

Production cross-section at 8 TeV

Decay
5.1 Higgs mass measurement

- Use the two decays that provide the best mass resolution: $H \rightarrow \gamma \gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$
- Categorize events with different S/B and different mass resolution to maximize sensitivity
- Measurement relies on detailed studies of energy/momentum calibration
5.1 Higgs mass measurement

- Higgs boson mass measured to < 0.2%!
- Individual measurements dominated by statistical uncertainty.

5.1 Higgs boson spin/CP

Exploit all available kinematic information in Higgs decaying to di-boson to test data against different spin/CP hypothesis.

All alternatives of pure spin/CP states tested against $J^P=0^+$ are strongly rejected.
5.1 Higgs total production cross-section

Not enough available luminosity at 13 TeV (~ 3 fb$^{-2}$) to reach Run-1 sensitivity.

Predicted total cross-section calculated at NNLO.
5.1 Higgs rate measurements

- Different Higgs production mode
- Different Higgs decay mode

\[ n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{ \sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}^f \right\}, \]

\[ = \mathcal{L}(k) \times \sum_i \sum_f \mu_i \mu^f \left\{ \sigma_i^{\text{SM}} \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}_i^f \right\} \]

- Signal yield from a category of events is an admixture of all possible production and decay modes.
- Higgs measurements at the LHC only sensitive to the product of cross-section x BR.
- Additional information and/or assumption required to determine separately the cross-sections and branching ratios.
5.1 Higgs ratios combinations

- Extract ratios of cross-sections and BRs
  - Independent of theoretical predictions of the inclusive cross-sections and BRs.
  - Avoid (dominant) theoretical uncertainty on inclusive cross-sections
- Most model-independent results
- Normalize to $gg \rightarrow H \rightarrow ZZ$

$$\sigma_i \cdot BR^f = \sigma(gg \rightarrow H \rightarrow ZZ) \times \left( \frac{\sigma_i}{\sigma_{ggF}} \right) \times \left( \frac{BR^f}{BR^{ZZ}} \right)$$

- Fit all the measured rates to extract ratios.
5.1 Higgs ratios combination

p-value of compatibility between measurements and SM predictions is 16%

$2.3\sigma$ excess compared to SM prediction

Best fit value pulled low due to "excess" in ZH and ttH production modes in decay channels other than $H \rightarrow bb$

~20% uncertainty
5.1 Higgs signal strength combination

\[ \mu_i^f = \frac{\sigma_i \cdot \text{BR}^f}{(\sigma_i)_{SM} \cdot (\text{BR}^f)_{SM}} = \mu_i \times \mu^f \]

Assume SM BR


Assume SM production cross-section


Observed with 5.4σ significance (exp 4.7σ)

Observed with 3.5σ significance (exp 4.2σ)

Observed with 4.4σ significance (exp 2σ)

Observed with 5.5σ significance (exp 5.0σ)
5.1 Higgs rate measurements

20-30% uncertainties
5.1 Higgs boson width

Width in the SM ~ 4 MeV

Direct upper limit from reconstructed mass distribution: \( \Gamma_H < 1.7 \) GeV

Direct lower limit from lifetime in \( H \rightarrow 4\ell \): \( \Gamma_H > 3.5 \times 10^{-9} \) MeV

\[ \Gamma_H < 22 \text{ MeV (33 MeV exp.) at 95\%CL} \quad \text{[CMS]} \]
\[ \Gamma_H < 22.7 \text{ MeV (33.0 MeV exp.) at 95\%CL} \quad \text{[ATLAS]} \]

Off-shell/On-shell ratio of \( H \rightarrow ZZ \rightarrow 4\ell \)

Assumptions:
- on-shell couplings = off-shell couplings
- No new particle at high \( VV \) mass
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5.2 Multi-boson production

Study of multi-boson production provides unique tests of SM.

