Fiducial and differential measurements of WW production in SUSY-inspired decay topologies

IOP half-day meeting on prospects of fiducial cross-section measurements and reinterpretations as a component of searches and measurements at LHC (15/6/22)

Sarah Williams (Uni. Cambridge)

Introduction

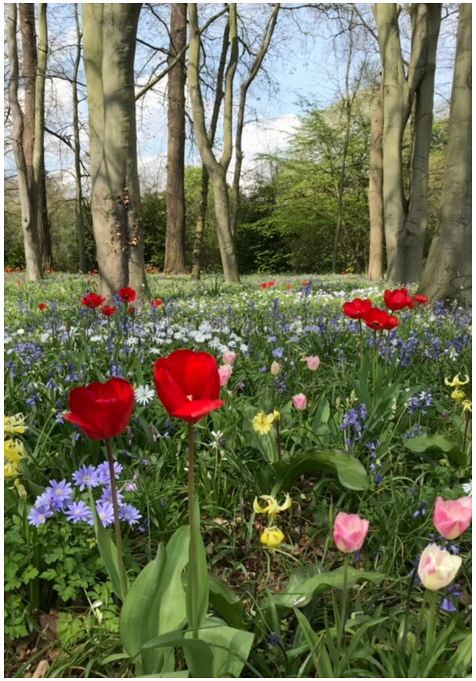
- Thanks to the organisers for the invitation, and to you all for the discussions so far today.
- This contribution will discuss a new ATLAS result on fiducial and differential measurements of WW production in a SUSY-inspired phase space, involving myself, Ben Bruers (DESY) and Sebastian Rutherford (Cambridge)
- Conference note was released for Moriond 2022, with paper submission ~ imminent.
- Very keen to discuss prospects/ideas for future re-interpretation(s).

This talk

ATLAS-CONF-2022-011

Will cover…

- Some historical context.
- A brief overview of typical SUSY searches.
- The motivation and overall design of the measurement.



Won't cover…

- Why producing differential particle-level measurements is an exciting way to probe new physics (others have already done that)
- Technical details of the unfolding calculation.

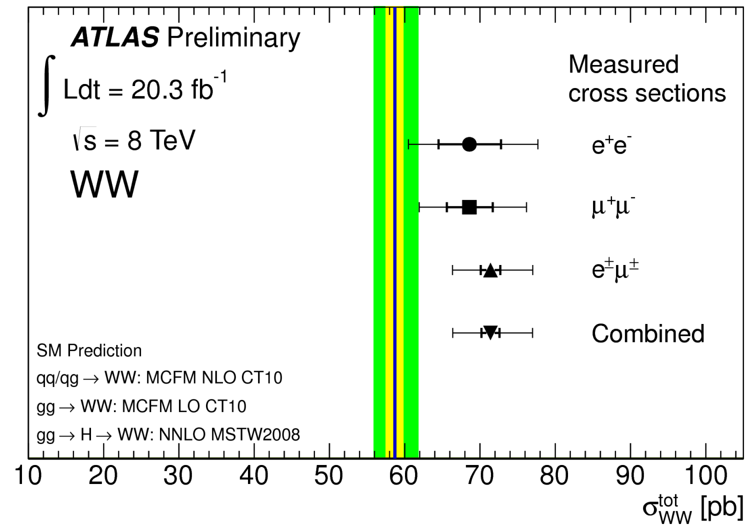
But I am happy to discuss technical aspects of this effort further "offline".

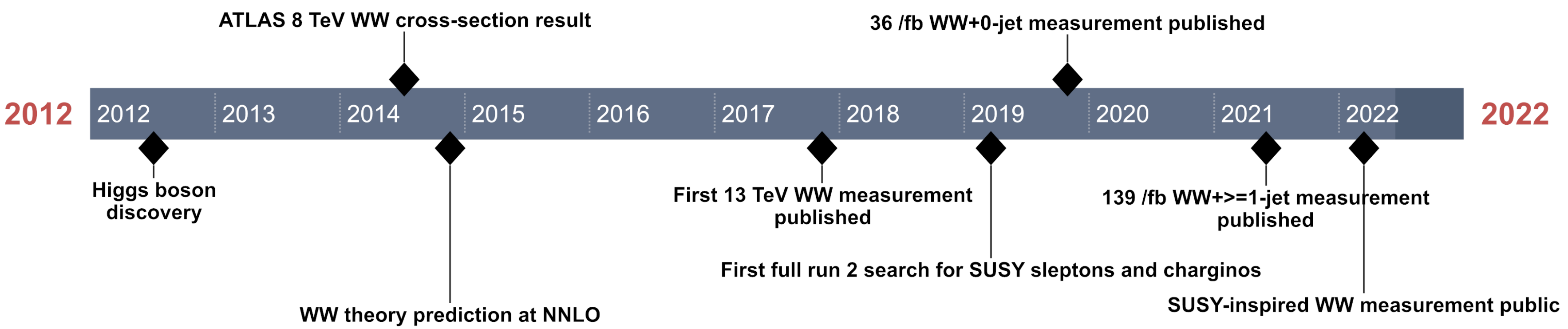
Some history

WW precision measurements a first hint of new physics at the LHC?

Quote from physics briefing

"And yes, we should also mention that the WW cross section result comes out a bit high compared to its Standard Model expectation. Not statistically significant, but enough to intrigue theorists and experimentalists to study this tricky channel in more detail."





Some history

SUSY to the rescue?

https://arxiv.org/abs/1303.5696

High Energy Physics – Phenomenology

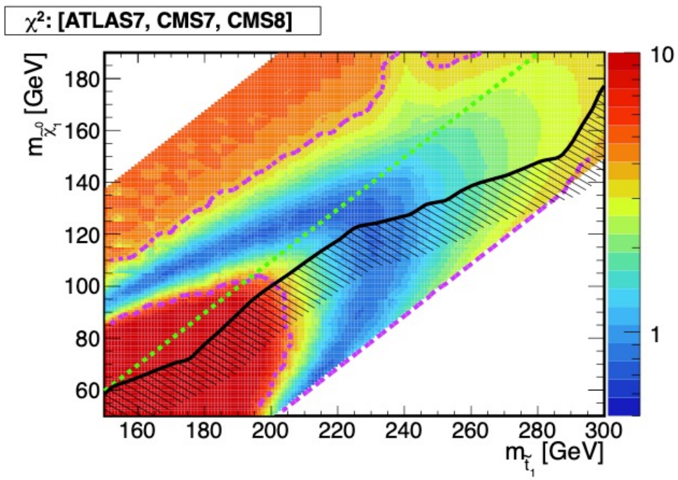
[Submitted on 3 Jun 2014 (v1), last revised 1 Dec 2014 (this version, v3)]

`Stop' that ambulance! New physics at the LHC?

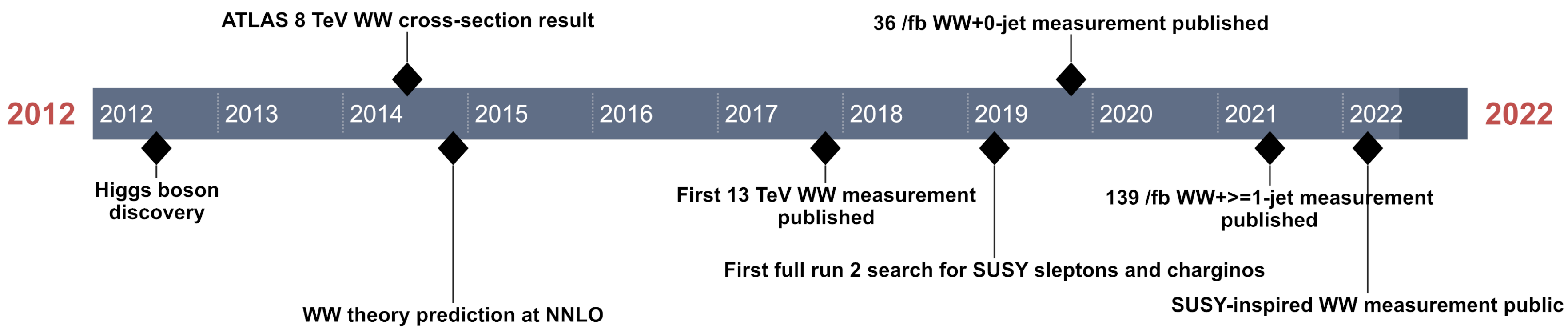
Jong Soo Kim, Krzysztof Rolbiecki, Kazuki Sakurai, Jamie Tattersall

A number of LHC searches now display intriguing excesses. Most prominently, the measurement of the W^+W^- cross-section has been consistently $\sim 20\%$ higher than the theoretical prediction across both ATLAS and CMS for both 7 and 8 TeV runs. More recently, supersymmetric searches for final states containing two or three leptons have also seen more events than predicted in certain signal regions. We show that a supersymmetric model containing a light stop, winos and binos can consistently match the data. We perform a fit to all measurements and searches that may be sensitive to our model and find a reduction in the log-likelihood of 15.4 compared to the Standard Model which corresponds to 3.5-σ once the extra degrees of freedom in the fit are considered.

