LHC Physics Discussion
DESY, June 2017

New results from the CMS Standard Model group

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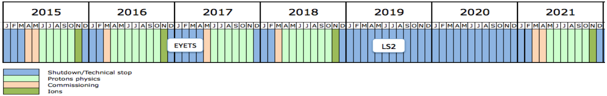
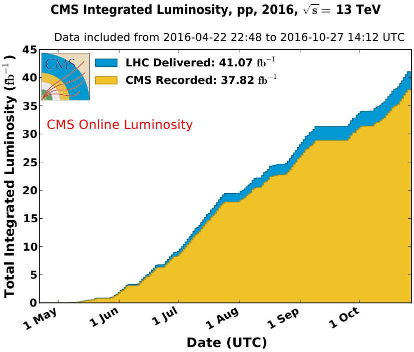
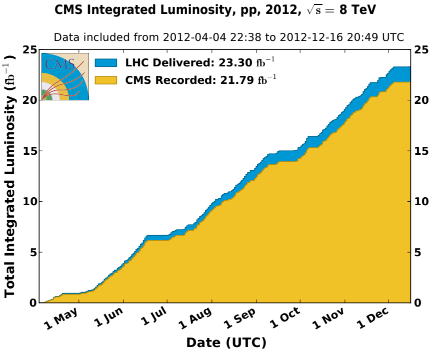
Outline

2017 means LHC restarting..new data, commissioning, understanding the detector..

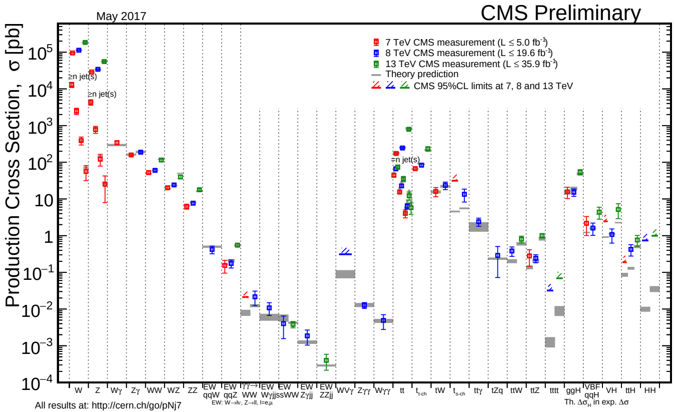


..but also data analysis and results with previous data!





Green points (@13 TeV) start to appear for the public :)

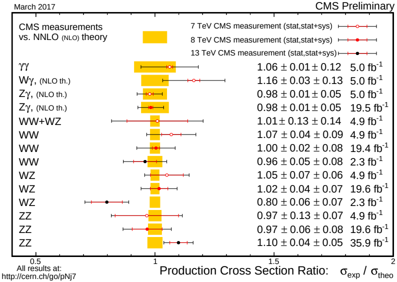


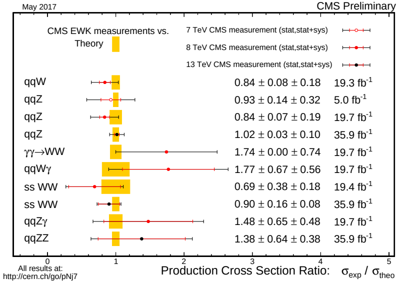
..and even previously unmeasured channels...

HUGE amount of results already published..

..impossible to cover everything!

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

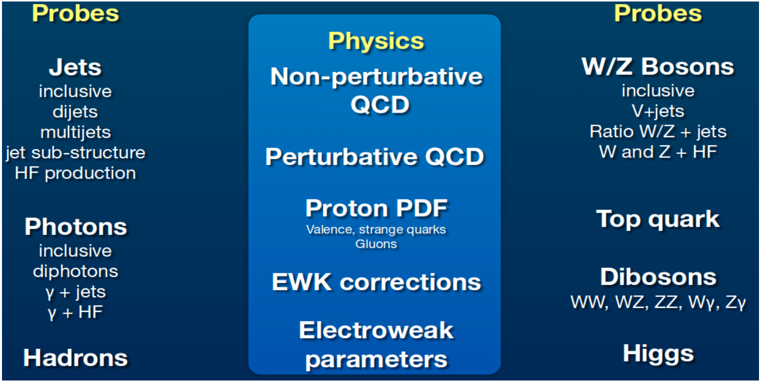




- Introduction: Standard Model
- Jet and QCD measurements
- Measurements of (single) weak boson production
- Measurements of diboson production
- Anomalous gauge coupling measurements
- Summary

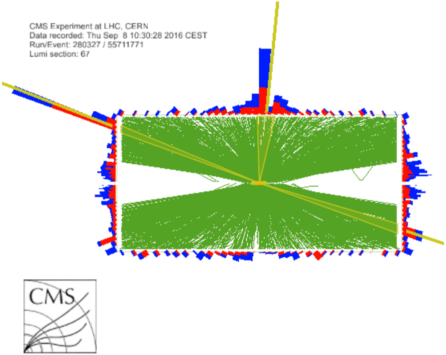
Why standard model physics?

