EFT Searches in Multiboson Final States: ATLAS and CMS

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for the **ATLAS** and **CMS** collaborations

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apology:

I cannot cover > 30 papers even though they are all interesting.

I did not choose to simply review the most recent papers from ATLAS & CMS.
Rather, I have tried to identify some interesting themes and topics for discussion.
I'll bring in a variety of analyses as illustrations and explanation.

I apologize if a new result or two is neglected.

searching for new physics (beyond the standard model)

- No overt sign of new physics (physics beyond the standard model) – unfortunately.
- (Let me set aside the hints of flavor anomalies.)
- Must hope to falsify the SM by comparing a prediction to precise measurements.
- $(g\text{-}2)_\mu$ is the current best example of this, but of course there are many others.

- Old approach: think of something you can measure very precisely with a minimum dependence on theory modeling. (LEP)
- See whether the SM predicts the value that you measure.

- 30 years ago, people were certain that the SM would be falsified.
- Nowadays, we know otherwise, and expect that falsifying the SM will be a major challenge.

Why EFTs?

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\, O_i^{(6)} + \frac{1}{\Lambda^4}\sum_i c_i^{(8)}\, O_i^{(8)} + \dots$$

New way (EFT) is better.
It is model-agnostic but still incorporates sensible, ”loose” theory prejudice.

Furthermore, a variety of measurements can be organized together and combined ultimately leading to a more stringent / precise result.

Finally, even without particle theory, nice idea:
- SM is a dim-4 EFT – fully validated
- new physics should show up at dim-6
- tidy scheme based on an expansion in $1/\Lambda$

Potentially very powerful.

Drawbacks:
- fundamentally invalid – at least at energies too close to L or above (unitarity)
- too much freedom!
- power of the data is dilute, at least in a realistic/serious treatment

Our task is to let Nature show us which Wilson Coefficients are significant – and what the pattern is.
Like hitting the right notes on a keyboard to make a beautiful chord.

topics:

1. dim-6 and the impact of differential cross sections
2. trying to deal with unitarity violation
3. dealing with dim-8 when dim-6 is unknown
4. global combined fits

1. dim-6 and the impact of differential cross sections

CMS WW (2020)

- use M(eμ) (clean and simple)
- decent results

ATLAS WW+1j (2021)

- demanding 1 jet enhances dim-6 signal
- better results

ATLAS Z+jj (2021)

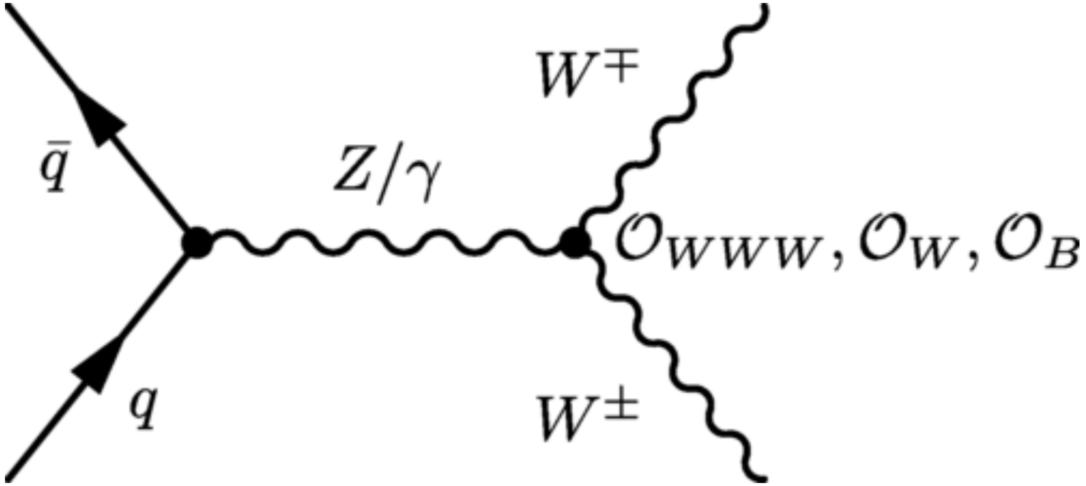
- not true multiboson, but
- use of signed azimuthal jet angle → enhancement

CMS Wg (2022)

- interference resurrection
- major enhancement

CMS PRD 102 (2020) 092001

CMS WW 2020

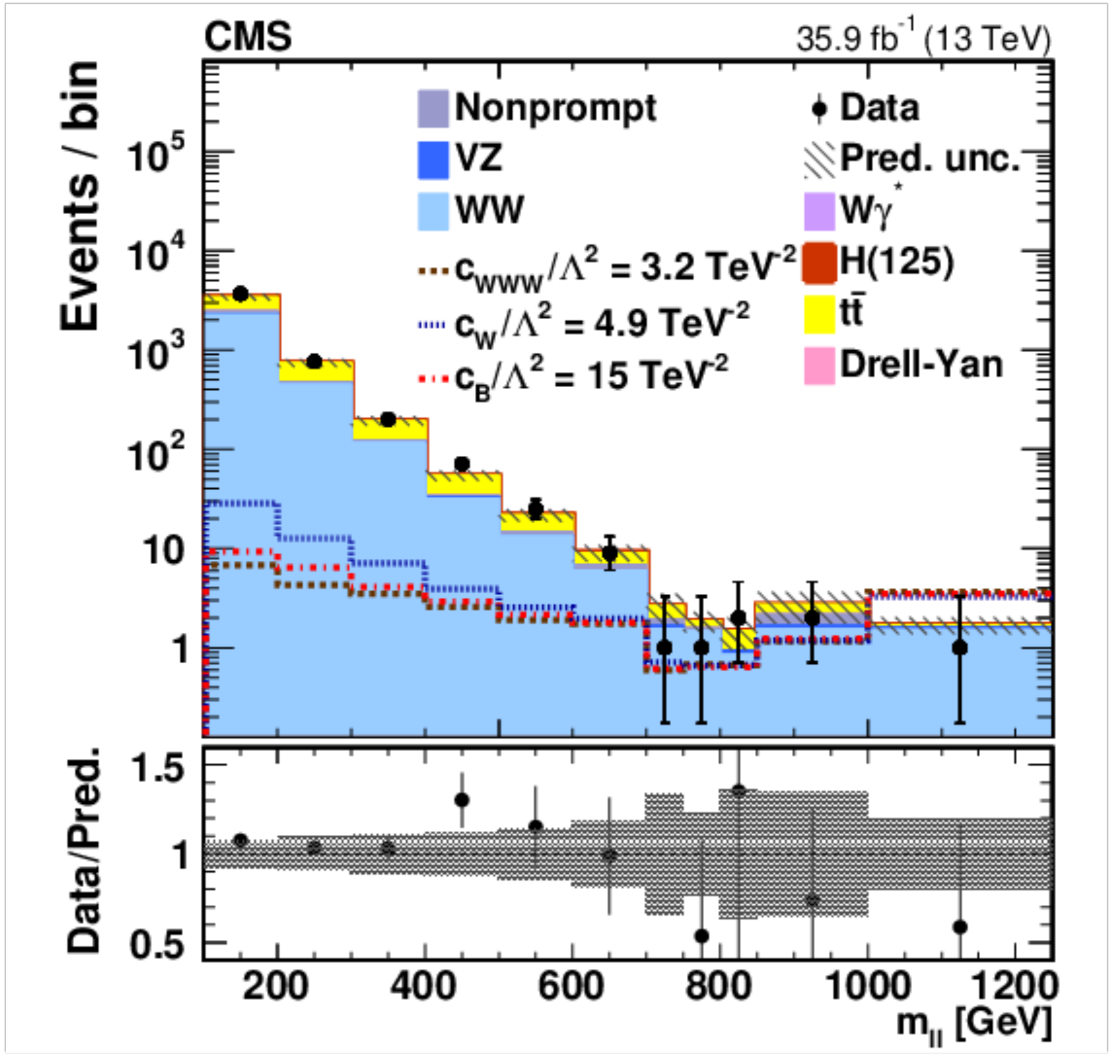


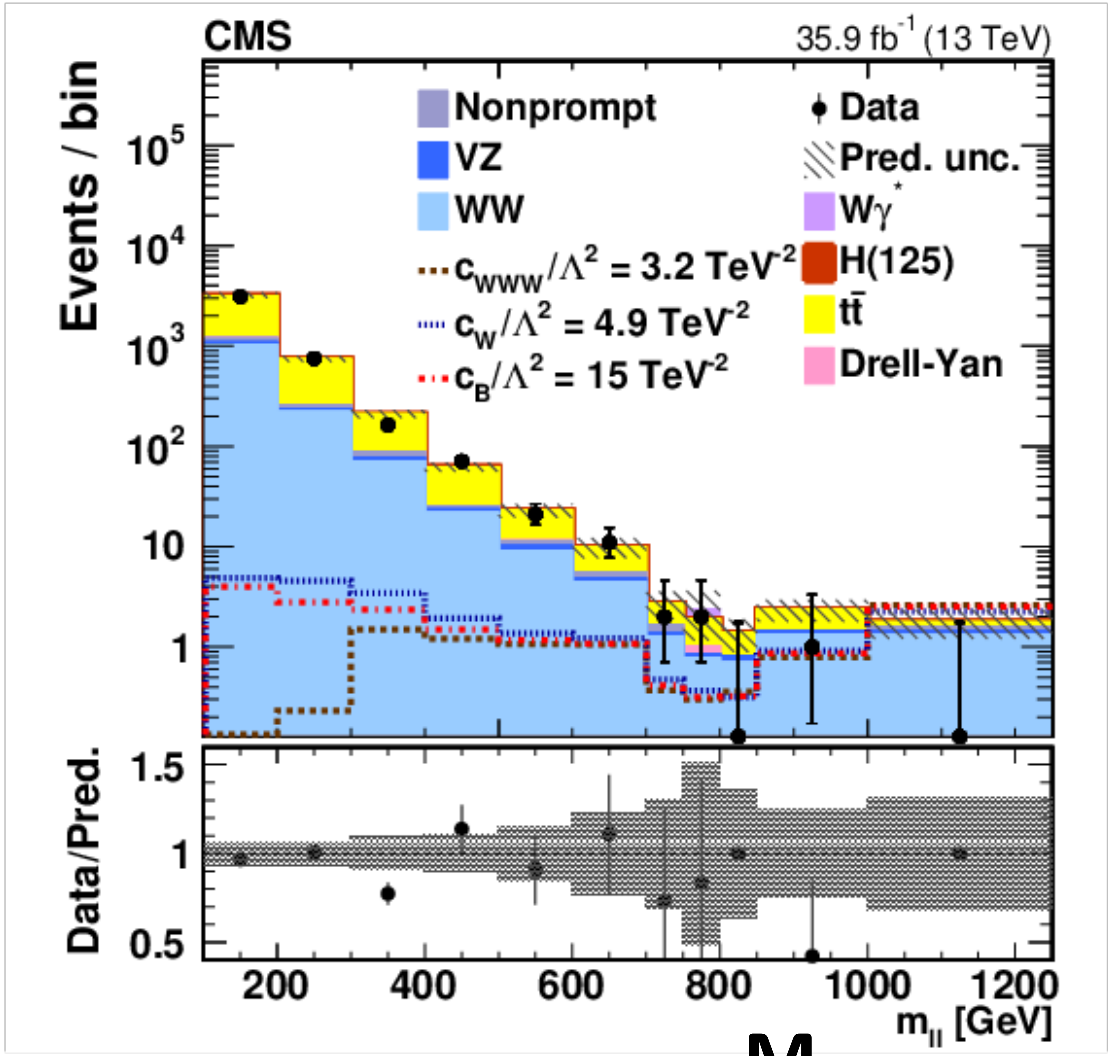
- relatively simple "cut-based" analysis
  - require one e and one μ, opposite signs
  - p_T^{miss}, avoid DY and apply b-veto
- pay attention to N_{jets}
  - separate events with N_{jets} = 0 and N_{jets} = 1
- many thousands of evets; sample purity around 45%
- cross section measurement precise to 6%
  - (in agreement with the SM, a minor issue back then)
- measure differential cross sections, including jet multiplicity
- use M(eμ) distribution for a dim-6 EFT study

CMS PRD 102 (2020) 092001

zero jets

one jet

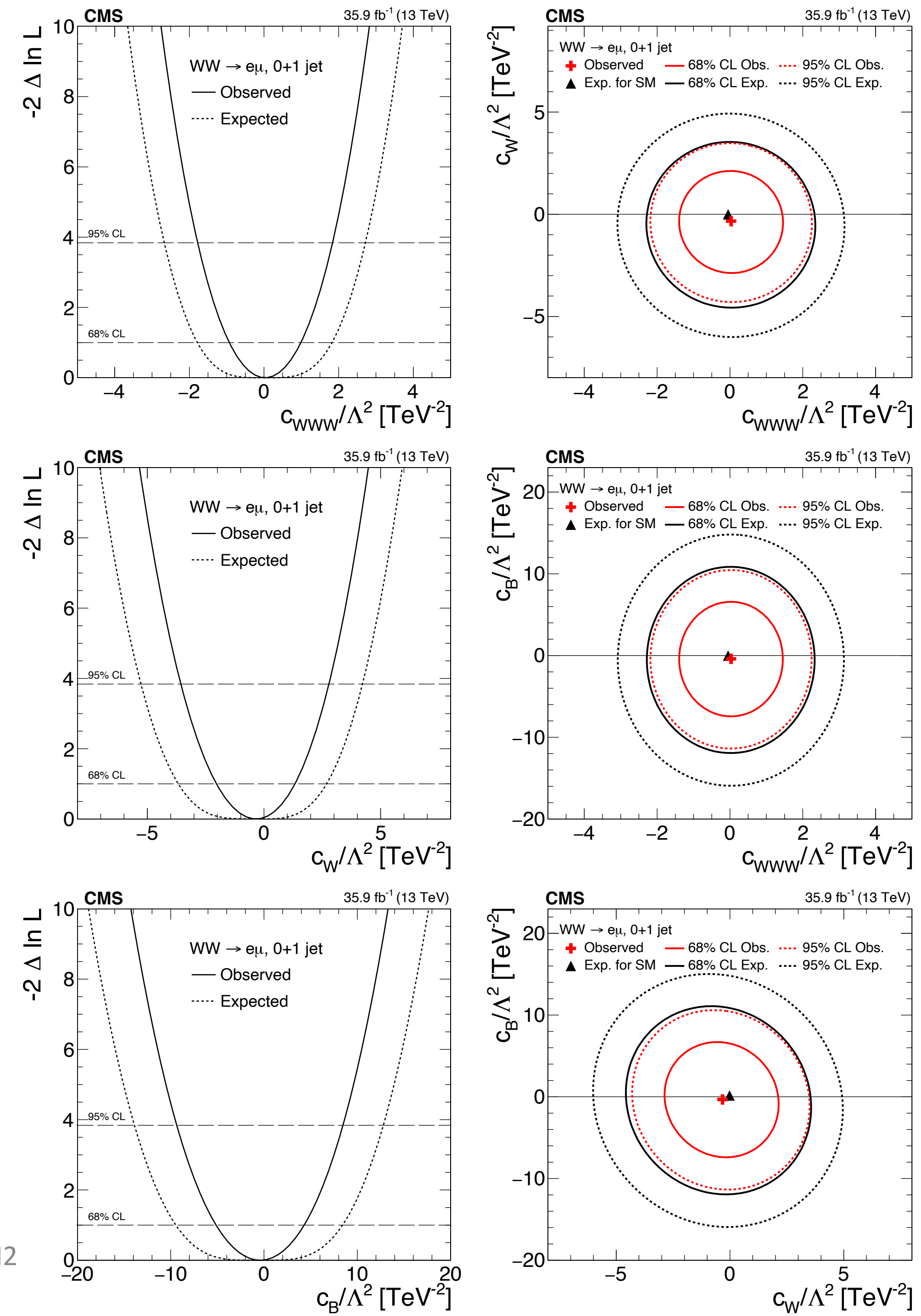




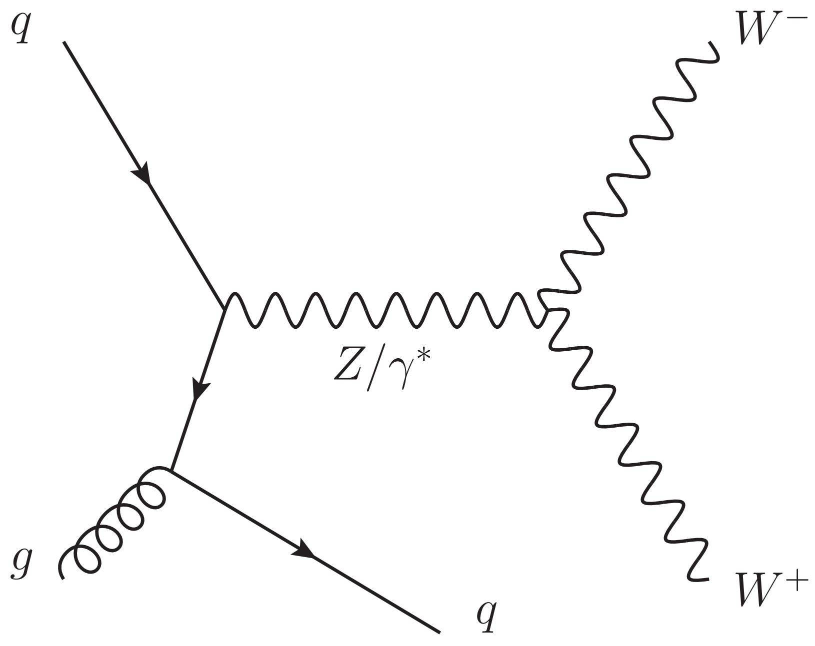
$M_{e\mu}$ $M_{e\mu}$

Coefficients (TeV^{-2})	68% confidence interval expected	68% confidence interval observed	95% confidence interval expected	95% confidence interval observed
c_{WWW}/Λ^2	$[-1.8, 1.8]$	$[-0.93, 0.99]$	$[-2.7, 2.7]$	$[-1.8, 1.8]$
c_W/Λ^2	$[-3.7, 2.7]$	$[-2.0, 1.3]$	$[-5.3, 4.2]$	$[-3.6, 2.8]$
c_B/Λ^2	$[-9.4, 8.4]$	$[-5.1, 4.3]$	$[-14, 13]$	$[-9.4, 8.5]$

Downward fluctuation leads to tighter constraints than expected.



ATLAS WW+j (2021)



This ATLAS analysis is similar to the CMS one:

Look at eμ final states.

There is a greater emphasis on the impact of jets on the interference term.

Analysis uses $m_{e\mu}$ separating events with zero jets, or at least one jet (p_T > 200 GeV).

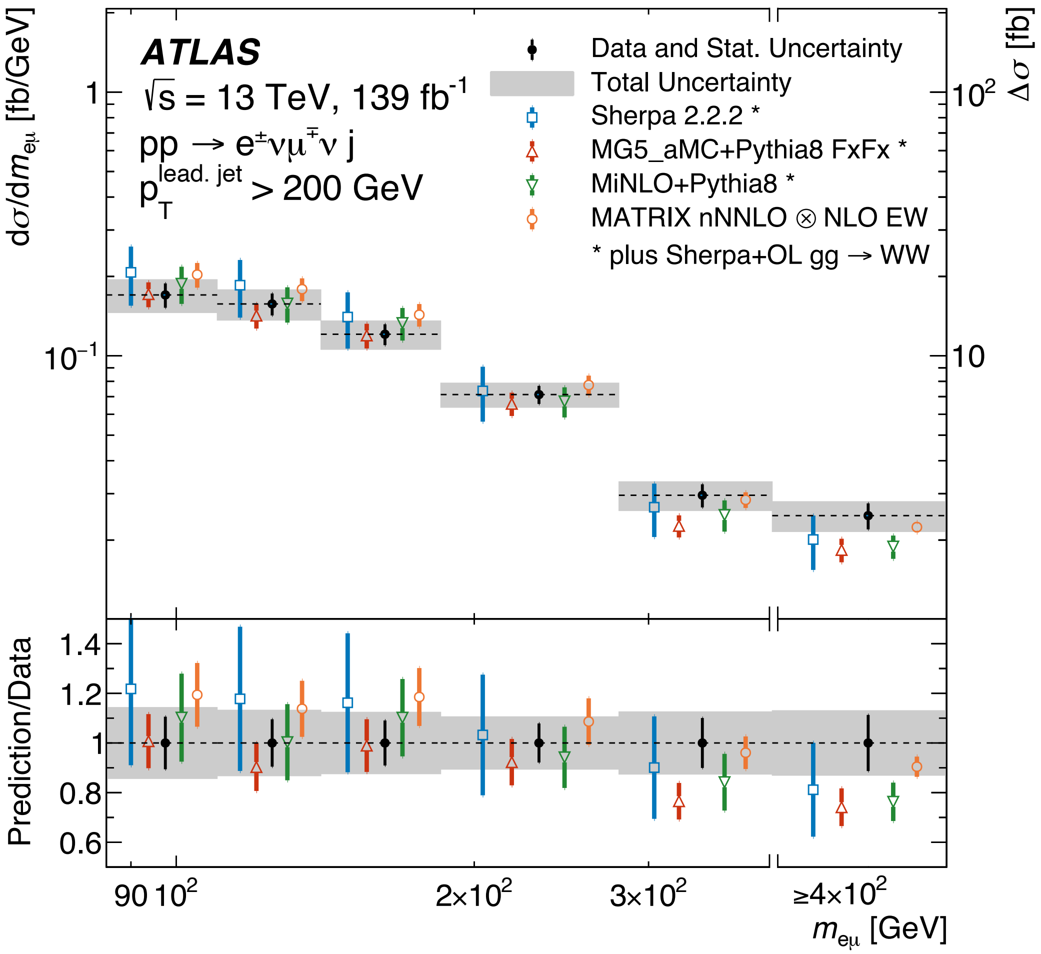
The latter shows enhanced sensitivity.

