



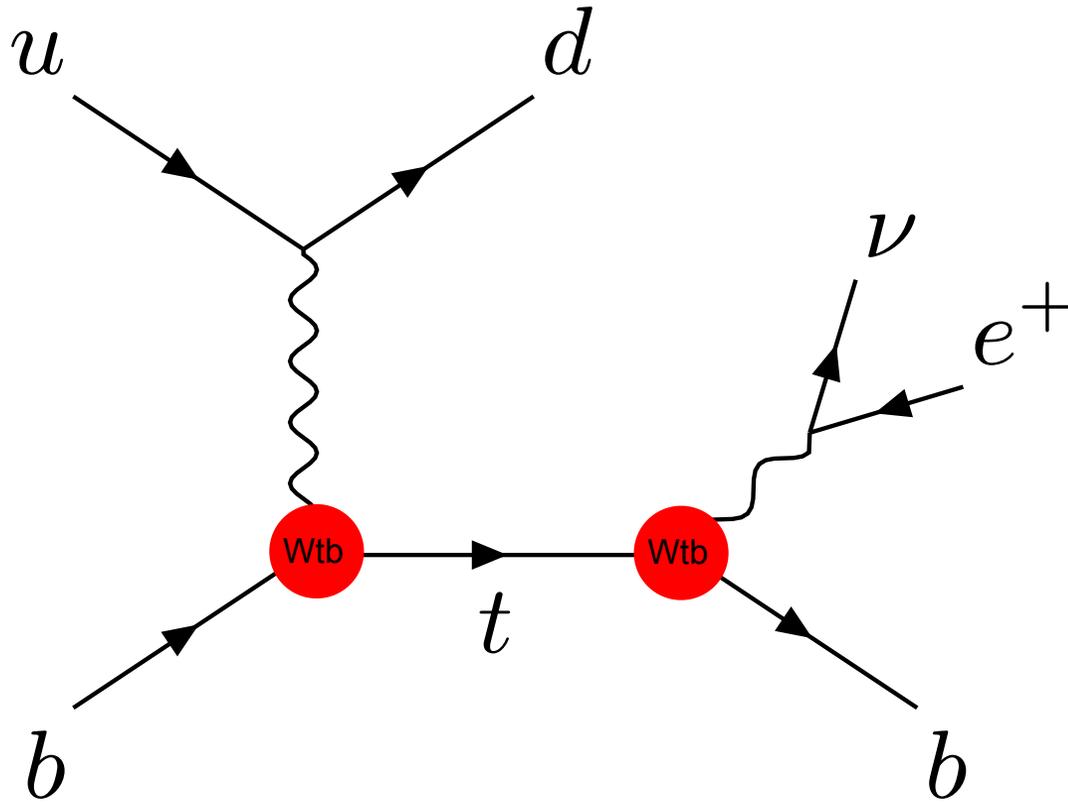
# **Off-shell single-top production in the Standard Model Effective Field Theory**

**based on arXiv:1903.11023**

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# Features of t-channel single-top



- Double deep inelastic scattering: consistency check for PDFs; PDF transverse momentum dependence
- Access to  $V_{tb}$ :  $\propto |V_{tb}|^2$
- Top-quark mass:  $m_{bl}$  lineshape
- As background with signature  $W, b$  + light jets
- Prime process to test V-A structure  $\gamma^\mu P_L$

# Status of SM theory predictions in a glimpse

- NLO: 4-flavor scheme, 5-flavor scheme, stable, on-shell, off-shell, ...