- Rate measurements of processes never observed before!
  - Vector Boson Scattering (VBS)
  - Tri-boson production

- Tests of non-Abelian structure of SM
  - Triple Gauge Couplings (TGC)
  - Quartic Gauge Couplings (QGC)  Set limits on anomalous couplings

- EWSB probe through VBS
5.2 Multi-boson production

![Graph showing CMS measurements vs. NLO (NNLO) theory for various multi-boson production processes at different CMS energies. The graph includes data for $\gamma\gamma$, $W\gamma$, $Z\gamma$, $Z\gamma$, $WW+WZ$, $WW$, $WW$, $WZ$, $WZ$, $WZ$, $ZZ$, and $ZZ$. The production cross section ratios are given for each process at 7 TeV, 8 TeV, and 13 TeV, with errors and data points plotted.](http://cern.ch/go/pNj7)
5.2 Multi-boson production

Dec. 2015

CMS measurements vs. NLO (NNLO) theory

γγ, (NNLO th.)
Wγ
Zγ
Zγ
WW+Z
WW
WW, (NNLO th.)
WZ
WZ
WZ
ZZ
ZZ

Production Cross Section Ratio: $\frac{\sigma_{\text{exp}}}{\sigma_{\text{theo}}}$

CMS Preliminary

7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)

1.06 ± 0.01 ± 0.12 5.0 fb$^{-1}$

ATLAS Preliminary

$s = 8$ TeV, 20.3 fb$^{-1}$

W$^3$Z

combined

$\sigma_{\text{fid.}}_{W^3Z} / \sigma_{\text{theory}}_{W^3Z}$

All results at:
http://cern.ch/go/pNj7

Brigitte Vachon, McGill

CNPLHC 2016
5.2 Multi-boson production

\[ \begin{align*}
q & \rightarrow W \\
\bar{q}' & \rightarrow W \\
W & \rightarrow TGC \\
W & \rightarrow Z \\
Z & \rightarrow \gamma
\end{align*} \]


**ATLAS Preliminary**

- \( s = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)
- \( \ell' \ell \ell \)
- \( \ell', \ell = e \text{ or } \mu \)

\[ \begin{align*}
\Delta g_1^Z &= 0, \Delta \kappa^Z = -0.19, \lambda^Z = 0 \\
\Delta g_3^Z &= 0, \Delta \kappa^Z = -0.25, \lambda^Z = 0.1
\end{align*} \]

**CMS**

- SM p-value: 0.37
- Data
- Standard Model
- \( h_3^Z = 0, h_4^Z = 0.001 \)
- \( h_3^Z = 0.03, h_4^Z = 0 \)
- \( h_3^Z = 0.06, h_4^Z = 0.0016 \)

\[ \begin{align*}
\text{Events} & \quad 10^5 \quad 10^4 \quad 10^3 \quad 10^2 \quad 10 \quad 1 \quad 10^{-1} \\
\text{Events / 4 GeV} & \quad 10^2 \quad 10 \quad 1 \quad 10^{-1} \\
\text{\( m_{T}^{WZ} \) [GeV]} & \quad 0 \quad 100 \quad 200 \quad 300 \quad 400 \quad 500 \\
\text{\( p_T^\gamma \) (GeV)} & \quad 0 \quad 100 \quad 200 \quad 300 \quad 400 \quad 500
\end{align*} \]
5.2 Electroweak WWjj production

• Key process to probe EW symmetry breaking:
  - VBS amplitude increases with $\sqrt{s}$; need Higgs to avoid violating unitarity at $\sim 1$ TeV
• First evidence for electroweak-only $W^\pm W^\pm jj$ production
  
  ATLAS: Significance 3.6$\sigma$ (exp. 2.8$\sigma$)
  CMS: Significance 2.0$\sigma$ (exp. 3.1$\sigma$)

• Set constraints on anomalous QGC
5.2 $W\gamma\gamma$ production

- First evidence of $W\gamma\gamma$ production
  - ATLAS significance $> 3\sigma$
  - CMS significance $= 2.4\sigma$

- Measured cross-section compatible with SM.
- Sensitive to anomalous quartic coupling

Summary

• Wealth of data from different physics processes at LHC.
  - Some new physics processes observed for the first time.

