Measurements of multi-boson production at ATLAS

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Multiboson Physics

Motivation:

- Multiboson physics provides a unique probe of the Standard Model through electroweak-boson self-interactions
  - Precision tests of SM theory predictions
  - Search for Beyond Standard Model physics
    - Effective field theory framework

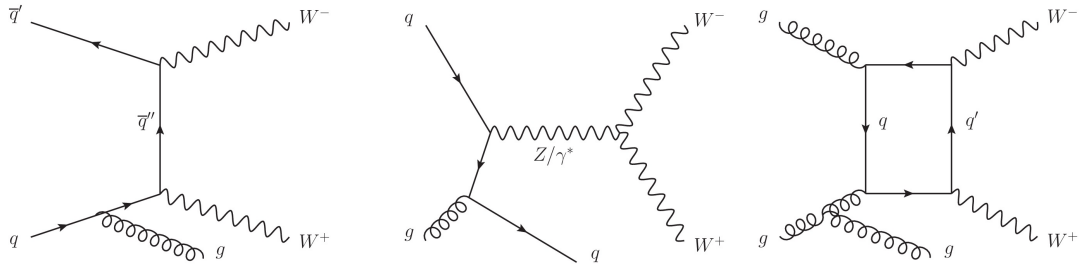
Differential cross-section measurements:

- Look deeper into the production mechanisms through measurements of differential cross-sections
  - WW + $\geq$ 1 jet
  - Inclusive 4-leptons

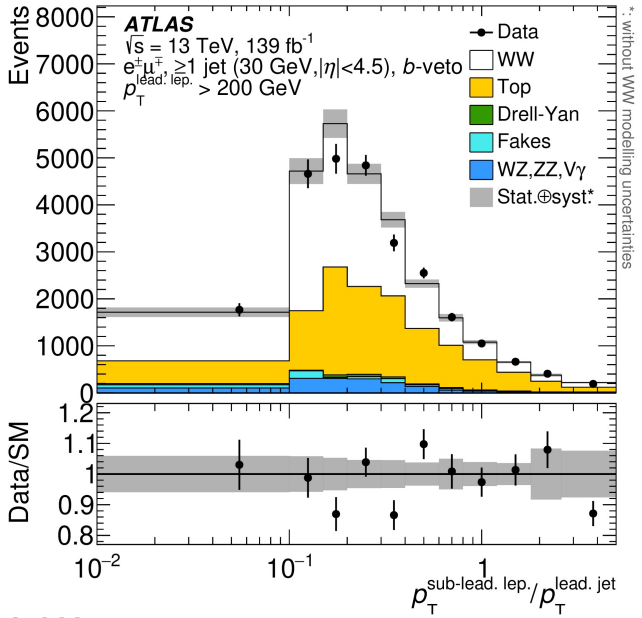
Triboson measurement:

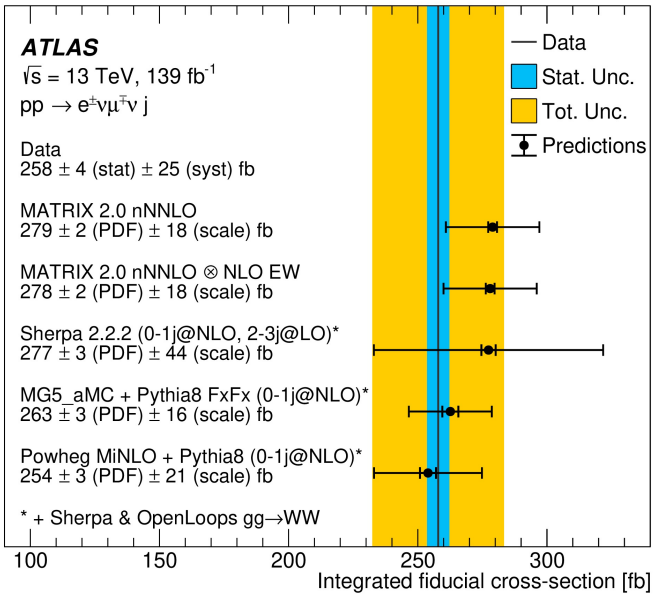
- Push to the edge of observation some of the most rare processes measured to date
  - **WWW New!**

WW + ≥1 jet



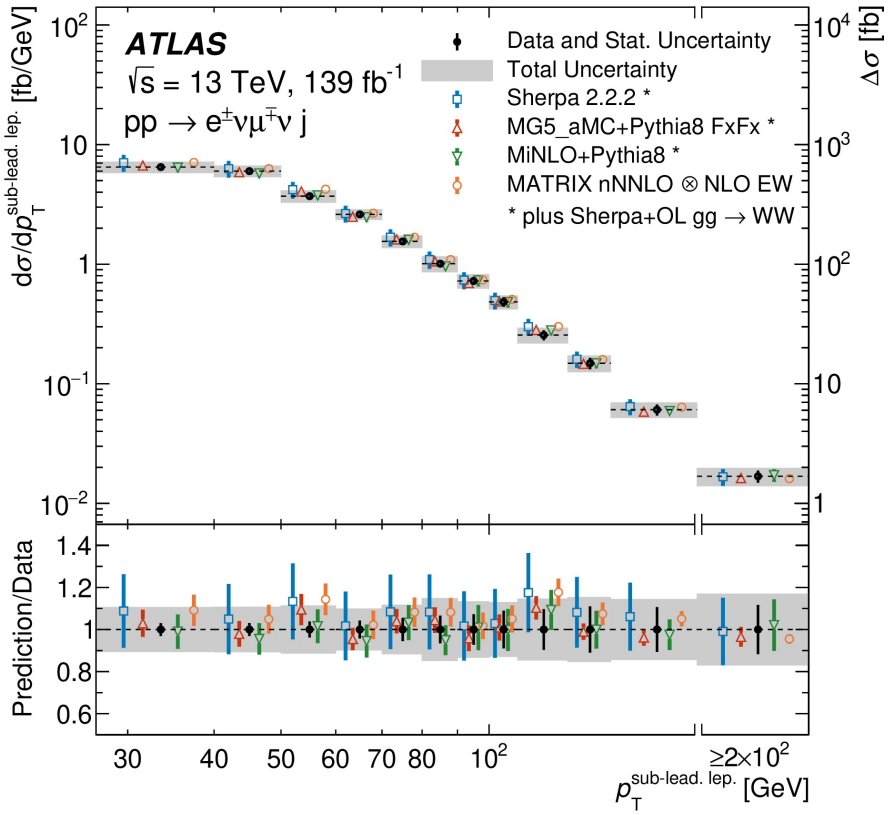
- Measurement of WW pair production with a jet inclusive phase space
  - Select one opposite sign eμ pair and at least one hadronic jet
  - Stringent test of theoretical predictions
    - Perturbative QCD
    - Higher order EWK corrections