*NLO 4/5-flavor, on-shell (in MCFM): Campbell, Ellis, Tramontano '04; Campbell, Frederix, Frixione, Maltoni, Tramontano '09; Campbell, Ellis '12; (in POWHEG and aMC@NLO): Frederix, Re, Torrielli '12; NLO off-shell + non-resonant + parton shower: Prestel, Torrielli, Papanastasiou, Frederix, Frixione, Hirschi, Maltoni '13 '16;*

- Threshold and transverse momentum resummation

*Kidonakis '12; Cao, Sun, Bin Yan, C.P. Yuan, F. Yuan '18*

- NNLO calculations *Brucherseifer, Caola, Melnikov '14 (on-shell); Berger, Gao, Yuan, Zhu '16 '17 (stable top)*

"We found a difference of  $\sim 1\%$  on the NNLO cross sections"

# Parametrizing new physics has gone a long way

From *anomalous couplings*

$$-\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu(V_L P_L + V_R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{m_W}(g_L P_L + g_R P_R)tW_\mu^-$$

- LO EFT / anomalous couplings Aguilar-Saavedra '08 '09; Bach, Ohl '12
- Analysis and fit to observables, specific model interpretation Cao, Bin Yan, Yu, Zhang '15

to *SMEFT*

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

# SMEFT: UV-model independent parametrization of NP

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi) (\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi) (\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	$Q_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$Q_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi) (\bar{u}_p \gamma^\mu d_r)$

Buchmueller, Wyler '86; Gradkowski, Iskrzynski, Misiak, Rosiek '10

- work up to including NLO EFT, on-shell Zhang, Willenbrock '11; Franzosi, Zhang '15; Zhang '14 '16
- connection to flavor physics and low energy precision measurements  
Alioli, Cirigliano, Dekens, Vries, Mereghetti '17
- most recently: partial NLO SMEFT, off-shell + PS Beurs, Laenen, Vreeswijk, Vryonidou '18

# And the experiment?

ATLAS anomalous couplings: 1702.08309

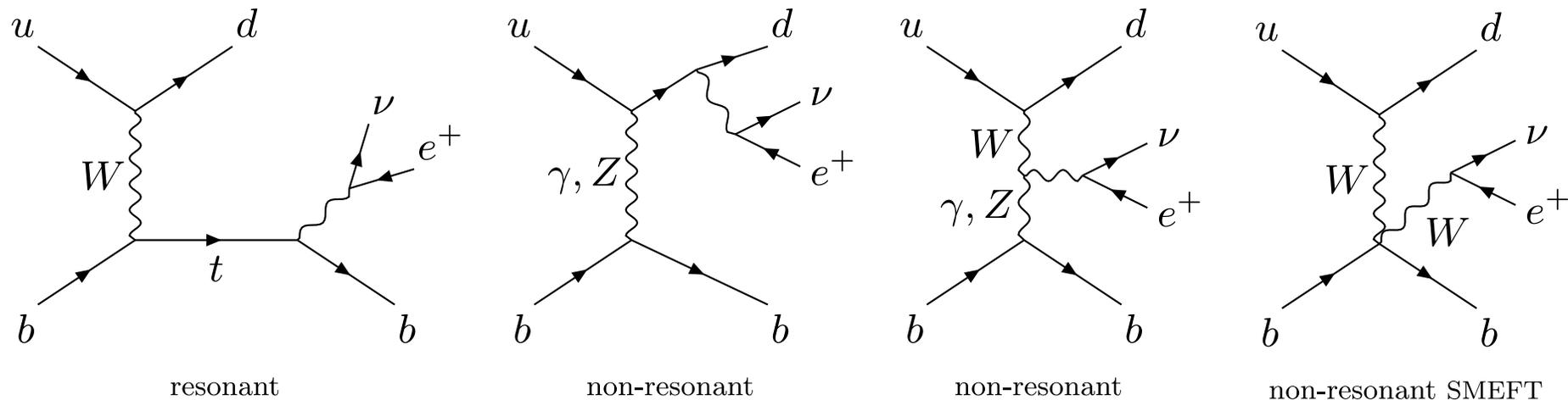
- SM NLO events: POWHEG BOX, 4f scheme, stable top, CT10 PDFs, scale choice A
- LO protos, CTEQ6 PDFs, scale choice B

CMS anomalous couplings: 1610.03545

- CompHEP LO generator
- "matching to simulate effective NLO approach"
- LO codes for everything else