https://arxiv.org/abs/1406.0858

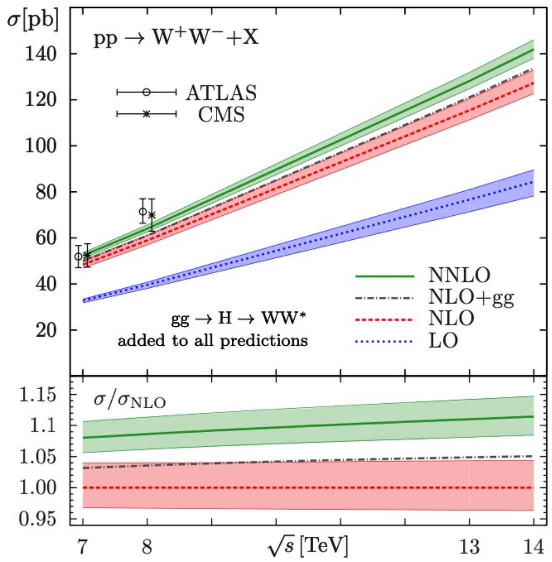


Alternative explanations included charginos and/or sleptons…



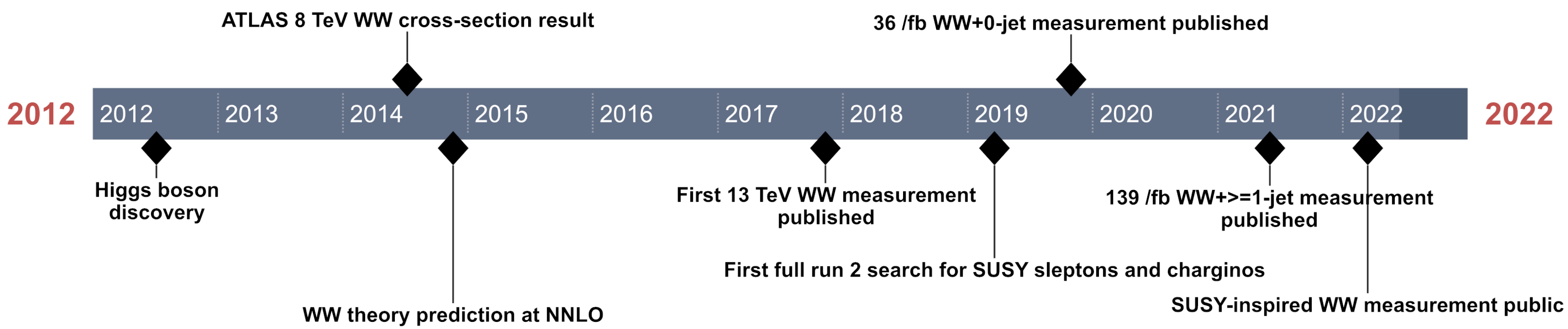
Some history

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2013-07/



- Jet veto adds introduces an additional scale into the theoretical calculation -> complicates NNLO calculations/approximations.
- Full calculations of WW to NNLO in QCD reduced tensions with SM measurements

https://arxiv.org/pdf/1408.5243.pdf



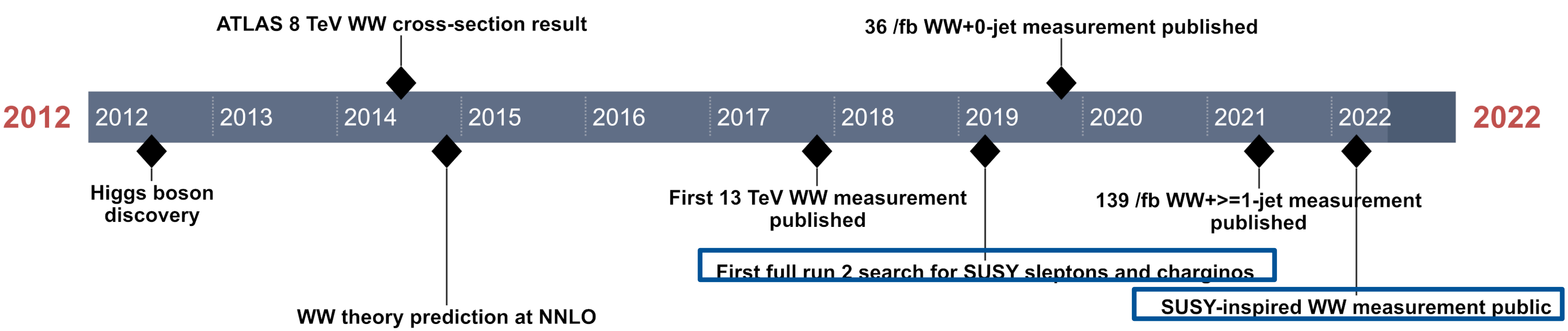
Some history

Plus exciting developments including $\gamma\gamma \rightarrow WW$ production

Recent run-2 measurements in di-leptonic final states

- 36 fb^{-1} WW+0-jet measurement: ***Eur. Phys. J. C 79 (2019) 884***
- 139 fb^{-1} WW+≥1-jet measurement: ***JHEP 06 (2021) 003***

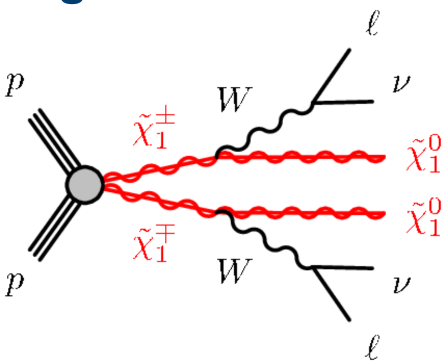
… and the result I will discuss on WW measurements in a SUSY-inspired topology…

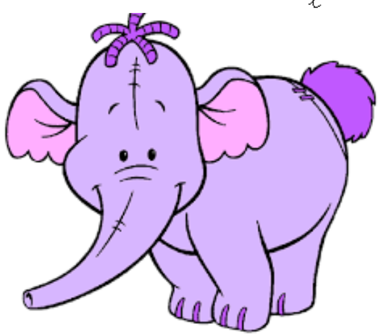


Reminder: direct searches for new physics

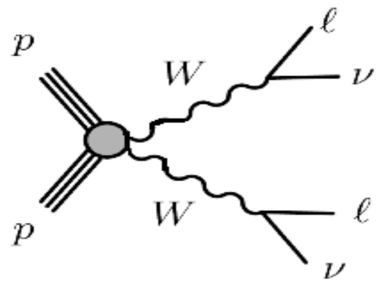
As mentioned by Jon- performed at ”detector-level”…

Signal

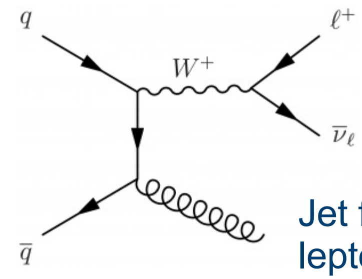




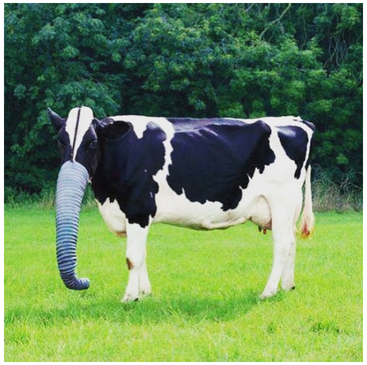
Irreducible background



Reducible backgrounds



Jet faking a lepton

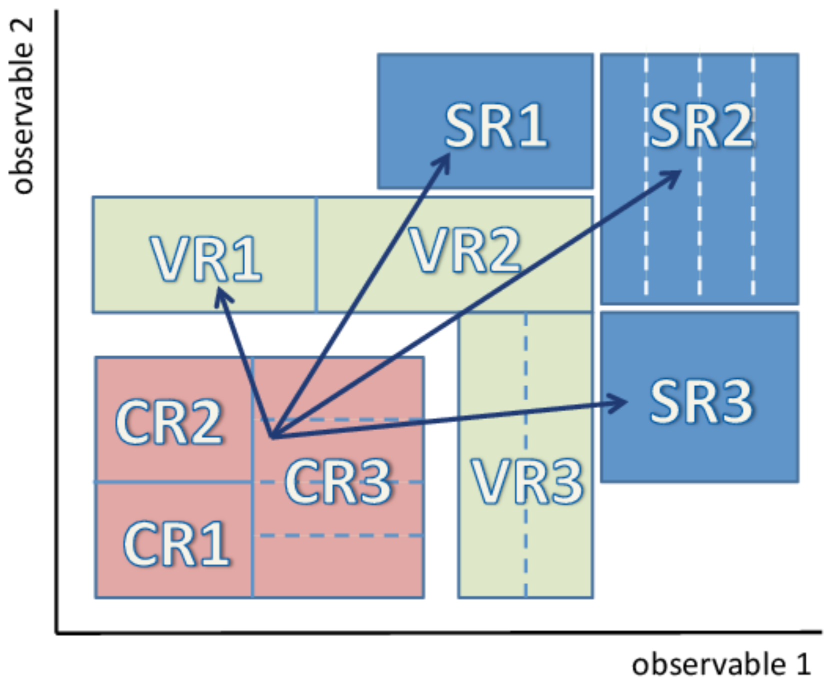


Cow faking an elephant (not very well)

=> Direct searches for new physics at the LHC involve searching for statistically significant deviations from the SM in particular decay channels/event topologies.

