## Highlights of EW and QCD results at the LHC

#### **PANIC 2021**

6th September 2021

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## Introduction

#### **Introduction**

- ATLAS and CMS are testing EW and QCD predictions in a wide range of processes.
- Exploring process rates over 9 orders of magnitude, from Z, W and top pair to rare processes as multiboson or four tops.
- Precise experimental results allow to test higher order calculations in QCD and EW.



Disclaimer: What follows is a selection of the most recent results. No H or b.

## **Differential cross-sections**



#### **Double-differential jet inclusive cross section**

- Partial 13 TeV data (33.5 fb<sup>-1</sup>). XS of jet vs transverse momentum and rapidity.
- Measured XS is compared to perturbative QCD at NLO, NNLO & NLO+NLL.
- QCD analysis of the measurement (+HERA data) used to improve PDF accuracy.
- Using an EFT-improved QCD, Wilson coefficient of a 4-quark contact interactions model is determined. Results are compatible with SM and previous analyses.



Major syst: PDF undertainties



0.09

0.08

0.07

0.06 0.05E

0.04

0.03

0.02

0.01

Signal

region

Fraction of events / 0.0033

#### Prompt photon pair production

10

Signal

**Direct photons** 

CFRN-FP-2021-105 Briefing

Non-promt photons

20 30 40

6

0

Integrated fiducial cross section [pb]

10

Background

- Full 13 TeV data (139 fb<sup>-1</sup>) targeting pp $\rightarrow \gamma \gamma$ .
- Important probe of the strong force.

MC signal (Sherpa)

- Dominant Background: non-prompt photons from hadron decays. Difficult to estimate by simulation. A data-driven method is used.
- 15 control regions defined by inverted  $\gamma\gamma$ identification and isolation requirements.



100

500

p<sub>T.vv</sub> [GeV]

50

Single- & double-

fragmentation photons

NNLOJET NLO

NNLOJET LO

**Diphox NLO** 



#### WZ inclusive and differential XS @ 13 TeV

CMS-PAS-SMP-20-014

W

- Full 13 TeV data (137 fb<sup>-1</sup>) targeting multileptonic WZ final states (3I).
- Differential XS for many observables compared to NNLO-QCDxNLO-EW

 $\sigma_{\text{Tot}}(\text{pp} \rightarrow \text{WZ}) = 50.6 \pm 0.8 \text{ (stat)} \pm 1.5 \text{ (syst)} \pm 1.1 \text{ (lumi)} \pm 0.5 \text{ (theo) pb}$ 



Major syst: statistical, lepton ID, b-tagging & luminosity



## tZq differential XS @ 13 TeV

- Full 13 TeV data (138 fb<sup>-1</sup>) targeting tZq (3 leptons channel).
- Involves tZ, tWb and WWZ couplings. Relatively QCD clean.

**CMS-PAS-TOP-20-010** 

- The top/antitop ratio yields sensitivity to different PDFs parametrization.
- BDT used to discriminate S/B. 3 SR according to #jets and #bjets
- Inclusive XS measured with ML fit to BDT distributions.
- Normalization of background included in the fit with CRs.





#### First differential tZg XS

- Differential top quark polarization used to determine top quark spin asymmetry.
- Multiclass NN splits events in 5 output nodes (tZq, ttZ and others).

Extracted polarization compatible with SM

$$A_\ell\,=\,0.58~^{+0.15}_{-0.16}$$
 (stat)  $\pm 0.06$  (syst)



Major syst: statistical, background modelling, b-tagging efficiency & lepton ID

# Rare processes



- A precise determination of pile-up tracks is needed. BS size corrections. Mimic Run-2 values.
- Additional correction to  $n_{tracks}(z, BS)$  from additional pp obtained using Z $\rightarrow$ II events.
- Charged particle multiplicity not well described by DY and diboson sim. Corrected with  $Z \rightarrow II$ .
- Profile Likelihood fit to extract signal. Uses EY in 3 CR and SR + Drell Yan CR.
- Background-only hypothesis is rejected with a significance of **8.4 standard deviations**.
- Measured fiducial cross section is in agreement with SM predictions:

```
\sigma_{\text{meas}} = 3.13 \pm 0.31 \text{ (stat.)} \pm 0.28 \text{ (syst.) fb}
```

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Major syst: statistical, lepton mis-ID & WW modelling



## WWW production @ 13 TeV

#### ATLAS-CONF-2021-039 Briefing

- Full 13 TeV data (139 fb<sup>-1</sup>) targeting WWW production.
- Final states: SSL+jets or 3L ( $e^{\pm}e^{\pm}\mu^{\wedge}$  or  $\mu^{\pm}\mu^{\pm}e^{\wedge}$ ).
- Direct probe of the strength of triple and quartic gauge couplings.



