Laboratoire d'Annecy de Physique des Particules

ATLAS Group Meeting

EFT Interpretation of the Drell-Yan Process

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Contents

Standard Model Effective Field Theory (SMEFT)

An Effective Field Theory (EFT) parametrizes new physics occurring at an energy scale Λ much larger than the electroweak scale v (246 GeV). Interactions of new particles are integrated and absorbed into operators and are added to the operators of the SM Lagrangian

- Odd dimensions e.g 5, 7,... violate lepton and/or baryon number conservation and are therefore excluded from the calculations.
- A complete set of dimension-six operators invariant under the SM gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ is constructed from the SM fields
- Λ is the energy scale at which new physics is assumed to appear, $O_i^{(D)}$ are the operators of the dimension-D invariant under the SM gauge group and $C_i^{(D)}$ are the corresponding dimensionless coupling constants, the so-called Wilson coefficients. The $1/\Lambda^2$ factor is absorbed into the Wilson coefficients, $c_i = C_i/\Lambda^2 = 1\ \text{TeV}^{-2}$

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots,$$

SMEFTsim model

- We use the Warsaw basis
- input parameters:
  $\{m_W, m_Z, G_F\}$ – Mw Scheme
  $\{\alpha_{em}, m_Z, G_F\}$ – alpha Scheme

- general: 2499 operators
- 3 flavour symmetry assumptions $U(3)^5$ with non-SM CP-violating phases
- $U(3)^5$: 85 operators

we used:

- SMEFTsim_U35_MwScheme_UFO
- SMEFTsim_U35_alphaScheme_UFO
- SMEFTsim_top_MwScheme_UFO
- SMEFTsim_topU3l_MwScheme_UFO

Ref.: I. Brivio. 2021. *SMEFTsim 3.0 - a practical guide*

	general		U35		MFV		top		topU3l	
	all	$\cancel{CP}$	all	$\cancel{CP}$	all	$\cancel{CP}$	all	$\cancel{CP}$	all	$\cancel{CP}$
$\mathcal{L}_6^{(1)}$	4	2	4	2	2	-	4	2	4	2
$\mathcal{L}_6^{(2,3)}$	3	-	3	-	3	-	3	-	3	-
$\mathcal{L}_6^{(4)}$	8	4	8	4	4	-	8	4	8	4
$\mathcal{L}_6^{(5)}$	54	27	6	3	7	-	14	7	10	5
$\mathcal{L}_6^{(6)}$	144	72	16	8	20	-	36	18	28	14
$\mathcal{L}_6^{(7)}$	81	30	9	1	14	-	21	2	15	2
$\mathcal{L}_6^{(8a)}$	297	126	8	-	10	-	31	-	16	-
$\mathcal{L}_6^{(8b)}$	450	195	9	-	19	-	40	2	27	2
$\mathcal{L}_6^{(8c)}$	648	288	8	-	28	-	54	4	31	4
$\mathcal{L}_6^{(8d)}$	810	405	14	7	13	-	64	32	40	20
tot	2499	1149	85	25	120	-	275	71	182	53

$$\sigma = \sigma_{\text{SM}} + \sum_\alpha \sigma_\alpha \bar{C}_a + \sum_{\alpha,\beta} \sigma_{\alpha\beta} \bar{C}_\alpha \bar{C}_\beta \,,$$

Drell-Yan process

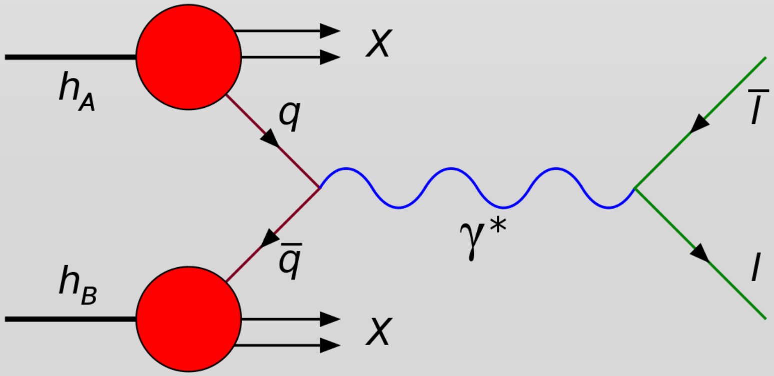
- Tests both the electroweak and QCD sectors
- Measured with great precision at the LHC
- 116 GeV < mll < 5000 GeV

Cuts:
$|\eta| < 2.5$
pT > 30 GeV

Backgrounds

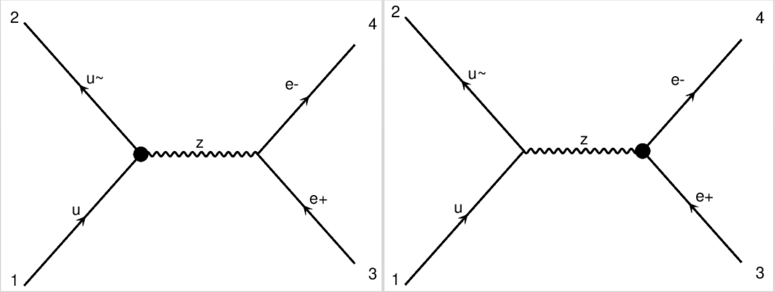
$$q\bar{q} \to Z/\gamma* \to l^+l^-, \;\; l = \mathrm{e}, \mu$$

- Diboson production of WW, WZ and ZZ pairs decaying to leptonic and semileptonic final states
- Top production including $\bar{t}t$ and single top
- $Z/\gamma* \to \tau\tau$ processes
- W+jets and multijets faking prompt leptons



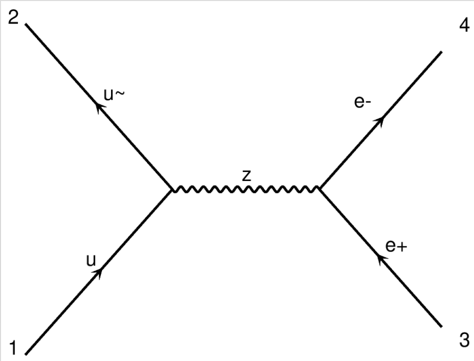
Generation of events (Madgraph + Pythia interfaced with the SMEFTsim model)

- MadGraph5_aMC@NLO is a framework that aims at providing all the elements necessary for SM and BSM phenomenology, such as the computations of cross sections, the generation of hard events and their matching with event generators, and the use of a variety of tools relevant to event manipulation and analysis.
- Pythia parton shower: Models of QCD are implemented in event generators to simulate hadron collisions and evolution of quarks and gluons into jets of hadrons. PYTHIA uses the parton shower model for simulating particle collisions and is optimized using experimental observations.
- We turn on one WC at a time
- We have generated SM contributions (**NP=0**), interference between WCs and SM (**NP<=1 NP^2==1**) and pure quadratic contributions (**NP<=1 NPc[a]^2==2**).