Typical SUSY search strategy

Diagram taken from the Histfitter paper



- Identify (binned) **”signal region(s)”** where we would expect to see an excess over the SM prediction if the signal were present.
- Use **“control region(s)”** to extract data-driven normalisation factor(s) for dominant background component(s) using simultaneous likelihood fit.
- Before unblinding, use **“validation regions”** to check that the background-estimates provide accurate normalisation and shapes of kinematic distributions.

We typically produce ”post-fit” yields tables and kinematic distributions, and quote the normalisation factors from the likelihood fit (which depends on the MC generator being used).

Search-inspired SM measurements in ATLAS

Eur. Phys. J. C 79 (2019) 733

Searches for scalar leptoquarks and differential cross-section measurements in dilepton–dijet events in proton–proton collisions at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV with the ATLAS experiment

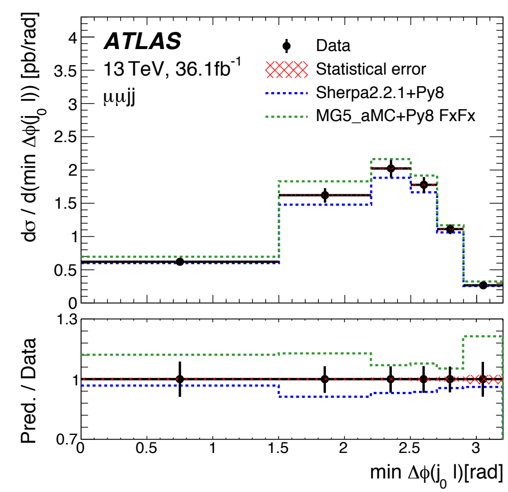
⇒ First result of its kind from ATLAS.

⇒ Used bin-by-bin unfolding (not possible here)

$$\frac{d\sigma_i^p}{dX} = \frac{(N_i - \sum_{q\neq p} R_i^q) \cdot \frac{T_i^p}{R_i^p}}{w_i \cdot L},$$

The result I will now discuss is the first effort to do a search inspired unfolding calculation in a SUSY-inspired phase space:

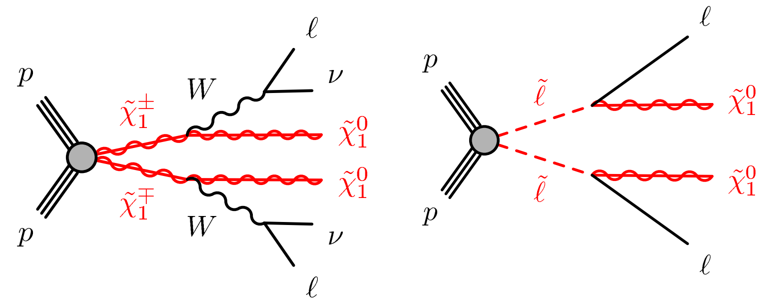
- Follows an early run 2 search for supersymmetric charginos and sleptons decaying to 2-lepton final states.
- Aim is to incorporate measurements into future search efforts.



Overview EWK 2l+0jets search

Eur. Phys. J. C 80 (2020) 123

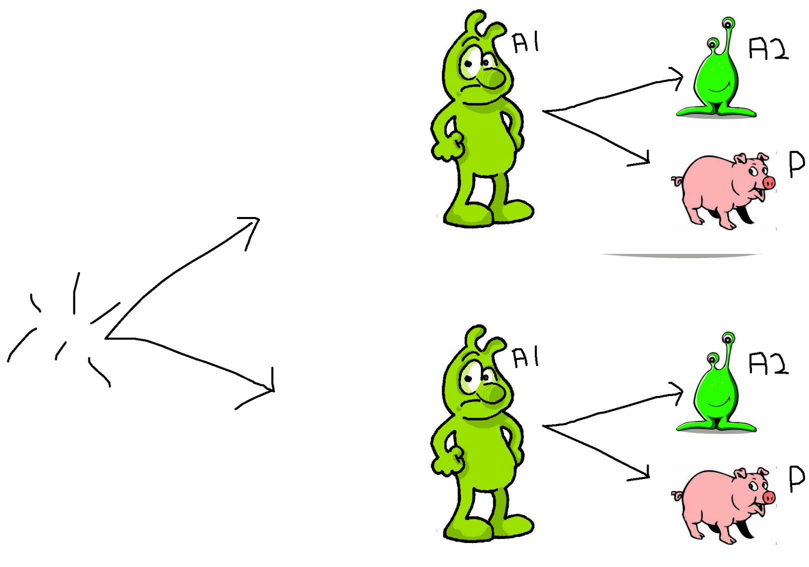
Signal region (SR)	SR-DF-0J	SR-DF-1J	SR-SF-0J	SR-SF-1J
$n_{\text{non-}b\text{-tagged jets}}$	= 0	= 1	= 0	= 1
$m_{\ell_1\ell_2}$ [GeV]	>100		>121.2	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>110			
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	>10			
$n_{b\text{-tagged jets}}$	= 0			
Binned SRs				
m_{T2} [GeV]	∈[100,105) ∈[105,110) ∈[110,120) ∈[120,140) ∈[140,160) ∈[160,180) ∈[180,220) ∈[220,260) ∈[260,∞)			
Inclusive SRs				
m_{T2} [GeV]	∈[100,∞) ∈[160,∞) ∈[100,120) ∈[120,160)			



Set of binned SRs in the 'stransverse mass variable' (m_{T2}) separated into same-flavour SF ($e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$) and different flavour DF ($e^{\pm}\mu^{\mp}$) categories and by the light (i.e. non-b-tagged) jet multiplicity, at high values of the missing transverse momentum and object-based missing transverse momentum significance.

Dominant background is SM WW background. Aim of this work was to provide a (differential) SM measurement in a region of phase space closer to this search.

The "stransverse mass" variable m_{T2}



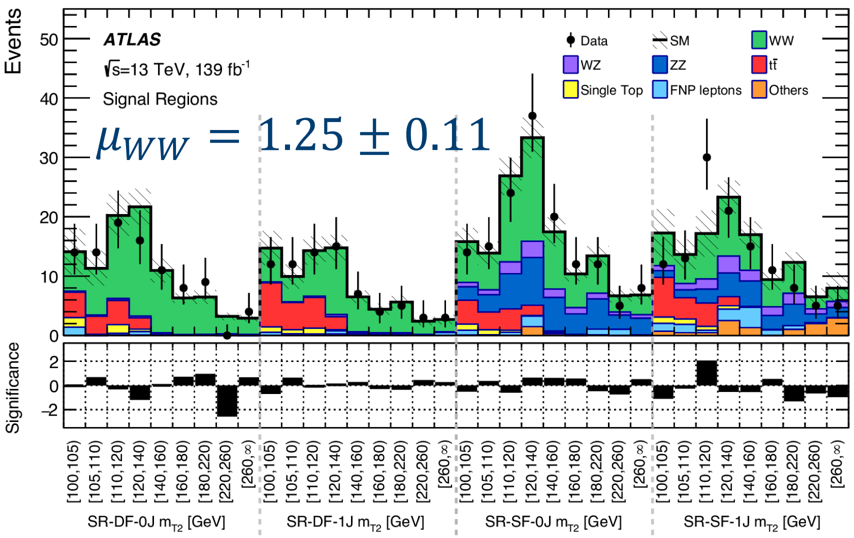
- Originally designed to measure SUSY masses at the LHC.
- Powerful discriminating variable in searches for semi-invisibly decaying pair-produced particles.
- For massless invisible particles, in the absence of reconstruction/misidentification effects expect a kinematic endpoint for $t\bar{t}$ and WW production at the W-boson mass.

$$m_{A2}^2 \geq m_{T2}^2 = \min_{\mathbf{p}_T^{miss} = \mathbf{p}_T^{A1,a} + \mathbf{p}_T^{A1,b}} \left[\max\{ m_T^2(\mathbf{p}_T^{P,a}, \mathbf{p}_T^{A1,a}), m_T^2(\mathbf{p}_T^{P,b}, \mathbf{p}_T^{A1,b}) \} \right]$$

This meant that the search required high m_{T2} , with events with $m_{T2} \in [60, 100]$ GeV being used for estimation and validation of the WW background

Why produce unfolded WW measurement?