- Dominant Background: WZ+jets. Normalized with 3 CR (#jets).
- Two BDTs to improve S/B separation (2L and 3L)
- XS from a binned maximum likelihood fit: Uses the 4 BDTs and the 3 CR WZ  $m_{\rm m}$  distributions.



Signal Strength		Normalization Factors			
$\mu(WWW)$		WZ + 0 jets	WZ + 1 jet	$WZ + \ge 2$ jets	
$1.66 \pm 0.28$		$1.12 \pm 0.11$	$0.98 \pm 0.04$	$0.88\pm0.18$	
$\operatorname{Fit}$	Observed (expected) significances $[\sigma]$			$\mu(WWW)$	
$e^{\pm}e^{\pm}$	2.3(1.4)			$1.69 \pm 0.79$	
$e^{\pm}\mu^{\pm}$	4.6(3.1)			$1.57 \pm 0.40$	
$\mu^{\pm}\mu^{\pm}$	5.6(2.8)			$2.13\pm0.47$	
$2\ell$	6.9(4.1)			$1.80 \pm 0.33$	
$3\ell$	4.8(3.7)			$1.33 \pm 0.39$	
Combined	8.2(5.4)			$1.66\pm0.28$	

 $\sigma(pp \rightarrow WWW) = 850 \pm 100 \text{ (stat.)} \pm 80 \text{ (syst.) fb.}$ 

WWW production observed with 8.2 (5.4) s.d.

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First observation 11

Major syst: statistical & data driven background estimation





#### <u>Zy+2jets EW production ( $Z \rightarrow ee, \mu\mu$ )</u>



- Full 13 TeV data (139 fb<sup>-1</sup>). Targets EW prod. Treats prod. via QCD as a background.
- EW vector boson pair is more centrally produced. Used to define SR and CR.
- Scattered quarks aren't color-connected: Large  $|\Delta y|$  between jets.



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#### Major syst: statistical & EW/QCD Zy+jets modelling



1.2 1.4 1.6 1.8



0

0.2 0.4 0.6 0.8



## Search for vector boson scattering

- Full 13 TeV data (137 fb<sup>-1</sup>) targeting EW VBS in semi-leptonic decay {vqq.
- Two event categories:
- Boosted: Hadronically decaying W/Z boson reconstructed as large-radius jet
- Resolved: Identified as a pair of jets with dijet mass close to the boson mass.
- A DNN discriminator is trained for every category. DNN tested in ttbar and W+jets CRs.
- Differential normalization corrections for W+jets vs  $p_T^{W,I}$  and trailing tag-jet  $p_T$ .



Three separate likelihood ratio fits are performed:

- Pure EW signal:  $\mu_{EW} = \sigma^{obs} / \sigma^{SM} = 0.85^{+0.24}_{-0.20} = 0.85^{+0.21}_{-0.17} (syst) {}^{+0.12}_{-0.12} (stat)$ First evidence for the EW SM signal at 4.4 (5.1) s.d.
- EW+QCD:  $\mu_{EW+QCD} = \sigma^{obs} / \sigma^{SM} = 0.98^{+0.20}_{-0.17} = 0.98^{+0.19}_{-0.16} (syst) +0.07_{-0.07} (stat)$
- 2D EW-QCD

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Major syst: Statistics and S&B modelling.



CMS-PAS-SMP-20-013





## 4 top production @ 13 TeV

#### TOPQ-2020-10 Briefina

- Full 13 TeV data (139 fb<sup>-1</sup>) targeting 1L/2LOS channel.
- Accounts for 57% of 4 top events, but large background.



- Evidence for 2LSS/3L previously measured (4.3 $\sigma$ ).\*
- Large multiplicity: up to 10 (8) jets in the 1L (2LOS).
- Main background is ttbb+jets. Significant theory uncert.
- Events in 21 categories according to #jets and #bjets.
- Allows tt+jets flavour and kinematic rescale/reweight.
- 6 BDTs trained for further discriminate S/B.







$$\sigma_{t\bar{t}t\bar{t}} = 26 \pm 8 \text{ (stat.)}_{-13}^{+15} \text{ (syst.) fb} = 26_{-15}^{+17} \text{ fb.}$$



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Major syst: modelling of signal and tt+HF

\*Eur. Phys. J. C80(2020) 1085

## **Properties measurements**



## <u>Universality of τ/μ lepton couplings in ttbar</u>

Nature Physics 17 813–818 (2021)



