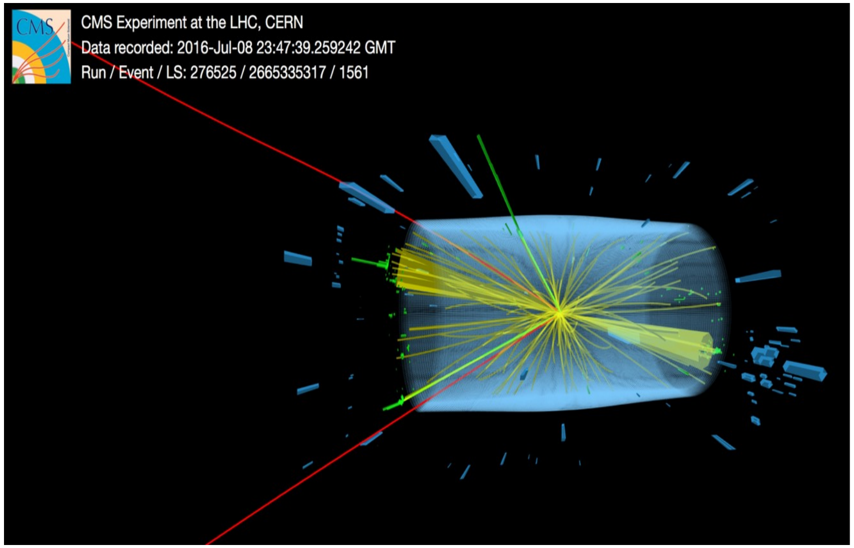
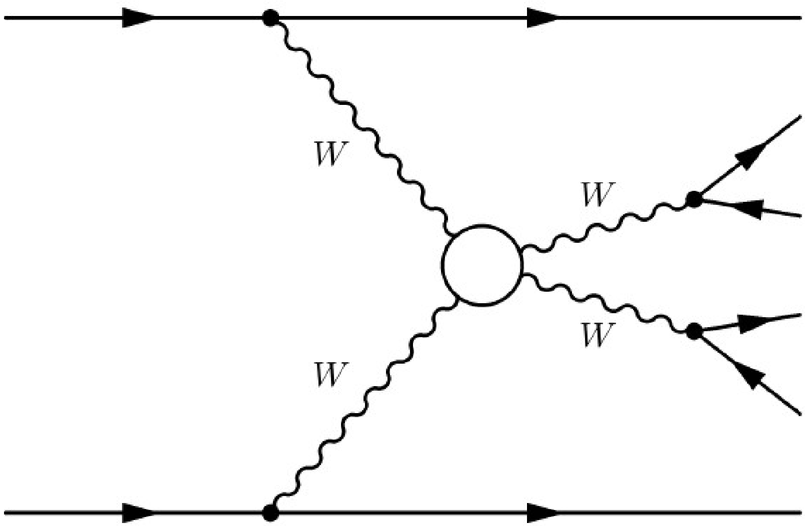
Combination of limits on anomalous quartic gauge couplings in leptonic same-sign WW and ZZ VBS at 13 TeV

Max Neukum

17th June 2019

Institute of Experimental Particle Physics, Karlsruhe Institute of Technology





Outline

1. Introduction

2. Workflow

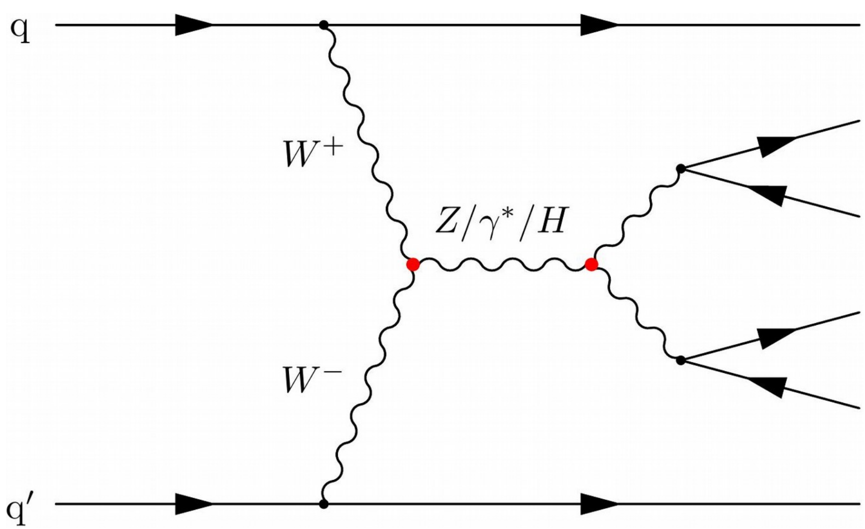
3. Reconstruction of limits in single analyses

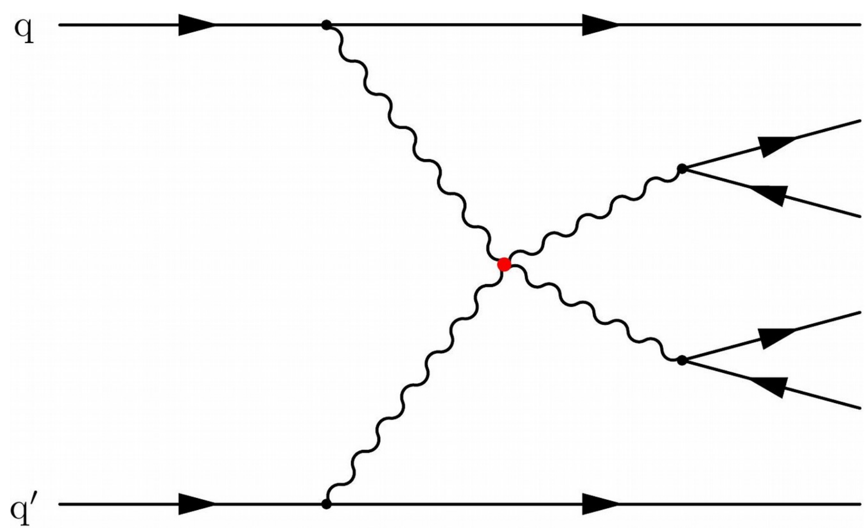
4. Combination

5. Summary & Outlook

Why Vector Boson Scattering?

- Connected to Higgs Production
- Unitarity violated in $V_L V_L \rightarrow V_L V_L$ without the Higgs Boson
- VBS grants access to quartic vertices
- Anomalies in TGC & QGC are interpreted in an EFT approach





Effective Field Theory approach

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{f_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{f_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

- Integrate out possible higher energy effects
- Include higher (mass-) dimension operators
- Theory invalid beyond UV cut-off Λ, no renormalization
- Higher orders suppressed by powers of Λ
- aTGC: dimension-6 aQGC: dimension-8, access in VBS!

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$,$\mathcal{L}_{M,6}$,$\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$,$\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$,$\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$,$\mathcal{L}_{T,1}$,$\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$,$\mathcal{L}_{T,6}$,$\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}$,$\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

Table 1: Quartic vertices modified by each dimension-8 operator are marked with X.

[O. Éboli et al.]

Combination

Karlsruhe Institute of Technology

- Combination of ATLAS and CMS publication
- ATLAS & CMS plan:
  - → Wait until all analyses are finished
  - → Combine during long shutdown
  - → Long review in both collaborations
- Our plan (VBSCan):

VBSCan COST Network

  - → Use only publicly available data
  - → Start Combination NOW
  - → Get improved constraints on aQGC earlier
  - → Gain experience for future projects

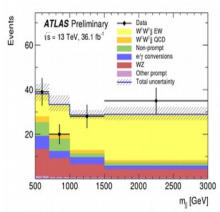
Channels to combine

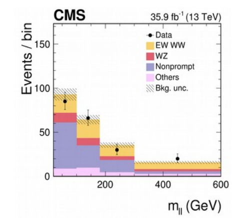
- Combine different channels (leptonic):

ATLAS

CMS

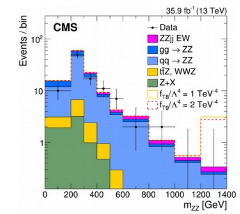
ATLAS-CONF -2018-030





ssWW

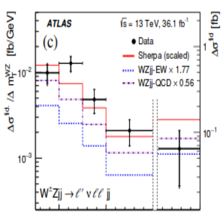
SMP-17-004



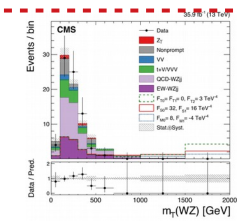
ZZ

SMP-17-006

ATLAS-CONF -2018-033



. . .



WZ

SMP-18-001

- Also possible to add further channels later, e.g. semileptonic VV
- Here: Focus on CMS ssWW & ZZ (public Data available!)

