Probing the CP structure of the top quark Yukawa coupling: Loop sensitivity vs. on-shell sensitivity

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Motivation

Why CP property matters?

- ✦ Baryon asymmetry of the universe requires CP violation
- ✦ CKM matrix is the only source of CP violation in SM , but can’t explain the baryon asymmetry
- ✦ Additional CP violation needed to explain baryon asymmetry
- ✦ CP violation might exist in Higgs sector in some new physics models: 2HDM, SUSY

Why Higgs-top interaction is interesting?

- ✦ Heaviest mass among fermions
- ✦ Interacts with the Higgs boson with the largest Yukawa coupling
- ✦ Lots of top quarks produced at LHC

Htt Effective Lagrangian

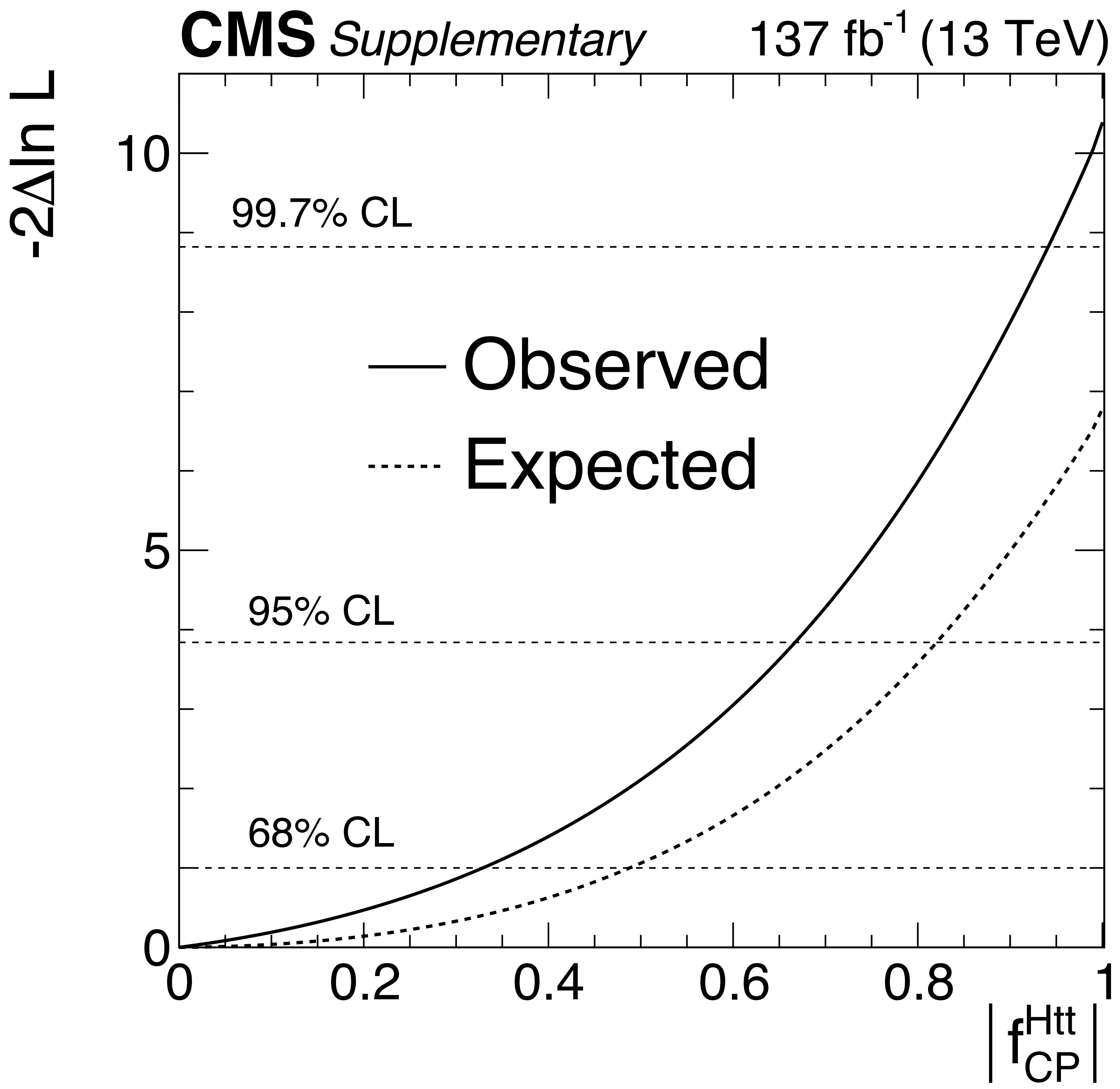
$$\mathscr{L}(Htt) = -\frac{m_t}{v}\bar{\psi}_t\left(\kappa + \mathrm{i}\tilde{\kappa}\gamma_5\right)\psi_t H$$

- 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
- $\kappa, \tilde{\kappa}$ correspond to $C_{33}^{u\varphi}$ in SMEFT:

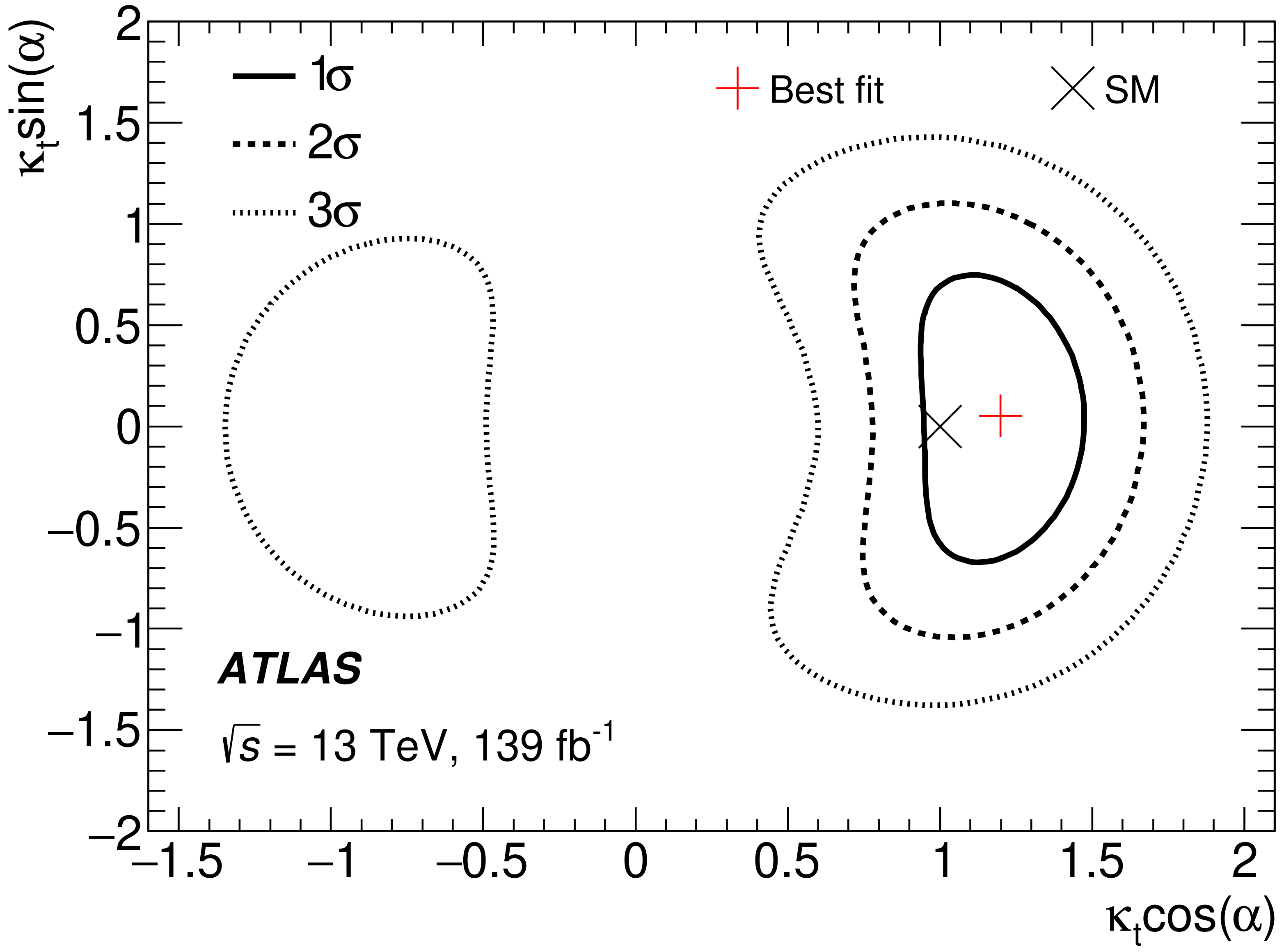
$$\kappa = 1 - \frac{v}{\sqrt{2}m_t}\frac{v^2}{\Lambda^2}\mathrm{Re}\left[C_{tt}^{u\varphi}\right], \tilde{\kappa} = -\frac{v}{\sqrt{2}m_t}\frac{v^2}{\Lambda^2}\mathrm{Im}\left[C_{tt}^{u\varphi}\right]$$