- In SM, W and Z boson couplings to charge leptons (τ,μ,e) are equal.
- Full 13 TeV data (139 fb<sup>-1</sup>) used to study ratio of W decay to  $\tau/\mu$ .
- т are identified from its decay to a muon
- T lepton has significant lifetime compared to W: displaced vertex.
- As T undergoes a multi-body decay, the muon is less energetic.
- Transverse impact parameter (d<sub>0</sub>) calibrated with  $Z \rightarrow \mu \mu$  events.
- $Z \rightarrow \mu \mu$  + jets background estimated around the Z mass peak.
- Non-prompt muons from b or c hadrons decays with SS events.
- Measured value exceeds LEP precision and is in agreement with SM

 $R(\tau/\mu) = 0.992 \pm 0.013 [\pm 0.007 \text{ (stat)} \pm 0.011 \text{ (syst)}]$ 



Major syst: stats, d0 tail, parton shower & hadronization modelling and muon selection



#### Z boson to invisible

- CMS exploits 13 TeV data (36.3 fb<sup>-1</sup>) targeting Z(vv)+jets production.
- Events categorized into 3 main regions: Z(vv)+jets, dilepton+jets ( $Z,\gamma^*$ ) and lepton+jets (W).
- Largest background: W+jets where lepton is missed. Correction as function of  $p_{T}^{miss}$ .
- Z boson invisible width extracted from simultaneous fit to SR and CRs.



Major syst: muon & electron identification efficiency & JES



#### **Top mass in single Top production**

- Top quark mass direct measurement with partial 13 TeV data (35.9 fb<sup>-1</sup>).
- Events contain one electron or muon and 2 jets, one tagged as b-jet.
- BDT is used to enhance S/B. Background dominated by ttbar and W jets.
- BDT threshold: Point with minimum offset correction uncertainty.
- Mass extracted from maximum likelihood fit to  $y = \ln m_{t}$ .



- Individual top and antitop masses are also measured.
- The ratio of both is compatible with unity.



#### First sub-GeV precision in single top

Major syst: JES, CR & FSR modelling

CMS-PAS-TOP-19-009



## **SM Effective Field Theory**

$$\mathcal{L}_{SM}(arphi) + \mathcal{L}_{Dim6}(arphi) + \cdots$$
 $\mathcal{L}_{Eff} = \mathcal{L}_{SM} + \sum_{i} rac{C_{i}^{(6)}O_{i}^{(6)}}{\Lambda^{2}} + \mathcal{O}(\Lambda^{-4})$ 

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#### Proving EFT with ttZ vertex in multi lepton

- Full 13 TeV data (138 fb<sup>-1</sup>) to test SM EFT extension of ttZ vertex.
- Five Dim-6 operators considered: O<sub>tZ</sub>, O<sub>tW</sub>, O<sup>3</sup><sub>φQ</sub>, O<sup>-</sup><sub>φQ</sub>, O<sub>φt</sub>

#### Multiclass



Extensive use of MVA (NNs):

• Multiclass classifier divides SR in tZq, ttZ and bckgd SRs.

ttZ

CMS-TOP-21-001

tZq w

tWZ

Briefing

- **Binary classifiers** separate SM events from WCs  $\neq$  0.
- Used to design observables with optimal sensitivity.
- Compatibility of WCs with data from a simultaneous ML fit to data in six categories (4 SR, 2 CR)
- Done for each WC, fixing the rest or for all 5 WCs free.
   In agreement with SM.





#### Single top quark polarization

- Full 13 TeV data (139 fb<sup>-1</sup>) used to measure single top quark polarization.
- In the t-channel at LO, top (antitop) quarks are produced with their spin aligned along the direction of the spectator (incoming) quark.
- The spin information is transferred to the top quark decays.
- 3D space divided into 8 Octants. Polarization vector extracted from ML fit.



top  $P_{x'} = 0.01 \pm 0.18, P_{y'} = -0.029 \pm 0.027, P_{z'} = 0.91 \pm 0.10$ antitop  $P_{x'} = -0.02 \pm 0.200, P_{y'} = -0.007 \pm 0.051, P_{z'} = -0.79 \pm 0.16$ 

 Unfolded angular distributions at particle level used to test SM EFT extension of Wtb vertex.

 $C_{tW} \in [-0.7, 1.5]$  and  $C_{itW} \in [-0.7, 0.2]$ 



ATLAS-CONF-2021-027

Briefing

COSO

Major syst: JER, JES & signal and background modelling.

## **ATLAS & CMS Briefings**

#### ATLAS & CMS Briefings

- Both ATLAS & CMS publish short outreach articles together with the main physic results.
- They highlight the new results, techniques or approaches followed in the analyses. •
- For the shown analyses, I added the link to the corresponding briefing when available.