Outline

1. Introduction

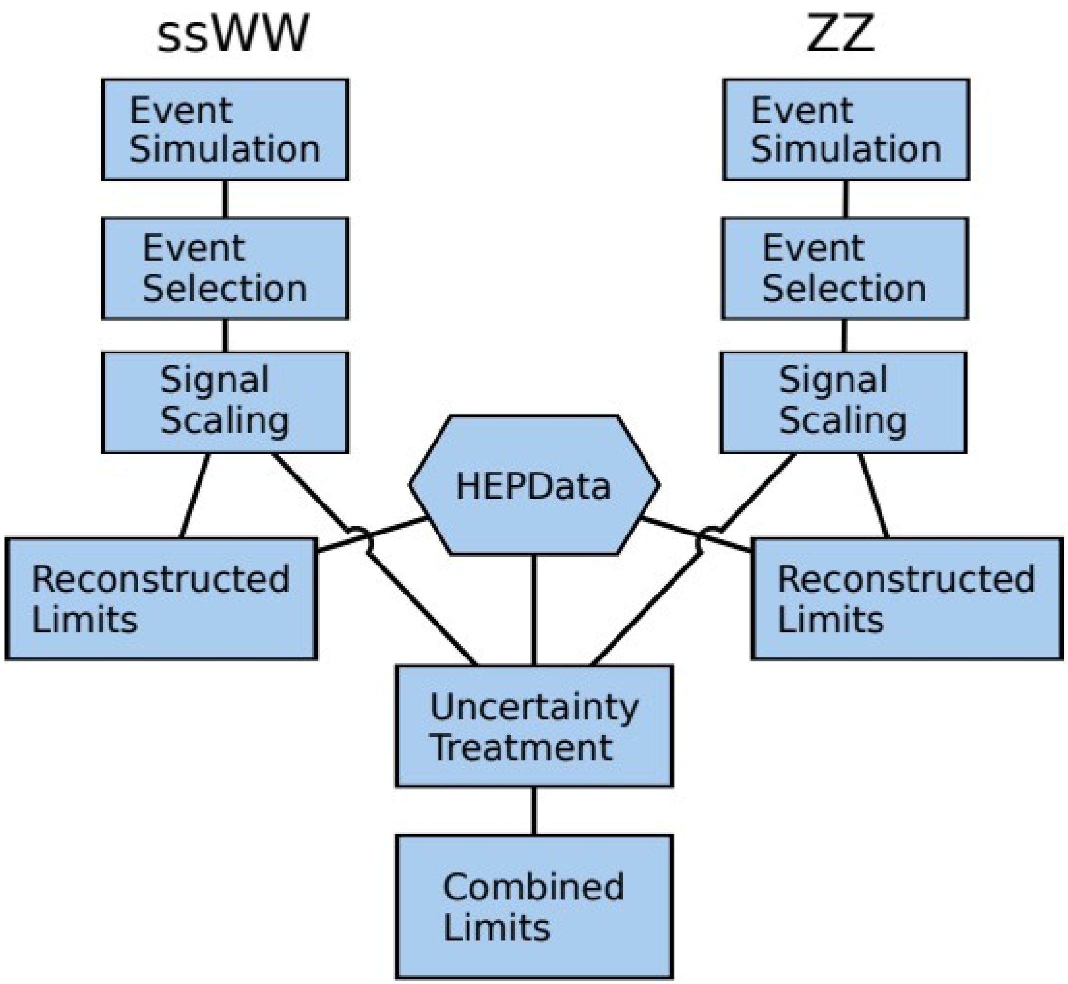
2. Workflow
3. Reconstruction of limits in single analyses
4. Combination
5. Summary & Outlook

The goal and ingredients

- Combination of aQGC limits
- Use **public information** only:
  - ➔ In HEPData format
  - ➔ Cannot use internal tools
  - ✔ No official approval process: much faster

- Ingredients:
  - ➔ CMS tool “combine” is public
  - ➔ HEPData: Signal, Background & Systematic uncertainties in sensitive variable
  - ➔ Signal modeling: generate it ourselves

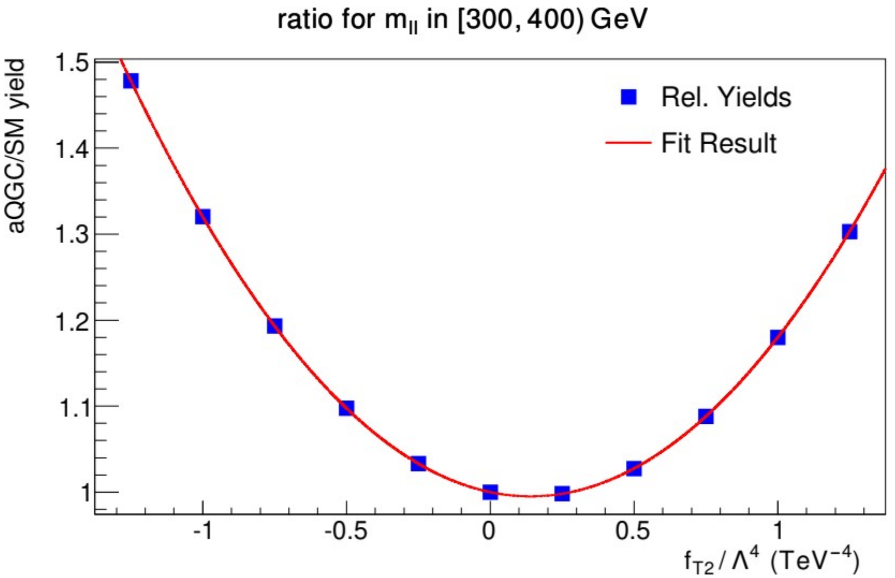
Description of the Workflow



Signal Modeling

- Generate MC events in LO-QCD:
  - ➔ Madgraph5 + Pythia8
- Use dim-8 EFT UFO model (available on Feynrules)
- LO matrix-element reweighting to different coefficients
- $|\mathcal{A}_{\mathrm{SM}} + \frac{f_i}{\Lambda^4}\mathcal{A}_i|^2 = |\mathcal{A}_{\mathrm{SM}}|^2 + 2\frac{f_i}{\Lambda^4}\,\mathrm{Re}(\mathcal{A}_{\mathrm{SM}}\mathcal{A}_i^*) + \frac{f_i^2}{\Lambda^8}|\mathcal{A}_i|^2$
- fit quadratic function in each bin

  to describe the signal scaling

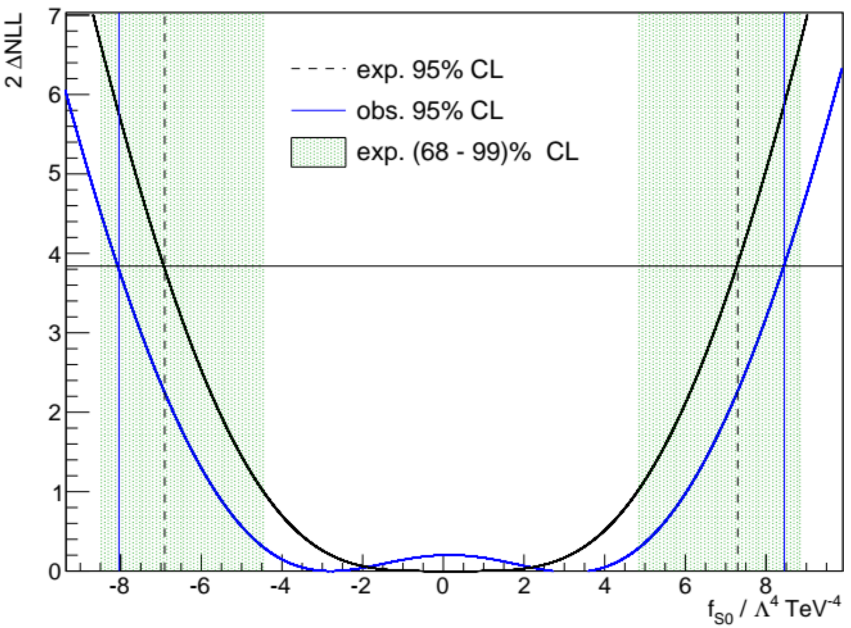


Limit setting

- Binned shape analysis ⬌ #bins * simple counting experiment
- Likelihood:
  (modulo interpolations)

$$L(\vec{\theta}\,|\,\vec{n}) = \prod_{b} \mathrm{Poisson}(\,n_b\,|\,S_b(\vec{\theta},\vec{f}) + \sum_{j} B_{b,j}(\vec{\theta})\,) \cdot \rho(\vec{\theta}\,|\,\hat{\vec{\theta}})$$

- with bins b, background j, and signal scaling f
- 95% CL limits with Wilk's Theorem



- Combination:
  - ➔ Multiplicative extension of L
  - ➔ Consider Correlations!
  - ➔ Avoid double counting!

