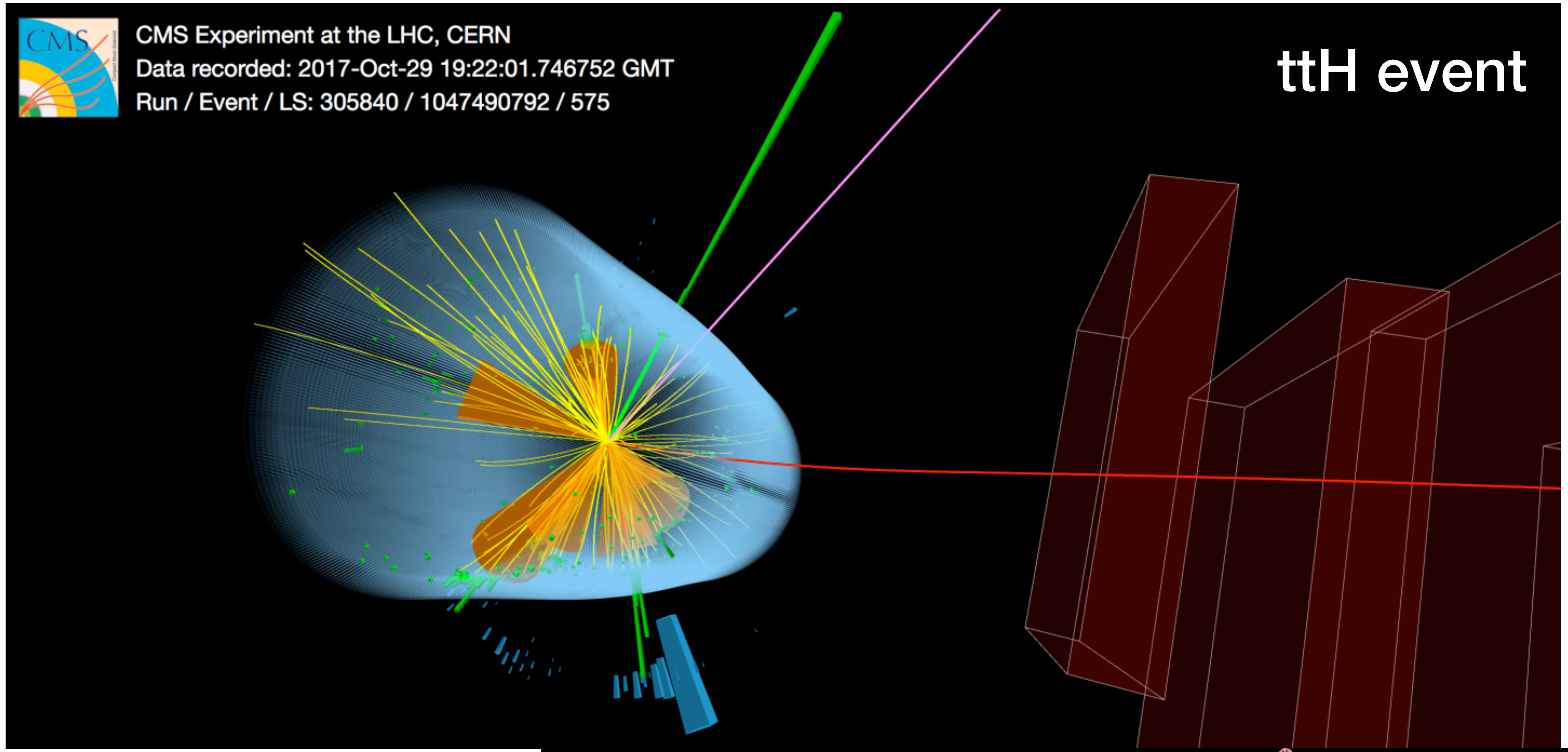
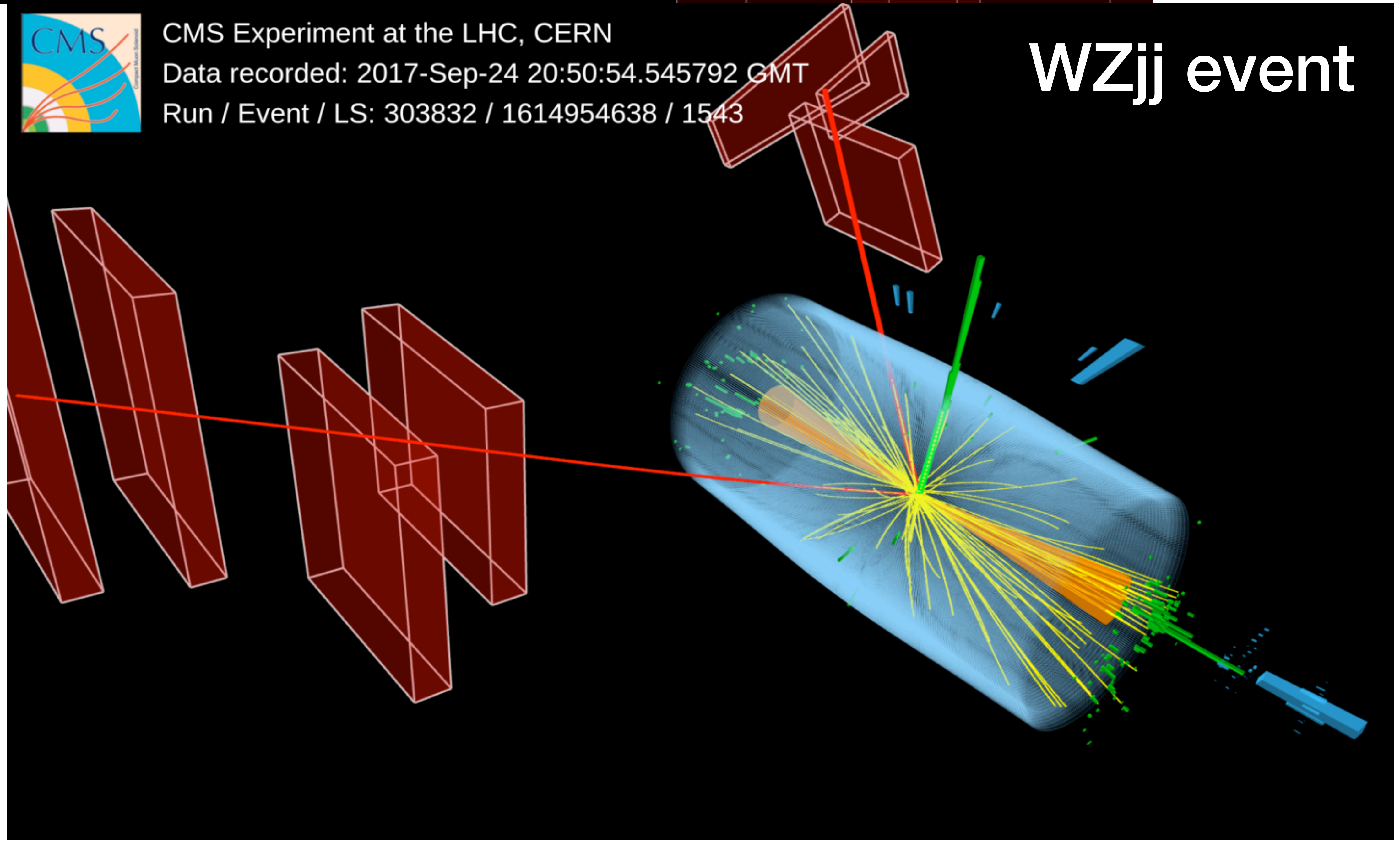
EFT in the EWK and TOP sectors in CMS

Andrea Piccinelli (University of Notre Dame)

6th General Meeting of the LHC EFT Working Group, 15-17 Nov. 2023, CERN

Outline

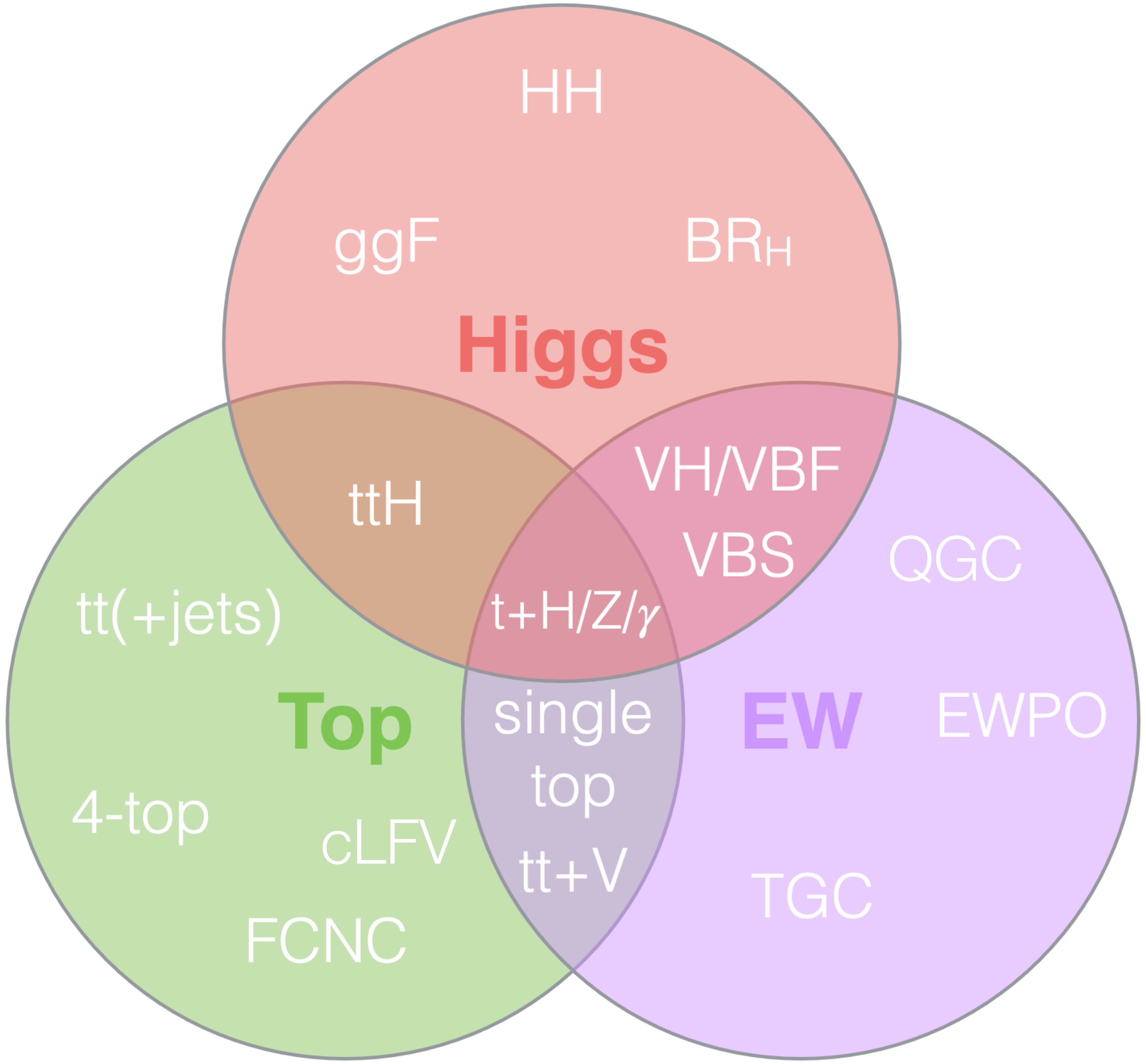




- Introduction
- Recent results in TOP sector
- Recent results in EWK sector
- Conclusions

Introduction

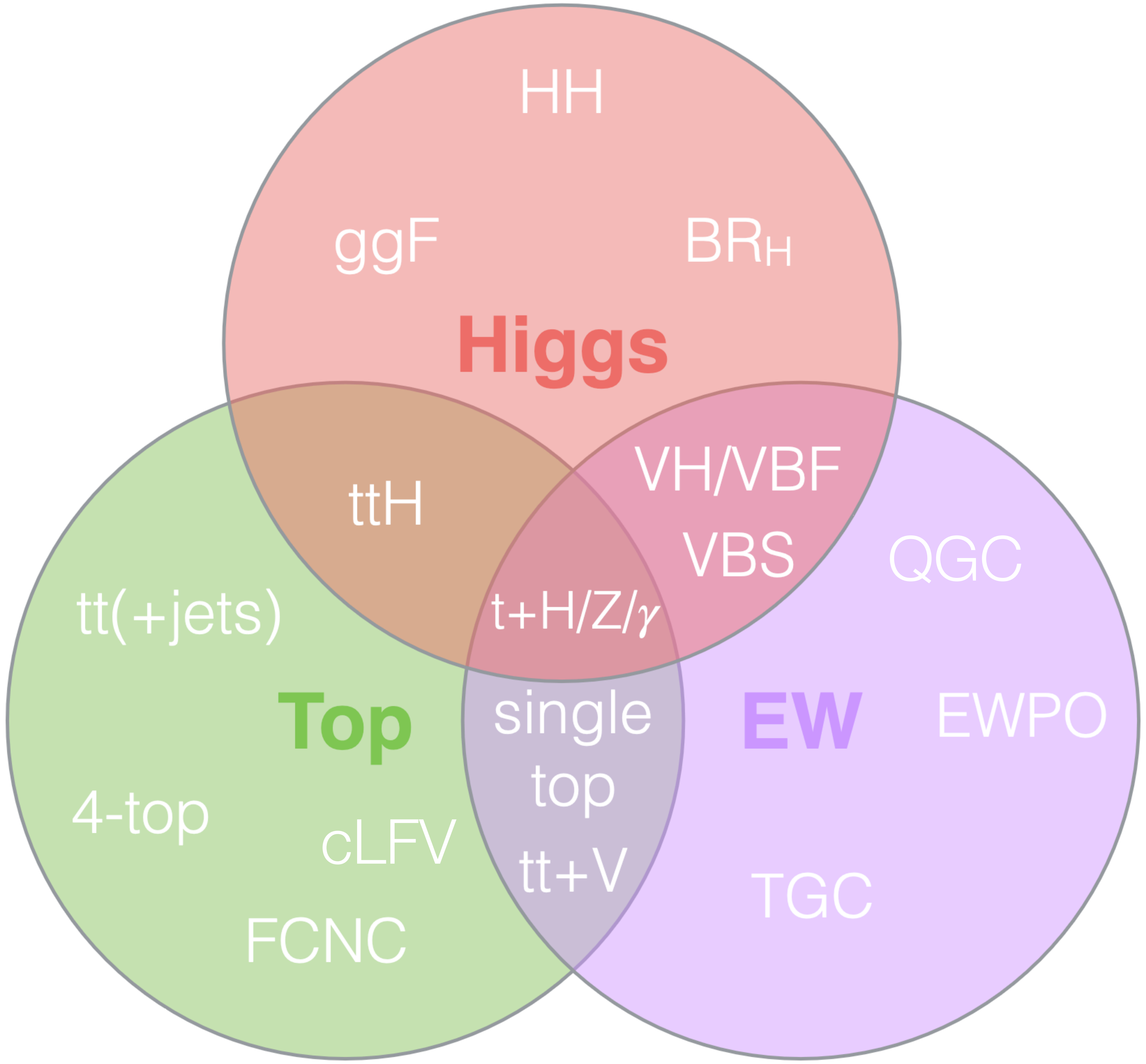
TOP and EWK EFT at CMS



$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathscr{O}_i^{(6)} + \sum_j \frac{f_j}{\Lambda^4}\mathscr{O}_j^{(8)} + \ldots$$

- Big efforts to scan all possible sources of indirect new physics effects with the EFT approach in CMS

TOP and EWK EFT at CMS



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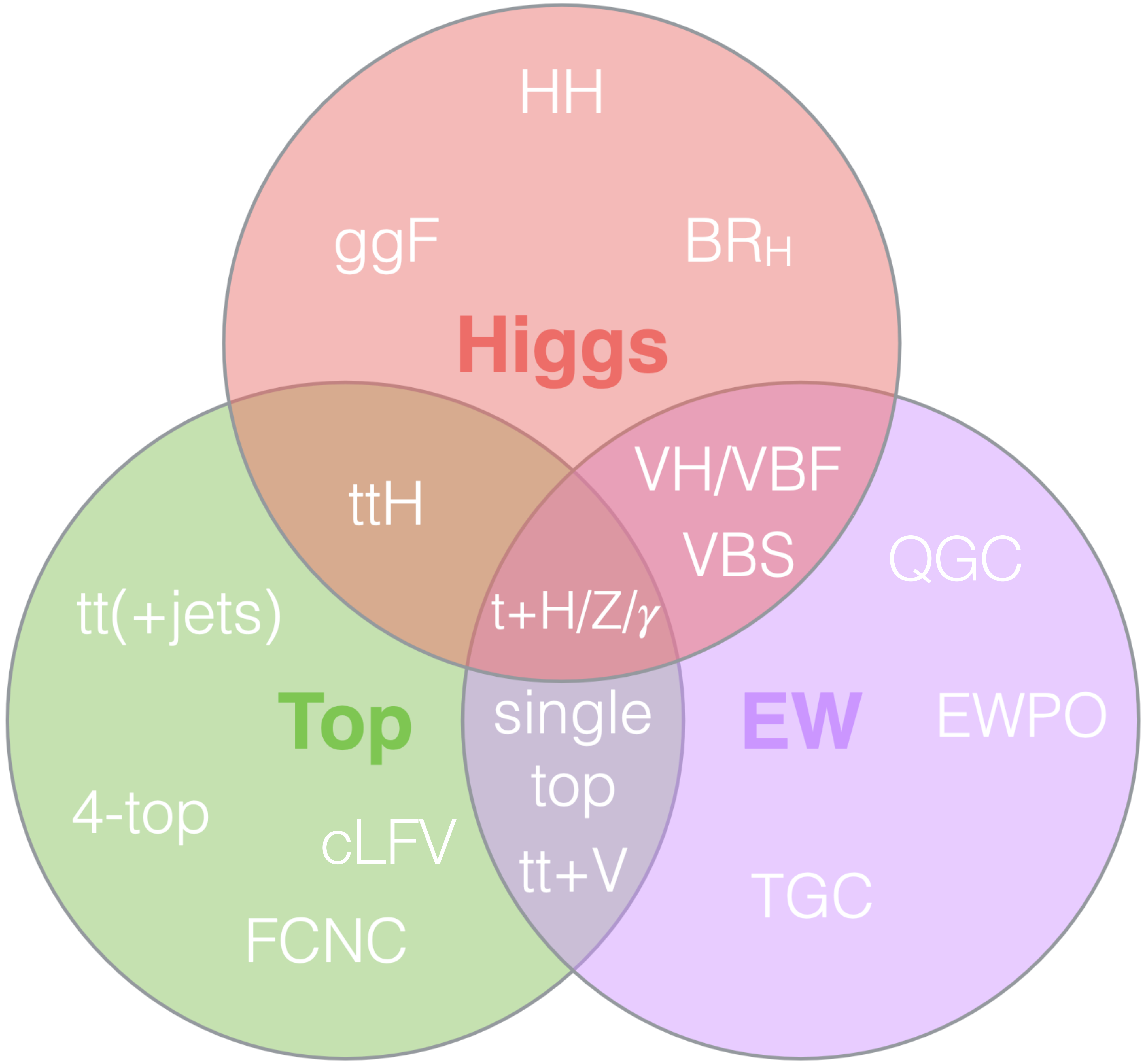
- Big efforts to scan all possible sources of indirect new physics effects with the EFT approach in CMS
- This presentation
  - **TOP sector**
    Spans a lot of processes involving single top and top pair productions, and flavor anomalies
    EFT effects modeled with Warsaw basis at dim6 order
      dim6top or SMEFT @ LO

TOP and EWK EFT at CMS



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  - **TOP sector**
    Spans a lot of processes involving single top and top pair productions, and flavor anomalies
    EFT effects modeled with Warsaw basis at dim6 order
      dim6top or SMEFT @ LO
  - **EWK sector**
    Focus on vector boson interactions
    anomalous Triple/Quartic Gauge Coupling (aTGC/aQGC)
      dim6 Warsaw basis (SMEFT @ LO)
      dim8 Éboli basis @ LO

Recent results from CMS

TOP

EWK

Recent results from CMS

TOP

- tt(X) multilepton
  Submitted to JHEP arxiv2307.15761
- Search for cLFV with trileptons
  CMS-PAS-TOP-22-005
- tt with a boosted H or Z
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EWK

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EWK

- aQGC in electroweak Wγjj
  PRD 108 (2023) 032017
- SMEFT dim6 in electroweak Wγjj
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Recent results from CMS

TOP

Covered in this talk

- tt(X) multilepton
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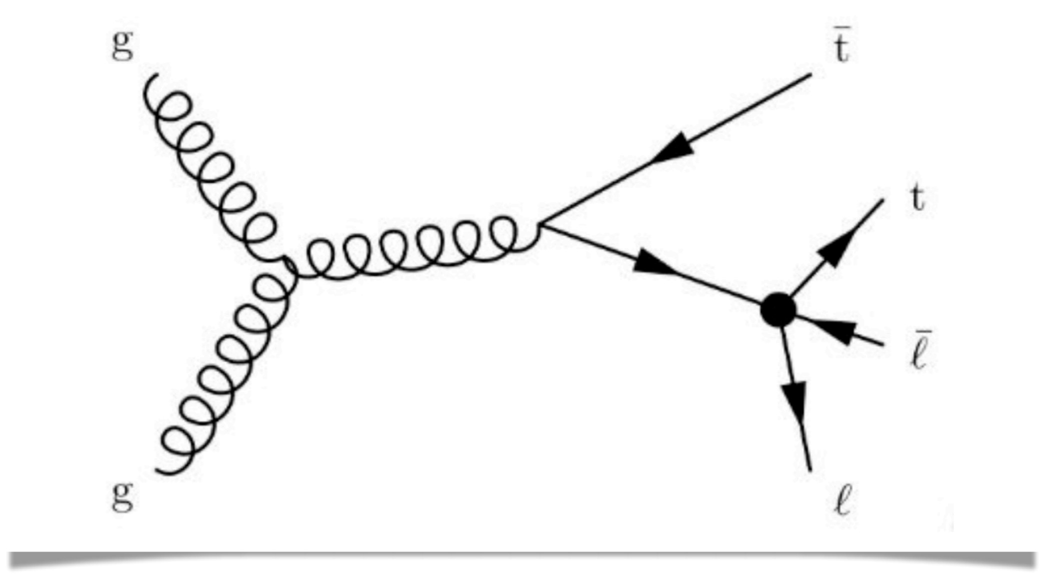
Results in TOP sector

tt(X) multilepton

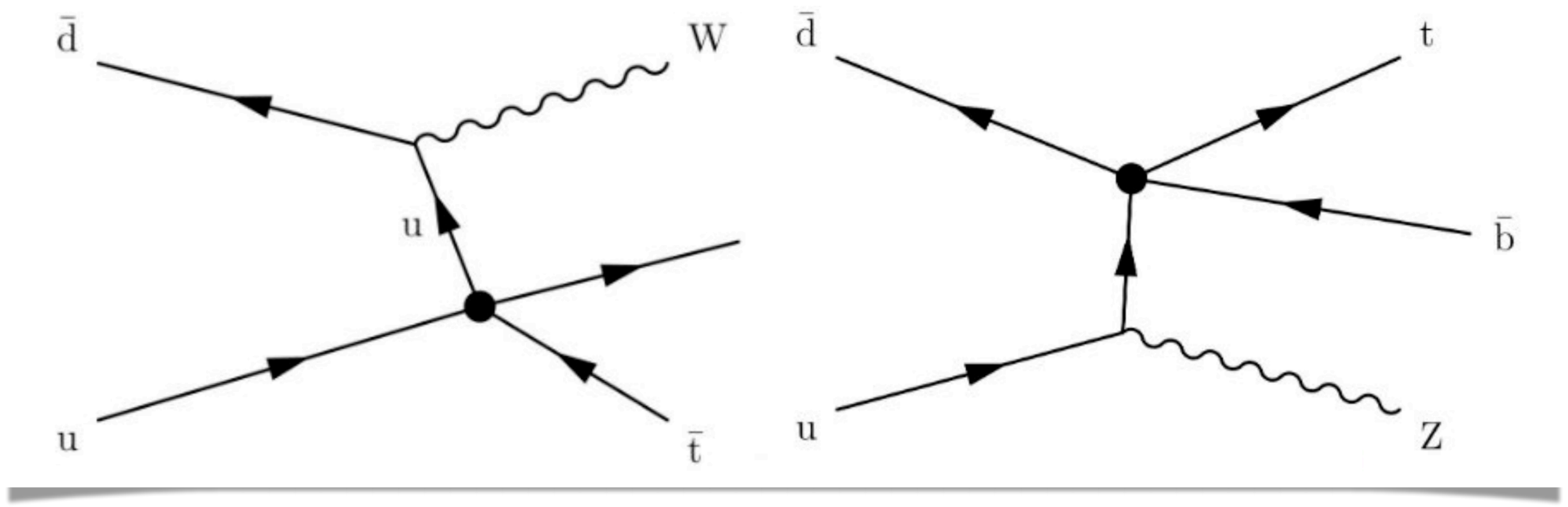
Overview

- Target multiple processes to capture as much sensitivity to EFT effects
  - ttH, ttll, ttlν, tHq, tllq, tttt
- dim6top @ LO + additional parton
  - 26 WCs fitted together

