Measurement of fiducial and differential W^+W^- production cross-sections at $\sqrt{s}$ =13 TeV with the ATLAS detector

Valerie Lang, DESY

HEP Experiment-Theory DESY Pizza Seminar
27.06.2019

- arXiv:1905.04242 -

Why measure WW production?

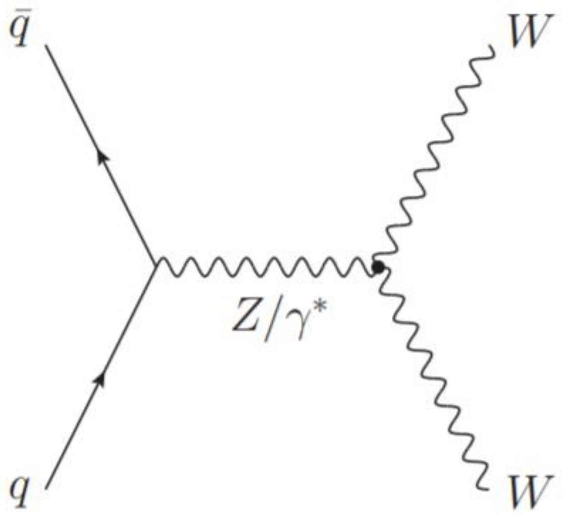
Gauge structure of the electroweak (EW) sector

- Electroweak interactions in the SM
  - W and Z bosons couple to weak isospin
  - W bosons carry weak isospin

  → Non-abelian

  → Self-coupling in SM allowed in certain combinations, e.g. WWZ, (WWγ,) WWZZ, WWWW

  → Triple (TGC) or Quartic Gauge Couplings (QGC)



- What about physics beyond the SM (BSM)?
  - Could increase TGC contributions → anomalous TGCs (aTGCs) → Enhance cross section
  - New contributions to SM Lagrangian $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i$ → Effective field theory (EFT) framework
  - Provide indirect bounds to BSM contributions → Requires high precision measurement

→ Measuring WW production = probe gauge structure of EW sector & check for BSM contributions

Why measure WW production?

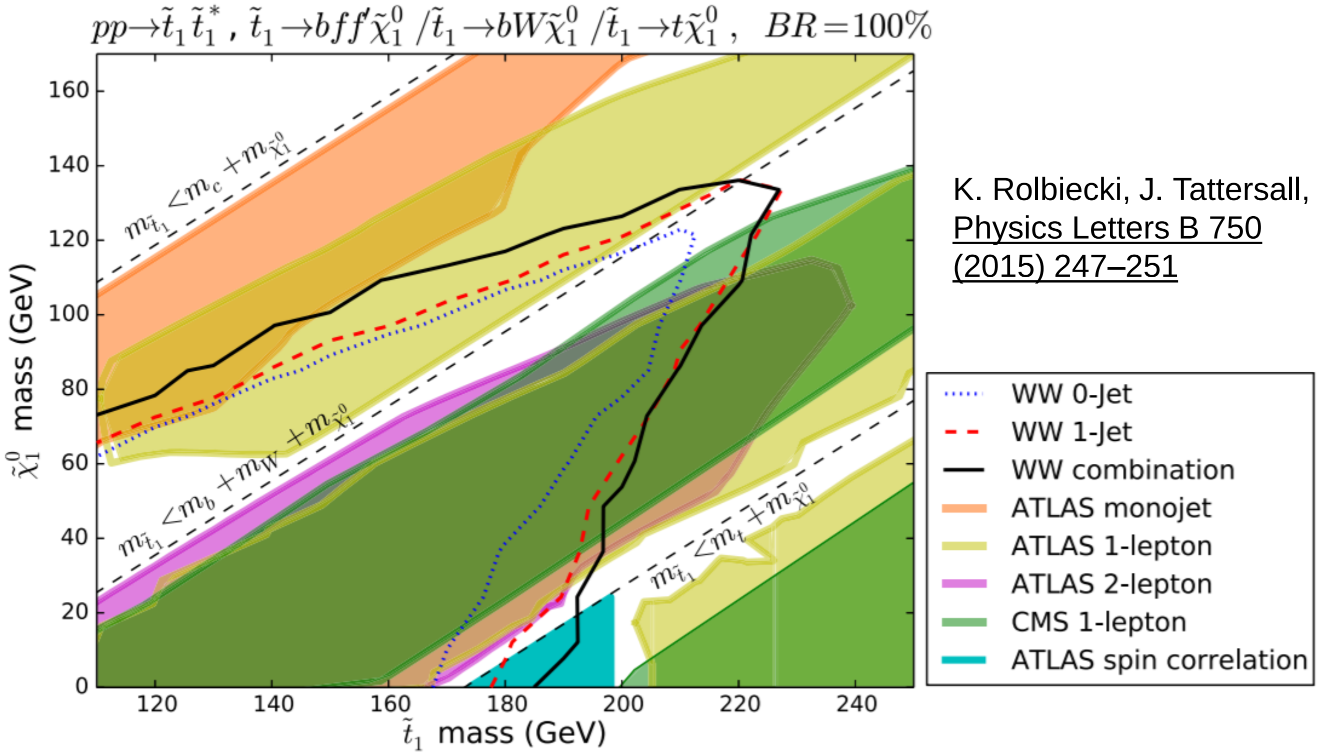
Constraining models for new physics scenarios

- WW precision measurements can also be interpreted to search for specific new physics scenarios
  - EW doublet or triplet scalars, degenerate or non-degenerate supersymmetric stops, compressed EW SUSY with low stop masses
  - Example: Light stop production with decays as:

$$\tilde{t}_1 \to \tilde{\chi}_1^0 t\,, \qquad \text{if } m_{\tilde{t}_1} \geq m_t + m_{\tilde{\chi}_1^0}\,,$$
$$\tilde{t}_1 \to \tilde{\chi}_1^0 W b\,, \qquad \text{if } m_{\tilde{t}_1} \geq m_W + m_b + m_{\tilde{\chi}_1^0}\,,$$
$$\tilde{t}_1 \to \tilde{\chi}_1^0 f f' b\,, \qquad \text{if } m_{\tilde{t}_1} < m_W + m_b + m_{\tilde{\chi}_1^0}\,.$$

    with 100% branching ratios

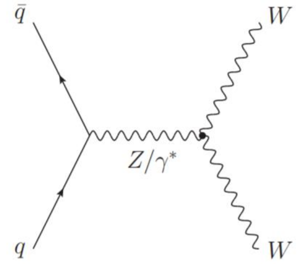
    - CMS 8TeV WW measurement provides constraints where stop production looks very much like SM WW production
    - W bosons almost on shell, b-jets too soft to be vetoed



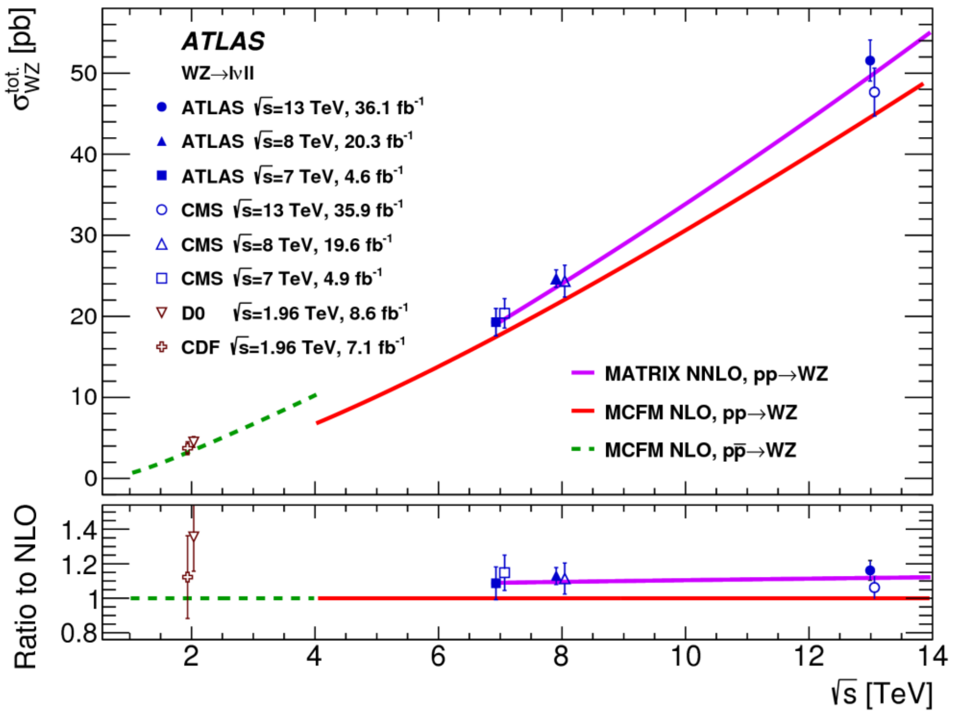
K. Rolbiecki, J. Tattersall, Physics Letters B 750 (2015) 247–251

What to expect?

High precision measurement vs. prediction



- High precision measurements require higher order predictions
  - Leading order in perturbative quantum chromodynamics (QCD) for qq initiated production: $O(\alpha_S^0)$ i.e. not jet emission
  - Why do we need higher orders: NLO = $O(\alpha_S^1)$, NNLO = $O(\alpha_S^2)$?