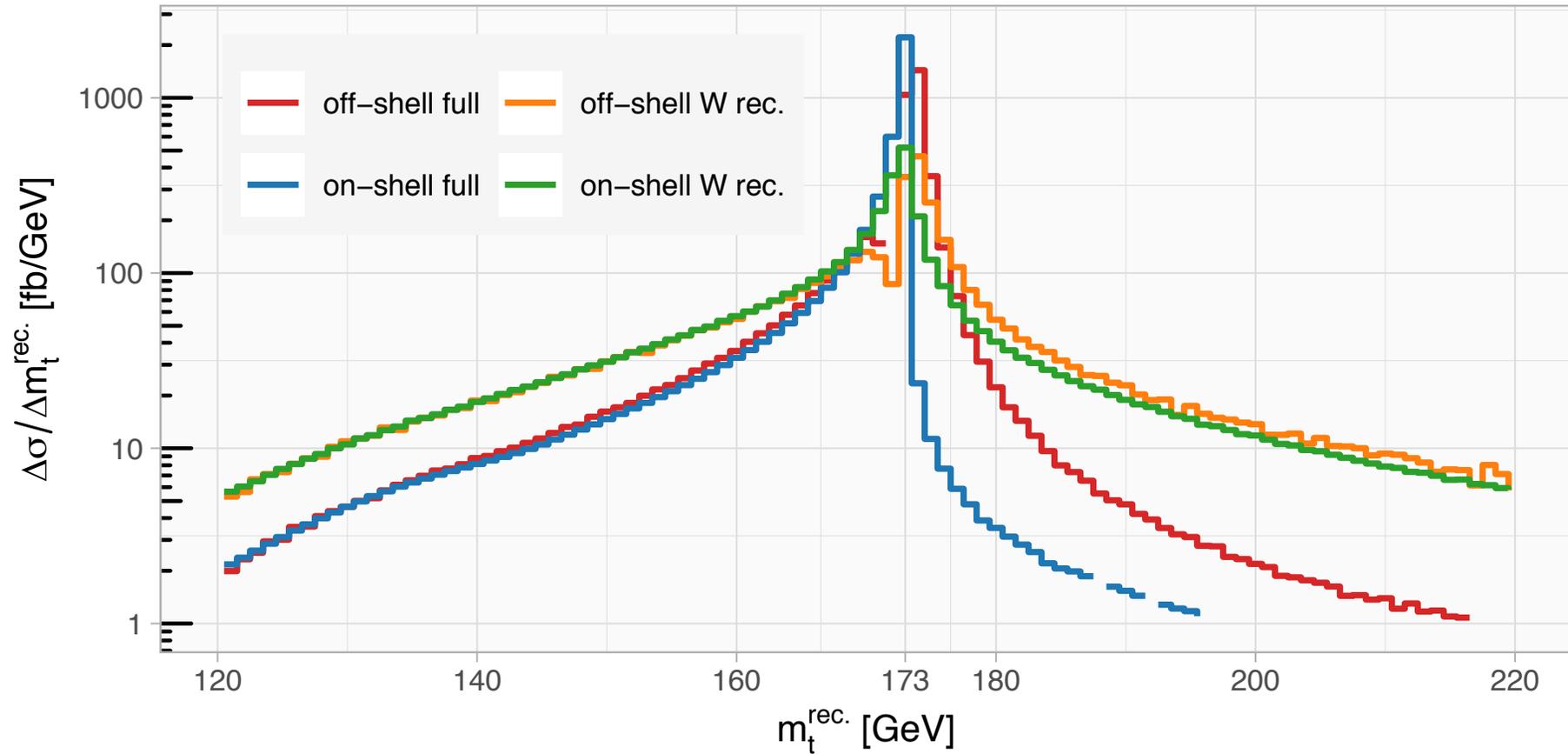
# Our setup

- Fully consistent off-shell calculation at NLO SM and NLO SMEFT
- uses complex mass scheme; full decay chain (no approx. in decays)
- compares with data as closely as possible: DDIS scales