SMEFT

$$\sigma = \sigma_{\mathrm{SM}} + \sum_{\alpha} \sigma_{\alpha} \bar{C}_a + \sum_{\alpha,\beta} \sigma_{\alpha\beta} \bar{C}_{\alpha} \bar{C}_{\beta} \,,$$



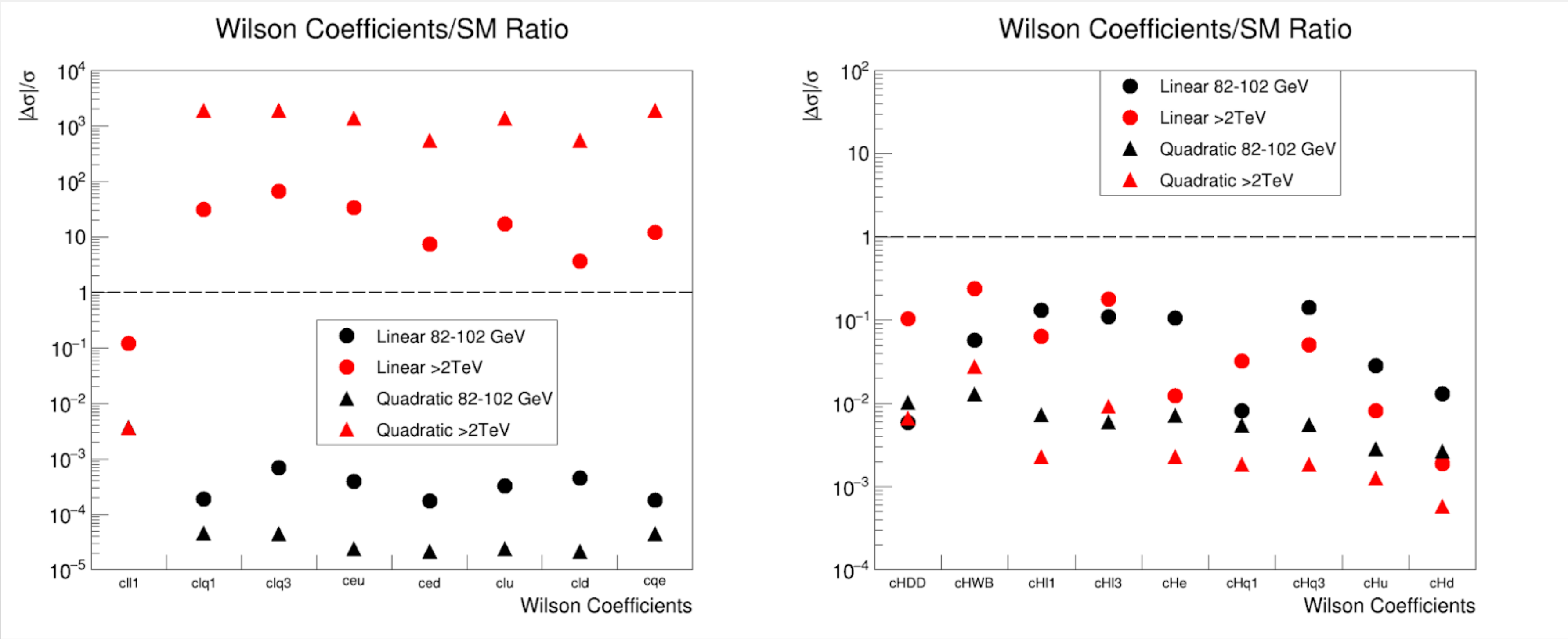
SM

Analysis Workflow

MadGraph + Pythia ⇨ EVNT.root file ⇨ Rivet ⇨ .root file containing the histograms

1. jobOption: python file that contains all information for the generation (MadGraph, SMEFTsim model, generation, NP mode, cuts, WC and value, Pythia, Rivet output)
2. Rivet Analysis File: cuts, implementation of correct binning, creation of mll histogram
3. Create histograms

Sensitivity Study



WCs to which Drell-Yan is sensitive to:

- Fermionic WCs: cll1, clq1, clq3, ceu, ced, clu, cld, cqe
- Higgs WCs: cHDD, cHWB, cHl1, cHl3, cHe, cHq1, cHq3, cHu, cHd

→ We notice high influence on the cross-section of the quadratic terms, especially for the mass window >2 TeV

→ Small influence of higgs WCs

Summary of checks

Tests between models for different mass windows:

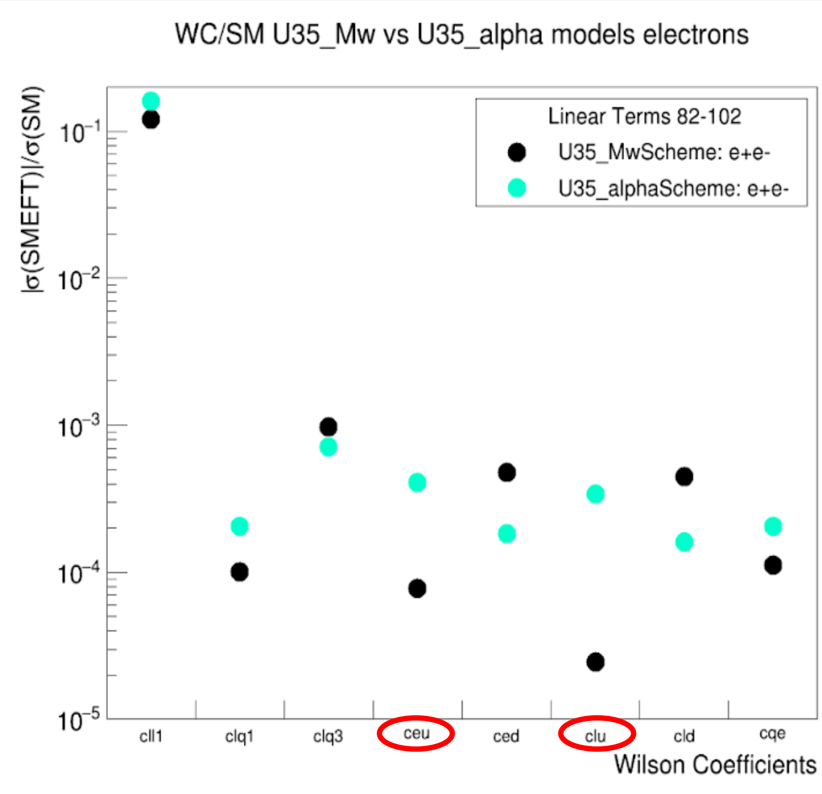
- U35_MwScheme vs U35_alphaScheme cross-sections
  → (linear terms) 82-102 GeV
- U35_MwScheme vs topU3l_MwScheme cross-sections
  → (linear terms) >2 TeV electrons vs muons
- U35_MwScheme vs topU3l_MwScheme cross-sections
  → (linear terms) 116-5000 GeV