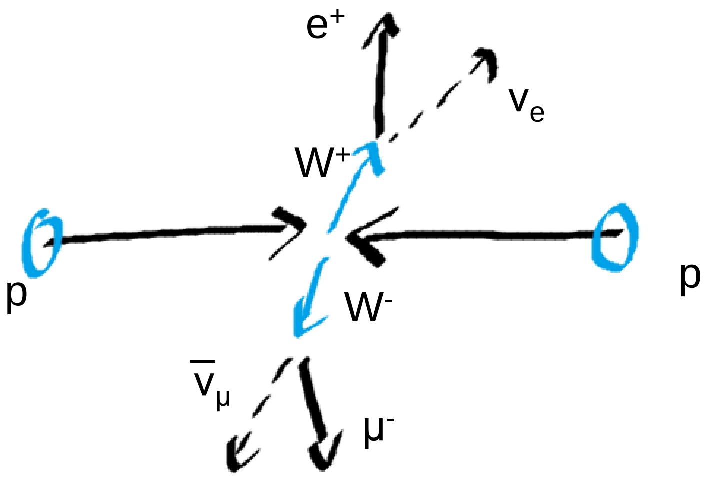
Which measurement precision do we target?

Measurement	Precision on σ_{fid}
ATLAS 8TeV (llvv) JHEP 09 (2016) 029	7.3 %
CMS 8TeV (total, different flavour, 0 jets) Eur. Phys. J. C (2016) 76:401	8.7 %

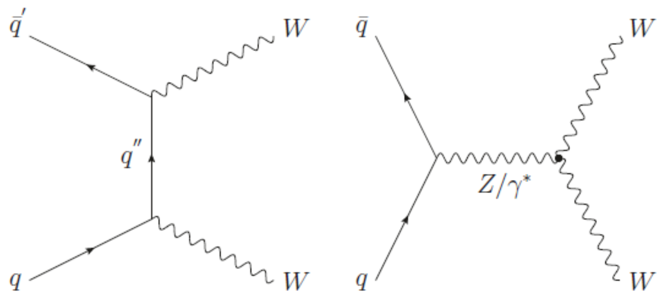
New measurement of WW production at 13 TeV by ATLAS

Based on 36.1fb^{-1} data from 2015+2016

- Measurement of the $WW \rightarrow e\nu_e\ \mu\nu_\mu$ final state



- Contributing signal processes

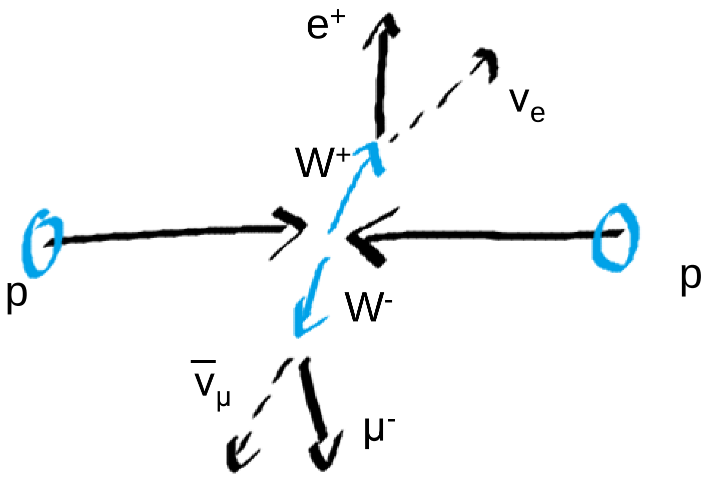


Via qq initiated
→ Contains TGC vertex
→ Largest part of cross section

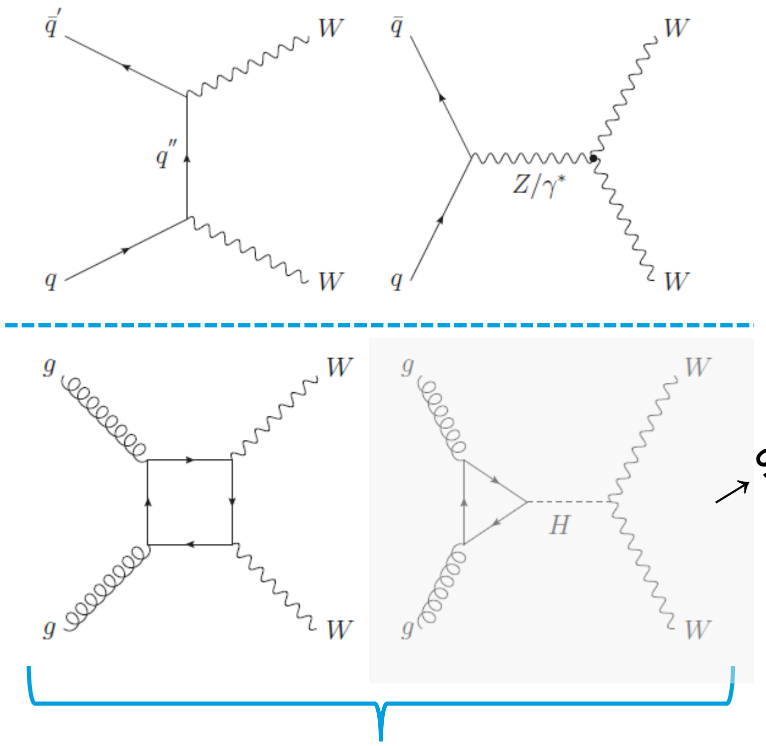
New measurement of WW production at 13 TeV by ATLAS

Based on 36.1fb^{-1} data from 2015+2016

- Measurement of the $WW \rightarrow e\nu_e\, \mu\nu_\mu$ final state



- Contributing signal processes



Via gg initiated
→ ~ 5% of the
measured
cross section

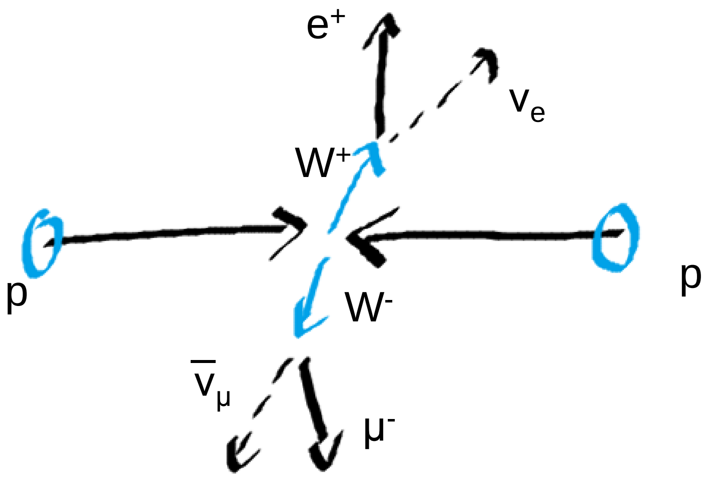
→ Suppressed by selection

→ Interfere!

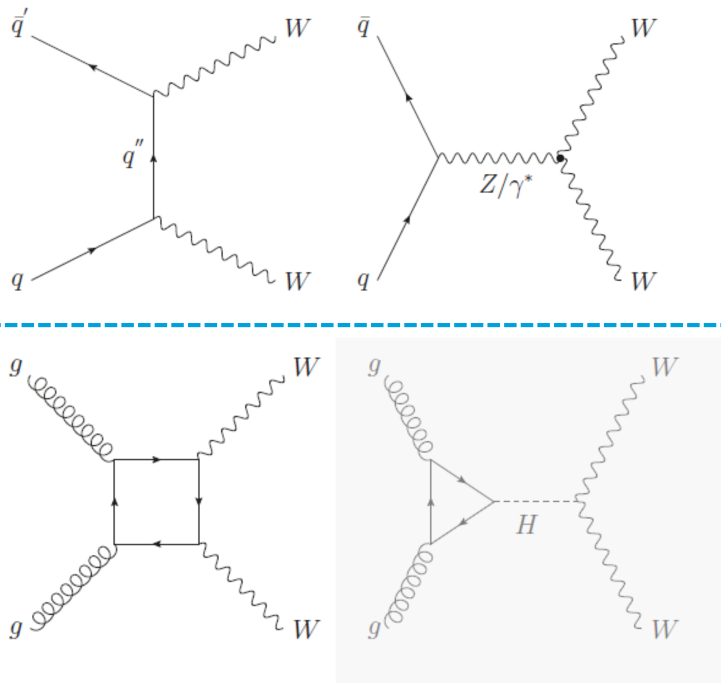
New measurement of WW production at 13 TeV by ATLAS

Based on 36.1fb^{-1} data from 2015+2016

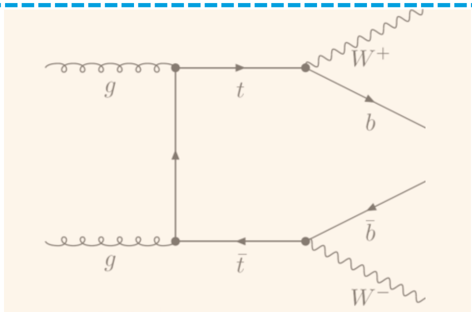
- Measurement of the $WW \rightarrow e\nu_e\ \mu\nu_\mu$ final state