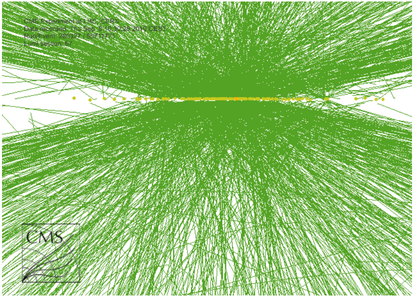
- Improve PDFs, measure quantities with high precision
- Search for deviations from Standard Model
- Establish understanding of backgrounds for new physics searches



Joao Guimares DIS 2017

Event display from CMS with 86 reconstructed vertices!



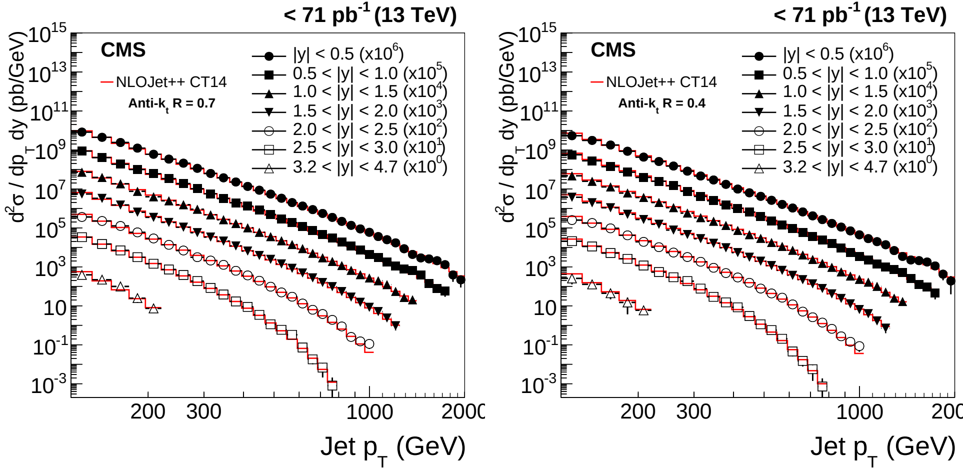


Obvious need for some methods of PU mitigation/subtraction
→ e.g. JETS: charged-hadron subtraction (removal of charged particles coming from vertices different wrt the jet one).

CMS-DP-2017/001

Inclusive jet measurements

Inclusive jet cross section at 13 TeV

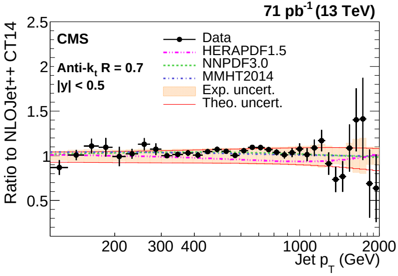


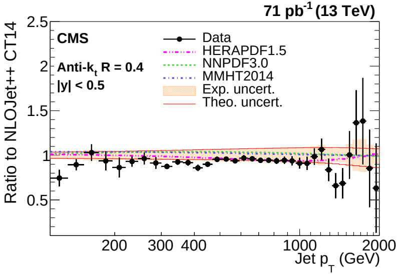
Unfolded results compared to predictions from:

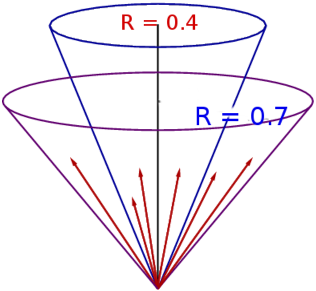
- NLOJet++ corrected for non-perturbative effects
- POWHEG NLO dijet matrix element + PYTHIA8 underlying event simulation
- PYTHIA 8 and HERWIG++ LO predictions

