Multiboson Production at CMS

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Introduction

- Multiboson final state = [WZɣ][WZɣ]+[j]*
  - Includes both leptonically decaying W and Z bosons and hadronically decaying W and Z bosons
  - Includes both precision measurements and searches
- Motivation
  - Test of Standard Model electroweak cubic and quartic interactions
  - Indirect study the Higgs boson
  - Background for direct Higgs measurements
- No recently released multiboson results from CMS, but several previously released multiboson results were recently published
  - Production of ZZ
  - Electroweak Production of $W^{\pm}W^{\pm}jj$
  - Electroweak Production of ZZjj

Generator Tools

- MadGraph_aMC@NLO
  - Automated LO and NLO generator
- Sherpa
  - Automated LO and NLO generator
- VBFNLO
  - For final states involving Higgs bosons and vector bosons
- Phantom
  - For QCD and electroweak for vector boson scattering (VBS) and vector boson fusion (VBF)
- POWHEG
  - NLO-QCD generator for specific list of processes with almost very few negative event weights
- MCFM
  - Generator and differential cross-section calculator with a long list of processes implemented
- Multiboson processes can involve thousands of diagrams --> stress test of generators

- Pythia8 or Herwig
  - for parton showering and hadronization

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1 processes with 18818 diagrams generated in 34.243 s
Total: 1 processes with 18818 diagrams
MG5_aMC>
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Anomalous Couplings Frameworks

- Quantify deviations from the Standard Model in a general or model-independent way
- Allows us to compare measurements in different channels and different experiments
- Anomalous Triple Gauge Couplings
  - For example: $Q_W = e \rightarrow Q_W = (\Delta g_1^Z + 1)e$
  - Charged triple gauge coupling parameters: $\Delta g_1^Z, \lambda_Z, \Delta\kappa_Z$
  - Neutral triple gauge coupling parameters: $h_3^\gamma, h_3^Z, h_4^\gamma, h_4^Z, f_5^\gamma, f_5^Z, f_4^\gamma, f_4^Z$
- Dimension 8 Effective Field Theory
  - $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{F_i}{\Lambda^4} \mathcal{O}_i$
  - Operators involving $D_\mu\phi$: $L_{S0\text{-}1}$
  - Operators involving $B_{\mu\nu}$ or $W^i_{\mu\nu}$: $L_{T0\text{-}9}$
  - Operators involving $D_\mu\phi$ and either $B_{\mu\nu}$ or $W^i_{\mu\nu}$: $L_{M0\text{-}7}$
  - For example: $L_{T8} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$

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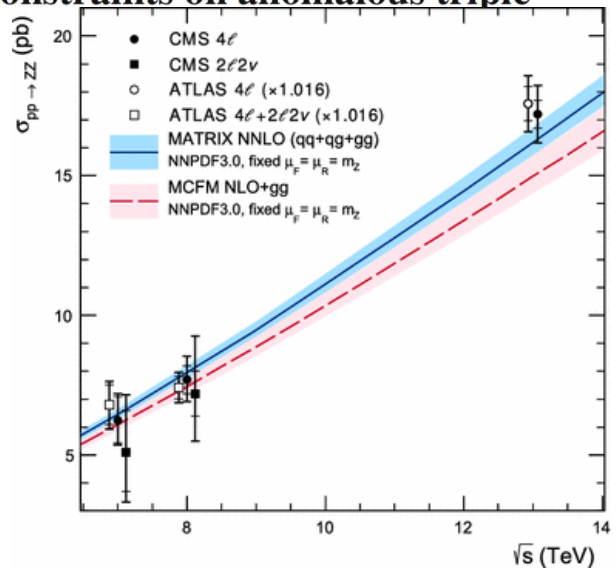
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

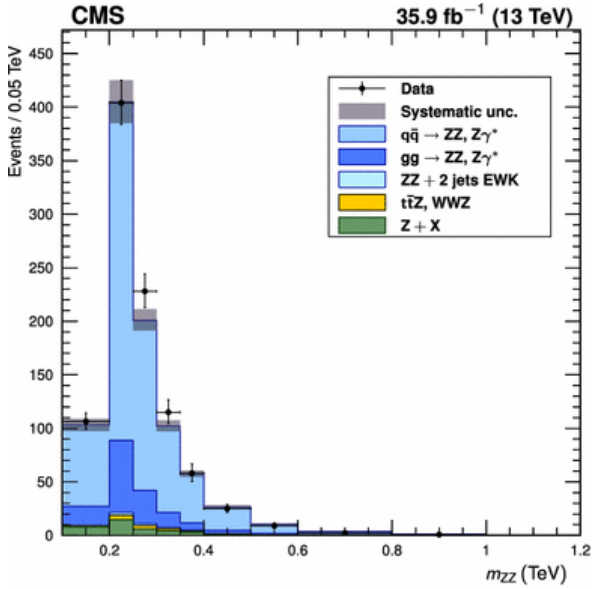
Production of ZZ (I)

Measurements of the pp → ZZ production cross section and the Z → 4ℓ branching fraction, and constraints on anomalous triple gauge couplings at $\sqrt{s}$ = 13 TeV

CMS Collaboration*



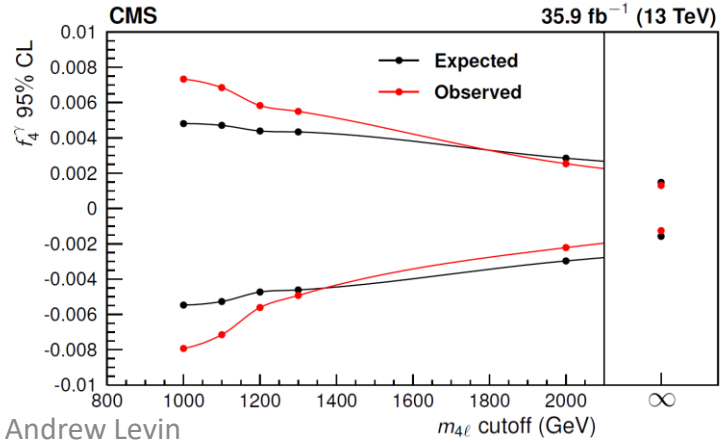
- Published in EPJC in February 2018
- Based on 36 fb^{-1} of data collected by CMS in 2016 at 13 TeV
- Use ZZ --> 4l channel (l = e or μ)
- Total cross-section measurement result: σ(pp-->ZZ) = $17.5^{+0.6}_{-0.5}$ (stat) ± 0.6(syst) ± 0.4(syst) ± 0.4(lumi) pb
- Can be compared to
  - NNLO prediction from MATRIX: $16.2^{+0.6}_{-0.4}$ pb
  - NLO prediction from MCFM: $15.0^{+0.7}_{-0.6}$ ± 0.2 pb