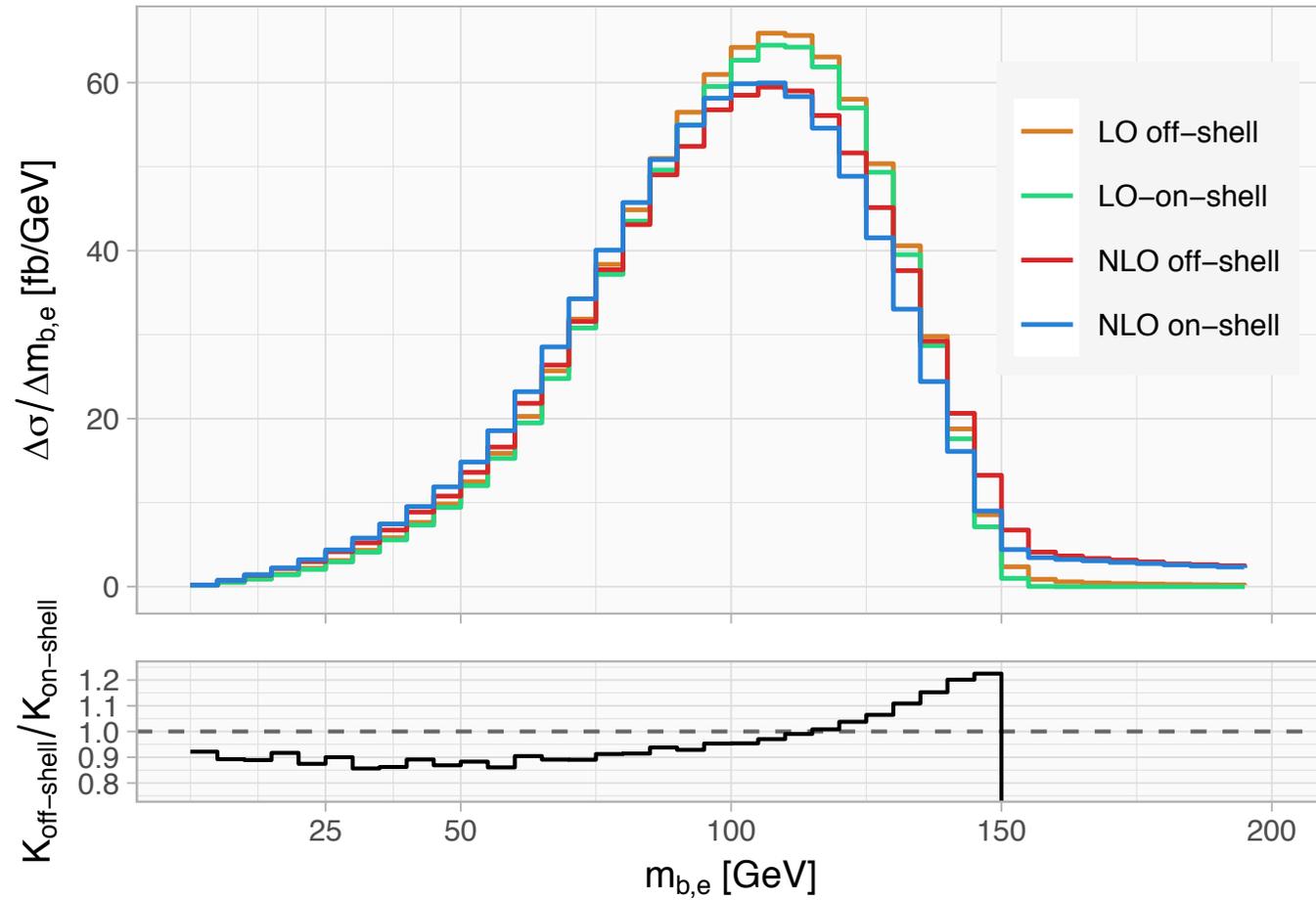


Inclusion of of eight SMEFT operators through NLO: two only enter at NLO