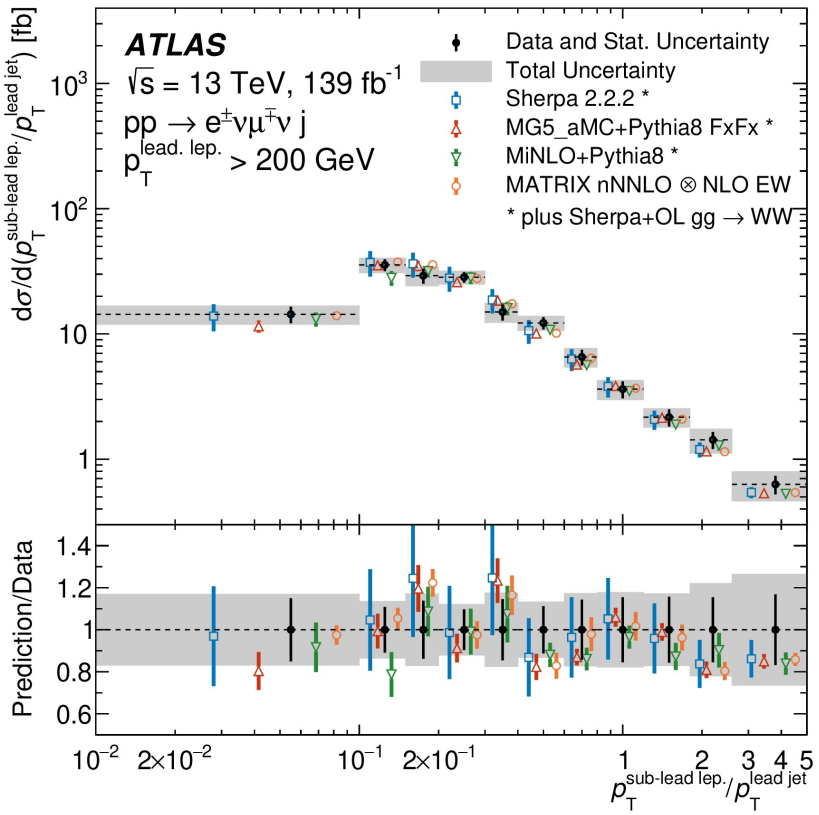




[JHEP 06 (2021) 003]

WW + ≥ 1 jet





Differential cross section measurements for many kinematic variables

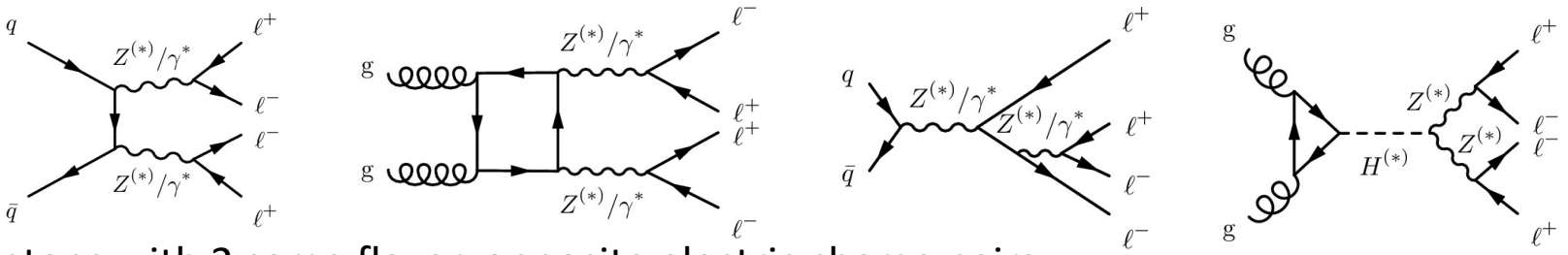
- Sub-leading lepton p_T
- Sub-leading lepton p_T /leading jet p_T for p_T (leading lepton) > 200 GeV
- Good agreement among the MC predictions and data

- Limits were also set on dim-6 EFT operators

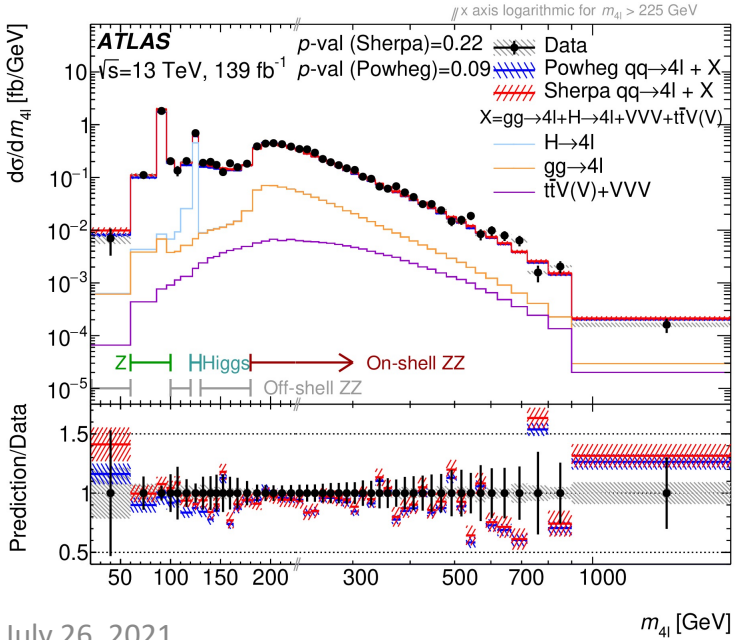
[WW + ≥ 1 jet Poster by Jack MacDonald]

