Electroweak loop as a Probe of New Physics in $t\bar{t}$ Production

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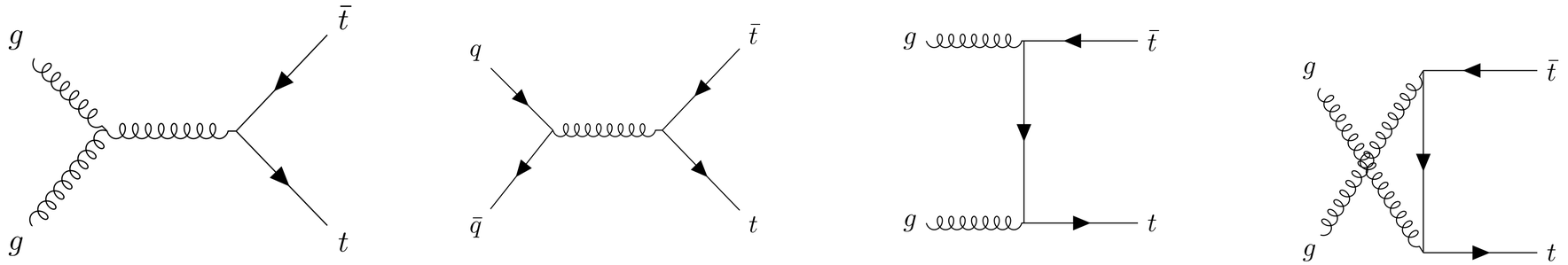
Top Quark Pairs Production at LHC



$t\bar{t}$ production at leading order

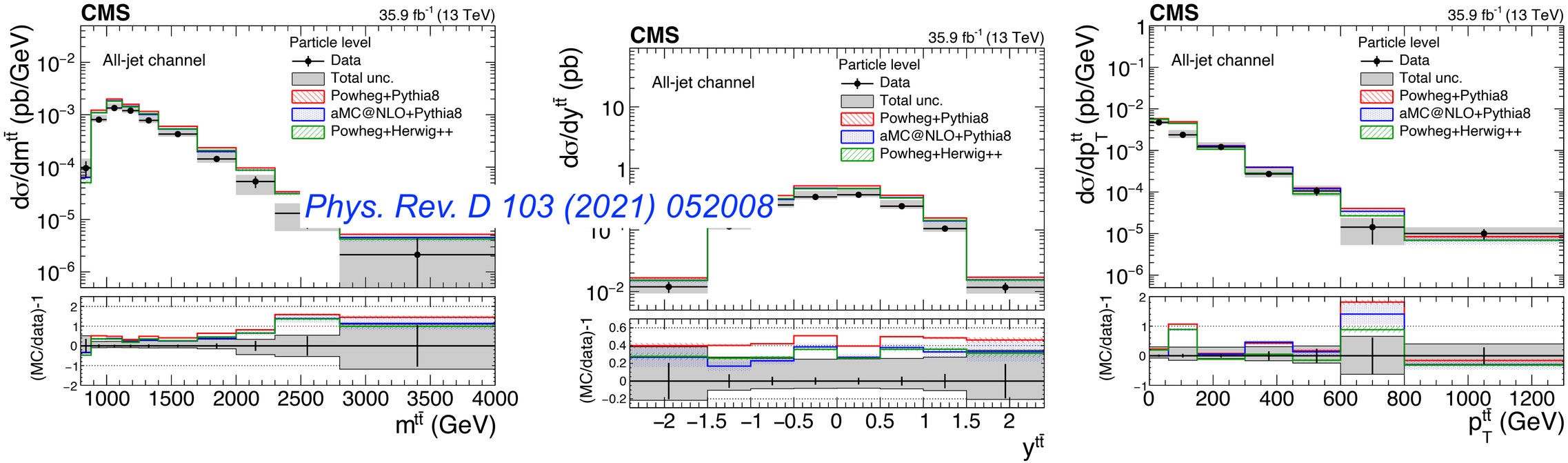
- **Large Cross section:** $\sigma_{t\bar{t}} = 832^{+40}_{-46}\text{pb}$
- **Around 114 million events produced at run2**
- **High accuracy at theory prediction**

Accuracy of $t\bar{t}$ Production

Theoretical predications of $t\bar{t}$ production reach an accuracy at a few percent level:

- QCD calculation up to NNLO+NNLL:
- High ambitions of the theory community towards N3LO calculations

LHC measured differential $t\bar{t}$ production cross sections and unfolded to particle level



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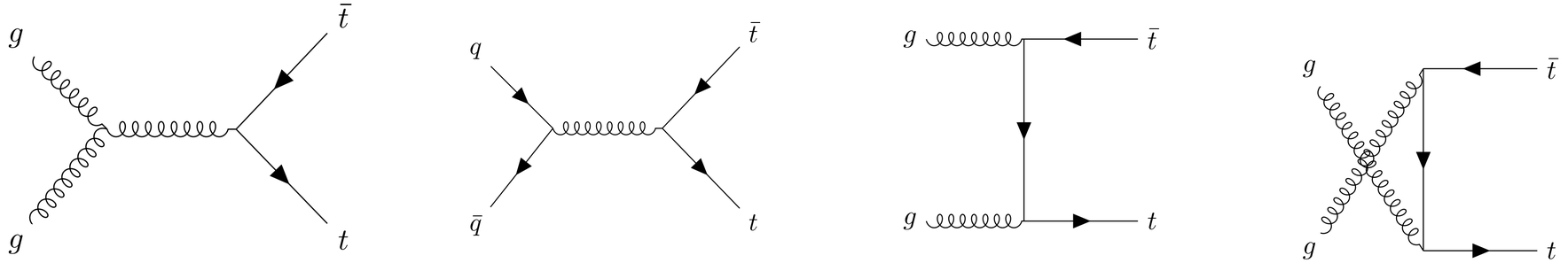
A promising process to search for new physics

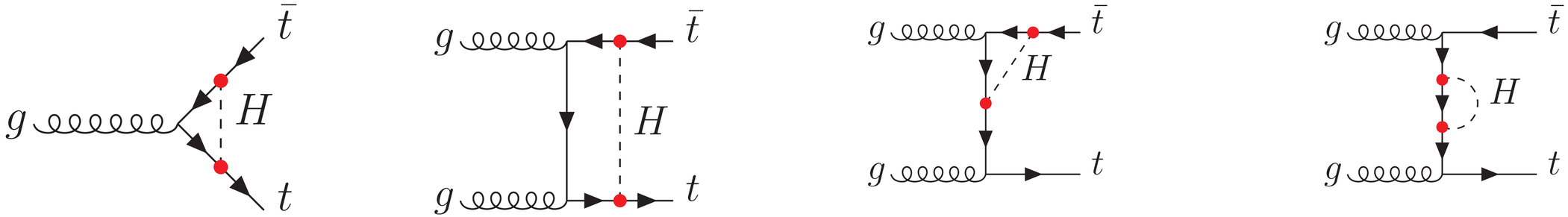
NLO EW Corrections



$t\bar{t}$ production at leading order

NLO EW corrections of $t\bar{t}$ production with arbitrary CP mixing:

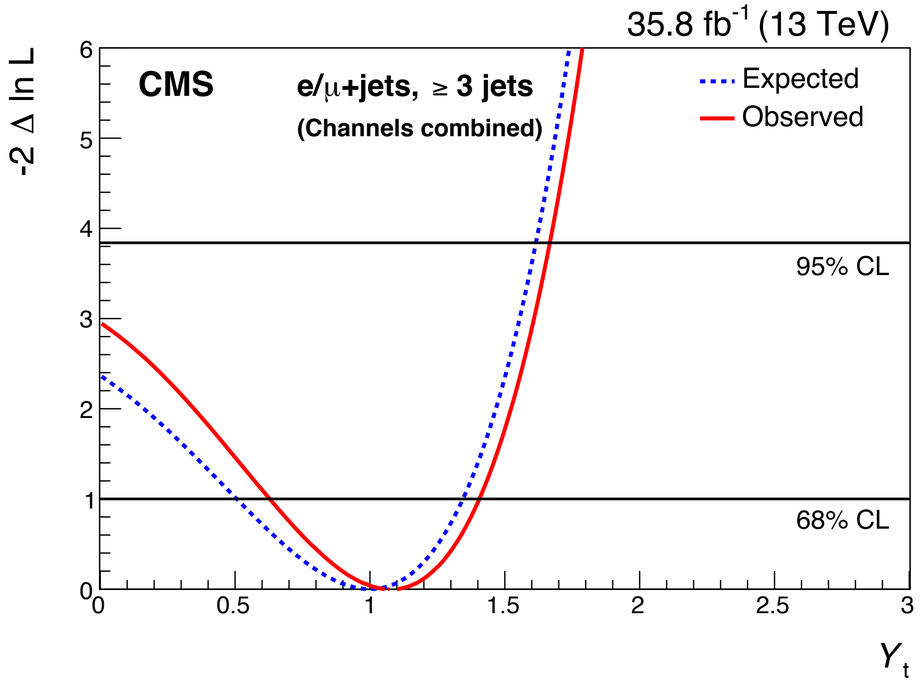
$$\mathscr{L}(Htt) = -\frac{m_t}{v}\bar{\psi}_t\left(\kappa + \mathrm{i}\tilde{\kappa}\gamma_5\right)\psi_t H$$



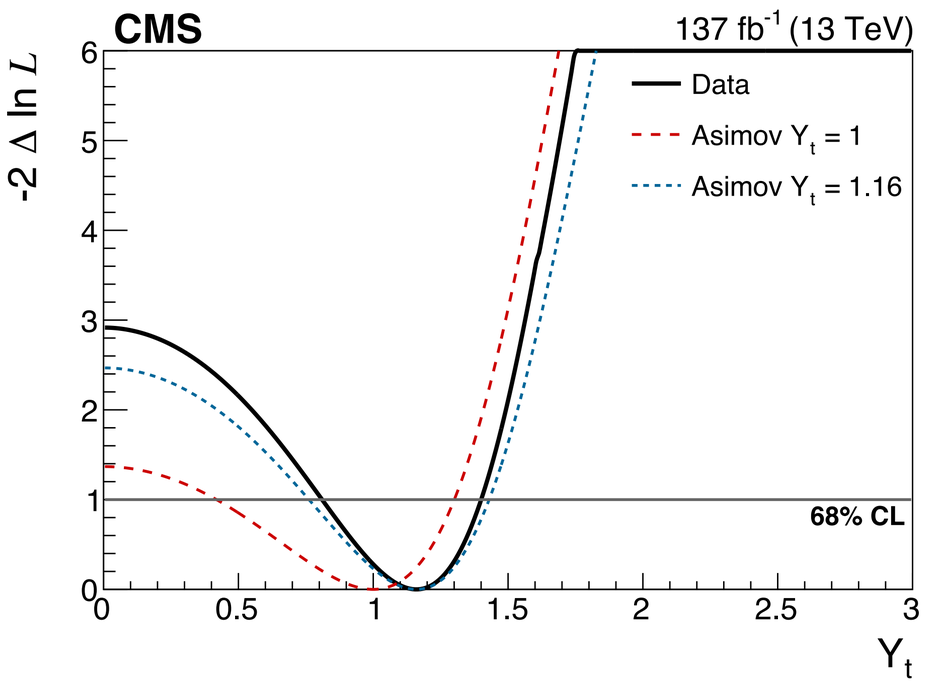
NLO EW corrections from Higgs loop; with EW corrections $t\bar{t}$ production is sensitive to top-Higgs Yukawa interaction and their CP structure.