- Contributing signal processes



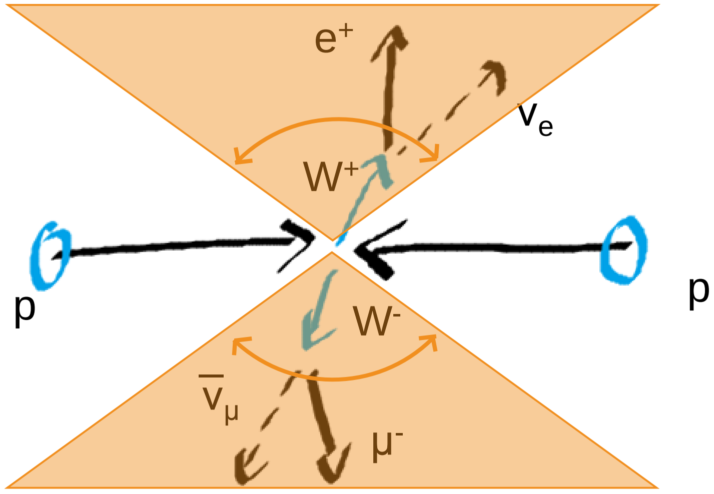
Via $t\bar{t}$ production
→ Treated as background
→ Suppressed by selection



Measurement of the fiducial cross section

Selection of events

- Restriction of phase space through selection
  - Reduce extrapolation into phase space areas where we don‘t have a detector



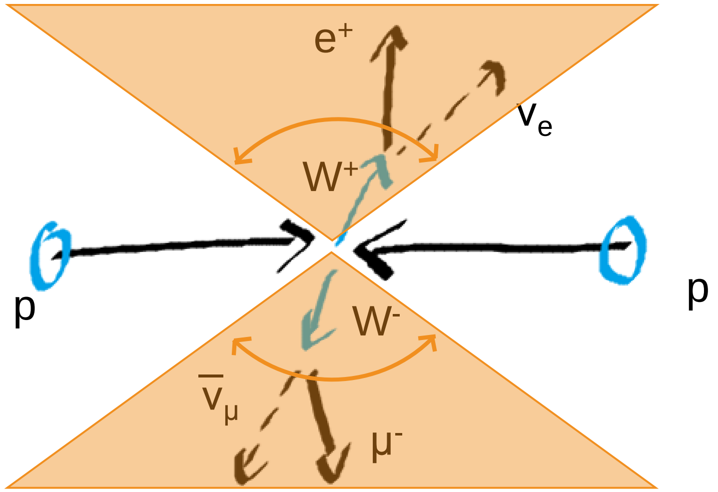
- Fiducial selection (highlights)
  - $m_{e\mu} > 55$ GeV
  - No jets with $p_T > 35$GeV, $|\eta| < 4.5$ (optimized for smallest total uncertainty)

No overlap with H→WW analysis
Phys. Lett. B 789 (2019) 508–529)

Measurement of the fiducial cross section

Selection of events

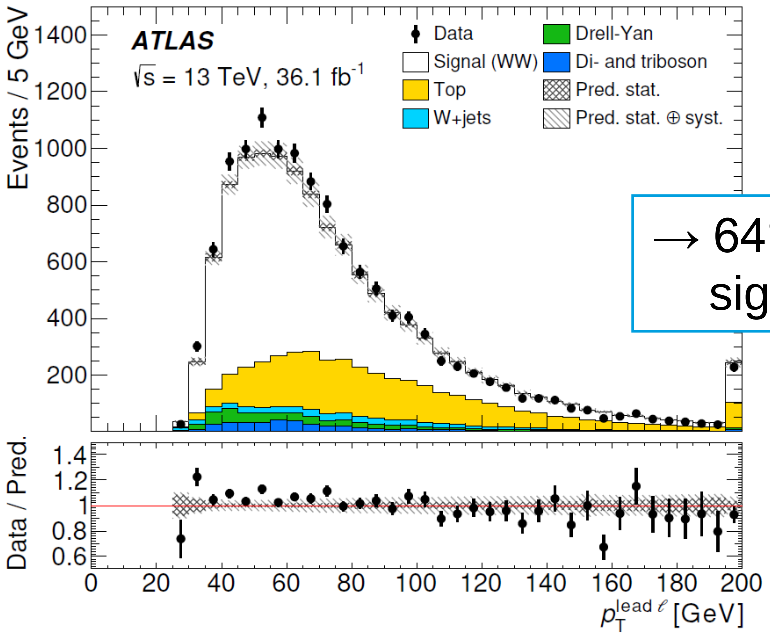
- Restriction of phase space through selection
  - Reduce extrapolation into phase space areas where we don‘t have a detector



  - Fiducial selection (highlights)
    - $m_{e\mu}$ > 55 GeV
    - No jets with p_T > 35GeV, |η| < 4.5 (optimized for smallest total uncertainty)

- In data → Signal region selection (highlight)

  + No b-tagged jets with p_T > 20GeV, |η| < 2.5



→ 64% WW signal purity

- Largest background:
  - $t\bar{t} + Wt$ → 26 % → partly data-driven

Background from top production

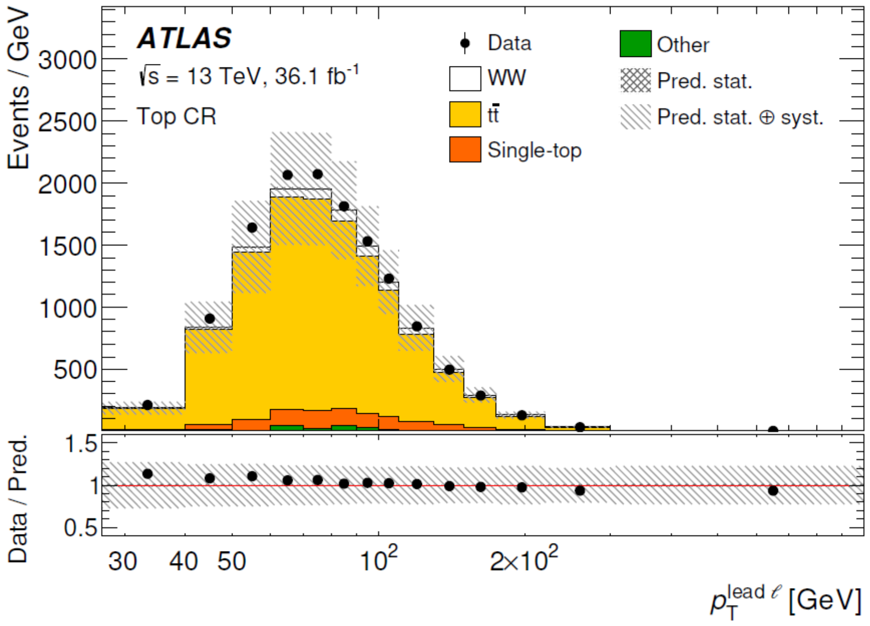
Jet veto survival probability method (JVSP)

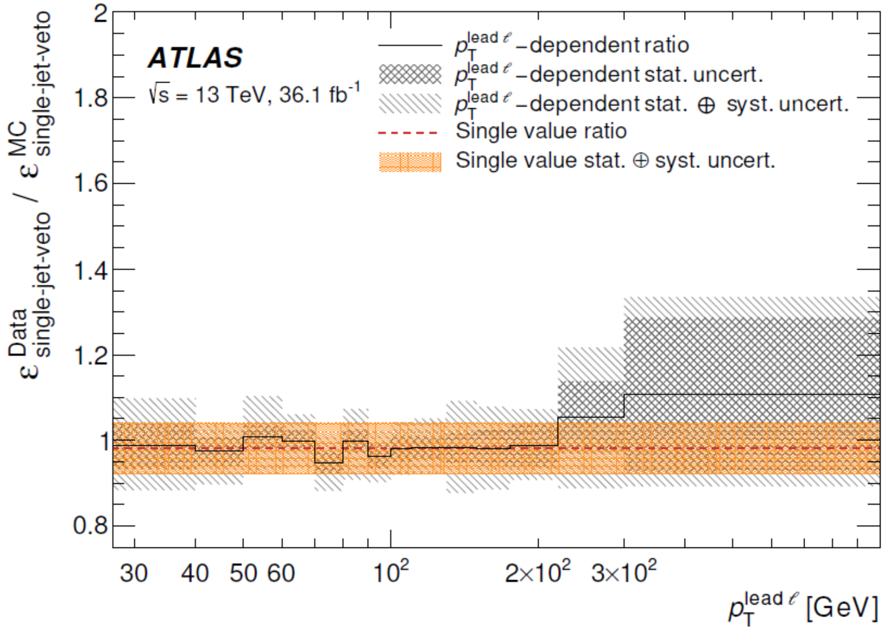
- Partly data-driven method → Use data to correct predictions from top production MC simulation

$$N_{top}^{SR} = N_{CR}^{top} / \epsilon_{H_T} \cdot \epsilon_{jet-veto}$$

Allow jets and b-jets

Estimate from simulation, but correct with data → $\epsilon_{jet-veto} = \epsilon_{jet-veto}^{MC} \cdot \left(\frac{\epsilon_{single-jet-veto}^{Data}}{\epsilon_{single-jet-veto}^{MC}} \right)^{\langle n_{jets} \rangle}$



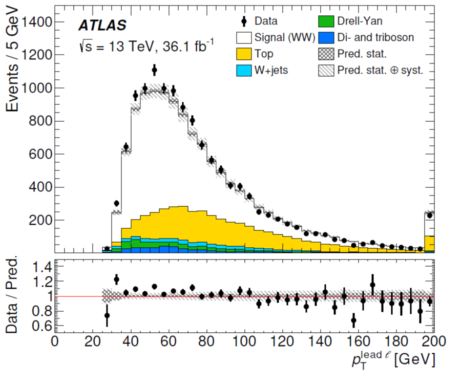


→ Close to 1
→ Allows good systematics cancellation, in particular top modelling systematics

Important improvement w.r.t. 2015 analysis

How does the physics look without detector?