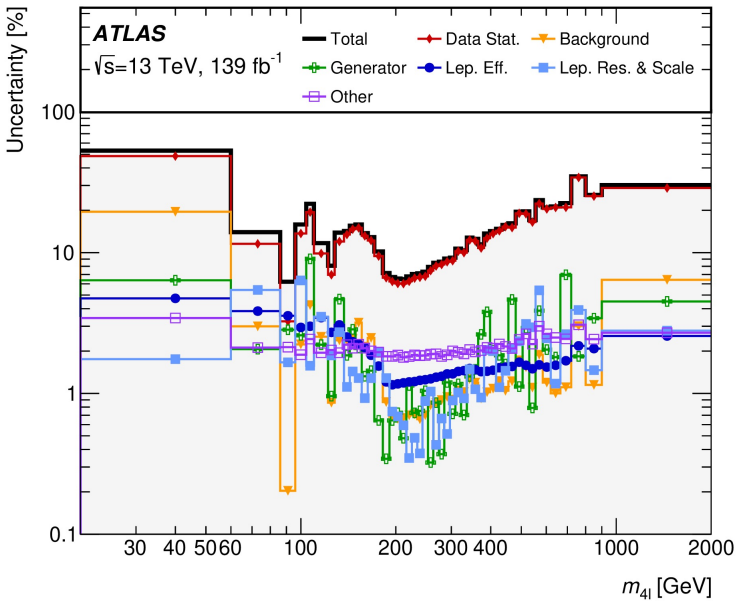
[JHEP 06 (2021) 003]

4 leptons



- 4 leptons with 2 same flavor, opposite electric charge pairs
- Minimal assumptions on theory for background subtraction and unfolding
- Production regions:
  - Single Z boson production, Higgs boson production, on-shell & off-shell ZZ production
  - Double-differential cross-section distributions shown for many kinematic variables (m_{4l} below) and in each of the regions





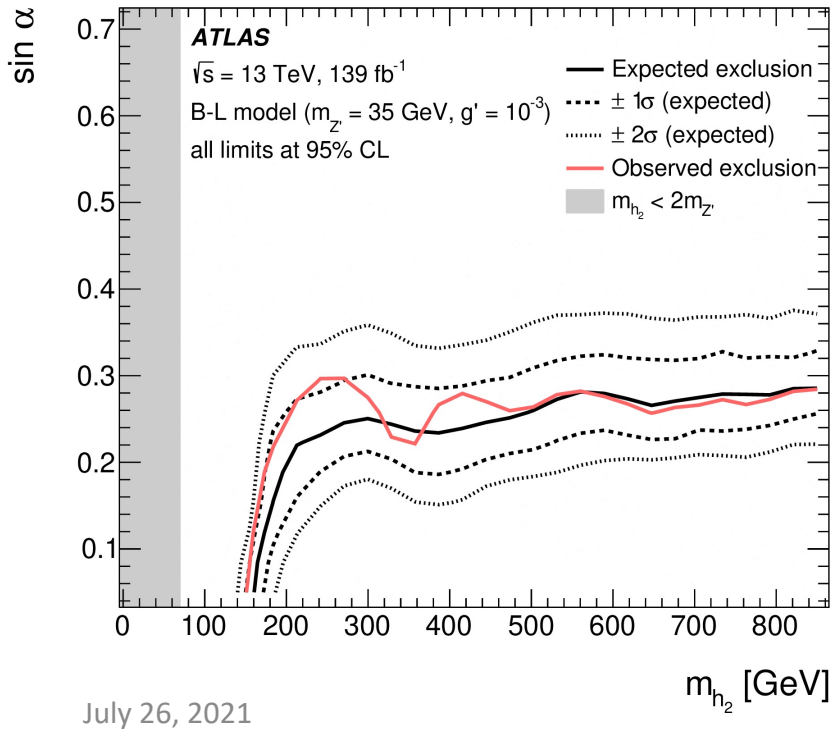
[JHEP 07 (2021) 005]

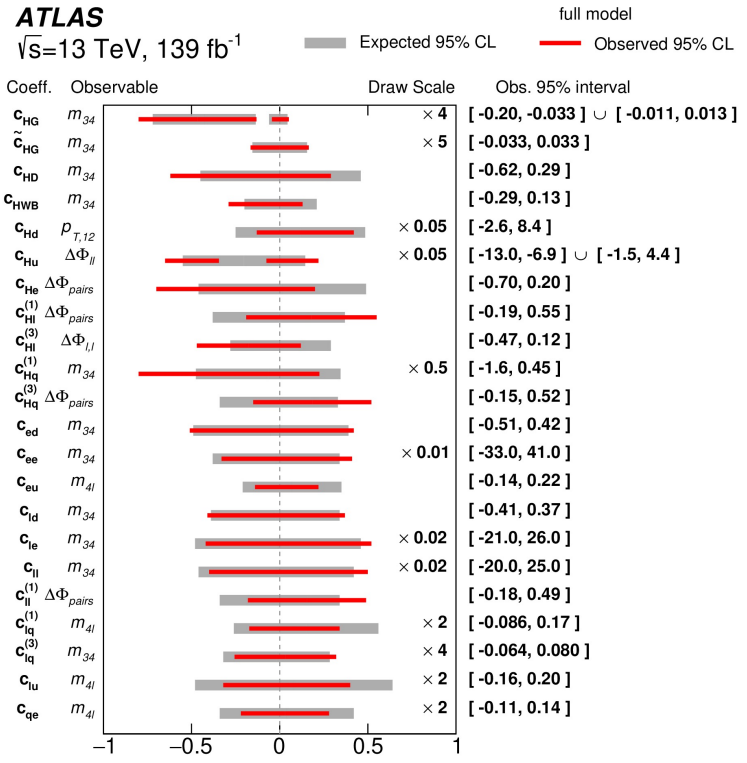
4 leptons

- Extract the branching fraction for Z -> 4l
  - Most precise measurement to date

$$\mathcal{B}_{Z\to 4\ell} = (4.41 \pm 0.13\,(\text{stat.}) \pm 0.23\,(\text{syst.}) \pm 0.09\,(\text{theory}) \pm 0.12\,(\text{lumi.})) \times 10^{-6}$$
$$= (4.41 \pm 0.30) \times 10^{-6},$$

- Baryon number – Lepton number gauge model:
  - Z' and an exotic Higgs boson h_2, mixing angle α
- BSM search in EFT framework: dim-6 operators



