Probing top quark electroweak couplings at the LHC

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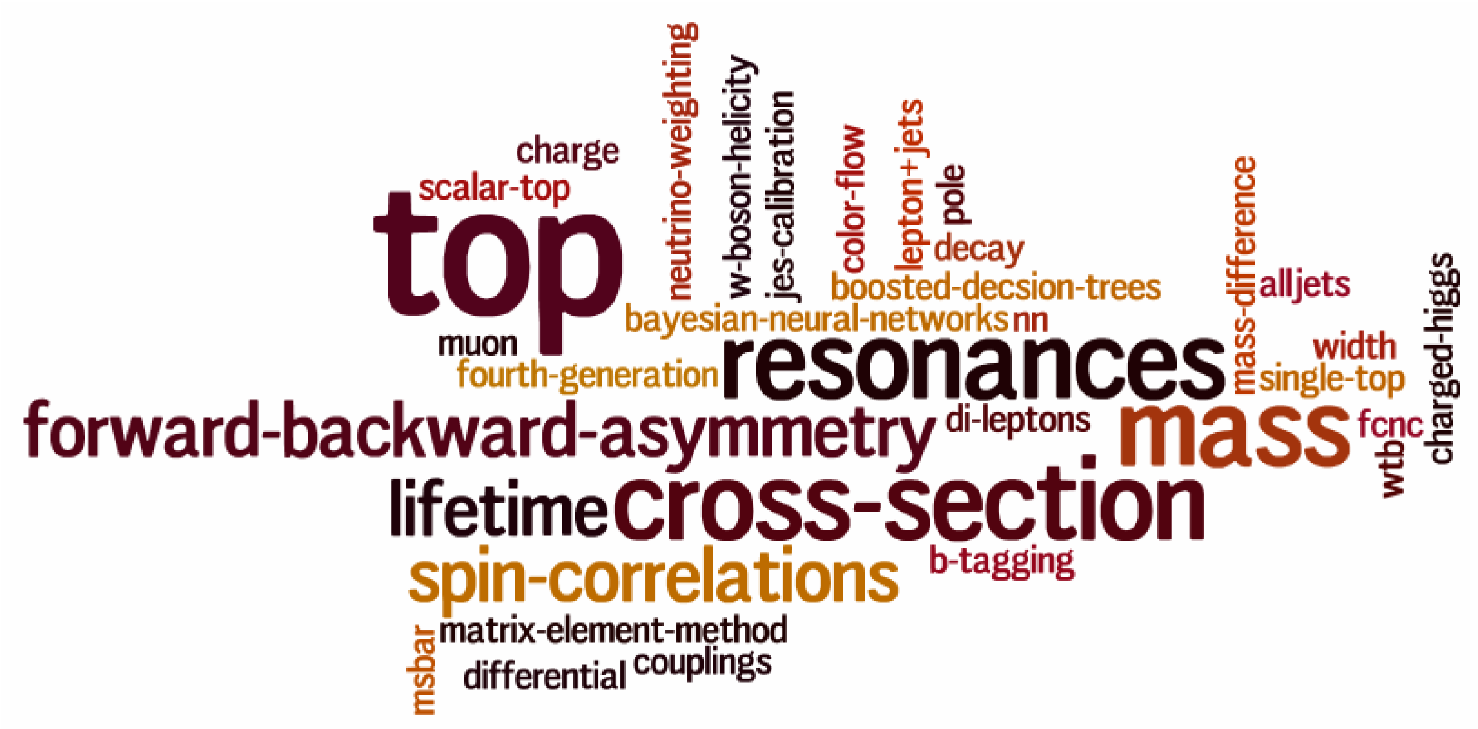

- Our understanding of the top quark as an elementary particle is very solid
- Basic properties were explored at the Tevatron
- Electroweak couplings are relatively unexplored in collider experiments

- P.Uwer (ICHEP'14): *„The time for predicted discoveries might be over for a while. We need to turn every stone and look below."*

Electroweak top quark couplings

We want to study *ttb*+electroweak gauge bosons

$$t\bar{t}+\gamma \qquad t\bar{t}+H$$

$$t\bar{t}+Z \qquad t\bar{t}+W^{\pm}$$

additional sensitivity: single top, top decay dynamics

Our framework:

NLO QCD corrections in top production and decay.

Top quarks treated in narrow width approximation.

Features:

- NLO spin correlations
- Any top quark decay channel at NLO
- Photon radiation off top decay products

Electroweak top quark couplings

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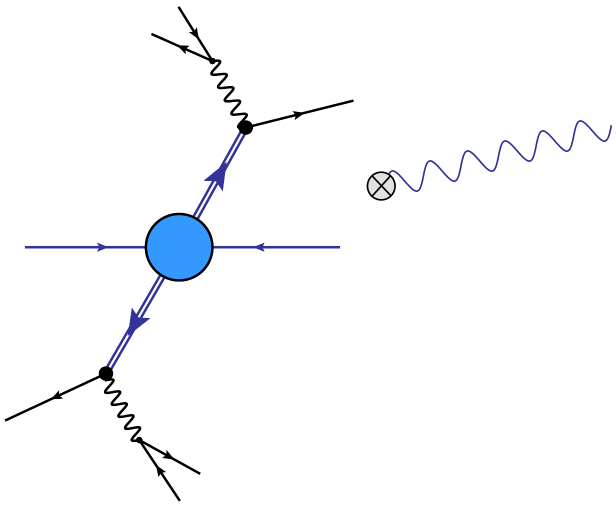
Neglect:

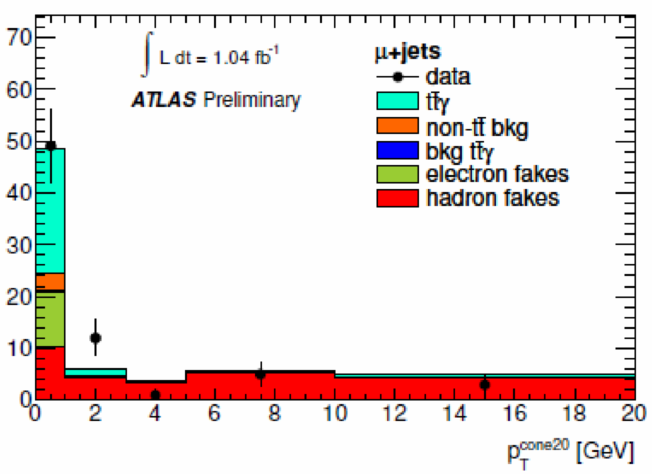
- Parton Showering (taken care of by NLO decay)
- Threshold corrections (expected to be small beyond NLO; Phasespace ~ $\boldsymbol{\beta}^4$)
- Top off-shell effects (parametrically small ~ Γ/m, explicitely verified in *ttbar*)

$$t\bar{t} + \gamma$$

ttbar + photon



- Directly sensitive to top quark electric charge
- At LHC *gg* dominated (small ISR contamination)
- Has FB asymmetry already at LO
- Serves as control sample for *ttb+H*



[Aguilar-Saavedra]