Unfolding from detector level to particle level



- Transform number of events in data to a cross section value
  - One bin → Fiducial cross section

$$\sigma^{\text{fid}}_{WW\rightarrow e\mu} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times \mathcal{L}}$$

  - *C*-factor contains detector inefficiencies
    → relates reconstructed (SR) to true events (FR)

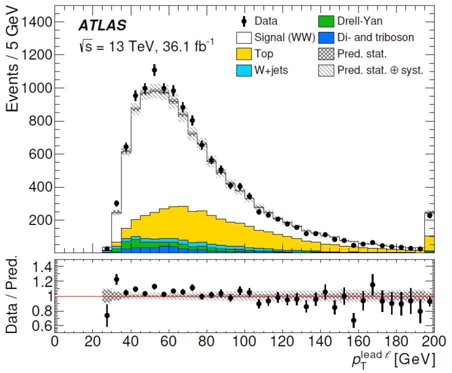
$$C = \frac{N_{SR}^{WW}}{N_{FR}^{WW}}$$

    → Use WW simulation to obtain this value

$$C = 0.613 \pm 0.019$$

How does the physics look without detector?

Unfolding from detector level to particle level



- Transform number of events in data to a cross section value
  - One bin → Fiducial cross section

$$\sigma^{\text{fid}}_{WW\to e\mu} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times \mathcal{L}}$$

  - *C*-factor contains detector inefficiencies
    → relates reconstructed (SR) to true events (FR)

$$C = \frac{N_{SR}^{WW}}{N_{FR}^{WW}}$$

    → Use WW simulation to obtain this value

$$C = 0.613 \pm 0.019$$

- Several bins → Differential cross section
  - *C*-factor per bin → Bin-by-Bin unfolding
  - Consider migrations → Split into:
    - Fiducial correction, f^i_{fid}
    - Unfolding matrix, M^{ij}
    - Reconstruction efficiency, $\varepsilon^j_{\text{reco}}$

Use Bayes‘ theorem

$$N^j_{\text{unf}} = \frac{1}{\varepsilon^j_{\text{reco}}} \sum_{i=1}^{n^{\text{reco}}_{\text{bins}}} \left[N^i_{\text{data}} - N^i_{\text{bkg}}\right] \cdot f^i_{\text{fid}} \cdot P(N^i_{\text{reco}}|N^j_{\text{true}}) P(N^j_{\text{true}})/C^i$$

→ Iterate on the prior
→ Iterative Bayesian unfolding

Systematic uncertainties in the WW measurement

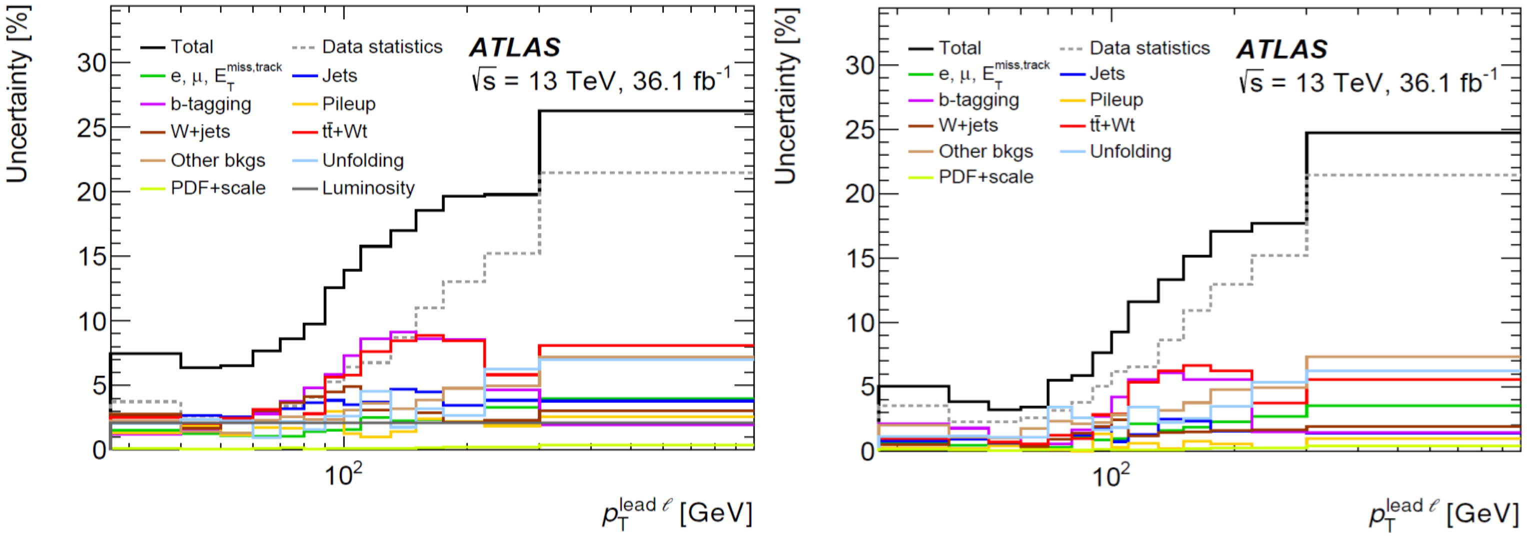
Integrated and differential cross section

- Fiducial cross section uncertainties

Uncertainty source	Uncertainty [%]
Electron	0.7
Muon	0.9
Jets	3.0
b-tagging	3.4
$E_T^{miss,track}$	0.4
Pile-up	1.6
W+jets background modelling	3.1
Top-quark background modelling	2.6
Other background modelling	1.3
Unfolding, incl. signal MC stat. uncertainty	1.4
PDF+scale	0.1
Systematic uncertainty	6.7
Statistical uncertainty	1.3
Luminosity uncertainty	2.1
Total uncertainty	7.1

→ Most precise measurement so far!

- Differential cross section uncertainties
  - Can look at absolute or normalized cross sections



  - Normalized: Partial uncertainty cancellation, in particular luminosity uncertainty
  - Statistically dominated at high leading lepton p_T

Systematic uncertainties in the WW measurement

Looking at top systematics in detail

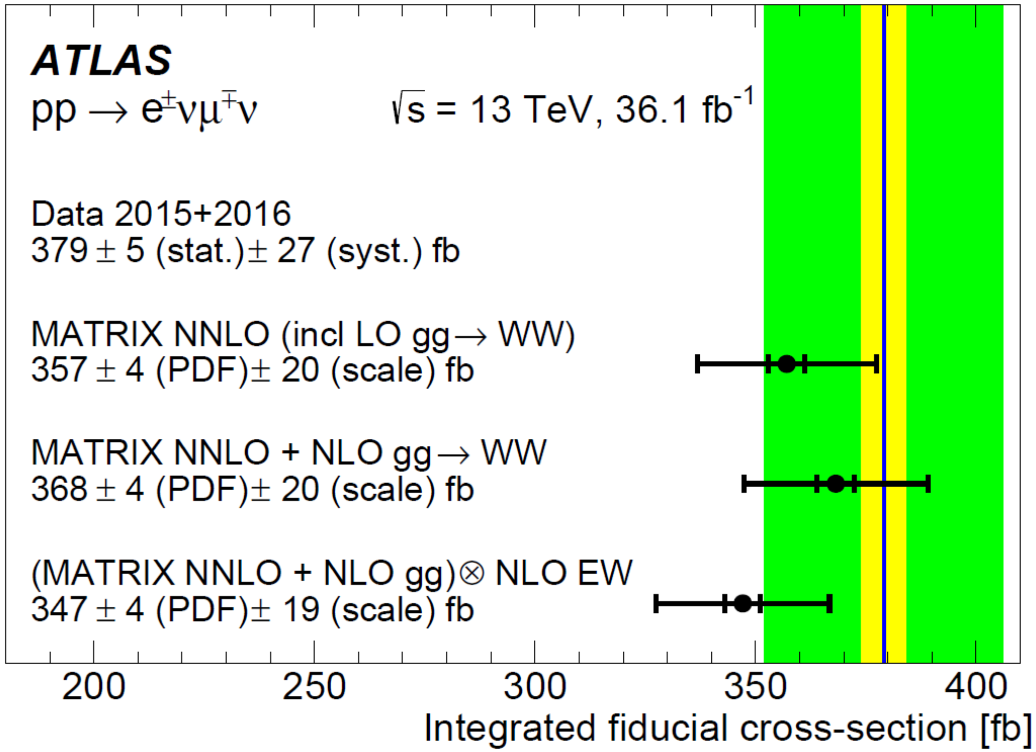
- Considered systematic variations
  - $t\bar{t}$:
    - Matrix element generator → Madgraph5_aMC@NLO+Pythia8 (Powheg+Pythia8 nominal)
    - Parton shower generator → Powheg+Herwig7 (Powheg+Pythia8 nominal)
    - Variation of amount of additional radiation → h_{damp}=3m_t (1.5m_t nominal), variation of set of tuned parameters for the underlying event (tune A14), variation of renormalization and factorization scales (μ_R and μ_F)
    - Cross section uncertainty 6%
  - Wt:
    - Matrix element + parton shower generator → Madgraph5_aMC@NLO+Herwig++ (Powheg+Pythia nominal)
    - Variation of amount of radiation → variation of tune (Perugia2012), variation of μ_R and μ_F
    - Different diagram removal scheme for the overlap between Wt and $t\bar{t}$
    - Cross section uncertainty 10%
  - JVSP method uncertainties
    - Variation of the exponent by ±1
    - Variation of H_T cut by ±20%