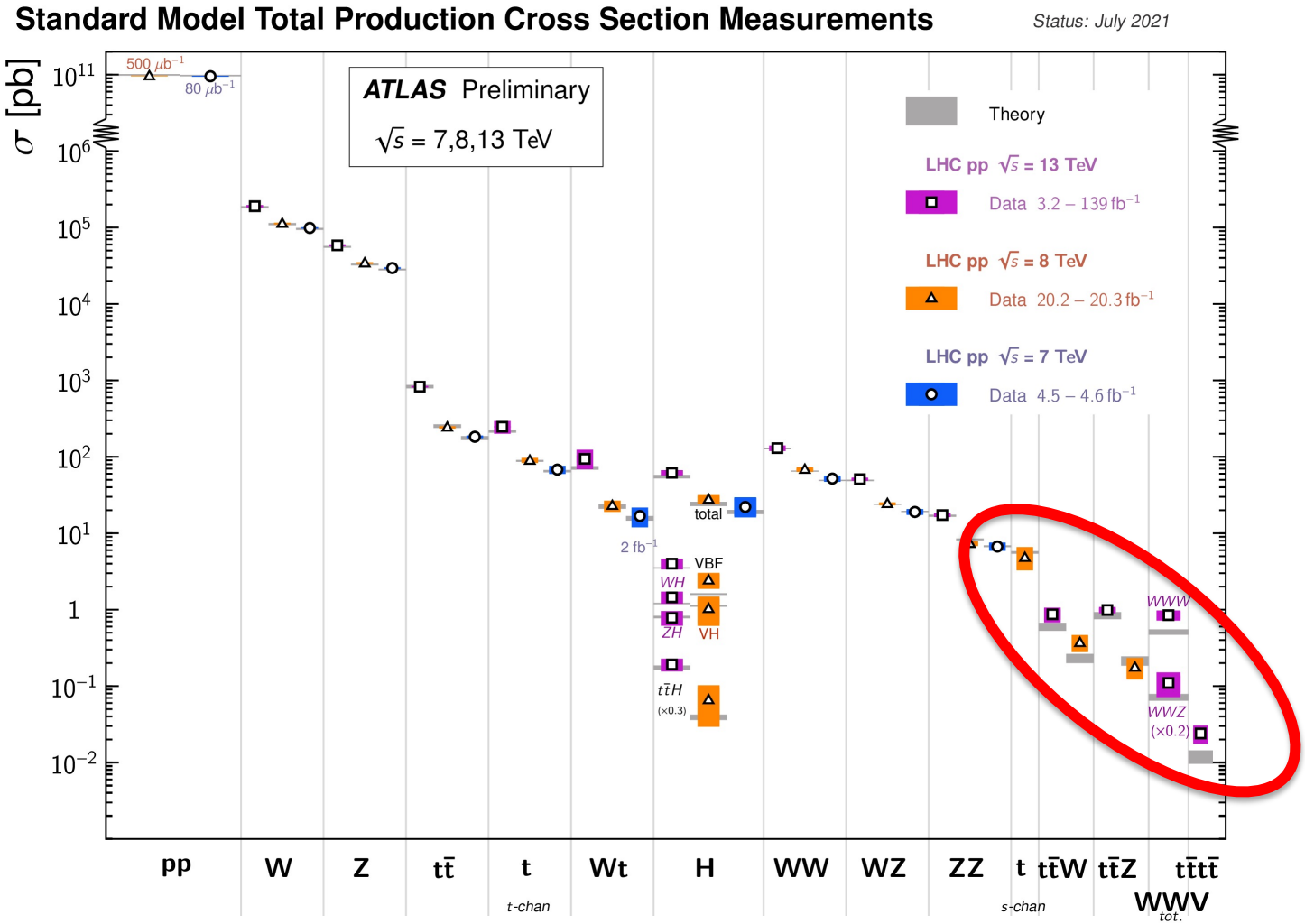


JHEP 07 (2021) 005

SM Cross-sections

Triboson processes are some of the most rare SM processes within reach

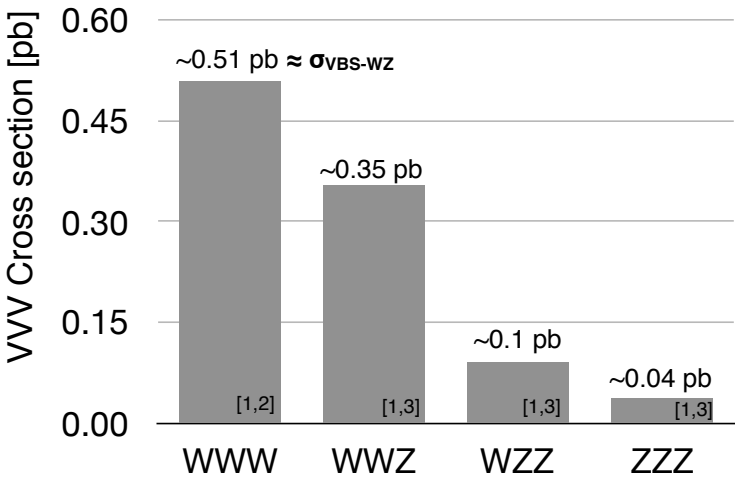
Evidence has already been measured in many cases → pushing for observation



ATL-PHYS-PUB-2021-032

Triboson

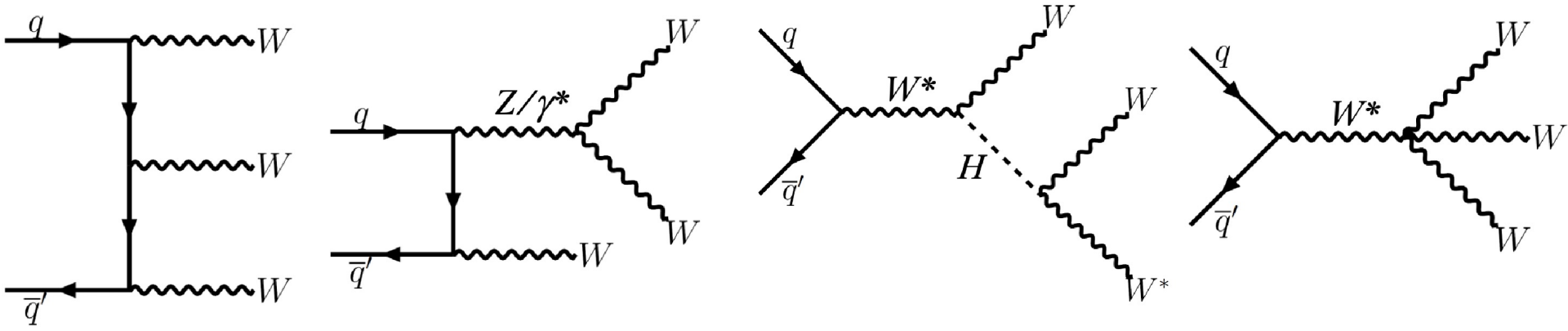
- Combined triboson measurements have reached first evidence & observation
- Evidence for $W^{\pm}W^{\mp}W^{\mp}$ with partial Run 2 data set 80 fb^{-1}
  - ATLAS 80 fb^{-1}: WVV 4.1 σ, WWW 3.2σ
- First observation of triboson production in the measurement of VVV production
  - CMS 137 fb^{-1}: VVV 5.7σ, WWW 3.3σ
- Individual channels are just coming into sensitivity
- **New: ATLAS 139 fb^{-1}: WWW 8.2σ**