7 CP-even top-lepton



6 two-heavy-two-light



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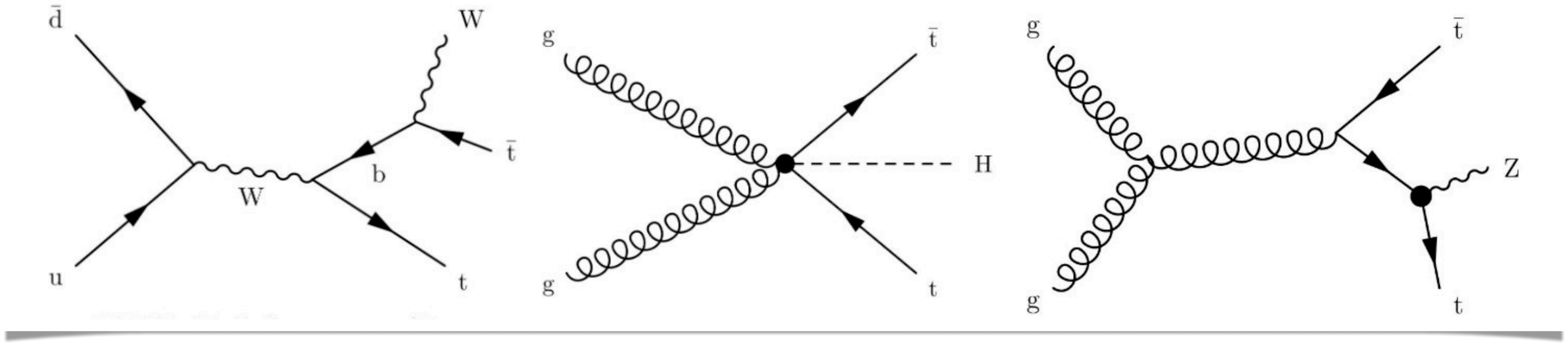
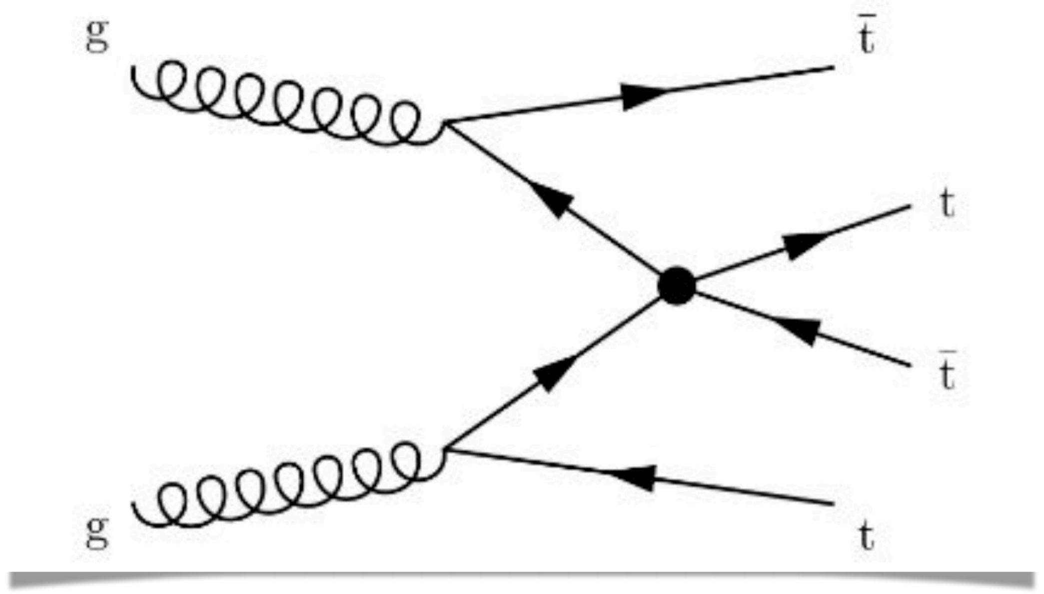


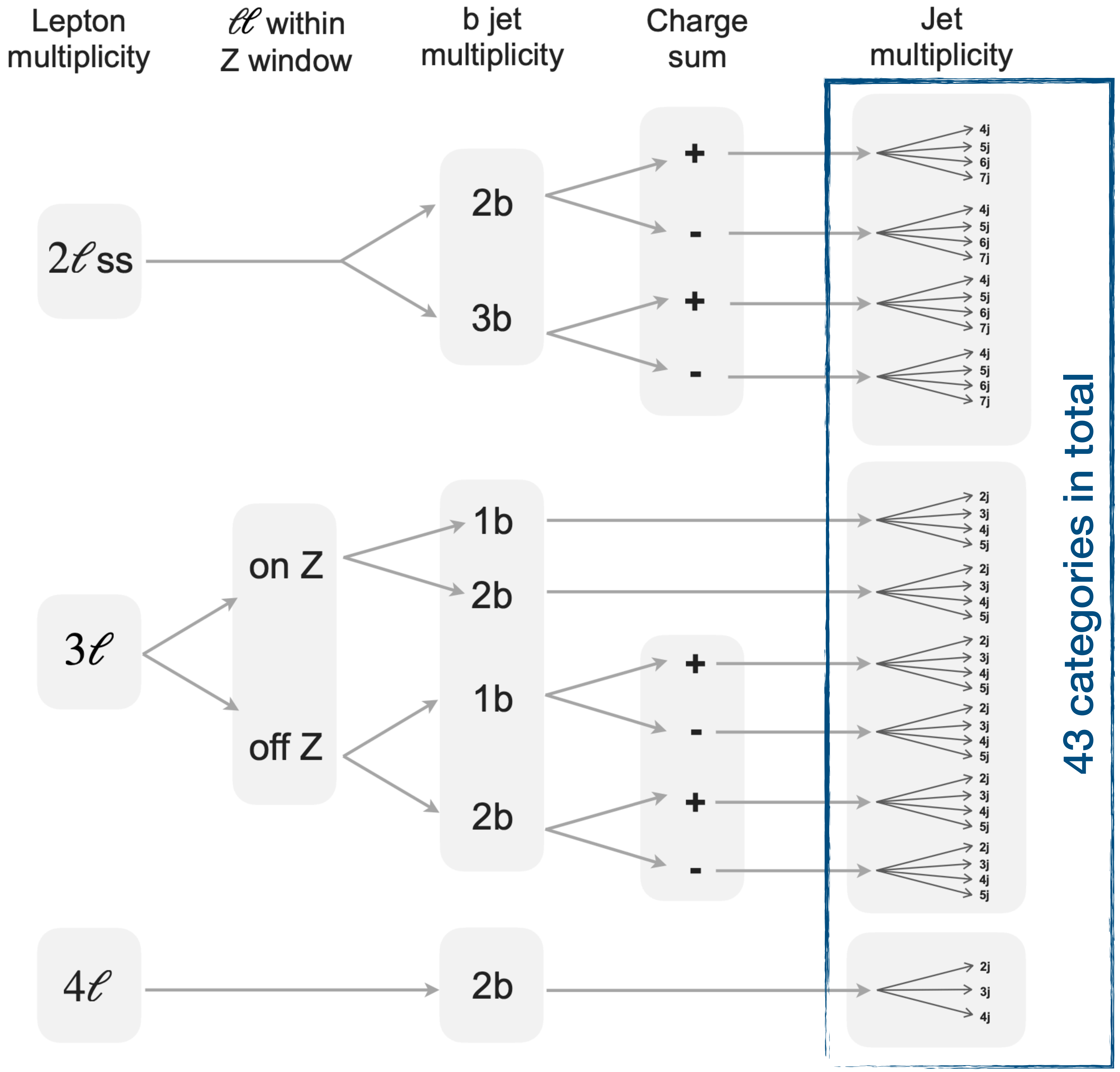
4 four-heavy quarks



tt(X) multilepton

Overview

- Target multiple processes to capture as much sensitivity to EFT effects
  - ttH, ttll, ttlν, tHq, tllq, tttt
- dim6top @ LO + additional parton
  - 26 WCs fitted together
- Wide coverage of the phase space exploiting lepton and jet multiplicities
- Fit performed with kinematic quantities sensitive to high-energy anomalies
  - $p_T(\ell j)_{\text{max}}$
    p_T of the object pair giving the largest one
  - $p_T(Z)$
    p_T of the reconstructed Z boson



tt(X) multilepton

Phase space and WCs

- Sensitivity optimized by the combination of the different bins

tt(X) multilepton

Phase space and WCs

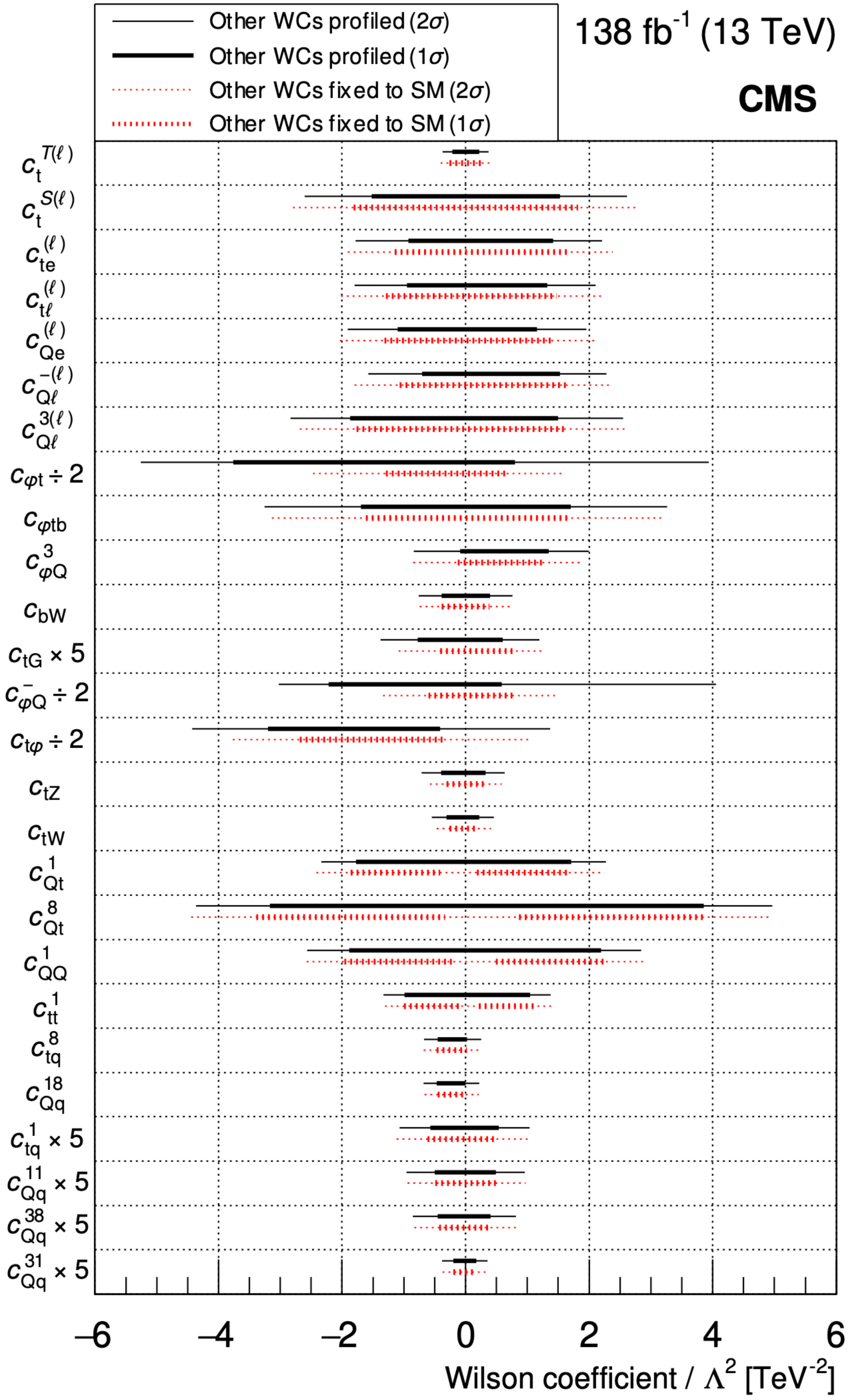
- Sensitivity optimized by the combination of the different bins
- For a specific WC, some categories are more significant than others
- Interference and correlations among WCs also play an important role

Grouping of WCs	WCs	Lead categories
Two heavy two leptons	$c_{Q\ell}^{3(\ell)}$, $c_{Q\ell}^{-(\ell)}$, $c_{Qe}^{(\ell)}$, $c_{t\ell}^{(\ell)}$, $c_{te}^{(\ell)}$, $c_{t}^{S(\ell)}$, $c_{t}^{T(\ell)}$	3ℓ off-Z
Four heavy	c_{QQ}^{1}, c_{Qt}^{1}, c_{Qt}^{8}, c_{tt}^{1}	2ℓss
Two heavy two light "$t\bar{t}l\nu$-like"	c_{Qq}^{11}, c_{Qq}^{18}, c_{tq}^{1}, c_{tq}^{8}	2ℓss
Two heavy two light "$tl\bar{l}q$-like"	c_{Qq}^{31}, c_{Qq}^{38}	3ℓ on-Z
Two heavy with bosons "$t\bar{t}l\bar{l}$-like"	c_{tZ}, $c_{\varphi t}$, $c_{\varphi Q}^{-}$	3ℓ on-Z and 2ℓss
Two heavy with bosons "tXq-like"	$c_{\varphi Q}^{3}$, $c_{\varphi tb}$, c_{bW}	3ℓ on-Z
Two heavy with bosons with significant impacts on many processes	c_{tG}, $c_{t\varphi}$, c_{tW}	3ℓ and 2ℓss

tt(X) multilepton

Constraints on single WC

- Very challenging to run fit over 26 parametres and 178 analysis bins



CMS

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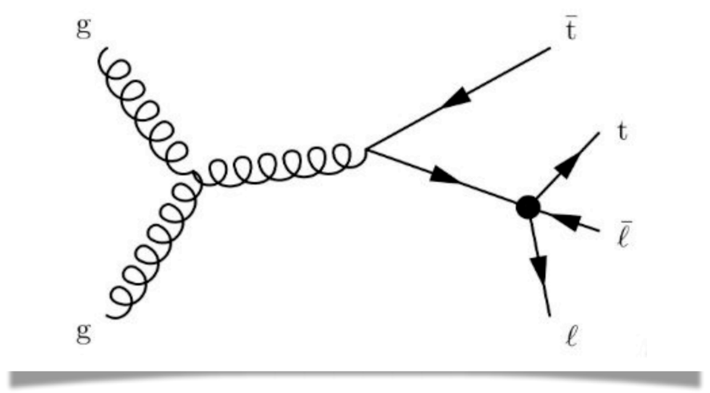
tt(X) multilepton

Constraints on single WC

- Very challenging to run fit over 26 parametres and 178 analysis bins
- Provided 1D constraints
  - Other WCs fixed to SM
  - Other WCs profiled
- No significant deviation from SM prediction

7 CP-even top-lepton



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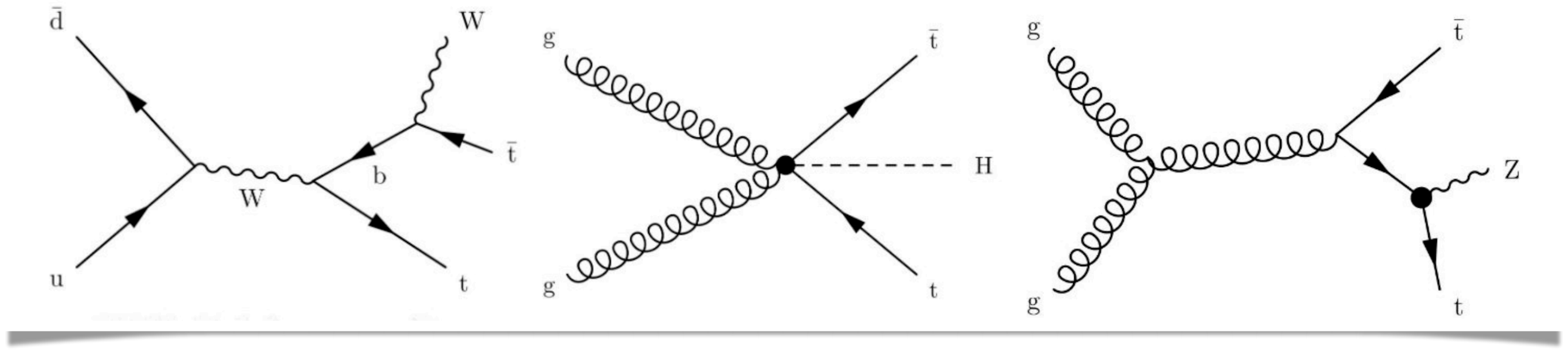

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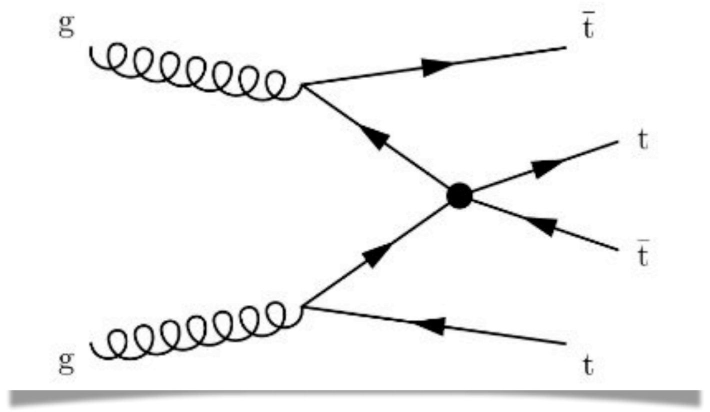

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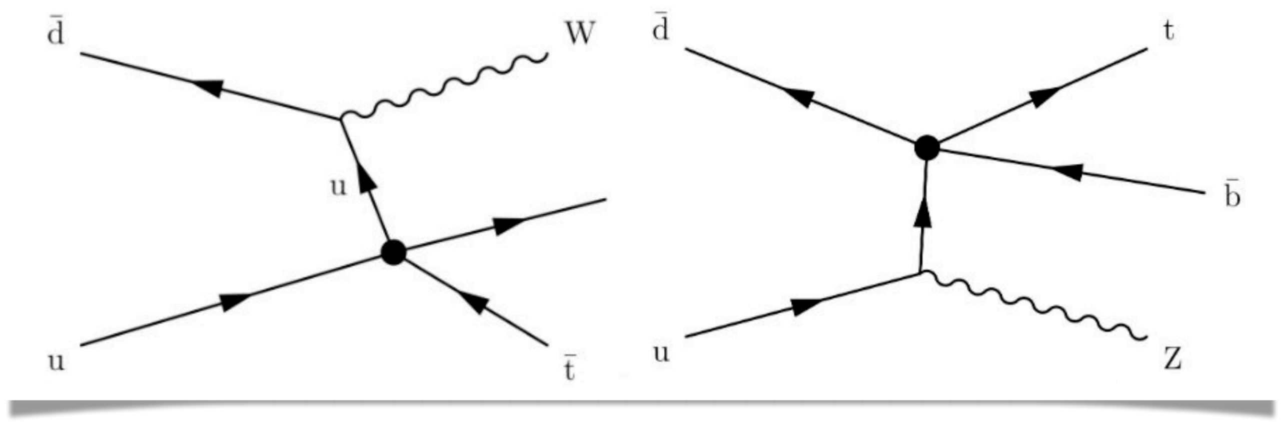
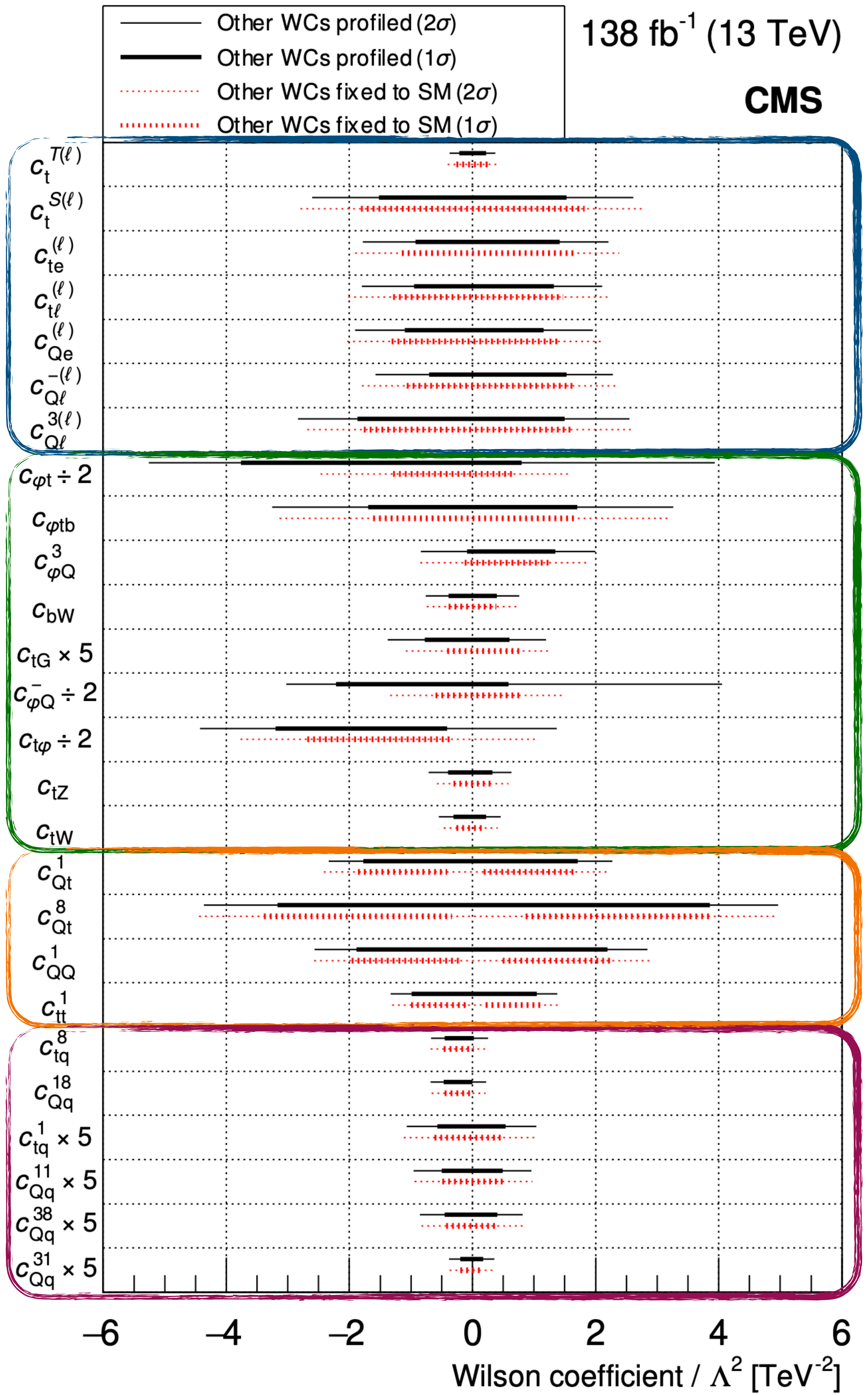
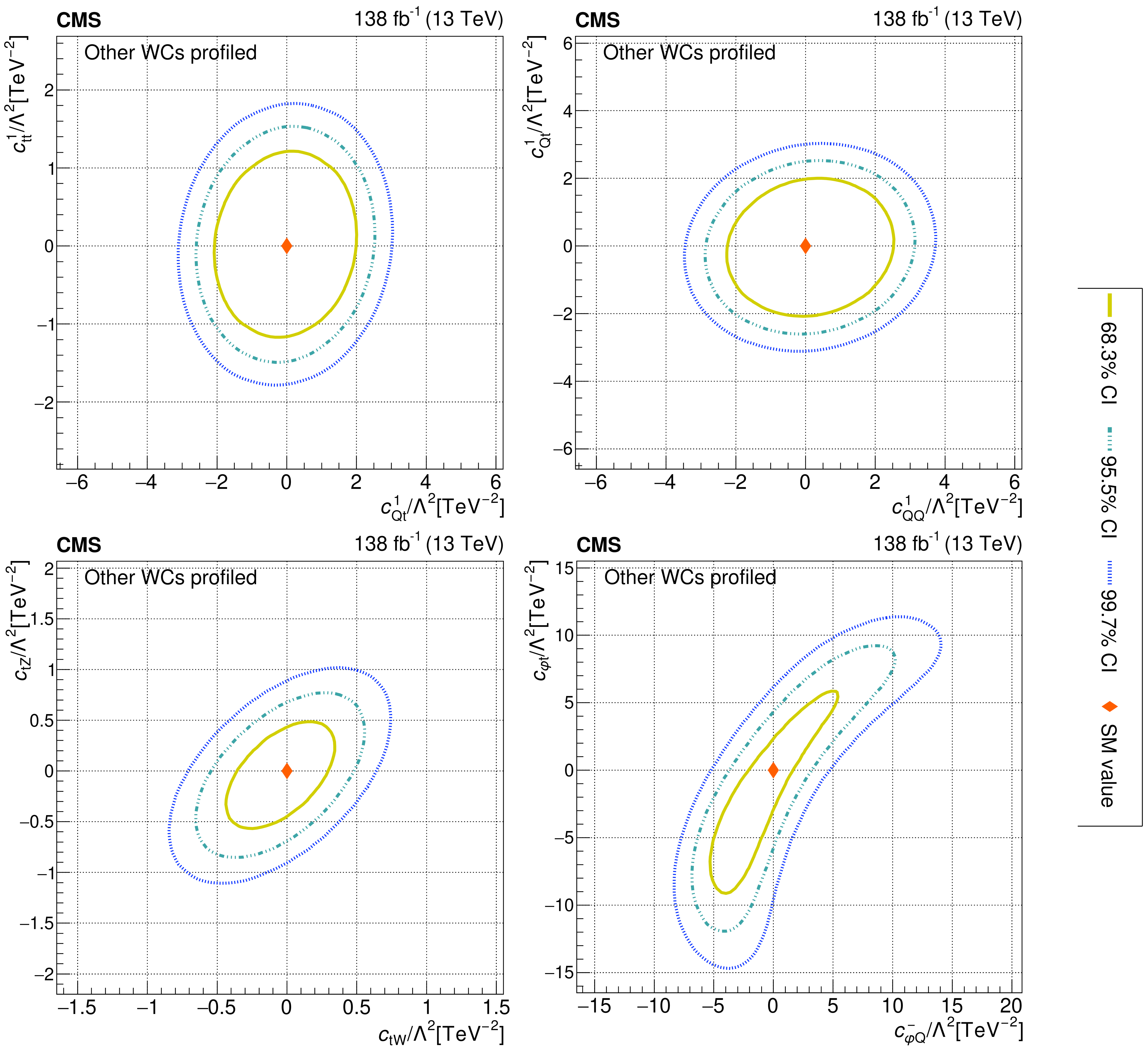




tt(X) multilepton

Constraints on two WCs at a time

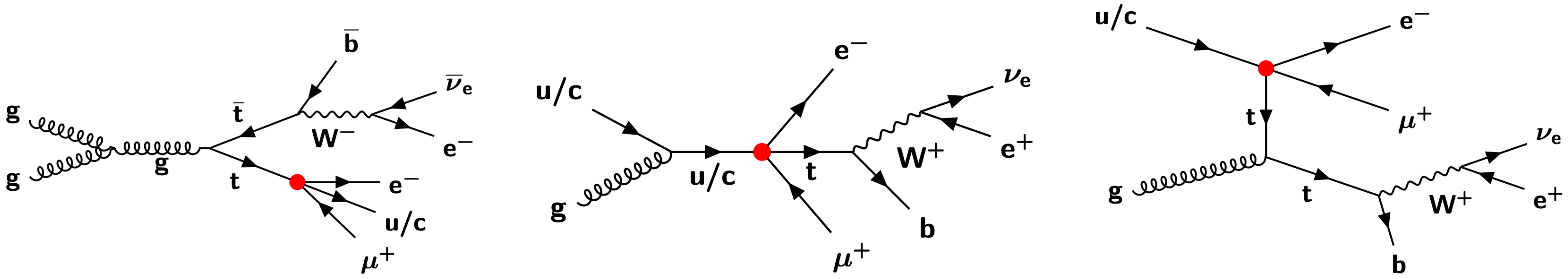
- Provided 2D constraints
  - Other WCs fixed to SM
  - Other WCs profiled
- No significant deviation from SM prediction
- Correlation depending on the specific pair



