ATLAS/CMS VBS combination of dim-8 operators

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Despoina Sampsonidou, Max Neukum on behalf of VBSCan WG3

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Introduction

Goal is to extract limits on dim-8 EFT parameters using public results from VBS analyses @13 TeV

- Combine ATLAS and CMS results of different VBS channels using hepdata information
- Use EFT parametrization from: O. Eboli, M. Gonzalez-Garcia (2016) (arxiv:1604.03555)
- Use MG5 + Pythia8 for EFT modeling and the approach of splitting the different EFT expansion terms
- Use the clipping method as unitarization procedure at large √s

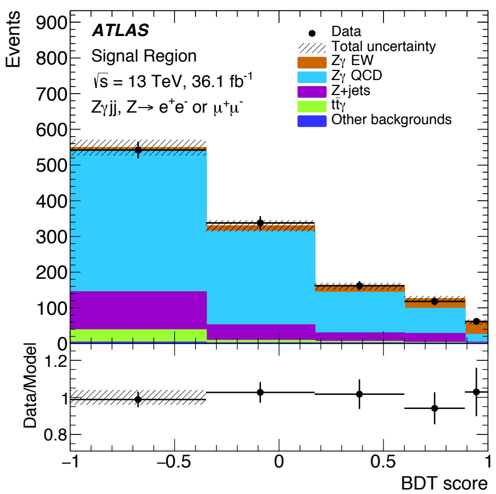
This talk present the progress in the last months including the validation of the truth level samples and ssWW ATLAS limits

Set of 18 dim-8 operators affecting quartic boson vertices:

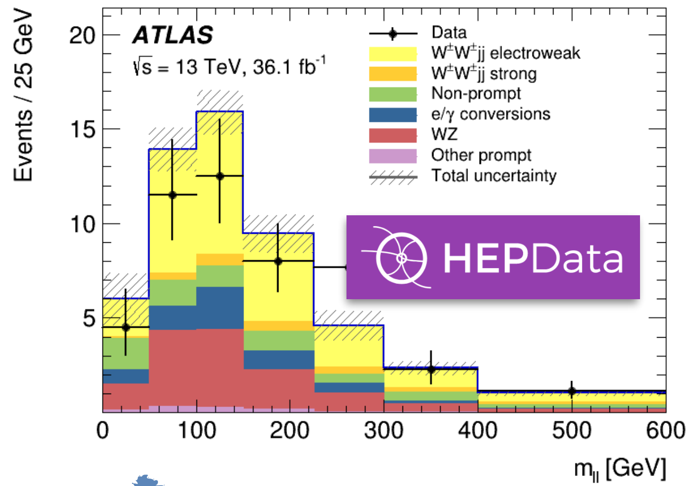
Quartic vertex \ Dim-8 operator	$\mathcal{O}_{S0}$ $\mathcal{O}_{S1}$ $\mathcal{O}_{S2}$	$\mathcal{O}_{M0}$ $\mathcal{O}_{M1}$ $\mathcal{O}_{M7}$	$\mathcal{O}_{M2}$ $\mathcal{O}_{M3}$ $\mathcal{O}_{M4}$ $\mathcal{O}_{M5}$	$\mathcal{O}_{T0}$ $\mathcal{O}_{T1}$ $\mathcal{O}_{T2}$	$\mathcal{O}_{T5}$ $\mathcal{O}_{T6}$ $\mathcal{O}_{T7}$	$\mathcal{O}_{T8}$ $\mathcal{O}_{T9}$
WWWW	✓	✓		✓		
W^+W^-ZZ	✓	✓	✓	✓	✓	
$W^+W^-Z\gamma$		✓	✓	✓	✓	
$W^+W^-\gamma\gamma$		✓	✓	✓	✓	
ZZZZ	✓	✓	✓	✓	✓	✓
$ZZZ\gamma$		✓	✓	✓	✓	✓
$ZZ\gamma\gamma$		✓	✓	✓	✓	✓
$Z\gamma\gamma\gamma$				✓	✓	✓
$\gamma\gamma\gamma\gamma$				✓	✓	✓

ATLAS and CMS recent results

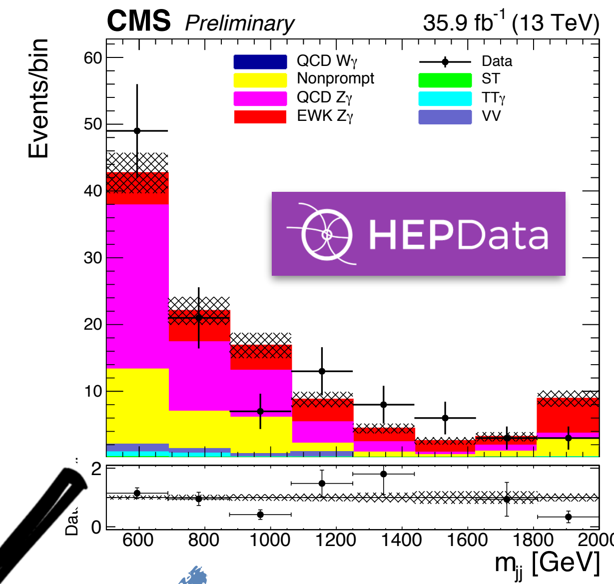
Zγ arXiv:1910.09503



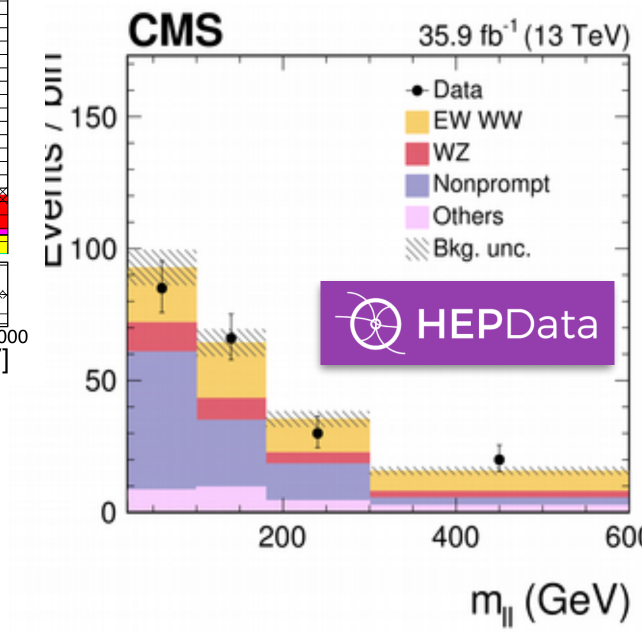
ssWW arXiv:1906.03203



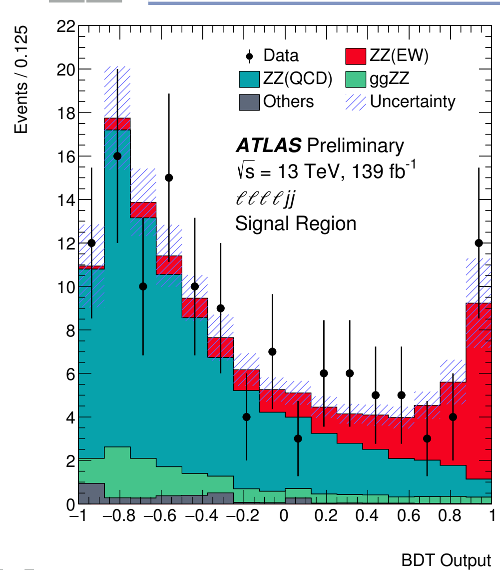
Zγ CMS-PAS-SMP-18-007

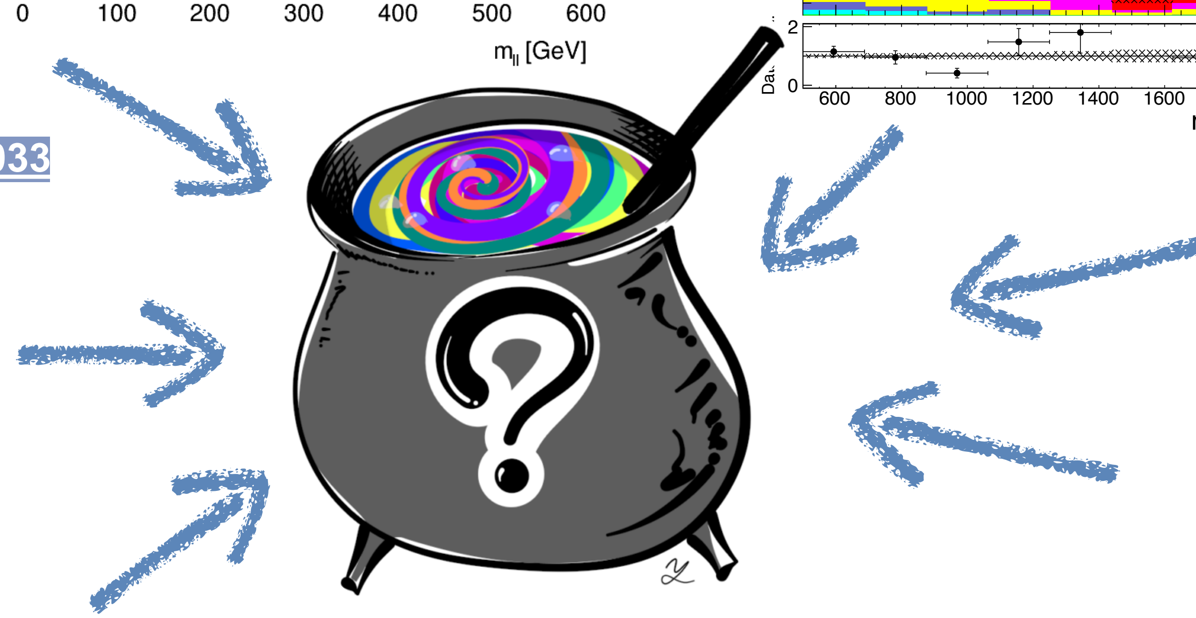


ssWW PRL 120 (2018) 081801

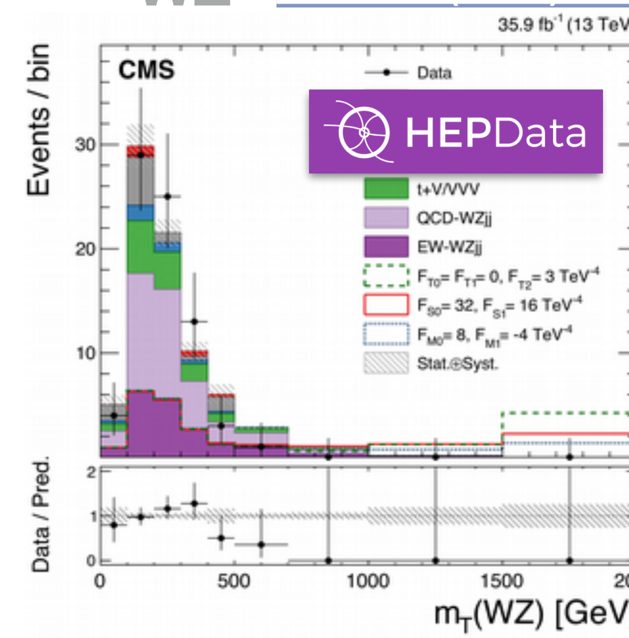


ZZ ATLAS-CONF-2019-033

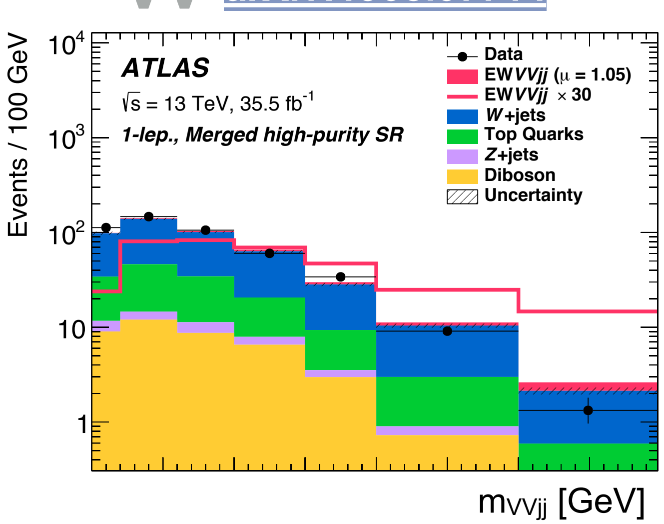




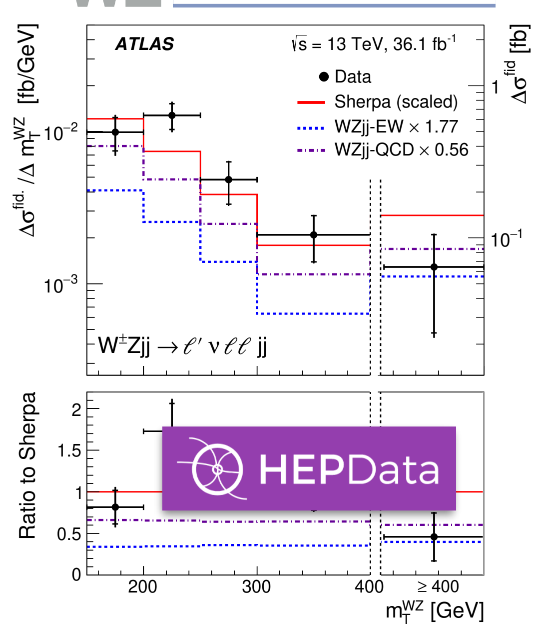
WZ PLB 795 (2019) 281



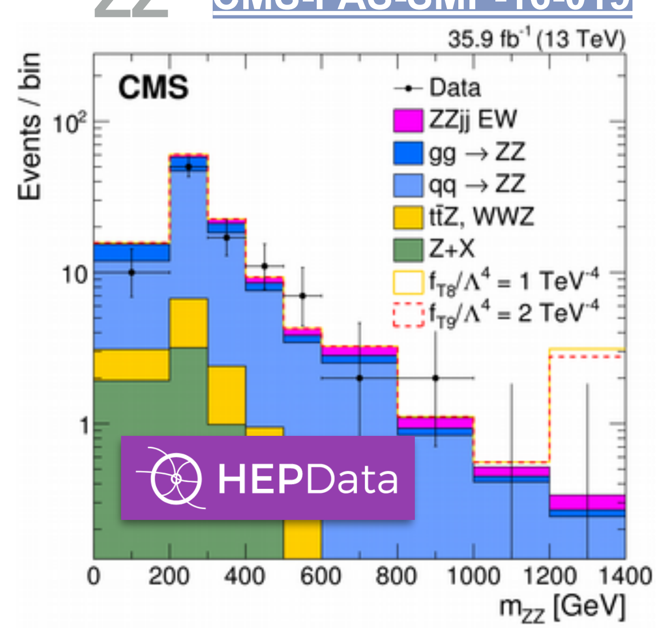
VV arXiv:1905.07714



WZ arXiv:1812.09740



ZZ CMS-PAS-SMP-16-019



Signal modelling

Generation with Madgraph+Pythia8

- Madgraph is able to generate the individual contributions of the SM+EFT amplitude:

$$\left|\mathcal{A}_{SM} + \sum_i \frac{f_i}{\Lambda^4}\mathcal{A}_i\right|^2 = |\mathcal{A}_{SM}|^2 + \underbrace{\sum_i 2\frac{f_i}{\Lambda^4}\mathcal{Re}(\mathcal{A}_i^*\mathcal{A}_{SM})}_{\text{Interference SM-EFT}} + \underbrace{\sum_i \frac{f_i^2}{\Lambda^8}|\mathcal{A}_i|^2}_{\text{Pure EFT (quadratic term)}} + \underbrace{\sum_{i,j,i\neq j} 2\frac{f_i f_j}{\Lambda^8}\mathcal{Re}(\mathcal{A}_i^*\mathcal{A}_j)}_{\text{EFT cross term}}$$

  - This splitting can be used to scan the whole parameter space with only a few generated samples (by scaling of the different terms)
  - Validation of this approach has to be done for every channel and process (ssWW and WZ channels extensive validation was show here)

- VBSCan proposal on metadata parameters for MG generation (SM parameters, theoretical uncertainties, PS cuts)

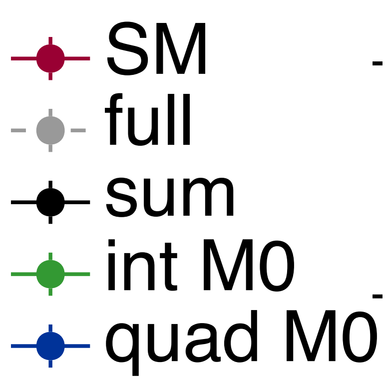
Signal modelling Validation

[Slides Stefanie Todt]

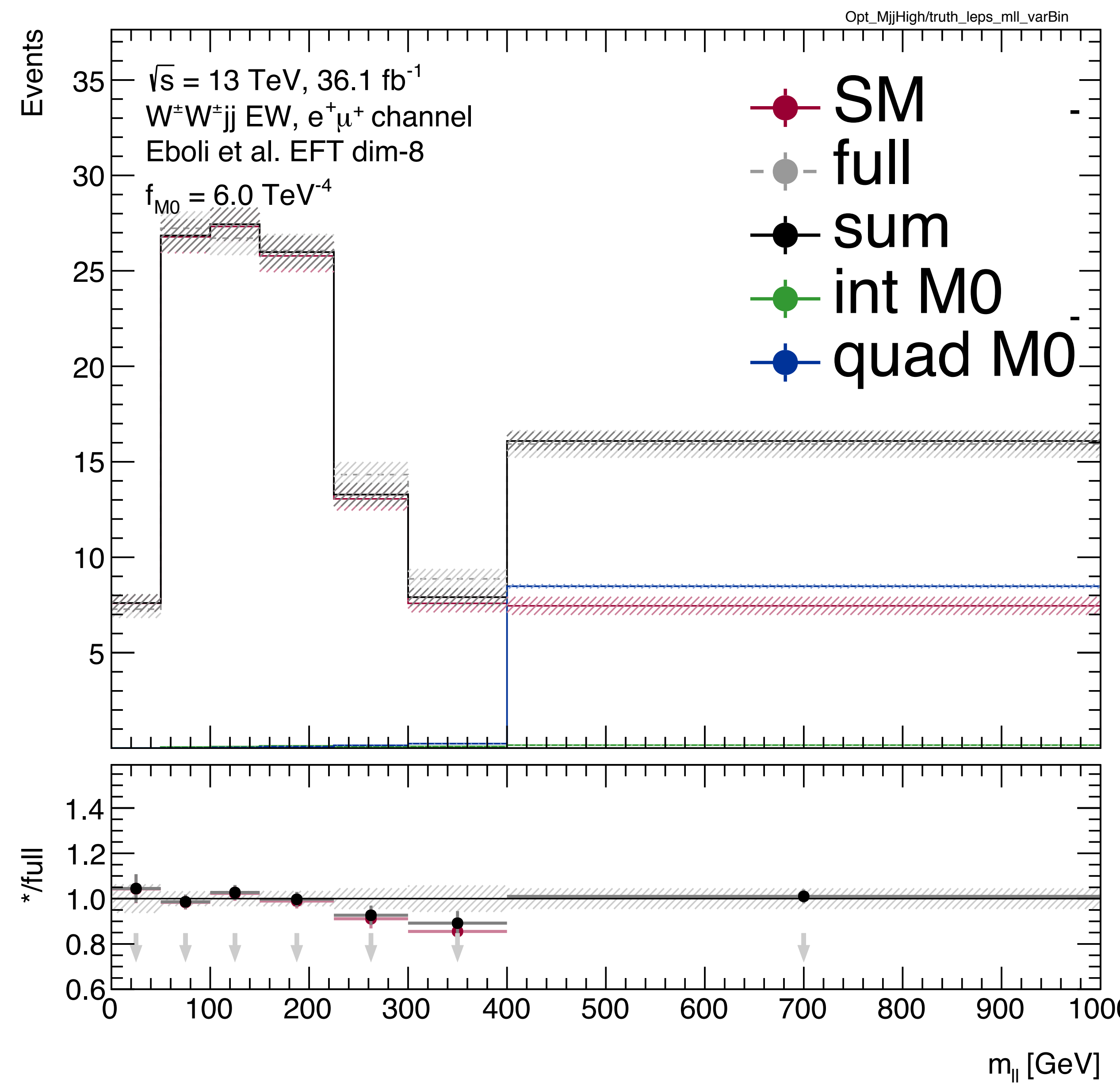
ssWW

$$f_{M0} = 6.0\,\mathrm{TeV}^{-4}$$

- Madgraph is able to generate the individual contributions of the SM+EFT amplitude
- Split contributions should sum up to the full cross section (independent generation)



- Quadratic term is always dominant over interference term



Signal modelling Validation

Slides Stefanie Todt

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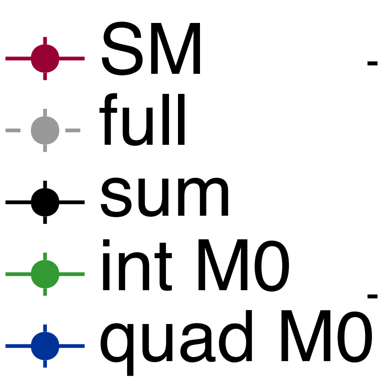
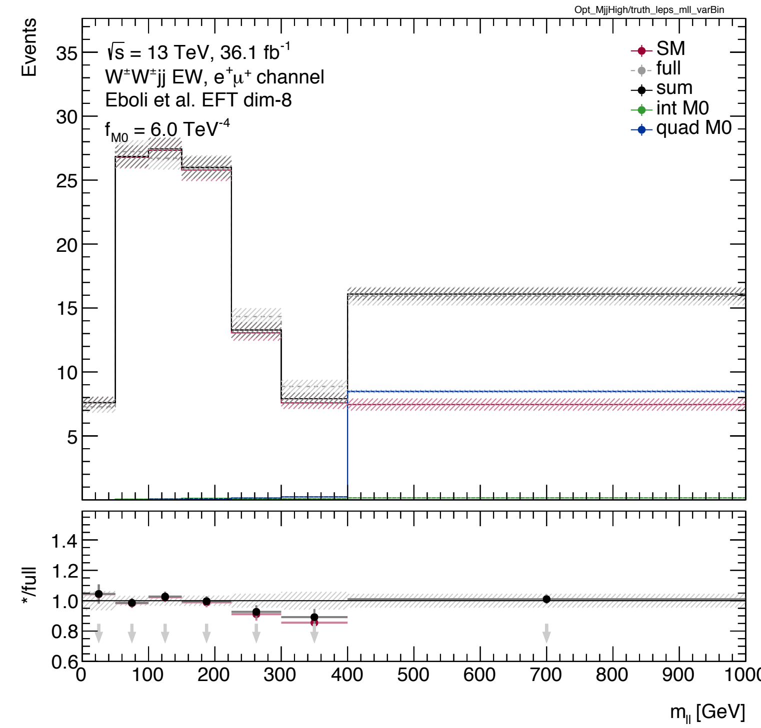
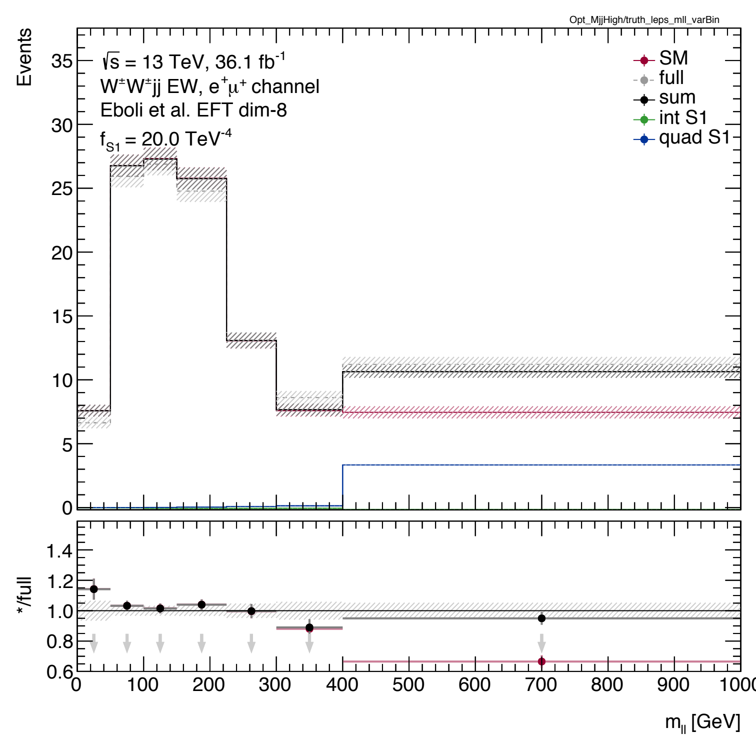