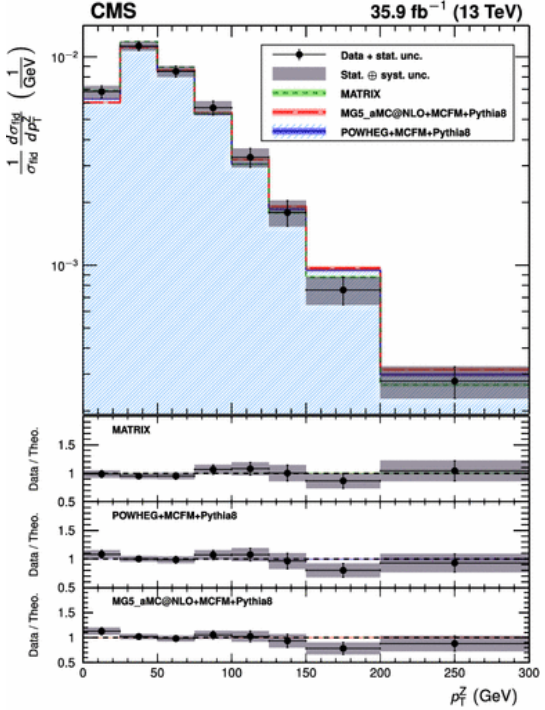


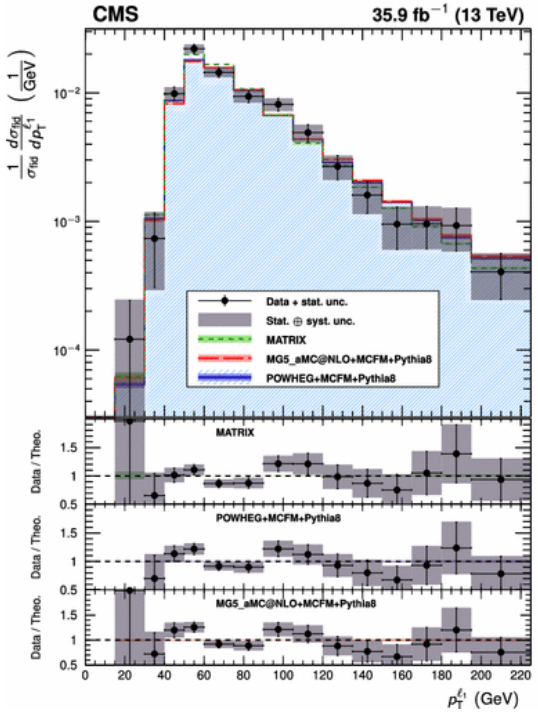
Production of ZZ (II)

- Unfolding
  - Unfolding performed by iterative technique, using RooUnfold
  - Unfolded distributions for m_{ZZ}, $\Delta R_{Z_1,Z_2}$, $p_T^{l_1}$, and p_T^Z provided
- Anomalous Couplings
  - World's best limits on f_5^γ, f_5^Z, f_4^γ, f_4^Z
  - Use m_{4l} cutoffs to impose unitarity constraints

$$-0.0012 < f_5^\gamma < 0.0013$$
$$-0.0010 < f_5^Z < 0.0013$$
$$-0.0012 < f_4^\gamma < 0.0013$$
$$-0.0012 < f_4^Z < 0.0010$$







Production of ZZ (III)

- Selection
  - Follows the H --> ZZ --> 4l analysis
  - Require Z boson masses > 60 GeV
- Systematic Uncertainties
- Background estimation
  - Main background comes from events in which a jet causes a lepton to be reconstructed are the main background
  - We use the following data-driven method to estimate this background:
    1. Define "lepton fake rate" to be the rate at which a reconstructed lepton which passes a loose ID also passes the final tight ID
    2. Using Z + 1 reconstructed lepton events in data, we measure lepton fake rate in data as a function of p_T, $|\eta|$, and lepton flavor
    3. We then apply appropriate factors of the lepton fake rates to control regions with one or more leptons failing the lepton ID to extrapolate to the signal region
  - There are a large number of subtleties and complications involved this method, and also a large number of validation studies

Uncertainty Source	Uncertainty Size (%)
Lepton efficiency	2–6
Trigger efficiency	2
Statistical (simulation)	0.5
Background	0.5–1
Pileup	1
PDF	1
μ_R, μ_F	1
Integrated luminosity	2.5

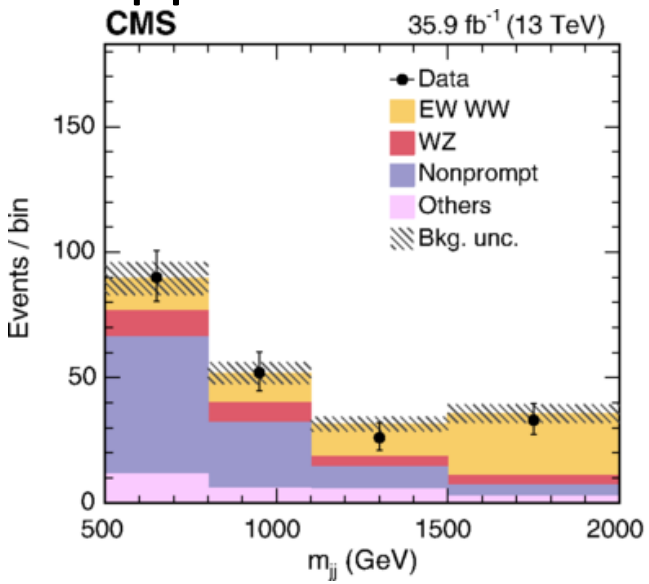
Electroweak Production of $W^{\pm}W^{\pm}jj$ (I)