Search for cLFV with trileptons

Overview

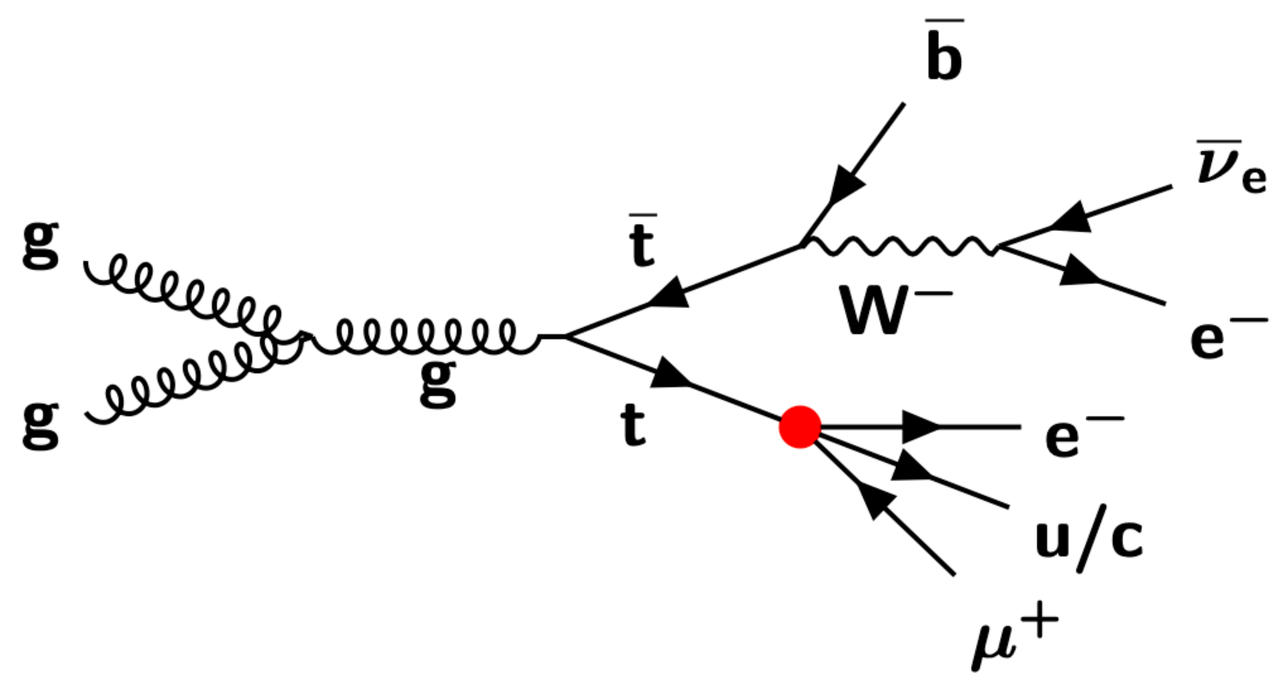
- Opposite-charged $e\mu$ pair from cLFV vertex, 1ℓ from top decay, 1 b-tagged jet



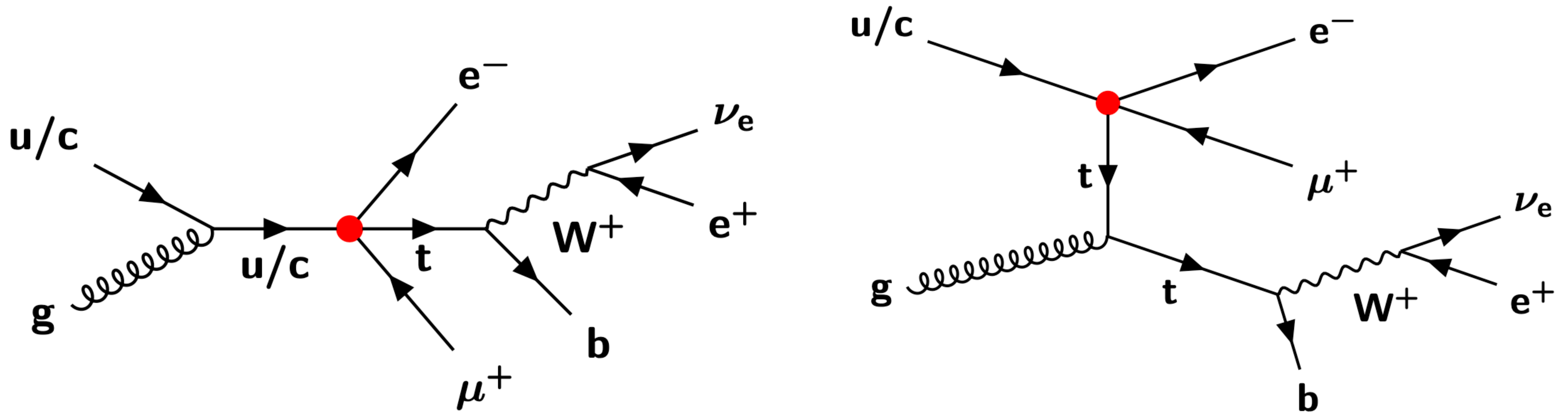
Search for cLFV with trileptons

Overview

- Opposite-charged $e\mu$ pair from cLFV vertex, 1ℓ from top decay, 1 b-tagged jet
- cLFV in top decay and top production
  - Highly suppressed in SM
  - No interference with SM diagrams



tt pair



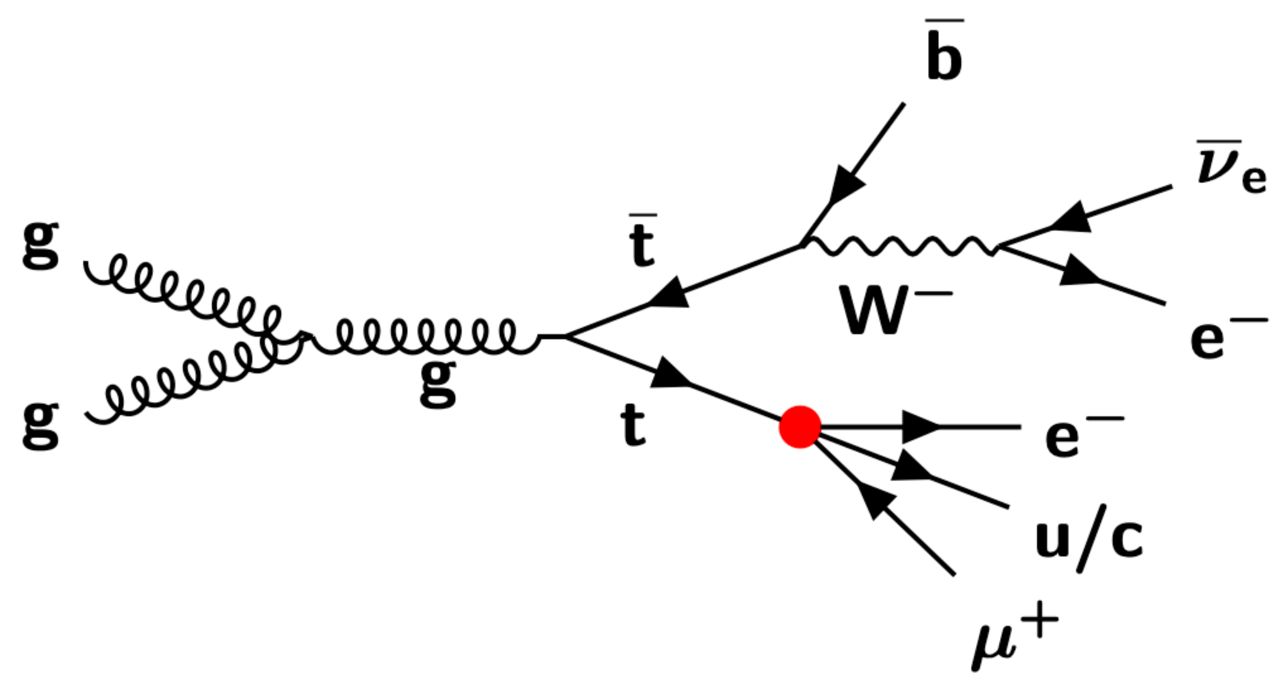
Single top

Search for cLFV with trileptons

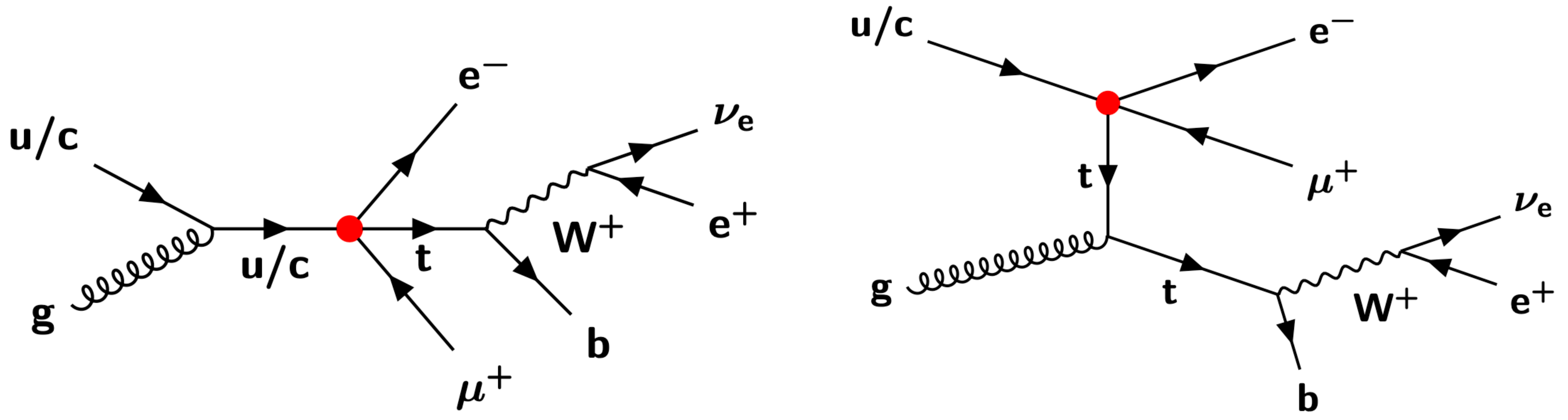
Overview

- Opposite-charged $e\mu$ pair from cLFV vertex, 1ℓ from top decay, 1 b-tagged jet
- cLFV in top decay and top production
  - Highly suppressed in SM
  - No interference with SM diagrams
- Target scalar, vector, and tensor BSM interactions
  - Interpreted in terms of four-fermion EFT operators (SMEFT-FR @ LO)

vector	$O_{lq}^{(1)ijkl}$	$(\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l)$
	O_{lu}^{ijkl}	$(\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l)$
	O_{eq}^{ijkl}	$(\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l)$
	O_{eu}^{ijkl}	$(\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l)$
scalar	$O_{lequ}^{(1)ijkl}$	$(\bar{l}_i e_j)\ \varepsilon\ (\bar{q}_k u_l)$
tensor	$O_{lequ}^{(3)ijkl}$	$(\bar{l}_i\sigma^{\mu\nu} e_j)\ \varepsilon\ (\bar{q}_k\sigma_{\mu\nu} u_l)$



tt pair

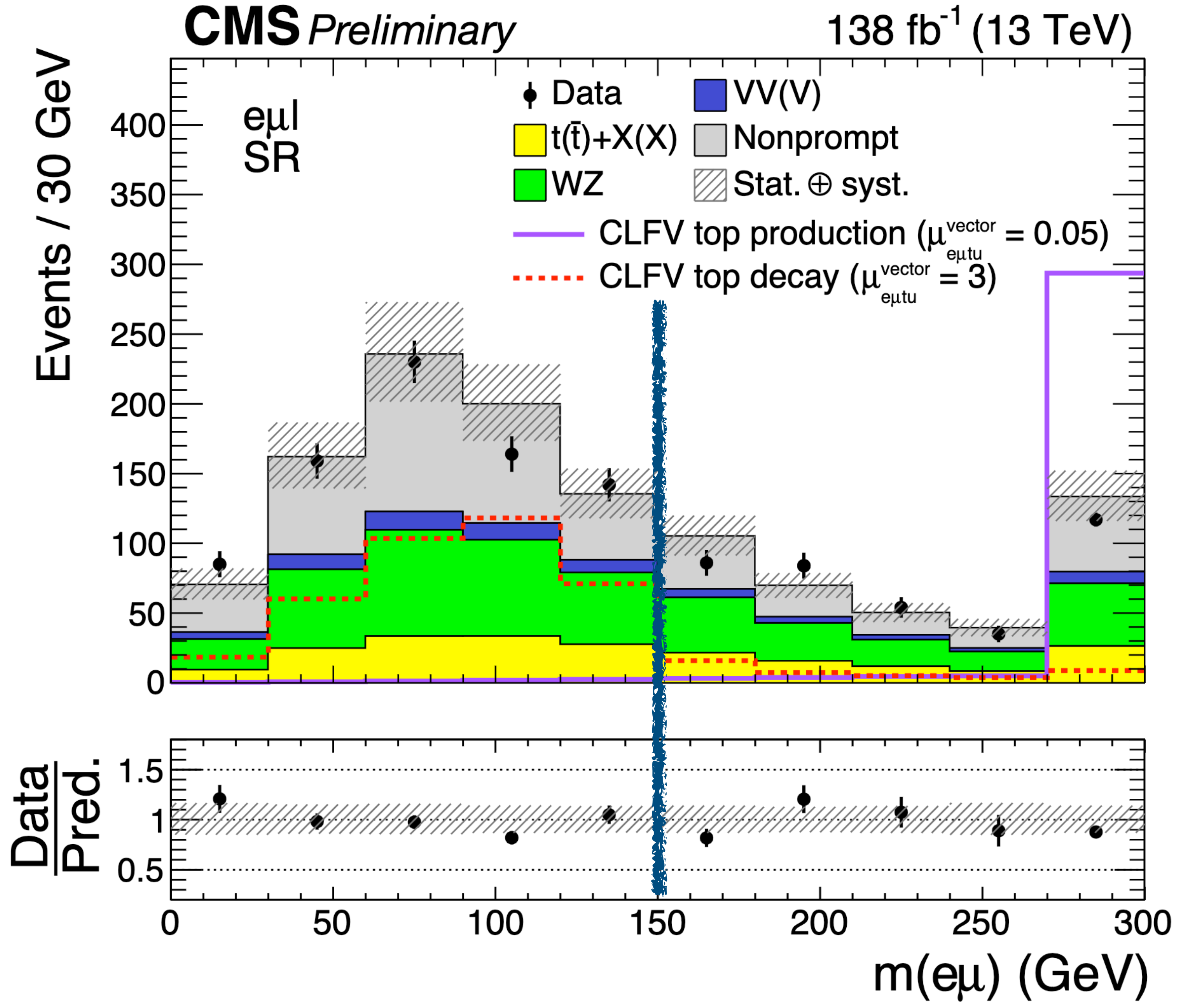


Single top

Search for cLFV with trileptons

Sensitivity optimization

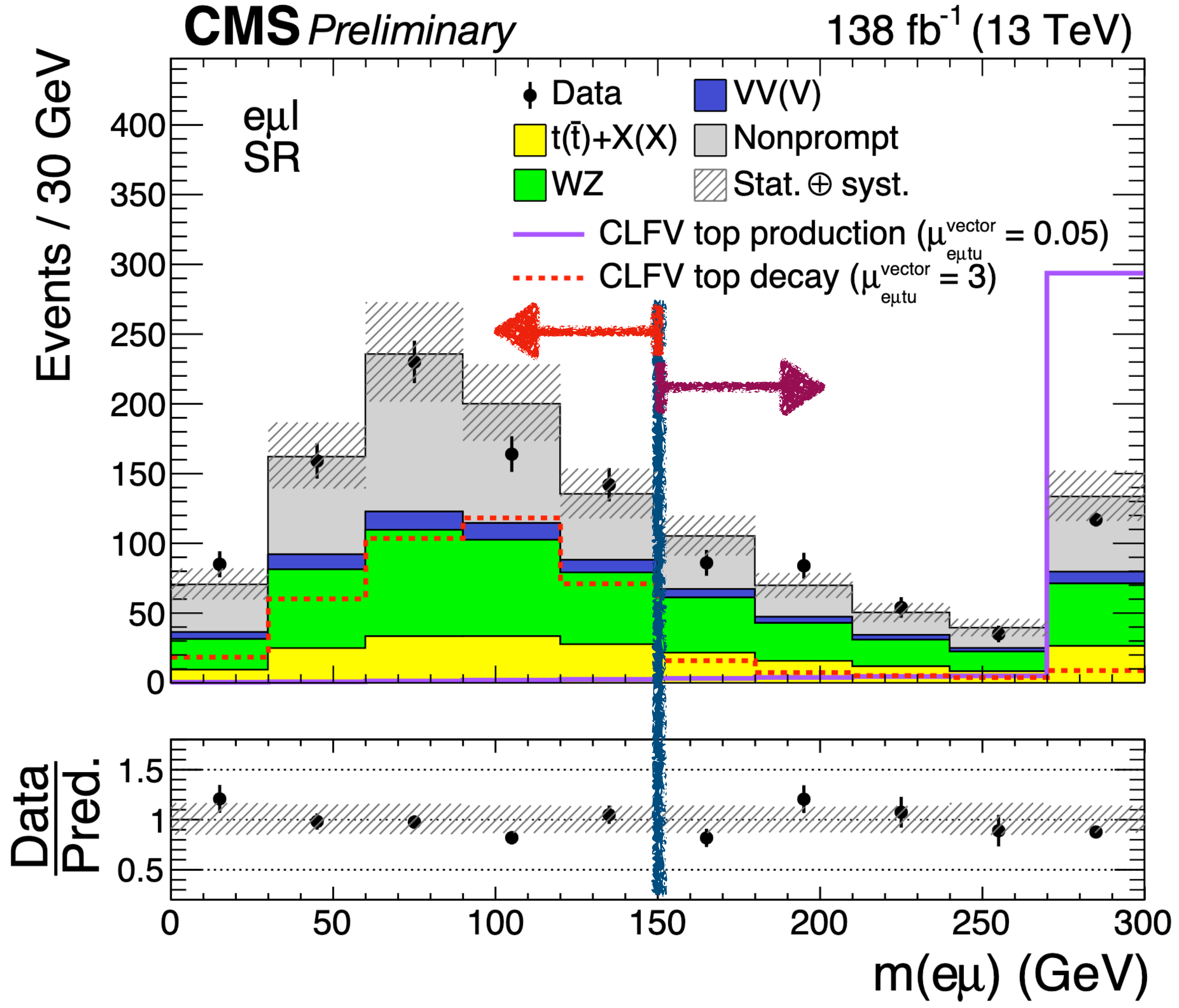
- $m_{e\mu}$ to separate the signals

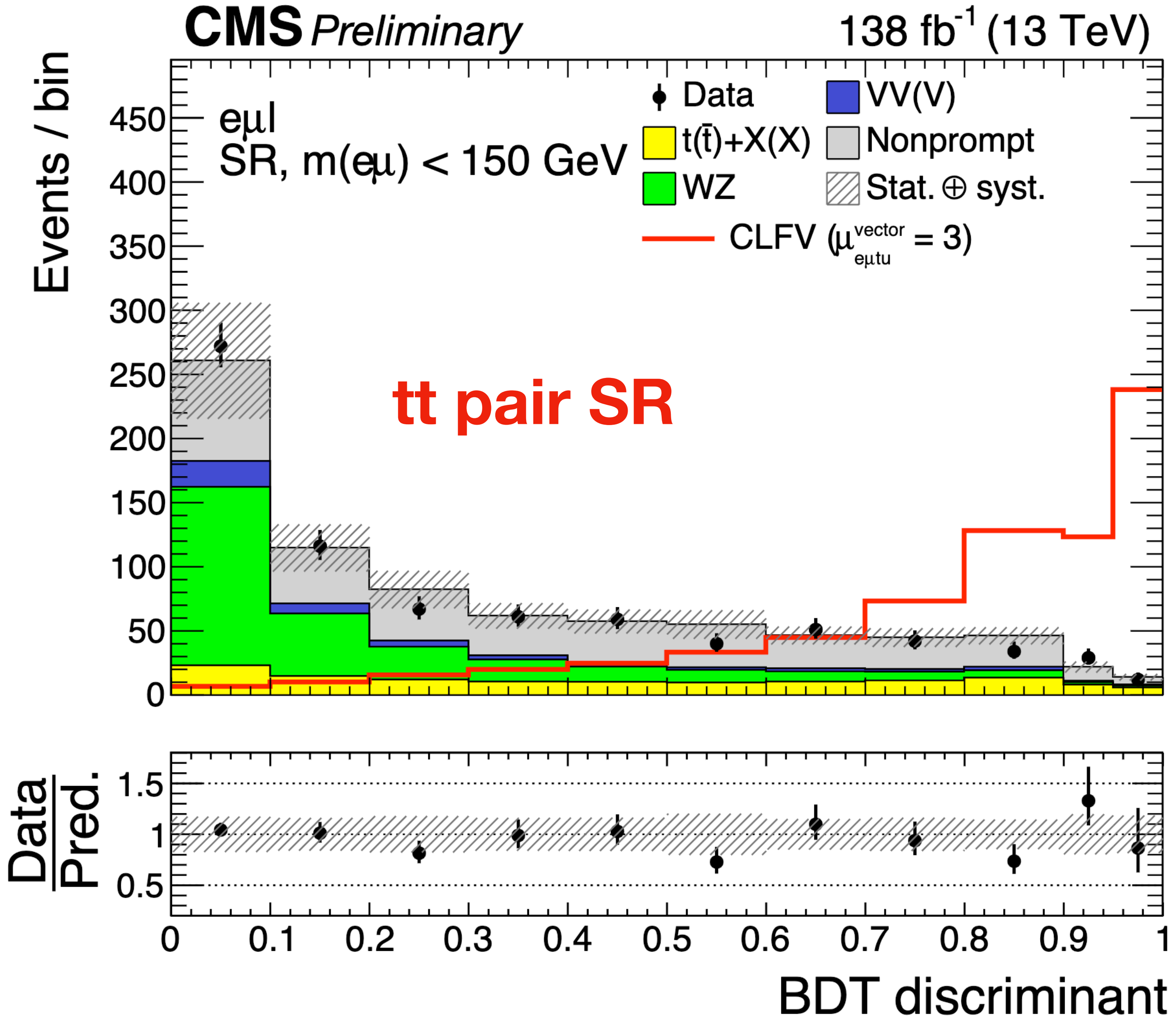


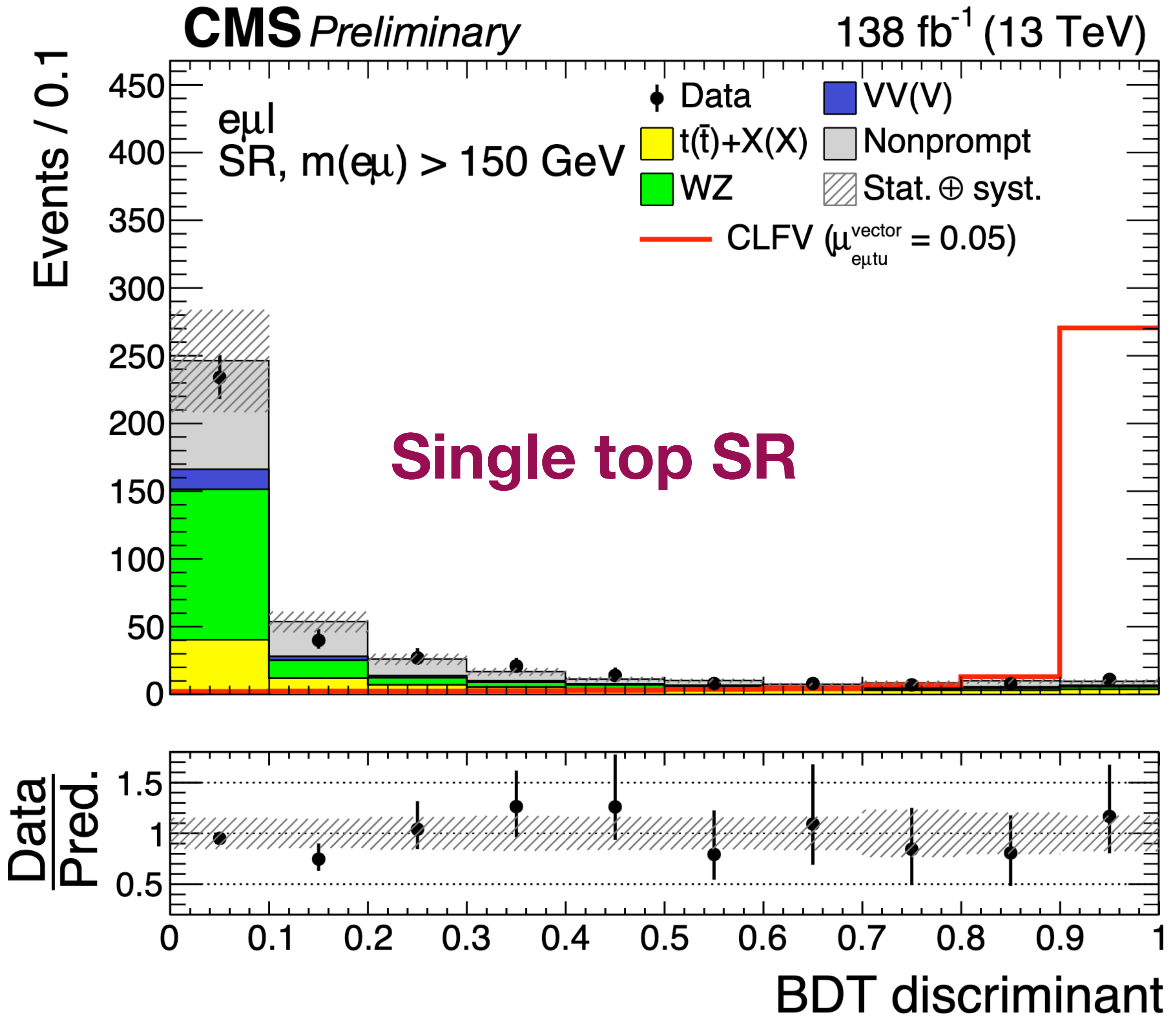
Search for cLFV with trileptons

Sensitivity optimization

- $m_{e\mu}$ to separate the signals
- 1 SR for **single top** (drives the sensitivity)
- 1 SR for **tt pair** production
- Trained BDT to discriminate signal against backgrounds
  - Score used to perform the fit