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-32/

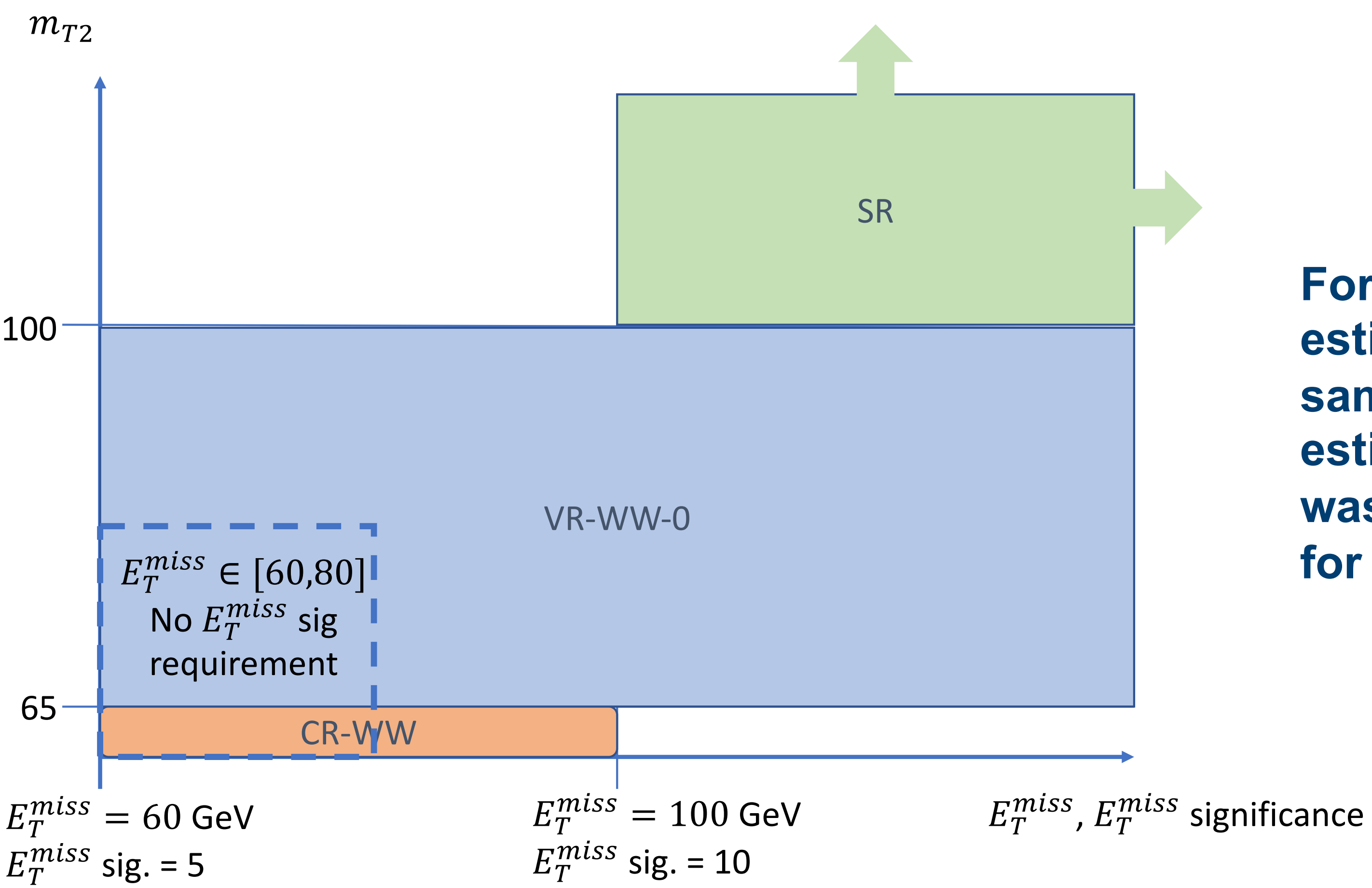


Region m_{T2} [GeV]	SR-DF-0J $\in[100,\infty)$
Total background expectation	96
MC statistical uncertainties	3%
WW normalisation	7%
VZ normalisation	$< 1\%$
$t\bar{t}$ normalisation	1%
Diboson theoretical uncertainties	7%
Top theoretical uncertainties	7%
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	1%
Jet energy scale	2%
Jet energy resolution	1%
Pile-up reweighting	$< 1\%$
b-tagging	$< 1\%$
Lepton modelling	1%
FNP leptons	1%
Total systematic uncertainties	15%

WW normalisation and diboson theory uncertainties were the main uncertainties in the 0-jet SRs -> reduce theory uncertainties for future searches?

Plus: exciting potential to use unfolded results to constrain BSM physics ☺ (looking for unexpected 'tails' in our distributions)

Signal region for unfolding



For background estimation- use same top estimation as was performed for the search!

Eur. Phys. J. C 79 (2019) 884

Comparison to ATLAS 36 fb^{-1} SM WW measurement

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-24/

Consider a fiducial region at higher E_T^{miss}, and $m_{e\mu}$, as well as having an m_{T2} requirement. There's also a different jet veto.

Selection requirement	Selection value
p_T^{ℓ}	> 27 GeV
η^{ℓ}	$\|\eta^e\| < 2.47$ (excluding $1.37 < \|\eta^e\| < 1.52$), $\|\eta^\mu\| < 2.5$
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, $\|\eta\| < 4.5$)	0
Number of b-tagged jets ($p_T > 20$ GeV, $\|\eta\| < 2.5$)	0
$E_T^{\text{miss,track}}$	> 20 GeV
$p_T^{e\mu}$	> 30 GeV
$m_{e\mu}$	> 55 GeV

For SM measurement top background was ~ 25% in SR. Lower than for this effort. Use a similar unfolding strategy (IBU)

By considering 0-jet events, naturally orthogonal to the WW+1jet measurement

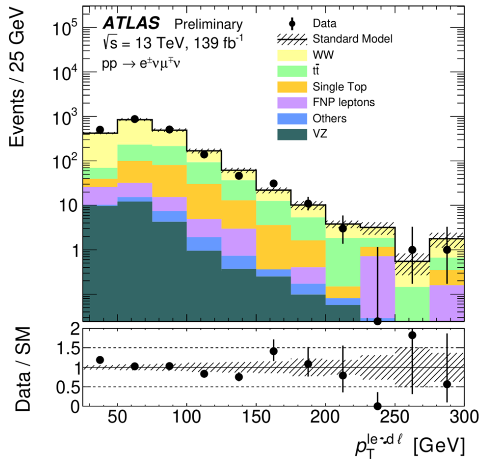
We plan produce differential measurements of the same 6 variables!

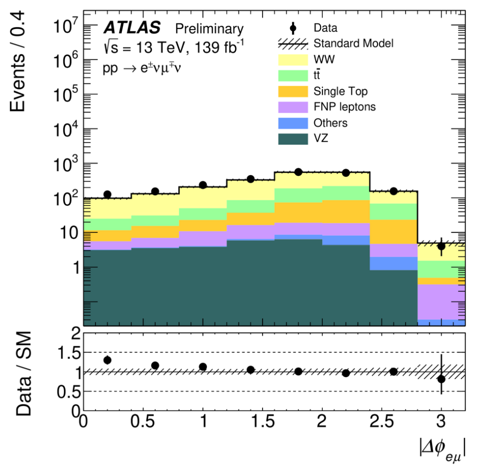
$$p_T^{e\mu}, m_{e\mu}, p_T^{lep1}, |y_{e\mu}|, \Delta\phi_{e\mu}, |\cos\theta^*| = \left|\tanh\left(\frac{\Delta\eta_{e\mu}}{2}\right)\right|$$

Results

First precision measurement performed in the ATLAS SUSY group

Detector-level

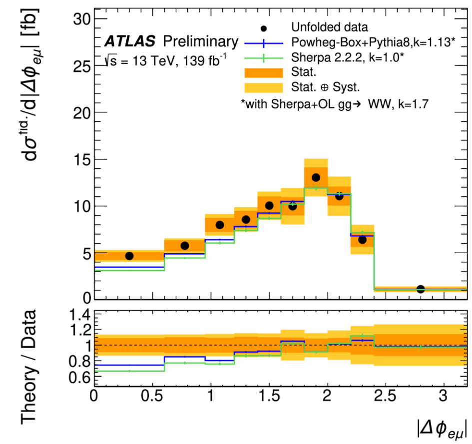


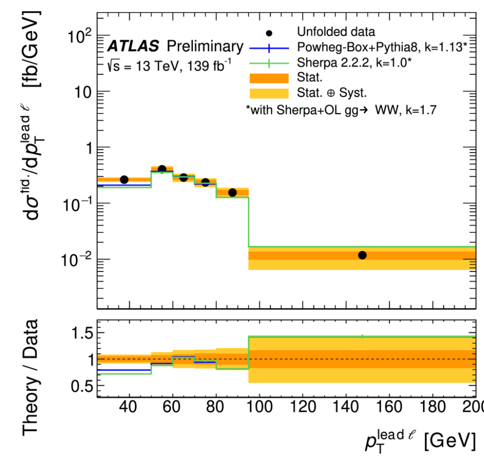


"Unfolding"

- Binning of distributions optimized as a function of bias/ statistical uncertainty.
- Compared to two NNLO predictions (Powheg+Pythia8 + Sherpa 2.2.2)

Particle-level





Consistency with SM measurements

$$\sigma_{WW\rightarrow e^{\pm}\nu\mu^{\mp}\nu} = 19.2 \pm 0.3\ (\text{stat})\ \pm 2.5\ (\text{syst})\ \pm 0.4\ (\text{lumi})\ \text{fb} = 19.2 \pm 2.6\ (\text{total})\ \text{fb}.$$

- Powheg+Pythia qq->WW + Sherpa gg->WW predicts 17.8 fb when the NLO k-factors are applied (1.13 for the powheg WW sample).