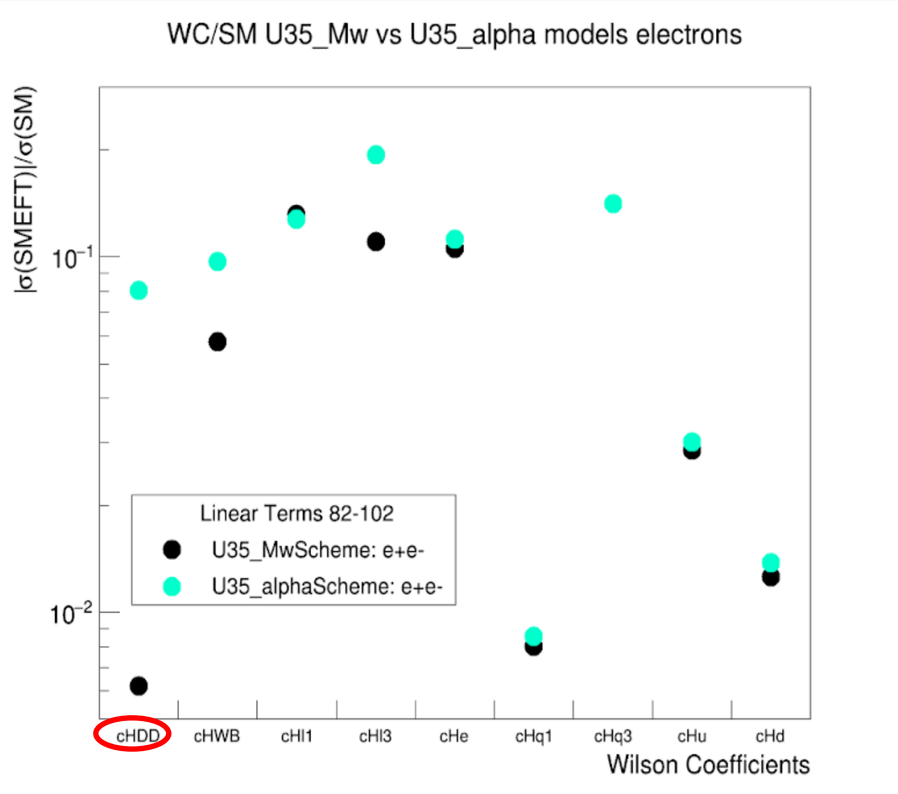
Checks for mll distribution:

- mll plot clu
  → all contributions 300-5000 GeV
- Mll distributions U35_MwScheme
  → (SM+linear terms) 82-102 GeV
- Mll distributions U35_MwScheme
  → 116-5000 GeV (pT>30 GeV)
- Mll distributions U35_alphaScheme
  → 116-5000 GeV (pT>30 GeV)

Backup plots

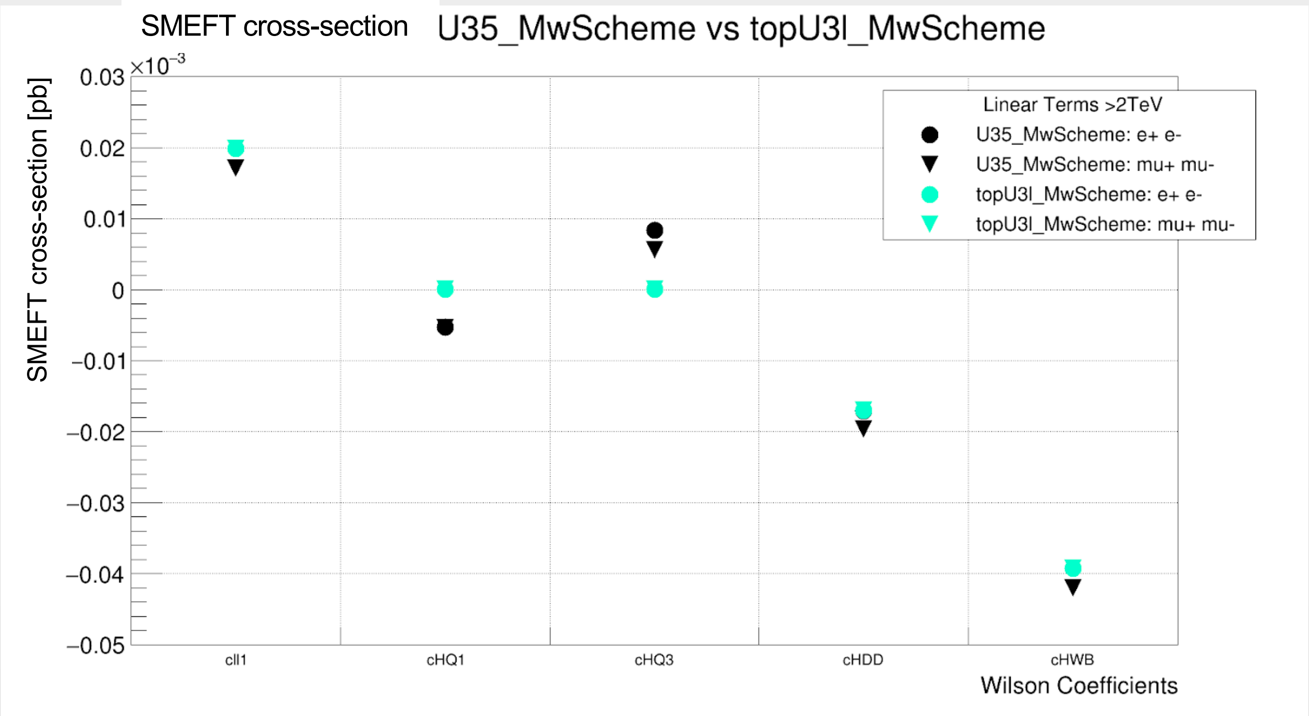
U35_MwScheme vs U35_alphaScheme cross-sections





- linear terms 82-102 GeV – without cuts
- Cross-sections of ceu, clu and cHDD appear to deviate the most
- Checks are ongoing to understand deviations