	$p_T^{\text{lead. lep.}} > 200\,\text{GeV}$	
Data	3873	
Total SM	3960 ± 120	
WW	1740 ± 50	44%
Total bkg.	2210 ± 110	56%
Top	1920 ± 90	49%
Drell–Yan	42 ± 6	1%
Fake leptons	70 ± 40	2%
$WZ, ZZ, V\gamma$	180 ± 40	4%

ATLAS JHEP06 (2021) 003

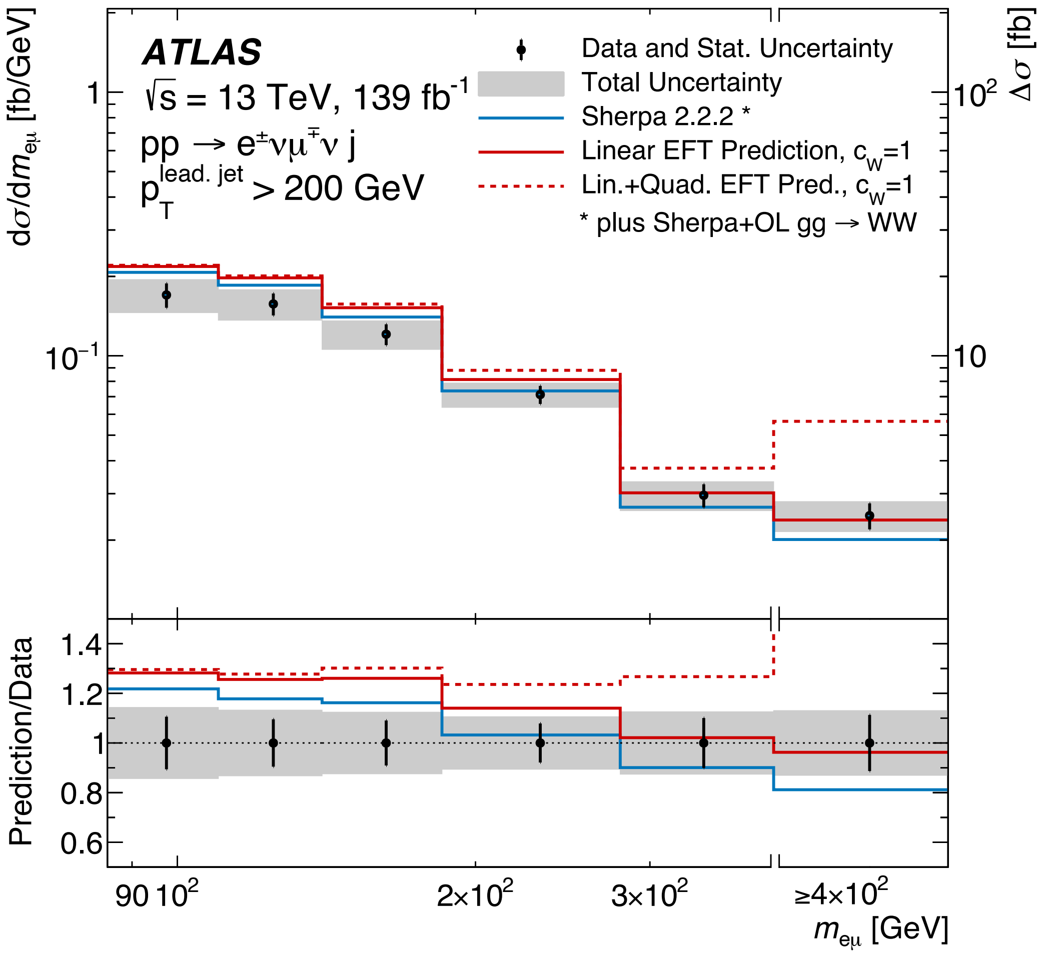
at least one jet p_T > 200 GeV

comparison to SM



$M_{e\mu}$

illustrate potential NP



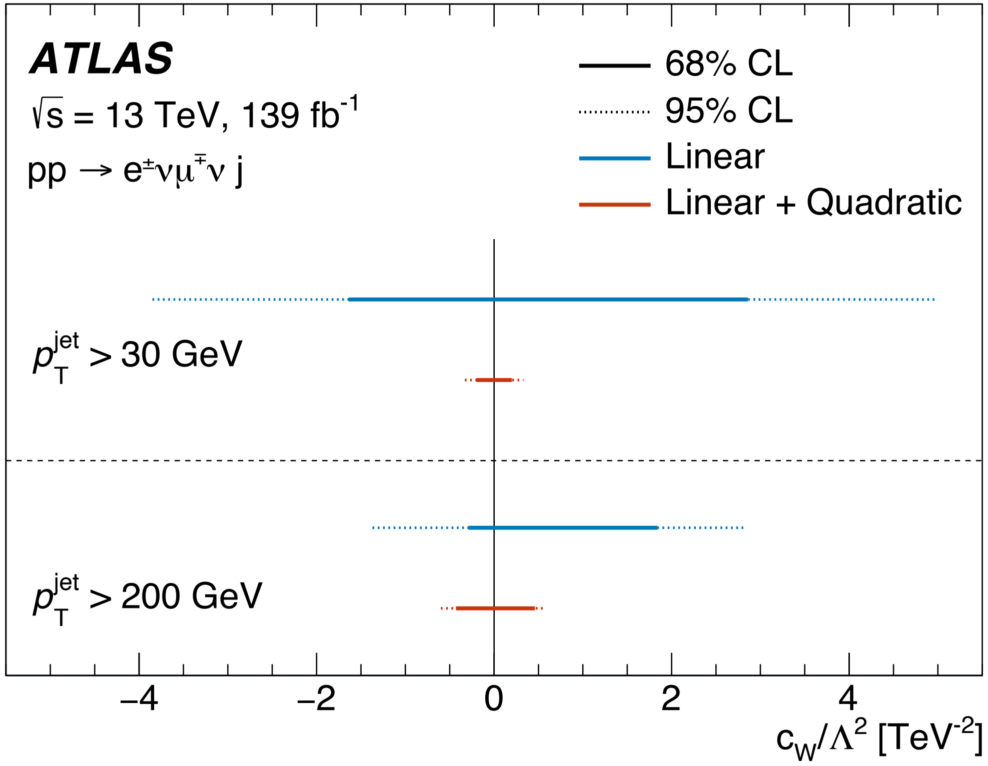
$M_{e\mu}$

ATLAS JHEP06 (2021) 003

Jet p_T	Linear only	68% CI obs.	95% CI obs.	68% CI exp.	95% CI exp.
> 30 GeV	yes	[–1.64, 2.86]	[–3.85, 4.97]	[–2.30, 2.27]	[–4.53, 4.41]
> 30 GeV	no	[–0.20, 0.20]	[–0.33, 0.33]	[–0.28, 0.27]	[–0.39, 0.38]
> 200 GeV	yes	[–0.29, 1.84]	[–1.37, 2.81]	[–1.12, 1.09]	[–2.24, 2.10]
> 200 GeV	no	[–0.43, 0.46]	[–0.60, 0.58]	[–0.38, 0.33]	[–0.53, 0.48]

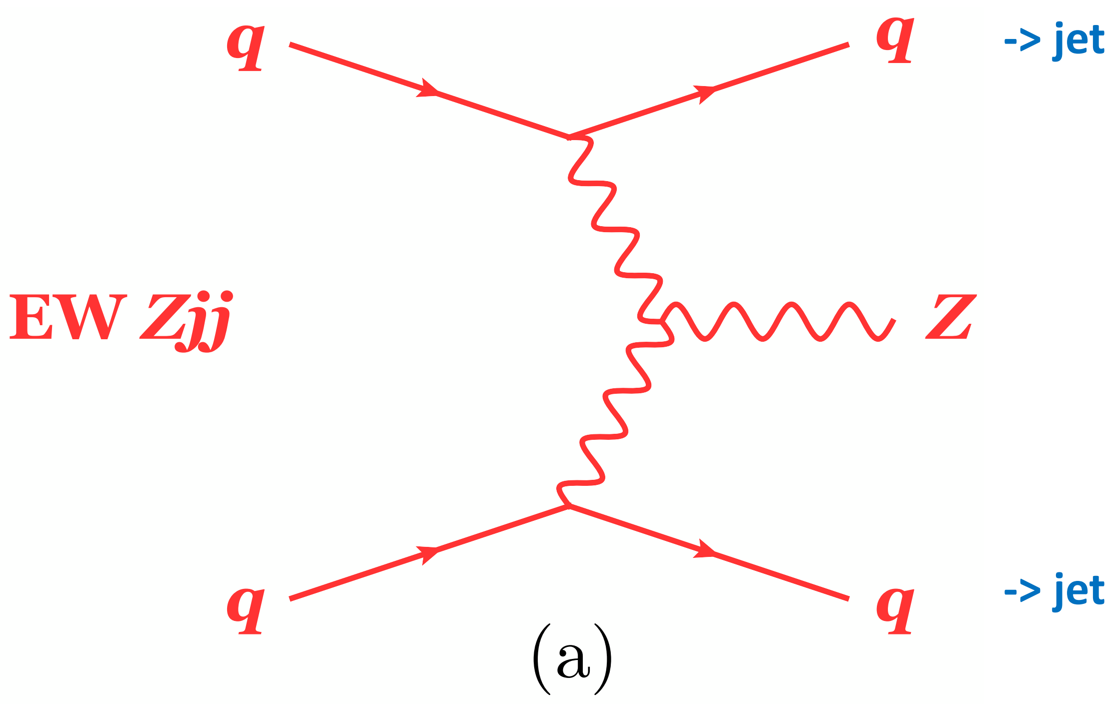
Requiring the jet reduces the suppression of the interference effects between SM and dim-8 operators.

Reduced suppression means greater sensitivity.



ATLAS Z+jj (2021)

ATLAS Eur. Phys. J. C (2021) 81



A different kind of process.
These jets are special – they are not ISR.

The two tagging jets change everything
This is not just plain Drell-Yan production.

The two energetic, high-mass, well-separated jets
enable ATLAS to study triple gauge couplings.

Event samples are large, enable detailed studies of this process.

Differential cross sections are measured, including the jet-jet signed azimuthal angle $\Delta\phi_{jj}$.

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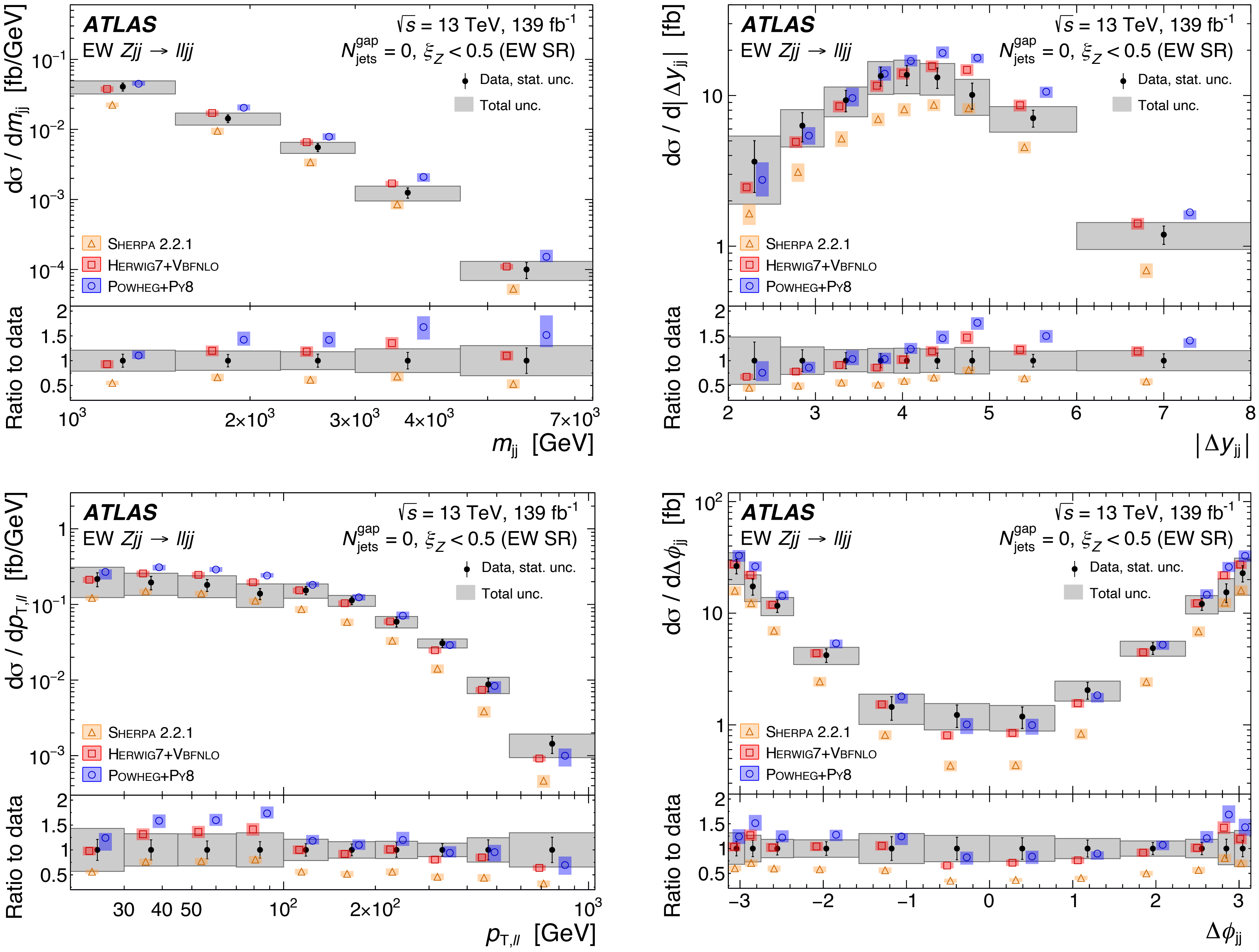
m_{jj}

$|\Delta y|_{jj}$

$p_{T,ll}$

$\Delta\phi_{jj}$



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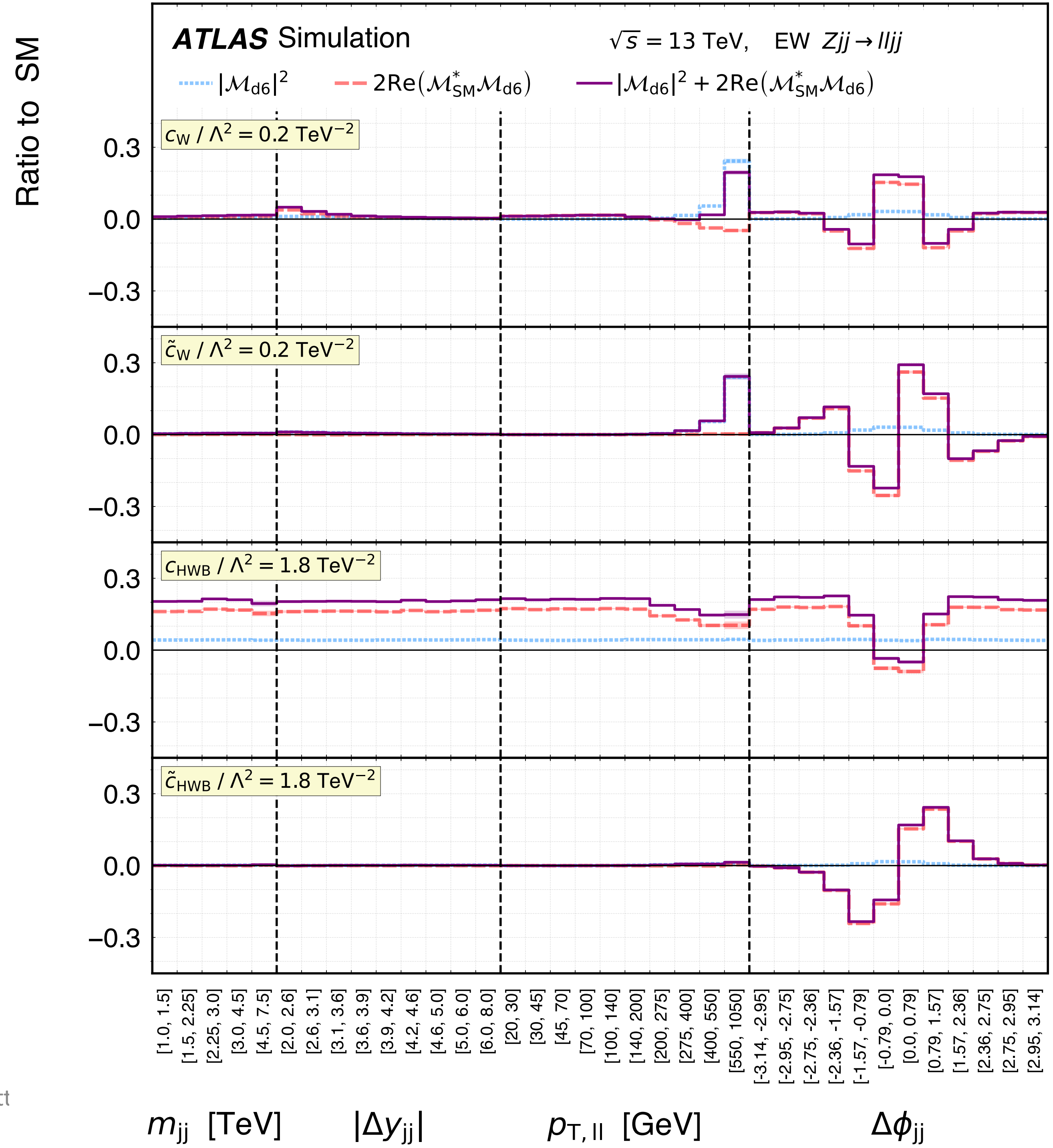
It turns out that these differential cross sections show tremendous sensitivity

Mainly through interference terms (which are linear in the W.C.)

Most interesting is angle $\Delta\phi_{jj}$.

$\Delta\phi_{jj} = \phi_f - \phi_b$ is signed according to $y_f > y_b$.



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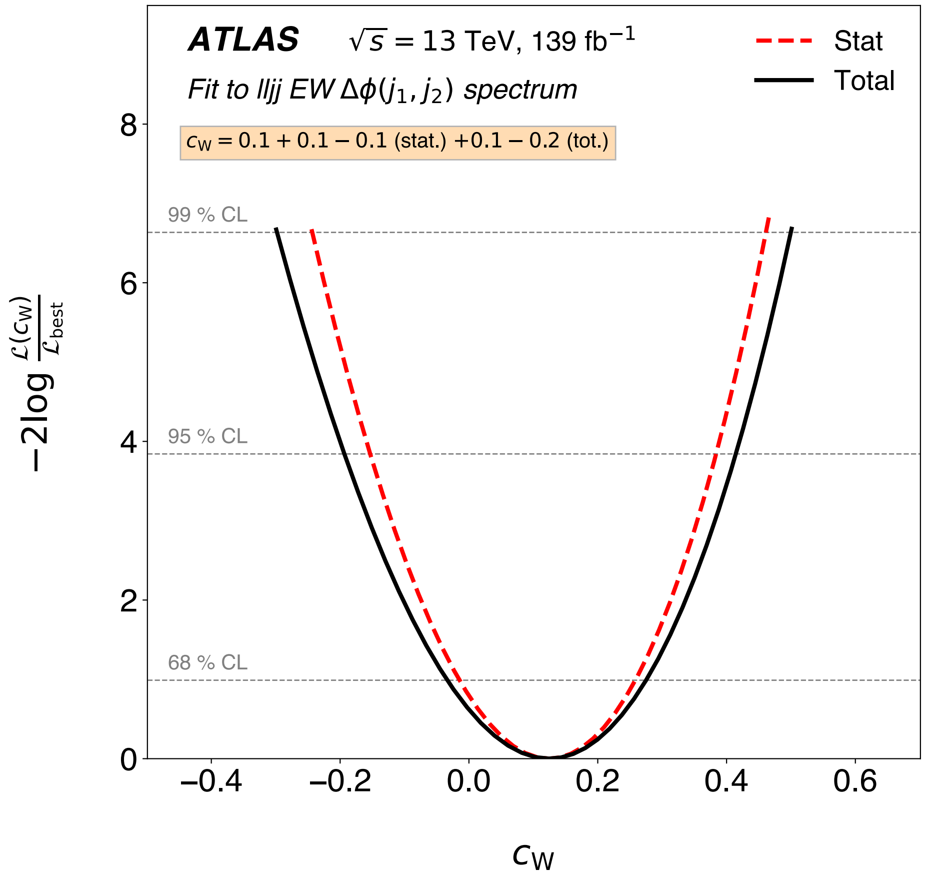
Bounds are very good even though there is only one boson in the final state.