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

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

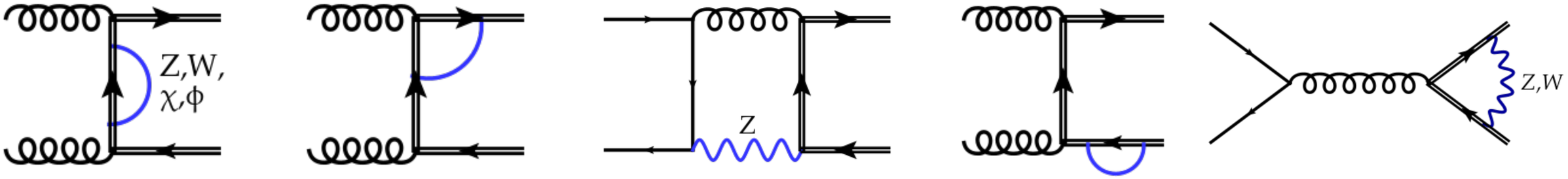


Semileptonic channel , CMS-TOP-17-004, arXiv:1907.01590

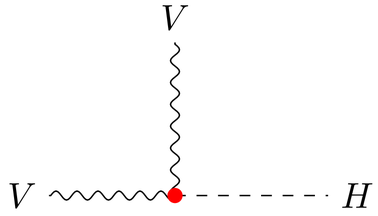


Dilepton channel, CMS-TOP-19-008, arXiv:2009.07123

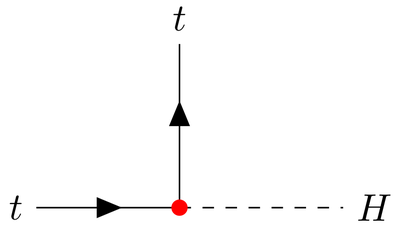
$t\bar{t}$ Production with NLO EW



arXiv:1911.11244, 1305.5773.



- Three vertices enter the Electroweak loops: Htt, Ztt, Wtb
- New physics could modify these couplings
- With EW Corrections $t\bar{t}$ is sensitive to new physics related to EW interaction



SMEFT

- **Effective Lagrangian:** $\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$
- **Matrix element:** $\mathscr{M} = \mathscr{M}_0 + \sum_i c_i \mathscr{M}_i$
- **Possible to search for NP in a model-independent way**
- **In Warsaw basis: 59 independent D-6 operators**

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

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

Interpretation in SMEFT

- **Ztt in SM:** $\Gamma^{\mu}_{Ztt} = \dfrac{-\mathrm{i}e}{s_{\mathrm{w}}c_{\mathrm{w}}}\gamma^{\mu}\left(d^{Z}_{\mathrm{L}}P_{\mathrm{L}} + d^{Z}_{\mathrm{R}}P_{\mathrm{R}}\right)$ **with** $P_{\mathrm{R/L}} = \dfrac{1}{2}\left(1 \pm \gamma_5\right)$

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

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

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

- **Htt Yukawa interaction:** $\mathscr{L}(Htt) = -\dfrac{m_t}{v}\bar{\psi}_t\left(\kappa + \mathrm{i}\,\tilde{\kappa}\gamma_5\right)\psi_t$

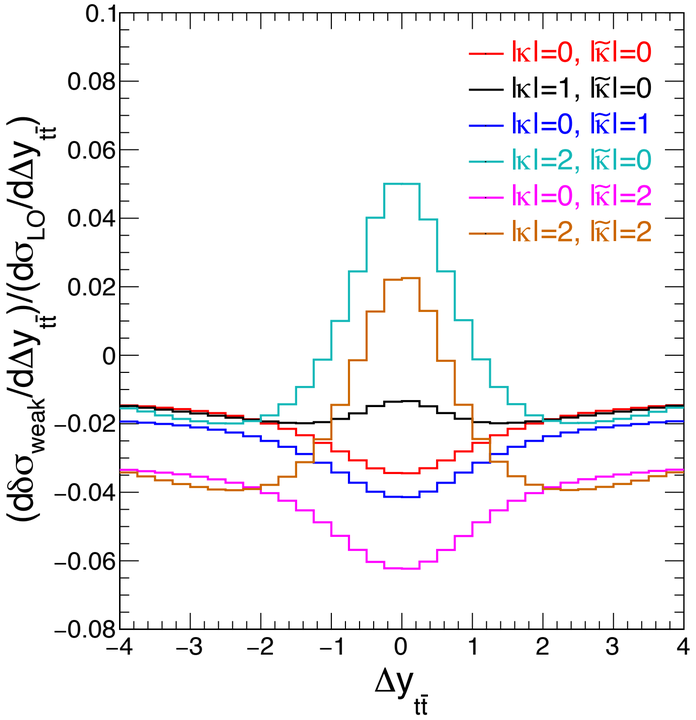
  $\kappa = 1 - \dfrac{v}{\sqrt{2}m_t}\dfrac{v^2}{\Lambda^2}\,\mathrm{Re}\left[C^{u\varphi}_{tt}\right]$, $\quad \tilde{\kappa} = -\dfrac{v}{\sqrt{2}m_t}\dfrac{v^2}{\Lambda^2}\,\mathrm{Im}\left[C^{u\varphi}_{tt}\right]$

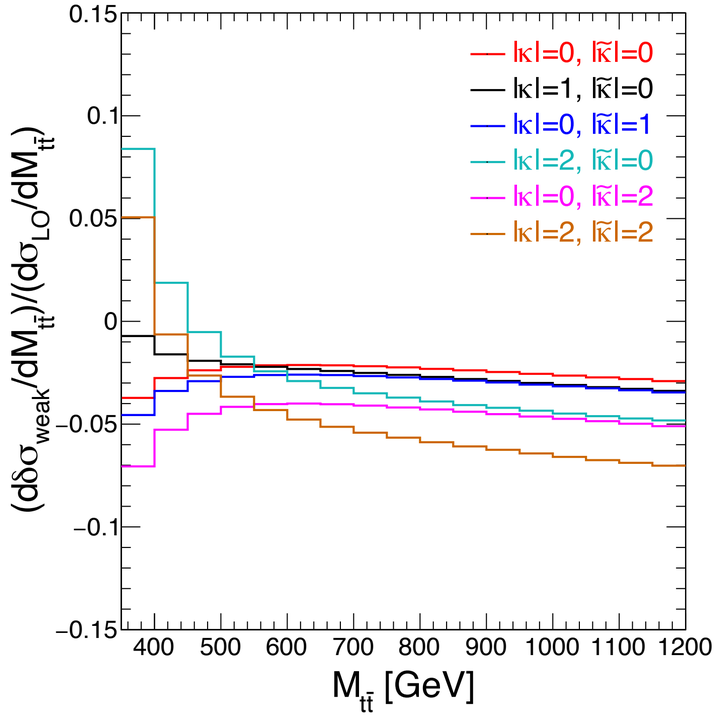
  - **κ term: CP-even, $\tilde{\kappa}$ term: CP-odd; In SM: $\kappa = 1, \tilde{\kappa} = 0$.**
  - **If $\kappa, \tilde{\kappa}$ both are non-zero, implies CP violation.**
- **take** $\dfrac{v^2}{\Lambda^2}\,\mathrm{Re}\left[C^{u\varphi}_{tt}\right], \dfrac{v^2}{\Lambda^2}\,\mathrm{Im}\left[C^{u\varphi}_{tt}\right], \dfrac{v^2}{\Lambda^2}C^{\varphi u}_{33}$ **as free parameters**

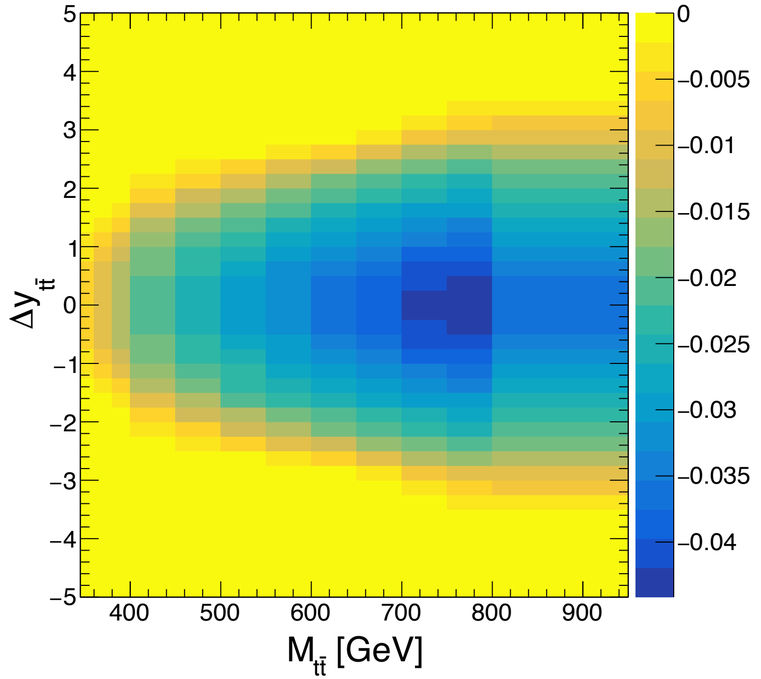
Ratio of EW Corrections

- **EW correction factor:** $\delta_{\mathrm{wk}} = \dfrac{d\sigma_{\mathrm{wk}}^{\mathrm{NLO}} - d\sigma^{\mathrm{LO}}}{d\sigma^{\mathrm{LO}}}$
- 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 CP structure of top Yukawa coupling**