- Quadratic term is always dominant over interference term

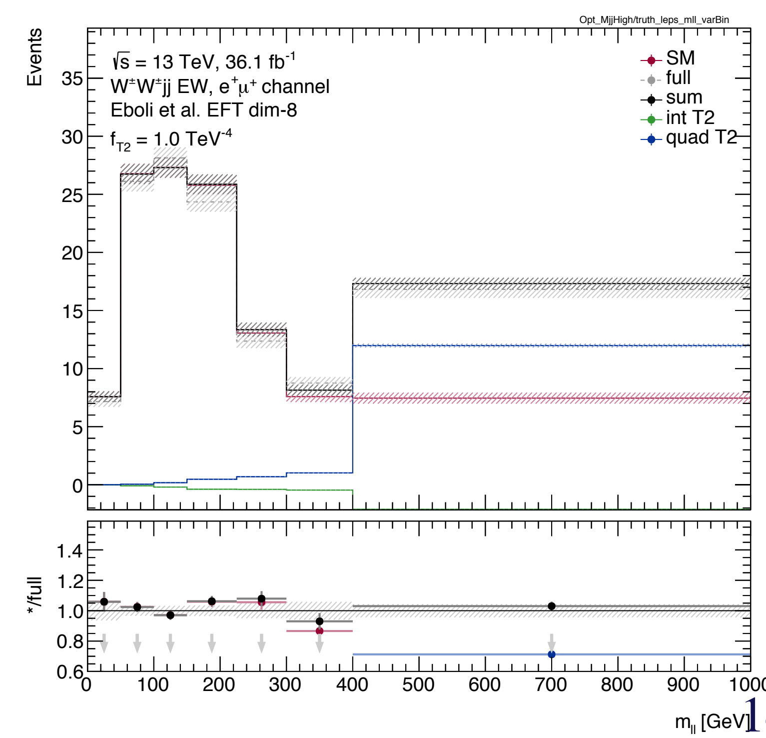
$f_{M0} = 6.0\,\mathrm{TeV}^{-4}$



$f_{S1} = 20.0\,\mathrm{TeV}^{-4}$



$f_{T2} = 1.0\,\mathrm{TeV}^{-4}$



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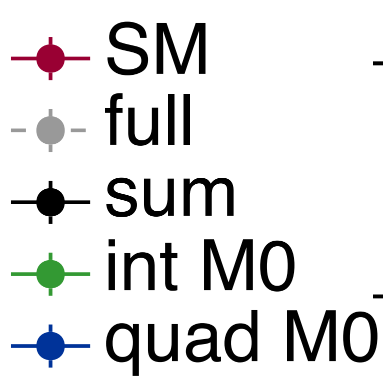
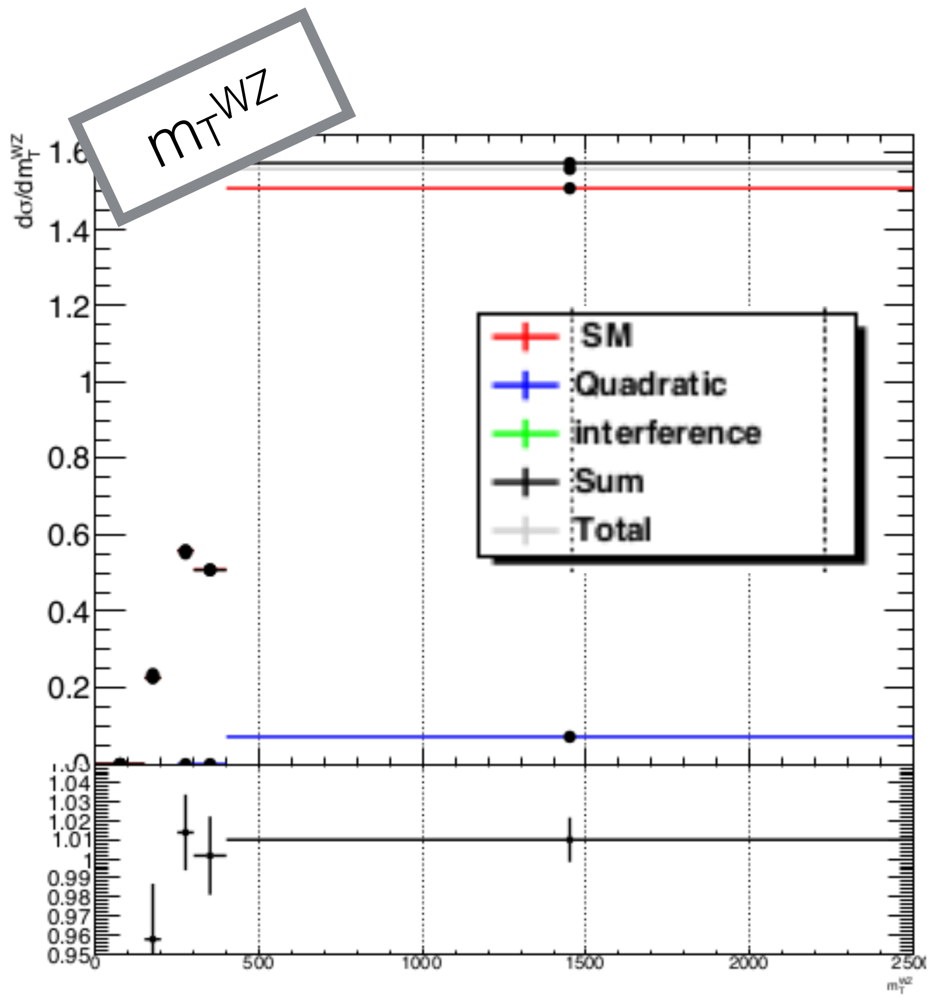
Signal modelling Validation

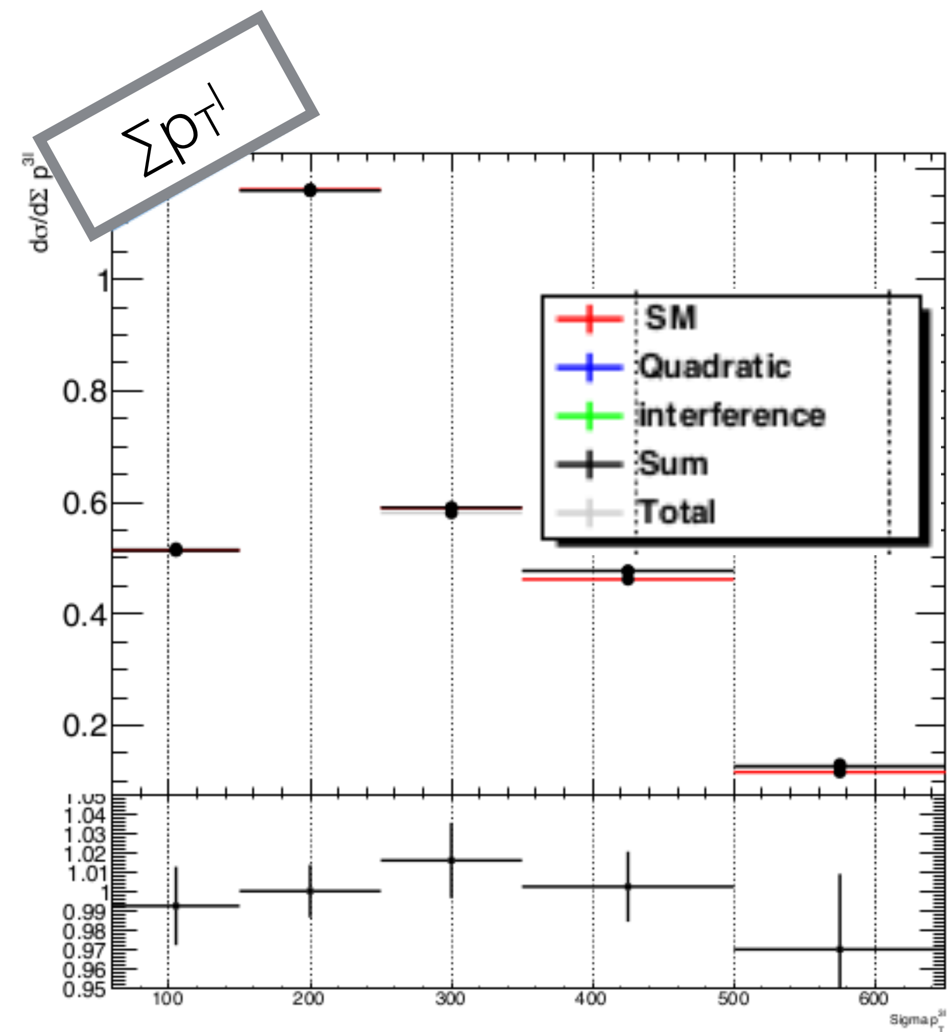
[Slides Despoina](#)

WZ

- Madgraph is able to generate the individual contributions of the SM+EFT amplitude
- Split contributions should sum up to the full cross section (independent generation)







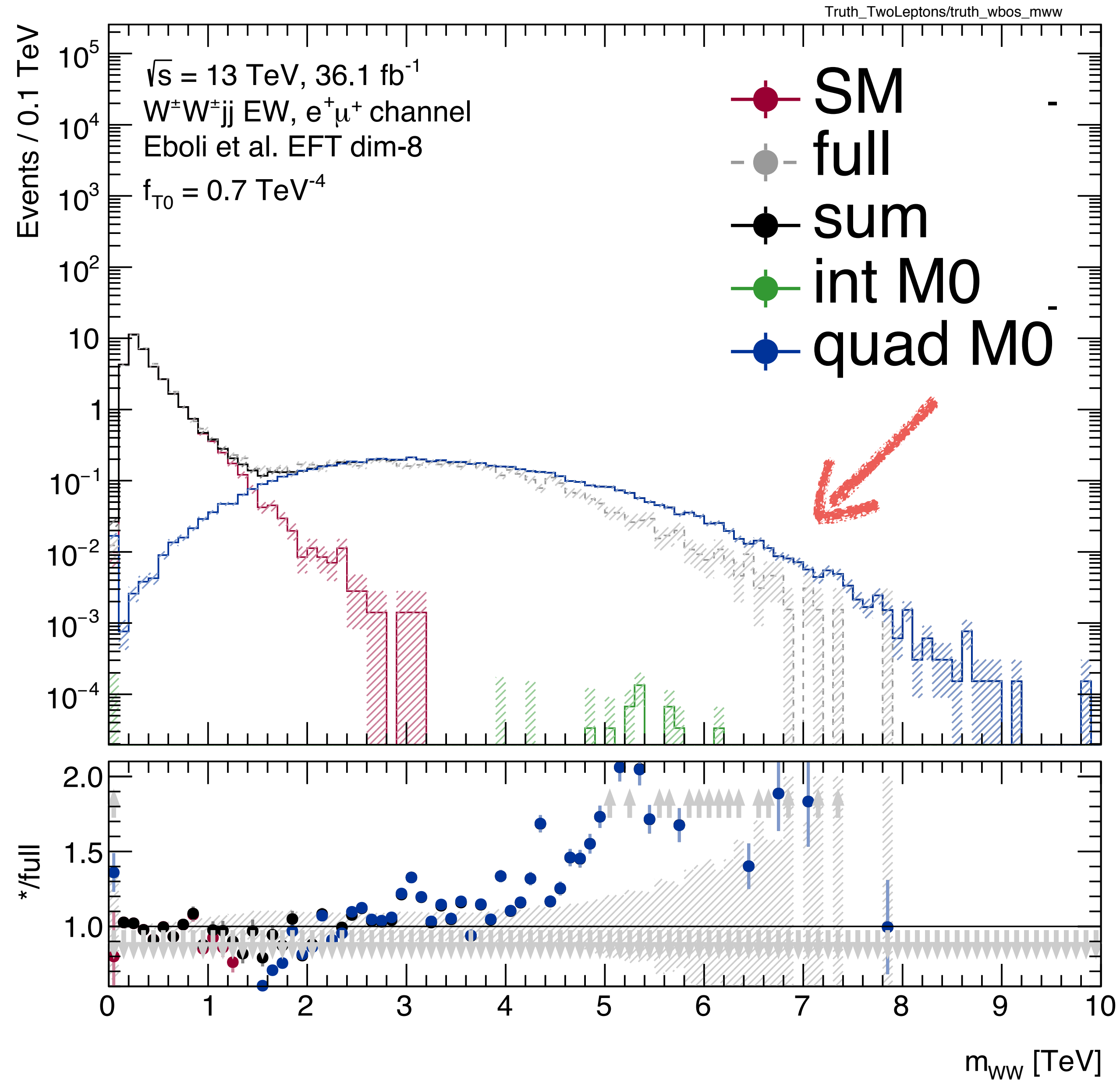
Signal modelling Validation

[Slides Stefanie Todt]

ssWW

- Madgraph is able to generate the individual contributions of the SM+EFT amplitude
- Split contributions should sum up to the full cros section (independent generation)

SM
full
sum
int M0
quad M0



  - Works for most of the distributions and parameter, but sometimes the full sample has integration problems in the tails.
  - The decomposition works fine also without the cut. Hence, the decomposition is preferred over the FULL generation now also from a physics point of view!

Signal modelling Validation

[Slides Stefanie Todt]