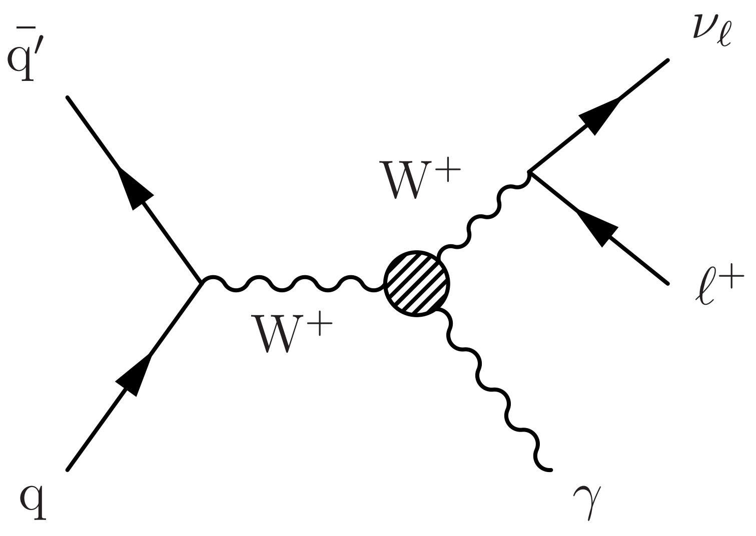


Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	$[-0.30,\ 0.30]$	$[-0.19,\ 0.41]$	45.9%
	yes	$[-0.31,\ 0.29]$	$[-0.19,\ 0.41]$	43.2%
$\tilde{c}_W/\Lambda^2$	no	$[-0.12,\ 0.12]$	$[-0.11,\ 0.14]$	82.0%
	yes	$[-0.12,\ 0.12]$	$[-0.11,\ 0.14]$	81.8%
c_{HWB}/Λ^2	no	$[-2.45,\ 2.45]$	$[-3.78,\ 1.13]$	29.0%
	yes	$[-3.11,\ 2.10]$	$[-6.31,\ 1.01]$	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	$[-1.06,\ 1.06]$	$[0.23,\ 2.34]$	1.7%
	yes	$[-1.06,\ 1.06]$	$[0.23,\ 2.35]$	1.6%

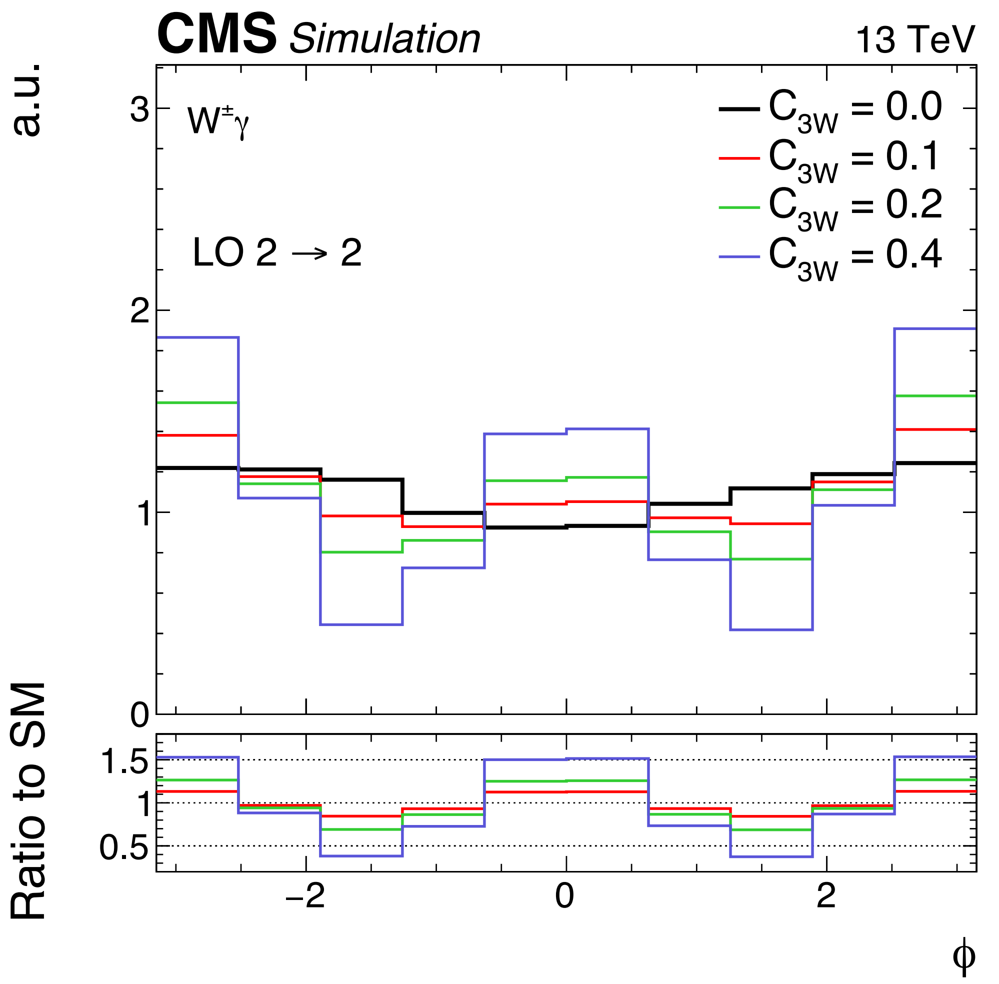
CMS PRD 105 (2022) 052003

CMS Wγ (2022)

CMS PRD 105 (2022) 052003



Not VBF – just Wγ production.
Similar to W^+W^- production though jets play no special role.



lepton azimuthal angle in the Wγ rest frame

As indicated in the ATLAS Zjj analysis, use of angular distributions greatly increases the sensitivity of the interference term.

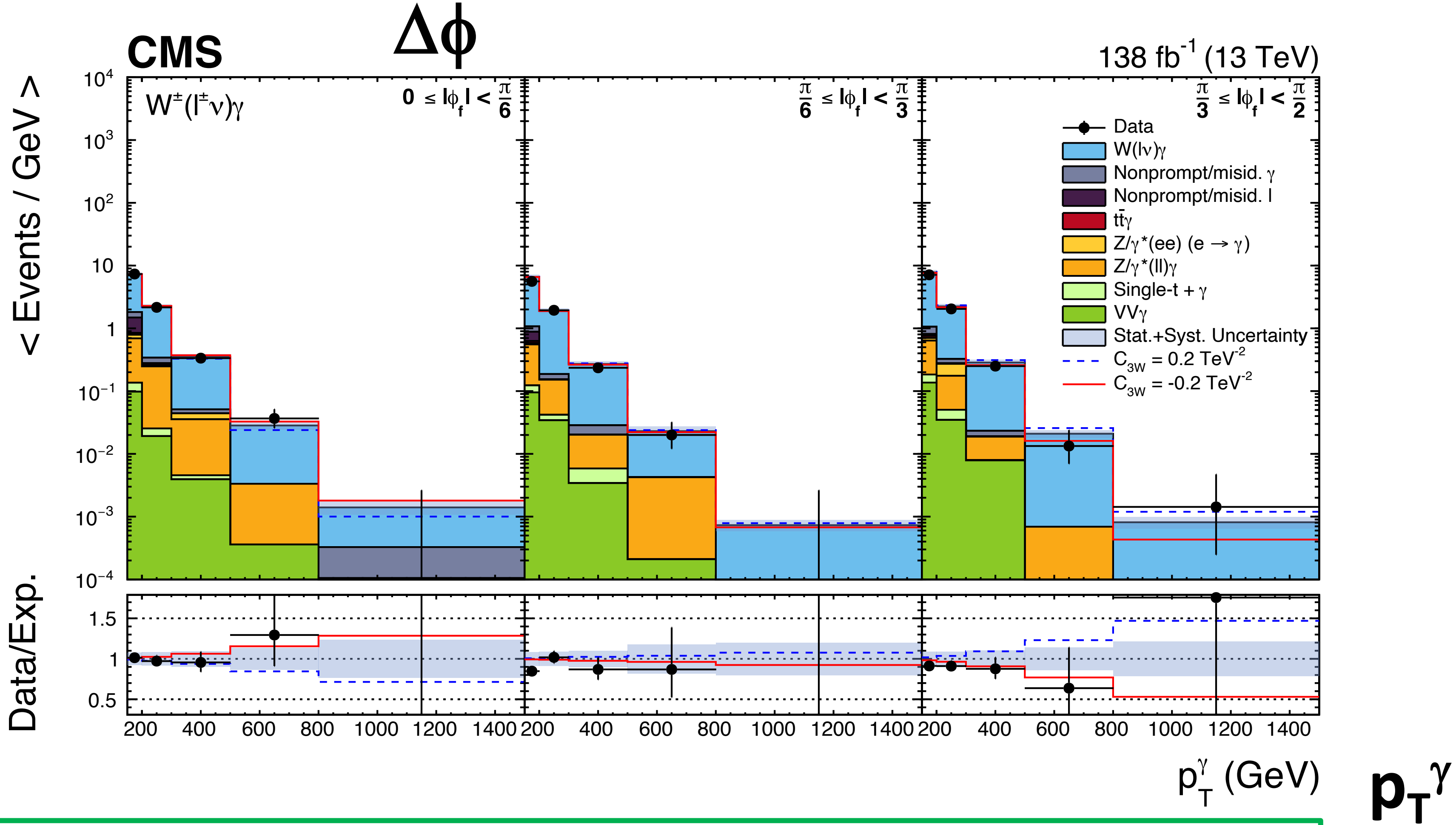
“interference resurrection” - potent

CMS PRD 105 (2022) 052003

tour de force paper
several interesting
measurements

focus on EFT part

fit to p_T^γ , $\Delta\phi$ grid



Exceptionally strong limits, thanks to the boosted sensitivity of the interference term:

Expect [-0.066,0.065] Observe [-0.062,0.052] at 95% CL

We will say more about these limits later.

Summary and Comparison of dim-6 bounds

CMS WW 0/1 jet (2020)

cW	exp [-5.3,4.2]	obs [-3.6,2.8]	baseline

ATLAS WW+1j (2021)

cW	exp [-0.39,0.38]	obs [-0.33,0.33]	+1 jet reduces the reduction

ATLAS Z+jj (2021)

cW	exp [-0.31,0.29]	obs [-0.19,0.41]	$\Delta\phi_{jj}$ makes a big differene

CMS Wγ (2022)

c3W	exp [-0.066,0.065]	obs [-0.062,0.052]	interference resurrection

2. attempts to deal with unitarity violation

Common viewpoint: the Wilson expansion used in EFTs is similar in spirit to a Taylor expansion (in s).

New physics (think: new resonances) at a higher energy scale Lambda.
Below Lambda, hope to see indirect evidence of New Physics in relevant kinematic distributions.
The expansion will be accurate only over a limited range of s and is best when the differential cross section does not vary rapidly.
Clearly, not a good approach at the scale Λ, where one expects peaking structures!

A truncated EFT expansion is not renormalizable and violates unitarity at some energy scale.
What action should we take?

1. Do nothing.
2. Report the unitarity bound
3. Clipping: zero-out the NP contribution above cutoff Ec (but keep SM contribution).
4. Censor data at high energy.

CMS 2212.12592

CMS $W\gamma$+2j (2023)

CMS 2212.12592

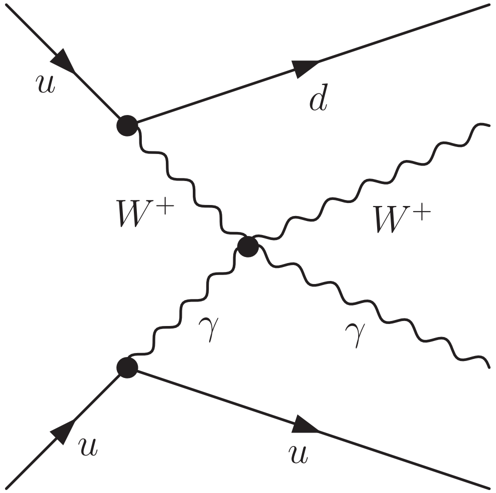
This new analysis is sensitive to quartic couplings.

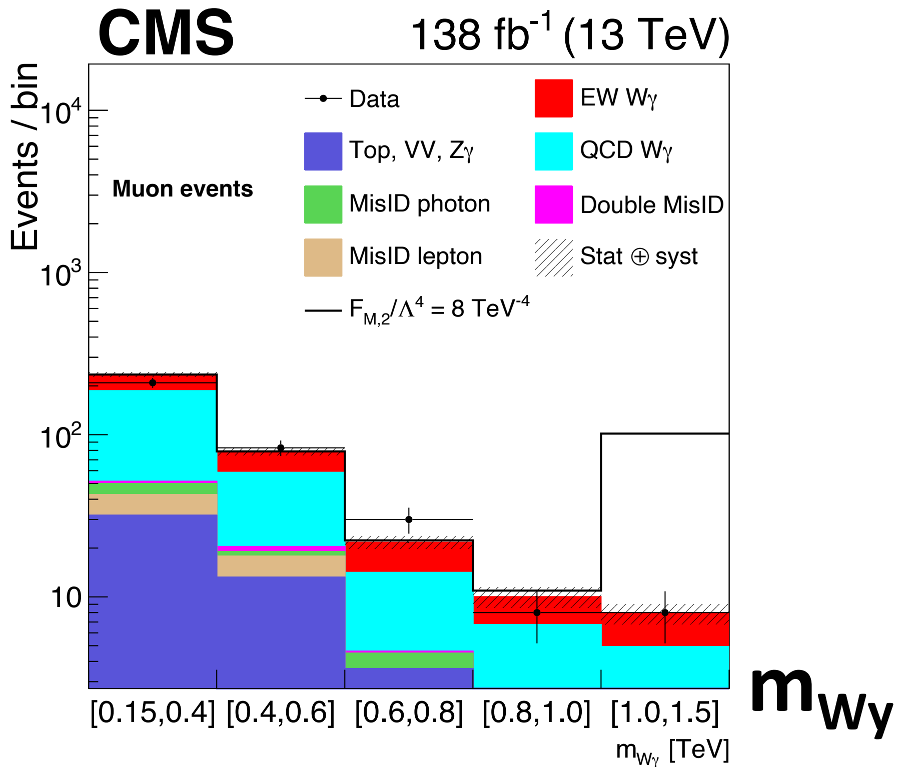
Hence, the focus is on dim-8 operators and coefficients.
(We'll return to the question of dim-6 operators.)

This pair of jets is special: m_{jj} is high, and they are separated in rapidity.

The presence of the two jets is crucial (similar to Zjj) this is vector boson scattering, not just Wγ production.

Use $m_{W\gamma}$ as the sensitive variable.

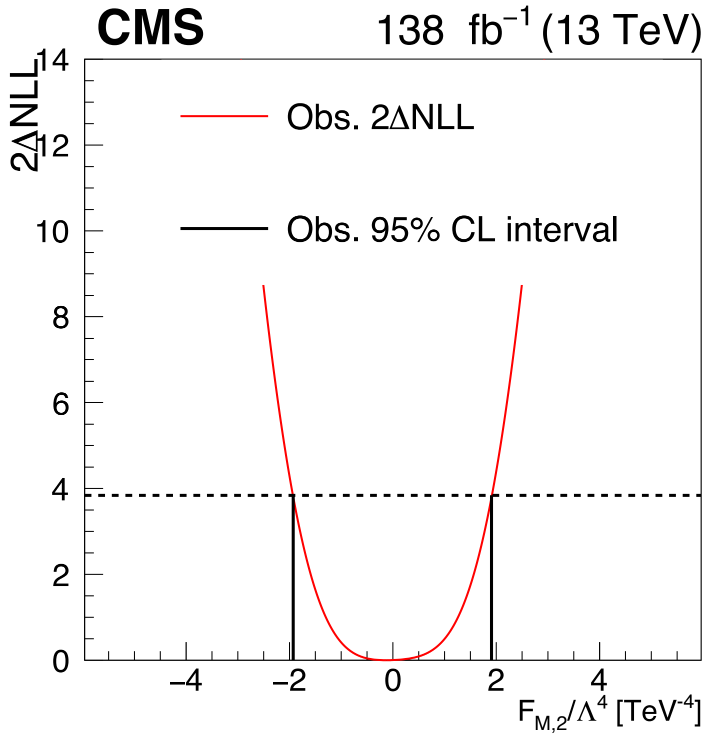




CMS 2212.12592

Example: reporting the unitary bound

Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M,4}/\Lambda^4 < 3.3$	$-3.7 < f_{M,4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M,5}/\Lambda^4 < 3.6$	$-3.9 < f_{M,5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M,7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T,0}/\Lambda^4 < 0.51$	$-0.47 < f_{T,0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T,1}/\Lambda^4 < 0.31$	$-0.31 < f_{T,1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T,2}/\Lambda^4 < 0.92$	$-0.85 < f_{T,2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T,5}/\Lambda^4 < 0.31$	$-0.31 < f_{T,5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T,6}/\Lambda^4 < 0.25$	$-0.25 < f_{T,6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T,7}/\Lambda^4 < 0.68$	$-0.67 < f_{T,7}/\Lambda^4 < 0.73$	3.1



This approach is simple and straight forward.

U_{bound} is like a warning: above this energy the theory is in trouble.

It does not tell us about any impact on W.C.

nice constraints on $f_{T,I}$ for i=0,1,2,5,6,7.

ATLAS Eur. Phys. J. C 83 (2023) 539

ATLAS $Z\gamma\gamma$ (2021)

ATLAS Eur. Phys. J. C 83 (2023) 539

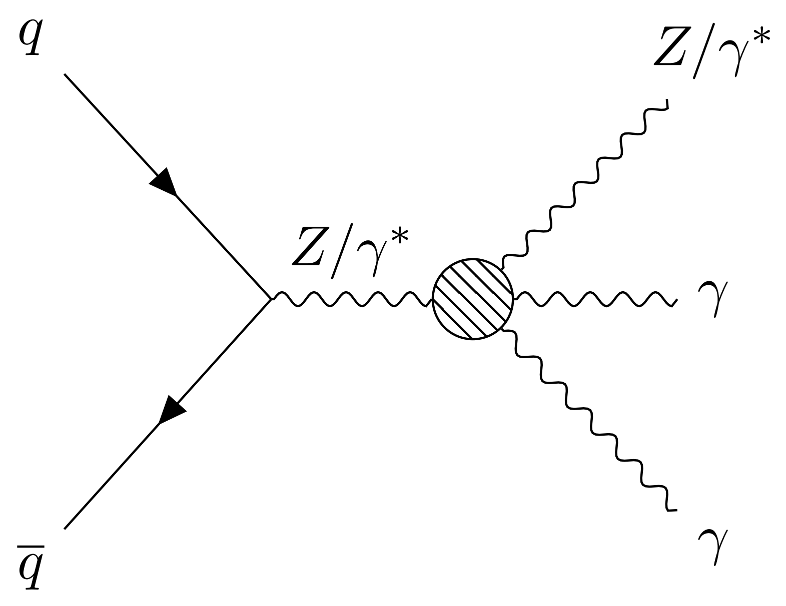
Example of "clipping"

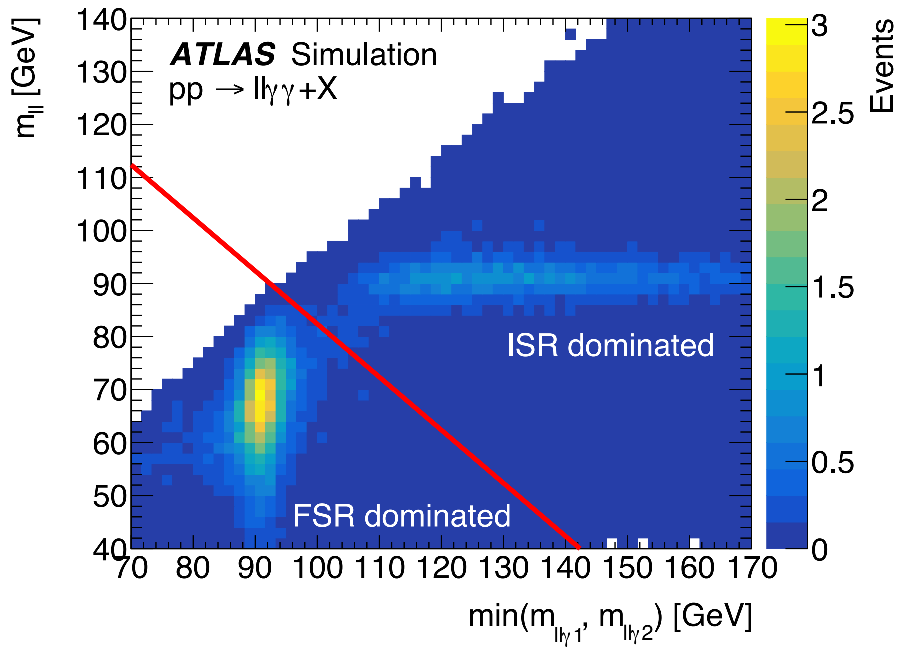
Choose an arbitrary energy cutoff $E_{c.}$

Above that cutoff, zero-out the non-SM contribution (both the pure BSM quadratic part and the interference term) and retain the SM part only.