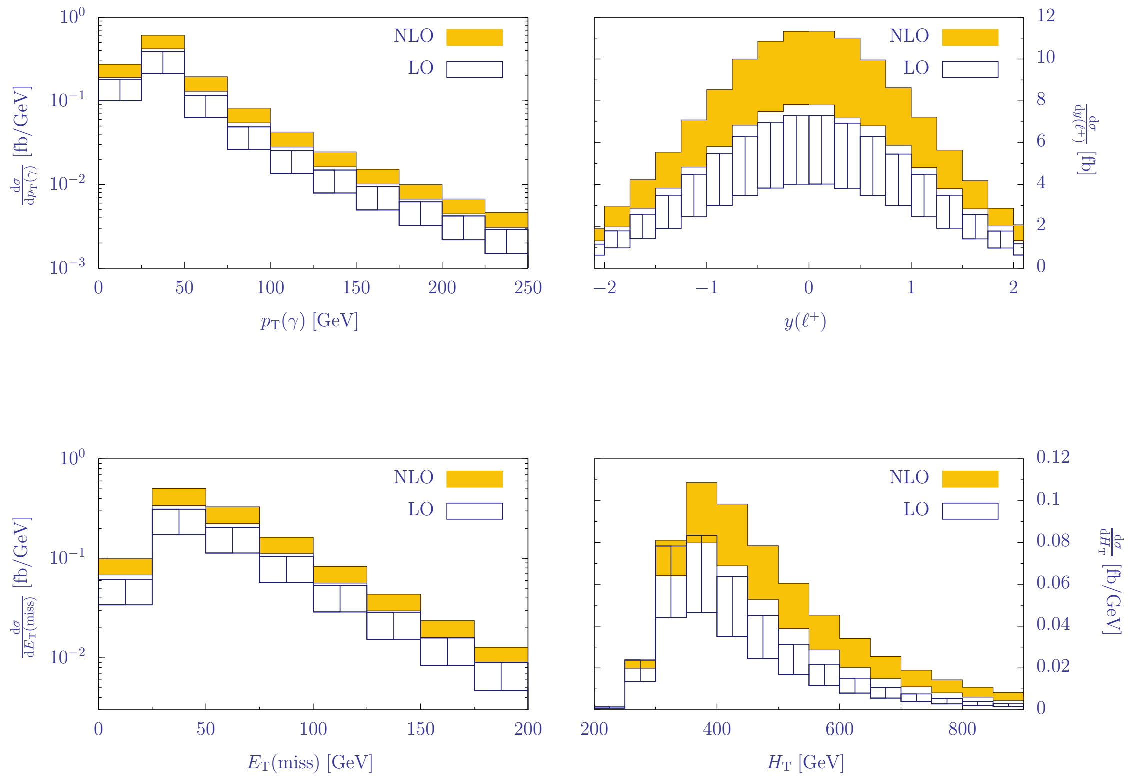
$$\mathcal{L}_{\gamma tt} = -eQ_t \bar{t}\,\gamma^\mu t\; A_\mu - e\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\,(d_V^\gamma + i d_A^\gamma \gamma_5)\,t\; A_\mu\,.$$

$$\delta d_V^\gamma = \frac{\sqrt{2}}{e}\,\mathrm{Re}\,\left[c_W C_{uB\phi}^{33} + s_W C_{uW}^{33}\right]\frac{v m_t}{\Lambda^2}\,,$$

$$\delta d_A^\gamma = \frac{\sqrt{2}}{e}\,\mathrm{Im}\,\left[c_W C_{uB\phi}^{33} + s_W C_{uW}^{33}\right]\frac{v m_t}{\Lambda^2}\,.$$

ttbar + photon

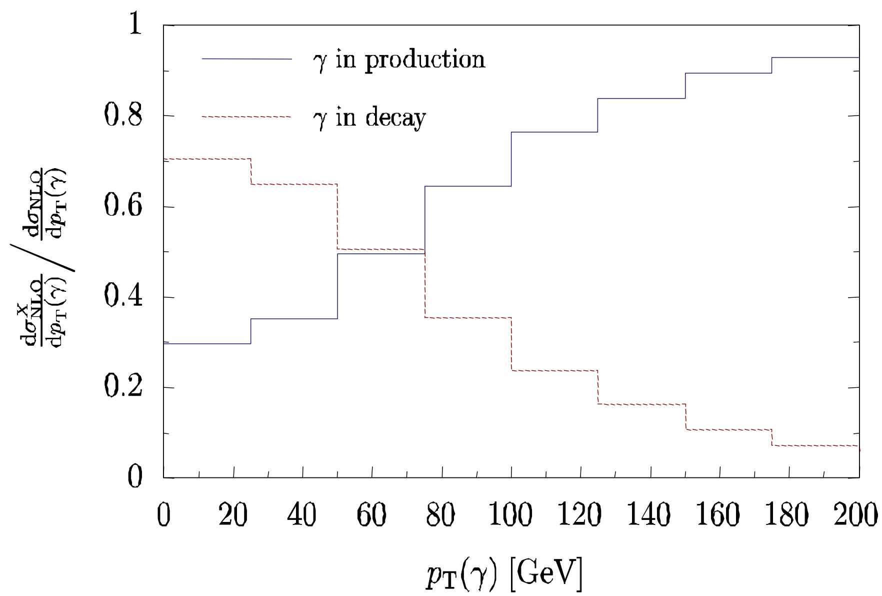
$$pp(7\text{TeV}) \to t\bar{t} + \gamma \to b\bar{b}\ \ell\nu\ jj + \gamma$$



$$\sigma^{\text{LO}}_{t\bar{t}\gamma} = 15.6 \pm 4.6 \text{ fb} \qquad \sigma^{\text{NLO}}_{t\bar{t}\gamma} = 26.8 \pm 5.0 \text{ fb}$$