• Good agreement of SM theoretical predictions with data (total and differential cross-sections).

• Determination of fundamental parameters of the SM model.

• LHC data improves constraints on PDFs.

• Detailed studies of known SM processes is paramount for the search of new physics phenomena.
Backup
1. Testing SM in new kinematic regime

- Increase in $\sqrt{s}$ allows study of SM processes in new kinematic regime.
- SM processes are background processes to searches for new physics.
- Theoretical predictions at (N)NLO+(N)NLL compatible with measured total/differential cross-section of different SM processes.
5.1 Higgs production rates

Assumptions

- Particle studied is a single SM-like Higgs boson state (i.e. CP-even scalar particle with the tensor structure of the SM interactions).

- Narrow width approximation valid.

- Production:
  - $\mu(bbH) = \mu(ggF)$
  - $\mu(tH) = \mu(ttH)$
  - $\mu(ggZH) = \mu(ZH \text{ via quark})$

- Decay:
  - $\mu(H \rightarrow gg) = \mu(H \rightarrow cc) = \mu(H \rightarrow bb)$
  - $\mu(H \rightarrow Z\gamma) = \mu(H \rightarrow \gamma\gamma)$

- Higgs boson total width free to vary within narrow width approximation
5.2 Multi-boson production

Sensitive probe to non-Abelian nature of SM

Diboson final states in scattering topologies and triboson final states can be used to set limits on quartic gauge couplings (aQGCs).
Coupling studies

For each "bin" (experiment, production mode i, decay j, analysis category k) compare measured rate to expectations

\[ \text{Luminosity} \times \sigma_i \times \text{BR}_j \times \text{Acceptance}_{ijk} \times \epsilon_{ijk} + \text{background}_{ijk} \]

Acceptance\text{\textsubscript{ijk}} \times \epsilon_{ijk} from simulation => Assume Standard Model kinematics

Systematic uncertainties (theory and experimental) propagated in profile likelihood fit as well as background uncertainties

Theoretical signal uncertainties and part of luminosity correlated between ATLAS and CMS, other not

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<th>H→VV</th>
<th>H→ZZ*→4l</th>
<th>H→WW*→2l2v</th>
<th>H→ttT</th>
<th>H→bb</th>
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<th>H→Zv</th>
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2. Precision tests of SM predictions

pQCD NNLO calculations available for several different SM processes, and in excellent agreement with measured total cross-sections.

All results at: http://cern.ch/go/pNj7

Brigitte
5.1 Higgs total production cross-section

\[ \sigma_{\text{fid}} \text{ [fb]} \]

- Data (stat. + sys. unc.)
- Systematic uncertainty
- Model dependence
- Standard model \( (m_H = 125 \text{ GeV}) \)

\( pp \rightarrow (H \rightarrow 4\ell) + X \)

5.1 fb\(^{-1}\) (7 TeV), 19.7 fb\(^{-1}\) (8 TeV)

anomalous QGC


\[
\begin{align*}
\mathcal{L}_1 &= \alpha_1 g g' \operatorname{tr} [B_{\mu\nu} W^{\mu\nu}], \\
\mathcal{L}_2 &= i\alpha_2 g' \operatorname{tr} [B_{\mu\nu} [V^\mu, V^\nu]], \\
\mathcal{L}_3 &= i\alpha_3 g \operatorname{tr} [W_{\mu\nu} [V^\mu, V^\nu]], \\
\mathcal{L}_4 &= \alpha_4 (\operatorname{tr} [V^\mu V^\nu])^2, \\
\mathcal{L}_5 &= \alpha_5 (\operatorname{tr} [V^\mu V^\nu])^2.
\end{align*}
\]
anomalous QGC


Nine independent C- and P-conserving dimension-eight effective operators to modify the quartic couplings between the weak gauge bosons.