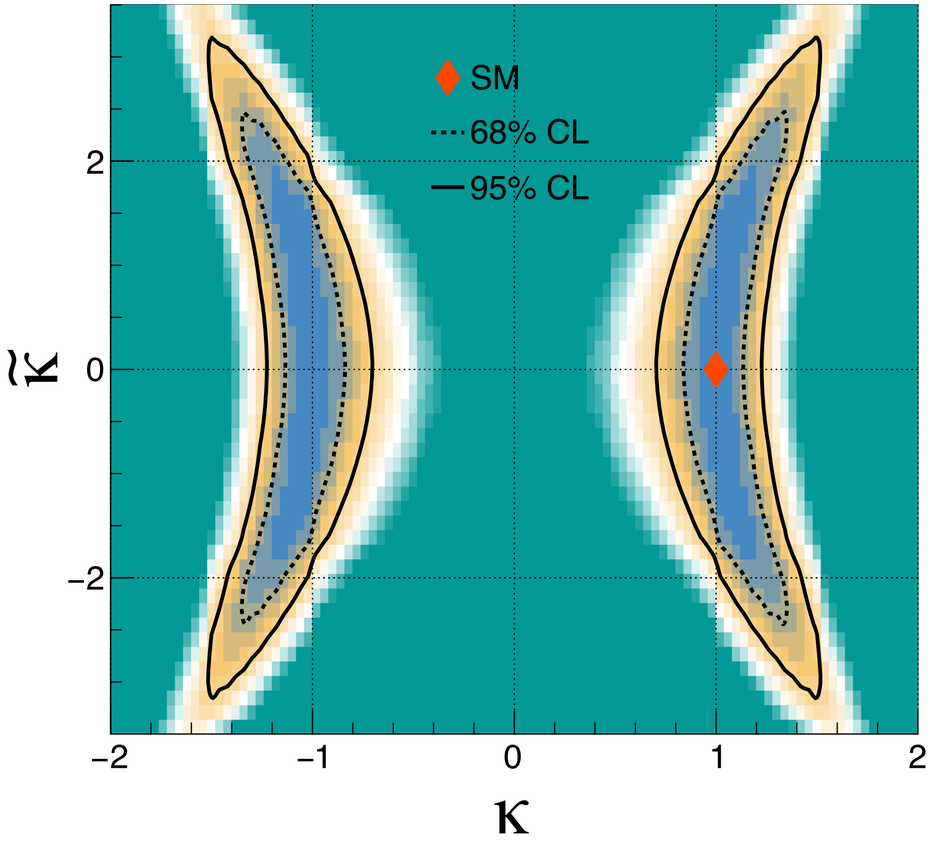
Till, Pan, Markus, Meng:
arXiv: 2104.04277





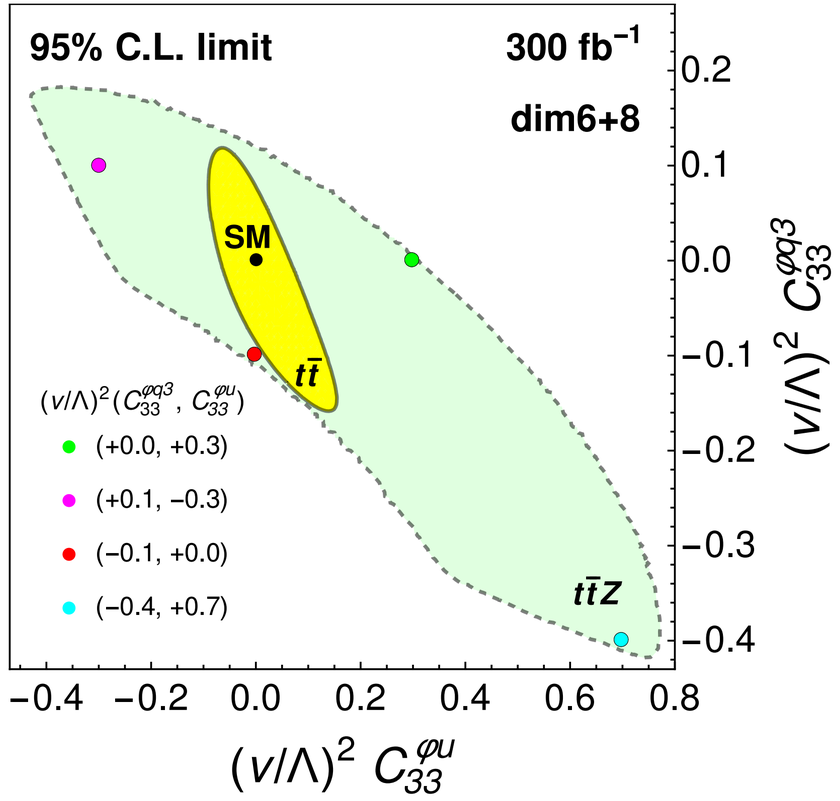


Phenomenological Results



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

Till, Pan, Markus, Meng, arXiv: 2104.04277



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

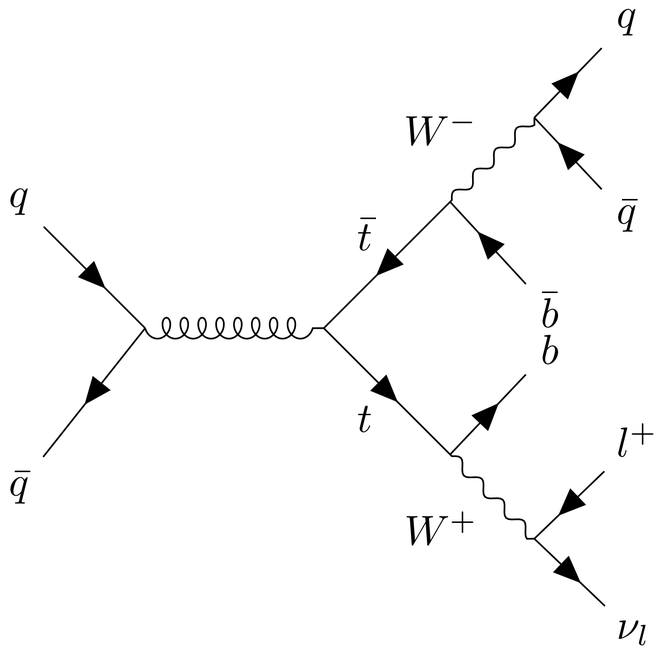
Till, Markus, arXiv:1911.11244

Analyze $t\bar{t}$ with EW Corrections at the CMS

Search for new physics in the SMEFT framework in $t\bar{t}$ production in the semileptonic final state at the CMS

Final state:

- At least 3 jets with at least two of them being b-tagged jets
- One isolated and high quality lepton



Primary Vertex Selection

Primary Vertex Selection

Require the events to have at least on primary vertex satisfying in following criteria:

- At least 4 degrees of freedom of the vertex reconstruction, n_{dof}
- The track impact parameter with respect to the beam spot on the z-axis, $|d_z|$ is smaller than 24 cm
- The track impact parameter with respect to the beam spot on the xy-plane , $|d_{xy}|$ is smaller than 2 cm

Muon Selection

Muon selection criteria

- $p_T > 30$ GeV, $|\eta| < 2.4$
- **Pass muon cut-baed identification criteria of the *tight* working point**
- **PF-based combined relative isolation value smaller than 0.15 in the tight working point**

Additional muon passing the following criteria will be vetoed:

- $p_T > 15$ GeV, $|\eta| < 2.4$
- **Pass muon identification criteria of *loose* working points**
- **Have PF-based combined relative isolation value smaller than 0.25 in the loose working point**

Electron Selection

Electron selection criteria

- $p_T > 30$ Gev, $|\eta| \notin [1.4442, 1.5660]$
- **Pass electron cut-based identification criteria of the tight working point**
- **Pass the recommended impact parameter cut defined the Egamma POG**
- **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.

Additional electron passing the following criteria will be vetoed:

- $p_T > 15$ Gev, $|\eta| \notin [1.4442, 1.5660]$
- **Pass electron cut-baed identification criteria of the loose working point**
- **Pass the recommended impact parameter cut defined by the Egamma POG**

Jet Selection

The selected jets should pass the following criteria:

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

b-jet

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

Reconstruct Top Quark Pairs

- Reconstruct transverse momentum of neutrino from missing ET , $\nu_x = \not{p}_x, \nu_y = \not{p}_y$.
- Consider all combination of jets
- Assume the distribution of invariant masses are Gaussian distributions

$$P(M_{W_{lep}}) = Gaus(M_{W_{lep}}, m_W, \sigma_W),$$

$$P(M_{W_{had}}) = Gaus(M_{W_{had}}, m_W, \sigma_W),$$

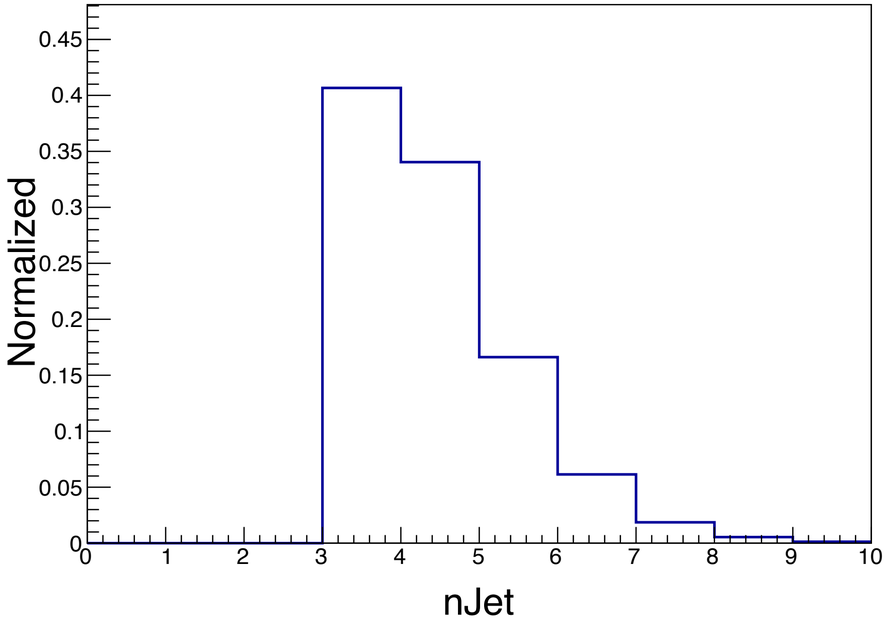
$$P(M_{t_{lep}}) = Gaus(M_{t_{lep}}, m_t, \sigma_t),$$