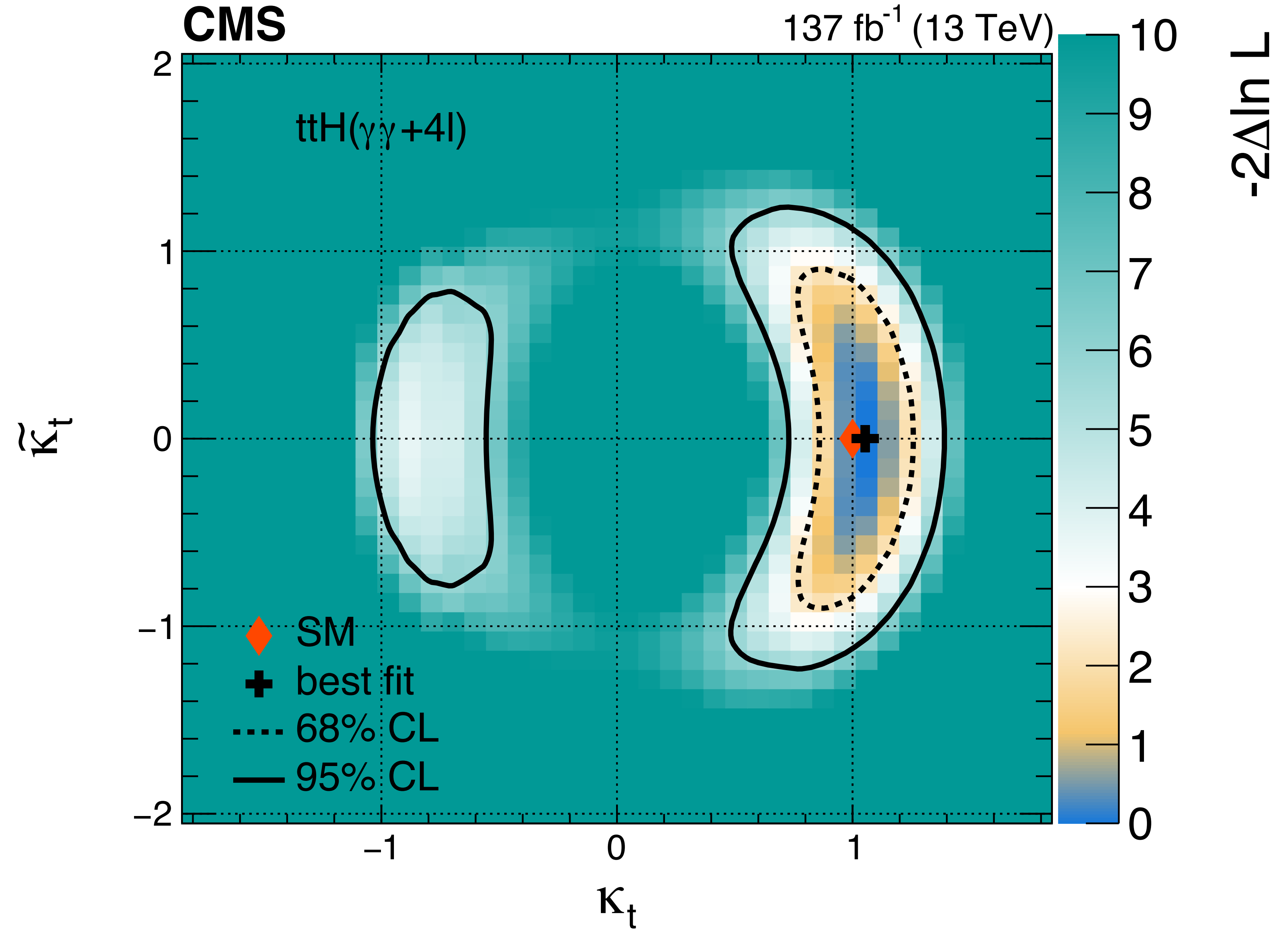
- In SMEFT Warsaw basis: $Q_{33}^{u\varphi} = \left(\varphi^\dagger\varphi\right)\left(\bar{q}'_{3L}t'_{\mathrm{R}}\tilde{\varphi}\right) \Leftrightarrow C_{33}^{u\varphi}$

Current Constraints from LHC



ttH+tHq+ggF: Phys. Rev. Lett. 125. 061802





ttH+tHq in 4 leptons and diphton: arXiv:2104.12152

ttH+tHq in diphoton: Phys. Rev. Lett. 125. 061801

- Fractional cross section of CP-odd component: $f_{CP} = \frac{|\tilde{\kappa}|^2}{|\kappa|^2 + |\tilde{\kappa}|^2} \text{sign}\left(\frac{\tilde{\kappa}}{\kappa}\right)$
- Pure CP-odd scenario is excluded at more than 3 σ
- Leaving large room of parameter space

$t\bar{t}$ And tHW Production

New approaches to access CP property:

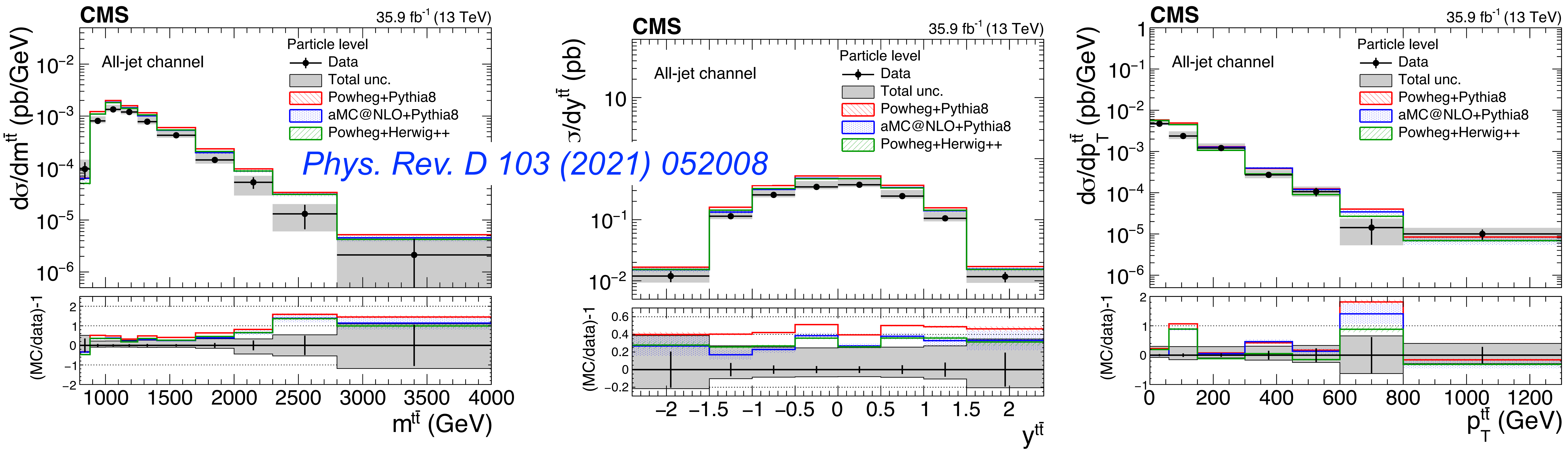
- $t\bar{t}$ production with electroweak loops
- tHW production

Top Quark Paris Production

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

- QCD calculation up to NNLO+NNLL: [Czakon,Fiedler,Heymes,Mitov],[Brucherseifer,Caola,Melnikov],[Berger,Gao,Yuan,Zhu], [Czakon,Mitov,Sterman],[Beneke,Czakon,Falgari,Mitov,Schwinn],[Beneke,Falgari,Klein,Schwinn],[Kidonakis], [Ferroglia,Pecjak,Yang],[Ferroglia,Marzani,Pecjak,Yang],[Czakon,Ferroglia,Heymes,Mitov,Pecjak,Scott]
- High ambitions of the theory community towards N3LO calculations: [Duhr, Mistlberger], [Piclum, Schwinn], [Duhr, Mistlberger]