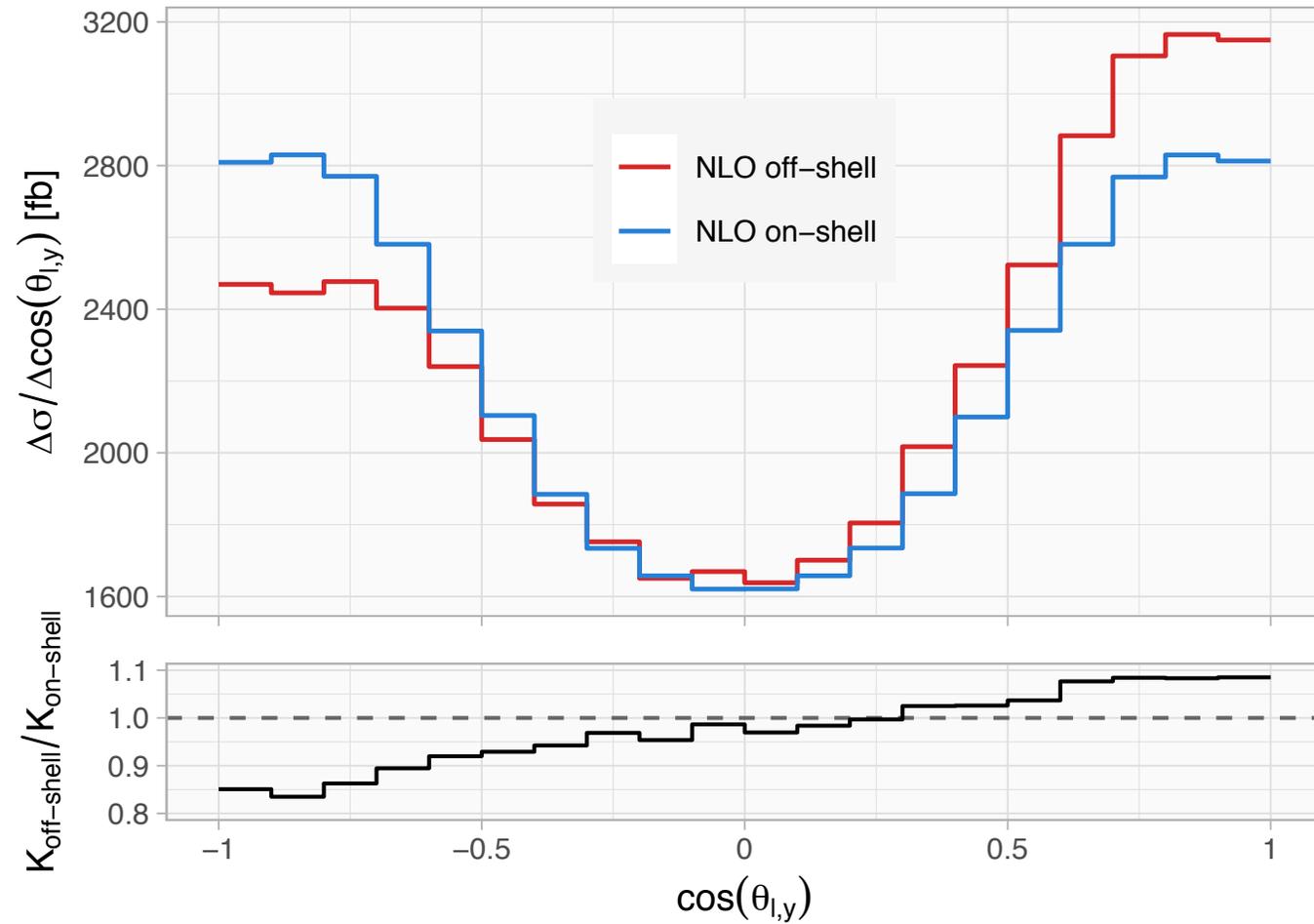
# Inclusively: Off-shell effects $\mathcal{O}(\Gamma_t/m_t)$



