Search for EFT Operators through $t\bar{t}$ Production with Electroweak Loops

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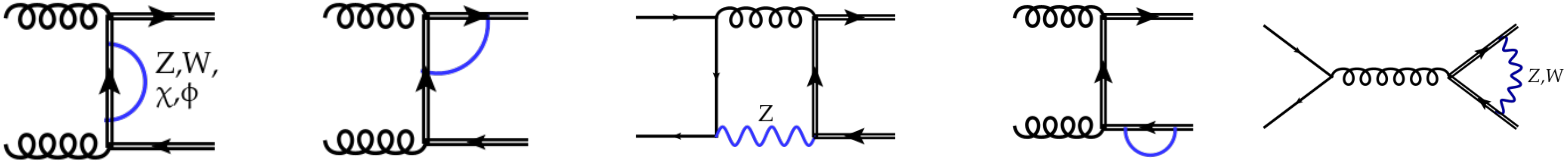
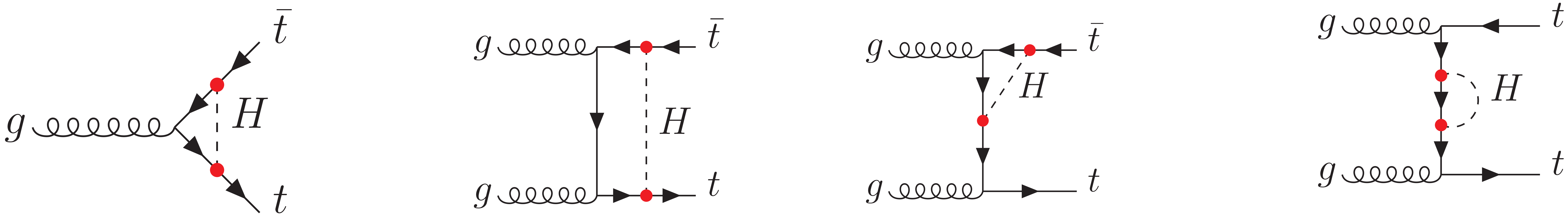




arXiv:1911.11244, 1305.5773

- Three vertices enter the Electroweak loops: **Htt, Ztt, Wtb**
- Possible to probe EW related EFT operators
- Corrections from **Higgs loop**, sensitive to Higgs **CP property**
- New physics could modify these couplings

SMEFT Framework

- Possible to search for NP in a model-independent way
- In Warsaw basis: 59 independent 6D operators
- Effective Lagrangian: $\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i \mathscr{O}_i + \cdots$
- $Q_{u\varphi} \to$ Htt, $Q_{\varphi u} \to$ Ztt,
- $Q_{\varphi q}^{(3)} \to$ Ztt , Wtb and Zbb, $Q_{\varphi q}^{(1)} \to$ Ztt and Zbb

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
	$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Dimension-six operators other than the four-fermion ones
arXiv: 1008.4884, 1704.03888

EW Couplings in the SMEFT

- **Ztt coupling:** $\Gamma^{\mu}_{Ztt} = \frac{-\mathrm{i}e}{s_{\mathrm{w}}c_{\mathrm{w}}}\gamma^{\mu}\left(d^{Z}_{\mathrm{L}}P_{\mathrm{L}} + d^{Z}_{\mathrm{R}}P_{\mathrm{R}}\right)$

  $d^{Z}_{\mathrm{L}} \to d^{Z,\mathrm{SM}}_{\mathrm{L}} + \frac{1}{2}\frac{v^2}{\Lambda^2}\left(C^{\varphi q3}_{33} - C^{\varphi q1}_{33}\right)$, **and** $d^{Z}_{\mathrm{R}} \to d^{Z,\mathrm{SM}}_{\mathrm{R}} - \frac{1}{2}\frac{v^2}{\Lambda^2}C^{\varphi u}_{33}$

- **Wtb coupling:** $\Gamma^{\mu}_{Wtb} = \frac{-\mathrm{i}e}{\sqrt{2}s_{\mathrm{w}}}\gamma^{\mu}d^{W}_{\mathrm{L}}P_{\mathrm{L}}$

  $d^{W}_{\mathrm{L}} \to d^{W,\mathrm{SM}}_{\mathrm{L}} + \frac{v^2}{\Lambda^2}C^{\varphi q3}_{33}$

- **Htt Yukawa interaction:** $\mathscr{L}(Htt) = -\frac{m_t}{v}\bar{\psi}_t\left(\kappa + \mathrm{i}\,\tilde{\kappa}\gamma_5\right)\psi_t$
  - $\kappa = 1 - \frac{v}{\sqrt{2}m_t}\frac{v^2}{\Lambda^2}\mathrm{Re}\left[C^{u\varphi}_{tt}\right], \quad \tilde{\kappa} = -\frac{v}{\sqrt{2}m_t}\frac{v^2}{\Lambda^2}\mathrm{Im}\left[C^{u\varphi}_{tt}\right]$
  - κ **term: CP-even,** $\tilde{\kappa}$ **term: CP-odd; In SM:** $\kappa = 1, \tilde{\kappa} = 0.$
  - **If** $\kappa, \tilde{\kappa}$ **both are non-zero, implies CP violation.**

- **take** $\frac{v^2}{\Lambda^2}\mathrm{Re}\left[C^{u\varphi}_{tt}\right], \frac{v^2}{\Lambda^2}\mathrm{Im}\left[C^{u\varphi}_{tt}\right], \frac{v^2}{\Lambda^2}C^{\varphi u}_{33}$ **as free parameters**

Theoretical calculation and codes offered by
Till Martini and Markus Schulze

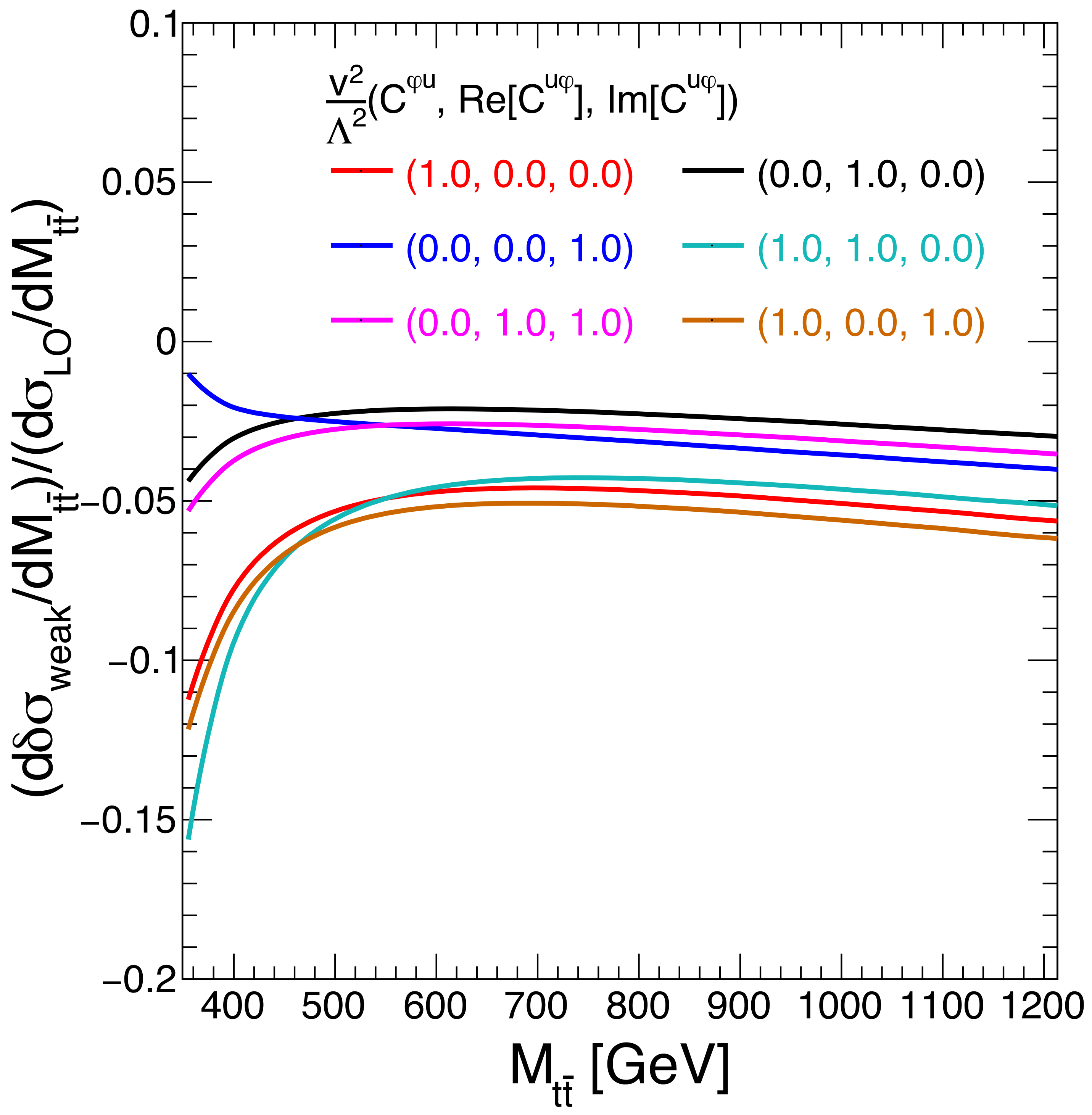
Note:
- $C^{\varphi q1}_{33}, C^{\varphi q3}_{33}$ influence Zbb couplings
- In codes: $C^{\varphi q1}_{33} = - C^{\varphi q3}_{33}$, considering $e^+e^- \to b\bar{b}$
- $C^{\varphi q3}_{33}$ change top decay, while not included in codes
- We don't consider $C^{\varphi q1}_{33}, C^{\varphi q3}_{33}$

