Results and Prospects for Charged Diboson Channels and aTGCs from the LHC

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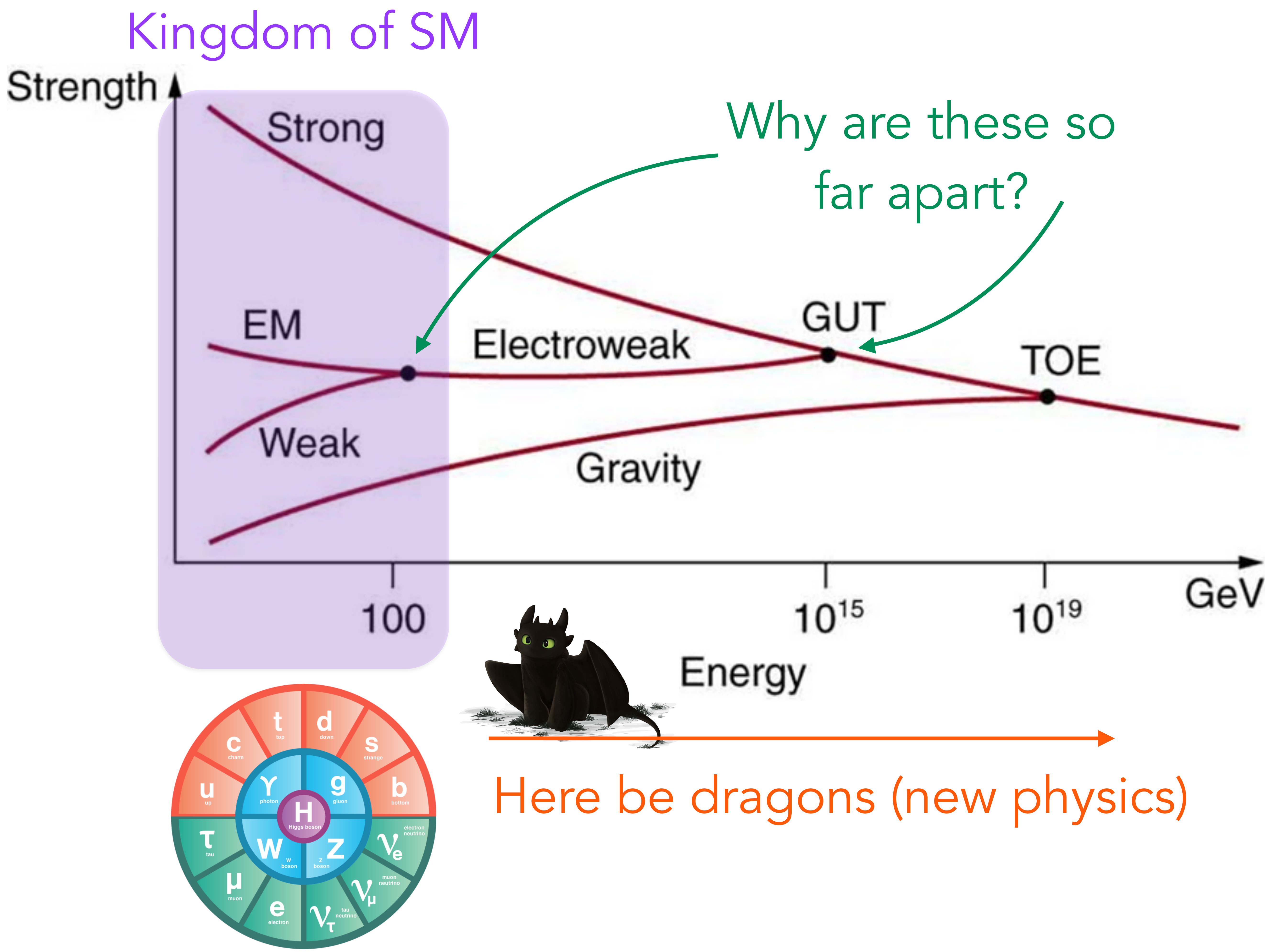
Double the bosons, double the fun!

“In the beginning there was symmetry.”

- Werner Heisenberg



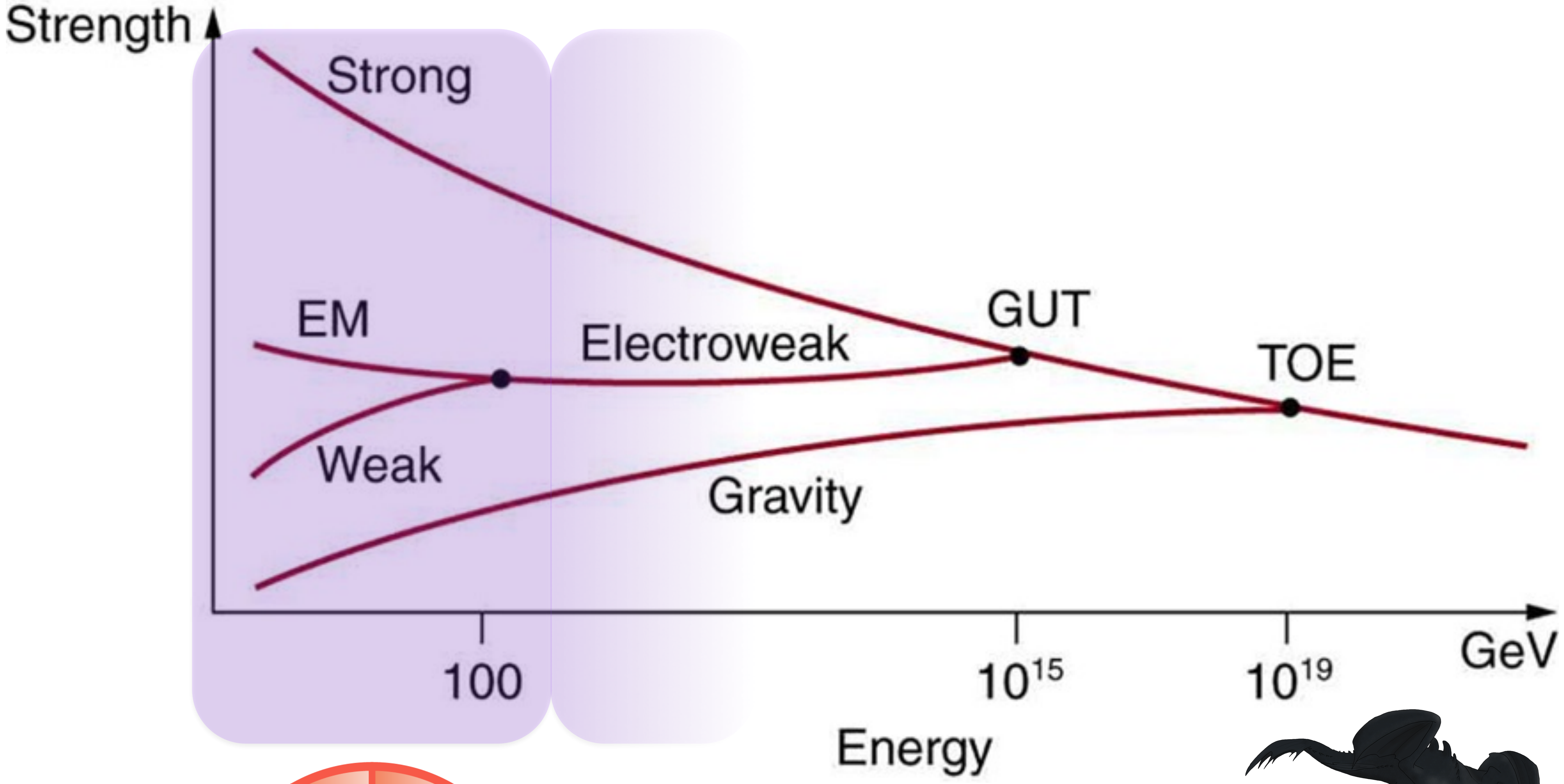
Kingdom of SM

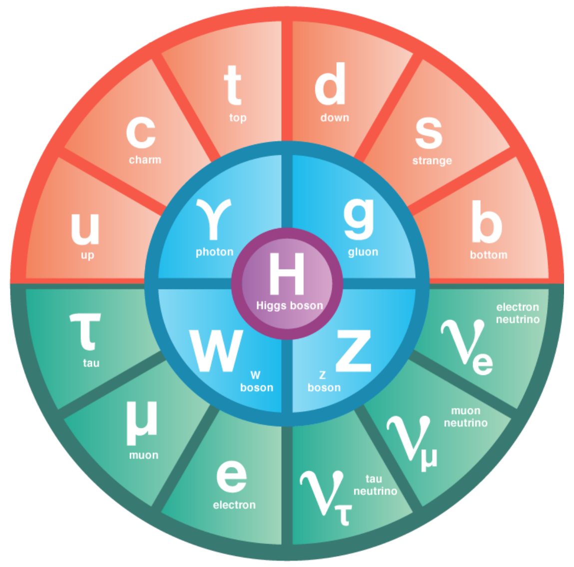
Why are these so far apart?

Here be dragons (new physics)

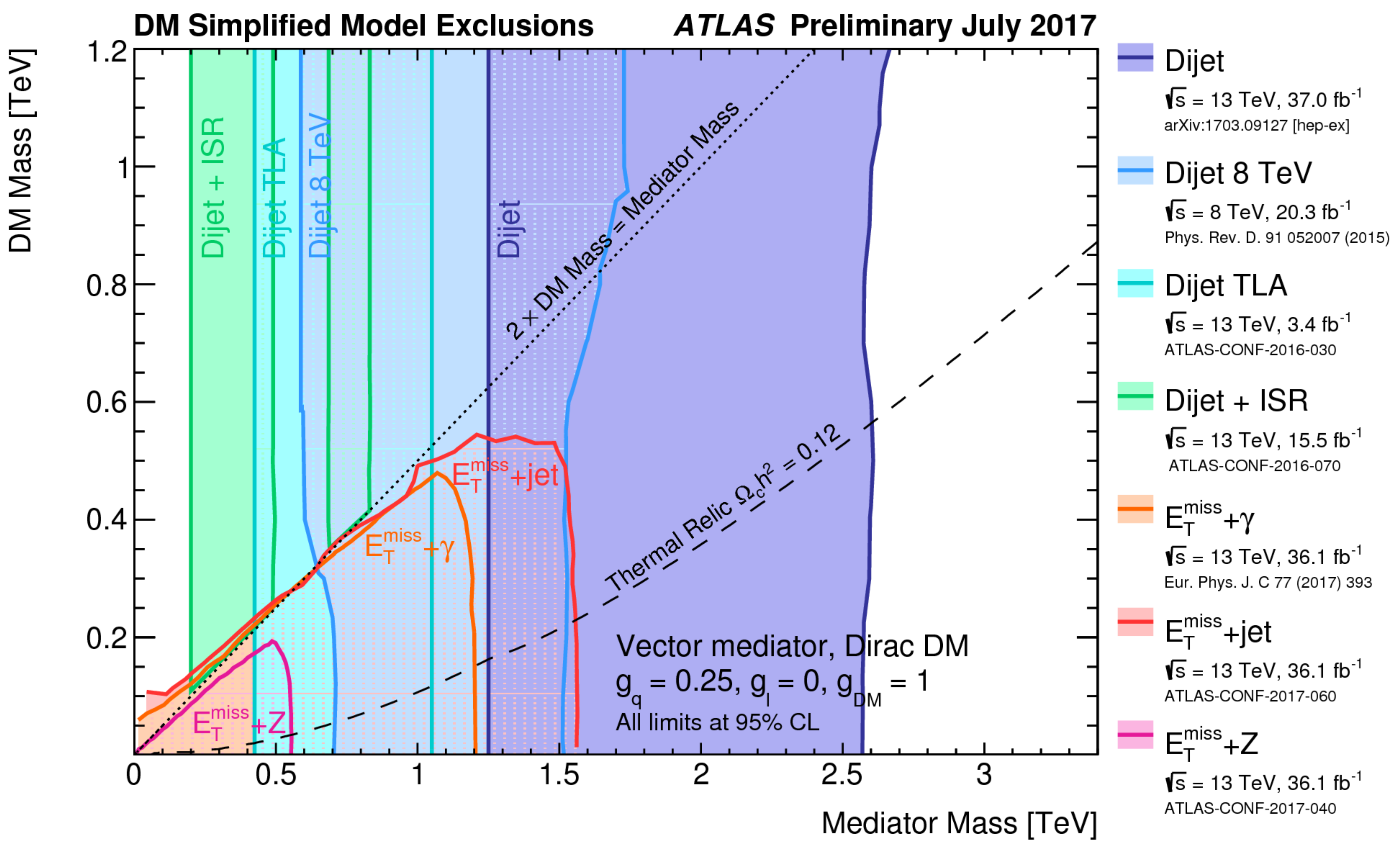
- …and then it broke. Now all we’ve got are particles.
- Despite the (ongoing) success of the SM, it is a natural theory only up to ~1TeV
- If there is no new physics beyond this, then this isn’t *really* a problem per se. However there are reasons to expect that this isn’t the case.
- Latest indications suggest that if there is new physics, it must be at a scale further away than we expected, so that SM stays natural beyond 1TeV (otherwise we should have seen some evidence by now)

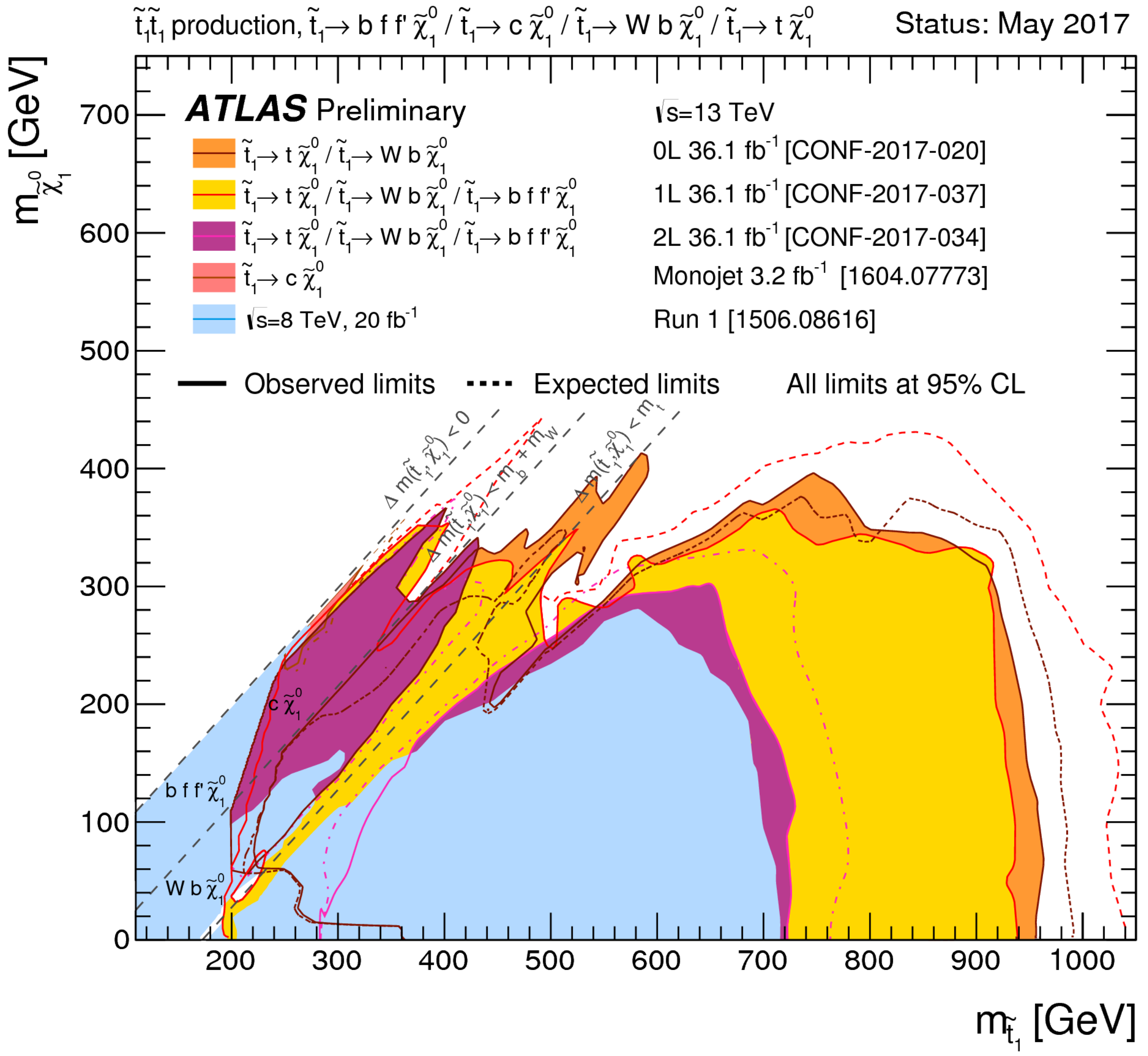
Kingdom of SM ⟶ ?



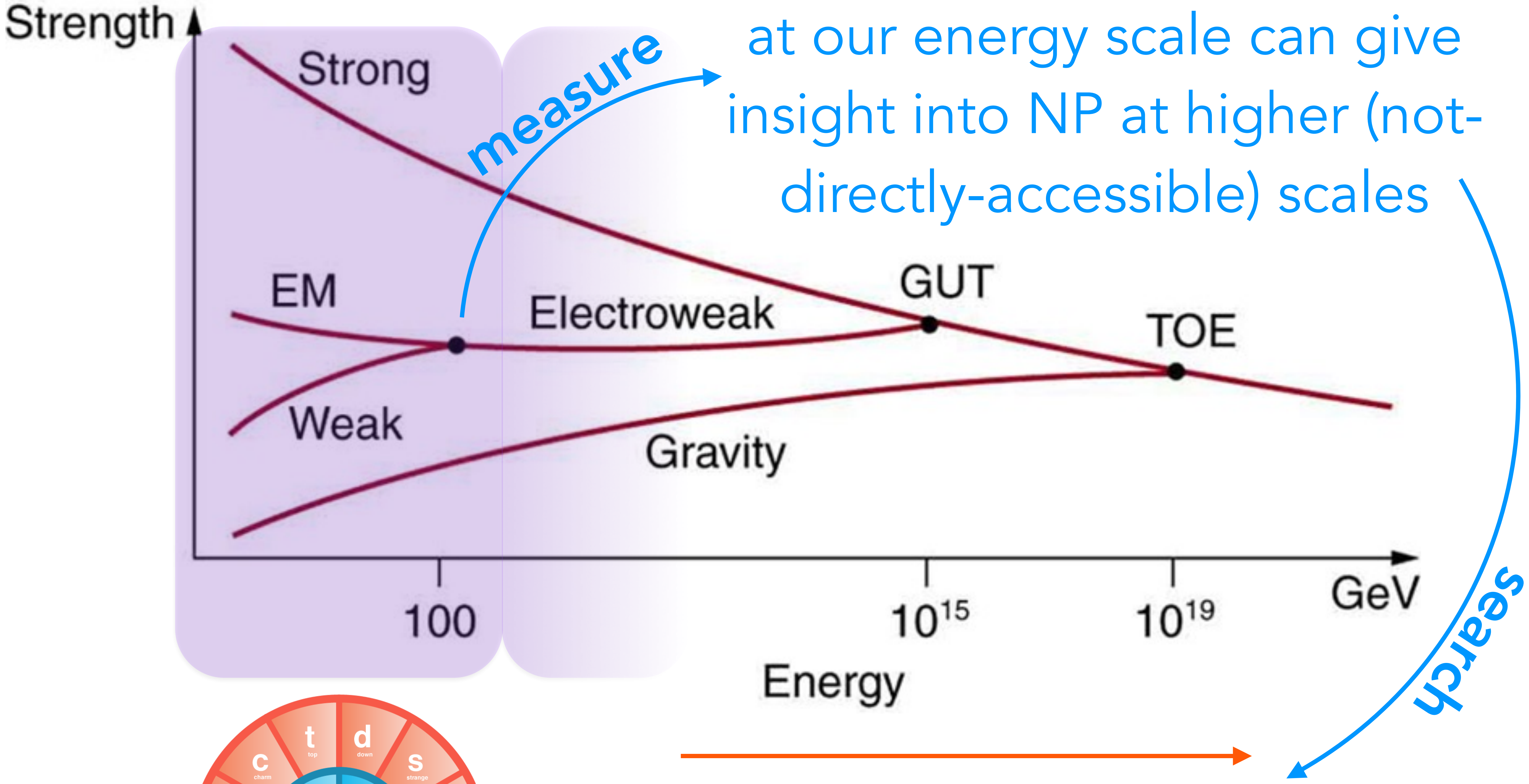


Here be dragons? →





Kingdom of SM ⟶ ?

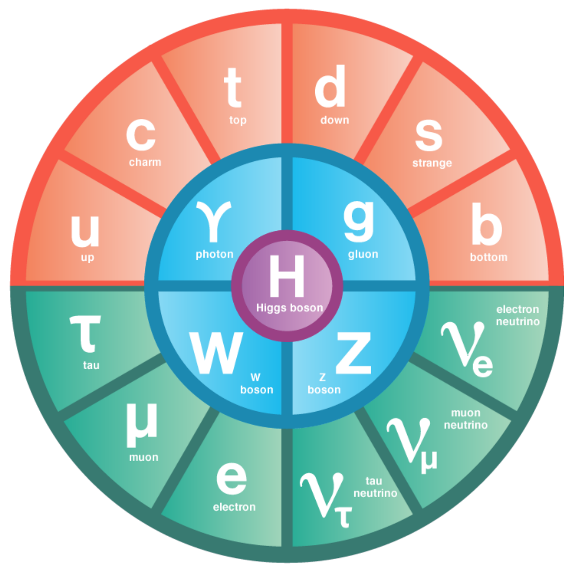


measure

Precision EWK measurements at our energy scale can give insight into NP at higher (not-directly-accessible) scales

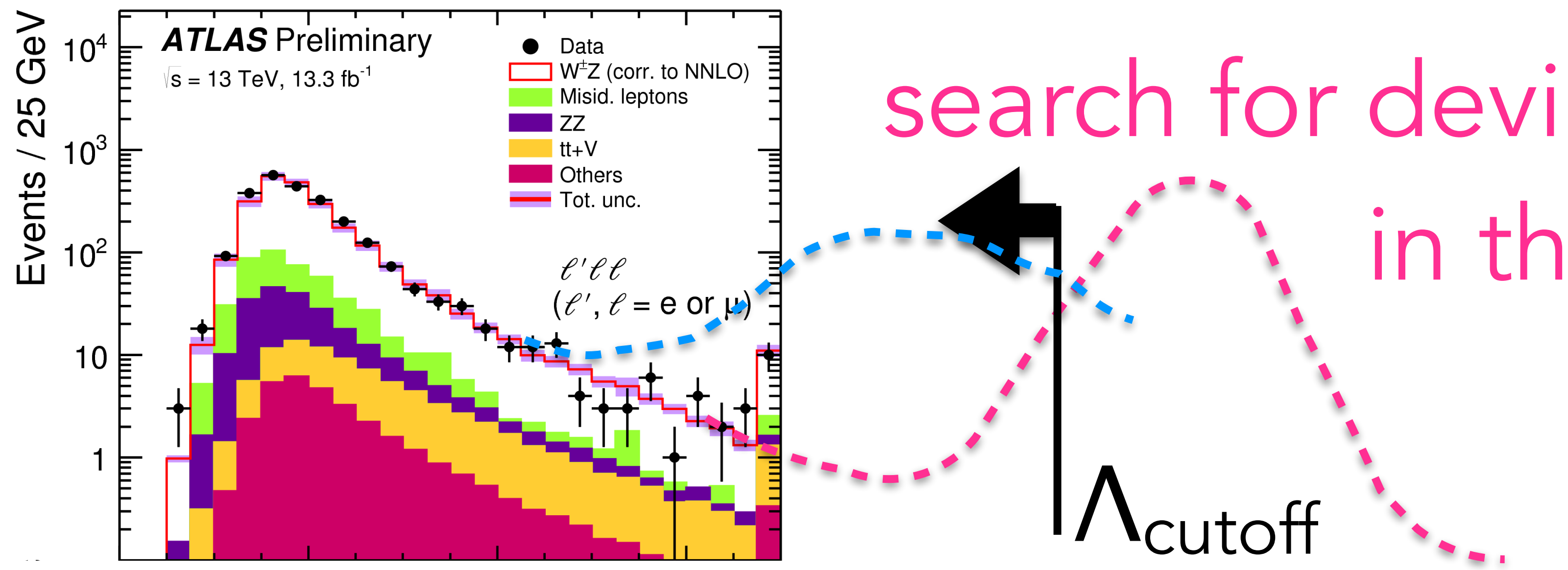
search

Here be dragons? (please?)



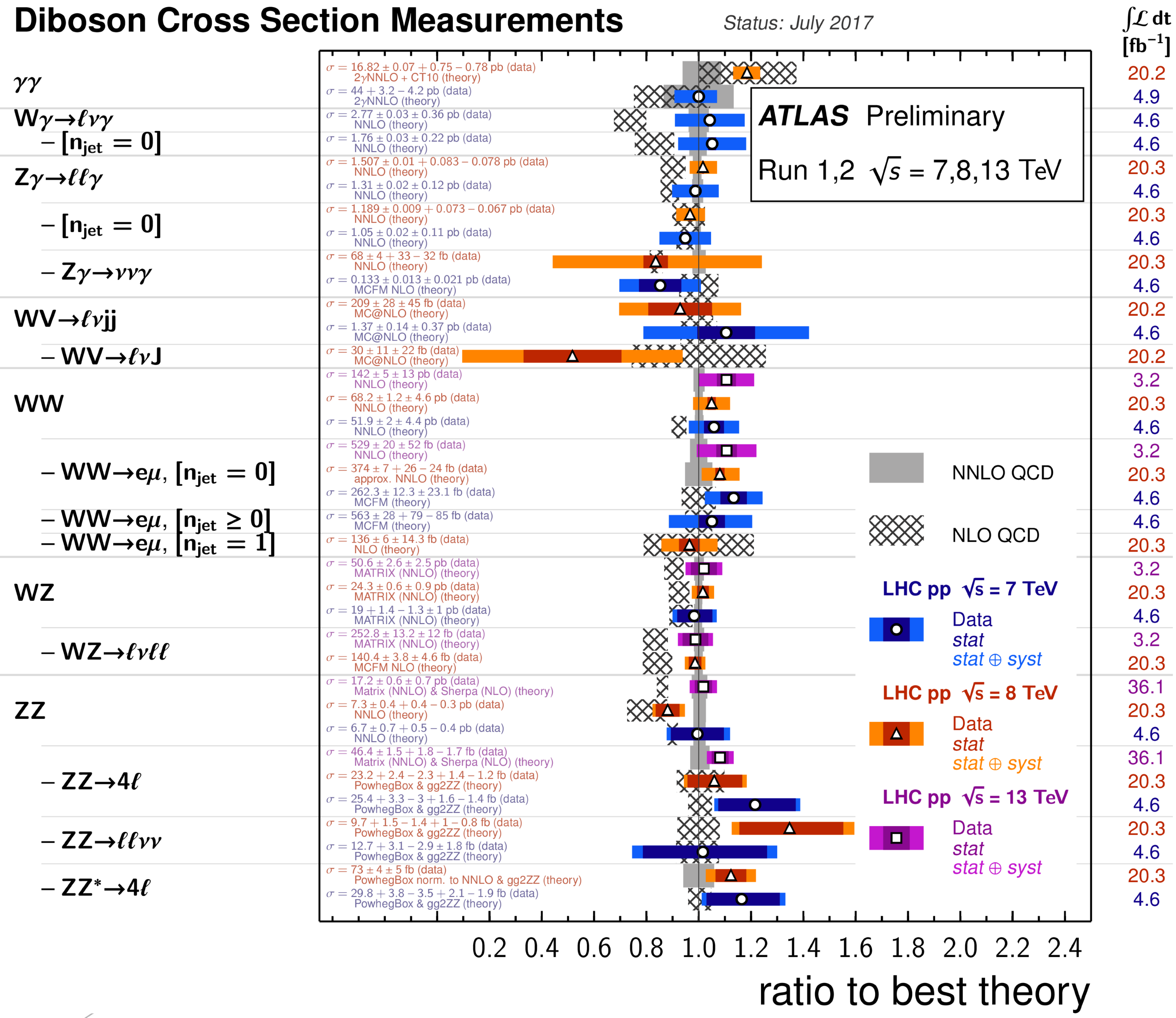
- New physics may introduce deviations in couplings at high energy scales leading to an enhancement of vector boson cross sections, especially at high pT.
- Can be seen via, e.g.:
  - Specific observables, eg shape of pT, m or mT distributions
  - (Differential) cross section measurements
  - Precision measurements of EWK couplings