For the first time HF region included! EPJC 76 (2016)451

Inclusive jet cross section at 13 TeV: central region



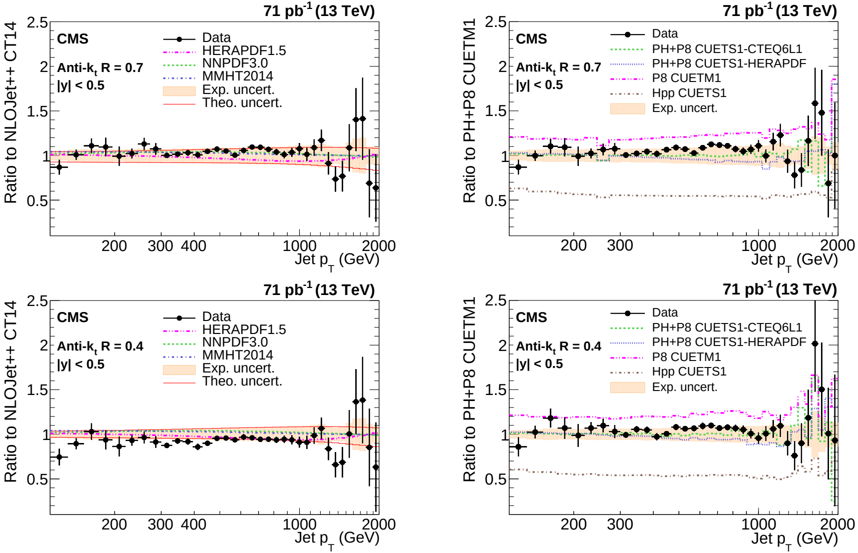




Jets with small cone size might miss some products of the evolution of the initial parton

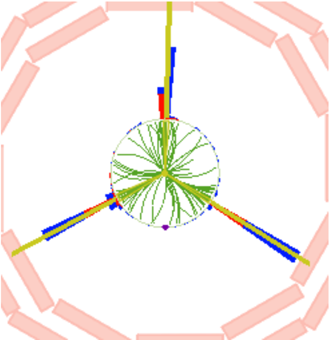
Predictions not including parton shower do not describe small cone-size measurements

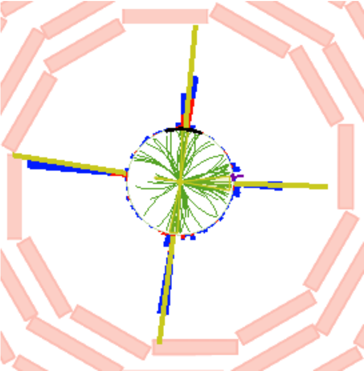
Inclusive jet cross section at 13 TeV: central region



Inclusion of parton-shower effects solves the issue!

Multijet scenarios

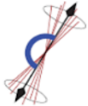




Increasing the number of jets in the event..

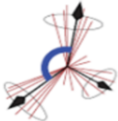
For more than one jet in the event, one can measure the azimuthal correlation between the two leading jets

At LO in pQCD the two final-state partons are produced back-to-back in transverse plane.



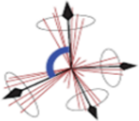
$\Delta\varphi_{\mathrm{dijet}} = \pi$

The production of a third jet leads to a decorrelation in azimuthal angle.



$2\pi/3 \leq \Delta\varphi_{\mathrm{dijet}} < \pi$

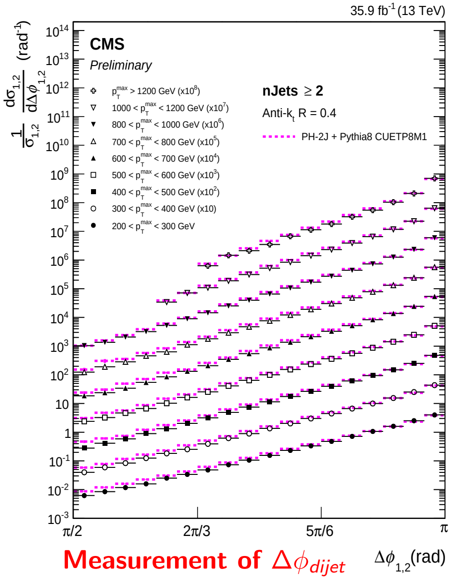
If more than three jets are produced, the azimuthal angle between the two leading jets can approach zero.

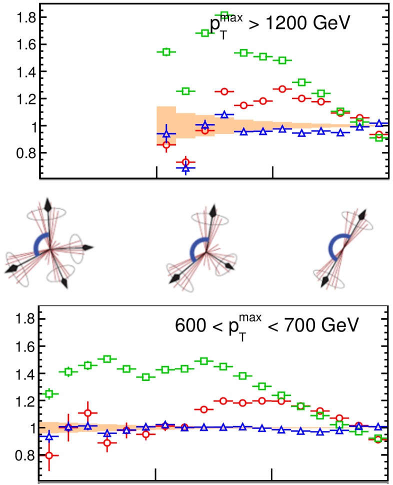


$0 < \Delta\varphi_{\mathrm{dijet}} \ll \pi$

CMS-SMP-16-014

Increasing the number of jets in the event..





