Theory update on tZj

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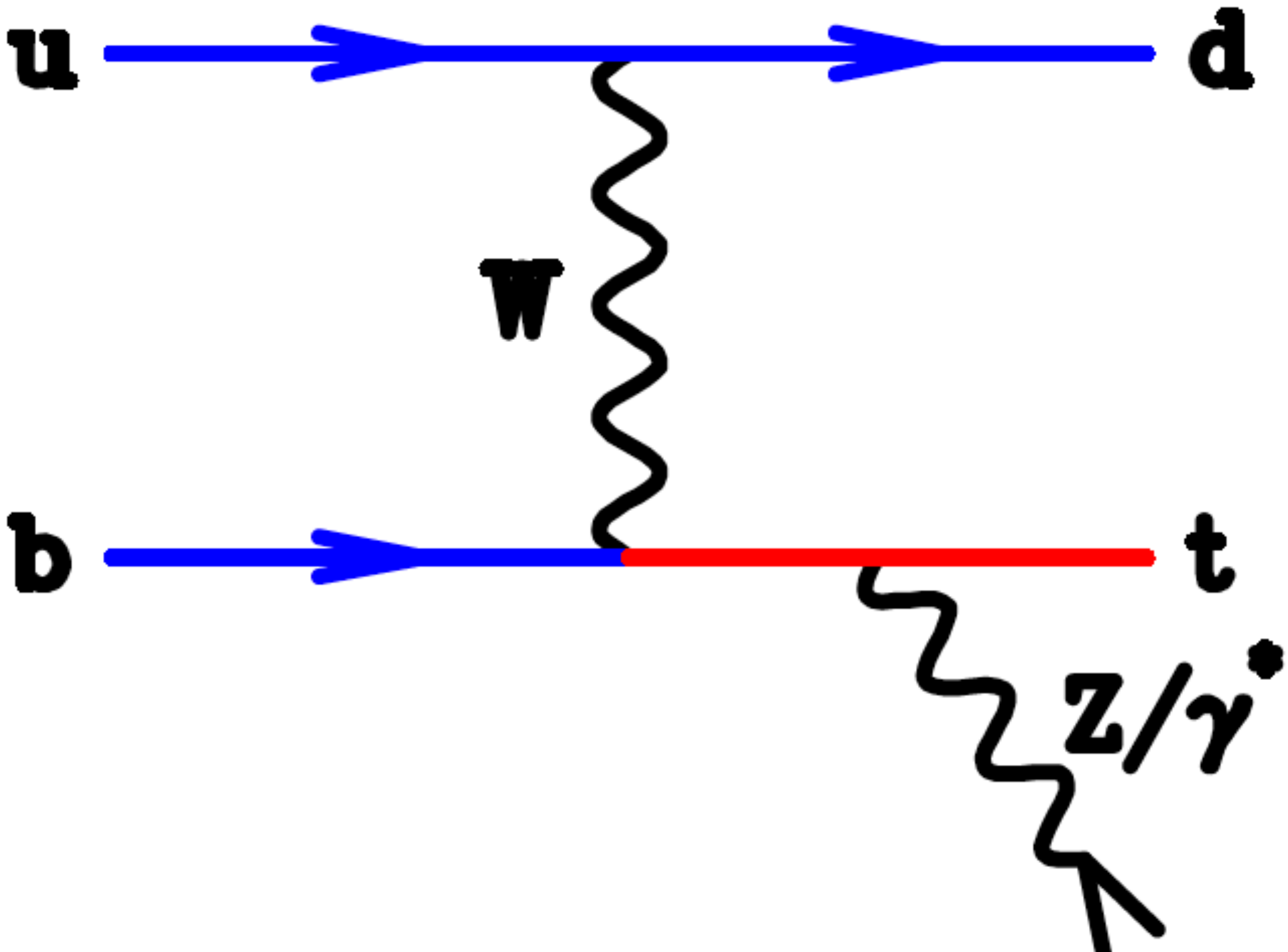
CERN TH

CMS Top Workshop
20/11/19

Outline

1. Standard Model
2. Effective Field Theory

Single top-Z associated production



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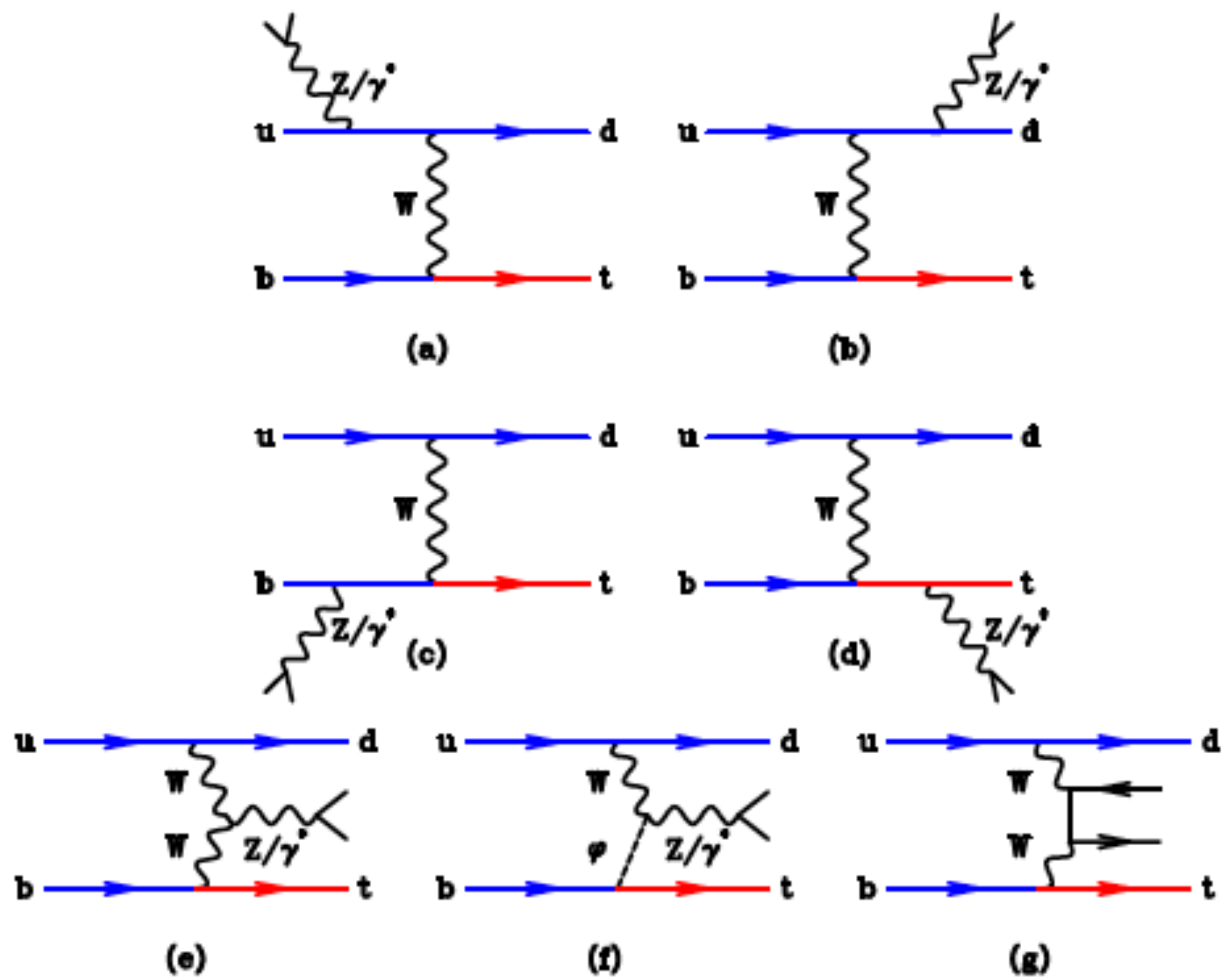


tZj in the SM: tools

MCFM: NLO 5F calculation including top and Z decays
Campbell, Ellis and Röntsch: arXiv:1302.3856