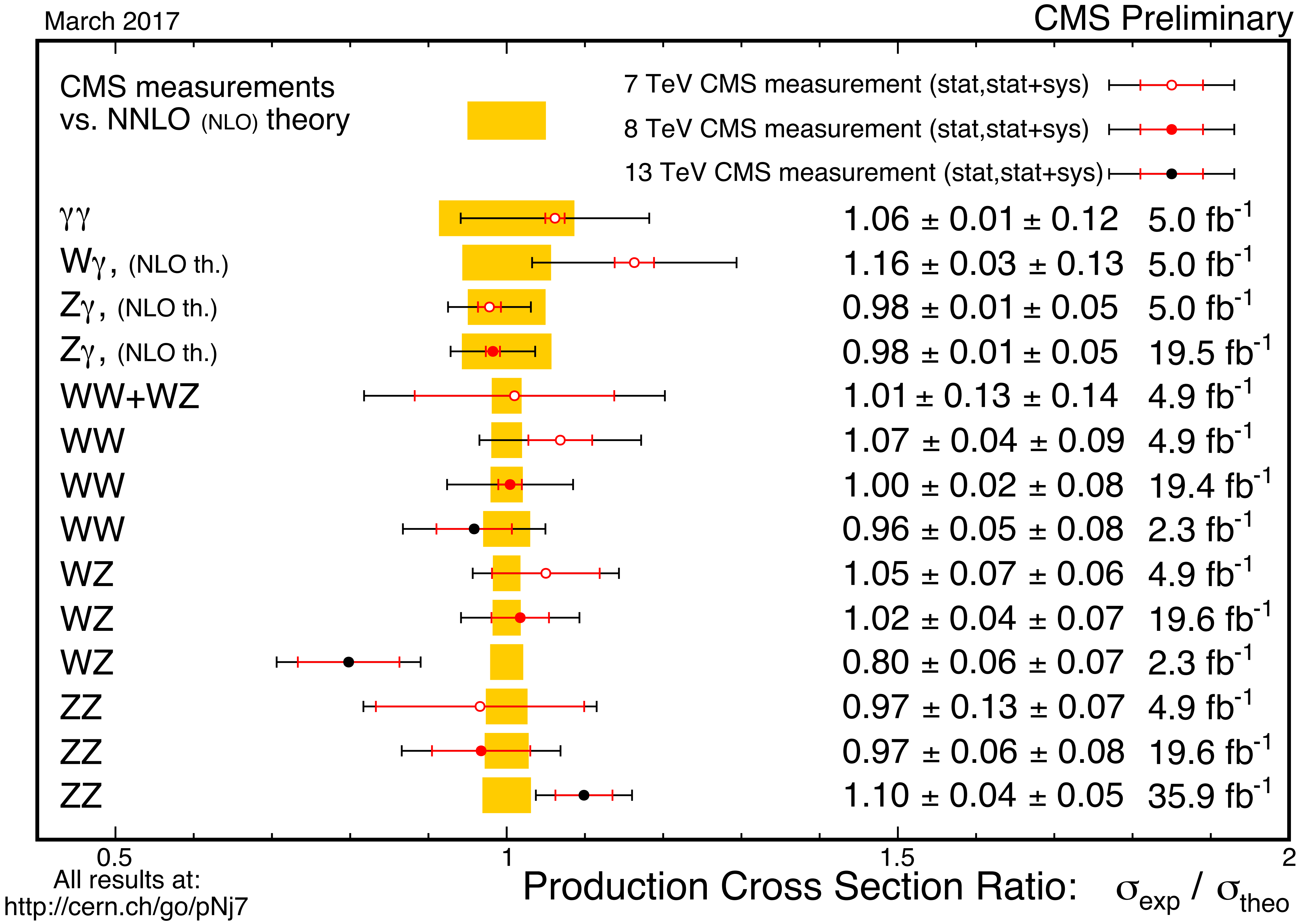
$M_T(WZ)$



search for deviations in the tails

Current Status of Diboson Measurements

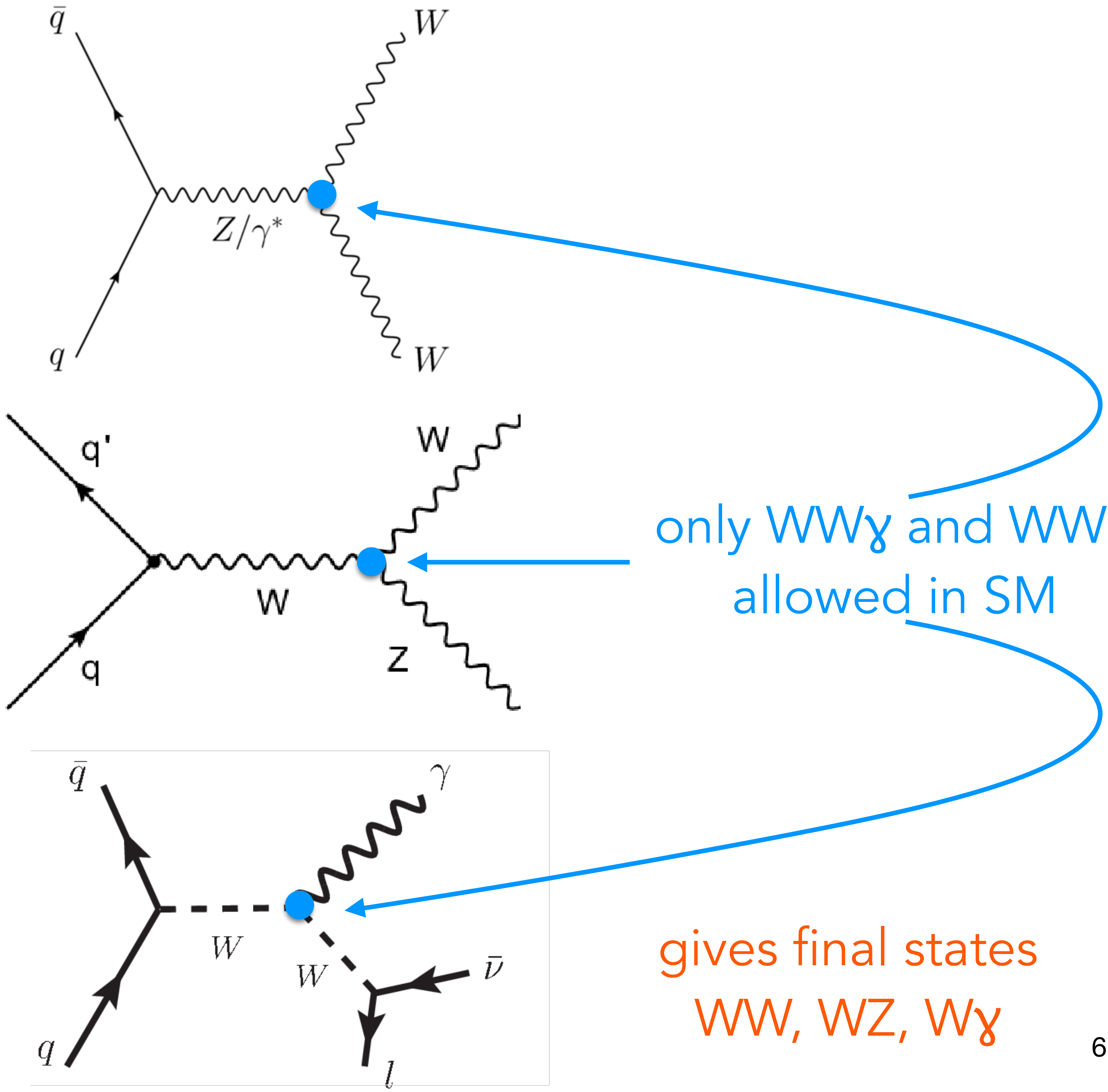




Charged TGCs and $\mathscr{L}$WWV

- Parameterisation of possible charged TGCs that is Lorentz invariant and obeys charge conservation: (V = Z or ɣ)

$$
\begin{aligned}
\mathcal{L}_{WWV} = {} & ig_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) \\
& + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) \\
& + g_5^V \epsilon^{\mu\nu\rho\sigma} \left(W^\dagger_\mu \overleftrightarrow{\partial} W_\nu\right) V_\sigma + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} \\
& + \frac{i\tilde{\lambda}_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu \tilde{V}^{\nu\lambda} + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu},
\end{aligned}
$$



only WWɣ and WWZ allowed in SM

gives final states WW, WZ, Wɣ

Charged TGCs and $\mathscr{L}_{WWV}$

- Parameterisation of possible charged TGCs that is Lorentz invariant and obeys charge conservation: (V = Z or ɣ)

Terms violating C and/or P

$$\begin{aligned}
\mathcal{L}_{WWV} &= i g_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu} \right) \\
&+ \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda} - \cancel{g_4^V W^\dagger_\mu W_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu \right)} \\
&+ \cancel{g_5^V \epsilon^{\mu\nu\rho\sigma} \left(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu \right)} V_\sigma + \cancel{i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu}} \\
&+ \cancel{\frac{i\tilde{\lambda}_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu \tilde{V}^{\nu\lambda}} + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu},
\end{aligned}$$

Charged TGCs and $\mathscr{L}_{WWV}$

- Parameterisation of possible charged TGCs that is Lorentz invariant and obeys charge conservation: (V = Z or γ)

$$
\begin{aligned}
\mathcal{L}_{WWV} = & \boxed{i g_1^V} \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu} \right) \\
& + \frac{\boxed{i\lambda_V}}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda} - \cancel{g_4^V W^\dagger_\mu W_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu \right)} \\
& + \cancel{g_5^V \epsilon^{\mu\nu\rho\sigma} \left(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu \right)} V_\sigma + \cancel{i \tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu}} \\
& + \cancel{\frac{i\tilde{\lambda}_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu \tilde{V}^{\nu\lambda}} + \boxed{i\kappa_V} W^\dagger_\mu W_\nu V^{\mu\nu},
\end{aligned}
$$

Terms violating C and/or P

$g_1^\gamma = 1$ from EM gauge invariance

$$
\left.\begin{array}{l}
g_1^Z - 1 \\
\kappa_\gamma - 1 \\
\kappa_Z - 1 \\
\lambda_\gamma \\
\lambda_Z
\end{array}\right\}
\text{remaining independent parameters, all = 0 in SM}
$$

EFT Approach

- An alternative framework for describing modifications of diboson production is an EFT that is assumed to be valid below an energy scale Λ, formed by adding higher-dimension operators to the SM Lagrangian:

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j + \ldots$$

- There are three CP-conserving dimension-6 operators, with coefficients that are zero in the SM, and are related to the LEP-constrained aTGC parameters.

-

$$\begin{aligned} \mathcal{O}_W &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)\,, \\ \mathcal{O}_B &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)\,, \\ \mathcal{O}_{WWW} &= Tr[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]\,. \end{aligned}$$

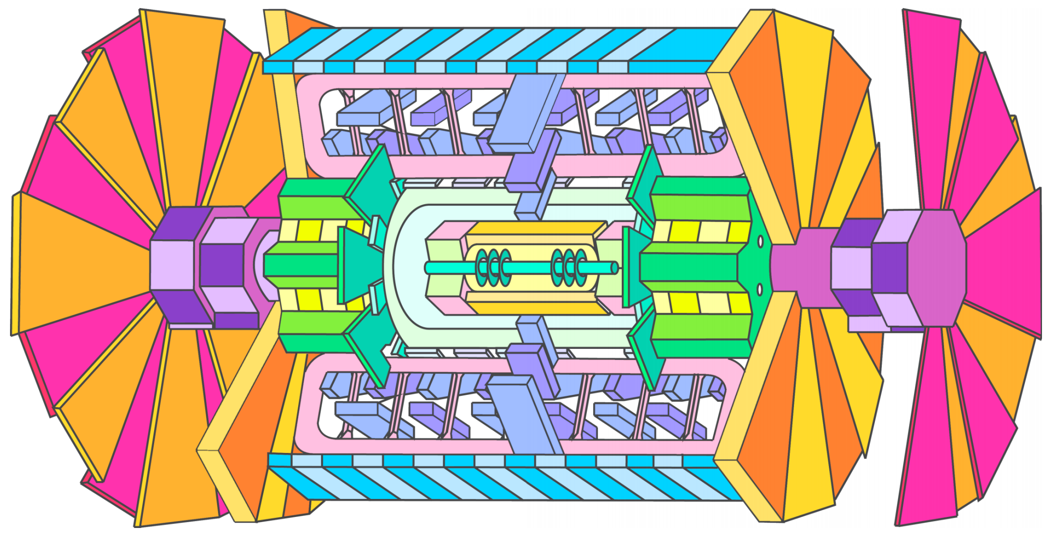
$$\begin{aligned} \frac{c_W}{\Lambda^2} &= \frac{2}{m_Z^2}\Delta g_1^Z\,, \\ \frac{c_B}{\Lambda^2} &= \frac{2}{m_W^2}\Delta\kappa_\gamma - \frac{2}{m_Z^2}\Delta g_1^Z\,, \\ \frac{c_{WWW}}{\Lambda^2} &= \frac{2}{3g^2m_W^2}\lambda\,. \end{aligned}$$

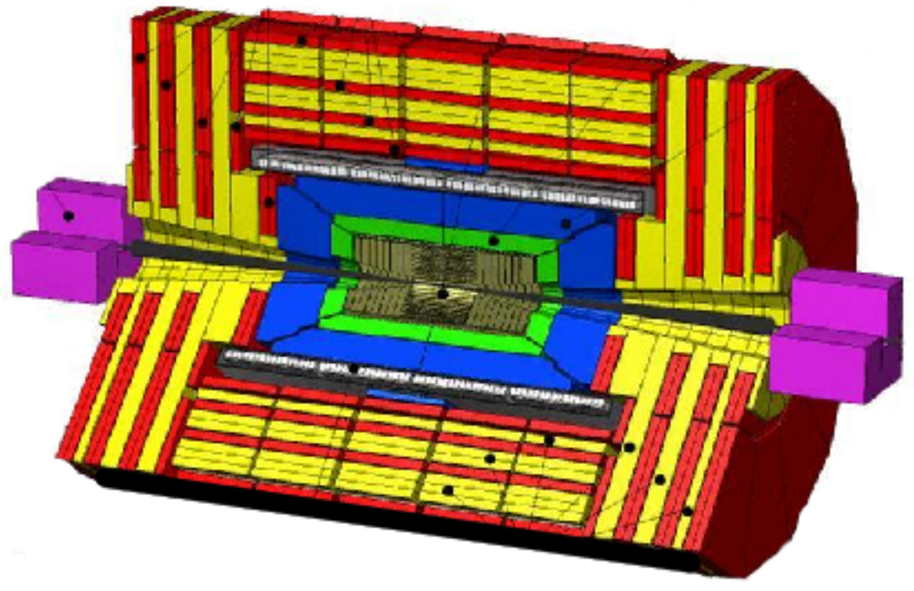
- Since the LHC results have now surpassed LEP/Tevatron limits, the LHC aGC Taskforce recommends to now move towards using the dimension-6 EFT operators in our results.

13TeV

8 TeV

ATLAS and CMS diboson results focusing on aTGCs





W^+W^-

$WW \to \ell\nu\ell\nu$

$WW \to \ell\nu\ell\nu$ + aTCG

$WW \to \ell\nu\ell\nu$

$WW \to \ell\nu\ell\nu$ + aTGC

WV

$WZ \to \ell\nu\ell\ell$ + aTGC

$WV \to \ell\nu qq$ + aTCG

$WZ \to \ell\nu\ell\ell$

$WZ \to \ell\nu\ell\ell$ + aTGC

$WV \to \ell\nu qq$ + aTCG

Wγ

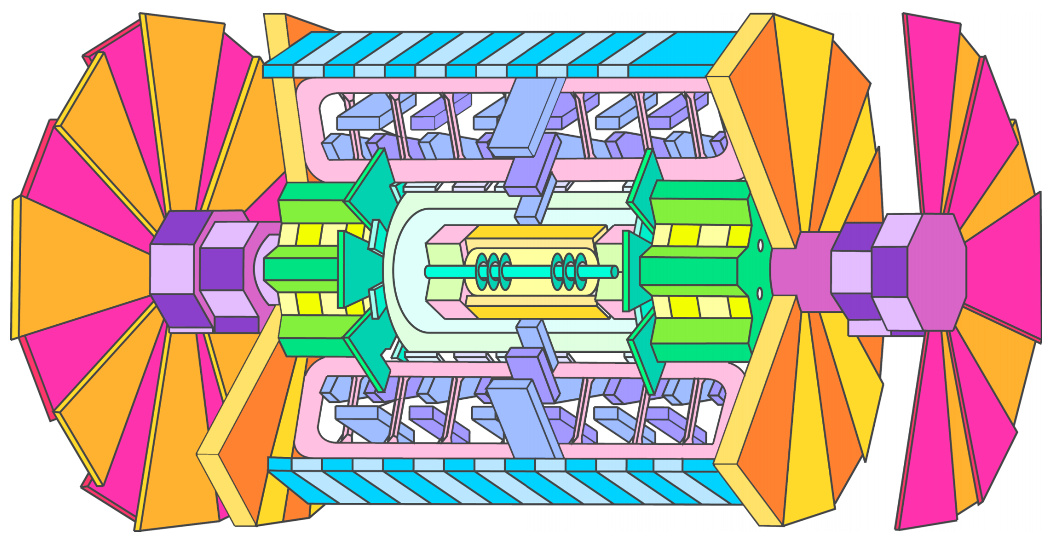
7 TeV measurement

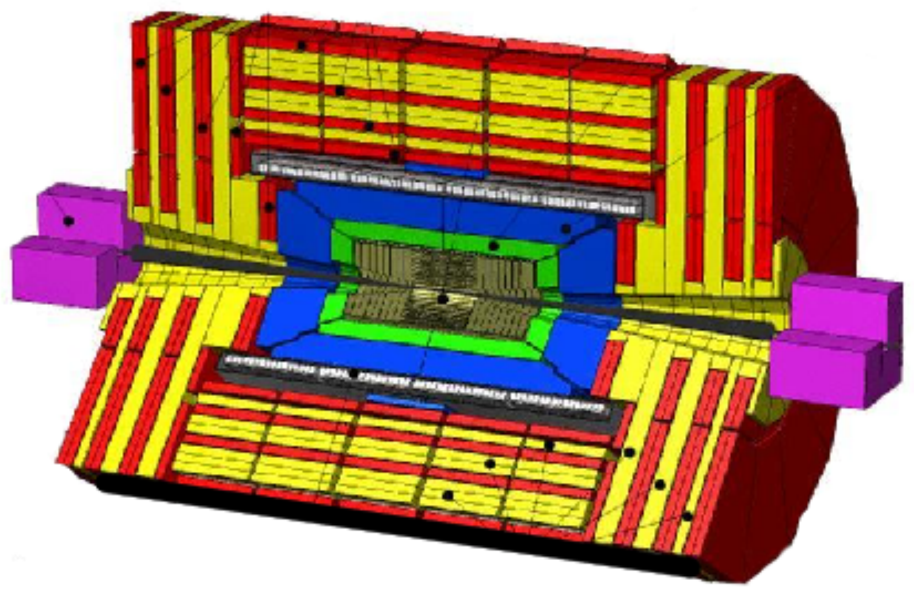
Covered in Md Naimuddin's talk (VBS)

13TeV

8 TeV

ATLAS and CMS diboson results focusing on aTGCs





W^+W^-	WW→ℓνℓν	**WW→ℓνℓν + aTCG**	WW→ℓνℓν	**WW→ℓνℓν + aTGC**
WV	WZ→ℓνℓℓ + aTGC	WV→ℓνqq + aTCG	WZ→ℓνℓℓ + aTGC	WV→ℓνqq + aTCG
Wγ	7 TeV measurement		Covered in Md Naimuddin's talk (VBS)	

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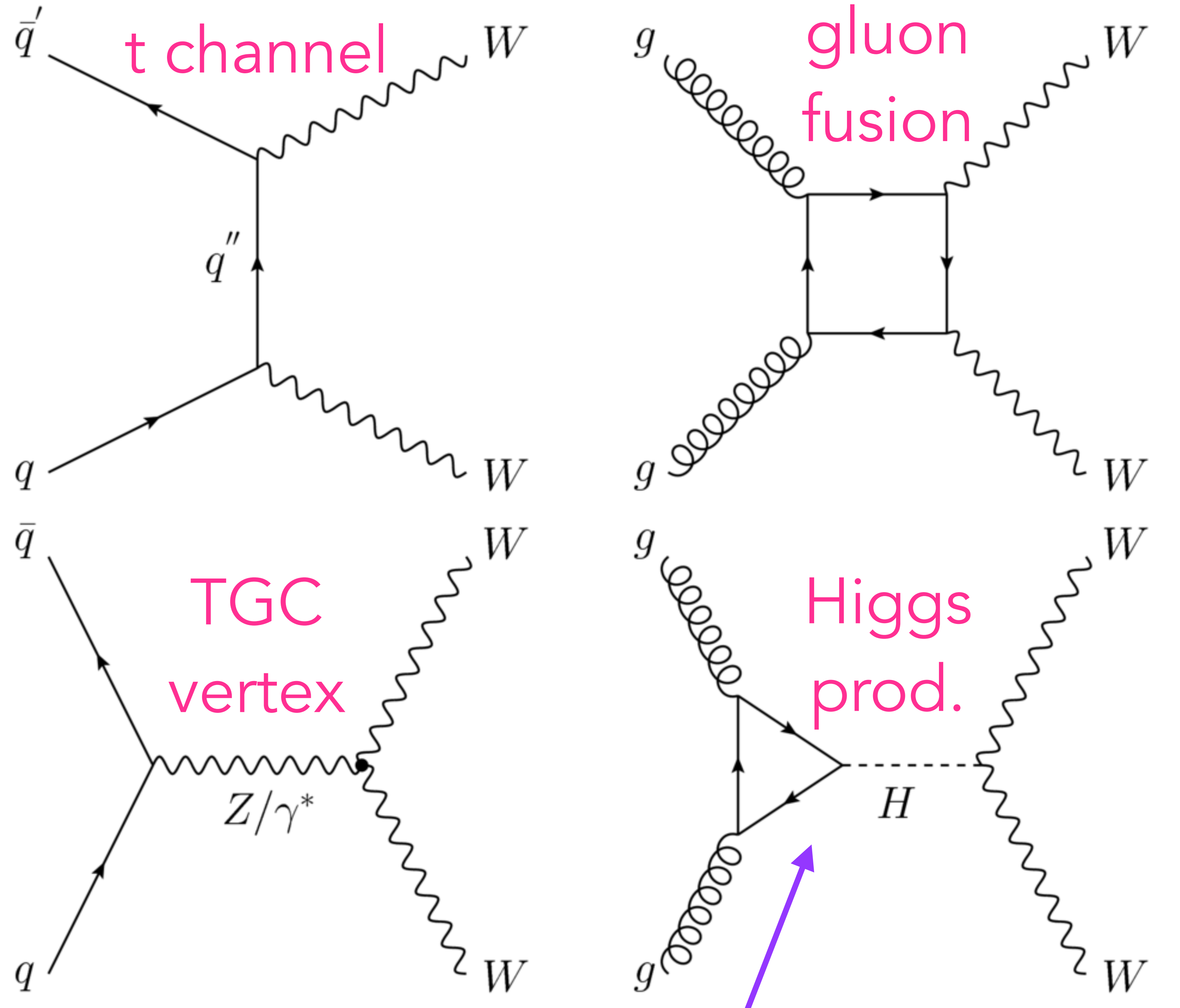
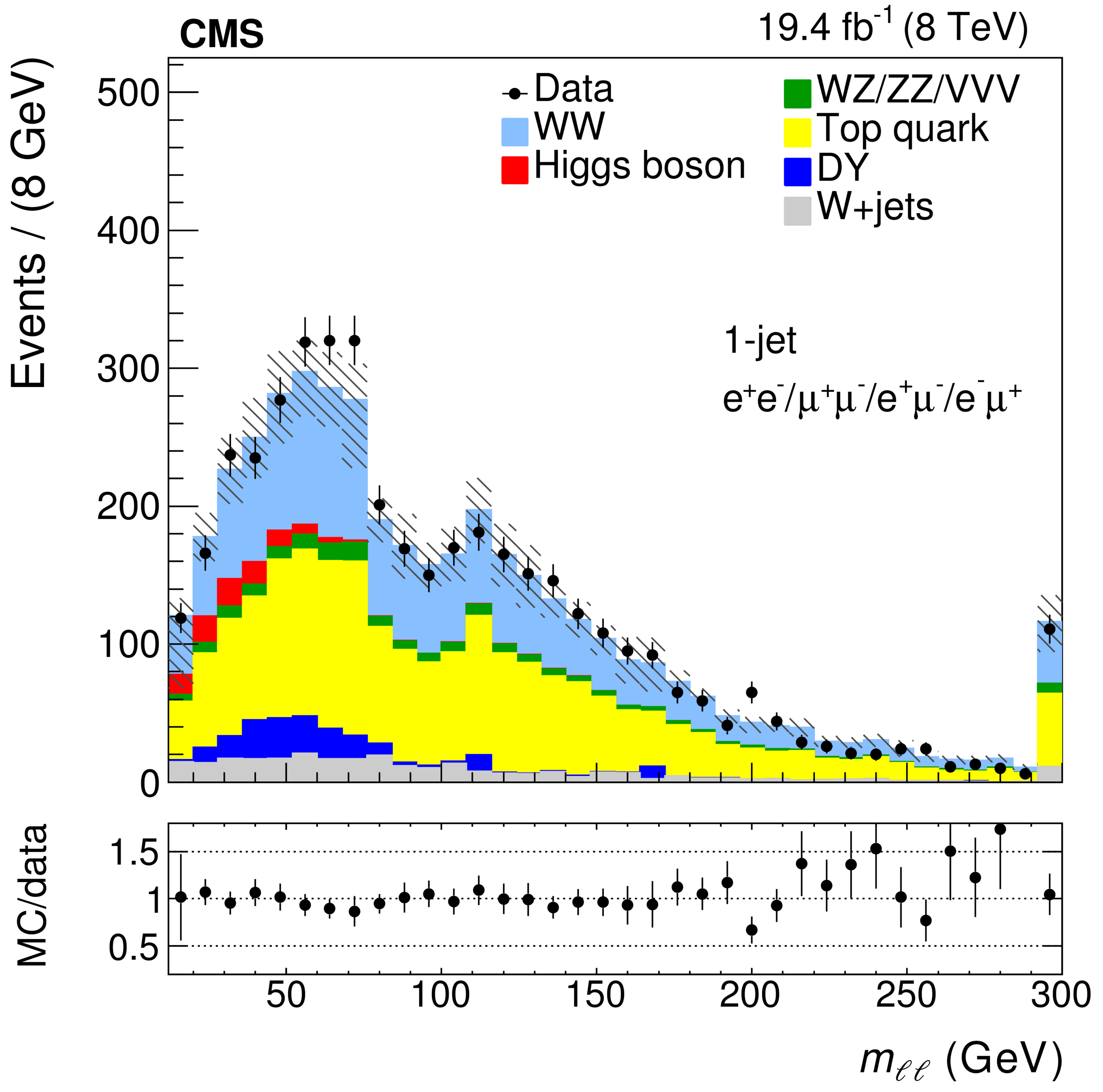
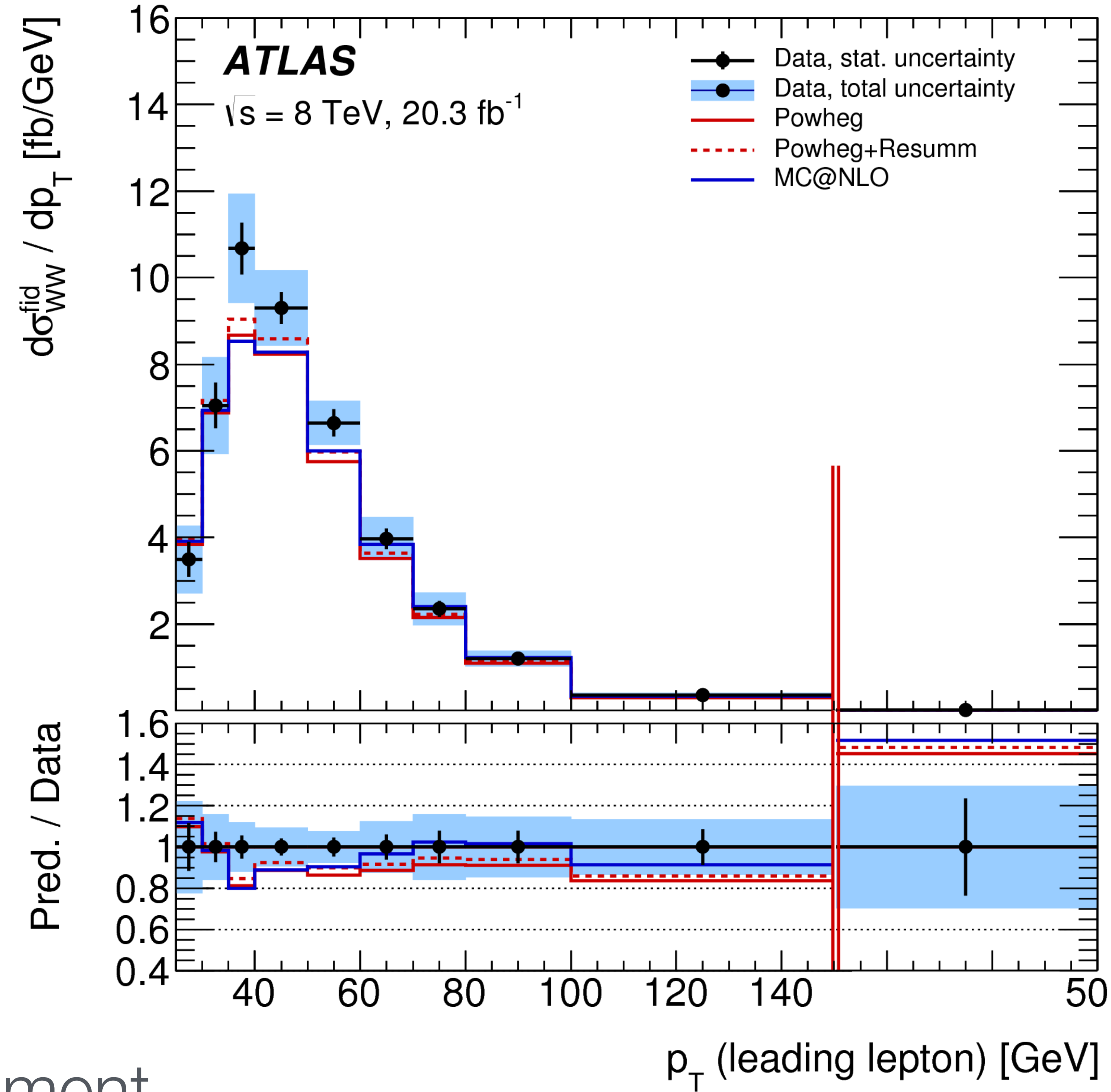
WW→$\ell\nu\ell\nu$ + aTCG at 8 TeV - Introduction



Higgs considered signal for ATLAS, background for CMS





- W^+W^- differential cross section measurement
- Same- and different-flavour channels , 0 jet (ATLAS) and 0,1 jet (CMS)
- Limits on aTGCs calculated from distribution of leading lepton p_T (ATLAS) and $m_{\ell\ell}$ (CMS)

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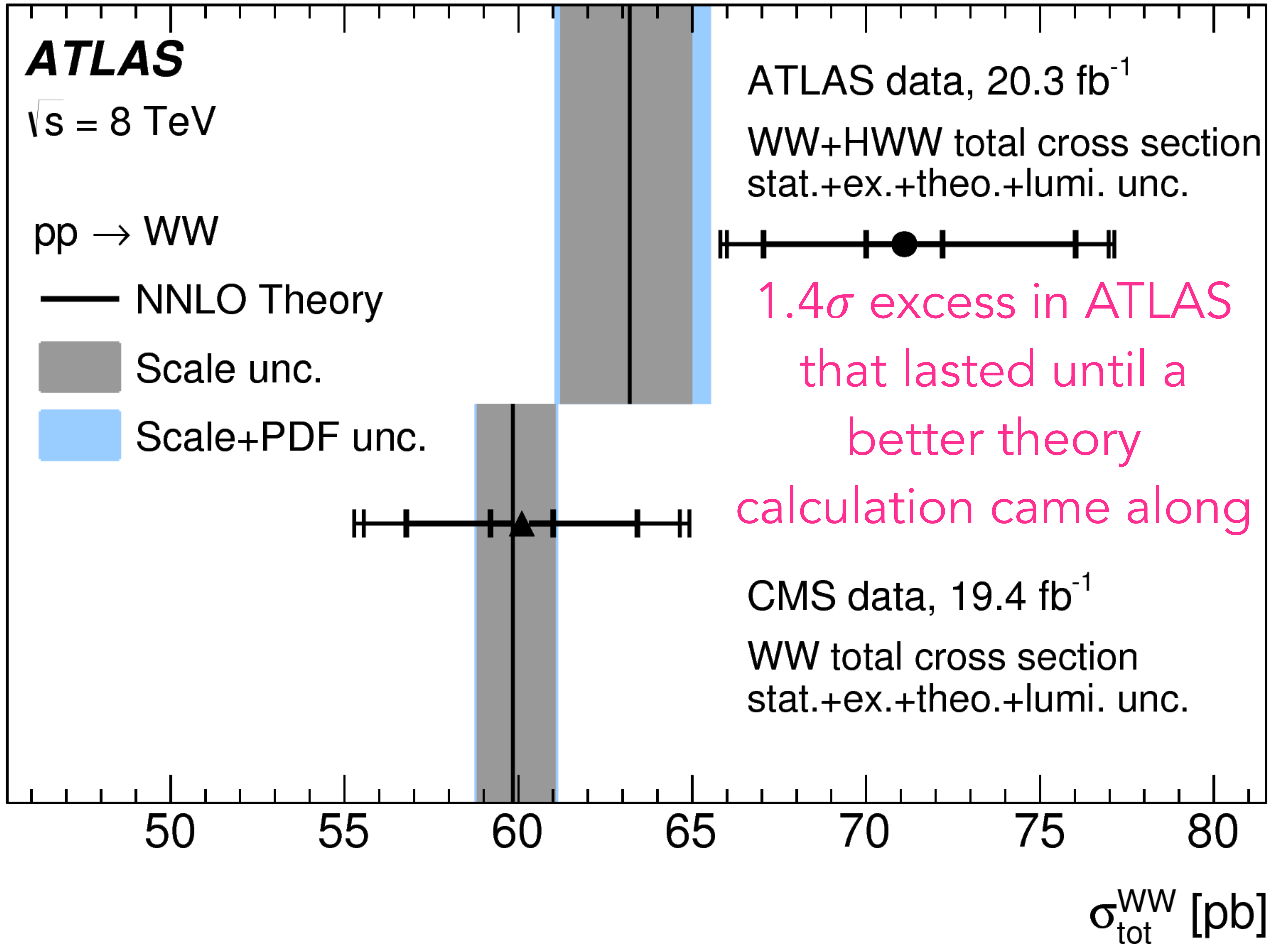
WW→ℓνℓν + aTCG at 8 TeV - Cross Sections



1.4σ excess in ATLAS that lasted until a better theory calculation came along

- CMS predicted cross section quoted is solely non-resonant NNLO WW production,
- ATLAS predicted cross section includes H→ WW at NNLO
- ATLAS scale choice: $\mu R=\mu F=m_{WW}/2$
- CMS scale choice: $\mu R=\mu F=m_{WW}$ (taking into account WW p_T resummation)
- Theoretical and statistical uncertainties in both measurements are fairly comparable
- CMS experimental uncertainties are smaller (background estimation, JES, and ETmiss)