About Reweighting

- Maximal use of MC samples
- LO Matrix element reweighting in MadGraph:

$$W_{\mathrm{new}} = \frac{|M_{\mathrm{new}}|^2}{|M_{\mathrm{old}}|^2} W_{\mathrm{orig}}$$

$$W_{\mathrm{orig}} = f_1(x_1, \mu_{\mathrm{F}}) \cdot f_2(x_2, \mu_{\mathrm{F}}) \cdot |M_{\mathrm{orig}}|^2 \cdot \Omega_{\mathrm{PS}}$$

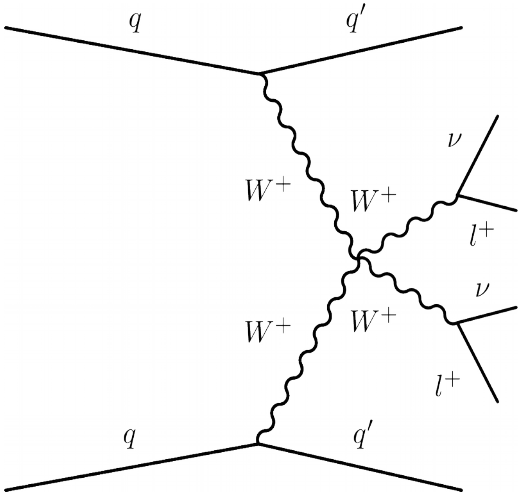
- Need non-negligible contributions in same parts of the phase-space Ω_{PS}
- Focus on relevant parts of PS
- Exploitation of resources vs. accuracy
- Need to be checked explicitly

Outline

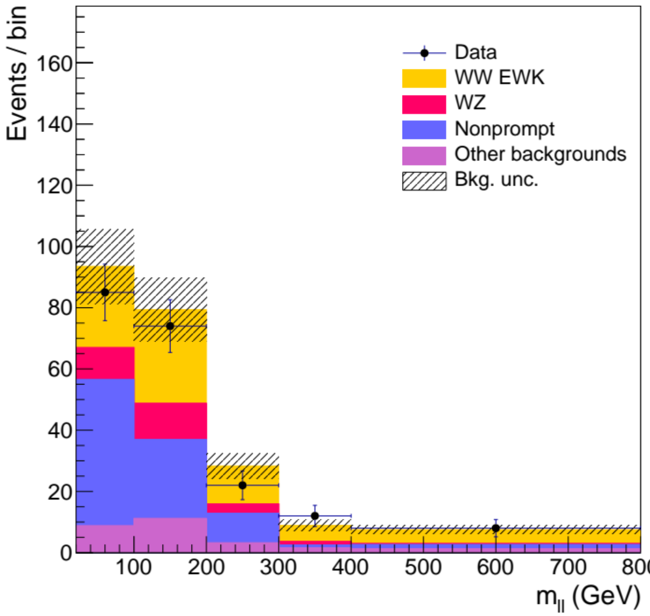
CMS ssWW: available Information

On HEPdata:

- Data, Signal & Background contributions
- Combined Uncertainties per bin
- Main uncertainties
- Gen-Reco efficiencies per bin
- Values are <u>post-fit</u>!

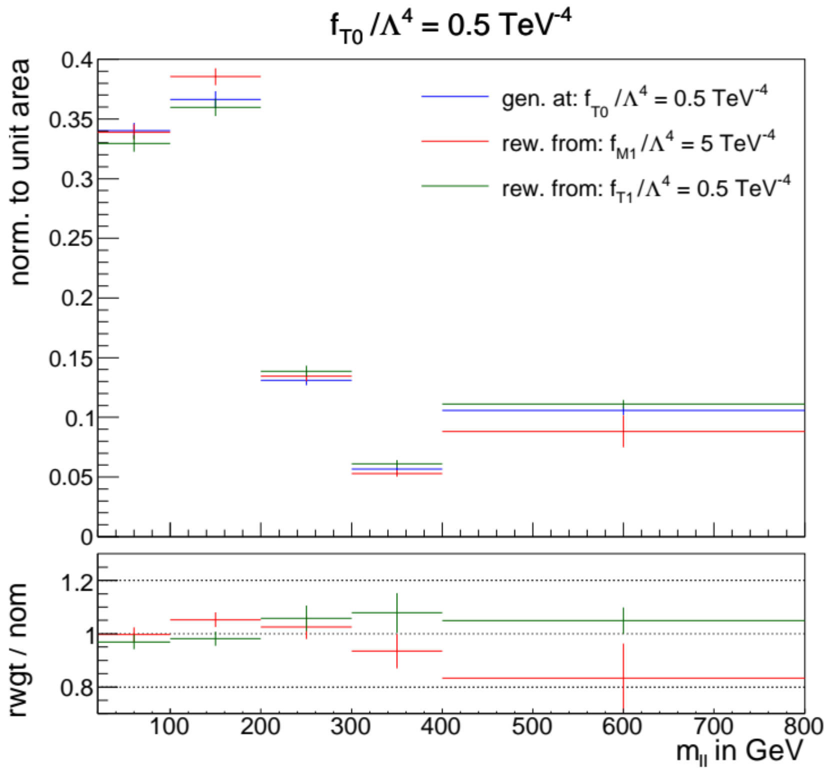


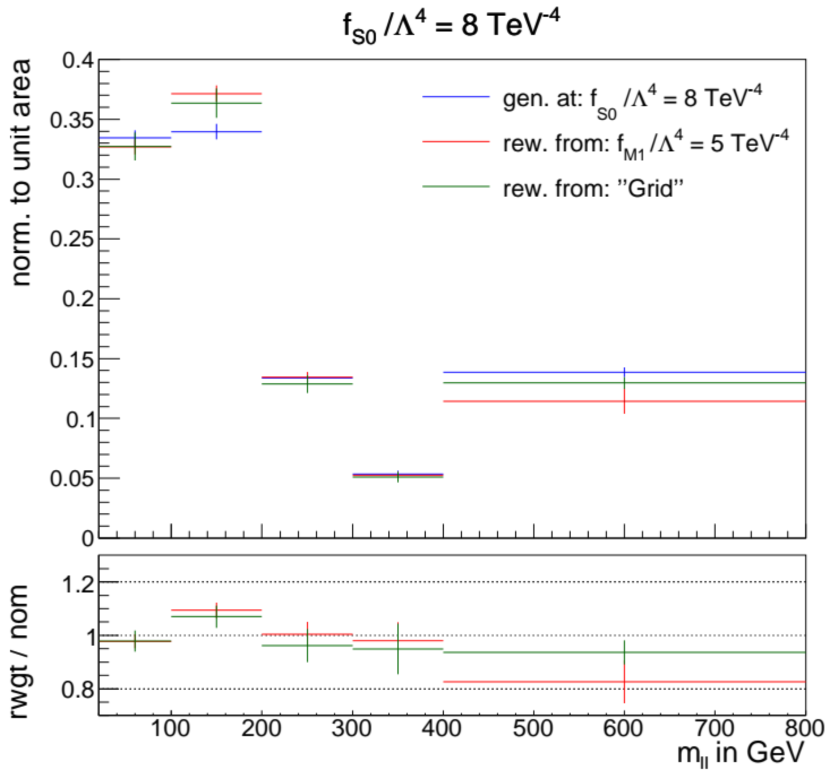
Source	Value (%)
Luminosity	2.5
Muon selection	2.0
Electron selection	2.0
Jet energy scale (JES)	3.0
PDF uncertainty	4.0
QCD scales	10.0



CMS ssWW: Reweighting (I)

- Explicitly check the reweighting procedure
- Reweighting to the same parameter works well
- Last bin is most important (as seen later)