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



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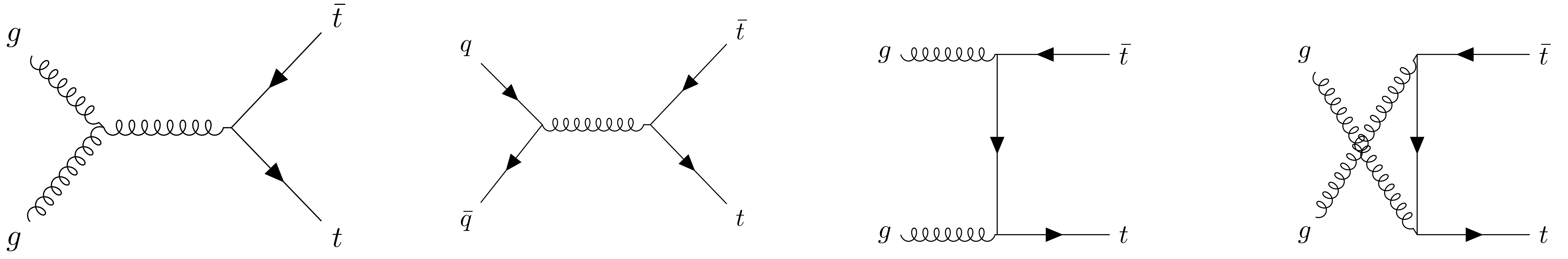
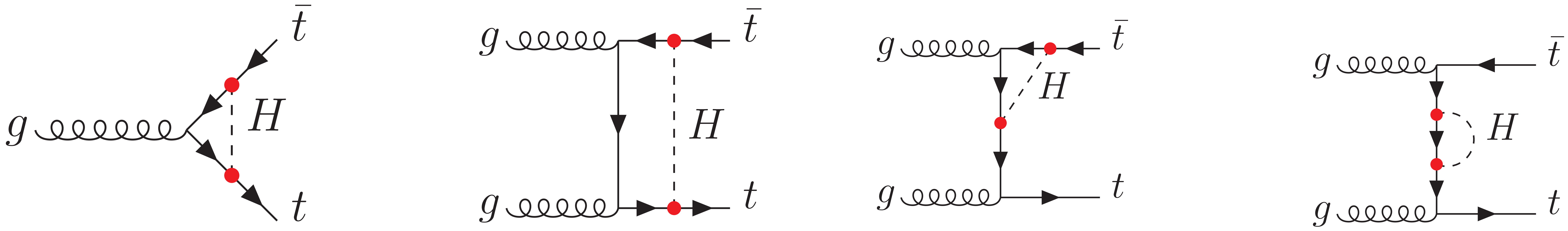
Top Quark Pairs Production



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

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

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



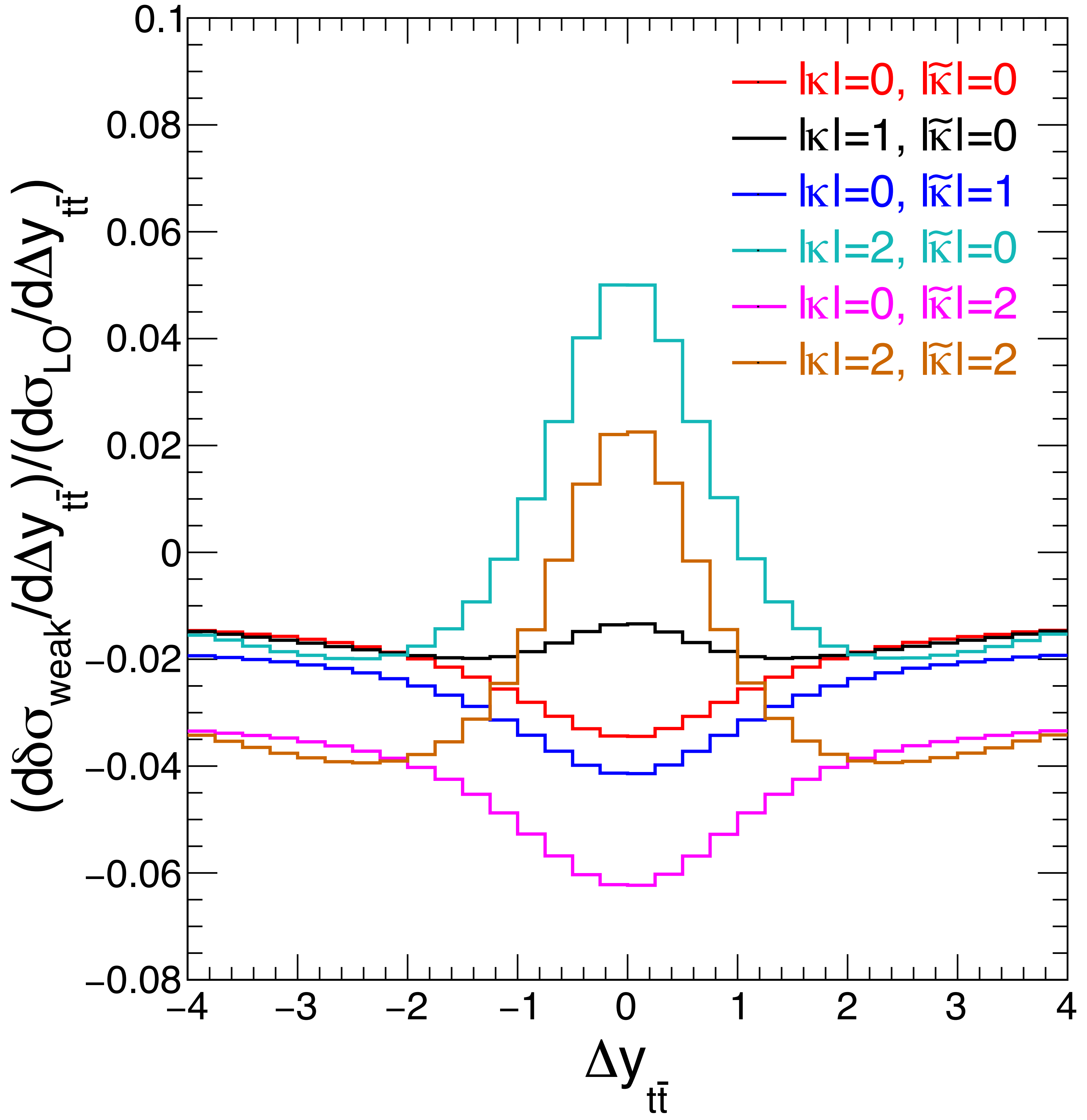
Typical Feynman diagrams of NLO EW Corrections

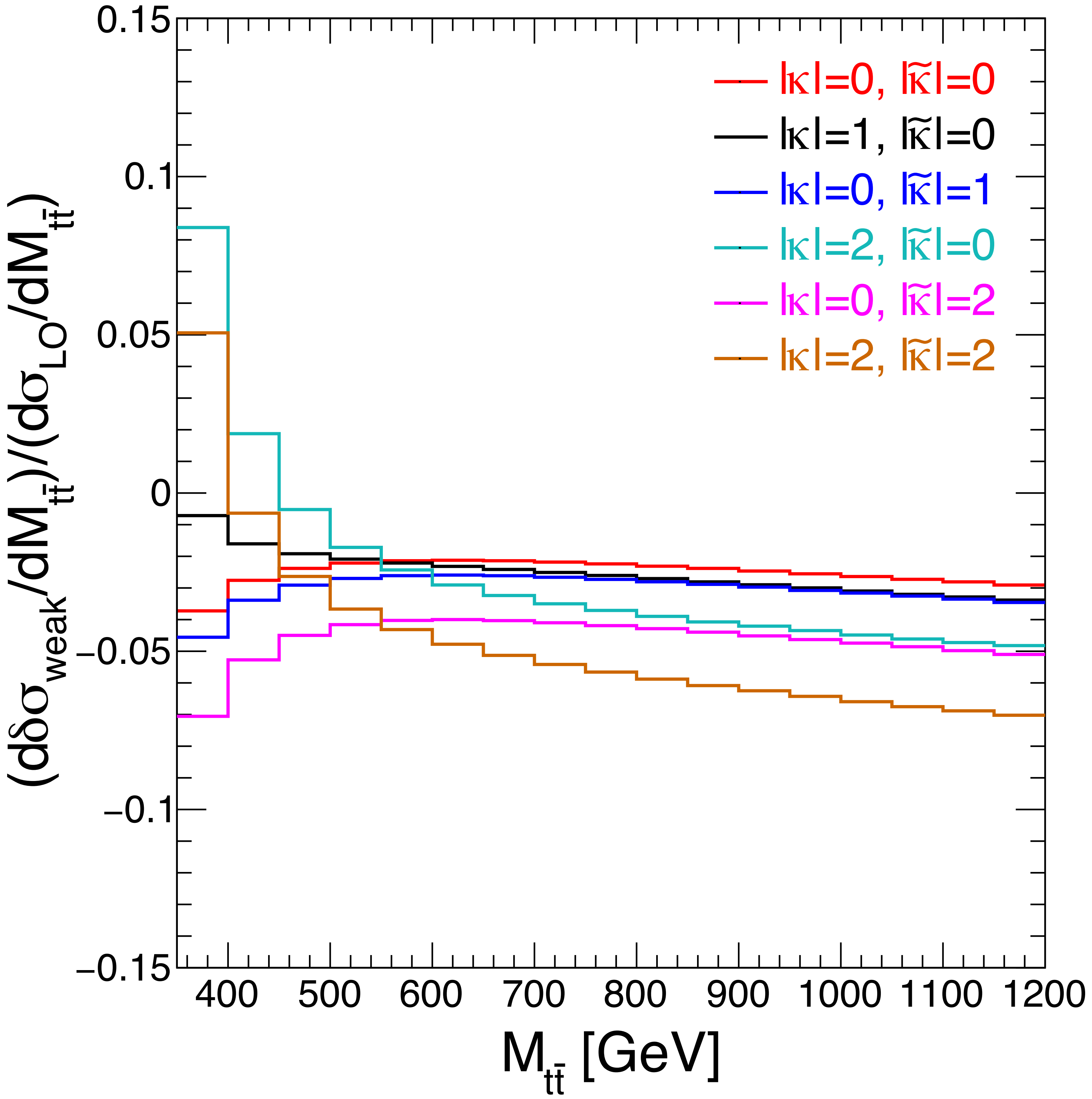
NLO EW Corrections

- Interference of diagrams with Higgs loops and Born level either $\propto \kappa^2$ or $\tilde{\kappa}^2$
- Loop diagrams involving the Higgs boson are IR finite but contain UV poles ; renormalization necessary within SMEFT
- One-loop amplitude is UV finite after renormalization
- EW correction factor: $\delta_{\rm wk} = \dfrac{d\sigma_{\rm wk}^{\rm NLO} - d\sigma^{\rm LO}}{d\sigma^{\rm LO}},$
- $\delta_{\rm wk}$ can be used to reweight distributions to include EW effects