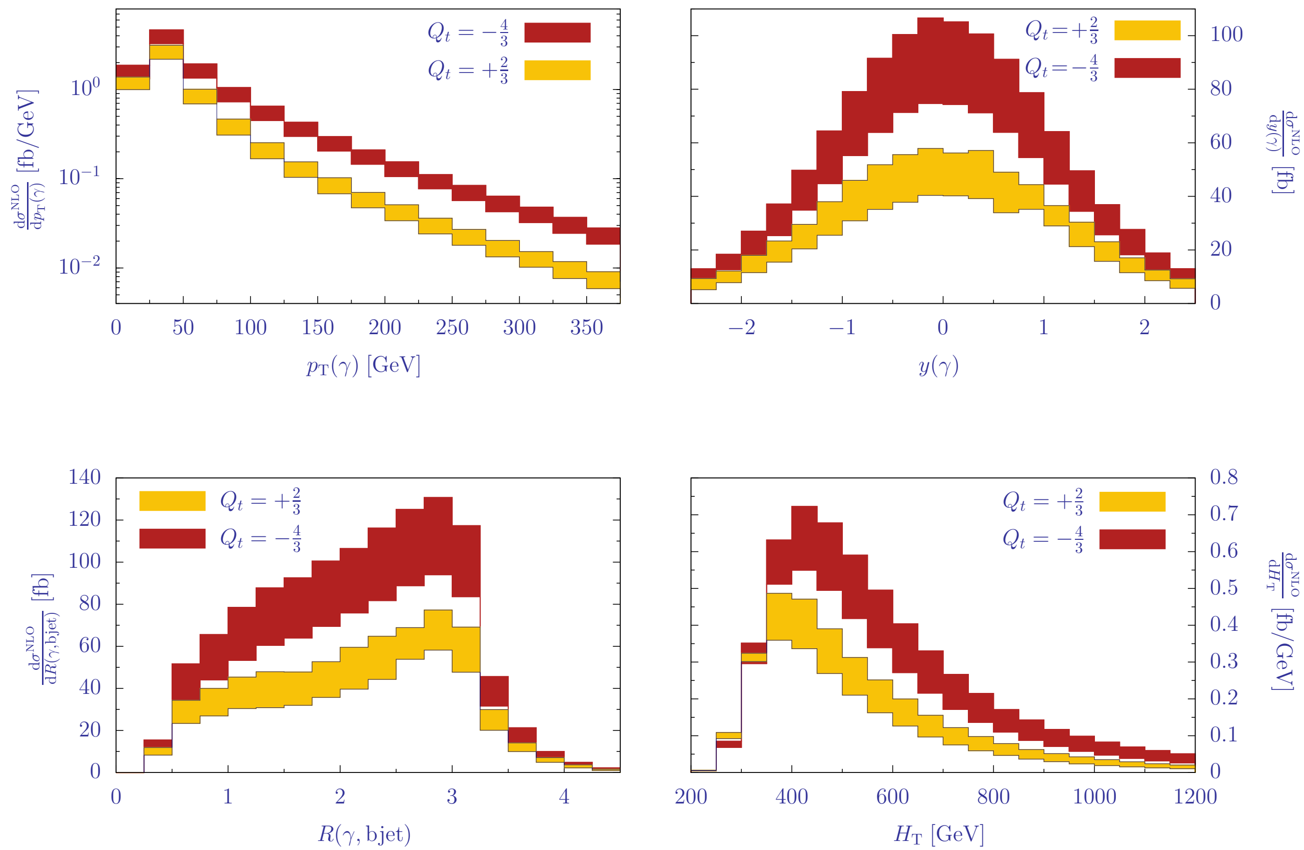
[Melnikov,Scharf,M.S]

ttbar + photon



Most of the photons with $p_T^{\gamma} < 50$ GeV are radiated in the top quark decay.

ttbar + photon

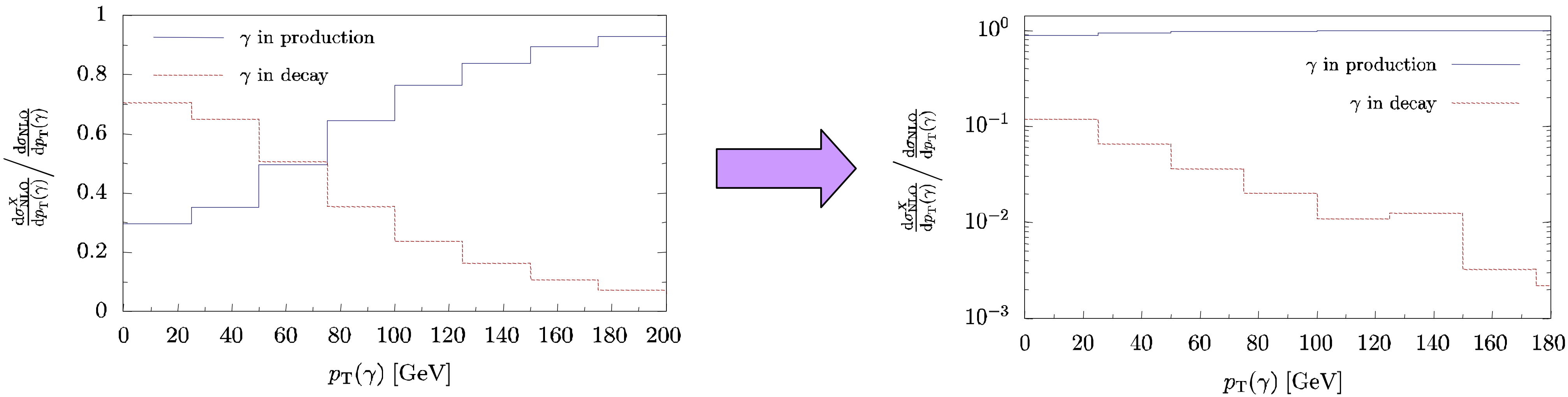


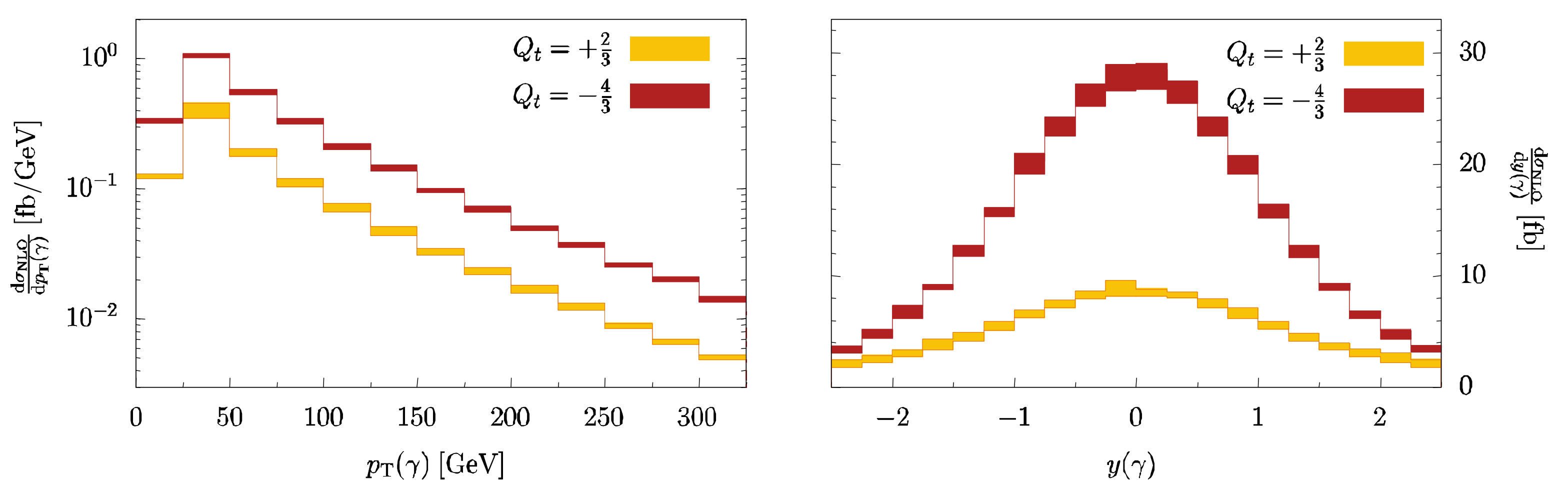
$$\sigma^{\rm NLO}_{t\bar{t}\gamma} = 138 \text{ fb} \xrightarrow{Q_t = \frac{2}{3} \to -\frac{4}{3}} \sigma^{\rm NLO}_{t\bar{t}\gamma} = 243 \text{ fb}$$

Naive expectation of Q_t^2 scaling fails.