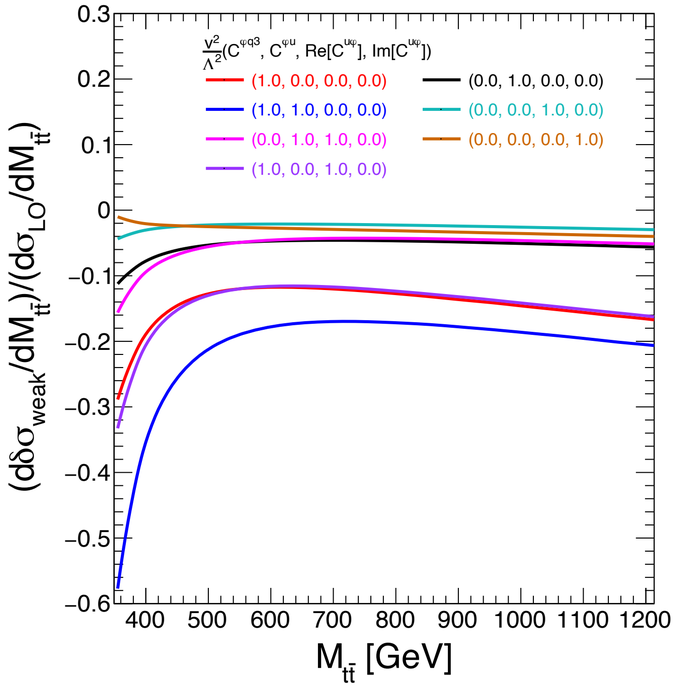
$$P(M_{t_{had}}) = Gaus(M_{t_{had}}, m_t, \sigma_t),$$

$$ln(p_{\nu_z}) = -ln(P(M_{W_{lep}})) - ln(P(M_{W_{had}})) - ln(P(M_{t_{lep}})) - ln(P(M_{t_{had}}))$$

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

Reconstruction in 3 Jets Final State

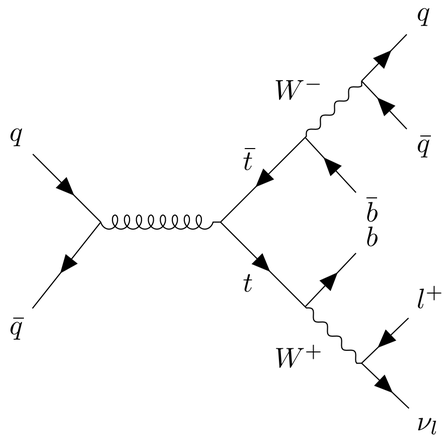




When only three jets are reconstructed, in 93% of the cases it is because a soft jet from W decay is out of acceptance: it is below the p_T or η criteria for jets.

$$P_{w_{\text{had}}} = P_b + P_j$$

arxiv: 1907.01590

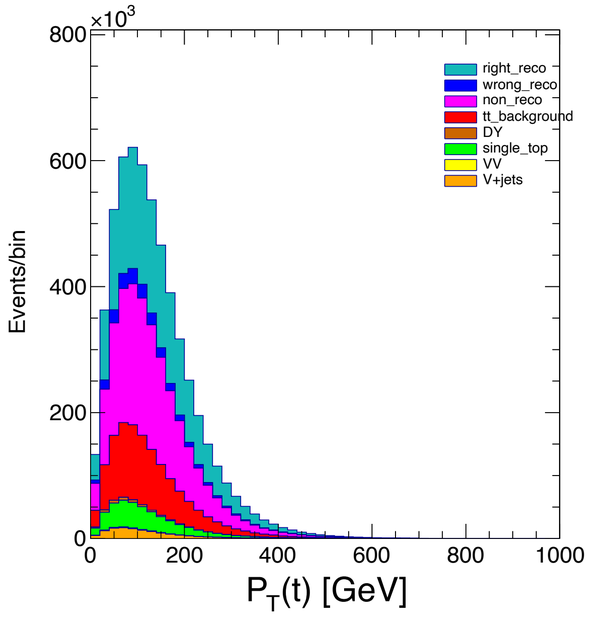


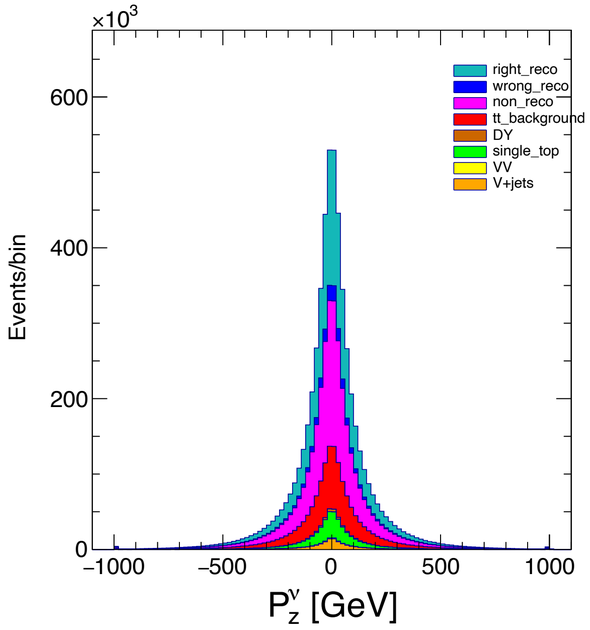
Signal Selection Efficiency

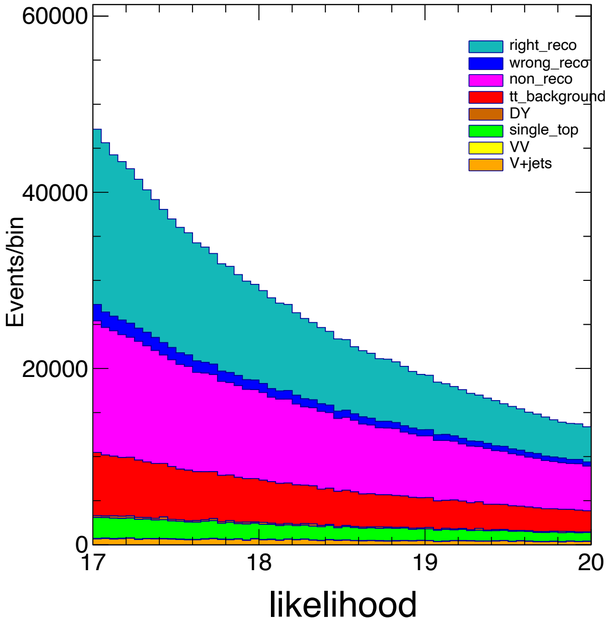
Selection efficiency of signal with cut likelihood <19.0

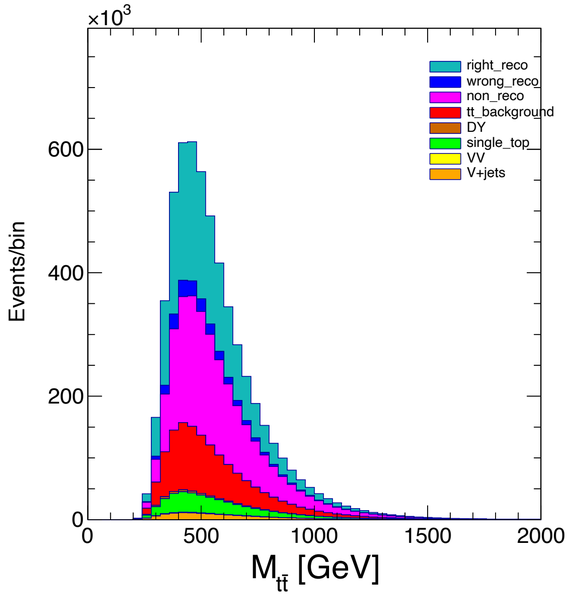
process	cross_section(pb)	efficiency(%)	efficiency(>=4jets)(%)	efficiency(3jets)(%)
TTToSemiLeptonic	366.9	6.339	4.148	2.191
TTTo2L2Nu	89.1	2.137	0.743	1.394
TTToHadronic	378.0	0.012	0.009	0.003