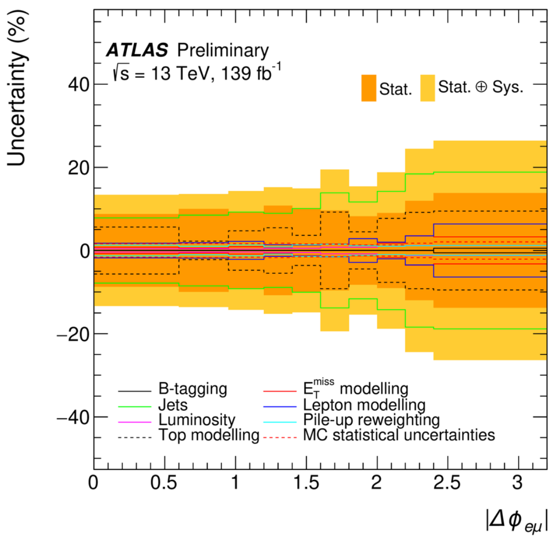
- Normalisation factor from the EWK 2l+0jets search was 1.25 +- 0.11.

- 1.13* 19.2/17.2 =1.22 -> very consistent.

When the higher order cross-section calculations are used, level of disagreement in the particle-level measurements is consistent with that seen in previous SM measurements

Systematic uncertainties

Our measurement



Jet uncertainties ~ 12% impact on fiducial cross-section

2l+0jets search

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Total background expectation	96
MC statistical uncertainties	3%
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VZ normalisation	< 1%
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Jet energy scale	2%
Jet energy resolution	1%
Pile-up reweighting	< 1%
b-tagging	< 1%
Lepton modelling	1%
FNP leptons	1%
Total systematic uncertainties	15%

WW+0jet 36 /fb measurement

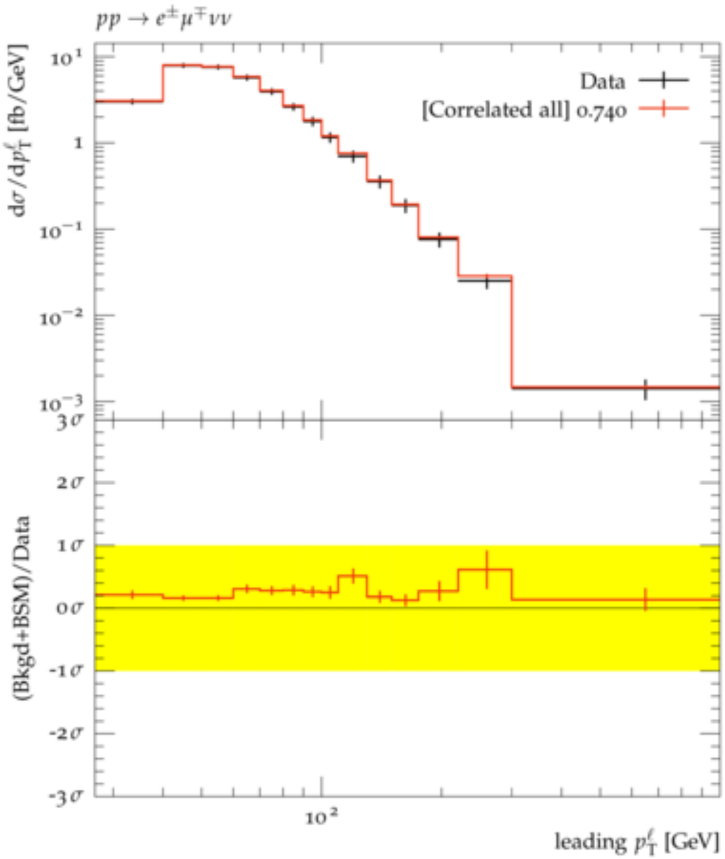
Uncertainty source	Uncertainty [%]
Electron	0.7
Muon	0.9
Jets	3.0
b-tagging	3.4
$E_T^{miss,track}$	0.4
Pile-up	1.6
W+jets background modelling	3.1
Top-quark background modelling	2.6
Other background modelling	1.3
Unfolding, incl. signal MC stat. uncertainty	1.4
PDF+scale	0.1
Systematic uncertainty	6.7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

(With jet veto optimized to reduce JES/JER uncertainties)

- Thoughts for the future: should we be optimizing further to reduce specific systematics in our searches?
- Think about possible SM measurements when designing searches.

Possible constraints on new physics from measurements?

https://hepcedar.gitlab.io/contur-webpage



CONTUR reports 74% exclusion for the C1C1 via WW (150,50) GeV point (unexcluded by the EWK 2l+0jets first wave search) using the SM WW+0-jet measurement:

- Adding additional measurements in more extreme topologies could improve this sensitivity.
- Next steps: calculate impact of our measurement on NP models using Rivet routine in CONTUR.

Thanks to Tony Yue + Jon Butterworth for technical help in this exercise ☺

Conclusions/outlook

- Have presented the first results of a precision measurement of WW production in a SUSY-inspired phase space.
- Continuing this programme of measurements will greatly enhance our future searches.
- Points for discussion:
  - How can we make these measurements most useful for further reinterpretation?
  - How to improve complementarity between SM measurements?
  - Any other questions or comments?

Lets continue to "bridge" the gap between searches and measurements…

BACKUP

Detailed results of unfolding exercise

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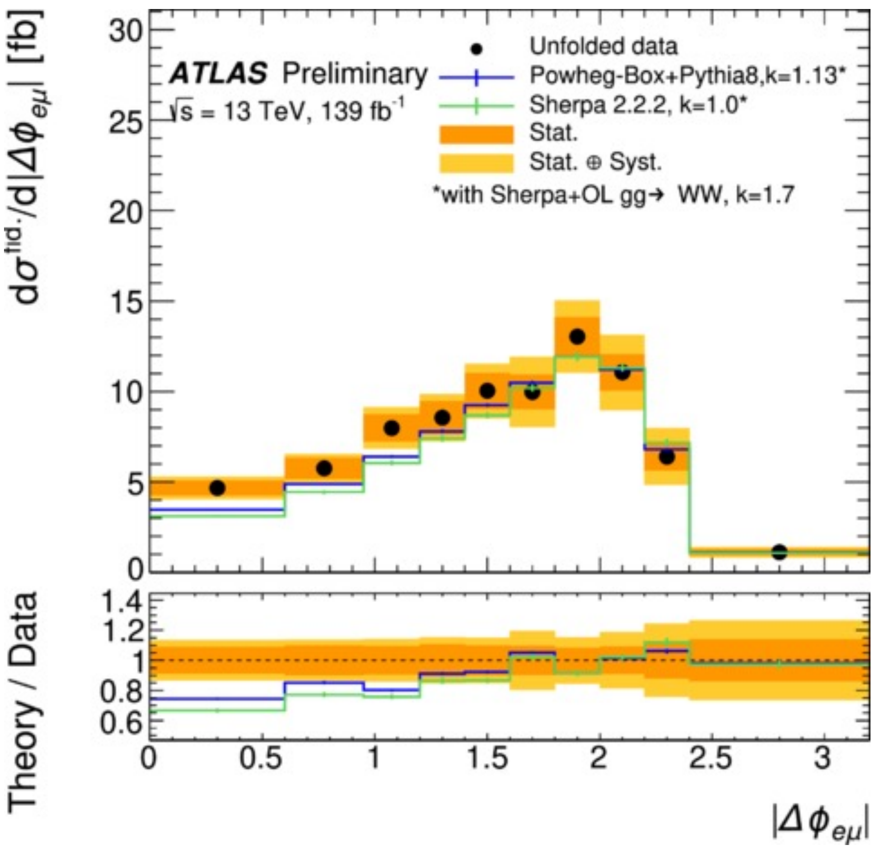