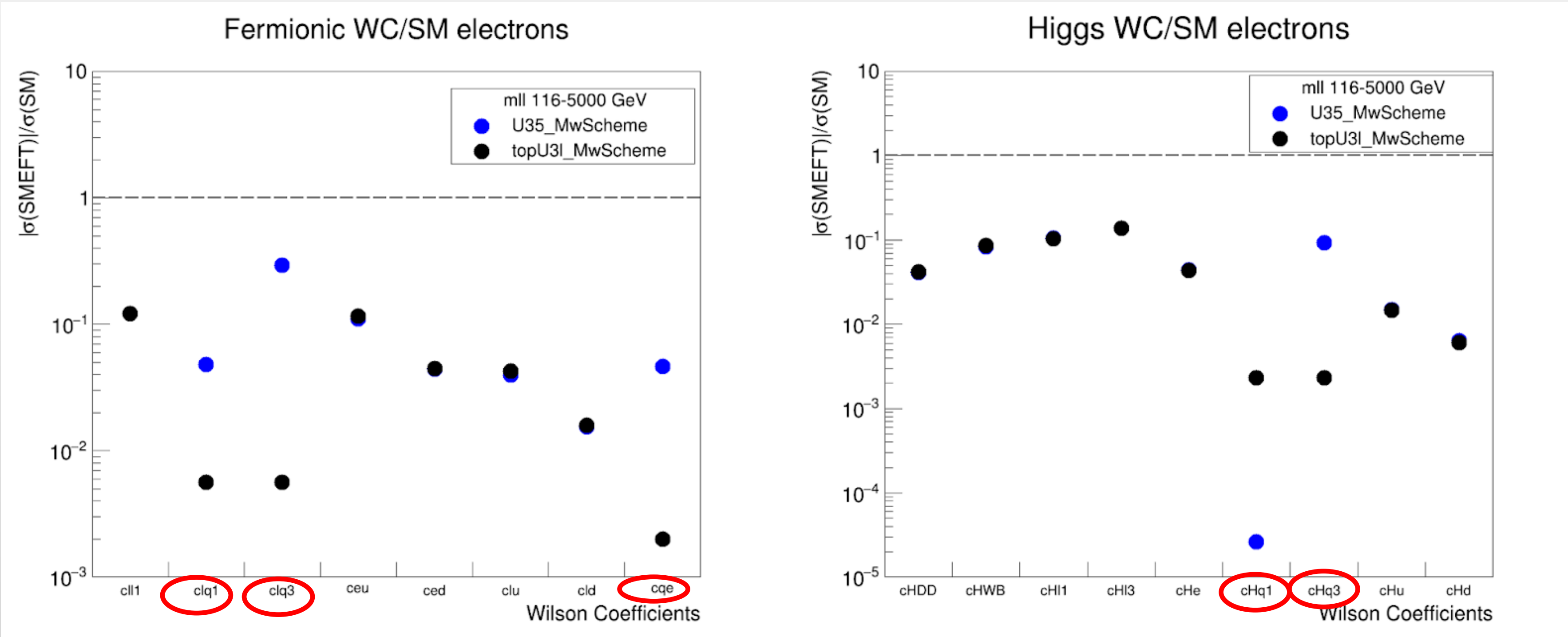
U35_MwScheme vs topU3l_MwScheme cross-sections



- linear terms >2 TeV
- The values for electrons and muons of the same model are almost the same, as expected, given the definition of the two flavour assumptions.
- Small differences between the two models are present for cHQ1 and cHQ3

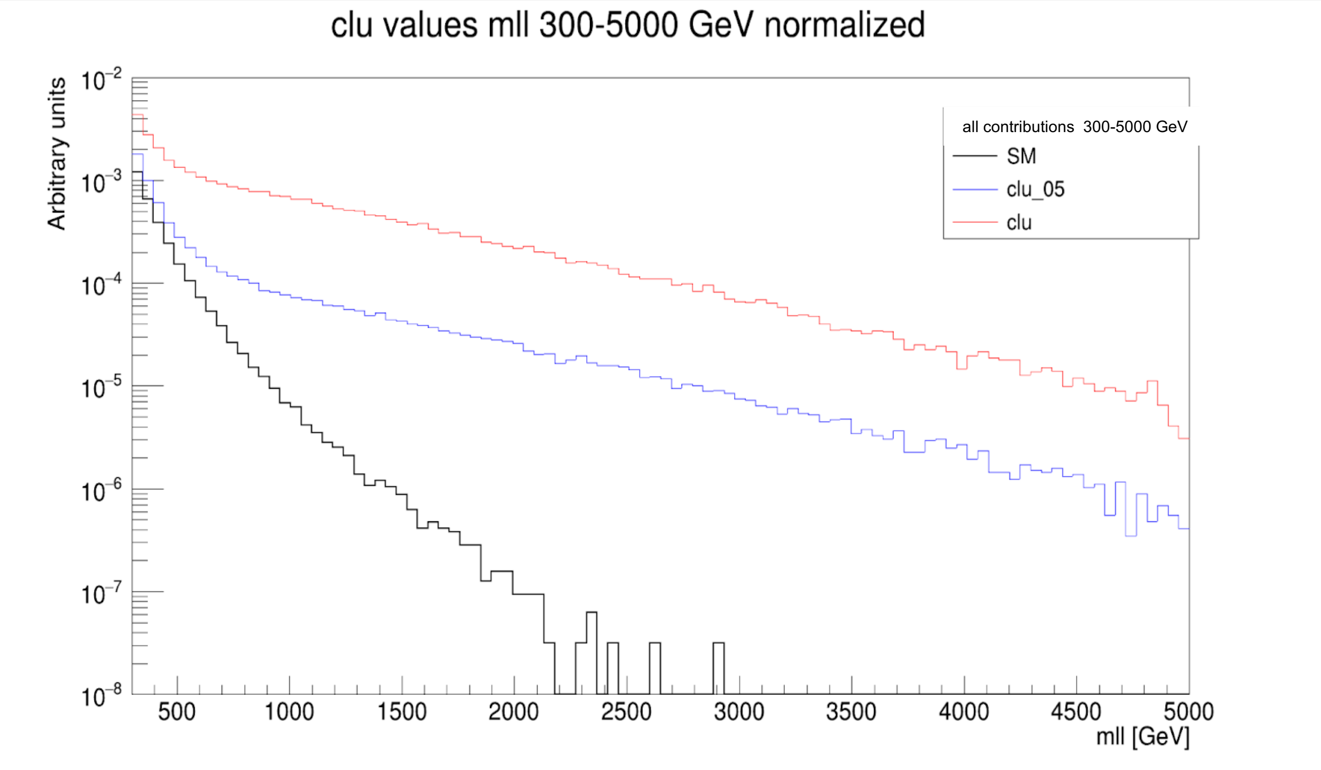
Testing a subset of WCs
cll1
cHQ1
cHQ3
cHDD
cHWB

U35_MwScheme vs topU3l_MwScheme cross-sections



- Checked all the WCs the Drell-Yan process is sensitive to
- linear terms 116-5000 GeV
- cHq1-->cHQ1, cHq3-->cHQ3, cqe-->cQe, clq1-->cQl1, clq3-->cQl3 further checks on the "translation" between the two flavour assumptions
- Negligible differences for most WCs