\[
\mathcal{L}_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi\right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi\right]
\]
\[
\mathcal{L}_{S,1} = \left[(D_\mu \Phi)^\dagger D^\mu \Phi\right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi\right]
\]
\[
\mathcal{L}_{M,0} = \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}\right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi\right]
\]
\[
\mathcal{L}_{M,1} = \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\nu\beta}\right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi\right]
\]
\[
\mathcal{L}_{M,2} = \left[B_{\mu\nu} B^{\mu\nu}\right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi\right]
\]
\[
\mathcal{L}_{M,3} = \left[B_{\mu\nu} B^{\nu\beta}\right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi\right]
\]
\[
\mathcal{L}_{M,4} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\mu \Phi\right] \times B^{\beta\nu}
\]
\[
\mathcal{L}_{M,5} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\nu \Phi\right] \times B^{\beta\mu}
\]
\[
\mathcal{L}_{M,6} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\nu} D^\mu \Phi\right]
\]
\[
\mathcal{L}_{M,7} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi\right]
\]
\[
\mathcal{L}_{T,0} = \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}\right] \times \text{Tr} \left[\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta}\right]
\]
\[
\mathcal{L}_{T,1} = \text{Tr} \left[\hat{W}_{\alpha\beta} \hat{W}^{\beta\nu}\right] \times \text{Tr} \left[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu}\right]
\]
\[
\mathcal{L}_{T,2} = \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}\right] \times \text{Tr} \left[\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha}\right]
\]
\[
\mathcal{L}_{T,3} = \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \hat{W}^{\nu\alpha}\right] \times B_{\beta\nu}
\]
\[
\mathcal{L}_{T,4} = \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\alpha\mu} \hat{W}^{\beta\nu}\right] \times B_{\beta\nu}
\]
\[
\mathcal{L}_{T,5} = \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}\right] \times B_{\alpha\beta} B^{\alpha\beta}
\]
\[
\mathcal{L}_{T,6} = \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}\right] \times B_{\mu\beta} B^{\alpha\nu}
\]
\[
\mathcal{L}_{T,7} = \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}\right] \times B_{\beta\nu} B^{\nu\alpha}
\]
\[
\mathcal{L}_{T,8} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}
\]
\[
\mathcal{L}_{T,9} = B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}
\]
Limits from CMS from electroweak WWjj production

<table>
<thead>
<tr>
<th>Operator coefficient</th>
<th>Exp. lower</th>
<th>Exp. upper</th>
<th>Obs. lower</th>
<th>Obs. upper</th>
<th>Unitarity limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{S,0}/\Lambda^4$</td>
<td>-42</td>
<td>43</td>
<td>-38</td>
<td>40</td>
<td>0.016</td>
</tr>
<tr>
<td>$F_{S,1}/\Lambda^4$</td>
<td>-129</td>
<td>131</td>
<td>-118</td>
<td>120</td>
<td>0.050</td>
</tr>
<tr>
<td>$F_{M,0}/\Lambda^4$</td>
<td>-35</td>
<td>35</td>
<td>-33</td>
<td>32</td>
<td>80</td>
</tr>
<tr>
<td>$F_{M,1}/\Lambda^4$</td>
<td>-49</td>
<td>51</td>
<td>-44</td>
<td>47</td>
<td>205</td>
</tr>
<tr>
<td>$F_{M,6}/\Lambda^4$</td>
<td>-70</td>
<td>69</td>
<td>-65</td>
<td>63</td>
<td>160</td>
</tr>
<tr>
<td>$F_{M,7}/\Lambda^4$</td>
<td>-76</td>
<td>73</td>
<td>-70</td>
<td>66</td>
<td>105</td>
</tr>
<tr>
<td>$F_{T,0}/\Lambda^4$</td>
<td>-4.6</td>
<td>4.9</td>
<td>-4.2</td>
<td>4.6</td>
<td>0.027</td>
</tr>
<tr>
<td>$F_{T,1}/\Lambda^4$</td>
<td>-2.1</td>
<td>2.4</td>
<td>-1.9</td>
<td>2.2</td>
<td>0.022</td>
</tr>
<tr>
<td>$F_{T,2}/\Lambda^4$</td>
<td>-5.9</td>
<td>7.0</td>
<td>-5.2</td>
<td>6.4</td>
<td>0.08</td>
</tr>
</tbody>
</table>
2. Precision tests of SM predictions

\[ \sigma_{AB \rightarrow X} = f_A(x_1, Q^2) \otimes f_B(x_1, Q^2) \otimes \sigma(x_1, x_2, Q^2) \otimes D_{i \rightarrow X}(z, Q^2) \]
5.1 Higgs differential cross-section