ttbar + photon

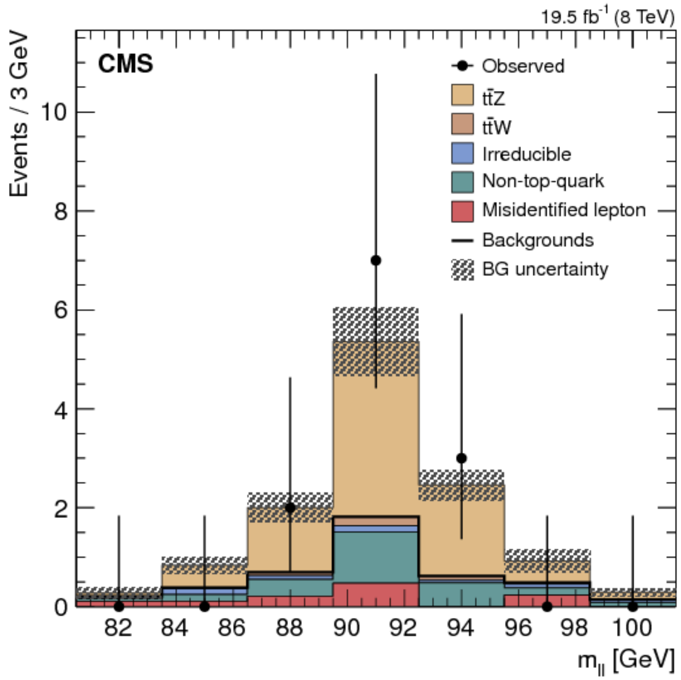
$$m_{\mathrm{T}}(b\ell\gamma; E_{\mathrm{T}}^{\mathrm{miss}}) > 180\ \mathrm{GeV}, \qquad m_{\mathrm{T}}(\ell\gamma; E_{\mathrm{T}}^{\mathrm{miss}}) > 90\ \mathrm{GeV},$$
$$160\,\mathrm{GeV} < m(bjj) < 180\ \mathrm{GeV},\ 70\,\mathrm{GeV} < m(j,j) < 90\ \mathrm{GeV}$$





$$t\bar{t} + Z$$

ttbar + Z



- Direct probe of *ttb-Z* interactions
- At LHC, *gg* dominated, $Z \to ll$ has small background
- Never observed at the Tevatron

$$\mathcal{L}_{t\bar{t}Z} = \mathrm{i}e\bar{u}(p_t)\left[\gamma^\mu\left(C_{1,V} + \gamma_5 C_{1,A}\right) + \frac{\mathrm{i}\sigma_{\mu\nu}q_\nu}{M_Z}\left(C_{2,V} + \mathrm{i}\gamma_5 C_{2,A}\right)\right]v(p_{\bar{t}})Z_\mu,$$

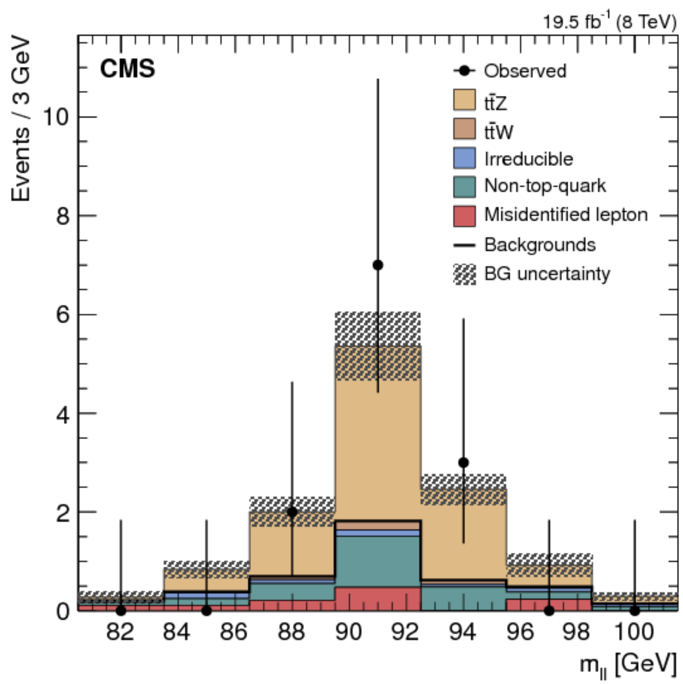
$$C_{\mathrm{V}}^{\mathrm{SM}} = \frac{T_t^3 - 2Q_t\sin^2\theta_w}{2\sin\theta_w\cos\theta_w},$$

$$C_{\mathrm{A}}^{\mathrm{SM}} = \frac{-T_t^3}{2\sin\theta_w\cos\theta_w},$$

$$C_{1,\mathrm{V}} = C_{1,\mathrm{V}}^{\mathrm{SM}}$$

$$C_{1,\mathrm{A}} = C_{1,\mathrm{A}}^{\mathrm{SM}}$$

ttbar + Z



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$$C_{1,\mathrm{V}} = C_{1,\mathrm{V}}^{\mathrm{SM}} + \Delta C_{1,V}$$

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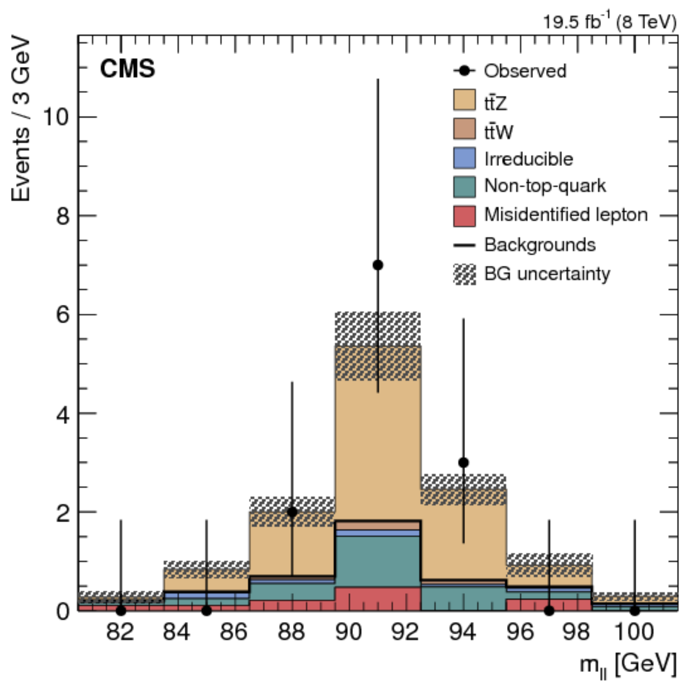
ttbar + Z