#### **CMS** Briefings



**ATLAS Briefings** 

Collaboration Site | Physics Results ABOUT DISCOVER RESOURCES UPDATES Q SEARCH All News Briefings Features Portraits Press Blog Hunting for forbidden decays of the Z boson In a new study, the ATLAS Collaboration looked for Z bosons decaying into an electron and an antimuon, or into a muon and a positron. Physics Briefing | 3rd August 2021



ATLAS measures key Higgs boson interaction with high precision The ATLAS Collaboration releases new measurements of the Higgs-boson decay to tau leptons. The result provides new insight into the "Yukawa coupling", a key interaction of the Higgs boson. Physics Briefing I 2nd August 2021



Two Higgs bosons are better than one

One of the long-term goals of the LHC is to measure the Higgs-boson self-coupling, which in turn can give us clues about the formation of the early Universe. This self-coupling can only be measured directly by studying the production of pairs of Higgs bosons (HH). Physics Briefing | 30th July 2021



#### Probing new physics with pairs of Higgs bosons

The ATLAS Collaboration has released a new result searching for pairs of Higgs bosons (HH) produced by new particles. The Higgs bosons would then each decay into pairs of bottom (b) quarks - known as the '4b decay channel'.

Physics Briefing | 28th July 2021



The interaction of the Higgs boson with its own field leads to its mass generation. Since the Higgs boson mass has already been measured, the study of the Higgs pair production at the LHC reveals directly the strength of the Higgs self coupling λннн

READ MORE



JETS-OF-ALL-TRADES: CONSTRAINING STANDARD MODEL AND BEYOND

For the first time, CMS physicists extract the fundamental parameters of QCD together with constraints on the New Physics. Any tiny failure of the Standard Model to explain data behaviour is a possible window for the New Physics. An example is.. READ MORE



A TALE OF TWO COLLIDERS AND THE UNRIVALLED PRECISION ON THE Z INVISIBLE WIDTH

The most powerful particle collider in the world, the Large Hadron Collider (LHC), was built in the 27 km tunnel originally excavated for the highest energy electron-positron collider ever built, LEP. As an extraordinarily sensitive machine, LEP was... READ MORE

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# Other ATLAS & CM recent results

#### **Other ATLAS & CMS recent results**

#### Links $\downarrow$

ATLAS: Differential XS of Z boson in association with high transverse momentum jets (13 TeV). CMS: Differential tt production XS in the full kinematic range using lepton+jets events (13 TeV). ATLAS: PDF determination from differential W± and Z boson plus jets XS (13 TeV). CMS: Measurement of tW production in the semileptonic channel (13 TeV). ATLAS: Differential production cross sections in four-lepton events (13 TeV). CMS: Measurement of the inclusive top-quark pair production cross section (13 TeV). ATLAS: Inclusive and differential production cross sections of ttZ events (13 TeV). CMS: Inclusive and differential tt+y XS and EFT interpretation in single lepton channel (13 TeV). ATLAS: Run 2 boosted top-pair differential cross section in I+jets channel (13 TeV). CMS: Z bosons plus jets using variables sensitive to double parton scattering (13 TeV). CMS: Electroweak production of  $Z_{\gamma}$ +2 jets & constraints on anomalous quartic gauge couplings. ATLAS: Production cross-section of top-quark pair using dilepton channel (5.02 TeV). CMS: Electroweak diboson production cross sections using leptonic decays (5.02 TeV).

ATLAS: Combined EFT interpretation of differential XS of WW, WZ, 4I, and Z+2-jets (13 TeV). CMS: Search for CP violation in top quark pair events in the lepton+jets channel (13 TeV). CMS: Search for charged lepton flavor violation in top quark production and decay (13 TeV). ATLAS: A precise interpretation for the top quark mass parameter in Monte Carlo simulation. ATLAS & CMS: Towards Common top-quark pair Monte-Carlo Settings for ATLAS and CMS.

#### **Conclusions**

- ATLAS & CMS are extensively testing the validity of the Standard Model. Only a small portion of the EW and QCD physics program has been covered in this talk.
- Precision measurements of differential processes allow to test the theory advancements.
- A precise understanding of QCD interactions is crucial (Background of many processes)
- Rare processes provide great insight towards BSM effects. Enhancements of the XS would point to the presence of new physics.
- The measurement of particle properties as polarizations, CP violations or masses allow also BSM tests. Among all quarks, top quark plays an important due to its large mass.
- The Effective Field Theory extension of the SM allow to do model independent searches of new physics.
- The use of MVA as BDTs and NNs has become the baseline for most analyses.

#### Many thanks for your attention!