High-energy data are not discarded but they do not contribute to the bounds.

Compute bounds as a function of E_c.





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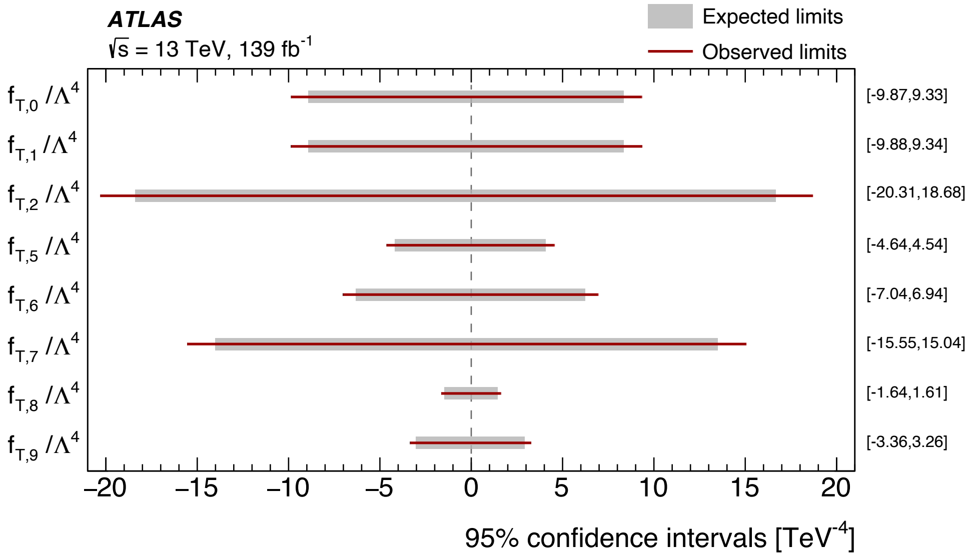
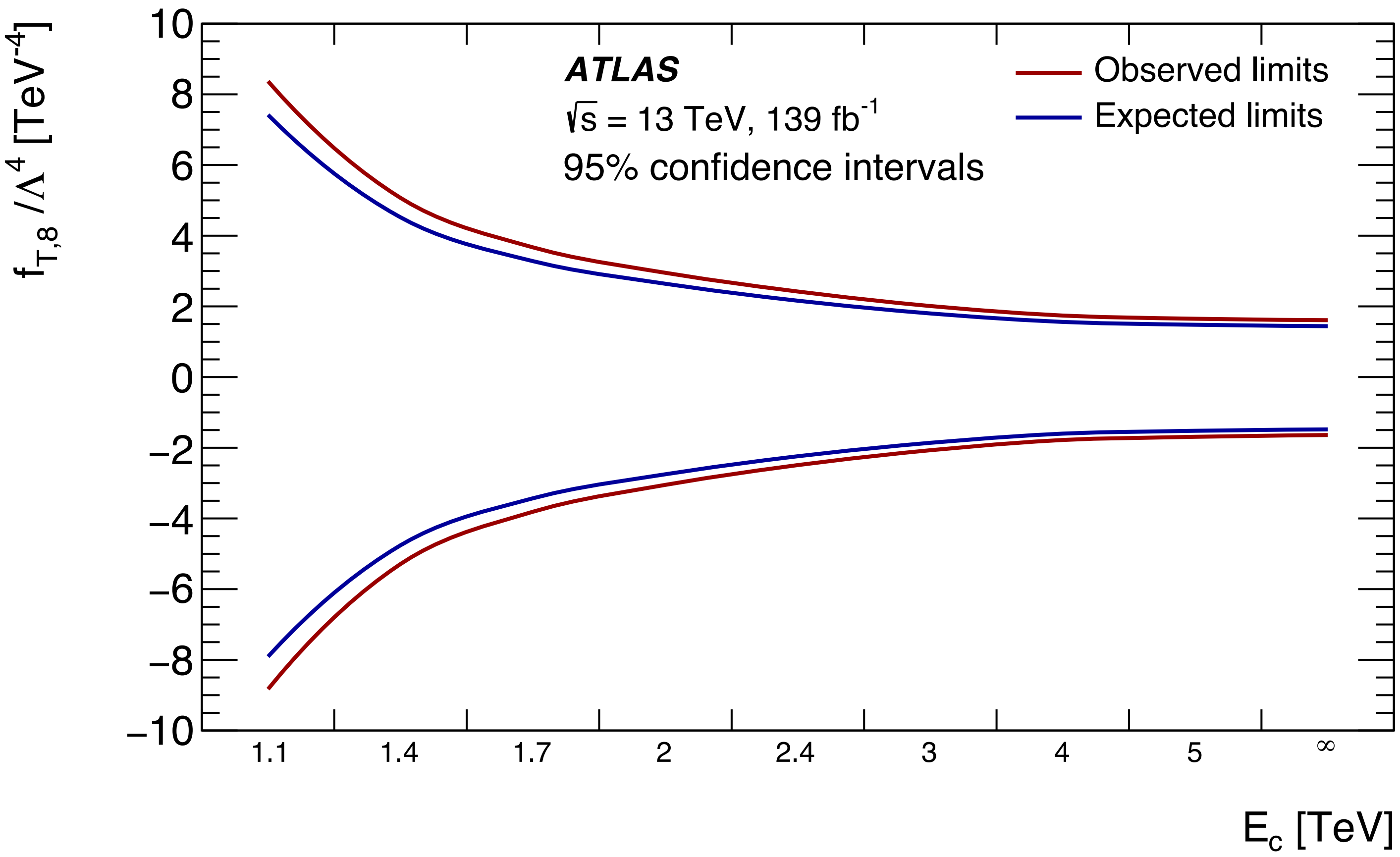
Example of "clipping"





Naturally, bounds on W.C. weaken when much of the NP at high energies is zeroed out.

Several analyses in ATLAS and CMS use this technique. This is a recent example.

CMS PRD 105 (2022) 052003

CMS Wγ (2022)

discussed earlier

CMS PRD 105 (2022) 052003

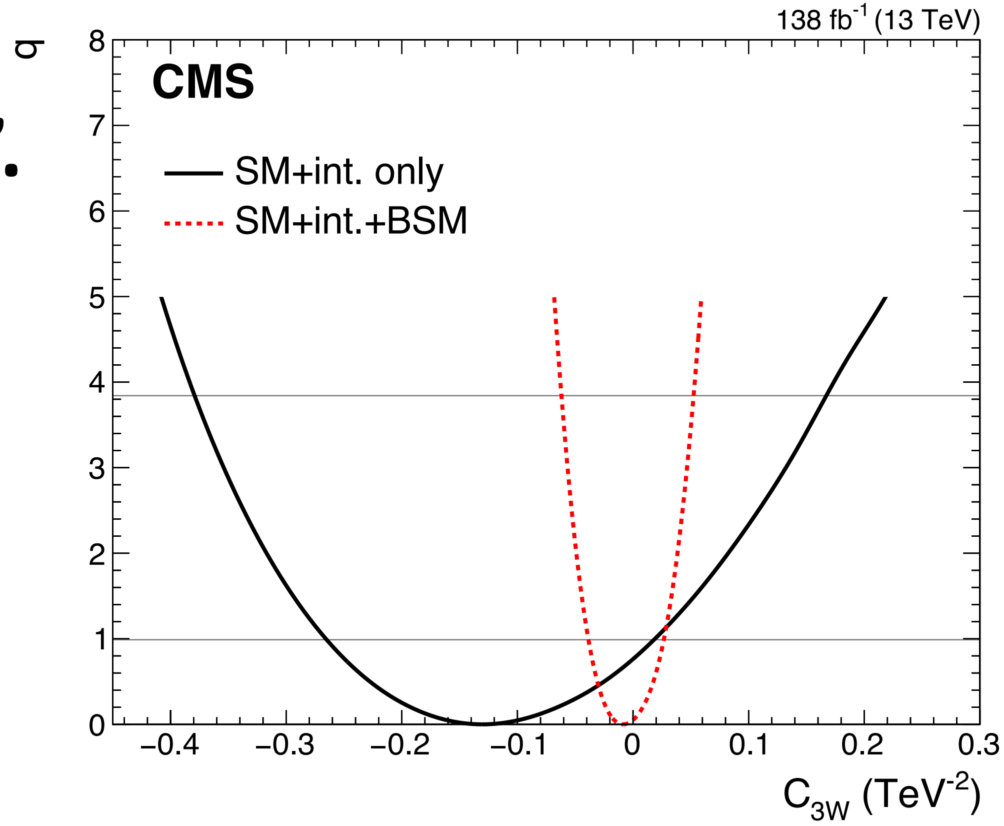
Example of "dropping the quadratic term".

The interference term is linear in the W.C.
and is the leading $1/\Lambda^2$ term.

$$\begin{aligned} \left|M_{\rm SM} + cM_{\rm NP}\right|^2 &= \left|M_{\rm SM}\right|^2 + 2c\,\Re\left[M_{\rm SM}M_{\rm NP}^*\right] + c^2\left|M_{\rm NP}\right|^2 \\ &= {\rm SM} + {\rm linear} + {\rm quadratic} \end{aligned}$$

Trouble enters with the quadratic term,
especially when the W.C. "c" is not small.

The growth at high s is associated with the quadratic term (b/c the linear term cannot be large where the SM term vanishes).



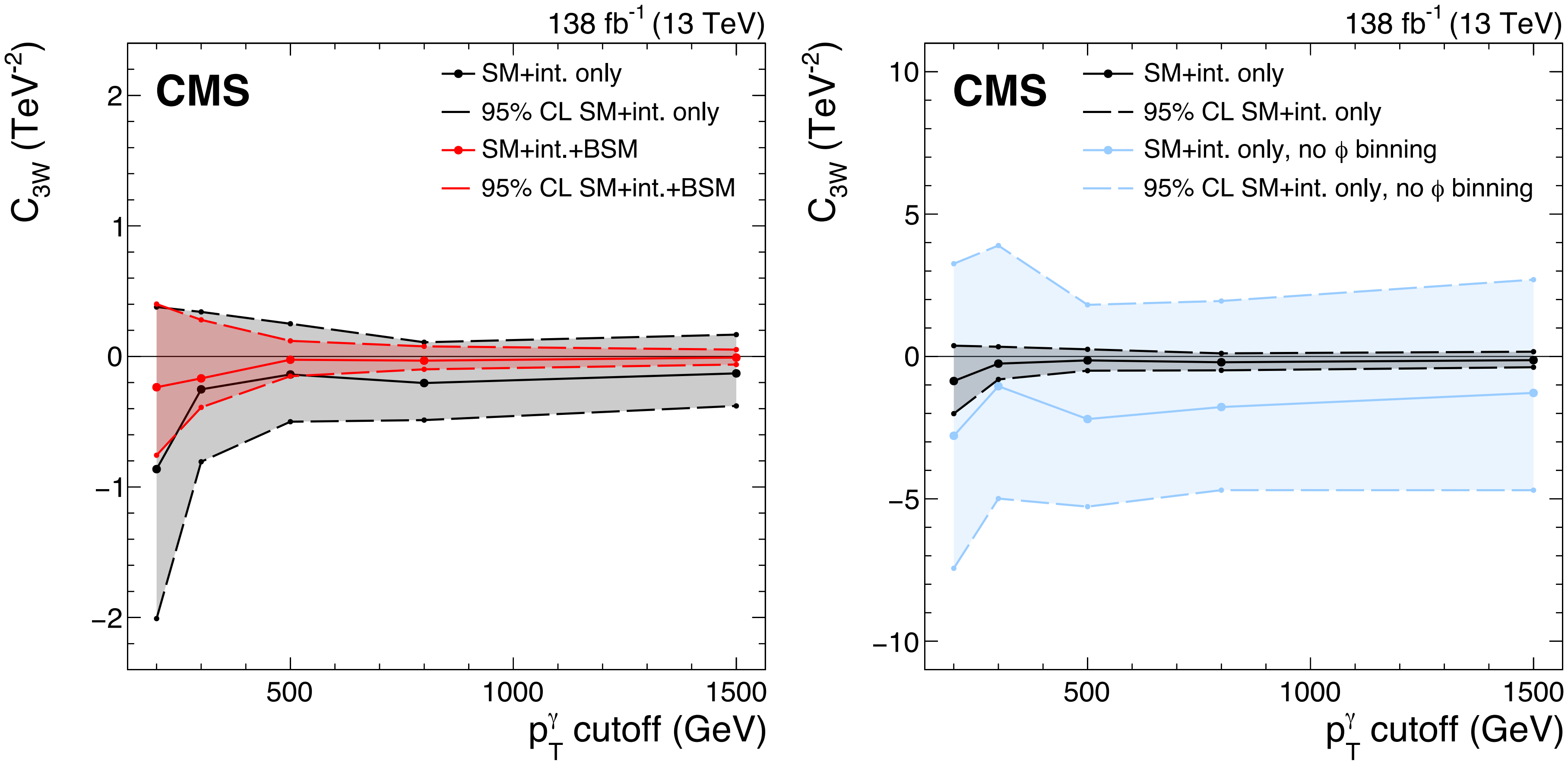
Several analyses in ATLAS and CMS use this technique. This is one example.

Approach: remove the quadratic terms from the likelihood (i.e., set the "pure BSM" term to zero, by hand) and derive new bounds on the W.C.

Another approach: **censor data which is too high in energy.**

These data cannot be explained by the theory (because it breaks down at those energies) so remove them from the analysis.

p_T^{γ} cutoff is an upper bound



This paper shows both the impact of

- dropping the quadratic term
- censoring data

p_T^γ cutoff (GeV)	Best fit C_{3W} (TeV^{-2})		Observed 95% CL (TeV^{-2})		Expected 95% CL (TeV^{-2})	
	SM+int. only	SM+int.+BSM	SM+int. only	SM+int.+BSM	SM+int. only	SM+int.+BSM
200	−0.86	−0.24	[−2.01, 0.38]	[−0.76, 0.40]	[−1.16, 1.27]	[−0.81, 0.71]
300	−0.25	−0.17	[−0.81, 0.34]	[−0.39, 0.28]	[−0.56, 0.60]	[−0.33, 0.33]
500	−0.13	−0.025	[−0.50, 0.25]	[−0.15, 0.12]	[−0.35, 0.38]	[−0.17, 0.16]
800	−0.20	−0.033	[−0.49, 0.11]	[−0.10, 0.08]	[−0.29, 0.31]	[−0.097, 0.095]
1500	−0.13	−0.009	[−0.38, 0.17]	[−0.062, 0.052]	[−0.27, 0.29]	[−0.066, 0.065]

Summary:

- Unitarity violation is a conundrum.
- It occurs at relatively “low” energies – typically between 1 and 2 TeV.
- Events above this energy cannot really be understood on the basis of a simple EFT.
- Dropping the quadratic term provides a sense of the problem:
  - Analyses which rely mainly on the interference term are OK
  - Analyses which rely mainly on the quadratic, “pure BSM” term are not
- Of course, we don’t want to prohibit analyses that could discover new physics at high mass scales – this is the essence of the LHC!
- Censoring data may seem logical, but it is hard to stomach.
- Is it time to bring back dipole form factors?
  - study how W.C. bounds change as a function of the dipole parameter

3. setting bounds on dim-8 when dim-6 is unknown

What should we do with quartic couplings (cf. VBS, VVV production)?
These are uniquely impacted by dim-8 operators.
Naturally, analyses seek to place bounds on dim-8 W.C.

But dim-6 operators can impact these same processes, and
generally one expects dim-6 terms ($\sim 1/\Lambda^2$) to be larger than dim-8 ($\sim 1/\Lambda^4$).

So far, analyzers evoke existing bounds on dim-6 W.C. coming from VV production, etc.,
and set dim-6 terms to zero. (We saw this in the CMS Wγ analysis above, but it is common).
Furthermore, VBS and VVV production tend to have limited sensitivity to dim-6 operators
(so they cannot themselves rule out dim-6 terms).

I suspect individual analysis are insufficient to constrain dim-6 and dim-8 simultaneously.

Is there a better way?

Perhaps dim-6 terms could be constrained by a prior tuned with a parameter α.
One would study how the derived bounds on dim-8 depended on α.
This is somewhat similar to clipping that we discussed earlier.

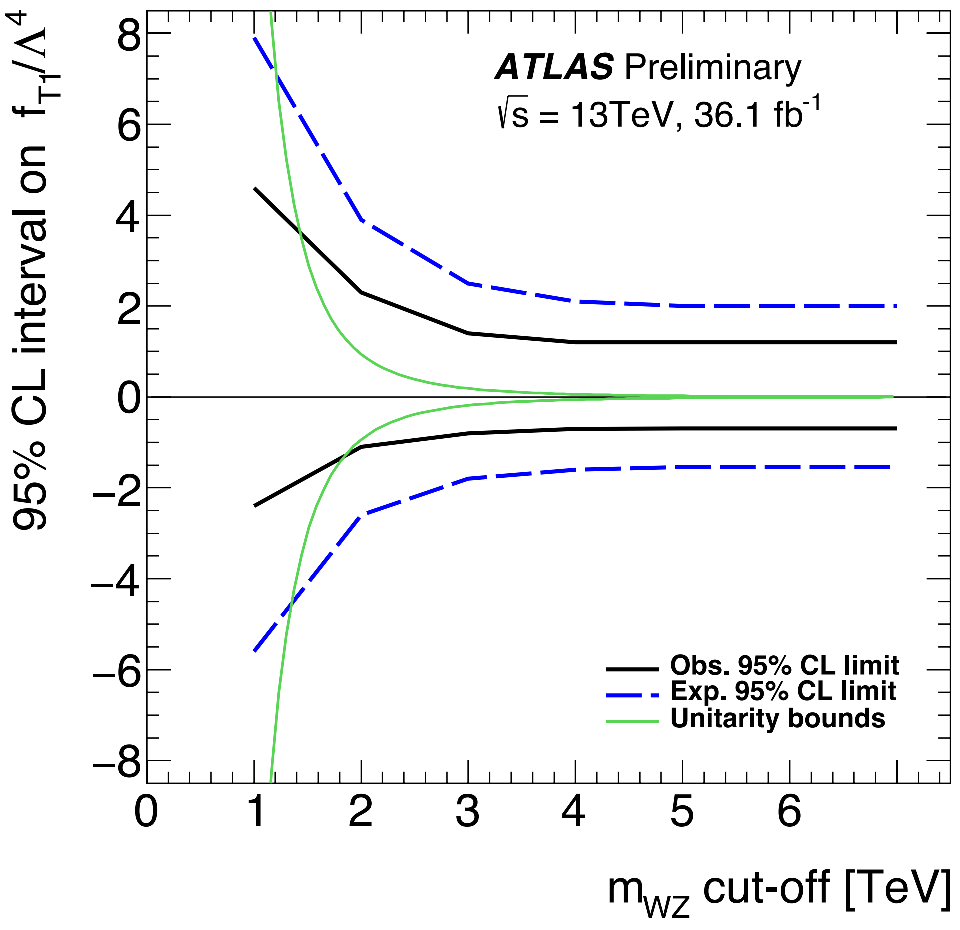
(Comment: this problem seems to me to be morally equivalent to the practice of deriving 1D bounds, ie, setting all coefficients to zero but one, and allowing that one coefficient alone to be constrained by the data.)

On the longer term, a better way is to build a global combined analysis that takes all experimental results into account.
Let VV production constrain dim-6 while VBS, VVV production constrain dim-8.