Mll plot for clu in high mass tails

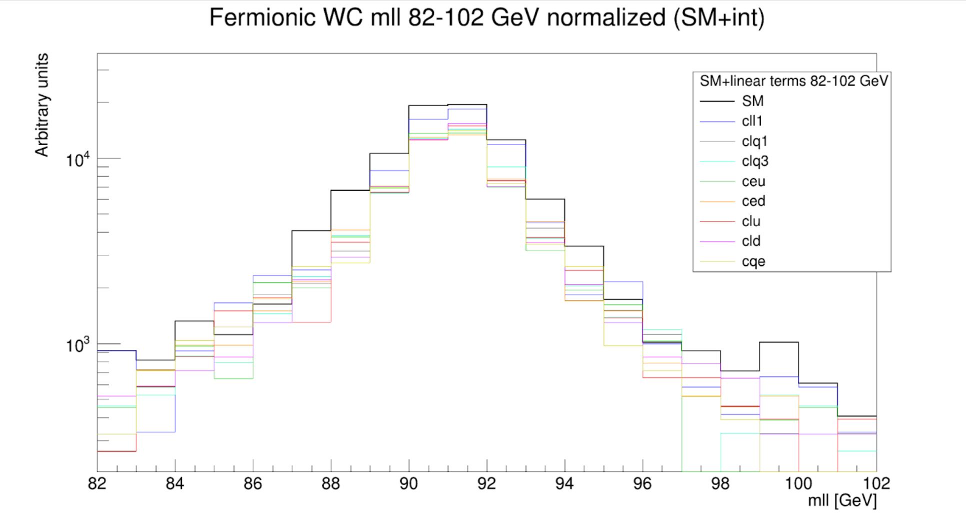


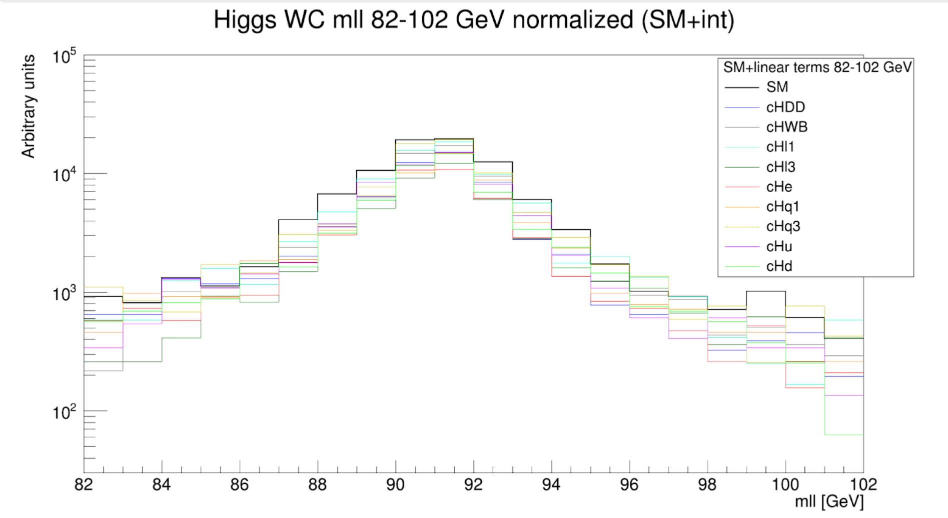
- all contributions 300-5000 GeV (high mass tails)

$$\sigma = \sigma_{SM} + \sigma_{\alpha}\bar{C}_{\alpha} + \sigma_{\alpha\alpha}\bar{C}_{\alpha}^{2}$$

- In high energies there is great deviation from the SM.
- The higher the value of clu, the greater the deviation.

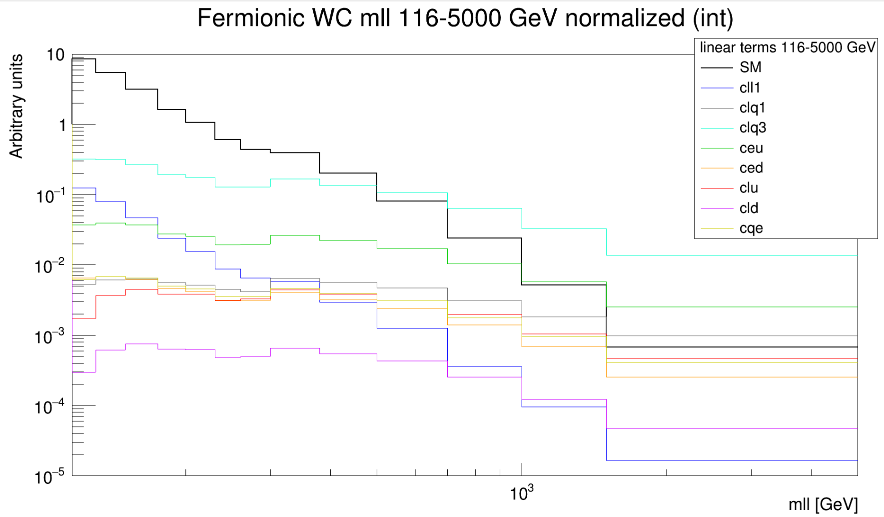
Mll distributions U35_MwScheme

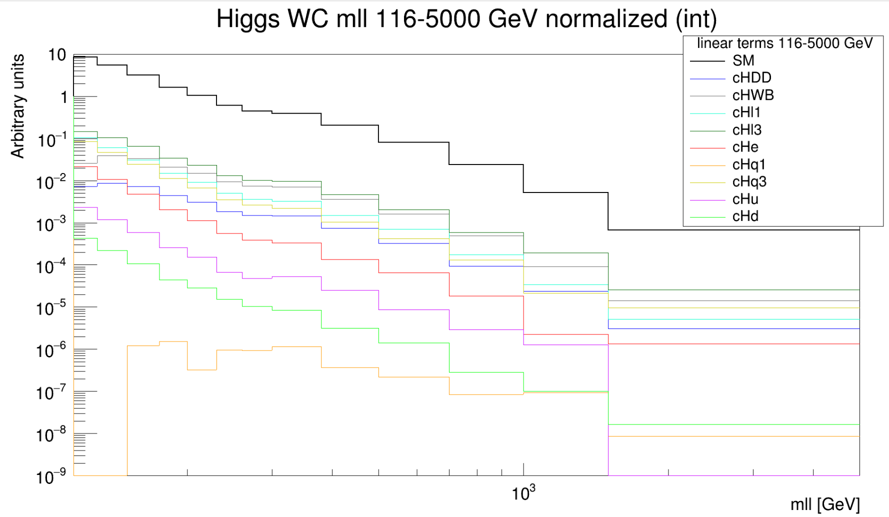




- (SM+linear terms) 82-102 GeV
- We see very small deviation from SM around the Z peak