ssWW

Testing the integration in the high mass tails

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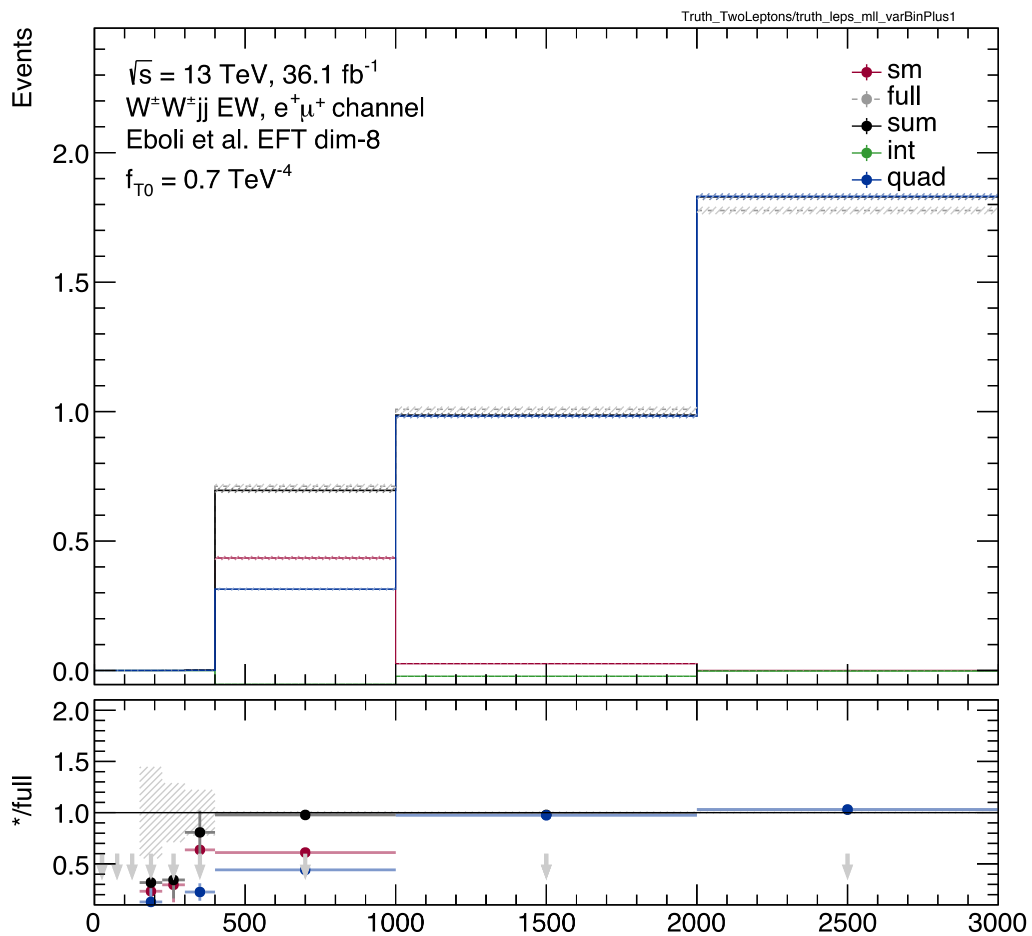
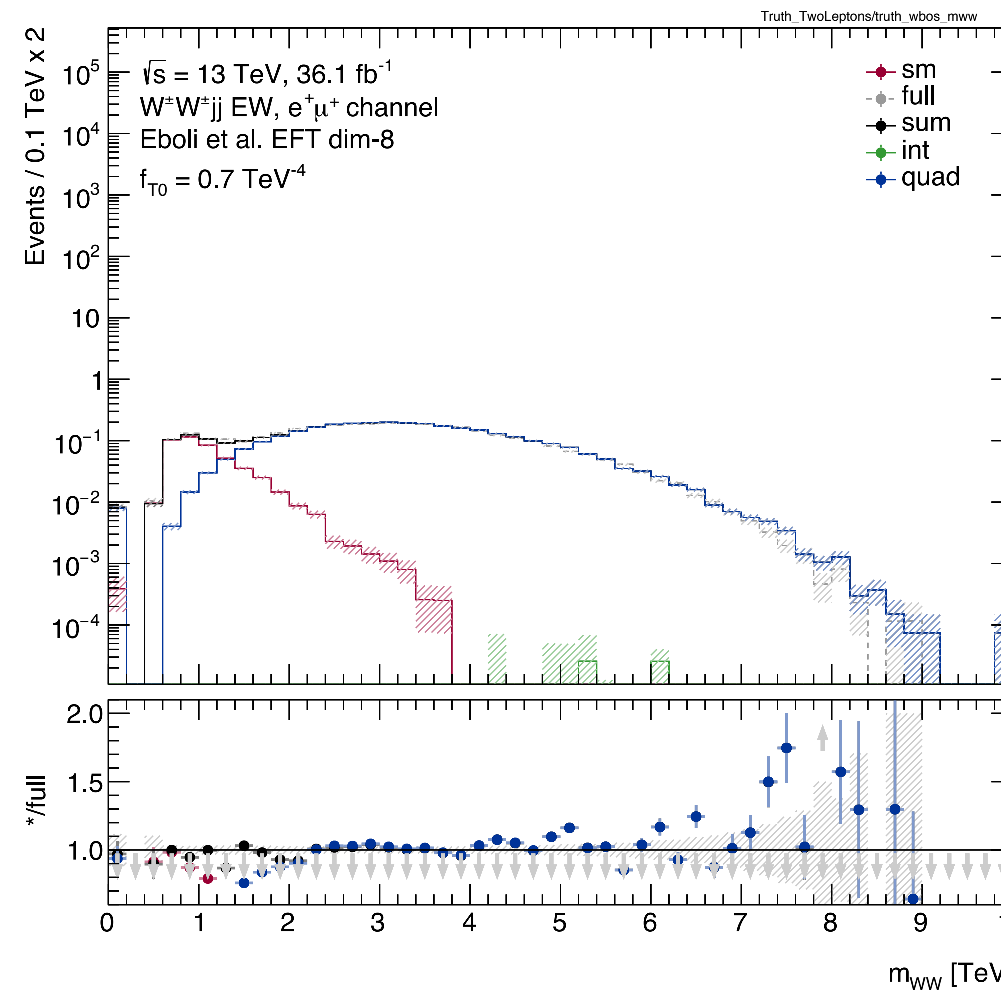
- $m_{ll} > 500\,\text{GeV}$ at MG generation level

  $\Rightarrow$ Improve the integration of the FULL sample in the high mass tails
- Process: $uu > dd\mu^+\mu^+\nu\nu$ (same flavour only technically possible in MG), parameter: $f_{T0} = 0.7\,\text{TeV}^{-4}$
- The agreement is good also in the very high tails!

  $\Rightarrow$ The FULL sample is problematic in the tails when no mass cut is placed. The decomposition works fine also without the cut. Hence, the decomposition is preferred over the FULL generation now also from a physics point of view!

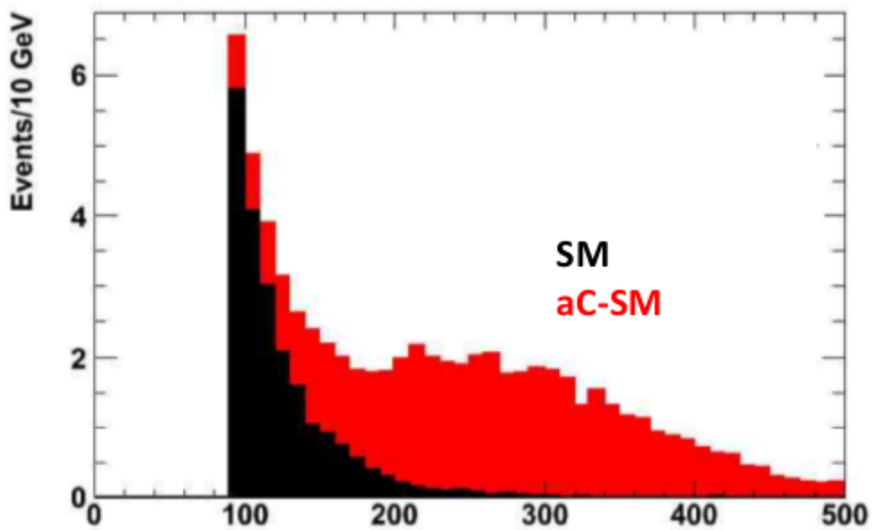




Restoring unitarity al large √s

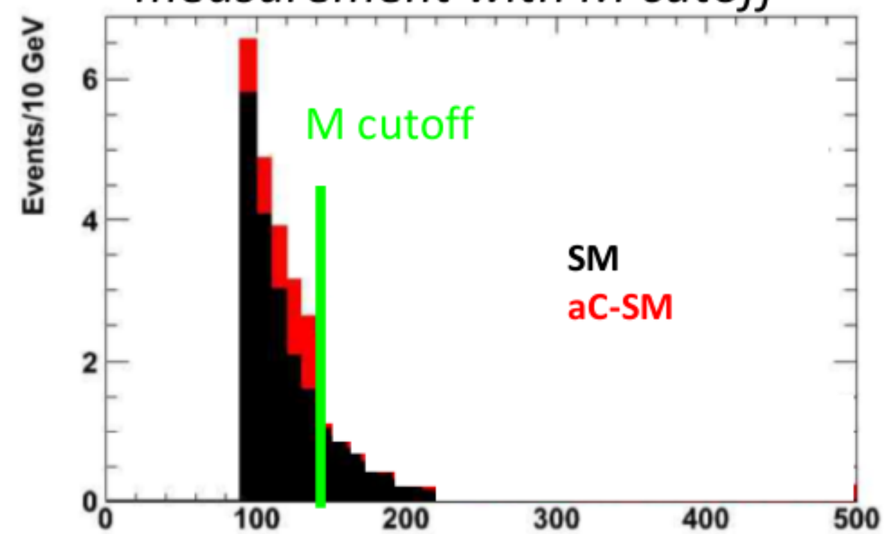
The clipping method

Inclusive anomalous coupling measurement



For every M cutoff value

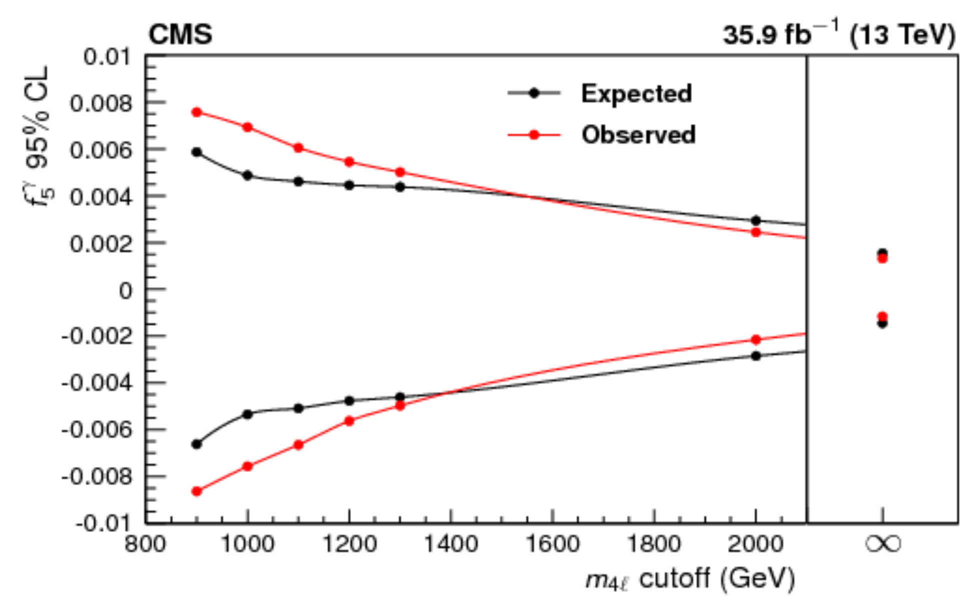
Anomalous coupling measurement with M cutoff



"√s"

from Senka Duric

- Use the EFT prediction only up to a clipping energy $\sqrt{s} = E_{clip}$ and set any contribution from this theory to 0 beyond this energy
- The clipping is done at parton level
- The SM predictions as well as the data remain untouched
- Derive aQGC limits for various Eclip



CMS-SMP-16-017-003

Clipping studies

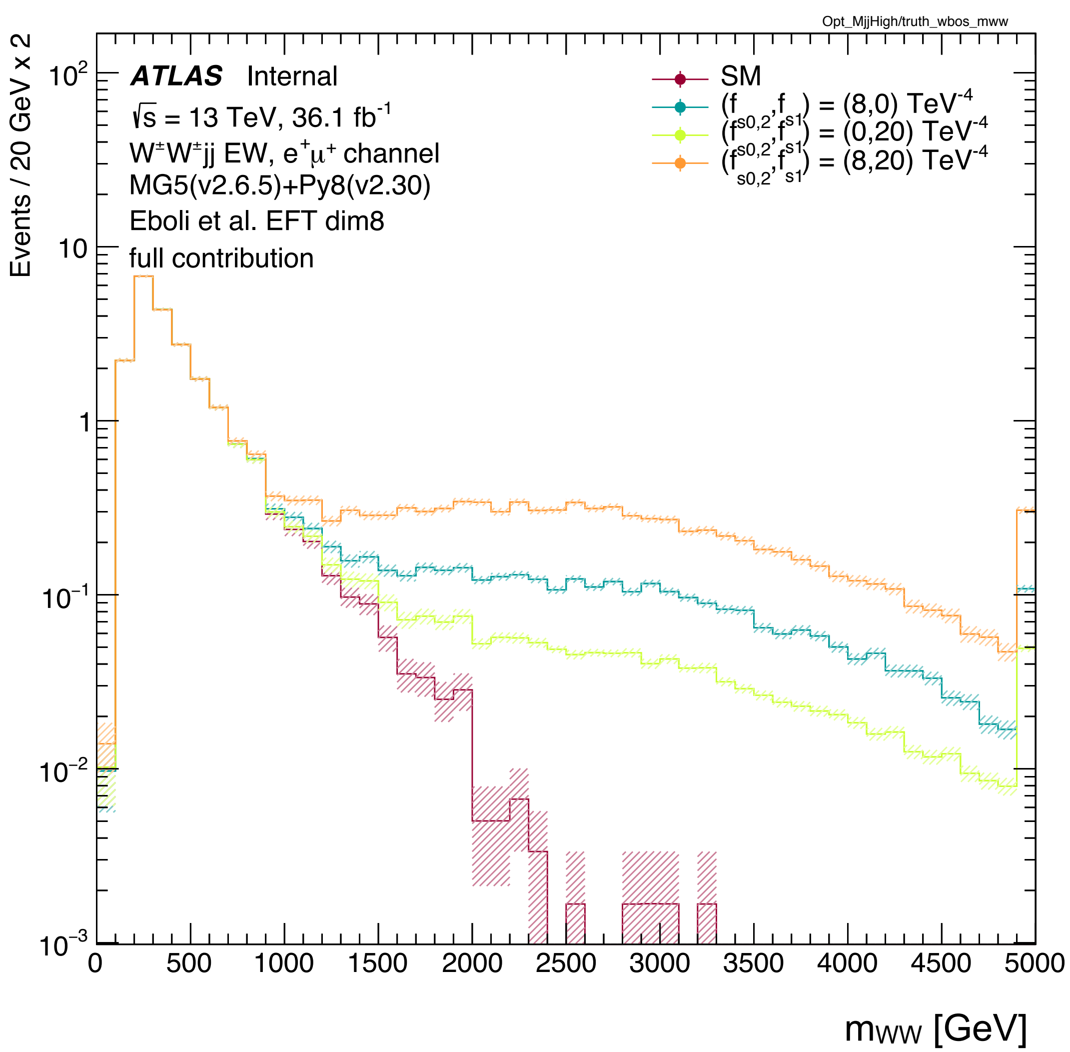
[Slides Stefanie Todt]