ATL-PHYS-PUB-2023-002

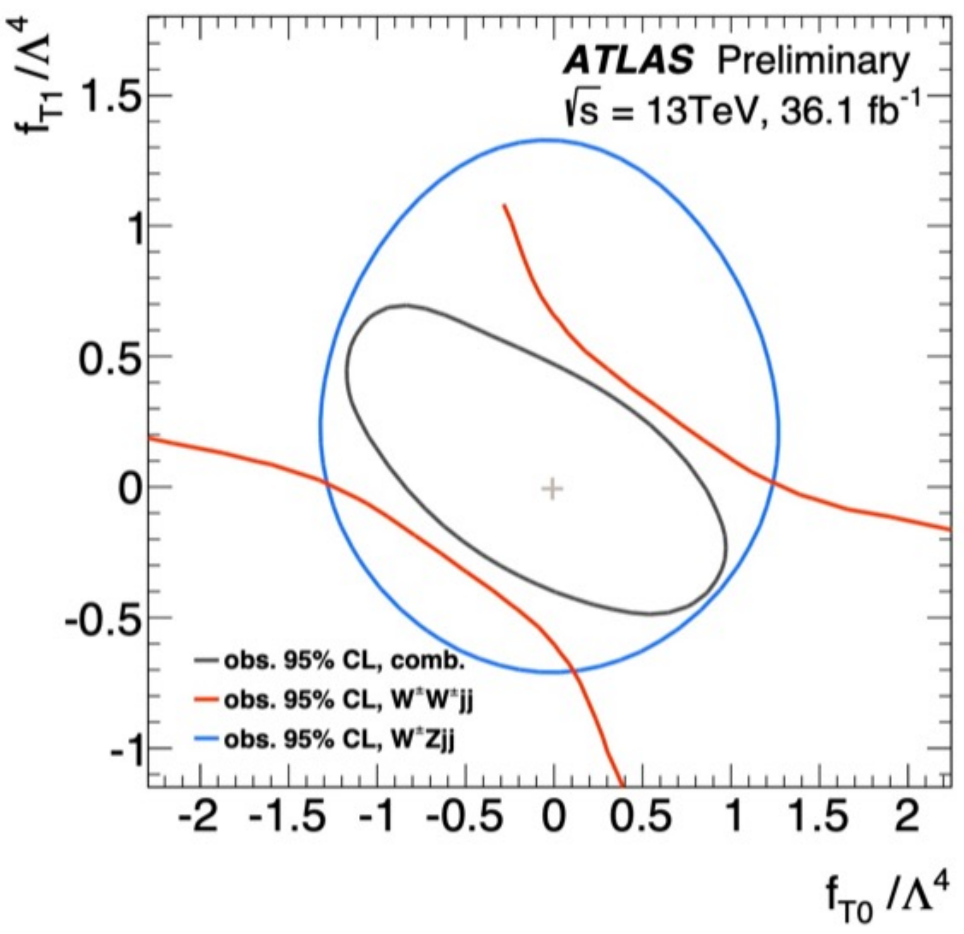
ATLAS combined ssWWjj & WZjj reinterpretation (2023)

Fit to m_{ll} in WWjj channel
fit to m_T(WZ) in WZjj channel.



WZ helps to close off flat directions.

(no unitarization applied)



ATL-PHYS-PUB-2023-002

no unitarization

	Observed ($W^\pm Zjj$) (TeV^{-4})	Expected ($W^\pm Zjj$) (TeV^{-4})	Observed ($W^\pm W^\pm jj$) (TeV^{-4})	Expected ($W^\pm W^\pm jj$) (TeV^{-4})	Combined Observed (TeV^{-4})	Combined Expected (TeV^{-4})
f_{S0}/Λ^4	[-20, 31]	[-43, 56]	[-16, 16]	[-14, 14]	[-13, 15]	[-14, 14]
f_{S1}/Λ^4	[-72, 72]	[-142, 141]	[-62, 63]	[-53, 55]	[-52, 53]	[-53, 54]
f_{T0}/Λ^4	[-1.3, 1.26]	[-2.5, 2.5]	[-1.1, 1.1]	[-0.94, 0.98]	[-0.92, 0.92]	[-0.93, 0.96]
f_{T1}/Λ^4	[-0.7, 1.2]	[-1.5, 2.0]	[-0.52, 0.54]	[-0.44, 0.48]	[-0.43, 0.52]	[-0.44, 0.48]
f_{T2}/Λ^4	[-2.7, 2.4]	[-5.2, 4.9]	[-1.7, 1.8]	[-1.4, 1.6]	[-1.53, 1.58]	[-1.39, 1.58]
f_{M0}/Λ^4	[-13, 13]	[-26, 26]	[-12, 12]	[-10, 10]	[-9.9, 10]	[-10, 10]
f_{M1}/Λ^4	[-20, 20]	[-40, 40]	[-18, 19]	[-15, 16]	[-15, 15]	[-15, 16]
f_{M7}/Λ^4	[-25, 25]	[-50, 50]	[-27, 27]	[-24, 23]	[-21, 21]	[-23, 23]

energy cutoff at 1 TeV

	Observed ($W^\pm Zjj$) (TeV^{-4})	Expected ($W^\pm Zjj$) (TeV^{-4})	Observed ($W^\pm W^\pm jj$) (TeV^{-4})	Expected ($W^\pm W^\pm jj$) (TeV^{-4})	Combined Observed (TeV^{-4})	Combined Expected (TeV^{-4})
f_{S0}/Λ^4	[-52, 122]	[-120, 211]	[100, 98]	[-60, 62]	[-50, 80]	[-56, 61]
f_{S1}/Λ^4	[-268, 266]	[-514, 510]	[-418, 389]	[-281, 266]	[-256, 248]	[-271, 258]
f_{T0}/Λ^4	[-4.4, 4.3]	[-8.6, 8.5]	[-24, 27]	[-3.84, 4.20]	[-3.39, 3.27]	[-3.71, 3.94]
f_{T1}/Λ^4	[-2.4, 4.6]	[-5.6, 7.9]	[-3.04, 2.37]	[-1.61, 2.06]	[-1.41, 2.18]	[-1.56, 2.06]
f_{T2}/Λ^4	[-10, 8.6]	[-20, 17]	[-8.9, 8.40]	[-5.33, 8.59]	[-5.94, 5.44]	[-5.31, 7.51]
f_{M0}/Λ^4	[-42, 41]	[-80, 80]	[-155, 147]	[-53, 51]	[-39, 40]	[-48, 47]
f_{M1}/Λ^4	[-71, 71]	[-138, 138]	[-185, 215]	[-67, 72]	[-60, 59]	[-65, 69]
f_{M7}/Λ^4	[-100, 100]	[-194, 194]	[-172, 295]	[-121, 110]	[-87, 88]	[-111, 104]

significant loss of sensitivity
(or was it overestimated without unitarization?)

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4. progress toward global combined fits

ATLAS have released several combined fits.

Their most global fit includes **Higgs**, **EW**, and **EWPO**.

- Higgs production and decay (STXS)
  - * reparametrize STXS in terms of W.C.
- certain gauge boson cross section measurements (WW, WZ, ZZ, Zjj)
  - * reparametrize binned distributions in terms of W.C.
- precision Z pole observables measured at LEP and SLC
  - * use theoretical predictions for EWPO values as functions of W.C.

Sensitive to operators that affect Higgs couplings, weak boson self-couplings, vector boson – fermion couplings, and four-fermion couplings.

Build individual likelihoods for Higgs, EW, EWPO.

- consider "ATLAS-only" data: combine Higgs & EW
- "global" data: include EWPO on top of Higgs & EW

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Higgs data

Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]	Ref.
$H \to \gamma\gamma$	$\mathrm{ggF, VBF}, WH, ZH, t\bar{t}H, tH$	139	[10]
$H \to ZZ^*$	$\mathrm{ggF, VBF}, WH, ZH, t\bar{t}H(4\ell)$	139	[11]
$H \to WW^*$	$\mathrm{ggF, VBF}$	139	[12]
$H \to \tau\tau$	$\mathrm{ggF, VBF}, WH, ZH, t\bar{t}H(\tau_{\mathrm{had}}\tau_{\mathrm{had}})$	139	[13]
	WH, ZH	139	[14,15,16]
$H \to b\bar{b}$	VBF	126	[17]
	$t\bar{t}H$	139	[18]

Z pole data

Observable	Measurement	Prediction	Ratio
Γ_Z [MeV]	2495.2 ± 2.3	2495.7 ± 1	0.9998 ± 0.0010
R^0_ℓ	20.767 ± 0.025	20.758 ± 0.008	1.0004 ± 0.0013
R^0_c	0.1721 ± 0.0030	0.17223 ± 0.00003	0.999 ± 0.017
R^0_b	0.21629 ± 0.00066	0.21586 ± 0.00003	1.0020 ± 0.0031
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	0.01718 ± 0.00037	0.995 ± 0.062
$A^{0,c}_{\mathrm{FB}}$	0.0707 ± 0.0035	0.0758 ± 0.0012	0.932 ± 0.048
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016	0.1062 ± 0.0016	0.935 ± 0.021
σ^0_{had} [pb]	41488 ± 6	41489 ± 5	0.99998 ± 0.00019

EW data

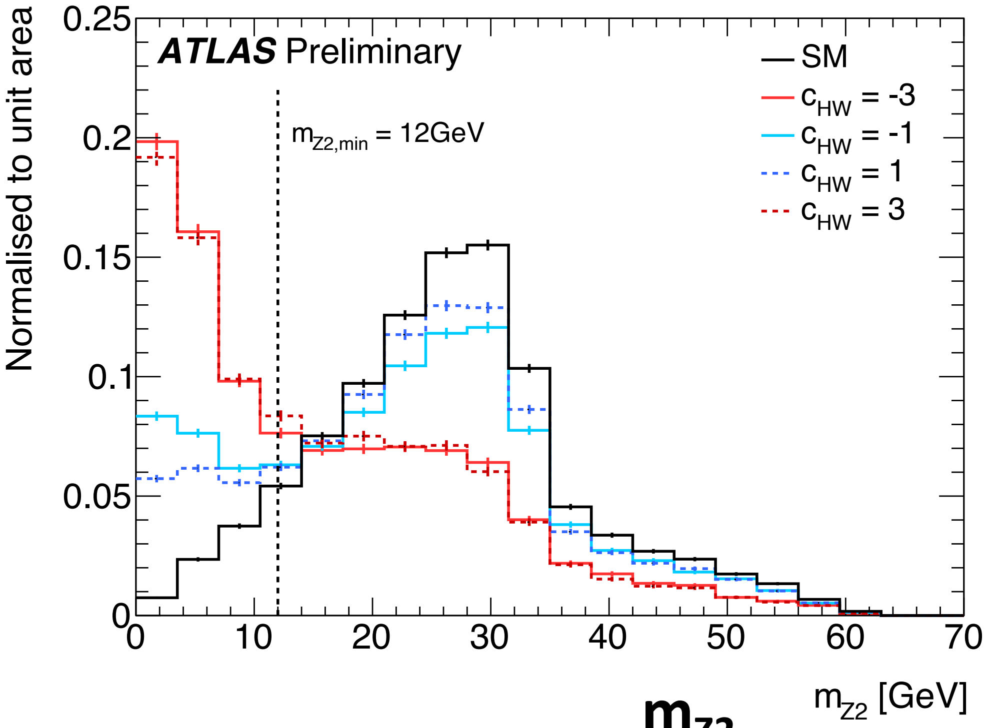
Process	Important phase space requirements	Observable	$\mathcal{L}$ [fb^{-1}]	Ref.
$pp \to e^\pm\nu\mu^\mp\nu$	$m_{\ell\ell} > 55\,GeV$, $p_{\mathrm{T}}^{\mathrm{jet}} < 35\,GeV$	$p_{\mathrm{T}}^{\mathrm{lead.\ lep.}}$	36	[19]
$pp \to \ell^\pm\nu\ell^+\ell^-$	$m_{\ell\ell} \in (81, 101)\,GeV$	m_{T}^{WZ}	36	[20]
$pp \to \ell^+\ell^-\ell^+\ell^-$	$m_{4\ell} > 180\,GeV$	m_{Z2}	139	[21]
$pp \to \ell^+\ell^- jj$	$m_{jj} > 1000\,GeV$, $m_{\ell\ell} \in (81, 101)\,GeV$	$\Delta\phi_{jj}$	139	[22]

Great care was taken to get details right.

- consider indirect impact of operators on Higgs BF
- consider impact of certain operators such as $C_{Hl}^{(3)}$ and C_{ll} which modify G_F.
- take propagator effects into account (i.e., when total width is modified)
- handle acceptance effects in certain Higgs decay kinematics

Unitarization: drop quadratic part and compare.

- attitude favors pure-linear part
- do not consider dim-8
- neglect cross terms
  (i.e. interference from two different dim-6)
- neglect double-insertions



m_{Z2}

The complementarity of these data sets is key.

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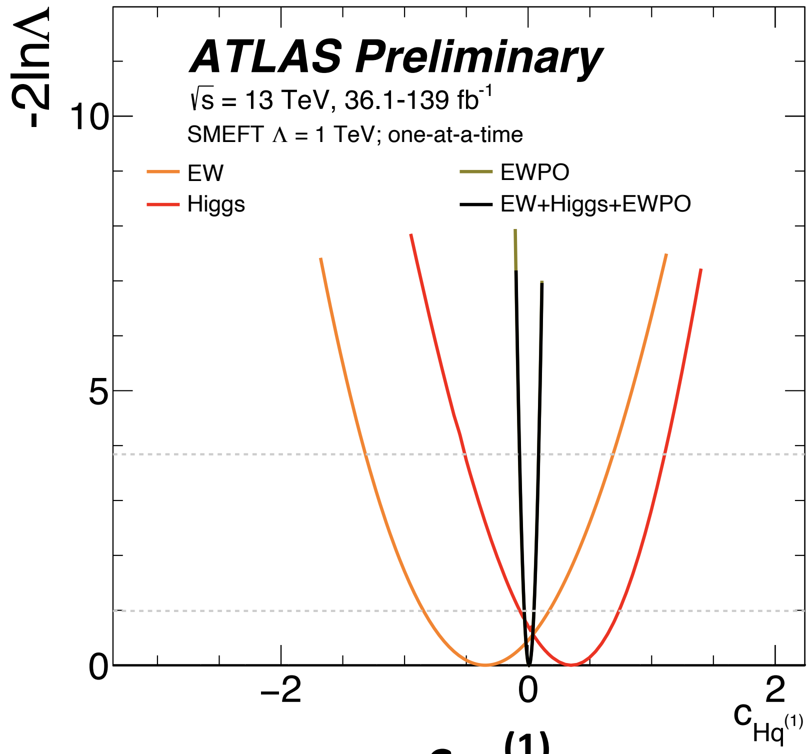
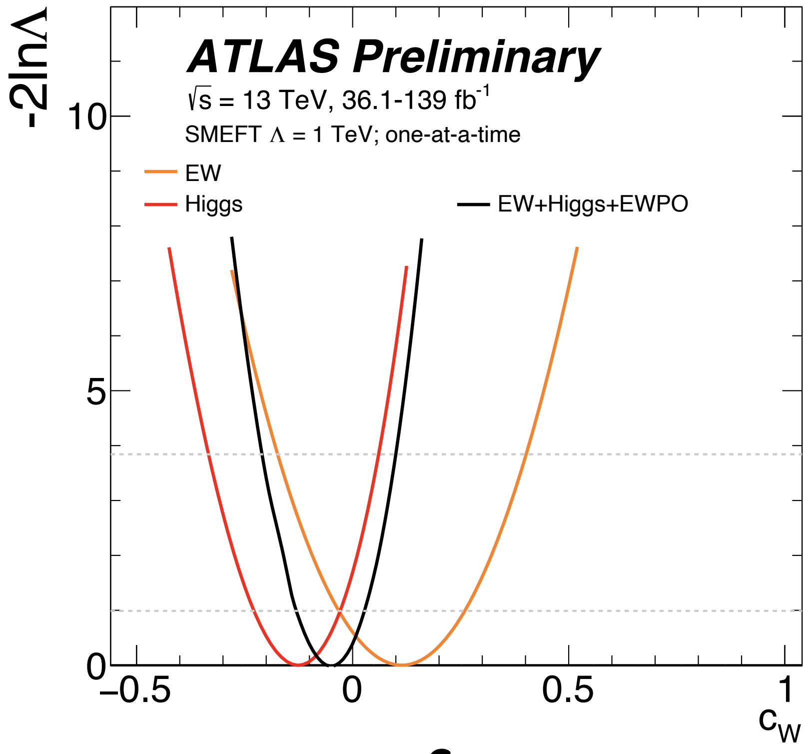
Tight EWPO constraints allow Vff to be distinguished from H-only and V-self interactions.

Example: compare two 1D scans. EWPO dominates $\mathbf{c_{Hq}^{(1)}}$ while Higgs+EW dominates $\mathbf{c_W}$.



$\mathbf{c_{Hq}^{(1)}}$



$\mathbf{c_W}$

Even so, these data are insufficient to determine all 28 W.C.
There are flat directions, even with all these measurements. → principal component analysis

PCA: ATLAS-only

Some eigenvectors are determined by one or two W.C.
Others depend on several.