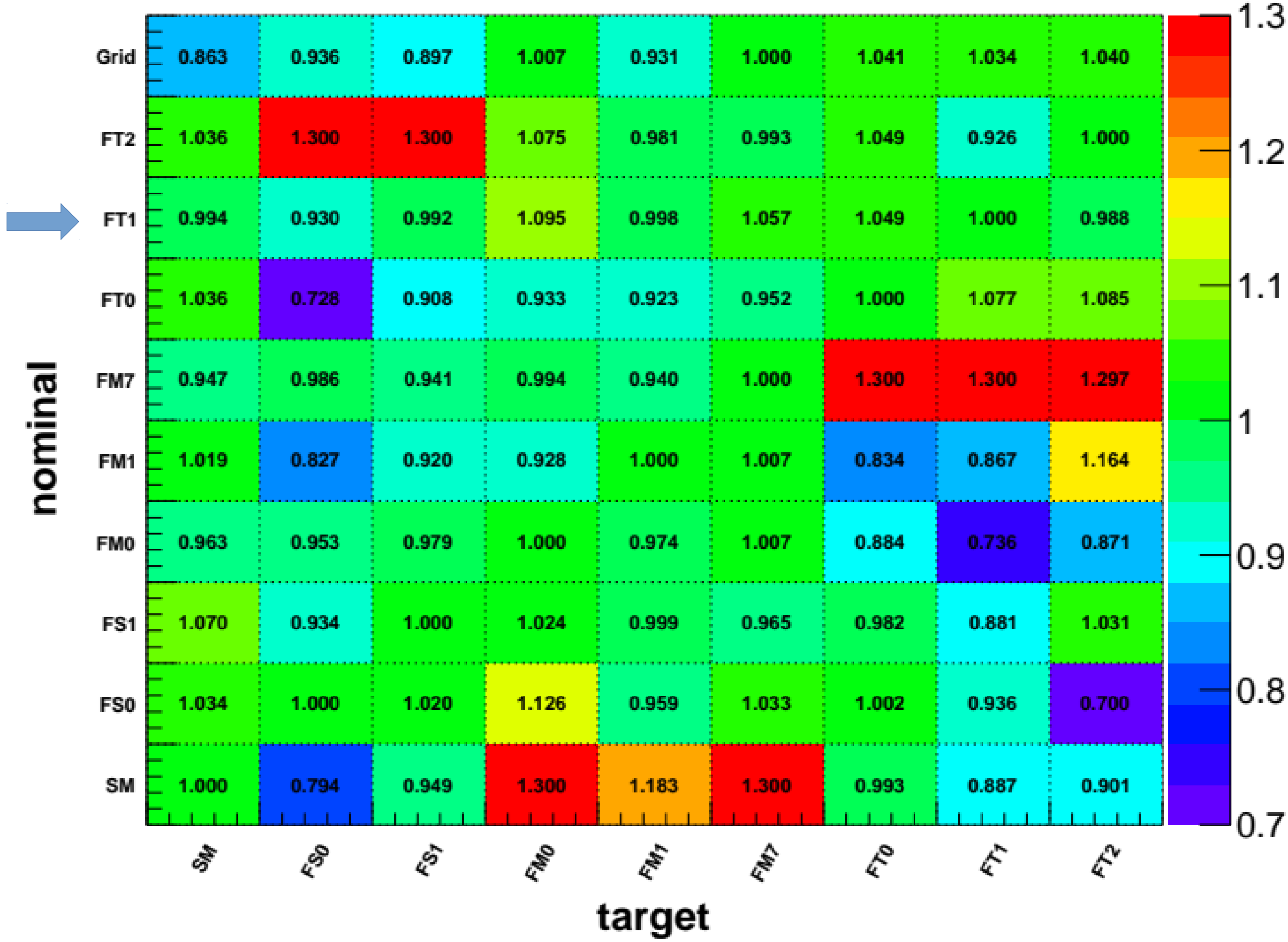




CMS ssWW: Reweighting (II)

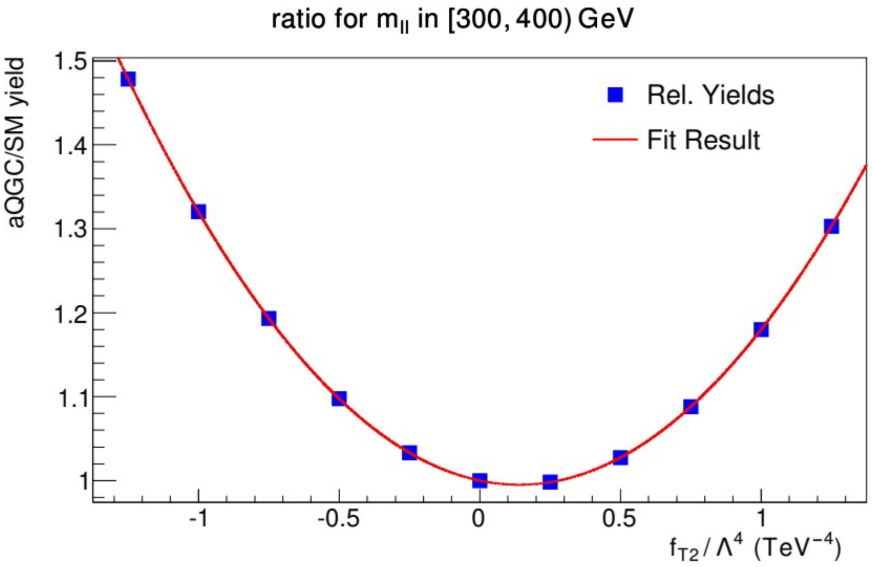
Karlsruhe Institute of Technology

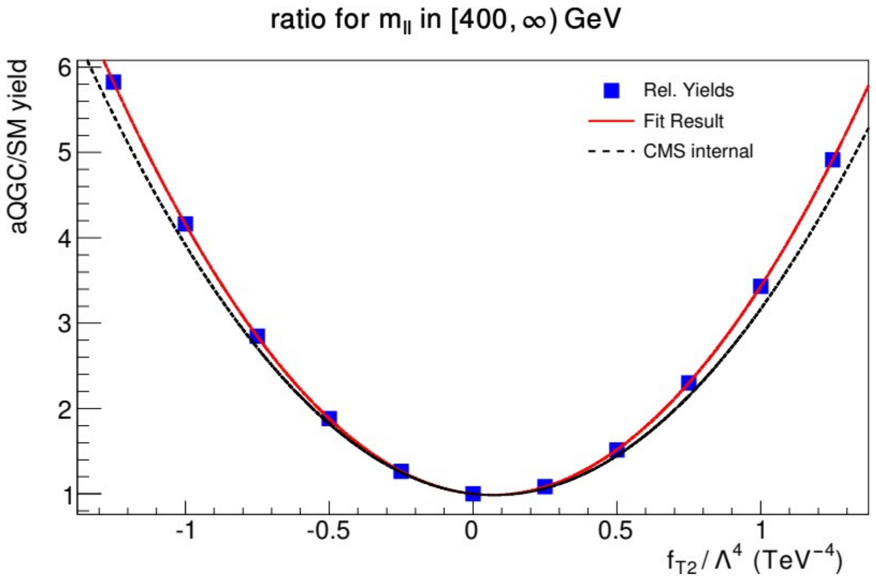
- Ratios in the last bin: nominal / target



CMS ssWW: Signal Scaling

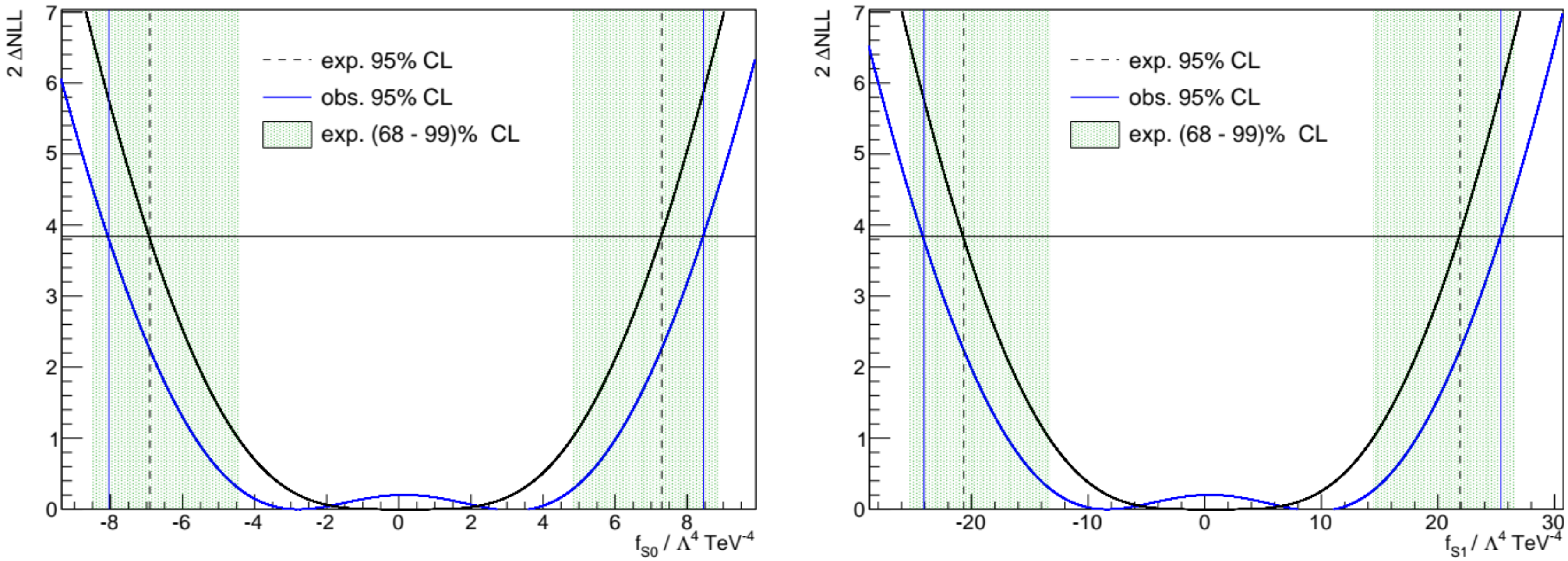
- Relative yields described by a parabola
- Greatest effect in high energy region, i.e., last bin
- Closure test: signal scaling used in published analysis (not public)
- SM expectation is multiplied by these functions





CMS ssWW: Reconstructed Limits

- Wilk’s Theorem used to derive 95% CL limits
- In the obs. case: minima not at 0
  - ➔ Data > Signal + Background in bin 4



CMS ssWW: Reconstructed Limits (obs)

- CMS internal scaling gives good results
  - ➔ Statistical Framework and uncertainty treatment verified
- Own generated scaling deviates ~5%
  - ➔ Detector effects are not negligible

