Probing CP property of H-tt and EFT operators through $t\bar{t}$ production with EW loops

Top LHC France 2026

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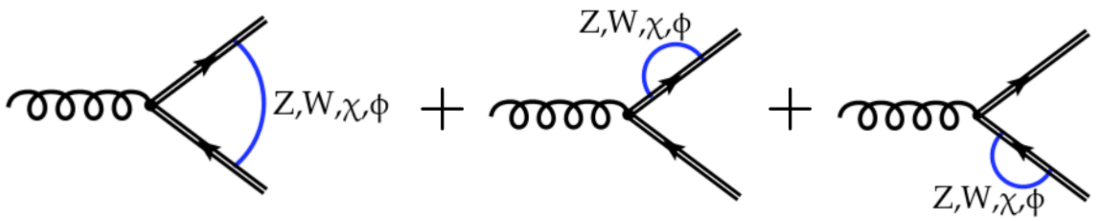
EFT in $t\bar{t}$ production

- LO EW corrections, tree-level:
  - **Tiny**, at **sub-permile** level

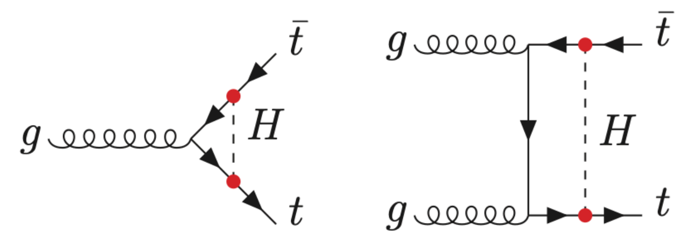
☆ NLO, one-loop: **Percent** level, with the enhancement by logarithms of $\hat{s}/M_W^2$

- $t\bar{t}Z$ and tWb



  - ✳ Relavant Wilson coefficients: $C_{\varphi t}, C^3_{\varphi Q}, C^-_{\varphi q}, C_{tZ}, C_{tW}, C_{tG}$
  - ✳ $C_{\varphi t}, C^3_{\varphi Q}, C^-_{\varphi q}$ available in theoretic framework: [MCFM add-on]

- $t\bar{t}H$



  - ✳ Relavant WCs: $C_{t\varphi}, C^I_{t\varphi}$
  - ✳ Degree of CP violation: f_{CP}

$t\bar{t}Z$ & tWb

- One-loop corrections for $t\bar{t}Z$ and tWb interactions
  - Modification formula:

$t\bar{t}Z$:

$$d^Z_R \to d^{Z,SM}_R - \frac{v^2}{\Lambda^2} \boxed{C_{\varphi t}}$$

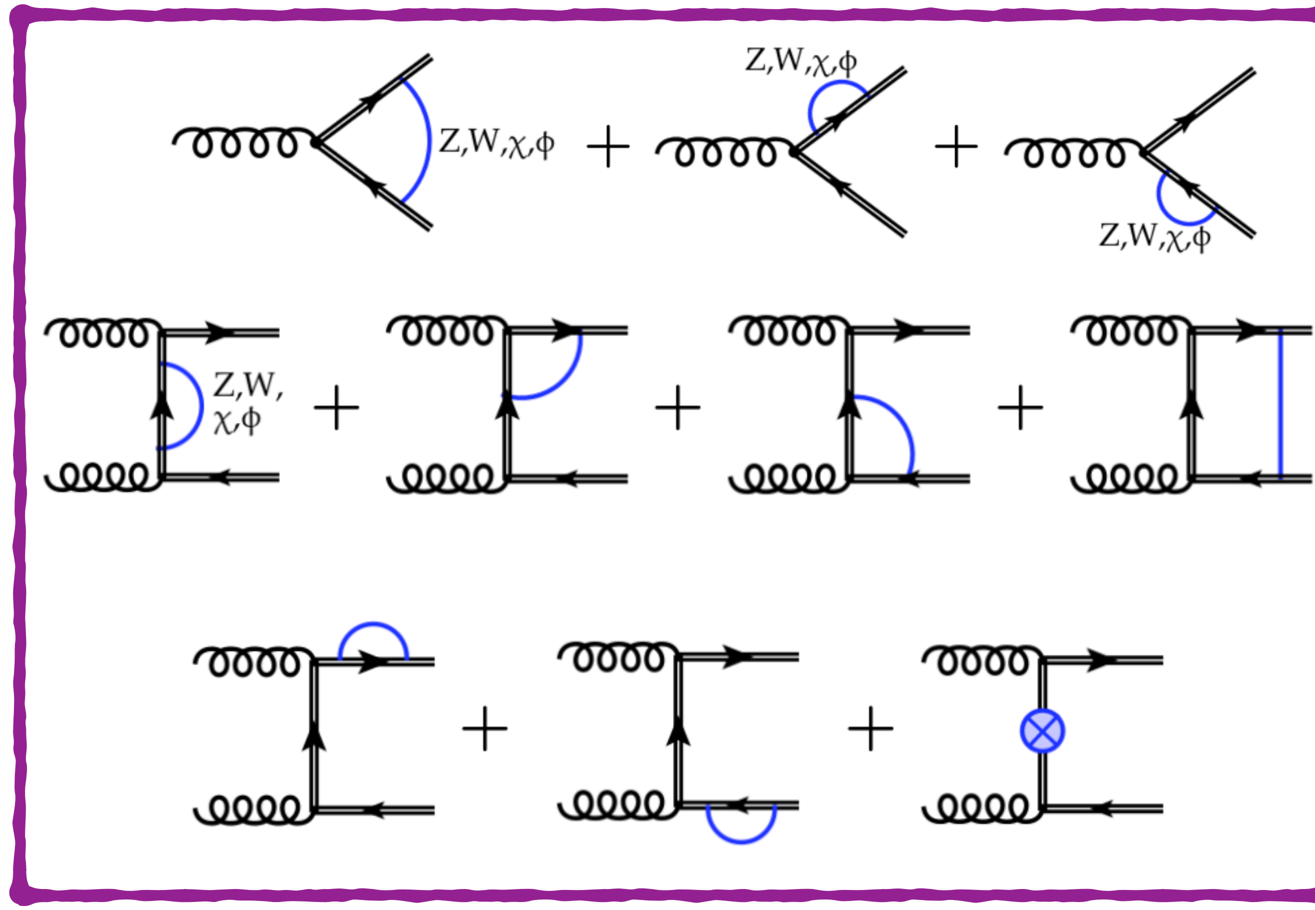
$$d^Z_L \to d^{Z,SM}_L - \frac{v^2}{\Lambda^2} \boxed{C^-_{\varphi q}}$$

||

tWb:

$$d^W_L \to d^{W,SM}_L + \frac{v^2}{\Lambda^2} \boxed{C^3_{\varphi Q}}$$

fixed to 0



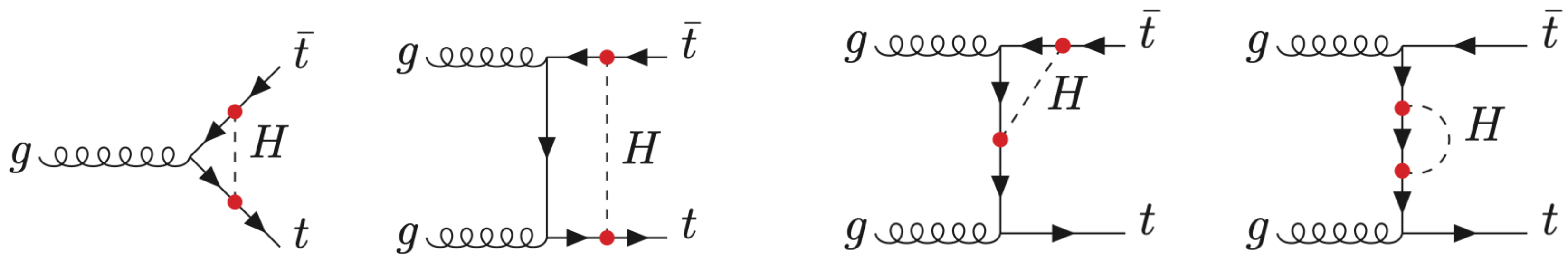
arXiv: [1911.11244]

  - Assumption in MCFM: $C^3_{\varphi Q} = C^-_{\varphi q}$, could not decoupled
  - tWb affecting both production and decay, to avoid bias, set $C^3_{\varphi Q} = 0$

$\boxed{C_{\varphi t} \text{ is the only one left}}$

$t\bar{t}H$ and CP violation

- $t\bar{t}H$ interaction:



  - Mixed CP state structure: $\mathscr{L}(Htt) = -\frac{m_t}{v}\bar{\psi}_t\left(\kappa + \mathrm{i}\,\tilde{\kappa}\gamma_5\right)\psi_t H$

    CP even → κ; CP odd → $\mathrm{i}\,\tilde{\kappa}\gamma_5$

  - Connected to WCs in EFT: $\kappa = 1 - \frac{v}{\sqrt{2}m_t}\frac{v^2}{\Lambda^2}C_{t\varphi}$ $\qquad \tilde{\kappa} = -\frac{v}{\sqrt{2}m_t}\frac{v^2}{\Lambda^2}C^I_{t\varphi}$

  - Degree of CP violation: $f_{\mathrm{CP}} = \frac{|\tilde{\kappa}|^2}{|\kappa|^2 + |\tilde{\kappa}|^2}sign\left(\frac{\tilde{\kappa}}{\kappa}\right)$

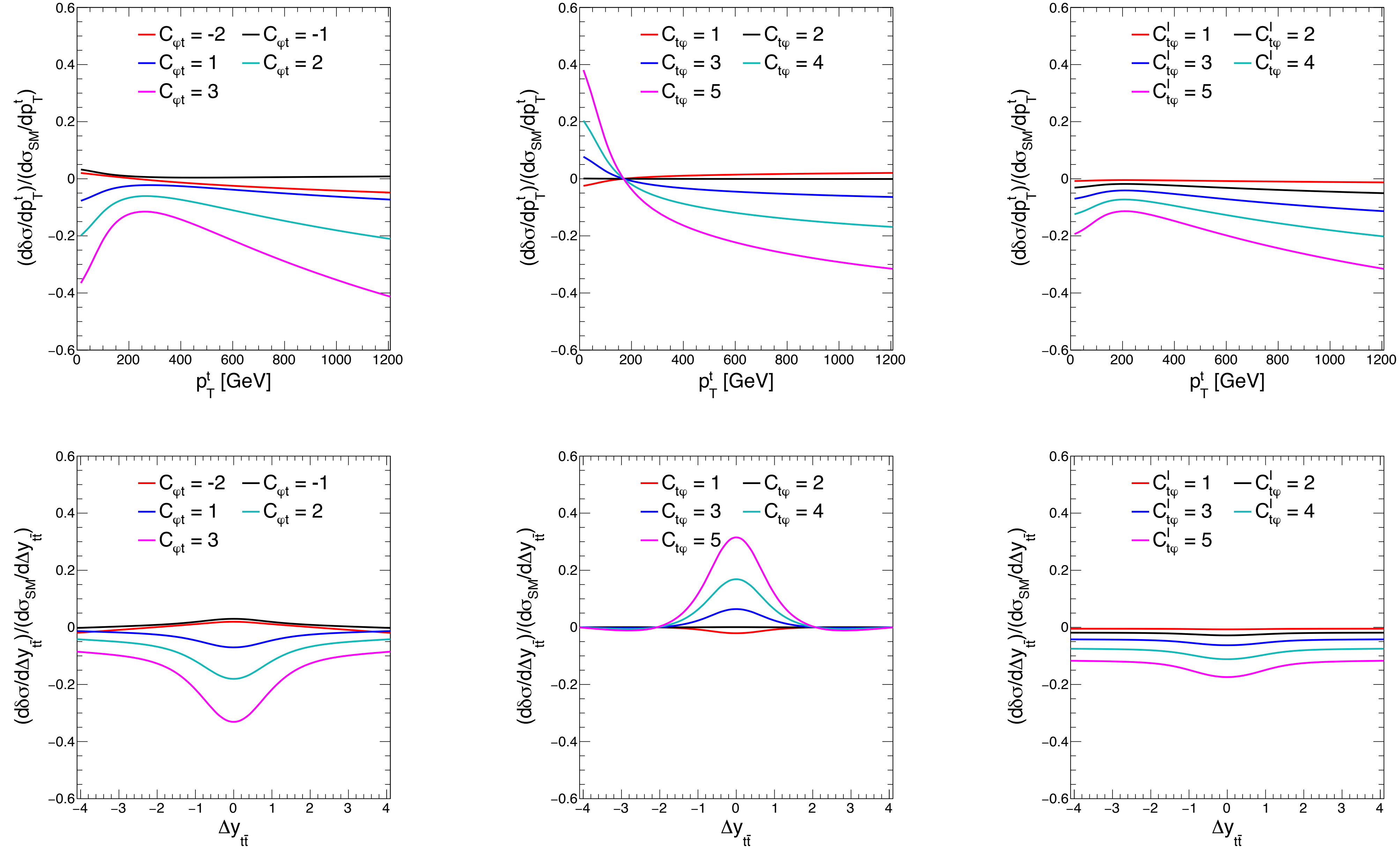
$C_{t\varphi}, C^I_{t\varphi}$ with f_{CP}

For convenience, the factor $\frac{v^2}{\Lambda^2}$ absorbed in to the 3 WCs

EW correction at gen-level

- Relative to SM

$-\ C_{\varphi t}$ $-\ C_{t\varphi}$ $-\ C^{I}_{t\varphi}$



From MCFM

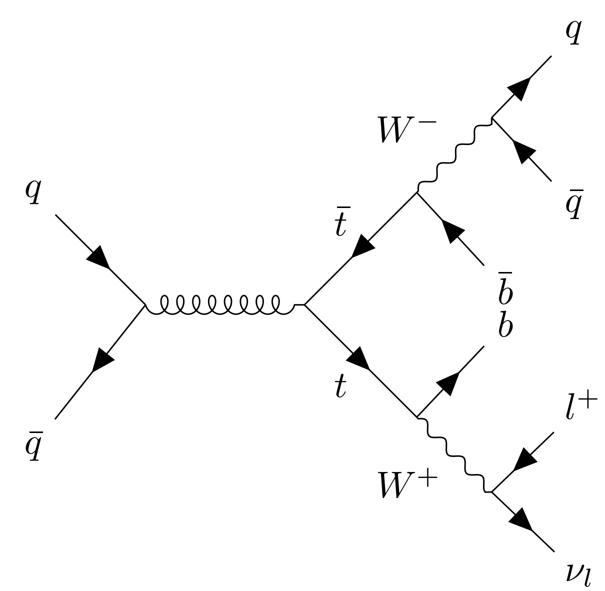
- Several observables sensitive to the EFT operators: p_T^{t}, $m_{t\bar{t}}$, $\Delta y_{t\bar{t}}$ and $\cos(\theta^*)$
- Optimal combination for measurement: p_T^t & $\Delta y_{t\bar{t}}$ & $\cos(\theta^*)$
  - θ^*: the angle between the 3-momentum of the top quark in the $t\bar{t}$ **rest frame** and the 3-momentum of the $t\bar{t}$ system in the lab frame

Basic information

- Data: 2016-2018, 137.6 fb^{-1}, Ultra Legacy
- Final state: **semi-leptonic** channel
  - **One and only** lepton (electron or muon)
  - At least **3** jets with at least **2** medium b-tagged jets
- Signal: POWHEG samples at NLO QCD
- Background: single Top, toponium, DY, VV, **W+jets, QCD**
  - QCD: estimated with data-driven techniques
  - W+jets: derived from MC and corrected in control region
  - Others: directly from MC simulation
    - Toponuim: color-singlet pseudo-scalar, m = 343 GeV, Γ = 2.8 GeV
    - Single top: overlap between tW & $t\bar{t}$ removed with Diagram Removal
- Observables: 3-dimensional distribution of p_T^t & $\Delta y_{t\bar{t}}$ & $\cos(\theta^*)$

- 16 categories:
  - e/μ, 3 jets/≥4 jets, 4 eras

Lepton Flavor	Jet Multiplicity	Year
electron	3jets	2016 pre-APV
electron	3jets	2016 post-APV
electron	3jets	2017
electron	3jets	2018
electron	4jets	2016 pre-APV
electron	4jets	2016 post-APV
electron	4jets	2017
electron	4jets	2018
muon	3jets	2016 pre-APV
muon	3jets	2016 post-APV
muon	3jets	2017
muon	3jets	2018
muon	4jets	2016 pre-APV
muon	4jets	2016 post-APV
muon	4jets	2017
muon	4jets	2018