MG5_aMC: possibility for NLO 5F and 4F calculations

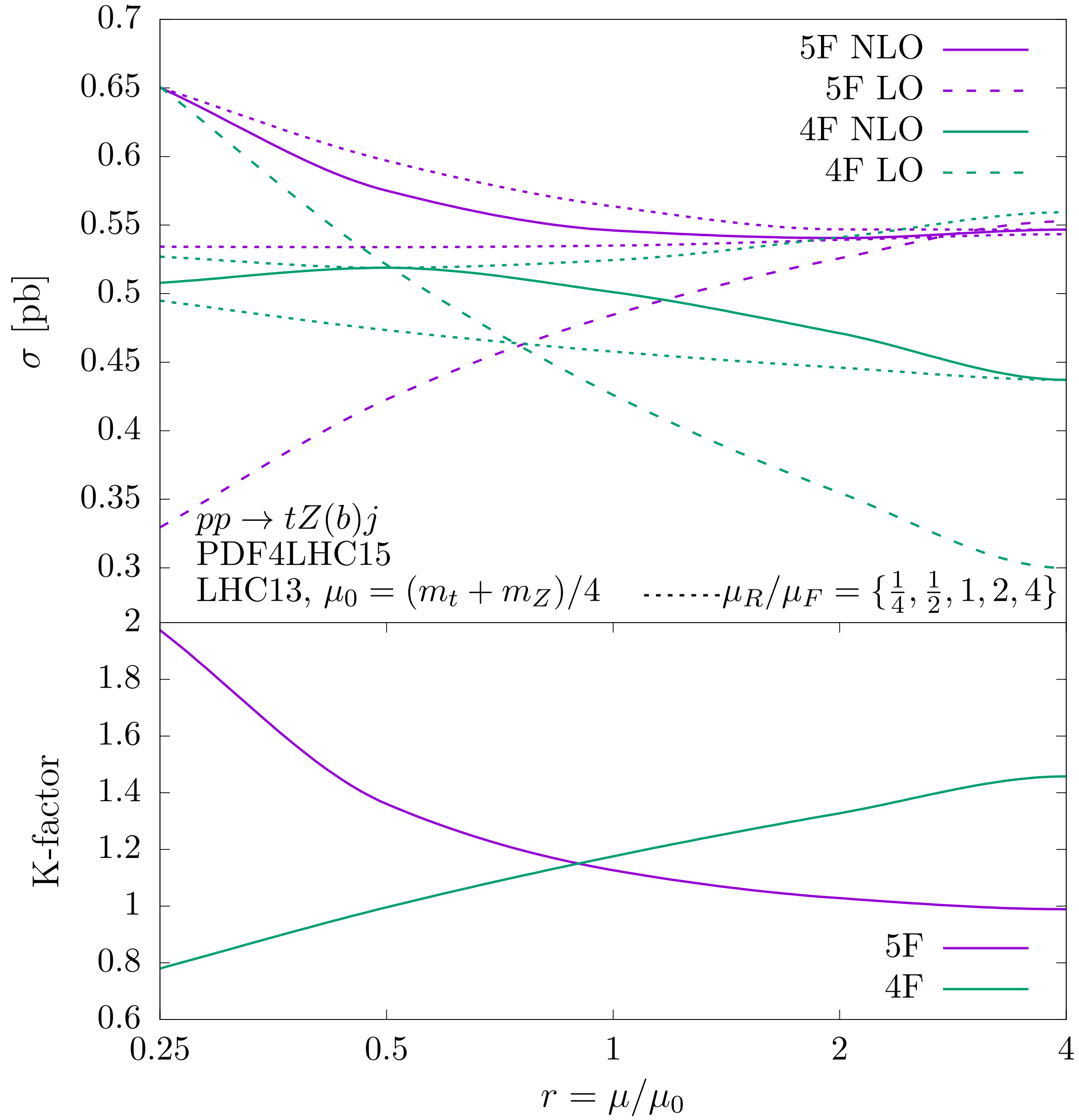
```
import model loop_sm
generate p p > t z b~ j $$ w+ w- [QCD]
output tZjsm4F

import model loop_sm-no_b_mass
generate p p > t Z j $$ w+ w- [QCD]
output tZjsm5F
```

Similarly for anti-top

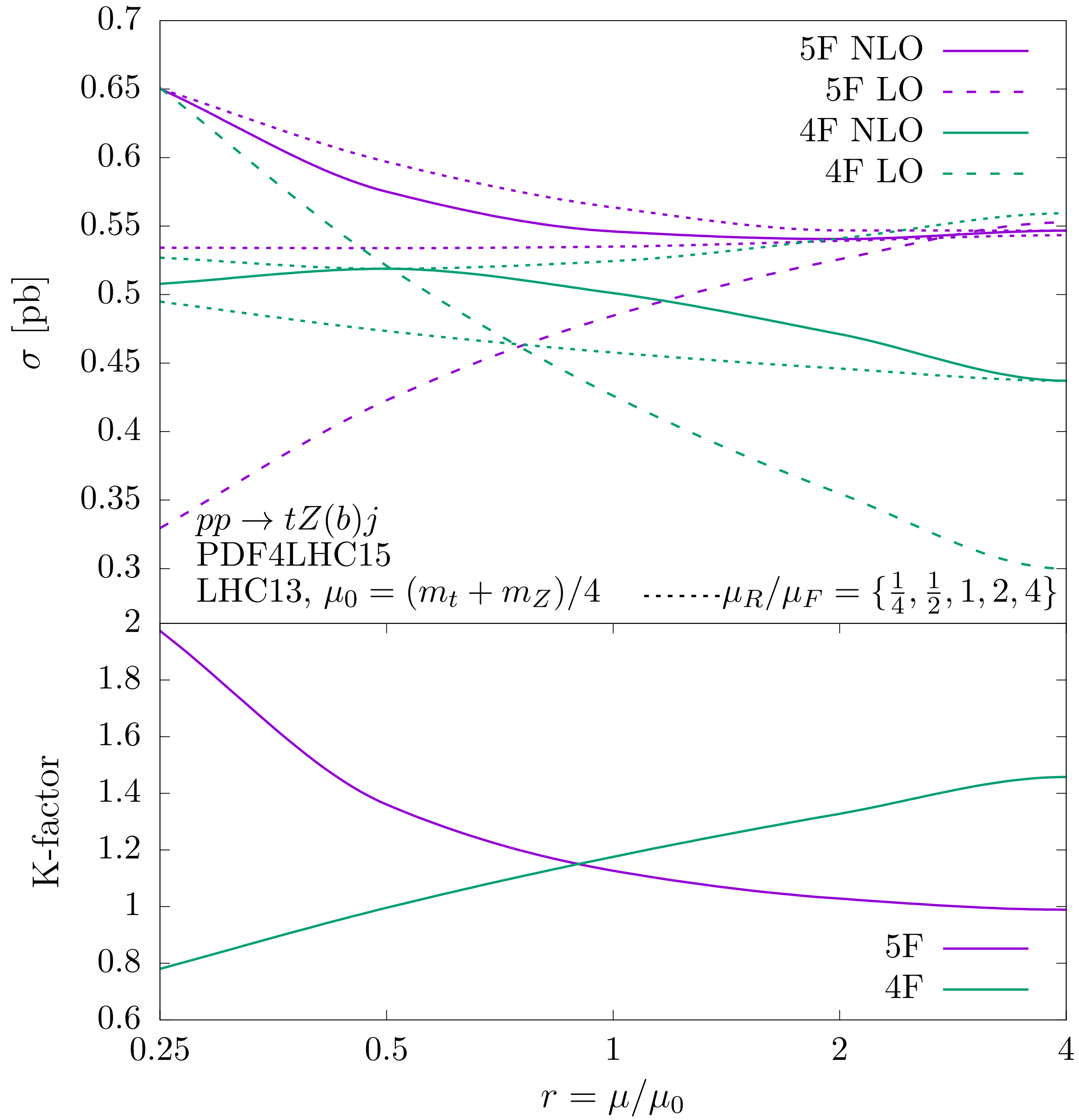
Both codes give the fully differential NLO results in relatively short runtimes

4F/5F comparison



- 5F tZj results cross-checked between MCFM and MG5_aMC: agreement to the per mille level for the inclusive cross section at various scales
- A central scale choice of $(m_t+m_Z)/4$ inspired by the tHj study Demartin et al. arXiv:1504.00611

4F/5F comparison



- Central choice appears to minimise the 4F-5F difference at NLO
- 5F NLO scale dependence and K-factor become flatter at $\mu > \mu_0$
- Independent variation of renormalisation and factorisation scales around μ_0 gives additional bands (dotted lines)
- Varying mb up and down by 0.5 GeV for 4F gives a ~4% uncertainty in the cross section

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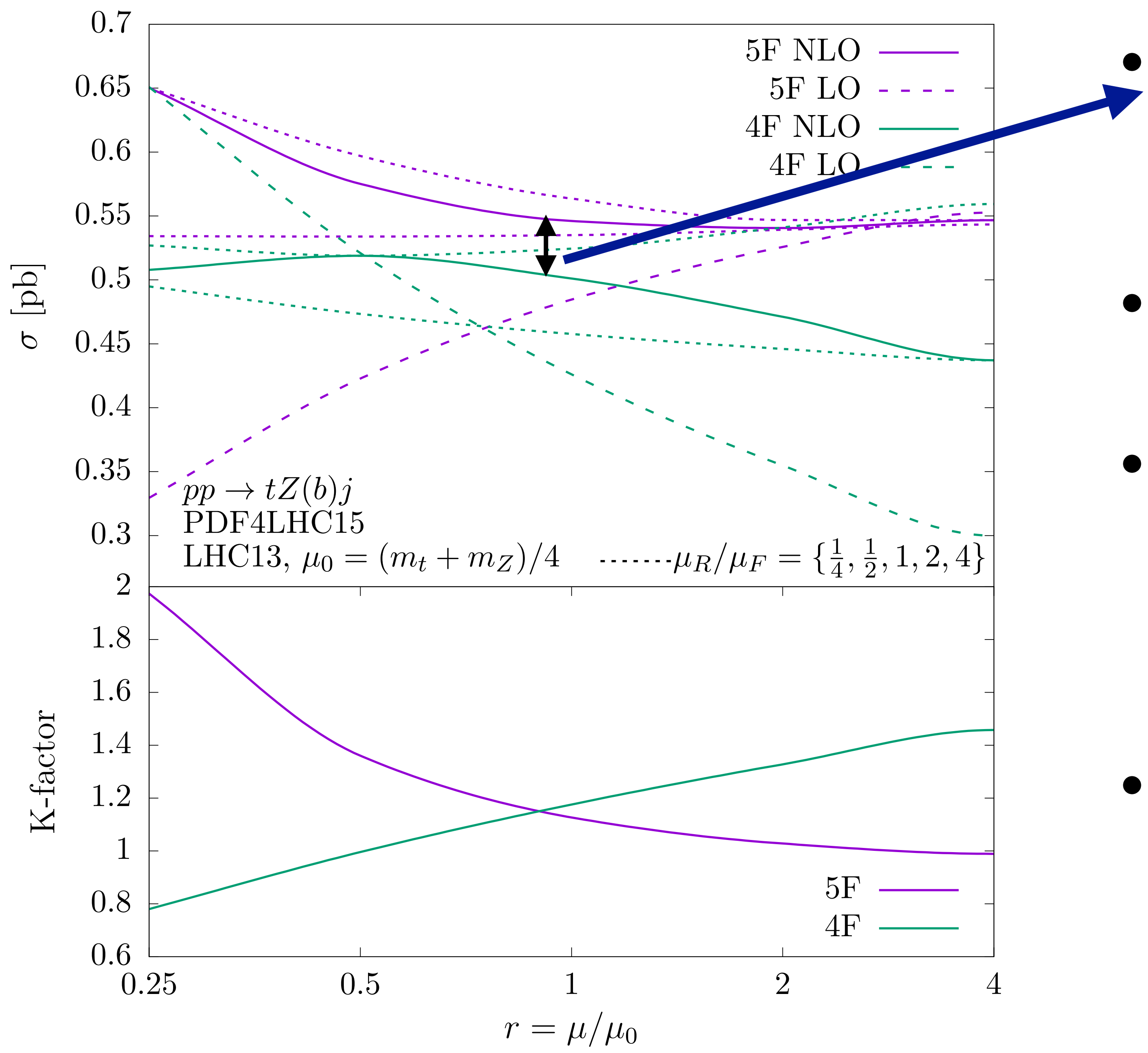