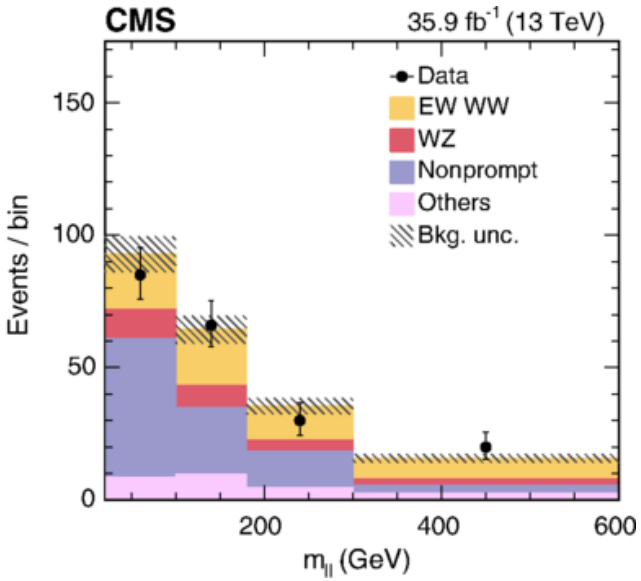
PHYSICAL REVIEW LETTERS **120,** 081801 (2018)

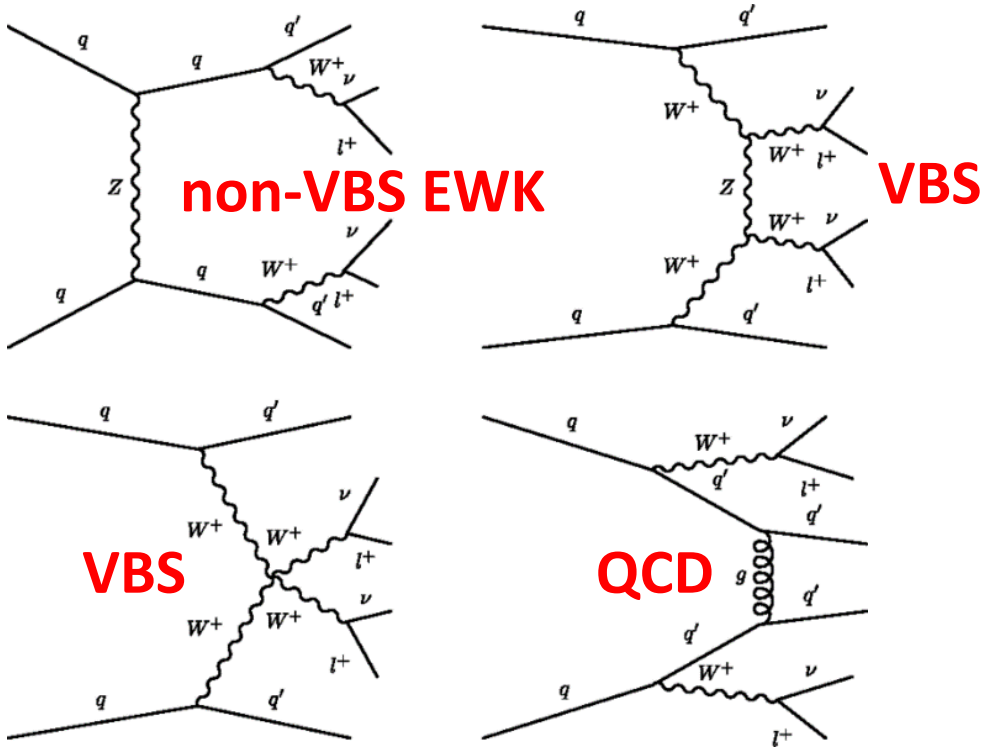
- Published in PRL in February 2018
- Signal significance: 5.5 σ observed, 5.7 σ expected
- World's first observation of electroweak-induced VVjj production at a pp collider

Observation of Electroweak Production of Same-Sign *W* Boson Pairs in the Two Jet and Two Same-Sign Lepton Final State in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

A. M. Sirunyan *et al.*[*]
(CMS Collaboration)

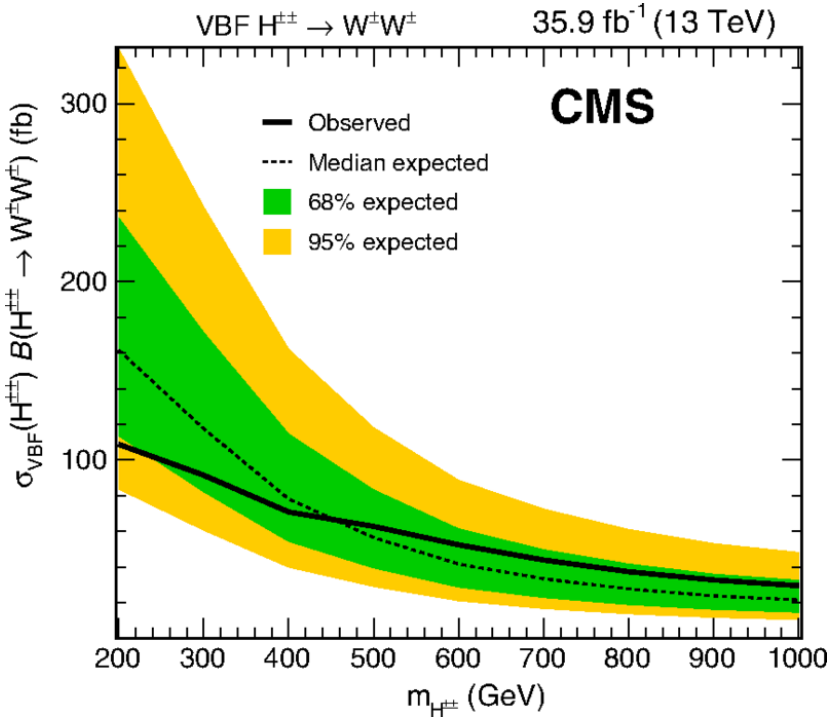






Electroweak Production of $W^{\pm}W^{\pm}jj$ (II)

- Limits on 9 dimension 8 EFT operator coefficients
- Limits on VBF production and decay to $W^{\pm}W^{\pm}$ of H^{++} boson in the Georgi-Macachek model



	Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
f_{S0}/Λ^4	[−7.7,7.7]	[−7.0,7.2]
f_{S1}/Λ^4	[−21.6,21.8]	[−19.9,20.2]
f_{M0}/Λ^4	[−6.0,5.9]	[−5.6,5.5]
f_{M1}/Λ^4	[−8.7,9.1]	[−7.9,8.5]
f_{M6}/Λ^4	[−11.9,11.8]	[−11.1,11.0]
f_{M7}/Λ^4	[−13.3,12.9]	[−12.4,11.8]
f_{T0}/Λ^4	[−0.62,0.65]	[−0.58,0.61]
f_{T1}/Λ^4	[−0.28,0.31]	[−0.26,0.29]
f_{T2}/Λ^4	[−0.89,1.02]	[−0.80,0.95]