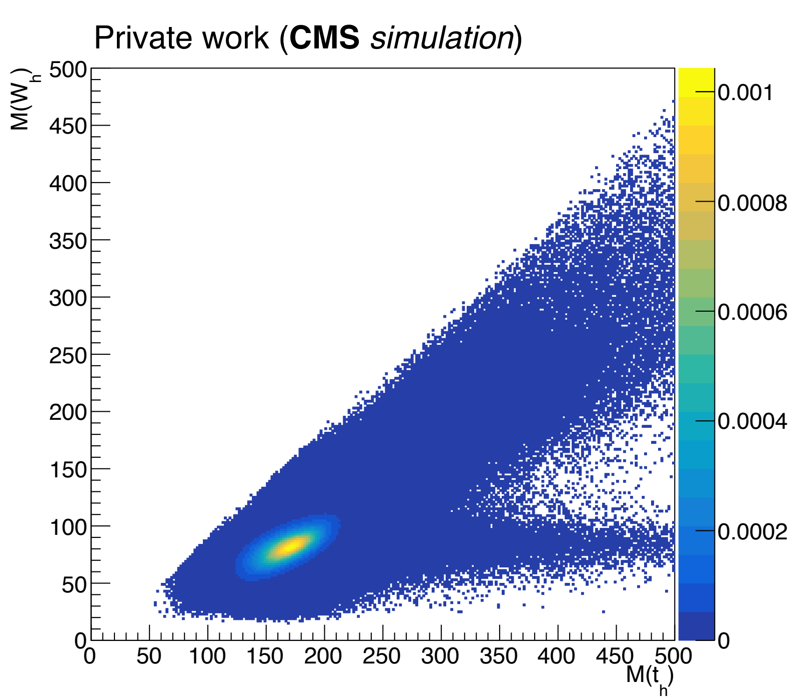


Reconstruction

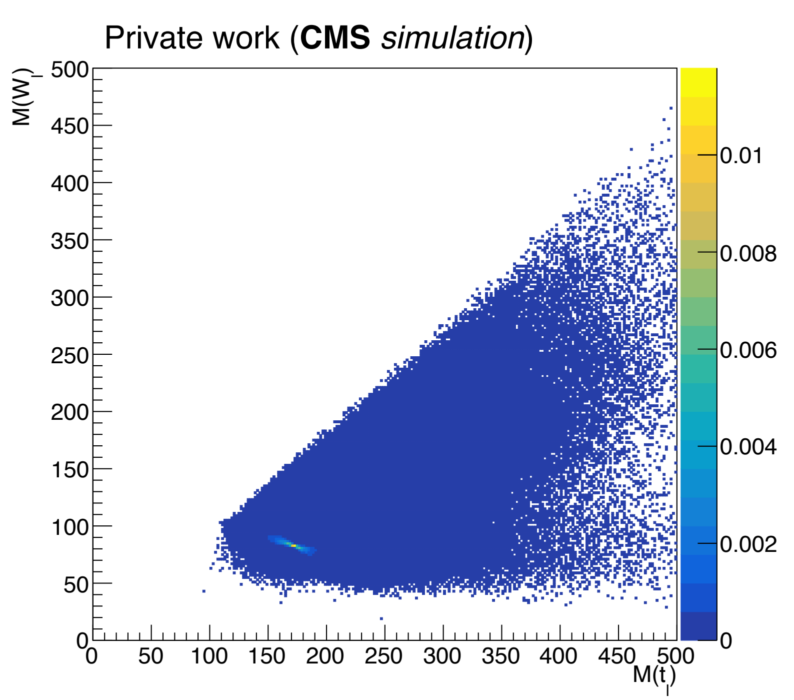
- Neutrino transverse momentum : $p_T^{\nu} = E_T^{miss}$
- Find p_z^{ν} and the **jets** permutation with largest likelihood:
  - For events with ≥4 jets:

$$ln(L_4) = ln(P_{had}(m_{t_h}, m_{W_h})) + ln(P_{lep}(m_{t_l}, m_{W_l}))$$

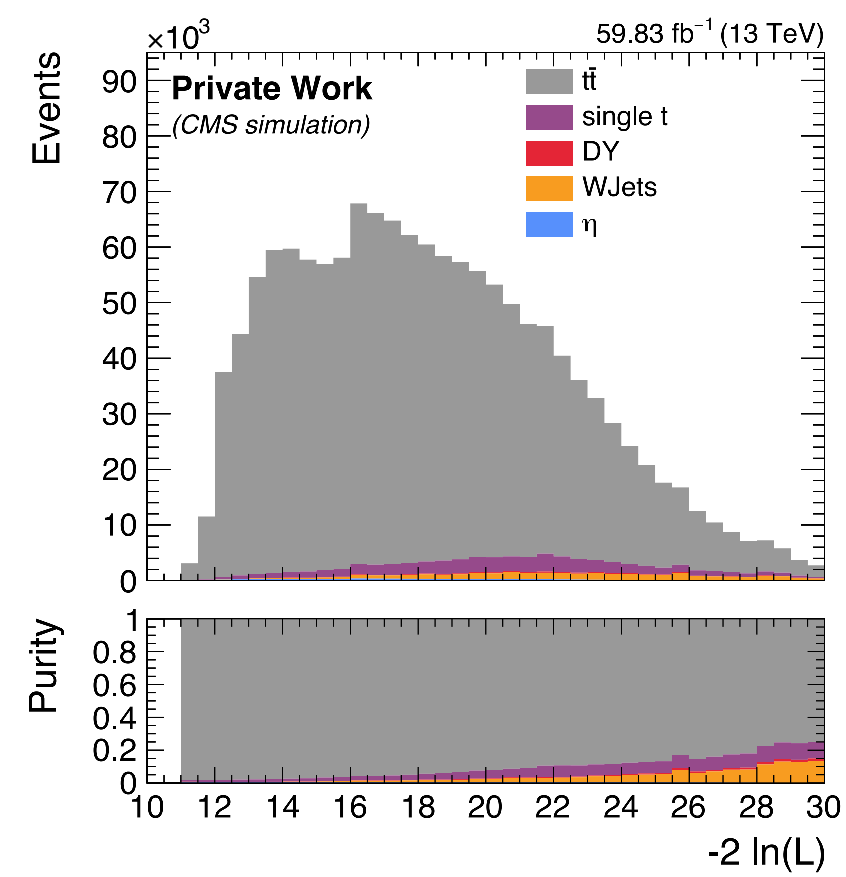
    - t_l, W_l: constructed with the lepton and neutrino (for t_l also the b-jet from **leptonic** top quark)
    - t_h, W_h: constructed with 2 light jets and 1 b-jet from **hadronic** top quark
    - P_{had}, P_{lep}: 2-dimensional PDF, derived from MC, for **correctly(ΔR-matching)** reconstructed objects:



P_{had}



P_{lep}

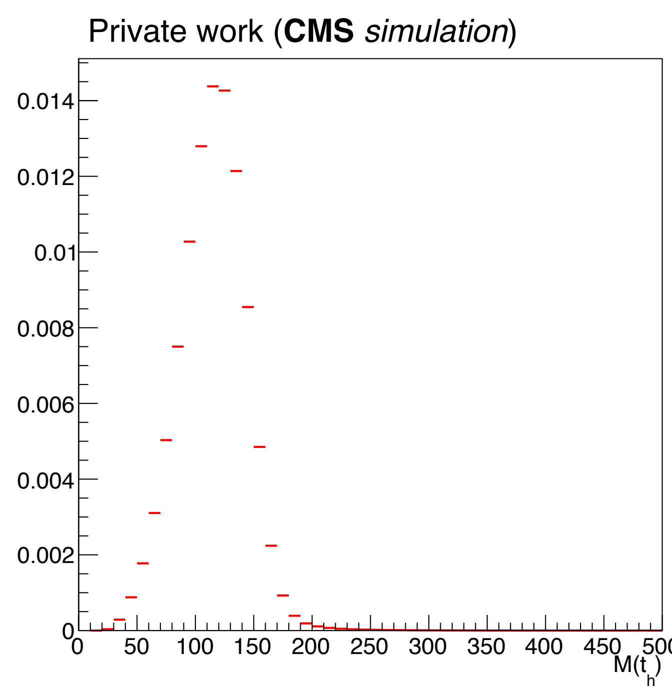


Reconstruction

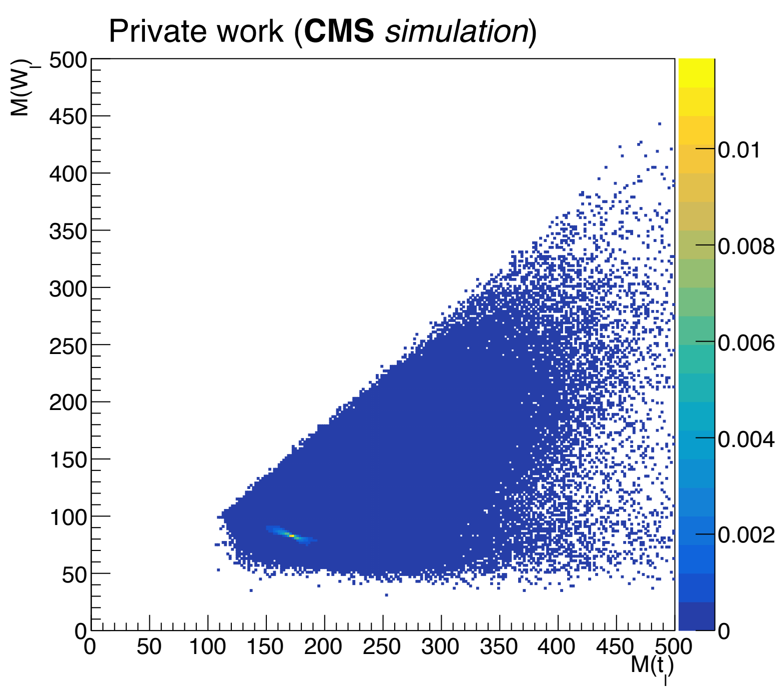
- For events with exactly 3 jets:

$$ln(L_3) = ln(P_{\text{had}}(m_{t_h})) + ln(P_{\text{lep}}(m_{t_l}, m_{W_l}))$$

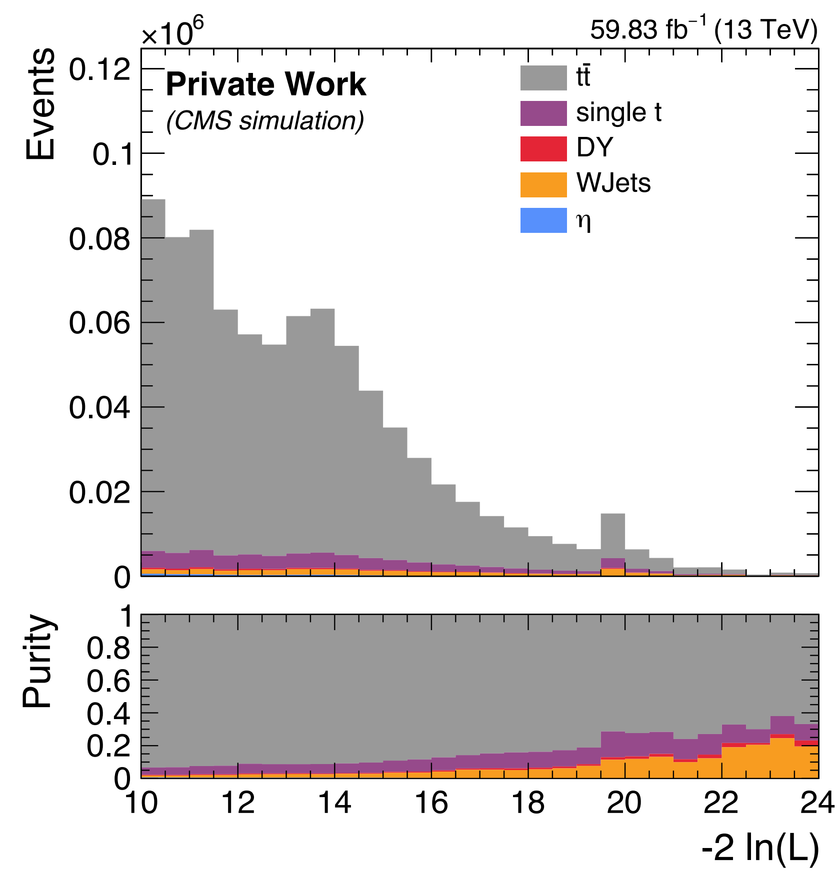
  - Assuming the missing jet from the hadronic W boson
  - t_h: constructed with the 1 light jet and 1 b-jet from **hadronic** top quark
  - -2 ln(L) < 15 required to improve signal purity, optimized based on sensitivity



P_{had}

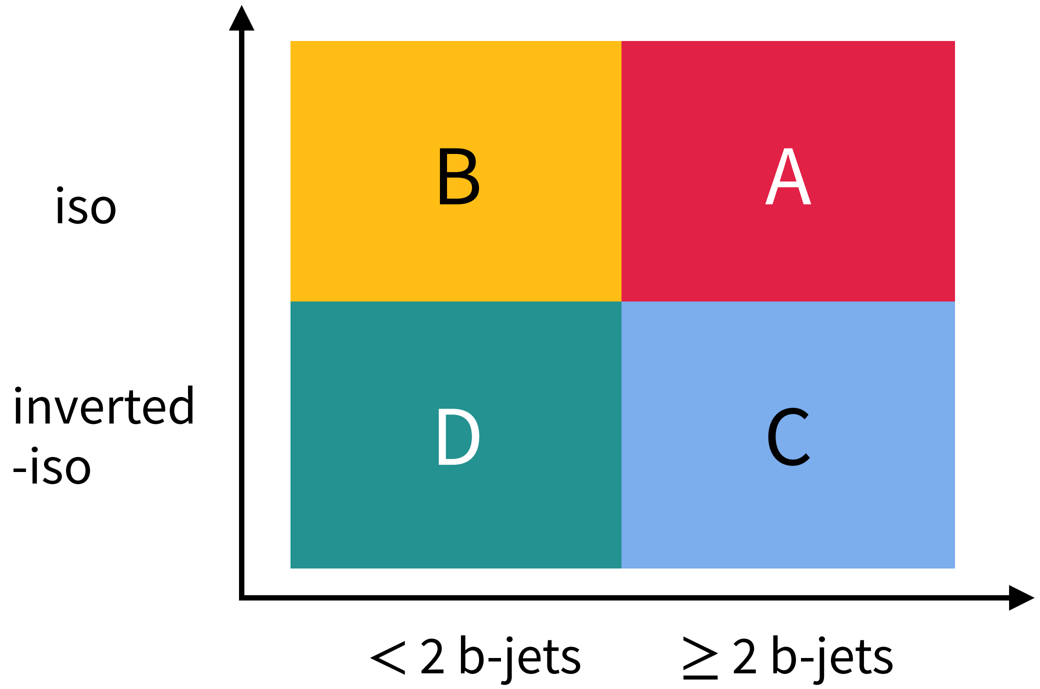


P_{lep}



QCD estimation

- Control regions:



- A: ≥ 2 b-tagged jets, 1 isolated lepton.
- B: < 2 b-tagged jet, 1 isolated lepton
- C: ≥ 2 b-tagged jets, 1 non-isolated lepton
- D: < 2 b-tagged jet, 1 non-isolated lepton

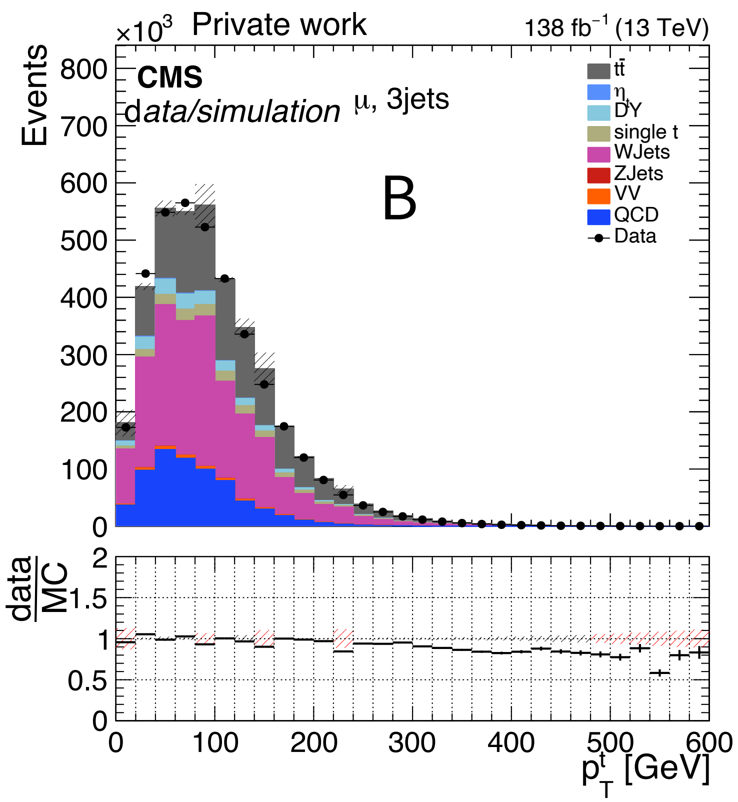
- Orthogonality:

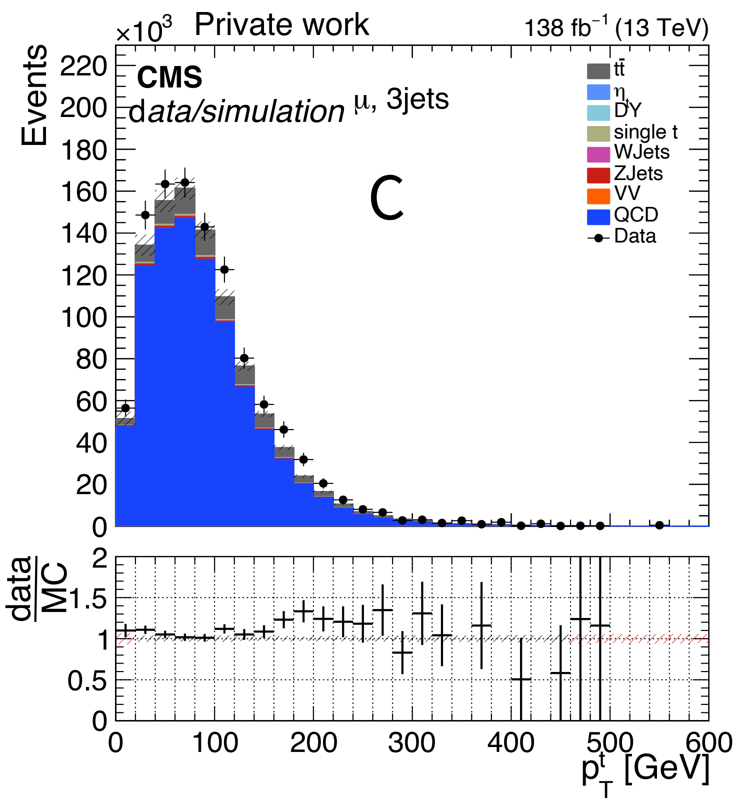
$$\frac{N_A}{N_C} = \frac{N_B}{N_D}$$

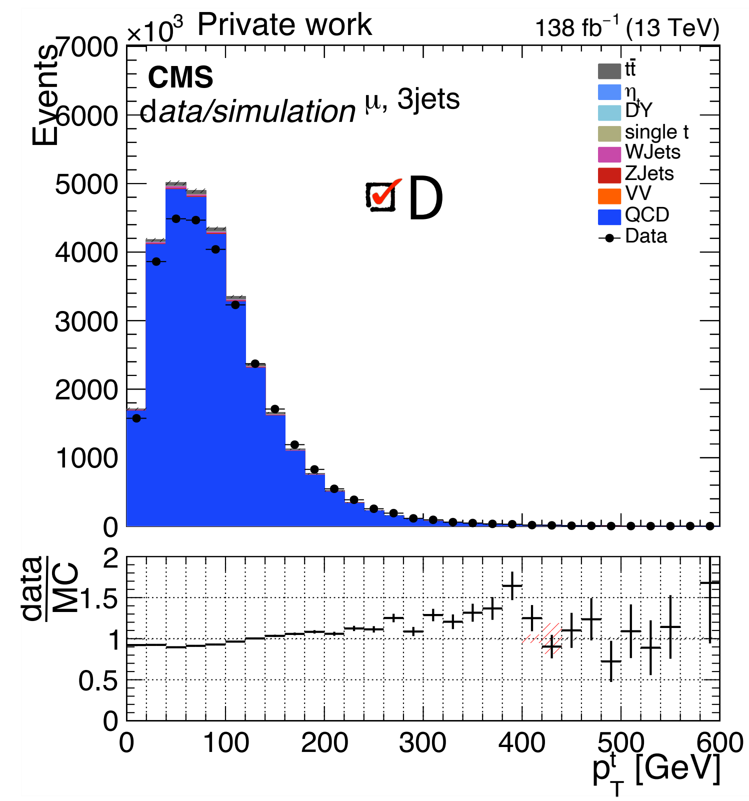
  - N: Event number for QCD in **each bin**
    - N(**MC**): Directly from MC
    - N(**data**): Data - MC of non-QCD

QCD estimation

- C & D: **QCD** dominants; B: **W+jets** & QCD dominant







- Strategy:

data - prompt MC

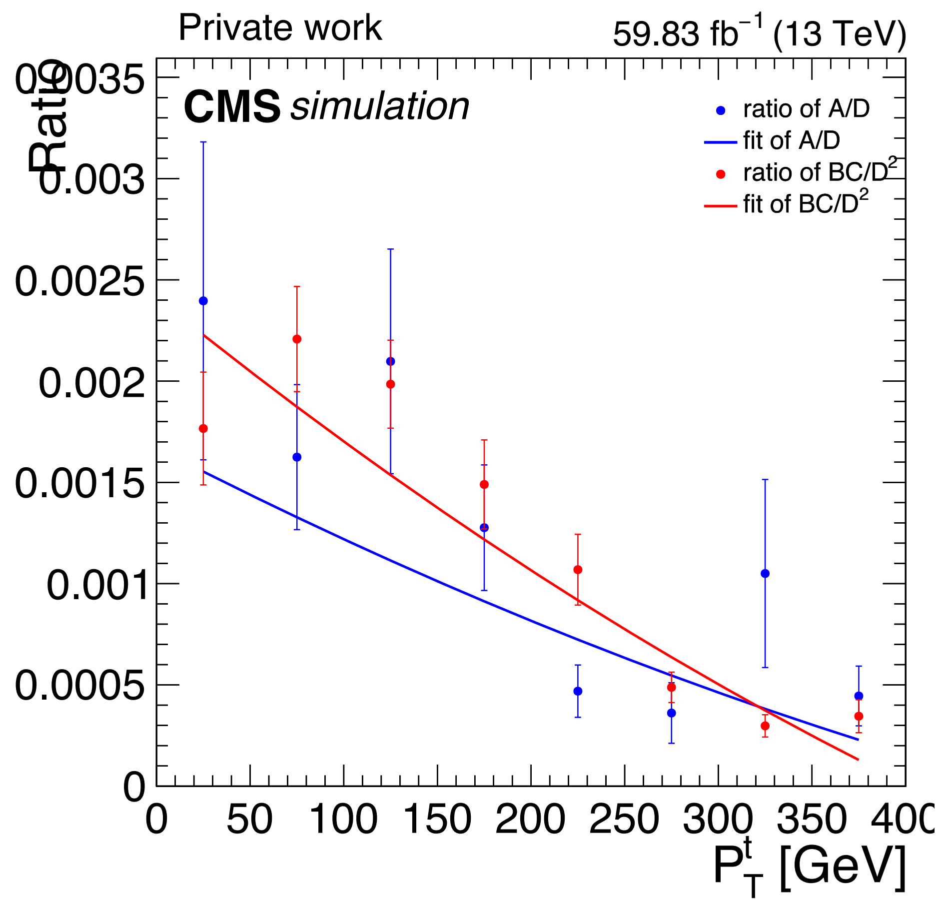
$$\frac{N_A}{N_C} = \frac{N_B}{N_D} \longrightarrow \boxed{\frac{N_A}{N_D}} = \frac{N_C}{N_D}\frac{N_A}{N_C} = \boxed{\frac{N_C N_B}{N_D^2}}$$

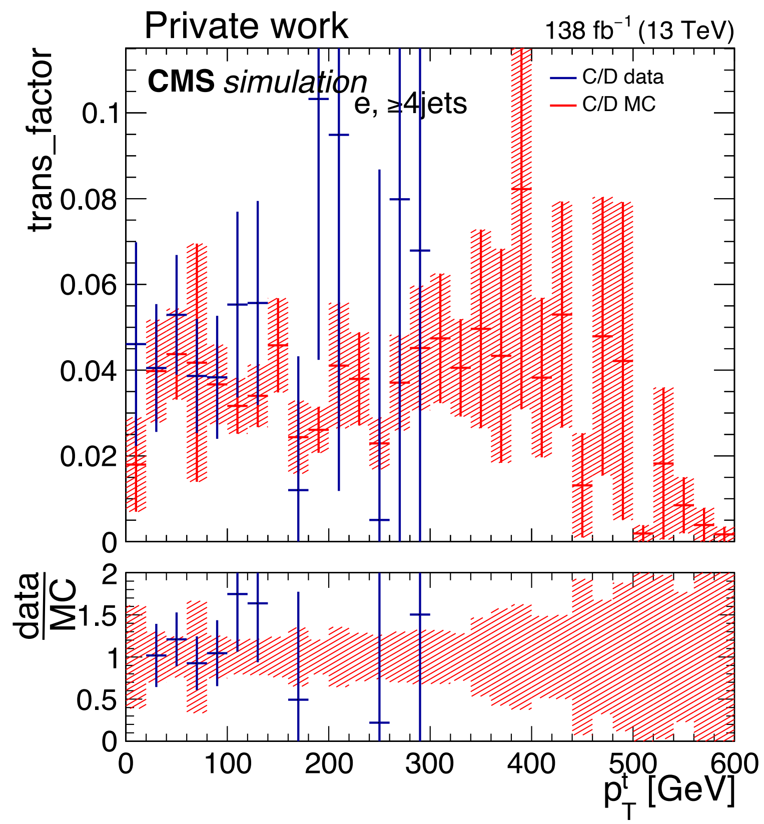
TF: Transfer factor, **shape** based, **MC**

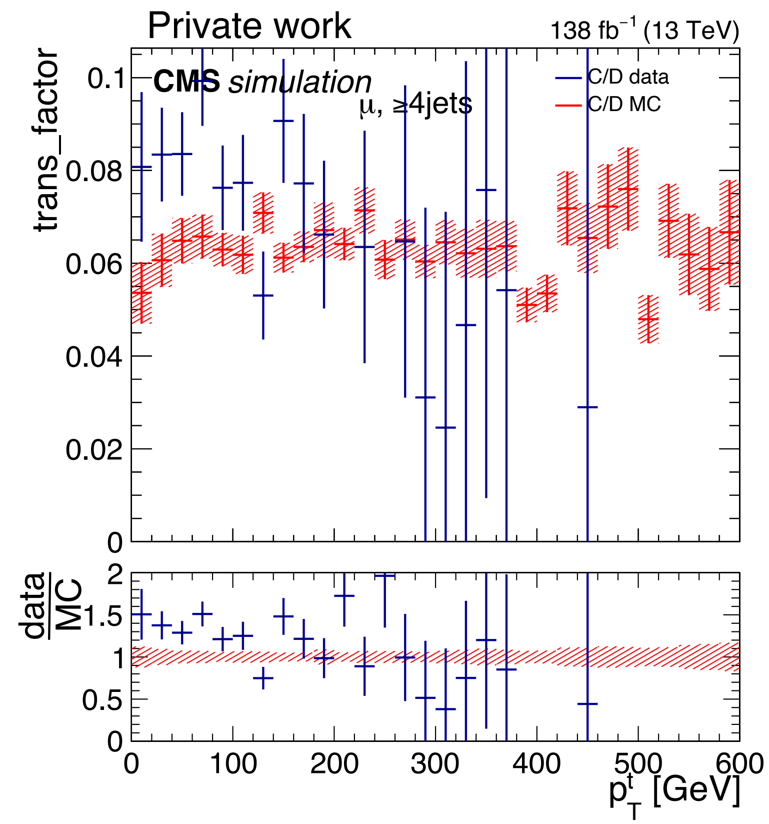
- Nominal: $N_A(\text{data-driven}) = N_D(\text{data})\frac{N_C N_B}{N_D^2}$
- Uncertainty sources:
  - Discrepancy between 2 kinds of TF
  - Difference between data and MC

QCD estimation: uncertainty

- Non-closure with **MC**: $\frac{N_A}{N_D} - \frac{N_C N_B}{N_D^2}$
- Data / MC discrepancy in $\frac{N_C}{N_D}$







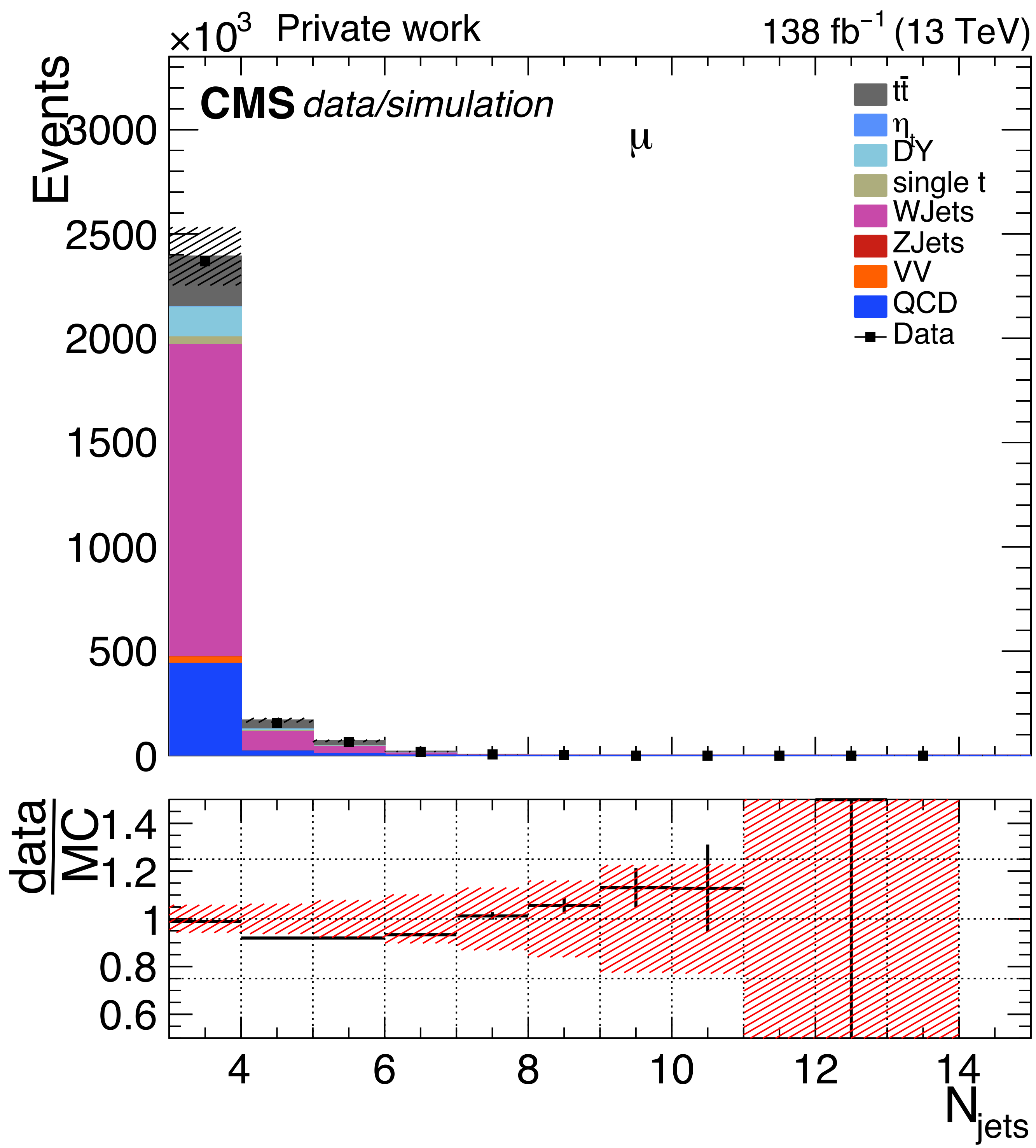
✳ Fitting with polynomials

✳ Smoothing

Uncertainties independent In each $\Delta y_{t\bar{t}}$ & $\cos(\theta^*)$ bin

W+jets estimation

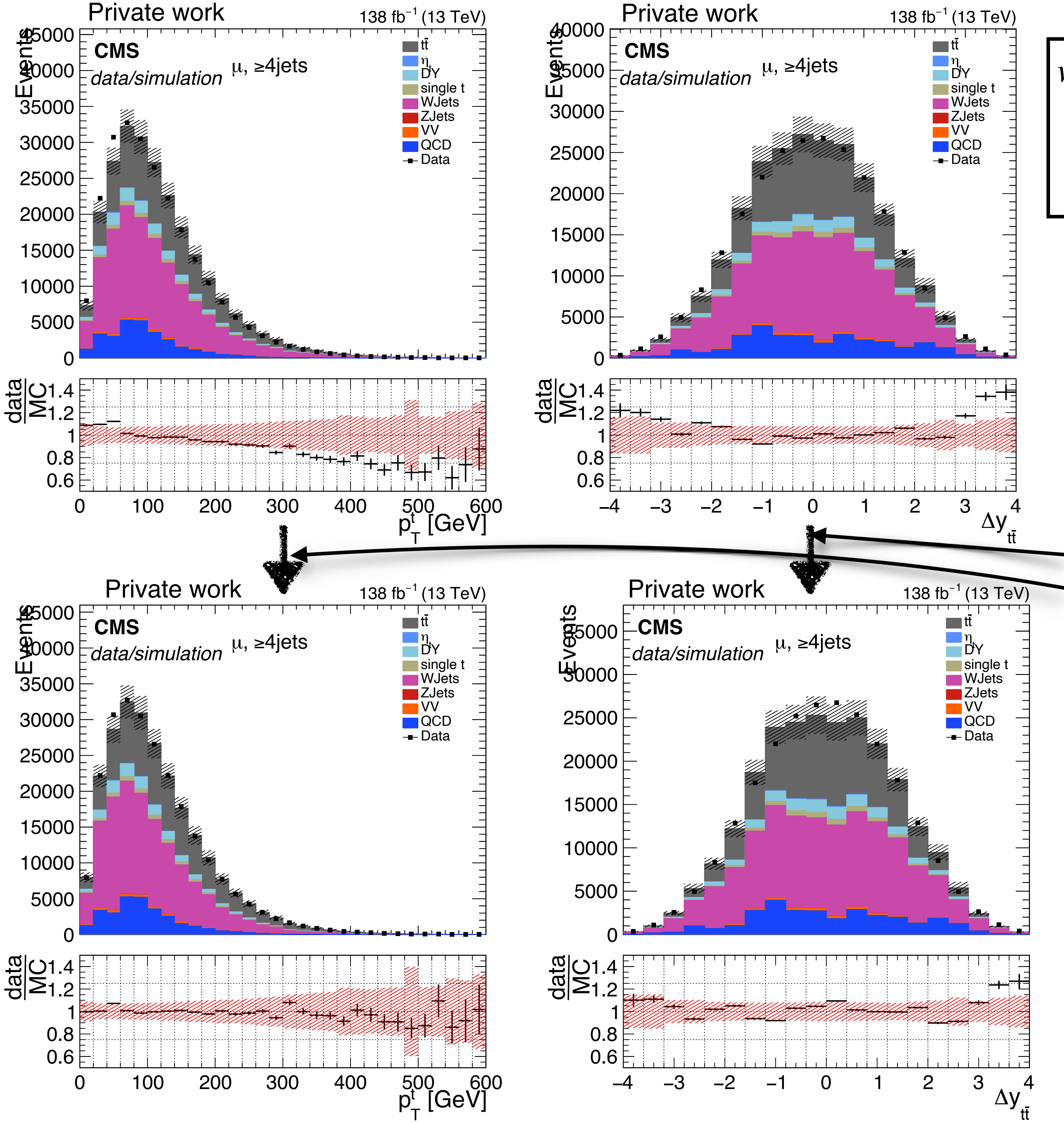
- Correction in dedicated control region: **no** b-tagged jet, part of B region
  - Correction based on jet multiplicities



$$w_1(N_{\text{jet}}) = \frac{N_{\text{data}}(N_{\text{jet}}) - \Sigma N_{\text{MC}}^{\text{other}}(N_{\text{jet}})}{N_{\text{MC}}^{\text{WJets}}(N_{\text{jet}})}$$