Results

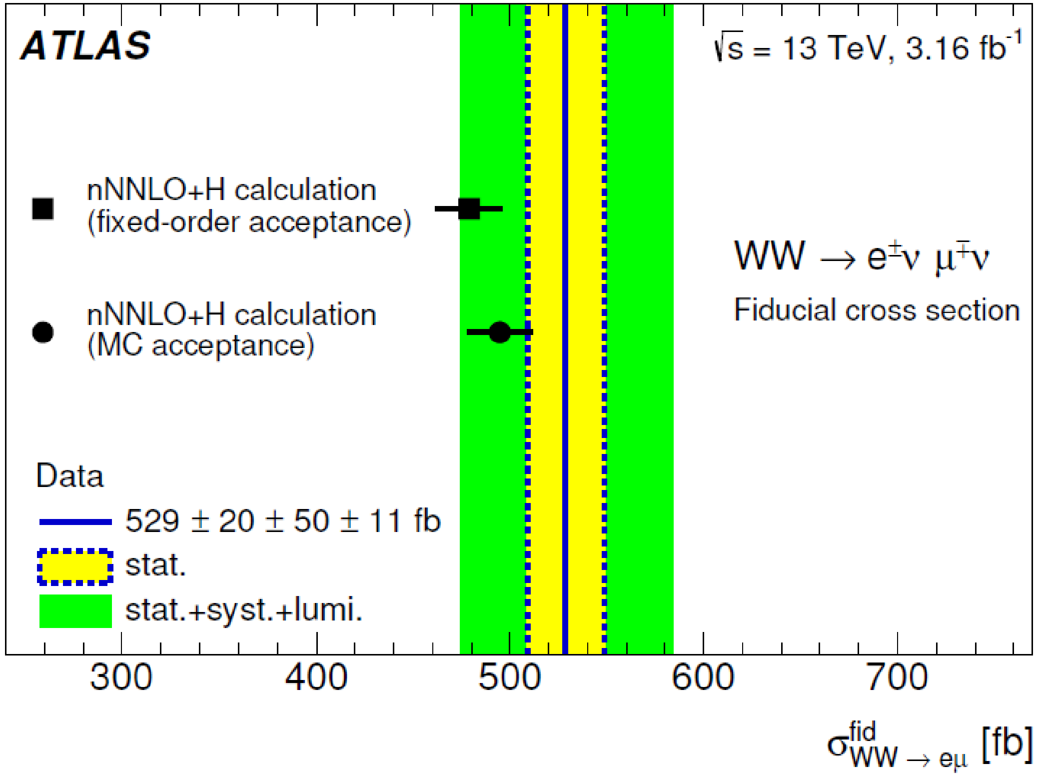
Integrated fiducial cross section

Note: Different fiducial phase space in 2015 analysis

- Fiducial cross section in $WW \rightarrow e\nu\mu\nu$ channel



For comparison: 2015 data only

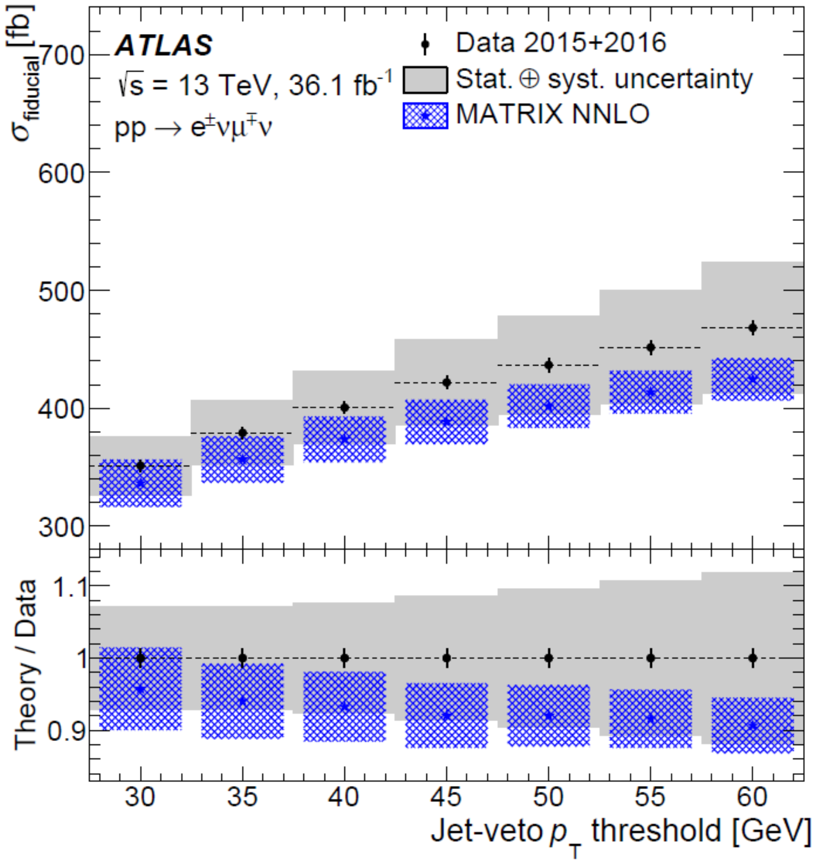


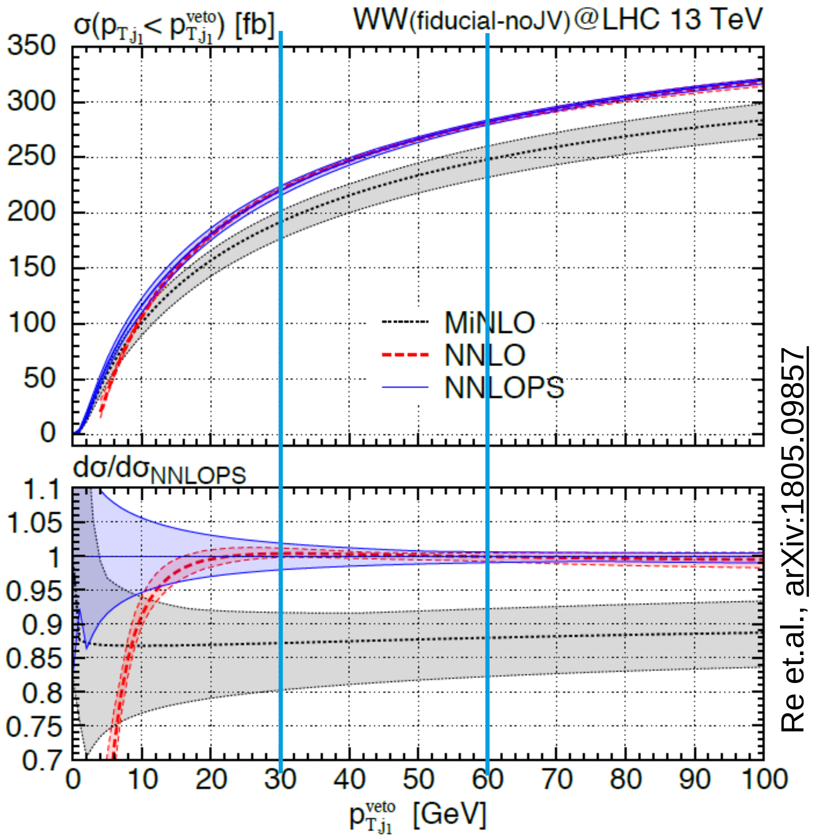
- Prediction at lower boundary of uncertainty band, but agrees within uncertainties

Results

Integrated fiducial cross section

- Measurement of jet kinematics in the absensce of jets → Cross section as function of jet-veto p_T threshold
  - Within measured range, jet-veto logarithms are small → NNLO is valid description





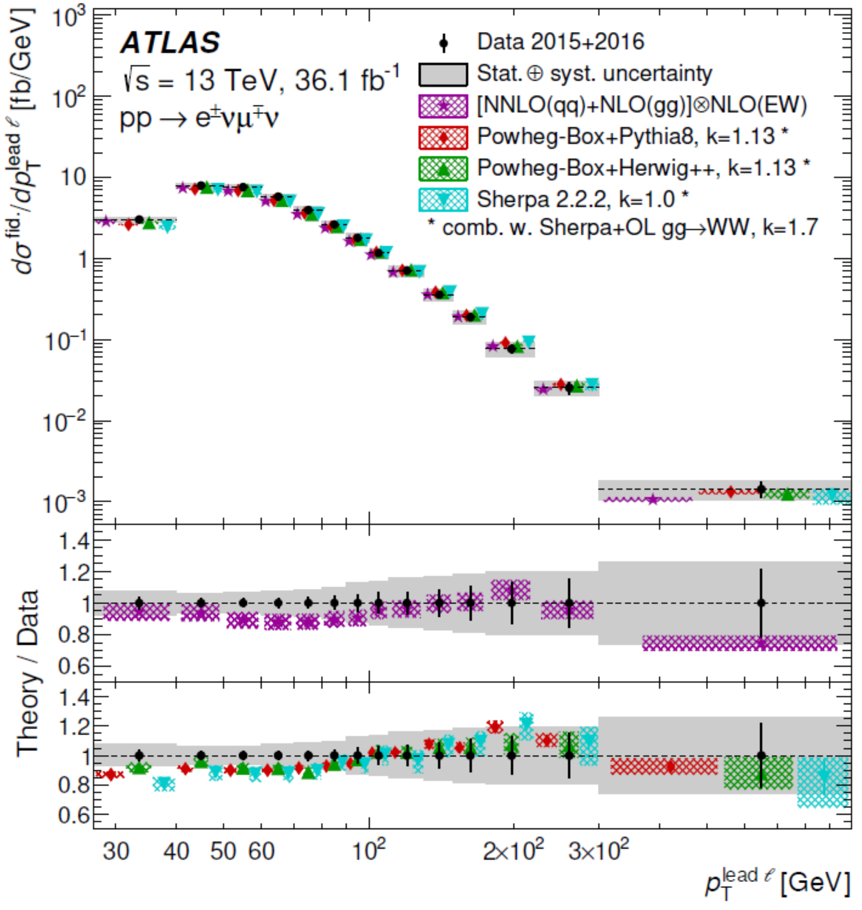
Re et.al., arXiv:1805.09857

Slightly different phase space (ATLAS 2015 measurement), so values not directly comparable