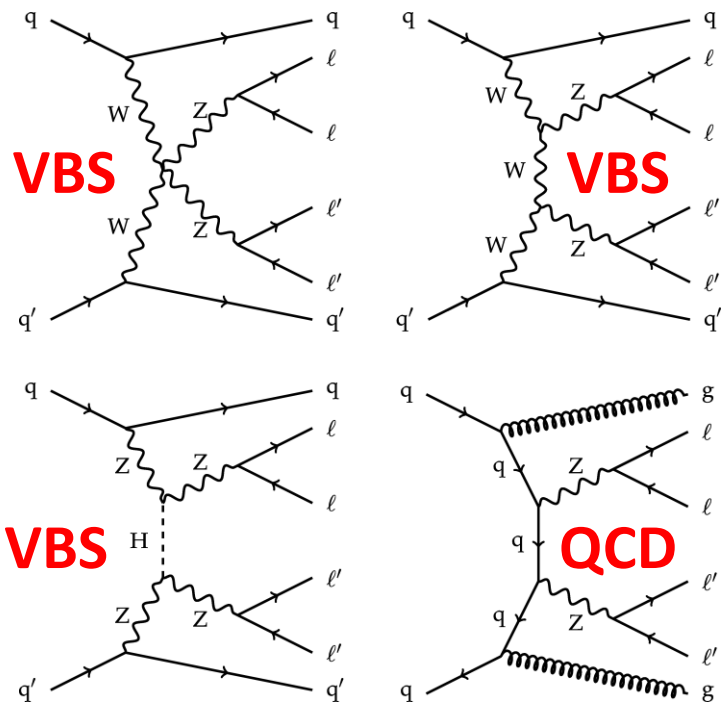
Electroweak Production of $W^{\pm}W^{\pm}jj$ (III)

- Selection
  - $m_{jj} > 500$ GeV
  - $|\Delta\eta_{jj}| > 2.5$
  - $\max\left(\left|\eta^{l_1} - \frac{\eta^{j_1}+\eta^{j_2}}{2}\right|, \left|\eta^{l_2} - \frac{\eta^{j_1}+\eta^{j_2}}{2}\right|\right)/|\Delta\eta_{jj}| < 0.75$
  - Missing Transverse Energy (MET) > 40 GeV
  - Third lepton veto, including hadronic τs
  - Veto events with high b-tagging discriminator jets
- Systematic Uncertainties
- Background estimation
  - WZ, where one lepton is somehow missed, including electroweak-induced WZjj production, estimated from Monte Carlo and normalized with a triboson control region
  - Semileptonic ttbar and w+jets, where one jet causes a lepton to be reconstructed, estimated using the same data-driven method as for the ZZ analysis

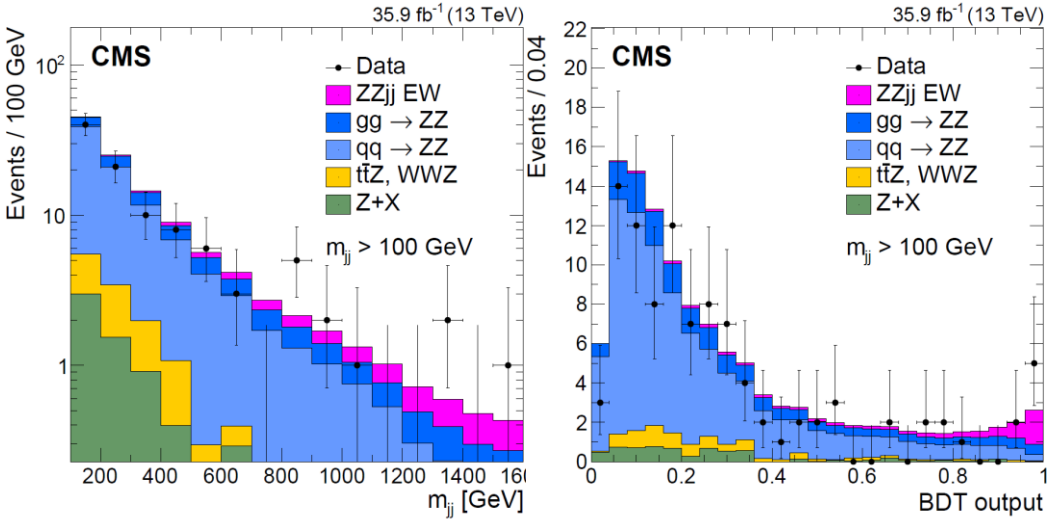
Uncertainty Source	Signal (%)	WZ (%)	Leptons caused by jets (%)
Lepton efficiency	< 2 per lepton	< 2 per lepton	
Jet energy scale/resolution	up to 7	up to 7	
Integrated luminosity	2.5	2.5	
EWK/QCD Interference	4.5		
PDF	5		
μ_R, μ_F	12		
Normalization with CR		20-40	
Data-driven method			30

Electroweak Production of ZZjj (I)

- Published in PLB in November 2017
- Use BDT to separate electroweak and QCD ZZjj
- Signal significance: 2.6 σ observed, 1.6 σ expected



Physics Letters B 774 (2017) 682–705



Contents lists available at ScienceDirect

Physics Letters B

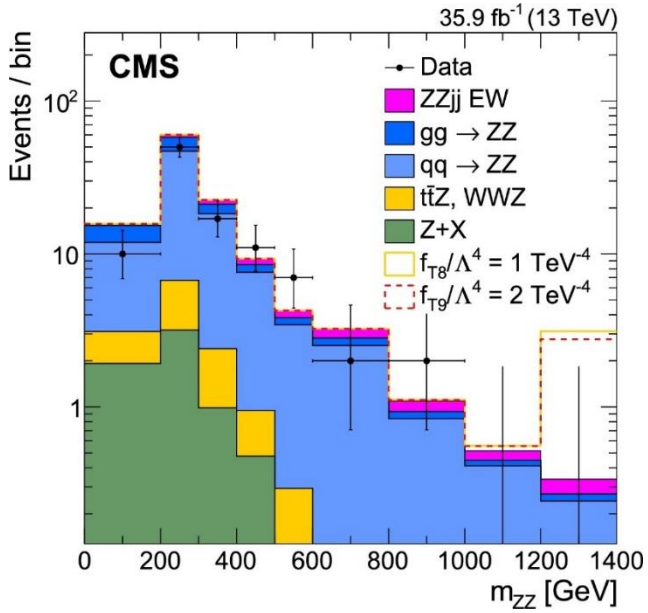
www.elsevier.com/locate/physletb

Measurement of vector boson scattering and constraints on anomalous quartic couplings from events with four leptons and two jets in proton–proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration *

Electroweak Production of ZZjj (II)

- Anomalous couplings
  - F_T operators introduces extra events in tail of the m_{ZZ} mass distribution
  - Shows up as bump when we use an overflow bin
  - World's best limits on F_{T0-2} and F_{T8-9}
  - Unitary bounds of 2.3 – 2.9



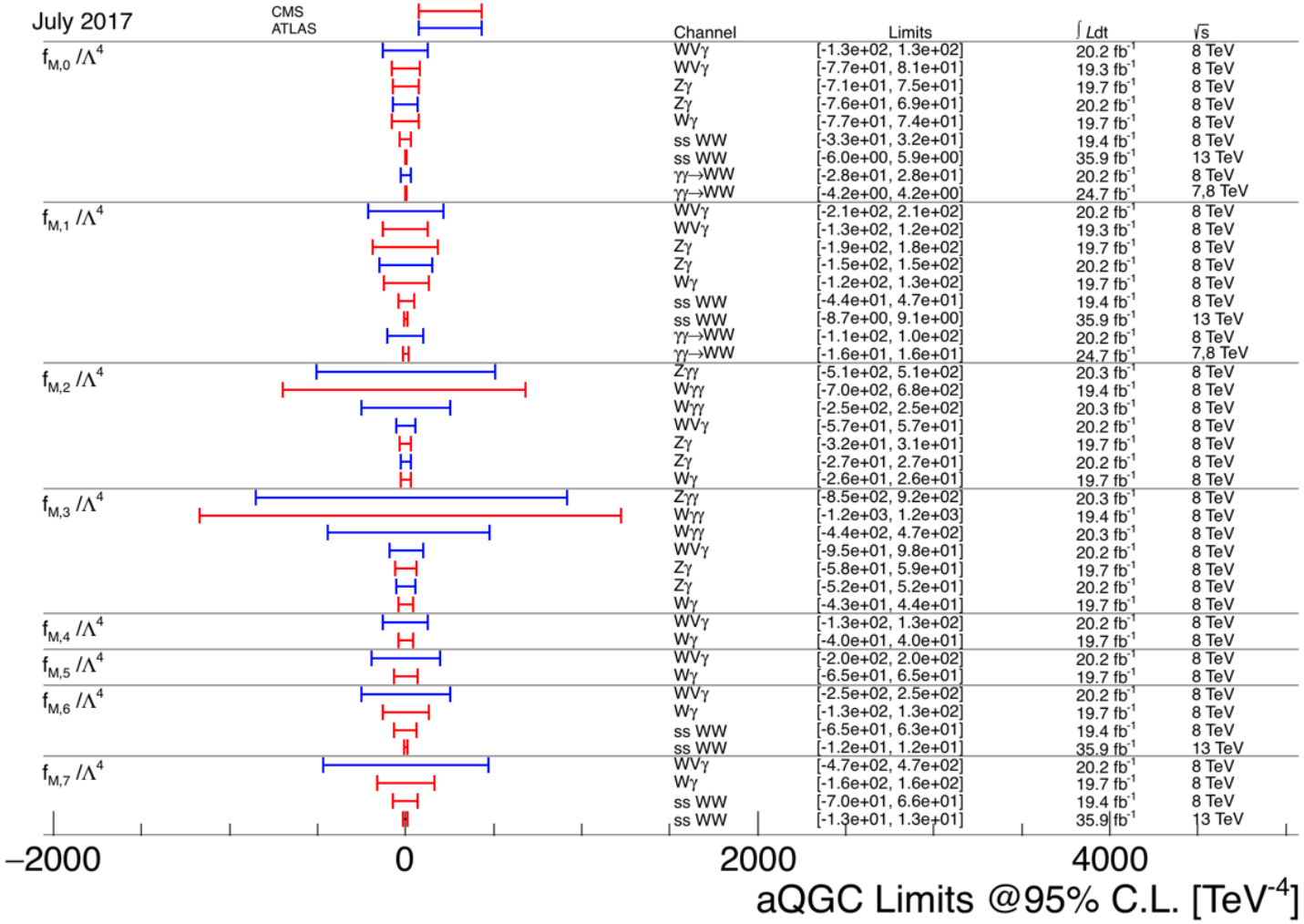
$-0.46\ \text{TeV}^{-4} < F_{T0} / \Lambda^4 < 0.44\ \text{TeV}^{-4}$
$-0.61\ \text{TeV}^{-4} < F_{T1} / \Lambda^4 < 0.61\ \text{TeV}^{-4}$
$-1.2\ \text{TeV}^{-4} < F_{T2} / \Lambda^4 < 1.2\ \text{TeV}^{-4}$
$-0.84\ \text{TeV}^{-4} < F_{T8} / \Lambda^4 < 0.84\ \text{TeV}^{-4}$
$-1.8\ \text{TeV}^{-4} < F_{T9} / \Lambda^4 < 1.8\ \text{TeV}^{-4}$

Electroweak Production of ZZjj (III)

- Selection
  - Again follows the CMS H --> ZZ -->4l analysis
  - + VBS cuts: $m_{jj} > 500$ GeV and $|\Delta\eta_{jj}| > 2.5$
- Systematic Uncertainties
  - NLO-EWK corrections on the signal process are not considered because they are not available, but they are expected to be smaller than data statistical uncertainties
- Background estimation
  - The dominant background, QCD-induced ZZ + jets production, is taken from Madgraph5_aMC@NLO simulation
  - The estimation of the background due to jets causing leptons to be reconstructed again uses the data-driven "lepton fake rate" method