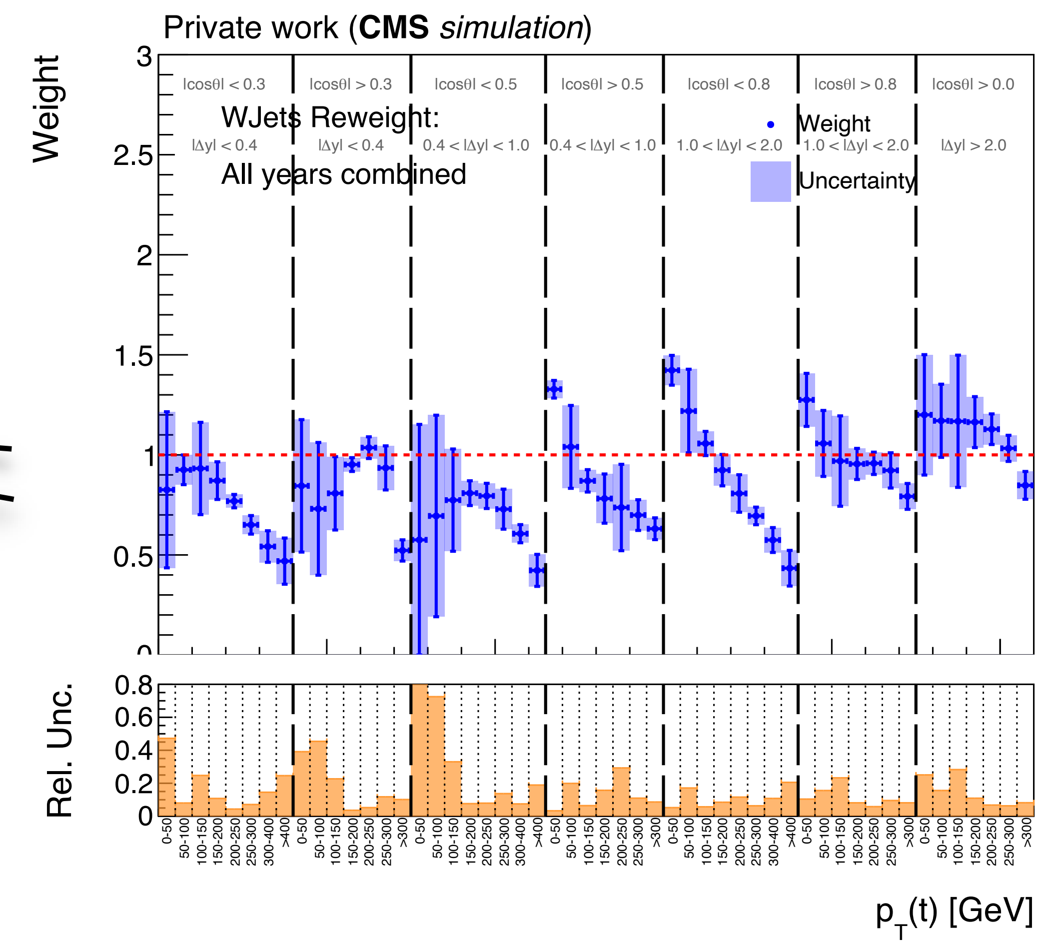
W+jets estimation

- After jet multiplicity correction



- Correction based on final observables

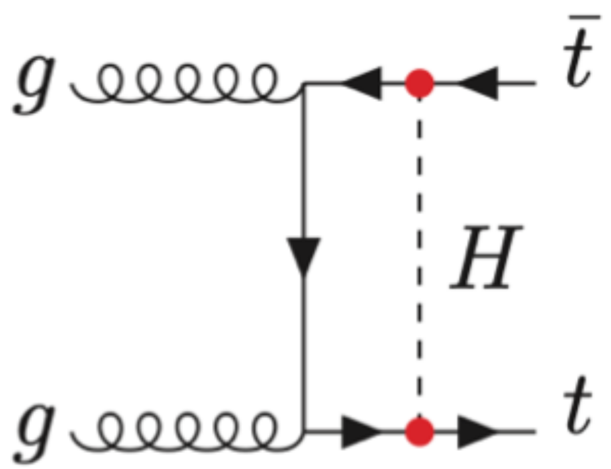
$$w_2(p_T^t, \Delta y, \cos\theta^*) = \frac{N_{\text{data}}(p_T^t, \Delta y, \cos\theta^*) - \sum N_{\text{MC}}^{\text{other}}(p_T^t, \Delta y, \cos\theta^*)}{N_{\text{MC}}^{\text{WJets}}(p_T^t, \Delta y, \cos\theta^*)}$$



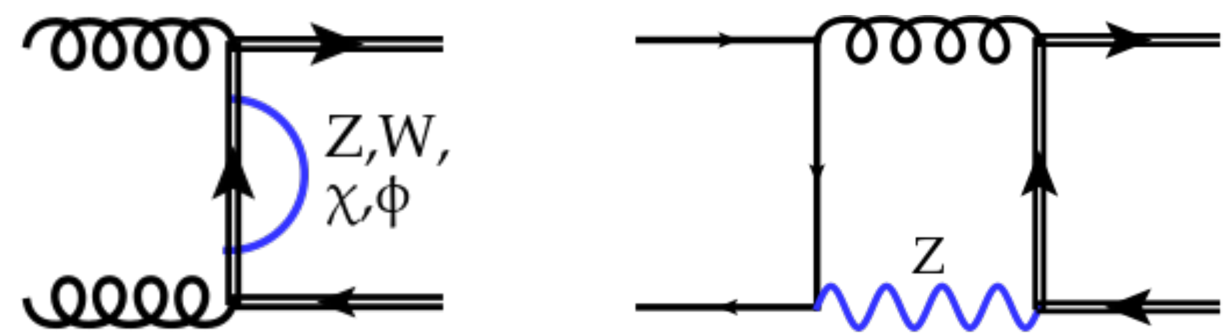
✴ **Corrections and uncertainties directly applied in signal region**

Signal parameterization

$$\mathcal{M} = \mathcal{M}_{\rm SM} + \kappa^2\mathcal{M}_1 + \tilde{\kappa}^2\mathcal{M}_2 + C_{\varphi t}\mathcal{M}_3 + C_{\varphi t}^2\mathcal{M}_4$$



Double insertions



Both double insertions and single insertions are included

$$\sigma \propto \left|\mathcal{M}\right|^2 \propto \left|\mathcal{M}_{SM}\right|^2 + \kappa^2 Re(\mathcal{M}_{SM}^*\mathcal{M}_1) + \tilde{\kappa}^2 Re(\mathcal{M}_{SM}^*\mathcal{M}_2) + C_{\varphi t} Re(\mathcal{M}_{SM}^*\mathcal{M}_3) + C_{\varphi t}^2 Re(\mathcal{M}_{SM}^*\mathcal{M}_4)$$

$$+\cdots$$

- BSM, higher order, **ignored** in this analysis

- **SM + int.**

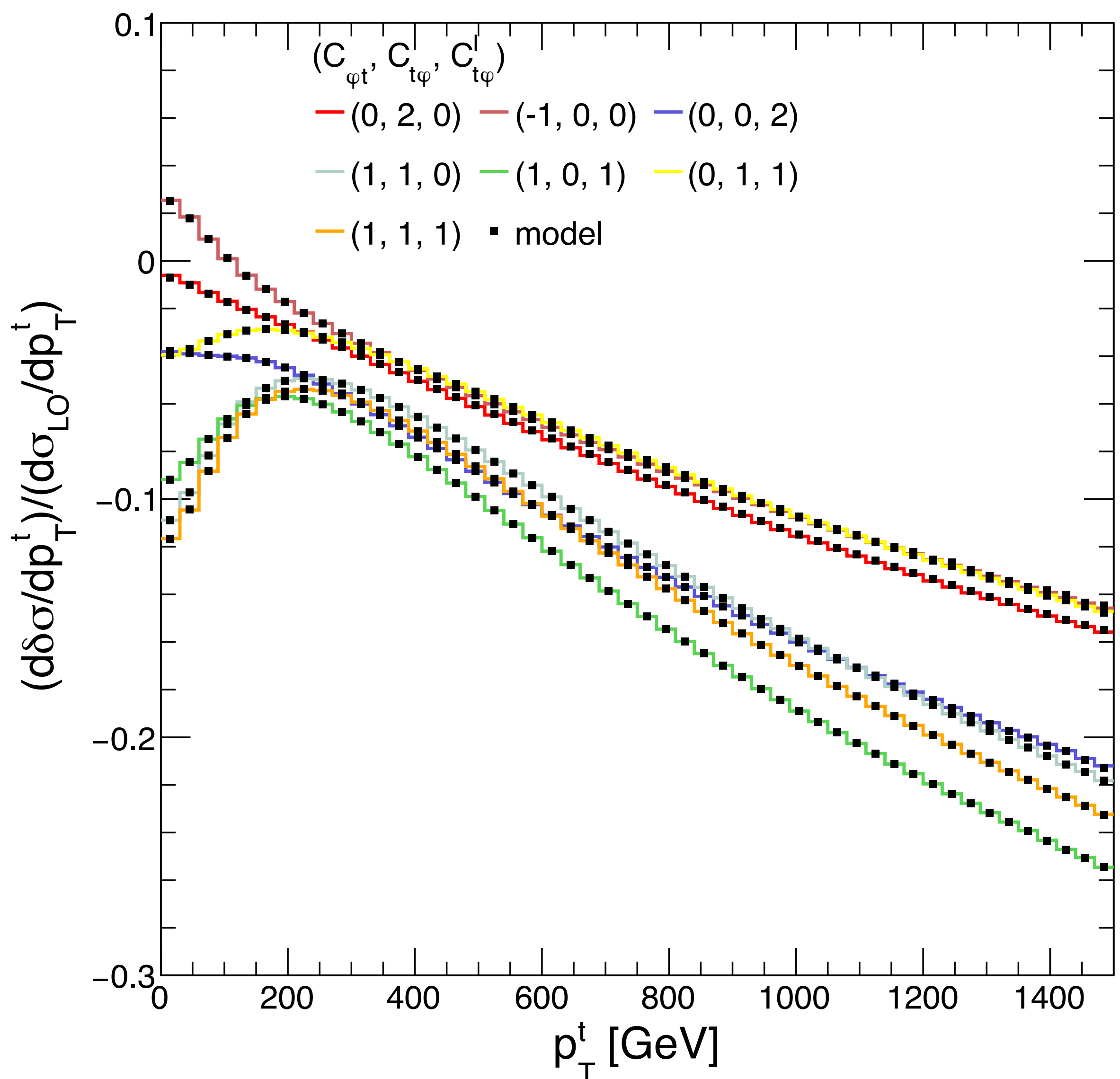
$$s^{\rm EFT} = s_0 + s_1(c_{t\varphi} - 1)^2 + s_2(c_{t\varphi}^I)^2 + s_3 c_{\varphi t}^2 + s_4 c_{\varphi t}$$

✳ For convenience, again we define: $c_* := \frac{v}{\sqrt{2}m_t}C_*$

Signal parameterization

$$s^{\text{EFT}}(c_{t\varphi}, c^I_{t\varphi}, c_{\varphi t}) = s_0 + s_1(c_{t\varphi} - 1)^2 + s_2(c^I_{t\varphi})^2 + s_3 c^2_{\varphi t} + s_4 c_{\varphi t}$$

- s_i : linear combination of 5 templates $s^{\text{EFT}}(a, b, c)$
- Validated at **GEN-level**:



From MCFM

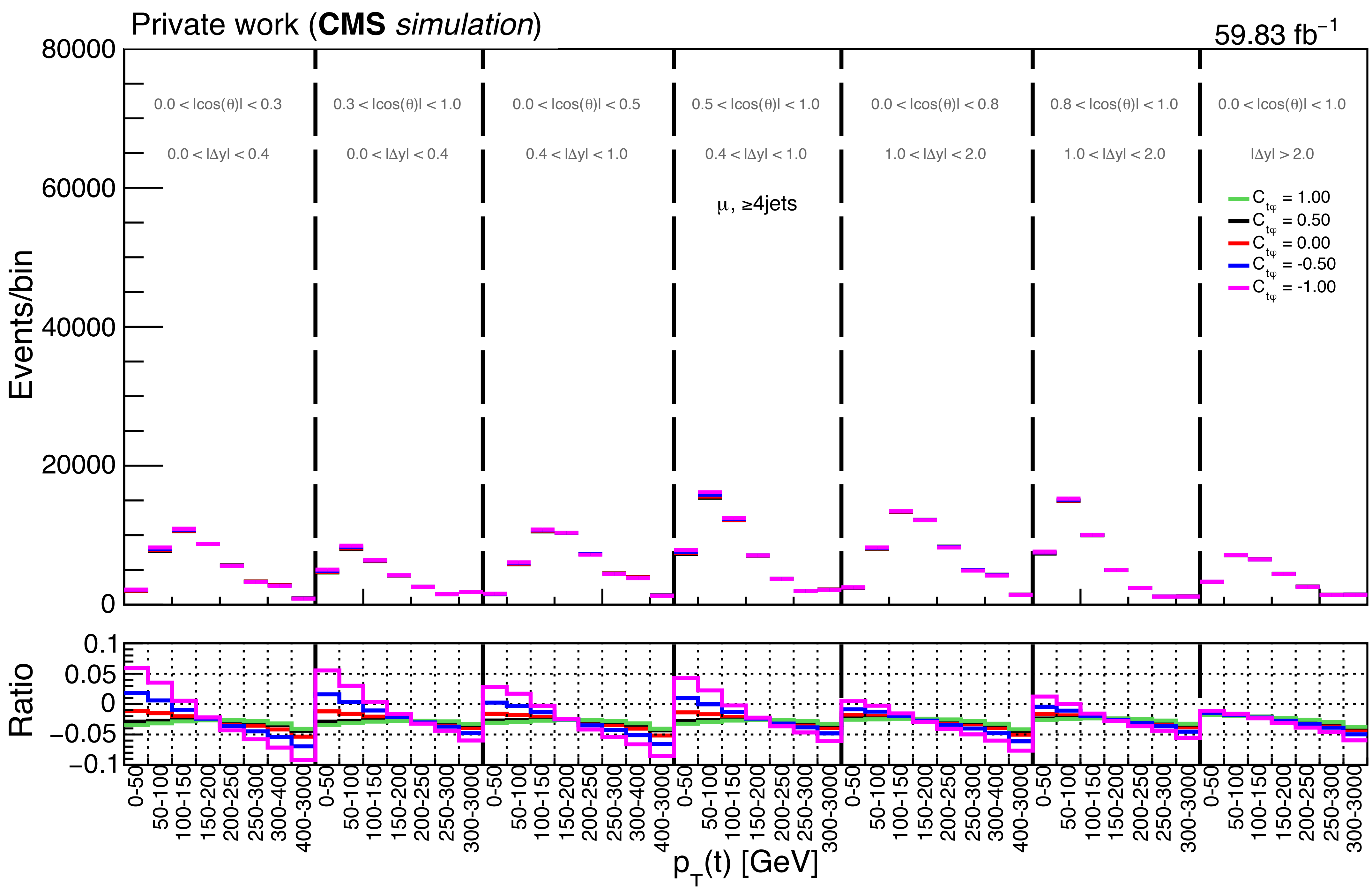
- : from parameterization model

—— : generated from MCFM

- GEN-level corrections propagated to **RECO-level** with event re-weighting

EFT corrections on signal: $t\bar{t}H$

- With RECO-level templates and parameterization model, differential cross section of **any WC values** constructed:



Signal EW & QCD corrections combined

- NNLO QCD:
  - Signal POWHEG NLO samples re-weighted to NNLO QCD with MATRIX

- 2 kinds of correction:
  - NNLO QCD: $\sigma_{\text{NNLO QCD}} = \sigma_{\text{LO QCD}} + \Sigma_{\text{NLO QCD}} + \Sigma_{\text{NNLO QCD}}$
  - NLO EW: $\sigma_{\text{NLO EW}} = \sigma_{\text{LO QCD}} + \Sigma_{\text{NLO EW}}$

- 2 ways to combine them:

Calculated by MCFM POWHEG Calculated by MATRIX

☑ Multiplicative:

$$\sigma_{\text{NNLO QCD}\times\text{EW}} = \boxed{\frac{\sigma_{\text{NLO EW}}}{\sigma_{\text{LO QCD}}}} \times \boxed{\sigma_{\text{NLO QCD}}} \times \boxed{\frac{\sigma_{\text{NNLO QCD}}}{\sigma_{\text{NLO QCD}}}}$$

- Additive:

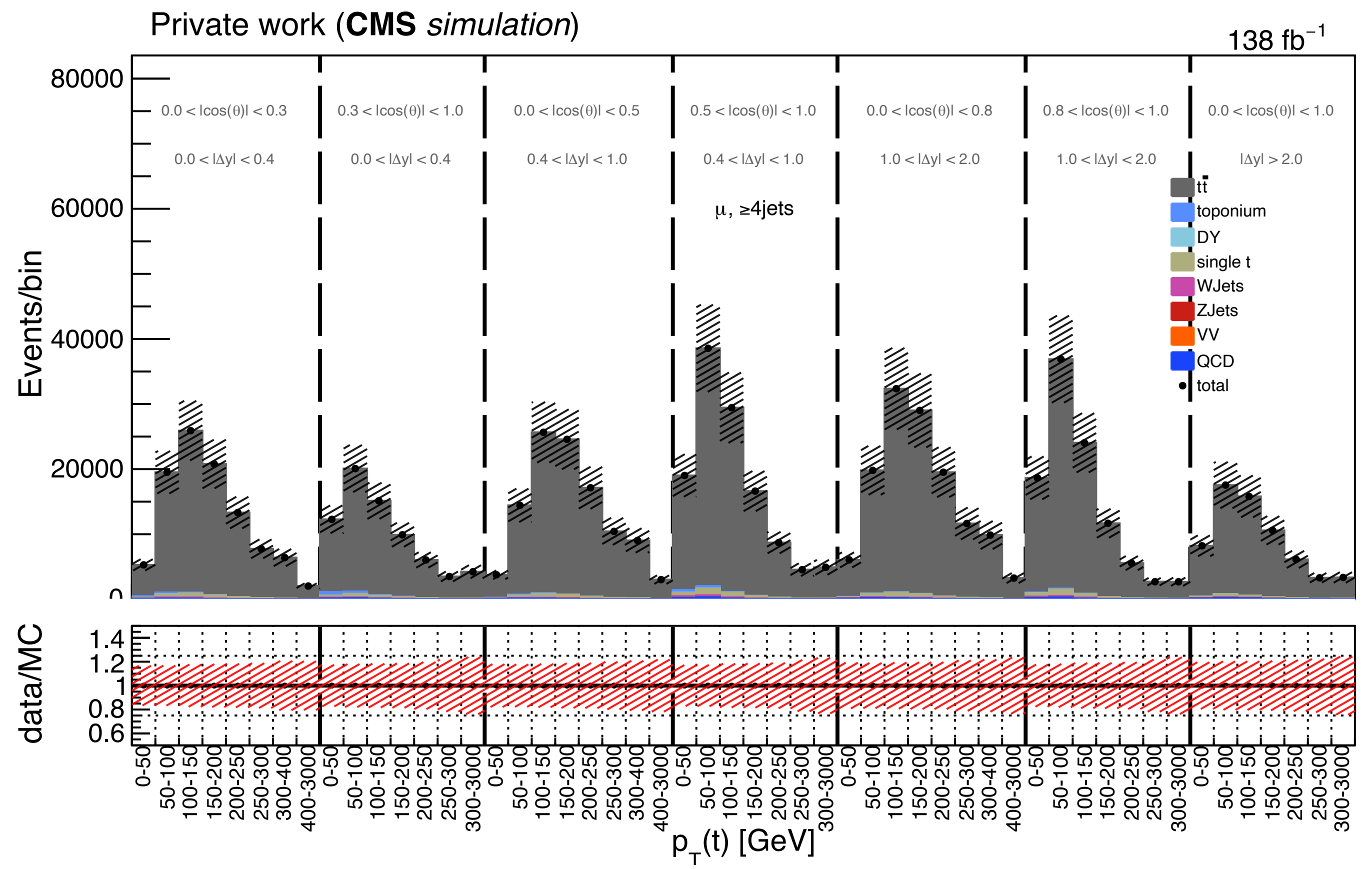
$$\sigma_{\text{NNLO QCD+EW}} = \sigma_{\text{NNLO QCD}} + \Sigma_{\text{NLO EW}}$$

- We choose the **multiplicative** method to include $\mathcal{O}(\alpha_S^3\alpha)$ and $\mathcal{O}(\alpha_S^4\alpha)$, as the scale uncertainties are smaller, see 1705.04105.

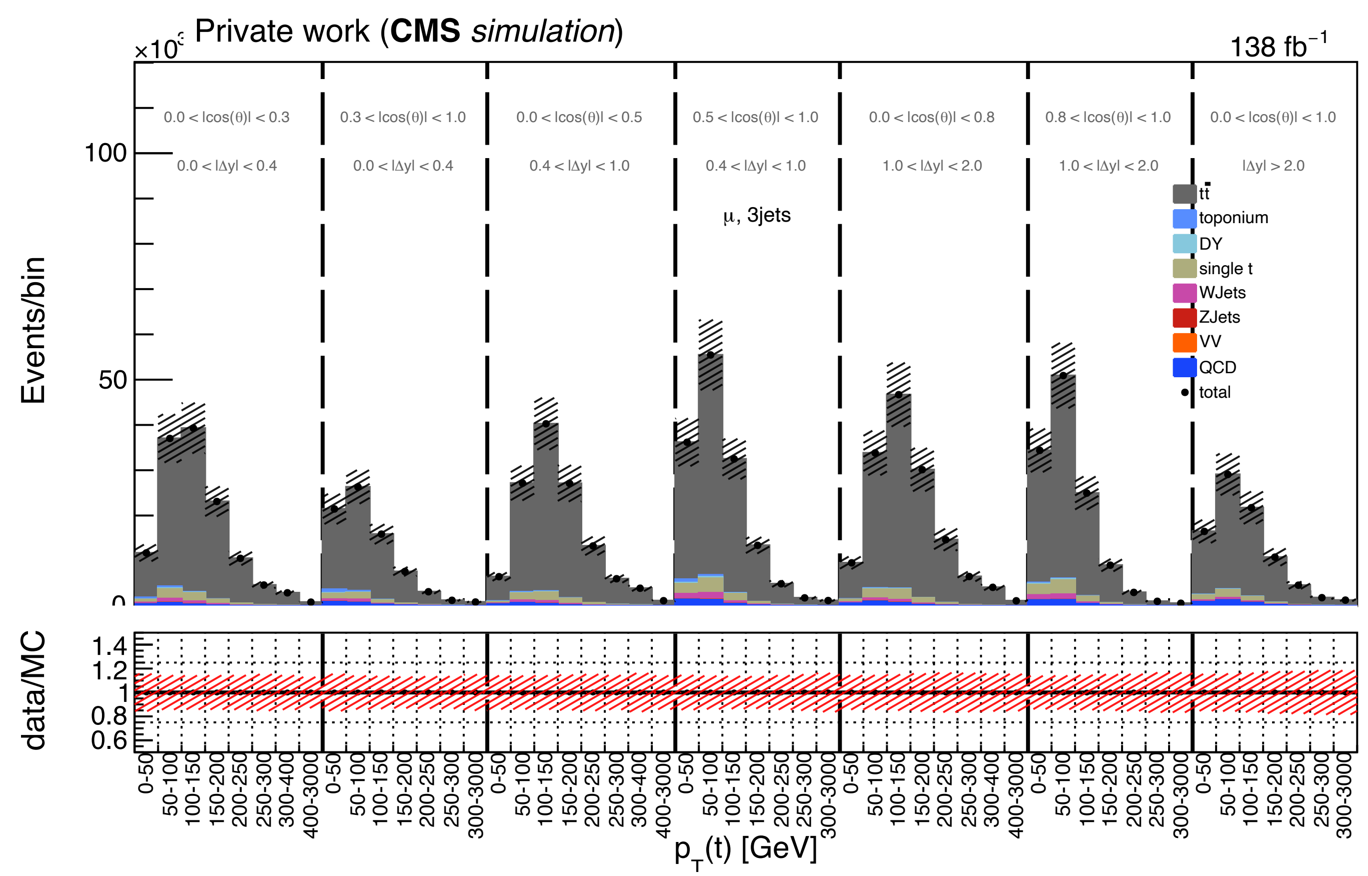
- The difference treated as a theoretical uncertainty.

Signal region with final observables

- **3D** $p_T(t), \cos(\theta^*), \Delta y_{t\bar{t}}$ as final observables for measurement
  - μ, ≥4 jets, full run2

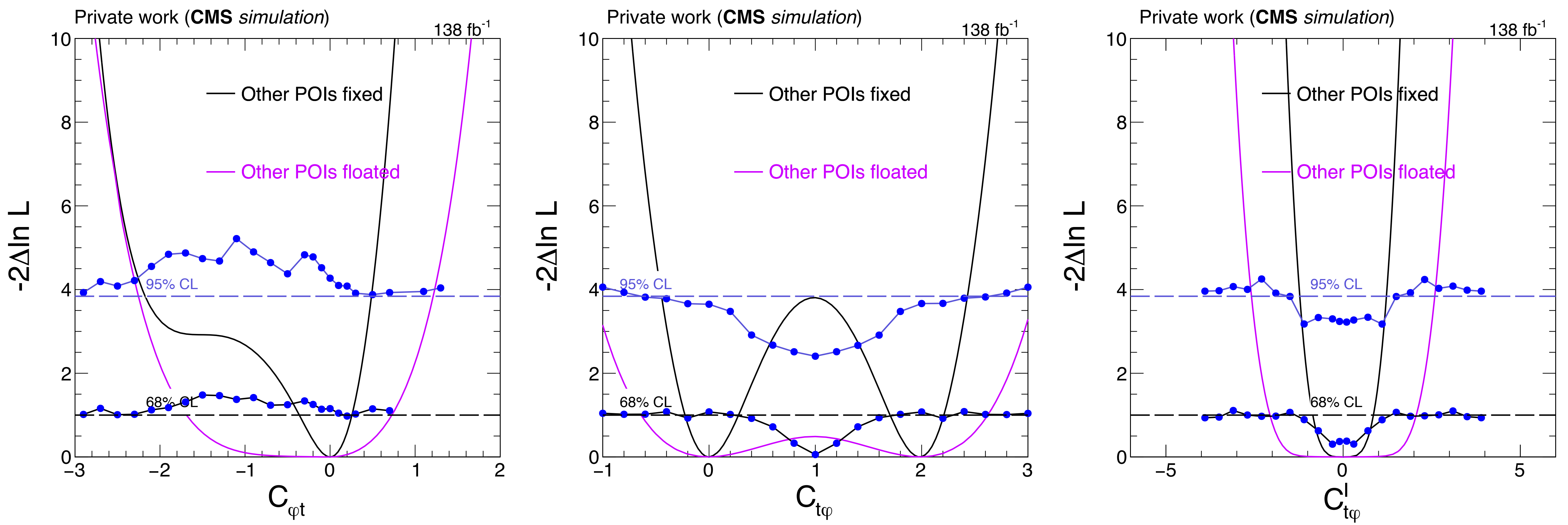


  - μ, 3 jets, full run2



Results

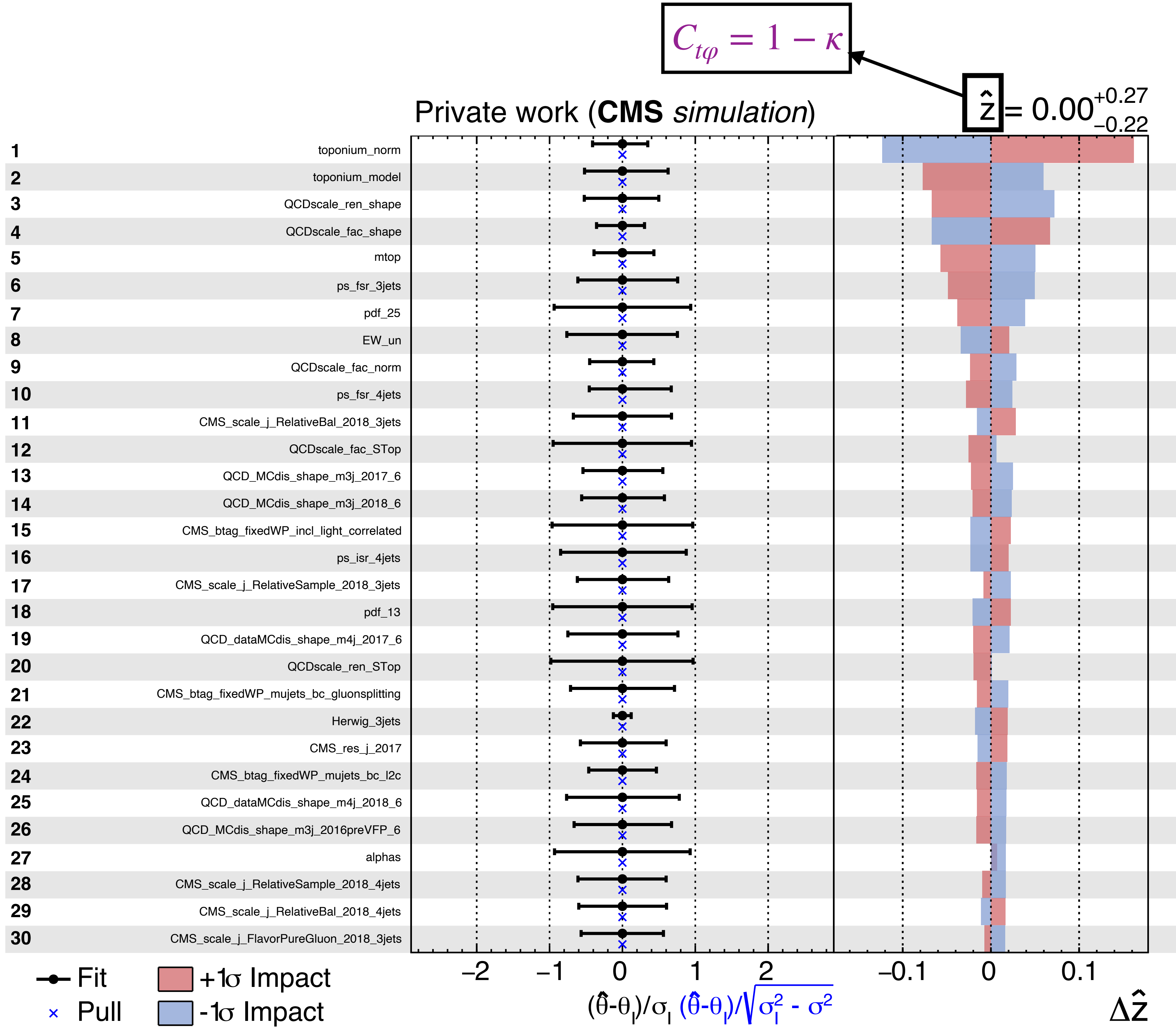
- 1D likelihood scan:



- Sensitivity compatible with previous **direct** measurements
- Validity tested with Wilks' theorem
  - For $C_{t\varphi}$, $C^{I}_{t\varphi}$, the asymptotic assumption almost always valid
  - For $C_{\varphi t}$, majority of the phase space, except mild difference in [-2, 0]