WW→$\ell\nu\ell\nu$ + aTCG at 8 TeV - EFT coefficients

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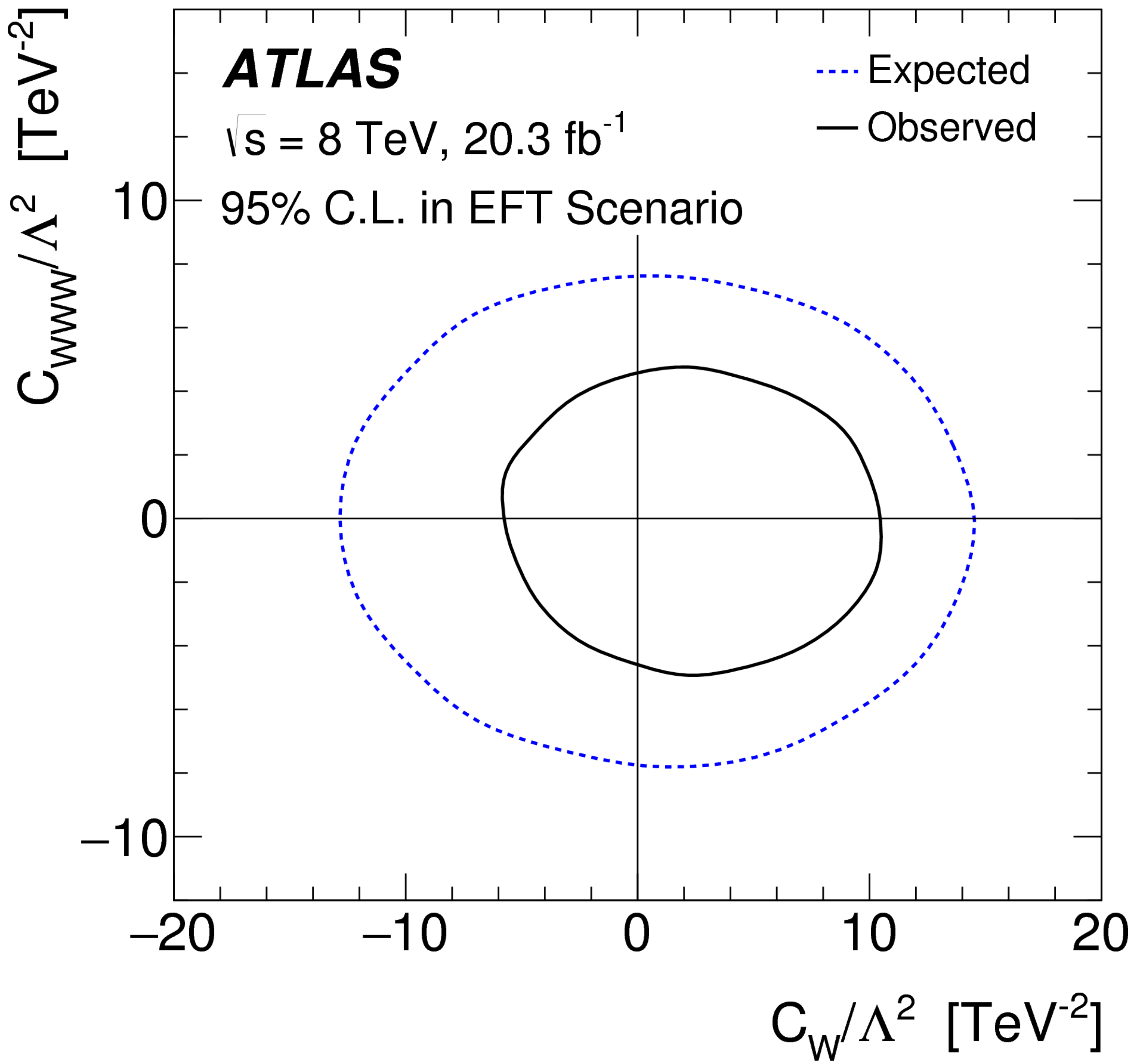
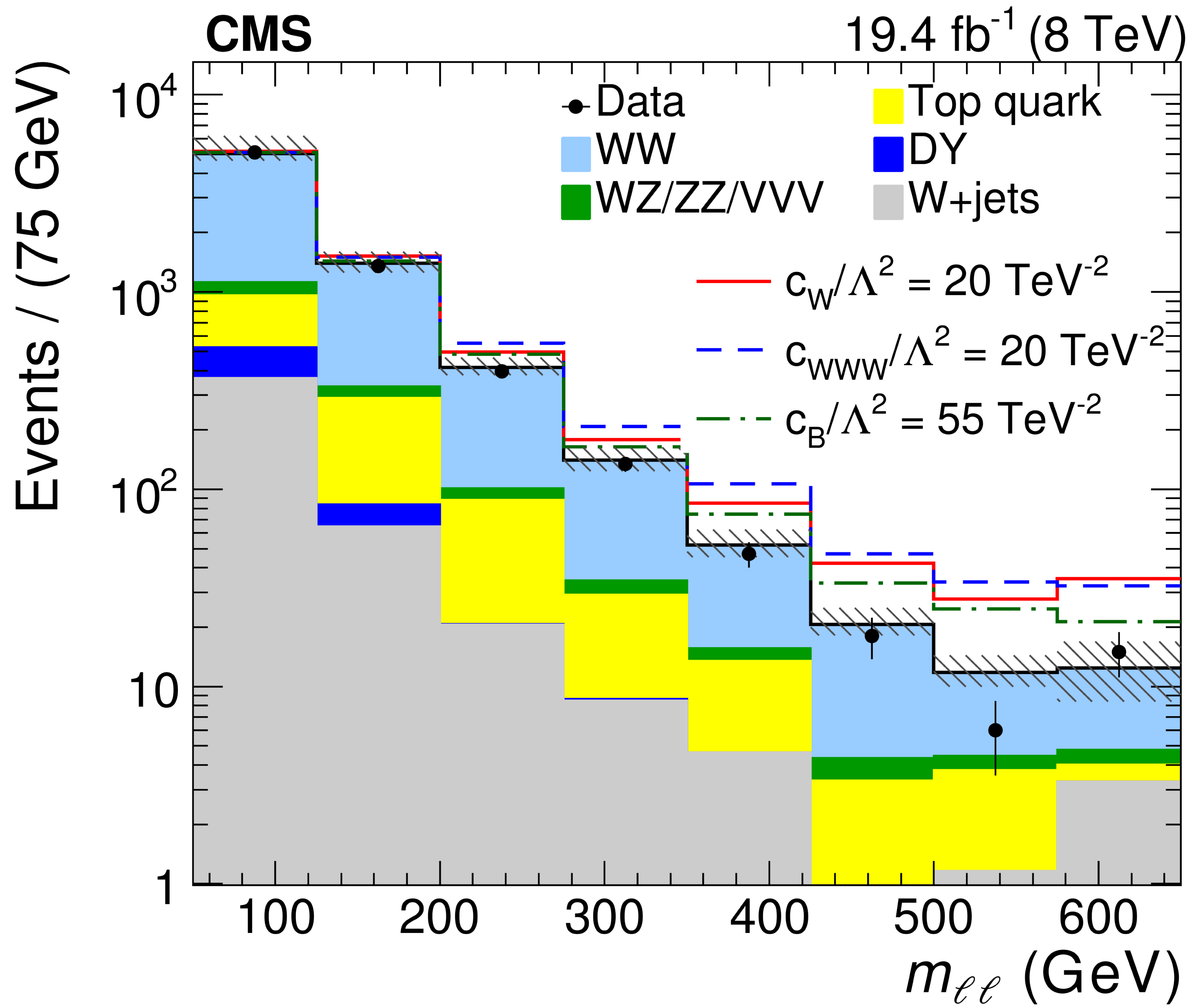


Scenario	Parameter	Expected [TeV^{-2}]	Observed [TeV^{-2}]
EFT	C_{WWW}/Λ^2	[−7.62, 7.38]	[−4.61, 4.60]
	C_B/Λ^2	[−35.8, 38.4]	[−20.9, 26.3]
	C_W/Λ^2	[−12.58, 14.32]	[−5.87, 10.54]

ATLAS

Coupling constant	This result (TeV^{-2})	Its 95% CL interval (TeV^{-2})	World average (TeV^{-2})
c_{WWW}/Λ^2	$0.1^{+3.2}_{-3.2}$	$[-5.7, 5.9]$	-5.5 ± 4.8 (from λ_γ)
c_W/Λ^2	$-3.6^{+5.0}_{-4.5}$	$[-11.4, 5.4]$	$-3.9^{+3.9}_{-4.8}$ (from g_1^Z)
c_B/Λ^2	$-3.2^{+15.0}_{-14.5}$	$[-29.2, 23.9]$	$-1.7^{+13.6}_{-13.9}$ (from κ_γ and g_1^Z)

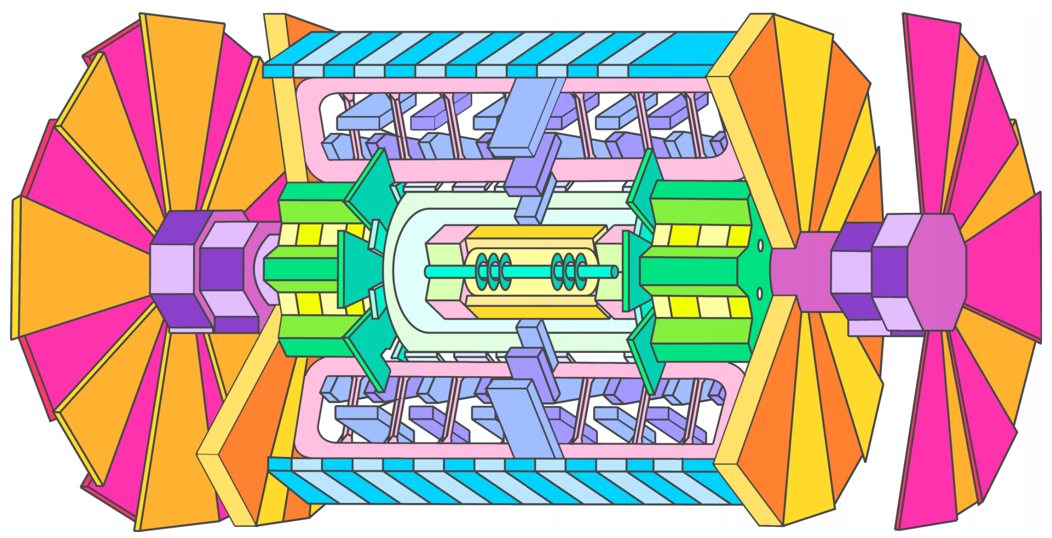
CMS

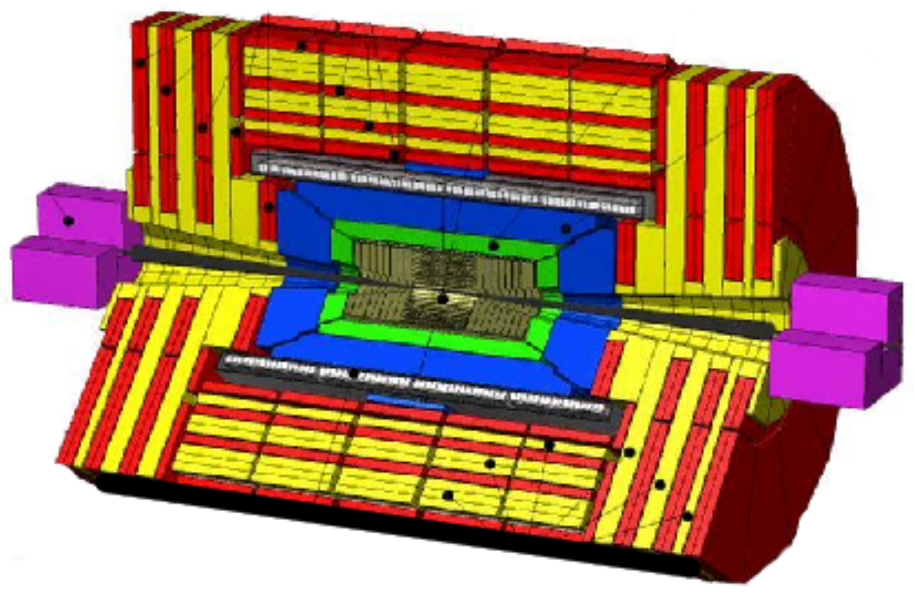


13TeV

8 TeV

ATLAS and CMS diboson results focusing on aTGCs





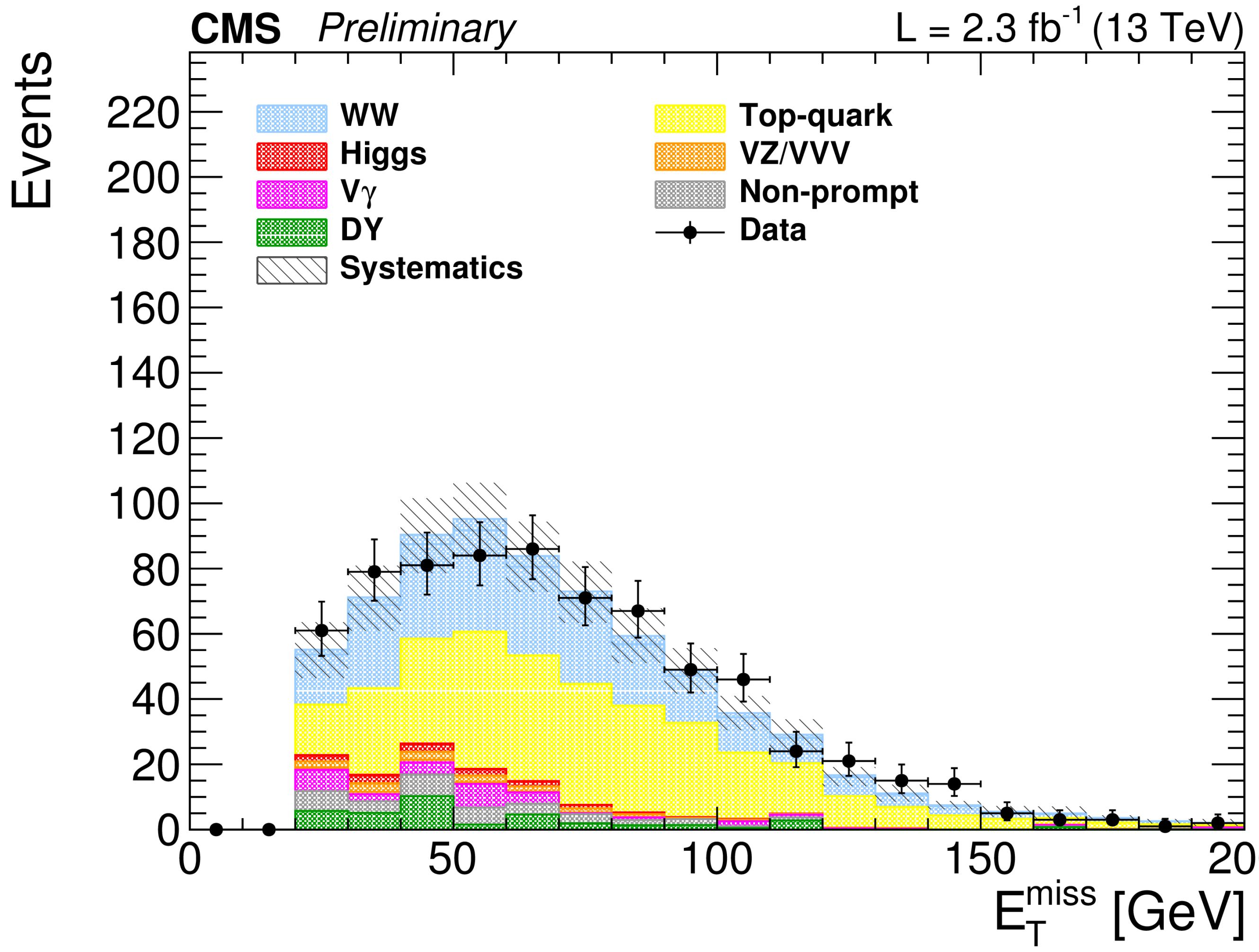
W^+W^-	**WW→ℓνℓν**	WW→ℓνℓν + aTCG	**WW→ℓνℓν**	WW→ℓνℓν + aTGC
WV	WZ→ℓνℓℓ + aTGC	WV→ℓνqq + aTCG	WZ→ℓνℓℓ + aTGC	WV→ℓνqq + aTCG
Wγ	[7 TeV measurement]()		Covered in Md Naimuddin’s talk (VBS)	

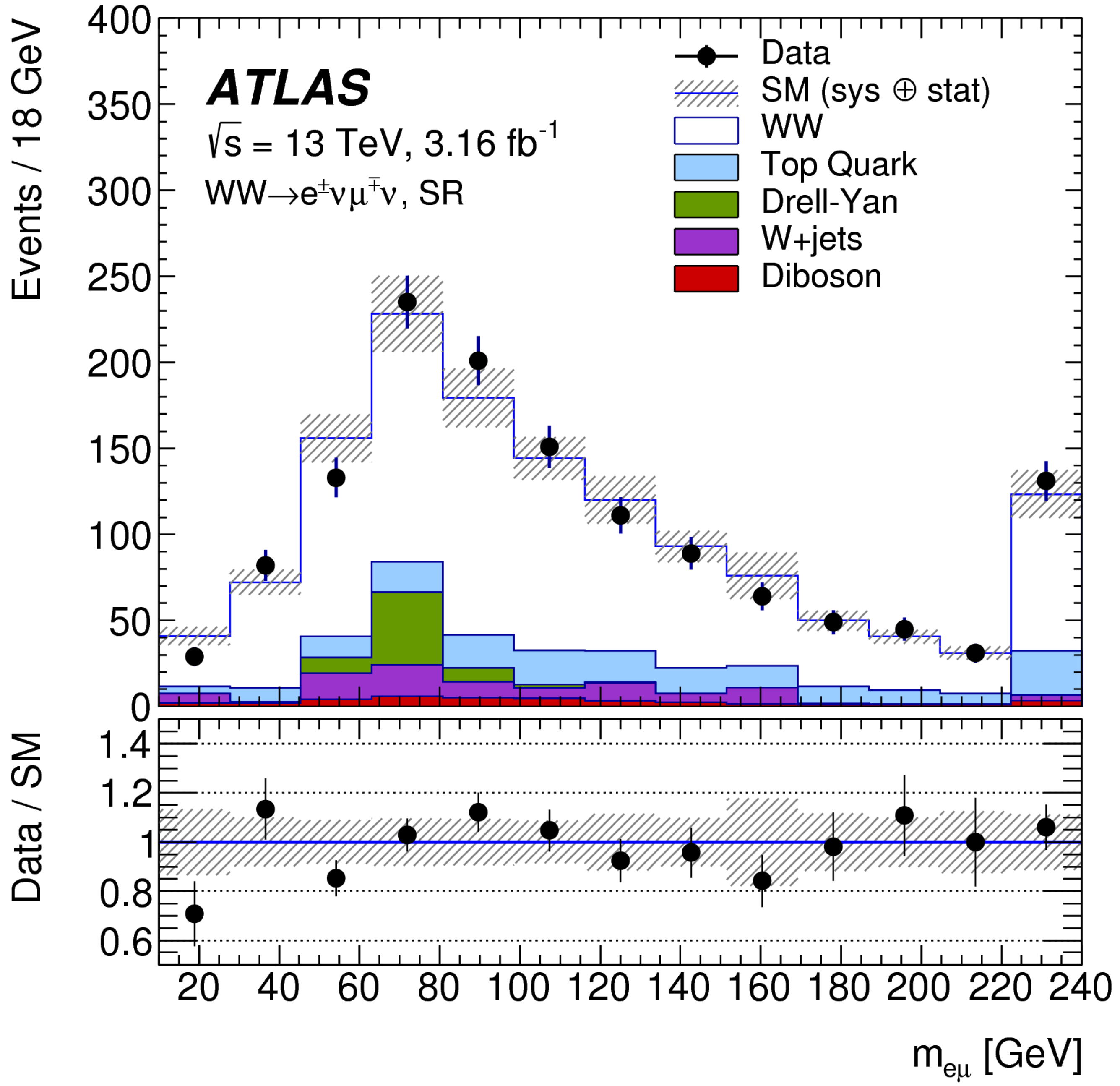
arXiv:1702.04519

CMS-PAS-SMP-16-006

WW→ℓνℓν at 13 TeV - Introduction

- Total (ATLAS & CMS) and fiducial (ATLAS) cross sections measured at 13 TeV
- *e*μ channel only, 0 jet (ATLAS) and 0,1 jet (CMS)
- Again, Higgs considered signal for ATLAS only
- DY and top backgrounds estimated using CR, W+jets with matrix method
- Main improvement from theory predictions





ATLAS

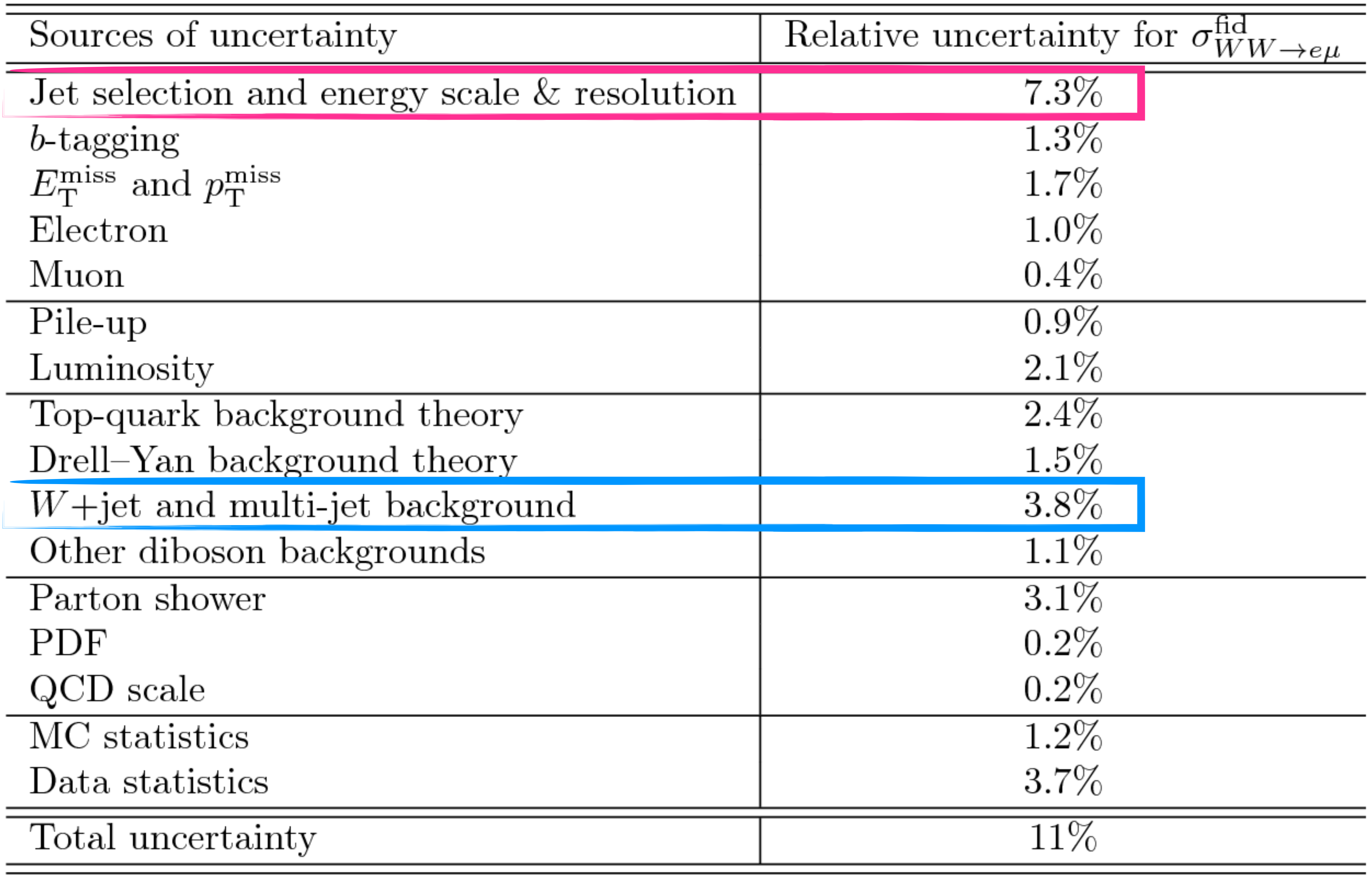
$pp \to WW$ sub-process	Order of α_s	σ^{tot}_{WW} [pb]	A [%]	$\sigma^{fid}_{WW\to e\mu}$ [fb]
$q\bar{q}$ [9,13]	$\mathcal{O}(\alpha_s^2)$	111.1 ± 2.8	16.20 ± 0.13	$422\,^{+12}_{-11}$
gg (non-resonant) [33]	$\mathcal{O}(\alpha_s^3)$	$6.82\,^{+0.42}_{-0.55}$	$28.1\,^{+2.7}_{-2.3}$	44.9 ± 7.2
$gg \to H \to WW$ [67][30]	$\mathcal{O}(\alpha_s^5)$ tot. / $\mathcal{O}(\alpha_s^3)$ fid.	$10.45\,^{+0.61}_{-0.79}$	4.5 ± 0.6	11.0 ± 2.1
$q\bar{q}$ + gg (non-resonant) + $gg \to H \to WW$	nNNLO+H	$128.4\,^{+3.5}_{-3.8}$	$15.87\,^{+0.17}_{-0.14}$	478 ± 17

arXiv:1702.04519

CMS-PAS-SMP-16-006

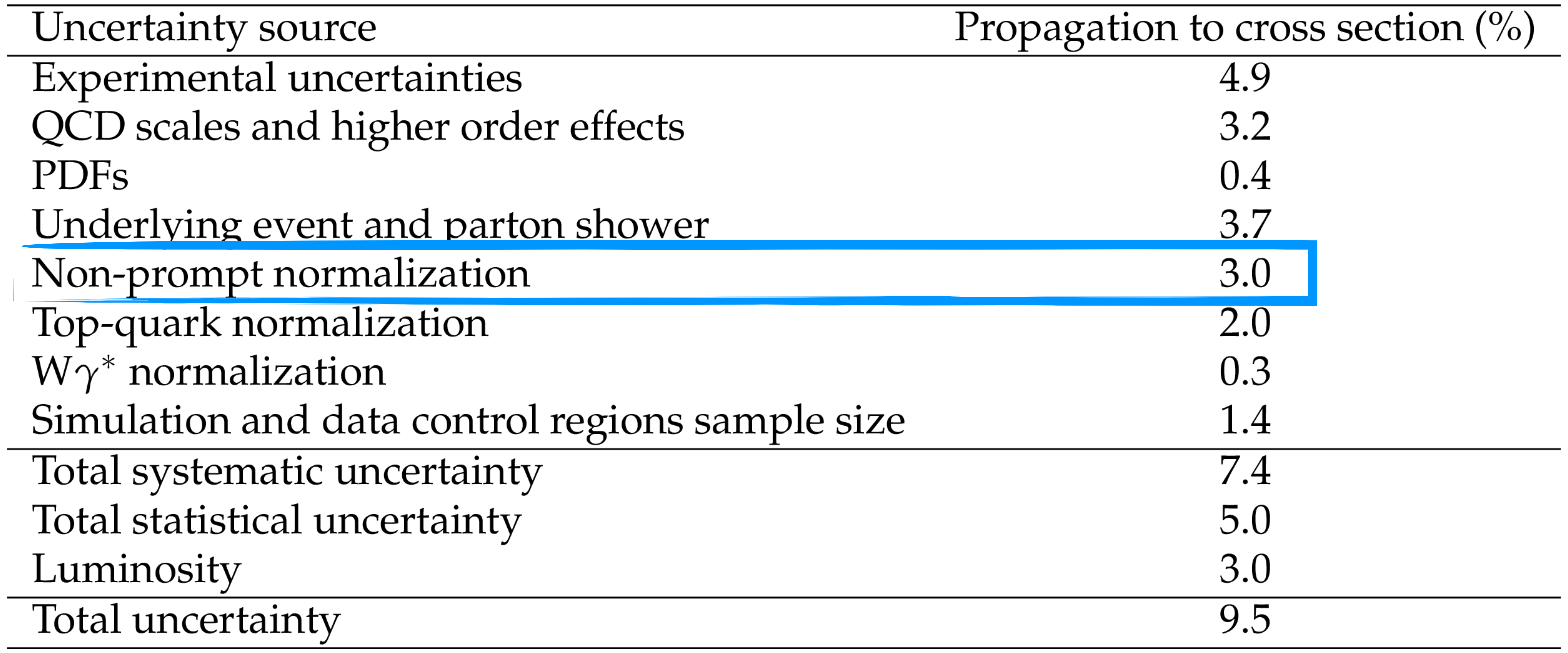
WW$\to\ell\nu\ell\nu$ at 13 TeV - Uncertainties

CMS



Sources of uncertainty	Relative uncertainty for $\sigma^{\text{fid}}_{WW\to e\mu}$
Jet selection and energy scale & resolution	7.3%
b-tagging	1.3%
$E_{\text{T}}^{\text{miss}}$ and $p_{\text{T}}^{\text{miss}}$	1.7%
Electron	1.0%
Muon	0.4%
Pile-up	0.9%
Luminosity	2.1%
Top-quark background theory	2.4%
Drell–Yan background theory	1.5%
W+jet and multi-jet background	3.8%
Other diboson backgrounds	1.1%
Parton shower	3.1%
PDF	0.2%
QCD scale	0.2%
MC statistics	1.2%
Data statistics	3.7%
Total uncertainty	11%

ATLAS



Uncertainty source	Propagation to cross section (%)
Experimental uncertainties	4.9
QCD scales and higher order effects	3.2
PDFs	0.4
Underlying event and parton shower	3.7
Non-prompt normalization	3.0
Top-quark normalization	2.0
Wγ^* normalization	0.3
Simulation and data control regions sample size	1.4
Total systematic uncertainty	7.4
Total statistical uncertainty	5.0
Luminosity	3.0
Total uncertainty	9.5

dominant experimental uncertainties

in ATLAS from JES & JER

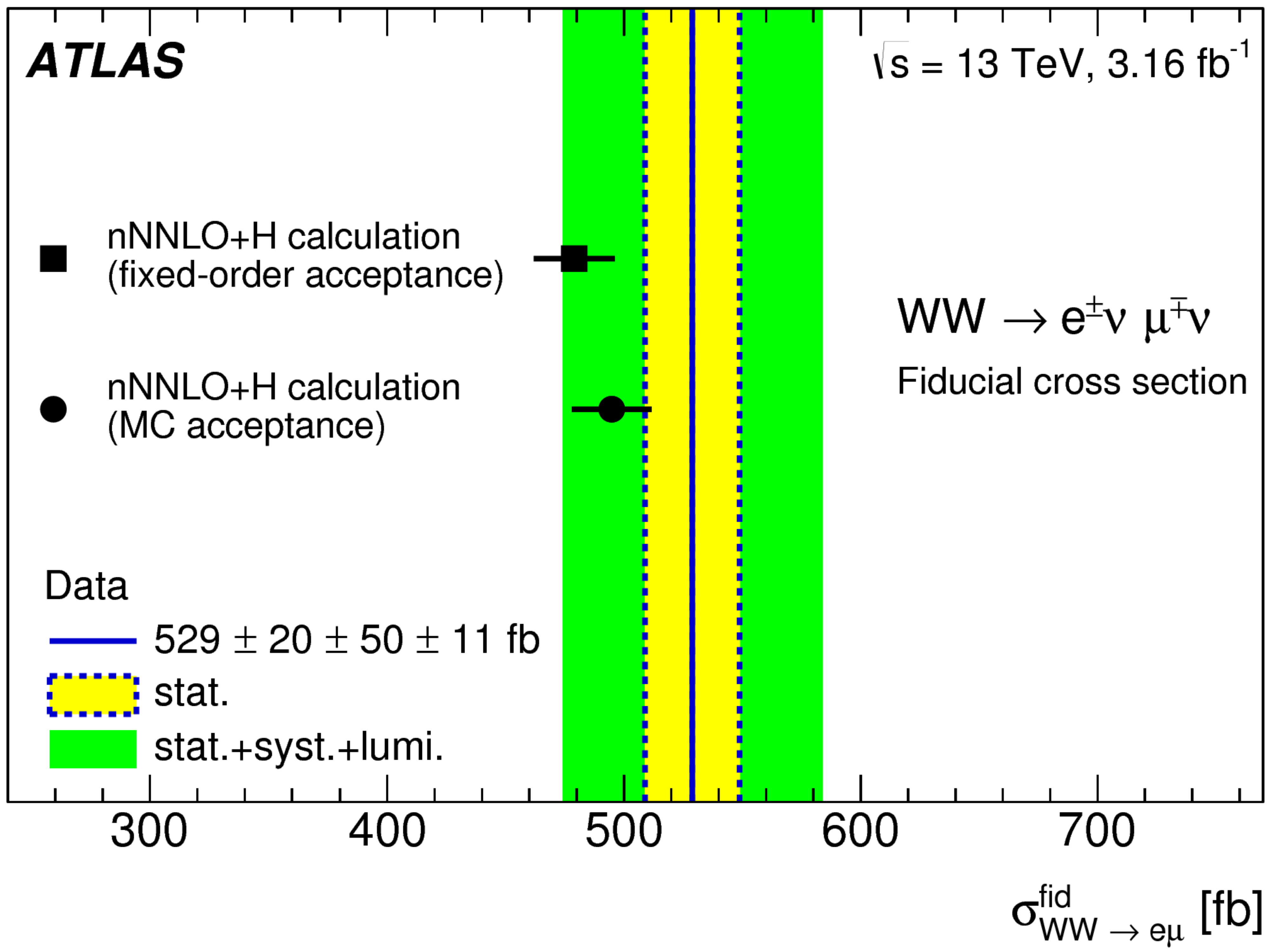
dominant background uncertainties

in both ATLAS and CMS from estimation of fakes

arXiv:1702.04519

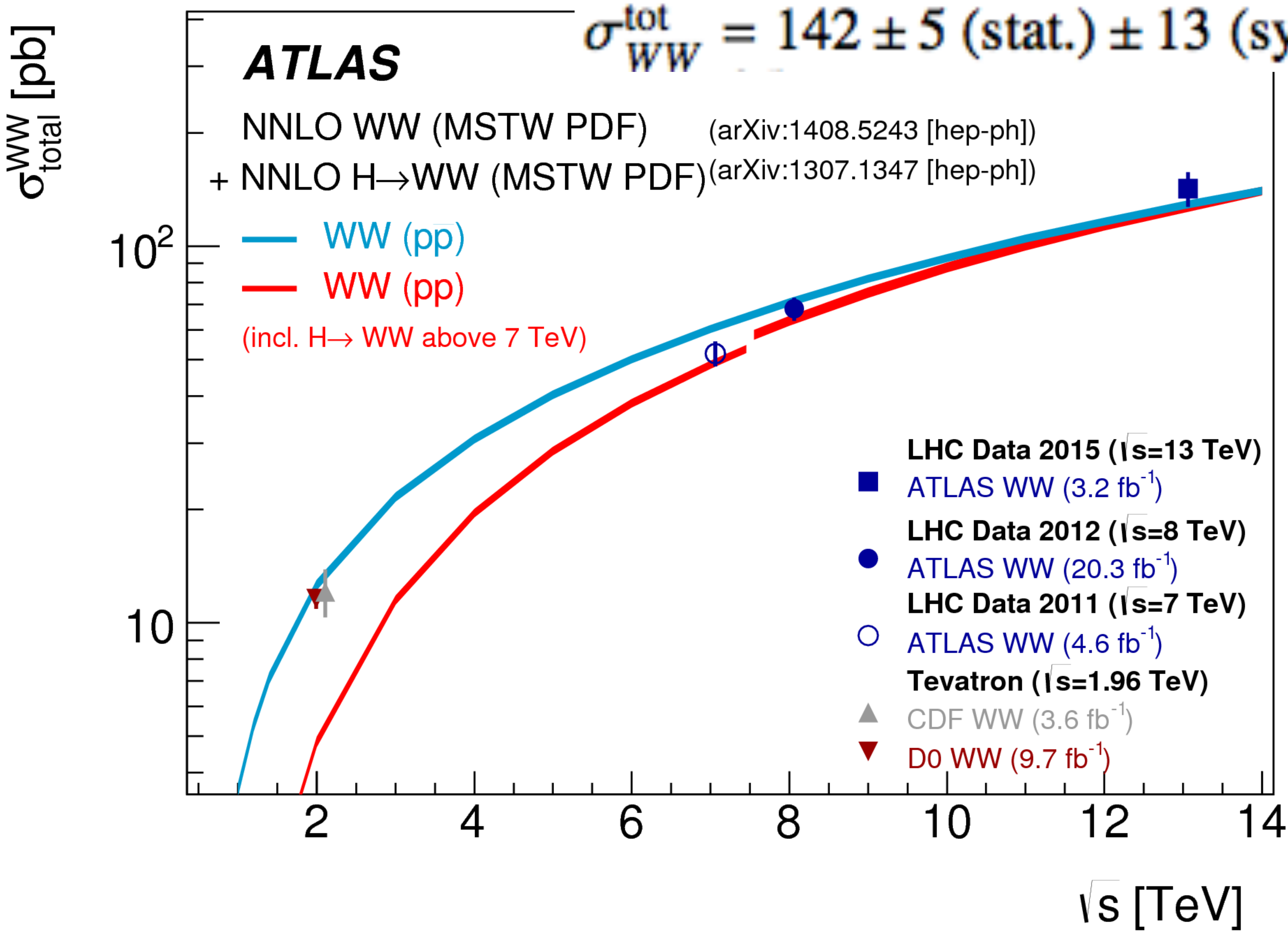
CMS-PAS-SMP-16-006

WW→ℓνℓν at 13 TeV - Cross Sections



$$\sigma^{tot}_{WW} = 142 \pm 5\,(\text{stat.}) \pm 13\,(\text{syst.}) \pm 3\,(\text{lumi.})\ \text{pb}.$$