Measurement of $\Delta\phi_{dijet}$ at 13 TeV, in bins of leading jet

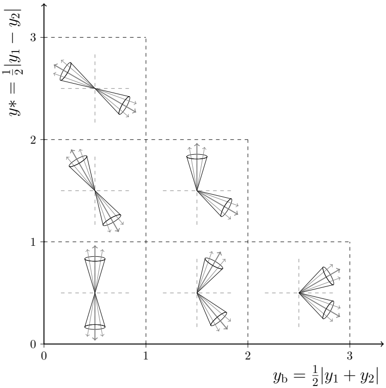
Madgraph+Pythia 8

Pythia 8 Herwig++

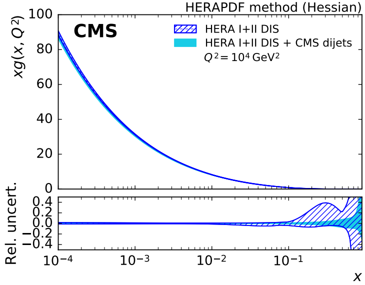
Higher-order predictions describe well the measurements

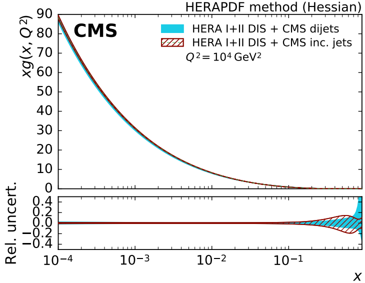
Triple differential dijet cross sections at 8 TeV

Absolute dijet cross sections measured as a function of p_T, y* and y_b



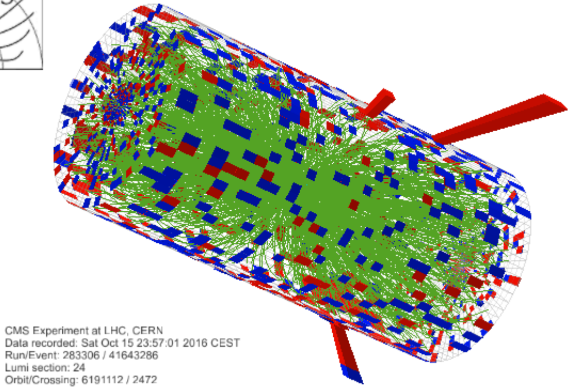
High-x gluon distr. is very sensitive to dijet cross sections and might add infos with respect to inclusive jets measurements





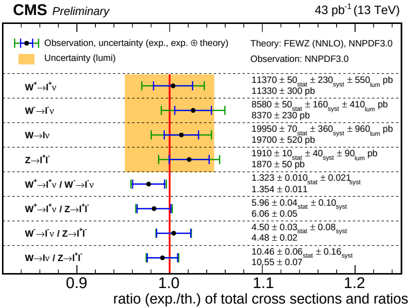
Submitt. to EPJC

Weak boson production cross section measurements

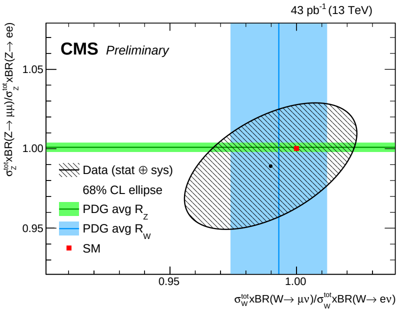


Inclusive cross sections with early data at 13 TeV

Both muonic and electronic final states are considered for the two measurements



CMS-SMP-15-004



CMS-SMP-15-004

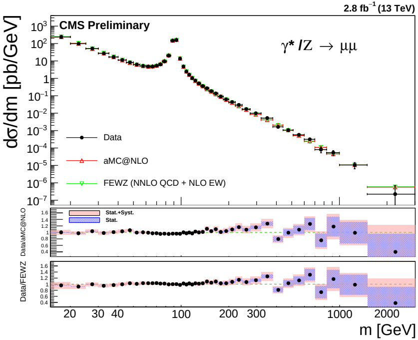
Available predictions reproduce the values

Compatibility between weak boson decay modes to unity

$\rightarrow$ decay universality "confirmed".

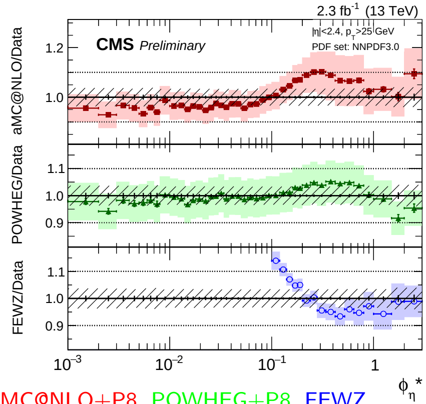
Z-boson differential cross sections at 13 TeV (I)

Going differential..
as a function of the dimuon invariant mass and ϕ^*_{ll}



"Rediscovery" of Z resonance at 13 TeV

Predictions @NLO and NNLO reproduce the spectrum in the measured range [15,3000] GeV