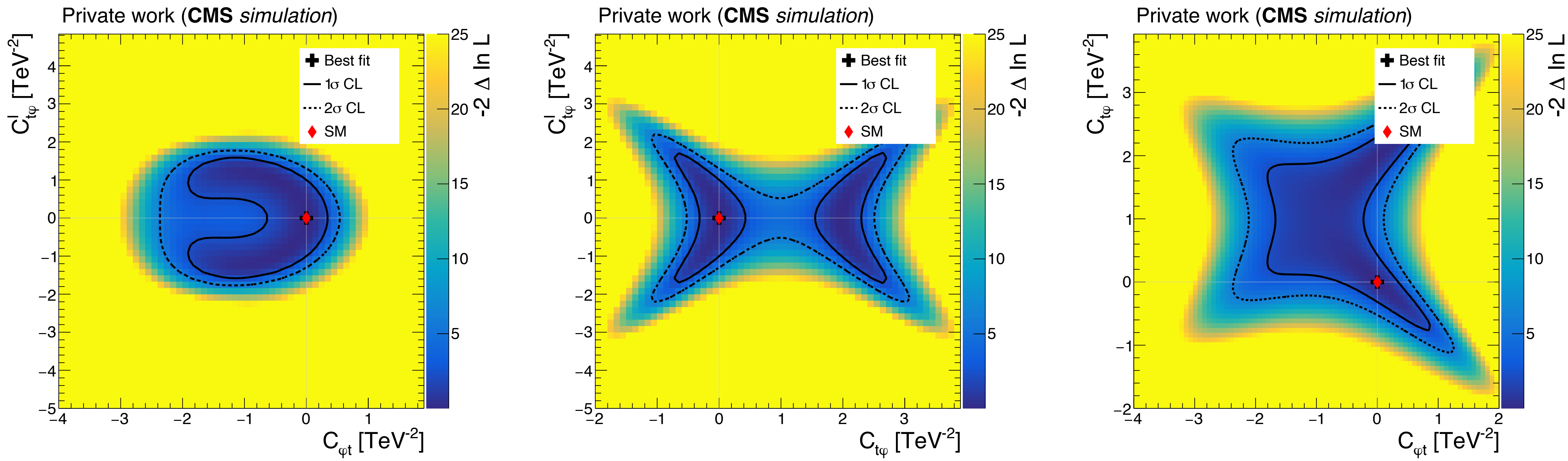
Results

- Impact on $C_{t\varphi}$
  - Systematic dominated
  - Dominant systematics:
    - toponium normalization
    - toponium model
    - top quark mass
    - NLO QCD scale

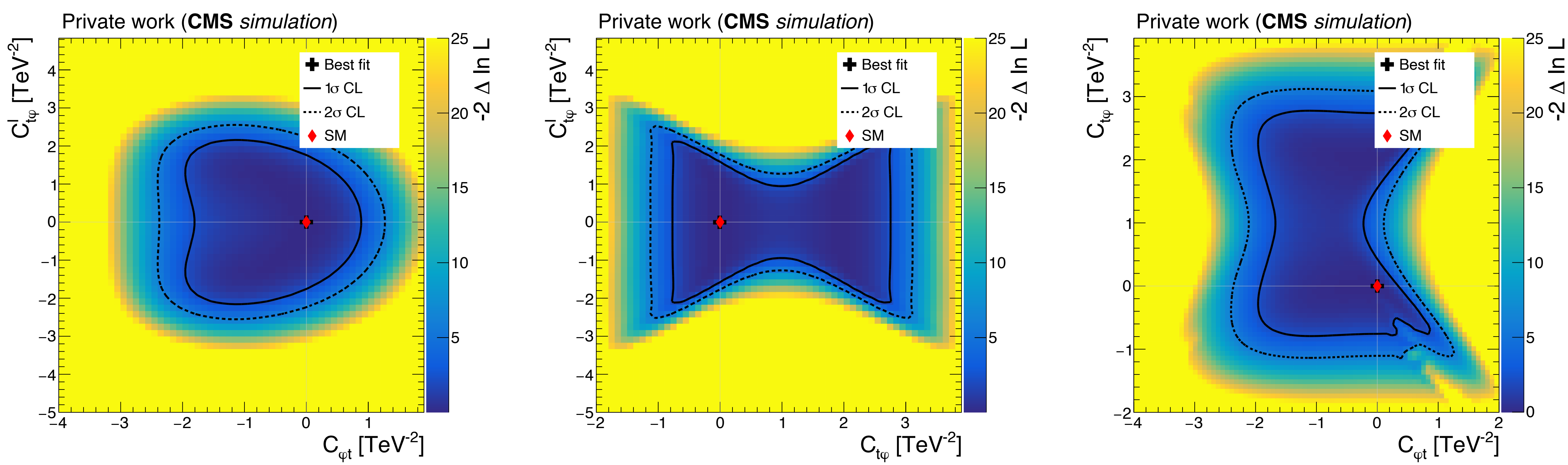


Results

- 2D likelihood scan:
  - With the other POI fixed:



  - With the other POI floated:

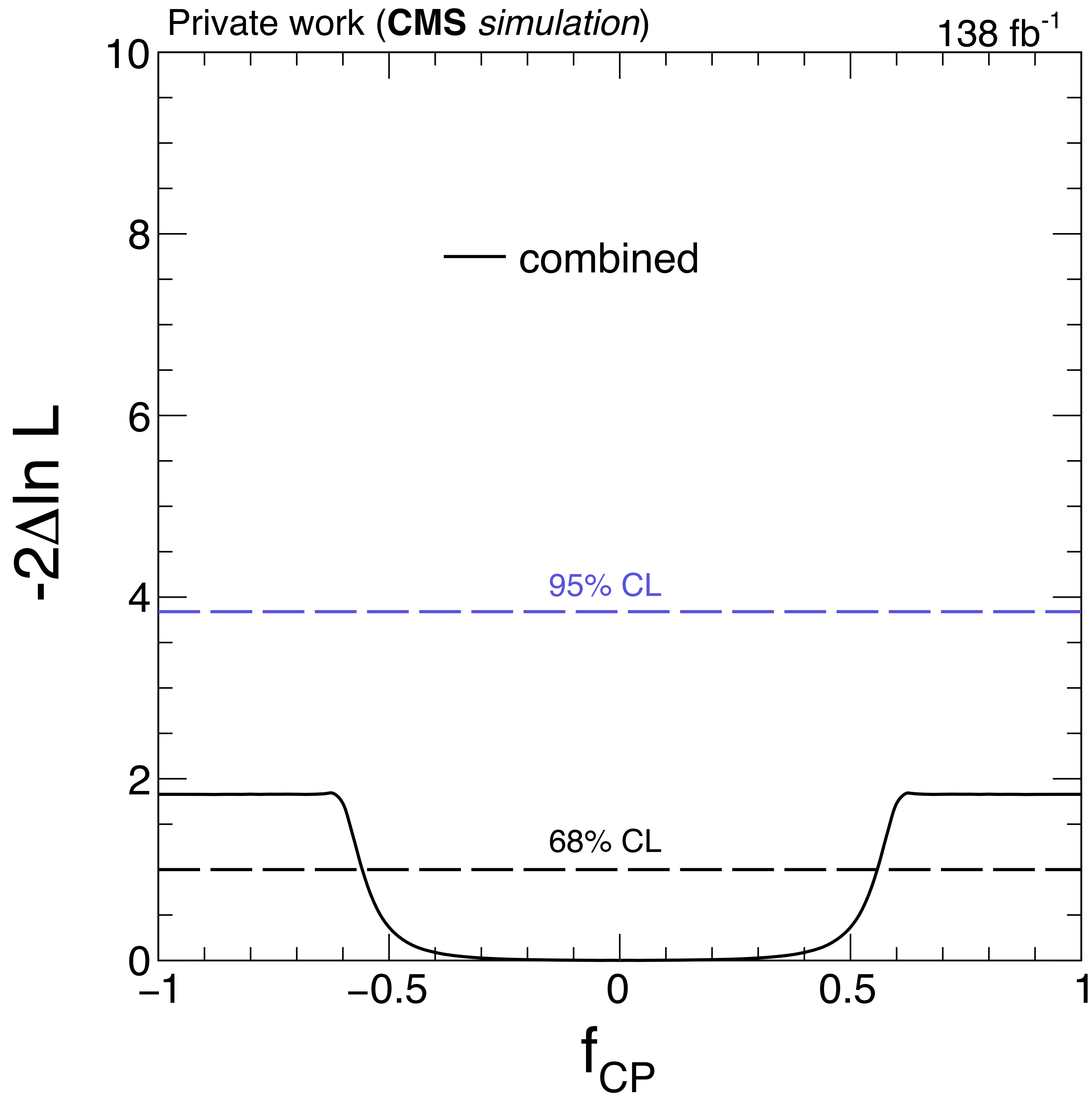


Results

- CP violation

  - $f_{CP} = \frac{|\tilde{\kappa}|^2}{|\kappa|^2 + |\tilde{\kappa}|^2} sign\left(\frac{\tilde{\kappa}}{\kappa}\right)$
  - $\mu = \sqrt{|\kappa|^2 + |\tilde{\kappa}|^2}$

  - Compatible results with previous measurements



- Fit with signal strength μ **floated**

Summary

- The first measurement of new physics in $\mathrm{t\bar{t}}$ production with NLO EW loops
  - Top-boson interactions probed
  - CP property of top-Higgs Yukawa coupling measured
  - Three dimension-6 operators modifying $\mathrm{t\bar{t}Z}$ and $\mathrm{t\bar{t}H}$ measured

- Work status and plans
  - All analysis components in place and expected sensitivity achieved
  - Unblinding has started after pre-approval

Backup

Selection

- Offline selection

Muon channel

Single muon trigger

$p_T > 30$ GeV, $|\eta| < 2.4$

Tight ID, PF rel. isolation < 0.15

Electron channel

Single electron trigger

$p_T > 30$ GeV for 2016 (37 GeV for 2017, 34 GeV for 2018)

$|\eta| < 2.4$, Veto $1.4442 < |\eta_{sc}| < 1.566$

Tight cut-based ID & Iso, d_{xy} & d_z

Additional lepton vetos:

$p_T > 15$ GeV, Loose cut-based ID for election **or** Loose ID & PF rel. isolation < 0.25 for muon

Jets (ΔR > 0.4 with e/μ)

anti-k_T AK4, $p_T > 30$ GeV, $|\eta| < 2.4$, tightLepVeto jetID, Veto with the strictest official jet-veto maps

At least **3** jets in one event, with at least **2** passing **medium DeepJet** working point

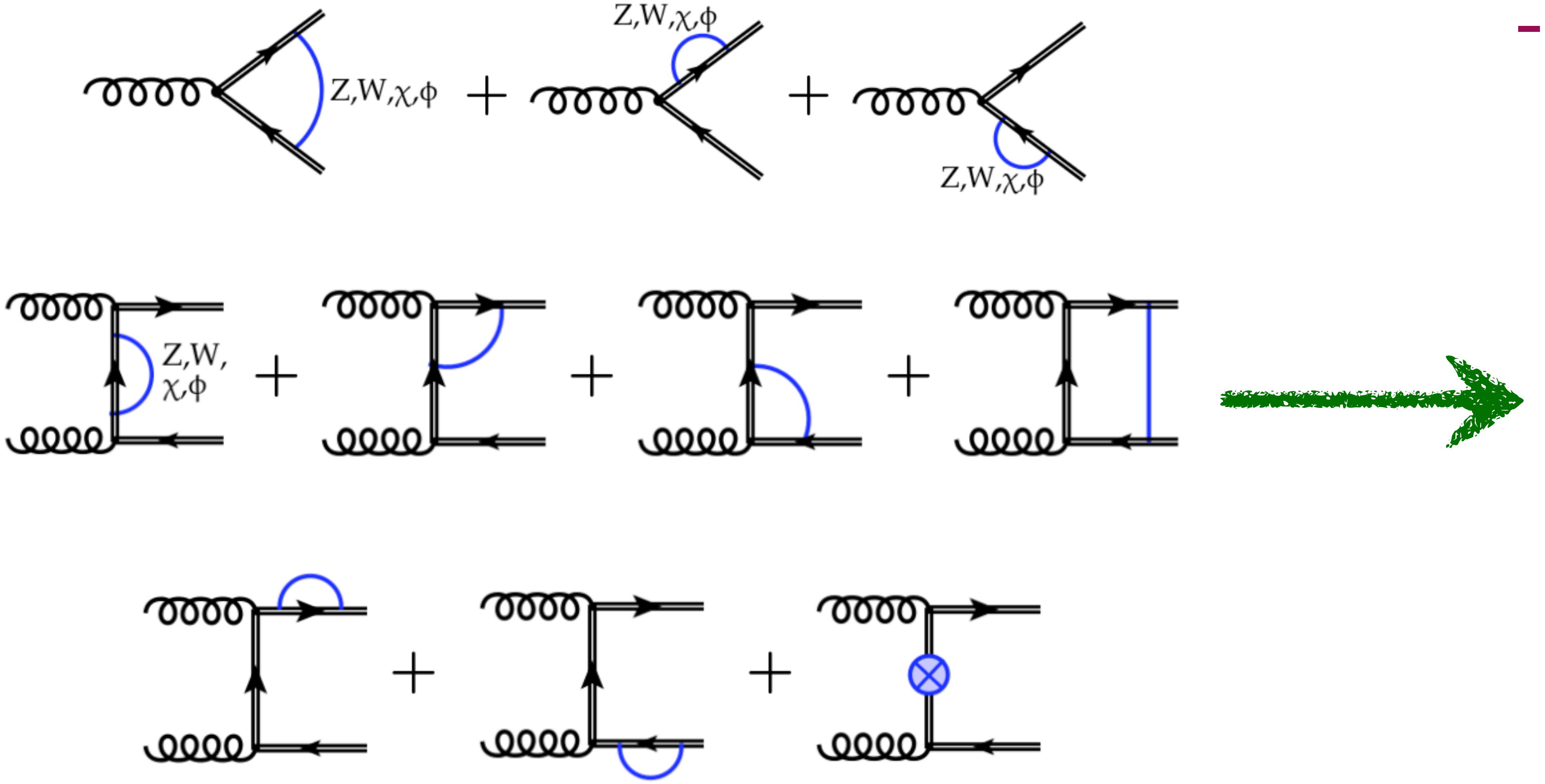
For events with exactly 3 jets, $p_T > 50$ GeV for leading-p_T jet

MET

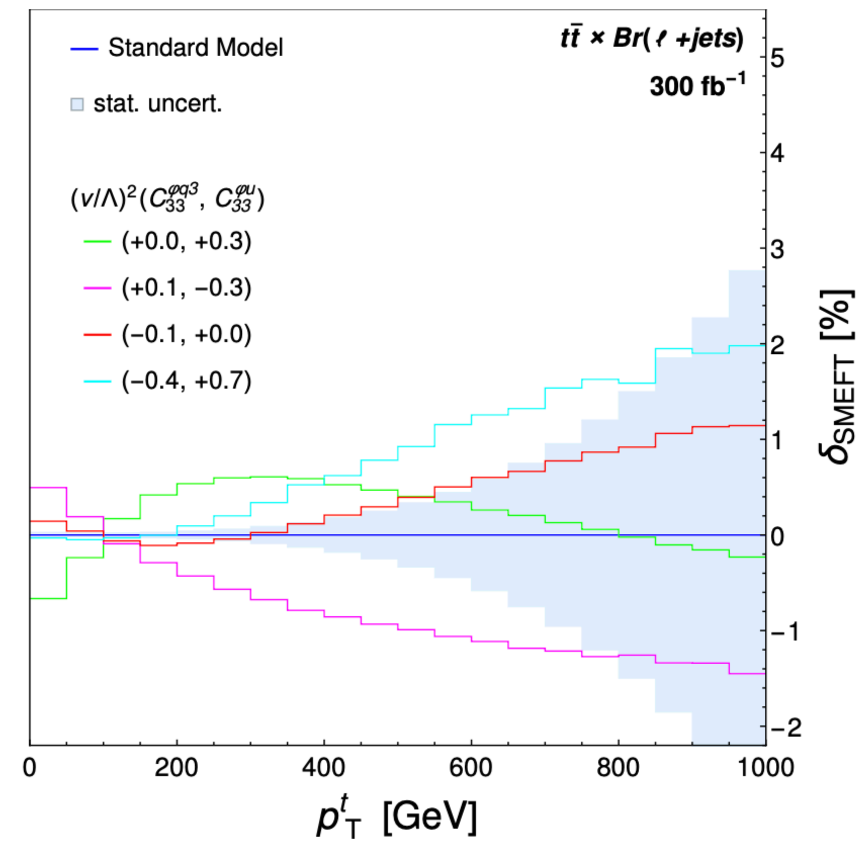
Event-level Type 1 PF MET filters applied