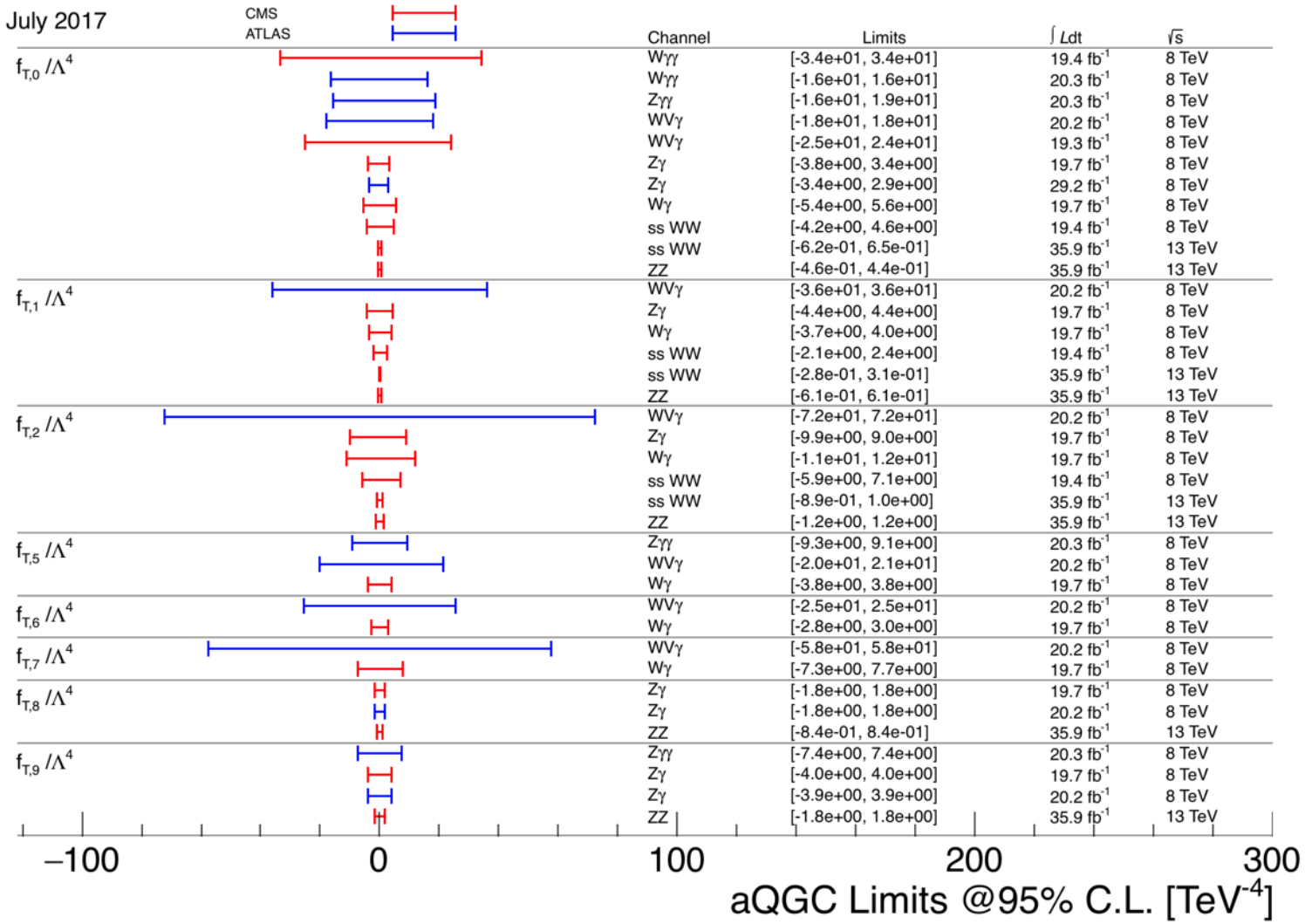
Uncertainty Source	signal (%)	QCD ZZjj (%)	leptons caused by jets (%)
μ_R, μ_F	7	10	
PDF	6-9	6-9	
Jet energy scale	4-20	4-20	
Jet energy resolution	8	8	
Lepton efficiency	2-6	2-6	
Integrated luminosity	2.5	2.5	
Data-driven method			40

Anomalous Couplings Summary Plots (I)



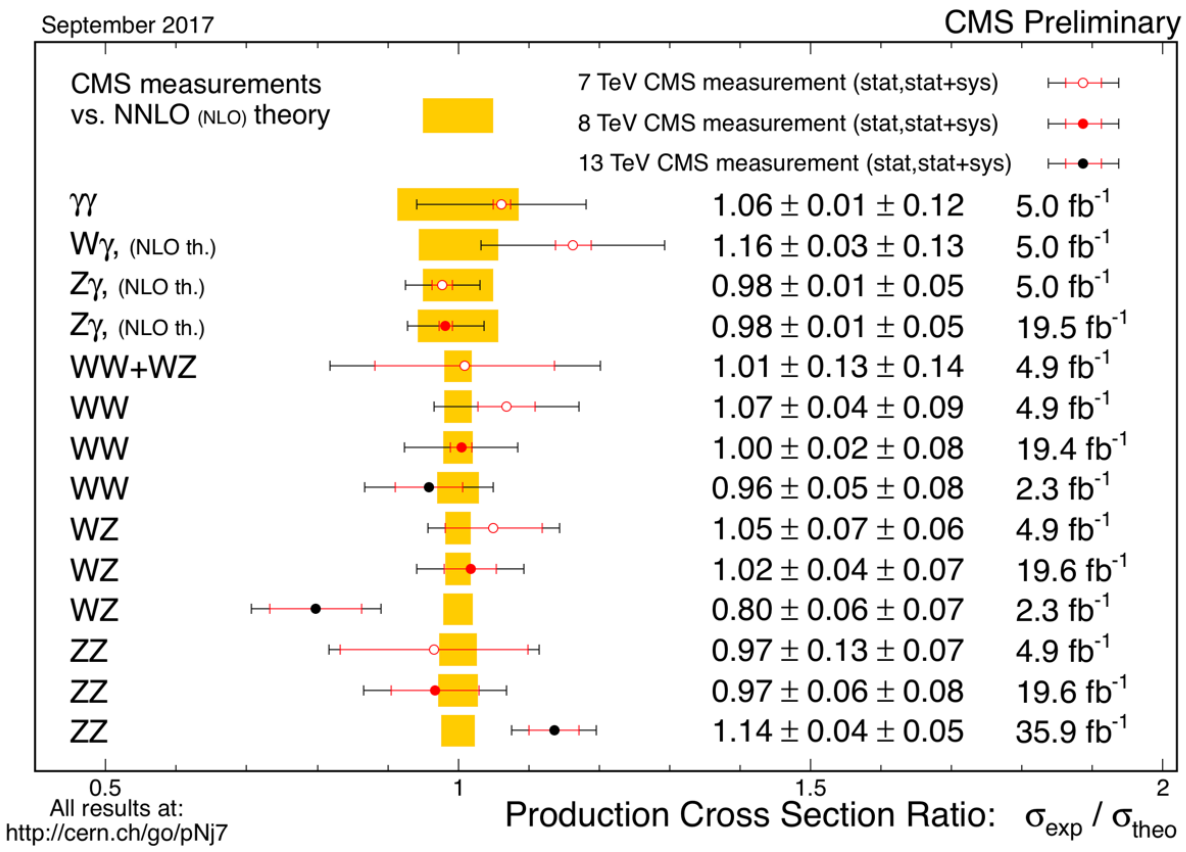
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