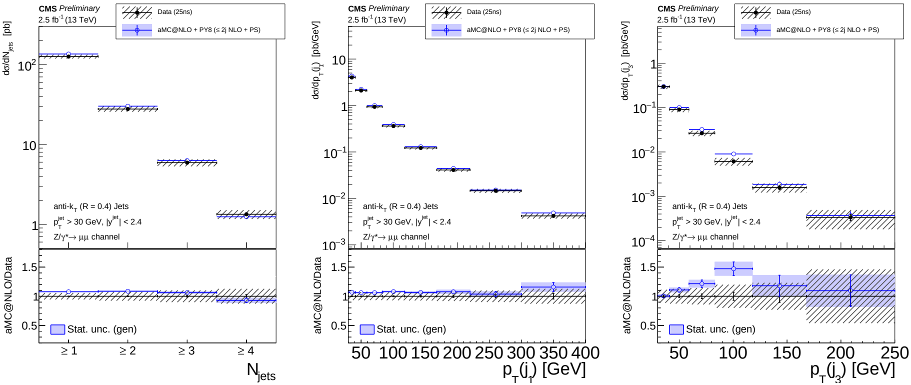
MC@NLO+P8, POWHEG+P8, FEWZ

ϕ^* is related to the Z p_T

CMS-SMP-16-009
CMS-SMP-15-011

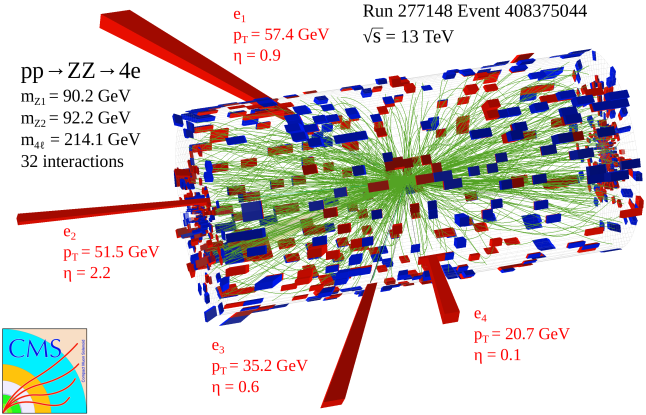
Parton-shower effects crucial for a good description of the measurement

Going differential..as a function of number of additional jets, leading jet p_T and third jet p_T.. (jets in the central region with $p_T > 30$ GeV)



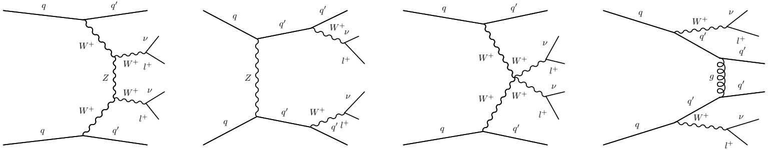
Predictions from MC generators at NLO (up to 2 partons) + PS describe very well the measurements..the agreement becomes worse when looking at jets simulated at LO CMS-SMP-15-010

Diboson production cross section measurements



EWK same-sign WW cross section associated with two jets

Events are selected by requiring exactly two leptons of the same charge, E_T^{miss}, and two jets with large rapidity separation and large dijet mass



$$\sigma_{fid}\ (W^{\pm}W^{\pm}jj) = 3.83 \pm 0.66\ (stat) \pm 0.35\ (syst)\ fb$$

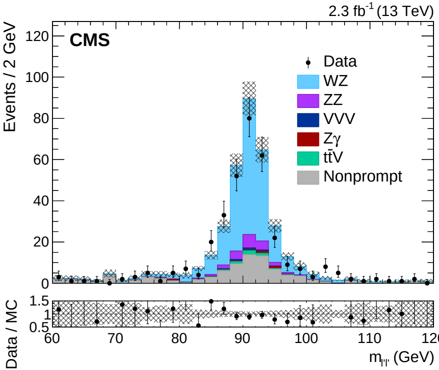
First evidence of this process! (Observed significance: 5.5σ)

Limits on anomalous quartic vector-boson interactions and production of doubly charged Higgs bosons could be extracted as well

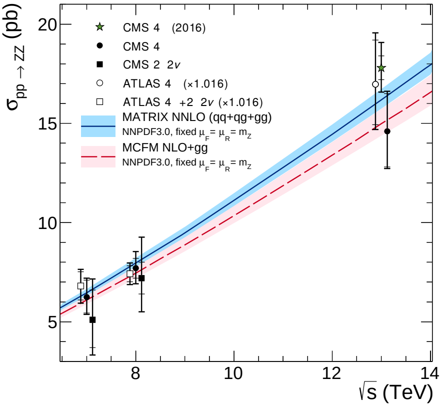
CMS-SMP-17-004

ZZ and WW cross section production

$$\sigma(pp \to ZZ) = 17.8 \pm 0.6\ (\text{stat})\ {}^{+0.7}_{-0.6}\ (\text{syst}) \pm 0.4\ (\text{theo}) \pm 0.5\ (\text{lumi})\ \text{pb}$$
$$\sigma(pp \to WZ) = 40.9 \pm 3.4\ (\text{stat})\ {}^{+3.1}_{-3.3}\ (\text{syst}) \pm 0.4\ (\text{theo}) \pm 1.3\ (\text{lumi})\ \text{pb}$$