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Search for cLFV with trileptons

Results

- No deviation from SM
- 1D limits on 6 $C_{e\mu tq}$ coefficients
  - More stringent limit on tensor WC than the others due to its large cross section

CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) exp $(-\sigma, +\sigma)$	**obs**
$e\mu tu$	tensor	0.019 (0.015, 0.023)	**0.020**
	vector	0.037 (0.031, 0.046)	**0.041**
	scalar	0.077 (0.064, 0.095)	**0.084**
$e\mu tc$	tensor	0.061 (0.050, 0.074)	**0.068**
	vector	0.130 (0.108, 0.159)	**0.144**
	scalar	0.269 (0.223, 0.330)	**0.295**

Search for cLFV with trileptons

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- No deviation from SM
- 1D limits on 6 $C_{e\mu tq}$ coefficients
  - More stringent limit on tensor WC than the others due to its large cross section
- Translating into limits on the branching fractions
  - More stringent limits on scalar operator

CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) exp $(-\sigma, +\sigma)$	obs	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ exp $(-\sigma, +\sigma)$	obs
$e\mu tu$	tensor	0.019 (0.015, 0.023)	**0.020**	0.019 (0.013, 0.029)	**0.023**
	vector	0.037 (0.031, 0.046)	**0.041**	0.013 (0.009, 0.020)	**0.016**
	scalar	0.077 (0.064, 0.095)	**0.084**	0.007 (0.005, 0.011)	**0.009**
$e\mu tc$	tensor	0.061 (0.050, 0.074)	**0.068**	0.209 (0.143, 0.311)	**0.258**
	vector	0.130 (0.108, 0.159)	**0.144**	0.163 (0.111, 0.243)	**0.199**
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Search for cLFV with trileptons

Results

- No deviation from SM
- 1D limits on 6 $C_{e\mu tq}$ coefficients
  - More stringent limit on tensor WC than the others due to its large cross section
- Translating into limits on the branching fractions
  - More stringent limits on scalar operator
- 2D limits from 1D limits assuming linearity between $B(t \to e\mu u)$ and $B(t \to e\mu c)$
- Most stringent limit on $B(t \to e\mu q)$

CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) exp $(-\sigma, +\sigma)$	obs	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ exp $(-\sigma, +\sigma)$	obs
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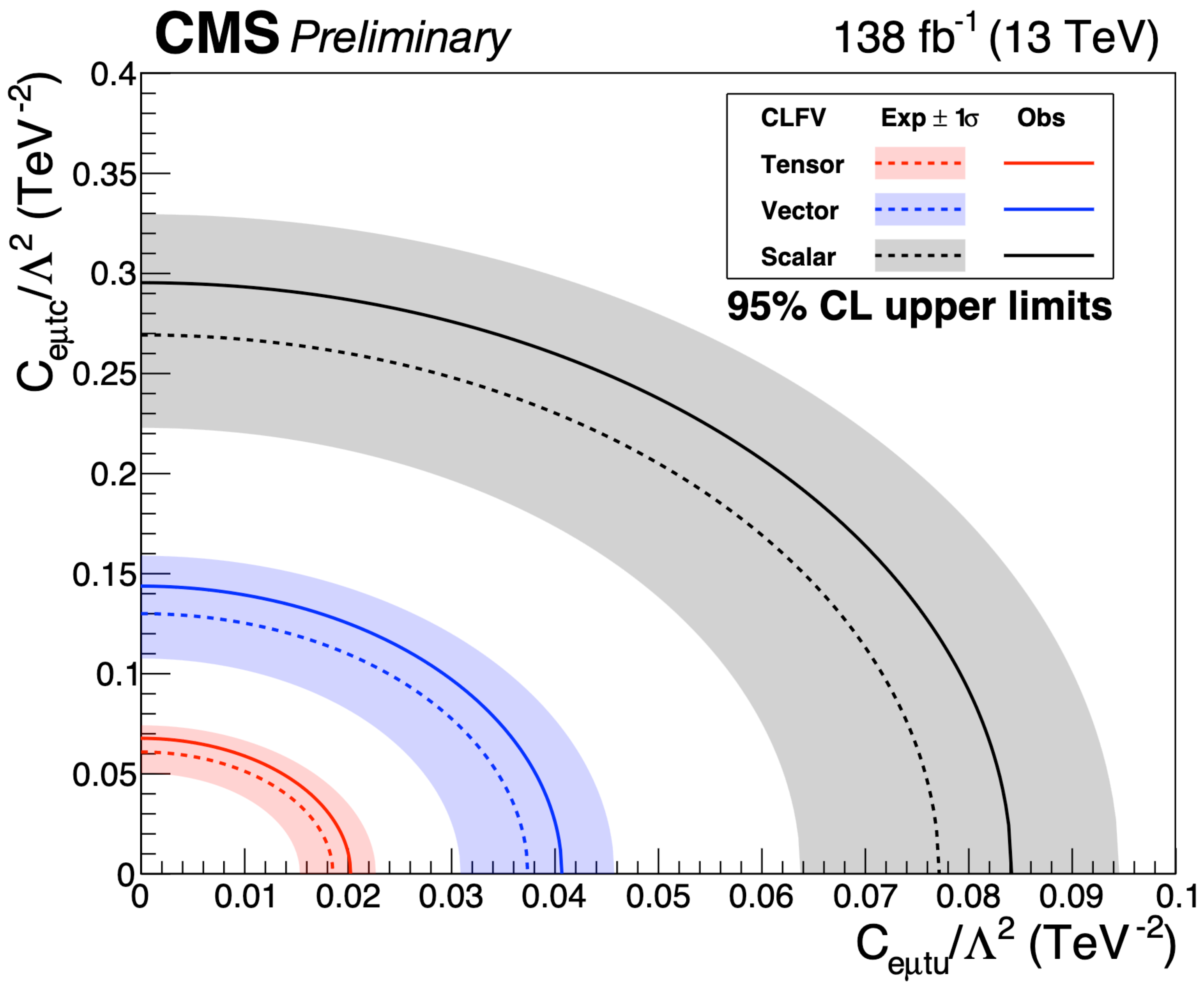
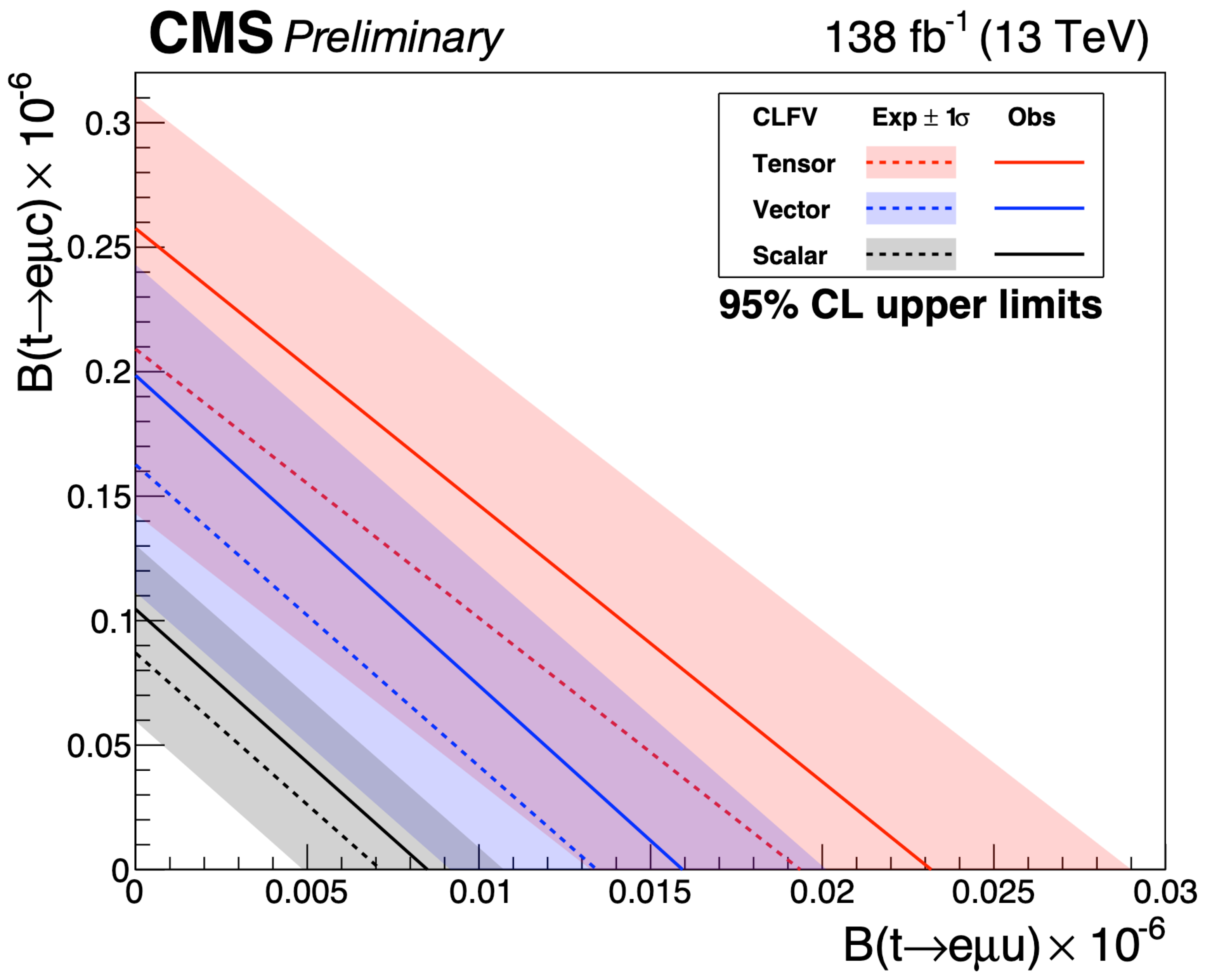
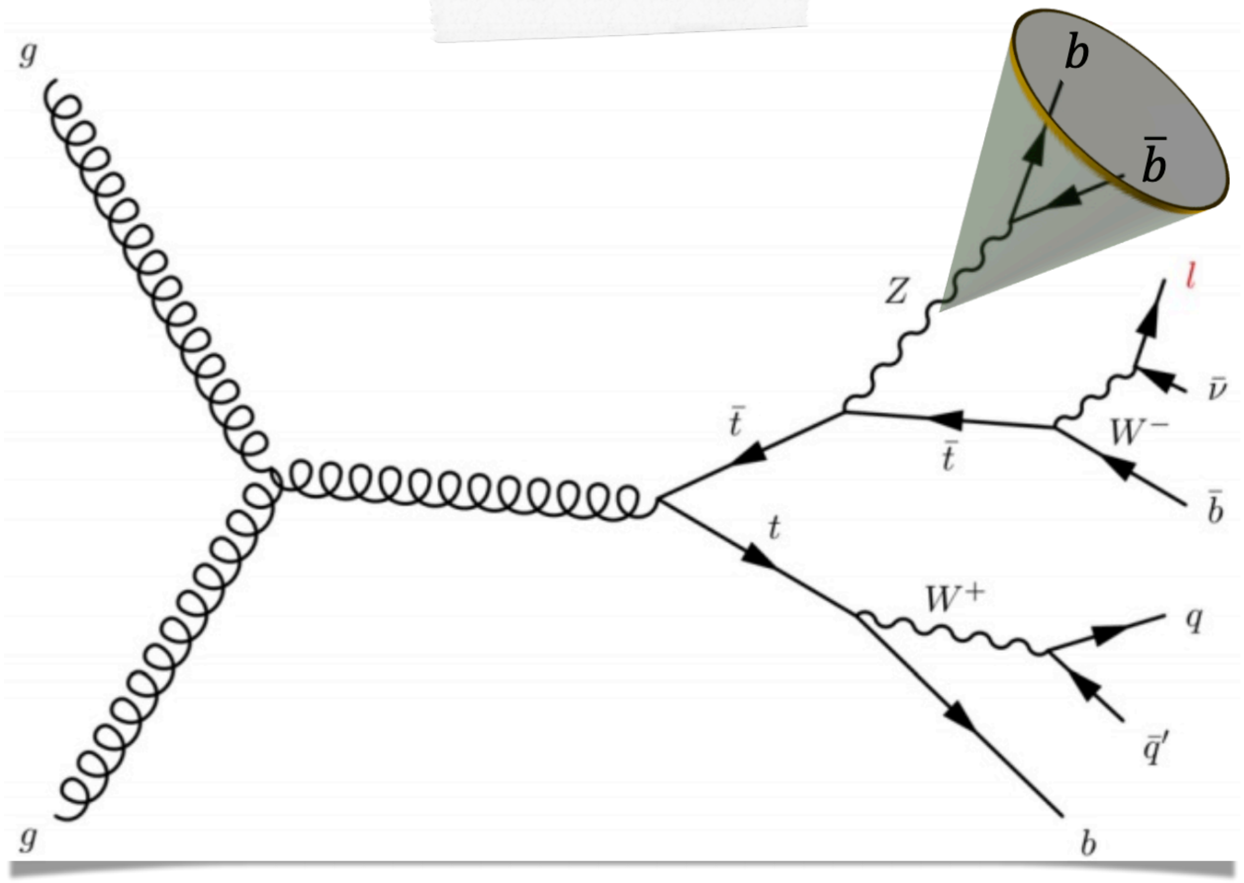




tt with a boosted H or Z

Overview

- Single lepton + 1 tagged AK8 jet (H → bb discriminator)
- Targeting EFT effects in tt + boosted H/Z along with SM measurements
  - 8 top+boson operators (dim6top @ LO + additional parton)
- Explore the EFT effect in a relevant background
  - c_{bW} and $c^3_{\varphi Q}$ affecting tt+bb



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- Explore the EFT effect in a relevant background
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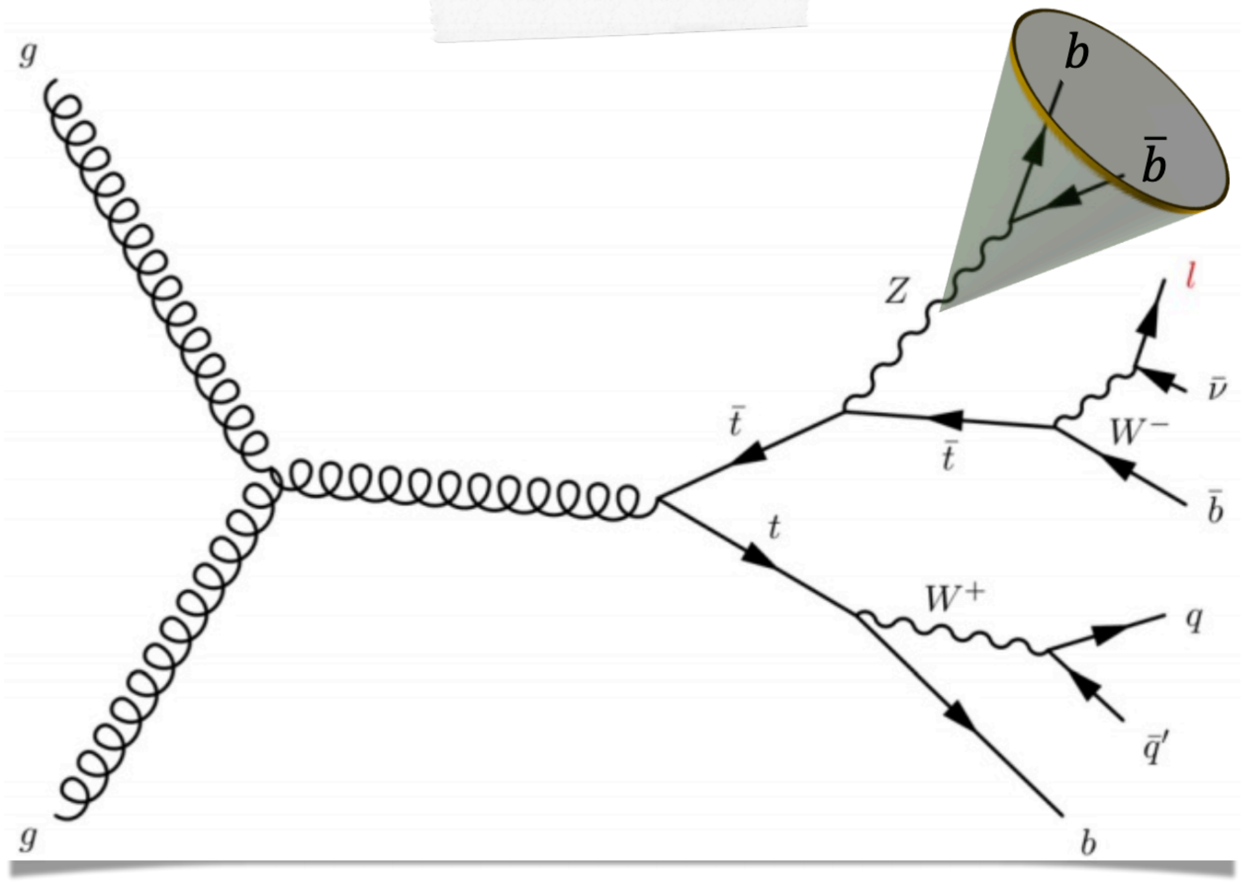
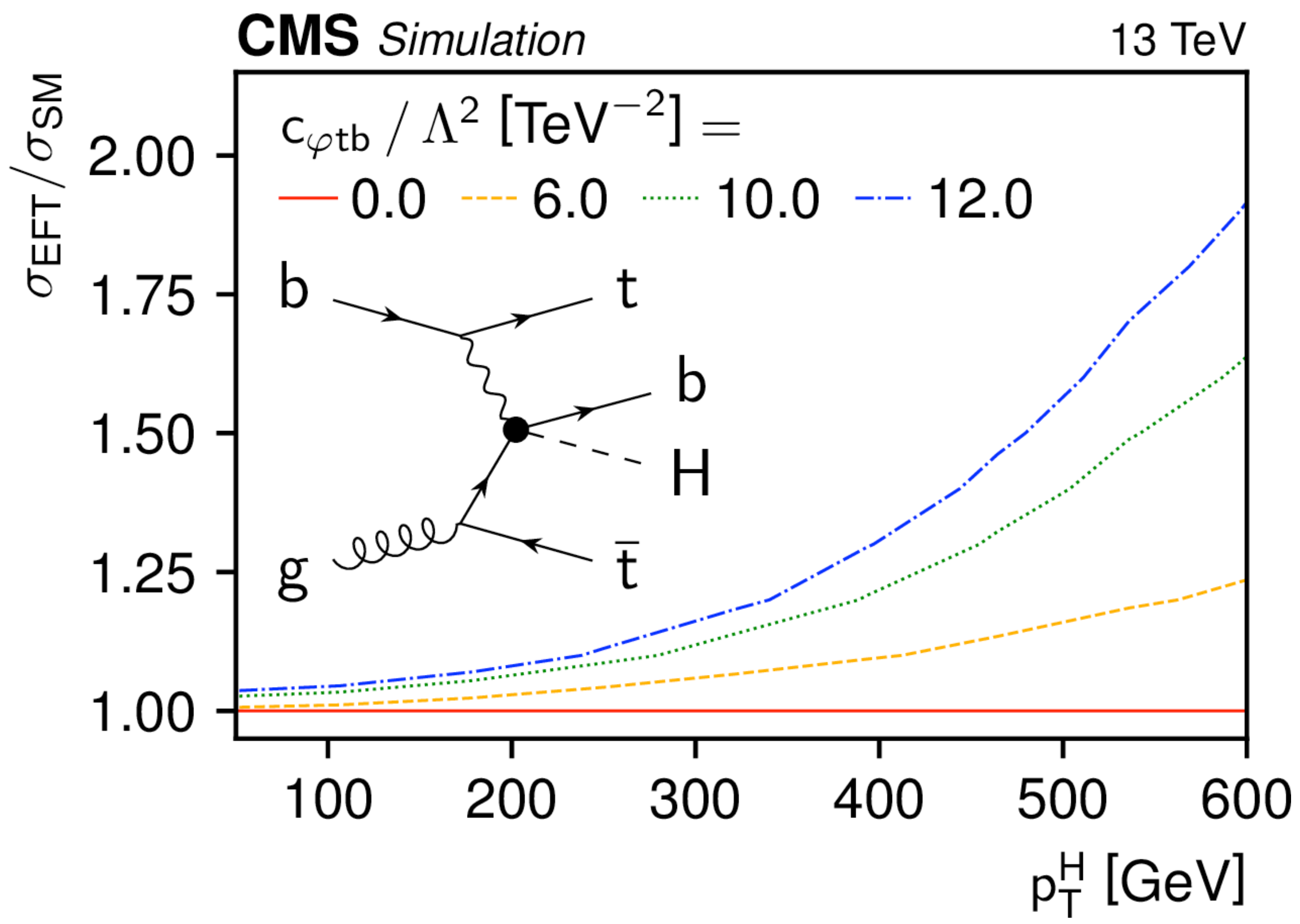
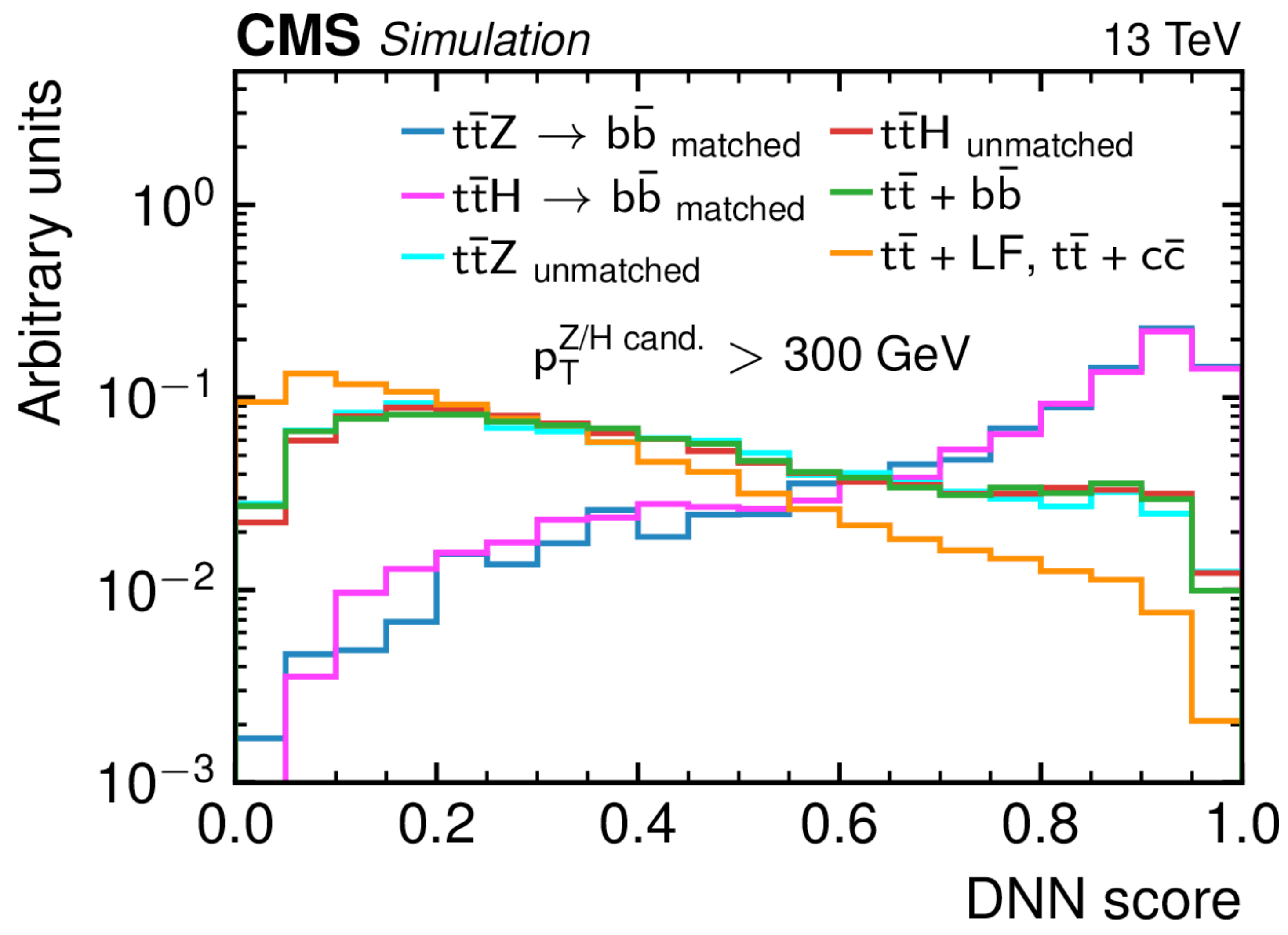
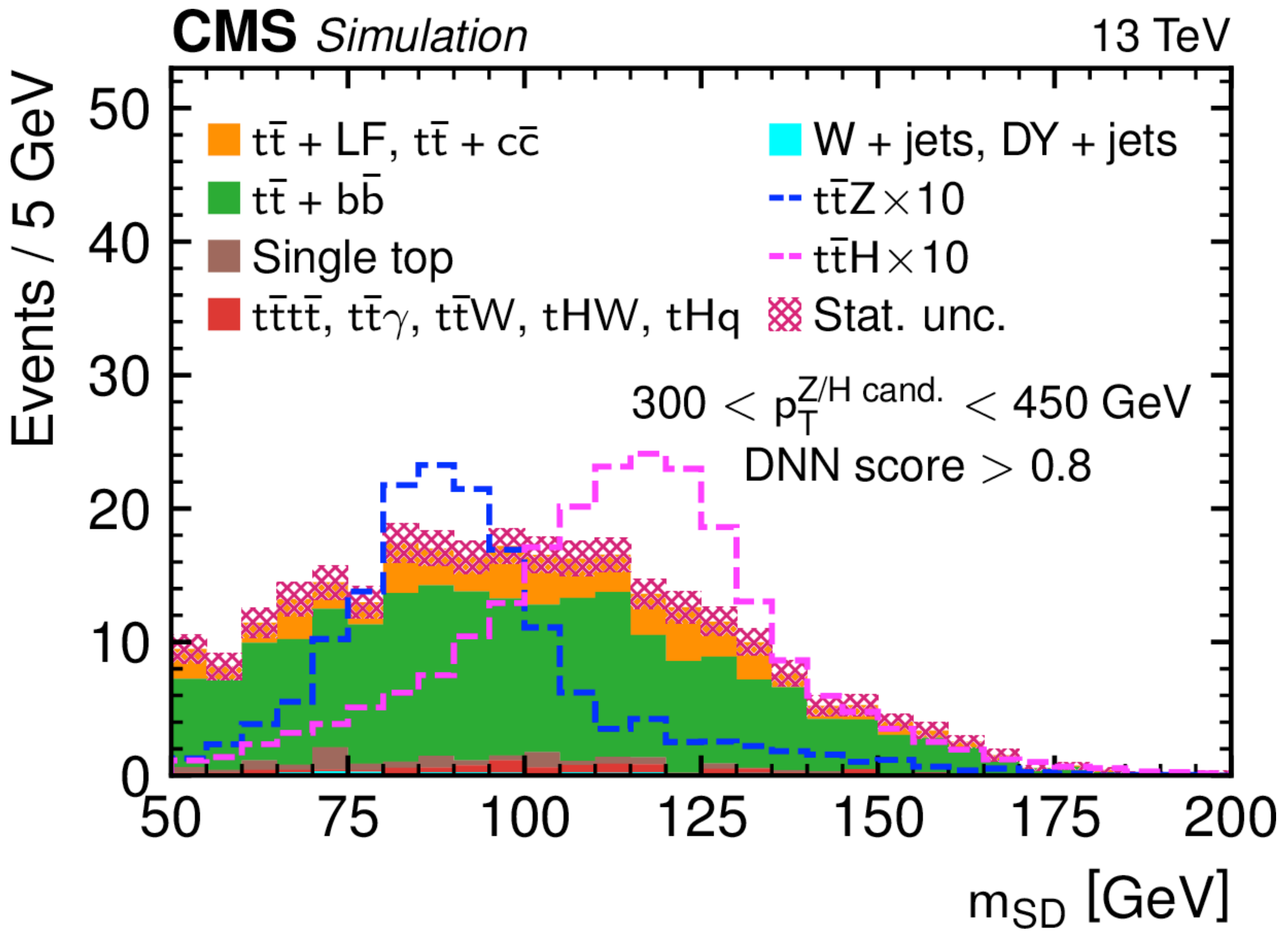
- Analysis bins defined upon 3 quantities
  - AK8 jet mass, Z/H candidate p_T, and multiclassifier DNN signal score