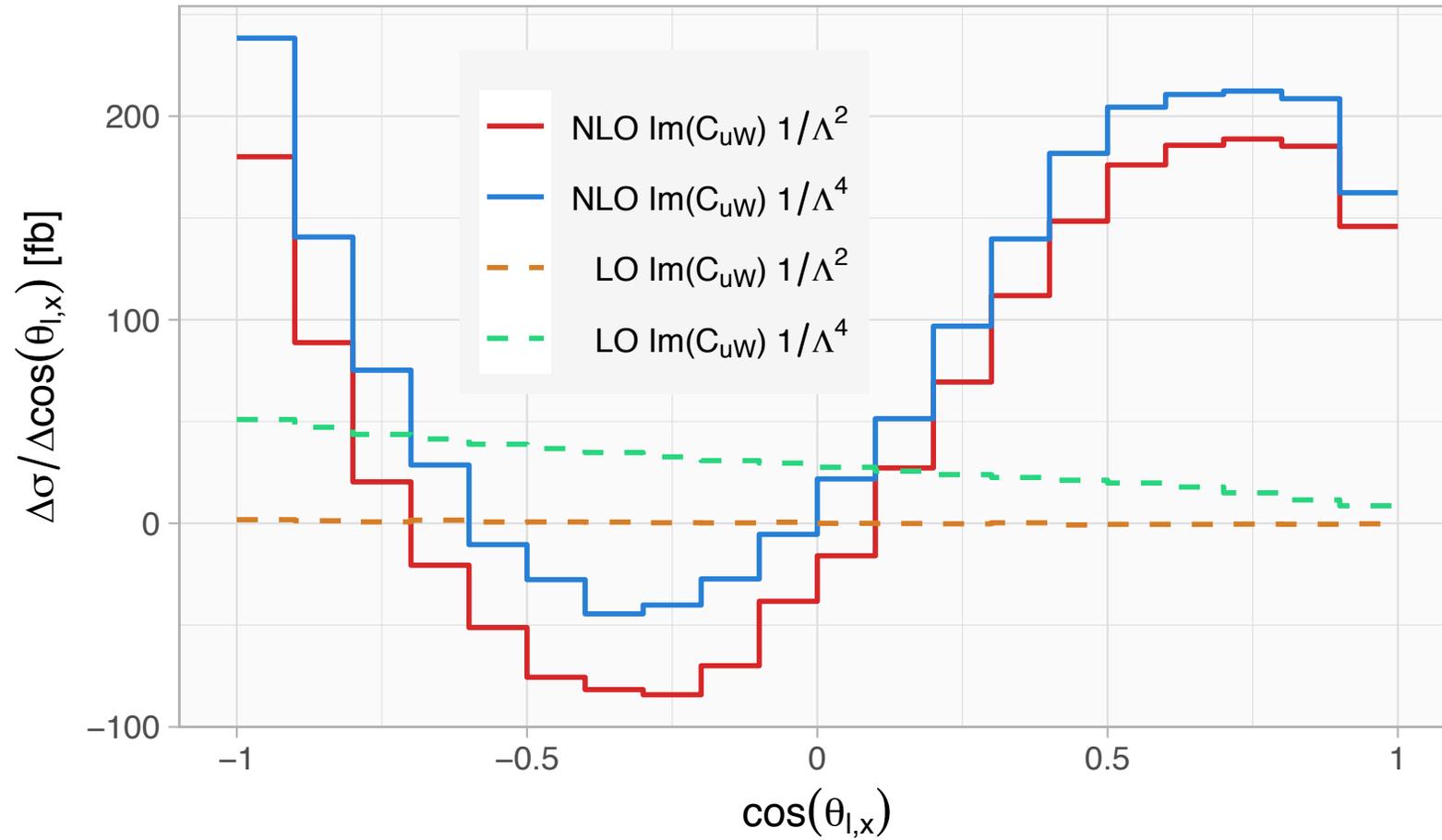
# $m_{bl}$ lineshape used for top-mass measurement