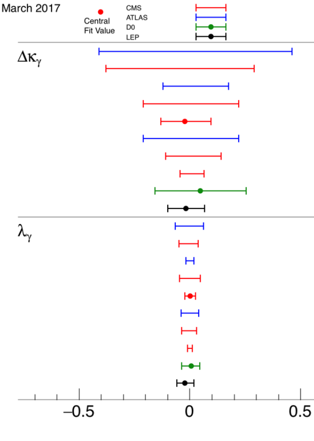
CMS-SMP-16-002



CMS-SMP-16-017

SM predictions reproduce well the measured cross sections

Anomalous gauge coupling measurements



	Channel	Limits	$\int L dt$	$\sqrt{s}$
$\Delta\kappa_\gamma$	Wγ	[-4.1e-01, 4.6e-01]	4.6 fb^{-1}	7 TeV
	Wγ	[-3.8e-01, 2.9e-01]	5.0 fb^{-1}	7 TeV
	WW	[-1.2e-01, 1.7e-01]	20.3 fb^{-1}	8 TeV
	WW	[-2.1e-01, 2.2e-01]	4.9 fb^{-1}	7 TeV
	WW	[-1.3e-01, 9.5e-02]	19.4 fb^{-1}	8 TeV
	WV	[-2.1e-01, 2.2e-01]	4.6 fb^{-1}	7 TeV
	WV	[-1.1e-01, 1.4e-01]	5.0 fb^{-1}	7 TeV
	WV	[-4.4e-02, 6.3e-02]	19 fb^{-1}	8 TeV
	D0 Comb.	[-1.6e-01, 2.5e-01]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-9.9e-02, 6.6e-02]	0.7 fb^{-1}	0.20 TeV
λ_γ	Wγ	[-6.5e-02, 6.1e-02]	4.6 fb^{-1}	7 TeV
	Wγ	[-5.0e-02, 3.7e-02]	5.0 fb^{-1}	7 TeV
	WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
	WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
	WW	[-2.4e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
	WV	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
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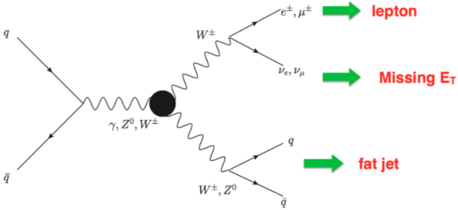
	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV

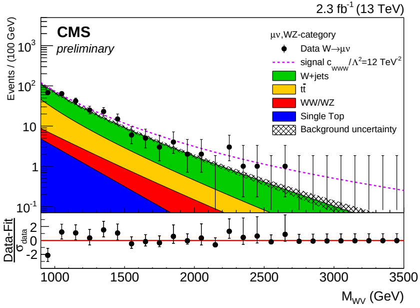
Search for anomalous triple gauge coupling

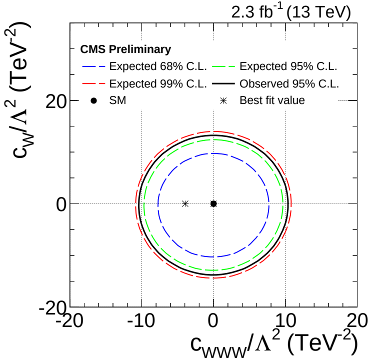
- Semileptonic channel



Semileptonic WW and WZ decays

Measurement of WV final state:
High p_T electron/muon
Missing E_T
fat jet





Limits on anomalous coupling terms on the effective field theory lagrangian

CMS-SMP-16-012

Summary

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- Jet measurements and associated jet production are used for:
  1. understanding QCD dynamics at different x ranges
  2. improve modelling of multijet scenarios
  3. measurement of strong coupling
  4. extraction of parton distribution functions

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- Available predictions reproduce well the measurement in the weak boson sector, associated jet production and diboson cross sections
- With higher statistics, more and more stringent limits are set for possible deviations from SM

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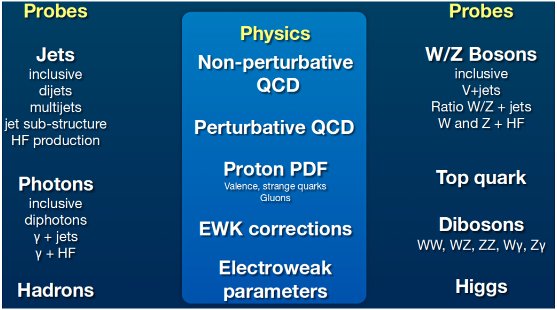
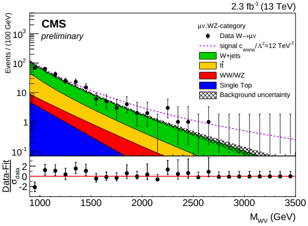
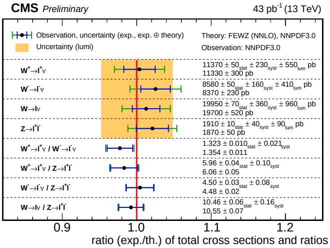
- Available predictions reproduce well the measurement in the weak boson sector, associated jet production and diboson cross sections
- With higher statistics, more and more stringent limits are set for possible deviations from SM
- Standard Model measurements and direct searches will play a fundamental role in the search for new physics

Summary





THANKS FOR YOUR ATTENTION!