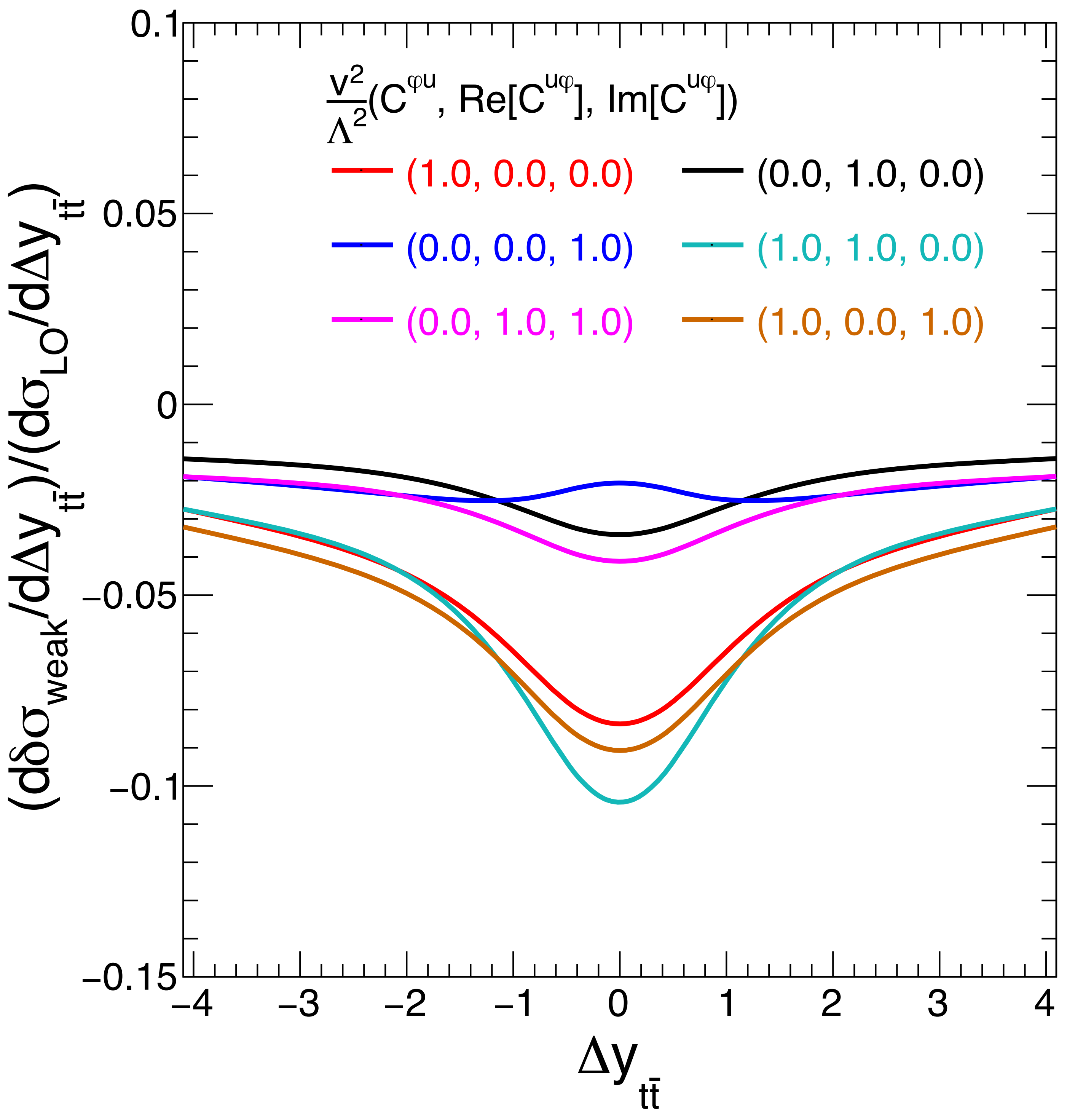
Ratio of EW Corrections

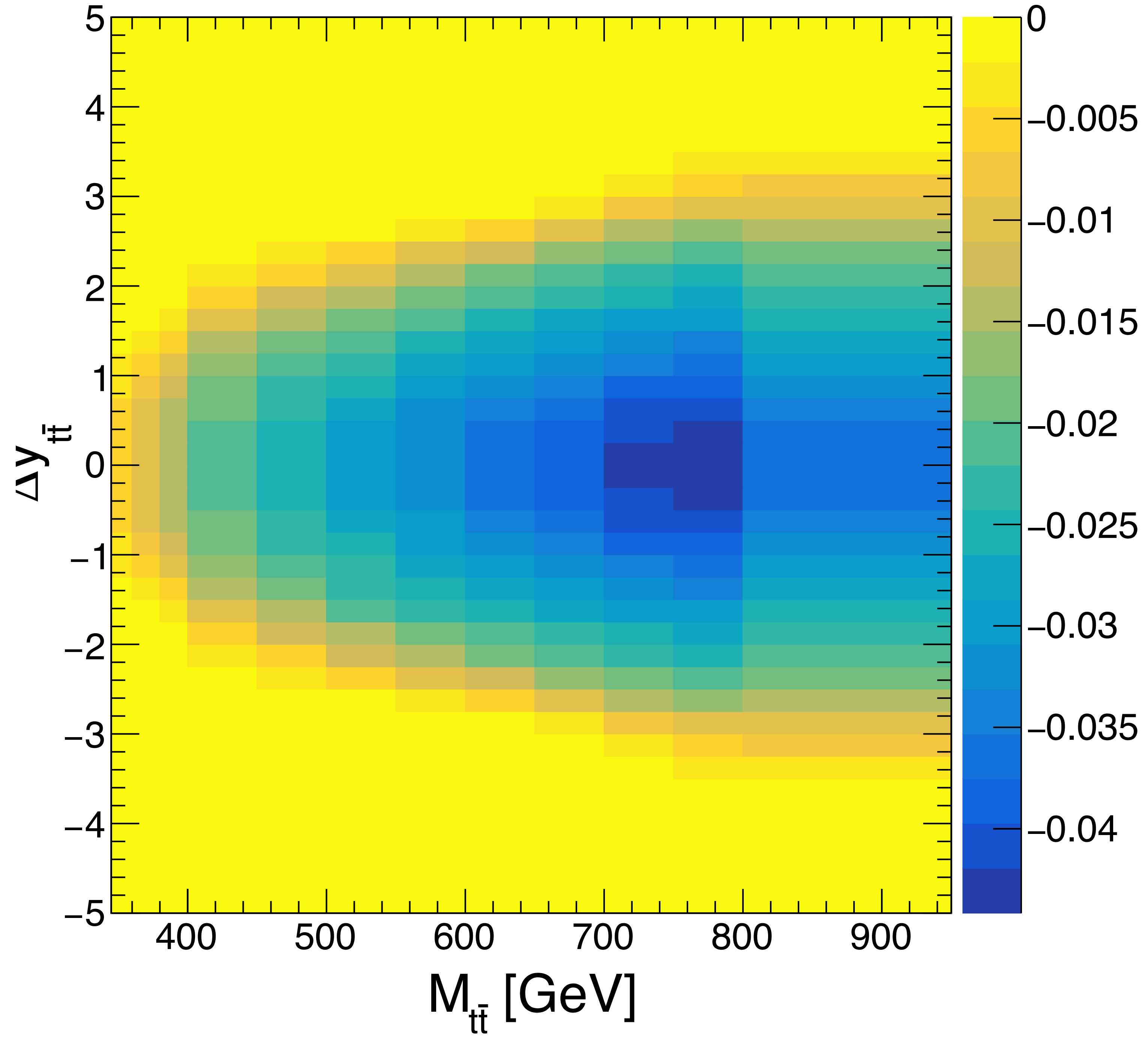
- EW correction factor: $\delta_{\text{wk}} = \dfrac{d\sigma^{\text{NLO}}_{\text{wk}} - d\sigma^{\text{LO}}}{d\sigma^{\text{LO}}}$
- δ_{wk} can be used to **reweight** distributions to include EW effects
- distributions of $\Delta y_{t\bar{t}}$ and $M_{t\bar{t}}$ sensitive to EFT operators
- Two variables have correlation, **reweight in 2D**

Martini, Schulze: arXiv:1911.11244

Martini, Pan, Schulze, Xiao: arXiv: 2104.04277



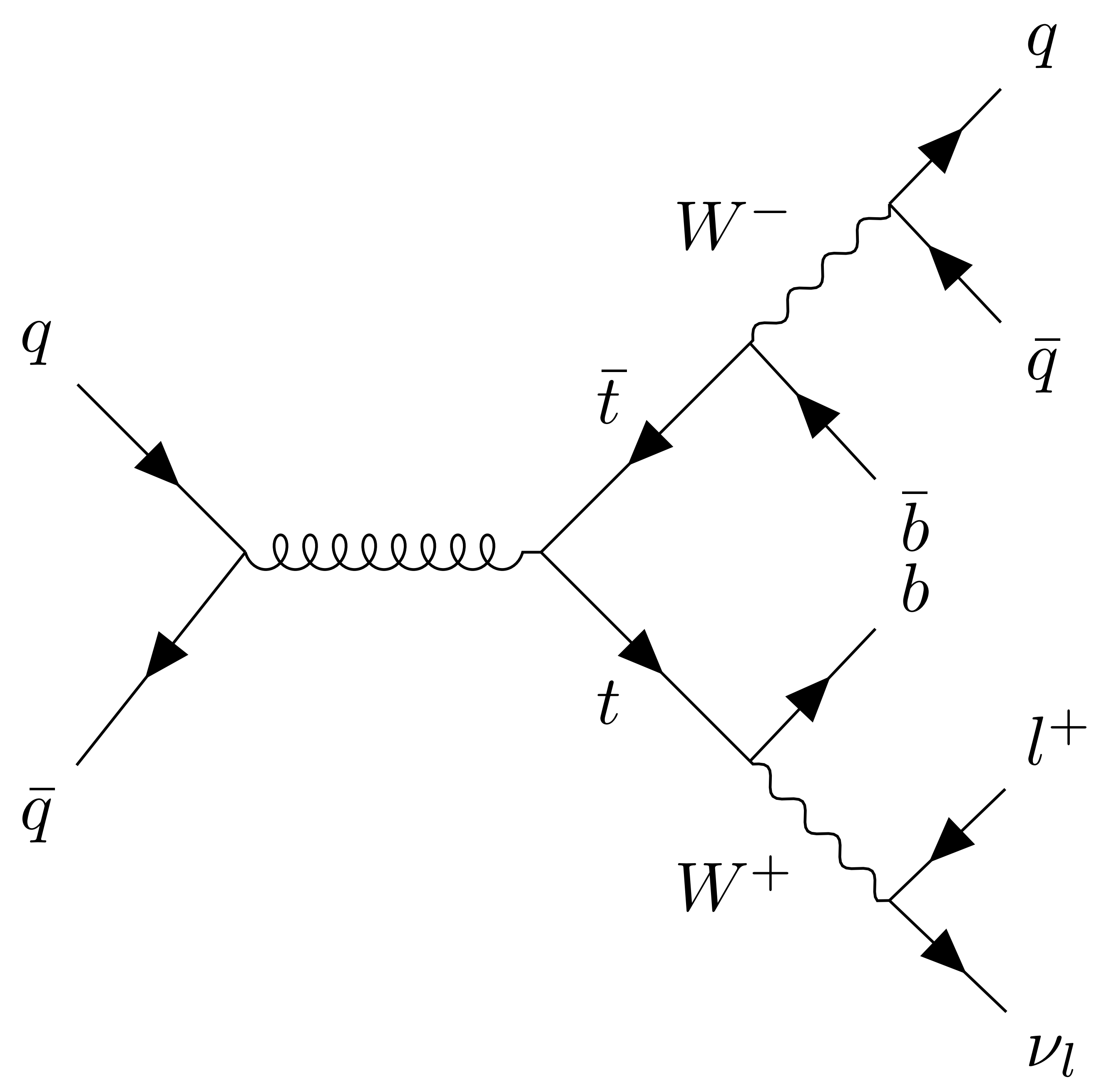




EW corrections in 2D, SM case

Analyze the $t\bar{t}$ Production

Analyze the $t\bar{t}$ production with Electroweak loops in the semileptonic channel at the CMS



Final state:

- At least 3 jets with at least two bjets
- One isolated and high quality lepton

Data: 2016-2018, 137fb^{-1}

Background: single top, VV, V+jets, DY, QCD

MC Datasets

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QCD background will be estimated through Data-Driven. To be done!

Data Datasets

```
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/SingleMuon/Run2018D-UL2018_MiniAODv2_NanoAODv9-v1/NANOAOD

...
And 2016, 2017 Datasets
```

Lepton Selection

Muon selection criteria

- $p_T > 30$ GeV, $|\eta| < 2.4$
- cut-baed identification criteria: ***tight***
- PF-based combined relative isolation value: **tight**

Vote events with additional electron:

- $p_T > 15$ GeV, $|\eta| < 2.4$
- Identification criteria: ***loose***
- PF-based combined relative isolation: **loose**

Electron selection criteria

- $p_T > 30$ Gev, $|\eta| \notin [1.4442, 1.5660]$
- cut-based identification: **tight**
- impact parameter:

  Barrel: $d_z \leq 0.10$ cm, $d_{xy} < 0.05$ cm .

  Endcap: $d_z \leq 0.2$cm, $d_{xy} \leq 0.10$ cm.

Vote events with additional electron:

- $p_T > 15$ Gev, $|\eta| \notin [1.4442, 1.5660]$
- cut-baed identification criteria: **loose**

Jet Selection

Jets should pass the following criteria:

- $p_T > 30$ GeV, $|\eta| < 2.4$
- $\Delta R > 0.4$ with the selected lepton
- Pass the **tight** jet ID

b-jet

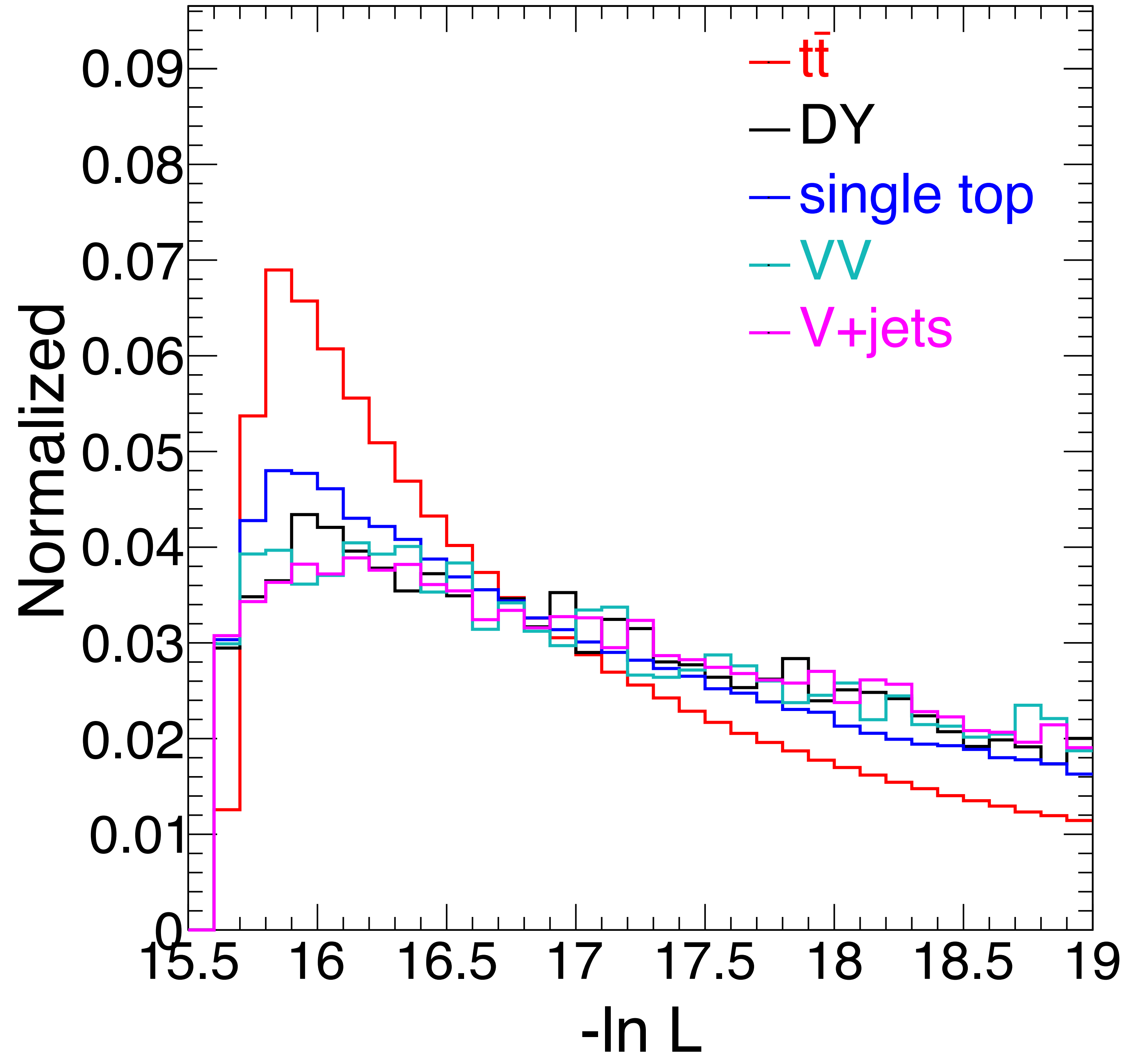
- pass the deep CSV algorithm at **medium** working point
- Correct identification efficiency : 68%
- misidentify light-flavor jets as b-jets : 1.1%

Reconstruct Top Quark Pairs

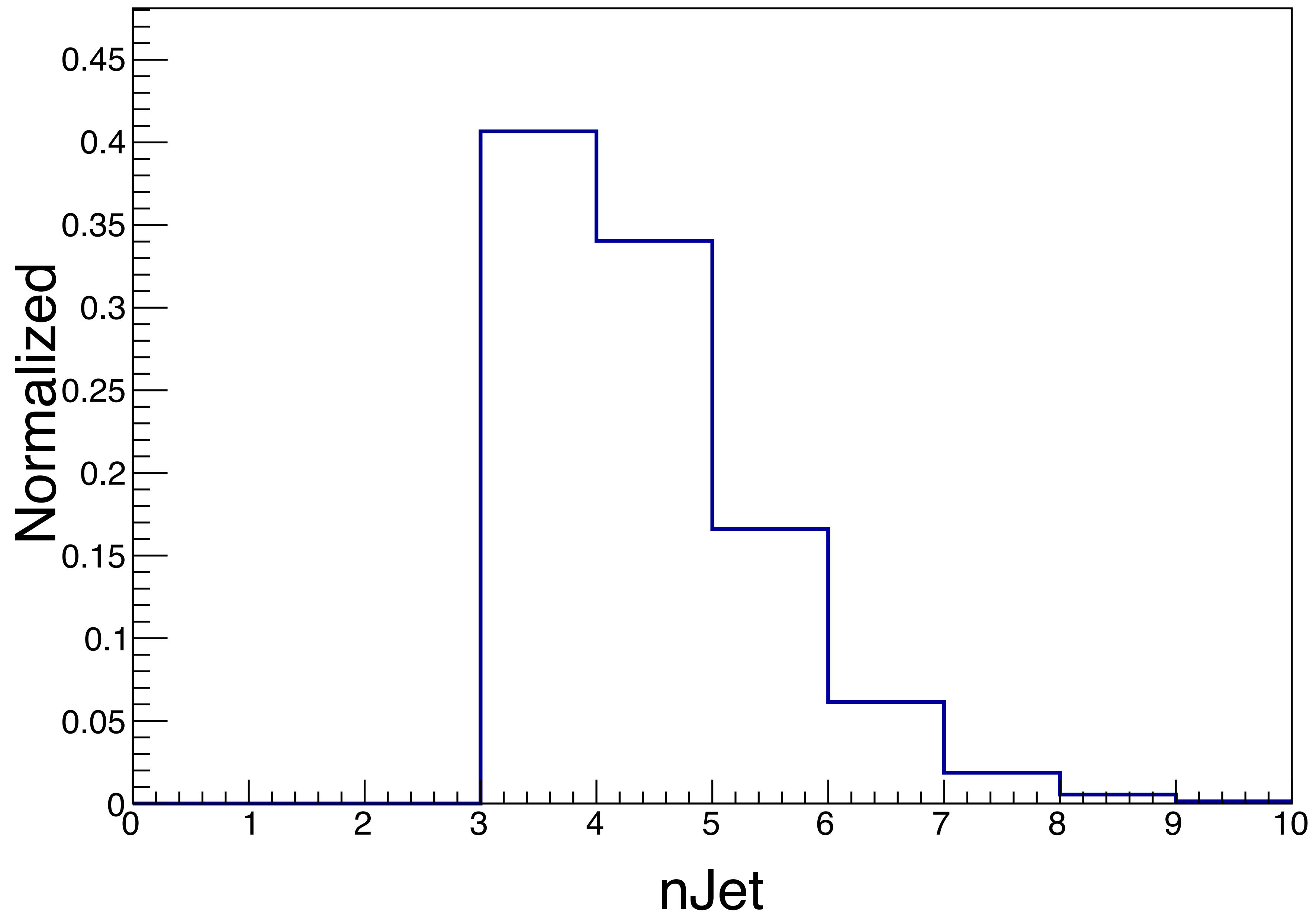
- Transverse momentum of neutrino from MET: $p_{\nu_x} = \not{p}_x, p_{\nu_y} = \not{p}_y$
- Consider all combination of jets
- Assume invariant masses have Gaussian distributions

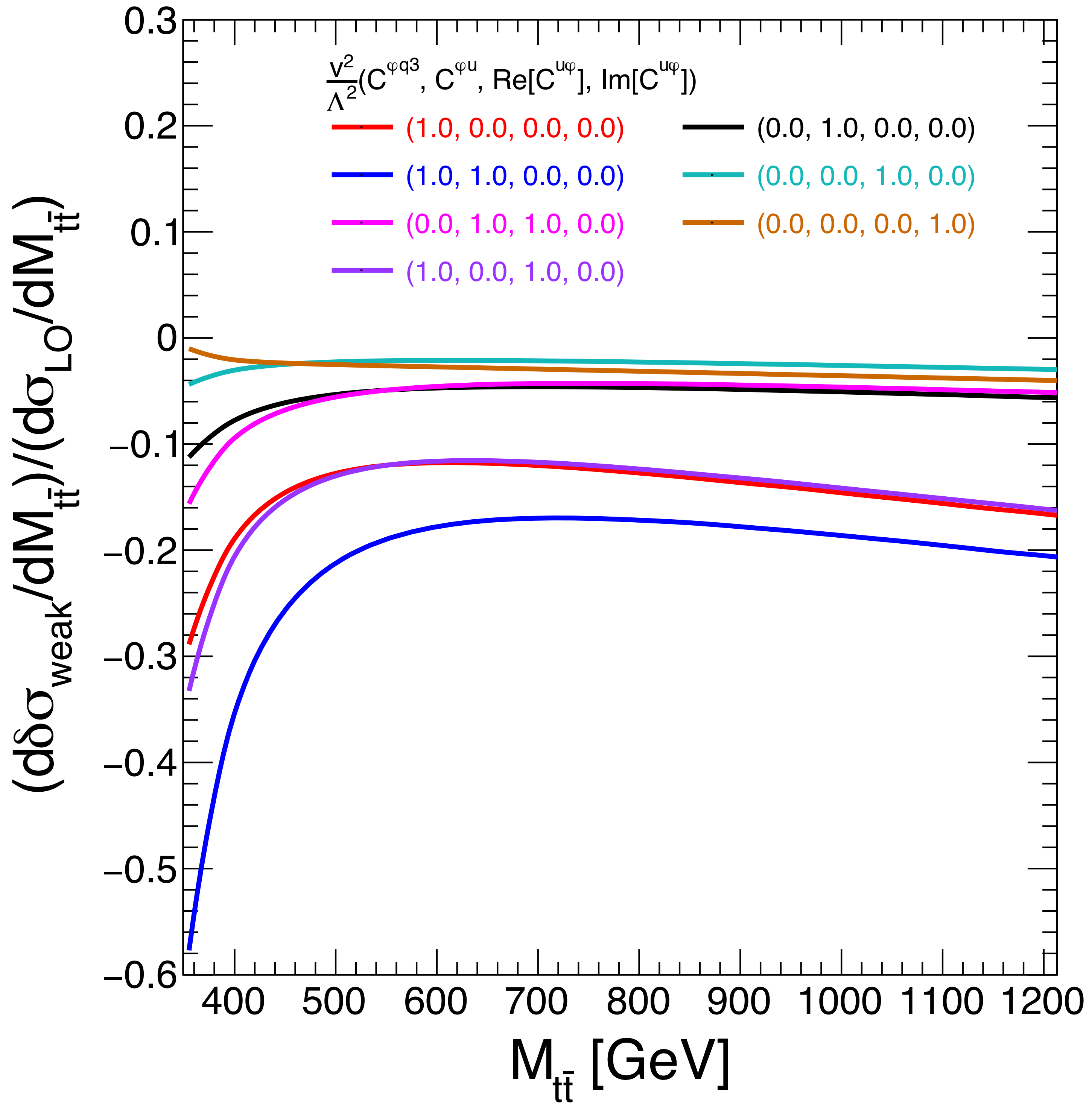
$$P(M_{W_{lep}}) = Gaus(M_{W_{lep}}, m_W, \sigma_W),$$
$$P(M_{W_{had}}) = Gaus(M_{W_{had}}, m_W, \sigma_W),$$
$$P(M_{t_{lep}}) = Gaus(M_{t_{lep}}, m_t, \sigma_t),$$
$$P(M_{t_{had}}) = Gaus(M_{t_{had}}, m_t, \sigma_t),$$
$$ln(L(\nu_z)) = ln(P(M_{W_{lep}})) + ln(P(M_{W_{had}})) + ln(P(M_{t_{lep}})) + ln(P(M_{t_{had}}))$$

- Find the value of p_{ν_z} such that the likelihood function $ln(L(\nu_z))$ has maximum.
- The value is the wanted p_{ν_z}



Include 3 Jets Final State





When only three jets are reconstructed, in 93% of the cases it is because a soft jet from W decay is out of acceptance criteria.