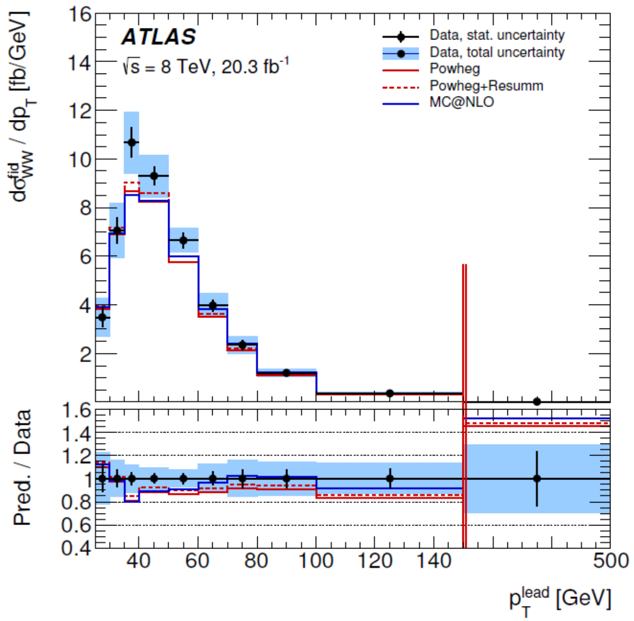
Results

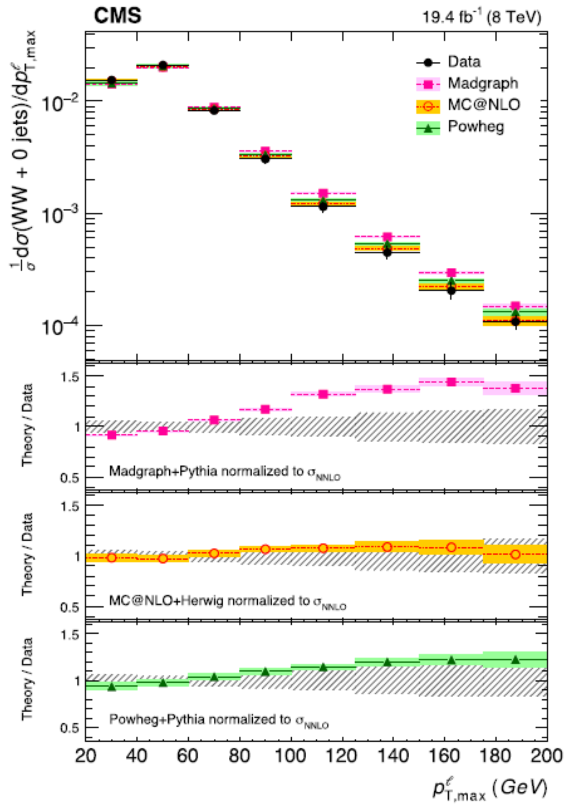
Fiducial differential cross sections

- Measured 6 differential distributions: $p_T^{lead\,l}$, $m_{e\mu}$, $p_T^{e\mu}$, $|y_{e\mu}|$, $\Delta\phi_{e\mu}$, $|\cos\theta^*|$



For comparison @8TeV



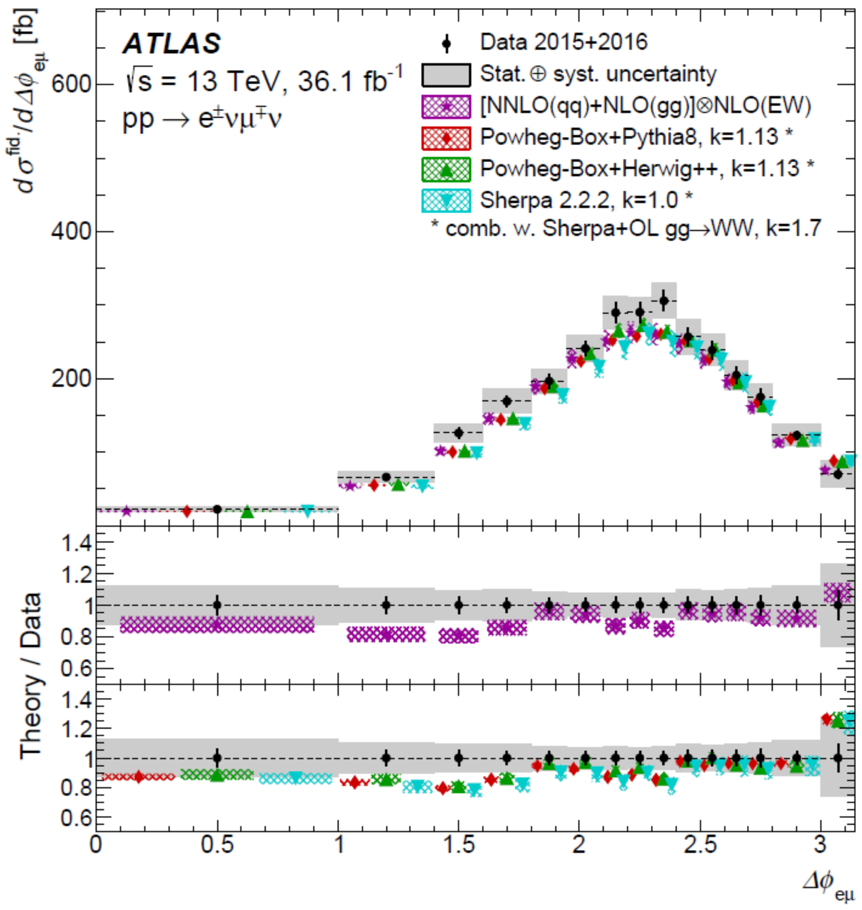


→ Feature of overprediction at ~200GeV present for all distributions

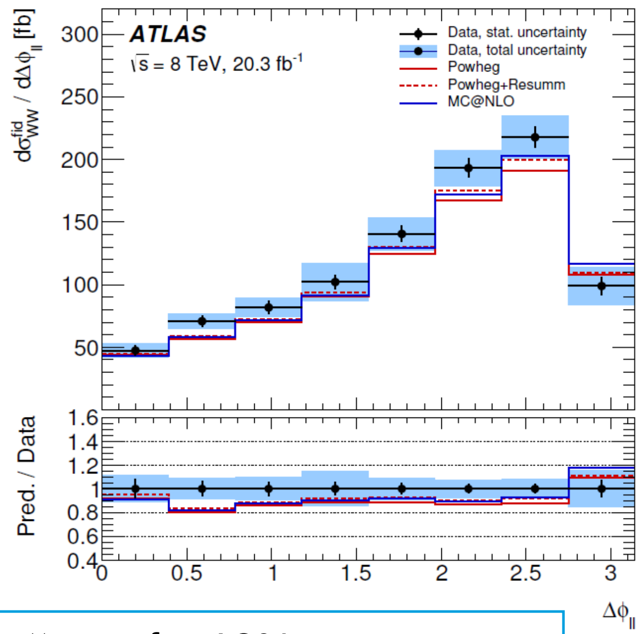
Results

Fiducial differential cross sections

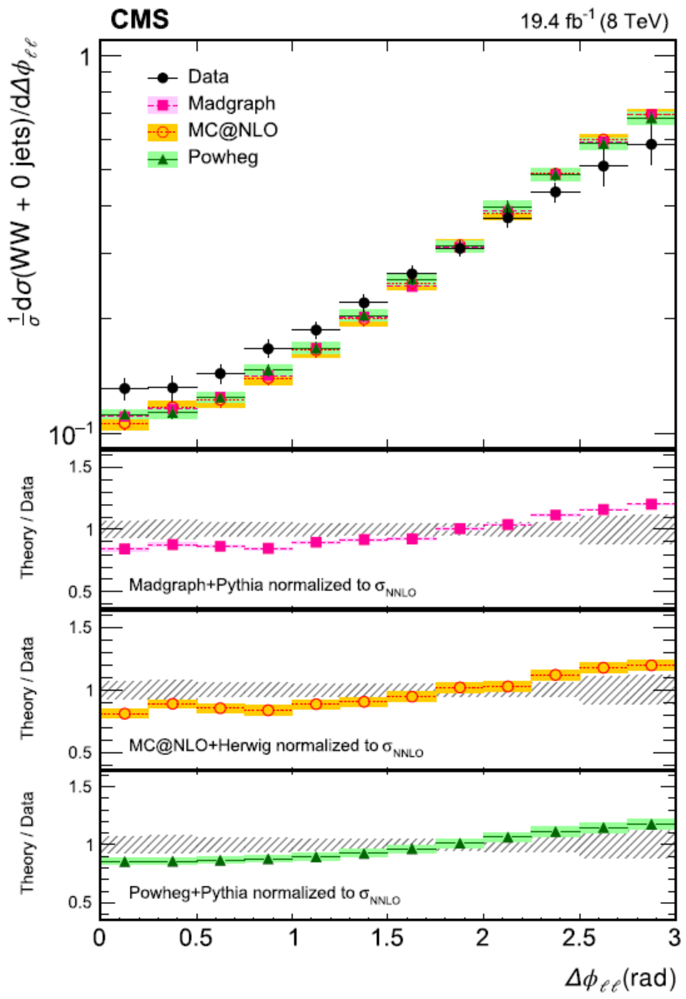
- Measured 6 differential distributions: $p_T^{lead\ l}$, $m_{e\mu}$, $p_T^{e\mu}$, $|y_{e\mu}|$, $\Delta\phi_{e\mu}$, $|\cos\theta^*|$



For comparison @8TeV



→ Pattern of ~10% underprediction at small $\Delta\phi_{e\mu}$ and ~5-20% overprediction at $\Delta\phi_{e\mu}$~3 seems persistent



What do we learn from the data?