The Large Hadron Collider at CERN, Geneva

- 27-km underground ring collider
- Bending magnetic field of 8.4 T
- Proton beams accelerated up to 6.5 TeV

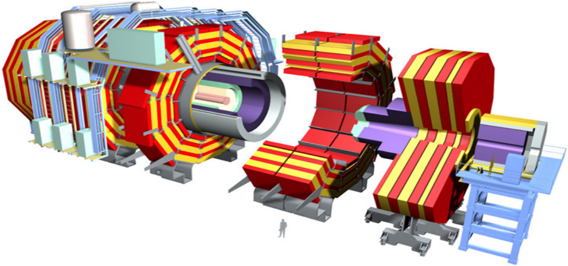
Three years of data taking in Run I:

$\sqrt{s} = 7\text{-}8$ TeV

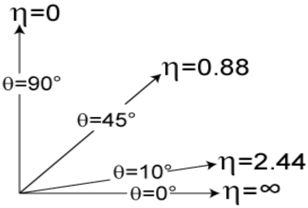
Run II started in 2015

$\sqrt{s} = 13$ TeV

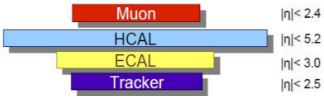
The Compact Muon Solenoid experiment



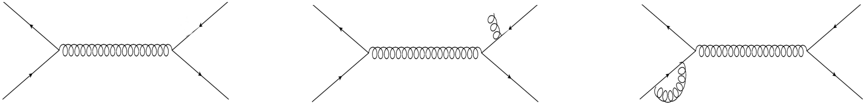
- Length: 21 m
- Diameter: 15 m
- Weight: 12500 ton



- Tracking system for measurement of the momentum of charged particles
- Calorimeter system for measurement of the particle energy
- Muon system for the muon identification



Theoretical tools in our hands

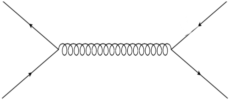


Leading order process | Real correction | Virtual correction

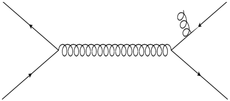
1. Pure matrix-element (ME) calculations
   - MC integration of cross section & PDF, but no hadronization
2. Monte Carlo event generators
   - Combination of ME and parton showers (PS), underlying event and hadronization

Leading Order ME + PS	Higher order ME (only real corrections) + PS	NLO ME + PS
PYTHIA, HERWIG	MADGRAPH	MC@NLO, POWHEG

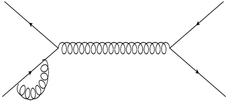
Theoretical tools in our hands



Leading order process



Real correction



Virtual correction

1. Pure matrix-element (ME) calculations
   - MC integration of cross section & PDF, but no hadronization
2. Monte Carlo event generators
   - Combination of ME and parton showers (PS), multiparton interactions (MPI) and hadronization (HAD)

Leading Order ME + PS

PYTHIA, HERWIG

Higher order ME (only real corrections) + PS

MADGRAPH

NLO ME + PS

MC@NLO, POWHEG

Very reliable tools $\rightarrow$ Tremendous progress on theoretical calculations at higher orders

The variable ϕ^*

$$\phi_\eta^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \cdot \sin(\theta_\eta^*)$$

$$\cos(\theta_\eta^*) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right),$$

The anomalous gauge coupling terms

Table 3: Values of anomalous triple gauge couplings used in the generation

	c_{WWW}/Λ^2 [TeV^{-2}]	c_W/Λ^2 [TeV^{-2}]	c_B/Λ^2 [TeV^{-2}]
0	12.0	20.0	60.0
1	12.0	0.0	0.0
2	-12.0	0.0	0.0
3	0.0	20.0	0.0
4	0.0	-20.0	0.0
5	0.0	0.0	60.0
6	0.0	0.0	-60.0
7	-12.0	-20.0	-60.0
8	0.0	0.0	0.0

$$\begin{aligned}
\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] \\
\mathcal{O}_{W} &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_{B} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_{\tilde{W}WW} &= \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] \\
\mathcal{O}_{\tilde{W}} &= (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi)
\end{aligned}$$