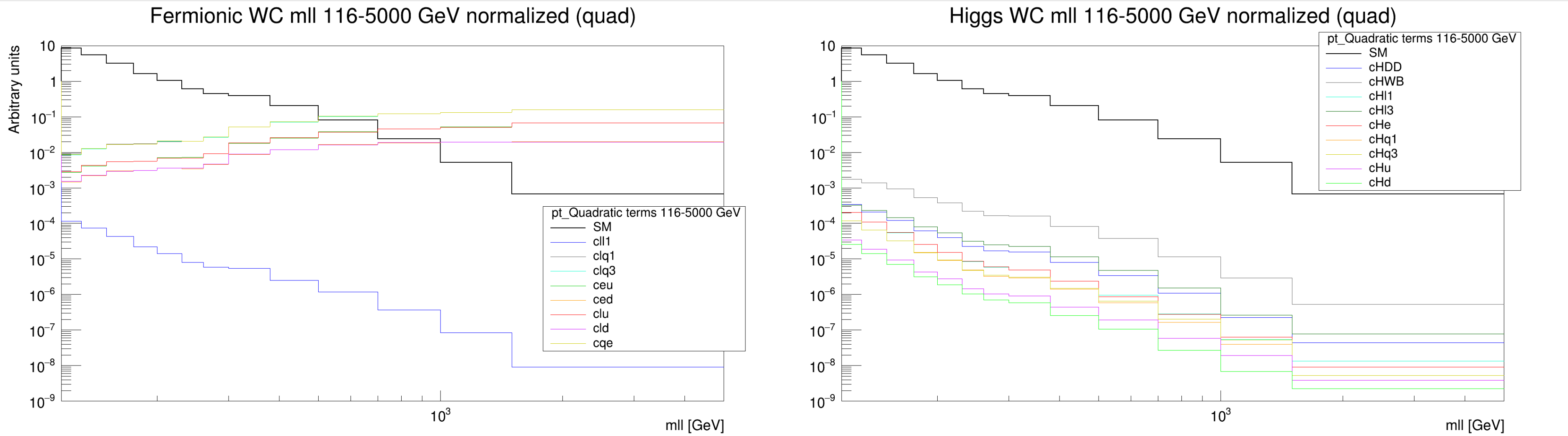
Mll distributions U35_MwScheme





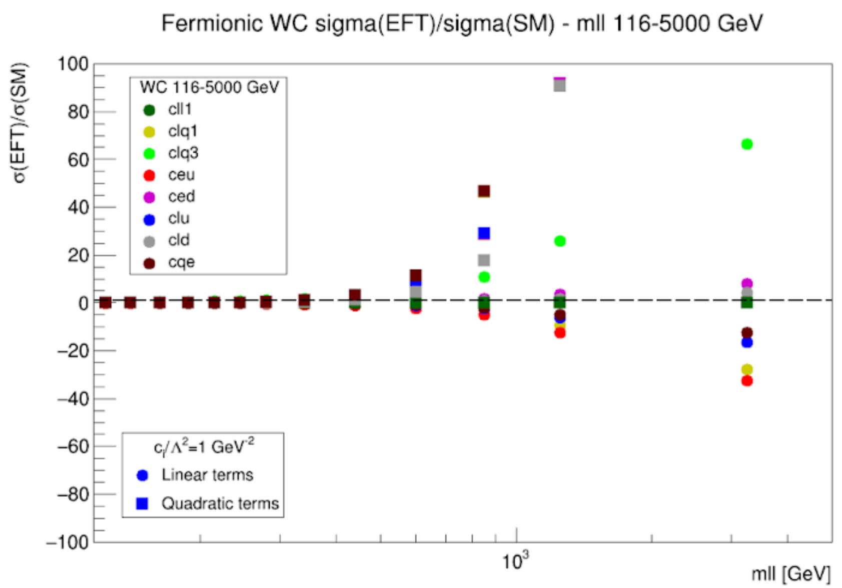
- Linear terms 116-5000 GeV, pt > 30 GeV
- Binning: {116, 130, 150, 175, 200, 230, 260, 300, 380, 500, 700, 1000, 1500, 5000}
- High mass – great deviation from SM
- clq1, clq3, ceu have great influence

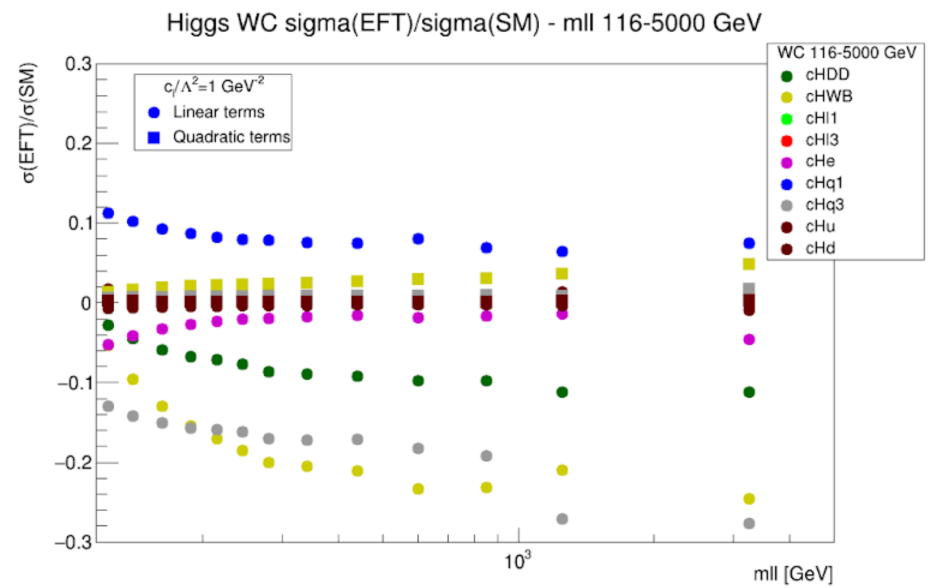
Mll distributions U35_MwScheme



- Quadratic terms 116-5000 GeV, pt > 30 GeV
- Binning: {116, 130, 150, 175, 200, 230, 260, 300, 380, 500, 700, 1000, 1500, 5000}
- Quadratic terms have a higher influence than linear terms at high mass
- Fermionic WCs have a greater deviation than higgs WCs

σ(EFT)/σ(SM) for each bin - mll





→ this is still under investigations, but this numbers are necessary to extract the expected uncertainty on the SMEFT parameters, assuming the measurement is gaussian and exploiting the yields of the analysis itself

The expected yield in category *k:*

$$n_k^{\exp}(\mathbf{c}) = s_k(1 + \sum_i a_{ki} c_i) + b_k$$

- *sk* is the expected signal yield in the SM
- *bk* is the expected background yield
- *aki* is the coefficient giving the dependence of the signal yield in bin *k* with respect to the coefficient *ci*.

Next Steps

- finalise checks on different schemes and flavour assumptions
- finalise checks on electrons/muons/taus
- document all the checks and conclusions for future studies
- extract the parameterisation for each analysis bin turning on one WC at the time
- estimate the expected uncertainty on the SMEFT parameter coming from the current analysis binning (and trying to test small modifications of this binning)

Thank you!