EFT at one-loop: $t\bar{t}Z$ & tWb

- One-loop corrections for $t\bar{t}Z$ and tWb interactions



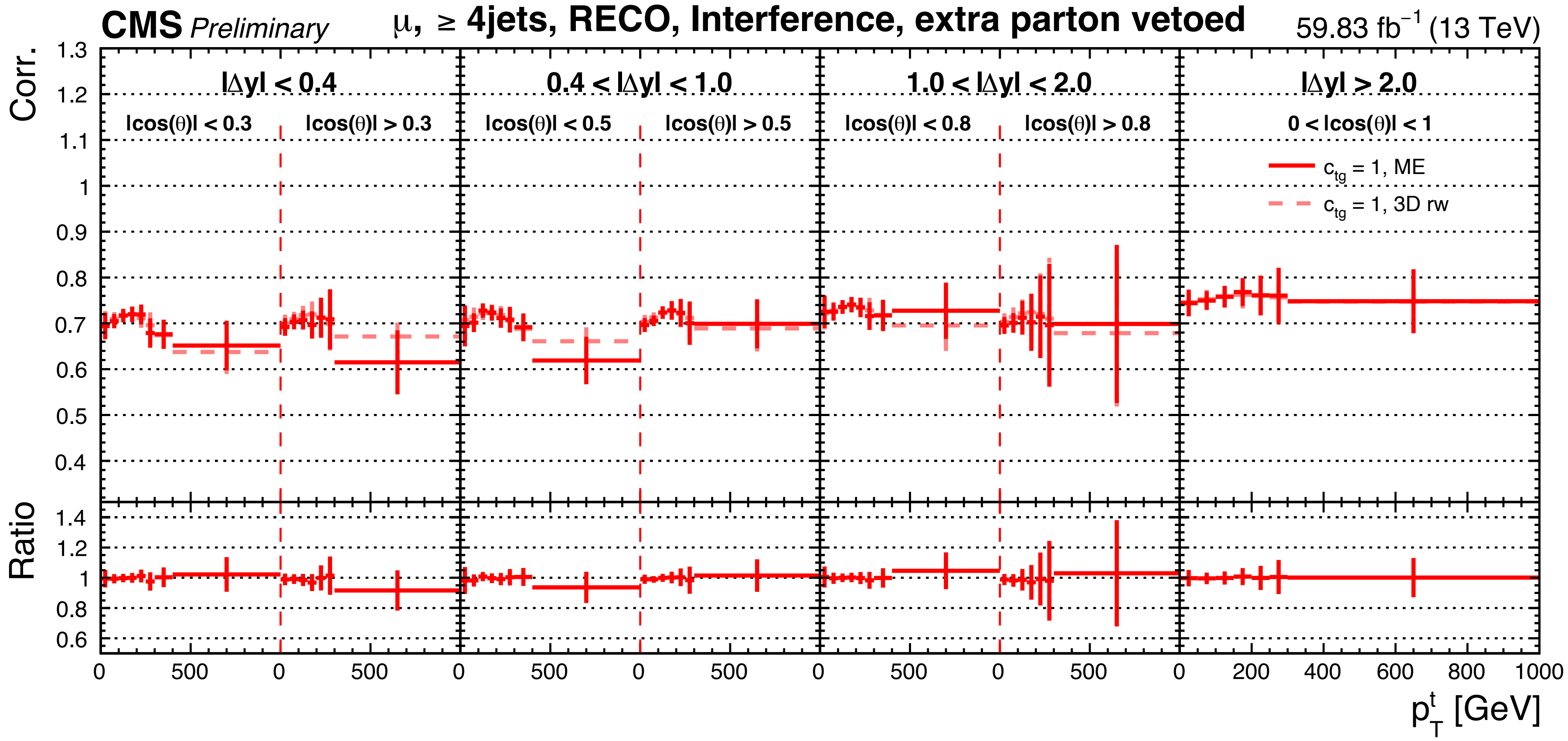
- Relative modifications to SM

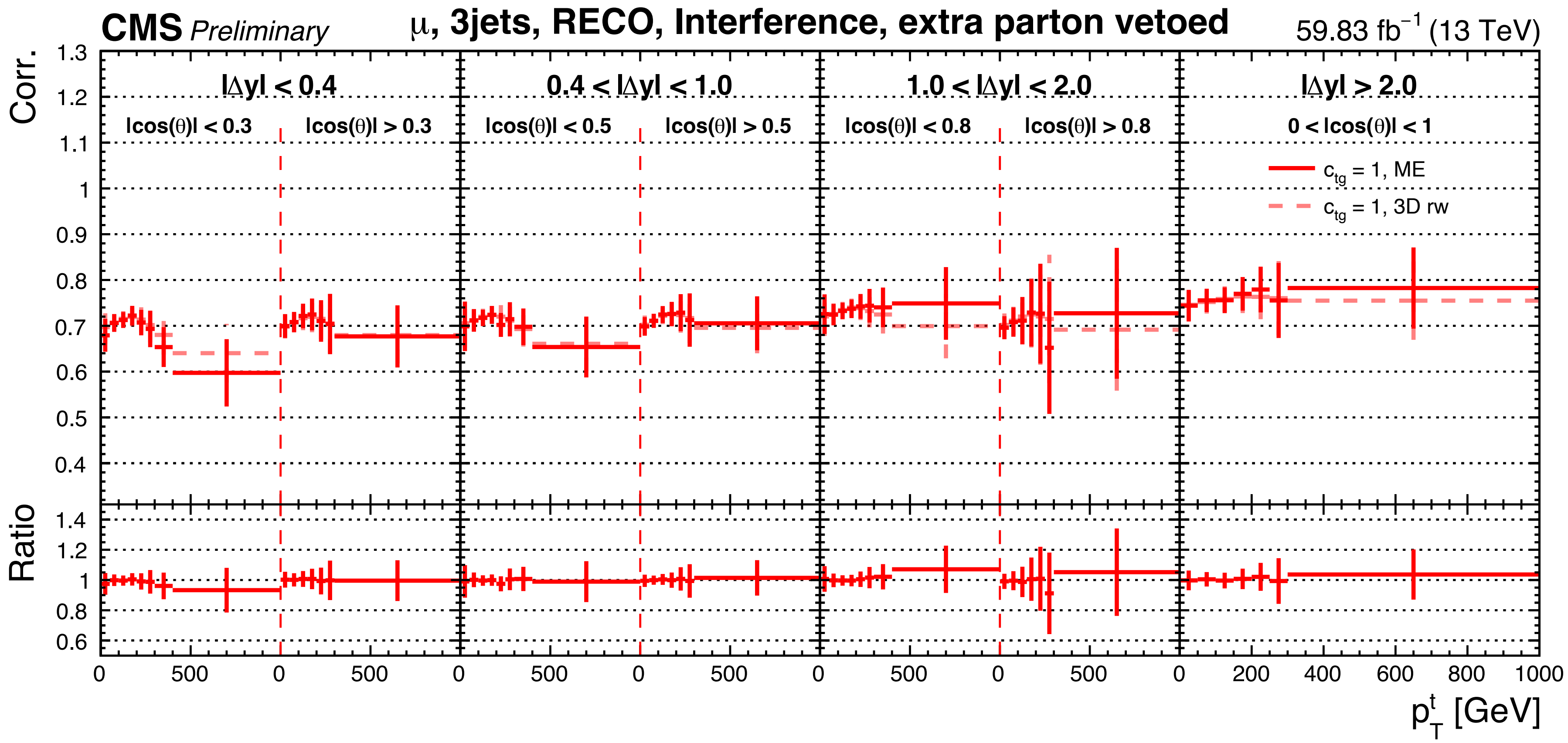


arXiv: [1911.11244](https://arxiv.org/abs/1911.11244)

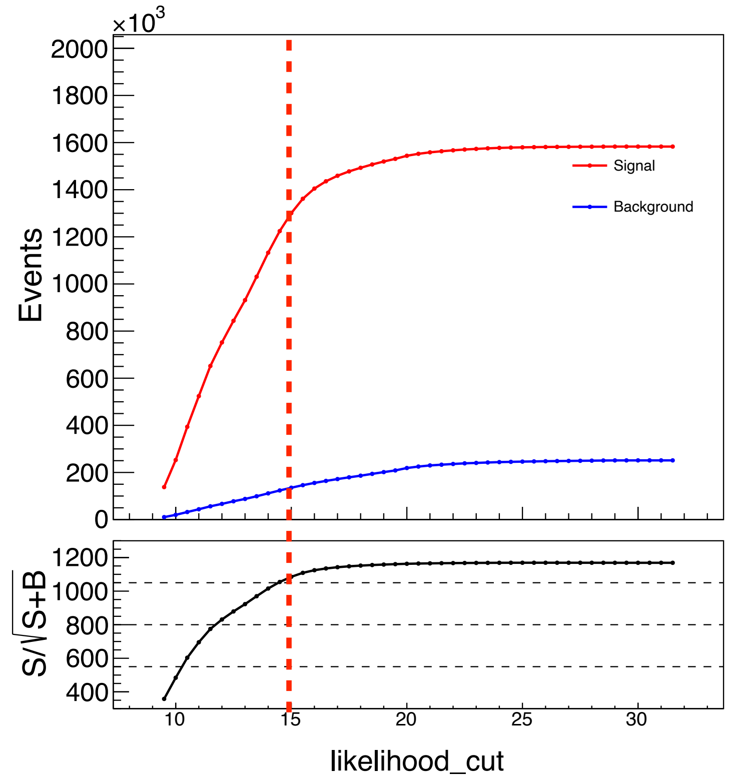
- **NLO one-loop** corrections: **percent** level, with the enhancement by logarithms of $\hat{s}/M_W^2$
- Focus on $C_{\varphi t}$, $C_{\varphi Q}^{3}$, $C_{\varphi q}^{-}$ for $t\bar{t}Z$ and tWb interactions, all the other related ones set to 0