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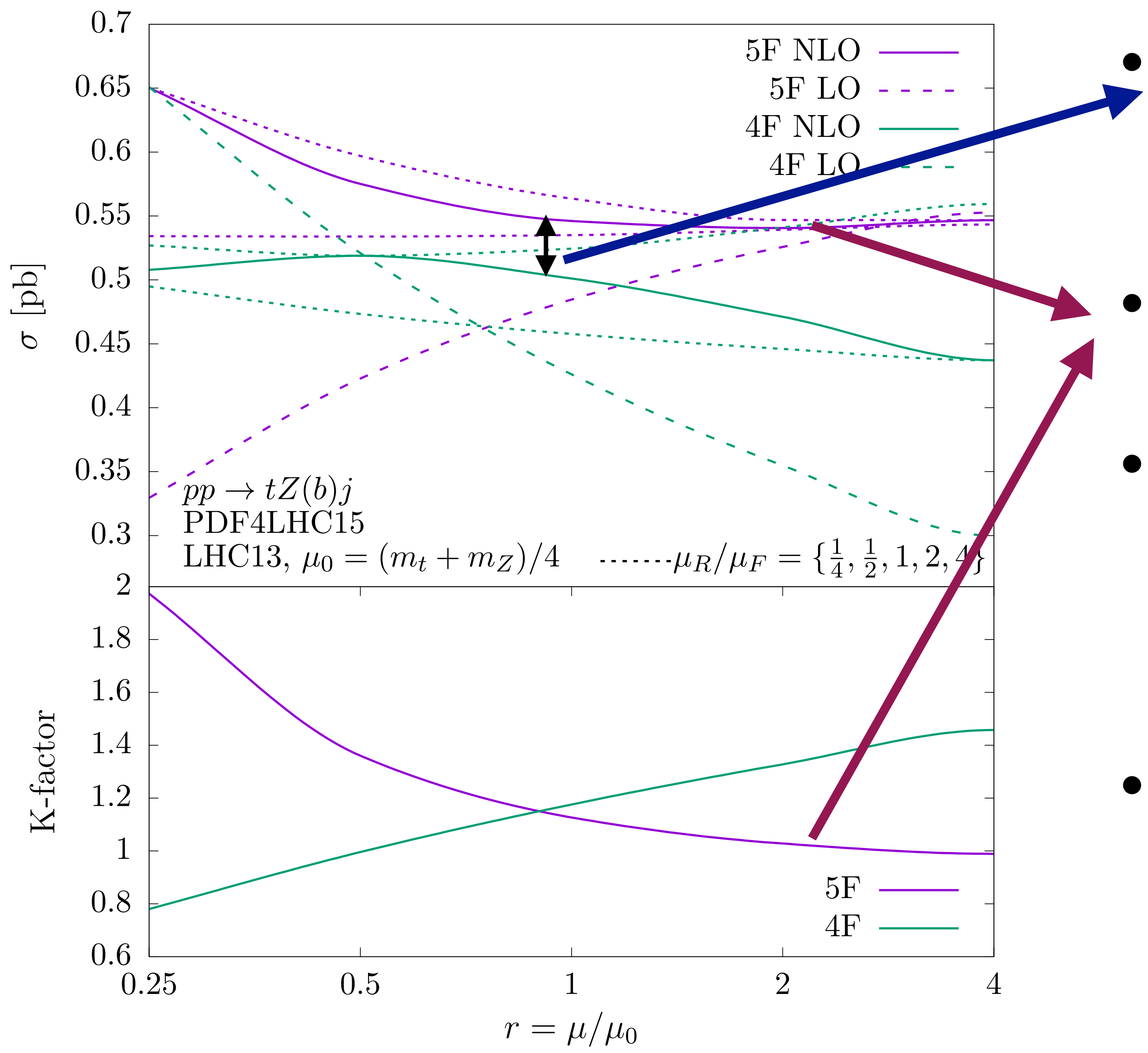

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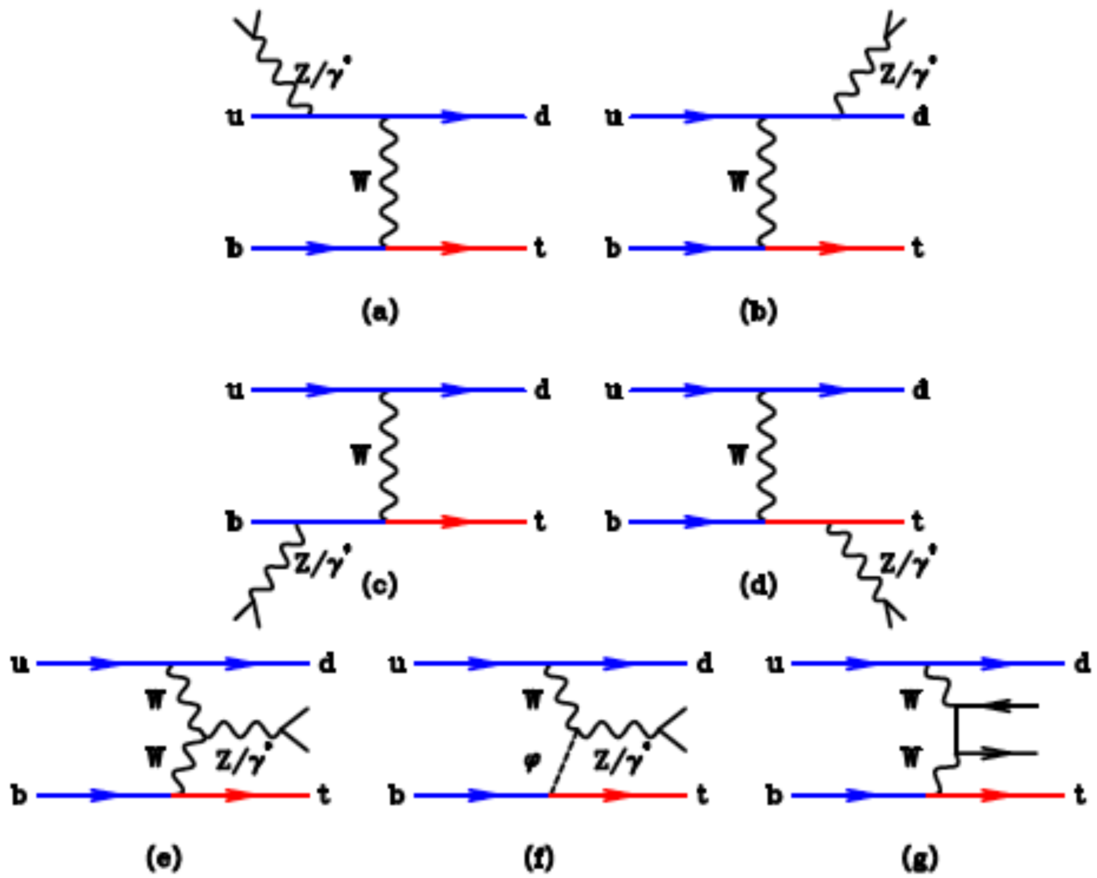
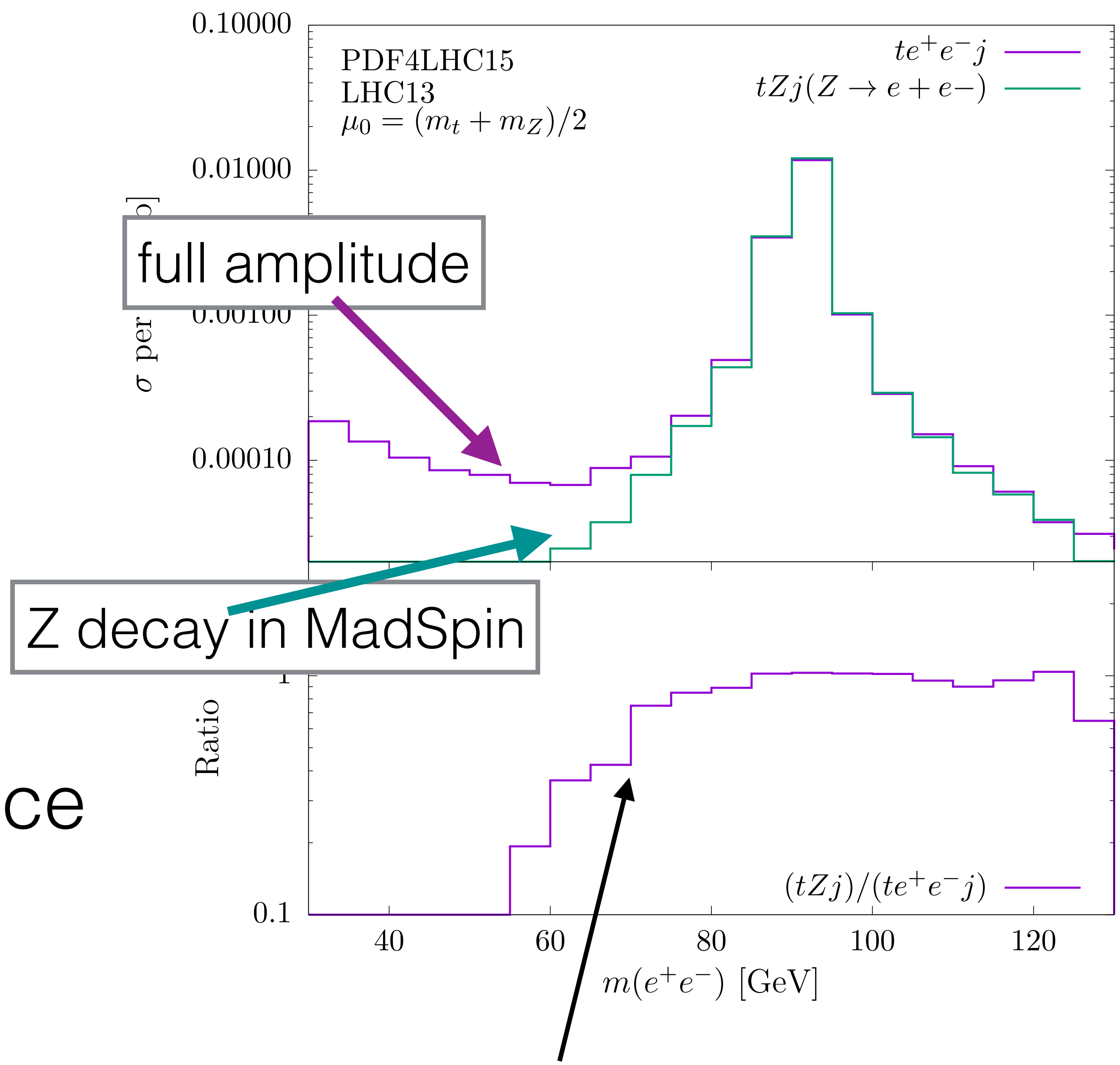
$t\ell^+\ell^- j$