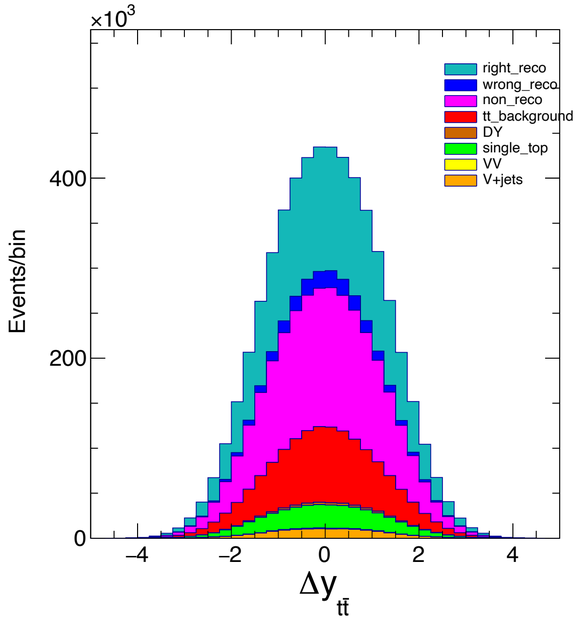
Event Distribution











Parameterize Signal Model

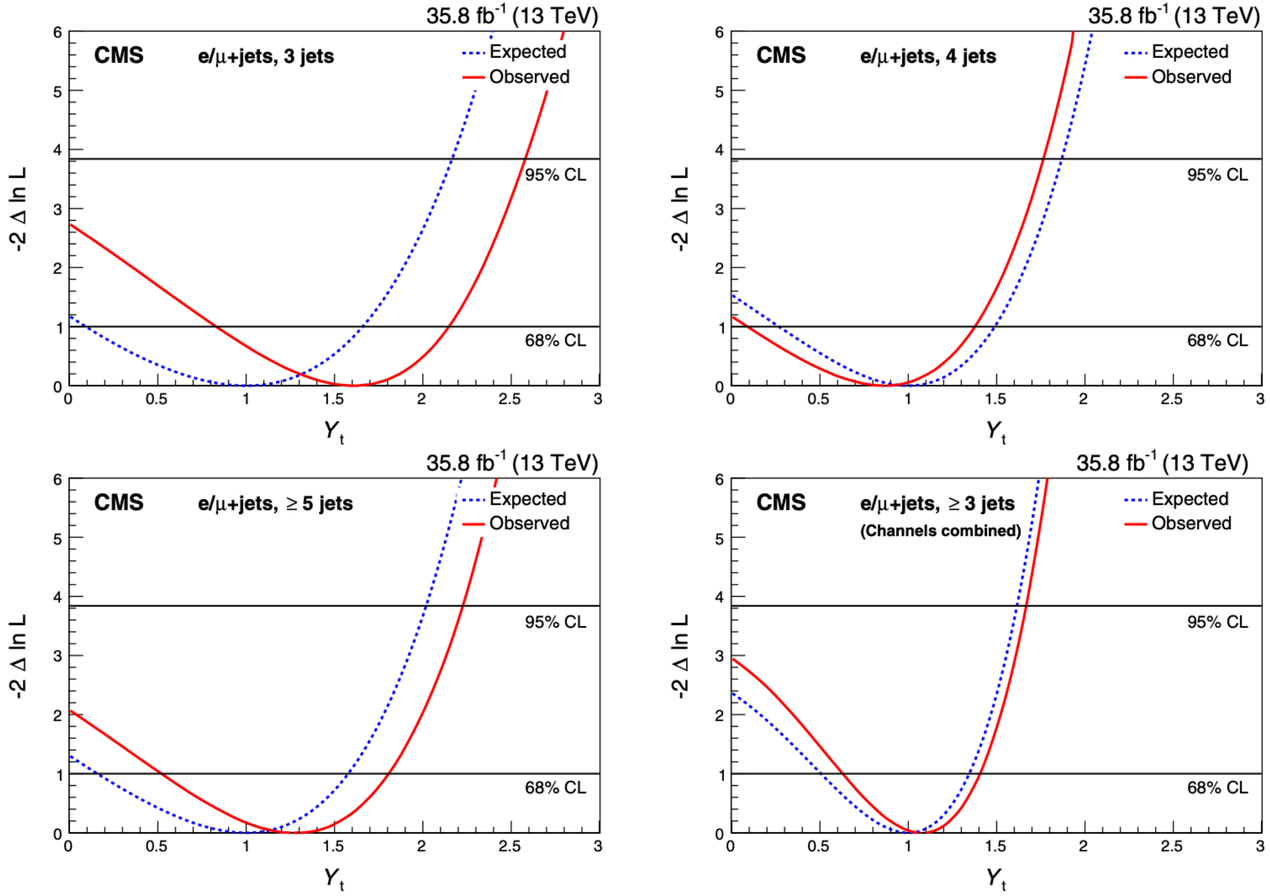
- **Matrix element:** $\mathscr{M} = \mathscr{M}_0 + \sum_i c_i \mathscr{M}_i$
- **Cross Section:** $\sigma \propto |\mathscr{M}_0 + \sum_i c_i \mathscr{M}_i|^2$

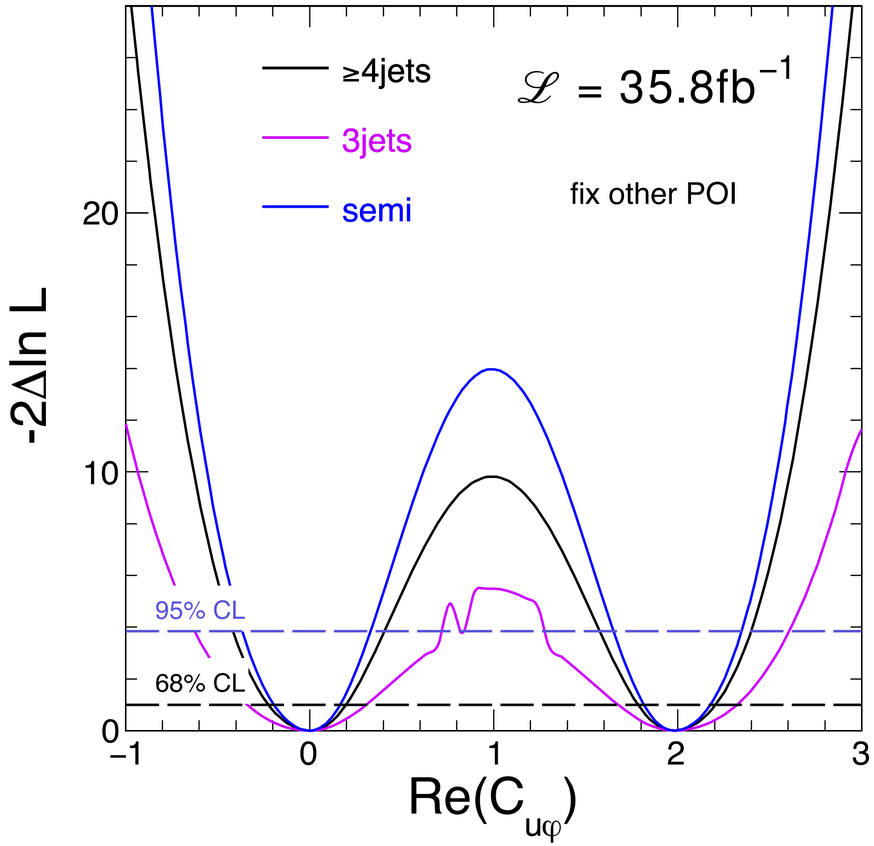
. Define notation: $\frac{v^2}{\Lambda^2} C_{33}^{\varphi u} \to y, \qquad \frac{v^2}{\Lambda^2} \mathrm{Re}\left[C_{tt}^{u\varphi}\right] \to z, \qquad \frac{v^2}{\Lambda^2} \mathrm{Im}\left[C_{tt}^{u\varphi}\right] \to k,$

. Define notation: $N_{y_0 z_0 k_0} \equiv N(y = y_0, z = z_0, k = k_0)$

$$N_{yzk} = k^2 N_{001} + (2y - y^2) N_{100} + (-\frac{y}{2} + \frac{y^2}{2}) N_{200} + (2z - z^2) N_{010} +$$
$$(-\frac{z}{2} + \frac{z^2}{2}) N_{020} + (1 - k^2 - \frac{3y}{2} + \frac{y^2}{2} - \frac{3z}{2} + \frac{z^2}{2}) N_{000}$$