Loop sensitivity on CP Property in $t\bar{t}$ production

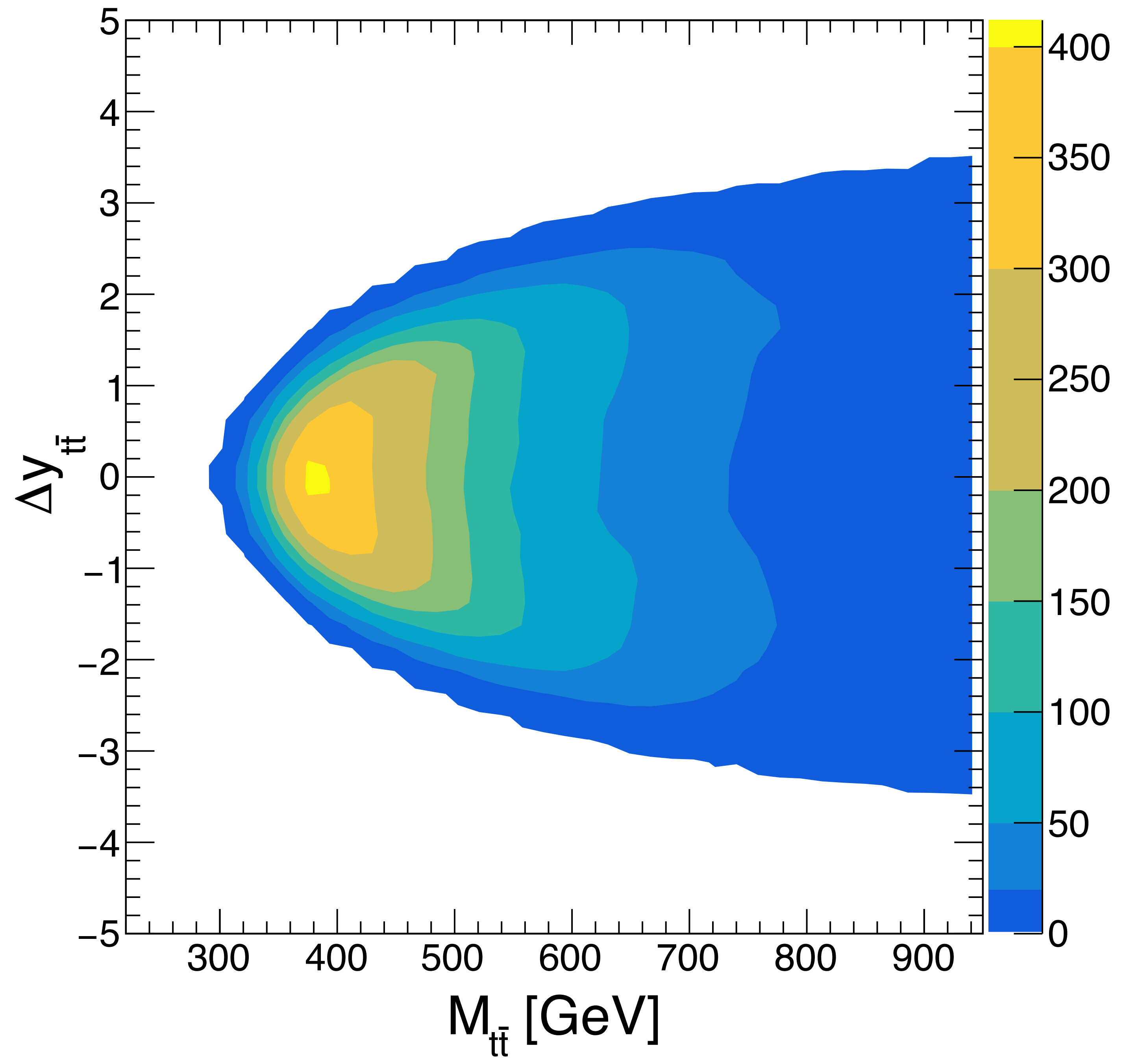
distributions of $\Delta y_{t\bar{t}}$ and $M_{t\bar{t}}$ sensitive to CP structure of top Yukawa coupling



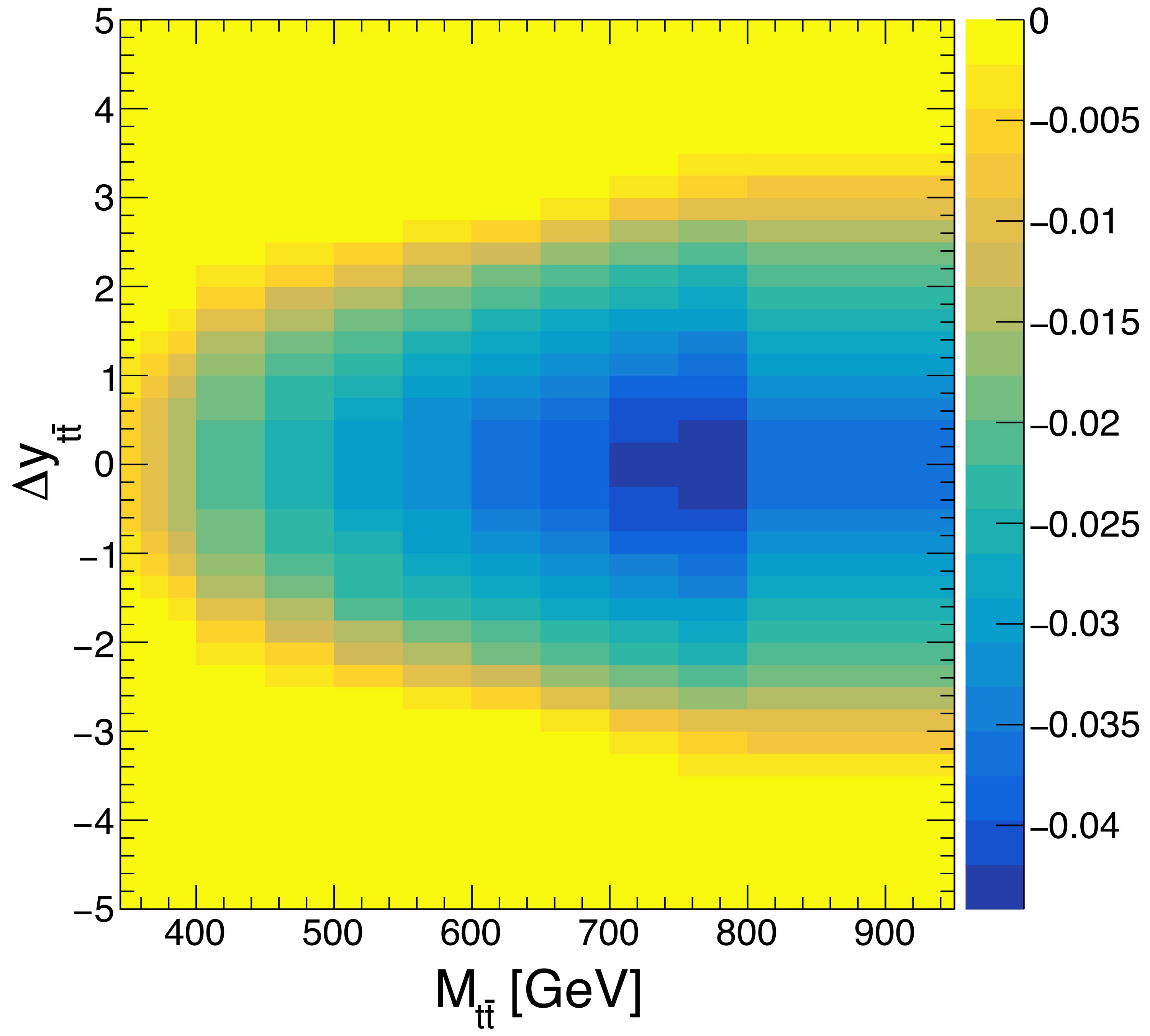


Loop sensitivity on CP Property in $t\bar{t}$ production

- **Extract CP structure in ($\Delta y_{t\bar{t}}$, $M_{t\bar{t}}$) 2-D distribution**
- **Events simulated at MadGraph and interfaced to Pythia8**
- **simulate detector effects through Delphes3**
- **NLO EW effects included through reweighting**
- **semileptonic channel; Main backgrounds: single top, V+jets, QCD multijets**