ATLAS



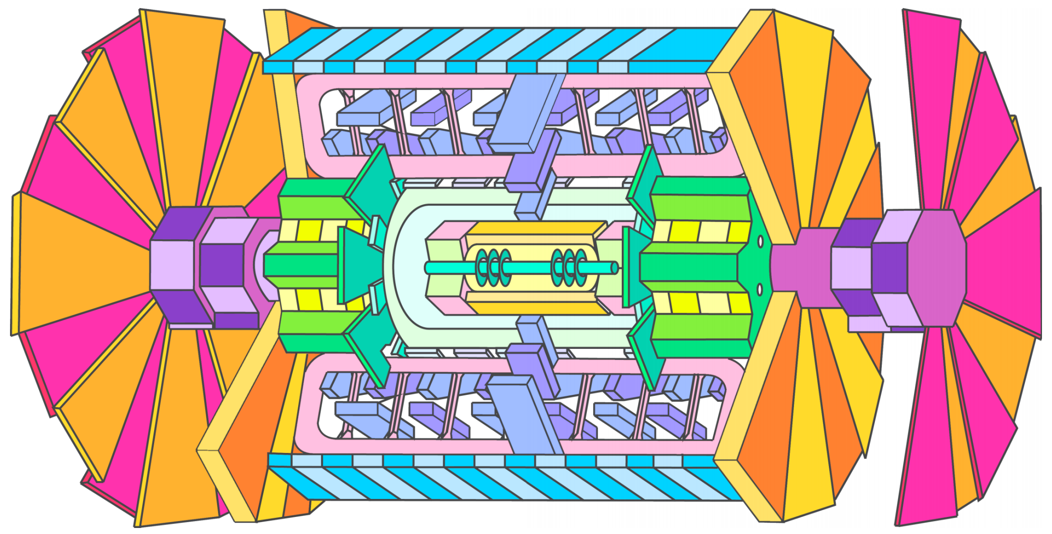
CMS

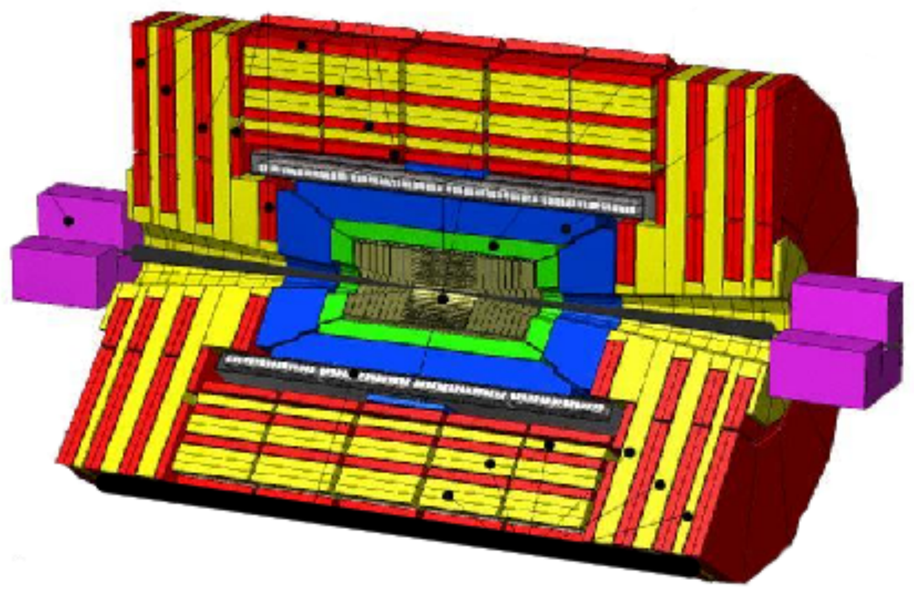
Category	Value ± stat. ± exp. syst. ± theo. syst. ± lumi. [pb]
0-jet	113.6 ± 6.3 ± 5.1 ± 6.5 ± 3.3
1-jet	135.3 ± 15.4 ± 34.0 ± 14.4 ± 6.0
Combination	115.3 ± 5.8 ± 5.7 ± 6.4 ± 3.6

13TeV

8 TeV

ATLAS and CMS diboson results focusing on aTGCs



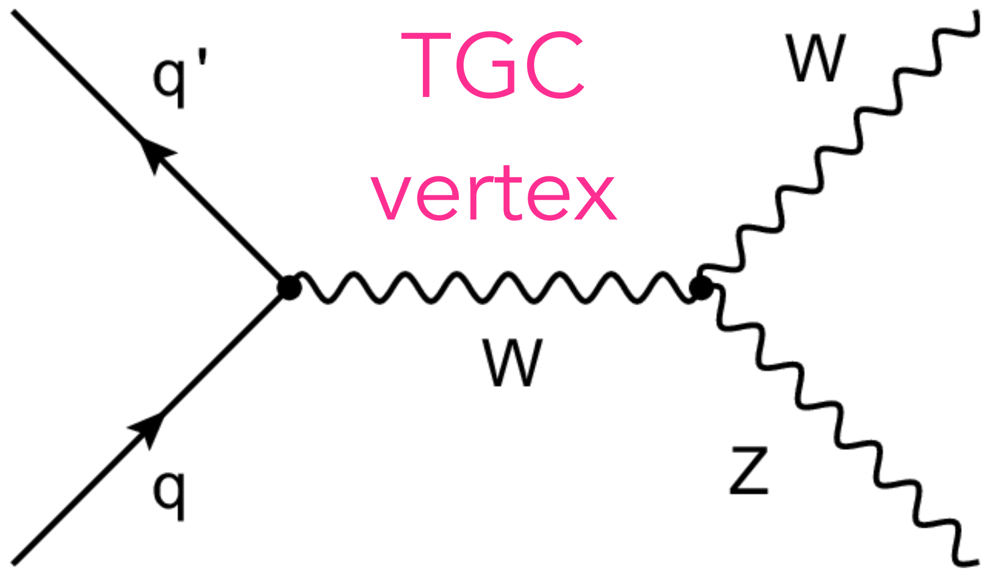


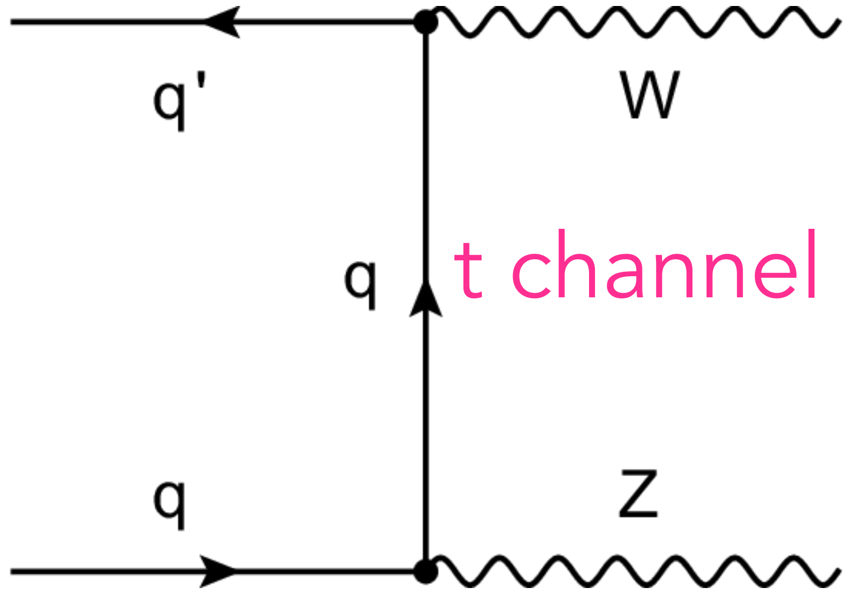
W^+W^-	WW→ℓνℓν	WW→ℓνℓν + aTCG	WW→ℓνℓν	WW→ℓνℓν + aTGC
WV	**WZ→ℓνℓℓ + aTGC**	WV→ℓνqq + aTCG	**WZ→ℓνℓℓ + aTGC**	WV→ℓνqq + aTCG
Wγ	7 TeV measurement		Covered in Md Naimuddin's talk (VBS)	

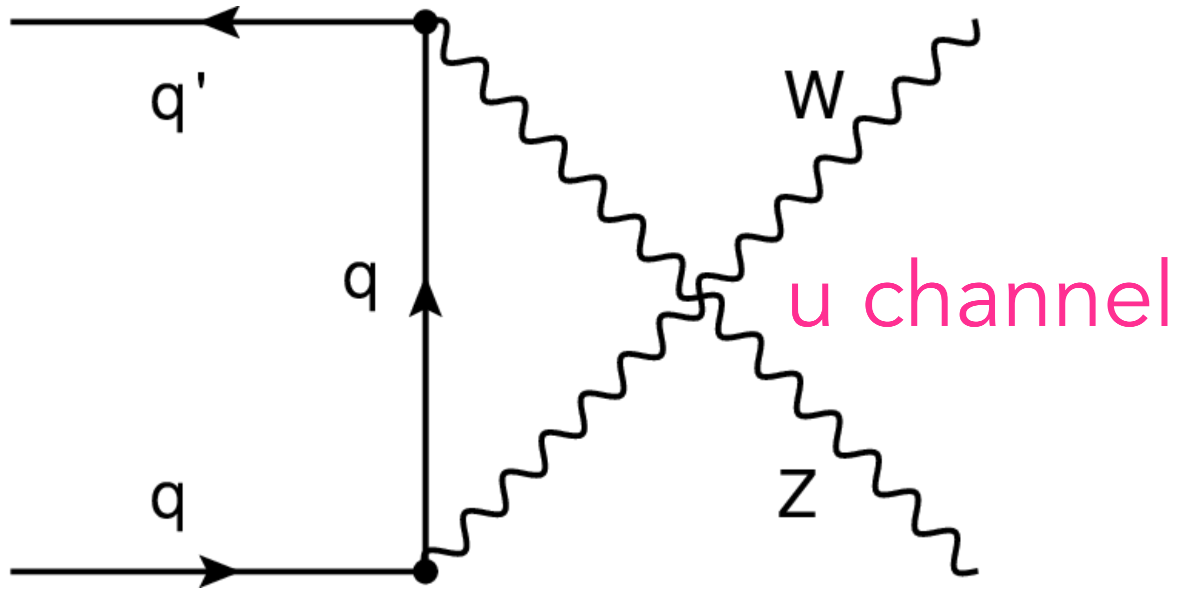
ATLAS-CONF-2016-043

Eur. Phys. J. C 77 (2017) 236

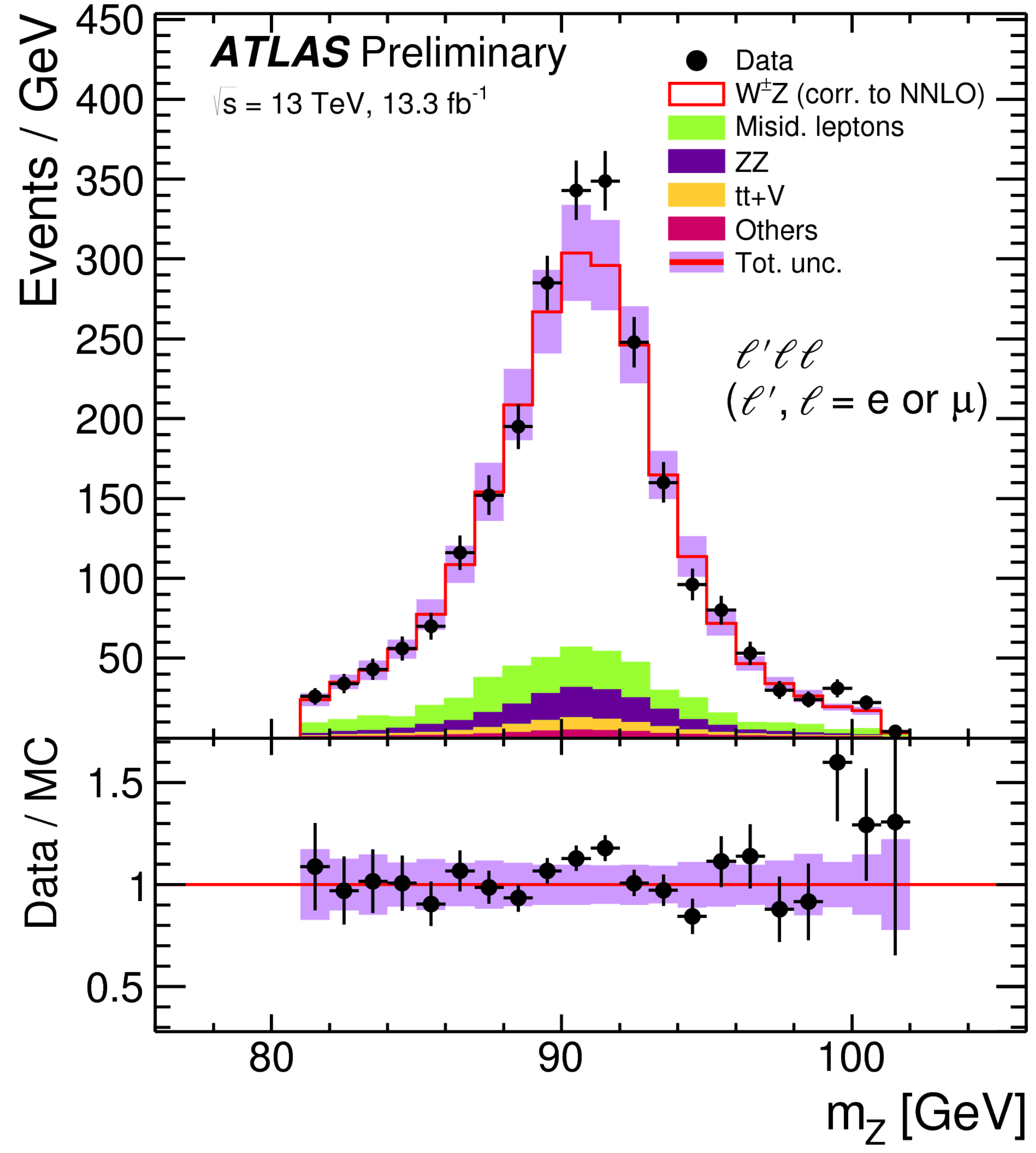
WZ→$\ell\nu\ell\ell$ + aTGC at 13 and 8 TeV - Introduction







- The WZ cross section is sensitive to WWZ couplings
- Fully leptonic final state in 4 channels combining e and μ
- The presence of aTGC would affect the $W^{\pm}Z$ integrated cross section and manifest itself as an increased yield of events at high values of p_T^Z or m_T^{WZ}
- aTGC confidence intervals determined from differential cross section distributions vs m_T^{WZ} (ATLAS) or p_T^Z (CMS)



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WZ→$\ell\nu\ell\ell$ + aTGC at 13 and 8 TeV - Samples

Signal

ATLAS

- Powheg-Box v2+Pythia8 (NLO) (NLO Sherpa 2.1.1 for sys)
- MC@NLO for aTGC signal events scaled by 1.11 based on NNLO QCD calculations

CMS

- MadGraph5 (LO)
- For aTGC modelling NLO MCFM 6.3 used to compute weights

Backgrounds with 3 or more prompt leptons

ATLAS

- qq->ZZ, tt and single top: Powheg-Box v2+Pythia (NLO)
- gg->ZZ: Sherpa (LO)
- ttV and tZ: MadGraph5 (LO)+Pythia8or6
- Other backgrounds evaluated using data-driven techniques

CMS

- qq->ZZ, tt and tW: Powheg 2(NLO)
- gg->ZZ: GG2ZZ (LO)
- Other backgrounds use MadGraph (LO)

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WZ→$\ell\nu\ell\ell$ + aTGC at 13 and 8 TeV - Selection

ATLAS

- Event Selection 13 TeV
- Various single lepton triggers (>24+ GeV)
- 3 “medium” isolated leptons with $p_{T\ell} > 15$ GeV (at least one with p_T>25 GeV and trigger-matched)
  - one SF pair with OS and $m_{\ell\ell}$ within 10 GeV of Z mass
  - m_T(3rd lep + ETmiss) > 30 GeV and p_T 3rd lep > 20 GeV (and tight ID for electrons)
- veto on 4th loose lepton with p_T > 7 GeV

CMS

- Event Selection 8 TeV
- Dilepton trigger (17,8 GeV)
- 3 isolated leptons with $p_{T\ell} > 10$ GeV
  .
  - one SF pair with OS and $m_{\ell\ell}$ within 20 GeV of Z mass
  - ETmiss > 30 GeV and p_T 3rd lep > 20 GeV (and tight ID for electrons)
- veto on 4th loose lepton with p_T > 10 GeV
- $m_{3\ell}$ > 100 GeV

ATLAS-CONF-2016-043

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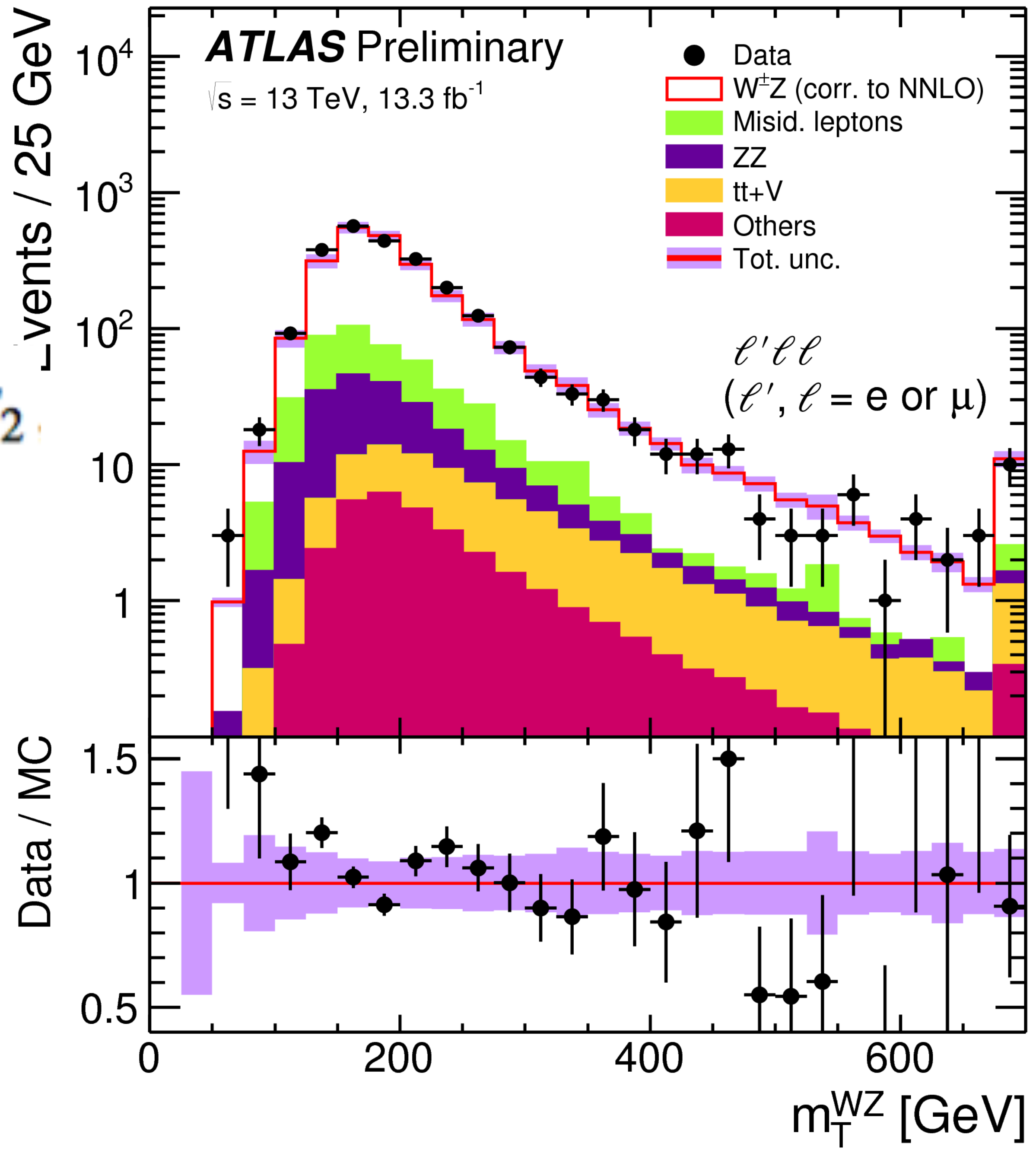
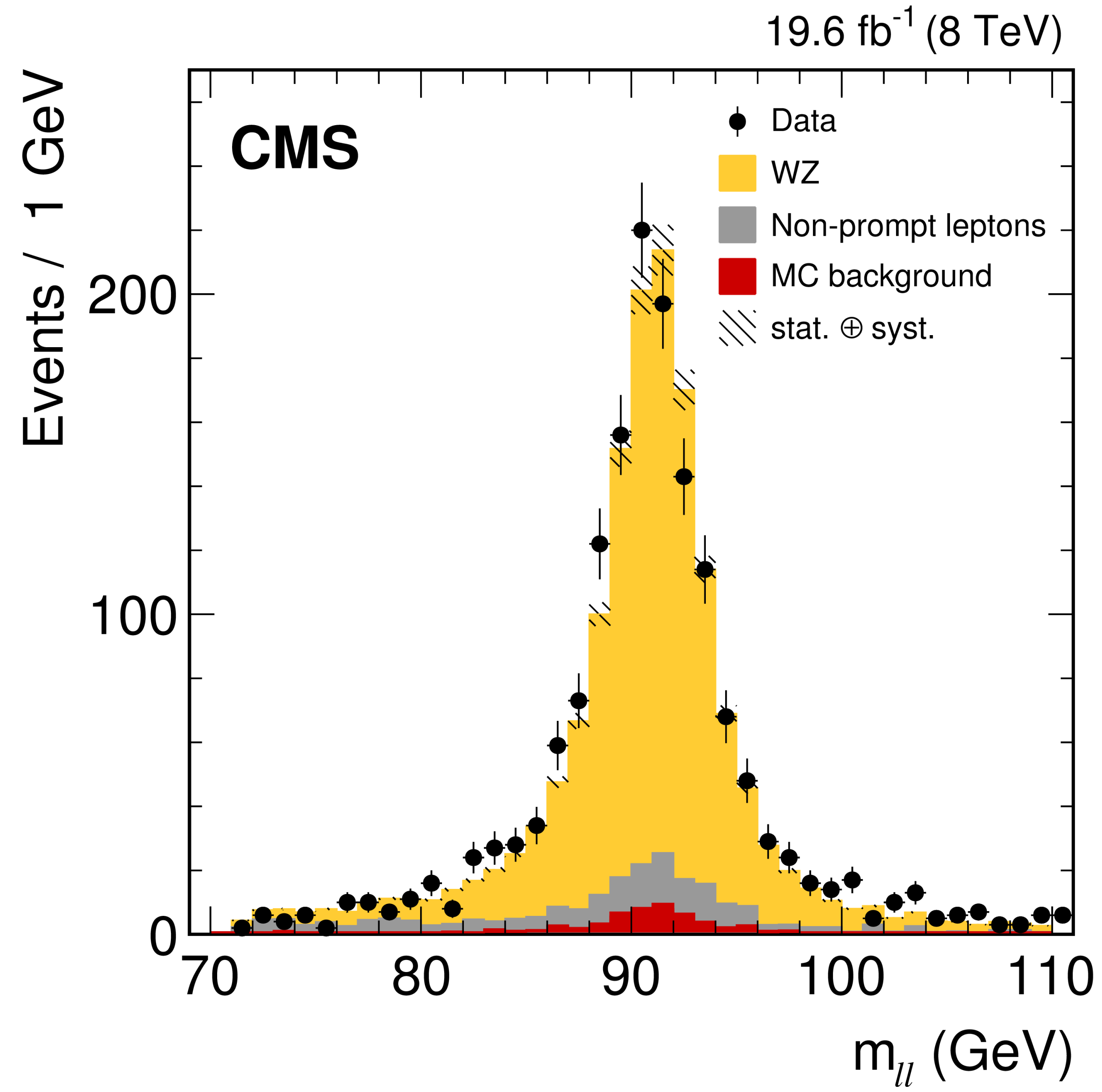
WZ→$\ell\nu\ell\ell$ + aTGC at 13 and 8 TeV - Backgrounds

- Reducible Backgrounds (Z+jets, Vγ, ttbar, WW) estimated in control regions using matrix method with loose vs tight classification

$$N_{\text{reducible}} = N^{\text{red.}}_{\text{TTL}}F_3 + N^{\text{red.}}_{\text{TLT}}F_2 + N^{\text{red.}}_{\text{LTT}}F_1 - N^{\text{red.}}_{\text{TLL}}F_2F_3 - N^{\text{red.}}_{\text{LTL}}F_1F_3 - N^{\text{red.}}_{\text{LLT}}F_1F_2$$

  - Misid leptons - 60% of total background
- Irreducible background (ZZ, ttV, VVV, tZ) estimated from simulation
  - 70% of irreducible background from ZZ
- WZ with tau decays considered background, estimated from simulation (about 6.5 to 7.6% in CMS case)
  - Dominated by WZ events where the W decays to a tau





ATLAS

Channel	eee	μee	$e\mu\mu$	$\mu\mu\mu$	All
Data	516	537	612	752	2417
Total Expected	504 ± 7	588 ± 5	552 ± 6	671 ± 4	2315 ± 11
$W^{\pm}Z$	354.0± 2.5	442.7± 2.9	453.2± 2.9	581.1± 3.4	1831 ± 6
ZZ	27.7 ± 0.4	36.0 ± 0.5	32.9 ± 0.4	46.5 ± 0.5	143.2± 0.9
Misid. leptons	103 ± 7	87 ± 4	45 ± 6	17.9 ± 2.5	253 ± 10
$t\bar{t}$+V	12.8 ± 0.1	14.49± 0.13	13.50± 0.12	15.59±0.13	56.41±0.25
tZ	5.506±0.029	6.674±0.033	6.653±0.032	8.22 ±0.04	27.05±0.07
VVV	0.974±0.029	1.219±0.034	1.166±0.031	1.44 ±0.04	4.80 ±0.07