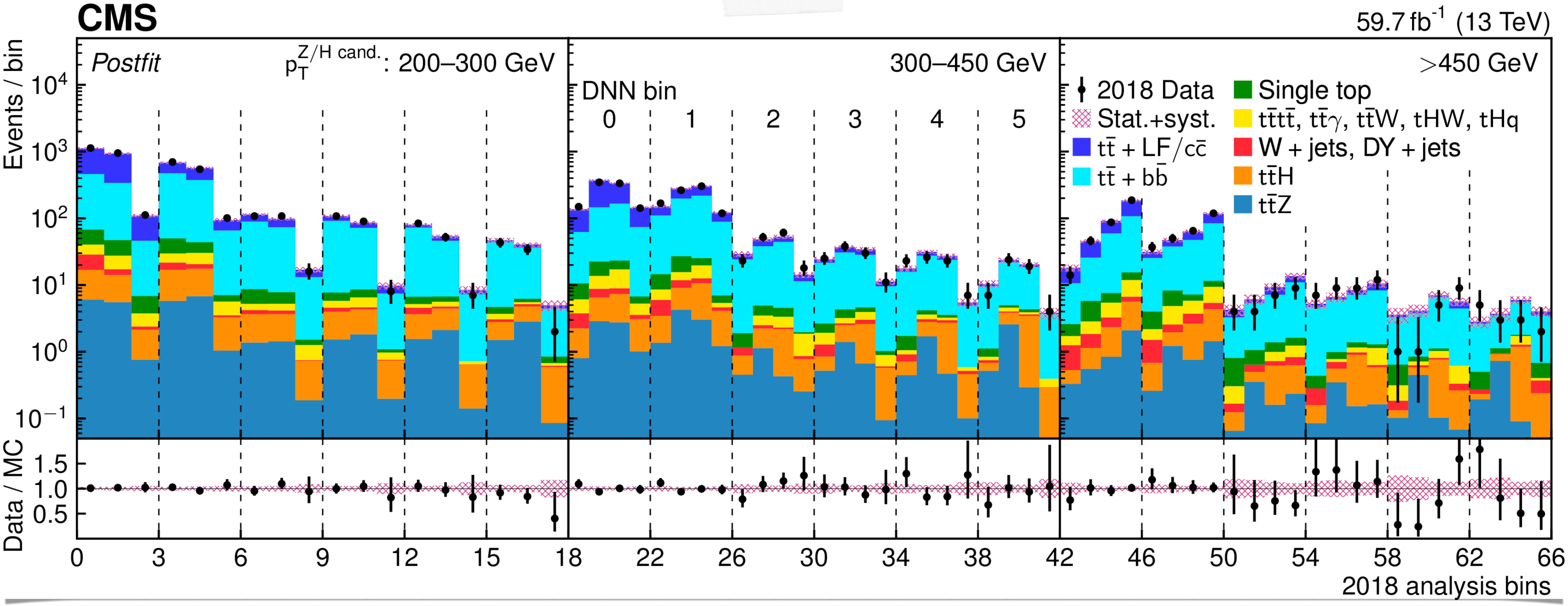




$t\bar{t}$ with a boosted H or Z

Event categorization

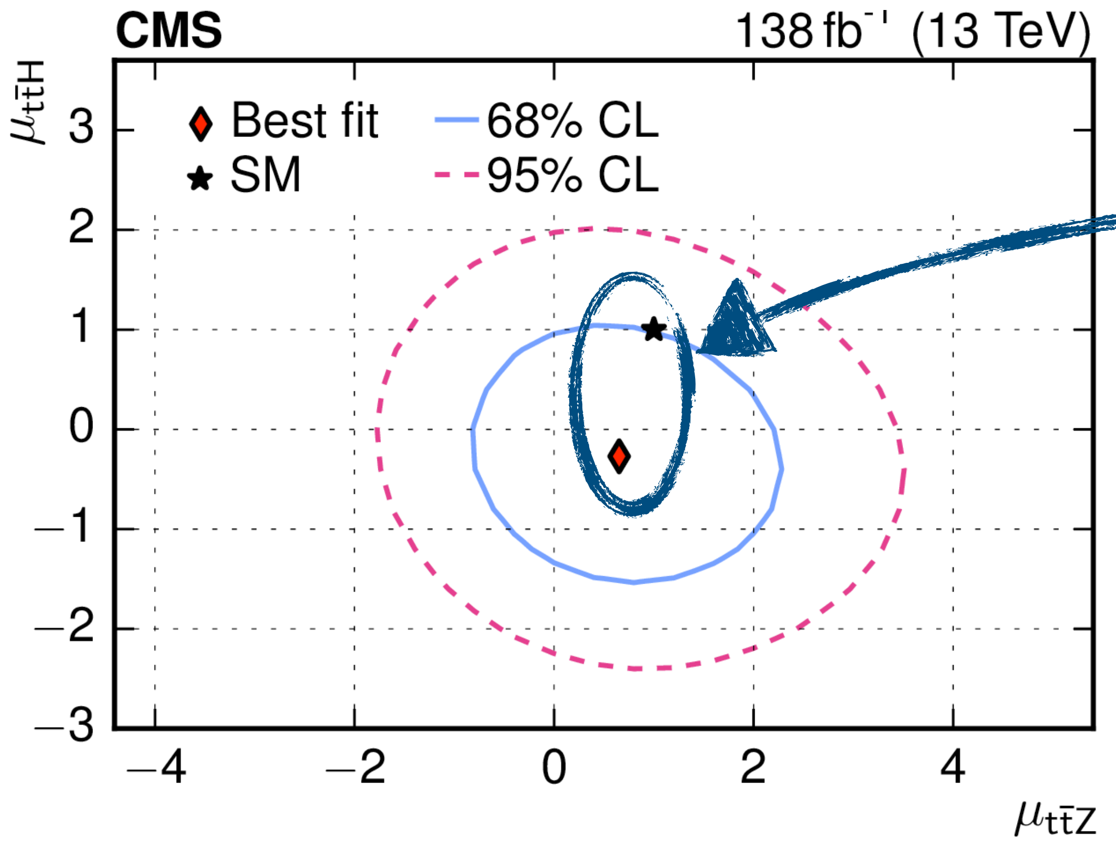
- "Flattened" 3D fit —> 66 bins per each year



tt with a boosted H or Z

EFT sensitivity studies

- EFT predictions renormalized to NLO SM
- From SM measurement, tt+bb higher than expected
    - ttH/ttZ signal strengths towards negative values



$$\frac{\sigma_{tt+bb}}{\sigma^{SM}_{tt+bb}} > 1$$

tt with a boosted H or Z

EFT sensitivity studies

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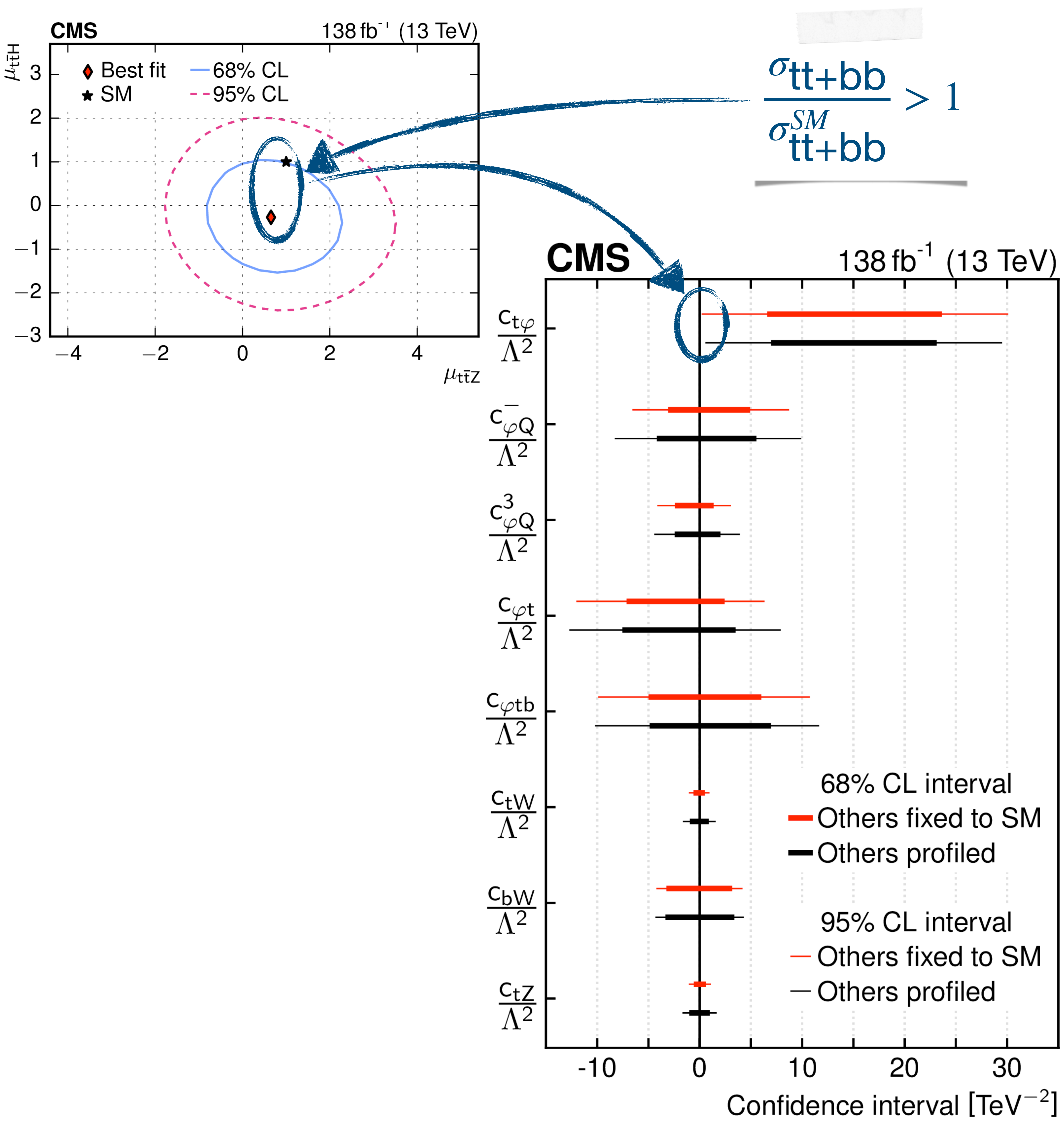
- Induces the tension wrt SM scenario for $c_{t\varphi}$
- Other 1D scans are compatible with SM



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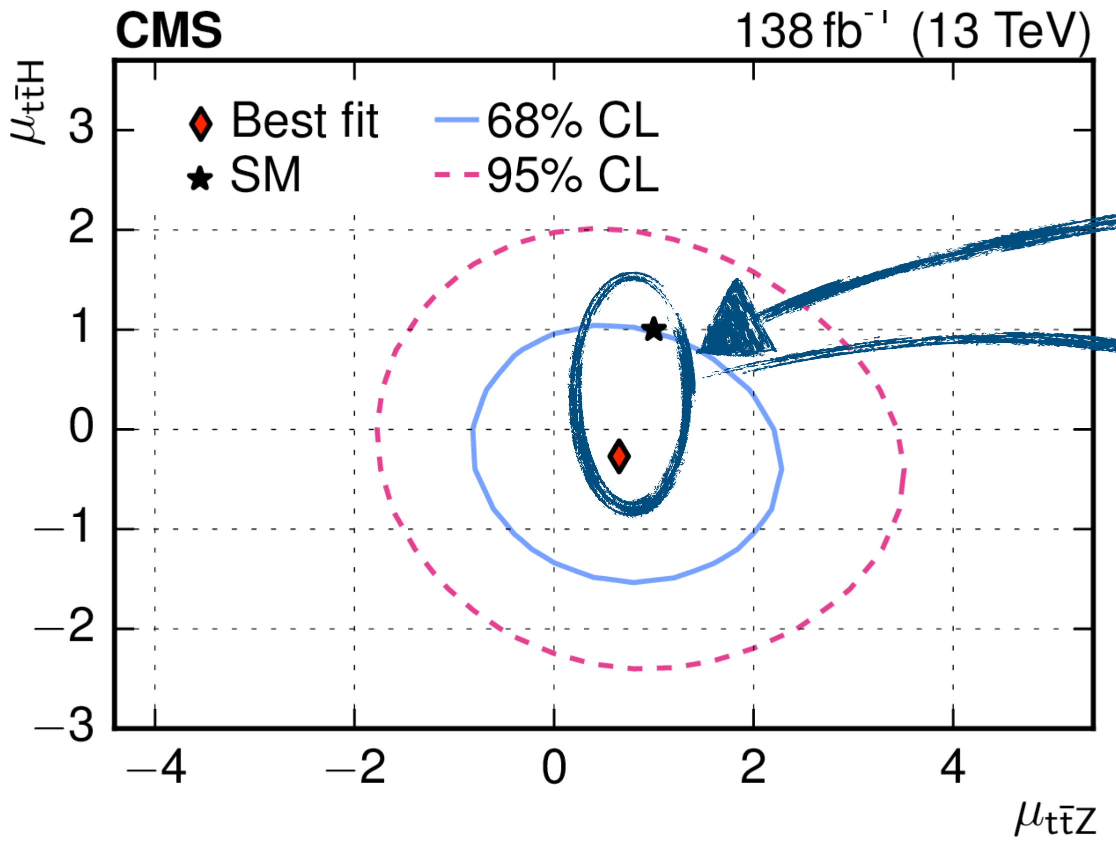
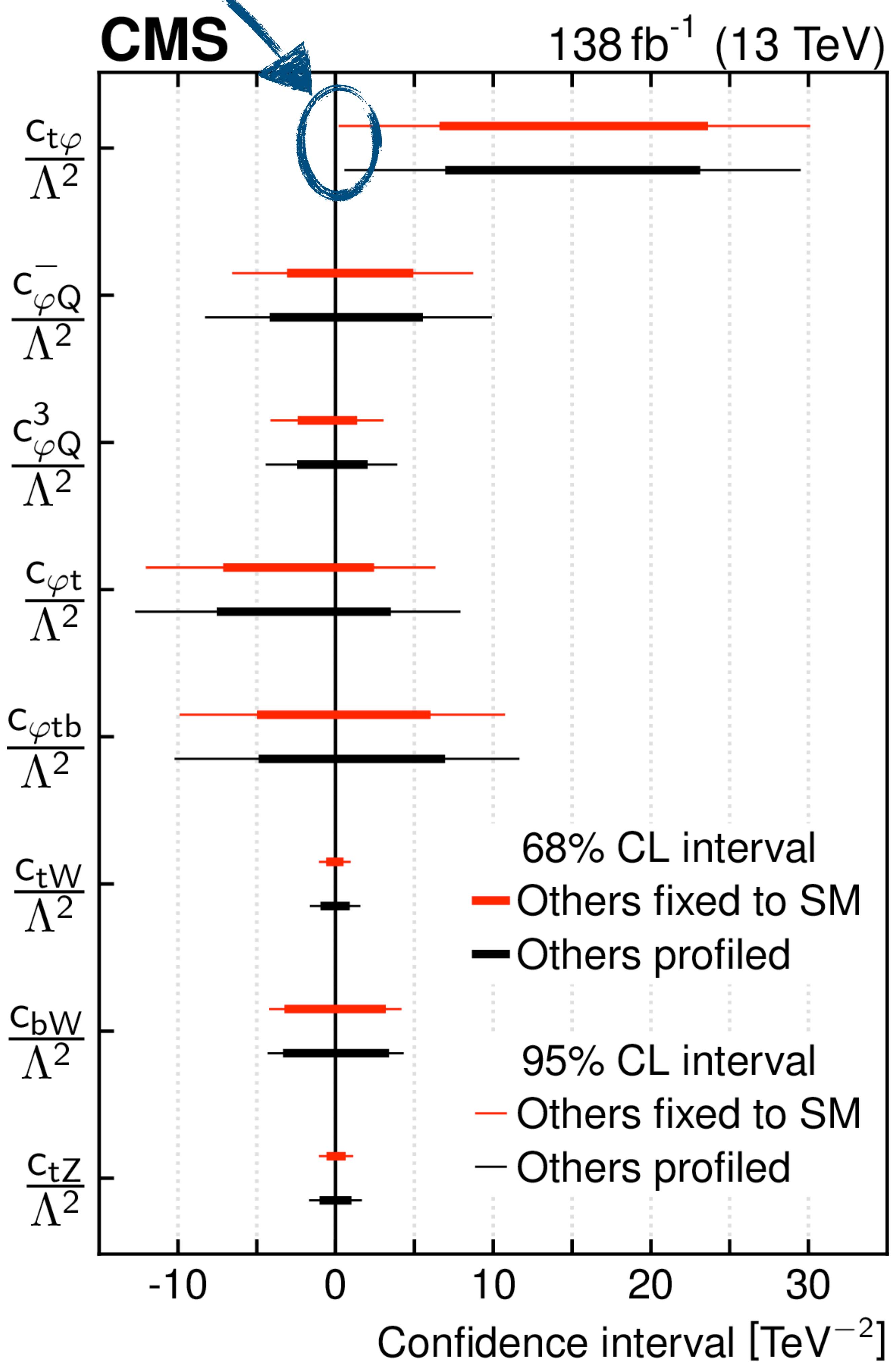
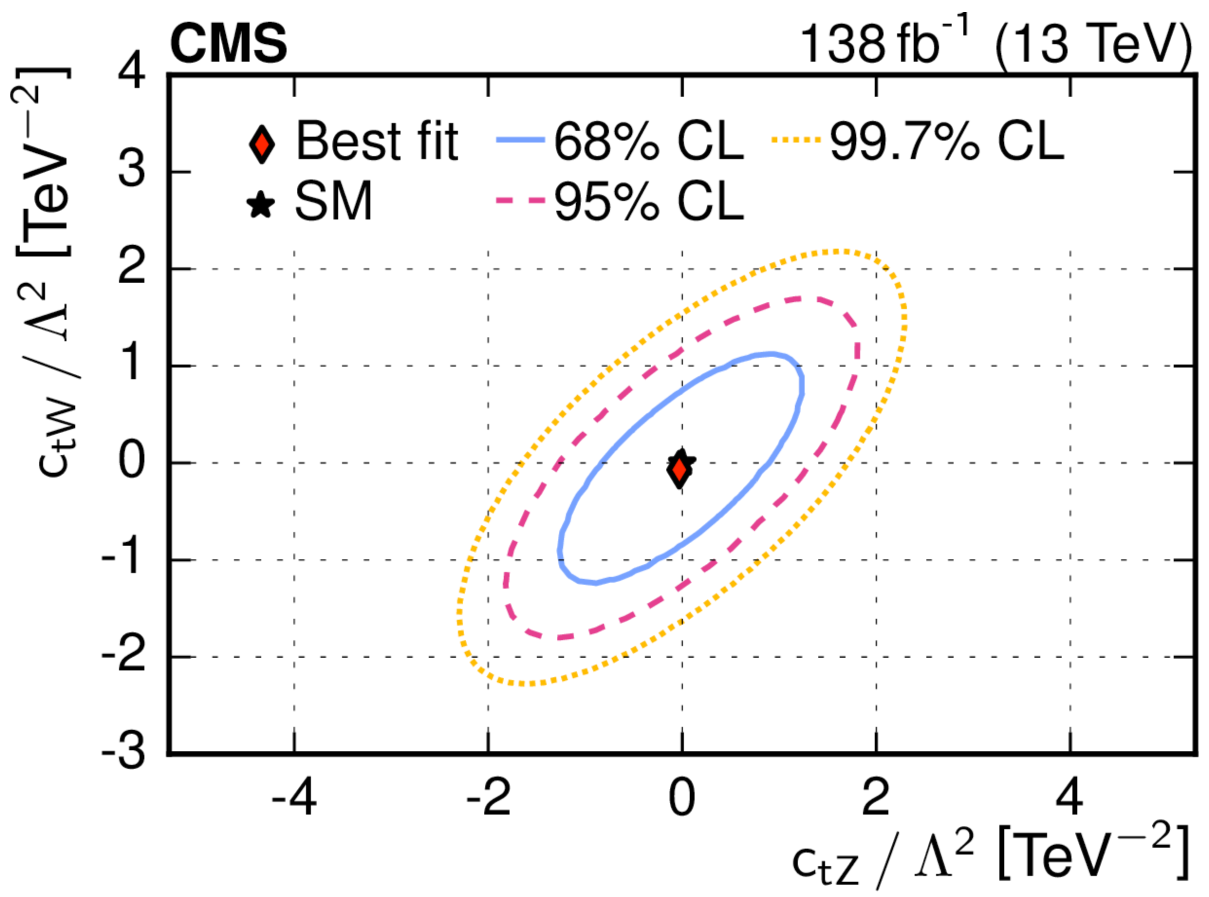
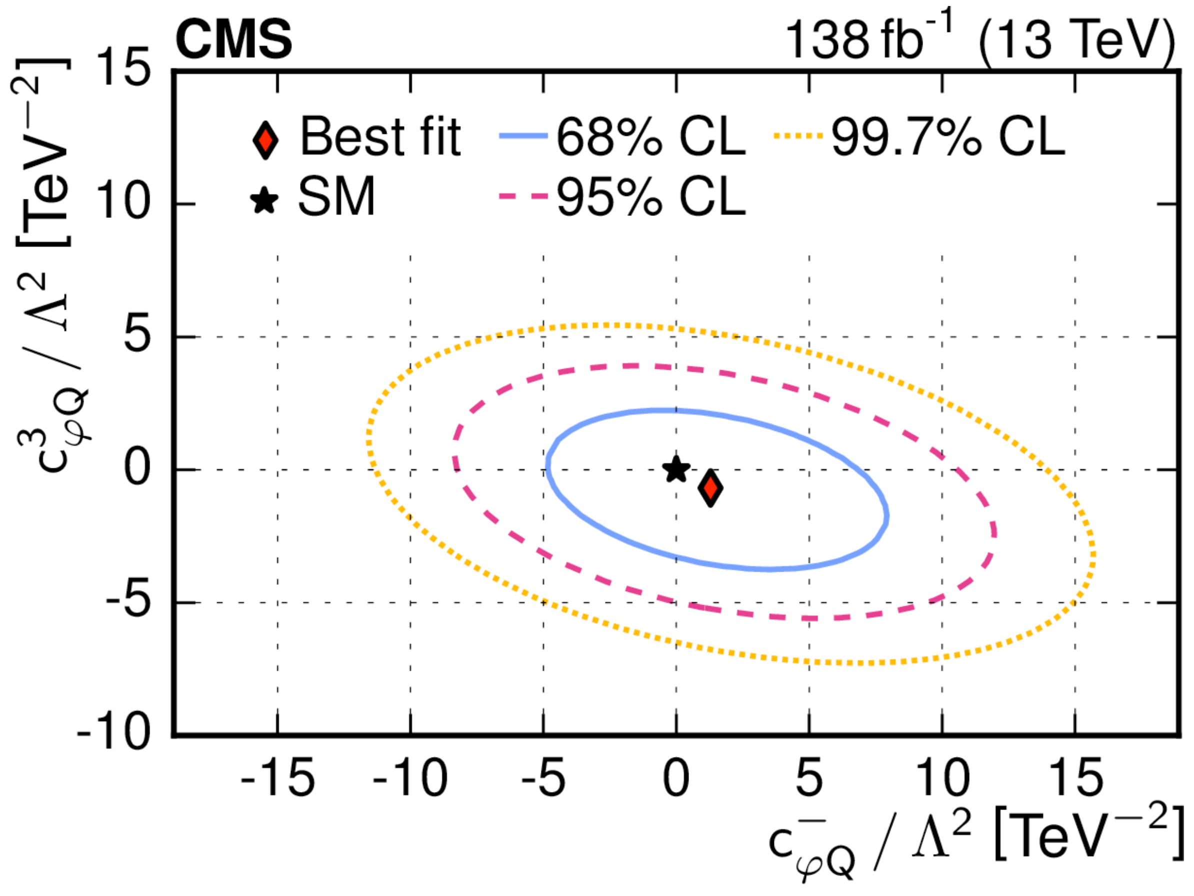
- Induces the tension wrt SM scenario for $c_{t\varphi}$
- Other 1D scans are compatible with SM
- 2D limits for WCs with the highest correlation