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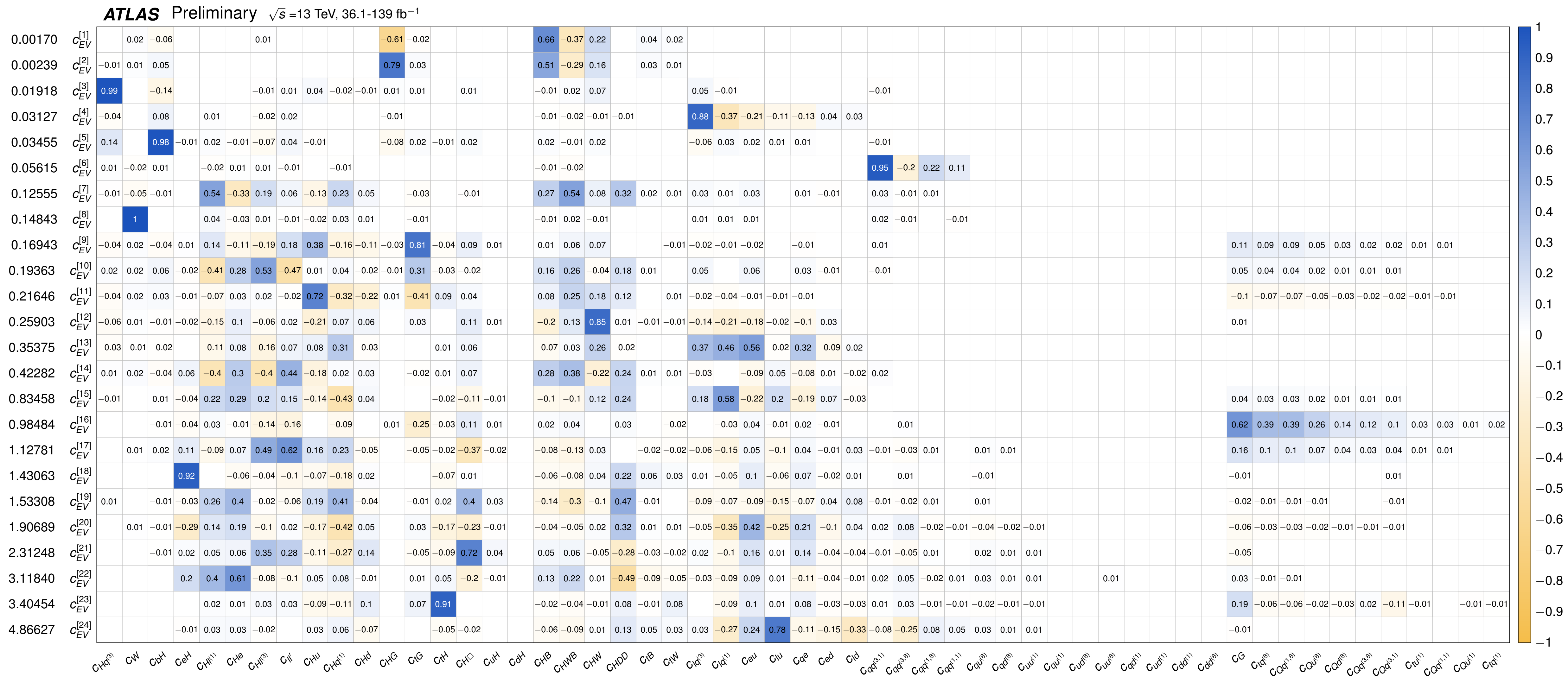
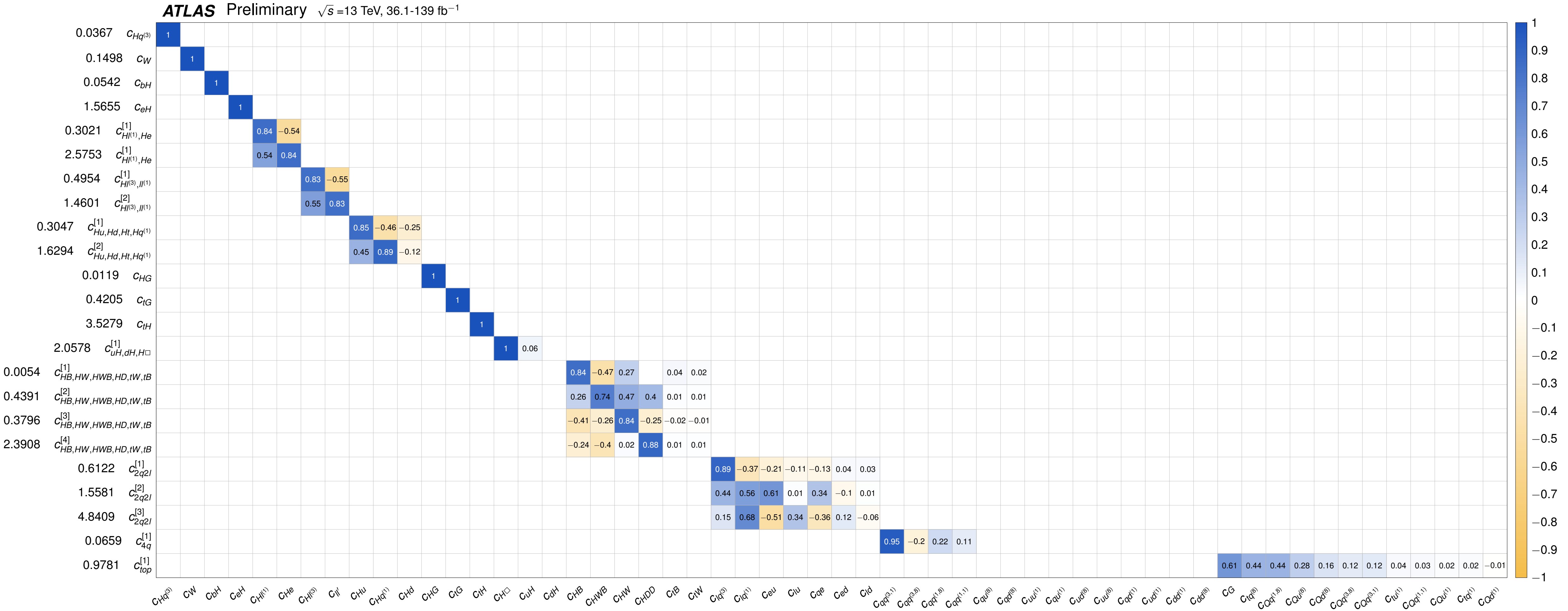
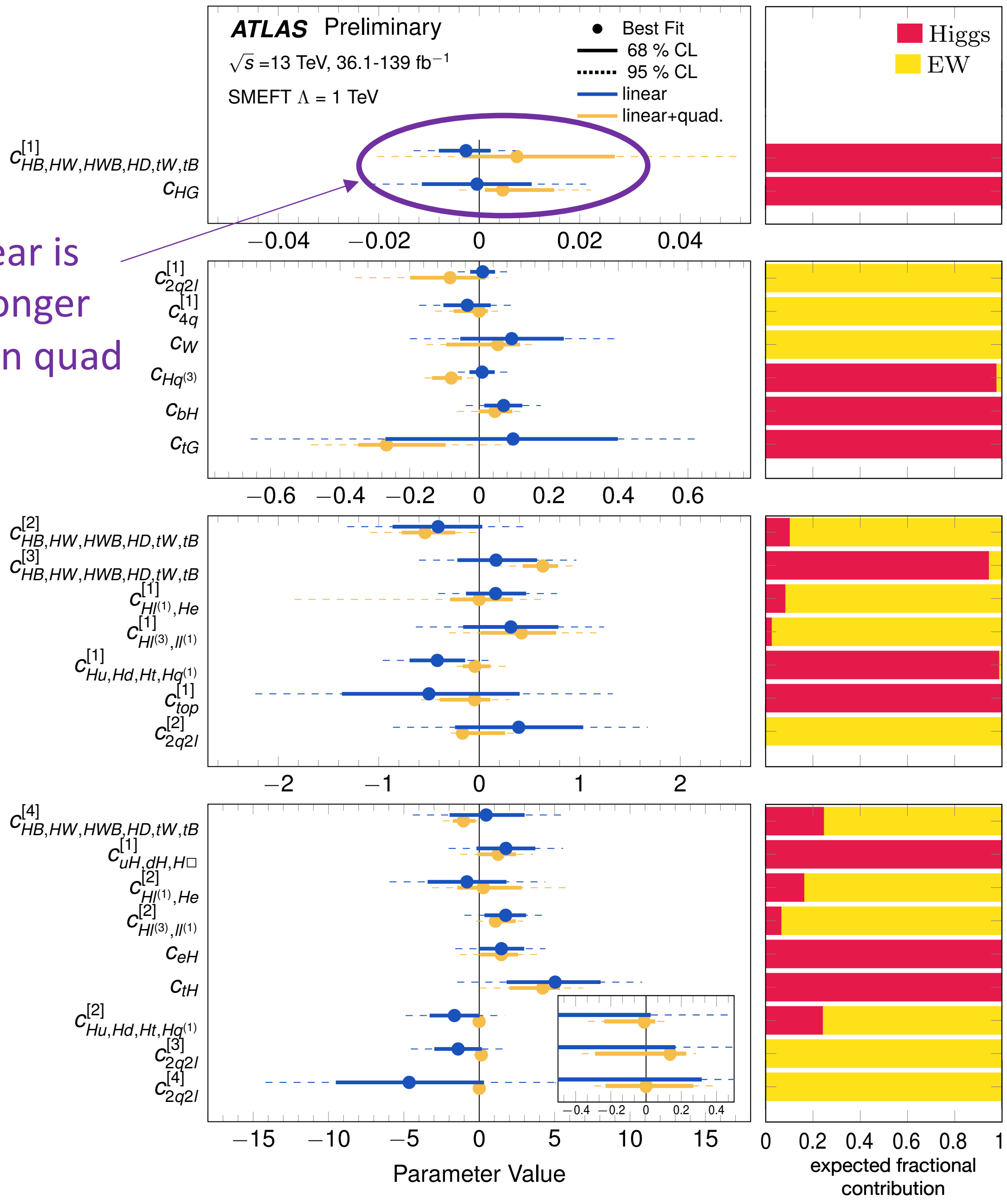


PCA: ATLAS-only

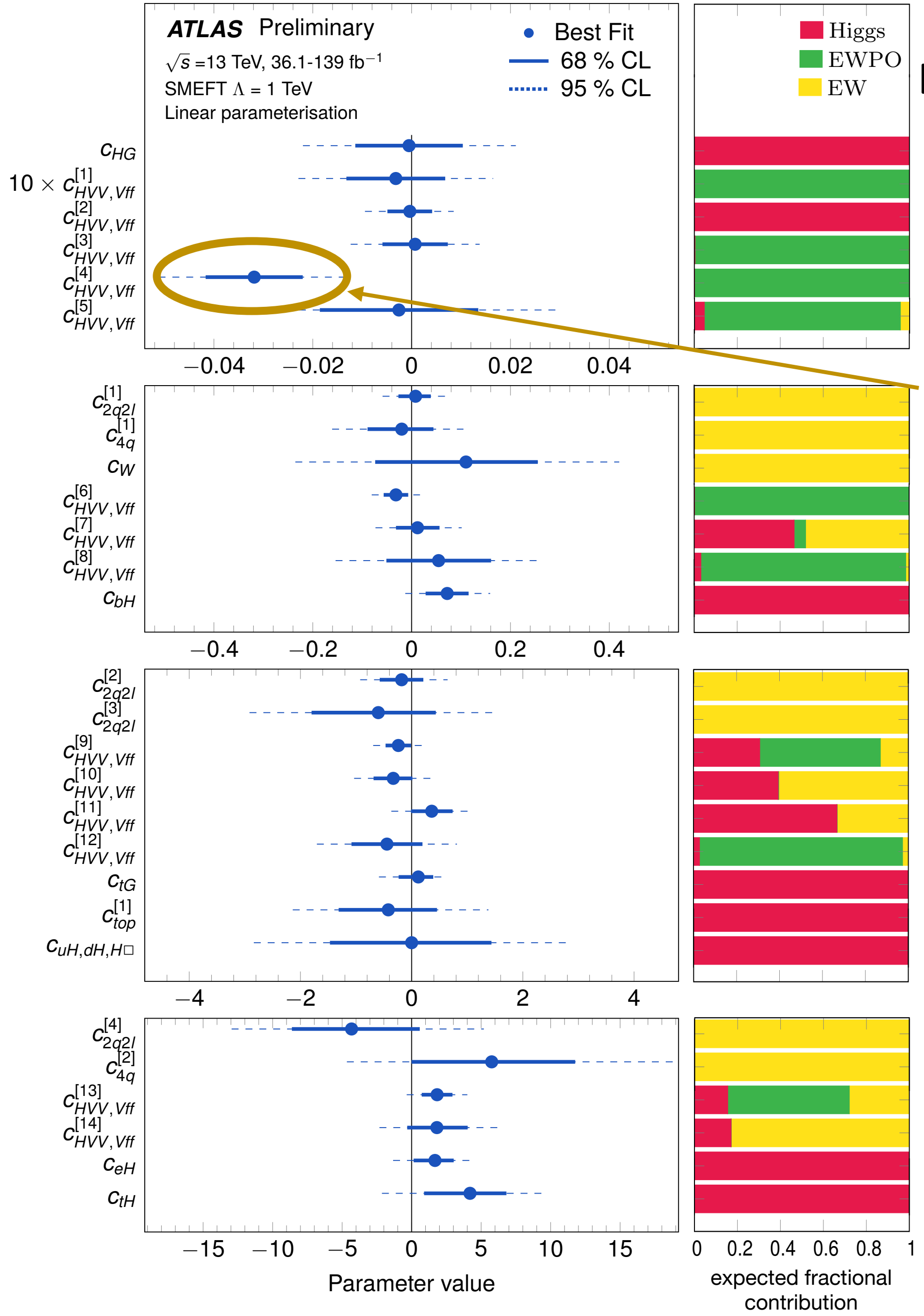
Restructure the PCA: form physics-motivated groups of W.C.
A pleasing and sensible/interpretable structure emerges.





linear is stronger than quad

B-2022-027



offset due to A_{FB}^{b} & A_{FB}^{c}

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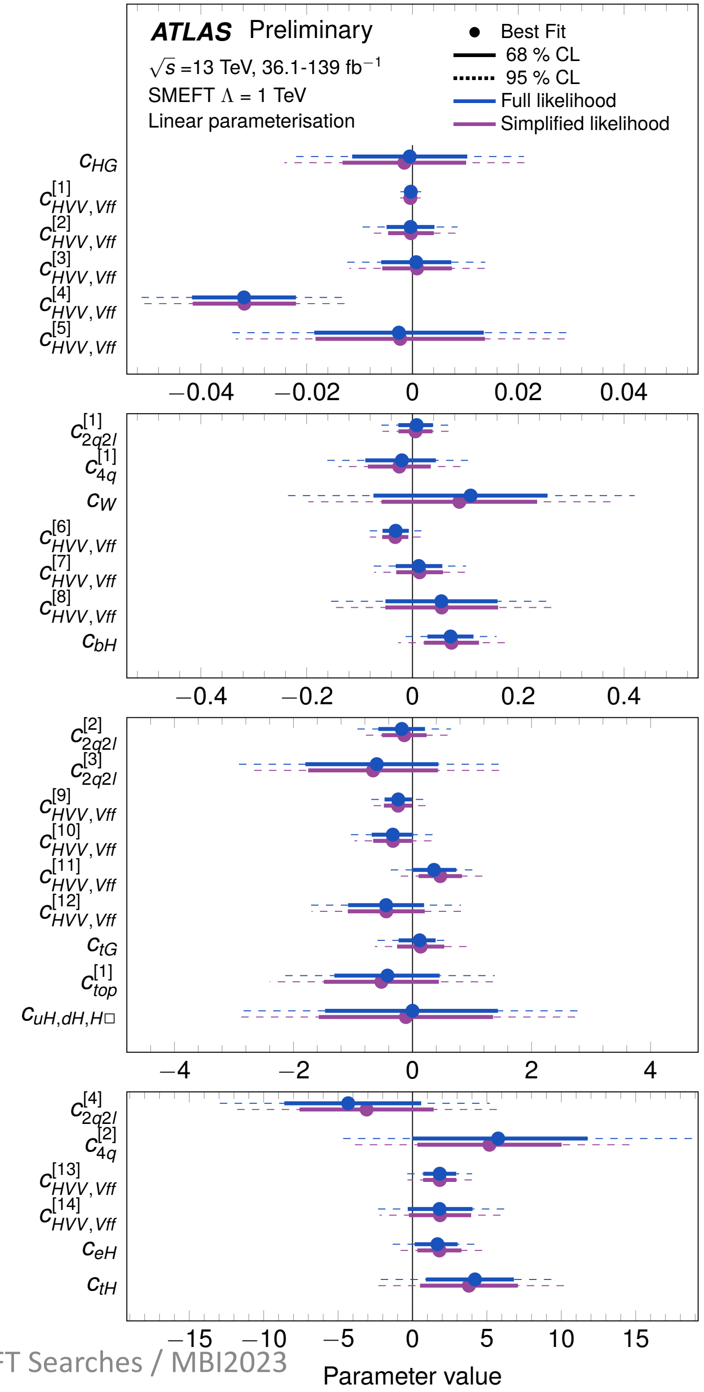
ATLAS developed a so-called “simplified NLL” which delivers results that are very close to those of the “full NLL”.

Will be very useful as the global analysis grows.

- easy to test out other schemes
- much faster to execute

Look forward to future developments!



Summary and Conclusion:

- This presentation could not include several interesting analyses, unfortunately.
- Main ideas:
  - Proper development of interference terms (e.g. angular or jet variables) can lead to much greater sensitivity
  - Dealing with unitarity violation is hard.
  - What is the best way to handle dim-8 constraints?
  - Global combined analyses are getting more inclusive, and more powerful. They will help solve many of these problems.

BACKUP

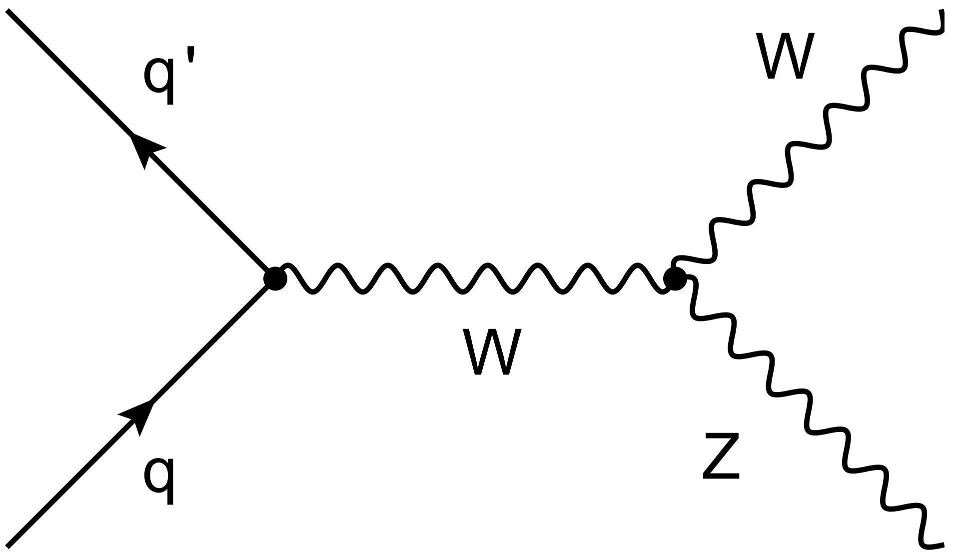
CMS WZ differential 2022

CMS WZ detailed differential cross sections

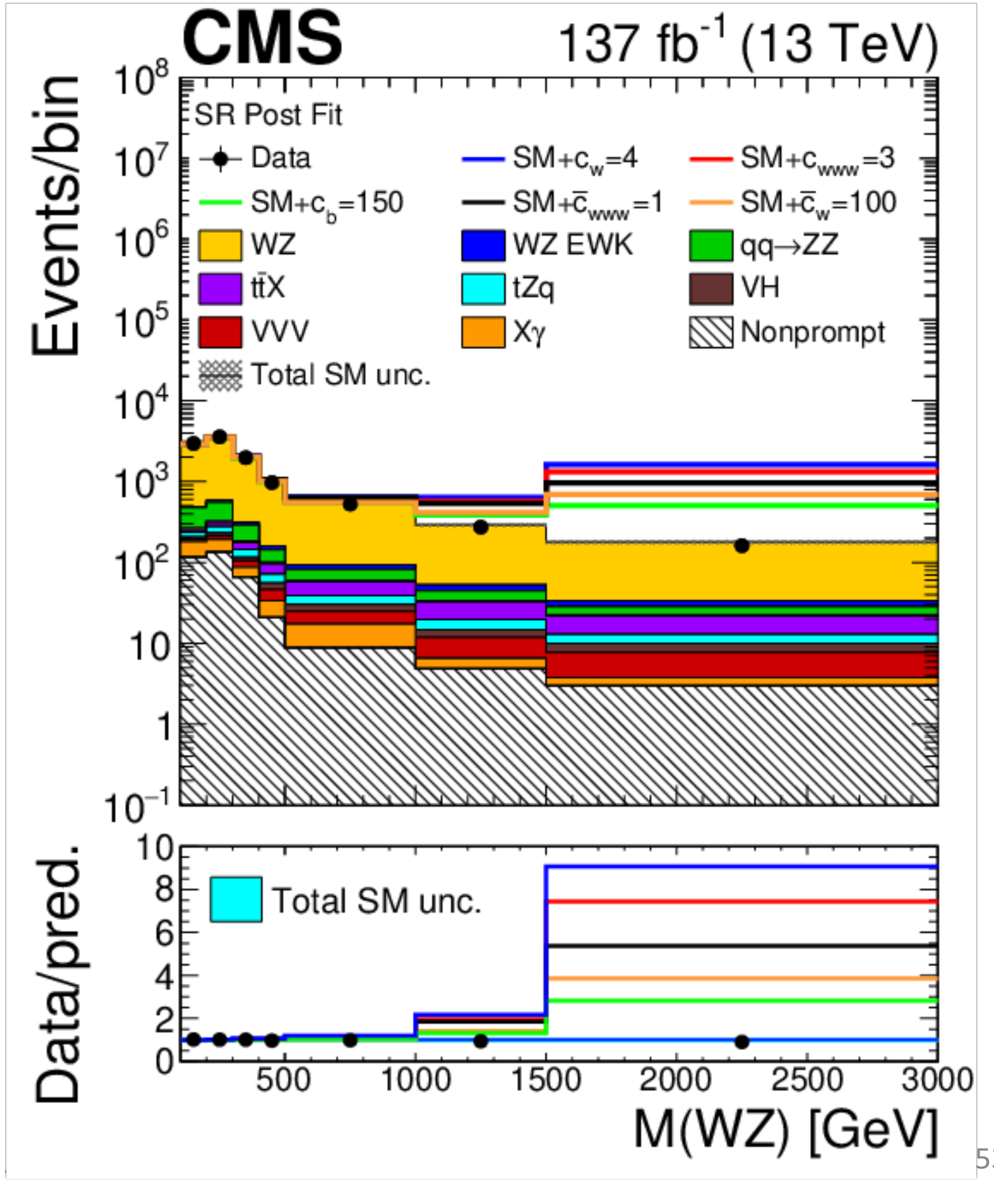
Use M(WZ) – not just the fiducial cross section
(look also at pTZ but do not use it in the fit)

Consider linear term only - compare

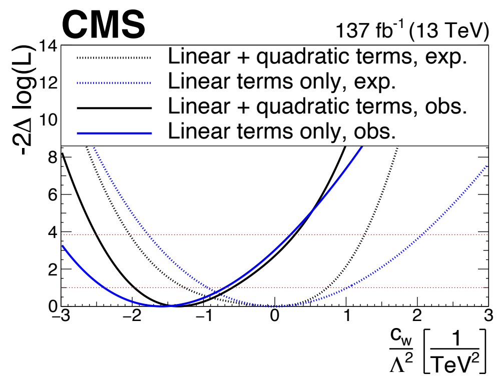
early example of “clipping”