ATLAS-CONF-2016-043

WZ→$\ell\nu\ell\ell$ + aTGC at 13 and 8 TeV - Uncertainties

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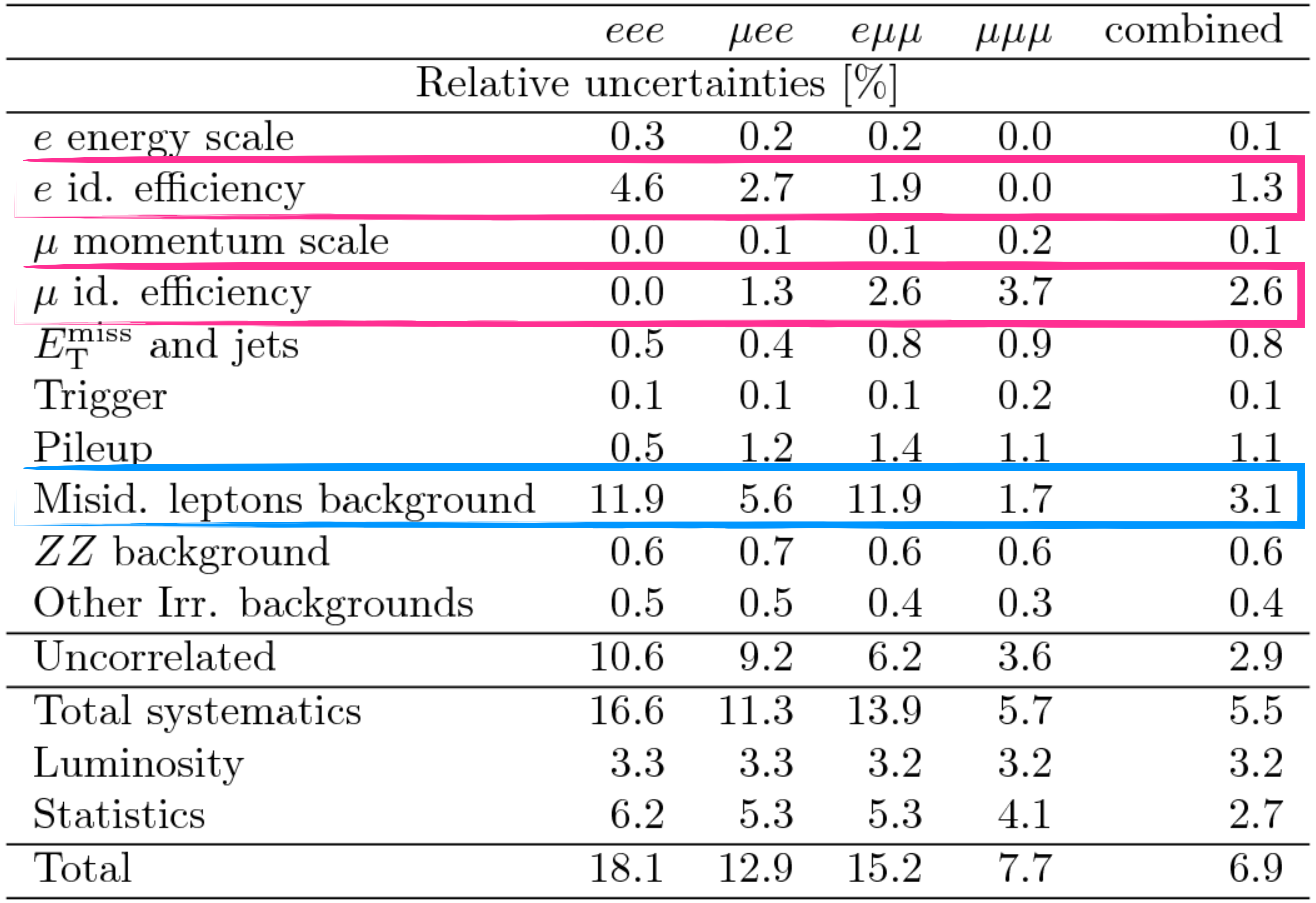
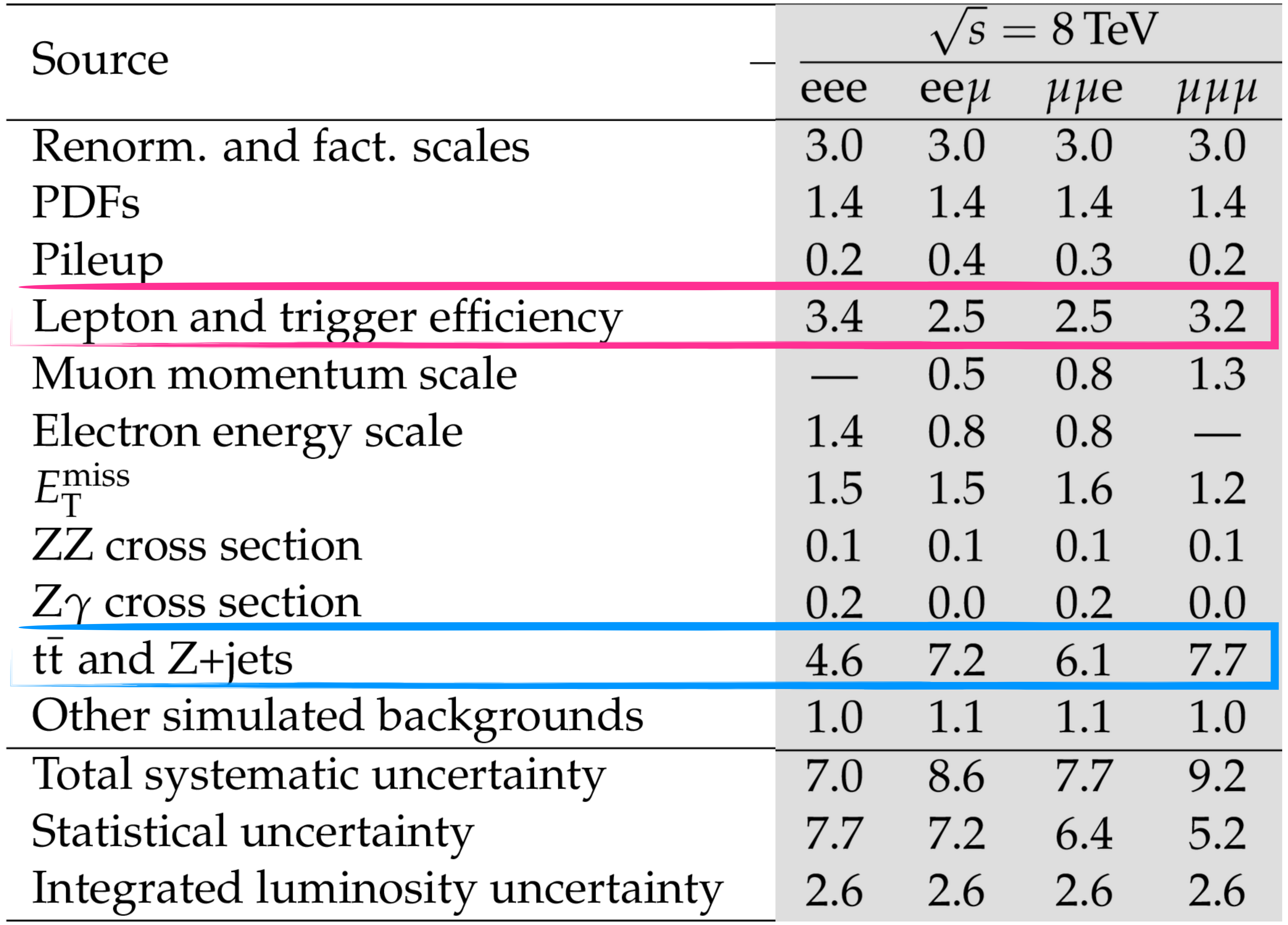
ATLAS



	eee	μee	$e\mu\mu$	$\mu\mu\mu$	combined
Relative uncertainties [%]					
e energy scale	0.3	0.2	0.2	0.0	0.1
e id. efficiency	4.6	2.7	1.9	0.0	1.3
μ momentum scale	0.0	0.1	0.1	0.2	0.1
μ id. efficiency	0.0	1.3	2.6	3.7	2.6
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jets	0.5	0.4	0.8	0.9	0.8
Trigger	0.1	0.1	0.1	0.2	0.1
Pileup	0.5	1.2	1.4	1.1	1.1
Misid. leptons background	11.9	5.6	11.9	1.7	3.1
ZZ background	0.6	0.7	0.6	0.6	0.6
Other Irr. backgrounds	0.5	0.5	0.4	0.3	0.4
Uncorrelated	10.6	9.2	6.2	3.6	2.9
Total systematics	16.6	11.3	13.9	5.7	5.5
Luminosity	3.3	3.3	3.2	3.2	3.2
Statistics	6.2	5.3	5.3	4.1	2.7
Total	18.1	12.9	15.2	7.7	6.9

CMS



Source	$\sqrt{s} = 8\,\mathrm{TeV}$			
	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$
Renorm. and fact. scales	3.0	3.0	3.0	3.0
PDFs	1.4	1.4	1.4	1.4
Pileup	0.2	0.4	0.3	0.2
Lepton and trigger efficiency	3.4	2.5	2.5	3.2
Muon momentum scale	—	0.5	0.8	1.3
Electron energy scale	1.4	0.8	0.8	—
$E_{\mathrm{T}}^{\mathrm{miss}}$	1.5	1.5	1.6	1.2
ZZ cross section	0.1	0.1	0.1	0.1
Zγ cross section	0.2	0.0	0.2	0.0
$\mathrm{t\bar{t}}$ and Z+jets	4.6	7.2	6.1	7.7
Other simulated backgrounds	1.0	1.1	1.1	1.0
Total systematic uncertainty	7.0	8.6	7.7	9.2
Statistical uncertainty	7.7	7.2	6.4	5.2
Integrated luminosity uncertainty	2.6	2.6	2.6	2.6

dominant experimental uncertainties from lepton efficiencies

dominant background uncertainties from fakes

ATLAS-CONF-2016-043

$WZ\to\ell\nu\ell\ell$ + aTGC at 13 and 8 TeV - Cross Section

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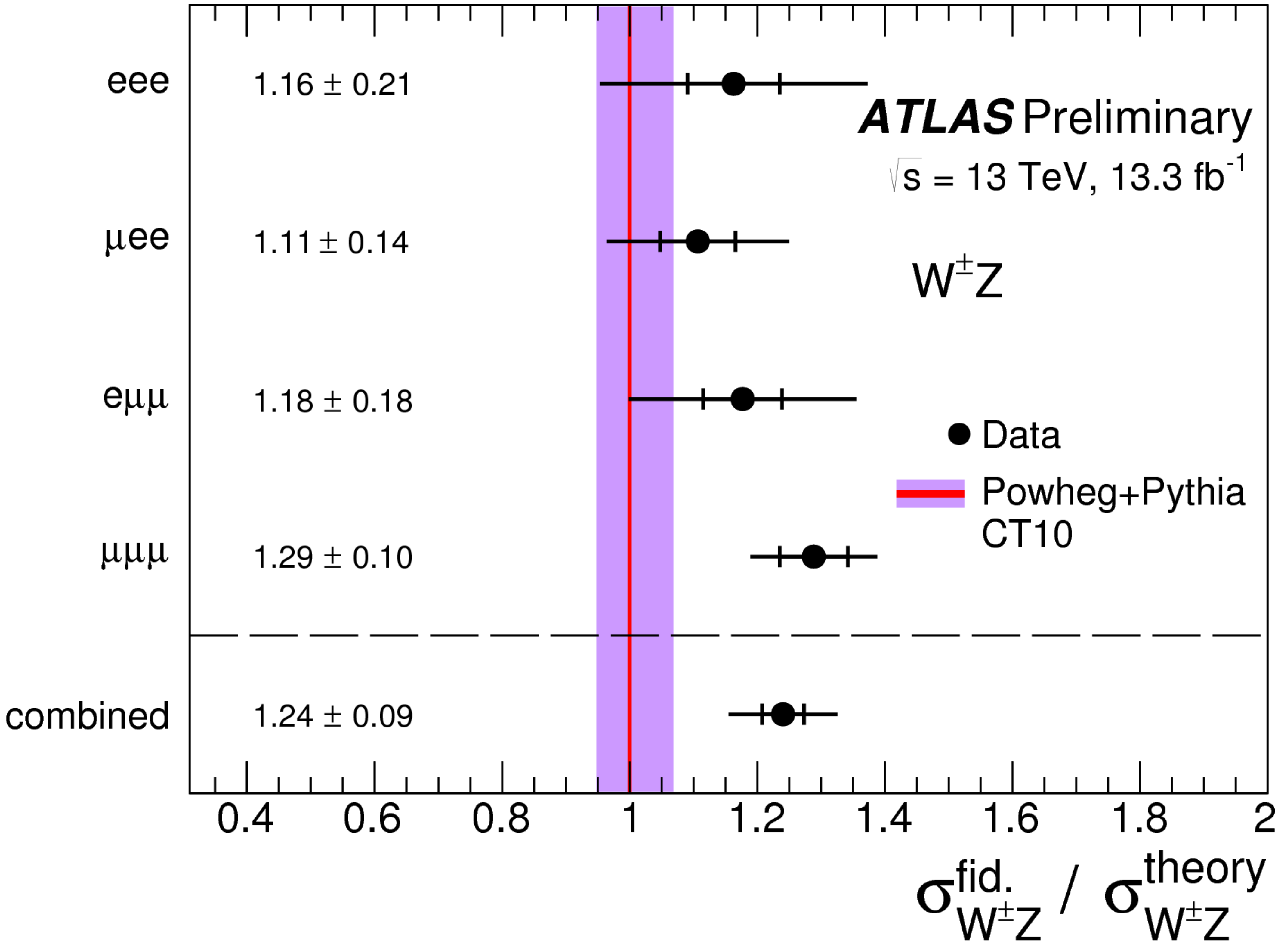

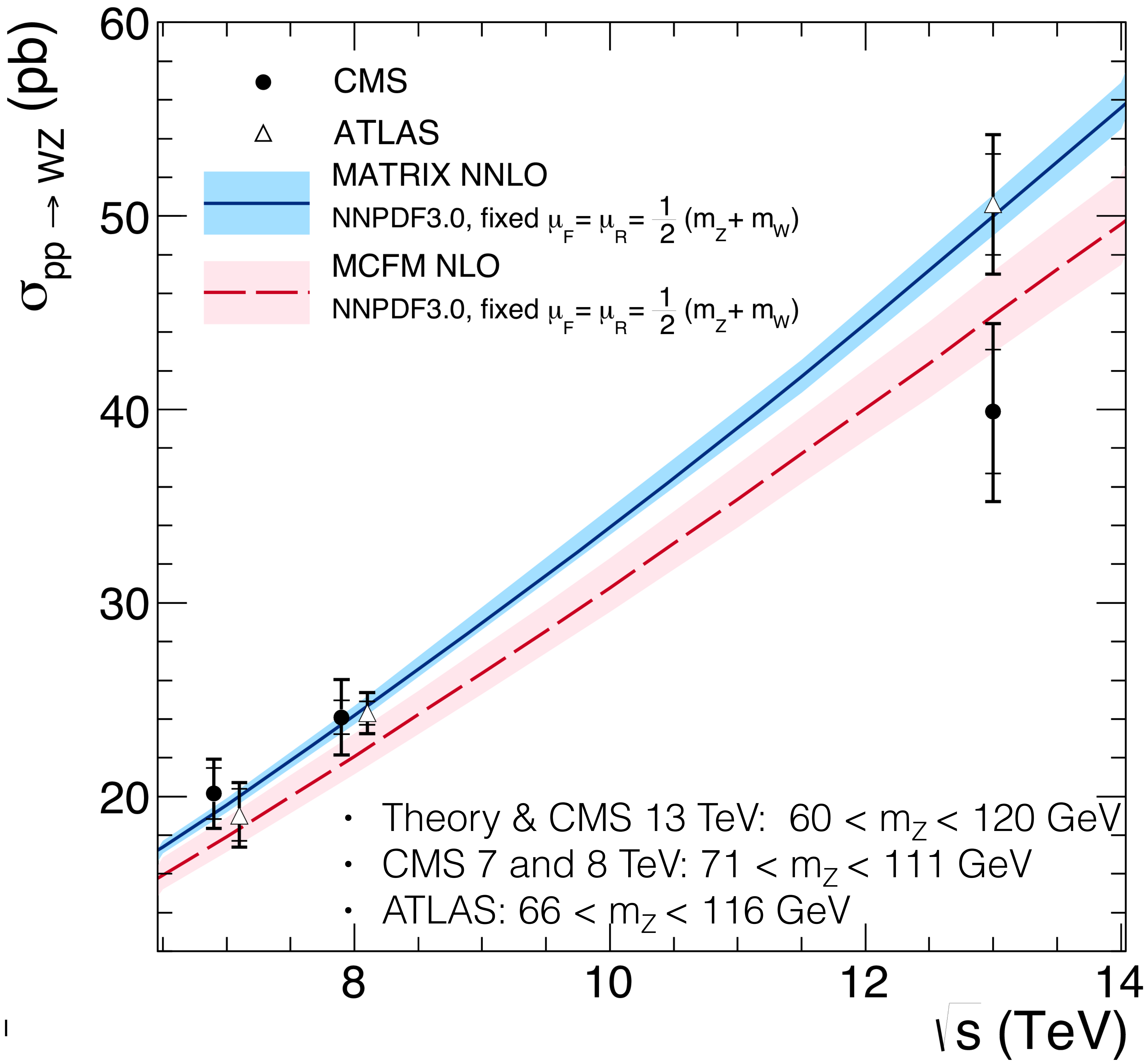

- Theory & CMS 13 TeV: $60 < m_Z < 120$ GeV
- CMS 7 and 8 TeV: $71 < m_Z < 111$ GeV
- ATLAS: $66 < m_Z < 116$ GeV

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WZ→$\ell\nu\ell\ell$ + aTGC at 13 and 8 TeV - Differential

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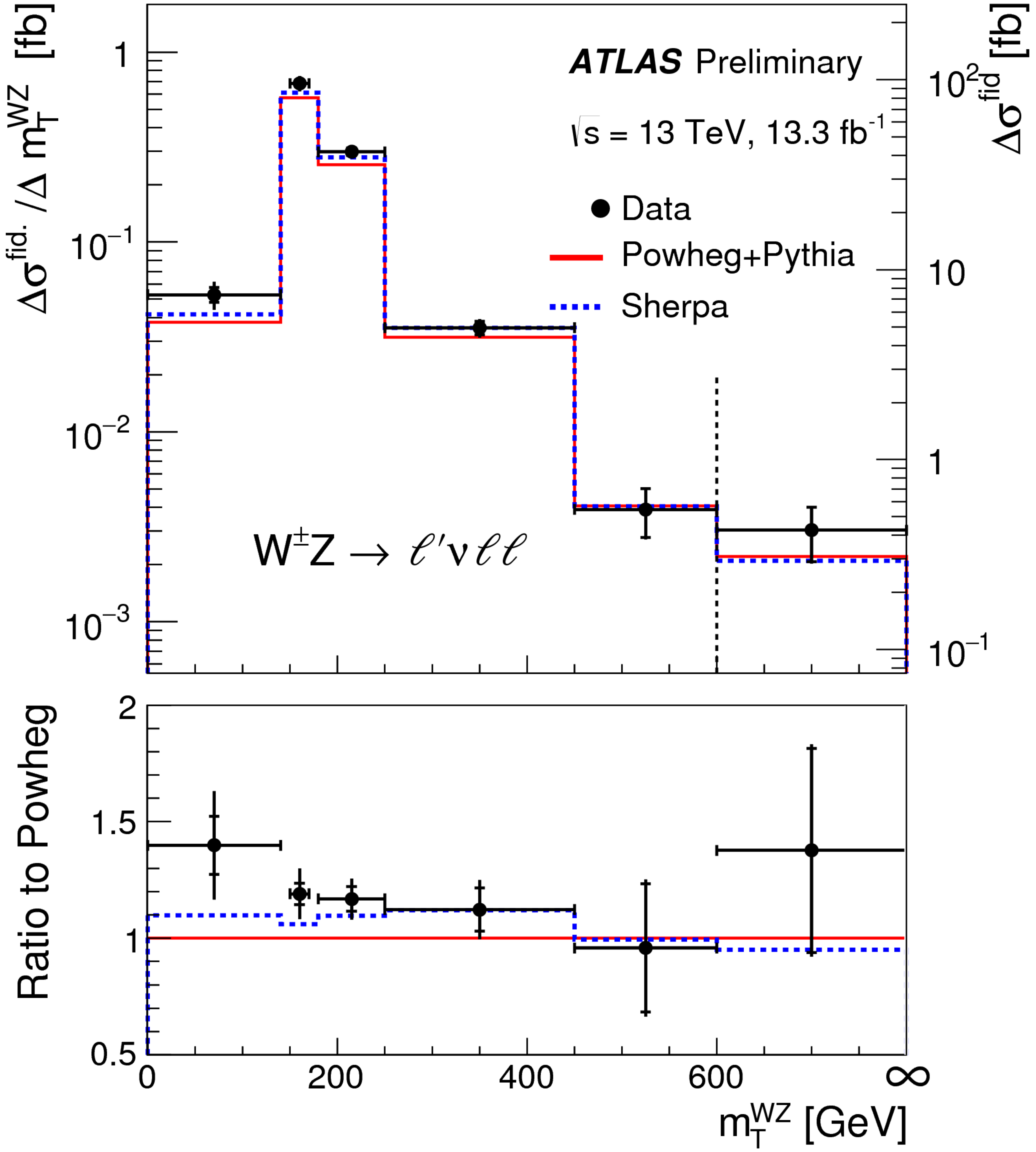
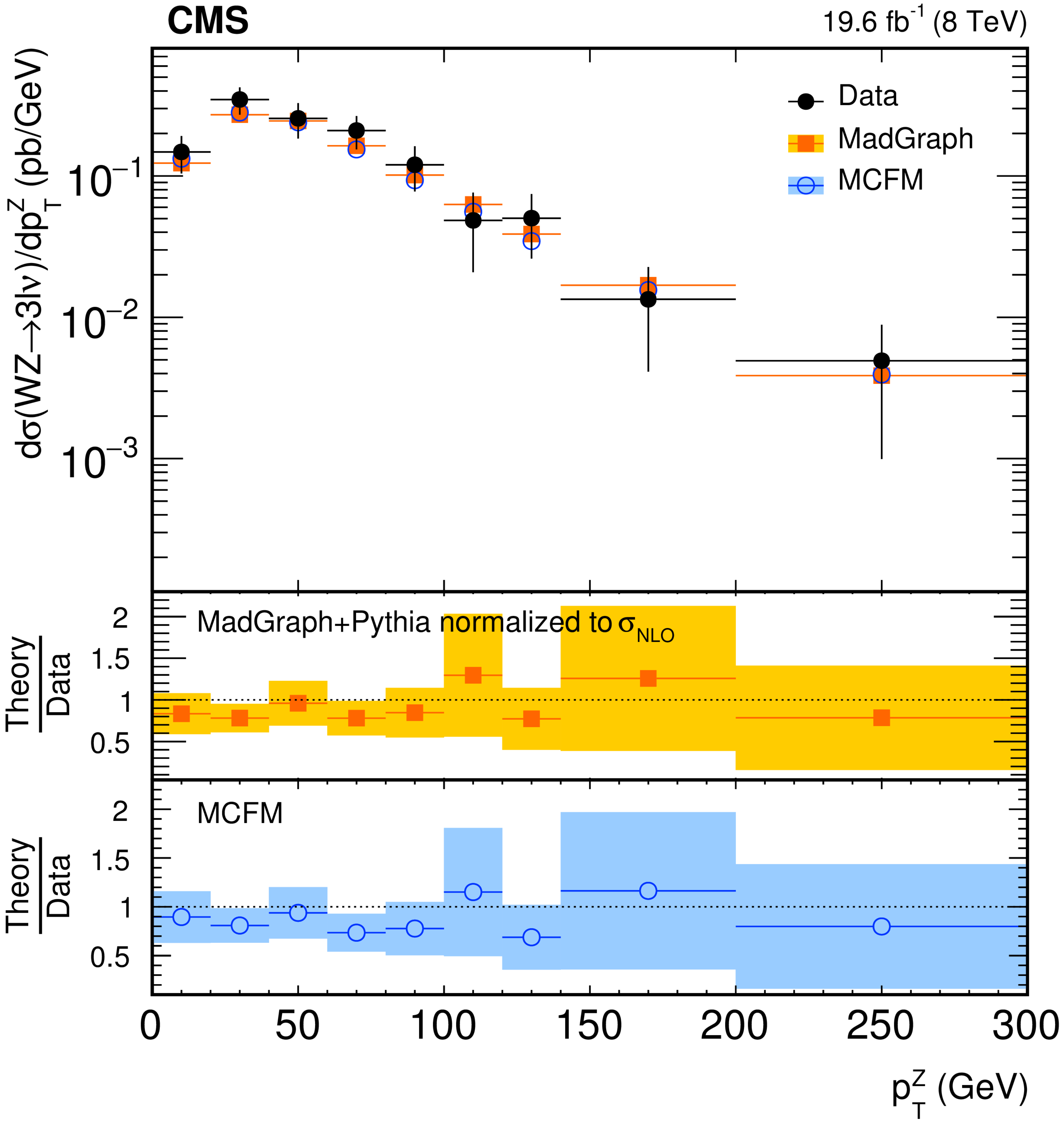
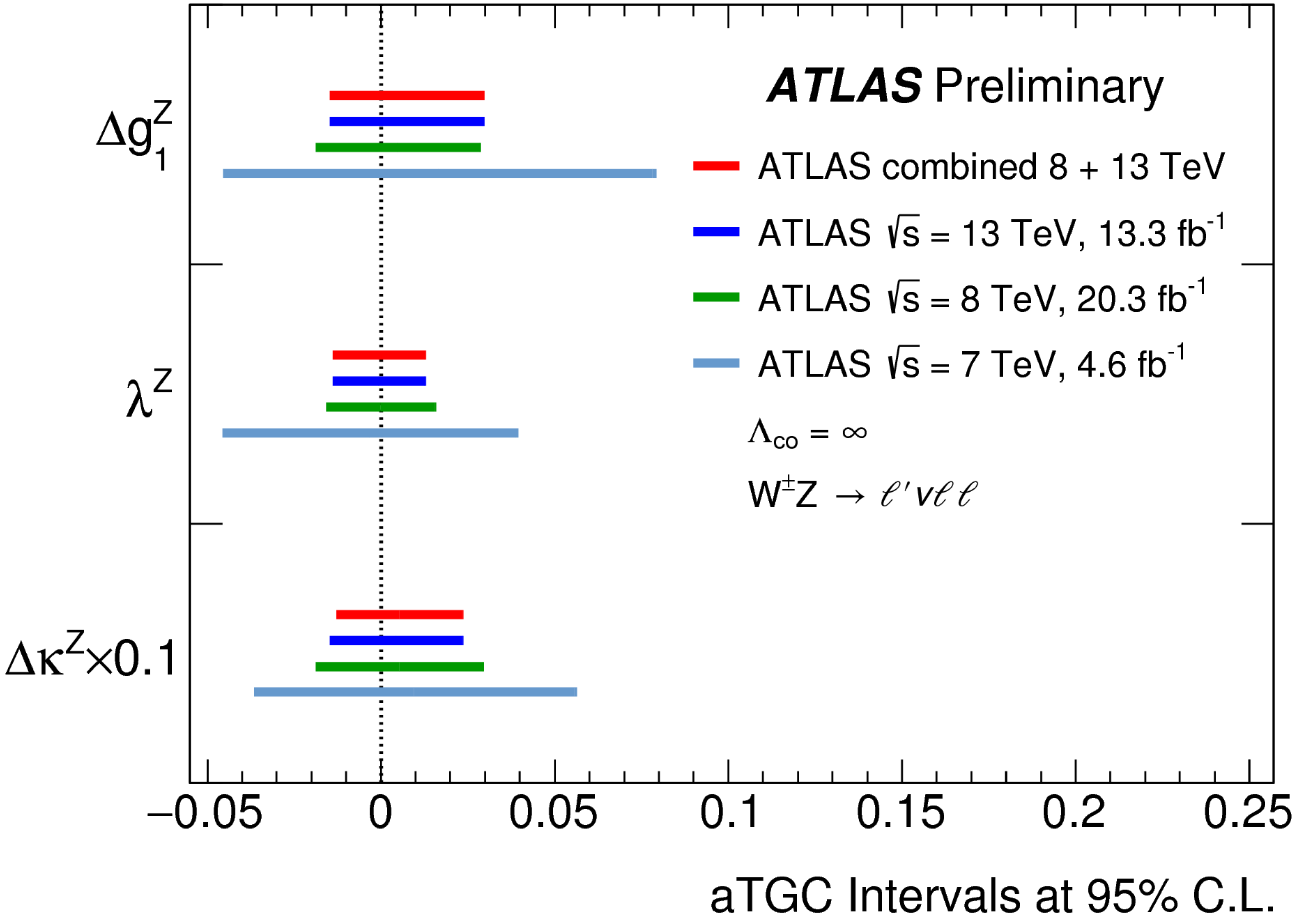
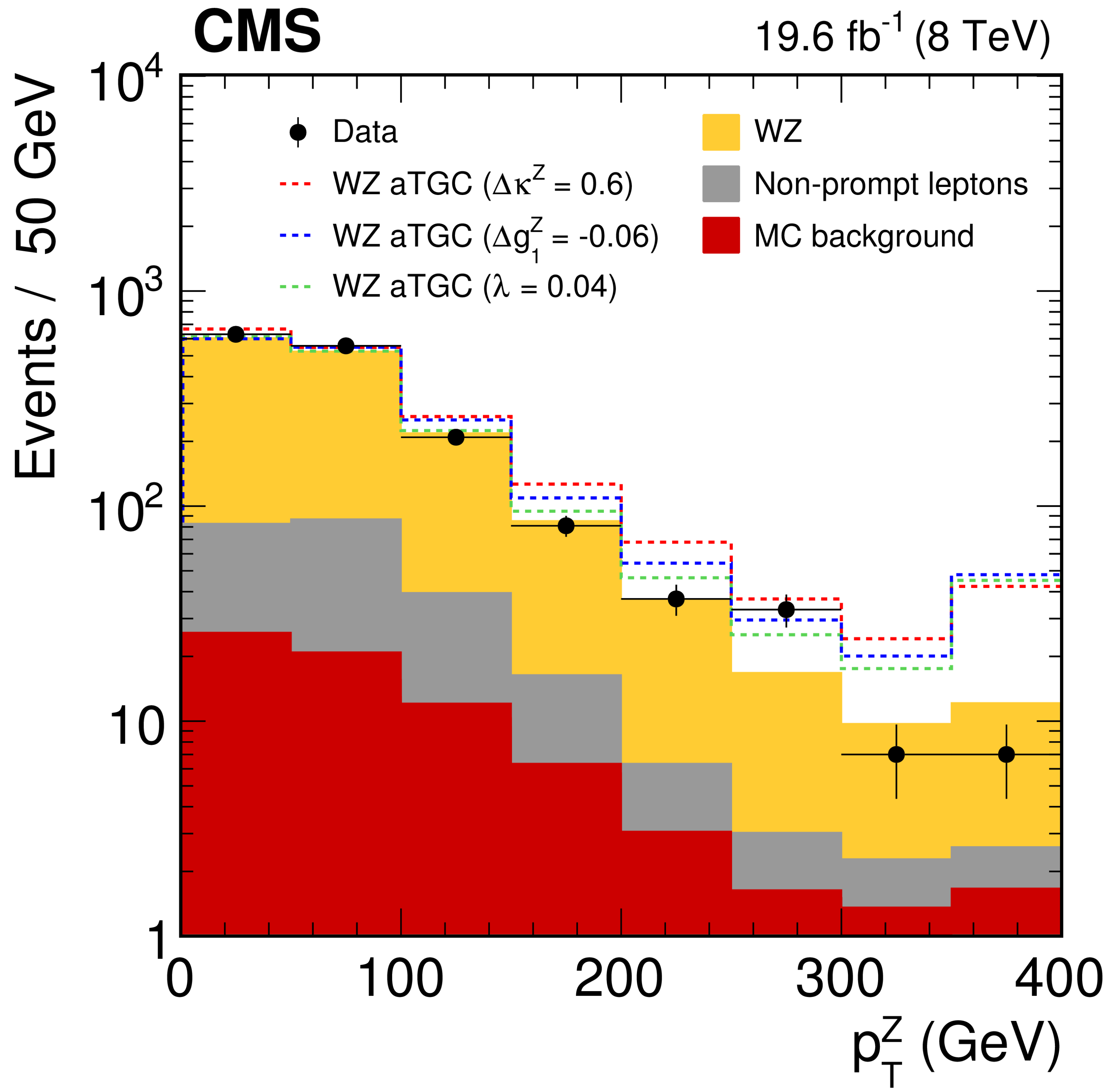




WZ→ℓνℓℓ + aTGC at 13 and 8 TeV - Limits





CMS

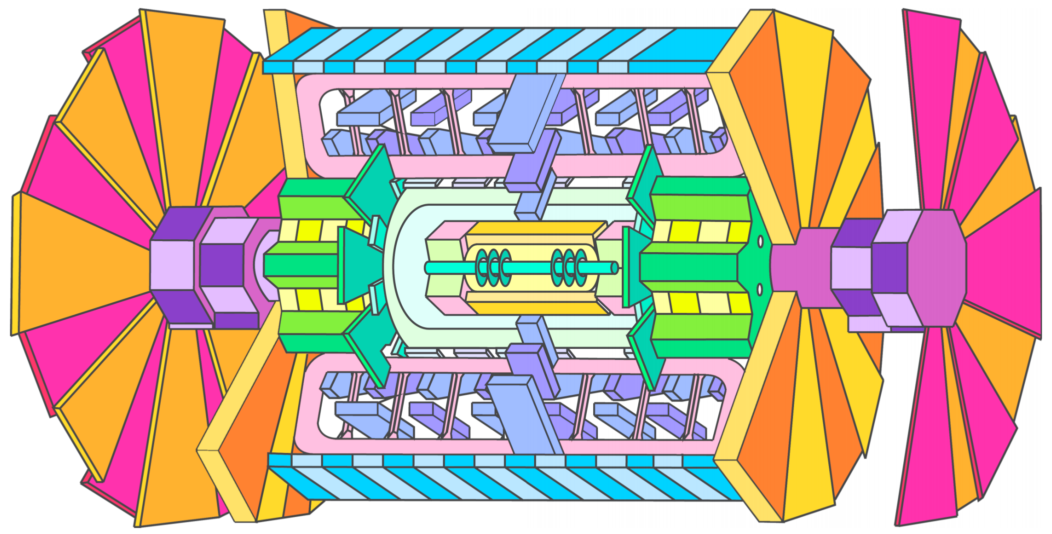
	Observed [TeV^{-2}]	Expected [TeV^{-2}]
c_B/Λ^2	$[-260, 210]$	$[-310, 300]$
c_W/Λ^2	$[-4.2, 8.0]$	$[-6.8, 9.2]$
c_{WWW}/Λ^2	$[-4.6, 4.2]$	$[-6.1, 5.6]$