$$P_{t_{\rm had}} = P_b + P_j$$

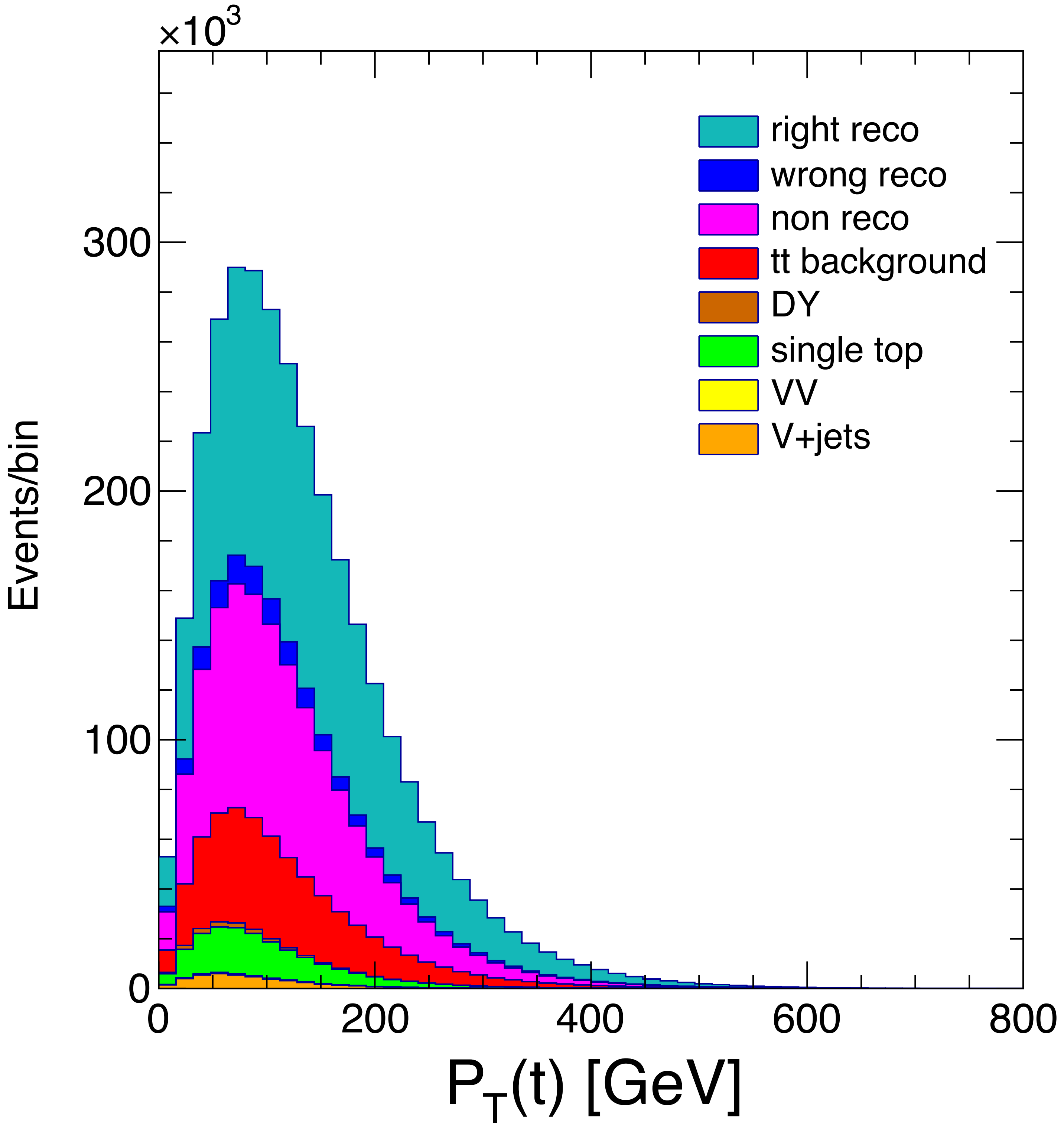
Larger corrections in low energy regions(soft jets)

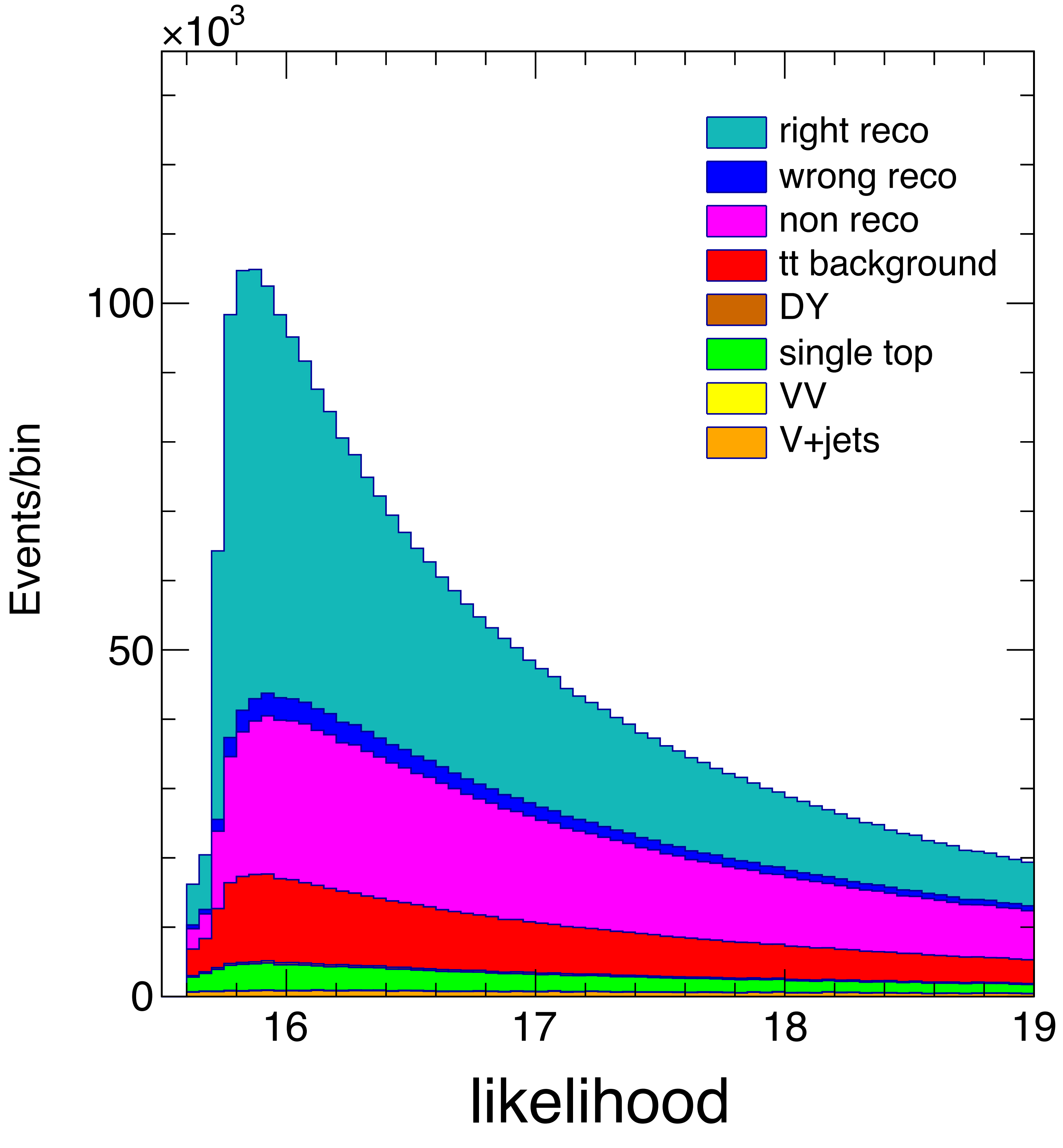
Signal Selection Efficiency

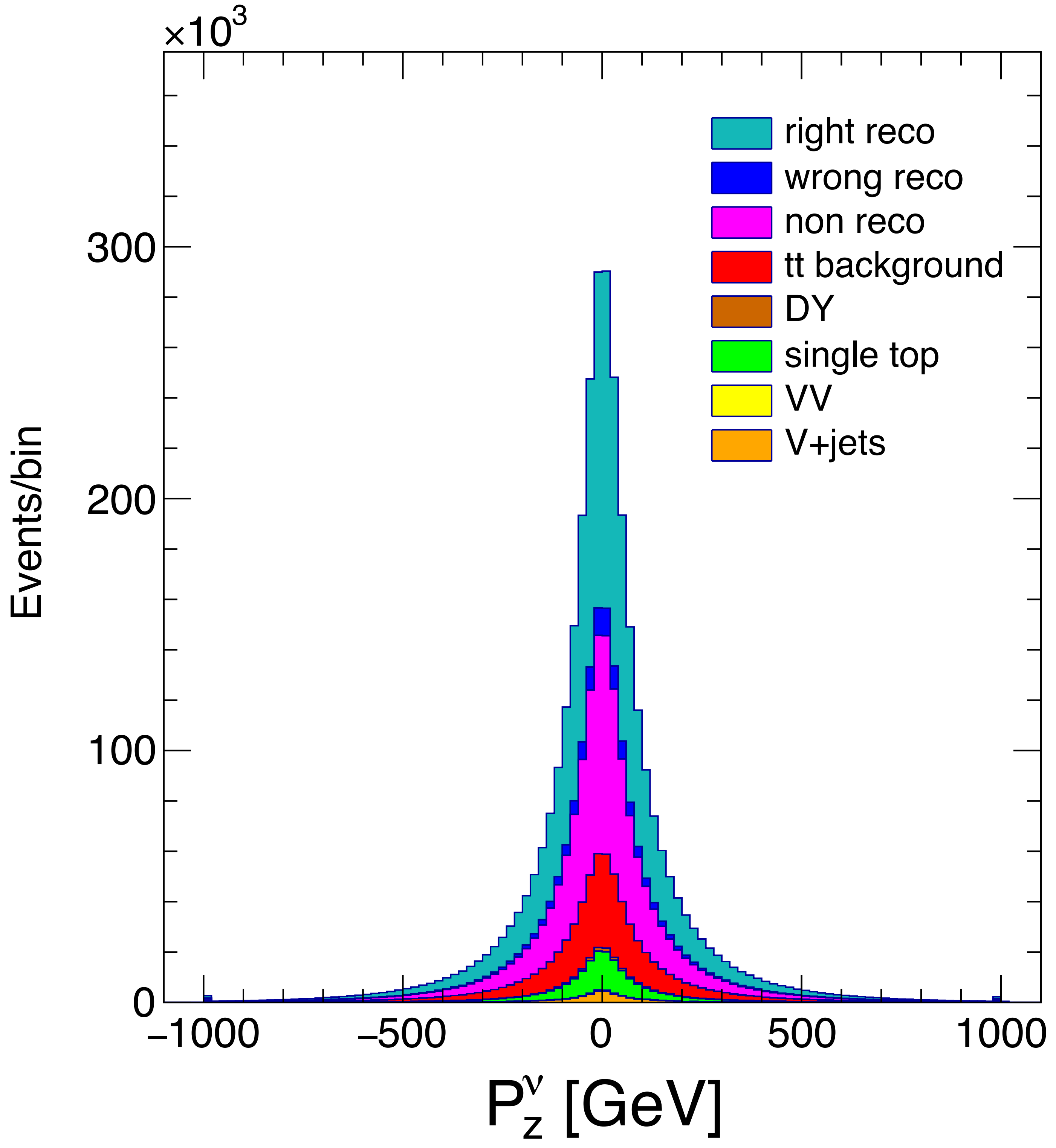
Selection efficiency of signal with cut likelihood <19.0

process	cross section(pb)	efficiency(%)	efficiency(>=4jets)(%)	efficiency(3jets)(%)
TTToSemiLeptonic	366.9	6.37	4.17	2.20
TTTo2L2Nu	89.1	2.15	0.75	1.40
TTToHadronic	378.0	0.01	0.00	0.01