[1] https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt13TeV, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR
[2] JHEP 09 (2017) 034
[3] MadGraph5 aMC@NLO calculation

Figure produced by Philip Chang

WWW



$$W^{\pm}W^{\mp}W^{\mp} \rightarrow \ell\nu\ell\nu jj \ \ OR \ \ \ell\nu\ell\nu\ell\nu$$

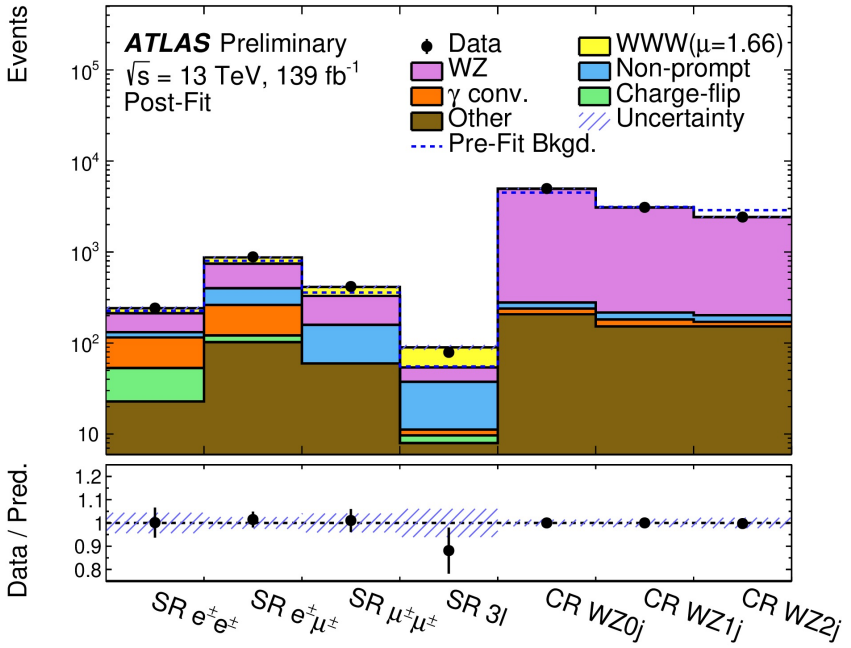
WWW production measured via 2 channels:

- 2 lepton channel: WWW → $\ell^{\pm}\nu\,\ell^{\pm}\nu$ jj
  - Two same-sign leptons (ee, eμ, μμ)+ W → jj
- 3 lepton channel: WWW → $\ell^{\pm}\nu\,\ell^{\mp}\nu\,\ell^{\mp}\nu$
  - Zero same-flavor opposite sign lepton pairs
- Off-shell WH contribution (3rd diagram) is included in the signal definition

ATLAS-CONF-2021-039

WWW: Analysis Strategy

- Dominated by WZ background
  - Employ data-driven method to scale WZ
    - use 0j, 1j, ≥2j control regions
  - Other data-driven backgrounds: Non-prompt, γ conversion, charge-flip
- BDT is used to fit signal and control regions simultaneously
  - 12 variables in 2l channels
  - 11 variables in the 3l channel



BDT variables (ordered by importance):

2ℓ	3ℓ
$\lvert m_{jj} - m_W \rvert$	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance $\times 10/E_{\mathrm{T}}^{\mathrm{miss}}$
p_{T} (forward jet)	$p_T(\ell_2)$
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	$N(\mathrm{jets})$
$p_T(j_2)$	same flavor $m_{\ell\ell}$
minimum $m(\ell, j)$	$m_T(\ell\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
$m(\ell_2, j_1)$	$m(\ell_2, \ell_3)$
$N(\mathrm{jets})$	$\Delta\phi(\ell\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
p_{T} (ℓ_2)	minimum $\Delta R(\ell, \ell)$
$m_{\ell\ell}$	p_{T} (ℓ_3)
$\lvert\eta(\ell_1)\rvert$	$m_T(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$
$N(\mathrm{leptons\ in\ jets})$	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance
$m(\ell_1, j_1)$	

Signal Strength	Normalization Factors		
$\mu(WWW)$	$WZ + 0$ jets	$WZ + 1$ jet	$WZ + \geq 2$ jets
1.66 ± 0.28	1.12 ± 0.11	0.98 ± 0.04	0.88 ± 0.18