Coupling	Official results (TeV^{-4})	CMS internal scaling (TeV^{-4})	This study (TeV^{-4})
f_{S0}/Λ^4	[-7.7, 7.7]	[-7.72, 7.77]	[-8.04, 8.45]
f_{S1}/Λ^4	[-21.6, 21.8]	[-21.8, 21.9]	[-24.1, 25.3]
f_{M0}/Λ^4	[-6.0, 5.9]	[-5.98, 5.94]	[-5.88, 5.80]
f_{M1}/Λ^4	[-8.7, 9.1]	[-8.79, 9.19]	[-8.43, 8.94]
f_{M7}/Λ^4	[-13.3, 12.9]	[-13.4, 13.0]	[-13.16, 12.53]
f_{T0}/Λ^4	[-0.62, 0.65]	[-0.627, 0.655]	[-0.586, 0.604]
f_{T1}/Λ^4	[-0.28, 0.31]	[-0.285, 0.308]	[-0.273, 0.293]
f_{T2}/Λ^4	[-0.89, 1.02]	[-0.894, 1.03]	[-0.873, 0.992]

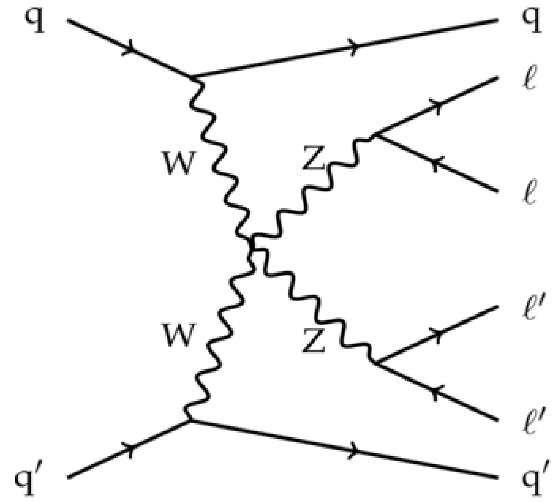
~ .5%

~ 5.%

CMS ZZ: available Information

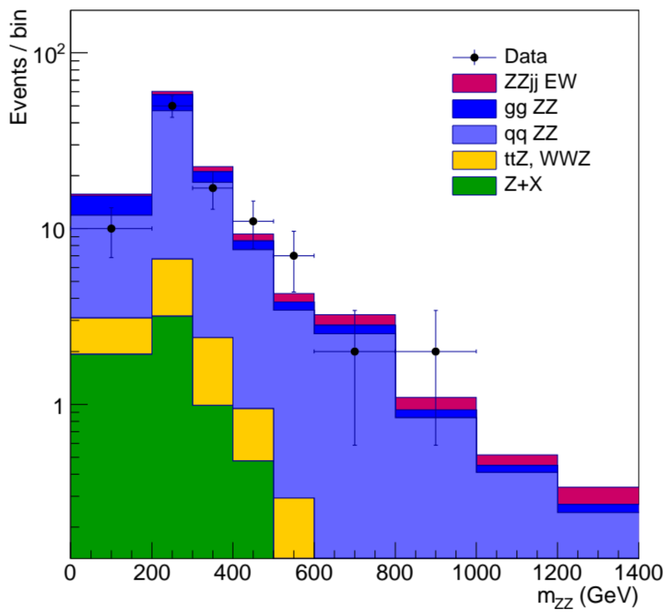
On HEPdata:

- Data, Signal & Background contributions
- Uncertainties per bin & source
- Gen-Reco efficiencies are flat
- Values are <u>pre-fit</u>!



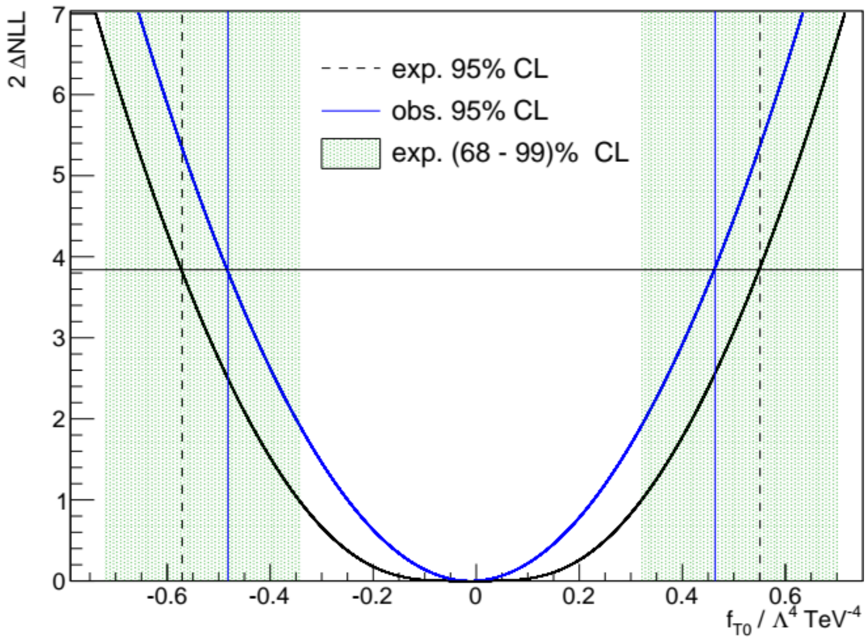
Differences to CMS ssWW:

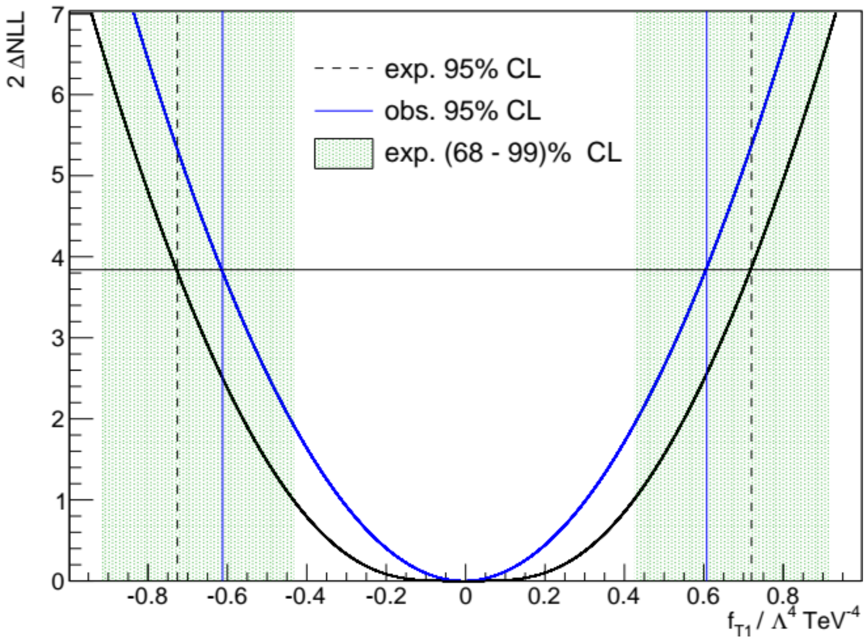
- post-fit vs. pre-fit
- MC generation uses MadSpin
- No neutrinos in final state (MET cut)
- Different background contributions
- Other than that, the procedure is the same



CMS ZZ: Reconstructed Limits

- Wilk's Theorem used to derive 95% CL limits
- Observed limits stricter than expected
  - ➔ No data in the last two bins





CMS ZZ: Reconstructed Limits (obs)

- Good results in both cases
- Greatest discrepancies in f_{T0} (~4%)
  - ➔ too few events as seen when looking at the reweighting

Coupling	Official results (TeV^{-4})	CMS internal scaling (TeV^{-4})	This study (TeV^{-4})
f_{S0}/Λ^4	-	-	[-34.7, 34.6]
f_{S1}/Λ^4	-	-	[-23.58, 23.4]
f_{M0}/Λ^4	-	-	[-1.99, 1.99]
f_{M1}/Λ^4	-	-	[-7.42, 7.44]
f_{M7}/Λ^4	-	-	[-14.5, 14.5]
f_{T0}/Λ^4	[-0.46, 0.44]	[-0.46, 0.44]	[-0.48, 0.46]
f_{T1}/Λ^4	[-0.61, 0.61]	[-0.61, 0.61]	[-0.61, 0.61]
f_{T2}/Λ^4	[-1.2, 1.2]	[-1.22, 1.18]	[-1.22, 1.18]
f_{T8}/Λ^4	[-0.84, 0.84]	[-0.85, 0.85]	[-0.85,0.85]
f_{T9}/Λ^4	[-1.8, 1.8]	[-1.81, 1.81]	[-1.83,1.83]

Outline

Towards a combination

Karlsruhe Institute of Technology

- CMS ssWW and ZZ: orthogonal set of events
- ssWW not affected by FT8, FT9
- Although analyses are not exactly reconstructed, combination could be fruitful.