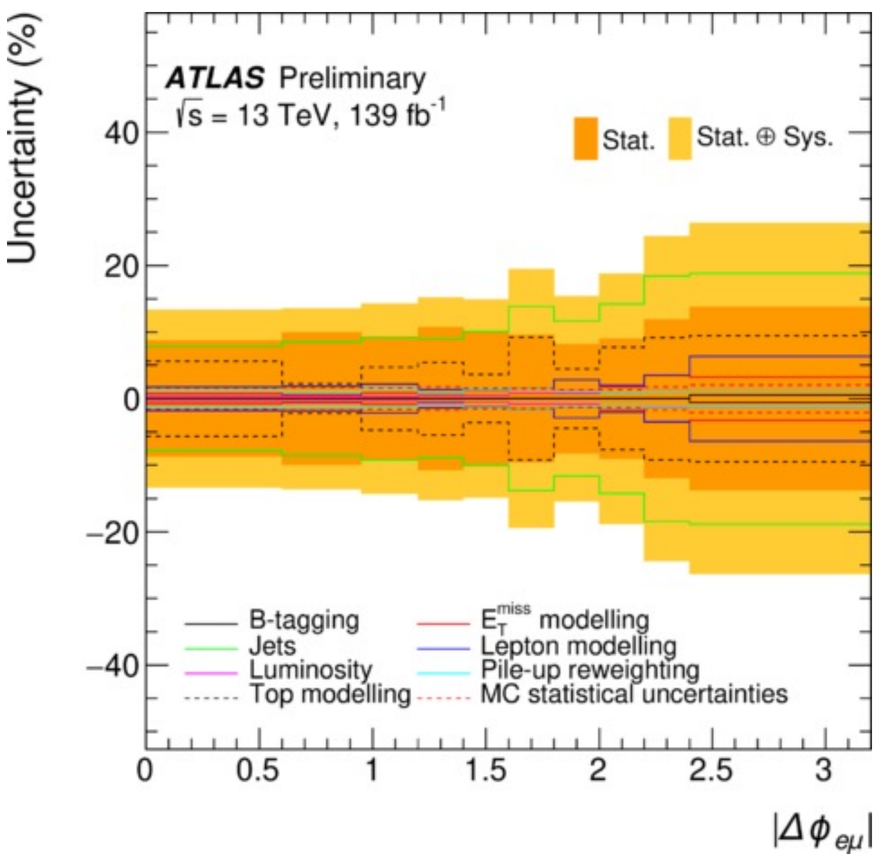

Detailed results of unfolding exercise

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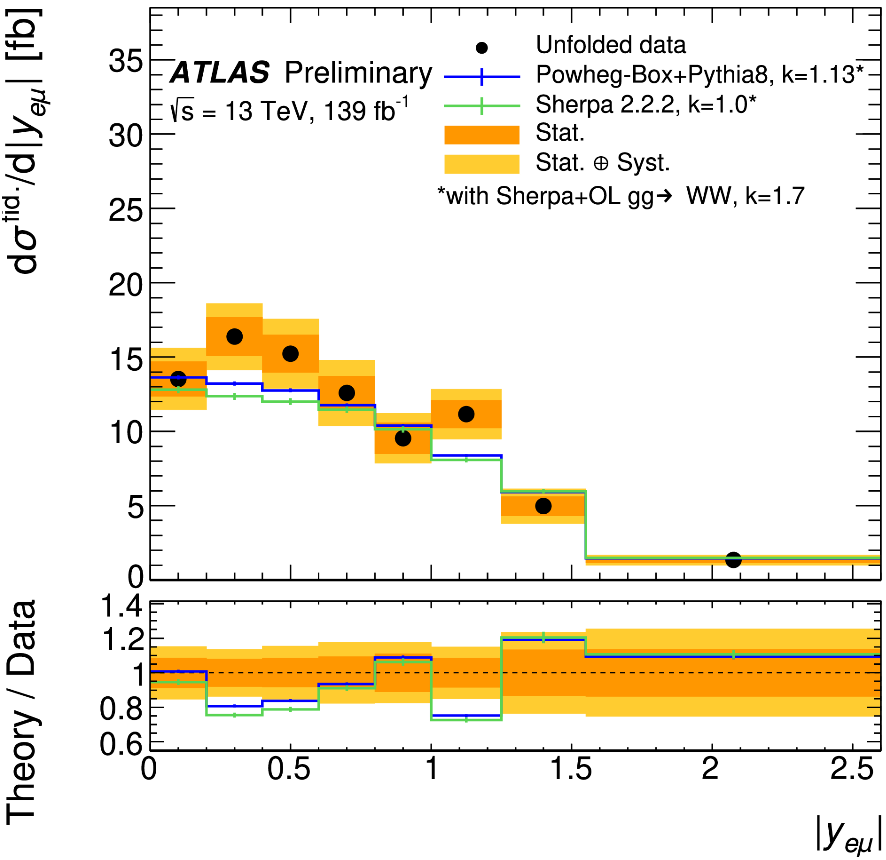

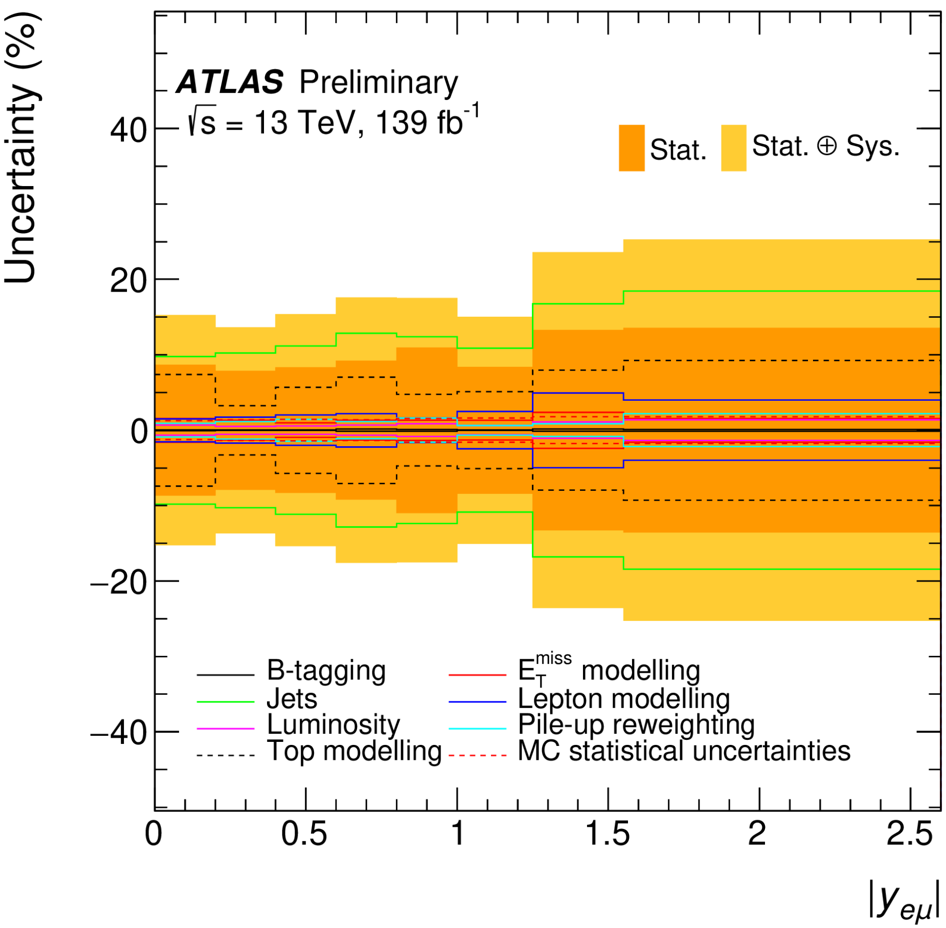

Detailed results of unfolding exercise

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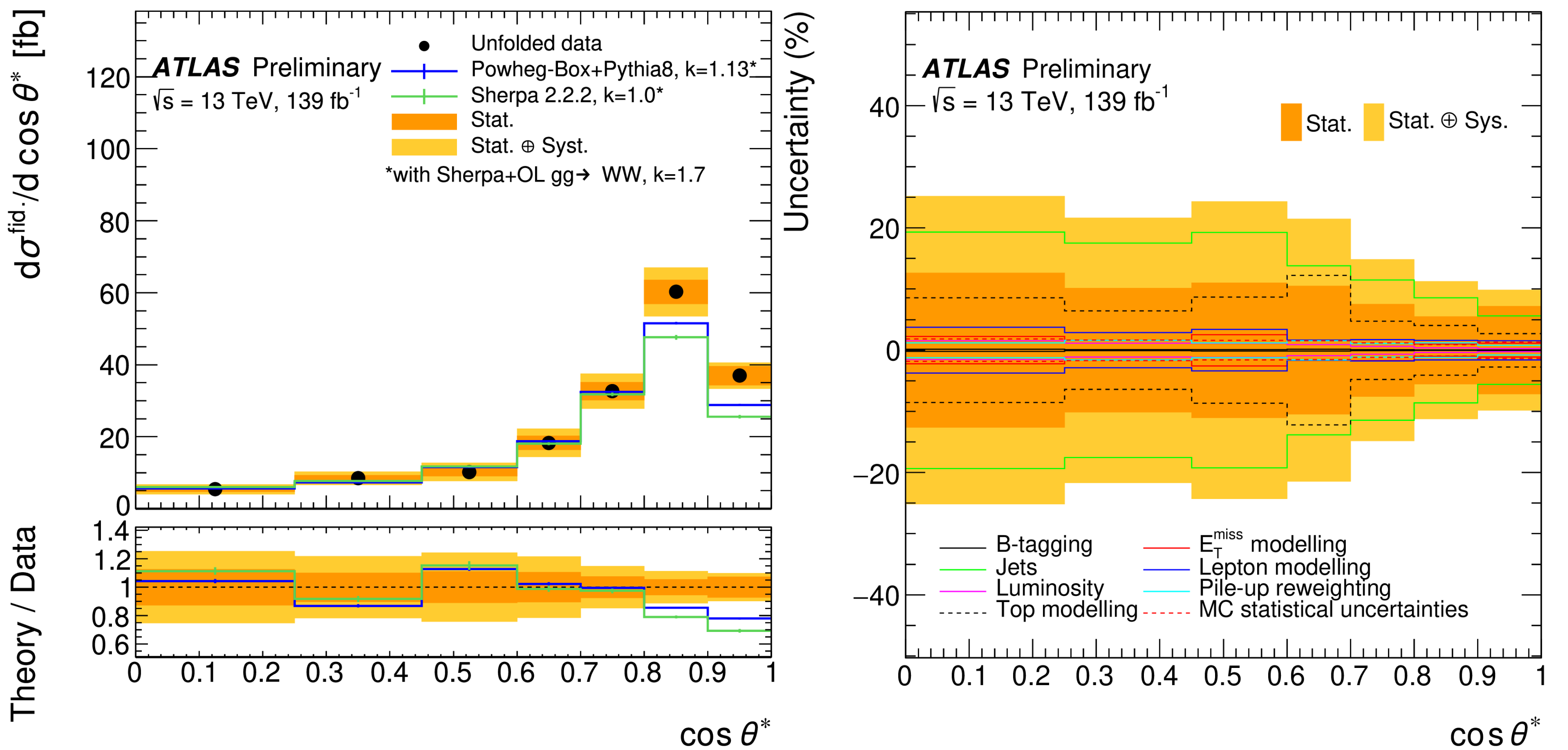