Limits in effective field theory (EFT) approach

- Fit unfolded data with EFT model (EWdim6 w/ HISZ basis)
  - SM-interference & pure-EFT effects templates
    → scale linearly or quadratically with Wilson coefficients c_i

$$\sigma = \sigma_{\rm SM} + \sum_i c_i \sigma_{{\rm SM},i}^{\rm interf} + \sum_i c_i^2 \sigma_i^{\rm NP}$$

  - Obtain limits in 3 CP-even and 2 CP-odd operators
  - Use leading lepton p_T distribution

Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_B/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]

What do we learn from the data?

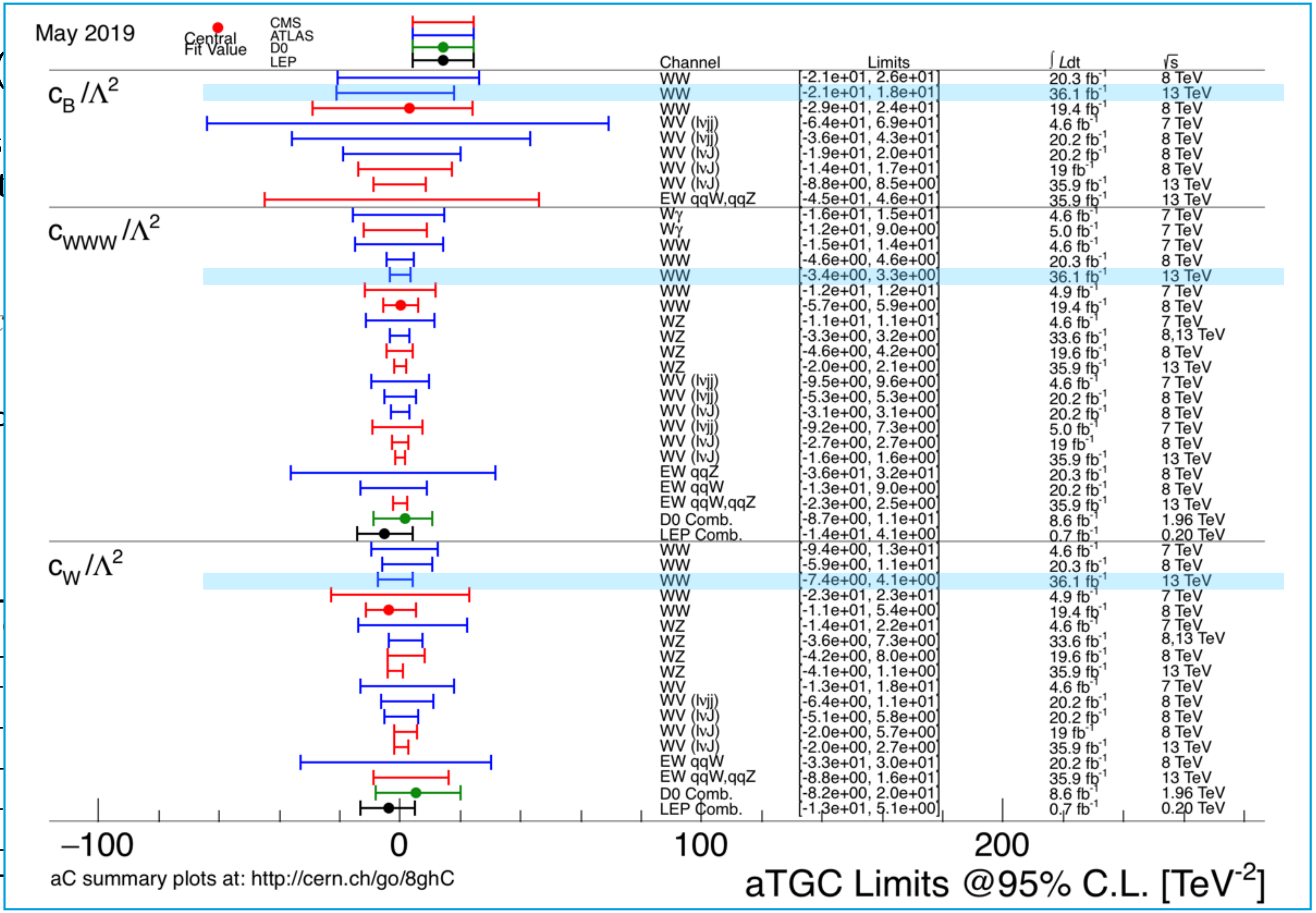
Limits in effective field theory (EFT) approach

- Fit unfolded data with EFT model (
  - SM-interference & pure-EFT effects
    → scale linearly or quadratically wit
    coefficients c_i

$$\sigma = \sigma_{\mathrm{SM}} + \sum_i c_i \sigma^{\mathrm{interf}}_{\mathrm{SM},i} + \sum_i c$$

  - Obtain limits in 3 CP-even and 2 CP
    operators
  - Use leading lepton p_T distribution

Parameter	Observed 95% CL [TeV^{-2}]	Expected
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−
c_W/Λ^2	[−7.4 , 4.1]	[−
c_B/Λ^2	[−21 , 18]	[-
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[-



Summary

WW production at 13TeV in 36.1fb^{-1} of data

- WW production measured at 13TeV by ATLAS - arXiv:1905.04242
  - Fiducial cross section in jet-veto phase space → jet-veto p_T optimized for smallest total uncertainty
  - Largest background $t\bar{t} + Wt$ → Estimated with partly data-driven method for small top modelling uncertainty
  - Most precise WW measurement at LHC so far → Uncertainty of 7.1%
    - Good agreement of NNLO predictions with data, though at lower uncertainty boundary
  - First differential measurement at 13TeV
    - Good agreement of NNLO predictions with data within uncertainties
    - Differential distributions statistically limited at large energy scales
  - Limits on contributions from EFT operators improved by factor > 2 in expected results compared to 8TeV

→ Looking forward to full run 2 analysis with about four times the amount of data

Thanks for your attention

Previous WW measurements

CDF, D0, ATLAS and CMS

- Measurement precision

Measurement	Precision on σ_{fid}
CDF 1.96TeV (llvv) Phys. Rev. Lett. **104**, 201801	15.2 %
D0 1.96TeV (lvqq, total) Phys. Rev. Lett. **108**, 18180	23.3 %
ATLAS 7TeV (eμ channel only) Phys. Rev. D 87, 112001 (2013)	10.0 %
ATLAS 8TeV (llvv) JHEP 09 (2016) 029	7.3 %
ATLAS 13TeV 2015 (eμ channel only) Phys. Lett. B 773 (2017) 354–374	11.0 %
CMS 7TeV (total) Eur. Phys. J. C (2013) 73:2610	9.7 %
CMS 8TeV (total, different flavour, 0 jets) Eur. Phys. J. C (2016) 76:401	8.7 %
CMS 13TeV 2015 (total, 0+1jet) CMS PAS SMP-16-006	9.5 %

Theoretical predictions for ATLAS WW measurements

History of publications

- 0-jet case

Analysis	**Data set [fb^{-1}]**	**Highest order prediction**	**Data**	**Prediction**	**Difference in σ_{exp}**	**Reference**
WW@7TeV	4.6	NLO [MC@NLO (qq)+ GG2WW (gg)	51.9 ±2.0 (stat) ±3.9 (syst) ±2.0 (lumi) pb [total cross section]	$44.7^{+2.1}_{-1.9}$ pb	2.1	Phys. Rev. D 87, 112001 (2013)
WW@8TeV	20.3	NNLO	71.1 ±1.1 (stat) $^{+5.7}_{-5.0}$ (syst) ±1.4 (lumi) pb [total cross section]	$63.2^{+1.6}_{-1.4}$ (scale) ±1.2 (PDF) pb	1.4	JHEP09 (2016) 029
WW@13TeV	3.16	nNNLO+H [NNLO (qq) + NLO (gg) + NLO (gg→H)	529 ±20 (stat.) ±50 (syst.) ±11 (lumi.) fb [fiducial]	478 ±17 fb	0.9	Phys. Lett. B 773 (2017) 354
WW@13TeV	36.1	[NNLO (qq) + NLO(gg)]xNLO EW	379 ±5 (stat) ±27 (syst,incl lumi) fb [fiducial]	347 ±4 (PDF) ±19 (scale) fb	1.2	STDM-2017-24