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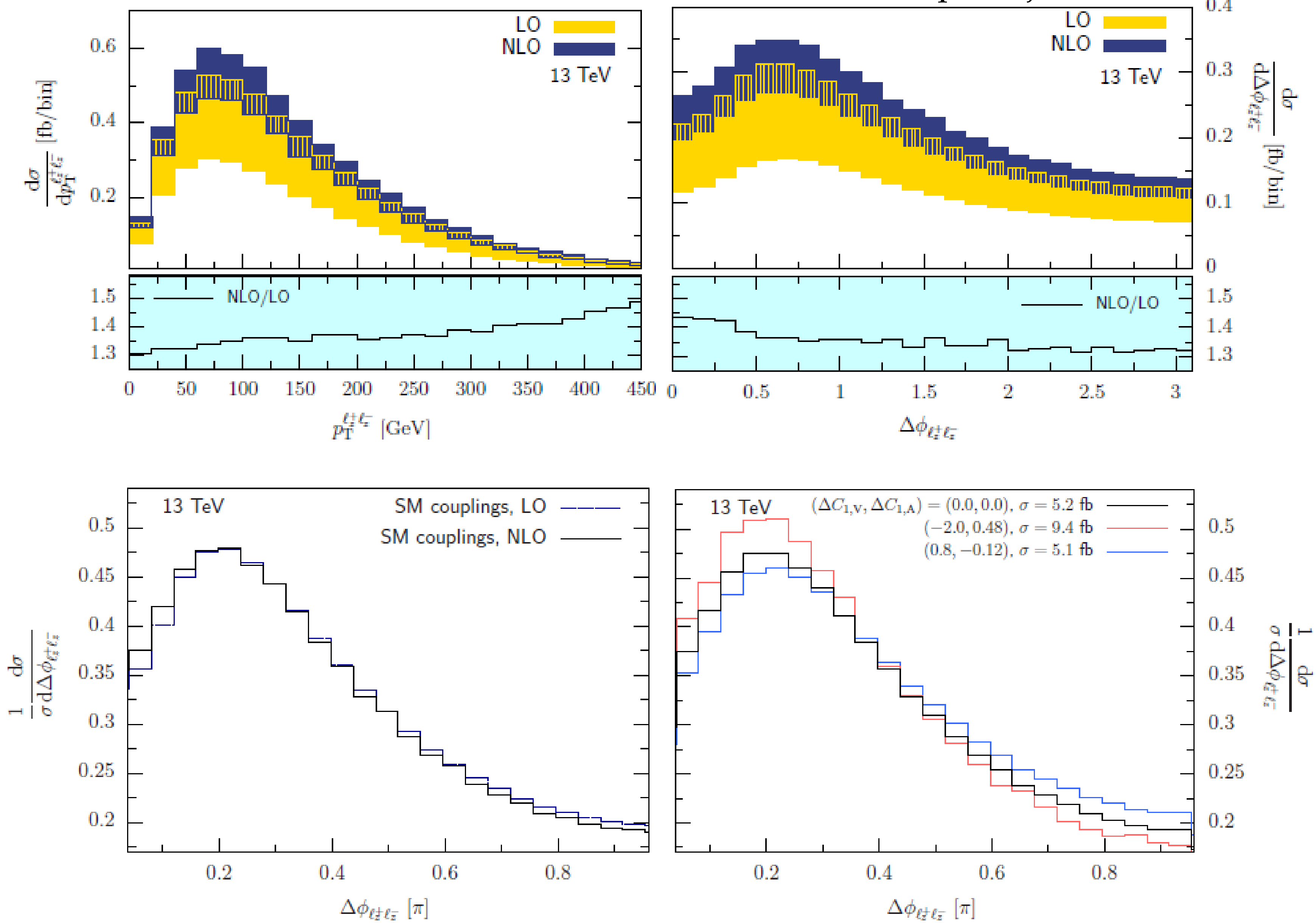
$$C_{1,\mathrm{V}} = C_{1,\mathrm{V}}^{\mathrm{SM}} + \left(\frac{v^2}{\Lambda^2}\right)\mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} - C_{\phi u}^{33}\right],$$

$$C_{1,\mathrm{A}} = C_{1,\mathrm{A}}^{\mathrm{SM}} + \left(\frac{v^2}{\Lambda^2}\right)\mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} + C_{\phi u}^{33}\right],$$

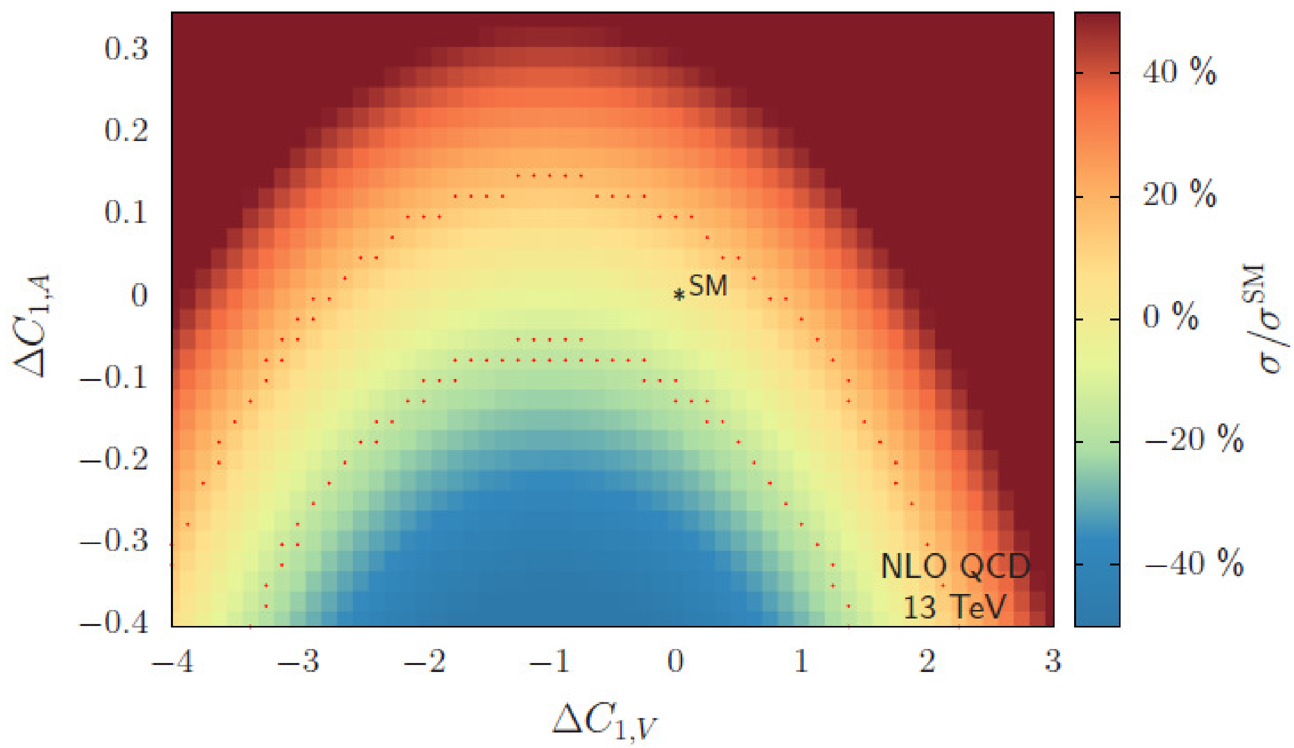
ttbar + Z

[Röntsch,M.S.]

ttbar → lepton+jets, Z → ll



ttbar + Z



- Non-SM coupling combinations within the 20% band cannot be distinguished from the SM.