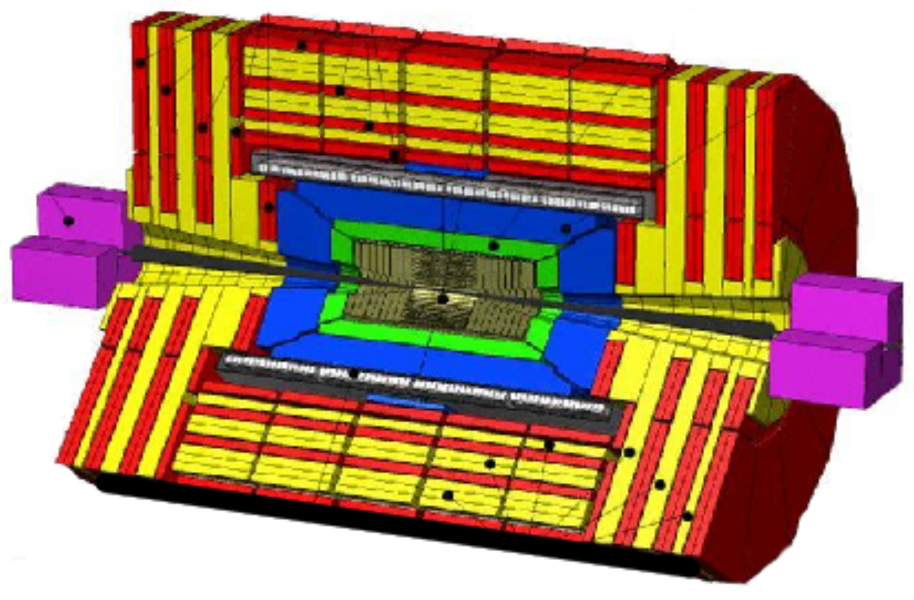
CMS	$\sqrt{s}$ [TeV]
From observed limit on c_B/Λ^2 parameter	1.6
From observed limit on c_W/Λ^2 parameter	5.1
From observed limit on c_{WWW}/Λ^2 parameter	4.3

13TeV

8 TeV

ATLAS and CMS diboson results focusing on aTGCs





W^+W^-

$WW\to\ell\nu\ell\nu$

$WW\to\ell\nu\ell\nu$ + aTCG

$WW\to\ell\nu\ell\nu$

$WW\to\ell\nu\ell\nu$ + aTGC

WV

$WZ\to\ell\nu\ell\ell$ + aTGC

$WV\to\ell\nu qq$ + aTCG

$WZ\to\ell\nu\ell\ell$ + aTGC

$WV\to\ell\nu qq$ + aTCG

$W\gamma$

7 TeV measurement

Covered in Md Naimuddin's talk (VBS)

arXiv:1706.01702

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WV→$\ell\nu qq$ + aTCG at 8 TeV - Introduction

- WW or WZ with one W boson decaying to $e\nu$ or $\mu\nu$ and one W or Z boson decaying hadronically
  - The presence of jets and the large background from W+jets and ttbar production limit the experimental precision, but ~6 times greater branching ratio
  - Also, for WW case the $\ell\nu qq$ kinematics can be better reconstructed
- Both resolved (two small-R jets, jj) (ATLAS) and boosted (one large-R jet, J) (ATLAS, CMS) cases considered
  - large R jet has increased reconstruction efficiency at high p_T (improved BSM sensitivity)
- After final event selection S/B is still low, signal extracted by fit to m_{jj} or m_J distribution
- aTGC contributions determined from p_T(jj,J) distribution

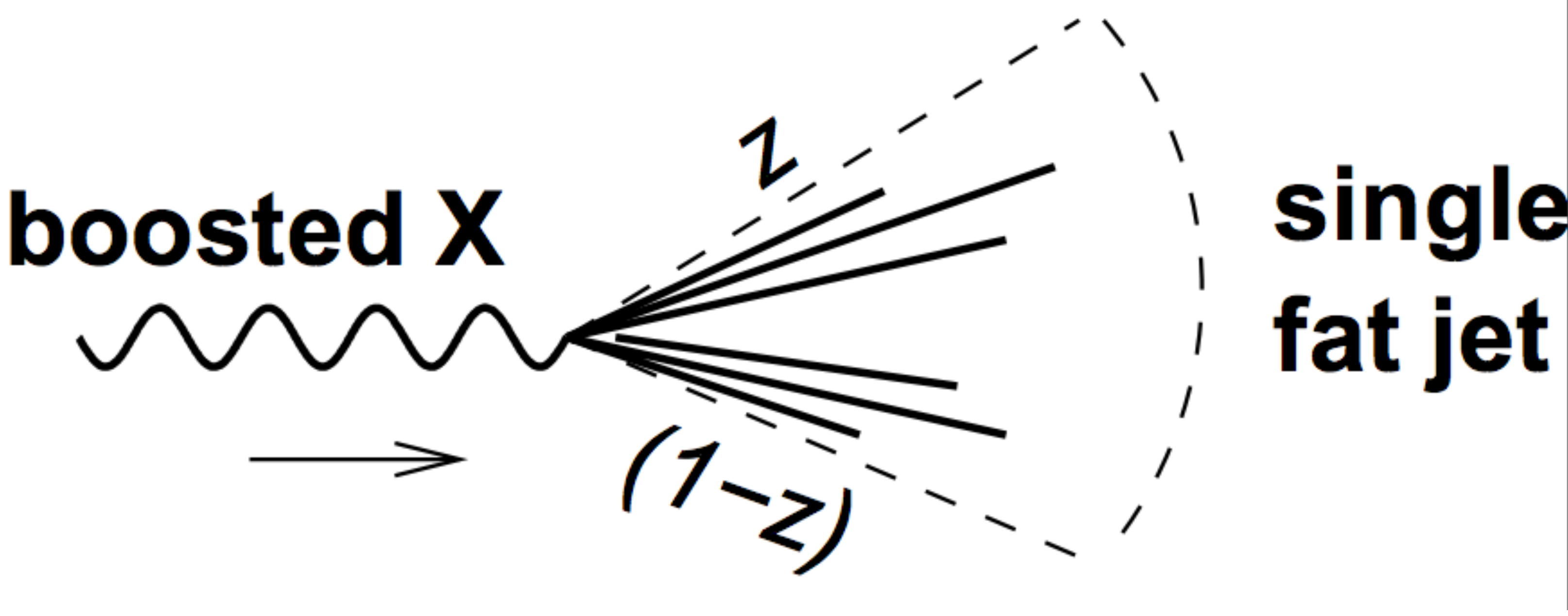

diagram credit: G Salam

arXiv:1706.01702

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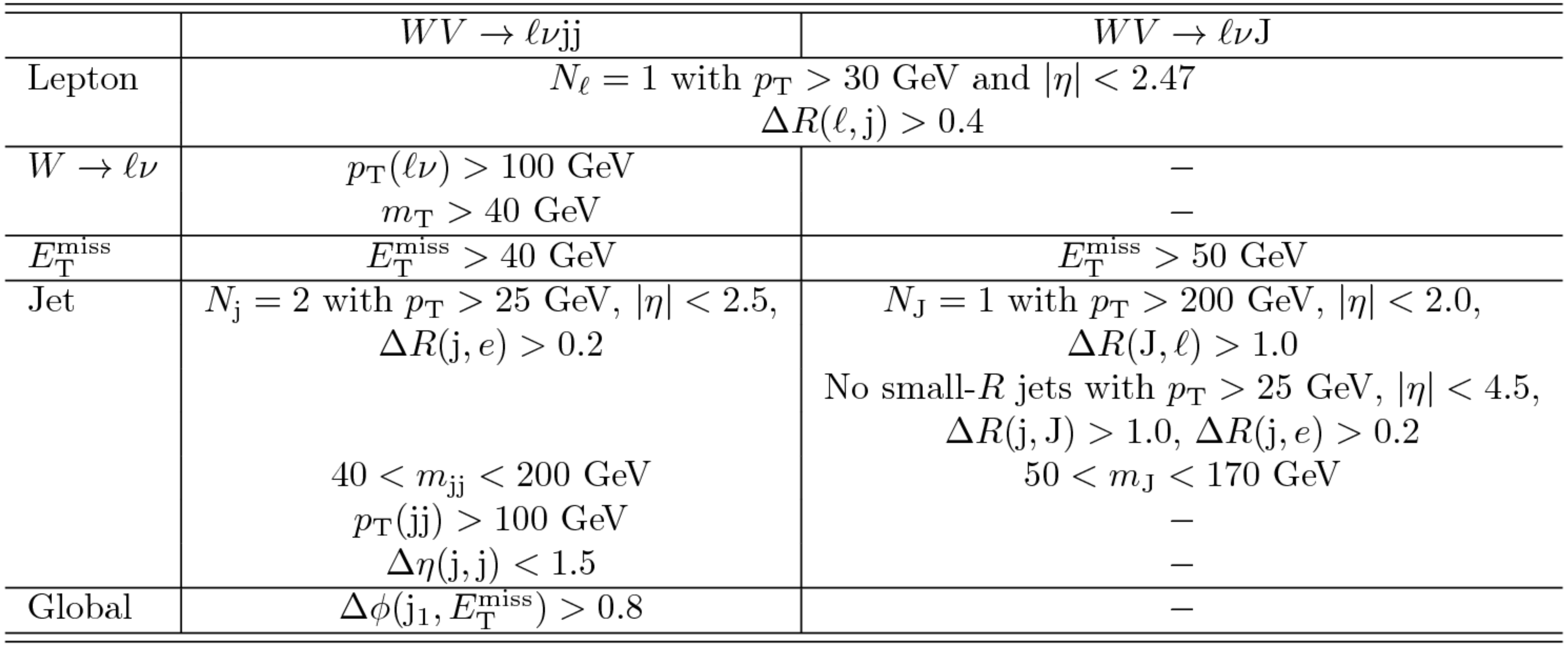
WV→ℓvqq + aTCG at 8 TeV - Event Selection

- Jet selection:
  - ATLAS: Small- and large-R jets are reconstructed using the anti-kT algorithm, with radii 0.4 and 1.0
  - CMS: Small-R jets reconstructed using anti-kT with radius 0.5; large-R jets using Cambridge-Aachen with radius 0.8

ATLAS



	$WV \to \ell\nu jj$	$WV \to \ell\nu J$
Lepton	$N_\ell = 1$ with $p_T > 30$ GeV and $\|\eta\| < 2.47$ $\Delta R(\ell, j) > 0.4$	
$W \to \ell\nu$	$p_T(\ell\nu) > 100$ GeV $m_T > 40$ GeV	– –
E_T^{miss}	$E_T^{miss} > 40$ GeV	$E_T^{miss} > 50$ GeV
Jet	$N_j = 2$ with $p_T > 25$ GeV, $\|\eta\| < 2.5$, $\Delta R(j, e) > 0.2$	$N_J = 1$ with $p_T > 200$ GeV, $\|\eta\| < 2.0$, $\Delta R(J, \ell) > 1.0$ No small-R jets with $p_T > 25$ GeV, $\|\eta\| < 4.5$, $\Delta R(j, J) > 1.0$, $\Delta R(j, e) > 0.2$
	$40 < m_{jj} < 200$ GeV	$50 < m_J < 170$ GeV
	$p_T(jj) > 100$ GeV	–
	$\Delta\eta(j, j) < 1.5$	–
Global	$\Delta\phi(j_1, E_T^{miss}) > 0.8$	–

CMS

- One CA8jet p_T>200, no additional CA8 jets with p_T>80 GeV
- ETmiss>50(70) for μ(*e*)
- similar cuts on ΔR variables and includes Δϕ(J, ETmiss) > 2.0
- Additional cut on ratio of 2-subjettiness to 1-subjettiness < 0.55 to discriminate against W+jets backgrounds.

arXiv:1706.01702

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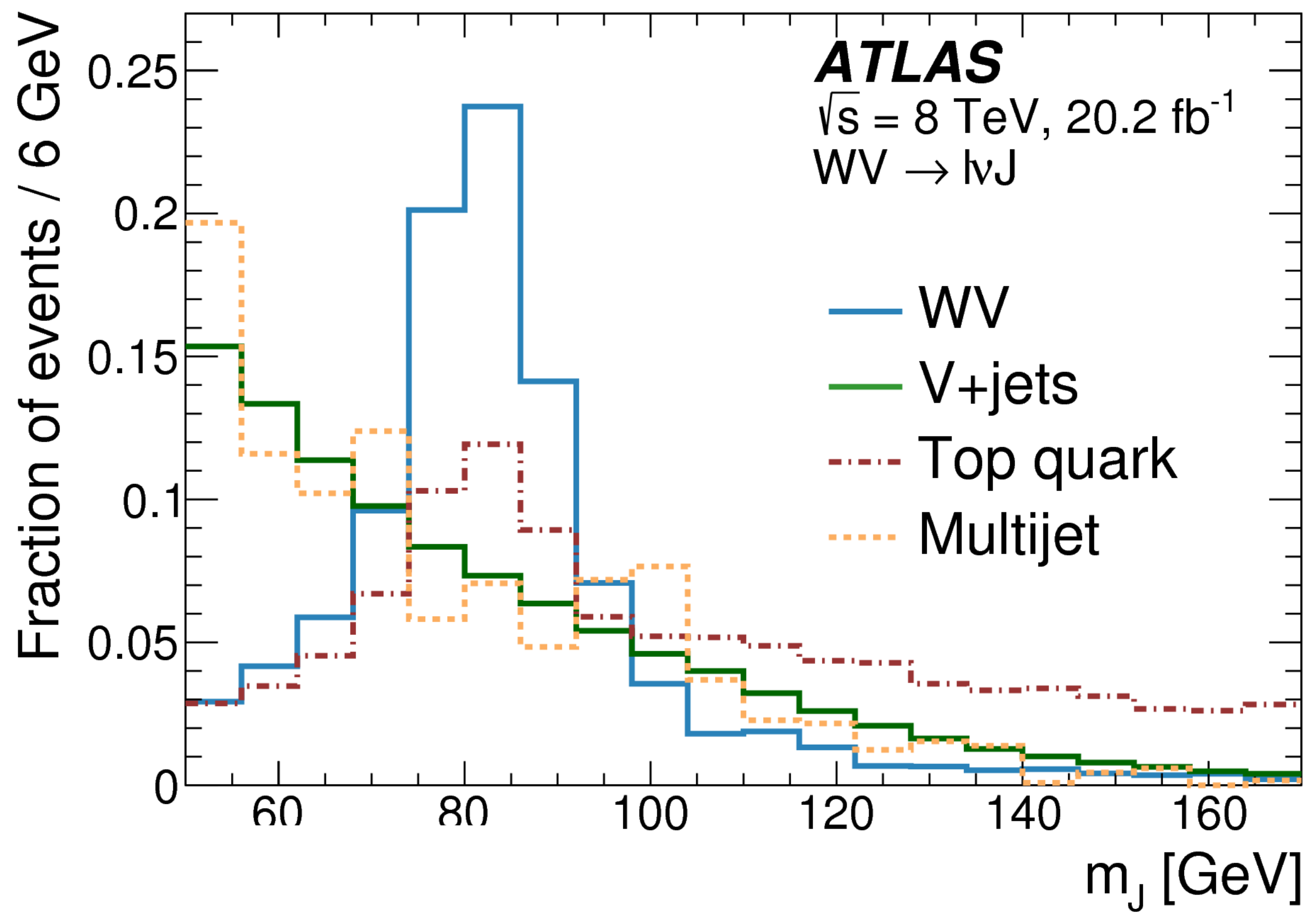
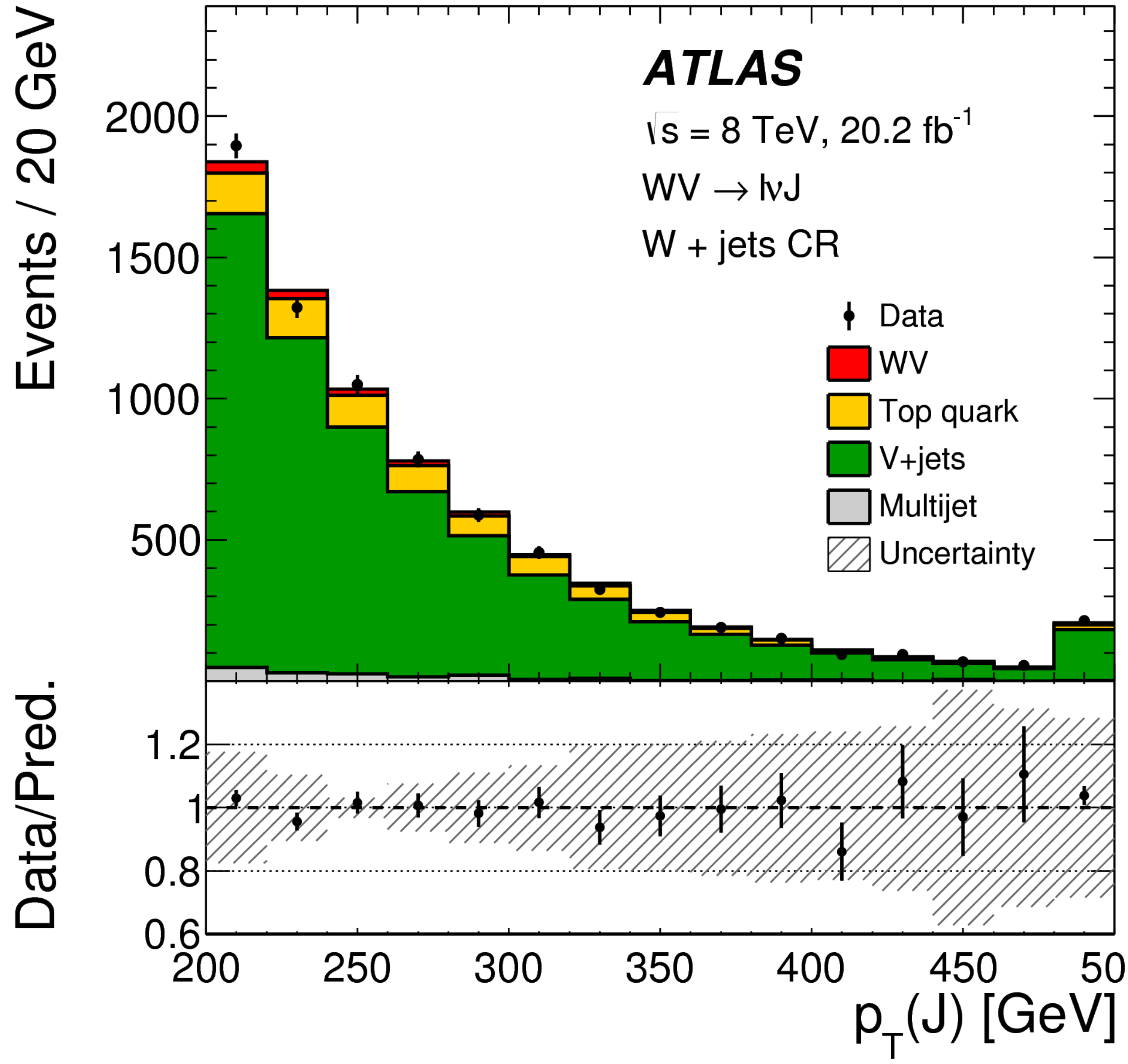
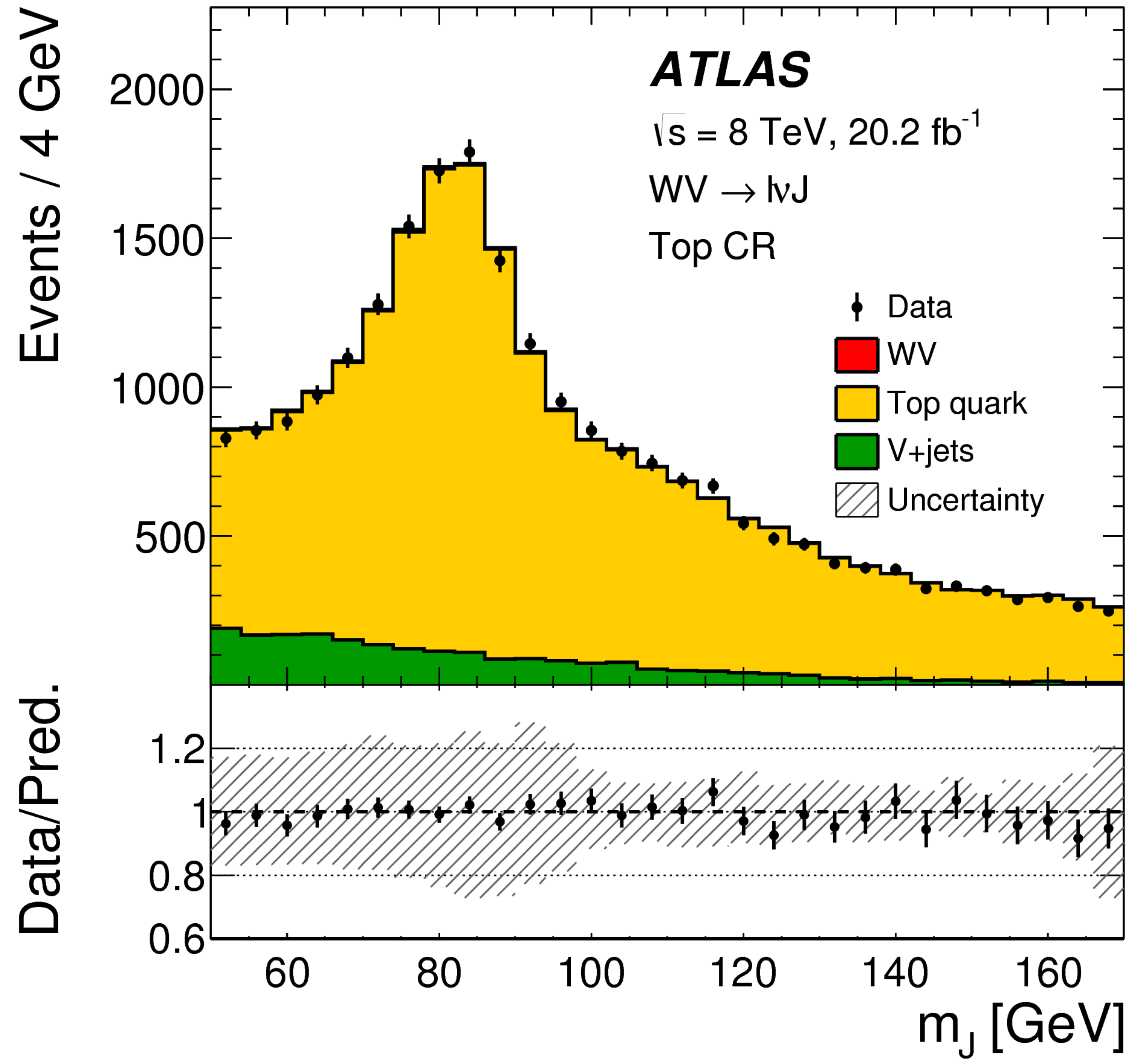
WV→ℓvqq + aTCG at 8 TeV - Backgrounds

- W+jets and top backgrounds by far dominant, followed by multijets, with data-driven corrections from CR for W+jets and top
- W+jets CR
  - ATLAS: SR and ($m_J < 65$ GeV or $m_J > 95$ GeV) (85% purity) - SF=0.84
- Top CR
  - ATLAS: require a b-tagged jet and require ΔR(j,J) > 1.0 (90% purity) SF=0.87
  - CMS: require a b-tagged jet







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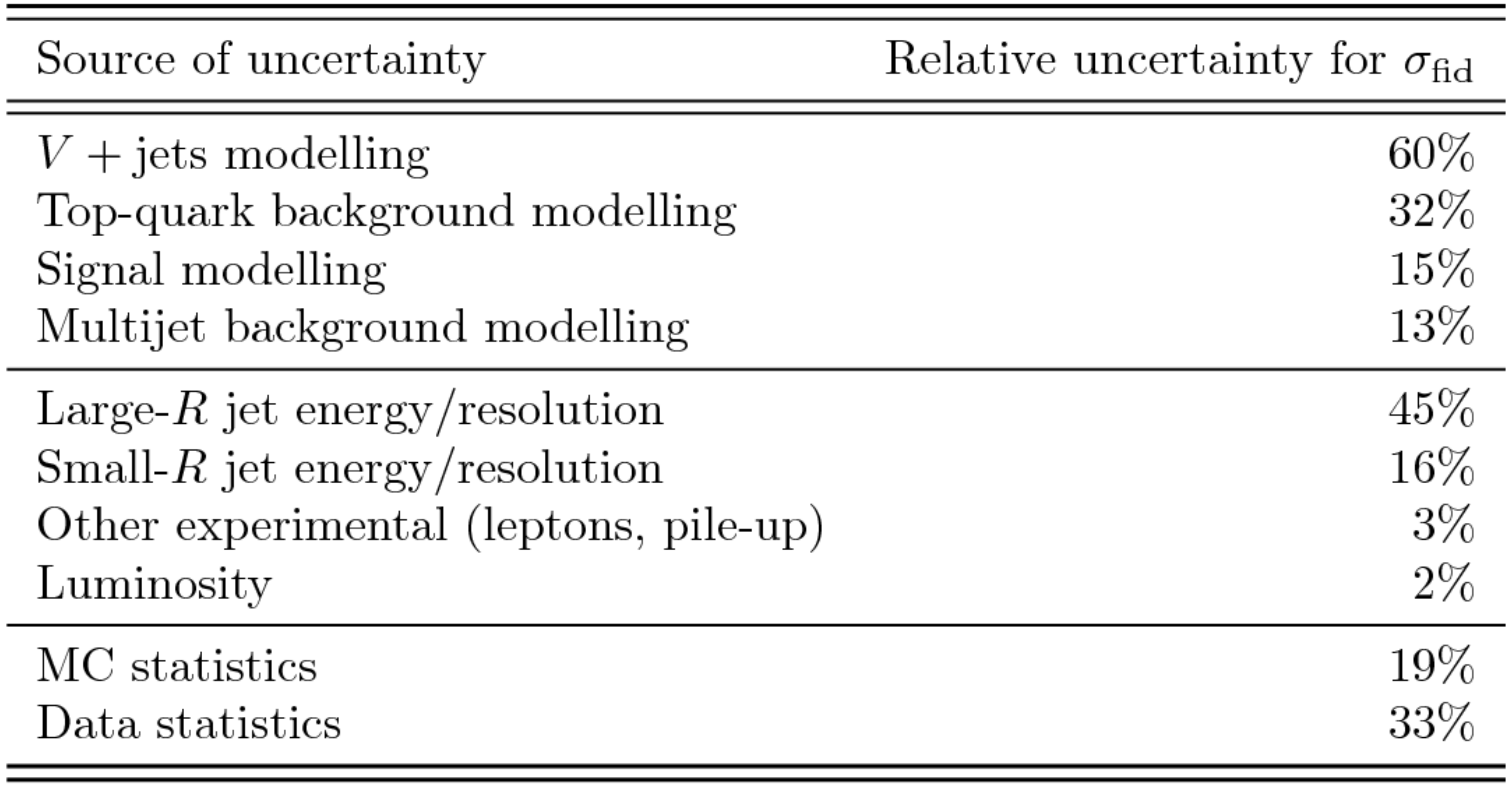
WV→ℓvqq + aTCG at 8 TeV - Uncertainties

ATLAS



Source of uncertainty	Relative uncertainty for σ_{fid}
V + jets modelling	60%
Top-quark background modelling	32%
Signal modelling	15%
Multijet background modelling	13%
Large-R jet energy/resolution	45%
Small-R jet energy/resolution	16%
Other experimental (leptons, pile-up)	3%
Luminosity	2%
MC statistics	19%
Data statistics	33%

CMS

- Estimates a 20% uncertainty in the total background normalisation by taking the precision of the ratio of curves fitted to the W+jets p_T^J distributions in the signal and sideband regions of W+jets simulation
- Scale and PDF uncertainties are estimated to be approximately 18–26%.

arXiv:1706.01702

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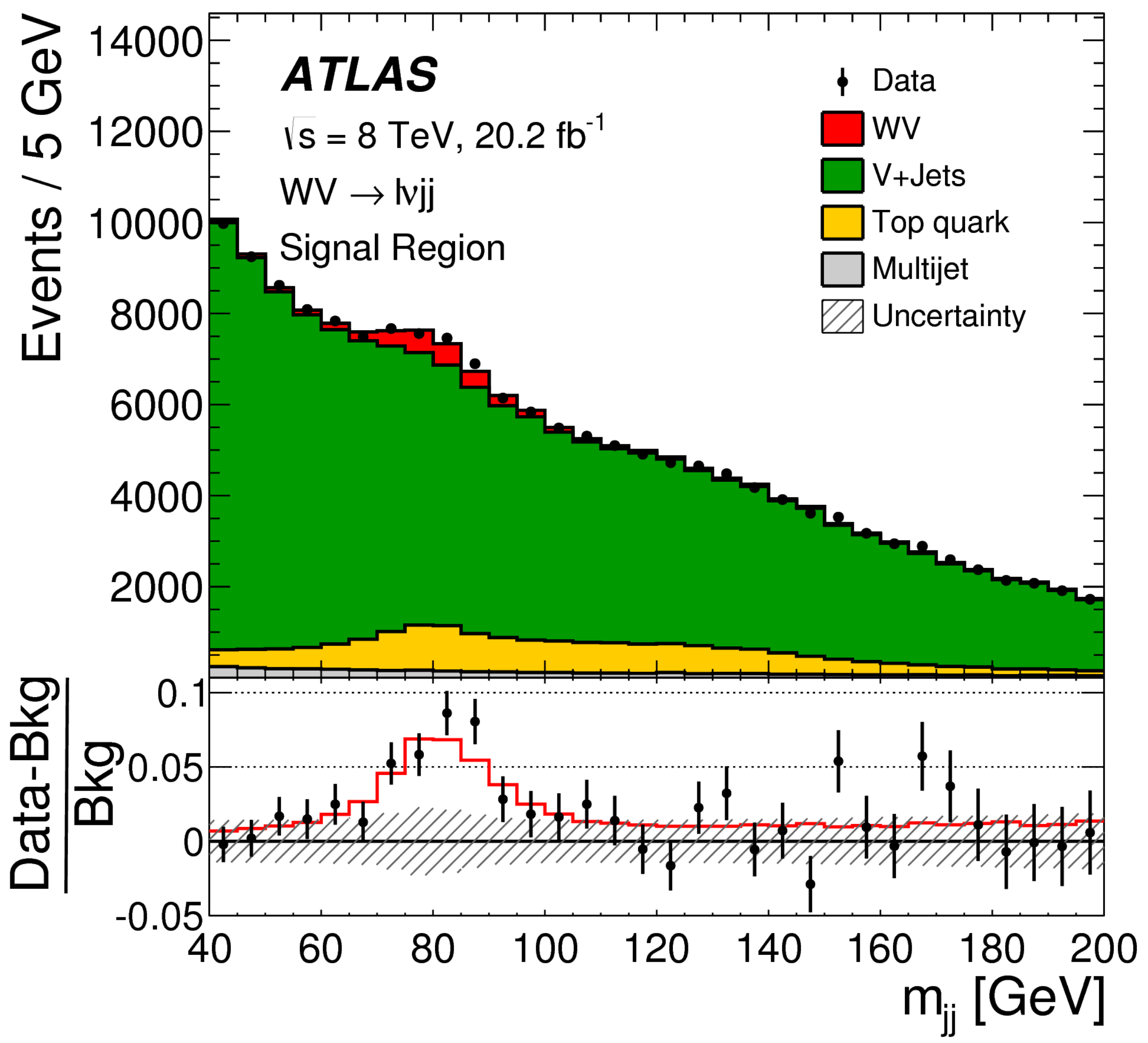
$WV \to \ell\nu qq$ + aTCG at 8 TeV - Signal Extraction

