# Standard Model measurements by ATLAS and CMS



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CMS

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## Outline

Many new Run 2 measurements released by ATLAS and CMS:

- Transverse energy-energy correlations and α<sub>s</sub> extraction
- Diphoton production
- Collinear Z boson emission
- Lepton Flavour Universality test
- $^{\circ}$  Search for  $W \rightarrow \pi \gamma$  in  $t\bar{t}$  events
- Observation of photon-induced WW and dilepton production
- Electroweak Zjj differential cross sections
- Polarization in electroweak W<sup>±</sup> W<sup>±</sup> jj production
- Observation of electroweak Wγjj, WZjj and ZZjj production
- Evidence of electroweak Z yjj production
- Observation of the production of three massive gauge bosons VVV
- Inclusive 4ℓ differential cross sections



#### Transverse energy-energy correlations and $\alpha_s$ extraction

#### ATLAS-CONF-2020-025

- $\circ~$  Event shape observables can be used to precisely test pQCD calculations and to extract the value of  $\alpha_{\rm s}$
- Transverse energy-energy correlations (TEEC) and their associated azimuthal asymmetries (ATEEC) used for hadron collider experiments

$$\frac{1}{\sigma} \frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi} \equiv \frac{1}{\sigma} \sum_{ij} \int \frac{\mathrm{d}\sigma}{\mathrm{d}x_{\mathrm{T}i} \mathrm{d}x_{\mathrm{T}j} \mathrm{d}\cos\phi} x_{\mathrm{T}i} x_{\mathrm{T}j} \mathrm{d}x_{\mathrm{T}i} \mathrm{d}x_{\mathrm{T}j} = \frac{1}{N} \sum_{A=1}^{N} \sum_{ij} \frac{E_{\mathrm{T}i}^{A} E_{\mathrm{T}j}^{A}}{\left(\sum_{k} E_{\mathrm{T}k}^{A}\right)^{2}} \delta(\cos\phi - \cos\phi_{ij})$$

where *i* and *j* run over all jets in the event,  $E_T$  is the sum of transverse energies of all jets,  $x_i = E_{T_i}/E_T$  and  $\phi$  is the angle between jets in the transverse plane

1	$d\Sigma^{asym}$	_ 1	dΣ	1	dΣ	
$\overline{\sigma}$	$d\cos\phi$	$\overline{\sigma}$	$d\cos\phi$	$\phi^{-}\sigma$	$d\cos\phi$	$ _{\pi-\phi}$



#### Transverse energy-energy correlations and $\alpha_s$ extraction

#### ATLAS-CONF-2020-025

- $\circ~$  Data binned in ten intervals of  $H_{\rm T2}$  (scalar  $p_{\rm T}$  sum of the two leading jets) to study the scale dependence of the TEEC and ATEEC observables
- $\circ \alpha_s$  determined from fits to the TEEC and ATEEC functions



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ICPPA-2020, 5 October 2020 4

## Measurement of diphoton production cross section

#### ATLAS-CONF-2020-024

• The main challenge and source of uncertainty in the experimental side is the estimation of the background from non-prompt photons in jet events



 The measured integrated cross section compatible with the NNLO predictions and multileg-merged calculations



Comparisons to the MC predictions:

• Sherpa [SciPost Phys. 7 (2019) 034]

Comparisons to the fixed-order predictions:

- Fixed-order NNLO with NNLOJET [PoS RADCOR2017 (2018) 074]
- Fixed-order NLO with Diphox [Eur. Phys. J. C16 (2000) 311]

## Measurement of diphoton production cross section

#### ATLAS-CONF-2020-024

 Agreement between measured differential cross sections and the most accurate predictions is generally good where expected



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## Collinear Z boson emission

CMS-PAS-SMP-19-010



# BR( $W \rightarrow \tau \nu$ )/BR( $W \rightarrow \mu \nu$ ) in e- $\mu t\bar{t}$ events

#### arXiv:2007.14040 [hep-ex]

- Testing Lepton-Flavour Universality (LFU)
- Probing universality of *W* coupling to charged leptons:  $R(\tau/\mu) = BR(W \rightarrow \tau v_{\tau})/BR(W \rightarrow \mu v_{\mu})$
- Using dileptonic *t* vents as a sample of probe *W* bosons, tag(*e*, *µ*)-and-probe(*µ*)
- In agreement with SM expectation:

 $\mathsf{R}(\tau/\mu) = 0.992 \pm 0.013$ 

- Flavour anomalies observed at LHCb: [JHEP 08 (2017) 055]
   [PRL 122 (2019) 191801]
- Long-standing 2.7σ deviation from LEP [Phys. Rept. 532 119]:

 $\mathsf{R}(\tau/\mu) = 1.070 \pm 0.026$ 

 Factor two in precision compared to LEP, best precision achieved up to now



## Search for $W \rightarrow \pi \gamma$ in $t\bar{t}$ events

CMS-PAS-SMP-20-008

- First LHC search of the rare exclusive hadronic decay  $W \rightarrow \pi \gamma$ : isolated photon plus isolated track compatible with a pion (dedicated variable developed)
- Select  $t\bar{t}$  events with  $W \rightarrow \ell v$  ( $\ell = \mu, e$ ), signal discrimination with a Boosted Decision Tree (BDT)
- Upper limits extracted from a fit to the  $m_{\pi\gamma}$  distribution:  $B(W \rightarrow \pi\gamma) < 1.51 \times 10^{-5}$  (theoretical calculations in the range  $10^{-9} - 10^{-6}$ )



## Observation of photon-induced WW production

#### ATLAS-CONF-2020-038

- $\circ~$  Test of the electroweak (EW) sector of the Standard Model
  - Direct access to triple  $\gamma WW$  and quartic  $\gamma \gamma WW$  interactions,  $O(\alpha_{EM}^2)$



Protons radiate ISR photons and stay intact or dissociate



Run 1 evidence of this process has turned into observation in Run 2:

ATLAS [Phys. Rev. D 94 (2016) 032011] and CMS [JHEP 08 (2016) 119]

## Observation of photon-induced WW production

ATLAS-CONF-2020-038

A  $\gamma\gamma \rightarrow W^+W^- \rightarrow \mu^+ v_\mu e^- v_e$  candidate event recorded in *pp* collisions in 2018



## Observation of photon-induced WW production

#### ATLAS-CONF-2020-038

	Signal region		Control regions	
$n_{\rm trk}$	$n_{\rm trk}$	= 0	$1 \le n_{trl}$	$_{k} \leq 4$
$p_T^{e\mu}$	> 30  GeV	< 30  GeV	> 30  GeV	$< 30 { m ~GeV}$
$\gamma \gamma \rightarrow WW$	$174 \pm 20$	$45 \pm 6$	$95 \pm 19$	$24 \pm 5$
$\gamma\gamma \rightarrow \ell\ell$	$5.5 \pm 0.3$	$39.6 \pm 1.9$	$5.6 \pm 1.2$	$32 \pm 7$
Drell-Yan	$4.5 \pm 0.9$	$280 \pm 40$	$106 \pm 19$	$4700 \pm 400$
$qq \rightarrow WW$	$101 \pm 17$	$55 \pm 10$	$1700 \pm 270$	$970 \pm 150$
Non-prompt	$14 \pm 14$	$36 \pm 35$	$220 \pm 220$	$500 \pm 400$
Other $qq$ initiated	$7.1 \pm 1.7$	$1.9 \pm 0.4$	$311 \pm 76$	$81 \pm 15$
Total	$305 \pm 18$	$459 \pm 19$	$2460 \pm 60$	$6320 \pm 130$
Data	307	449	2458	6332

Interaction vertex:

$$z_{\rm vtx}^{\ell\ell} = \frac{z_{\ell_1} \sin^2 \theta_{\ell_1} + z_{\ell_2} \sin^2 \theta_{\ell_2}}{\sin^2 \theta_{\ell_1} + \sin^2 \theta_{\ell_2}}$$

 $n_{
m trk}$ : number of tracks in a window  $\Delta z = \pm 1$  mm around  $z_{
m vrkx}^{\ell\ell}$  excluding the tracks from leptons

Observation with 8.4 $\sigma$  (6.7 $\sigma$  exp)



## Observation of photon-induced dilepton production

arXiv:2009.14537 [hep-ex]

- $^{\circ}$  2017 dataset with the ATLAS Forward Proton (AFP) detector inserted, 14.6 fb<sup>-1</sup>
- Observation with significances of 9.7 $\sigma$  (13 $\sigma$ ) for ee ( $\mu\mu$ )
- The first cross section measurement using proton tagging at the LHC



#### Electroweak Zjj differential cross sections

arXiv:2006.15458 [hep-ex]

- $\circ~$  Sensitive to the Vector Boson Fusion (VBF) production mechanism
- Measured data are sufficiently precise to distinguish between different state-of-the-art theoretical predictions calculated using POWHEG+PYTHIA8, HERWIG7+VBFNLO and SHERPA 2.2



#### Electroweak Zjj differential cross sections

#### arXiv:2006.15458 [hep-ex]



## Electroweak Zjj differential cross sections

arXiv:2006.15458 [hep-ex]



## Electroweak *WZjj* and $W^{\pm}W^{\pm}jj$ production

Phys. Lett. B 809 (2020) 135710

Vector Boson Scattering (VBS) contributing to the EW-induced production:



• QCD-induced production:



- Observation of electroweak production of WZ at 6.8 $\sigma$  (5.3 $\sigma$  exp) significance
- Differential cross sections measured as a function of several observables
- Constrain anomalous Quartic Gauge Couplings (aQGCs) in the EFT framework