Event Distribution at $\mathscr{L} = 137\text{fb}^{-1}$



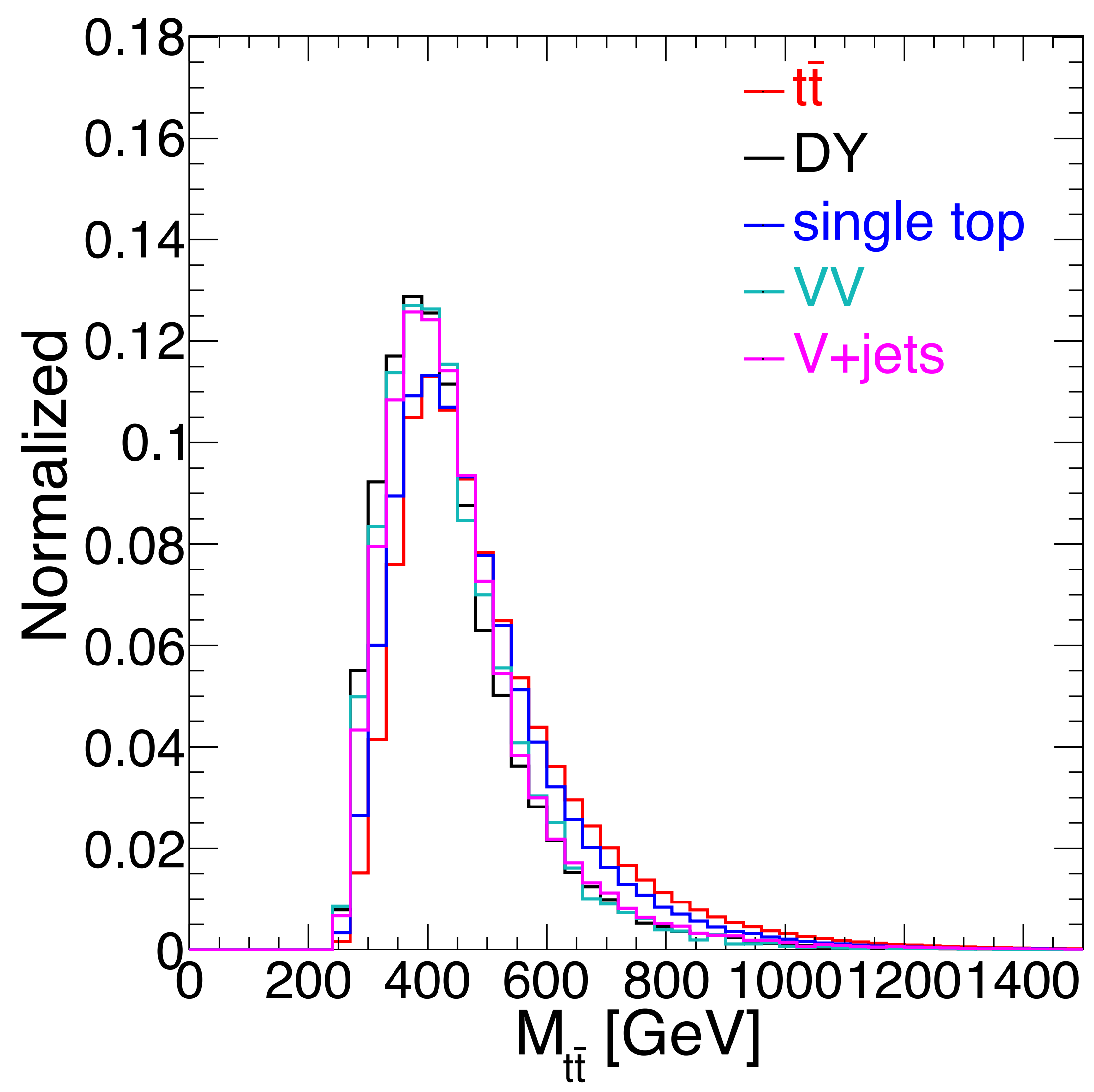


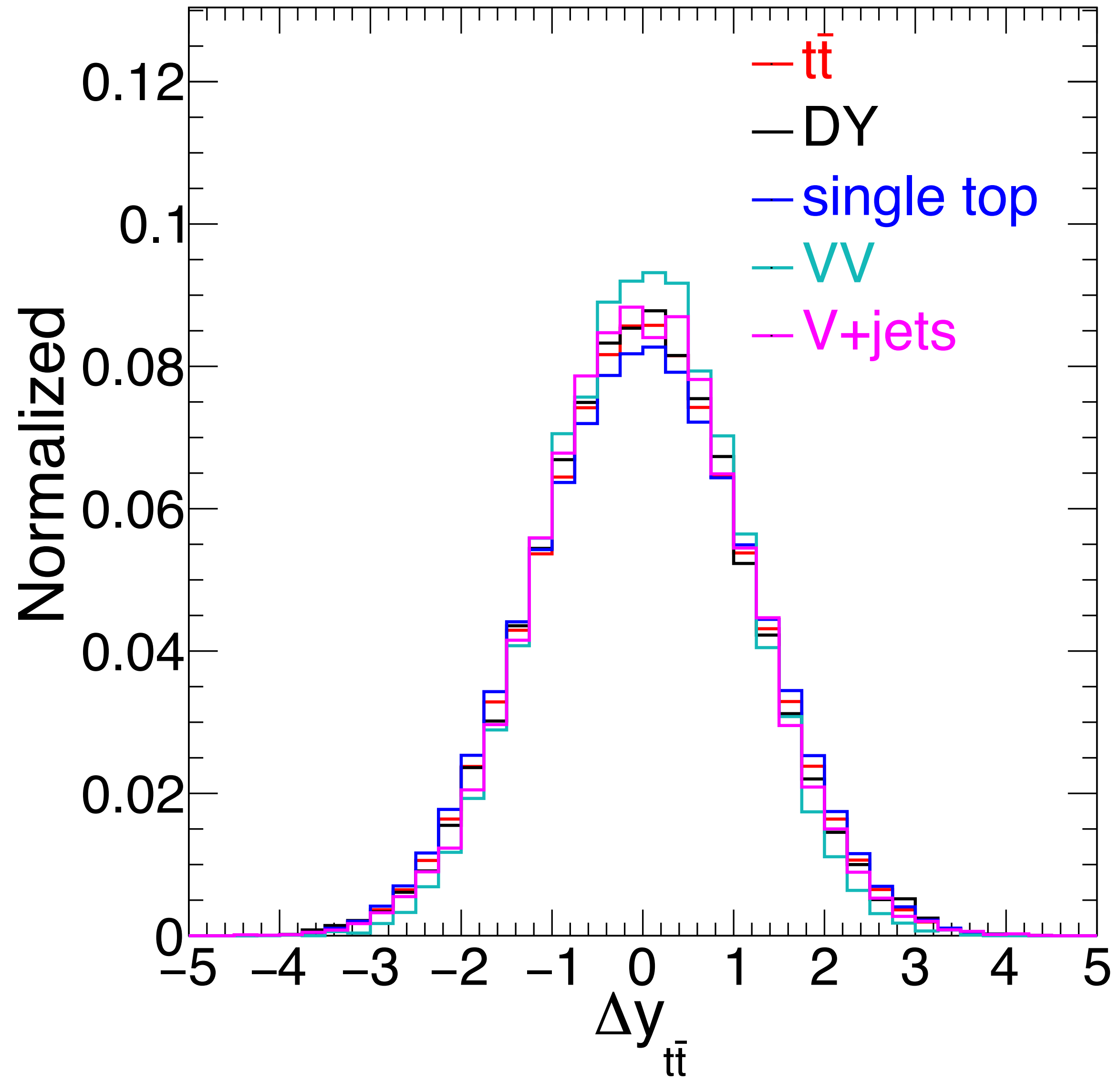


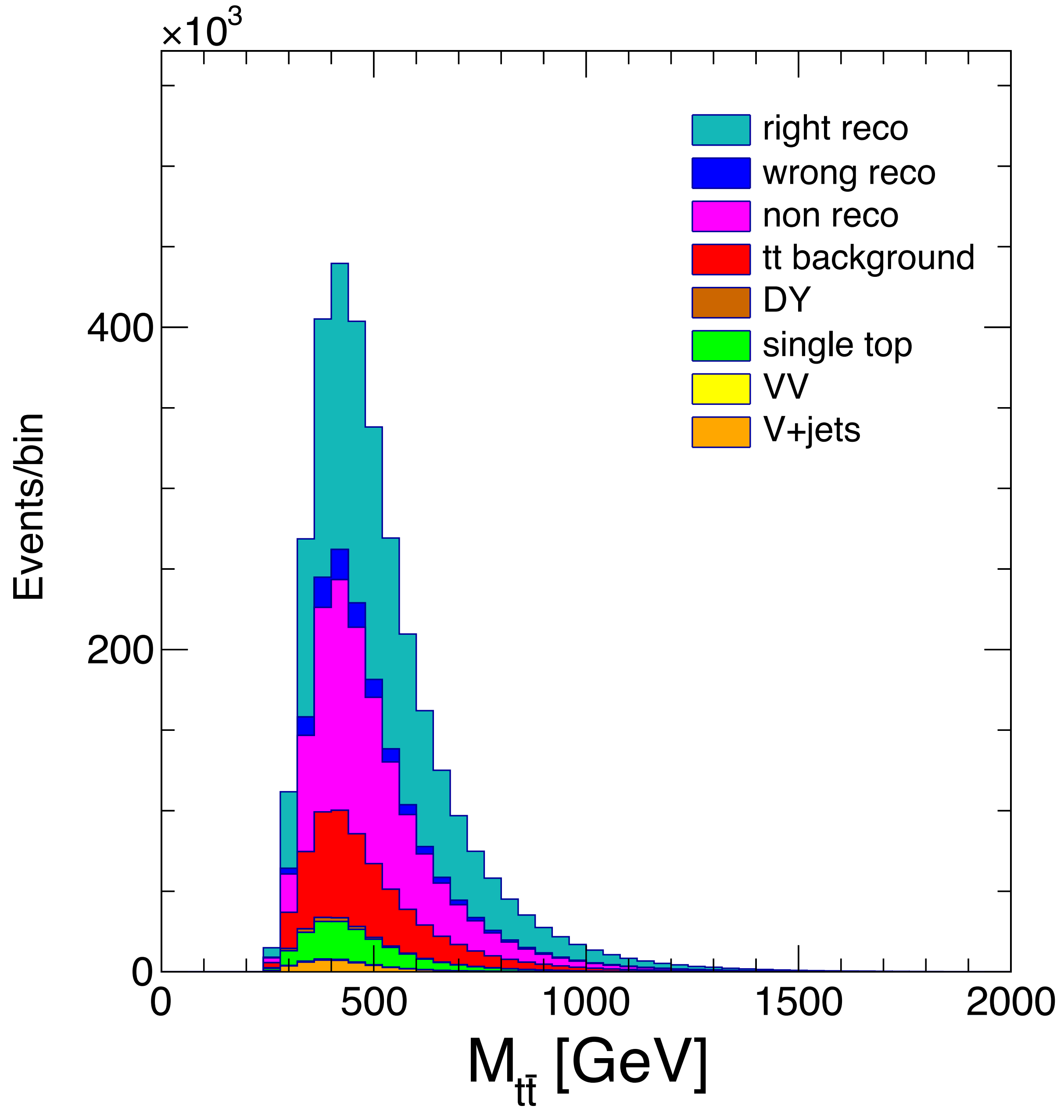
- right reco: correctly reconstructed $t\bar{t}$
- wrong reco: all decay products available, but fail to match jets
- non reco: at least one decay products missing
- tt background: dileptonic, hadronic, $W \to \tau\nu$

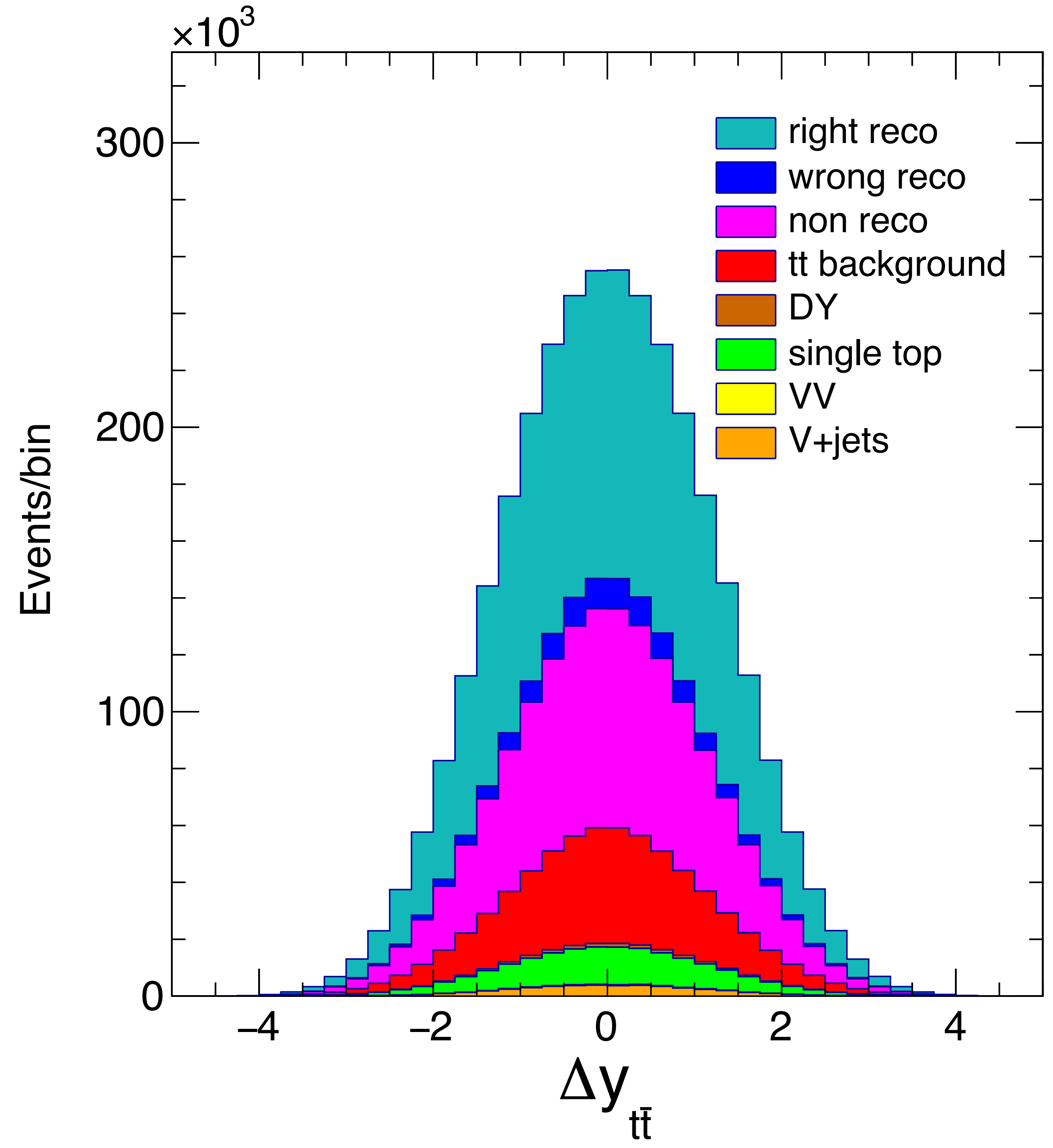
QCD bkg to be added

Observables









- $M_{t\bar{t}}$, $\Delta y_{t\bar{t}}$ are sensitive to D6 operators
- Fit 2D ($M_{t\bar{t}}$, $\Delta y_{t\bar{t}}$) distributions to get sensitivity