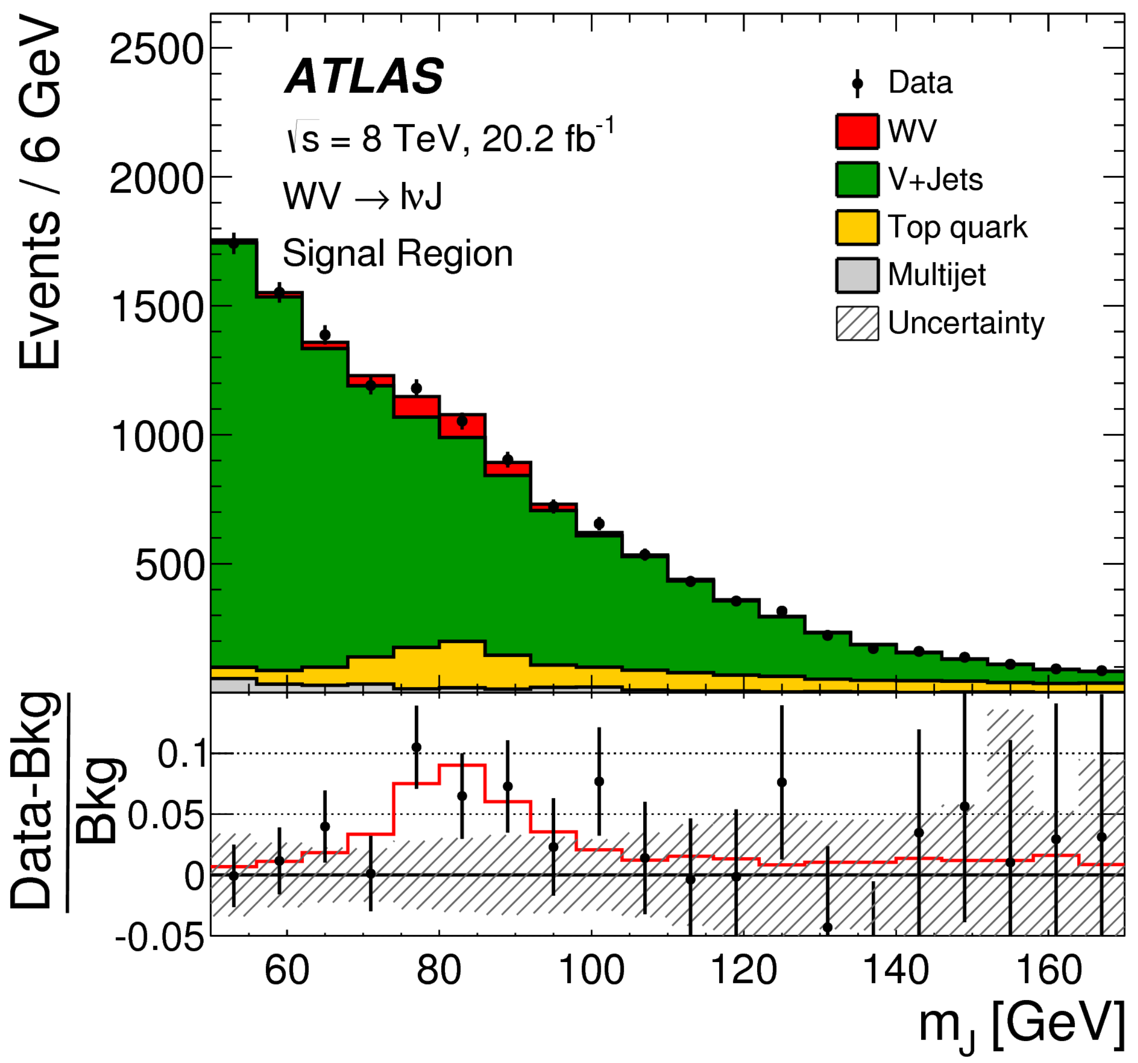
ATLAS

- Binned maximum-likelihood fit to m_{jj} or m_J distribution
- Performed on combined e and μ channels
- mass range 40 GeV < m_{jj} < 200 GeV and 50 < m_J < 170 GeV

CMS

- Unbinned maximum-likelihood fit to m_J distribution
- Performed for e and μ channels separately
- mass range 40 < m_J < 140 GeV





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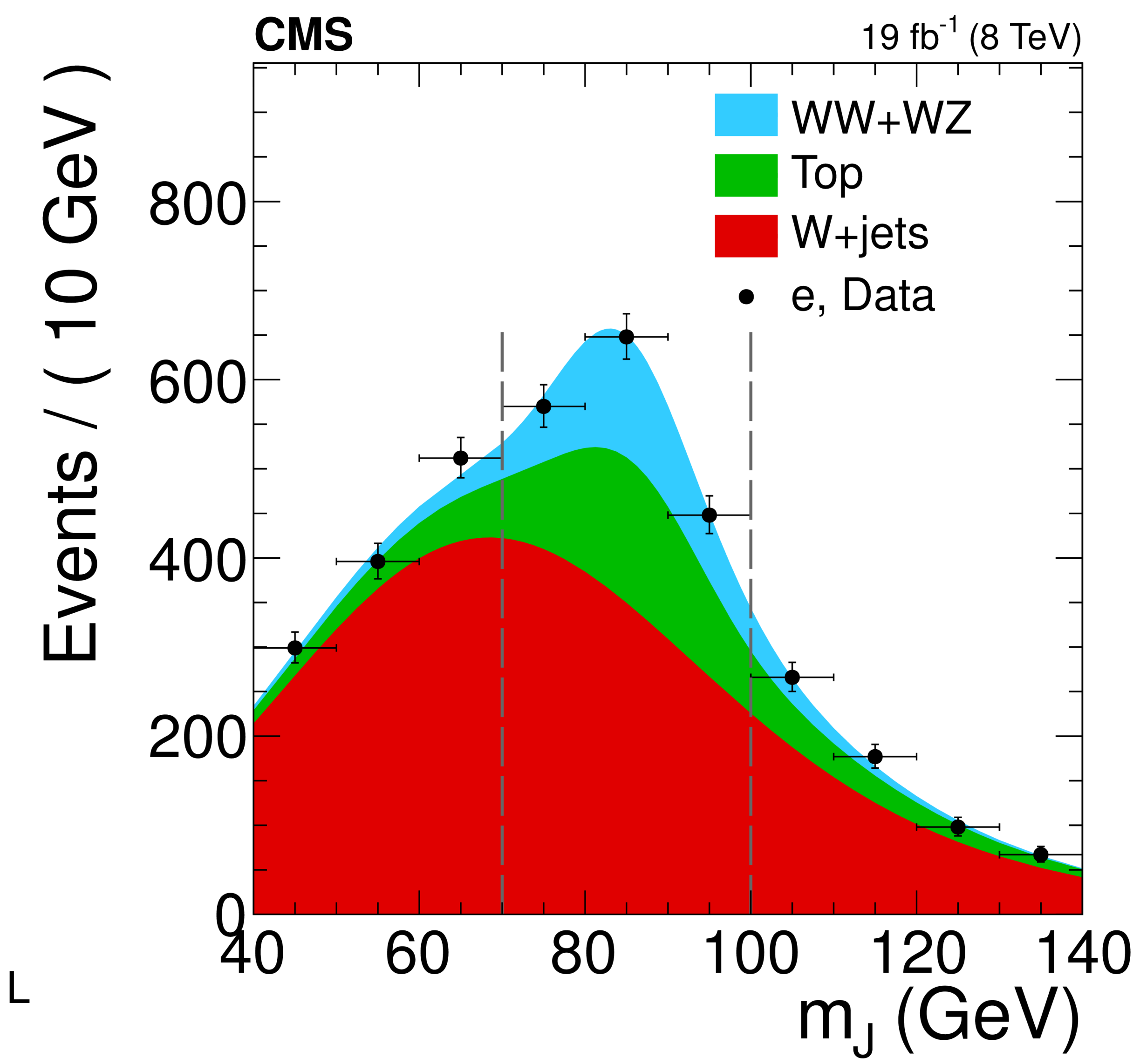
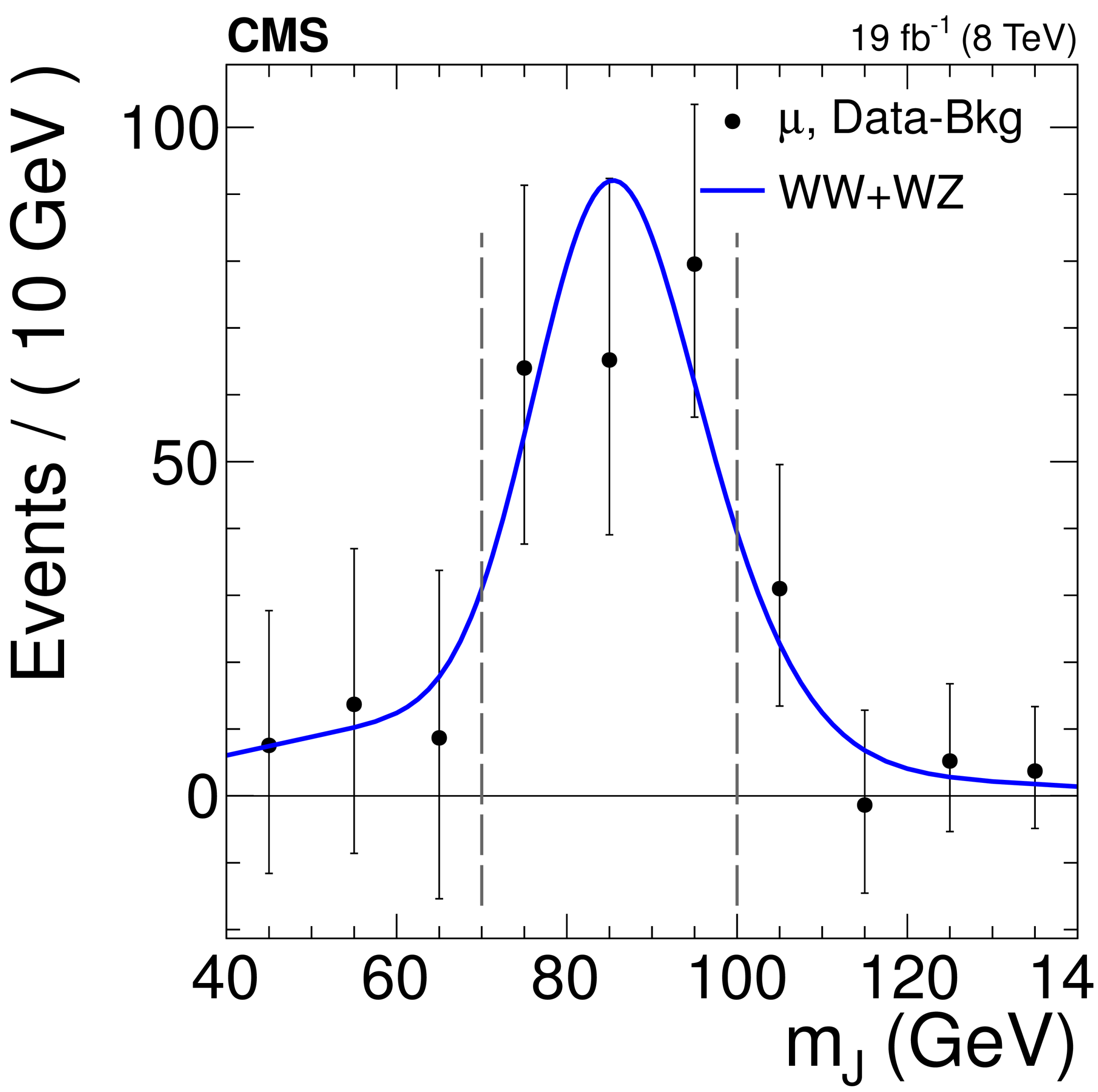
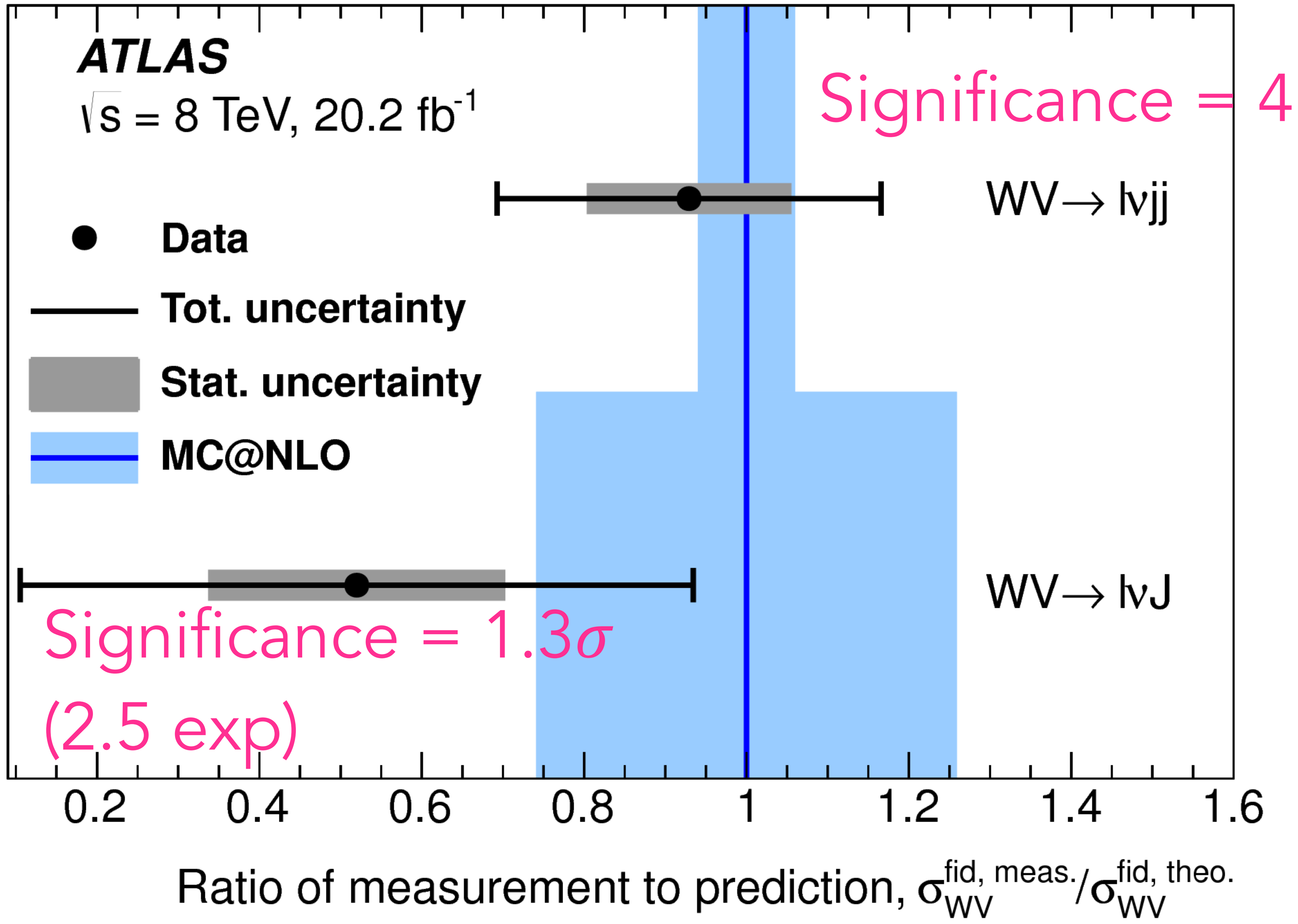




WV→ℓvqq + aTCG at 8 TeV - Cross Section & Coupling Parameters



Significance = 4.5σ (5.2 exp)

Significance = 1.3σ (2.5 exp)

The theoretical uncertainty in the WV → lνJ channel is dominated by scale uncertainties because of the aggressive jet veto

ATLAS

Parameter	Observed	Expected	Observed	Expected
	$WV \to \ell\nu jj$		$WV \to \ell\nu J$	
Δg_1^Z	$[-0.027, 0.045]$	$[-0.036, 0.051]$	$[-0.021, 0.024]$	$[-0.024, 0.027]$
$\Delta\kappa_\gamma$	$[-0.11, 0.13]$	$[-0.15, 0.16]$	$[-0.061, 0.064]$	$[-0.071, 0.075]$
$\lambda_Z = \lambda_\gamma$	$[-0.022, 0.022]$	$[-0.027, 0.026]$	$[-0.013, 0.013]$	$[-0.015, 0.015]$

CMS

Parameter	Expected Limits	Observed Limits
λ_Z	$[-0.014, 0.013]$	$[-0.011, 0.011]$
$\Delta\kappa_\gamma$	$[-0.068, 0.082]$	$[-0.044, 0.063]$
Δg_1^Z	$[-0.018, 0.028]$	$[-0.0087, 0.024]$

arXiv:1706.01702

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arXiv:1706.01702

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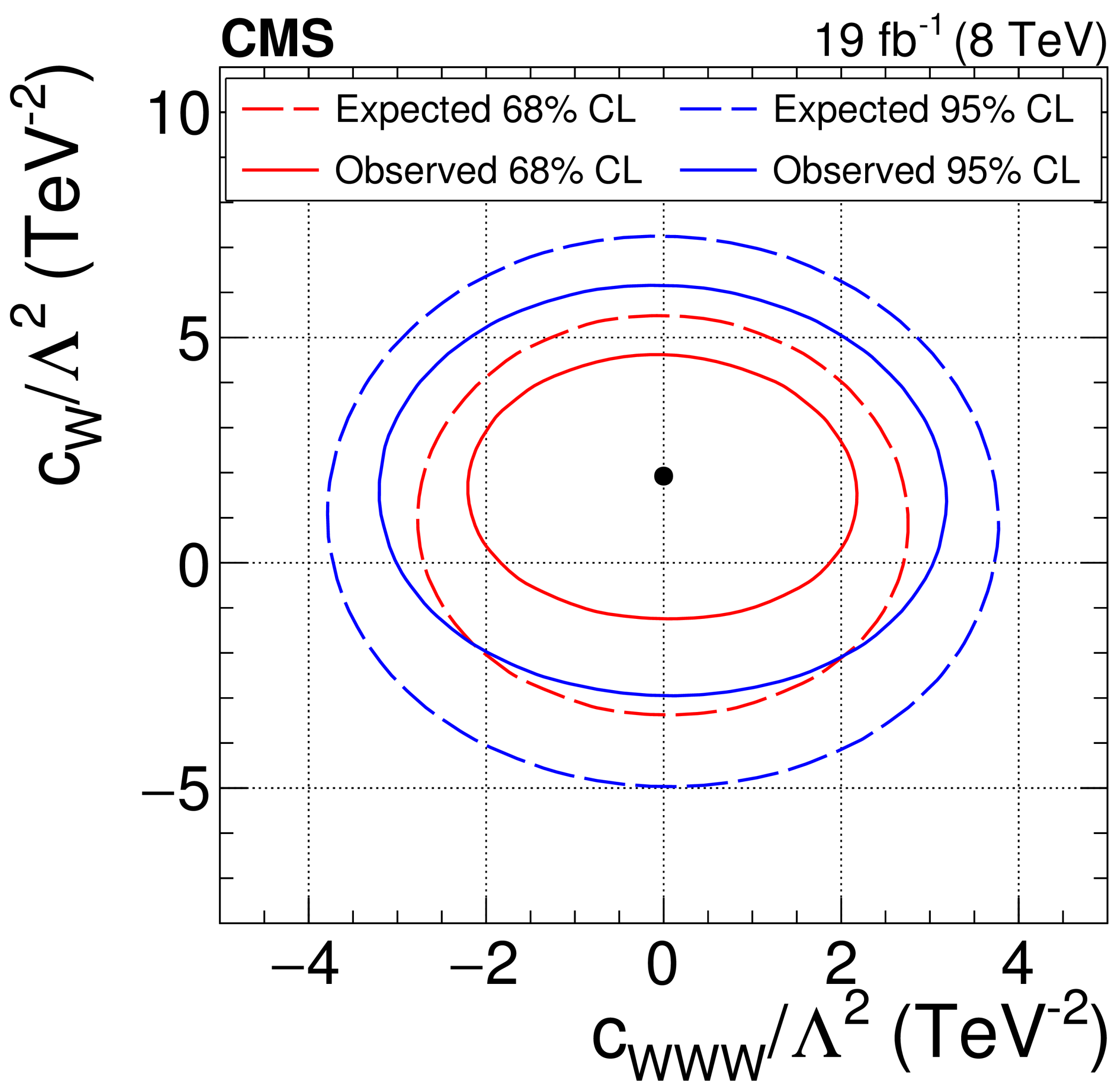
WV→ℓvqq + aTCG at 8 TeV - EFT Coefficients

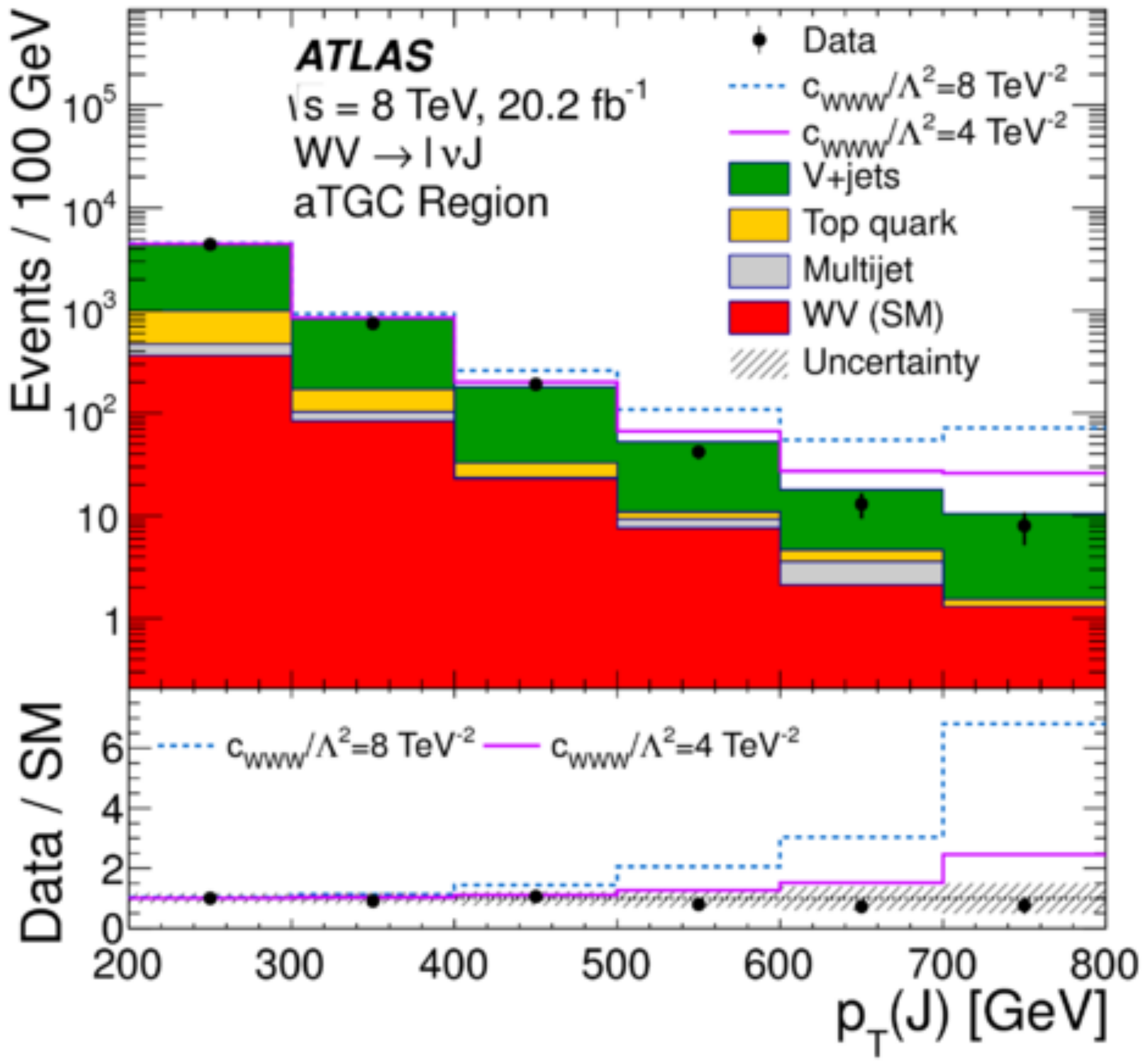
ATLAS

Parameter	Observed [TeV^{-2}]	Expected [TeV^{-2}]	Observed [TeV^{-2}]	Expected [TeV^{-2}]
	$WV \to \ell\nu jj$		$WV \to \ell\nu J$	
c_{WWW}/Λ^2	$[-5.3, 5.3]$	$[-6.4, 6.3]$	$[-3.1, 3.1]$	$[-3.6, 3.6]$
c_B/Λ^2	$[-36, 43]$	$[-45, 51]$	$[-19, 20]$	$[-22, 23]$
c_W/Λ^2	$[-6.4, 11]$	$[-8.7, 13]$	$[-5.1, 5.8]$	$[-6.0, 6.7]$

CMS

	c_{WWW}/Λ^2 (TeV^{-2})	c_B/Λ^2 (TeV^{-2})	c_W/Λ^2 (TeV^{-2})
*	$[-2.7, 2.7]$	$[-14, 17]$	$[-2.0, 5.7]$
[6]	$[-5.7, 5.9]$	$[-29.2, 23.9]$	$[-11.4, 5.4]$
[7]	$[-4.61, 4.60]$	$[-20.9, 26.3]$	$[-5.87, 10.54]$
[43]	$[-4.6, 4.2]$	$[-260, 210]$	$[-4.2, 8.0]$
[44]	$[-3.9, 4.0]$	$[-320, 210]$	$[-4.3, 6.8]$



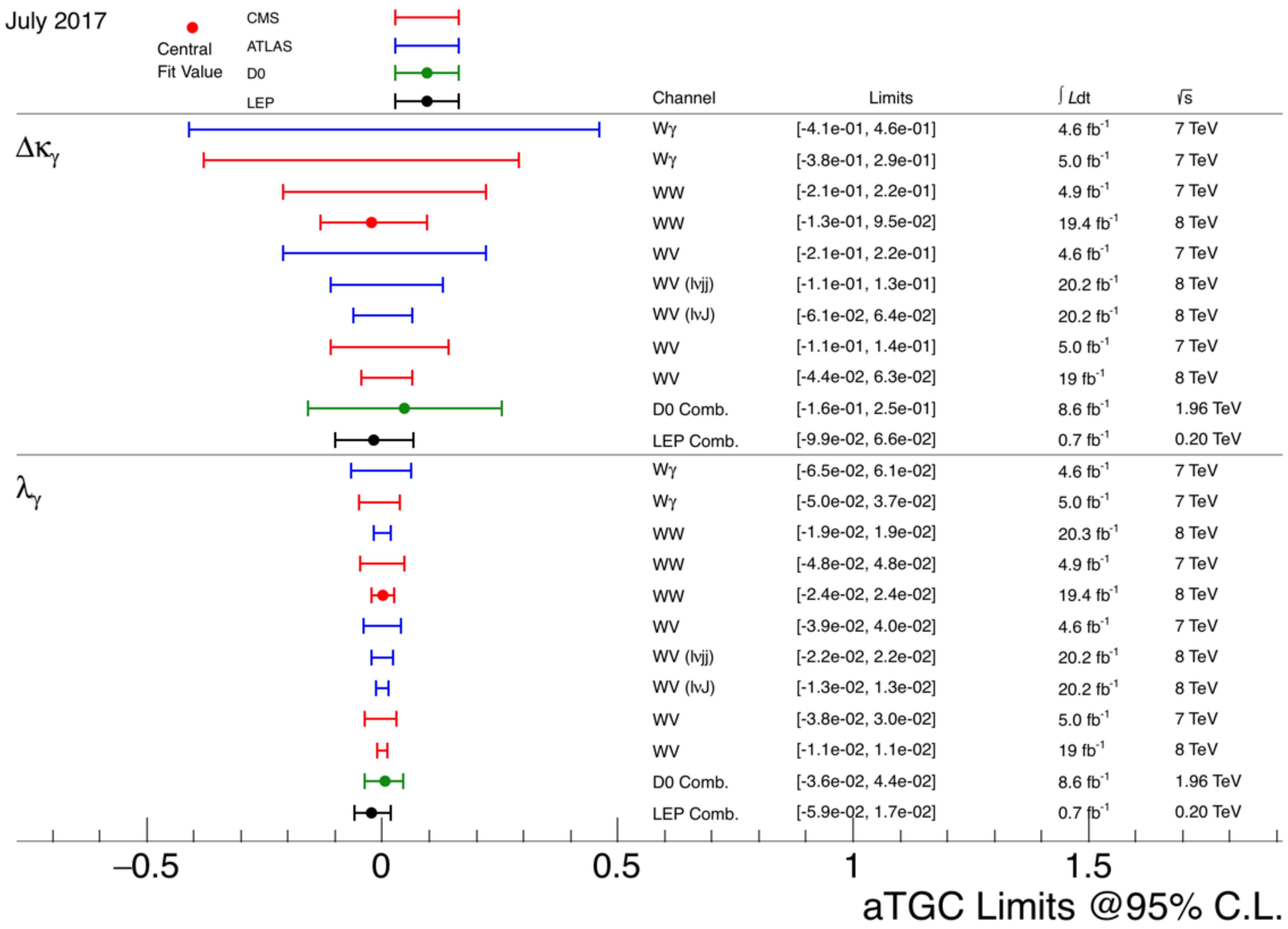


BROOKHAVEN NATIONAL LABORATORY

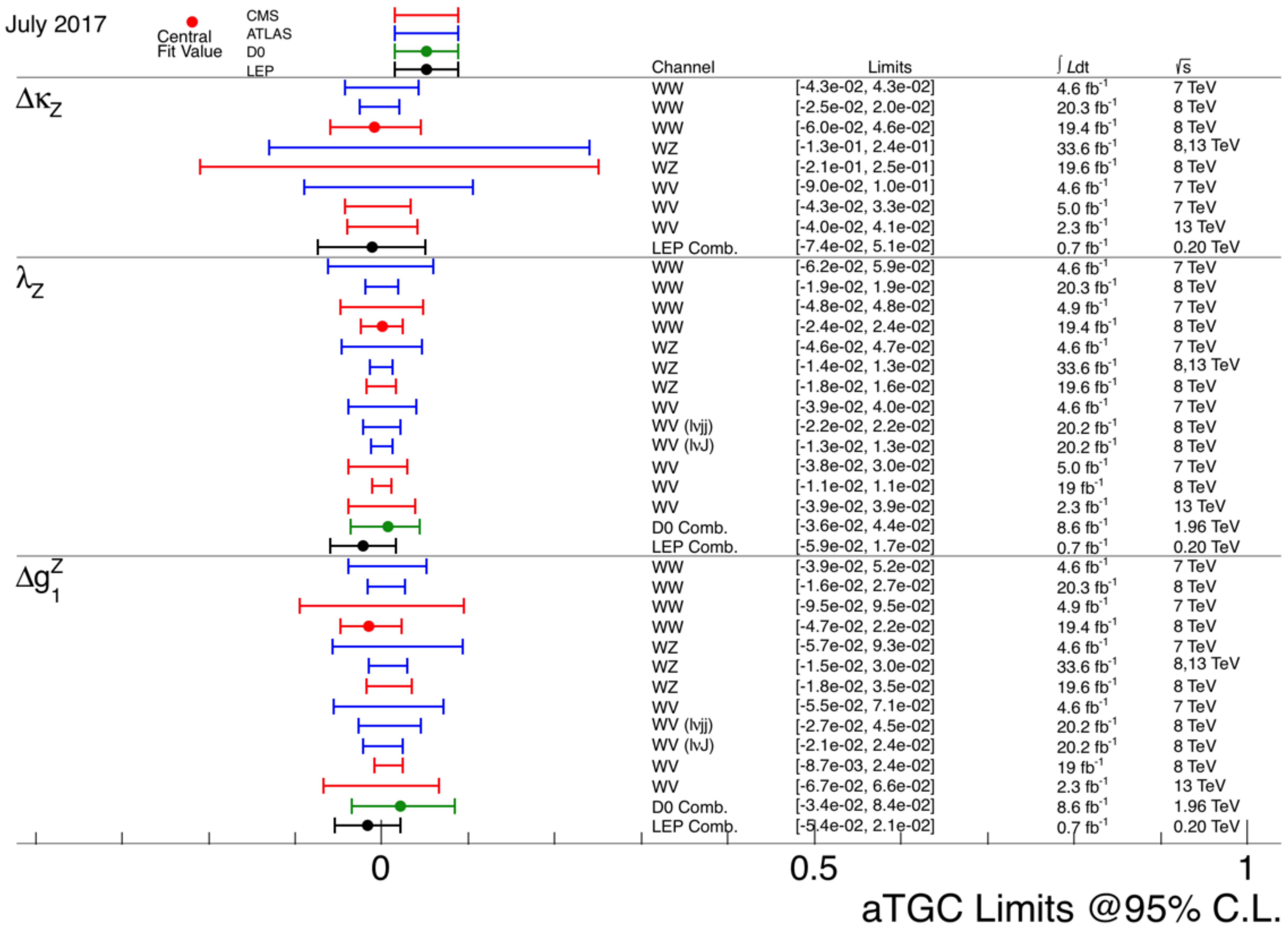
Claire A. Lee

Current Status of Charged aTGC Limits

Coupling	Parameter	Channel
WWɣ	$\lambda_\gamma, \Delta\kappa_\gamma$	WW,Wɣ
WWZ	$\lambda_Z, \Delta\kappa_Z, \Delta g_1^Z$	WW,WZ