Can the additional contributions be ignored?



All needed for gauge-invariance



Off-shell effects important for $|m-m_Z|>20$ GeV

$t\ell^+\ell^- j$

MG5_aMC

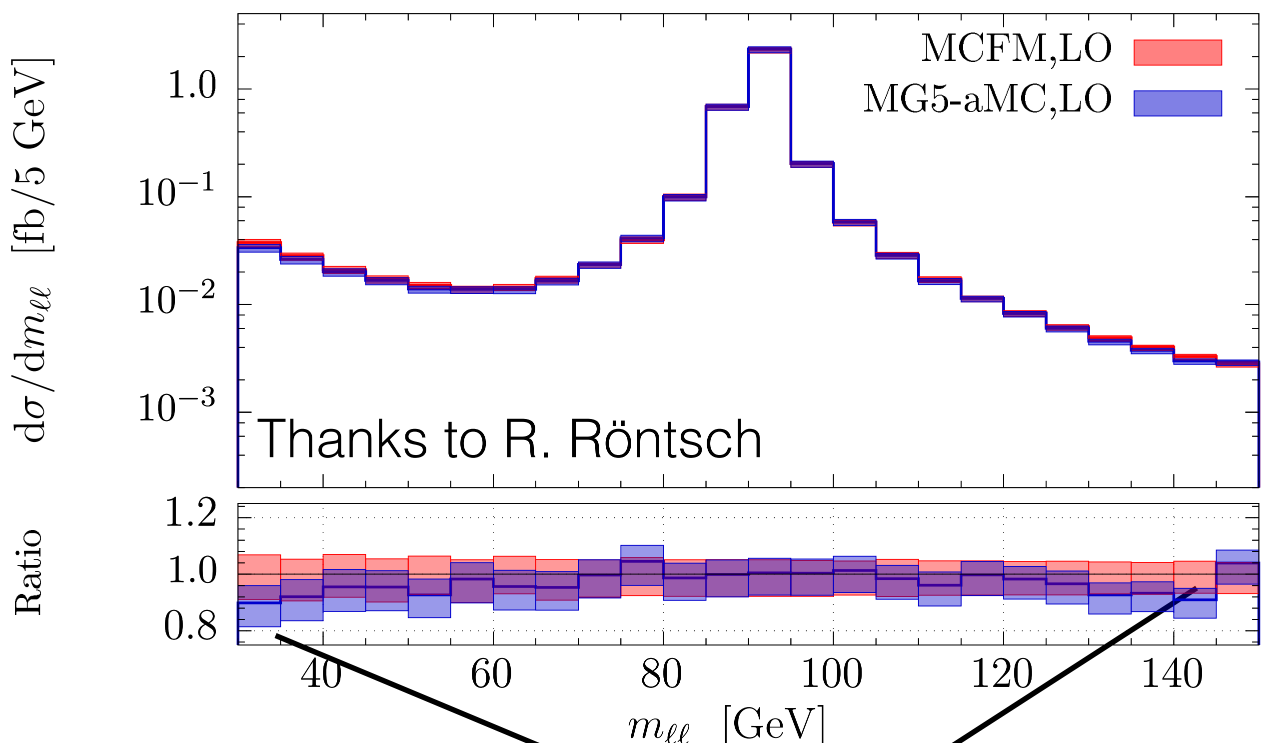
```
import model loop_sm-no_b_mass
set complex_mass_scheme True
generate p p > t j e+ e- $$w+ w- QED=4 QCD=0 [QCD]
output tjelelnlo
```

Z width included in a gauge-invariant way

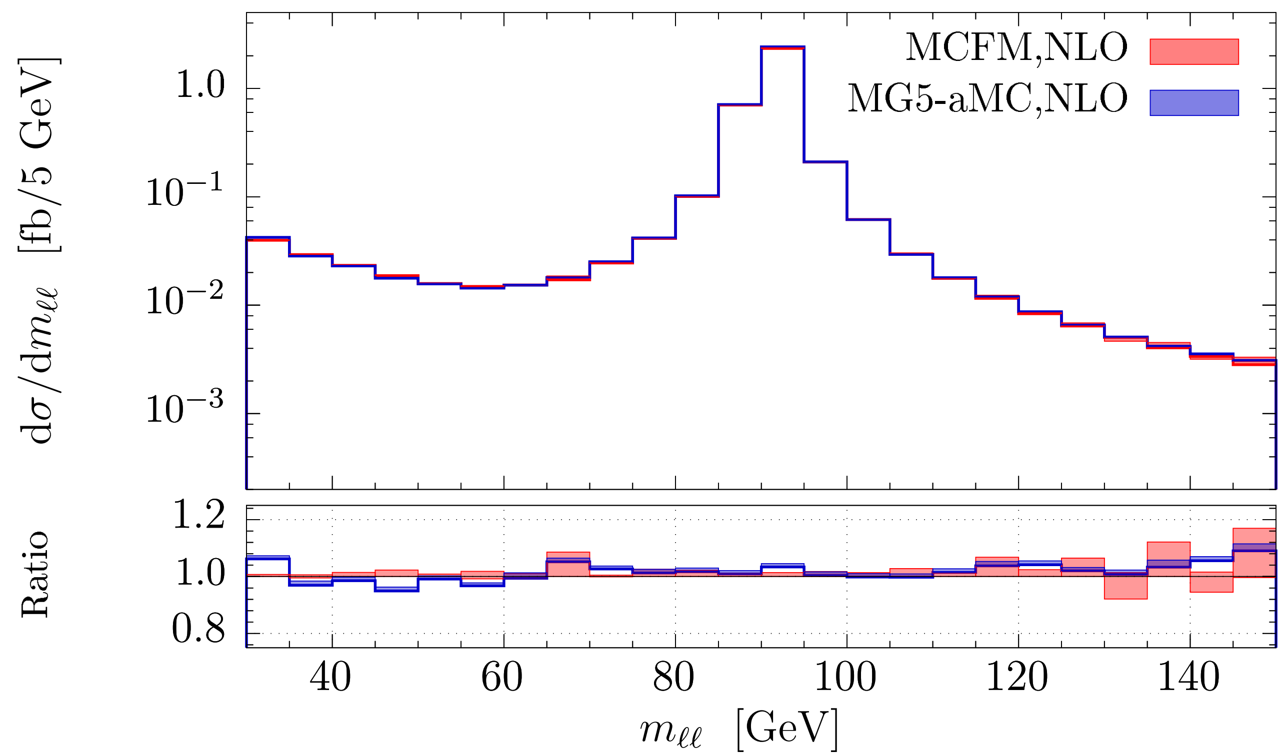
$$m_k \longrightarrow \sqrt{m_k^2 - i m_k \Gamma_k}$$