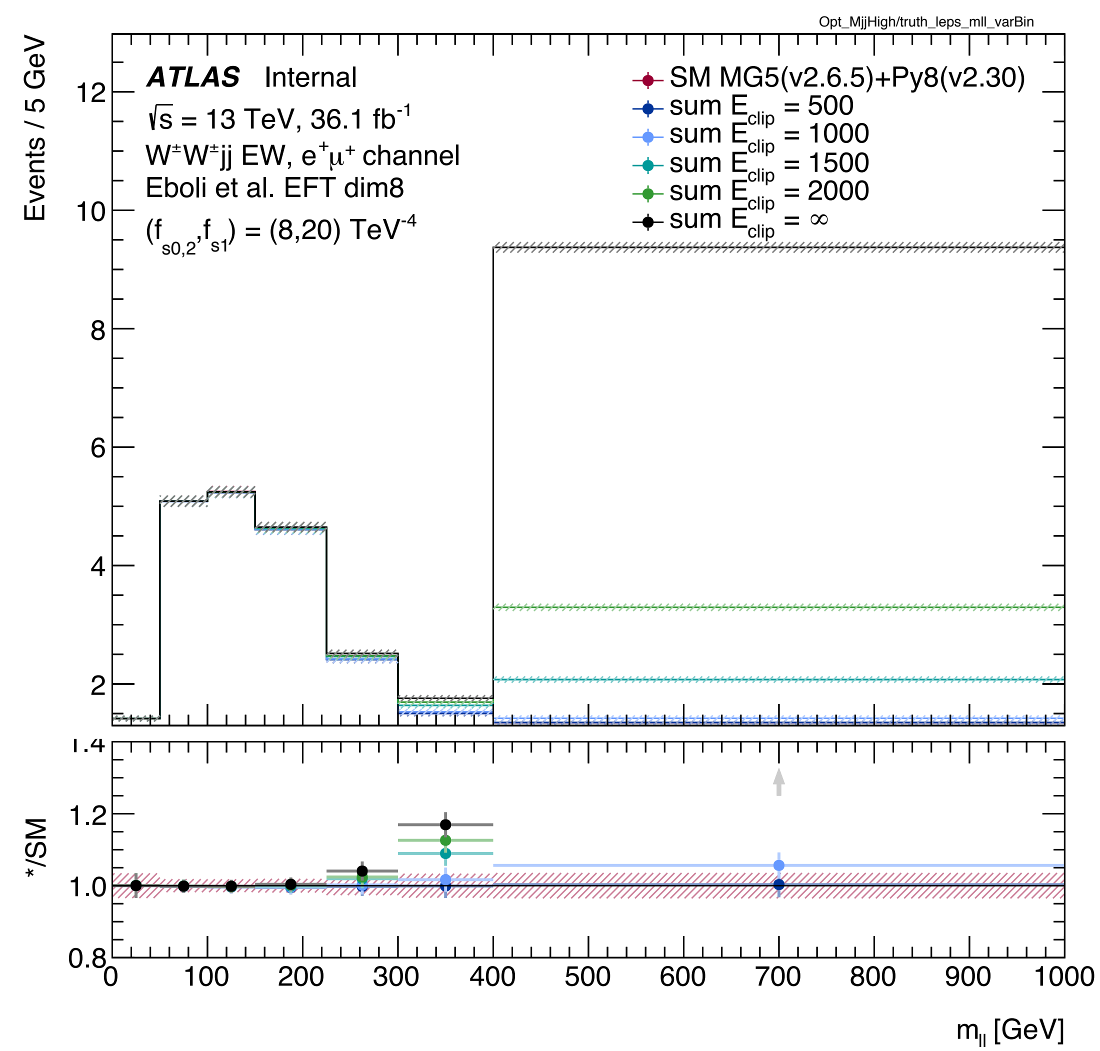
ssWW

- Calculate m_{WW} before showering to mimic $\sqrt{s}$
- Clip the m_{WW} at different values

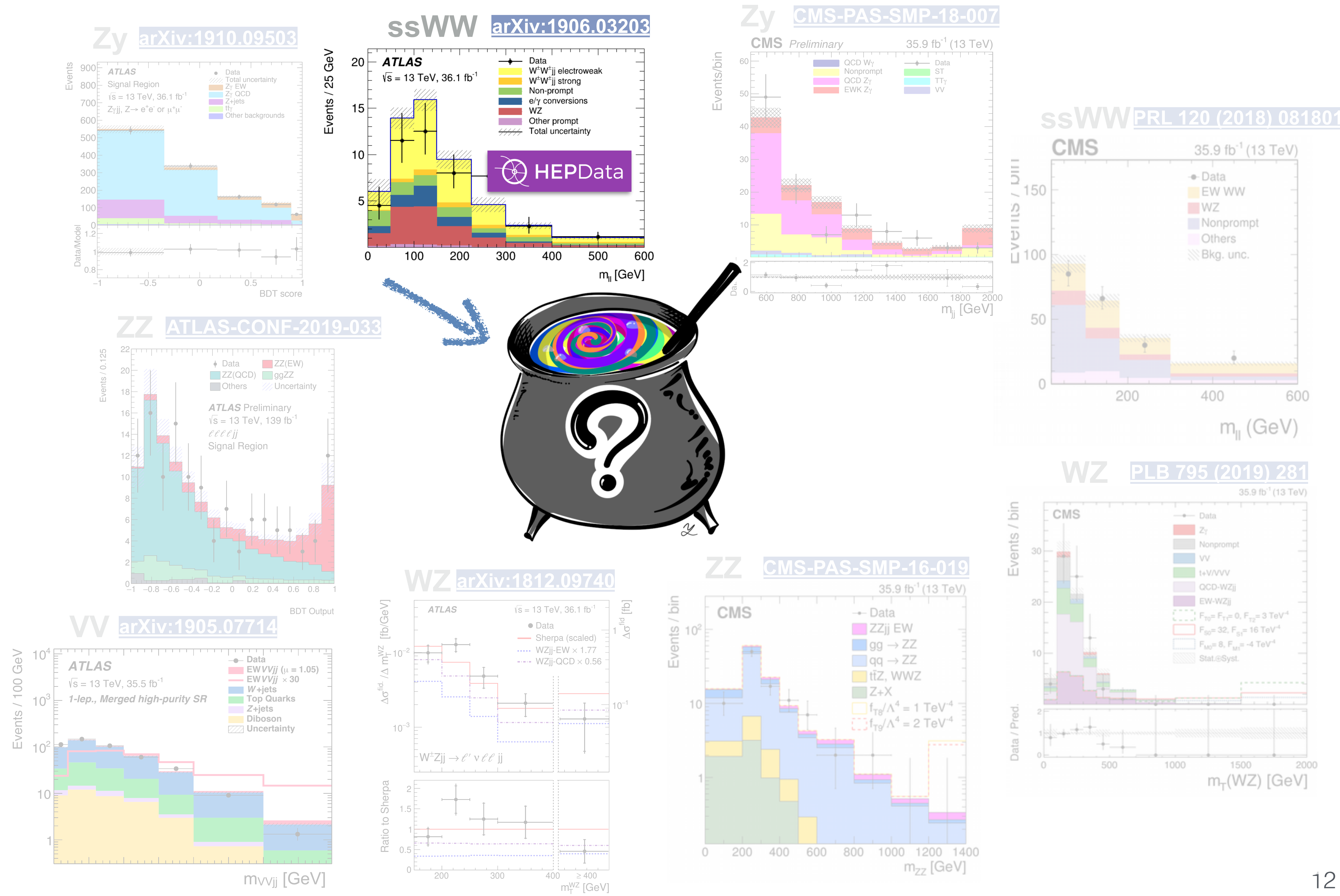
  - sum E_{clip} = 500
  - sum E_{clip} = 1000
  - sum E_{clip} = 1500
  - sum E_{clip} = 2000
  - sum E_{clip} = ∞

- ATLAS ssWW has published the position of the last data point in m_{ll} that could be use as reference for first clipping point





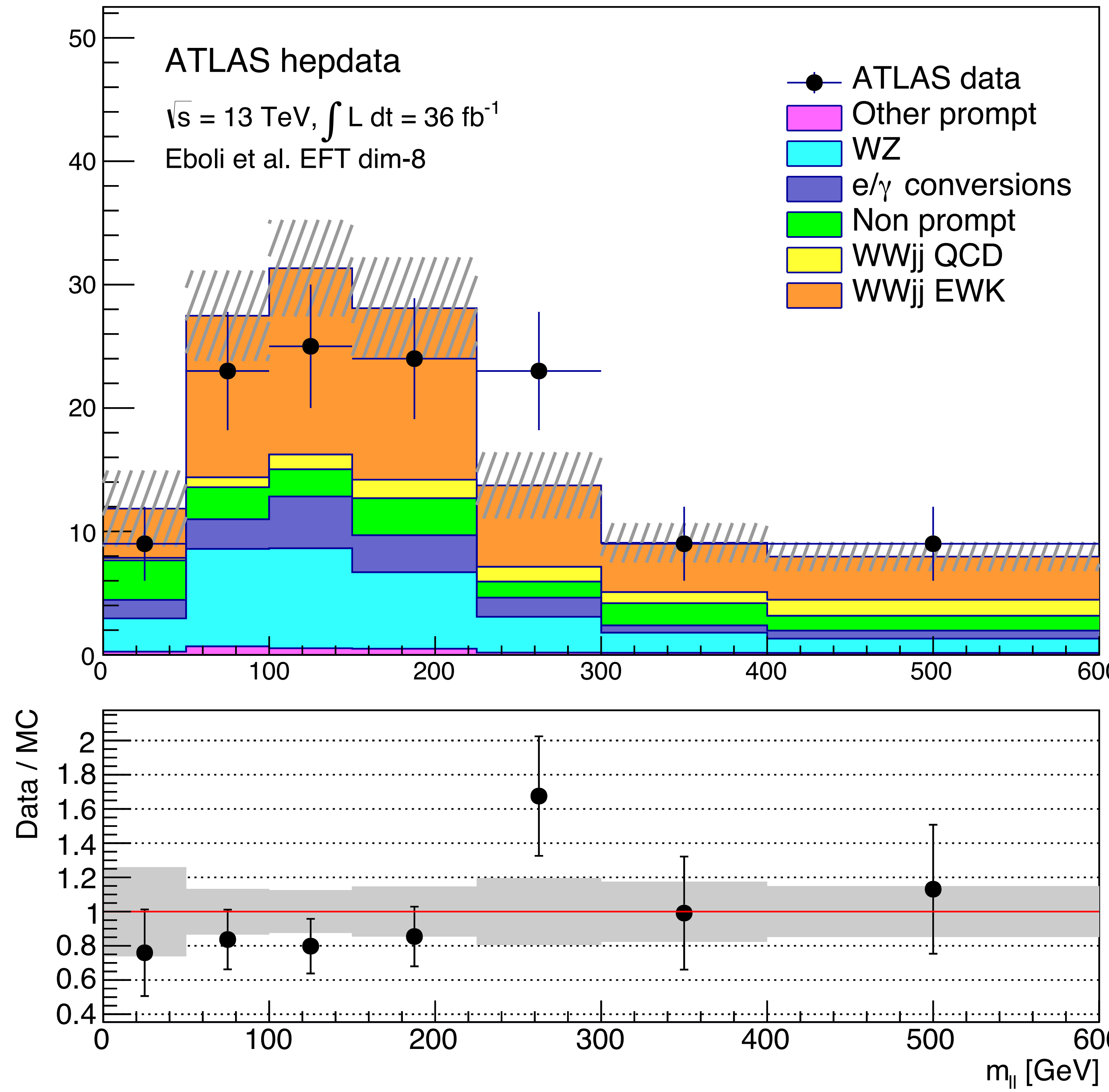
Focus now on the ssWW ATLAS channel



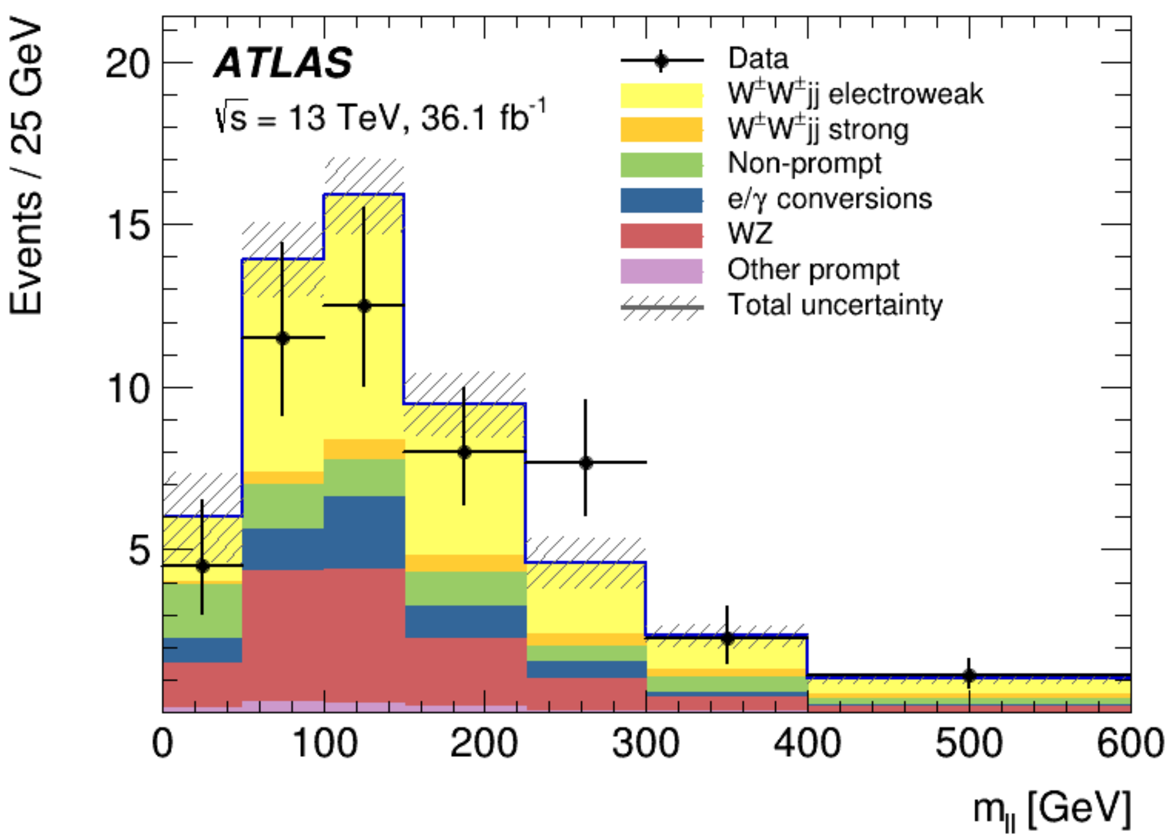
ssWW hepdata inputs

- Take the data and MC yields from Hepdata
  - Postfit dilepton invariant mass (m_{ll}) in 7 bins was provided together with uncertainties for data and simulation