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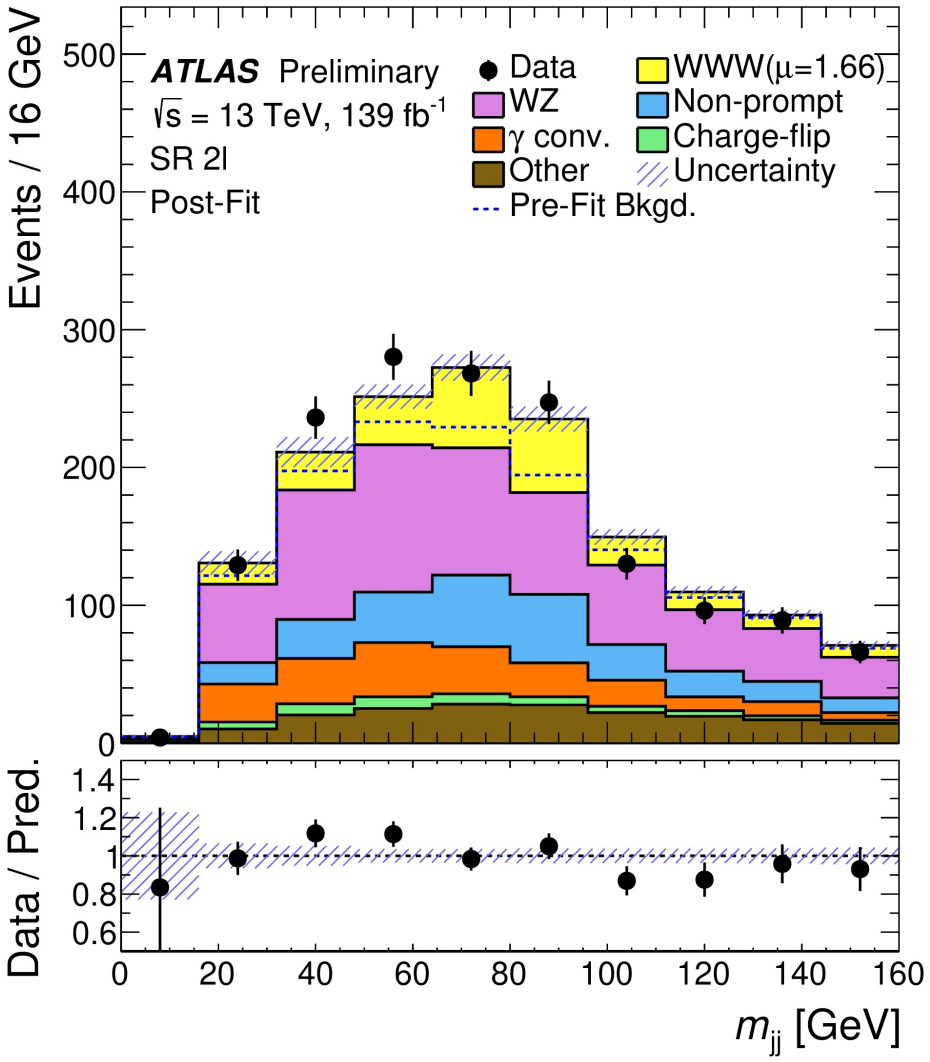
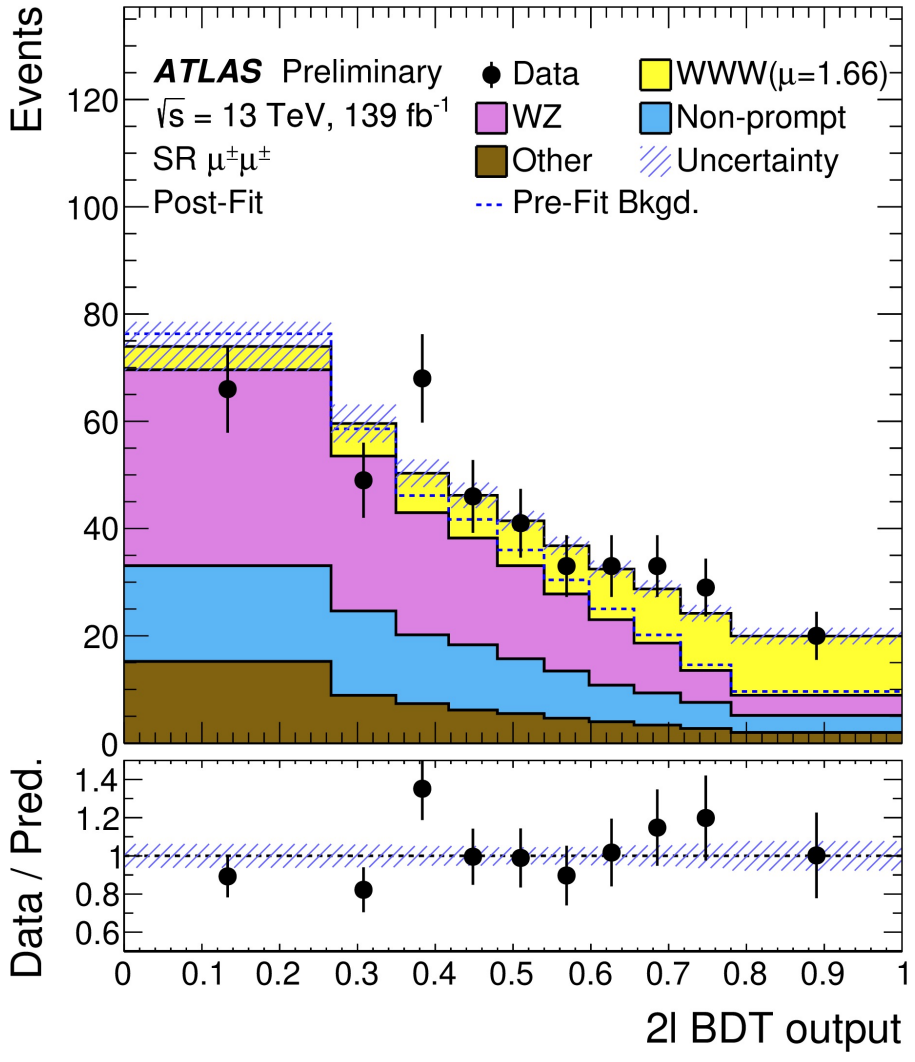
WWW: 2l