MCFM uses the Baur-Zeppenfeld scheme

Propagator: $D_Z(s_{34}) = \frac{1}{s_{34} - m_Z^2}$ Amplitude multiplied by: $\left(\frac{s_{34} - m_Z^2}{s_{34} - m_Z^2 + i m_Z \Gamma_Z}\right)$



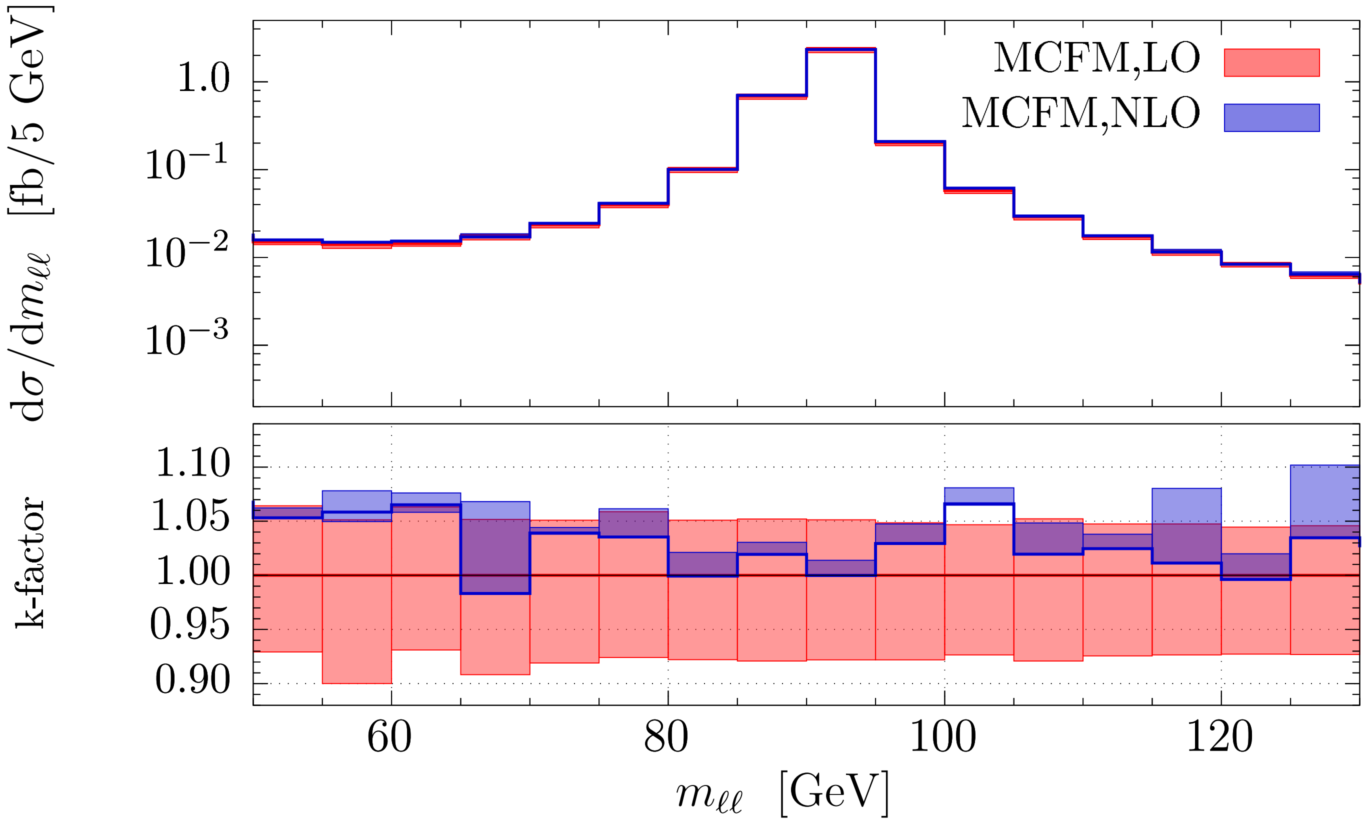
small differences in the tails

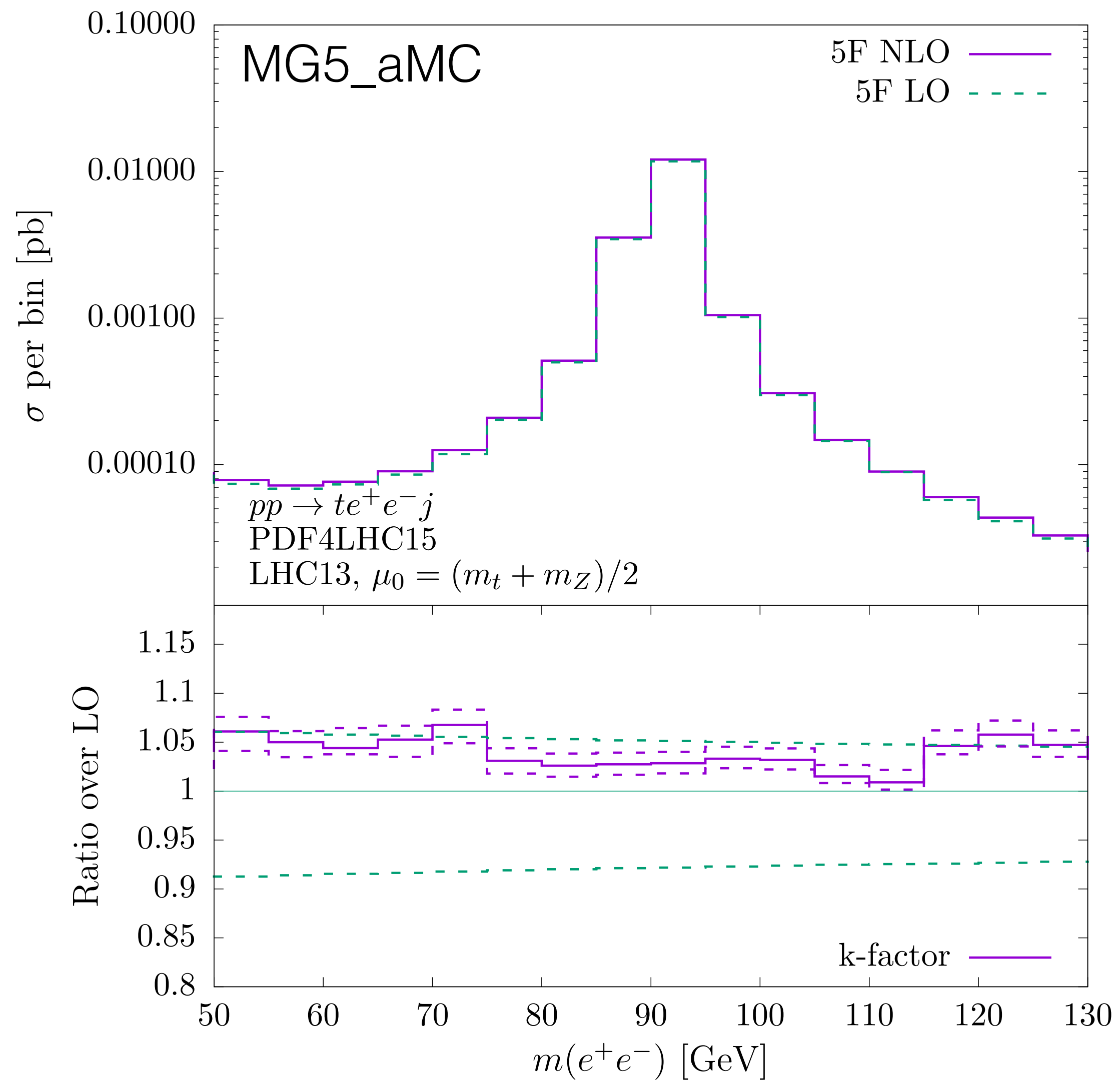


No systematic difference at NLO

Differential k-factors

$t\ell^+\ell^- j$





Differential k-factors: flat

Significant reduction of the scale uncertainties

SMEFT basics

→ New Interactions of SM particles

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

Grzadkowski et al arXiv:1008.4884

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu \varphi\right)^\star \left(\varphi^\dagger D_\mu \varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	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}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

How to probe top operators?