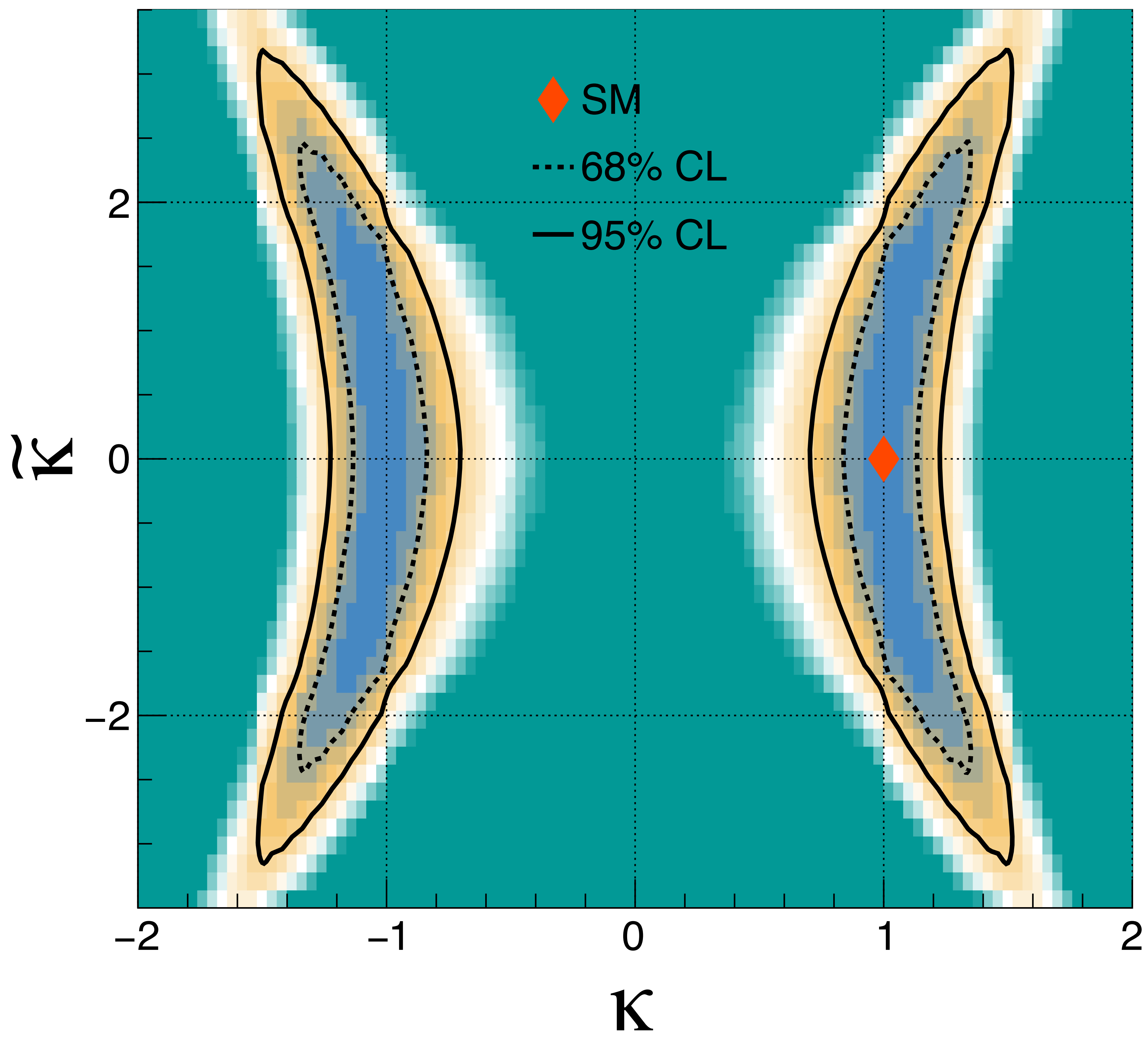


Distribution of reconstructed events



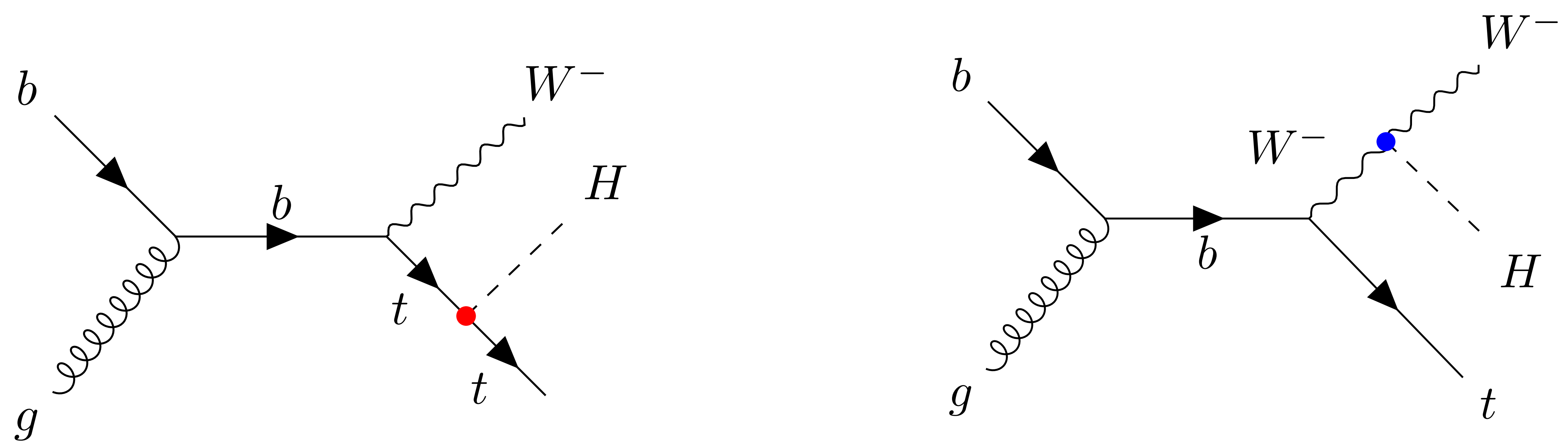
Relative EW corrections when $\kappa = 1$ and $\tilde{\kappa} = 0$