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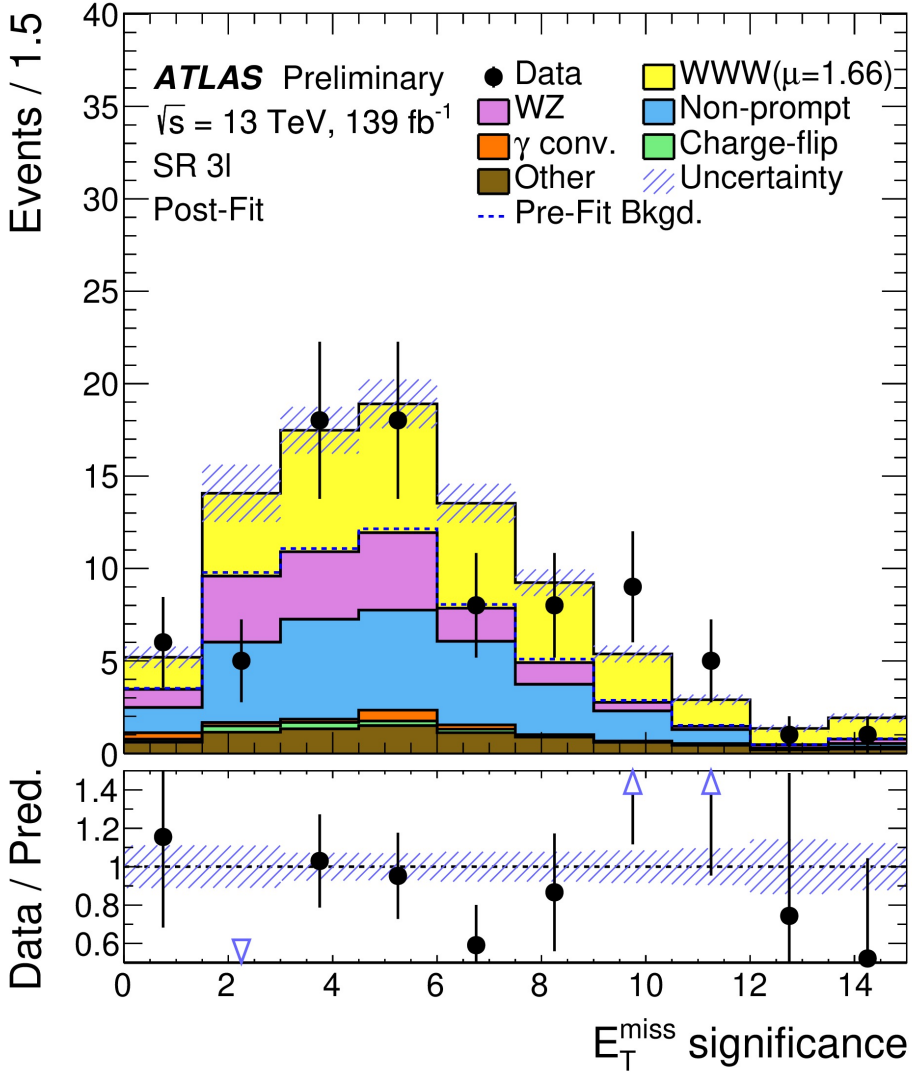
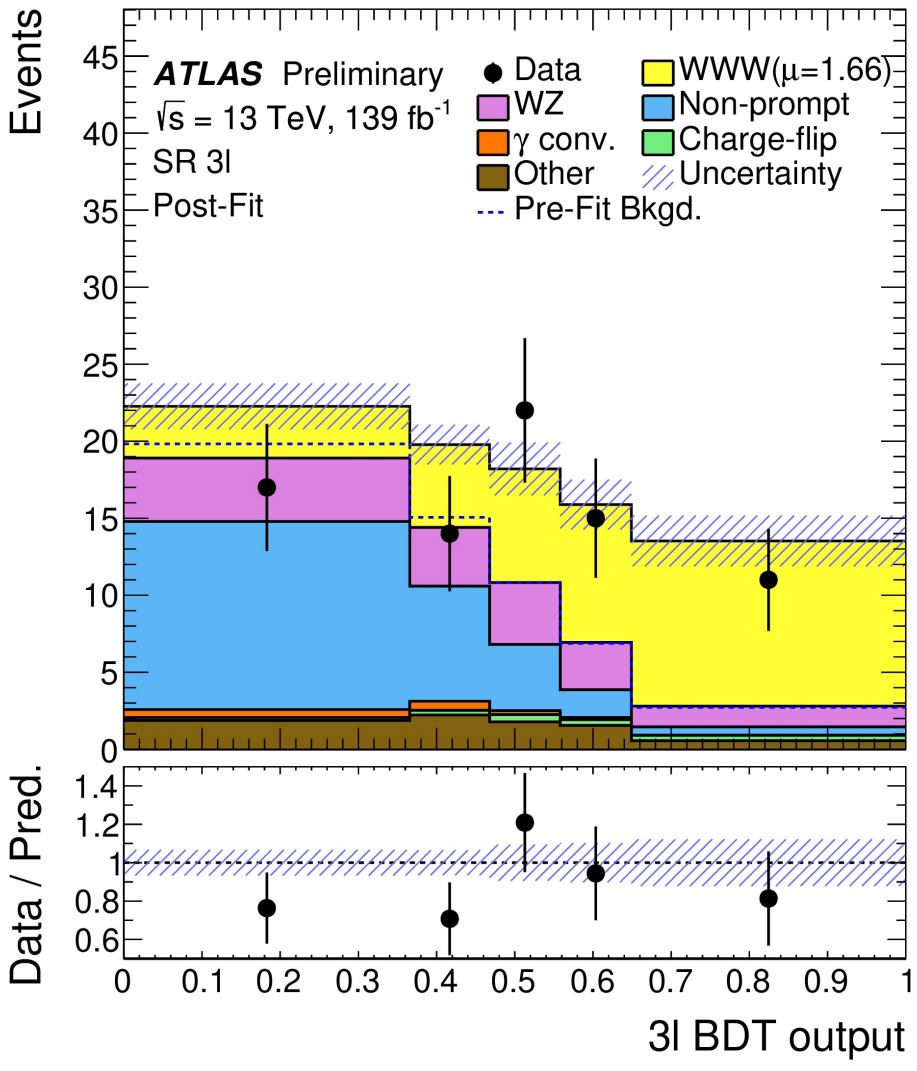
WWW: 3l





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Fit	Observed (expected) significances [σ]	$\mu(WWW)$
$e^{\pm}e^{\pm}$	2.3 (1.4)	1.69 ± 0.79
$e^{\pm}\mu^{\pm}$	4.6 (3.1)	1.57 ± 0.40
$\mu^{\pm}\mu^{\pm}$	5.6 (2.8)	2.13 ± 0.47
2ℓ	6.9 (4.1)	1.80 ± 0.33
3ℓ	4.8 (3.7)	1.33 ± 0.39
Combined	**8.2 (5.4)**	$\mathbf{1.66 \pm 0.28}$

The SM background-only hypothesis is rejected.