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$

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$$O_{\varphi t} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

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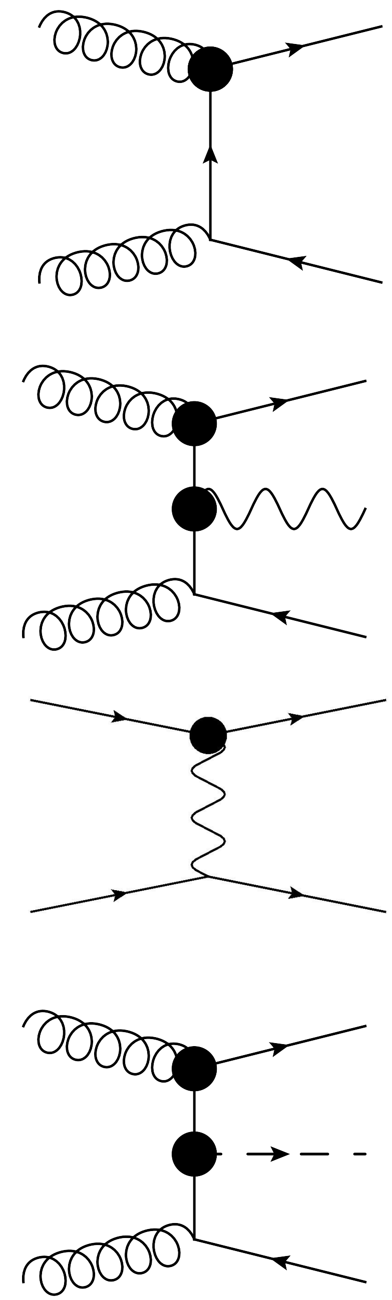

see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

+four-fermion operators

+non-top operators (mixing)

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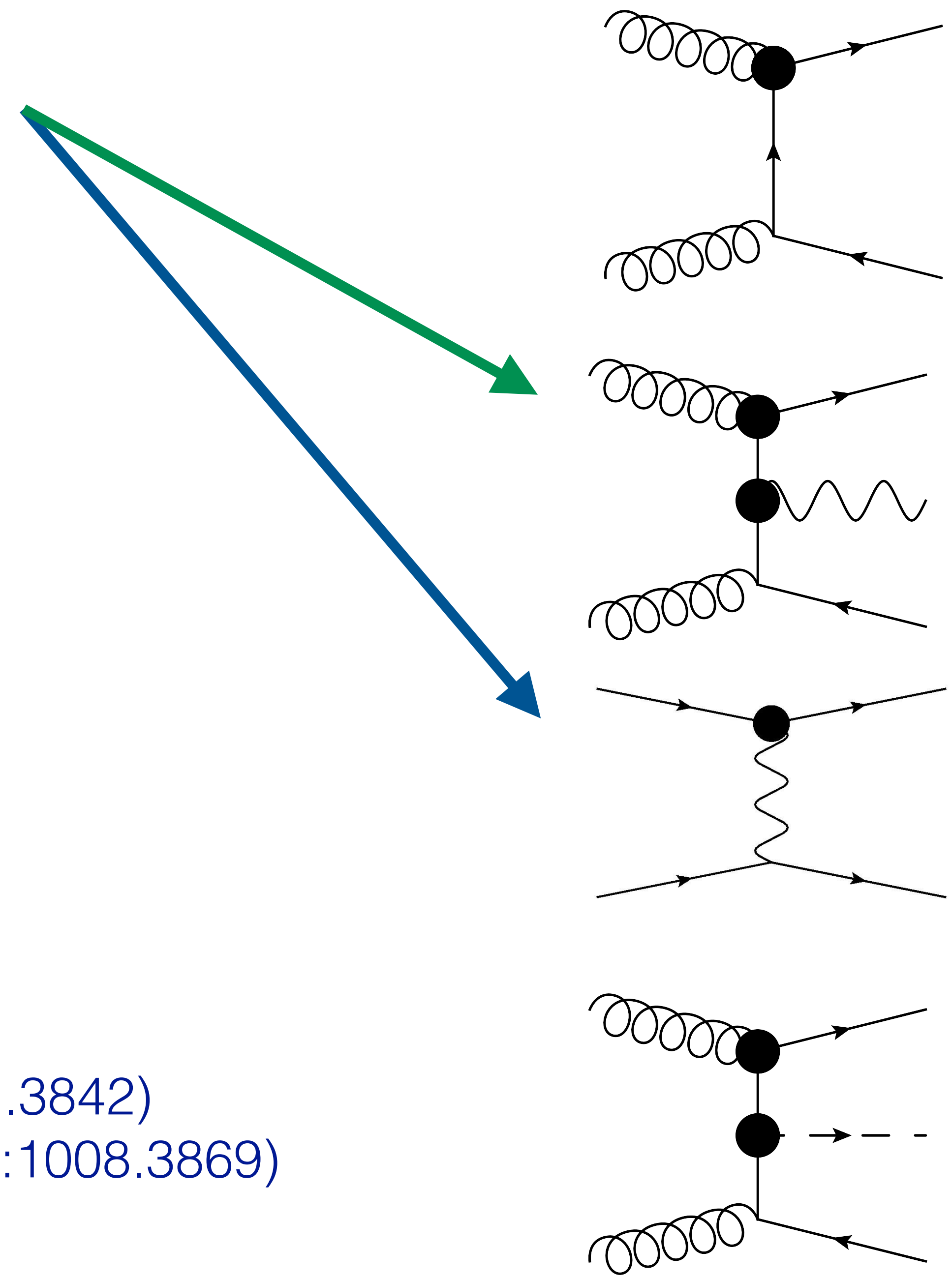

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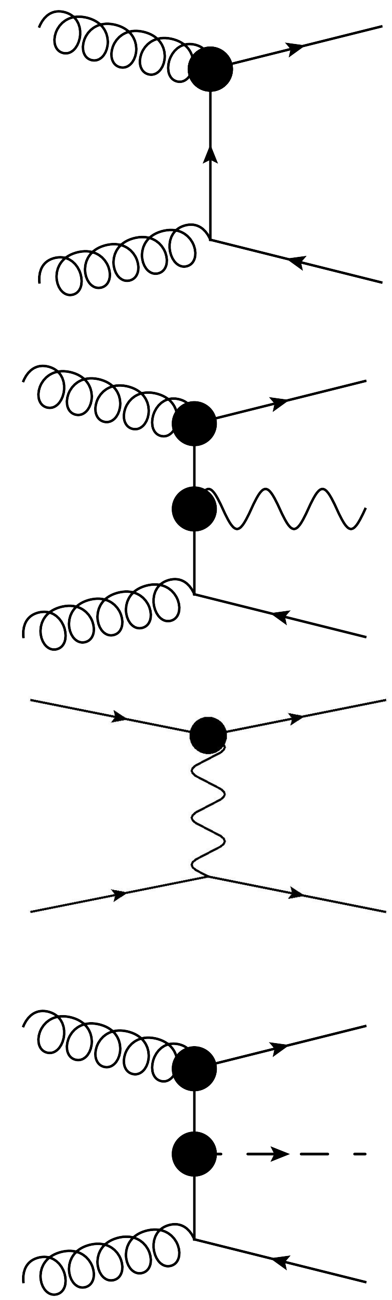

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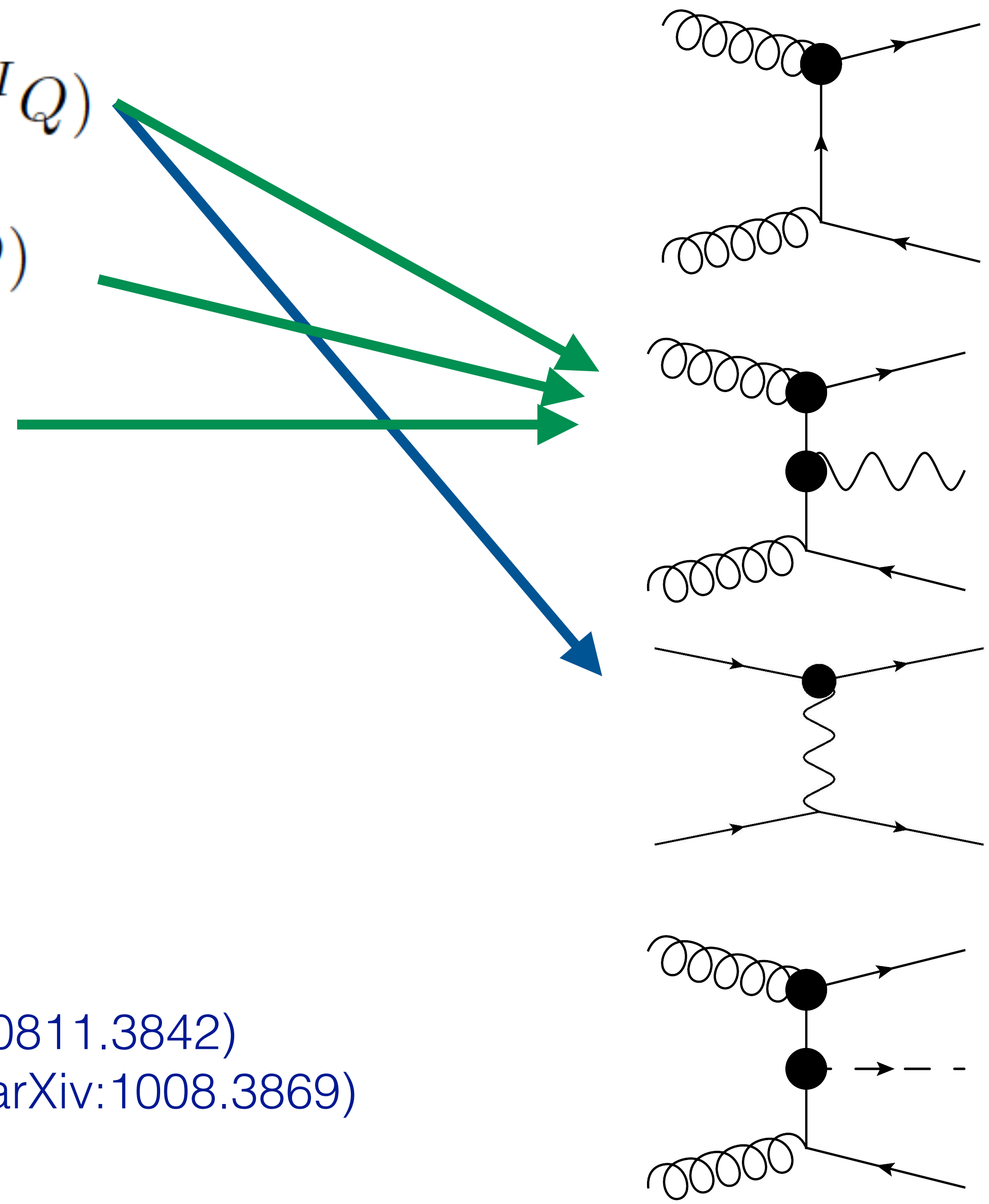