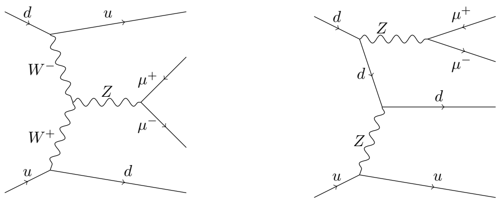
$\mathcal{O}_{\tilde{W}WW}$ and $\mathcal{O}_{\tilde{W}}$ do not conserve CP and are not considered in this study. Thus we extend the Standard model Lagrangian in the following way:

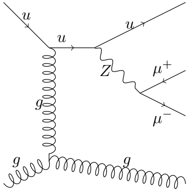
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{eff} \quad (1)$$

where $\mathcal{L}_{eff}$ is :

$$\mathcal{L}_{eff} = \frac{c_{WWW}}{\Lambda^2}\mathcal{O}_{WWW} + \frac{c_W}{\Lambda^2}\mathcal{O}_W + \frac{c_B}{\Lambda^2}\mathcal{O}_B \quad (2)$$

Events with two opposite-charged leptons and a dijet system with high invariant mass $\rightarrow$ separation btw sign. and bkg through MV analysis





SIGNAL DIAGRAMS **BACKGROUND**

$$\sigma_{EWK}\ (\text{lljj}) = 552 \pm 19\ (\text{stat}) \pm 55\ (\text{syst})\ \text{fb}$$

First measurement of this process at 13 TeV (agreement with SM)

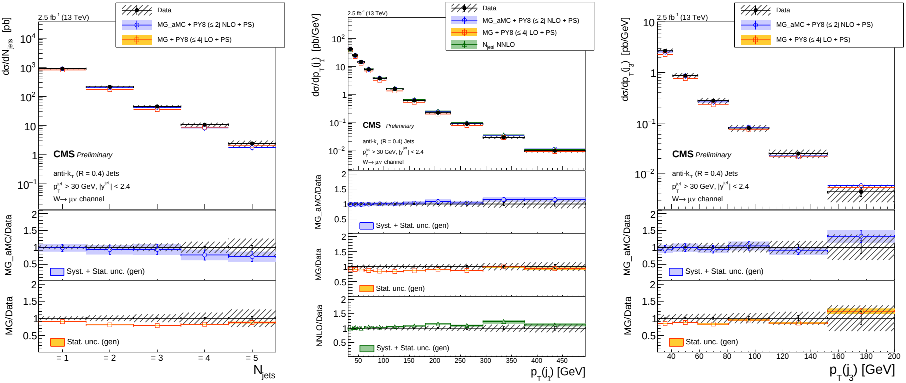
$$\sigma_{LO}\ (\text{lljj}) = 543 \pm 24\ \text{fb}$$

The associated jet activity in signal events is found to be in agreement with QCD LO predictions as a function of kinematical observables

CMS-SMP-16-018

W-boson differential cross sections at 13 TeV

Going differential..as a function of number of additional jets, leading jet p_T and third jet p_T.. (jets in the central region with $p_T > 30$ GeV)

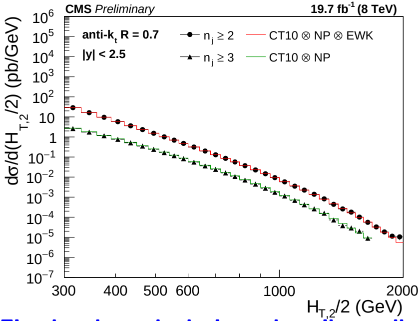


Predictions from MC generators at NLO (up to 2 partons) + PS describe very well the measurements..LO predictions are slightly worse in terms of normalization CMS-SMP-16-005

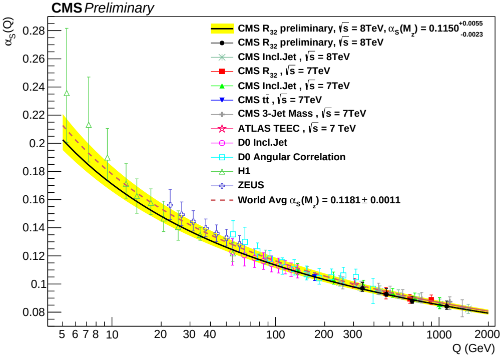
Multijet cross section at 8 TeV

Absolute dijet and three-jet cross sections measured as a function of $H_{T,2}/2$

Two leading jets with
$p_T > 150$ GeV in $|y| < 2.5$
$H_T = 0.5 \cdot (p_T^1 + p_T^2)$



Fixed-order calculations describe well the measurements and their ratio



CMS multijet measurements allow extraction of value of α_S:

$\alpha_S(\mathrm{M}_Z) = \mathbf{0.1150} \pm 0.0010(\mathbf{PDF}) \pm ^{+0.005}_{-0.000} (\mathbf{scale})\ldots$

CMS-SMP-16-008