Cross-section measurement:

- **$850 \pm 100\,(\text{stat.}) \pm 80$ (syst.) fb**

- SM prediction used to estimate μ
  - WWW+WH: NLO QCD MC: 511 ± 42 fb
- Also available Fixed order prediction
  - WWW: NLO QCD+NLO EW Ref.
  - WH(H→WW*) N3LO QCD+NLO EW Ref.
  - WWW+WH = 505 fb
    - (approximately 6% uncertainty)

Uncertainty source	$\Delta\sigma/\sigma$ [%]
Data-driven background	5.3
Prompt-lepton-background modeling	3.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	2.8
MC statistics	2.8
Lepton	2.1
Luminosity	1.9
Signal modeling	1.5
Pile-up modeling	0.9
Total systematic uncertainty	9.5
Data statistics	11.2
WZ normalizations	3.3
Total statistical uncertainty	11.6

ATLAS-CONF-2021-039

Summary

- New multiboson differential cross-section measurements & BSM searches in an EFT framework in
  - WW+jets
  - Inclusive 4-leptons

- $W^{\pm}W^{\mp}W^{\mp}$ observed for the first time 8.2σ (5.4σ expected)!
  - Cross-section measured: $850 \pm 100\ (\text{stat.}) \pm 80$ (syst.) fb

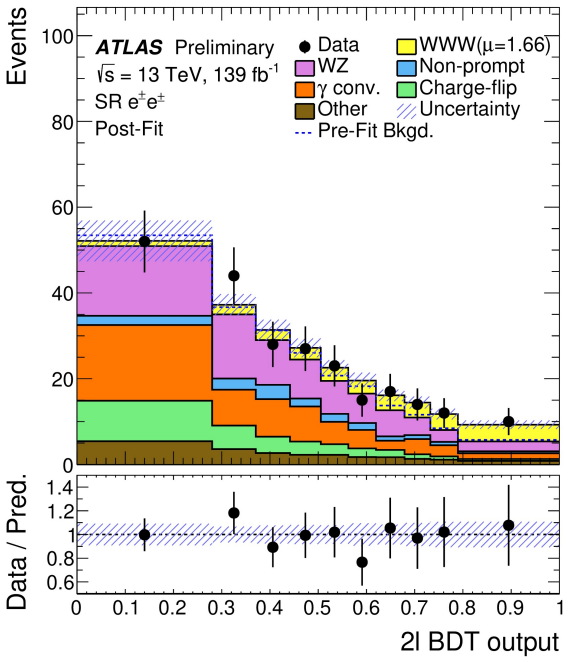
Backup

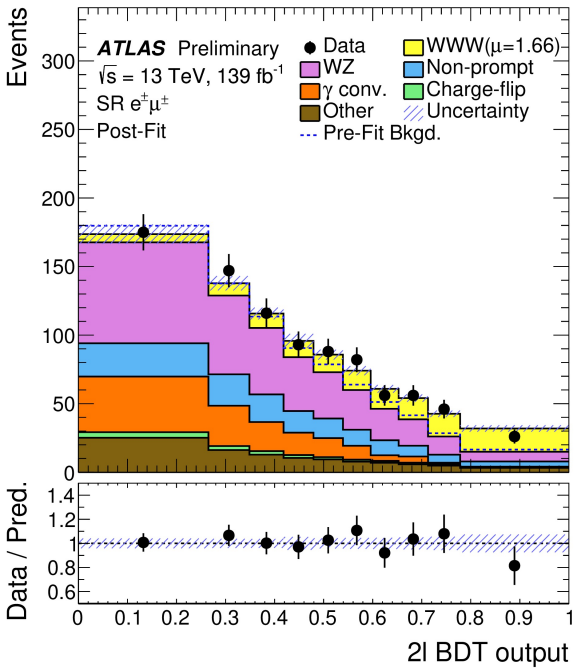
Event Yields:

	$e^{\pm}\,e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	3ℓ
WWW	29.3 ± 4.4	128 ± 19	84 ± 12	35.8 ± 5.2
WZ	80.6 ± 5.7	344 ± 22	171 ± 10	16.4 ± 1.4
Charge-flip	30.3 ± 7.2	18.8 ± 4.5	–	1.7 ± 0.4
γ conversions	62.1 ± 8.7	142 ± 15	–	1.5 ± 0.1
Non-prompt	16.6 ± 4.1	138 ± 24	98 ± 21	26.3 ± 2.9
Other	22.8 ± 3.7	102 ± 15	59.7 ± 9.0	8.0 ± 0.9
Total predicted	242 ± 11	872 ± 22	414 ± 17	89.7 ± 5.4
Data	242	885	418	79

Table 2: Post-fit signal, background and observed yields in the 2ℓ and 3ℓ SRs. The uncertainties include the statistical and systematic uncertainties of the yields, computed considering the correlations among nuisance parameters.

WWW: 2l BDT


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
SR e±e±
Post-Fit
Data
WZ
γ conv.
Other
WWW(μ=1.66)
Non-prompt
Charge-flip
Uncertainty
Pre-Fit Bkgd.
Events
Data / Pred.
2l BDT output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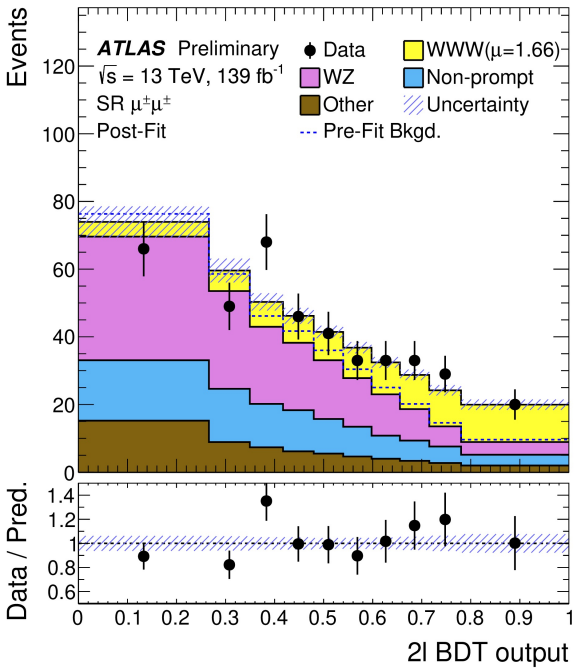
ATLAS Preliminary
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SR μ±μ±
Post-Fit
Data
WZ
Other
WWW(μ=1.66)
Non-prompt
Uncertainty
Pre-Fit Bkgd.
Events
Data / Pred.
2l BDT output

WWW: Kinematic Plots