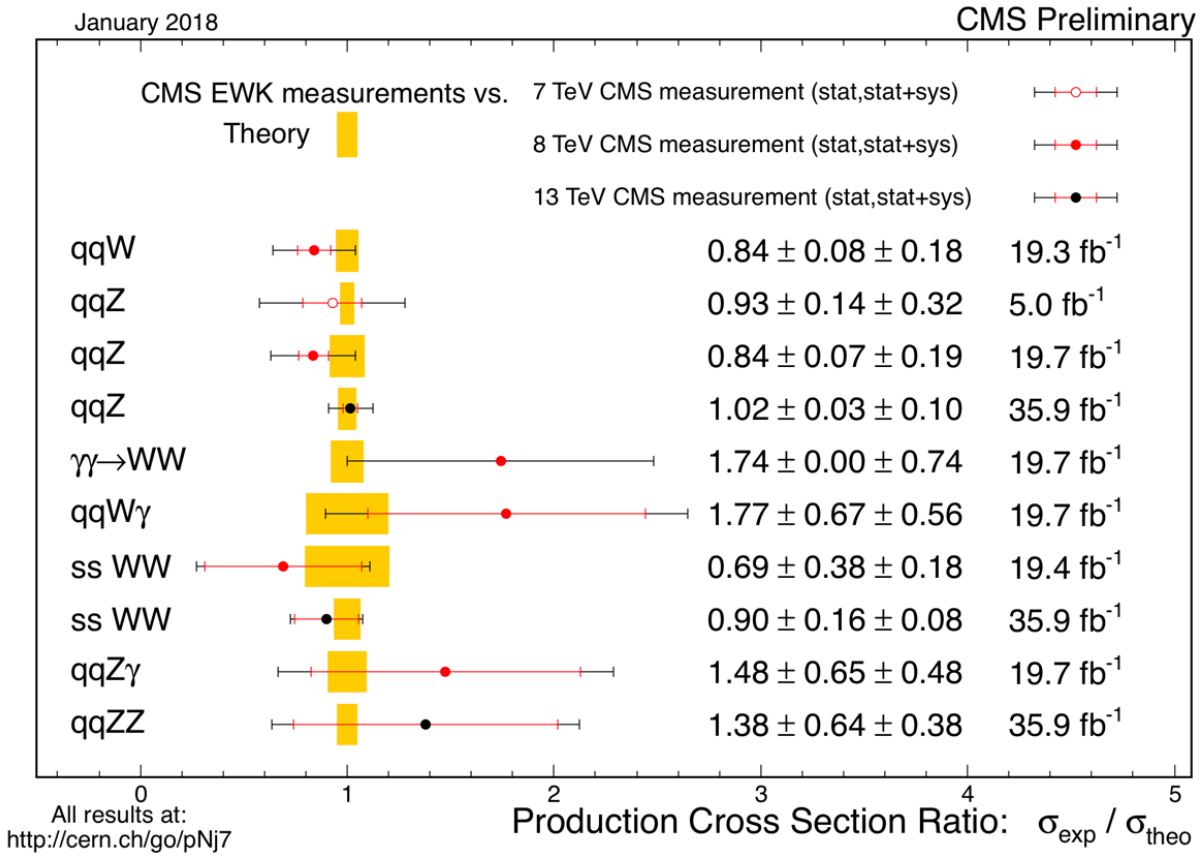
Anomalous Couplings Summary Plots (II)