References

[1] T. Berry, M. Bret, M. Zhe, S. Lawlor, Y. Liu, T. Hrynova, R. Gonzalez Lopez, U. Klein, J. Kretzschmar, U. Mallik, D. Hayden, J. R. Hinds, X. Li, M. Lu, E. Rizvi. 2022. *Measurement of the high-mass Drell-Yan double-differential cross-section in p p collisions at √s = 13 TeV*. CERN for the benefit of the ATLAS Collaboration

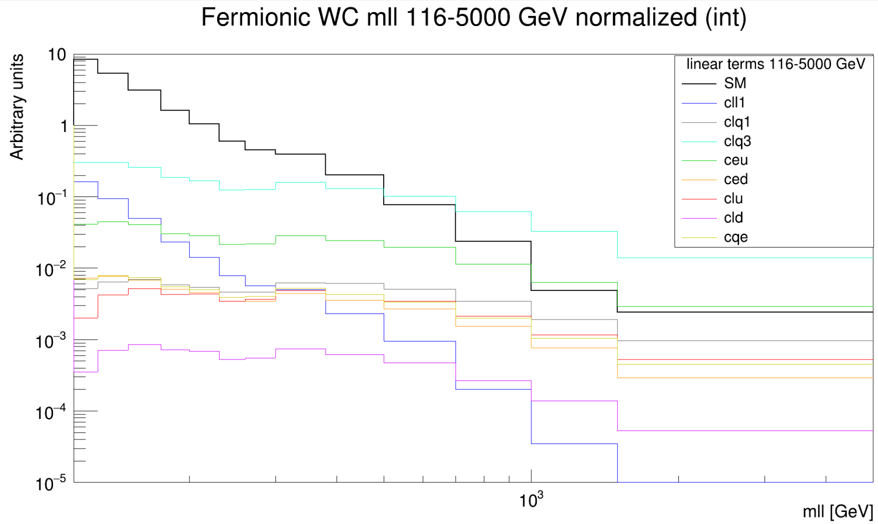
[2] I. Brivio. 2021. *SMEFTsim 3.0 - a practical guide*

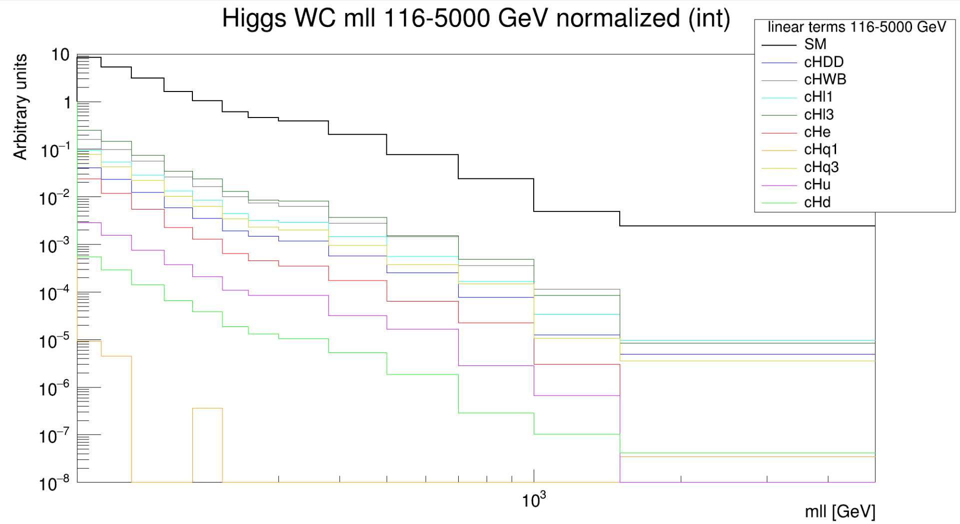
WCs investigated

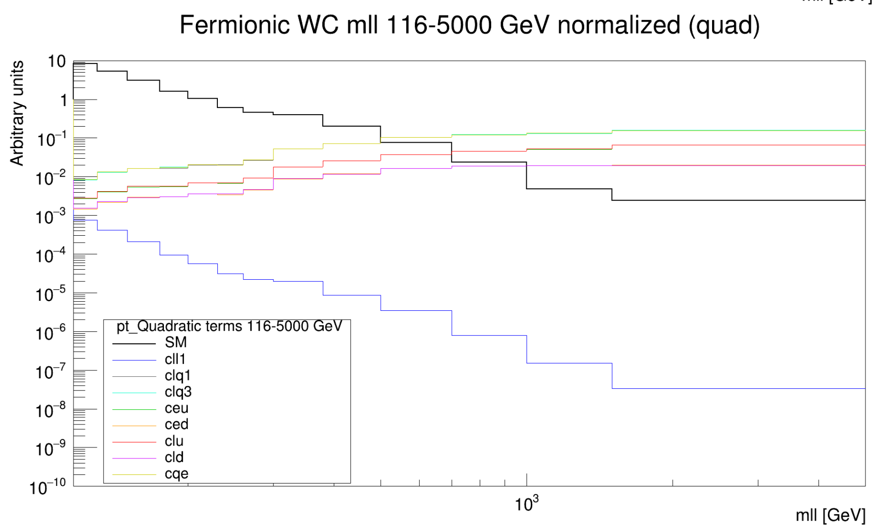
4-fermion operators	Higgs-related operators
$C_{ll}^{(1)}$	C_{HDD}
$C_{lq}^{(1)}$	C_{HWB}
$C_{lq}^{(3)}$	$C_{Hl}^{(1)}$
C_{eu}	$C_{Hl}^{(3)}$
C_{ed}	C_{He}
C_{lu}	$C_{Hq}^{(1)}$
C_{ld}	$C_{Hq}^{(3)}$
C_{qe}	C_{Hu}
	C_{Hd}

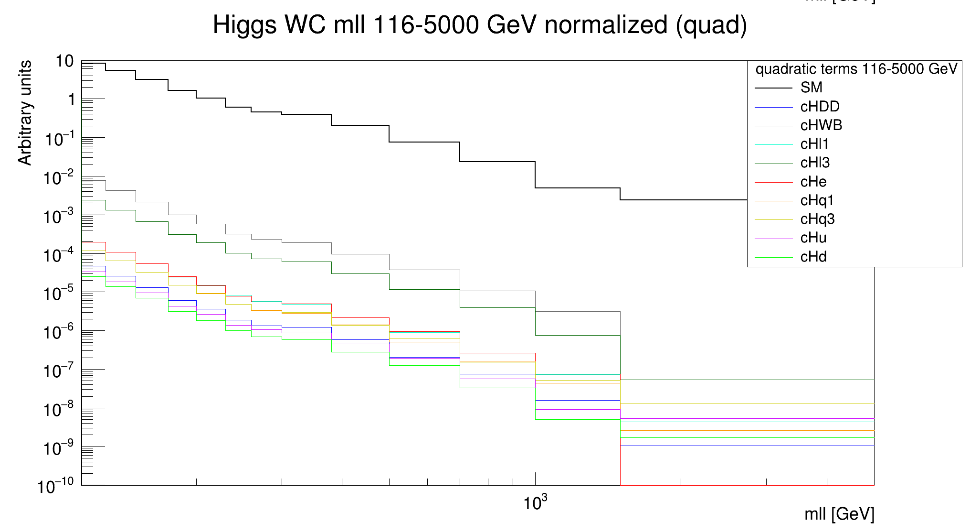
	σ_{SM}	σ_{α}	σ_{β}	$\sigma_{\alpha\alpha}$	$\sigma_{\beta\beta}$	$\sigma_{\alpha\beta}$
NP=0	✓					
NP<=1	✓	✓	✓	✓	✓	✓
NP==1				✓	✓	✓
NP<=1 NP^2<=1	✓	✓	✓			
NP<=1 NP^2==1		✓	✓			
NP<=1 NPc[a]^2<=1	✓	✓				✓
NP<=1 NPc[a]^2<=1 NPc[b]^2<=1	✓	✓	✓			✓
NP<=1 NPc[a]==1		✓		✓		
NP<=1 NPc[a]^2==1		✓				✓
NP<=1 NPc[a]^2==2				✓		
NP<=1 NP^2==1 NPc[a]^2==1		✓				
NP<=1 NP^2==2 NPc[a]^2==1						✓