Parameterize Signal Model

- Define notation: $\frac{v^2}{\Lambda^2} C_{33}^{\varphi u} \to c_1, \quad \frac{v^2}{\Lambda^2} \mathrm{Re}\left[C_{tt}^{u\varphi}\right] \to c_2, \quad \frac{v^2}{\Lambda^2} \mathrm{Im}\left[C_{tt}^{u\varphi}\right] \to c_3,$

- **Cross Section:** $\sigma \propto |\mathscr{M}_0|^2 + 2Re[\sum_{i=1,2,3} (g_i^{\mathrm{SM}} + c_i)^2 \mathscr{M}_i M_0]$ 4 independent terms

LO

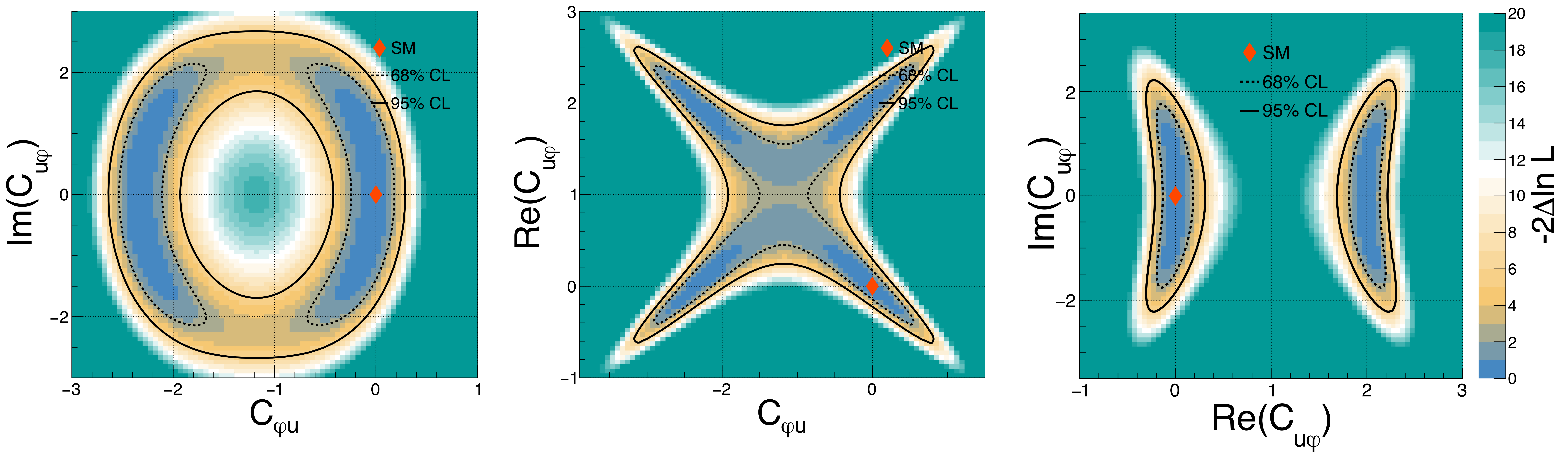
NLO EW corrections

- $g_1^{\mathrm{SM}} = 1.2, \quad g_2^{\mathrm{SM}} = 1.0, \quad g_3^{\mathrm{SM}} = 0.0$
- $\sigma = a(c_1 + g_1^{\mathrm{SM}})^2 + b(c_2 + g_2^{\mathrm{SM}})^2 + c(c_3 + g_3^{\mathrm{SM}})^2 + d$ 4 independent terms
- Define notation: $N_{mnp} \equiv N(c_1 = m, c_2 = n, c_3 = p)$
- $$N = N_{100}(-0.42 + 0.29(c_1 + 1.2)^2) + N_{010}(1.0 - (c_2 - 1.0)^2) + \\ N_{001}c_3^2 + N_{000}(0.42 - 0.29(c_1 + 1.2)^2 + (c_2 - 1.0)^2 - c_3^2)$$

Systematic Uncertainty

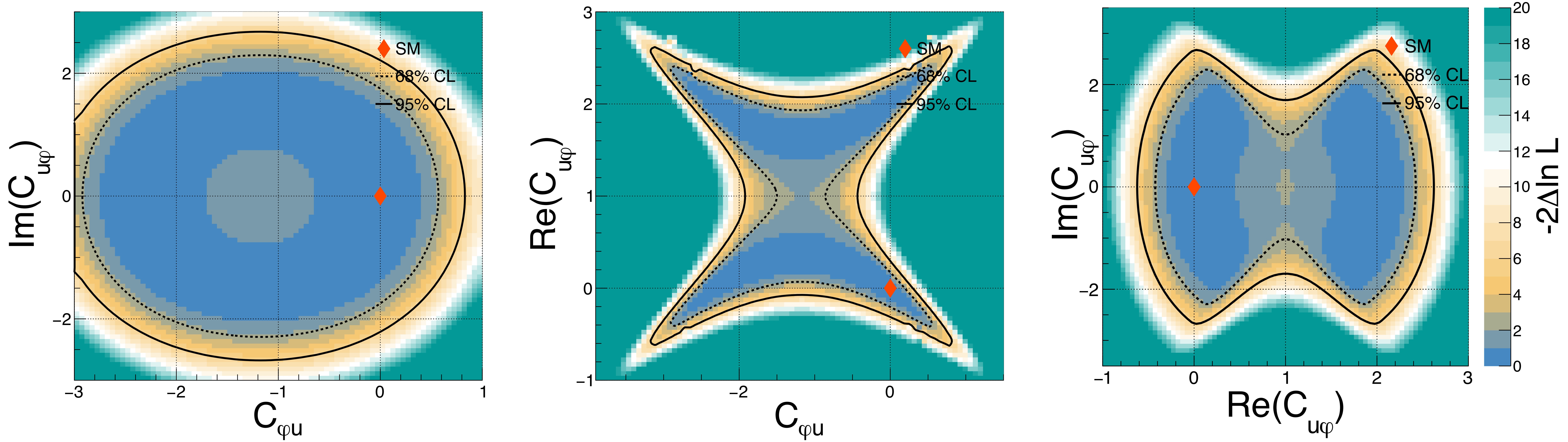
- **Considered theoretical uncertainty:**
  - μ_F, μ_R
  - PDF
  - EW corrections (only signal)
  - FSR, ISR
- **Considered experimental uncertainty:**
  - CMS luminosity
  - JER, JES, MET
- **To be considered:**
  - m_t, lepton ID, bjet tagging, ...

2D Likelihood Scan with Other POI Fixed

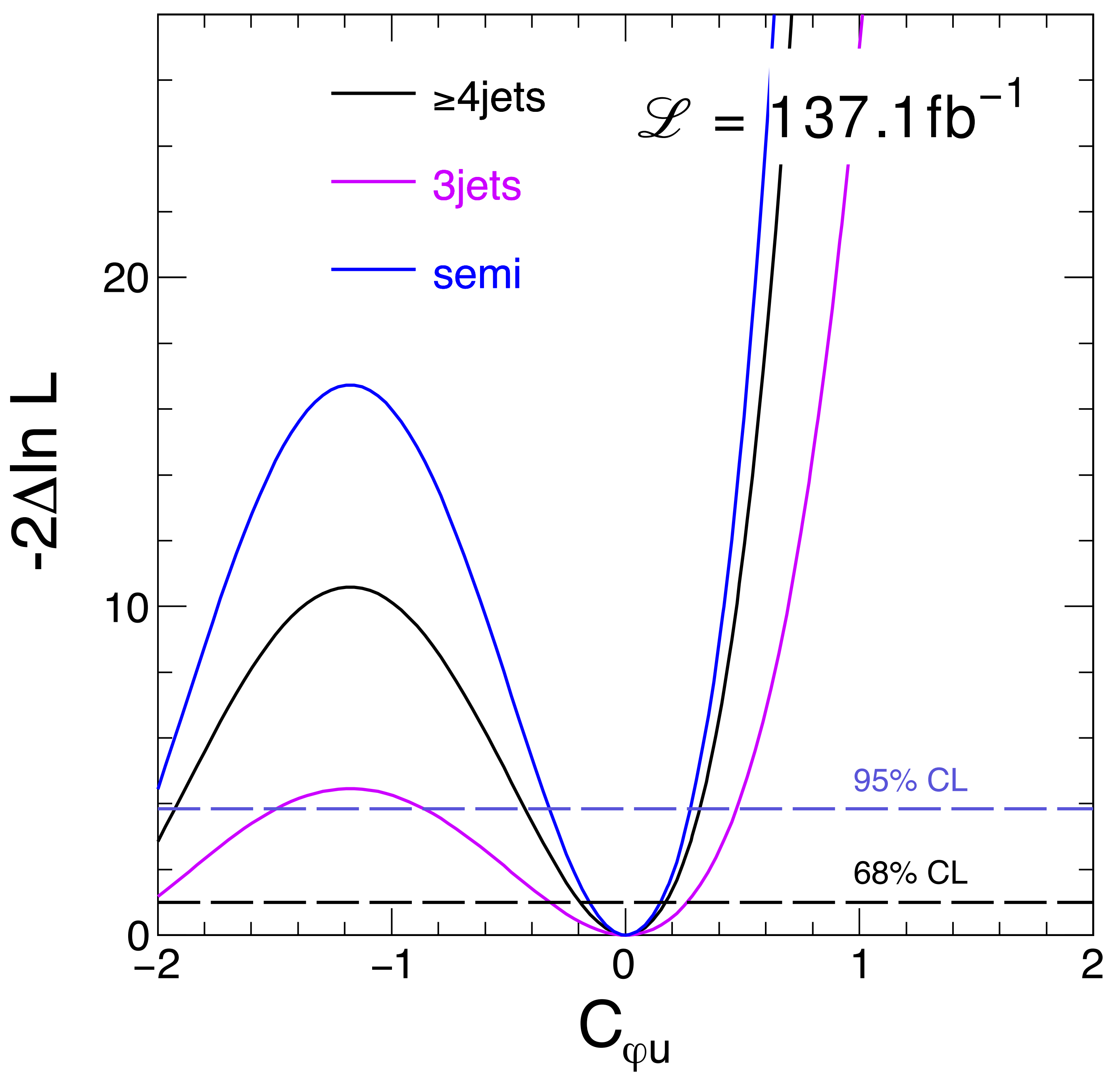


- Have absorbed factor $\frac{v^2}{\Lambda^2}$ into C_i: $\frac{v^2}{\Lambda^2}C_i \to C_i$
- Based on 2018 MC samples, scaled to luminosity $\mathscr{L} = 137\text{fb}^{-1}$
- QCD background haven't been considered yet