Distribution using HEPData



Publication Arxiv:1912.09837

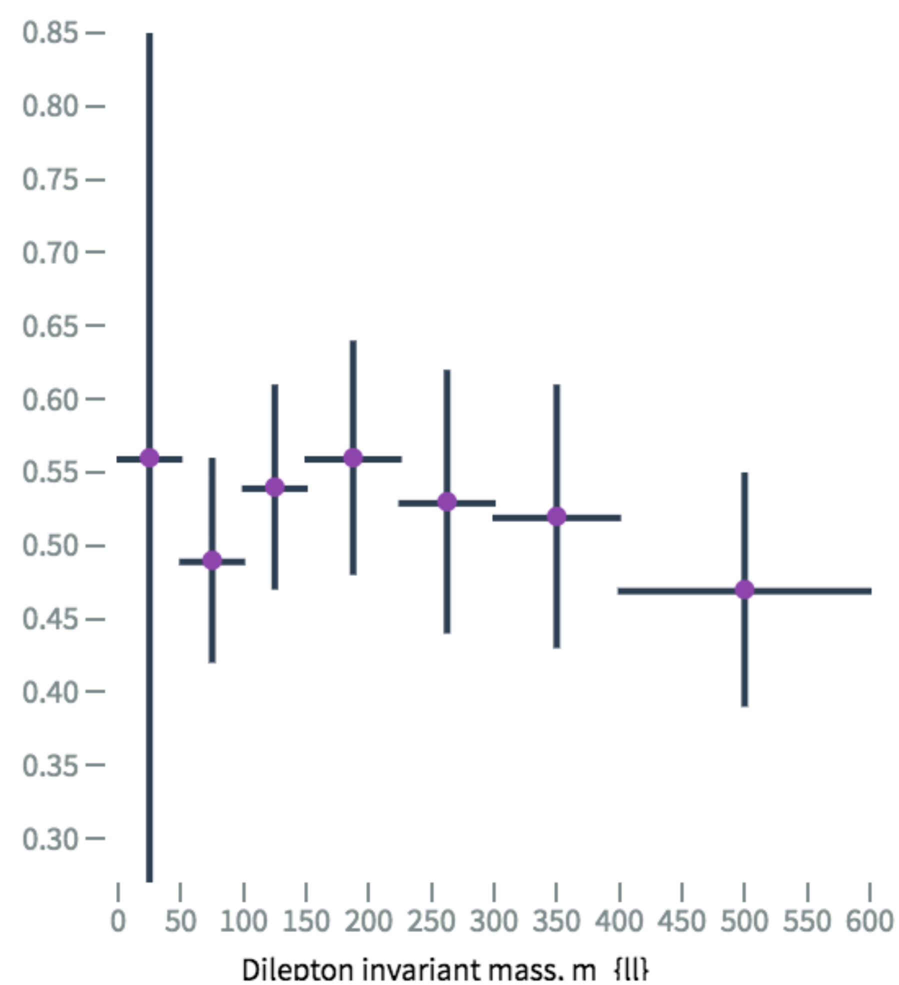


ssWW hepdata inputs

- Take the data and MC yields from Hepdata
  - Postfit dilepton invariant mass (m_{ll}) in 7 bins was provided together with uncertainties for data and simulation
  - Per bin detector efficiency C_{WW} also provided in m_{ll} bins

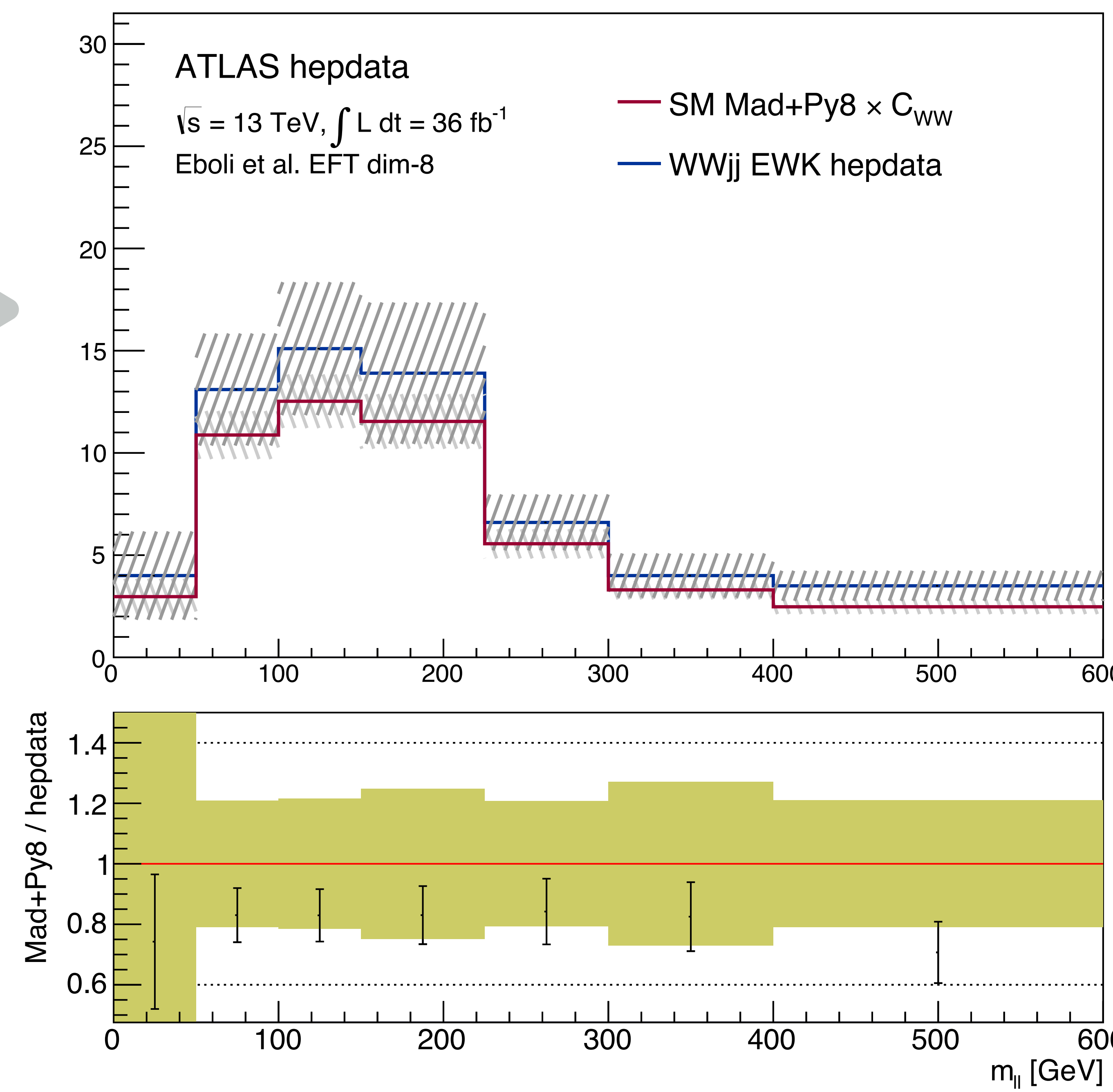
C_{WW} in m_{ll} bins HEPData

Dilepton invariant mass, m_{ll}	C_{WW}
0 - 50	0.56 ±0.29 total
50 - 100	0.49 ±0.07 total
100 - 150	0.54 ±0.07 total
150 - 225	0.56 ±0.08 total
225 - 300	0.53 ±0.09 total
300 - 400	0.52 ±0.09 total
400 - 600	0.47 ±0.08 total



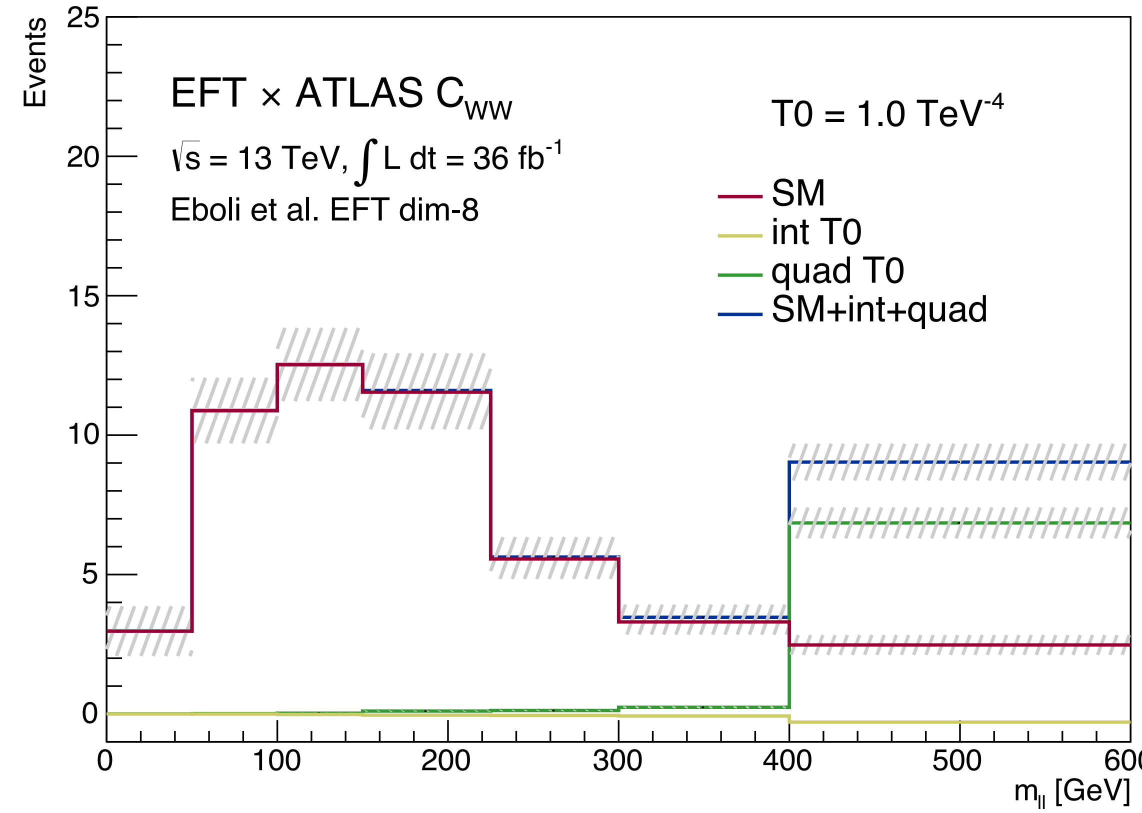
ssWW EWK hepdata inputs

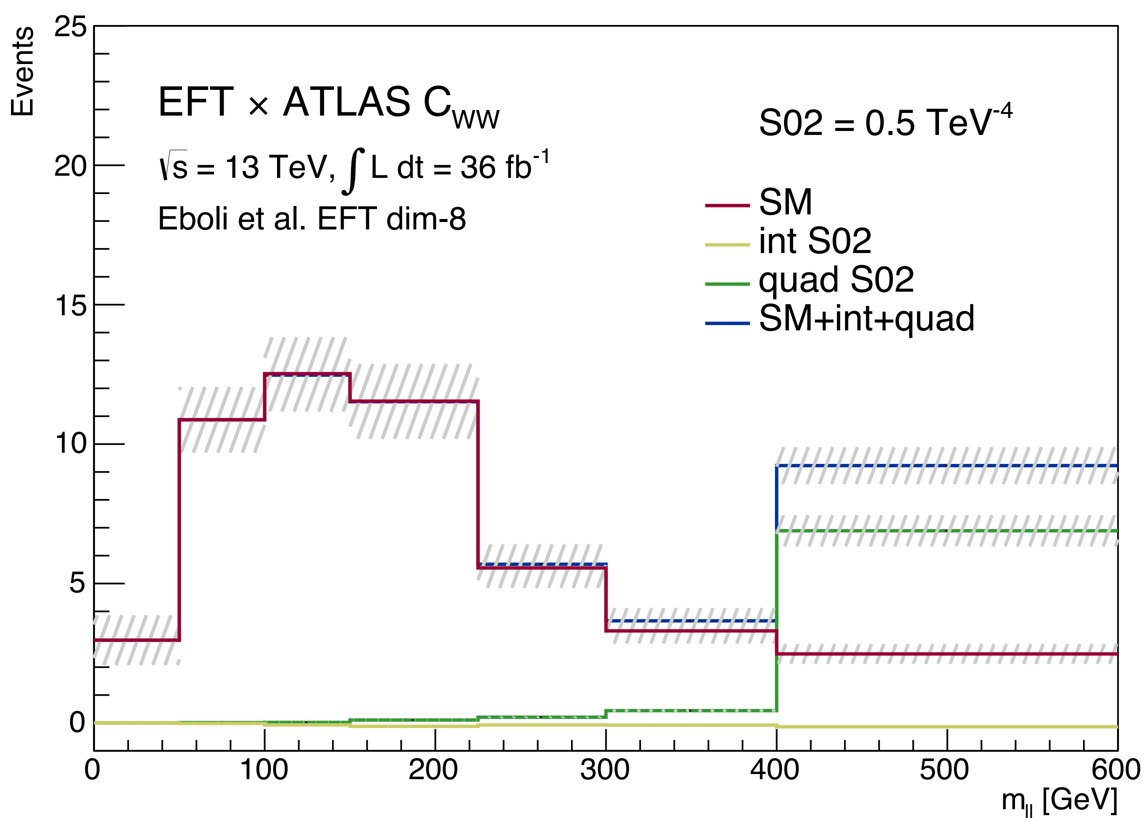
- Multiply our Madgraph+Pythia8 truth level simulation by the provided efficiency values per bin
    - Compare our SM simulation with the post-fit results from ATLAS