Sensitivity of $t\bar{t}$ Production



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

tHW Production



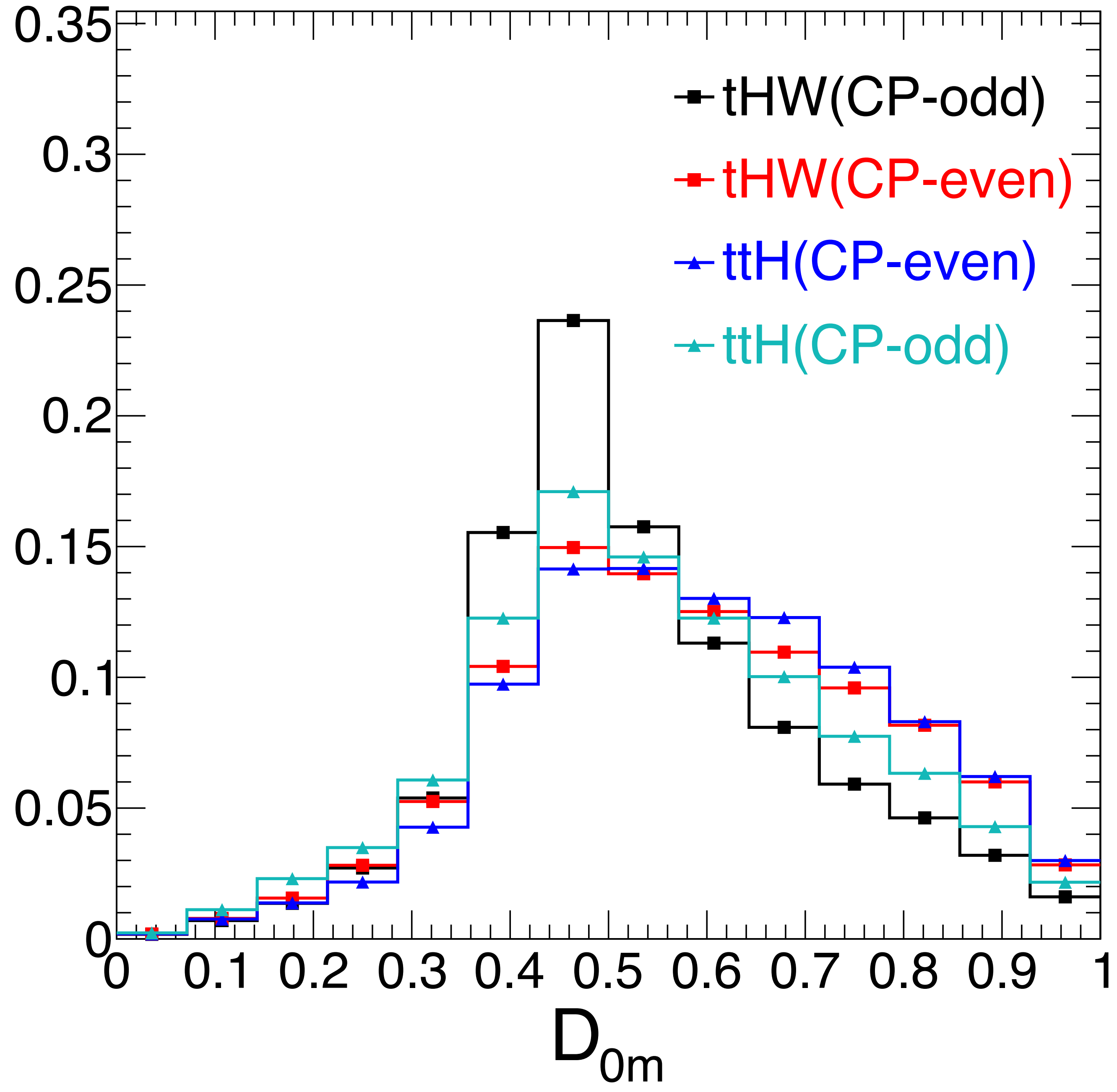
Two typical Feynman diagrams of the tHW

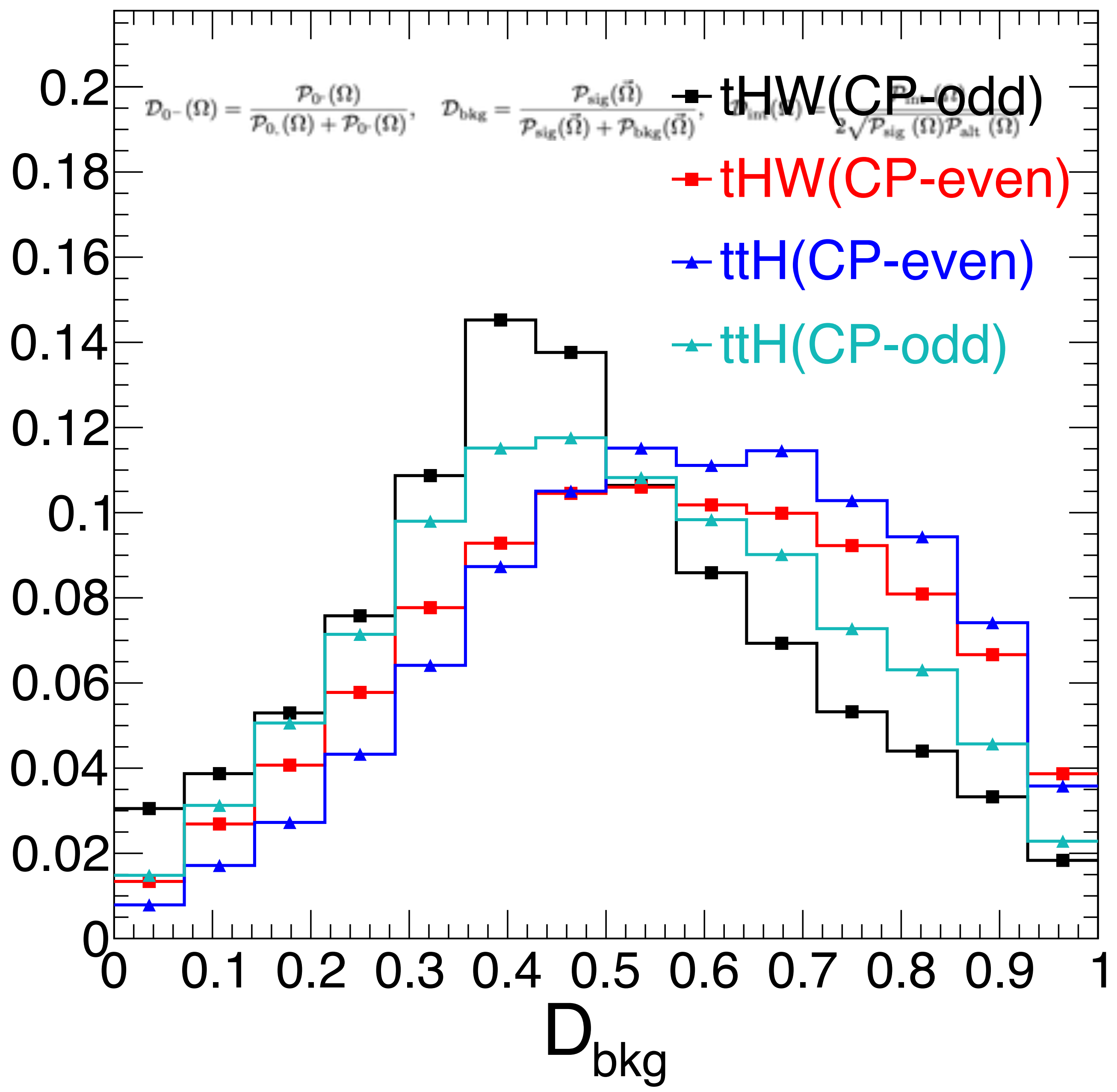
- **Htt induced diagram interferes with HWW induced diagram**
- **Destructive interference in the SM, leading to small cross section**
- **If the relative sign of Htt and HWW flips, cross section would increase obviously**
- $\sigma(\kappa, \tilde{\kappa})_{tHW} = \sigma_{SM}^{tHW}(2.82\,|\kappa|^2 + 2.08\,|\tilde{\kappa}|^2 - 3.87\kappa + 2.05)$
- **HWW coupling is set same as the value in the SM**