Selections in 2015+2016 analysis

Fiducial vs. Signal region

- Fiducial region

Fiducial selection requirements		
p_T^ℓ	>	27 GeV
$\lvert\eta^\ell\rvert$	<	2.5
$m_{e\mu}$	>	55 GeV
$p_T^{e\mu}$	>	30 GeV
E_T^{miss}	>	20 GeV
No jets with p_T	>	35 GeV, $\lvert\eta\rvert < 4.5$

Signal region

Selection requirement	Selection value
p_T^ℓ	> 27 GeV
η^ℓ	$\lvert\eta^e\rvert < 2.47$ (excluding $1.37 < \lvert\eta^e\rvert < 1.52$), $\lvert\eta^\mu\rvert < 2.5$
Lepton identification	*TightLH* (electron), *Medium* (muon)
Lepton isolation	*Gradient* working point
Number of additional leptons (p_T > 10 GeV)	0
Number of jets (p_T >35 GeV, $\lvert\eta\rvert$ <4.5)	0
Number of b-tagged jets (p_T > 20 GeV, $\lvert\eta\rvert$ <2.5)	0
$E_T^{miss,track}$	> 20 GeV
$p_T^{e\mu}$	> 30 GeV
$m_{e\mu}$	> 55 GeV

Selections in 2015 analysis

Fiducial vs. Signal region

- Fiducial region

Fiducial selection requirement	Cut value
p_T^ℓ	> 25 GeV
$\lvert\eta_\ell\rvert$	< 2.5
$m_{e\mu}$	> 10 GeV
Number of jets with $p_T > 25(30)$ GeV, $\lvert\eta\rvert < 2.5(4.5)$	0
$E_{T,\ Rel}^{miss}$	> 15 GeV
E_T^{miss}	> 20 GeV

Signal region

Selection requirement	Selection value
p_T^ℓ	> 25 GeV
η^ℓ	$\lvert\eta^e\rvert < 2.47$ (excluding $1.37 < \lvert\eta^e\rvert < 1.52$), $\lvert\eta^\mu\rvert < 2.4$
Lepton identification	Tight (electron), Medium (muon)
Lepton isolation	Gradient working point
Number of additional leptons ($p_T > 10$ GeV)	0
$m_{e\mu}$	> 10 GeV
Number of jets with $p_T > 25(30)$ GeV, $\lvert\eta\rvert < 2.5(4.5)$	0
Number of b-tagged jets ($p_T > 20$ GeV, 85% op. point)	0
$E_{T,\ Rel}^{miss}$	> 15 GeV
p_T^{miss}	> 20 GeV

Selections in 2012 analysis

Fiducial vs. Signal region

- ATLAS
  - Fiducial region

	$e\mu$	$ee/\mu\mu$
p_T^ℓ (leading/sub-leading)	> 25 / 20 GeV	
$\|\eta^\ell\|$	$\|\eta^\mu\| < 2.4$ and $\|\eta^e\| < 2.47$, excluding $1.37 < \|\eta^e\| < 1.52$	
$m_{\ell\ell}$	> 10 GeV	> 15 GeV
$\|m_Z - m_{\ell\ell}\|$	—	> 15 GeV
Number of jets with $p_T > 25$ GeV, $\|\eta\| < 4.5$	0	0
$\|\Sigma \mathbf{p}_T^{\nu_i}\|$ if $\Delta\phi_\ell > \pi/2$; $\|\Sigma \mathbf{p}_T^{\nu_i}\| \times \sin(\Delta\phi_\ell)$ if $\Delta\phi_\ell < \pi/2$ ($E_{T,\,Rel}^{miss}$)	> 15 GeV	> 45 GeV
Transverse magnitude of the vectorial sum of all neutrinos, $\|\Sigma \mathbf{p}_T^{\nu_i}\|$ (p_T^{miss})	> 20 GeV	> 45 GeV

Signal region

	$e\mu$	$ee/\mu\mu$
p_T^ℓ (leading/sub-leading)	> 25 / 20 GeV	
$\|\eta^\ell\|$	$\|\eta^\mu\| < 2.4$ and $\|\eta^e\| < 2.47$, excluding $1.37 < \|\eta^e\| < 1.52$	
Number of additional leptons with $p_T > 7$ GeV	0	0
$m_{\ell\ell}$	> 10 GeV	> 15 GeV
$\|m_Z - m_{\ell\ell}\|$	—	> 15 GeV
$E_{T,\,Rel}^{miss}$	> 15 GeV	> 45 GeV
p_T^{miss}	> 20 GeV	> 45 GeV
$\Delta\phi(\mathbf{E}_T^{miss}, \mathbf{p}_T^{miss})$	< 0.6	< 0.3
Number of jets with $p_T > 25$ GeV, $\|\eta\| < 4.5$	0	0

- CMS
  - (no table for fiducial region in paper)

Signal region

Variable	Different-flavor	Same-flavor
Opposite-sign charge requirement	Applied	Applied
p_T^ℓ [GeV]	>20	>20
min(proj. E_T^{miss}, proj. track E_T^{miss}) [GeV]	>20	>20
DY MVA	–	>0.88 in zero-jet (>0.84 in one-jet)
$\|m_{\ell\ell} - m_Z\|$ [GeV]	–	>15
$p_T^{\ell\ell}$ [GeV]	>30	>45
$m_{\ell\ell}$ [GeV]	>12	>12
Additional leptons ($p_T^\ell > 10$GeV)	Veto	Veto
Top-quark veto	Applied	Applied
Number of reconstructed jets	<2	<2

Results

At detector level

- Selected events in data and estimated contributions

	Number of events	Statistical uncertainty	Systematic uncertainty
Top-quark	3120	± 50	± 370
Drell–Yan	431	± 13	± 44
W+jets	310	± 60	± 280
WZ	290	± 11	± 33
ZZ	16	± 1	± 2
$V\gamma$	66	± 11	± 10
Triboson	8	± 1	± 3
Total background	4240	± 80	± 470
Signal (WW)	7690	± 30	± 220
Total signal+background	11 930	± 90	± 520
Data	12 659	-	-

(Partially) Data-driven

MC with validation region

MC

W+jets background in WW production

Matrix Method

- Background with at least one fake lepton → Estimate data-driven → Matrix method
  - How often do fake (real) leptons pass the tight SR identification, if they passed a looser ID before?
    → Measure ε_{real} & ε_{fake} in bins of η and p_T, separately for triggered and non-triggered leptons
  - Four equations

In data

$$
\begin{aligned}
N^{LL} &= N^{LL}_{\text{fake,fake}} + N^{LL}_{\text{real,fake}} + N^{LL}_{\text{fake,real}} + N^{LL}_{\text{real,real}} \\
N^{LT} &= \epsilon_{\text{fake}} N^{LL}_{\text{fake,fake}} + \epsilon_{\text{fake}} N^{LL}_{\text{real,fake}} + \epsilon_{\text{real}} N^{LL}_{\text{fake,real}} + \epsilon_{\text{real}} N^{LL}_{\text{real,real}} \\
N^{TL} &= \epsilon_{\text{fake}} N^{LL}_{\text{fake,fake}} + \epsilon_{\text{real}} N^{LL}_{\text{real,fake}} + \epsilon_{\text{fake}} N^{LL}_{\text{fake,real}} + \epsilon_{\text{real}} N^{LL}_{\text{real,real}} \\
N^{TT} &= \epsilon^2_{\text{fake}} N^{LL}_{\text{fake,fake}} + \epsilon_{\text{fake}}\epsilon_{\text{real}} N^{LL}_{\text{real,fake}} + \epsilon_{\text{real}}\epsilon_{\text{fake}} N^{LL}_{\text{fake,real}} + \epsilon^2_{\text{real}} N^{LL}_{\text{real,real}}
\end{aligned}
$$

Solve for $N^{LL}_{\text{real,fake/fake,real}}$ and $N^{LL}_{\text{fake,fake}}$

$$
\begin{aligned}
N_{\text{Wjets}} &= \epsilon_{\text{real}}\epsilon_{\text{fake}} N^{LL}_{\text{real,fake}} + \epsilon_{\text{fake}}\epsilon_{\text{real}} N^{LL}_{\text{fake,real}} \\
N_{\text{multijet}} &= \epsilon^2_{\text{fake}} N^{LL}_{\text{fake,fake}}
\end{aligned}
$$

→ Only 2.6% contribution in SR, but large uncertainty

Comparing ATLAS and CMS limits

Limits in effective field theory (EFT) approach

- Limits obtained from WW measurement
  - From differential cross section as function of $p_T^{lead\ l}$

Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_B/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]

  - Limits from 8 TeV ATLAS measurement
    - From reconstructed event counts

Scenario	Parameter	Expected [TeV^{-2}]	Observed [TeV^{-2}]
EFT	C_{WWW}/Λ^2	[−7.62, 7.38]	[−4.61, 4.60]
	C_B/Λ^2	[−35.8, 38.4]	[−20.9, 26.3]
	C_W/Λ^2	[−12.58, 14.32]	[−5.87, 10.54]

- Search for BSM contributions in WW and WZ events by CMS (CMS PAS SMP-18-008)
  - From reconstructed event counts

Parametrization	aTGC	Expected limit	Observed limit	Run I limit
EFT	c_{WWW}/Λ^2 (TeV^{-2})	[-1.44, 1.47]	[-1.58, 1.59]	[-2.7, 2.7]
	c_W/Λ^2 (TeV^{-2})	[-2.45, 2.08]	[-2.00, 2.65]	[-2.0, 5.7]
	c_B/Λ^2 (TeV^{-2})	[-8.38, 8.06]	[-8.78, 8.54]	[-14, 17]