Detailed results of unfolding exercise

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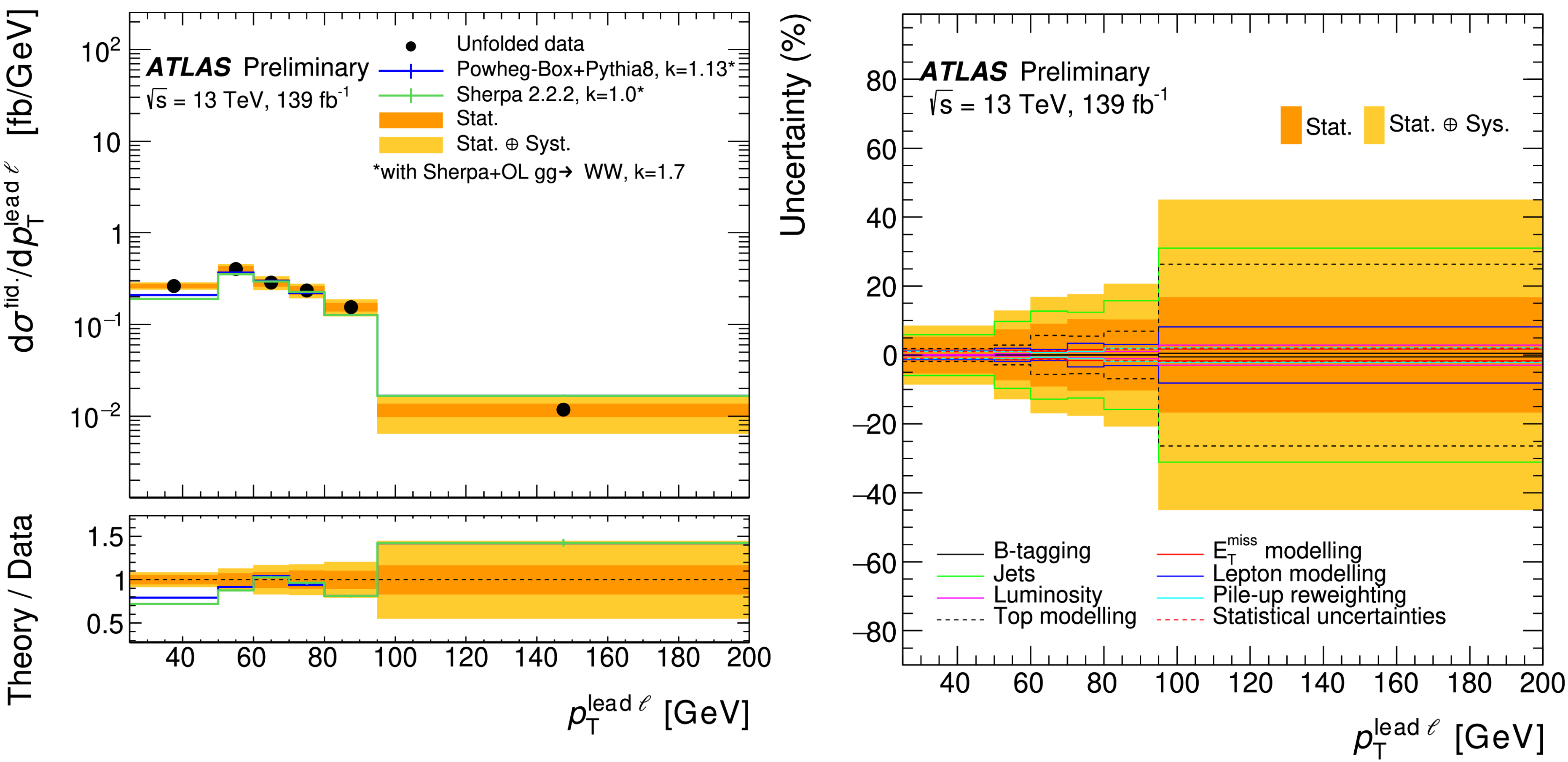

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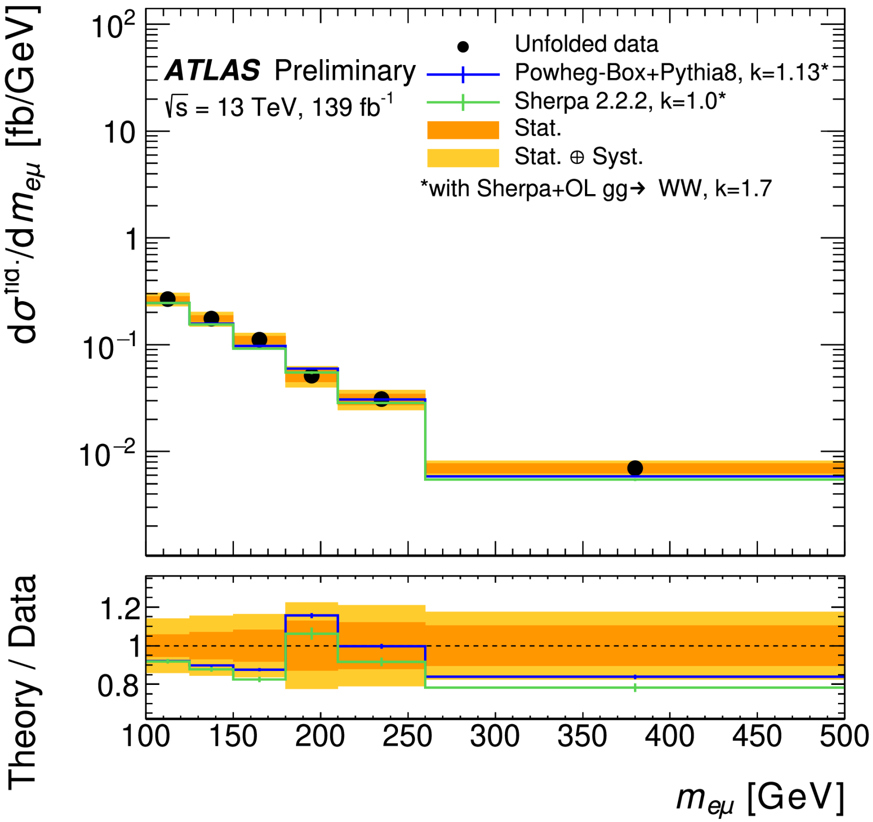