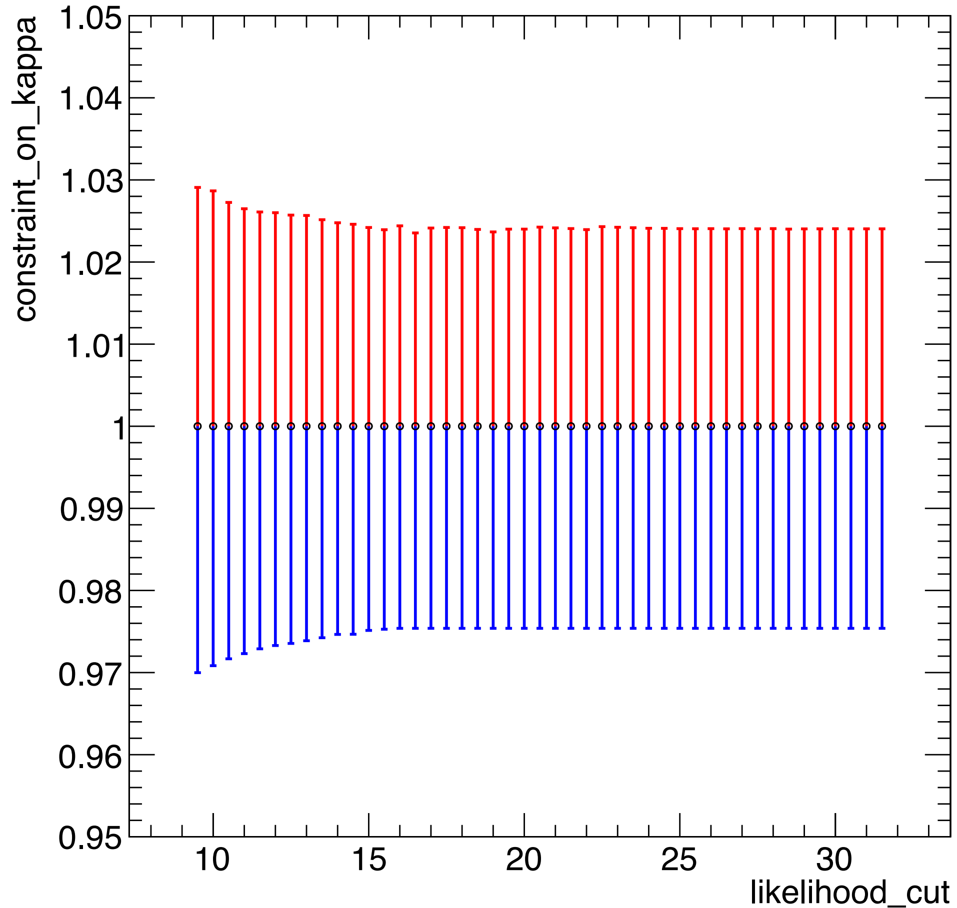
Reweighting

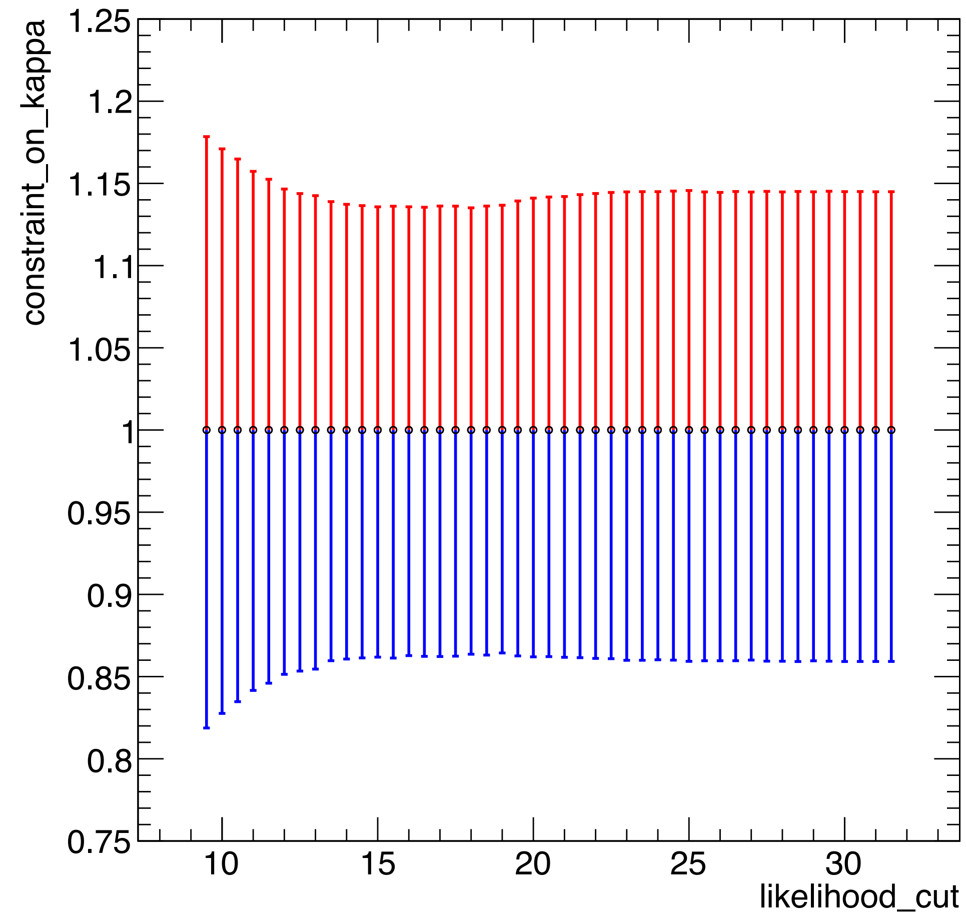




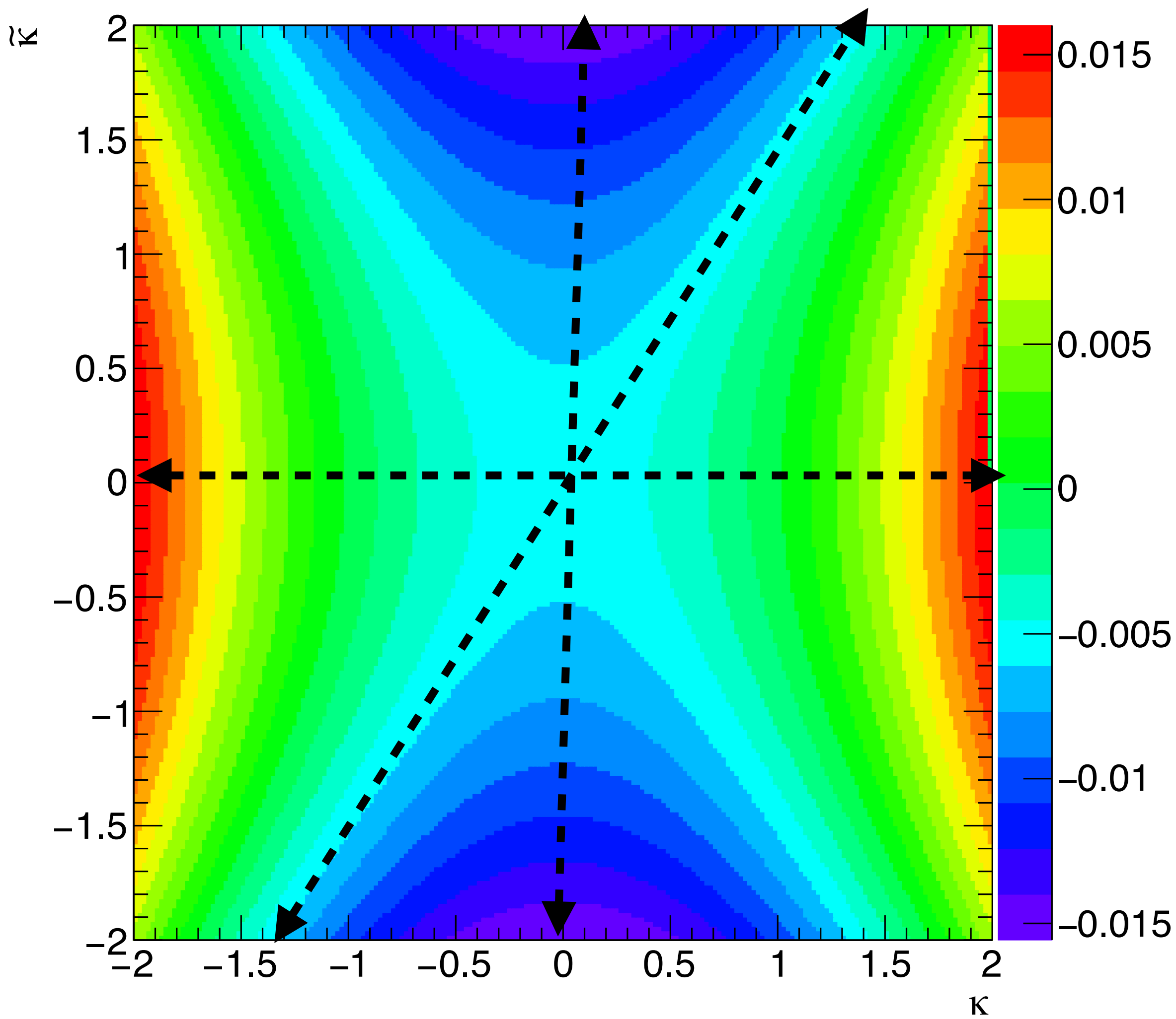
Likelihood cut

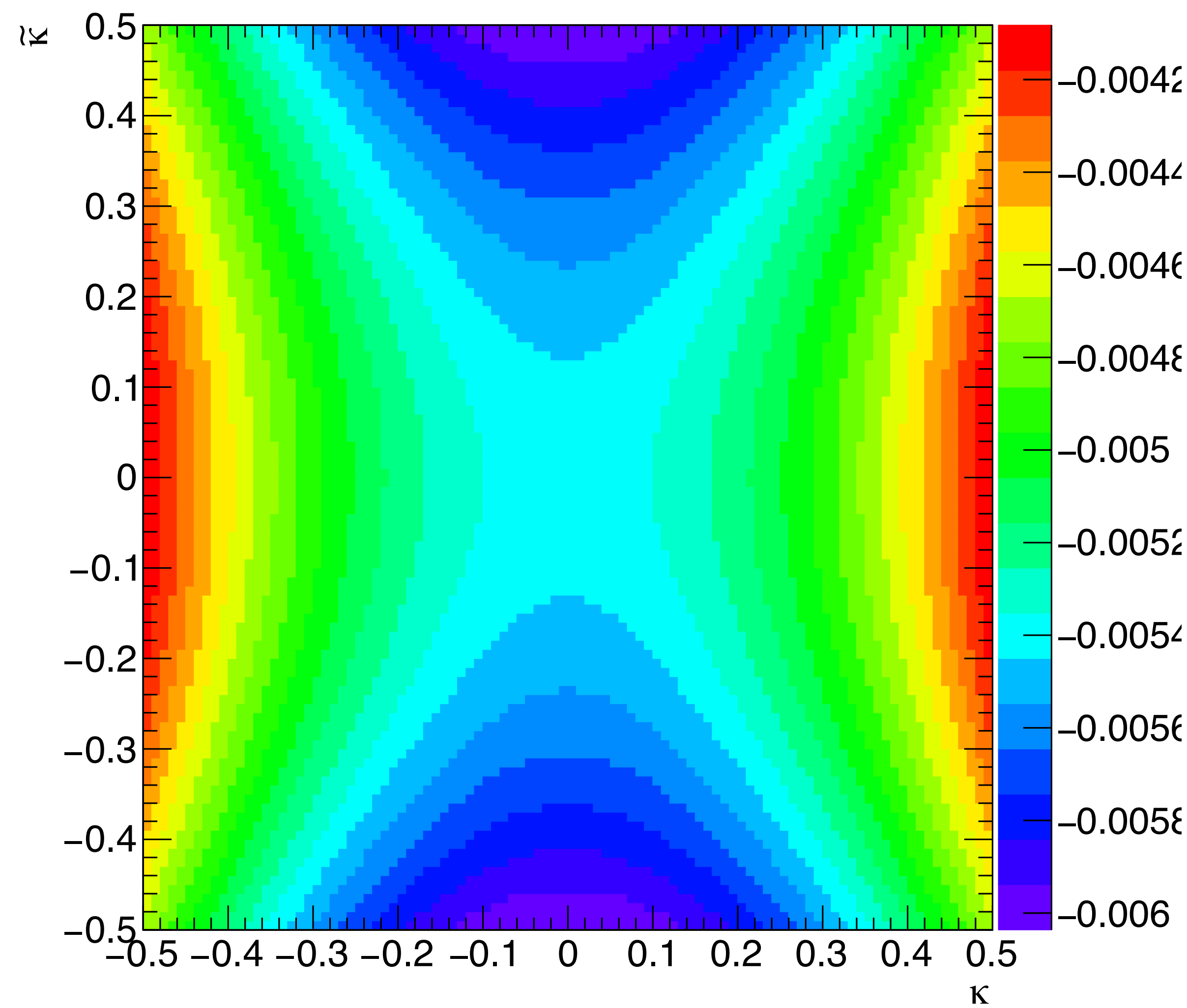






CP violation





- f_{CP} corresponding to lines with certain gradient line
- Signal strength μ modifying cross section in an opposite direction when f_{CP} surpass a **threshold**
- After that, the best-fit values of μ would shift slightly backward to yield the same correction as the previous value of f_{CP}

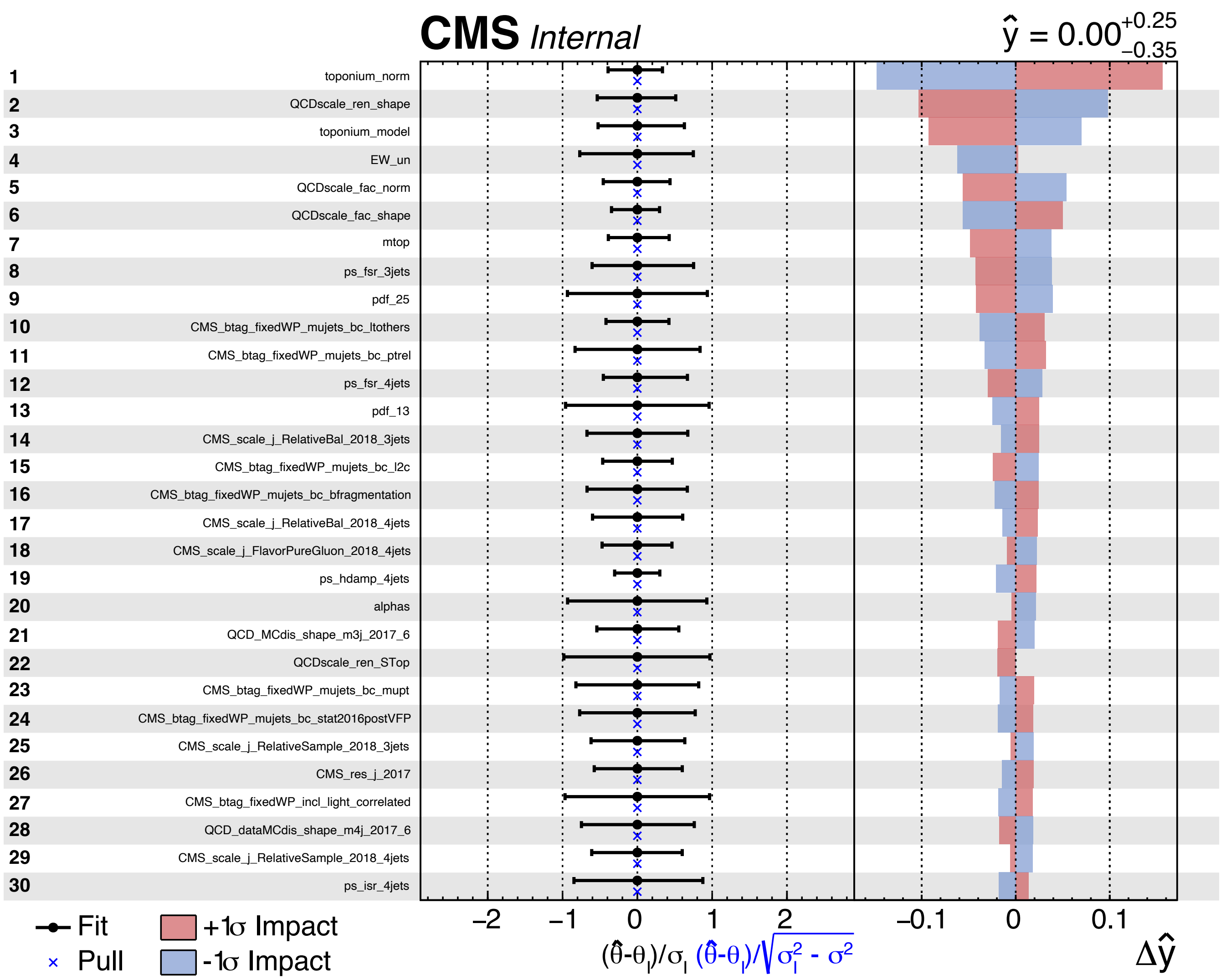
Theoretical uncertainties

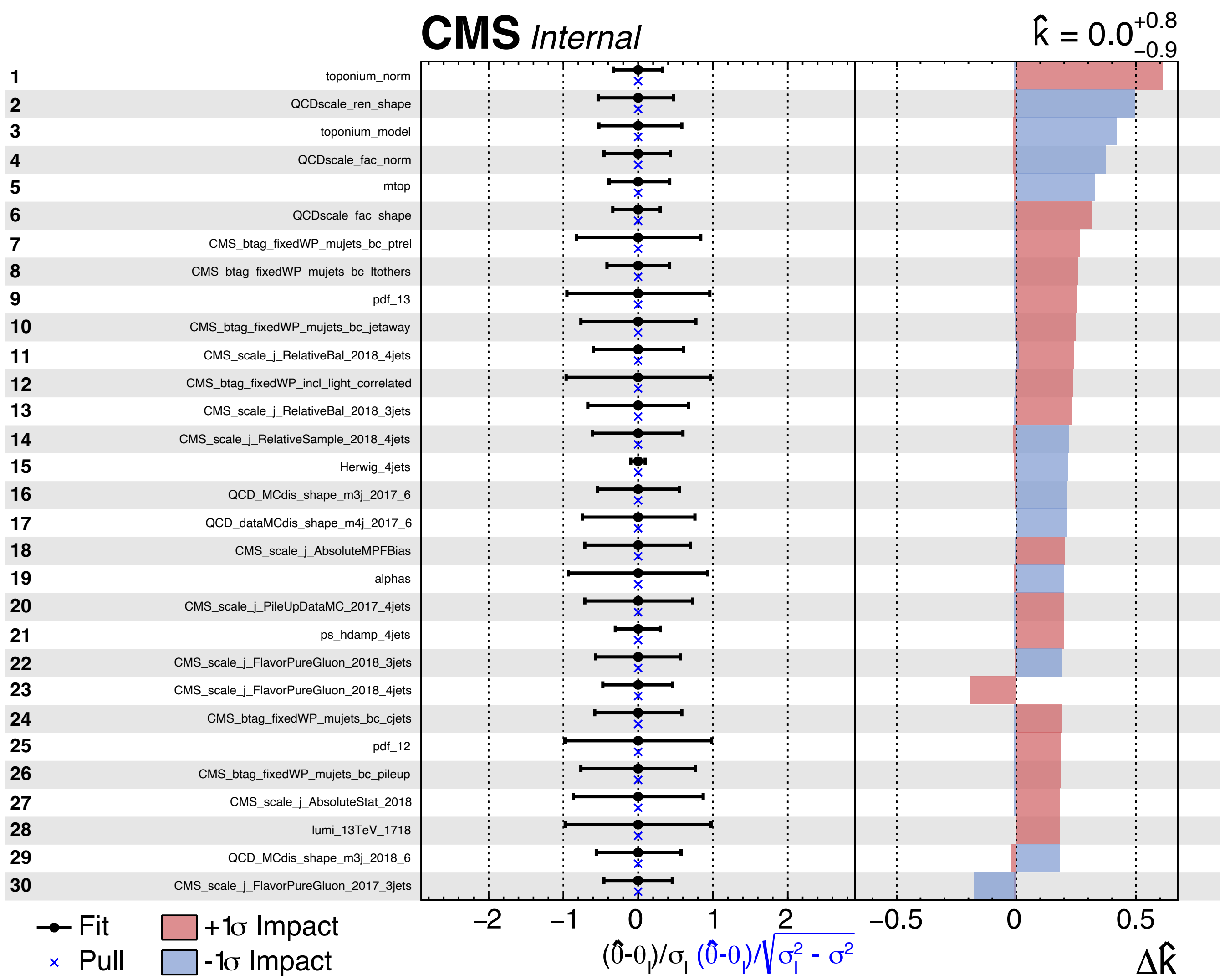
	Type	Correlation		Note
		year	Process	
☆ Renormalization and factorization scale	shape	☑	—	NLO, on top of NNLO/NLO reweighted prediction of tt
Electroweak uncertainty	shape	☑	—	see previous slide
PDFs	Shape	☑	—	10 variations exhibiting largest impacts included
Alphas	shape	☑	—	PDF uncertainty arising from the choice of α_s
☆ Top quark mass (±1GeV)	shape	☑	—	From ±3 GeV variation, divided by 3
NLO Matrix element/ parton shower matching	shape	☑	—	
Underlying event	shape	☑	—	
Initial and final state radiation	shape	☑	—	
☆ Toponium normalization and models	lnN	☑	—	100 % normalization uncertainty assigned to toponium events
Parton shower	shape	☑	—	Pythia vs. Herwig
Diagram removal vs. subtraction	lnN	☑	—	Methods to treat the interference between tW and tt

Experimental uncertainties

	Type	Correlation		Note
		year	Process	
Integrated luminosity, corr./uncorr.	lnN	Partial	☑	
Integrated luminosity, corr. 17-18	lnN	☑	☑	only for 2017, 2018
⭐ Jet Energy Scale	shape	Partial	☑	26 variations and 4 flavor breakdown
Jet Energy Resolution	shape	—	☑	
Unclustered MET	shape	—	☑	
Lepton scale factor	shape	☑	☑	combined separately for e & μ channels
b tagging and mistagging	shape	Partial	☑	breakdown to 17 variations
QCD background, from different TFs	shape	—	—	A separate nuisance parameter assigned to each $\Delta y_{t\bar{t}}$ & cos(θ) bin in each channel.
QCD background, data/MC differences	shape / lnN	—	—	
W+jets background	shape	—	—	
L1 ECAL Prefireing reweighting	shape	—	☑	only for 2016 and 2017

Impacts


CMS Internal
$\hat{y} = 0.00^{+0.25}_{-0.35}$
1 toponium_norm
2 QCDscale_ren_shape
3 toponium_model
4 EW_un
5 QCDscale_fac_norm
6 QCDscale_fac_shape
7 mtop
8 ps_fsr_3jets
9 pdf_25
10 CMS_btag_fixedWP_mujets_bc_ltothers
11 CMS_btag_fixedWP_mujets_bc_ptrel
12 ps_fsr_4jets
13 pdf_13
14 CMS_scale_j_RelativeBal_2018_3jets
15 CMS_btag_fixedWP_mujets_bc_l2c
16 CMS_btag_fixedWP_mujets_bc_bfragmentation
17 CMS_scale_j_RelativeBal_2018_4jets
18 CMS_scale_j_FlavorPureGluon_2018_4jets
19 ps_hdamp_4jets
20 alphas
21 QCD_MCdis_shape_m3j_2017_6
22 QCDscale_ren_STop
23 CMS_btag_fixedWP_mujets_bc_mupt
24 CMS_btag_fixedWP_mujets_bc_stat2016postVFP
25 CMS_scale_j_RelativeSample_2018_3jets
26 CMS_res_j_2017
27 CMS_btag_fixedWP_incl_light_correlated
28 QCD_dataMCdis_shape_m4j_2017_6
29 CMS_scale_j_RelativeSample_2018_4jets
30 ps_isr_4jets
Fit
Pull
+1σ Impact
-1σ Impact
$(\hat{\theta}-\theta_I)/\sigma_I$ $(\hat{\theta}-\theta_I)/\sqrt{\sigma_I^2 - \sigma^2}$
$\Delta\hat{y}$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3 toponium_model
4 QCDscale_fac_norm
5 mtop
6 QCDscale_fac_shape
7 CMS_btag_fixedWP_mujets_bc_ptrel
8 CMS_btag_fixedWP_mujets_bc_ltothers
9 pdf_13
10 CMS_btag_fixedWP_mujets_bc_jetaway
11 CMS_scale_j_RelativeBal_2018_4jets
12 CMS_btag_fixedWP_incl_light_correlated
13 CMS_scale_j_RelativeBal_2018_3jets
14 CMS_scale_j_RelativeSample_2018_4jets
15 Herwig_4jets
16 QCD_MCdis_shape_m3j_2017_6
17 QCD_dataMCdis_shape_m4j_2017_6
18 CMS_scale_j_AbsoluteMPFBias
19 alphas
20 CMS_scale_j_PileUpDataMC_2017_4jets
21 ps_hdamp_4jets
22 CMS_scale_j_FlavorPureGluon_2018_3jets
23 CMS_scale_j_FlavorPureGluon_2018_4jets
24 CMS_btag_fixedWP_mujets_bc_cjets
25 pdf_12
26 CMS_btag_fixedWP_mujets_bc_pileup
27 CMS_scale_j_AbsoluteStat_2018
28 lumi_13TeV_1718
29 QCD_MCdis_shape_m3j_2018_6
30 CMS_scale_j_FlavorPureGluon_2017_3jets
Fit
Pull
+1σ Impact
-1σ Impact
$(\hat{\theta}-\theta_I)/\sigma_I$ $(\hat{\theta}-\theta_I)/\sqrt{\sigma_I^2 - \sigma^2}$
$\Delta\hat{k}$