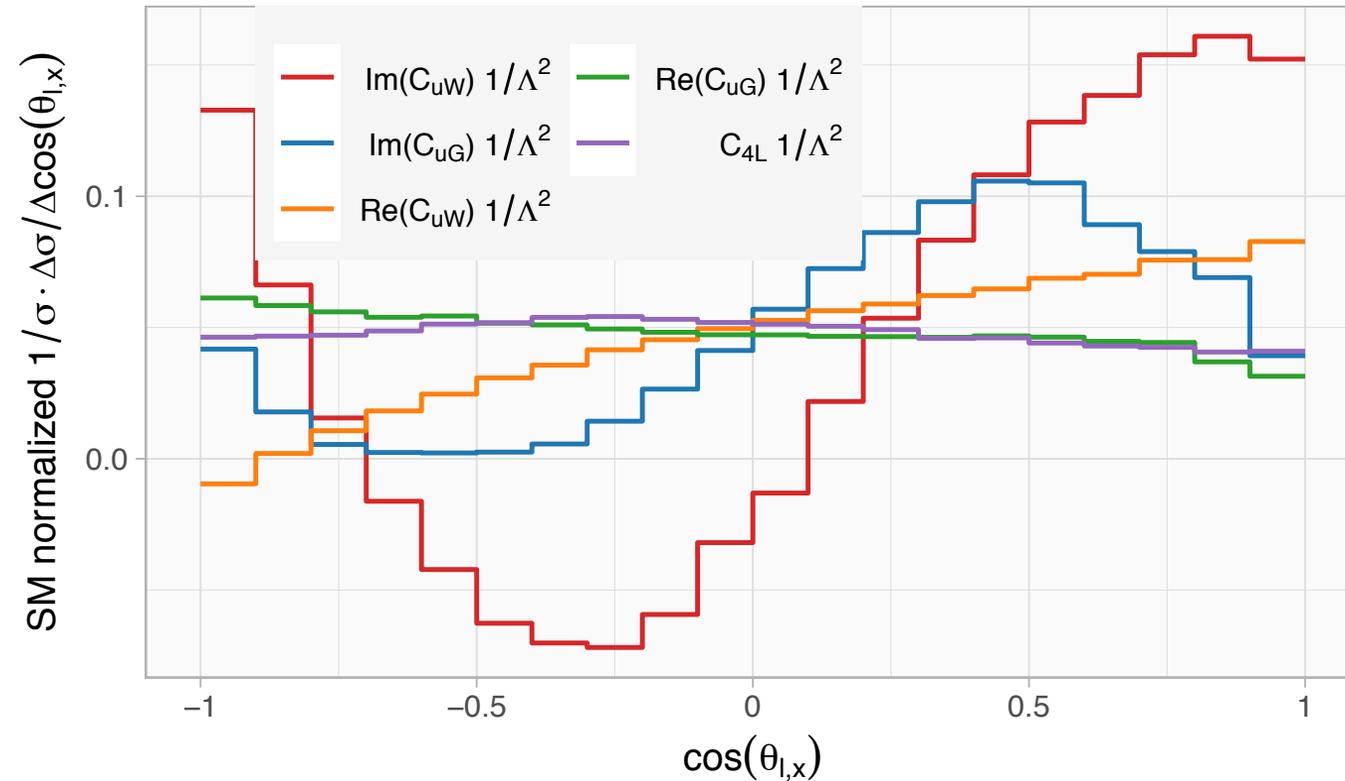
# Example for angle sensitive to new physics



# One of the most interesting structures: $\Im C_{uW}$



# Example of the whole spectrum...



$$\mu_X \frac{d}{d\mu_X} \begin{pmatrix} Q_{uG}^{33} \\ Q_{uW}^{33} \end{pmatrix} = \frac{\alpha_s}{4\pi} C_F \begin{pmatrix} 1 & 0 \\ 2 & 2 \end{pmatrix} \begin{pmatrix} Q_{uG}^{33} \\ Q_{uW}^{33} \end{pmatrix}$$

# Conclusions

Unified and consistent NLO SM + NLO SMEFT framework for t-channel single top analyses

- analytical implementation in MCFM 8.3  $\Rightarrow$  fast, easy and hackable
- off-shell top in the complex mass scheme: full semi-leptonic decay, no approximations in decays
- eight operators, two sets with non-vanishing anomalous dimension and mixing at NLO
- compare with data as closely as possible: DDIS scales