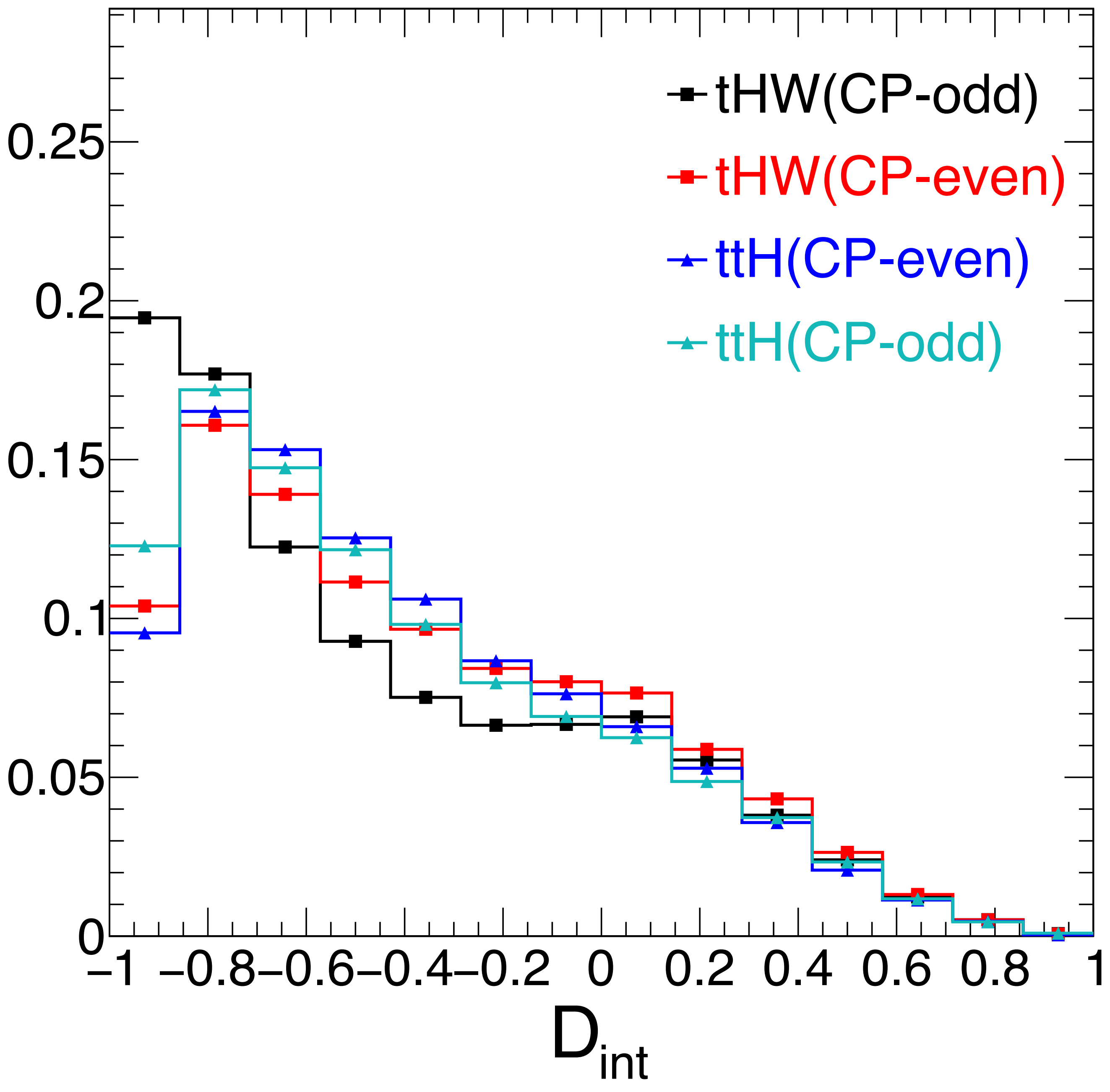
Matrix Element Approach

$$\mathcal{D}_{0-}(\Omega) = \frac{\mathcal{P}_{0^-}(\Omega)}{\mathcal{P}_{0^-}(\Omega) + \mathcal{P}_{0^+}(\Omega)}, \quad \mathcal{D}_{\mathrm{bkg}} = \frac{\mathcal{P}_{\mathrm{sig}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{sig}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{bkg}}(\vec{\Omega})}, \quad \mathcal{D}_{\mathrm{int}}(\Omega) = \frac{\mathcal{P}_{\mathrm{int}}(\Omega)}{2\sqrt{\mathcal{P}_{\mathrm{sig}}(\Omega)\mathcal{P}_{\mathrm{alt}}(\Omega)}}$$

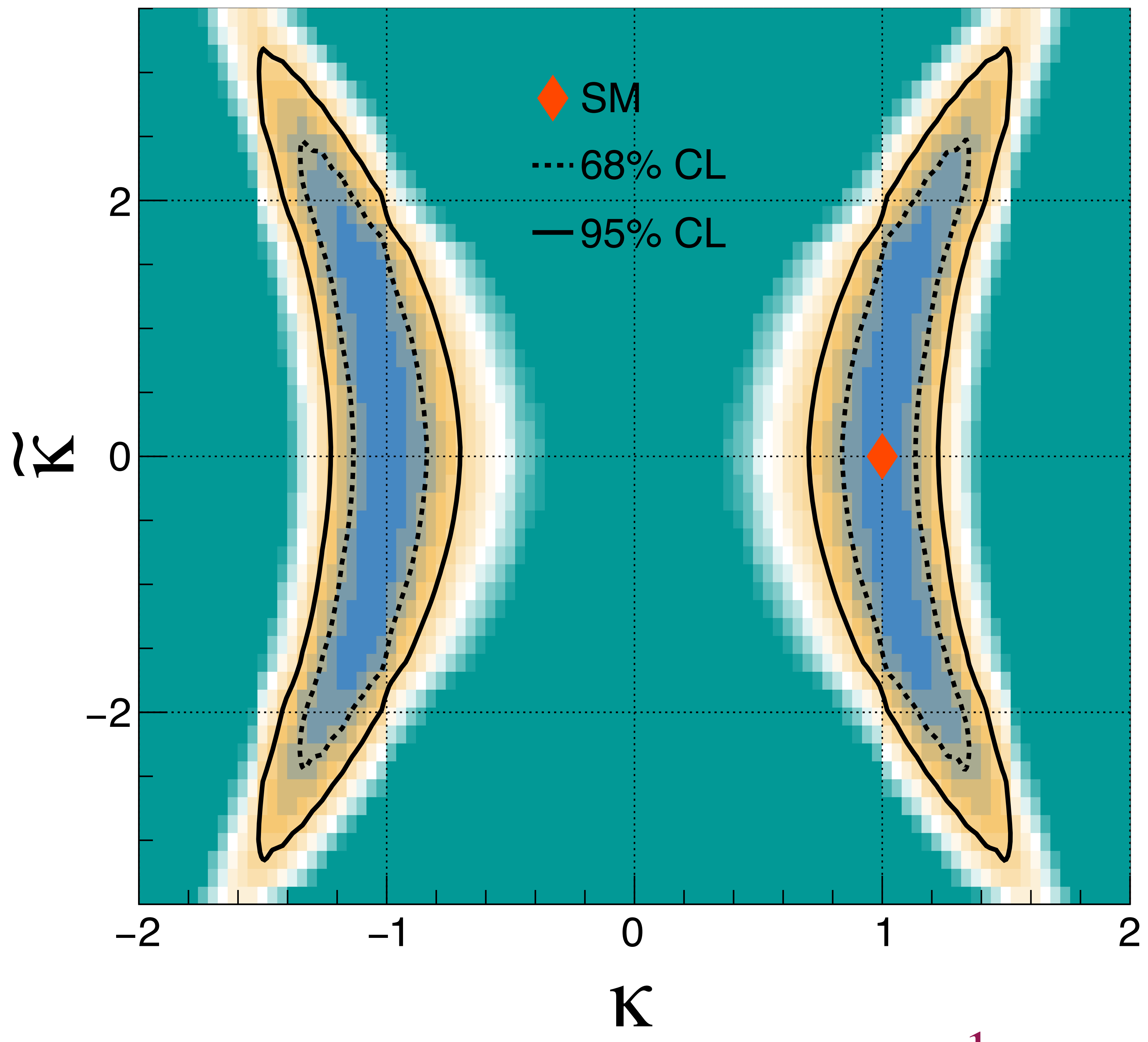
- $\mathscr{D}_{0-}(\Omega)$: distinguish CP-odd from CP-even
- $\mathscr{D}_{bkg}(\Omega)$: separate Htt contribution from HWW
- $\mathscr{D}_{int}(\Omega)$: sensitive to interference term