- Multiplication of Likelihoods with correlations

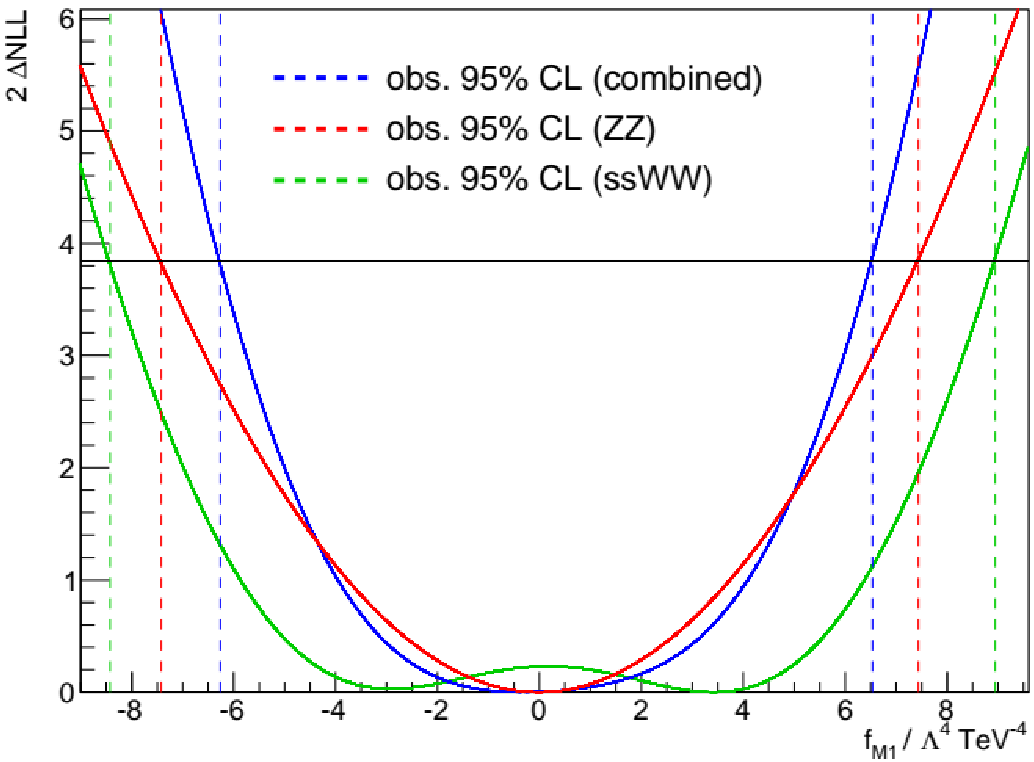
- Only “main uncertainties” in ssWW channel
- Luminosity uncertainty is correlated
- Theory uncertainties are correlated

Systematic Uncertanties

	ssWW channel (%)									ZZ channel (%)					
Source	EWK	QCD	WZ	ZZ	VVV	Wrong Sign	$W\gamma$	DPS	Nonprompt	EWK	QCD	QCD (loop)	WWZ	$t\bar{t}Z$	reducible
Luminosity	2.5	2.5	-	2.5	2.5	2.5	2.5	2.5	-	2.5	2.5	2.5	2.5	2.5	-
JES	3.0	3.0	-	3.0	3.0	3.0	3.0	3.0	-	1.2 – 1.5	6.9 – 14.5	3.7 – 9.4	-	0.0 –.3.7	-
PDF	4.0	4.0	-	4.0	4.0	4.0	4.0	4.0	-	6.8 – 13.0	3.2 – 8.2	-	2.6 – 8.6	2.3 – 11.1	-
ℓ-selection	2.8	2.8	-	2.8	2.8	2.8	2.8	2.8	-	2.7 – 5.9	2.5 – 5.2	2.8 – 4.3	-	3.3 – 11.1	-
QCD scale_ZZ	-	-	-	10	-	-	-	-	-	5.5 – 14.7	-	-	-	-	-
QCD scale_VVV	-	-	-	-	10	-	-	-	-	-	-	-	9.7 – 10.3	-	-
other (WW EWK)	20 – 83	-	-	-	-	-	-	-	-	-	-	-	-	-	-
other (WW QCD)	-	25 – 29	-	-	-	-	-	-	-	-	-	-	-	-	-
other (WZ)	-	-	22 – 84	-	-	-	-	-	-	-	-	-	-	-	-
other (ZZ)	-	-	-	26 – 28	-	-	-	-	-	-	-	-	-	-	-
other (VVV)	-	-	-	-	13 – 27	-	-	-	-	-	-	-	-	-	-
other (Wrong Sign)	-	-	-	-	-	27 – 49	-	-	-	-	-	-	-	-	-
other ($W\gamma$)	-	-	-	-	-	-	27 – 124	-	-	-	-	-	-	-	-
other (DPS)	-	-	-	-	-	-	-	14 – 47	-	-	-	-	-	-	-
other (Non-prompt)	-	-	-	-	-	-	-	-	20 – 80	-	-	-	-	-	-
Trigger	-	-	-	-	-	-	-	-	-	2.0	2.0	2.0	2.0	2.0	-
JER	-	-	-	-	-	-	-	-	-	0.2 – 0.6	0.0 – 5.3	0.0 – 2.9	-	0.0 – 2.0	-
Pileup	-	-	-	-	-	-	-	-	-	1.1 – 1.9	0.2 – 2.2	0.0 – 1.1	8.4 – 8.6	0.0 – 4.5	-
QCD scale QCD ZZ	-	-	-	-	-	-	-	-	-	-	19.8 – 21.6	-	-	-	-
QCD scale $t\bar{t}Z$	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0 – 100.0	-
norm. ggZZ	-	-	-	-	-	-	-	-	-	-	-	40.0	-	-	-
norm. reducible	-	-	-	-	-	-	-	-	-	-	-	-	-	-	40.0

Comparison of ΔNLL

- Combined distribution is a mix of single distributions
- There is a (limited) range in which the combined is ‘worse’
- In general stricter limits



Combined Results (obs.)

- In most cases: stricter limits
- Up to 17% better (f_{m7})
- Looser limit only in the case of f_{m0}

Coupling	CMS ssWW (TeV^{-4})	CMS ZZ (TeV^{-4})	combined (TeV^{-4})
f_{S0}/Λ^4	[-8.04, 8.45]	[-34.7, 34.6]	[-7.88, 8.28]
f_{S1}/Λ^4	[-24.1, 25.3]	[-23.6, 23.4]	[-18.8, 19.5]
f_{M0}/Λ^4	[-5.88, 5.80]	[-1.99, 1.99]	[-2.05, 2.05]
f_{M1}/Λ^4	[-8.43, 8.94]	[-7.42, 7.44]	[-6.26, 6.54]
f_{M7}/Λ^4	[-13.16, 12.53]	[-14.5, 14.5]	[-10.8, 10.4]
f_{T0}/Λ^4	[-0.586, 0.604]	[-0.48, 0.46]	[-0.421, 0.418]
f_{T1}/Λ^4	[-0.273, 0.293]	[-0.61, 0.61]	[-0.258, 0.274]
f_{T2}/Λ^4	[-0.873, 0.992]	[-1.22, 1.18]	[-0.763, 0.837]

combination useful

Outline

Summary

- Combination of limits on aQGC with public information
  - HEPData and public paper
- “Combine” tool is public and reproduces results with internal data
- **CMS ssWW:**
  - MG5 + Pythia reproduce the limits within ~10%
  - Detector effects are likely to be an issue
- **CMS ZZ:**
  - Limits reproduced within ~1%
  - Detector effects play a negligible role
- **Combination:**
  - Machinery runs smoothly, assumptions about correlations
  - Combination gives sensible results

Outlook

- Investigation of detector effects in the ssWW channel
- 2D limits show correlations
- Unitarisation: “clipping method”

- Add further analyses as data becomes public
- ATLAS + CMS combination

- In the future: compare with official combination

- Also: same effort exists with respect to dim-6 operators

Backup Slides

CMS ssWW: Reconstructed Limits (exp)

Coupling	Official results (TeV^{-4})	CMS internal scaling (TeV^{-4})	This study (TeV^{-4})
f_{S0}/Λ^4	[-7.0, 7.2]	[-6.75, 6.84]	[-6.91, 7.30]
f_{S1}/Λ^4	[-19.9, 20.2]	[-19.1,19.3]	[-20.6, 21.9]
f_{M0}/Λ^4	[-5.6, 5.5]	[-5.31, 5.24]	[-5.21, 5.11]
f_{M1}/Λ^4	[-7.9, 8.5]	[-7.59, 8.08]	[-7.34, 7.71]
f_{M7}/Λ^4	[-11.1, 11.0]	[-11.9, 11.4]	[-11.37, 10.78]
f_{T0}/Λ^4	[-0.58, 0.61]	[-0.553, 0.582]	[-0.518, 0.530]
f_{T1}/Λ^4	[-0.26, 0.29]	[-0.249, 0.274]	[-0.234, 0.255]
f_{T2}/Λ^4	[-0.80, 0.95]	[-0.763, 0.903]	[-0.728, 0.851]

CMS ZZ: Reconstructed Limits (exp)