$H \rightarrow \gamma \gamma$
$H \rightarrow ZZ^* \rightarrow 4\ell$

Sensitive to higher order corrections in pQCD

$H \rightarrow \gamma \gamma$


NNLO+NNLL

Sensitive proton PDF and production mechanism.
Higgs coupling modifiers

\[
\begin{align*}
\kappa_{gZ} & \quad \text{ATLAS} \quad \text{CMS} \\
\lambda_{Zg} & \quad \text{ATLAS} \quad \text{CMS} \\
\lambda_{t\gamma} & \quad \text{ATLAS} \quad \text{CMS} \\
\lambda_{WZ} & \quad \text{ATLAS} \quad \text{CMS} \\
\lambda_{\gamma Z} & \quad \text{ATLAS} \quad \text{CMS} \\
\lambda_{\tau Z} & \quad \text{ATLAS} \quad \text{CMS} \\
\lambda_{bZ} & \quad \text{ATLAS} \quad \text{CMS}
\end{align*}
\]

Parameter value
5.1 Higgs boson spin/CP

**Spin 2**

**Spin 1**

TABLE II. List of spin-two models with the production and decay couplings of an exotic $X$ particle. The subscripts $m$ (minimal couplings), $h$ (couplings with higher-dimension operators), and $b$ (bulk) distinguish different scenarios.

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>Model</th>
<th>$gg \to X$ Couplings</th>
<th>$q\bar{q} \to X$ Couplings</th>
<th>$X \to VV$ Couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2^+_m$</td>
<td>$c_{1}^{gg} \neq 0$</td>
<td>$\rho_1 \neq 0$</td>
<td>$c_1^{VV} = c_5^{VV} \neq 0$</td>
<td></td>
</tr>
<tr>
<td>$2^+_h$</td>
<td>$c_{2}^{gg} \neq 0$</td>
<td>$\rho_1 \neq 0$</td>
<td>$c_2^{VV} \neq 0$</td>
<td></td>
</tr>
<tr>
<td>$2^+_h$</td>
<td>$c_{3}^{gg} \neq 0$</td>
<td>$\rho_1 \neq 0$</td>
<td>$c_3^{VV} \neq 0$</td>
<td></td>
</tr>
<tr>
<td>$2^+_h$</td>
<td>$c_{4}^{gg} \neq 0$</td>
<td>$\rho_1 \neq 0$</td>
<td>$c_4^{VV} \neq 0$</td>
<td></td>
</tr>
<tr>
<td>$2^+_b$</td>
<td>$c_{1}^{gg} \neq 0$</td>
<td>$\rho_1 \neq 0$</td>
<td>$c_1^{VV} \ll c_5^{VV} \neq 0$</td>
<td></td>
</tr>
<tr>
<td>$2^+_h$</td>
<td>$c_{1}^{gg} \neq 0$</td>
<td>$\rho_1 \neq 0$</td>
<td>$c_6^{VV} \neq 0$</td>
<td></td>
</tr>
<tr>
<td>$2^+_h$</td>
<td>$c_{1}^{gg} \neq 0$</td>
<td>$\rho_1 \neq 0$</td>
<td>$c_7^{VV} \neq 0$</td>
<td></td>
</tr>
<tr>
<td>$2^-_h$</td>
<td>$c_{8}^{gg} \neq 0$</td>
<td>$\rho_2 \neq 0$</td>
<td>$c_8^{VV} \neq 0$</td>
<td></td>
</tr>
<tr>
<td>$2^-_h$</td>
<td>$c_{8}^{gg} \neq 0$</td>
<td>$\rho_2 \neq 0$</td>
<td>$c_9^{VV} \neq 0$</td>
<td></td>
</tr>
<tr>
<td>$2^-_h$</td>
<td>$c_{8}^{gg} \neq 0$</td>
<td>$\rho_2 \neq 0$</td>
<td>$c_{10}^{VV} \neq 0$</td>
<td></td>
</tr>
</tbody>
</table>