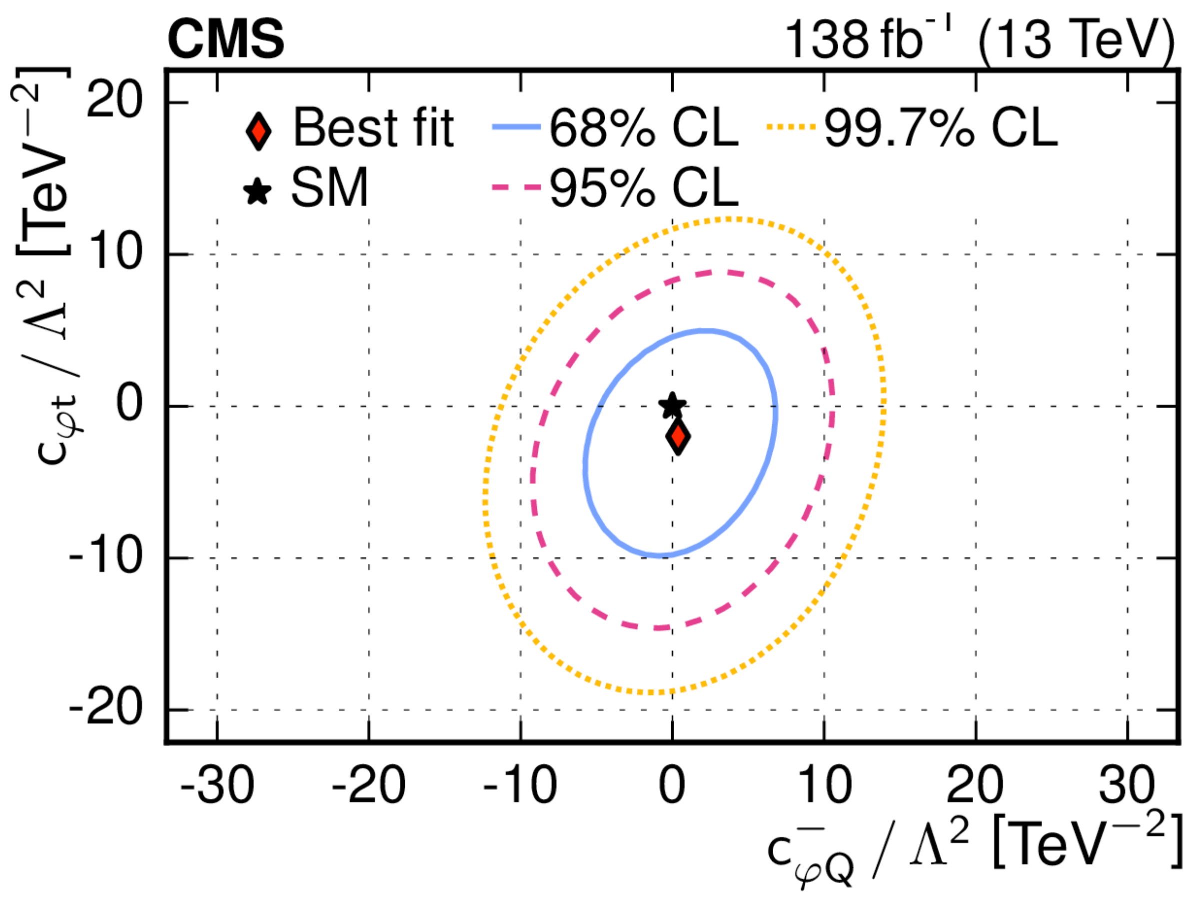


$$\frac{\sigma_{tt+bb}}{\sigma^{SM}_{tt+bb}} > 1$$









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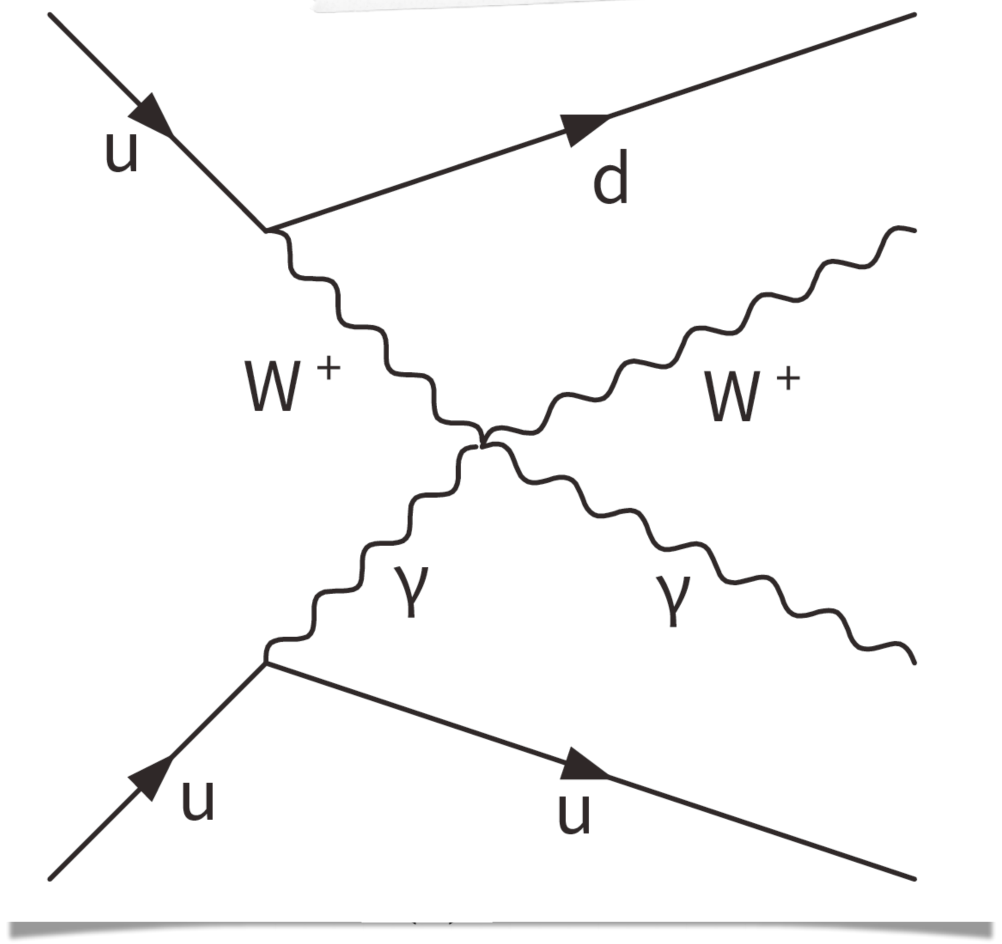
Results in EWK sector

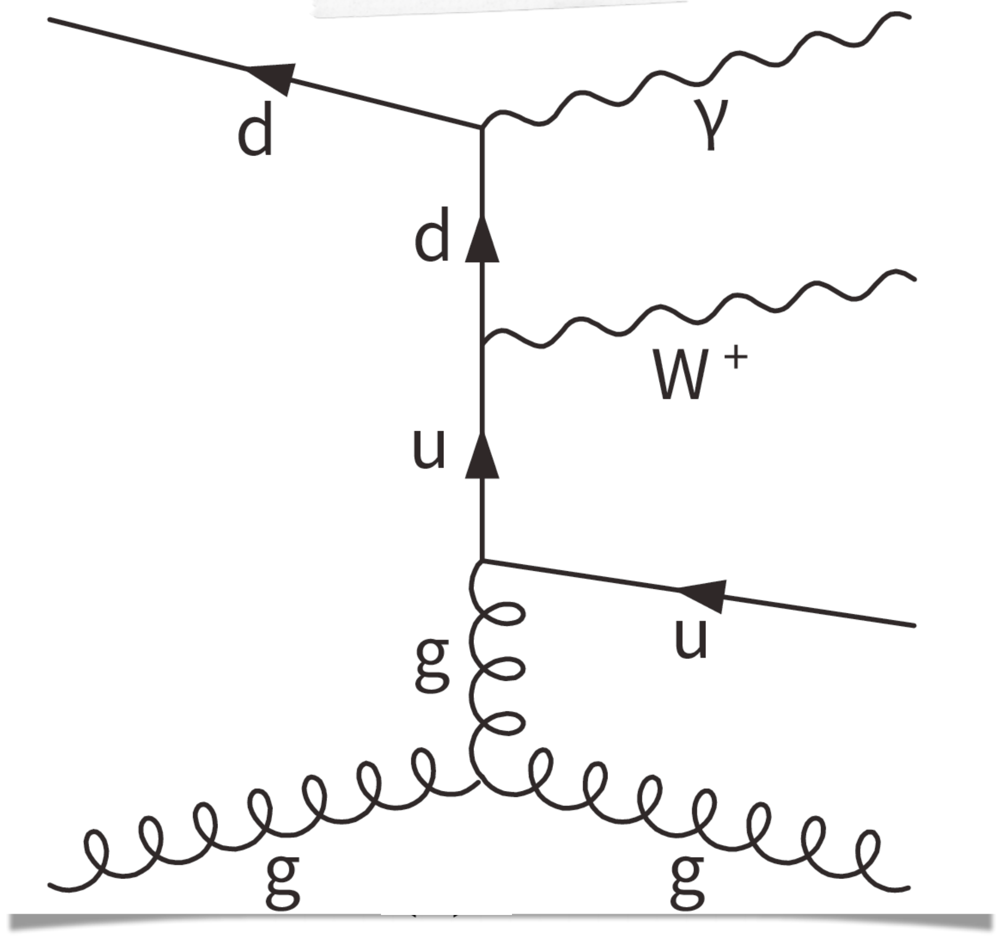
aQGC in electroweak Wγjj

Overview

- Well-displaced jets, 1 photon, and 1 ℓ coming from W boson
- Measure inclusive and differential cross-sections in a VBS phase space considering any LO diagram relevant to VBS



Pure EW

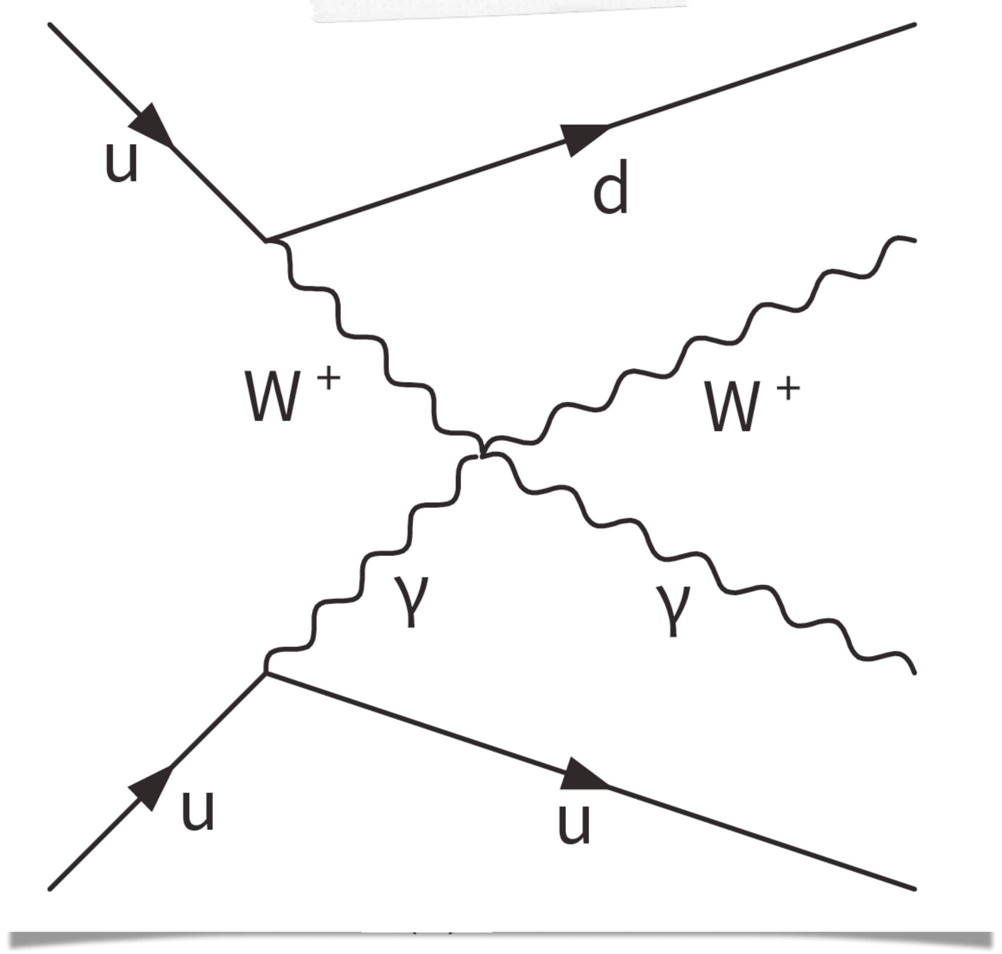


QCD-induced

aQGC in electroweak Wγjj

Overview

- Well-displaced jets, 1 photon, and 1 ℓ coming from W boson
- Measure inclusive and differential cross-sections in a VBS phase space considering any LO diagram relevant to VBS
- Target aQGC in **EW VBS** process modeled with EFT dim8 operators (Éboli basis @ LO)
- Separate SRs for barrel and endcap
  - SM fit performed using m_{jj} and $m_{\ell\gamma}$
  - aQGC fit with $m_{W\gamma}$



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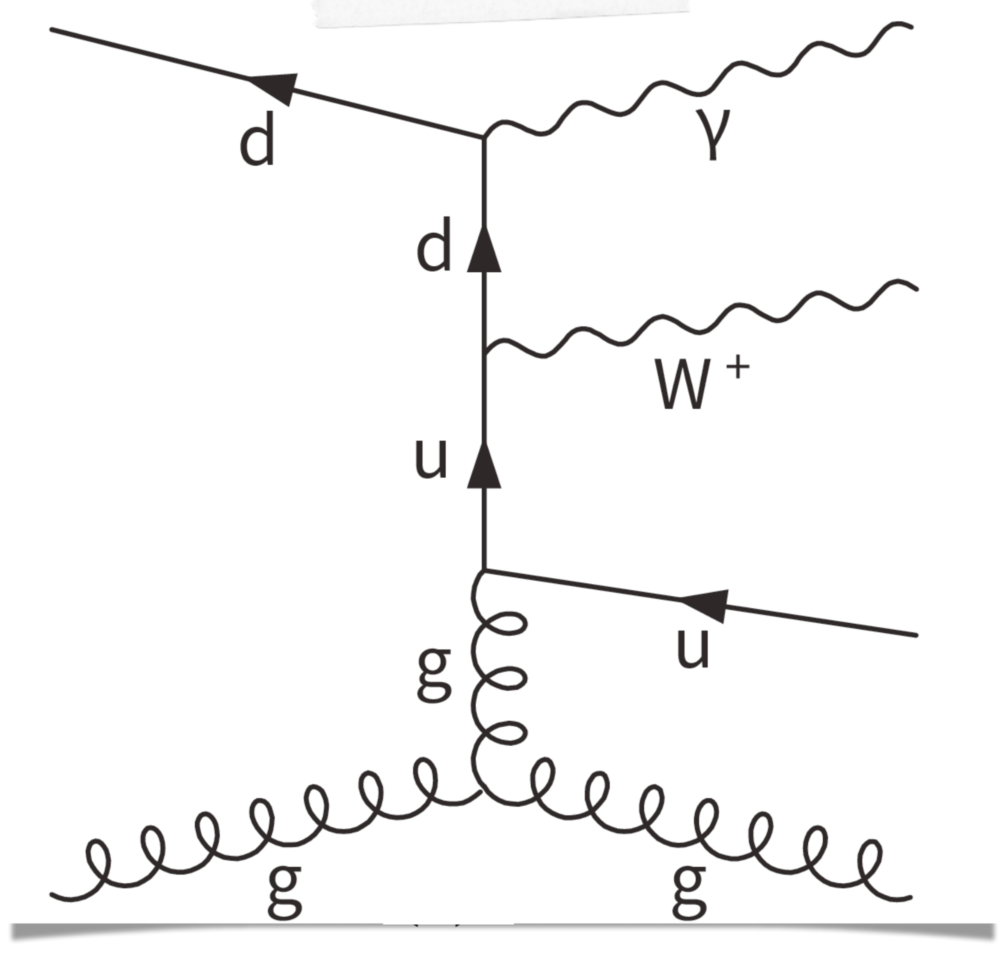

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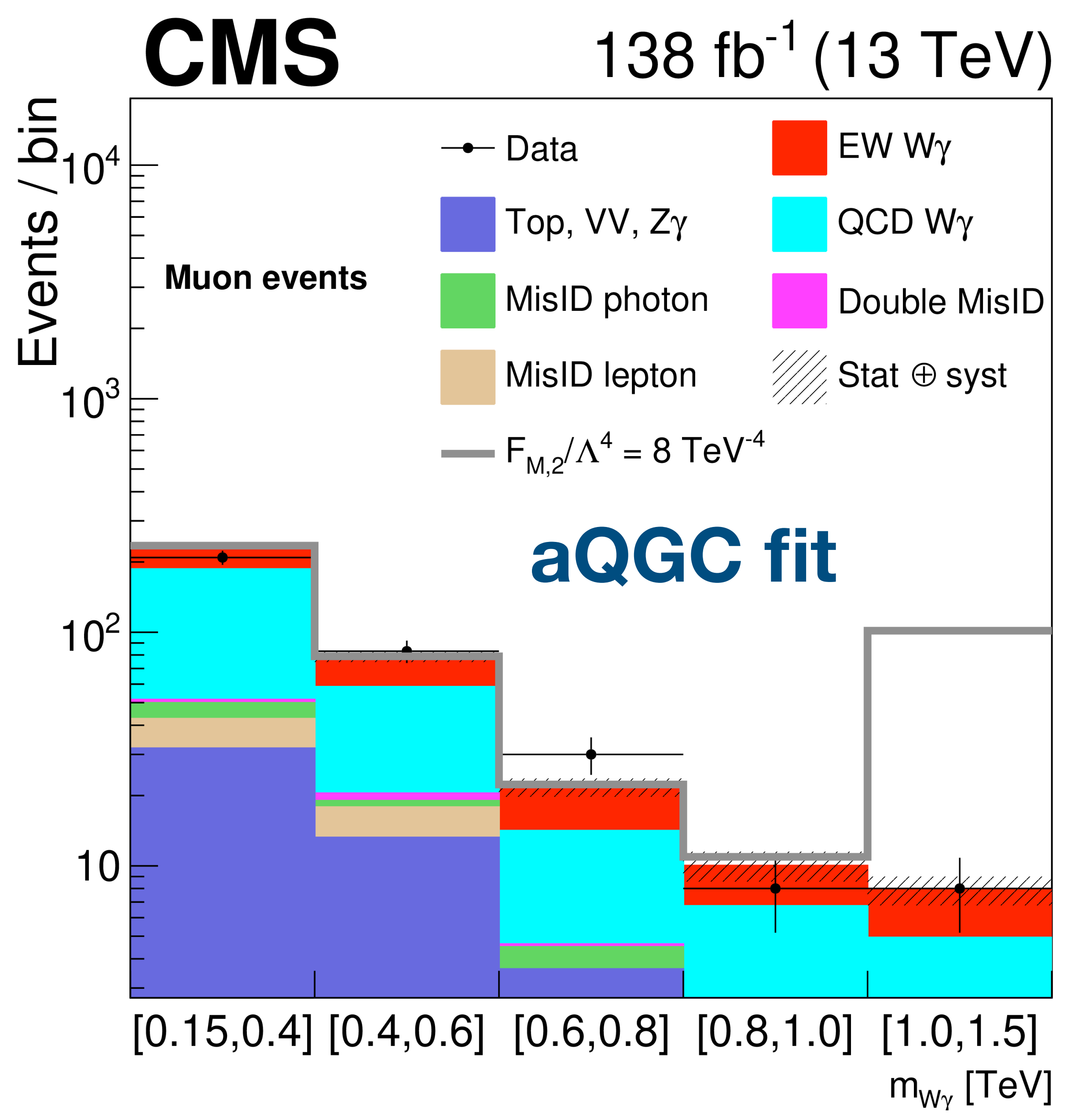

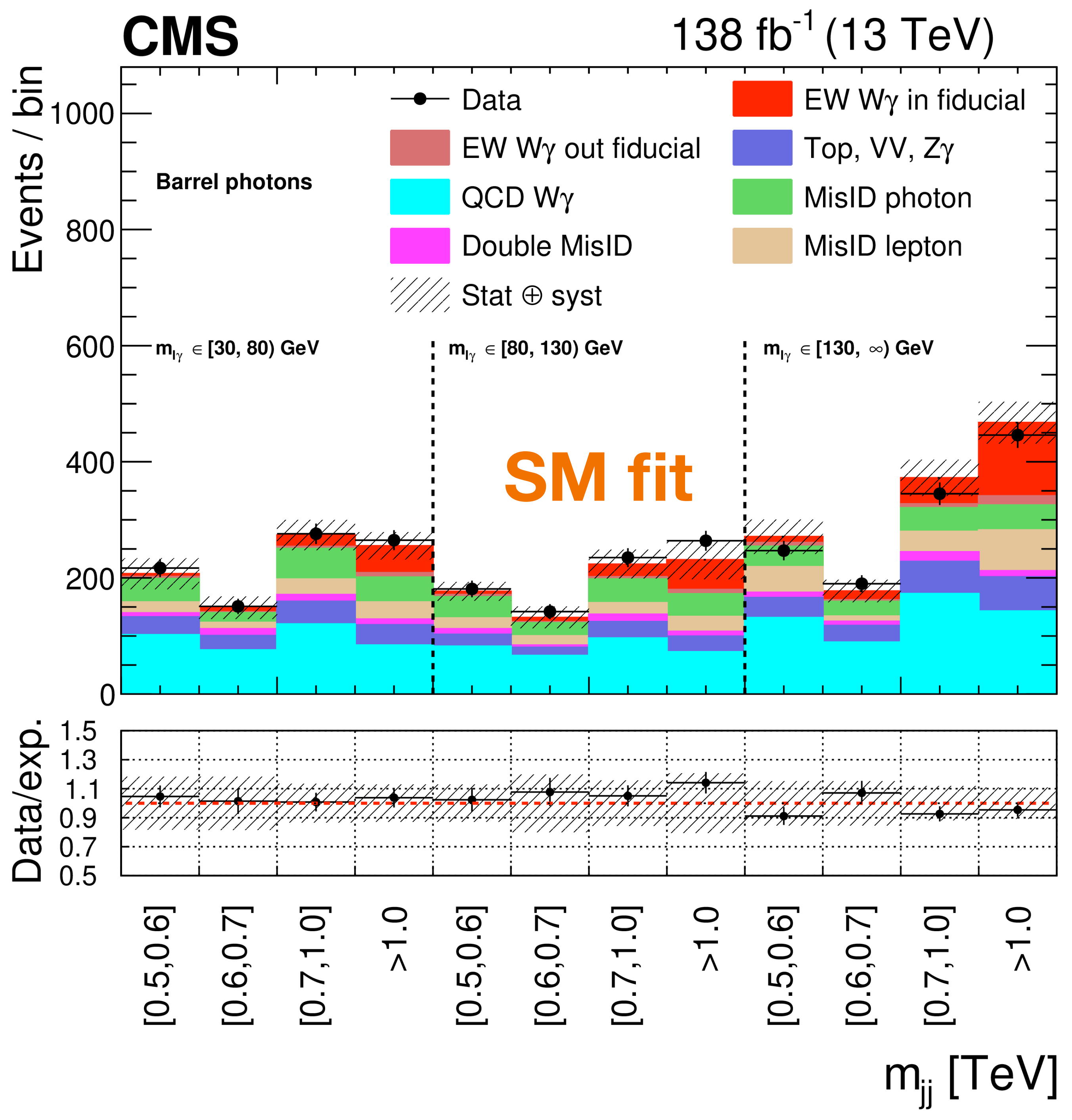

aQGC in electroweak Wγjj

Sensitivity to aQGC with EFT

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

aQGC in electroweak Wγjj

Sensitivity to aQGC with EFT

- Most stringent limits to date on f_{M2-5} and f_{T6-7}

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
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aQGC in electroweak Wγjj