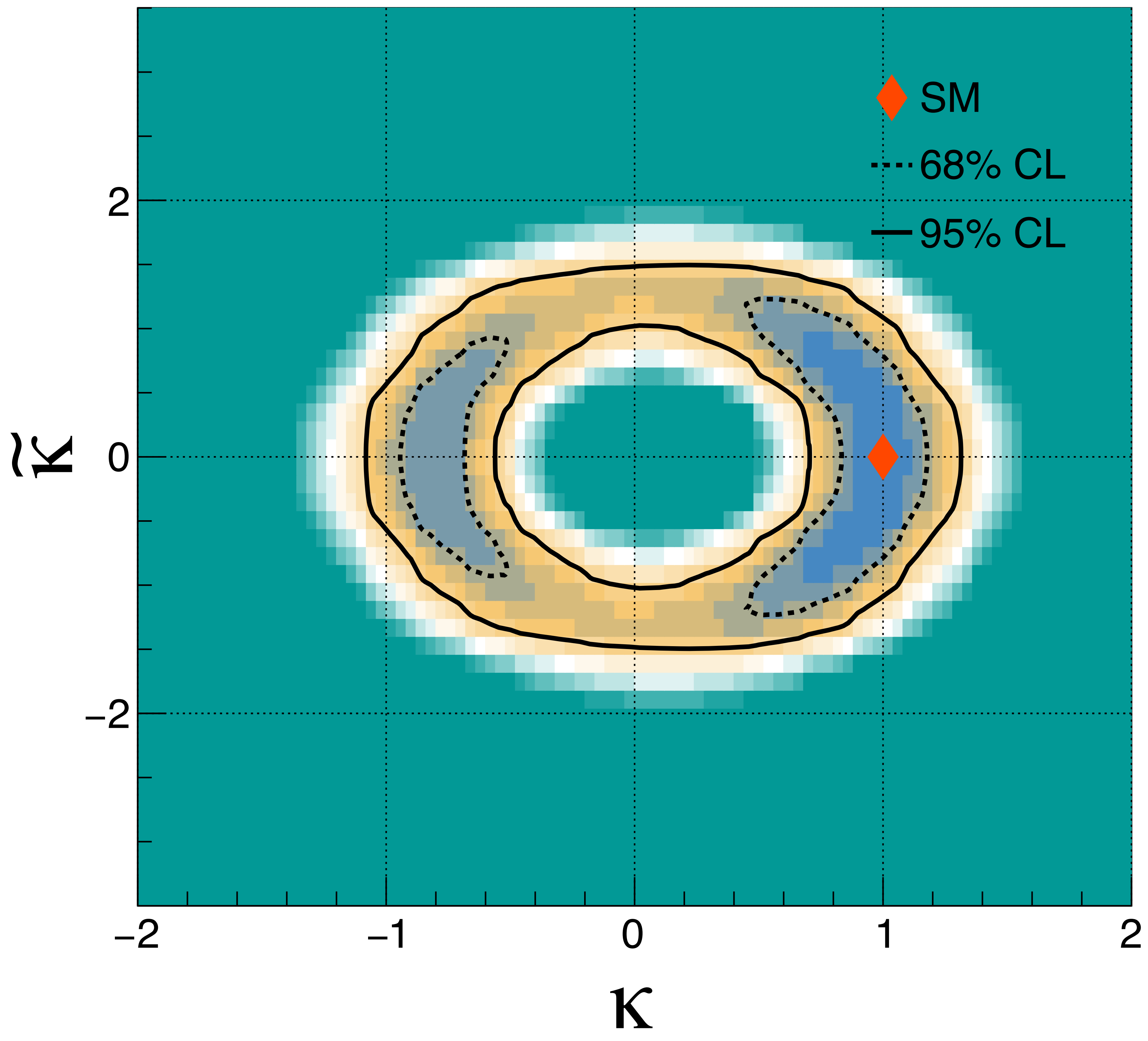




Results: 2D Likelihood Scan of κ and $\tilde{\kappa}$



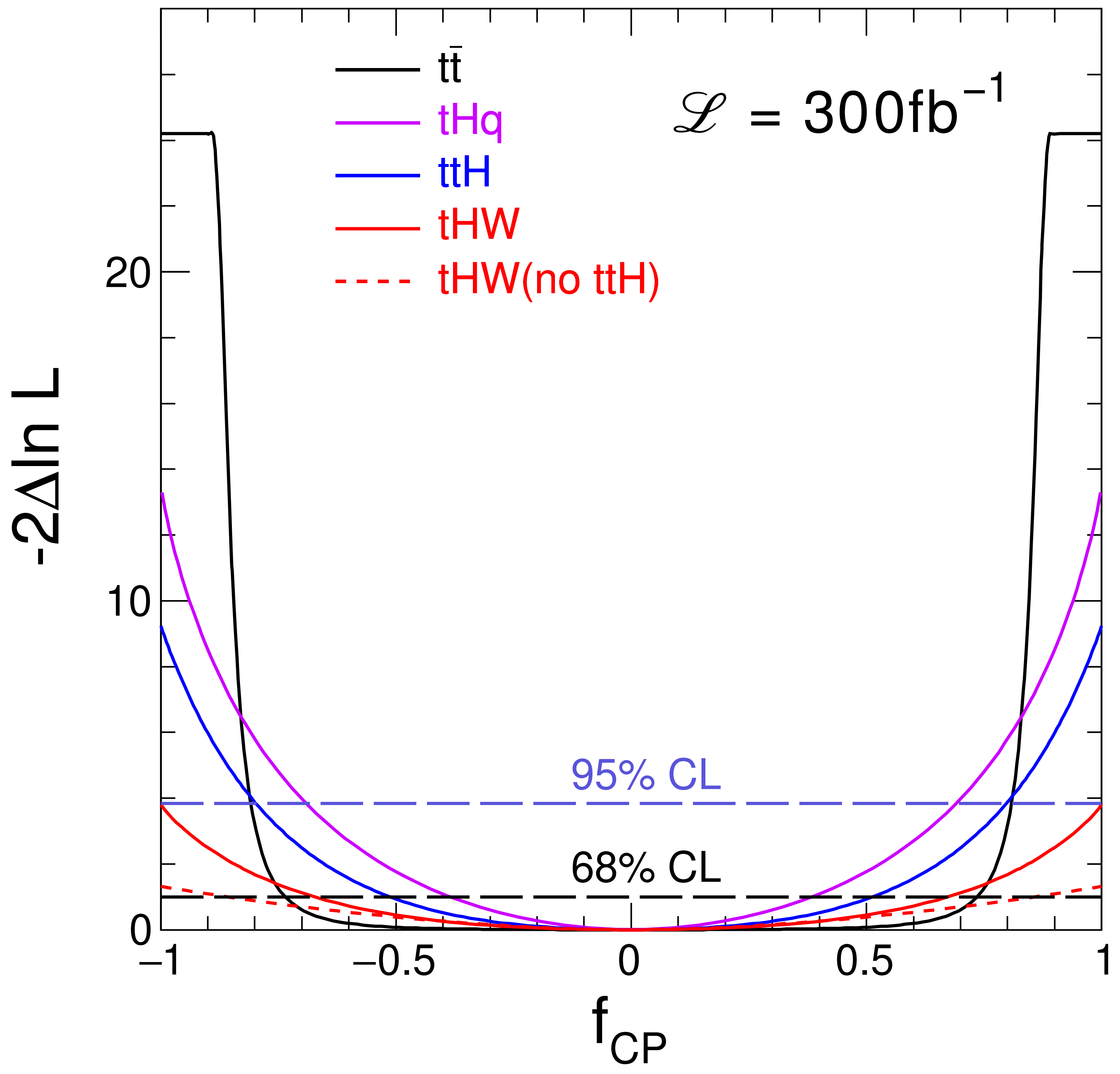
$t\bar{t}$ production at 300 fb^{-1}

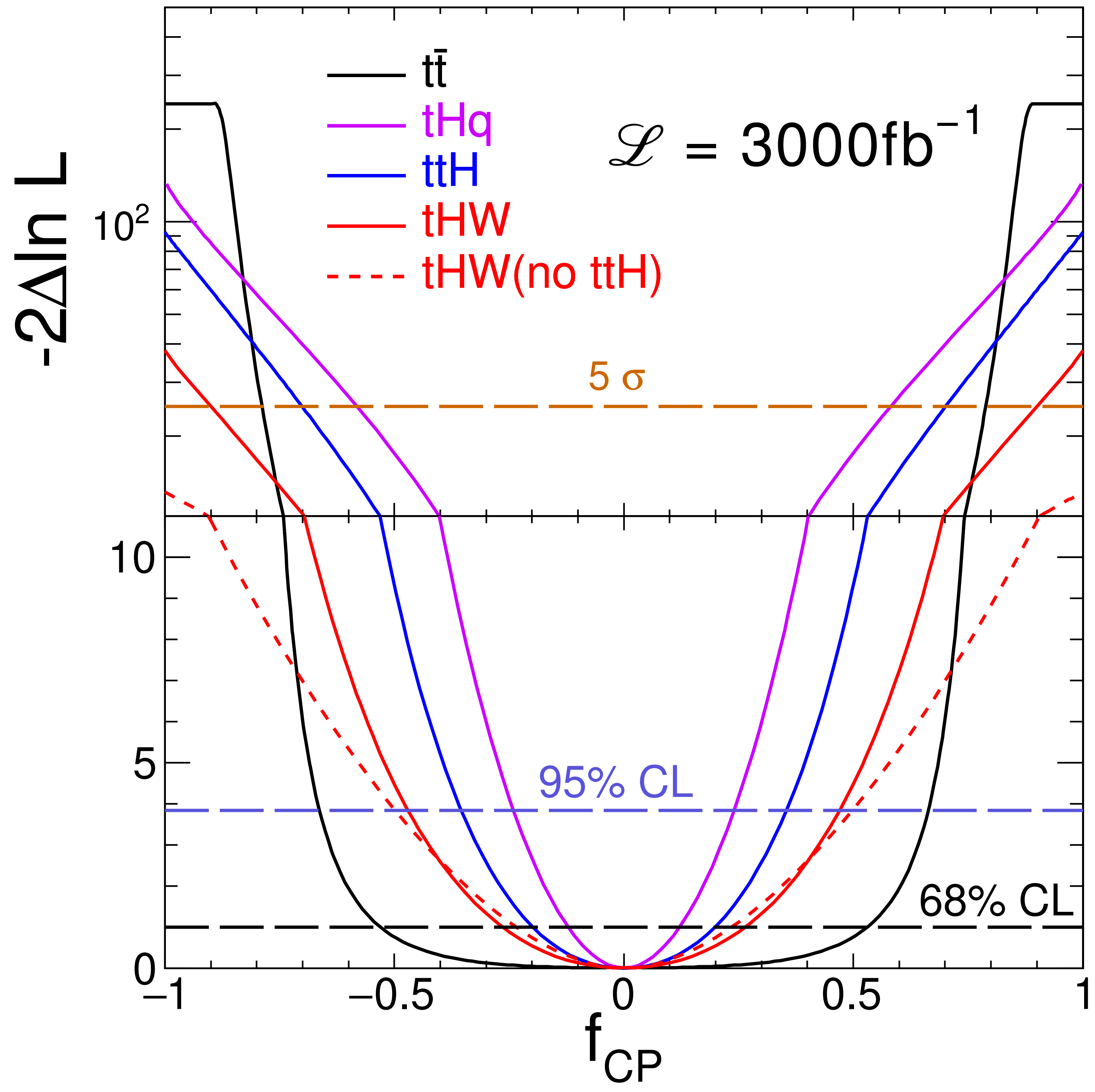


tHW production at 300 fb^{-1}

Results: Likelihood Scan of f_{CP}

Fractional contribution of CP-odd component: $f_{CP} = \dfrac{|\tilde{\kappa}|^2}{|\kappa|^2 + |\tilde{\kappa}|^2}\,\mathrm{sign}\left(\dfrac{\tilde{\kappa}}{\kappa}\right)$





ttH and tHq results cited from [arXiv: 1606.03107]

Summary

- Probing CP structure of top Yukawa coupling through EW loops in $t\bar{t}$ production
- Analyze tHW production using matrix element approach
- Compare constraints on CP structure from EW loops in $t\bar{t}$ production with on-shell Higgs production(ttH, tHq, tHW)
- Loop sensitivity in $t\bar{t}$ production and on-shell sensitivity in ttH and tH provide complementary handles over a wide range of parameter space