$L(X_{J=1}VV) \sim b_1 \partial_{\mu}X_{\nu}Z_{\mu}Z_{\nu} + b_2 \epsilon_{\alpha\mu\beta\gamma}X^{\alpha}Z^{\mu}\partial^{\beta}Z^{\nu} + b_1^{WW} \partial_{\mu}X_{\nu}(W^{+\mu}W^{-\nu} + W^{-\mu}W^{+\nu}) + b_2^{WW} \epsilon_{\alpha\mu\beta\gamma}X^{\alpha}(W^{-\mu}\partial^{\beta}W^{+\nu} + W^{+\mu}\partial^{\beta}W^{-\nu})$.
anomalous TGC in WWγ

### September 2015

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limits</th>
<th>$\int L dt$</th>
<th>$\sqrt{s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W\gamma$</td>
<td>[-4.1e-01, 4.6e-01]</td>
<td>4.6 fb(^{-1})</td>
<td>7 TeV</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>[-3.8e-01, 2.9e-01]</td>
<td>5.0 fb(^{-1})</td>
<td>7 TeV</td>
</tr>
<tr>
<td>$WW$</td>
<td>[-2.1e-01, 2.2e-01]</td>
<td>4.9 fb(^{-1})</td>
<td>7 TeV</td>
</tr>
<tr>
<td>$WW$</td>
<td>[-1.3e-01, 9.5e-02]</td>
<td>19.4 fb(^{-1})</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$WV$</td>
<td>[-2.1e-01, 2.2e-01]</td>
<td>4.6 fb(^{-1})</td>
<td>7 TeV</td>
</tr>
<tr>
<td>$WV$</td>
<td>[-1.1e-01, 1.4e-01]</td>
<td>5.0 fb(^{-1})</td>
<td>7 TeV</td>
</tr>
<tr>
<td>D0 Comb.</td>
<td>[-1.6e-01, 2.5e-01]</td>
<td>8.6 fb(^{-1})</td>
<td>1.96 TeV</td>
</tr>
<tr>
<td>LEP Comb.</td>
<td>[-9.9e-02, 6.6e-02]</td>
<td>0.7 fb(^{-1})</td>
<td>0.20 TeV</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>[-6.5e-02, 6.1e-02]</td>
<td>4.6 fb(^{-1})</td>
<td>7 TeV</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>[-5.0e-02, 3.7e-02]</td>
<td>5.0 fb(^{-1})</td>
<td>7 TeV</td>
</tr>
<tr>
<td>$WW$</td>
<td>[-4.8e-02, 4.8e-02]</td>
<td>4.9 fb(^{-1})</td>
<td>7 TeV</td>
</tr>
<tr>
<td>$WW$</td>
<td>[-2.4e-02, 2.4e-02]</td>
<td>19.4 fb(^{-1})</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$WV$</td>
<td>[-3.9e-02, 4.0e-02]</td>
<td>4.6 fb(^{-1})</td>
<td>7 TeV</td>
</tr>
<tr>
<td>$WV$</td>
<td>[-3.8e-02, 3.0e-02]</td>
<td>5.0 fb(^{-1})</td>
<td>7 TeV</td>
</tr>
<tr>
<td>D0 Comb.</td>
<td>[-3.6e-02, 4.4e-02]</td>
<td>8.6 fb(^{-1})</td>
<td>1.96 TeV</td>
</tr>
<tr>
<td>LEP Comb.</td>
<td>[-5.9e-02, 1.7e-02]</td>
<td>0.7 fb(^{-1})</td>
<td>0.20 TeV</td>
</tr>
</tbody>
</table>