## Electroweak WZjj and $W^{\pm}W^{\pm}jj$ production

#### Phys. Lett. B 809 (2020) 135710



2500 3000 m<sub>ii</sub> [GeV]

1500 m<sup>WZ</sup> [GeV]

## Polarization in electroweak $W^{\pm}W^{\pm}jj$ production

arXiv:2009.09429 [hep-ex]

- Deviations in VBS production of longitudinally polarized gauge bosons predicted in many BSM models
- ° First measurements of production cross sections for polarized  $W^{\pm}W^{\pm}$
- Two different BDTs used to separate either the  $W_L^{\pm}W_L^{\pm}$  and  $W_X^{\pm}W_T^{\pm}$  processes or the  $W_L^{\pm}W_X^{\pm}$  and  $W_T^{\pm}W_T^{\pm}$  processes
- EW W<sup>±</sup>W<sup>±</sup> production with at least one longitudinally polarized W boson measured at 2.3σ (3.1σ exp) significance



## Evidence/Observation of electroweak ZZjj production

ATLAS: arXiv:2004.10612 [hep-ex], CMS: arXiv:2008.07013 [hep-ex]

Typical diagrams for the production of ZZjj: EW VBS diagrams



Typical diagrams for the production of ZZjj: QCD diagrams



## Evidence/Observation of electroweak ZZjj production

ATLAS: arXiv:2004.10612 [hep-ex], CMS: arXiv:2008.07013 [hep-ex]

- 0 ZZjj analysis performed exploiting leptonic decays:
  - ATLAS: *llllij* and *llvvjj* channels
  - CMS: *lllljj* channel
- All VVjj channels have been observed now 0
- ATLAS observation: 5.5 $\sigma$  (4.3 $\sigma$ ), CMS evidence: 4.0 $\sigma$  (3.5 $\sigma$ )

ATLAS (s = 13 TeV, 139 fb

-0.8 -0.6 -0.4 -0.2 0

Signal Region

eevvii

20



ATLAS *llljj* 

ATLAS *llvvii* Multivariate discriminant

Uncertainty

0.2 0.4 0.6 0.8

MD

CMS *lllljj* 



#### Matrix element discriminant

## Observation of electroweak Wyjj production

arXiv:2008.10521 [hep-ex]

 VBS processes comprise an independent and complementary method to study EW symmetry breaking



- $^{\circ}$  Observed (expected) significance is 4.9 $\sigma$  (4.6 $\sigma$ )
- $^{\circ}~$  Observed (expected) significance is 5.3  $\sigma$  (4.8  $\sigma$ ) after combining with 8 TeV data



## Evidence of electroweak Zyjj production

JHEP 06 (2020) 076

- $Z\gamma jj$  measurement with 36 fb<sup>-1</sup>: 3.9 $\sigma$  (5.2 $\sigma$  exp) significance (4.7 $\sigma$  obtained if combined with 8 TeV data)
- Signal extracted from a  $m_{ii}$  and  $\Delta \eta_{ii}$  two-dimensional fit
- Fiducial cross-section in agreement with the SM
- Constraints on aQGCs



#### Observation of the production of three massive gauge bosons

arXiv:2006.11191 [hep-ex]

- First observation of the combined production of three massive gauge bosons VVV with V = W, Z
- Searches for individual *WWW*, *WWZ*, *WZZ*, and *ZZZ* production performed in final states with 3, 4, 5, and 6 leptons (*e* or μ)
- $^{\circ}~$  Observed (expected) significance of the combined VVV production is 5.7  $\sigma~(5.9\sigma)$





#### Inclusive four-lepton differential cross sections

#### ATLAS-CONF-2020-042

- The 4 $\ell$  final state has contributions from interesting Standard Model processes: single Z boson production, Higgs boson production and on-shell ZZ production
- Sensitive to New Physics / BSM contributions: modifications to the couplings of the Higgs or gauge boson, possible four-fermion interactions, models with leptonic decays of Z bosons or new particles



## Conclusions

- Many new results with the latest and greatest Run 2 dataset by ATLAS and CMS, legacy Run 2 measurements being finalized
- Comprehensive tests of the Standard Model over 15 orders of magnitude in cross section and going more differential, results compared to theory predictions from state-of-the-art MC and fixed-order calculations.
- LFU test in agreement with SM with the best precision achieved up to now
- $\circ~$  First LHC search of the rare exclusive hadronic decay  $W \to \pi \gamma$
- First measurements of production cross sections for polarized  $W^{\pm}W^{\pm}$
- Evidence/Observation of rare processes:
  - Observation of photon-induced processes:  $\gamma\gamma \rightarrow WW$  and  $\gamma\gamma \rightarrow \ell\ell$
  - Observation of electroweak production of Wγjj, WZjj and ZZjj
  - Evidence of electroweak production of Zyjj
  - Observation of production of VVV (with V = W, Z)
- More information:

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