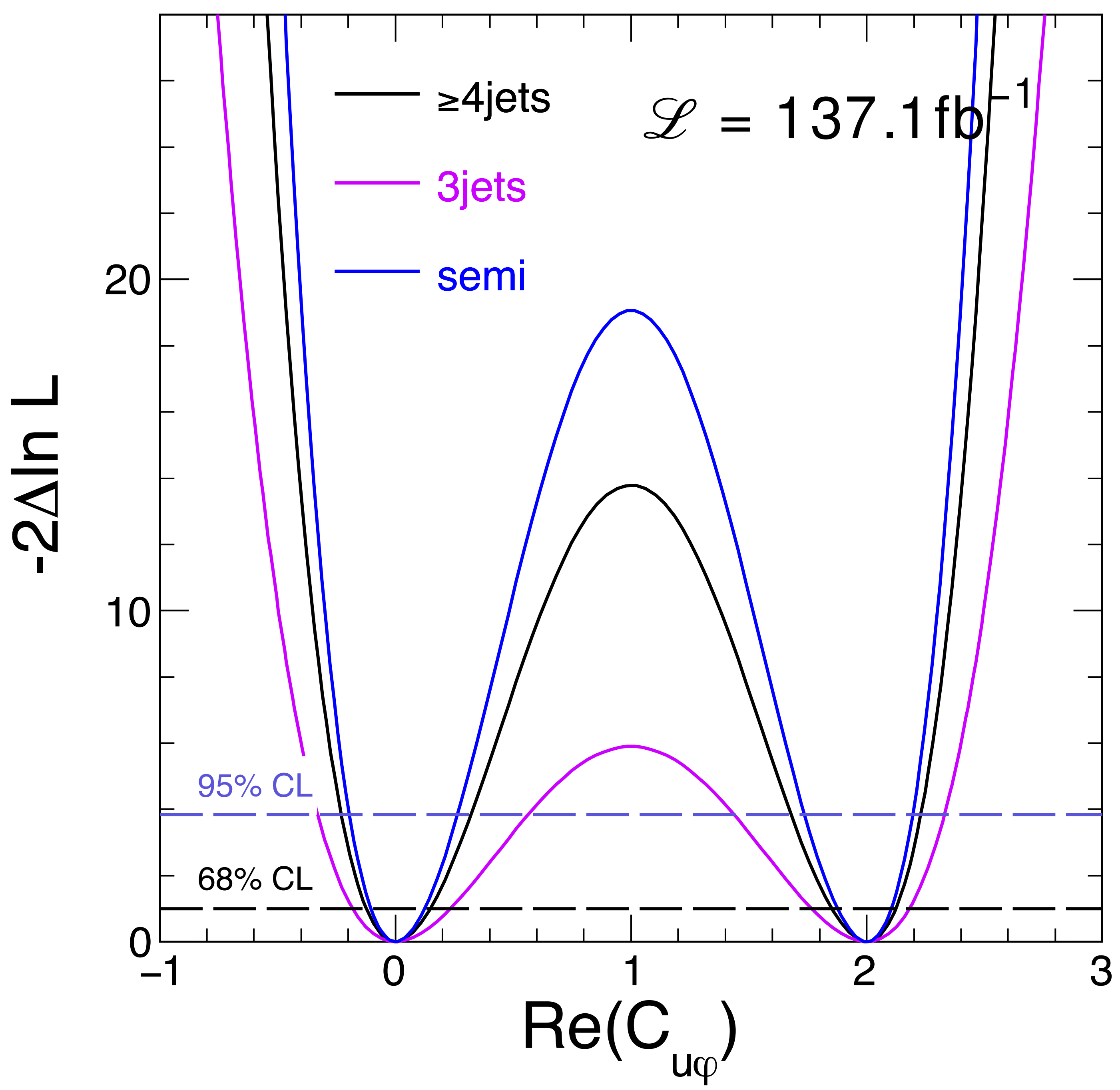
2D Likelihood Scan with Other POI Floated



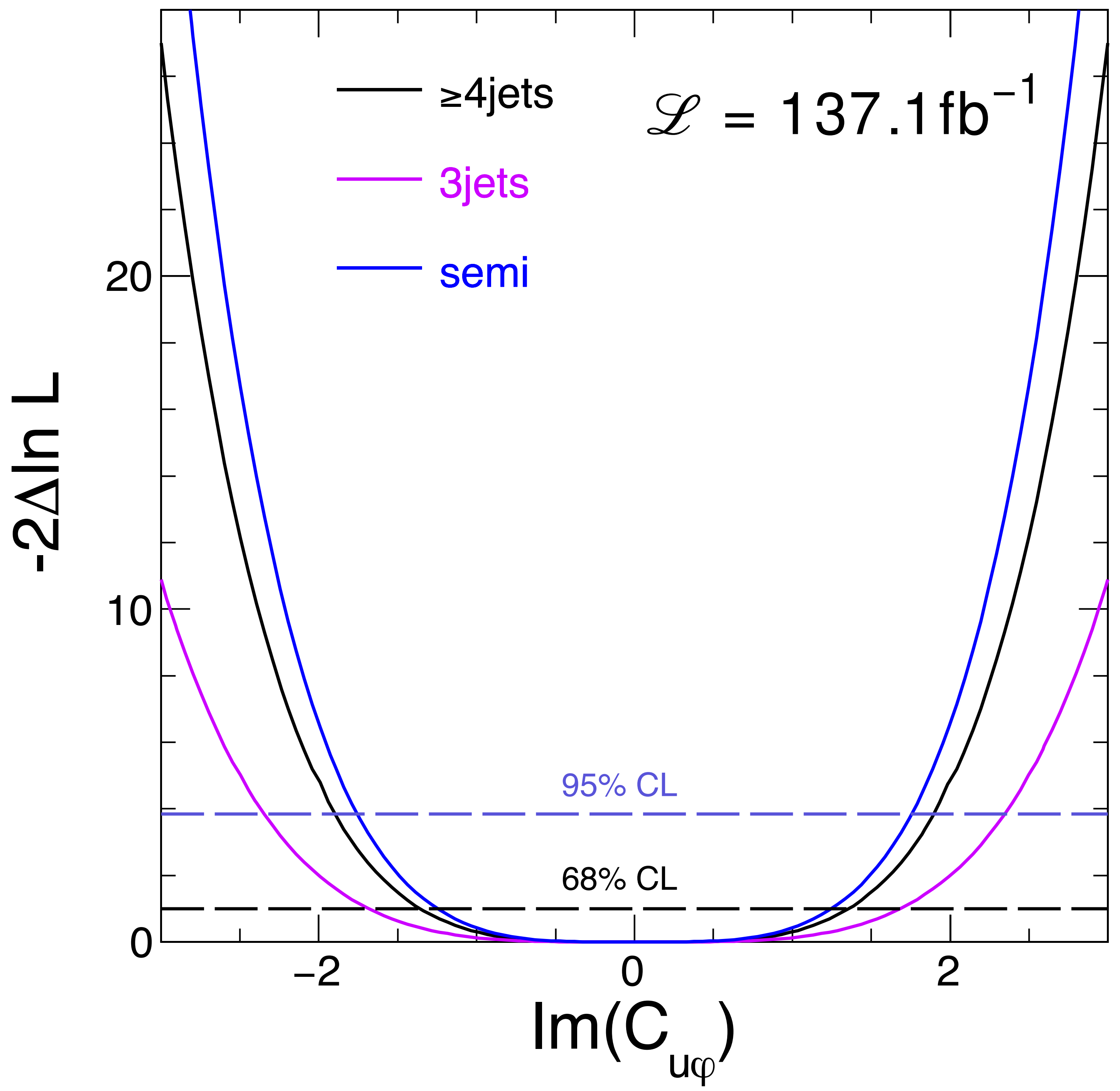
1D Likelihood Scan with Other POI Fixed



68%: [-0.16, 0.15]
95%: [-0.32, 0.26]



68%: [-0.10, 0.12]
95%: [-0.20, 0.26]



68%: [-1.24, 1.24]
95%: [-1.75, 1.75]

Summary and unfinished tasks

Summary:

- measure EW related EFT operators in $t\bar{t}$ production
- Sensitive to the CP structure of Htt couplings
- Possible give more stringent constraints than $t\bar{t}H$ and $t\bar{t}Z$

Tasks to be done:

- Consider all systematic uncertainties
- Deal with 2016 and 2017 MC samples
- QCD background estimation

Backup

Puzzles about $t\bar{t}$ Samples

Separate samples:

- **TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8**
- **TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8**
- **TTToHadronic_TuneCP5_13TeV-powheg-pythia8**

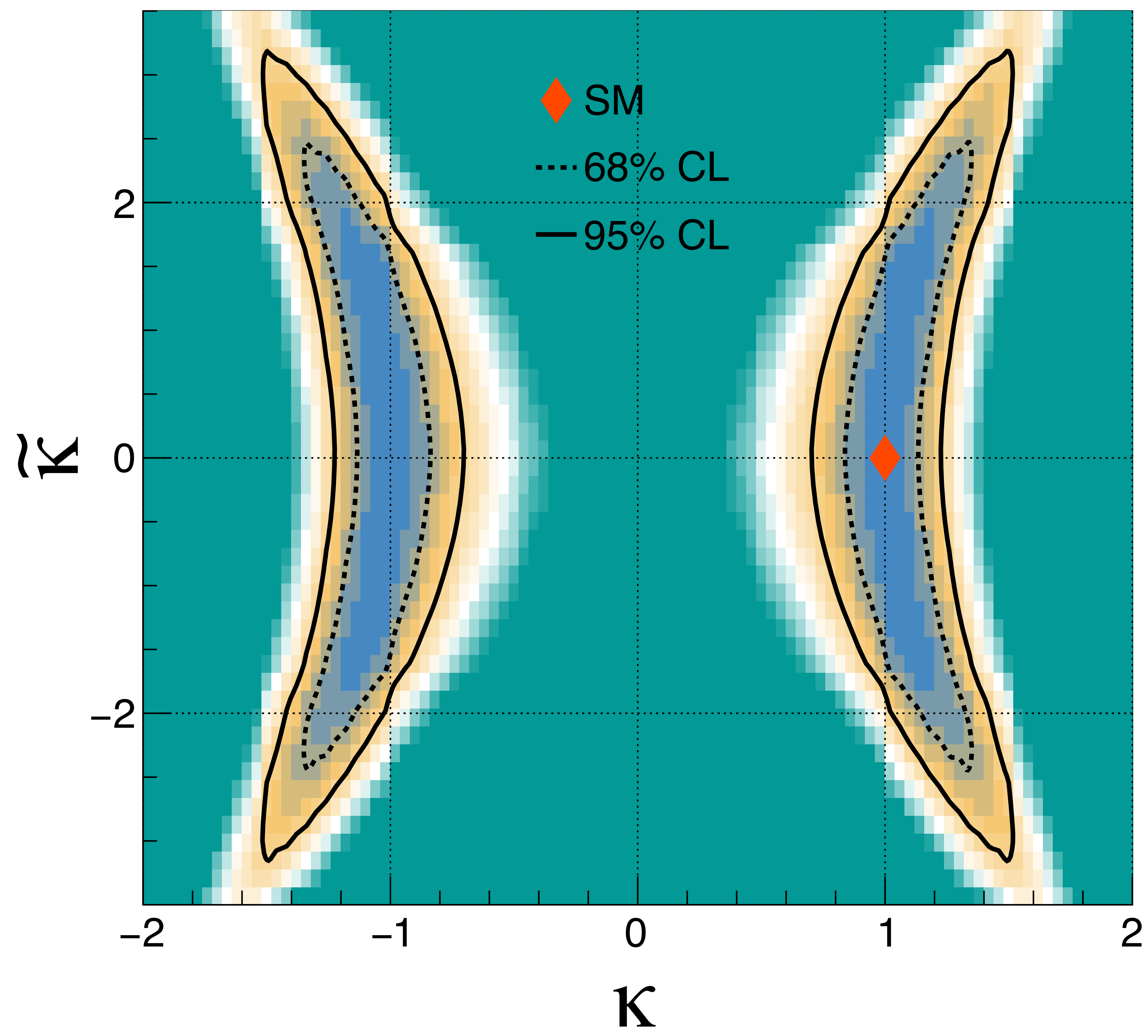
Inclusive sample:

- **TT_TuneCH3_13TeV-powheg-herwig7**

	Sig(semi)	Sig(3jets)	Sig(4jets)
Separate	1428313	503004	925308
Inclusive	1304615	468682	835933
Difference	8%	7%	10%