Compare with Previous Results





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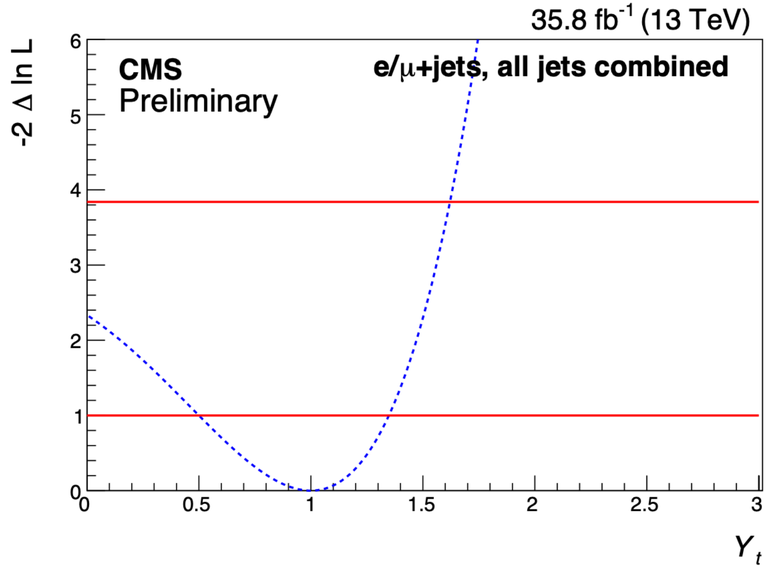
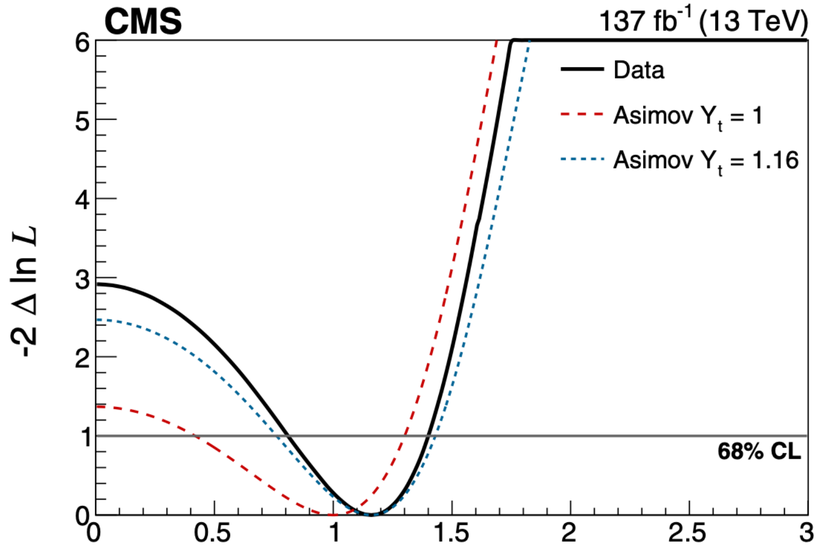
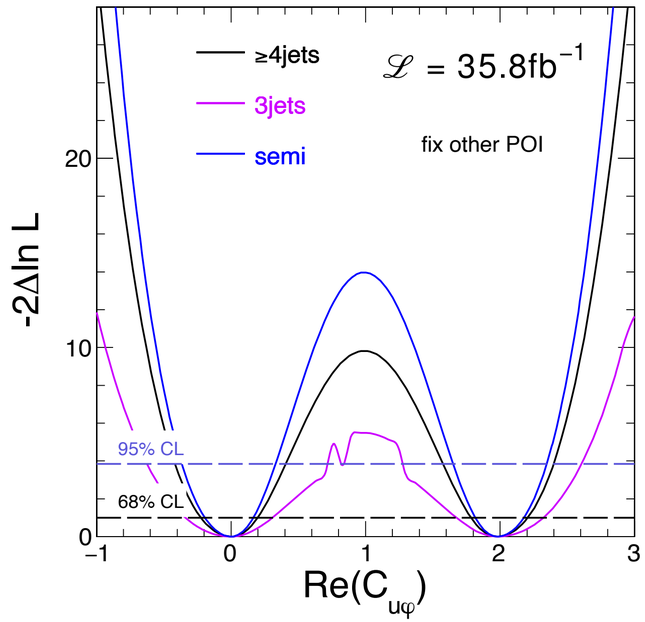
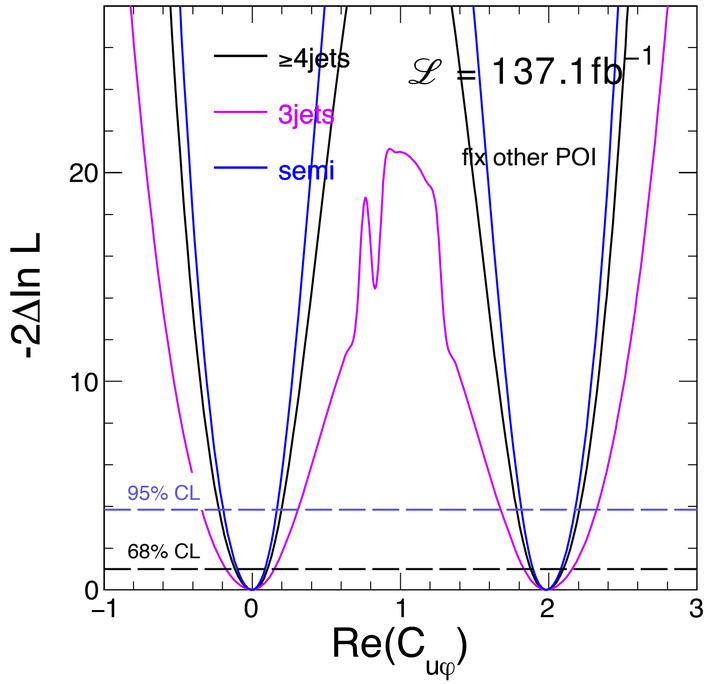
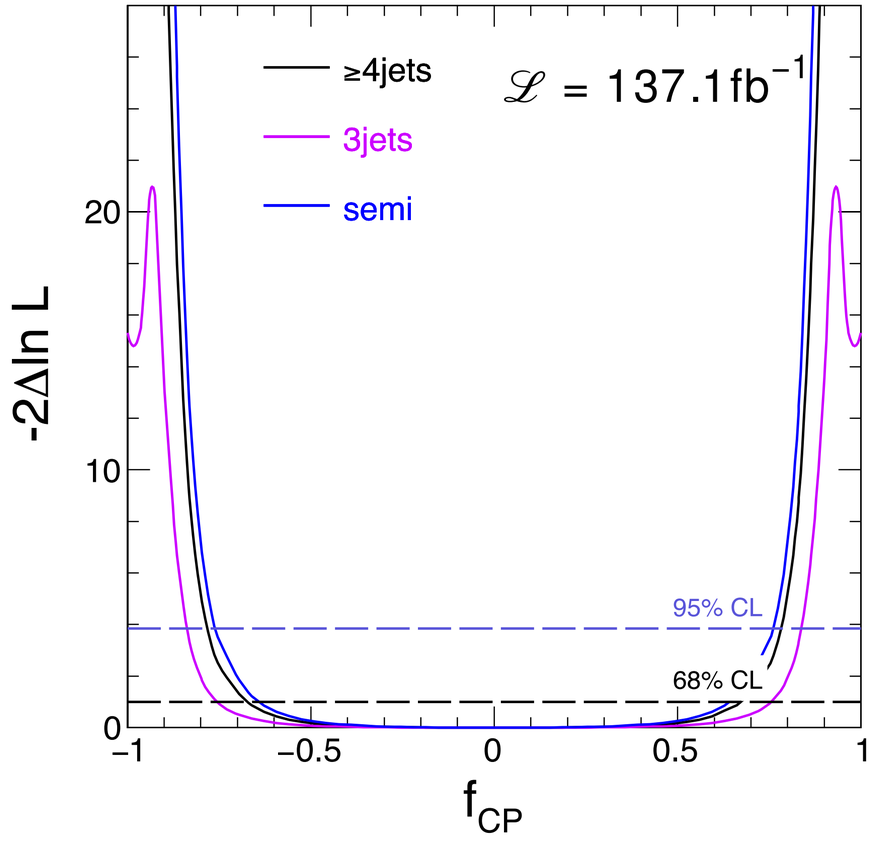