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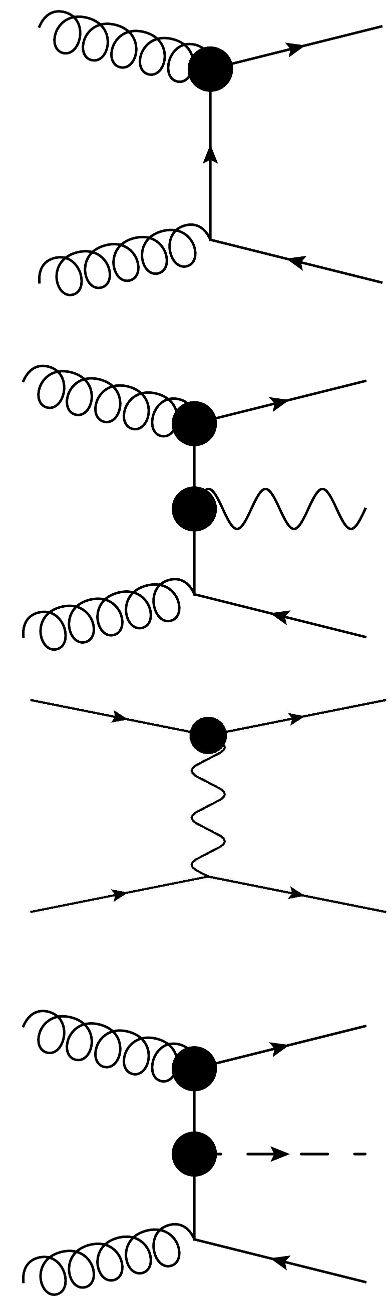

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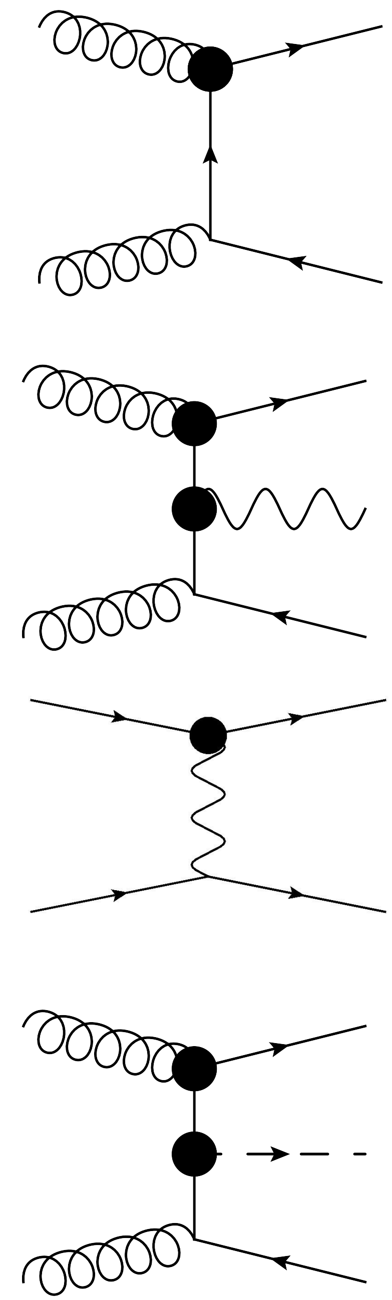

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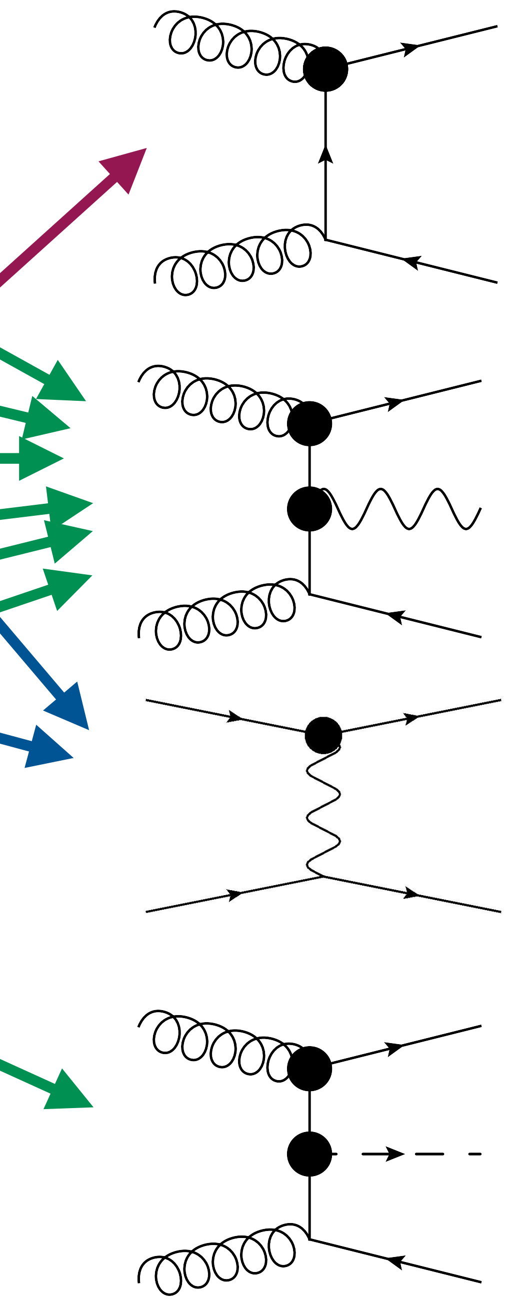
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu},$$

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right)(\bar{Q}t)\,\tilde{\phi}$$



see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

+four-fermion operators

+non-top operators (mixing)

How to probe top operators?

$$O^{(3)}_{\varphi Q} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$O^{(1)}_{\varphi Q} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

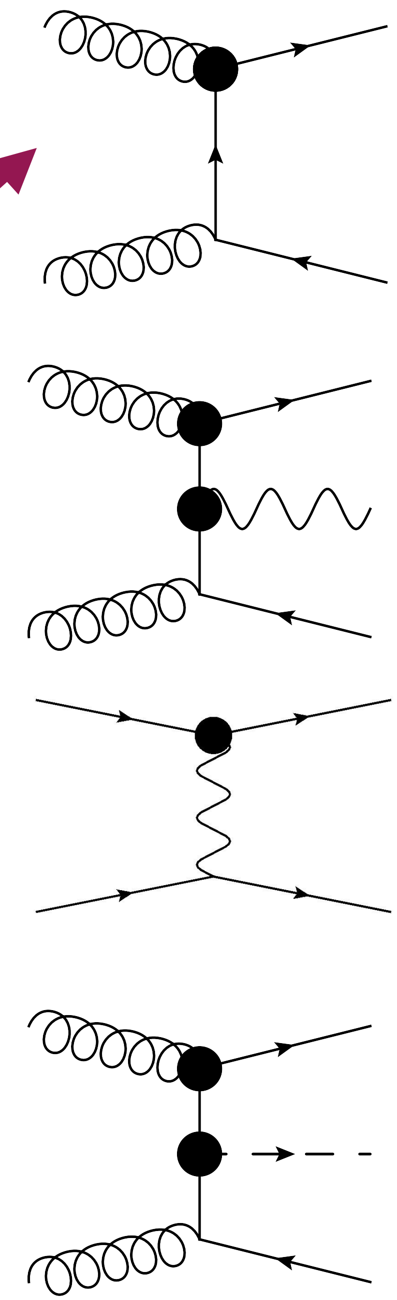
$$O_{\varphi t} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}\,,$$

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right)(\bar{Q}t)\,\tilde{\phi}$$



see for example: Aguilar-Saavedra (arXiv:0811.3842)
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+four-fermion operators

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How to probe top operators?