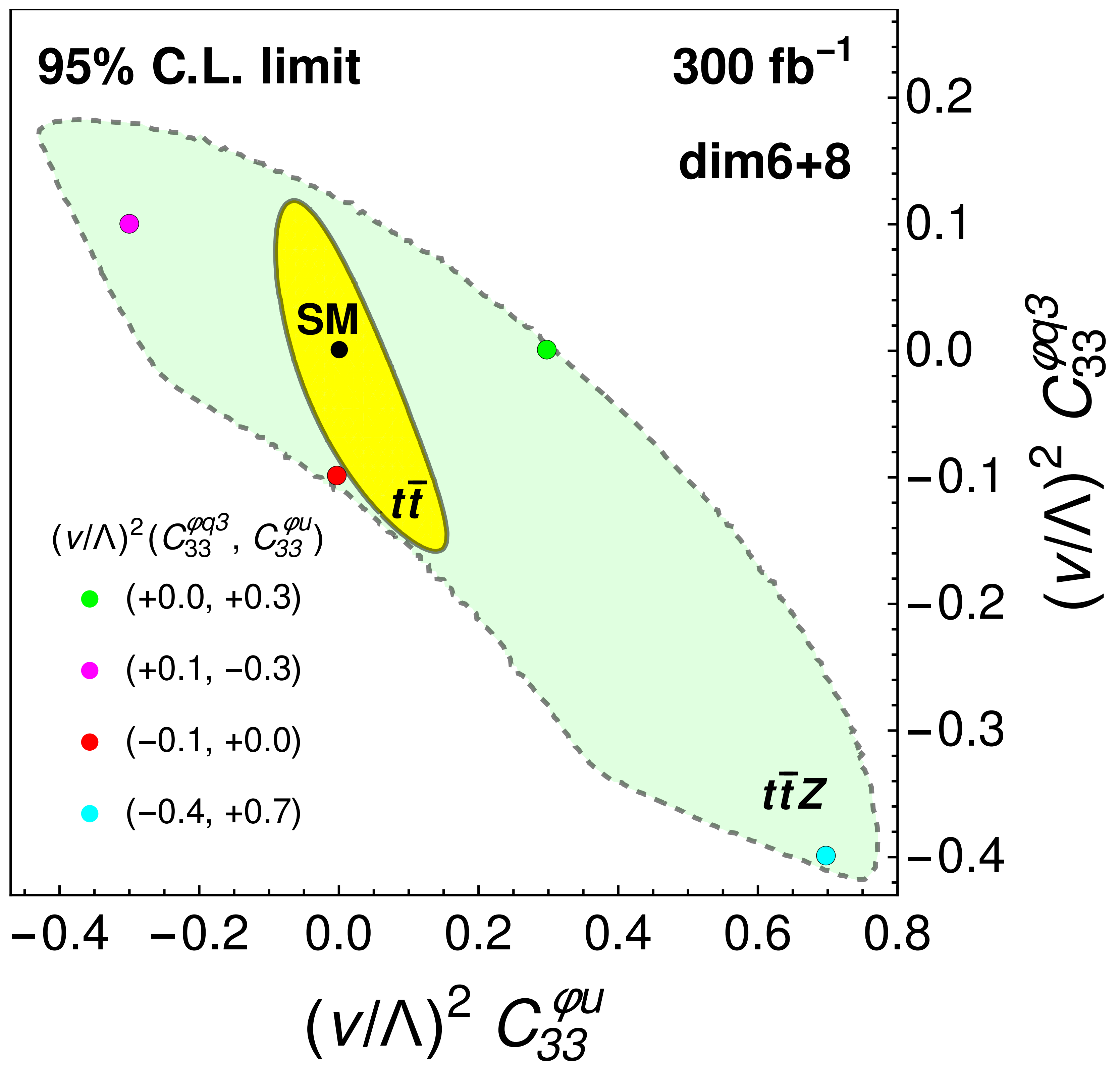
Inconsistent in expect number of events for separate and inclusive $t\bar{t}$ samples

Phenomenological Results



Sensitivity of $t\bar{t}$ production at 300 fb^{-1}.

Martini, Pan, Schulze, Xiao, arXiv: 2104.04277



Compare $t\bar{t}$ with $t\bar{t}Z$ at 300 fb^{-1}.

Martini, Schulze, arXiv:1911.11244

Cross Section

$$\sigma_{t\bar{t}} \approx 832 \text{ pb}$$

$$\sigma_{t\bar{t}H} \approx 0.5 \text{ pb}$$

$$\sigma_{t\bar{t}Z} \approx 1 \text{ pb}$$

EW corrections: 1-5%

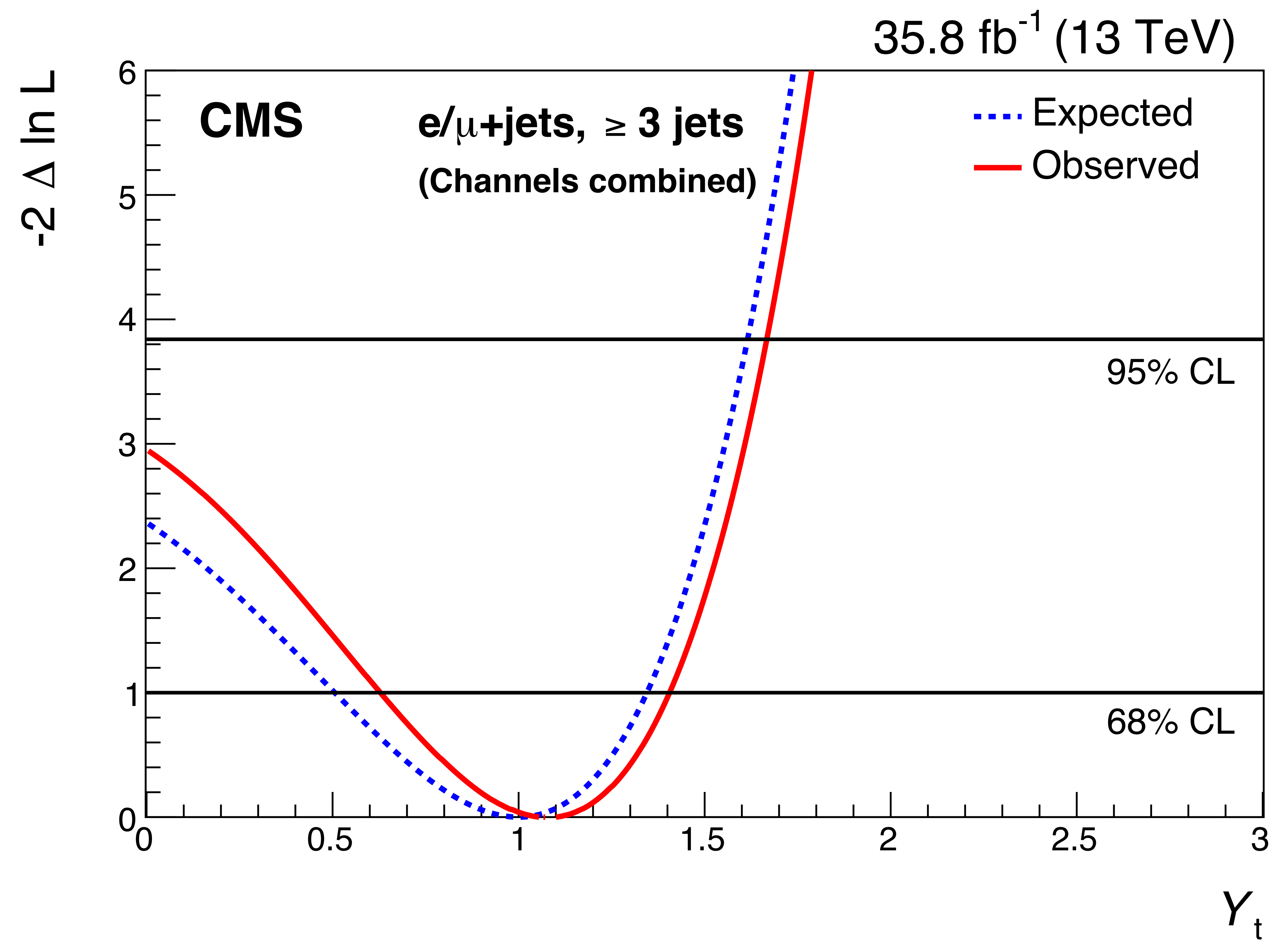
Compare with Other Analysis

$35.8\mathrm{fb}^{-1}$	$\mathrm{Re}(C_{u\varphi})(68\%)$	$\mathrm{Re}(C_{u\varphi})(95\%)$
TOP-17-004	$[-0.35, 0.50]$	$[-0.60,]$
our work	$[-0.19, 0.24]$	$[-0.33, 0.56]$

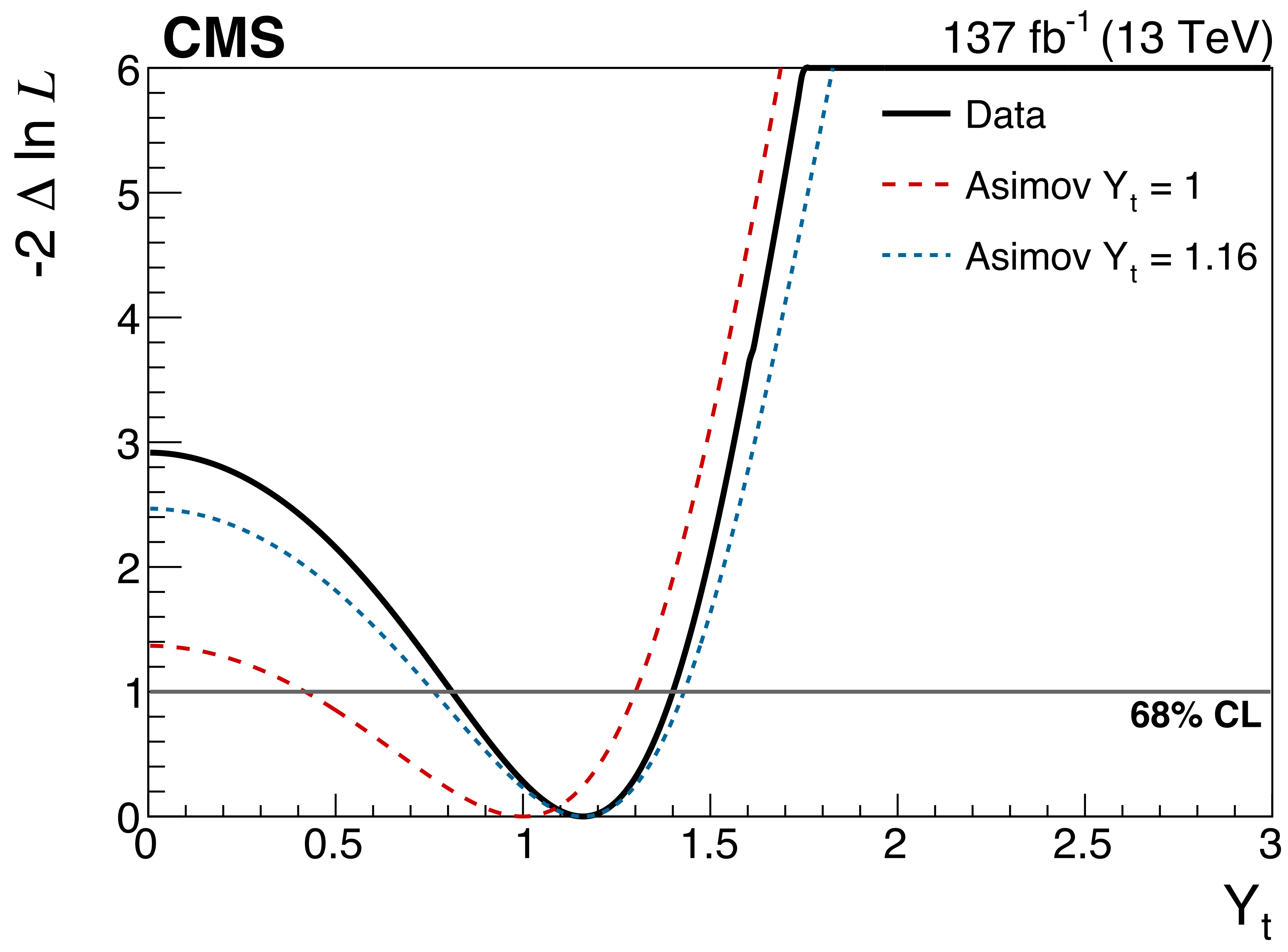
$137.1\mathrm{fb}^{-1}$	$C_{\varphi u}(68\%)$	$C_{\varphi u}(95\%)$	$\mathrm{Re}(C_{u\varphi})(68\%)$	$\mathrm{Re}(C_{u\varphi})(95\%)$
TOP19-008	$-$	$-$	$[-0.30, 0.57]$	$[-0.51,]$
TOP-21-003	$[-0.60, 0.36]$	$[-1.03, 0.54]$	$[-0.30, 0.40]$	$[-0.60,]$
our work	$[-0.16, 0.15]$	$[-0.32, 0.26]$	$[-0.10, 0.12]$	$[-0.20, 0.26]$

Top Yukawa couplings through $t\bar{t}$ with EW Corrections

Measurement of the top quark Yukawa couplings from $t\bar{t}$ from kinematic distributions



Semileptonic channel , arXiv:1907.01590



Dilepton channel, arXiv:2009.07123