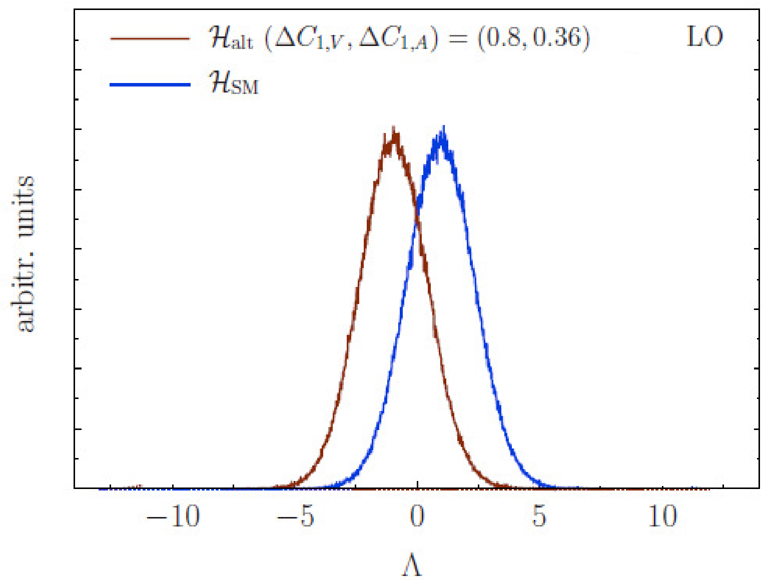
→ Additional shape information is needed

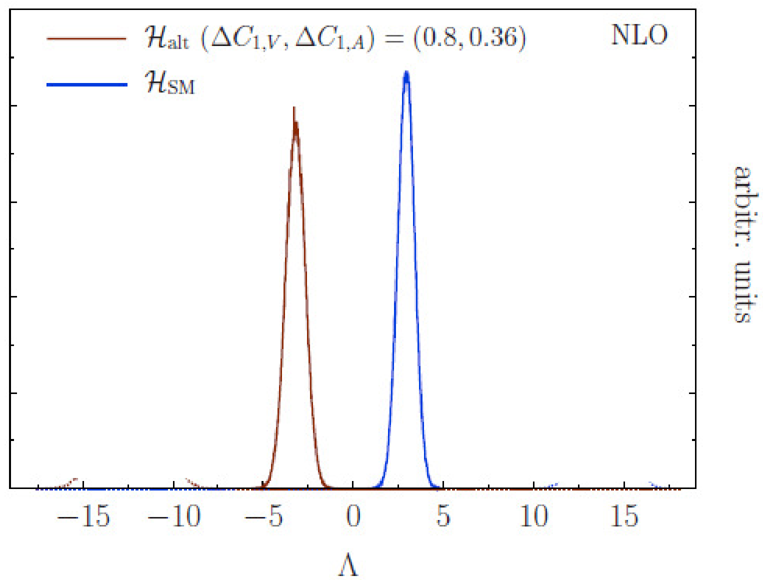
ttbar + Z

- We employ a log-likelihood ratio test which accounts for statistical uncertainties, experimental systematics and theoretical uncertainties from scales+pdfs

$$\mathcal{L}(\mathcal{H}|\vec{n}) = \prod_{i=1}^{N_{\rm bins}} P_i(n_i|\nu_i^{\mathcal{H}})$$

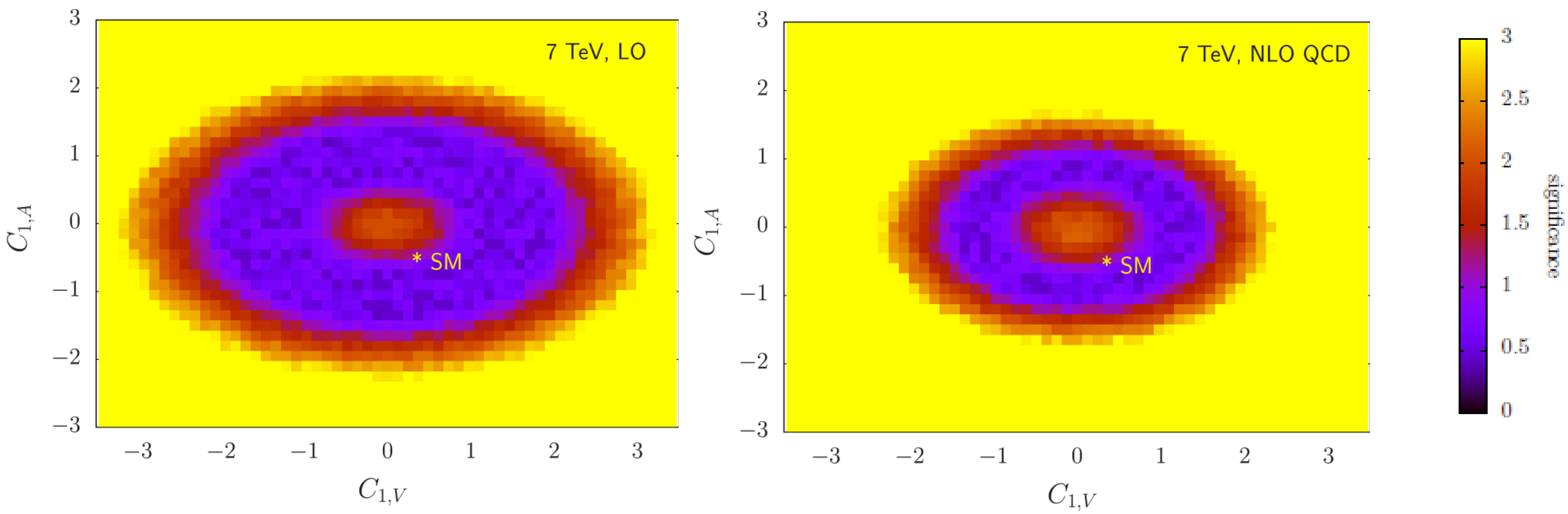
$$\Lambda(\vec{n}_{\rm obs}) = \log\Big(\mathcal{L}(\mathcal{H}_{\rm SM}|\vec{n}_{\rm obs})/\mathcal{L}(\mathcal{H}_{\rm alt}|\vec{n}_{\rm obs})\Big)$$





ttbar + Z

- First measurement of total cross section by CMS
- H_{null} = CMS data vs. H_{alt} = some BSM coupling choice
- Uncertainty treatment:
  Theoretical: scale + pdfs 40% at LO and 15% at NLO (uniform/flat distr.)
  Experimental: statistical (Poisson) + 20% systematics (Gaussian)