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Cross-Section Summary Plots



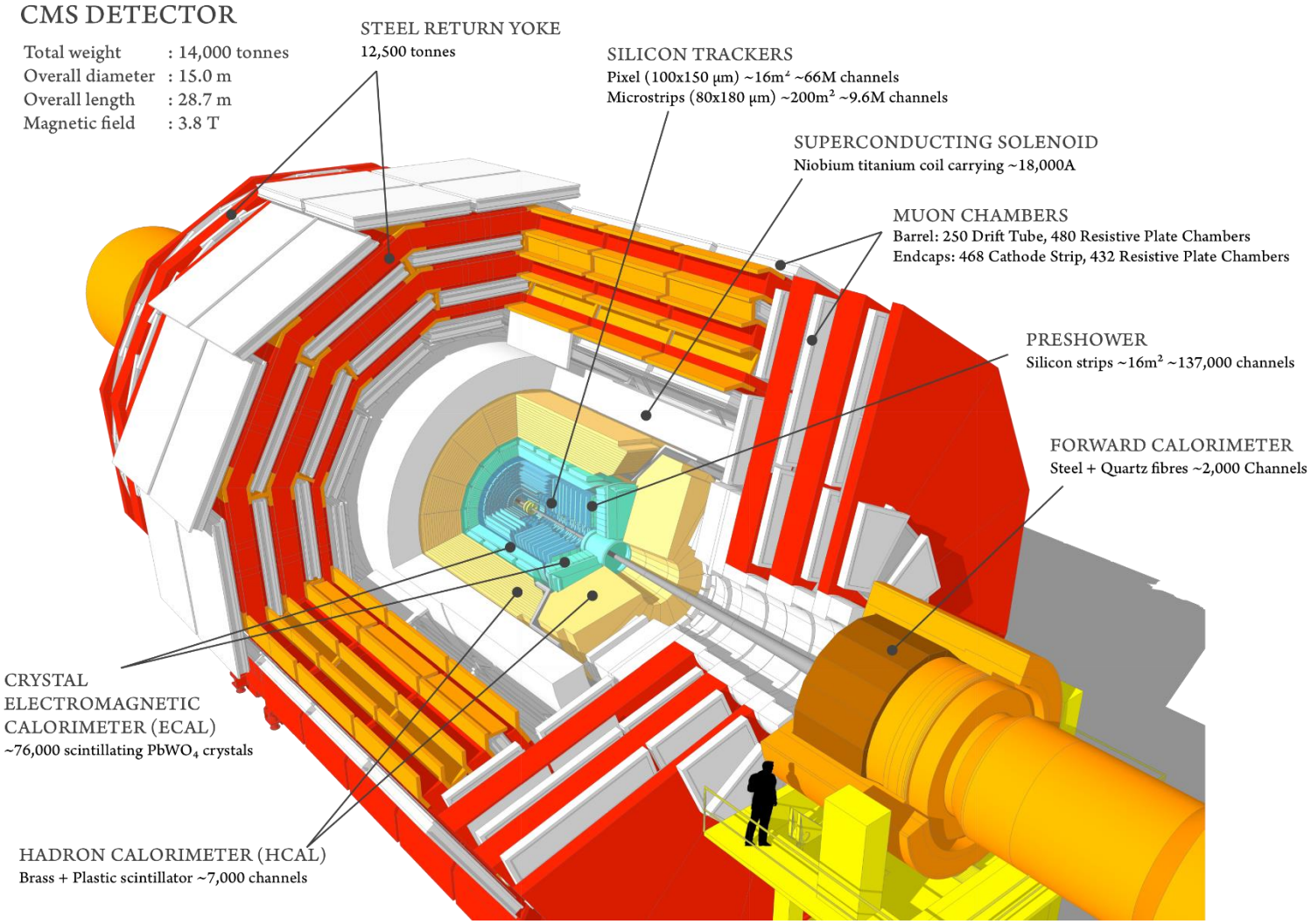


Conclusions

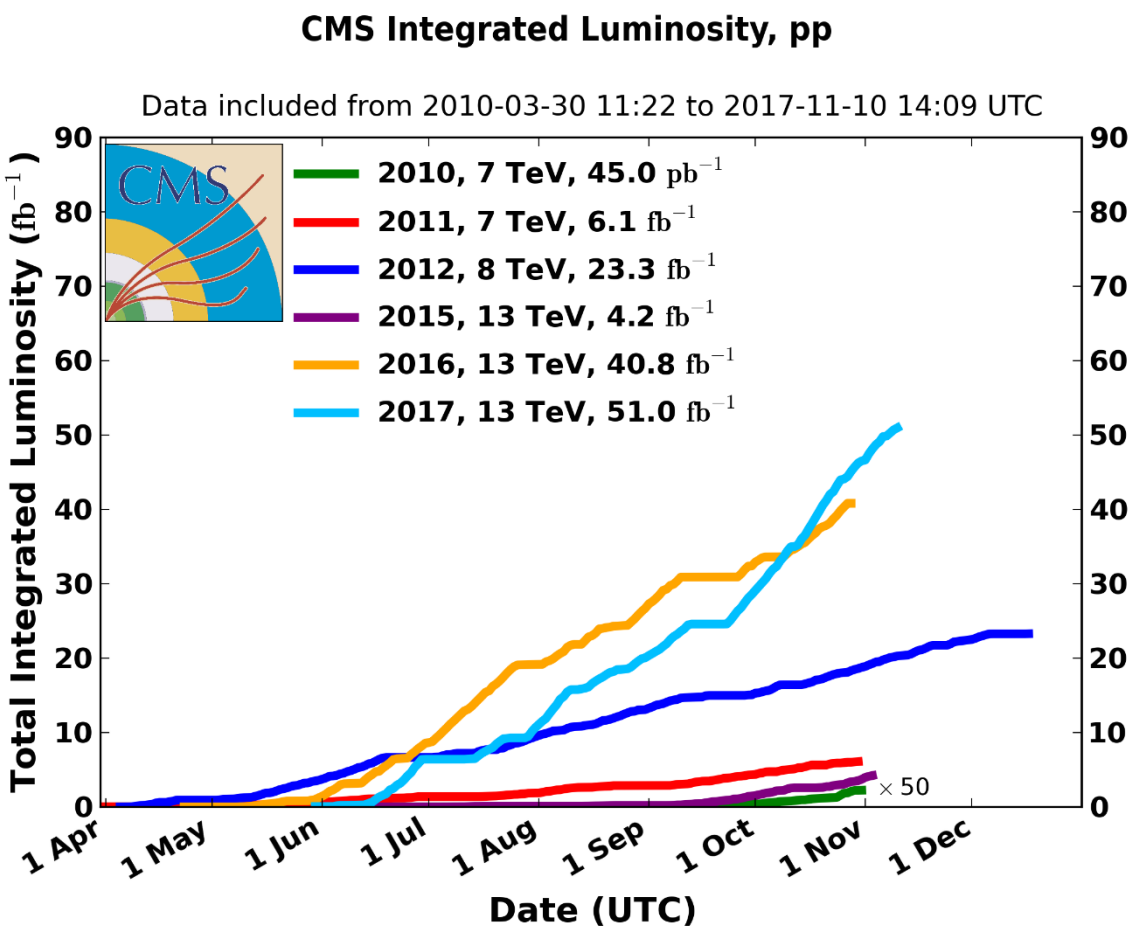
- Several newly published papers from the CMS Collaboration multiboson group
- CMS has accumulated a large set of multiboson results → major efforts to interpret the results in a uniform way and combine them
- As many measurements are statistically limited, the total run 2 dataset will reduce uncertainties a lot
- More and more triboson production measurements and vector boson scattering measurements are becoming possible

Backup

The CMS Detector



CMS Integrated Luminosity



Dimension 8 Operator Definitions

$$
\begin{aligned}
\mathcal{L}_{T,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \\
\mathcal{L}_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \\
\mathcal{L}_{T,2} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \\
\mathcal{L}_{T,5} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,6} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \\
\mathcal{L}_{T,7} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} \\
\mathcal{L}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{L}_{S,1} &= \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{L}_{M,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,2} &= \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,3} &= \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,4} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu} \\
\mathcal{L}_{M,5} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu} \\
\mathcal{L}_{M,6} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu}D^\mu\Phi\right] \\
\mathcal{L}_{M,7} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu}D^\nu\Phi\right]
\end{aligned}
$$