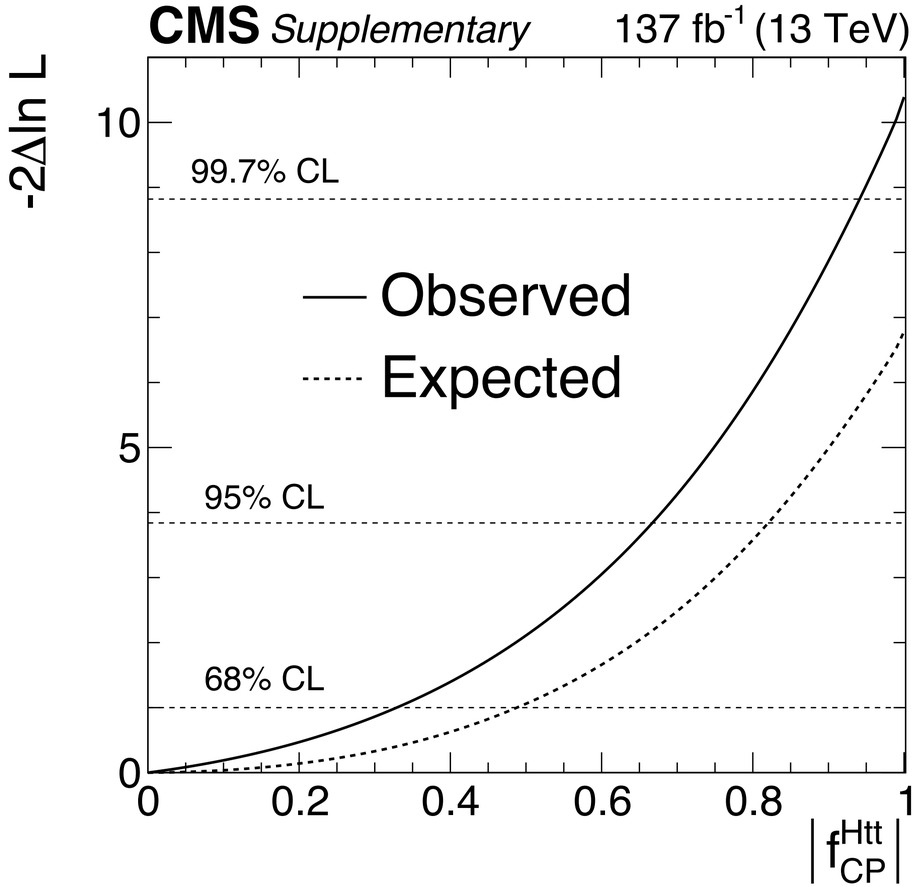




Compare with Previous Results

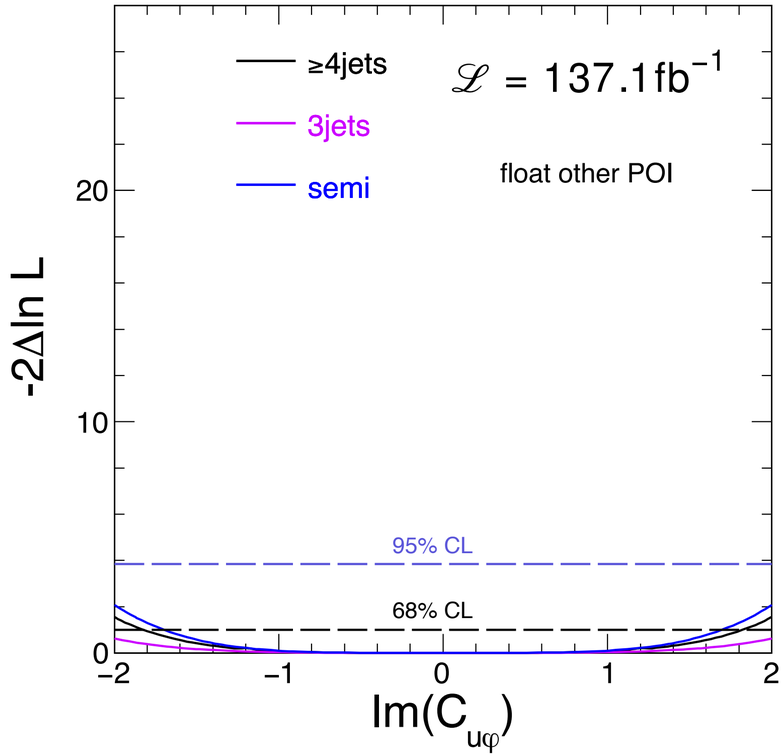


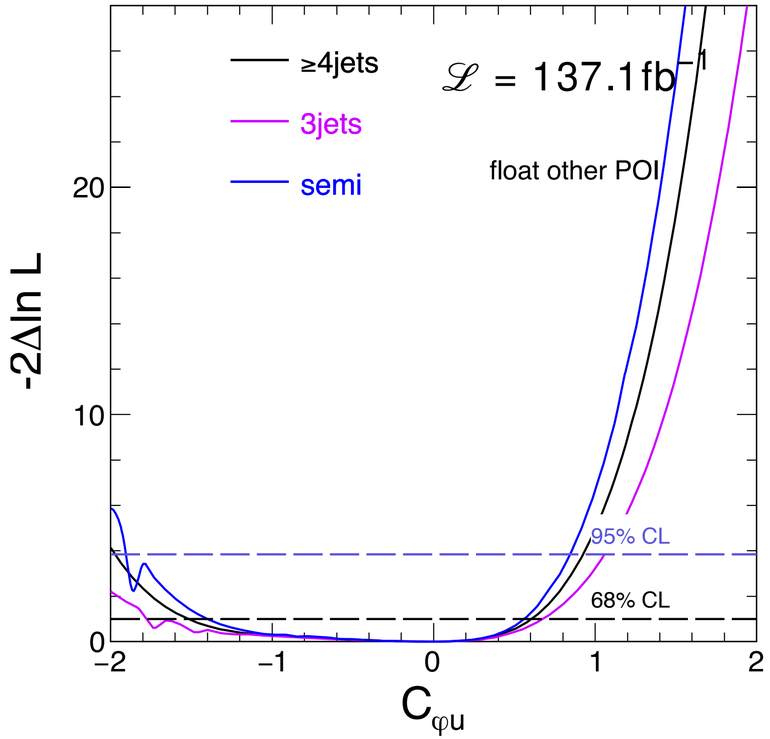
$t\bar{t}$ production

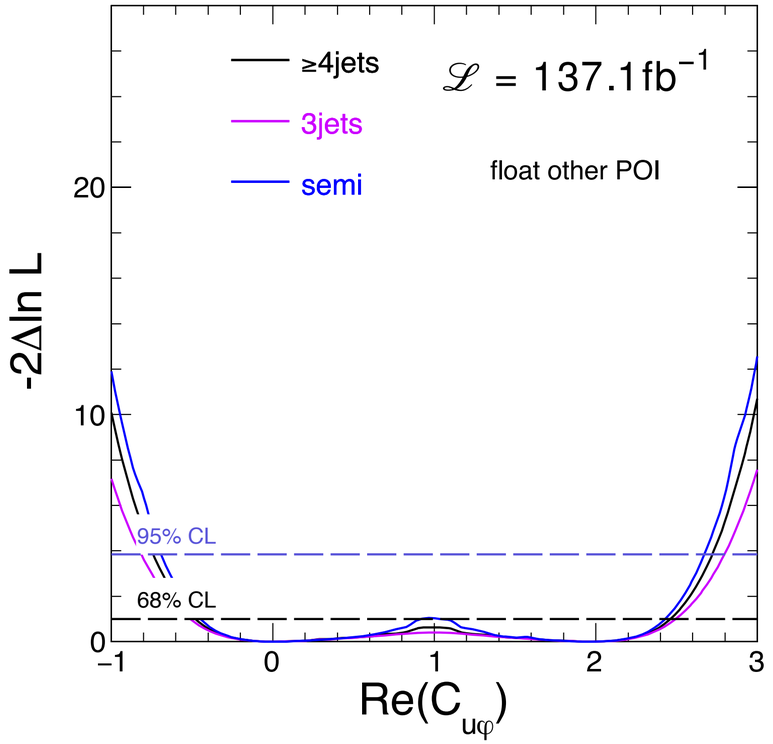


ttH production

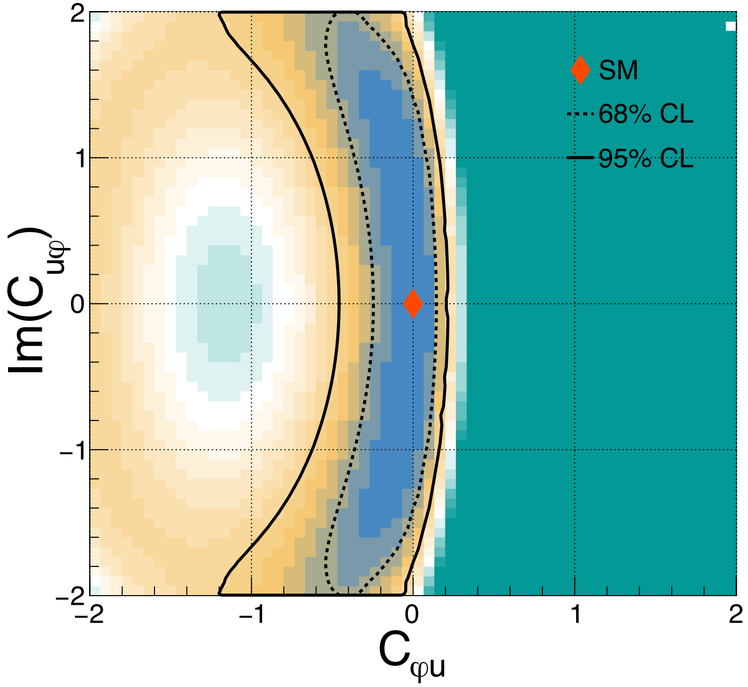
Likelihood 1D Scan with Other POI Floated