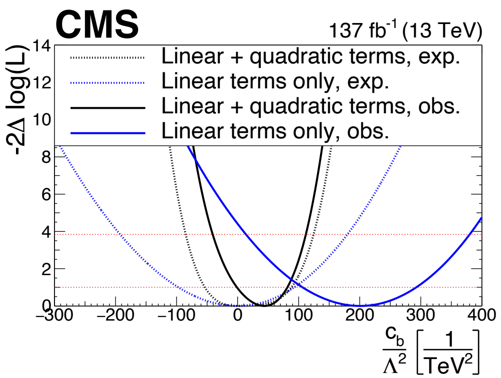


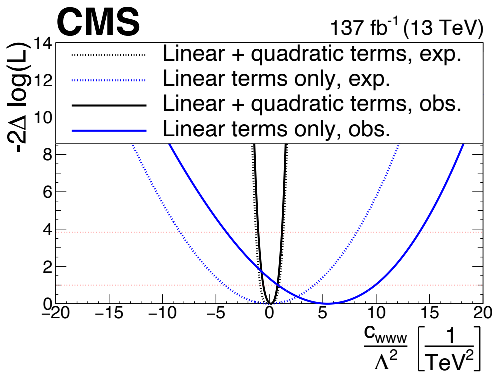
CMS JHEP07 (2022) 032

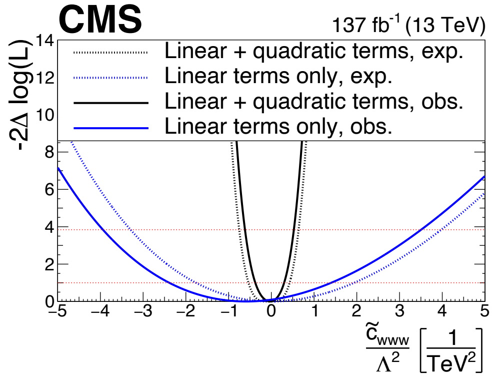


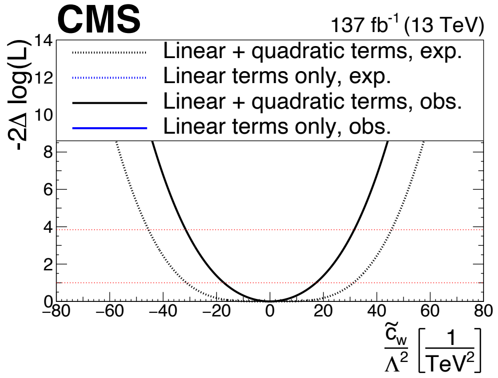
CMS JHEP07 (2022) 032

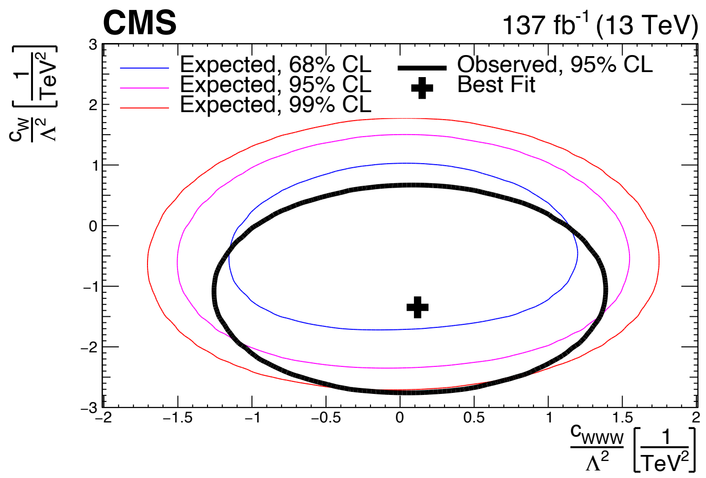


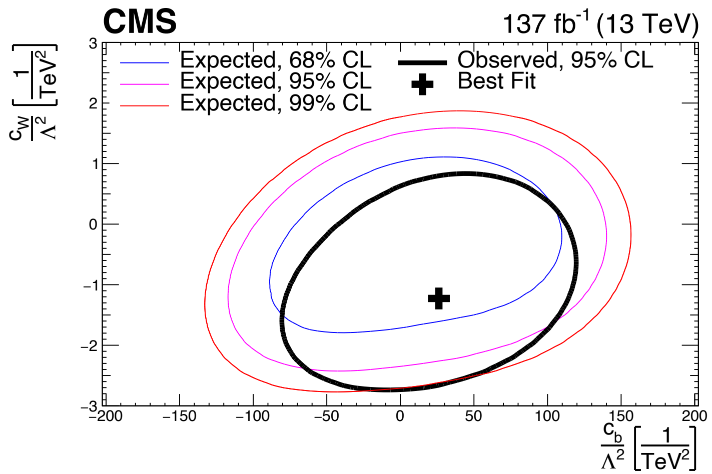


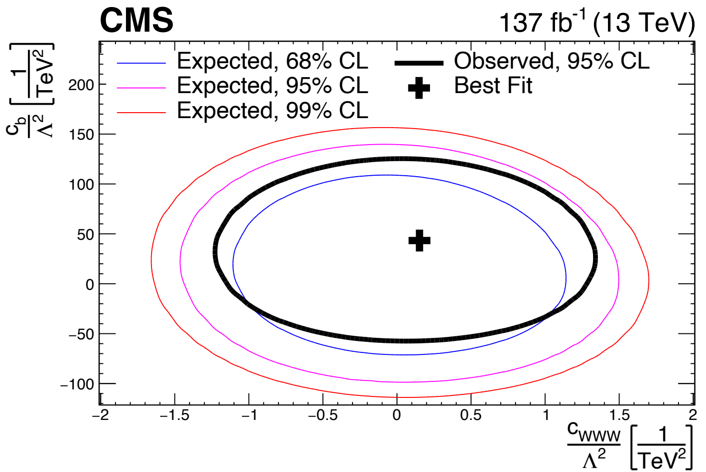


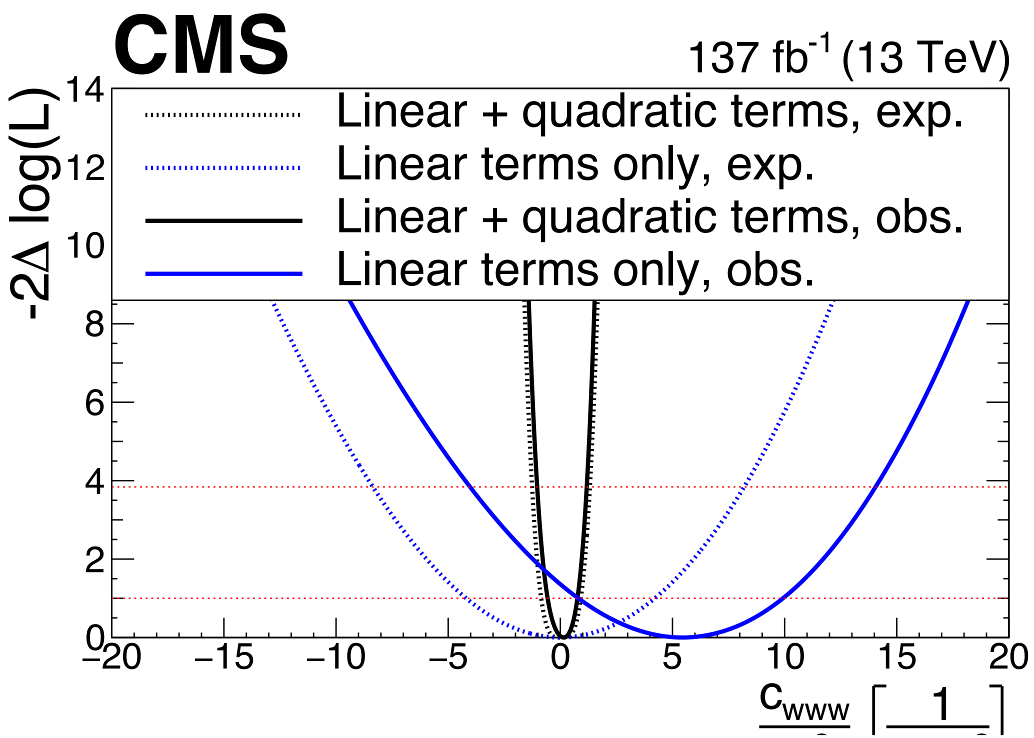


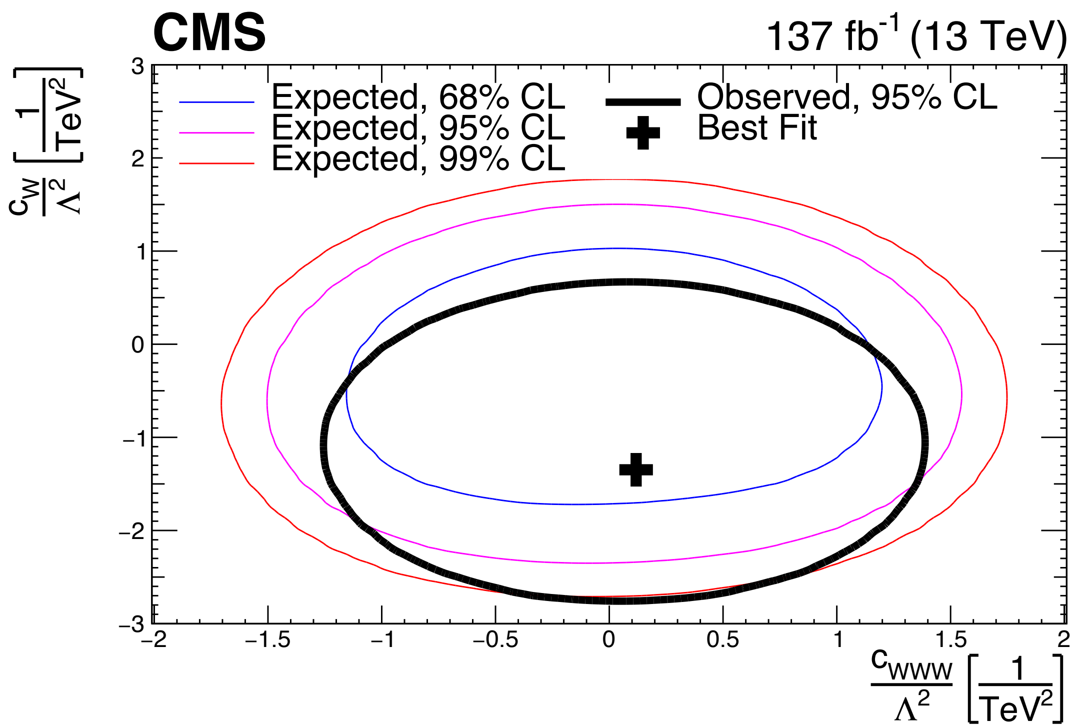


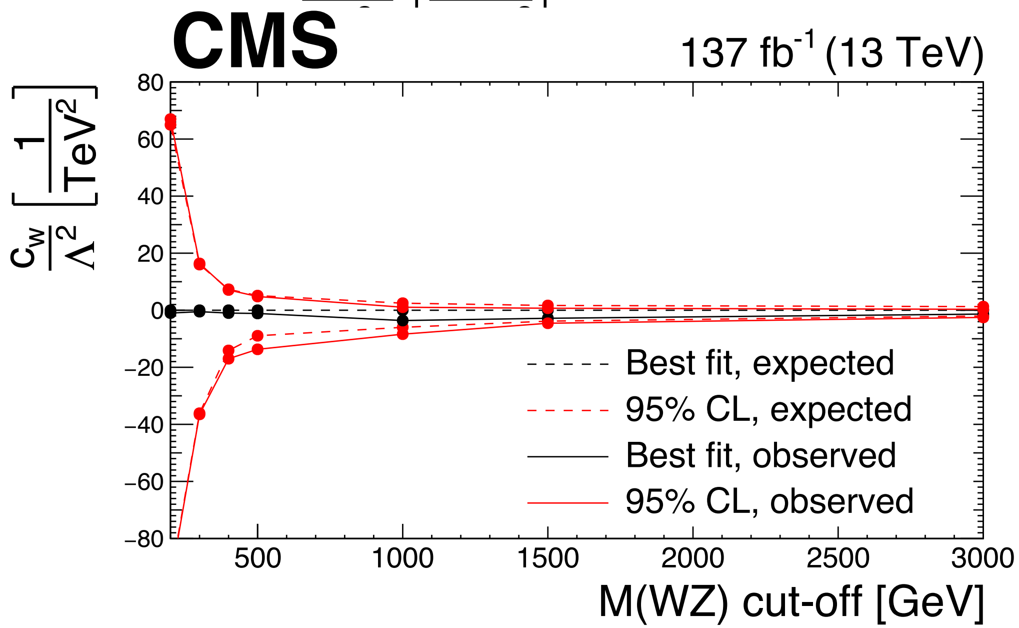


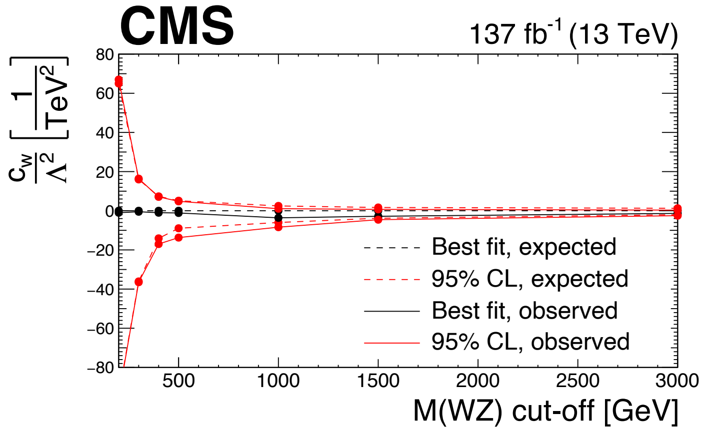


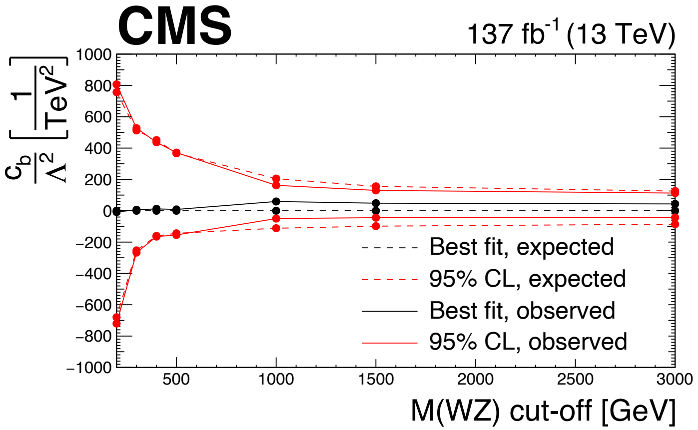



CMS
137 fb-1 (13 TeV)
Linear + quadratic terms, exp.
Linear terms only, exp.
Linear + quadratic terms, obs.
Linear terms only, obs.
-2Δ log(L)
cWWW [1/TeV2]

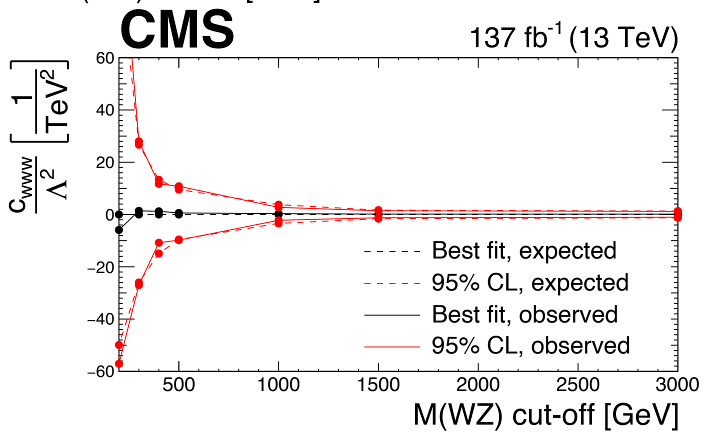

CMS
137 fb-1 (13 TeV)
Expected, 68% CL
Expected, 95% CL
Expected, 99% CL
Observed, 95% CL
Best Fit
cW/Λ2 [1/TeV2]
cWWW/Λ2 [1/TeV2]

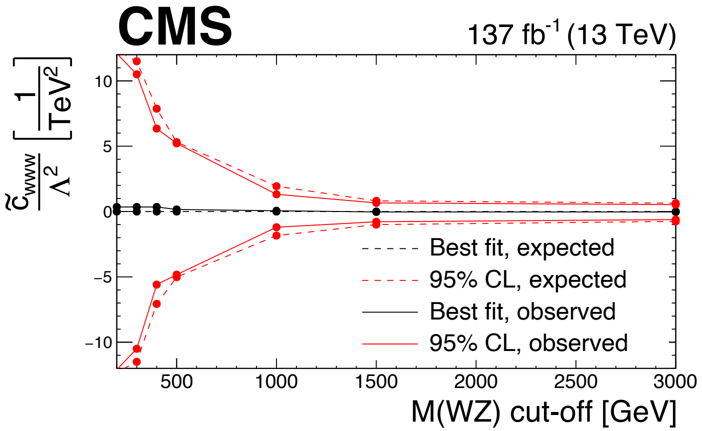

CMS
137 fb-1 (13 TeV)
Best fit, expected
95% CL, expected
Best fit, observed
95% CL, observed
cW/Λ2 [1/TeV2]
M(WZ) cut-off [GeV]

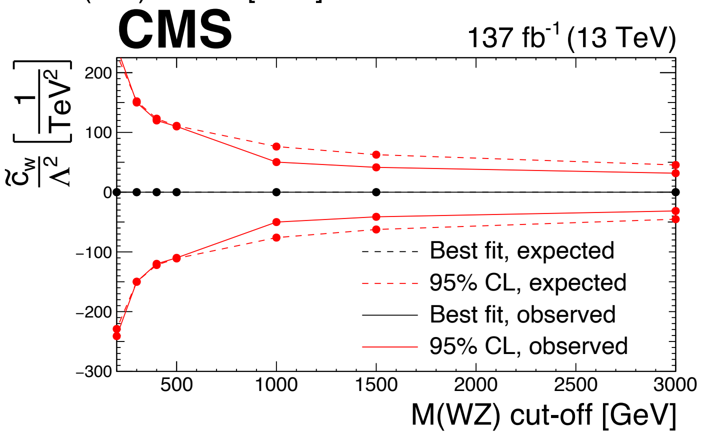




CMS JHEP07 (2022) 032







CMS JHEP07 (2022) 032

linear + quadratic

Parameter	95% CI, exp. (TeV^{-2})	95% CI, obs. (TeV^{-2})	Best fit, obs. (TeV^{-2})
c_{w}/Λ^2	$[-2.0, 1.3]$	$[-2.5, 0.3]$	-1.3
c_{www}/Λ^2	$[-1.3, 1.3]$	$[-1.0, 1.2]$	0.1
c_{b}/Λ^2	$[-86, 125]$	$[-43, 113]$	44
$\widetilde{c}_{www}/\Lambda^2$	$[-0.76, 0.65]$	$[-0.62, 0.53]$	-0.03
$\widetilde{c}_{w}/\Lambda^2$	$[-46, 46]$	$[-32, 32]$	0

linear only

Parameter	95% CI, exp. (TeV^{-2})	95% CI, obs. (TeV^{-2})	Best fit, obs. (TeV^{-2})
c_{w}/Λ^2	$[-1.8, 2.1]$	$[-3.1, 0.3]$	-1.6
c_{www}/Λ^2	$[-8.5, 8.5]$	$[-4.2, 14.2]$	5.5
c_{b}/Λ^2	$[-200, 180]$	$[10, 380]$	200
$\widetilde{c}_{www}/\Lambda^2$	$[-3.3, 4.1]$	$[-4.0, 3.6]$	-0.6
$\widetilde{c}_{w}/\Lambda^2$	—	—	—

ATLAS ZZjj 2023

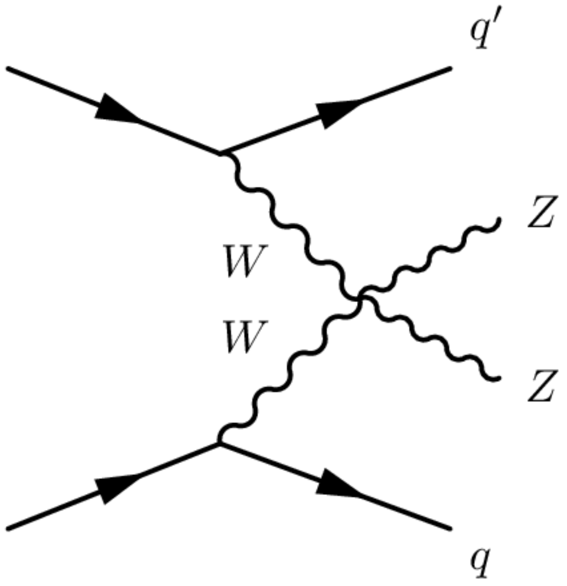
ATLAS ZZ+2j just published 2308.12324

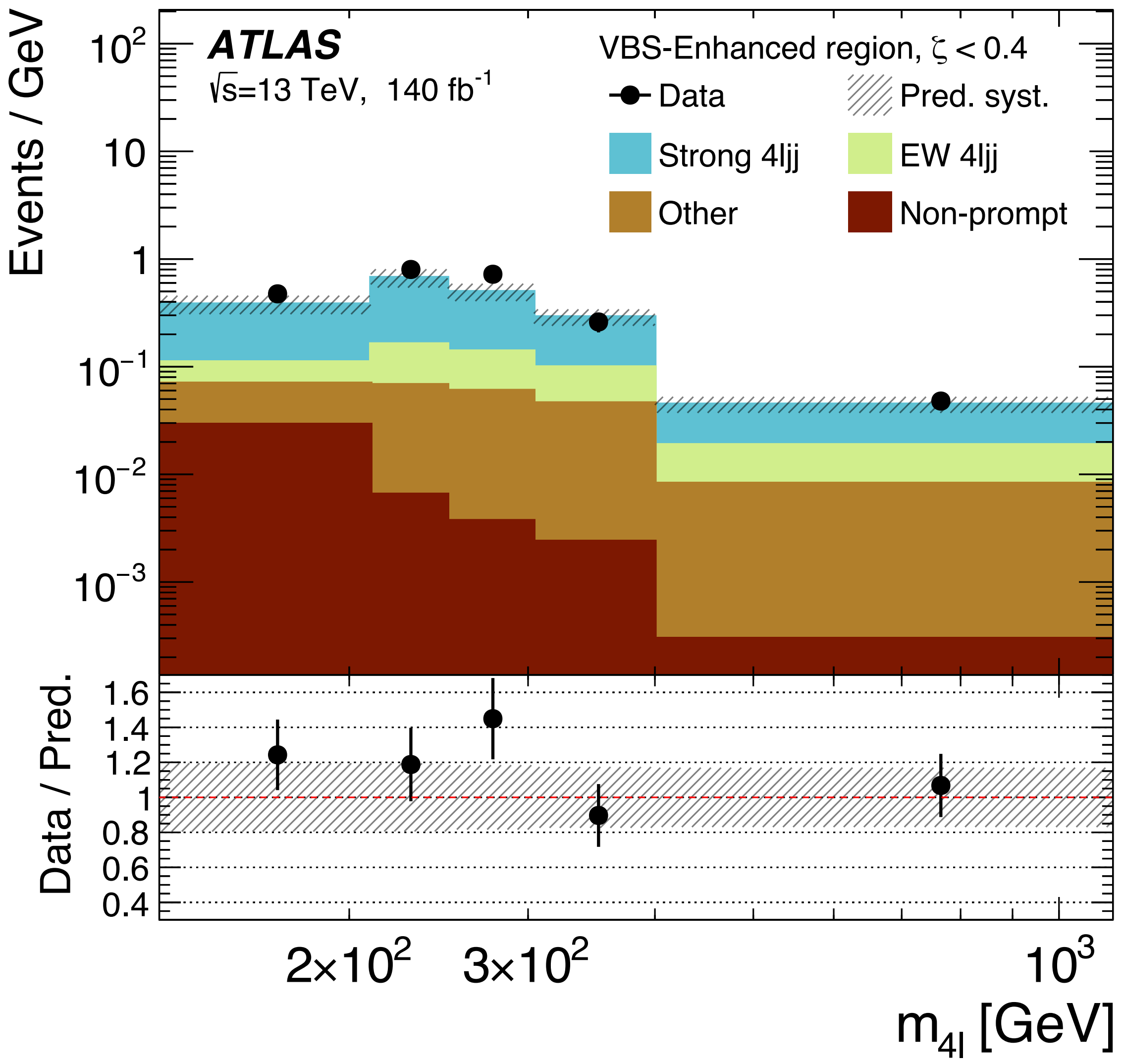
- 4 leptons, 2 jets
- vector boson scattering
- quartic coupling: dimension 8 as well as dim-6