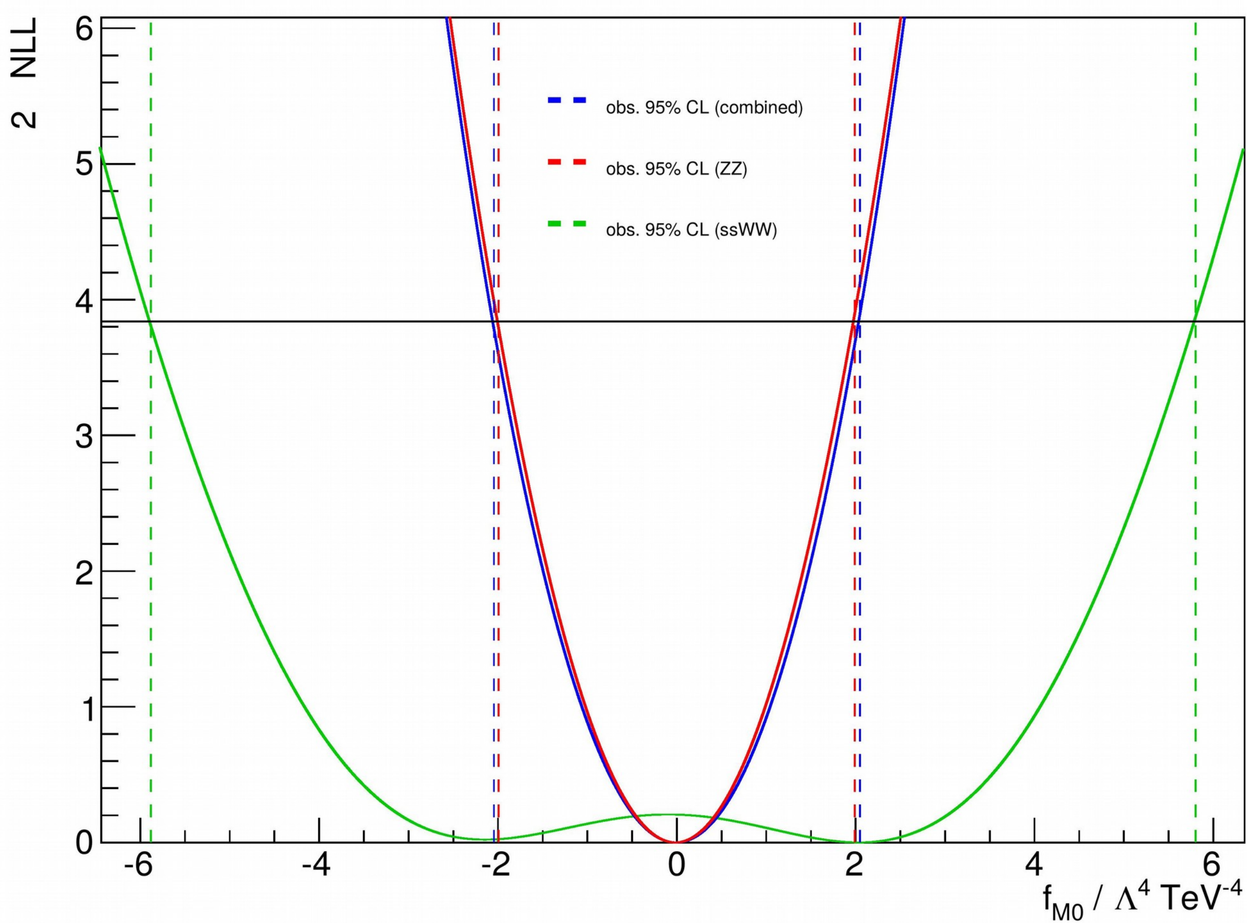
Coupling	Official results (TeV^{-4})	CMS internal scaling (TeV^{-4})	This study (TeV^{-4})
f_{S0}/Λ^4	-	-	[-41.5, 41.5]
f_{S1}/Λ^4	-	-	[-27.6, 27.5]
f_{M0}/Λ^4	-	-	[-2.35, 2.35]
f_{M1}/Λ^4	-	-	[-8.79, 8.78]
f_{M7}/Λ^4	-	-	[-17.1, 17.2]
f_{T0}/Λ^4	[-0.53, 0.51]	[-0.54, 0.52]	[-0.57, 0.55]
f_{T1}/Λ^4	[-0.72, 0.71]	[-0.72, 0.72]	[-0.72, 0.72]
f_{T2}/Λ^4	[-1.4, 1.4]	[-1.4, 1.4]	[-1.45, 1.40]
f_{T8}/Λ^4	[-0.99, 0.99]	[-1.00, 1.00]	[-1.01,1.01]
f_{T9}/Λ^4	[-2.1, 2.1]	[-2.15, 2.15]	[-2.17,2.17]

Combined Results (exp.)

Coupling	CMS ssWW (TeV^{-4})	CMS ZZ (TeV^{-4})	combined (TeV^{-4})
f_{S0}/Λ^4	[-6.91, 7.30]	[-41.5, 41.5]	[-6.88, 7.26]
f_{S1}/Λ^4	[-20.6, 21.9]	[-27.6, 27.5]	[-18, 18.8]
f_{M0}/Λ^4	[-5.21, 5.11]	[-2.35, 2.35]	[-2.29, 2.28]
f_{M1}/Λ^4	[-7.34, 7.71]	[-8.79, 8.78]	[-6.08, 6.38]
f_{M7}/Λ^4	[-11.37, 10.78]	[-17.1, 17.2]	[-10.25, 9.81]
f_{T0}/Λ^4	[-0.518, 0.530]	[-0.57, 0.55]	[-0.416, 0.419]
f_{T1}/Λ^4	[-0.234, 0.255]	[-0.72, 0.72]	[-0.23, 0.249]
f_{T2}/Λ^4	[-0.728, 0.851]	[-1.45, 1.40]	[-0.692, 0.787]

About FM0 in the Combination

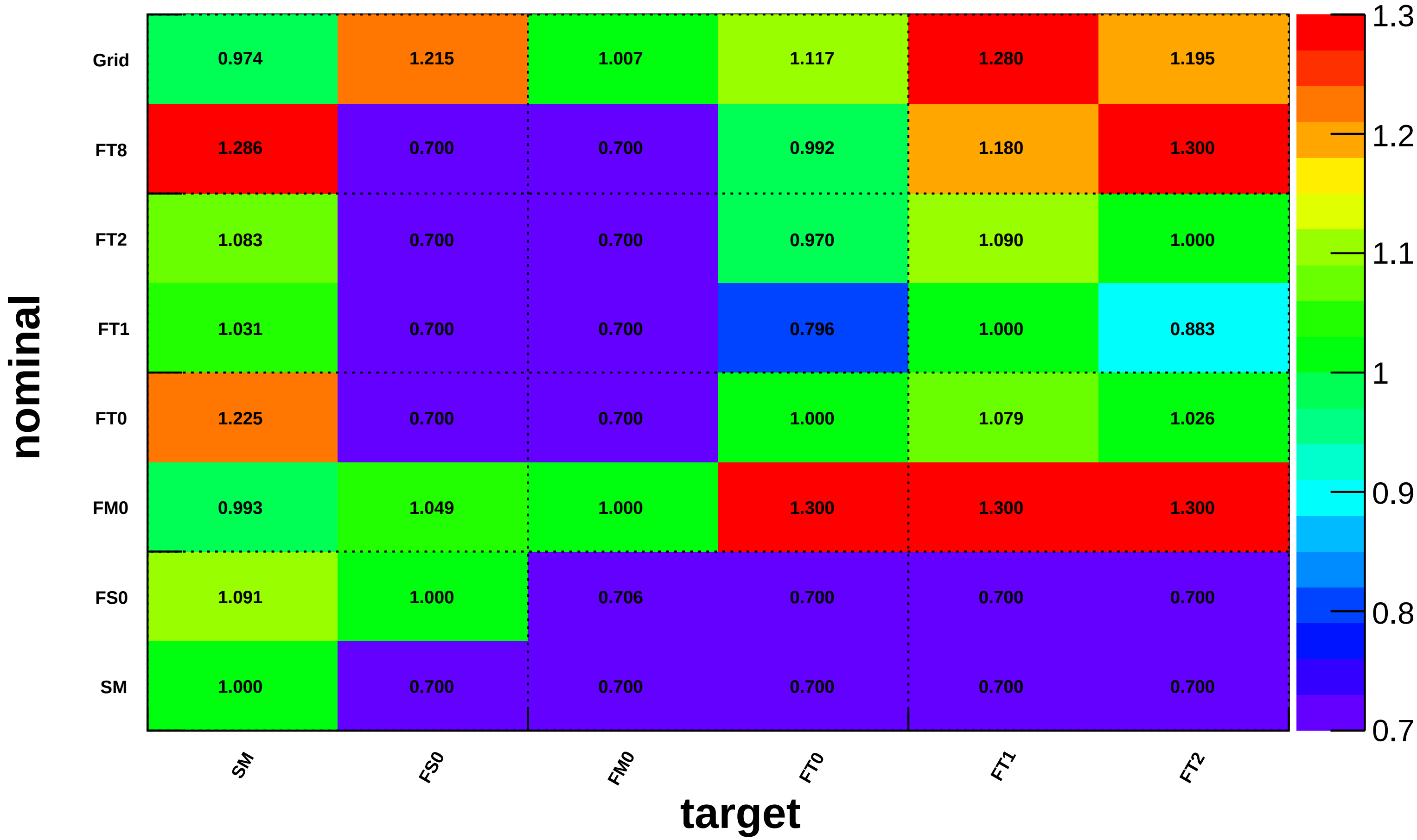
- Combined > ZZ, if $|f_{M0}| > 2$
- ssWW: non-zero minimum
- caused by stat. fluctuation
  in ssWW channel



ssWW: Reweighting – sample names

Sample names	f_{S0}/Λ^4	f_{S1}/Λ^4	f_{M0}/Λ^4	f_{M1}/Λ^4	f_{M7}/Λ^4	f_{T0}/Λ^4	f_{T1}/Λ^4	f_{T2}/Λ^4
				in TeV^{-4}				
SM	0	0	0	0	0	0	0	0
FS0	8	0	0	0	0	0	0	0
FS1	0	12	0	0	0	0	0	0
FM0	0	0	5	0	0	0	0	0
FM1	0	0	0	5	0	0	0	0
FM7	0	0	0	0	10	0	0	0
FT0	0	0	0	0	0	0.5	0	0
FT1	0	0	0	0	0	0	0.5	0
FT2	0	0	0	0	0	0	0	1
Grid	10	25	10	10	20	1	0.5	1.5