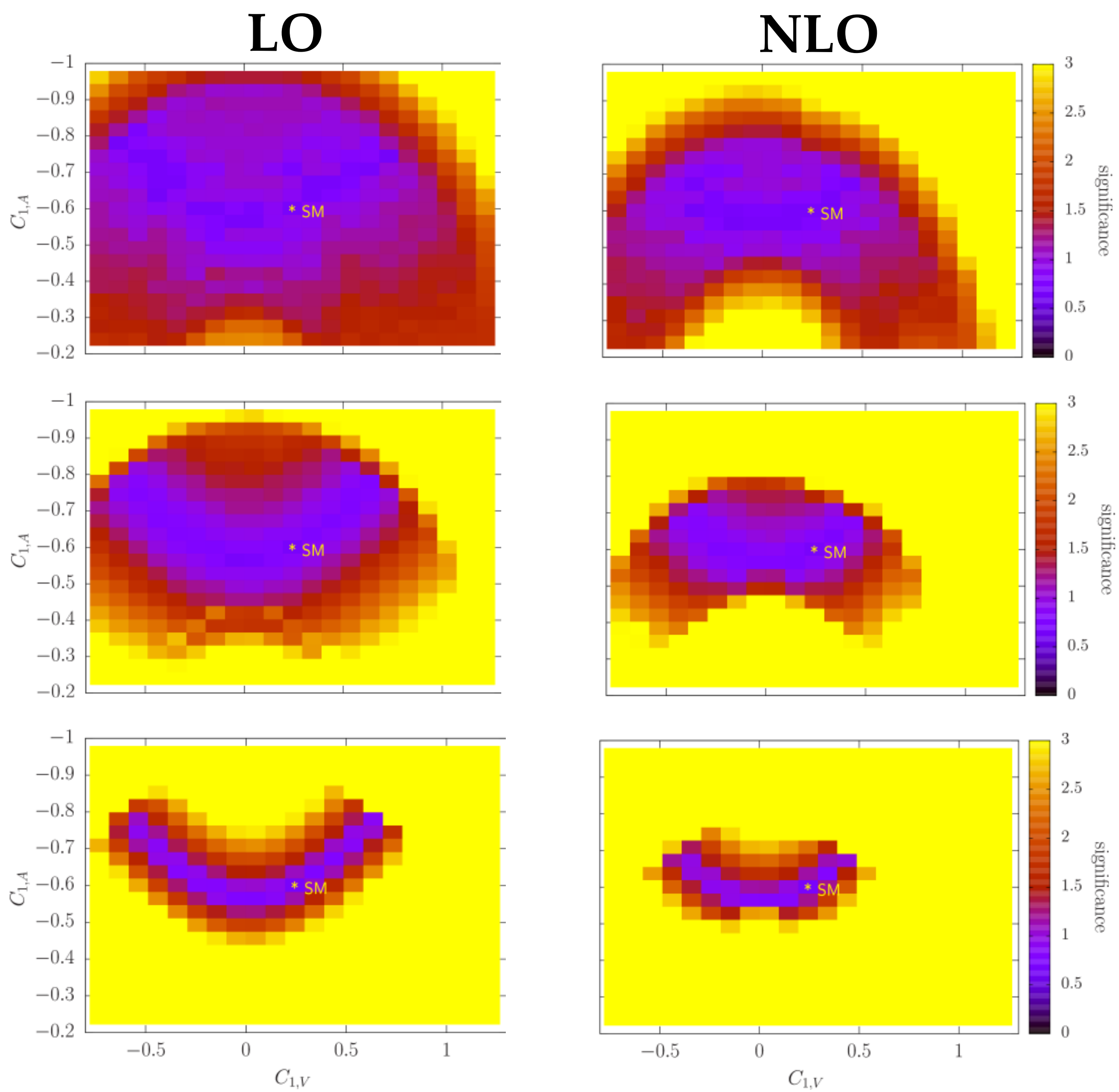
ttbar + Z

Future projection of sensitivities at the 13 TeV LHC

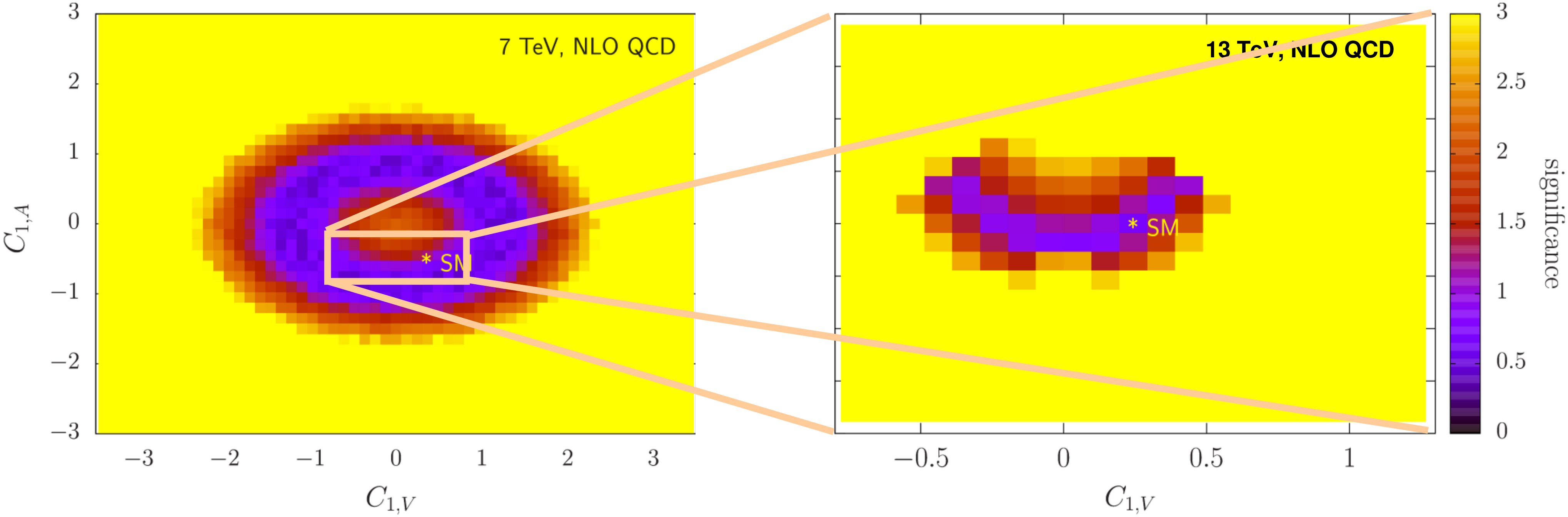
$\mathcal{L} = 30\,\mathrm{fb}^{-1}$

$\mathcal{L} = 300\,\mathrm{fb}^{-1}$

$\mathcal{L} = 3000\,\mathrm{fb}^{-1}$



ttbar + Z



ttbar + Z

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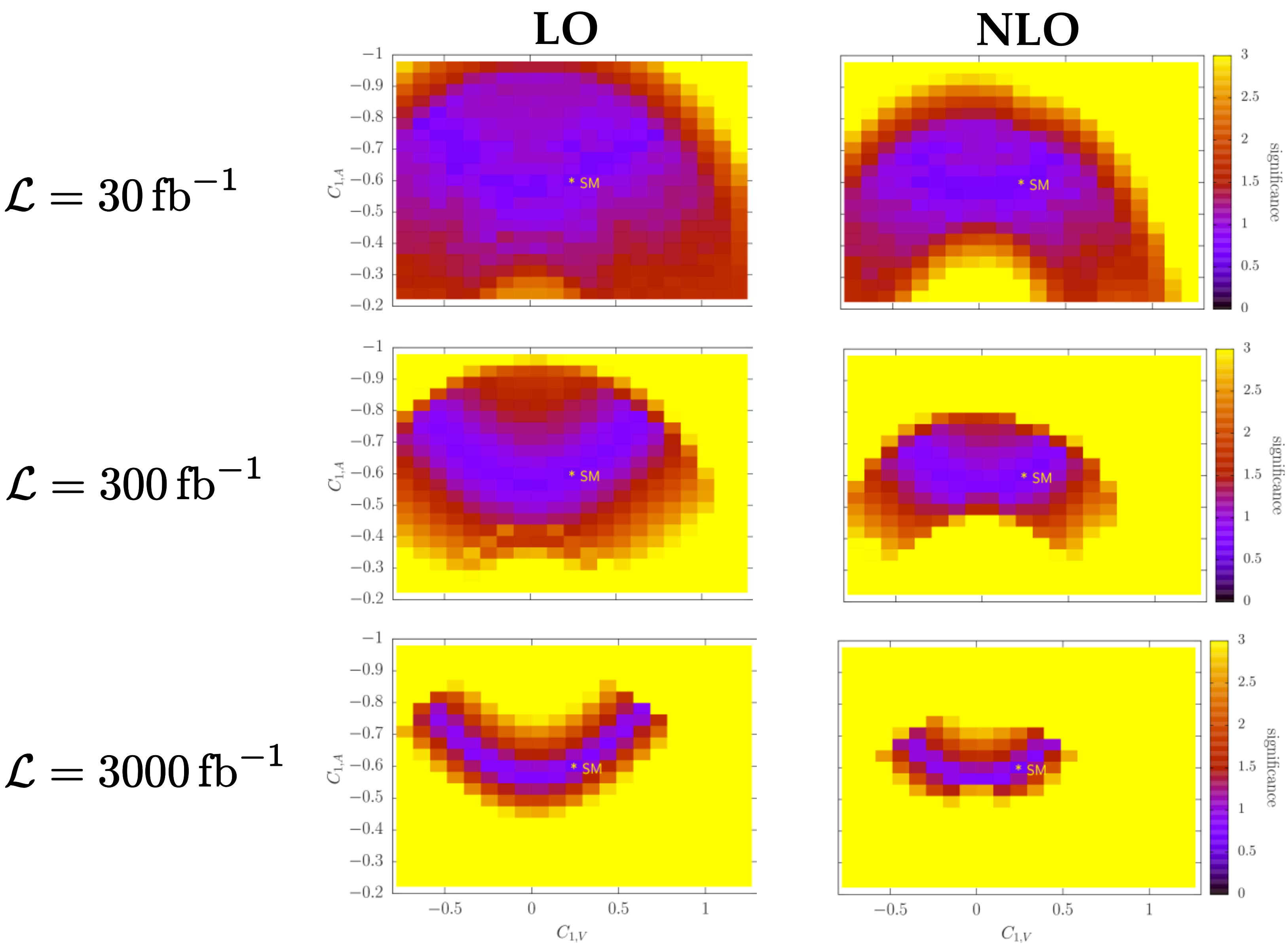
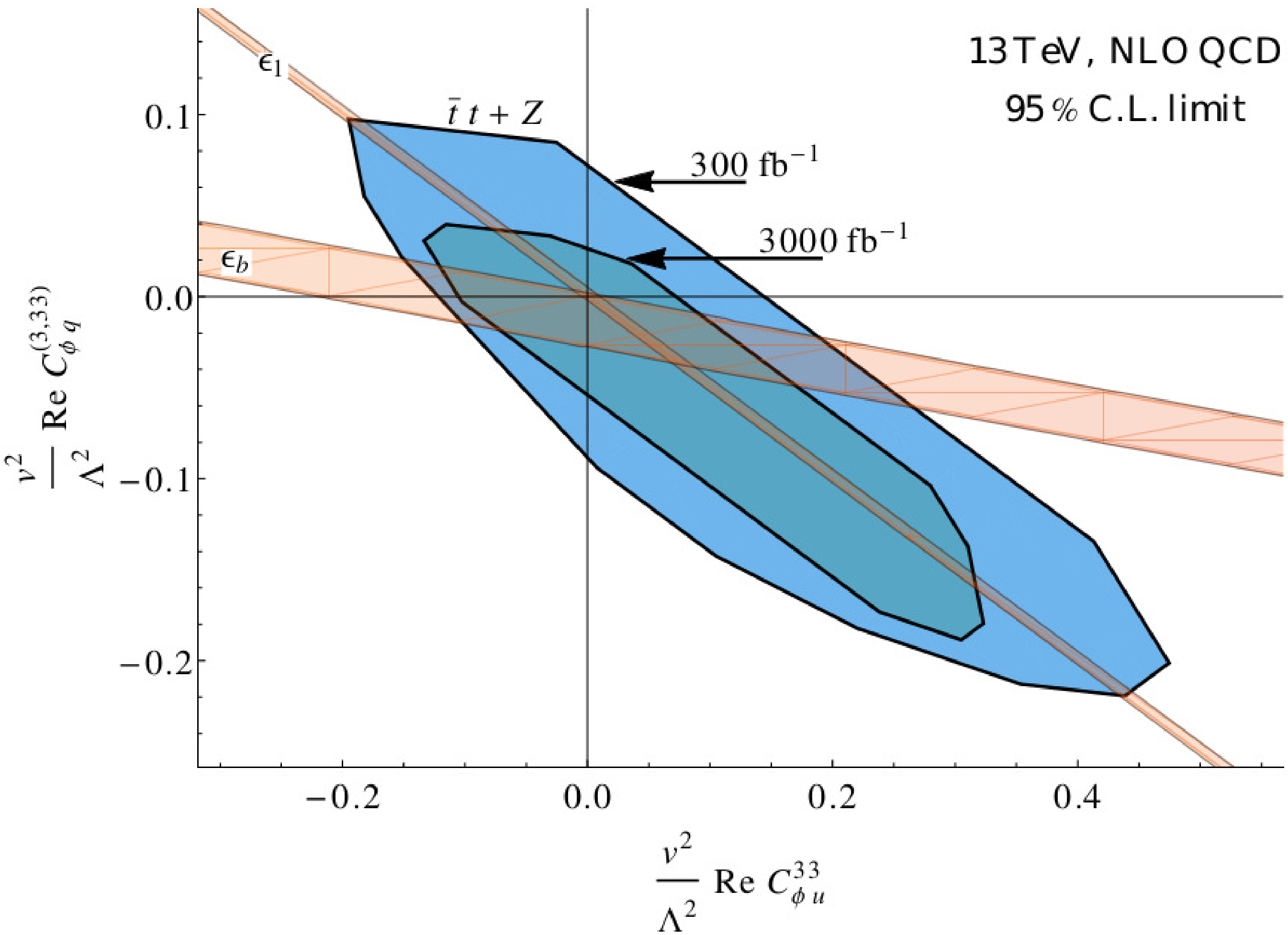


ttbar + Z



13 TeV, NLO QCD
95 % C.L. limit
ϵ_1
$\bar{t}\,t + Z$
300 fb^{-1}
3000 fb^{-1}
ϵ_b
0.1
0.0
−0.1
−0.2
−0.2
0.0
0.2
0.4
$\frac{v^2}{\Lambda^2}$ Re $C_{\phi q}^{(3,33)}$
$\frac{v^2}{\Lambda^2}$ Re $C_{\phi u}^{33}$

SUMMARY

- LHC will provide large event samples of top quark pairs in association with electroweak bosons. The study of these processes will mark a new era in top quark physics.

- Direct sensitivity to top electroweak couplings

- Photon radiation off the decay products is crucial for accurate description

- Analyses at NLO significantly improve the sensitivity to couplings