	Channel	Limits	$\int Ldt$	$\sqrt{s}$
$\Delta\kappa_\gamma$	Wγ	[-4.1e-01, 4.6e-01]	4.6 fb^{-1}	7 TeV
	Wγ	[-3.8e-01, 2.9e-01]	5.0 fb^{-1}	7 TeV
	WW	[-2.1e-01, 2.2e-01]	4.9 fb^{-1}	7 TeV
	WW	[-1.3e-01, 9.5e-02]	19.4 fb^{-1}	8 TeV
	WV	[-2.1e-01, 2.2e-01]	4.6 fb^{-1}	7 TeV
	WV (lvjj)	[-1.1e-01, 1.3e-01]	20.2 fb^{-1}	8 TeV
	WV (lvJ)	[-6.1e-02, 6.4e-02]	20.2 fb^{-1}	8 TeV
	WV	[-1.1e-01, 1.4e-01]	5.0 fb^{-1}	7 TeV
	WV	[-4.4e-02, 6.3e-02]	19 fb^{-1}	8 TeV
	D0 Comb.	[-1.6e-01, 2.5e-01]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-9.9e-02, 6.6e-02]	0.7 fb^{-1}	0.20 TeV
λ_γ	Wγ	[-6.5e-02, 6.1e-02]	4.6 fb^{-1}	7 TeV
	Wγ	[-5.0e-02, 3.7e-02]	5.0 fb^{-1}	7 TeV
	WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
	WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
	WW	[-2.4e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
	WV	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
	WV (lvjj)	[-2.2e-02, 2.2e-02]	20.2 fb^{-1}	8 TeV
	WV (lvJ)	[-1.3e-02, 1.3e-02]	20.2 fb^{-1}	8 TeV
	WV	[-3.8e-02, 3.0e-02]	5.0 fb^{-1}	7 TeV
	WV	[-1.1e-02, 1.1e-02]	19 fb^{-1}	8 TeV
	D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV



	Channel	Limits	$\int Ldt$	$\sqrt{s}$
$\Delta\kappa_Z$	WW	[-4.3e-02, 4.3e-02]	4.6 fb^{-1}	7 TeV
	WW	[-2.5e-02, 2.0e-02]	20.3 fb^{-1}	8 TeV
	WW	[-6.0e-02, 4.6e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-1.3e-01, 2.4e-01]	33.6 fb^{-1}	8,13 TeV
	WZ	[-2.1e-01, 2.5e-01]	19.6 fb^{-1}	8 TeV
	WV	[-9.0e-02, 1.0e-01]	4.6 fb^{-1}	7 TeV
	WV	[-4.3e-02, 3.3e-02]	5.0 fb^{-1}	7 TeV
	WV	[-4.0e-02, 4.1e-02]	2.3 fb^{-1}	13 TeV
	LEP Comb.	[-7.4e-02, 5.1e-02]	0.7 fb^{-1}	0.20 TeV
λ_Z	WW	[-6.2e-02, 5.9e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
	WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
	WW	[-2.4e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-4.6e-02, 4.7e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.4e-02, 1.3e-02]	33.6 fb^{-1}	8,13 TeV
	WZ	[-1.8e-02, 1.6e-02]	19.6 fb^{-1}	8 TeV
	WV	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
	WV (lvjj)	[-2.2e-02, 2.2e-02]	20.2 fb^{-1}	8 TeV
	WV (lvJ)	[-1.3e-02, 1.3e-02]	20.2 fb^{-1}	8 TeV
	WV	[-3.8e-02, 3.0e-02]	5.0 fb^{-1}	7 TeV
	WV	[-1.1e-02, 1.1e-02]	19 fb^{-1}	8 TeV
	WV	[-3.9e-02, 3.9e-02]	2.3 fb^{-1}	13 TeV
	D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV
Δg_1^Z	WW	[-3.9e-02, 5.2e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.6e-02, 2.7e-02]	20.3 fb^{-1}	8 TeV
	WW	[-9.5e-02, 9.5e-02]	4.9 fb^{-1}	7 TeV
	WW	[-4.7e-02, 2.2e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-5.7e-02, 9.3e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.5e-02, 3.0e-02]	33.6 fb^{-1}	8,13 TeV
	WZ	[-1.8e-02, 3.5e-02]	19.6 fb^{-1}	8 TeV
	WV	[-5.5e-02, 7.1e-02]	4.6 fb^{-1}	7 TeV
	WV (lvjj)	[-2.7e-02, 4.5e-02]	20.2 fb^{-1}	8 TeV
	WV (lvJ)	[-2.1e-02, 2.4e-02]	20.2 fb^{-1}	8 TeV
	WV	[-8.7e-03, 2.4e-02]	19 fb^{-1}	8 TeV
	WV	[-6.7e-02, 6.6e-02]	2.3 fb^{-1}	13 TeV
	D0 Comb.	[-3.4e-02, 8.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.4e-02, 2.1e-02]	0.7 fb^{-1}	0.20 TeV

Ref: LHC EW WG twiki

Smug Standard Model
@smugsmphys

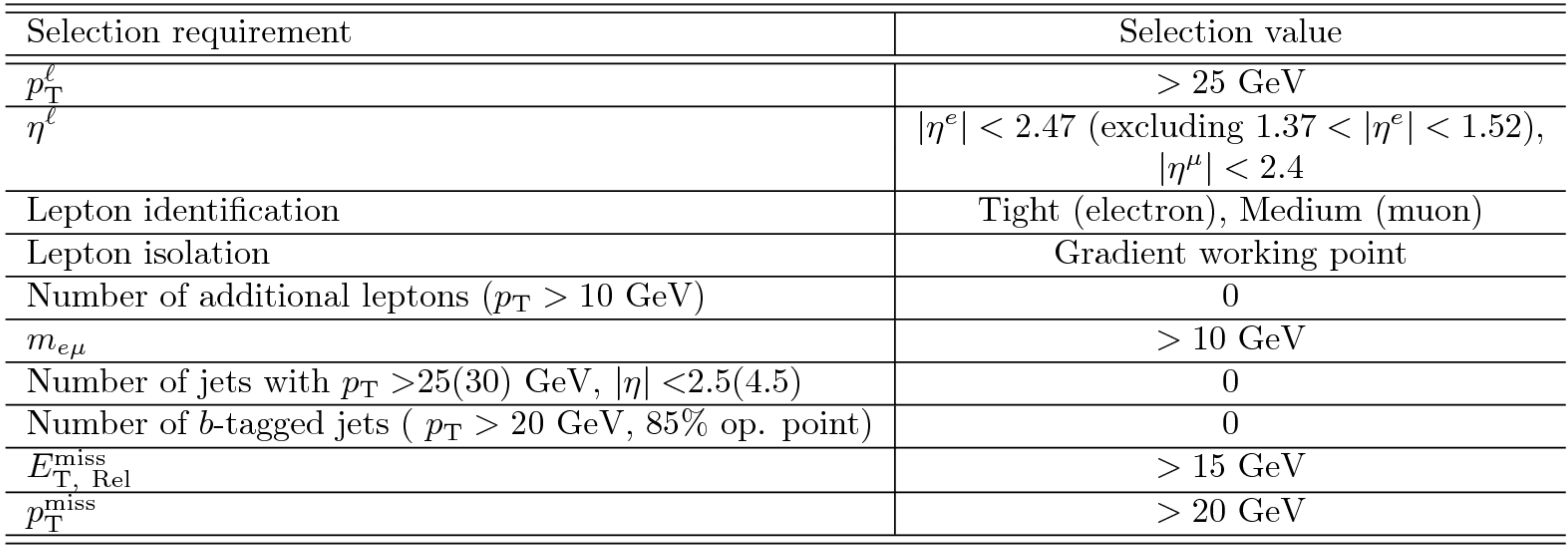
I win… always.

Summary

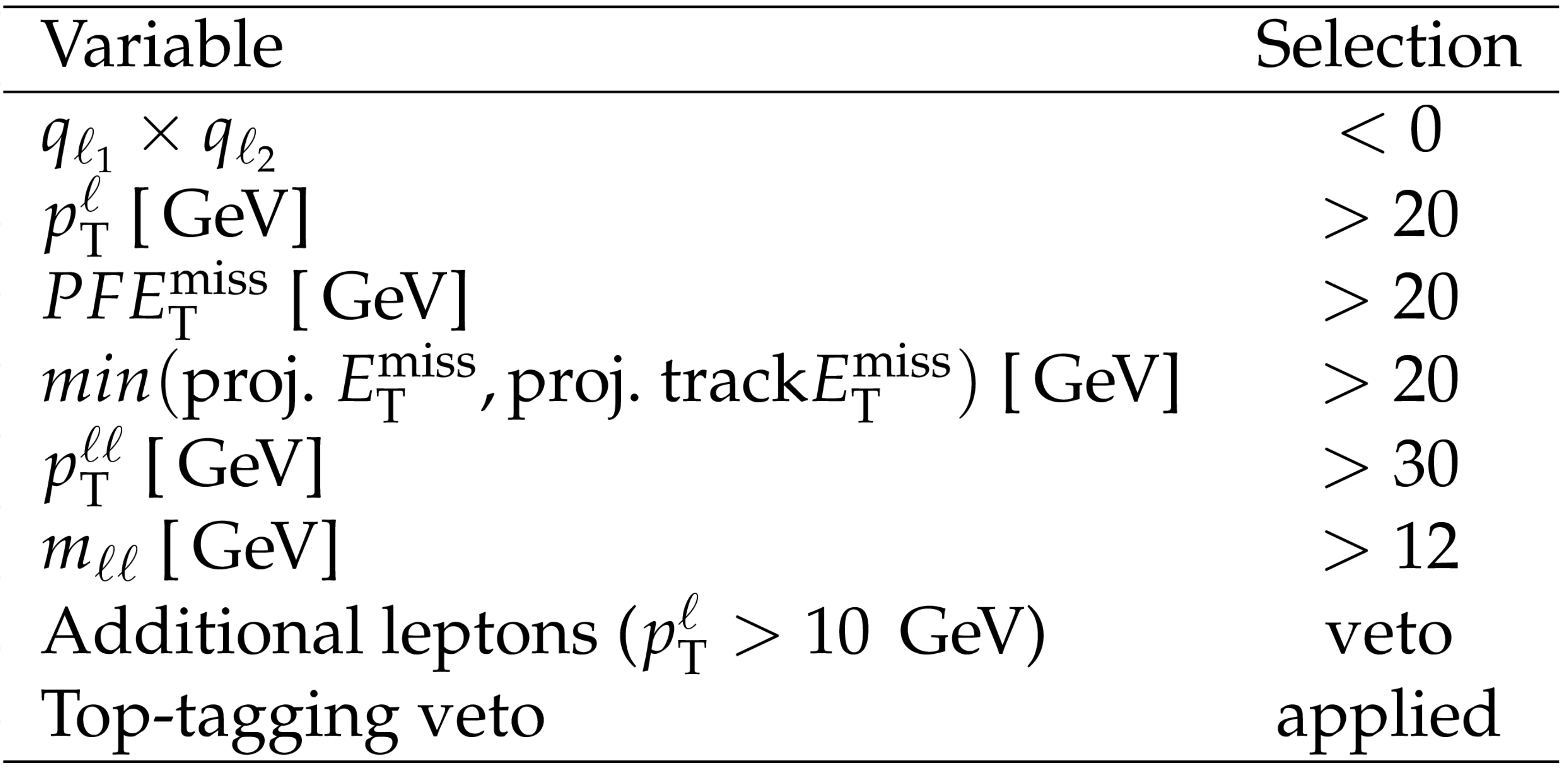
- Whatever new physics there is seems (for the moment) to be lurking out of our grasp
- But new physics may introduce deviations in couplings at high energy scales, leading to an enhancement of vector boson cross sections especially at high p_T.
- Current results from the LHC mainly cover the 7 and 8 TeV datasets (though the first aTGC result is available from ATLAS in WZ fully leptonic channel), and have surpassed LEP/Tevatron limits for essentially all parameters.
- With the excellent performance of the LHC in run 2 at 13 TeV, we now have the opportunity to complete the set of measurements, placing the tightest restrictions on aTGC parameters and EFT coefficients yet.

backup

WW→ℓνℓν at 13 TeV - Event Selection



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 ($p_{\mathrm{T}} > 10$ 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 ($p_{\mathrm{T}} > 20$ GeV, 85% op. point)	0
$E_{\mathrm{T,\ Rel}}^{\mathrm{miss}}$	> 15 GeV
$p_{\mathrm{T}}^{\mathrm{miss}}$	> 20 GeV



Variable	Selection
$q_{\ell_1} \times q_{\ell_2}$	< 0
p_{T}^{ℓ} [GeV]	> 20
$PFE_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 20
min(proj. $E_{\mathrm{T}}^{\mathrm{miss}}$, proj. track$E_{\mathrm{T}}^{\mathrm{miss}}$) [GeV]	> 20
$p_{\mathrm{T}}^{\ell\ell}$ [GeV]	> 30
$m_{\ell\ell}$ [GeV]	> 12
Additional leptons ($p_{\mathrm{T}}^{\ell} > 10$ GeV)	veto
Top-tagging veto	applied

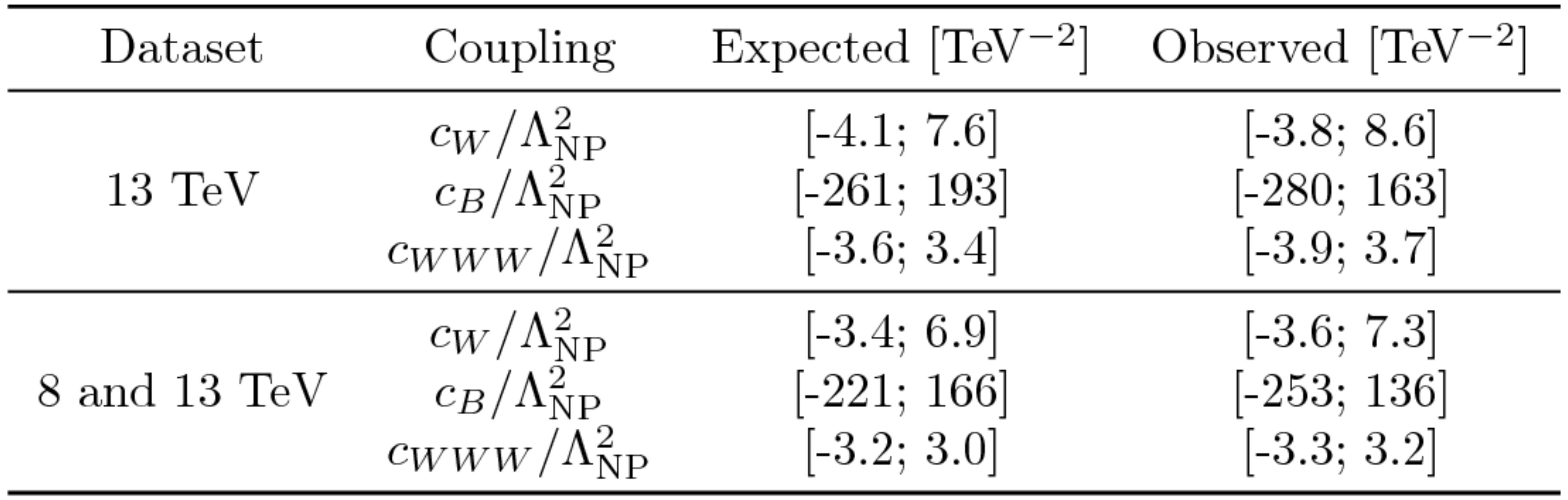
WW→ℓvℓv at 13 TeV - Event Yields

Process	Signal region	Top-quark control region	Drell–Yan control region
WW signal	997 ± 69	49 ± 12	75.3 ± 5.4
Drell–Yan	62 ± 23	49 ± 29	1568 ± 45
$t\bar{t}$+single top	177 ± 33	2057 ± 81	3.5 ± 1.6
W+jets/multi-jet	78 ± 41	70 ± 55	0 ± 17
Other dibosons	38 ± 12	6.3 ± 3.5	19.2 ± 6.1
Total	1351 ± 37	2232 ± 47	1666 ± 41
Data	1351	2232	1666

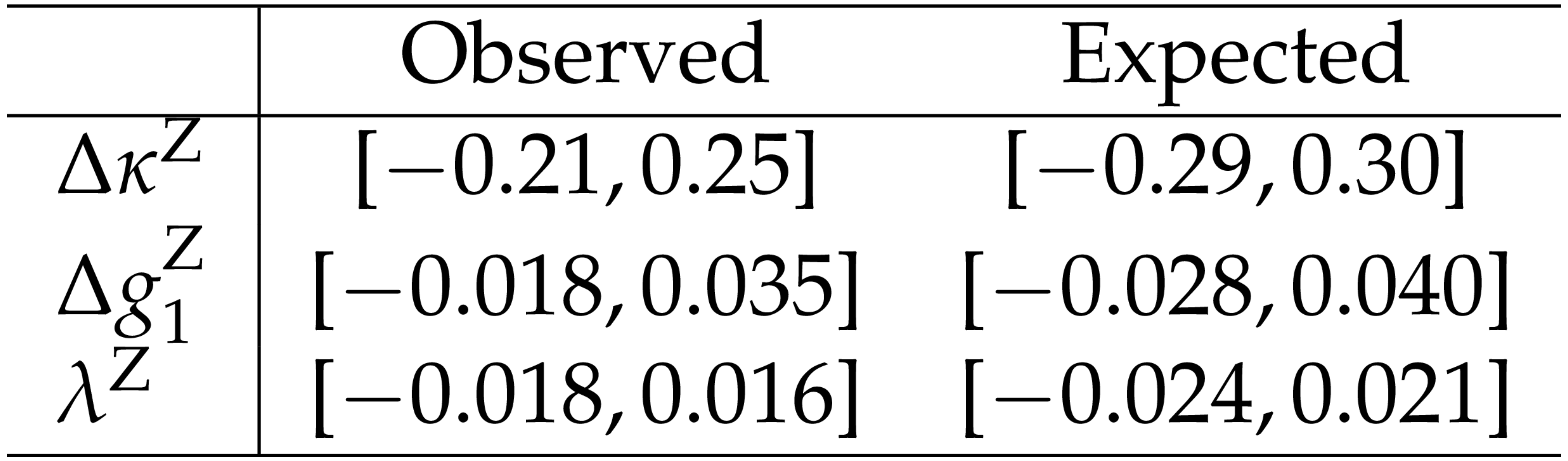
Process	0-jet	1-jet
$qq \rightarrow \mathrm{W}^+\mathrm{W}^-$	585 ± 38	228 ± 19
$gg \rightarrow \mathrm{W}^+\mathrm{W}^-$	51 ± 8	25 ± 4
$\mathrm{W}^+\mathrm{W}^-$	636 ± 40	253 ± 20
$\mathrm{ZZ} + \mathrm{WZ}$	16 ± 1	15 ± 1
Top-quark	177 ± 18	338 ± 34
$Z/\gamma^* \rightarrow \ell^+\ell^-$	3 ± 4	31 ± 7
$\mathrm{W}\gamma^*$	8 ± 2	6 ± 2
$\mathrm{W}\gamma$	25 ± 4	30 ± 5
Non-prompt	70 ± 19	33 ± 10
Higgs	25 ± 2	14 ± 1
Total bkg.	324 ± 27	467 ± 37
$\mathrm{W}^+\mathrm{W}^-$ + Total bkg.	961 ± 49	720 ± 42
Data	927	719

WZ→$\ell\nu\ell\ell$ + aTGC at 13 and 8 TeV - aTGC and EFT limits

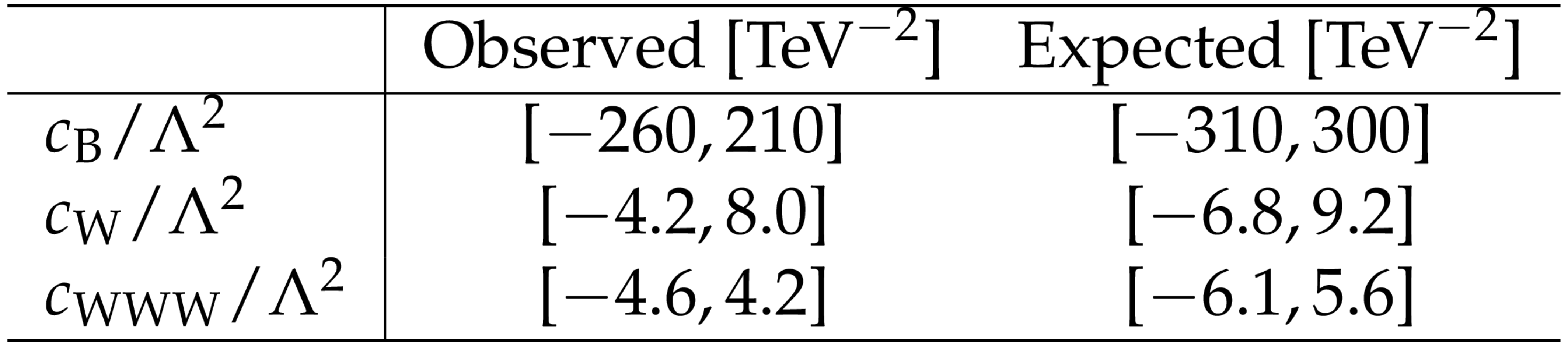
Dataset	Coupling	Expected	Observed
13 TeV	Δg_1^Z	[-0.017; 0.032]	[-0.016; 0.036]
	$\Delta\kappa_1^Z$	[-0.18; 0.24]	[-0.15; 0.26]
	λ^Z	[-0.015; 0.014]	[-0.016; 0.015]
8 and 13 TeV	Δg_1^Z	[-0.014; 0.029]	[-0.015; 0.030]
	$\Delta\kappa_1^Z$	[-0.15; 0.21]	[-0.13; 0.24]
	λ^Z	[-0.013; 0.012]	[-0.014; 0.013]



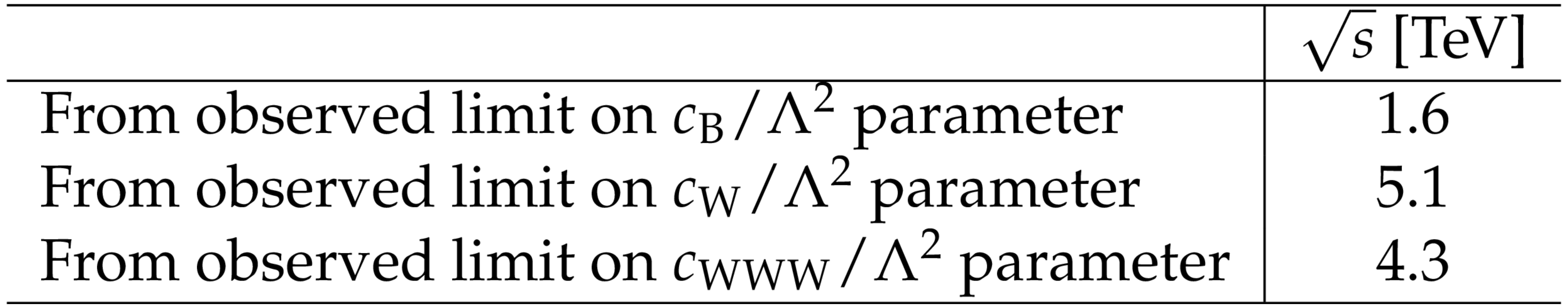
Dataset	Coupling	Expected [TeV^{-2}]	Observed [TeV^{-2}]
13 TeV	$c_W/\Lambda^2_{\rm NP}$	[-4.1; 7.6]	[-3.8; 8.6]
	$c_B/\Lambda^2_{\rm NP}$	[-261; 193]	[-280; 163]
	$c_{WWW}/\Lambda^2_{\rm NP}$	[-3.6; 3.4]	[-3.9; 3.7]
8 and 13 TeV	$c_W/\Lambda^2_{\rm NP}$	[-3.4; 6.9]	[-3.6; 7.3]
	$c_B/\Lambda^2_{\rm NP}$	[-221; 166]	[-253; 136]
	$c_{WWW}/\Lambda^2_{\rm NP}$	[-3.2; 3.0]	[-3.3; 3.2]



	Observed	Expected
$\Delta\kappa^Z$	$[-0.21, 0.25]$	$[-0.29, 0.30]$
Δg_1^Z	$[-0.018, 0.035]$	$[-0.028, 0.040]$
λ^Z	$[-0.018, 0.016]$	$[-0.024, 0.021]$



	Observed [TeV^{-2}]	Expected [TeV^{-2}]
c_B/Λ^2	$[-260, 210]$	$[-310, 300]$
c_W/Λ^2	$[-4.2, 8.0]$	$[-6.8, 9.2]$
c_{WWW}/Λ^2	$[-4.6, 4.2]$	$[-6.1, 5.6]$



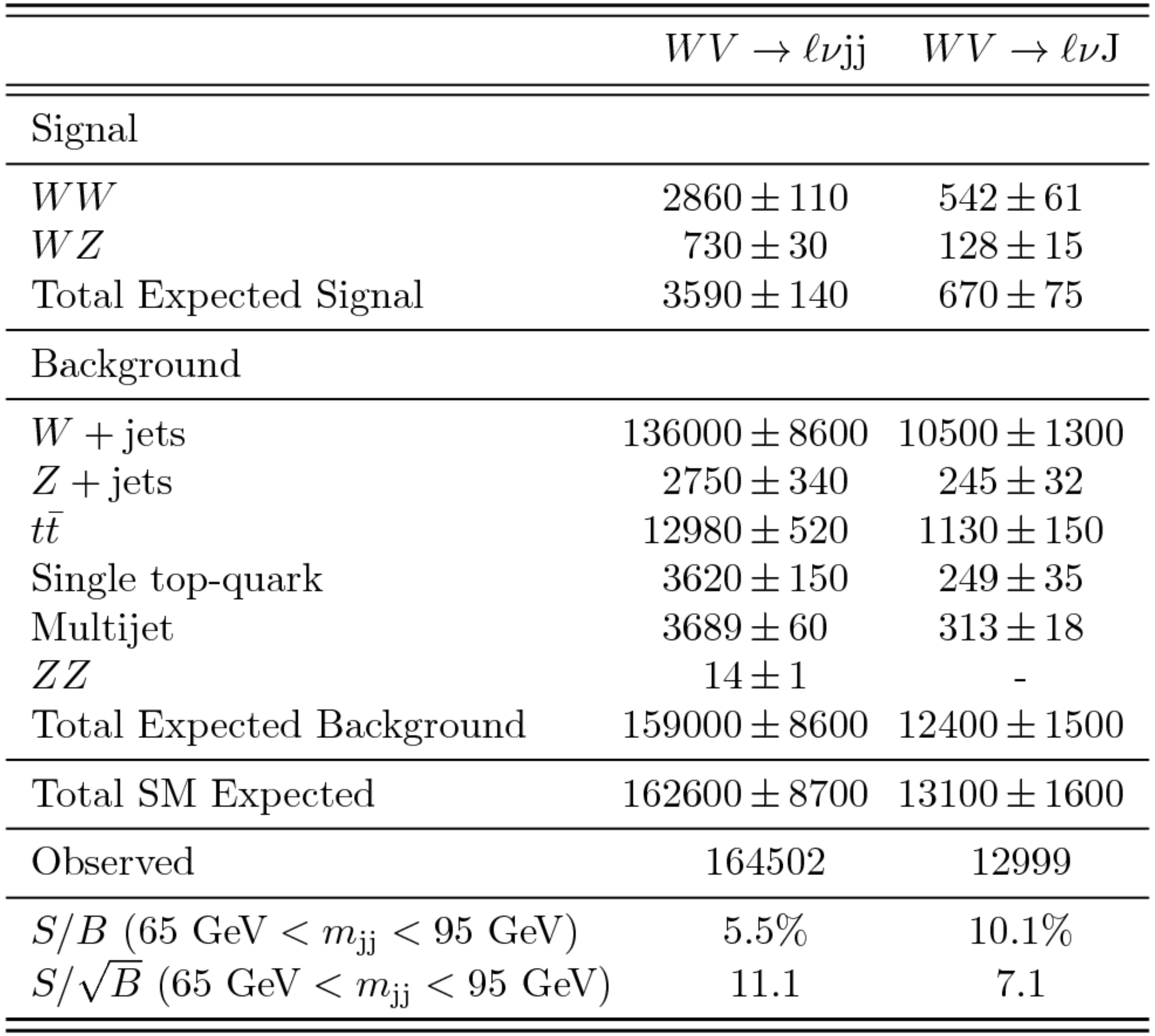
	$\sqrt{s}$ [TeV]
From observed limit on c_B/Λ^2 parameter	1.6
From observed limit on c_W/Λ^2 parameter	5.1
From observed limit on c_{WWW}/Λ^2 parameter	4.3

WV→ℓvqq + aTCG at 8 TeV - Samples

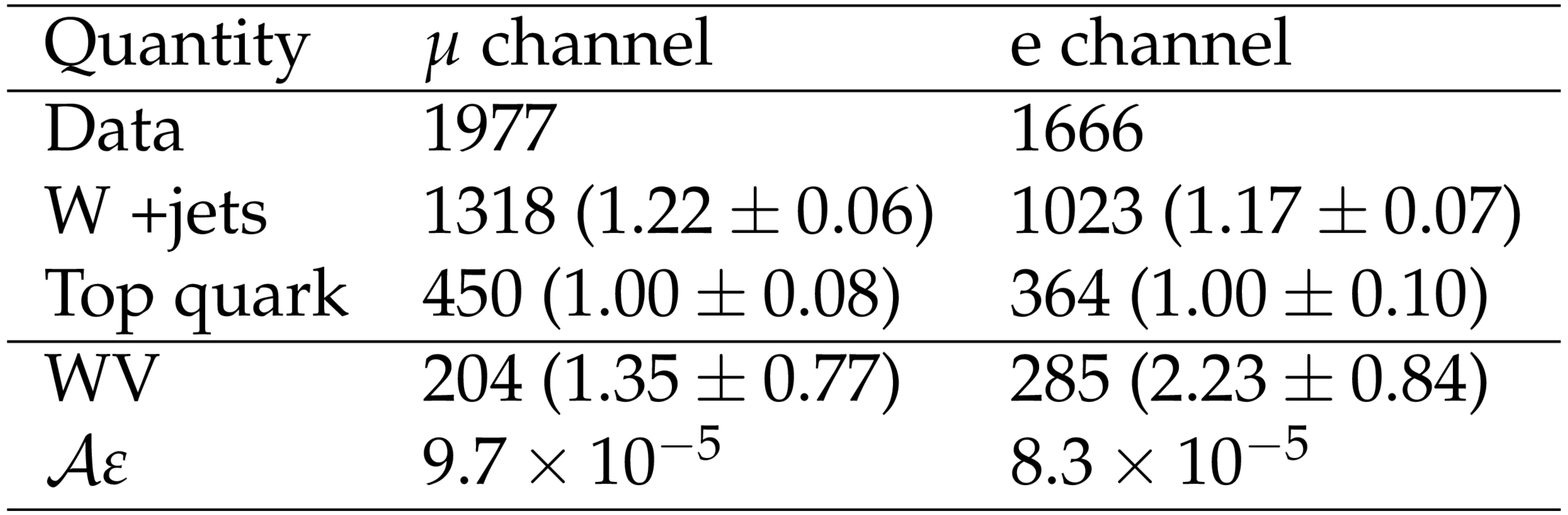
- Signal
  - qq → WV: MC@NLO+Herwig (Powheg-Box & Sherpa 1.4.1 for systematics)
  - aTGC contributions use built-in reweighting feature of MC@NLO
- V+jets
  - Sherpa 1.4.1 (LO) normalised to NNLO with FEWZ
- tt and single top
  - Powheg-Box+Pythia6
- ZZ
  - Powheg+Pythia8 normalised using MCFM NLO

- Signal
  - MadGraph5_AMC@NLO
- V+jets
  - MadGraph5
- ttbar and single top
  - Powheg 1.0

WV→ℓvqq + aTCG at 8 TeV - Yields



	$WV \to \ell\nu$jj	$WV \to \ell\nu$J
Signal		
WW	2860 ± 110	542 ± 61
WZ	730 ± 30	128 ± 15
Total Expected Signal	3590 ± 140	670 ± 75
Background		
$W +$ jets	136000 ± 8600	10500 ± 1300
$Z +$ jets	2750 ± 340	245 ± 32
$t\bar{t}$	12980 ± 520	1130 ± 150
Single top-quark	3620 ± 150	249 ± 35
Multijet	3689 ± 60	313 ± 18
ZZ	14 ± 1	-
Total Expected Background	159000 ± 8600	12400 ± 1500
Total SM Expected	162600 ± 8700	13100 ± 1600
Observed	164502	12999
S/B (65 GeV $< m_{\text{jj}} <$ 95 GeV)	5.5%	10.1%
$S/\sqrt{B}$ (65 GeV $< m_{\text{jj}} <$ 95 GeV)	11.1	7.1



Quantity	μ channel	e channel
Data	1977	1666
W +jets	1318 (1.22 ± 0.06)	1023 (1.17 ± 0.07)
Top quark	450 (1.00 ± 0.08)	364 (1.00 ± 0.10)
WV	204 (1.35 ± 0.77)	285 (2.23 ± 0.84)
$\mathcal{A}\varepsilon$	9.7×10^{-5}	8.3×10^{-5}