Sensitivity to aQGC with EFT

- Most stringent limits to date on f_{M2-5} and f_{T6-7}
- Provided U_{bound}
  - Scattering energy violating unitarity for the scattering amplitude
  - Calculated imposing aQGC coupling equal to the observed limit

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
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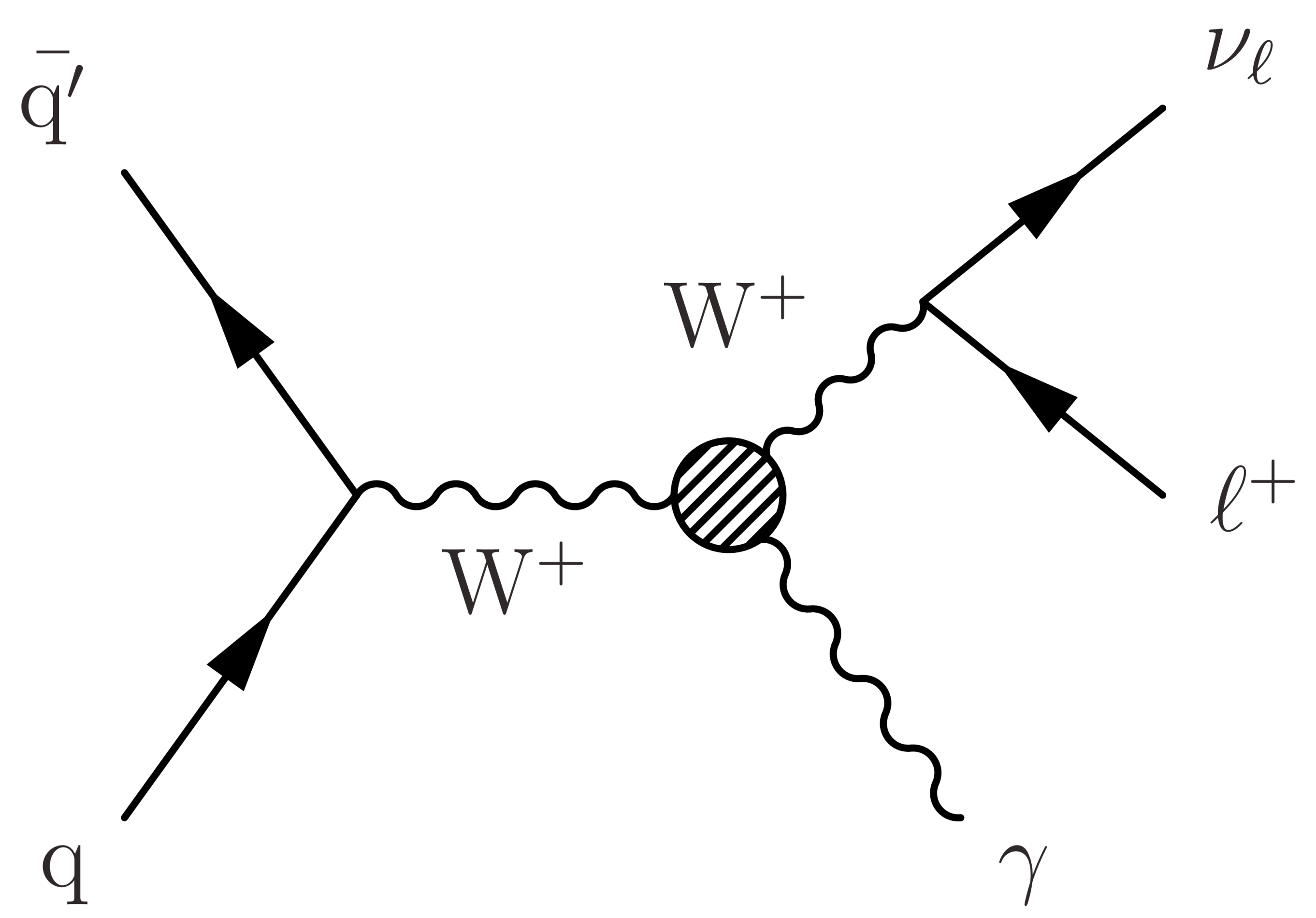
SMEFT dim6 in Wγ

Overview

- 1 photon and 1 ℓ coming from W
- Measurement of the differential cross section with RIVET
- Target C_{3W} effects in Wγ (SMEFTsim @ LO)



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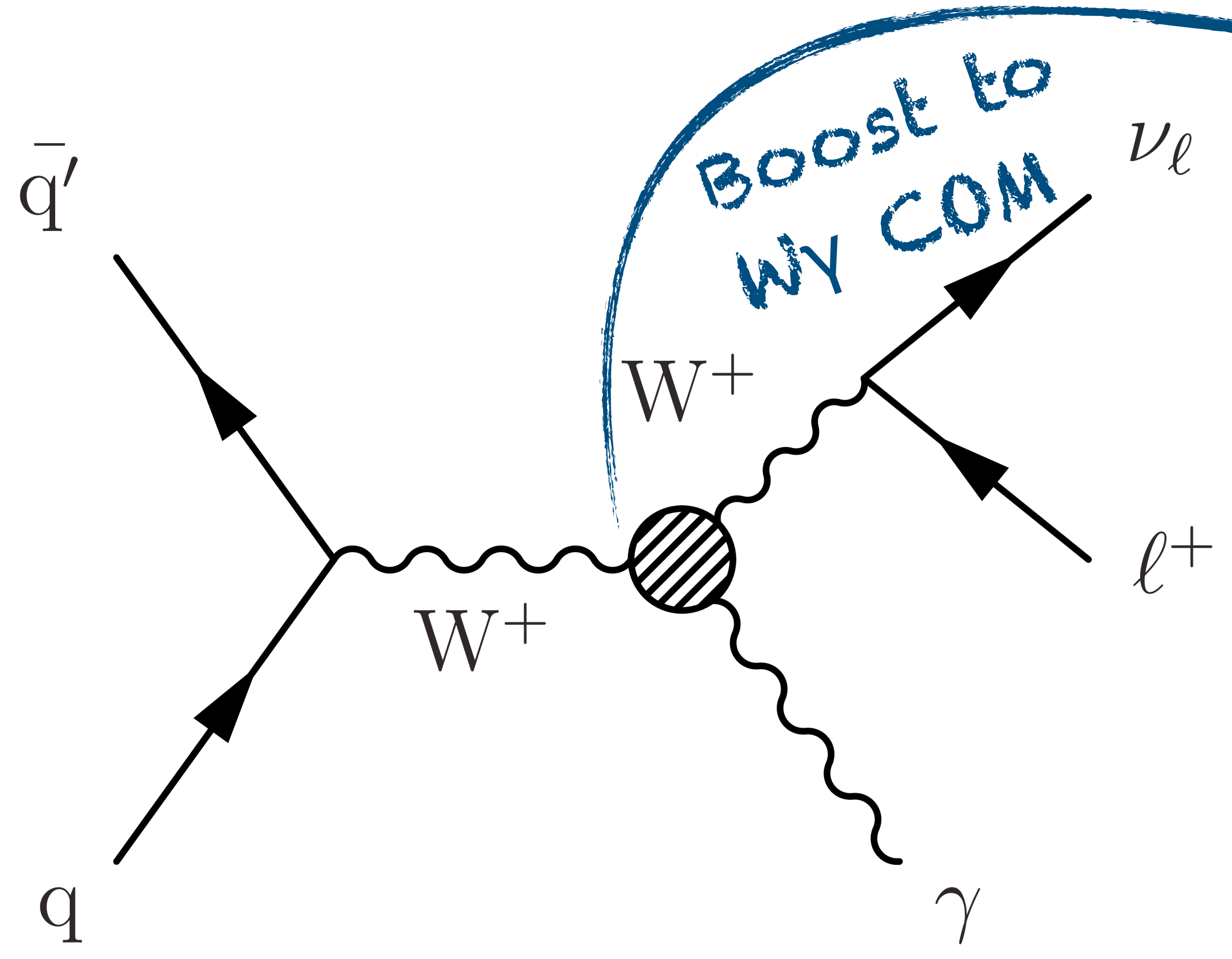
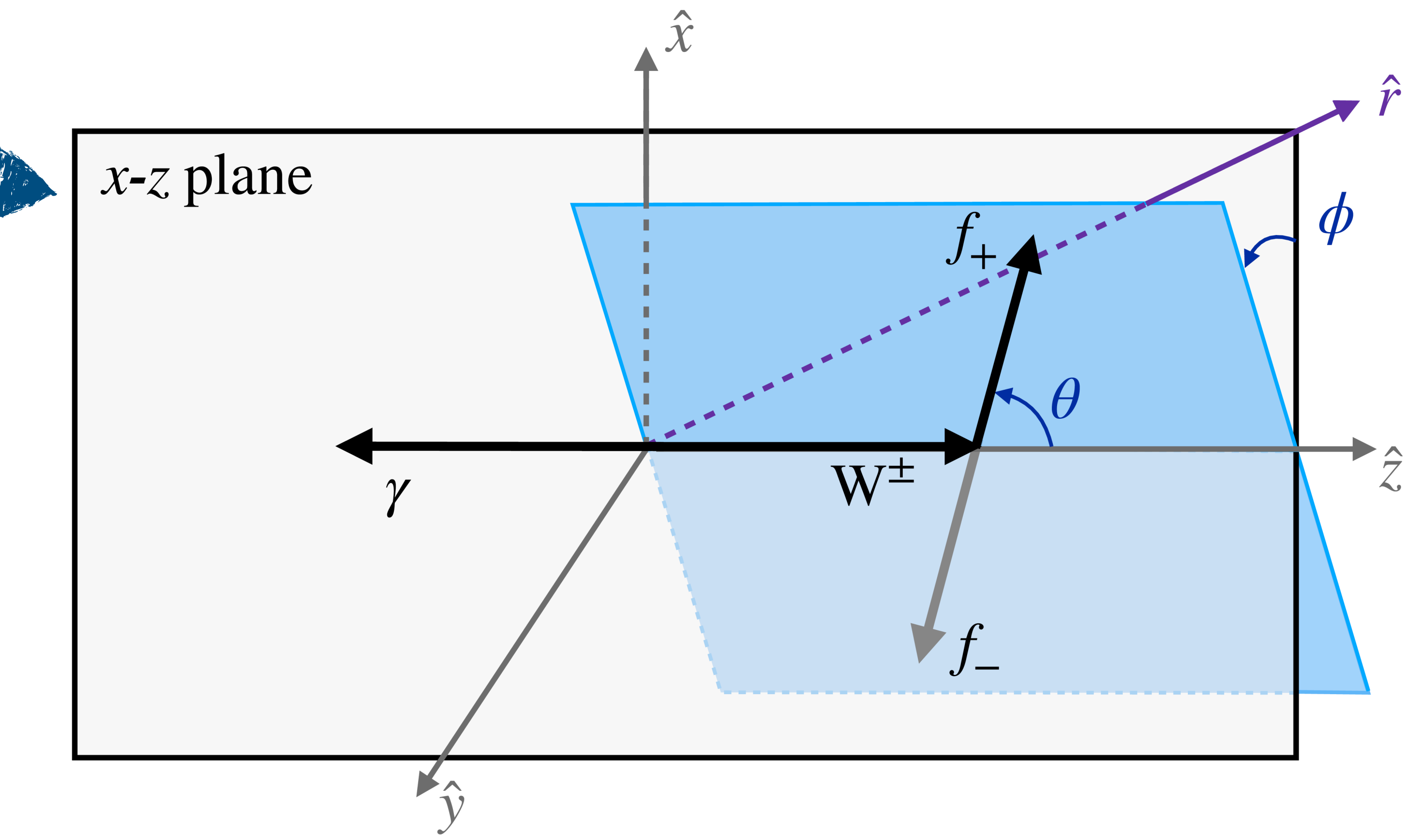
- EFT effects in decay angle φ_f in the Wγ center-of-mass frame to enhance sensitivity to SM-EFT interference
    - "Interference resurrection"
    - Important to capture the different final-state helicity configurations for the SM and BSM $W_T V_T$ components





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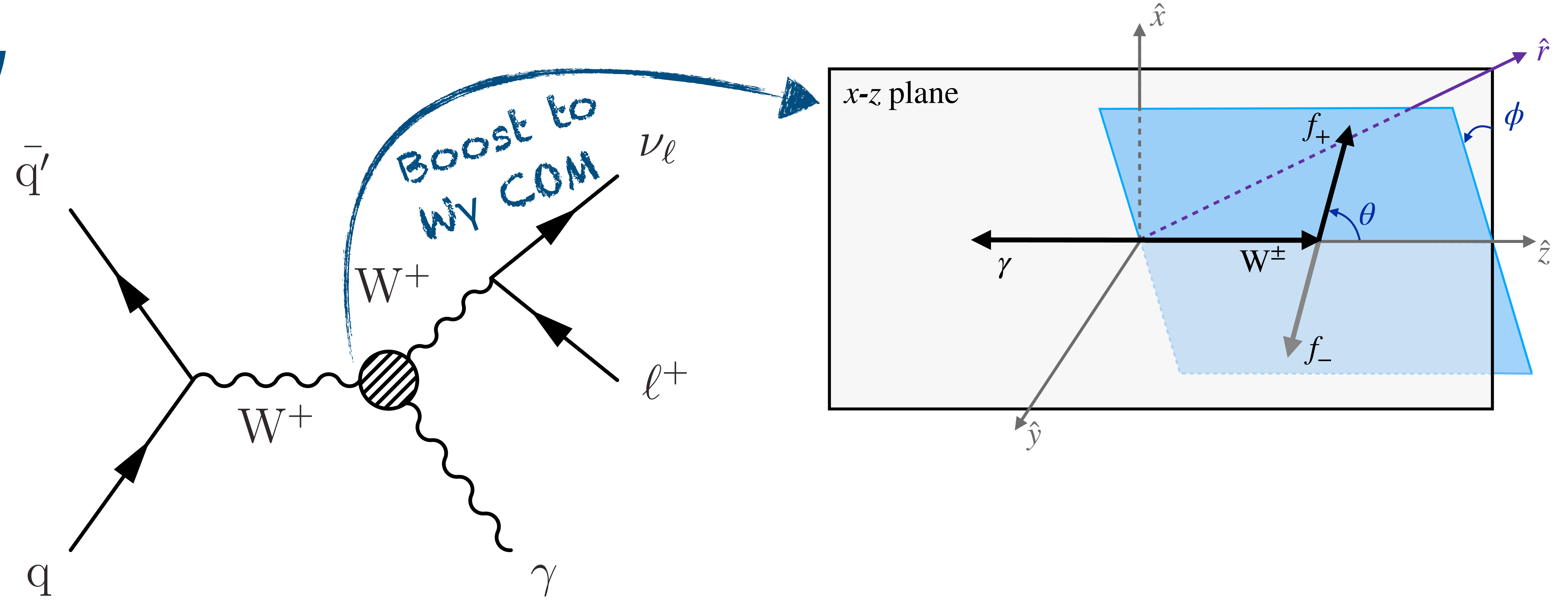
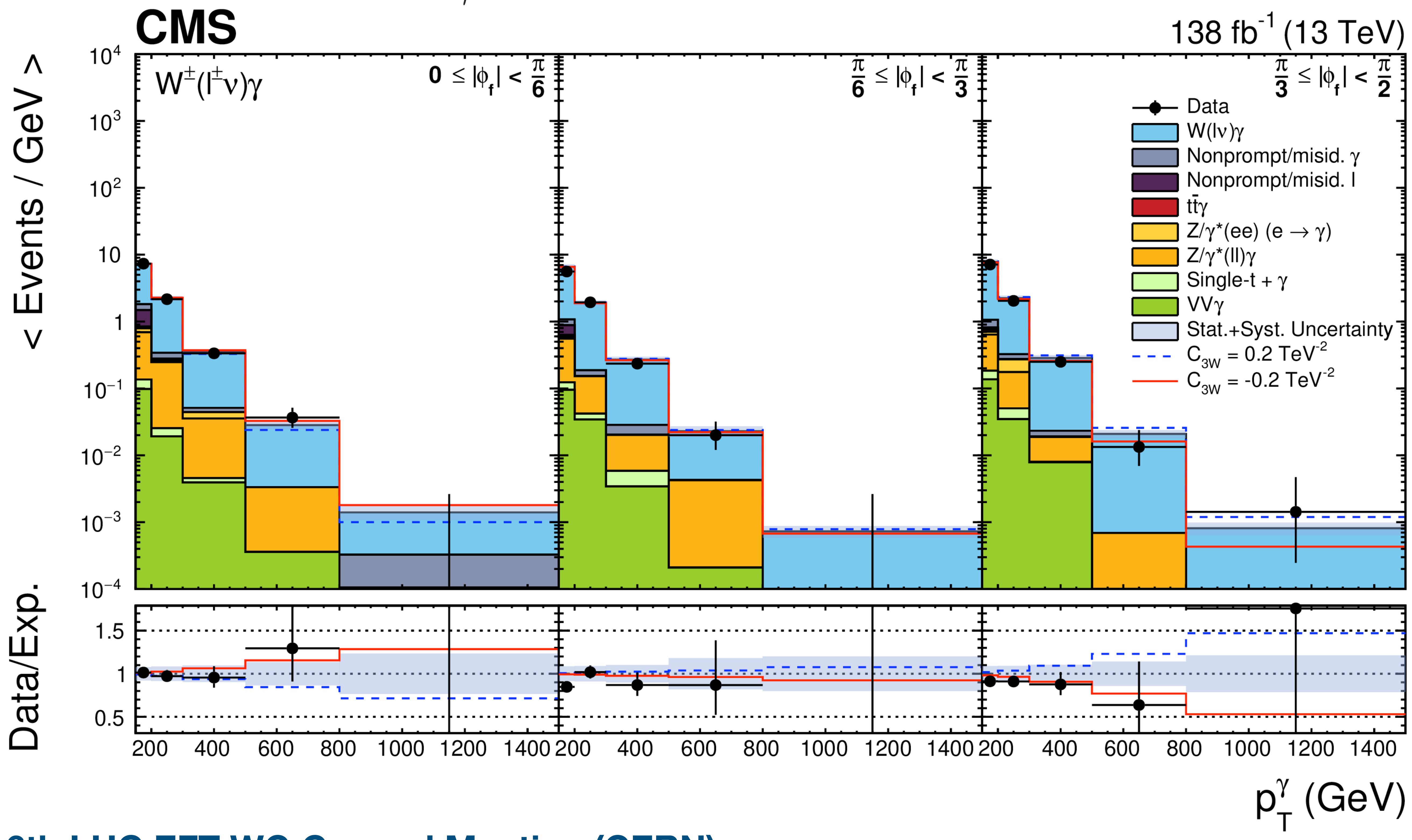
  - “Interference resurrection”
  - Important to capture the different final-state helicity configurations for the SM and BSM $W_T V_T$ components
- Fit with 2D $\varphi_f - p_T^\gamma$ bins

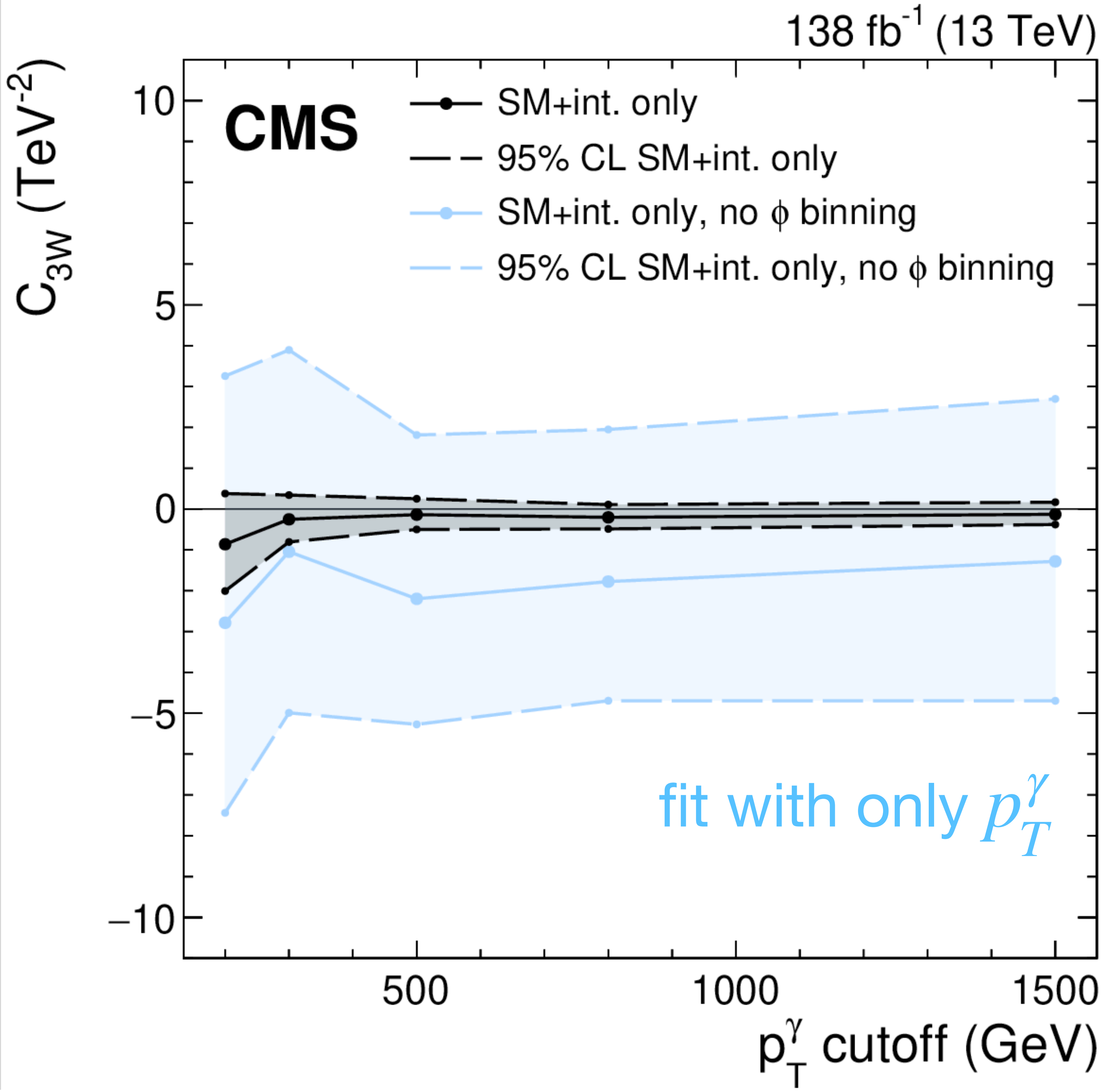




SMEFT dim6 in Wγ

Results

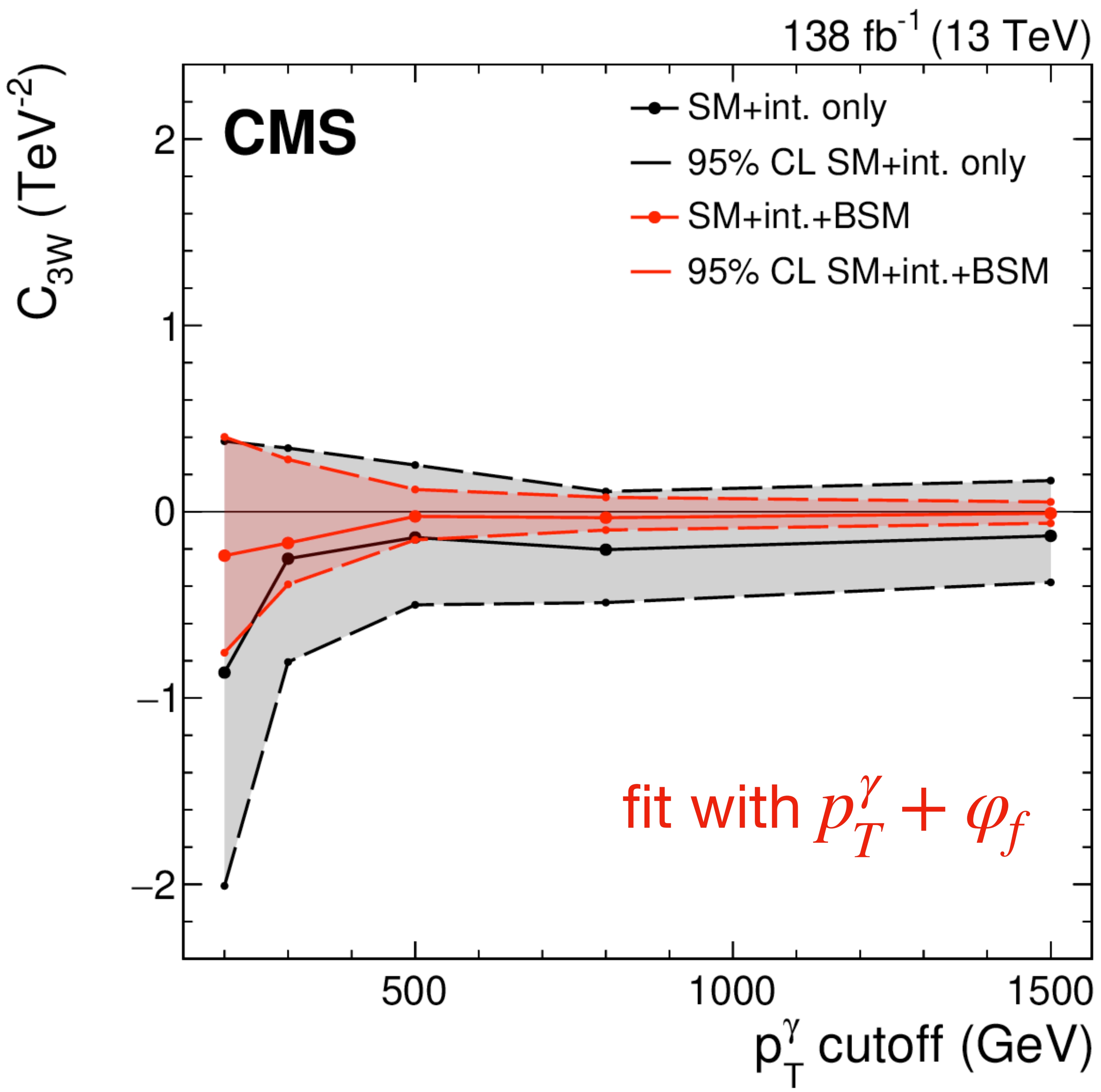
- 2σ limits as a function of p_T^{γ} cutoff