Mll distributions U35_alphaScheme (116-5000 GeV)

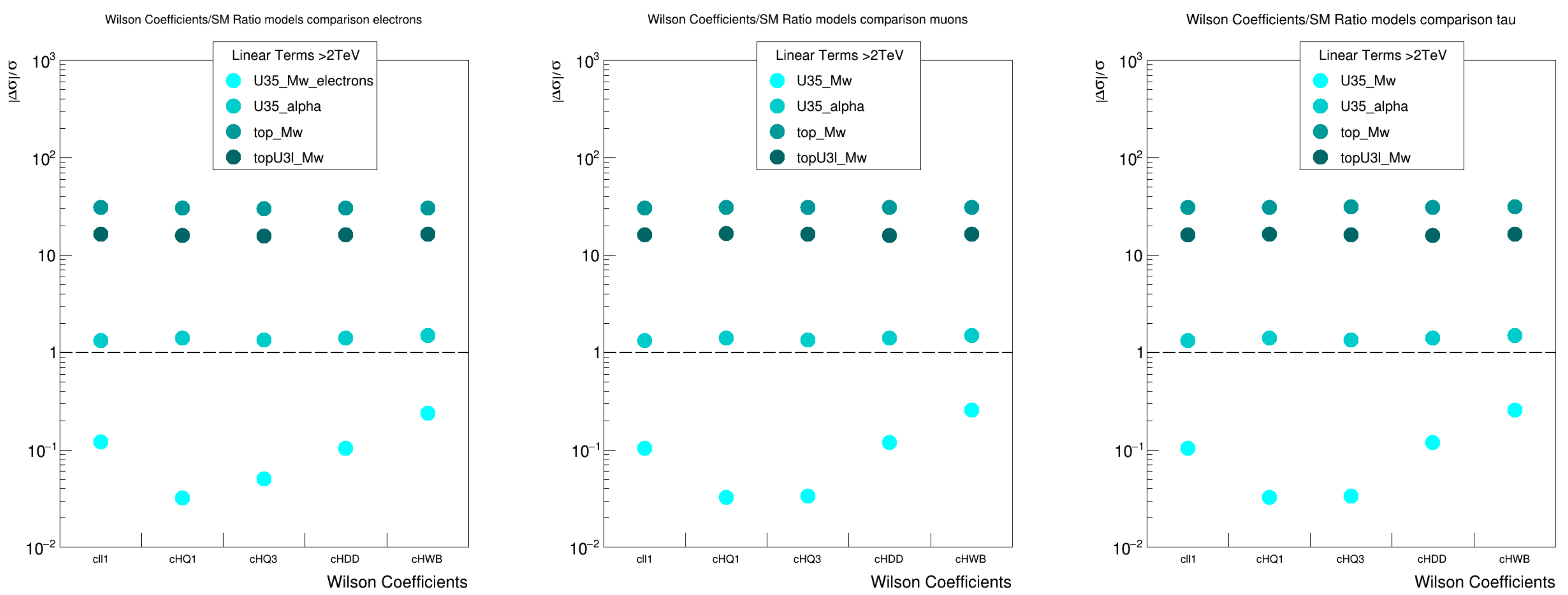






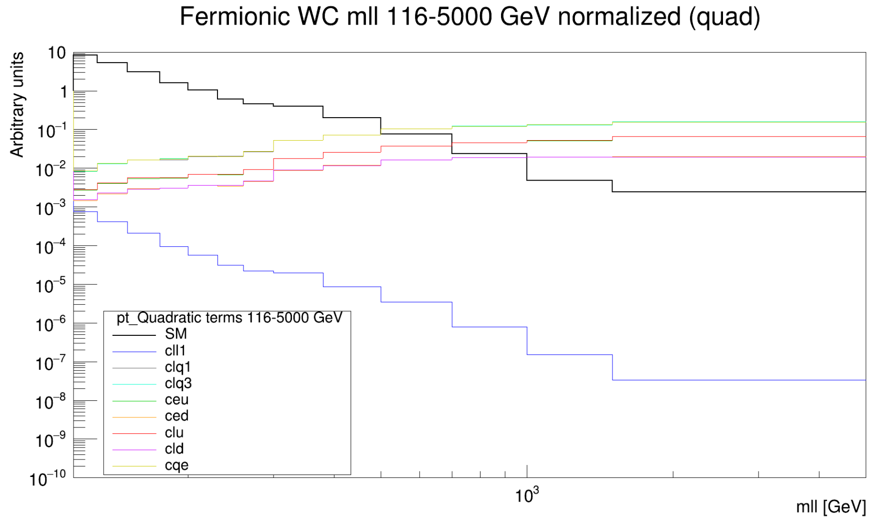


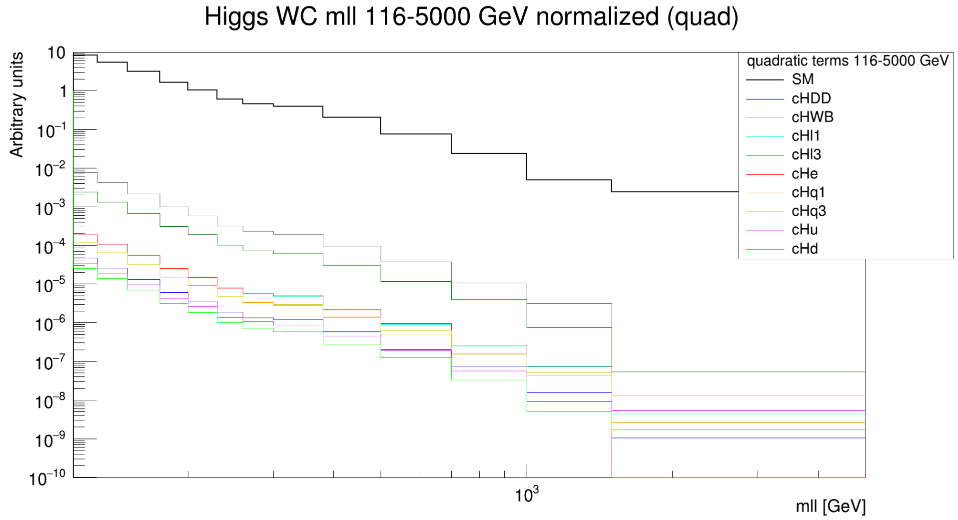
Models' comparison cross-sections (linear terms) >2 TeV



- Different values for different models

Mll distributions U35_alphaScheme (quadratic terms) 116-5000 GeV





- Same observations for the behaviour of the mass distribution
- Some WCs give different values for this scheme, but the general tendency has been kept