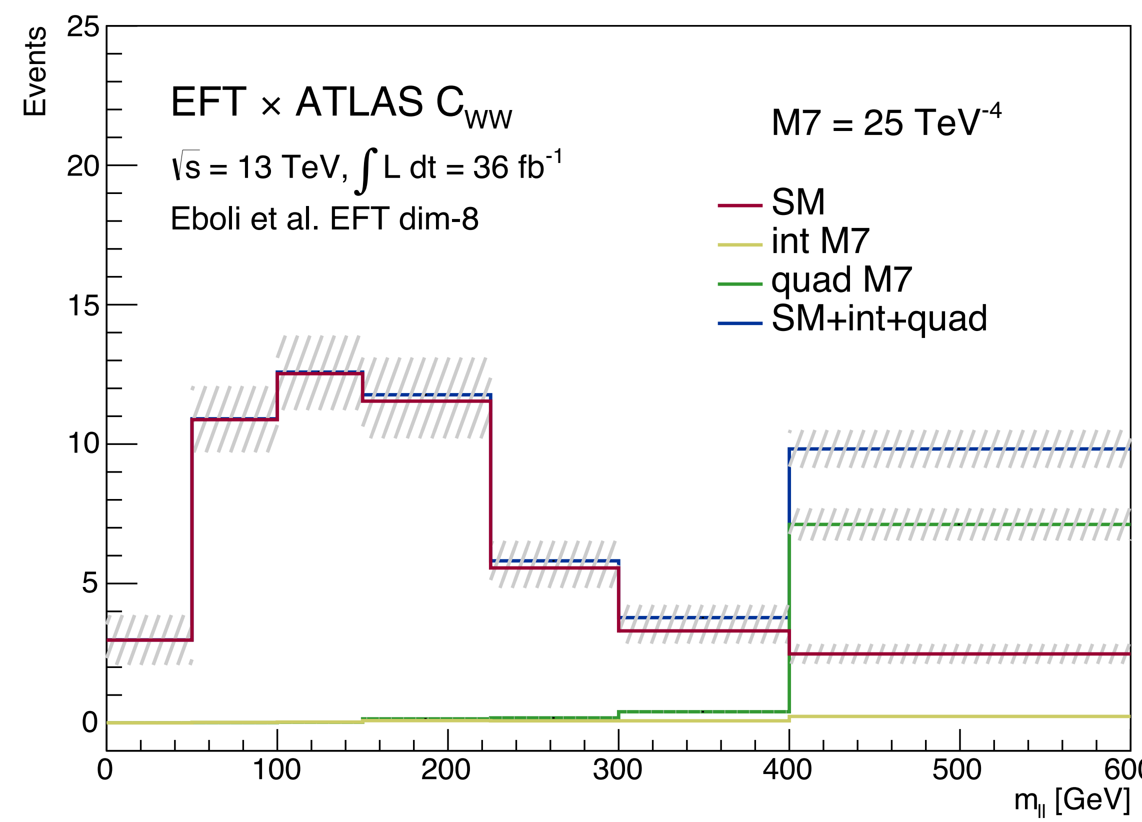


dim-8 inputs for ssWW

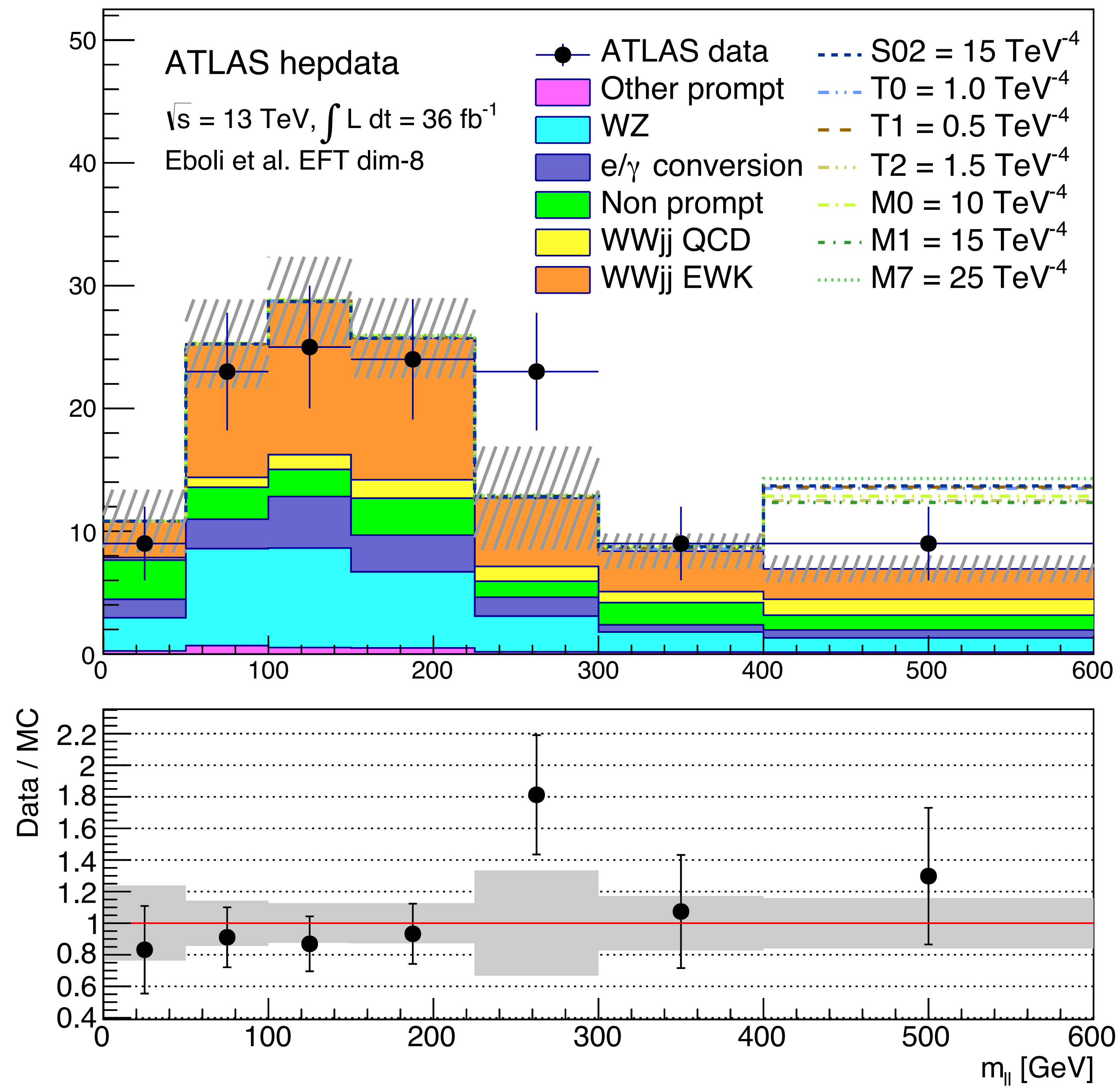
- Multiply our Madgraph+Pythia8 EFT truth level simulation by the provided efficiency values per bin







All ingredients together



Systematic Uncertainties

- ATLAS provides a per bin decomposition of the systematics on modeling and experimental systematics (here all added in quadrature)
- Modeling uncertainties on the new SM EWK and EFTs templates were calculated they include:
  - Perturbative ME uncertainties: PDFs+α_S, scale μ_R, μ_F variations
  - Shower uncertainties: Pythia8 vs Herwig7 or OTF weight with internal variations
  - Some are asymmetric (scales, shower)

Process \ Uncertainty	μ_R, μ_F	PDF	α_S	Shower	NLO corrections	SM interference	dim-6 EFT
$W^{\pm}Z$	$\sim 20-30\%$	$1-3\%$	$< 1-3\%$	$3-30\%$	- ???-	–	(various)
$W^{\pm}W^{\pm}$ EWK	$6-10\%$	$< 1\%$	$< 1\%$	$< 1\%$	- ???-	$< 1-4\%$	–
Quad f_{S02}	$7-15\%$	$< 1-2\%$	$< 1\%$	$\sim 40-1\%$	–	–	–

Fitting status

- The fitting framework allow us to extract 1D limits using the asymptotic formula approximation or the frequentist approach
- Systematics can be correlated among bins and channels
- Asymmetric uncertainties can also be included
- 1D limits fitting checklist:
  - [x] Stat only limits
  - [ ] Nominal: Limits including all systematics
  - [ ] Nominal+clipping
  - [ ] Combination with WZ channel
  - [ ] Include dim-6 effects in all of the above

First stat only ssWW dim-8 limits

ATLAS stat only dim-8 limits

Parameter (f_i/Λ^4)	Stat only Asimov (TeV^{-4})
f_{S02}	[-12,12]
f_{S1}	
f_{M0}	[-9,9]
f_{M1}	[-14,14]
f_{M7}	[21,20]
f_{T0}	[-0.9,0.9]
f_{T1}	[-0.5,0.5]
f_{T2}	[-1.2,1.5]

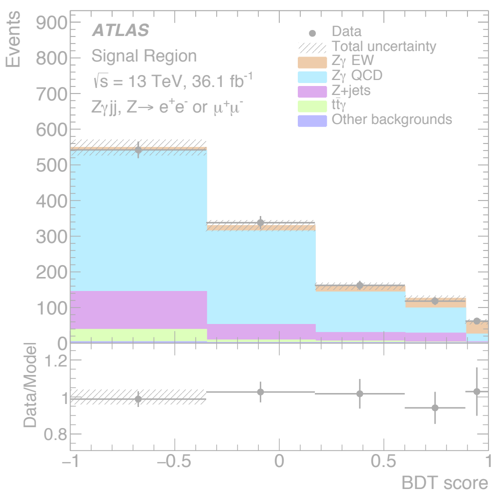
CMS 13 TeV published results

	Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
f_{S0}/Λ^4	$[-7.7, 7.7]$	$[-7.0, 7.2]$
f_{S1}/Λ^4	$[-21.6, 21.8]$	$[-19.9, 20.2]$
f_{M0}/Λ^4	$[-6.0, 5.9]$	$[-5.6, 5.5]$
f_{M1}/Λ^4	$[-8.7, 9.1]$	$[-7.9, 8.5]$
f_{M6}/Λ^4	$[-11.9, 11.8]$	$[-11.1, 11.0]$
f_{M7}/Λ^4	$[-13.3, 12.9]$	$[-12.4, 11.8]$
f_{T0}/Λ^4	$[-0.62, 0.65]$	$[-0.58, 0.61]$
f_{T1}/Λ^4	$[-0.28, 0.31]$	$[-0.26, 0.29]$
f_{T2}/Λ^4	$[-0.89, 1.02]$	$[-0.80, 0.95]$

PRL 120 (2018) 081801

Focus now on the ssWW and ZZ CMS channels

Zγ arXiv:1910.09503



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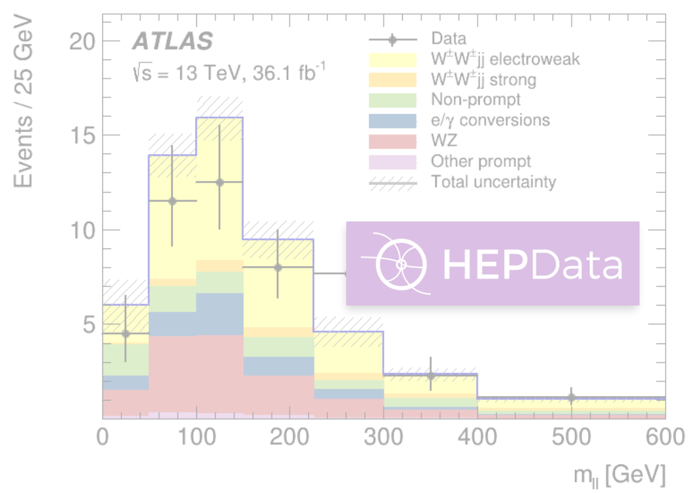
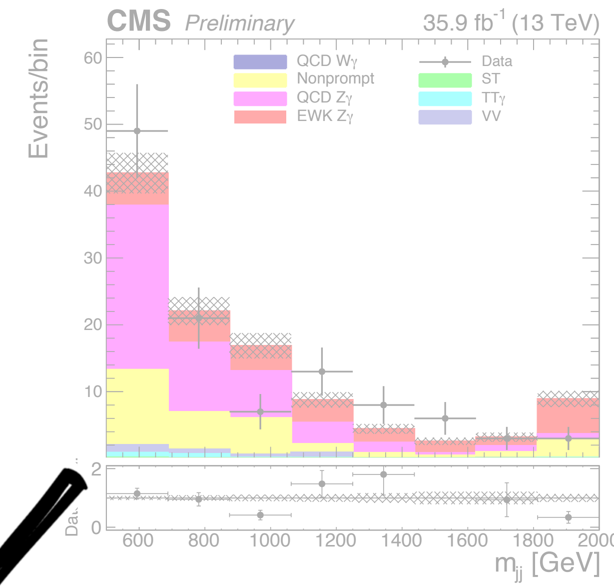
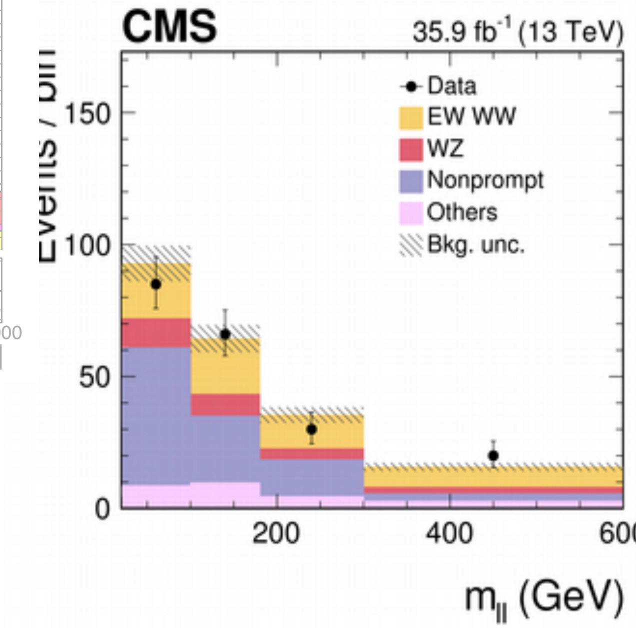