### aTGC Limits @95% C.L.
anomalous TGC in WWZ
### Anomalous $WW_{\gamma\gamma}$ Quartic Coupling limits @95% C.L.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limits</th>
<th>$L$</th>
<th>$\gamma s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW_{\gamma}$</td>
<td>[- 15000, 15000]</td>
<td>0.43fb$^{-1}$</td>
<td>0.20 TeV</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow WW$</td>
<td>[- 430, 430]</td>
<td>9.70fb$^{-1}$</td>
<td>1.96 TeV</td>
</tr>
<tr>
<td>$WW_{\gamma}$</td>
<td>[- 21, 20]</td>
<td>19.30fb$^{-1}$</td>
<td>8.0 TeV</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow WW$</td>
<td>[- 4, 4]</td>
<td>5.05fb$^{-1}$</td>
<td>7.0 TeV</td>
</tr>
<tr>
<td>$WW_{\gamma}$</td>
<td>[- 48000, 26000]</td>
<td>0.43fb$^{-1}$</td>
<td>0.20 TeV</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow WW$</td>
<td>[- 15000, 15000]</td>
<td>9.70fb$^{-1}$</td>
<td>1.96 TeV</td>
</tr>
<tr>
<td>$WW_{\gamma}$</td>
<td>[- 34, 32]</td>
<td>19.30fb$^{-1}$</td>
<td>8.0 TeV</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow WW$</td>
<td>[- 15, 15]</td>
<td>5.05fb$^{-1}$</td>
<td>7.0 TeV</td>
</tr>
<tr>
<td>$WW_{\gamma}$</td>
<td>[- 25, 24]</td>
<td>19.30fb$^{-1}$</td>
<td>8.0 TeV</td>
</tr>
</tbody>
</table>
The $k$-framework relation is given by:

$$\sigma_i \cdot \text{BR}^f = \frac{\sigma_i(k) \cdot \Gamma^f(k)}{\Gamma_H},$$

where $\sigma_i(k) \propto \kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$ for $\sigma(ggF)$, $\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$ for $\sigma(VBF)$, $\sim \kappa_W^2$ for $\sigma(WH)$, $\sim \kappa_Z^2$ for $\sigma(qq/qg \to ZH)$, $\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$ for $\sigma(gg \to ZH)$, $\sim \kappa_t^2$ for $\sigma(ttH)$, $\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$ for $\sigma(gb \to WtH)$, $\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$ for $\sigma(qb \to tHq)$, and $\sim \kappa_b^2$ for $\sigma(bbH)$.

The partial decay widths are as follows:

- $\Gamma^{ZZ} \sim \kappa_Z^2$
- $\Gamma^{WW} \sim \kappa_W^2$
- $\Gamma^{\gamma\gamma} \sim \kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
- $\Gamma^{\tau\tau} \sim \kappa_\tau^2$
- $\Gamma^{bb} \sim \kappa_b^2$
- $\Gamma^{\mu\mu} \sim \kappa_\mu^2$
Search for a \textbf{Two Photons Resonance (II)}

\textbf{Results:} Events with mass in excess of 200 GeV are included in \textit{unbinned fit}

- \textbf{In the NWA search}, an excess of 3.6\(\sigma\) (local) is observed at a mass hypothesis of minimal \(p_0\) of 750 GeV

- Taking a LEE in a mass range (fixed before unblinding) of 200 GeV to 2.0 TeV the \textit{global significance} of the excess is 2.0\(\sigma\)

- As expected the local significance increases to 3.9\(\sigma\)

- Taking into account a LEE in mass and width of up to 10\% of the mass hypothesis of 2.3\(\sigma\) \textit{(Note: upper range in resolution fixed after unblinding)}
Combined limits and p-values

Narrow Width
~ 25 GeV

Wide (6%) Width

Local p-value: 2.6σ
@ 760 GeV

Including LEE (0.5 - 4.5 TeV; narrow width), global p-value < 1.2σ
CMS ttH excess in di-muon
2. Precision tests of SM predictions

$pp \rightarrow t\bar{t} \rightarrow \ell+\text{jets}$

Measure differential cross-section at parton level and compare to different pQCD calculations.

Improved description of data with NNLO