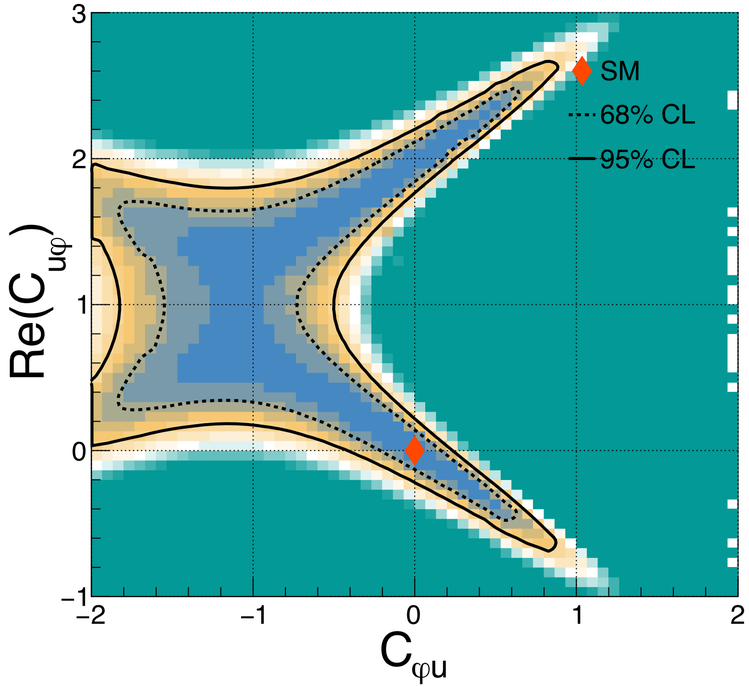


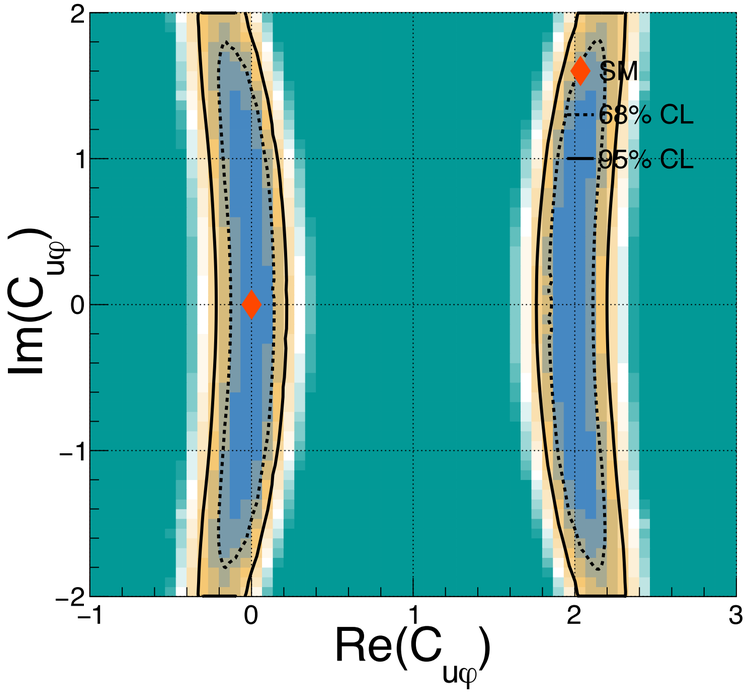




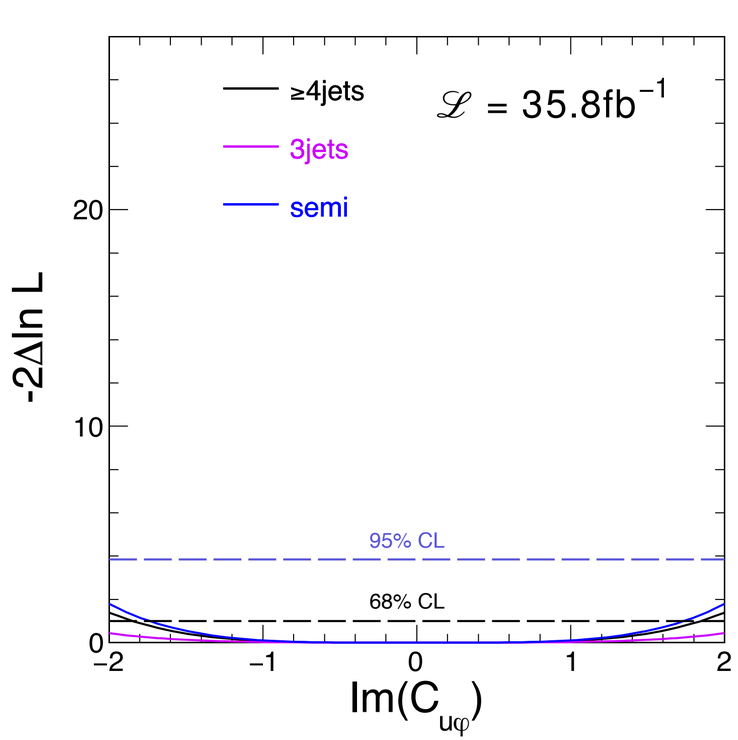
Likelihood 2D Scan with Other POI Fixed

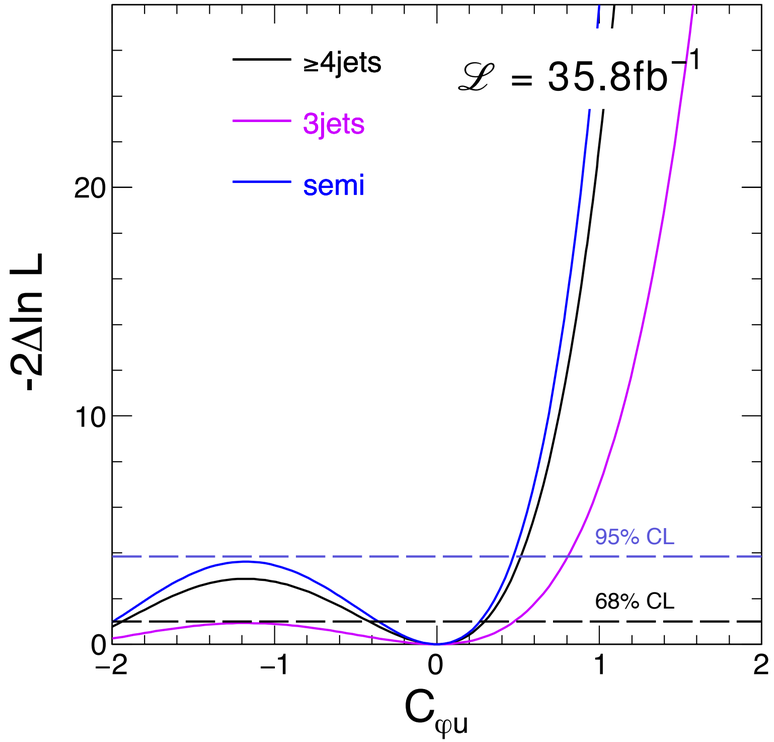


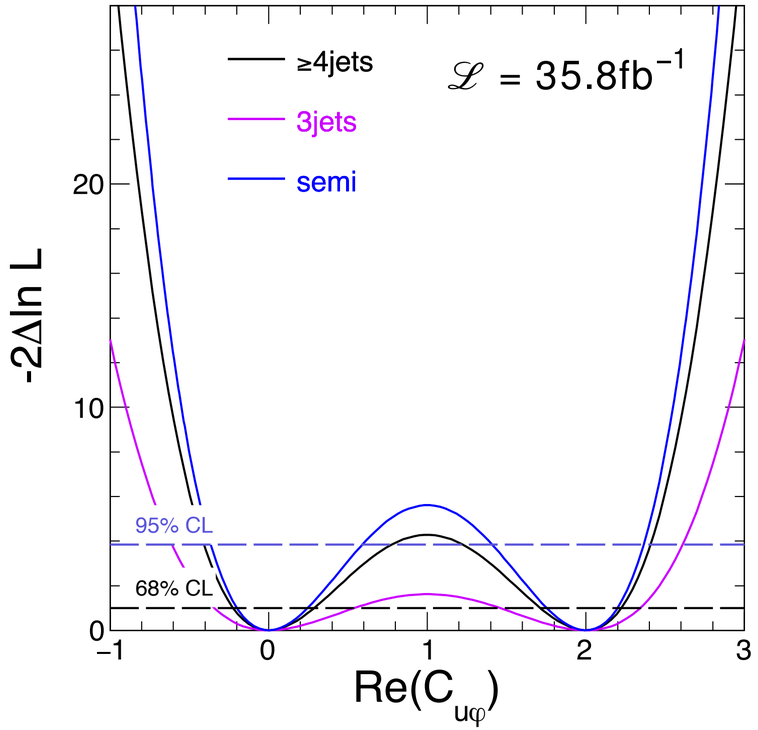




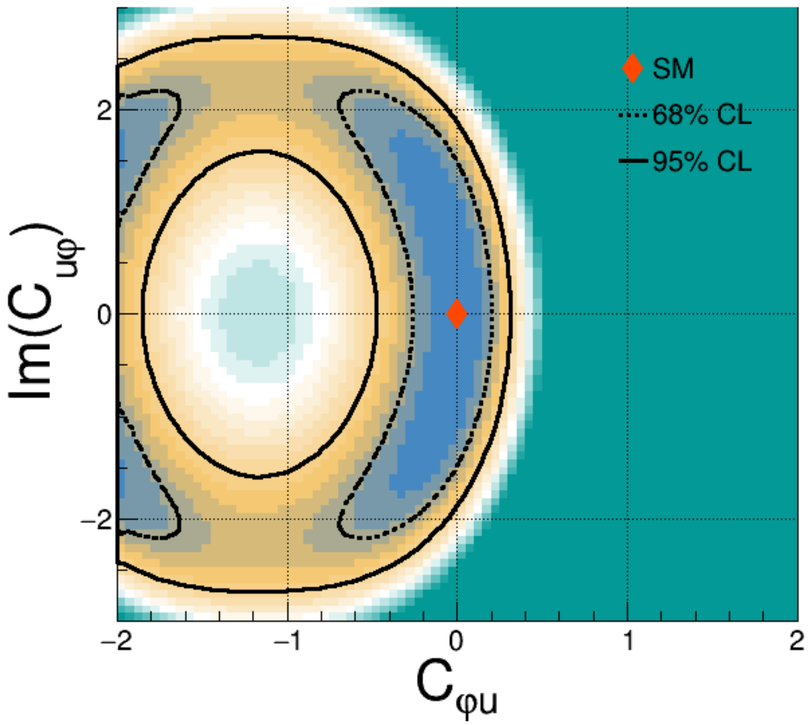
Likelihood 1D Scan with Other POI Fixed

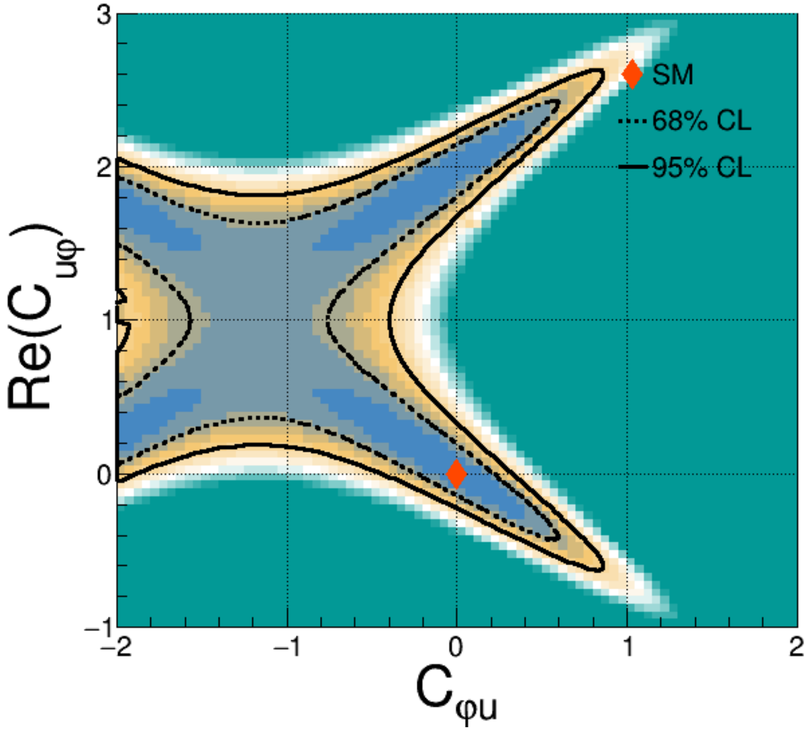


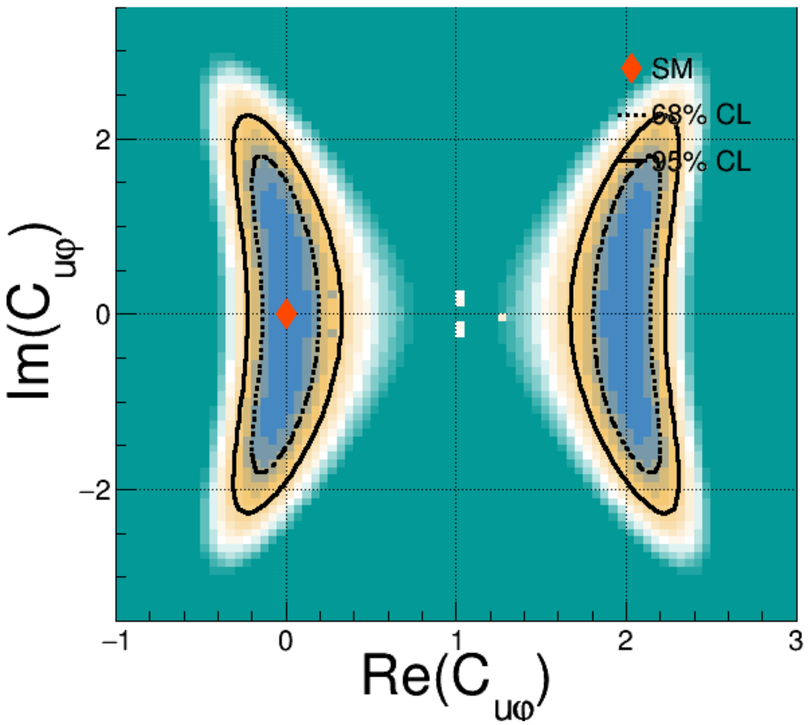




Likelihood 2D Scan with Other POI Fixed







Likelihood 2D Scan with Other POI Floated