ZZ: Reweighting



ZZ: Reweighting – sample names

Sample names	f_{S0}/Λ^4	f_{S1}/Λ^4	f_{M0}/Λ^4	f_{M1}/Λ^4	f_{M7}/Λ^4	f_{T0}/Λ^4	f_{T1}/Λ^4	f_{T2}/Λ^4	f_{T8}/Λ^4
	in TeV^{-4}								
SM	0	0	0	0	0	0	0	0	0
FS0	8	0	0	0	0	0	0	0	0
FM0	0	0	10	0	0	0	0	0	0
FT0	0	0	0	0	0	0.5	0	0	0
FT1	0	0	0	0	0	0	0.5	0	0
FT2	0	0	0	0	0	0	0	1	0
FT8	0	0	0	0	0	0	0	0	2
Grid	10	25	10	10	20	1	0.5	1.5	0

ssWW: selection cuts

- Two same-sign leptons, electrons or muons, with $p_T > 25\,(20)$ GeV for the lepton with highest (second highest) transverse momentum and $|\eta| < 2.5\,(2.4)$ for electrons (muons) are required. The invariant mass of this lepton pair needs to satisfy $m_{\ell\ell} > 20$ GeV and in the case of two electrons $|m_{\ell\ell} - m_Z| > 15$ GeV to suppress charge misidentification.
- The event needs to contain at least two jets, which are reconstructed using the anti-k_T algorithm and $R = 0.4$, with transverse momentum $p_T > 30$ GeV and $|\eta| < 5$. The two jets with highest transverse momentum need a large invariant mass $m_{jj} > 500$ GeV and rapidity separation $\Delta\eta_{jj} > 2.5$.
- Moderate missing transverse momentum is required to suppress Drell-Yan contributions: $p_T^{miss} > 40$ GeV.
- A cut on the Zeppenfeld variable [105] of the leptons is applied: $z_\ell < 0.75$, where $z_\ell = |\eta_\ell - (\eta_{j1} + \eta_{j2})/2|/|\Delta\eta_{jj}|$ for each lepton ℓ and the two jets j_1, j_2 with highest p_T. This means that the leptons are in the central region relative to the two tagging jets.
- Events with jets originating from b quarks, additional loosely identified leptons with $p_T > 10$ GeV, or τ leptons decaying hadronically and with $p_T > 18$ GeV are rejected.

ZZ: selection cuts

- Leptons with rapidity $|\eta| < 2.5\,(2.4)$ and transverse momentum $p_\mathrm{T} > 7\,(5)\,\mathrm{GeV}$ for electrons (muons) are selected. The lepton with highest p_T needs to fulfill $p_\mathrm{T} < 20\,\mathrm{GeV}$ and the second highest $p_\mathrm{T} < 12\,(10)\,\mathrm{GeV}$ for electrons (muons). They have to be separated from each other with $\Delta R_{\ell_1,\ell_2} > 0.02$ and $\Delta R_{\mathrm{e},\mu} > 0.05$.
- Pairs of oppositely charged electrons or muons form candidates for a Z boson. At least two of such candidates per event are required.
- A pair of Z boson candidates forms a ZZ candidate. The Z boson candidate with a mass closer to the real Z boson mass is called Z_1, the other one Z_2. They have to fulfill $m_{\mathrm{Z}_1} > 40\,\mathrm{GeV}$ and $m_{\mathrm{Z}_1}, m_{\mathrm{Z}_2} < 120\,\mathrm{GeV}$, as well as $m_{\ell\ell'} > 4\,\mathrm{GeV}$ for all lepton pairs with opposite charge.
- In case of any ambiguity, the pair with smallest value of $|m_{\mathrm{Z}_1} - m_\mathrm{Z}|$ and then with highest sum of transverse momenta $\sum p_{\mathrm{T},\ell}$ is chosen.
- The last requirement on the leptons is that both Z boson candidates fulfill $60\,\mathrm{GeV} < m_{\mathrm{Z}_1}, m_{\mathrm{Z}_2} < 120\,\mathrm{GeV}$.
- Jets reconstructed with the anti-k_T algorithm and $R = 0.4$ and within $|\eta_\mathrm{j}| < 4.7$ need a minimum transverse momentum $p_\mathrm{T} > 30\,\mathrm{GeV}$ and are separated from leptons contributing to the ZZ system $\Delta R_{\mathrm{j}\ell} \geq 0.4$. There have to be at least two such jets with $m_\mathrm{jj} > 100\,\mathrm{GeV}$ for the two jets leading in p_T.

MadGraph cards for ZZ production

Proc_card

```
set low_mem_multicore_nlo_generation False
set loop_color_flows False
set gauge unitary
set max_npoint_for_channel 0
set group_subprocesses Auto
set ignore_six_quark_processes False
set loop_optimized_output True
set complex_mass_scheme False
import model SM_LS_LM_LT_UFO
define l+ = e+ mu+
define l- = e- mu-
define vl = ve vm vt
define vl~ = ve~ vm~ vt~
define p = g u c d s u~ c~ d~ s~
define j = p
generate    p p > z z j j QED=5 QCD=0 NP=1
output ZZ_gp_aqgc -nojpg
```

MadSpin_card

```
set seed 144831447
set ms_dir ./madspingrid
set Nevents_for_max_weigth 250
set max_weight_ps_point 400
set max_running_process 1
define l+ = e+ mu+
define l- = e- mu-
decay z > l+ l-
decay z > l+ l-
launch
```

HEPData: Uncertainties

ZZ

```
dependent_variables:
- header: {name: Number of entries per bin}
  qualifiers:
  - {name: Process, value: EW P P --> Z0 Z0 JET JET}
  values:
  - errors:
    - {label: 'Trigger (exp.)', symerror: 0.007 }
    - {label: 'Lepton efficiency (exp.)', asymerror: {minus: -0.010, plus: +0.010} }
    - {label: 'JES (exp.)', asymerror: {minus: -0.005, plus: +0.004} }
    - {label: 'JER (exp.)', asymerror: {minus: -0.001, plus: +0.001} }
    - {label: 'PU (exp.)', asymerror: {minus: -0.004, plus: +0.004} }
    - {label: 'QCD scales (theo.)', asymerror: {minus: -0.019, plus: +0.020} }
    - {label: 'PDF (theo.)', asymerror: {minus: -0.025, plus: +0.027} }
    - {label: 'Luminosity (exp.)', symerror: 0.009 }
    value: 0.367
```

+ other bins & contributions

ssWW

```
#: keyword reactions: P P --> W+W+/W-W-
#: keyword observables: Standard Model analysis
#: keyword phrases: VBS | WW | Georgi-Machacek Model | HIGGS++ --> W+ W+ | Anomalous couplings
#: keyword cmenergies: 13000.0
'Source','Value (%)'
'Integrated luminosity',2.5
'Muon selection',2.0
'Electron selection',2.0
'Jet energy scale',3.0
'PDFs',4.0
'QCD scales',10.0
```

+ shape uncertainties per bin & contribution

2D Limits

- 3 5x5 grids:

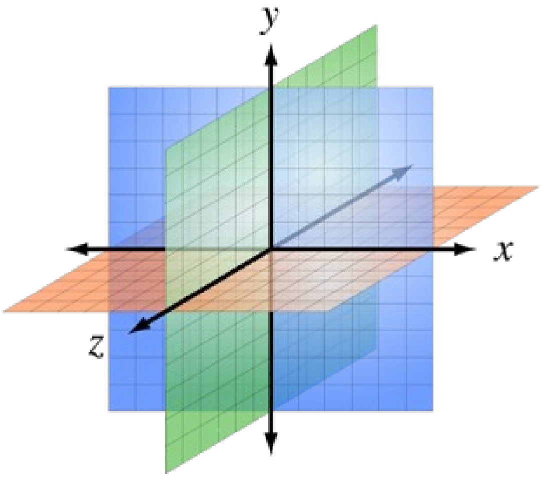
  25 + (25-5) + (25-5-4) = 61 weights

- 2D Fit for each bin in discr. variable:

  weight on e.g. $f_{s0} – f_{s1}$ – plane

- Fitfunction:

  [0]+[1]*x+[2]*y+[3]*x*x+[4]*y*y+[5]*x*y



- Implementation in stat. Framework straightforward
- ATGCRooStats based on Higgs “combine” tool based on RooFit/RooStats