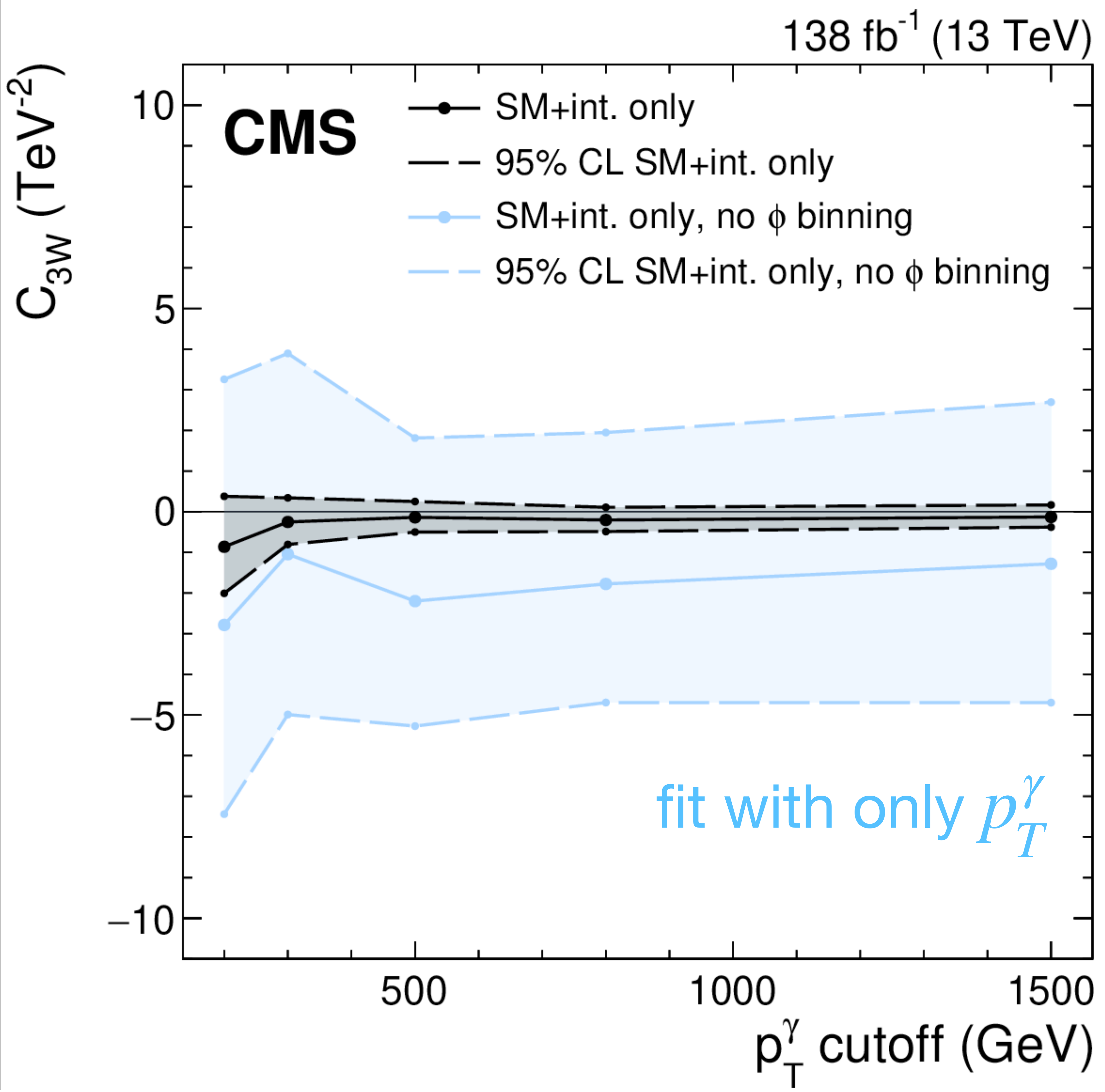


SMEFT dim6 in Wγ

Results

- 2σ limits as a function of p_T^γ cutoff
- Information from φ_f dramatically improves sensitivity to interference



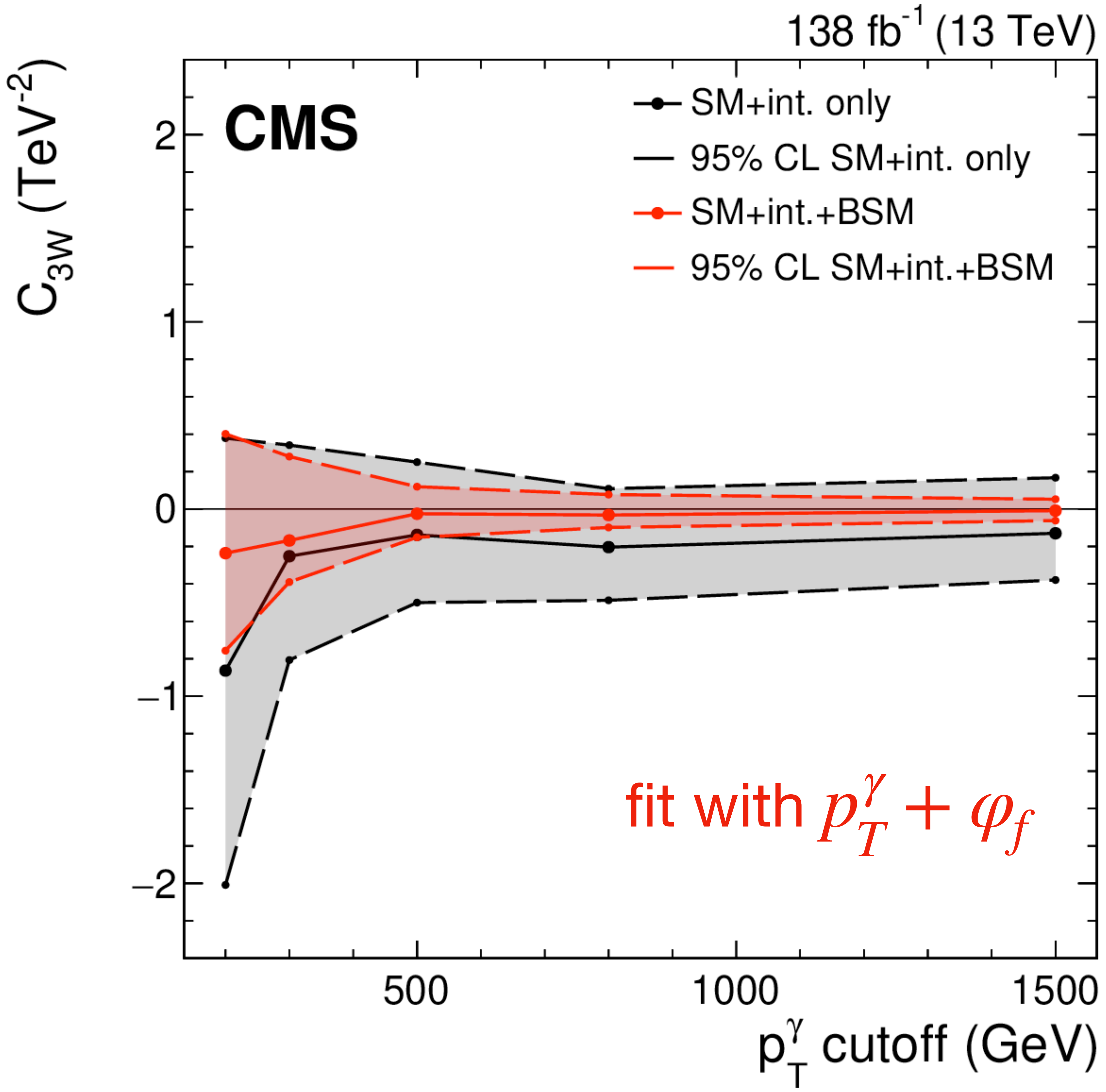


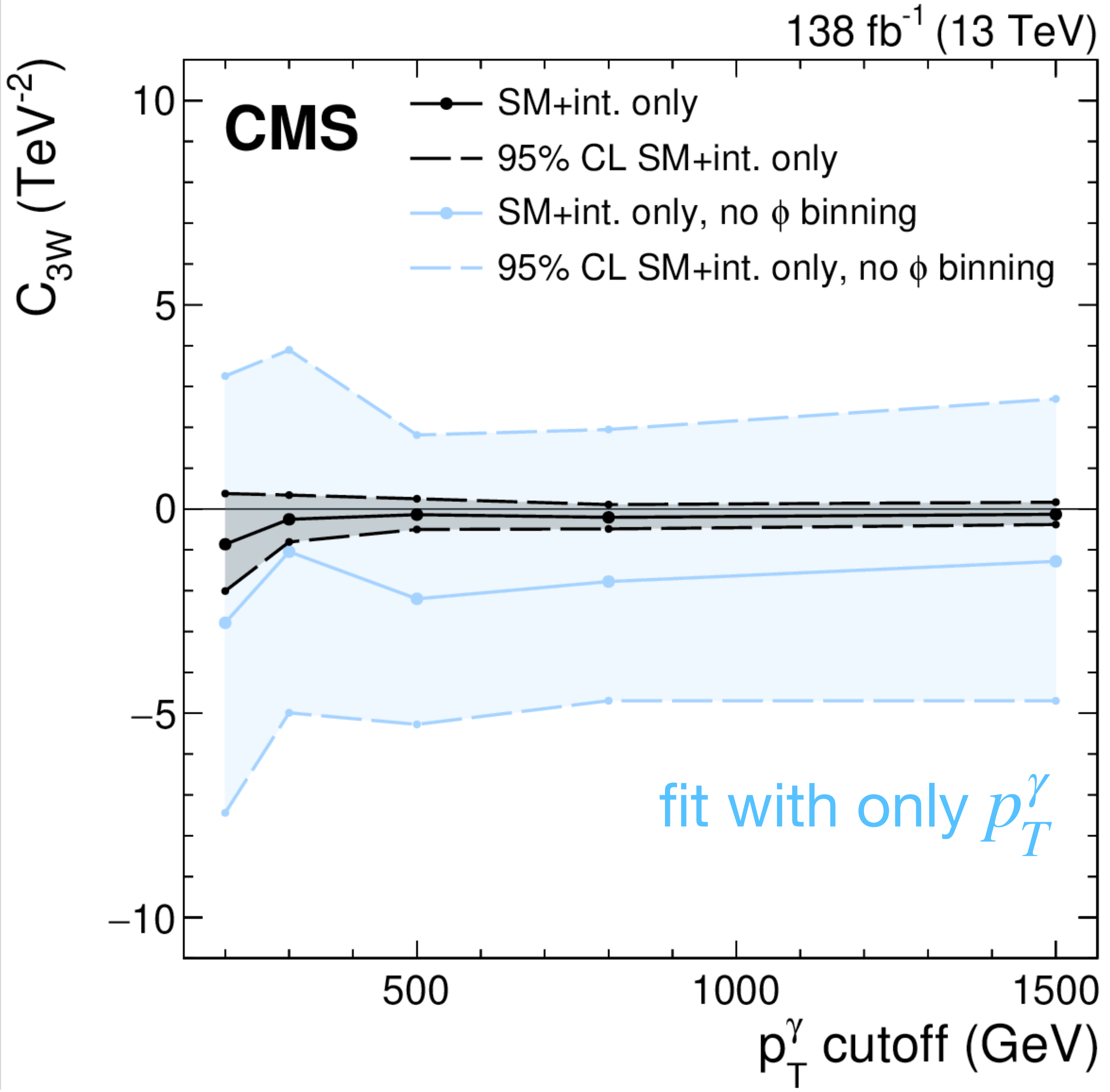
SMEFT dim6 in Wγ

Results

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]

- 2σ limits as a function of p_T^γ cutoff
- Information from φ_f dramatically improves sensitivity to interference
- Pure BSM term drives the overall results

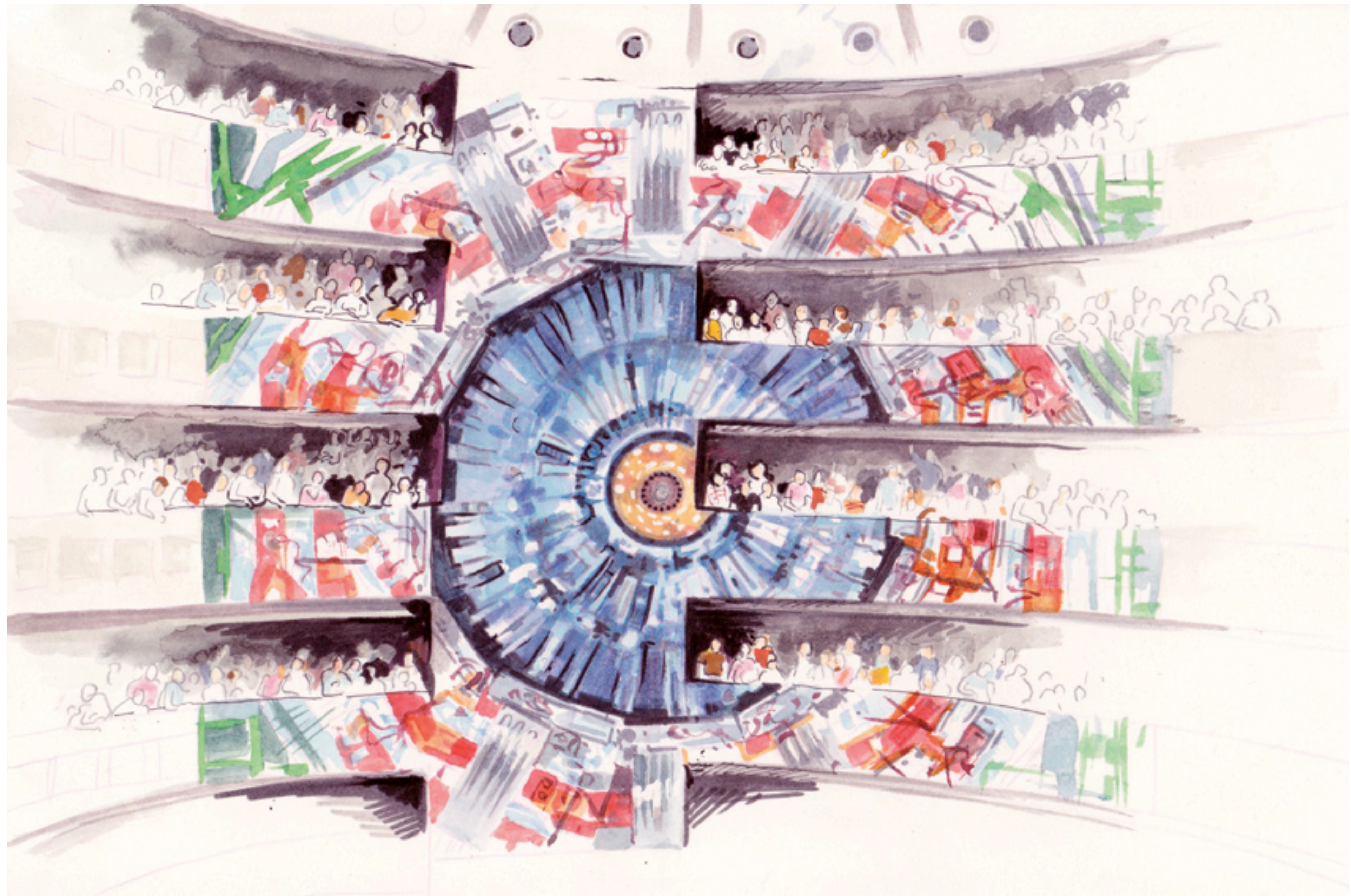




Conclusions

Summary

- CMS developed a huge program of EFT searches with the Run-2 dataset
to look at all possible directions
  - TOP: broad investigations on peculiar top processes and flavor anomalies
  - EWK: detailed studies of processes involving EWSB actors
- Simultaneous studies of multiple same-dimension EFT operators at a time



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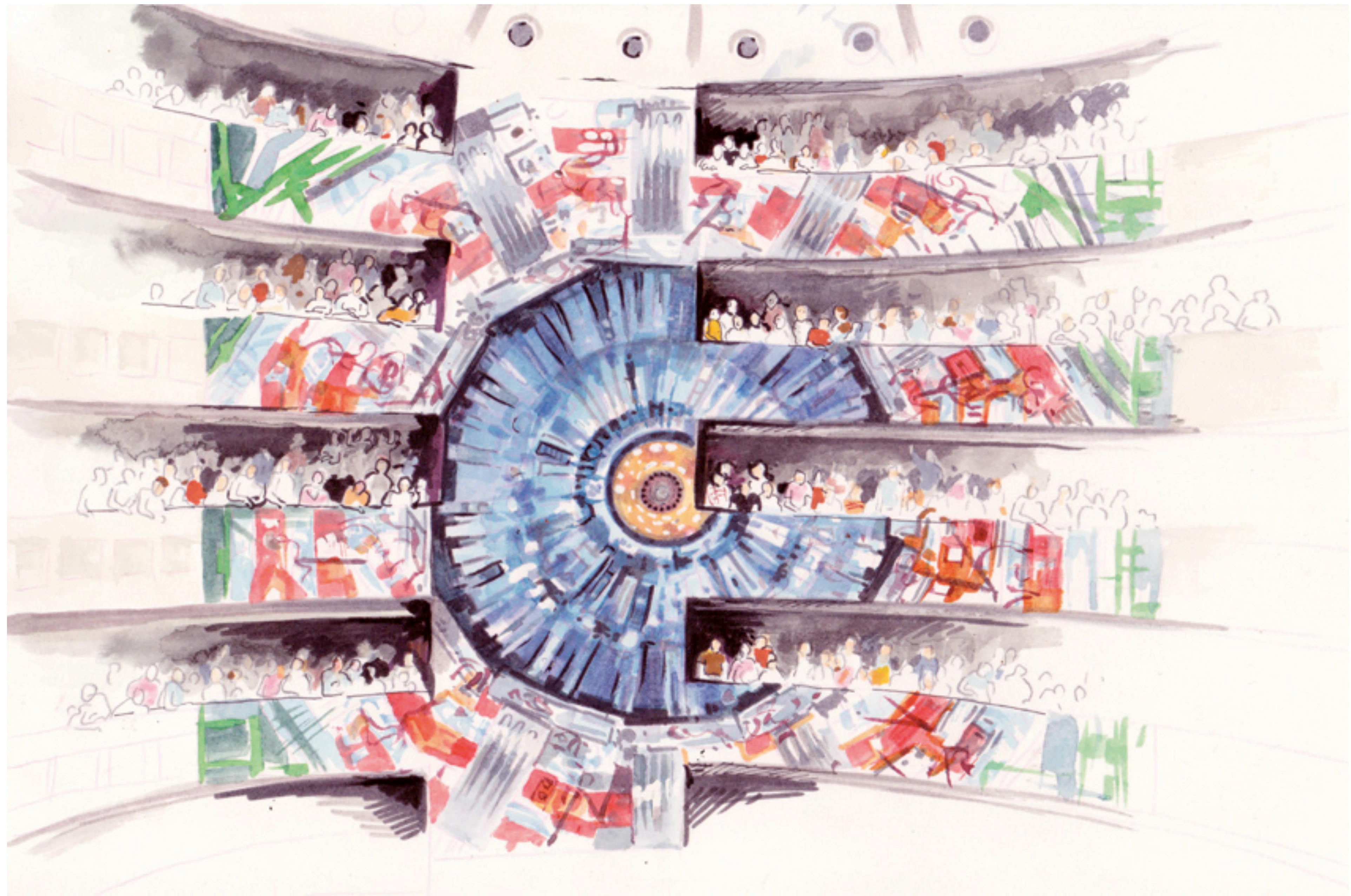
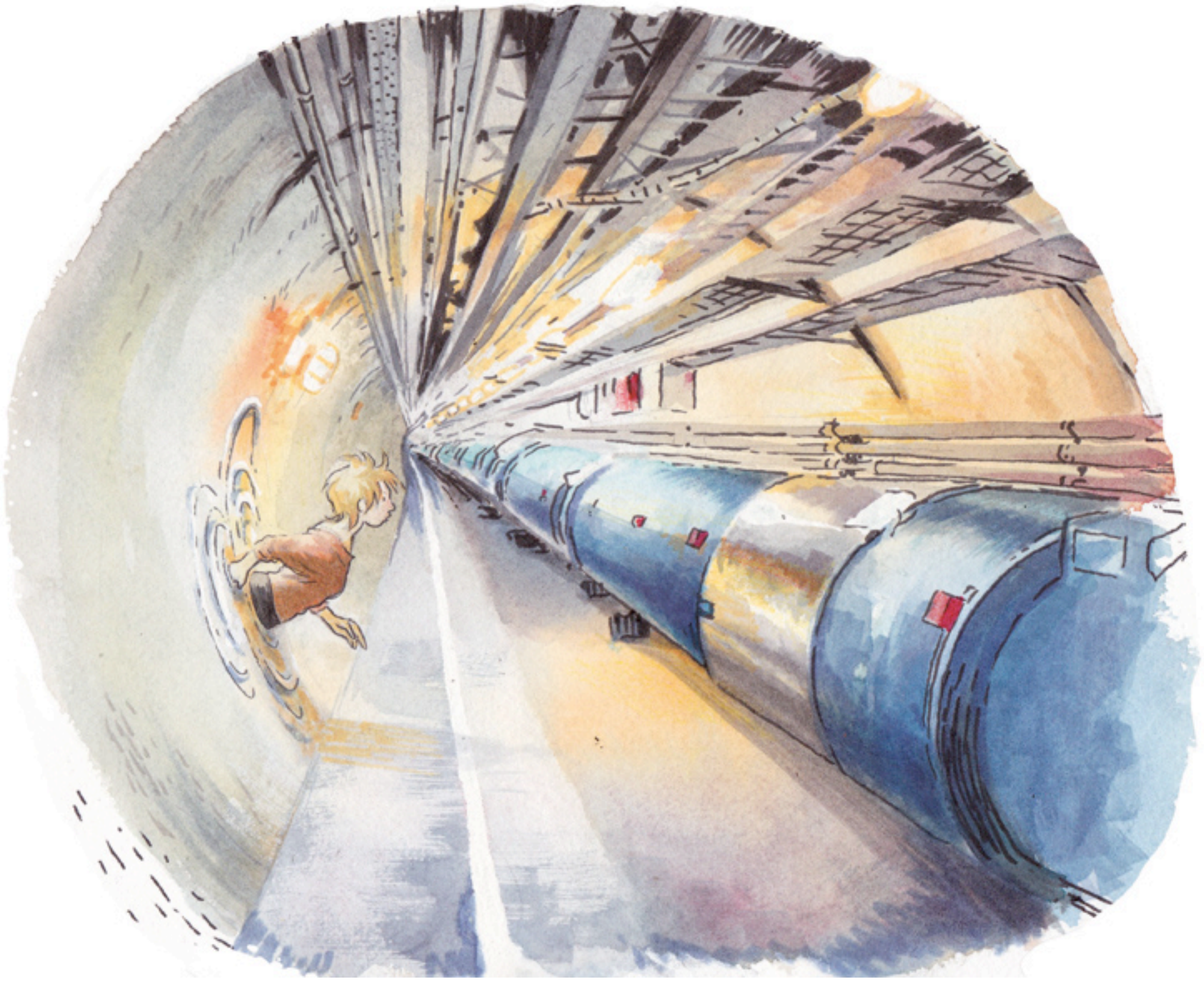
- On the way to uniformize basis choices
  - Pave the way to combinations inside and across sectors
- No deviation from SM
- Established solid bases for further developments with the Run-3 dataset





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