- cuts to enhance or suppress VBS
- measure differential cross sections in both cases

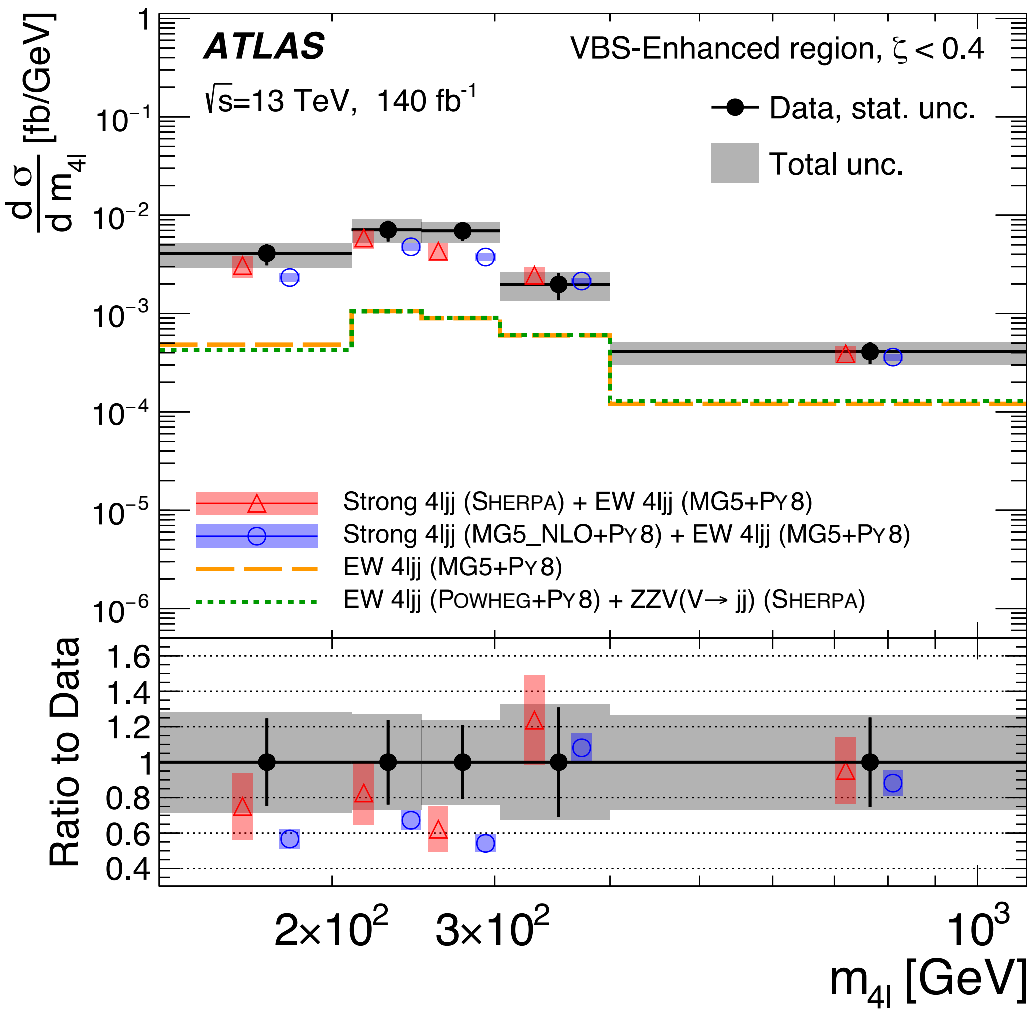
- careful comparison to theory
    - EW: MadGraph5 at LO (which is adequate)
    - QCD: Sherpa, MG5_NLO (Sherpa is better)

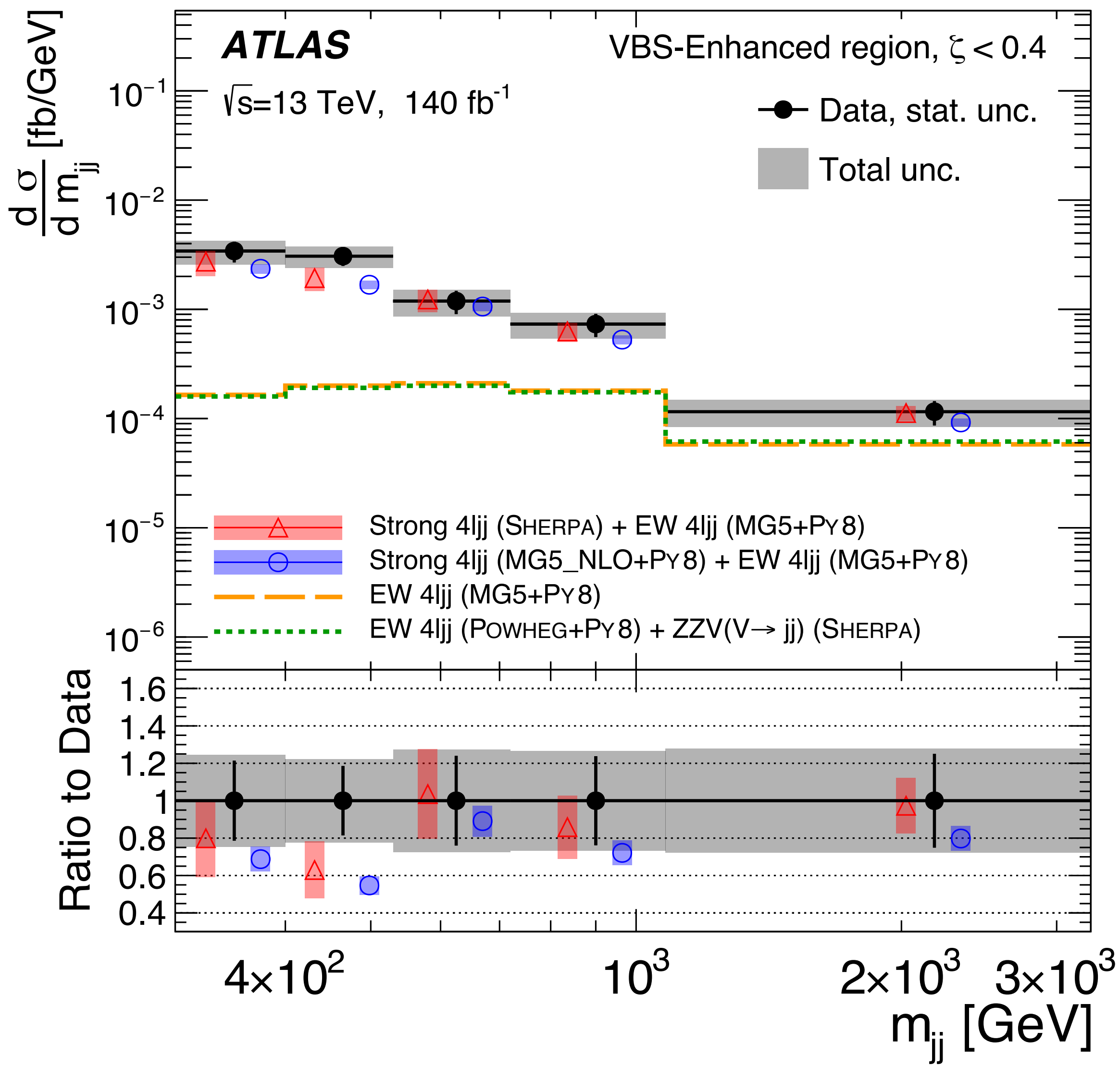
- interesting kinematic quantities
    - m4l
    - mjj
    - costheta*
    - dphi
- Use m4l and mjj for EFT analysis



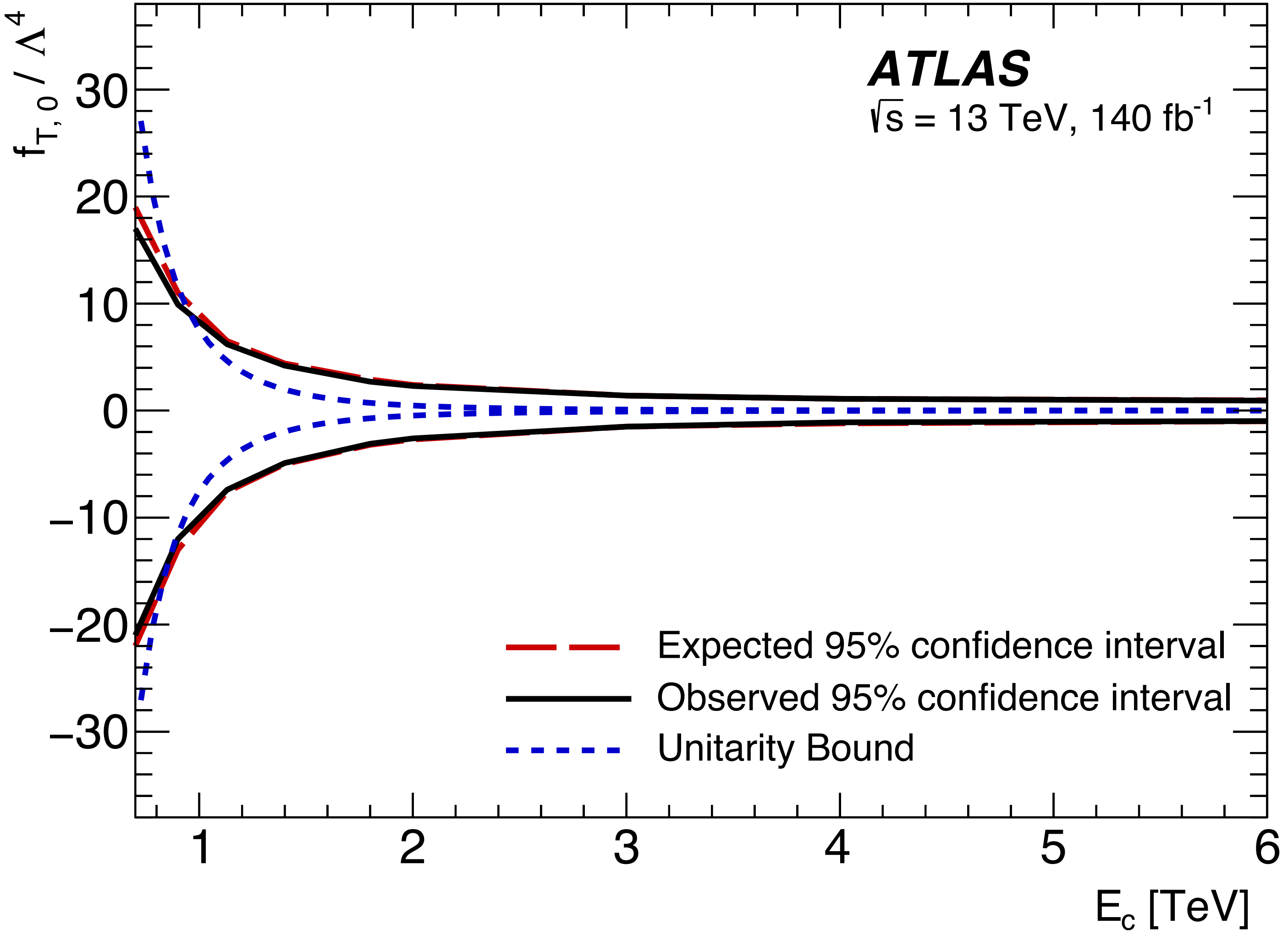


ATLAS
√s=13 TeV, 140 fb-1
VBS-Enhanced region, ζ < 0.4
Data
Pred. syst.
Strong 4ljj
EW 4ljj
Other
Non-prompt
Events / GeV
Data / Pred.
m4l [GeV]


ATLAS
VBS-Enhanced region, ζ < 0.4
√s=13 TeV, 140 fb⁻¹
Data, stat. unc.
Total unc.
Strong 4ljj (SHERPA) + EW 4ljj (MG5+PY8)
Strong 4ljj (MG5_NLO+PY8) + EW 4ljj (MG5+PY8)
EW 4ljj (MG5+PY8)
EW 4ljj (POWHEG+PY8) + ZZV(V→ jj) (SHERPA)
dσ/dm4l [fb/GeV]
Ratio to Data
m4l [GeV]


ATLAS
VBS-Enhanced region, ζ < 0.4
√s=13 TeV, 140 fb⁻¹
Data, stat. unc.
Total unc.
Strong 4ljj (SHERPA) + EW 4ljj (MG5+PY8)
Strong 4ljj (MG5_NLO+PY8) + EW 4ljj (MG5+PY8)
EW 4ljj (MG5+PY8)
EW 4ljj (POWHEG+PY8) + ZZV(V→ jj) (SHERPA)
dσ/dmjj [fb/GeV]
Ratio to Data
mjj [GeV]

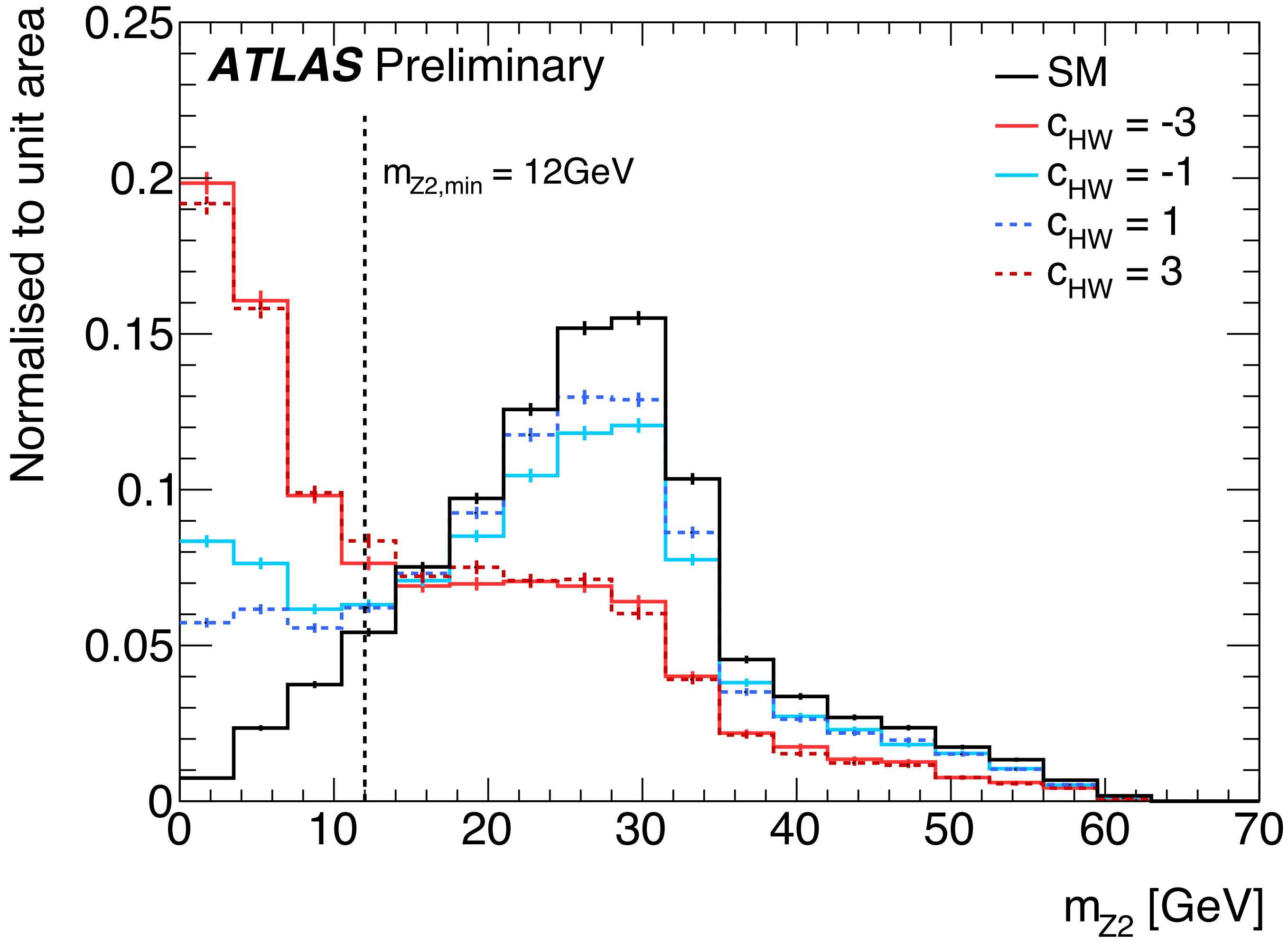
Wilson coefficient	$\|\mathcal{M}_{d8}\|^2$ Included	95% confidence interval [TeV^{-4}] Expected	Observed
$f_{T,0}/\Lambda^4$	yes	[-0.98, 0.93]	[-1.00, 0.97]
	no	[-23, 17]	[-19, 19]
$f_{T,1}/\Lambda^4$	yes	[-1.2, 1.2]	[-1.3, 1.3]
	no	[-160, 120]	[-140, 140]
$f_{T,2}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-74, 56]	[-63, 62]
$f_{T,5}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-79, 60]	[-68, 67]
$f_{T,6}/\Lambda^4$	yes	[-3.9, 3.9]	[-4.1, 4.1]
	no	[-64, 48]	[-55, 54]
$f_{T,7}/\Lambda^4$	yes	[-8.5, 8.1]	[-8.8, 8.4]
	no	[-260, 200]	[-220, 220]
$f_{T,8}/\Lambda^4$	yes	[-2.1, 2.1]	[-2.2, 2.2]
	no	[-4.6, 3.1]$\times 10^4$	[-3.9, 3.8]$\times 10^4$
$f_{T,9}/\Lambda^4$	yes	[-4.5, 4.5]	[-4.7, 4.7]
	no	[-7.5, 5.5]$\times 10^4$	[-6.4, 6.3]$\times 10^4$



backup

Wilson coefficient	$\lvert\mathcal{M}_{\rm d6}\rvert^2$ Included	95% confidence interval [TeV^{-2}] Expected	Observed
c_W/Λ^2	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-32, 32]	[-37, 28]
$c_{\widetilde{W}}/\Lambda^2$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-17, 17]*	[0, 30]*
c_{HWB}/Λ^2	yes	[-16, 7]	[-16, 6]
	no	[-12, 12]	[-15, 10]
$c_{H\widetilde{W}B}/\Lambda^2$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-67, 67]*	[-25, 130]*
c_{HB}/Λ^2	yes	[-13, 13]	[-12, 12]
	no	[-38, 38]	[-38, 38]
$c_{H\widetilde{B}}/\Lambda^2$	yes	[-13, 13]	[-12, 12]
	no	[-420, 420]*	[-200, 790]*

ATLAS combined H, EW, EWPO 2023


ATLAS Preliminary
Normalised to unit area
$m_{Z2,min}$ = 12GeV
SM
c_{HW} = -3
c_{HW} = -1
c_{HW} = 1
c_{HW} = 3
m_{Z2} [GeV]
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
70