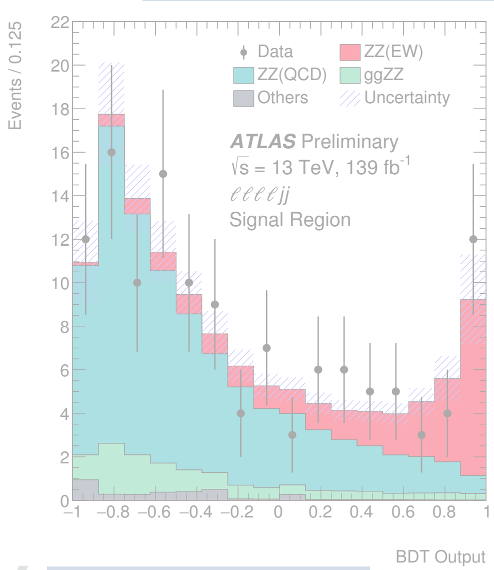
Zγ CMS-PAS-SMP-18-007



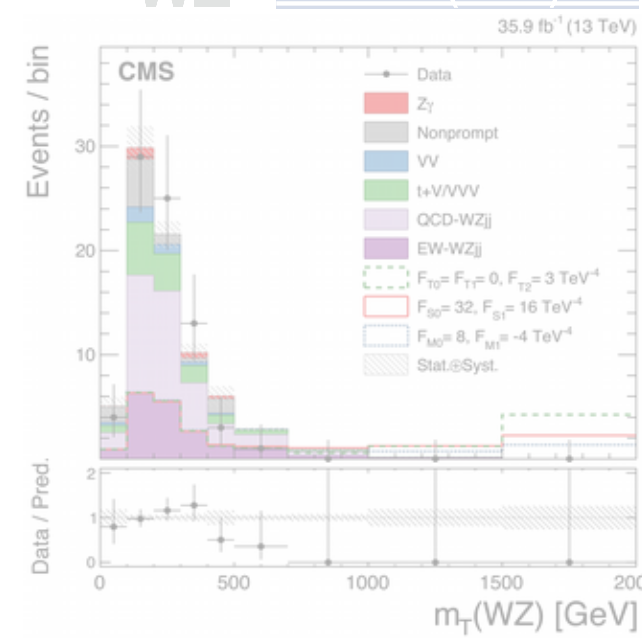
ssWW PRL 120 (2018) 081801



ZZ ATLAS-CONF-2019-033



WZ PLB 795 (2019) 281



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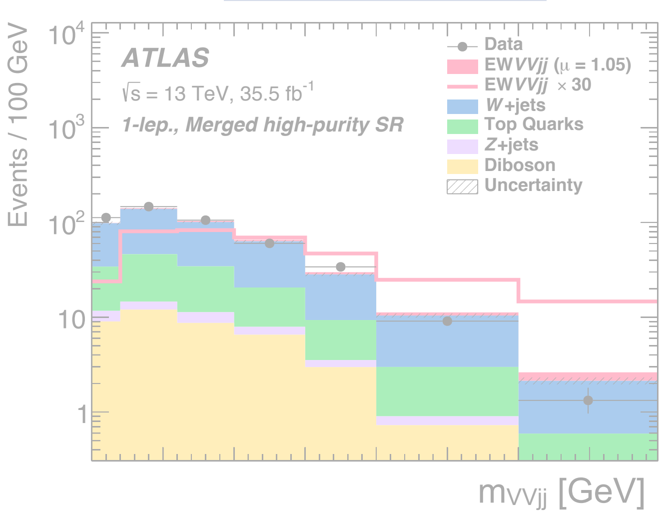

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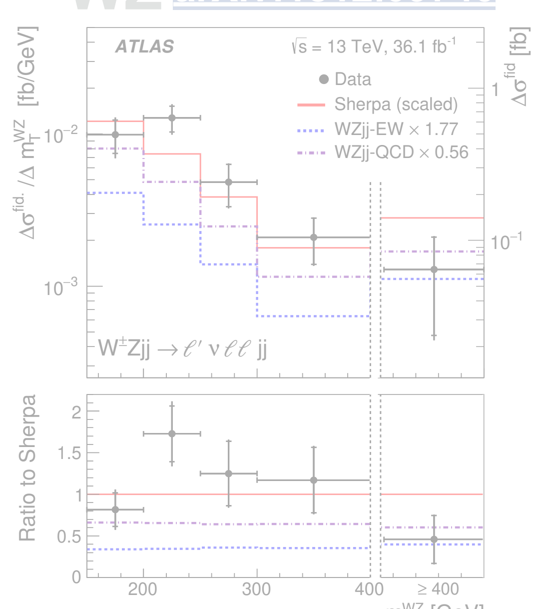

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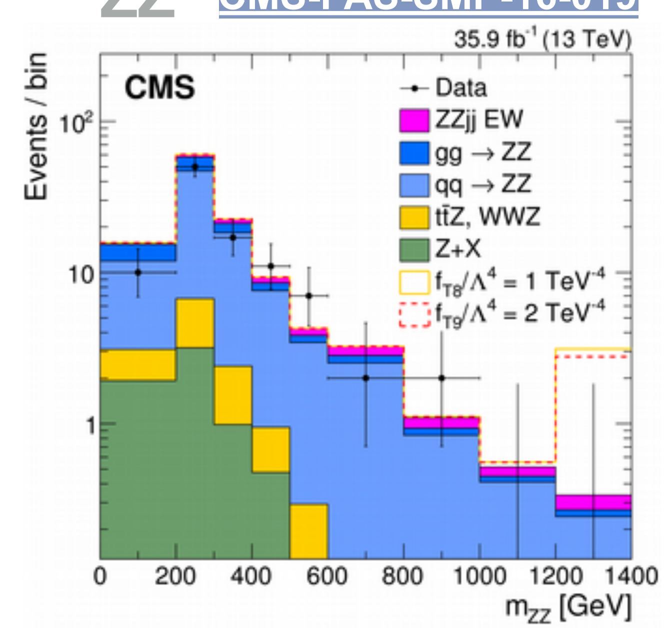

ssWW and ZZ limits

Slides Max Neukum

- Use data from CMS hepdata
- Signal from MG5 + Reweight + Pythia8 → Using MG reweighting
  - Analysis cuts applied at generator level
  - Efficiency applied to compare with data\
- Compare with published results
  - 10% agreement in the ssWW channel
  - 15% agreement in the WZ channel

ssWW

	Published results	Calculated limits
	obs. limits (TeV^{-4})	reconstructed limits (TeV^{-4})
f_{S0}/Λ^4	[-7.7, 7.7]	[-7.20, 7.21]
f_{S1}/Λ^4	[-21.6, 21.8]	[-21.5, 23.3]
f_{M0}/Λ^4	[-6.0, 5.9]	[-5.41, 5.51]
f_{M1}/Λ^4	[-8.7, 9.1]	[-7.89, 8.14]
f_{M7}/Λ^4	[-13.3, 12.9]	[-12.00, 11.90]
f_{T0}/Λ^4	[-0.62, 0.65]	[-0.506, 0.529]
f_{T1}/Λ^4	[-0.28, 0.31]	[-0.252, 0.271]
f_{T2}/Λ^4	[-0.89, 1.02]	[-0.805, 0.925]

ZZ

	Published results	Calculated limits
	obs. limits (TeV^{-4})	reconstructed limits (TeV^{-4})
f_{S0}/Λ^4	-	[-62.1, 63.1]
f_{S1}/Λ^4	-	[-66.3, 66.6]
f_{M0}/Λ^4	-	[-10.1, 10.5]
f_{M1}/Λ^4	-	[-33.6, 32.1]
f_{M7}/Λ^4	-	[-62.5, 65.7]
f_{T0}/Λ^4	[-0.46, 0.44]	[-0.41, 0.39]
f_{T1}/Λ^4	[-0.61, 0.61]	[-0.64, 0.64]
f_{T2}/Λ^4	[-1.2, 1.2]	[-1.19, 1.14]
f_{T8}/Λ^4	[-0.84, 0.84]	-
f_{T9}/Λ^4	[-1.8, 1.8]	-

ssWW and ZZ limits

Slides Max Neukum

- Use data from CMS hepdata
- Signal from MG5 + Reweight + Pythia8 → Using MG reweighting
  - Analysis cuts applied at generator level
  - Efficiency applied to compare with data
- Compare with published results
  - 10% agreement in the ssWW channel
  - 15% agreement in the WZ channel

ssWW

	Published results	Calculated limits
	obs. limits (TeV^{-4})	reconstructed limits (TeV^{-4})
f_{S0}/Λ^4	[-7.7, 7.7]	[-7.20, 7.21]
f_{S1}/Λ^4	[-21.6, 21.8]	[-21.5, 23.3]
f_{M0}/Λ^4	[-6.0, 5.9]	[-5.41, 5.51]
f_{M1}/Λ^4	[-8.7, 9.1]	[-7.89, 8.14]
f_{M7}/Λ^4	[-13.3, 12.9]	[-12.00, 11.90]
f_{T0}/Λ^4	[-0.62, 0.65]	[-0.506, 0.529]
f_{T1}/Λ^4	[-0.28, 0.31]	[-0.252, 0.271]
f_{T2}/Λ^4	[-0.89, 1.02]	[-0.805, 0.925]

ZZ

	Published results	Calculated limits
	obs. limits (TeV^{-4})	reconstructed limits (TeV^{-4})
f_{S0}/Λ^4	-	[-62.1, 63.1]
f_{S1}/Λ^4	-	[-66.3, 66.6]
f_{M0}/Λ^4	-	[-10.1, 10.5]
f_{M1}/Λ^4	-	[-33.6, 32.1]
f_{M7}/Λ^4	-	[-62.5, 65.7]
f_{T0}/Λ^4	[-0.46, 0.44]	[-0.41, 0.39]
f_{T1}/Λ^4	[-0.61, 0.61]	[-0.64, 0.64]
f_{T2}/Λ^4	[-1.2, 1.2]	[-1.19, 1.14]
f_{T8}/Λ^4	[-0.84, 0.84]	-
f_{T9}/Λ^4	[-1.8, 1.8]	-

ssWW more sensitive

ssWW not sensitive

First CMS ssWW and ZZ combination

Slides Max Neukum

- The detector uncertainties available in hepdata are included
  - So far only luminosity correlated
- Signal from MG5 + Pythia8 → Using MG reweighting
  - Analysis cuts applied at generator level
  - Efficiency applied to compare with data

reconstructed limits	CMS ssWW (TeV^{-4})	CMS ZZ (TeV^{-4})	combined (TeV^{-4})	
f_{S0}/Λ^4	[-7.20, 7.21]	[-62.1, 63.1]	[-7.22, 7.71]	not significant gain
f_{S1}/Λ^4	[-21.5, 23.3]	[-66.3, 66.6]	[-21.7, 23.4]	
f_{M0}/Λ^4	[-5.41, 5.51]	[-10.1, 10.5]	[-5.34, 5.59]	
f_{M1}/Λ^4	[-7.89, 8.14]	[-33.6, 32.1]	[-7.76, 8.02]	
f_{M7}/Λ^4	[-12.00, 11.90]	[-62.5, 65.7]	[-12.1, 12.0]	
f_{T0}/Λ^4	[-0.506, 0.529]	[-0.41, 0.39]	[-0.369, 0.361]	Gain by combination!
f_{T1}/Λ^4	[-0.252, 0.271]	[-0.64, 0.64]	[-0.241, 0.257]	
f_{T2}/Λ^4	[-0.805, 0.925]	[-1.19, 1.14]	[-0.711, 0.784]	

Combination summary and next steps

Lots of progress towards the dim-8 VBS ATLAS+CMS combination

- Extensive validation of the signal model (details here)
  - New version of Eboli model allows to modify several parameters at the same time (i.e 2D limit possible)
  - The decomposition approach validated and preferred because of stability in the tails
  - Clipping procedure in place (ATLAS ssWW has published the position of the last data point in mll that could be use as reference for clipping)
- ATLAS
  - First dim-8 stat only limits shown. Need to work on including the systematics uncertainties.
  - Some differences with CMS published limits need to be understood → Maybe different phase space?
- CMS
  - ssWW and ZZ limits reproduced using hepdata with ~15% agreement (Slides Max Neukum)
  - First preliminary combination combination of WZ and ssWW in CMS shown

Next steps:

- Machinery now runs smoothly and gives sensible results
- We should expect updates soon!
- Combination relies on public information, we should provide feedback to the collaborations with our experience

Some more activities of the WG

Studies of Dimension-Six EFT effects in Vector Boson Scattering

- First study in ZZjj channel (Arxiv:1809.04189) now extended to more VV channels (more details here)
- Study using the ATLAS WZjj channel (master thesis L. Wüst here)
- Study using the CMS ssWWjj channel (bachelor thesis here)