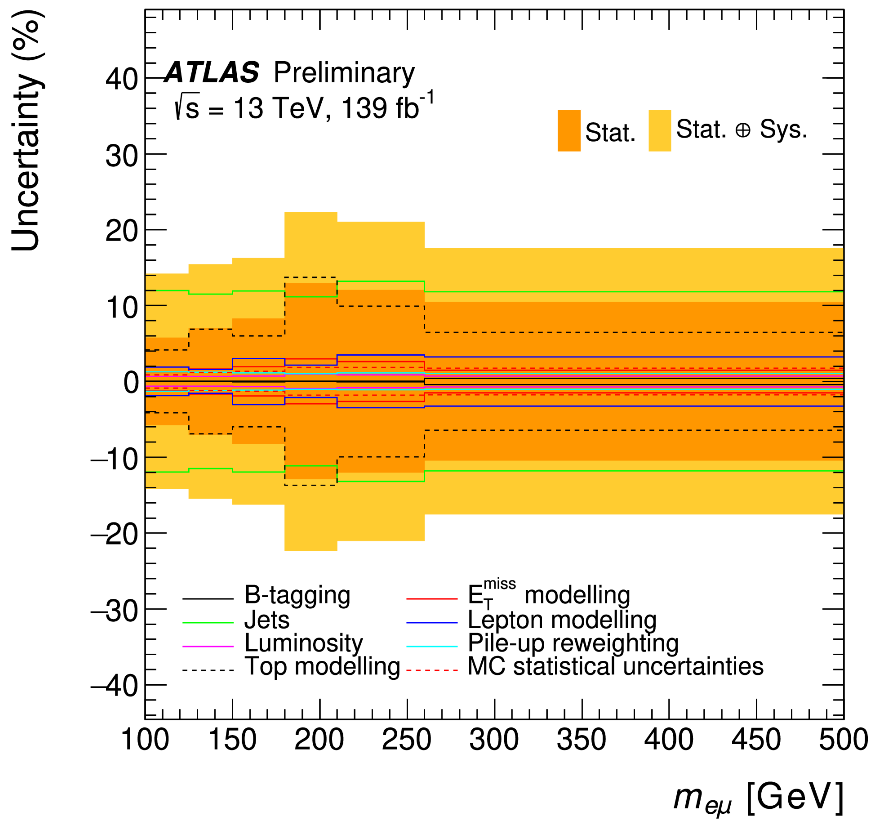

Detailed results of unfolding exercise

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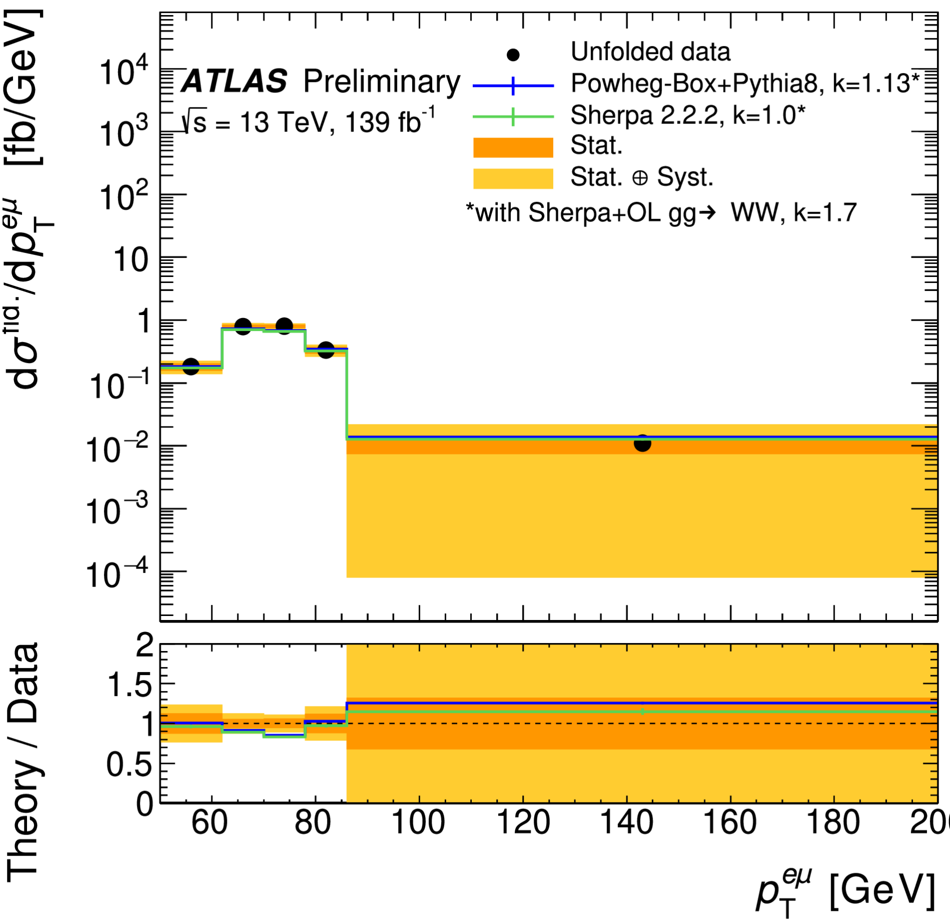

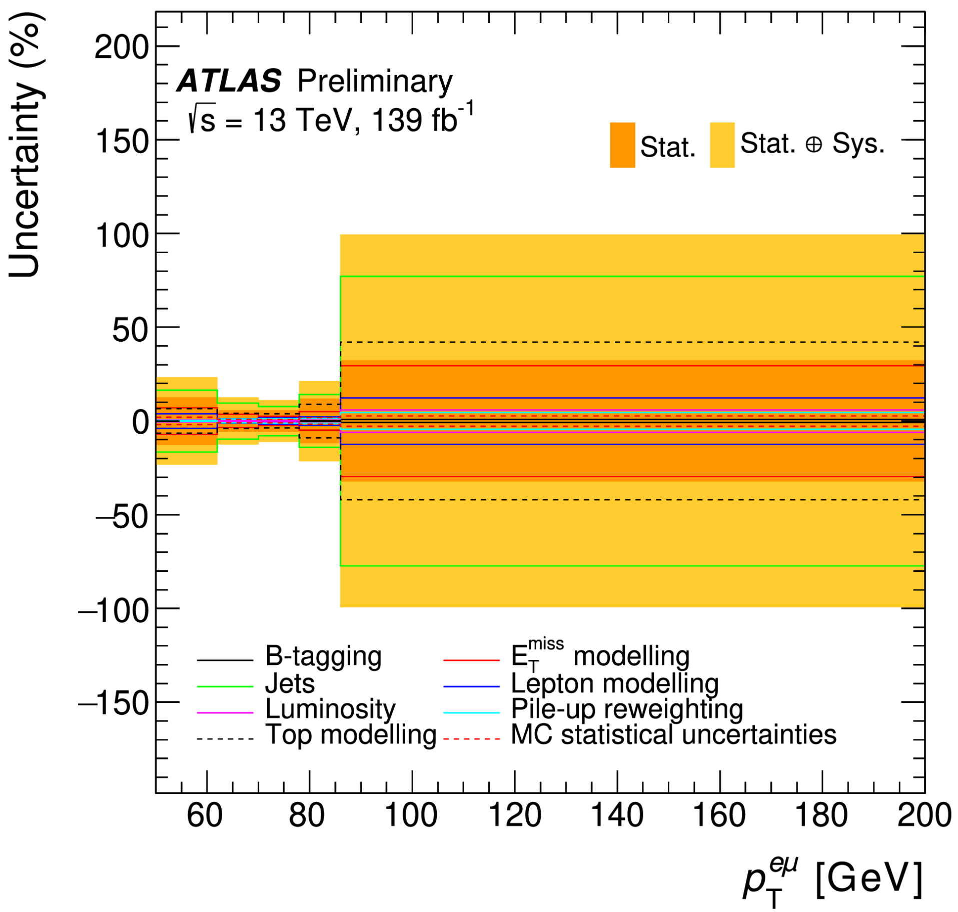

2L+0jets control and validation regions

Region	CR-WW	CR-VZ	CR-top
Lepton flavour	DF	SF	DF
$n_{b\text{-tagged jets}}$	$= 0$	$= 0$	$= 1$
$n_{\text{non-}b\text{-tagged jets}}$	$= 0$	$= 0$	$= 0$
m_{T2} [GeV]	$\in [60,65]$	> 120	> 80
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$\in [60,100]$	> 110	> 110
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	$\in [5,10]$	> 10	> 10
$m_{\ell_1\ell_2}$ [GeV]	> 100	$\in [61.2,121.2]$	> 100

Regions with $m_{T2} \in [60,100]$ GeV used for estimation and validation of the WW background. Lowest m_{T2} range used for CR to maximise the WW purity.

Region	VR-WW-0J	VR-WW-1J	VR-VZ	VR-top-low	VR-top-high	VR-top-WW
Lepton flavour	DF	DF	SF	DF	DF	DF
$n_{b\text{-tagged jets}}$	$= 0$	$= 0$	$= 0$	$= 1$	$= 1$	$= 1$
$n_{\text{non-}b\text{-tagged jets}}$	$= 0$	$= 1$	$= 0$	$= 0$	$= 1$	$= 1$
m_{T2} [GeV]	$\in [65,100]$	$\in [65,100]$	$\in [100,120]$	$\in [80,100]$	> 100	$\in [60,65]$
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 60	> 60	> 110	> 110	> 110	$\in [60,100]$
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	> 5	> 5	> 10	$\in [5,10]$	> 10	$\in [5,10]$
$m_{\ell_1\ell_2}$ [GeV]	> 100	> 100	$\in [61.2,121.2]$	> 100	> 100	> 100

VR-top-WW was introduced to validate the top modelling in CR-WW, which is at lower E_T^{miss} and E_T^{miss} significance than CR-top. Detailed studying on the top (mis) modelling at lower E_T^{miss} significance values in 0-jet events were performed, but should (hopefully) impact this effort less (no explicit E_T^{miss} significance requirement)