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

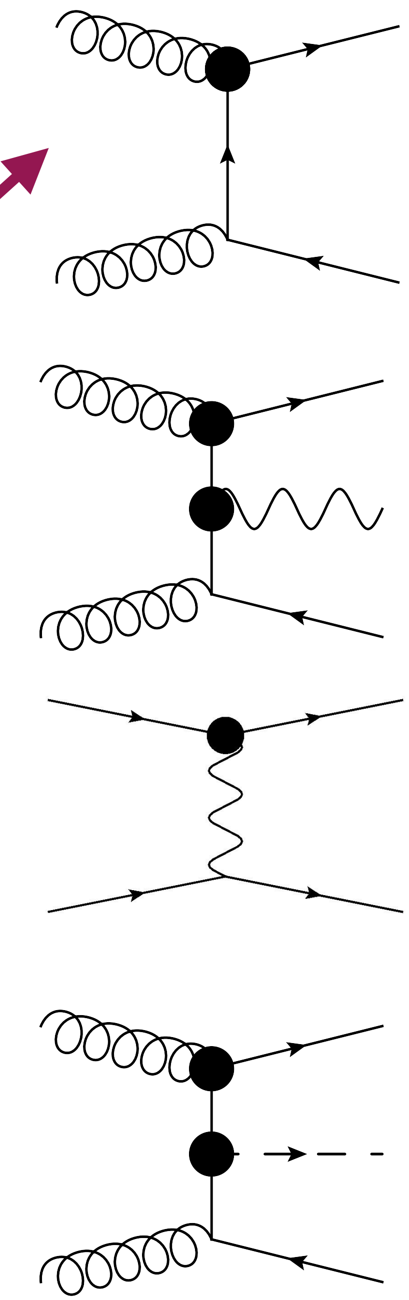
$$O_{\varphi t} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}\,,$$

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right)(\bar{Q}t)\,\tilde{\phi}$$



see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

+four-fermion operators

+non-top operators (mixing)

Operators entering various processes: Global approach needed

EFT@NLO

Aim to obtain a complete Monte Carlo implementation based on:

- Warsaw basis
- Degrees of freedom for top operators as in arXiv:1802.07237 (LHCTopWG)

Current status:

- 73 degrees of freedom (top, Higgs, gauge):
  - CP-conserving
  - Flavour assumption: $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$
- 0/2F@NLO operators validated (with previous partial NLO implementations) → **http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO**
- 4F@NLO operators validation: on-going

Future plans

- Full NLO model release (4F@NLO)
- Other flavour assumptions
- CP-violating effects

Work in progress with: C. Degrande, G. Durieux, F. Maltoni, K. Mimasu, C. Zhang

In practice

UFO model with UV+R2 counterterms
Import to MG5_aMC@NLO
Proceed as in SM case

```
MG5_aMC>import model EFT
MG5_aMC>generate p p > t t~ z NP=2 [QCD]
MG5_aMC>output
MG5_aMC>launch
```

In practice

Behind the scenes…

In practice

UFO model with UV+R2 counterterms
Import to MG5_aMC@NLO
Proceed as in SM case

```
MG5_aMC>import model EFT
MG5_aMC>generate p p > t t~ z NP=2 [QCD]
MG5_aMC>output
MG5_aMC>launch
```

Results:
Fixed order NLO
NLO+PS with MC@NLO

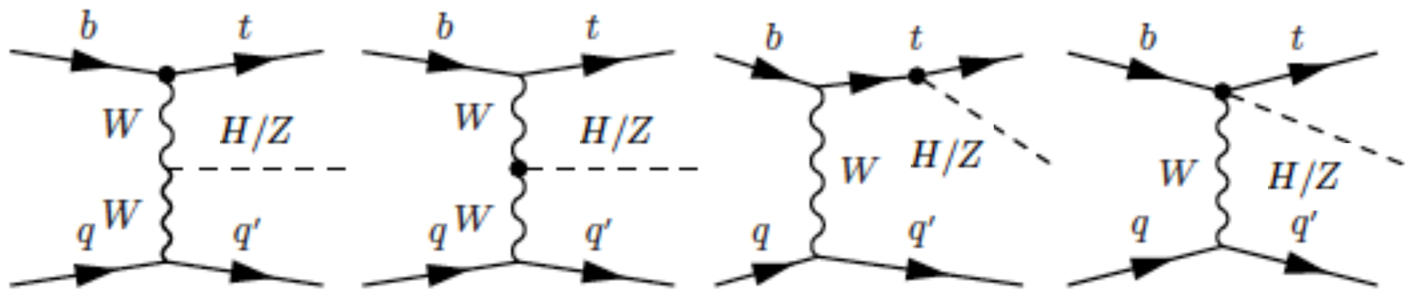
Implementation gives:

$$\sigma = \sigma_{\rm SM} + \sum_i \frac{1{\rm TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \le j} \frac{1{\rm TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}.$$

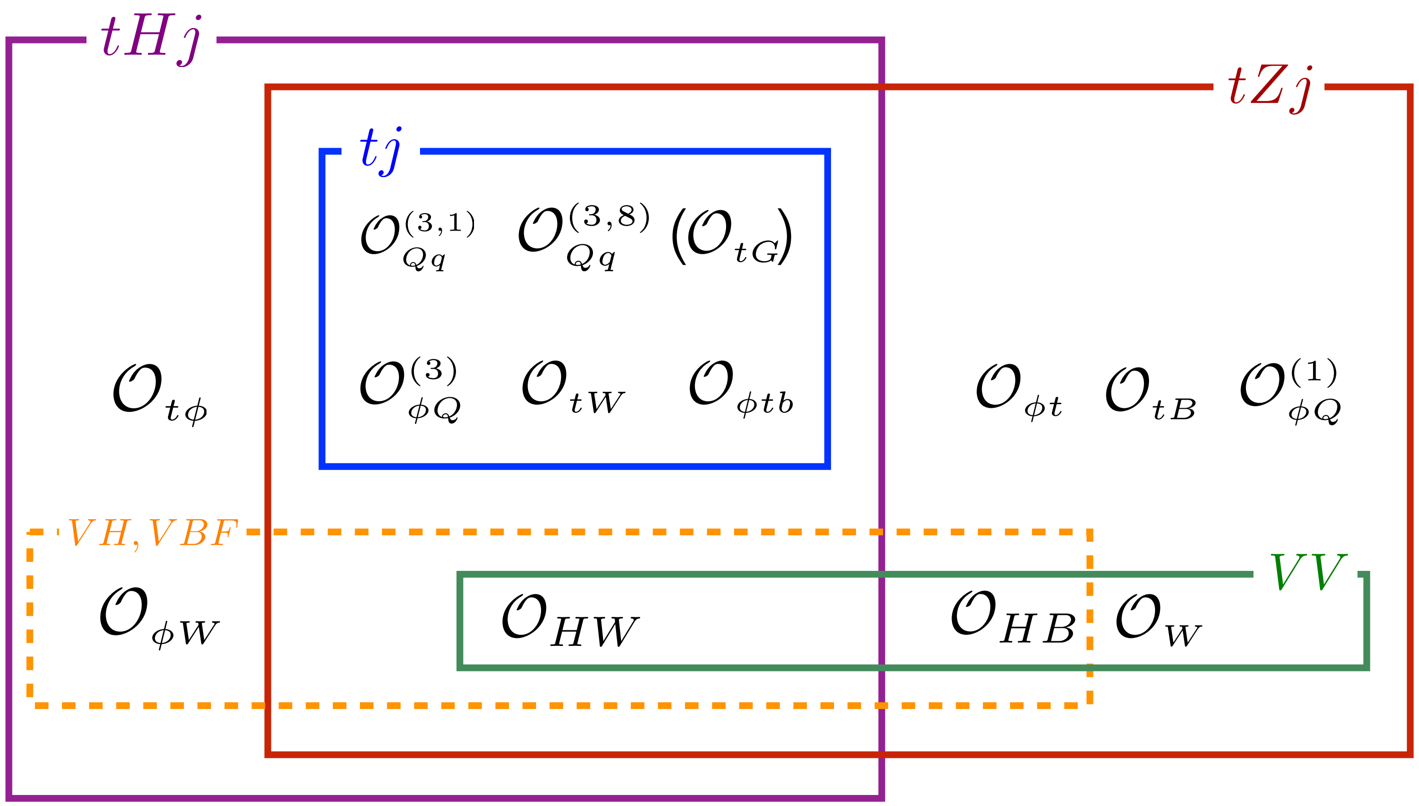
interference with SM

interference between operators, squared contributions

tZj/tHj associated production



Gauge-Higgs
Top couplings
TGC



$\mathcal{O}_{W}$	$\varepsilon_{IJK}\, W^{I}_{\mu\nu}\, W^{J,\nu\rho}\, W^{K,\mu}_{\rho}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{Q}\gamma^\mu \tau^I Q) + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W^{\mu\nu}_{I}\, W^{I}_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\gamma^\mu Q) + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi)\, B^{\mu\nu} W^{I}_{\mu\nu}$	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t) + \text{h.c.}$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$	$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi}\, D_\mu \varphi)(\bar{t}\gamma^\mu b) + \text{h.c.}$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}^{(1)}_{\varphi q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}_i\gamma^\mu q_i) + \text{h.c.}$
$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$	$\mathcal{O}^{(3)}_{\varphi q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{q}_i\gamma^\mu \tau^I q_i) + \text{h.c.}$
$\mathcal{O}_{tW}$	$i(\bar{Q}\sigma^{\mu\nu}\tau_I\, t)\,\tilde{\varphi}\, W^{I}_{\mu\nu} + \text{h.c.}$	$\mathcal{O}_{\varphi u}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{u}_i\gamma^\mu u_i) + \text{h.c.}$
$\mathcal{O}_{tB}$	$i(\bar{Q}\sigma^{\mu\nu}\, t)\,\tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{(3,1)}_{Qq}$	$(\bar{q}_i\gamma_\mu \tau_I q_i)(\bar{Q}\gamma^\mu \tau^I Q)$
$\mathcal{O}_{tG}$	$i(\bar{Q}\sigma^{\mu\nu} T_A\, t)\,\tilde{\varphi}\, G^{A}_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{(3,8)}_{Qq}$	$(\bar{q}_i\gamma_\mu \tau_I T_A q_i)(\bar{Q}\gamma^\mu \tau^I T^A Q)$

Unique interplay

Pure gauge operators (4): $\mathcal{O}_{\varphi W}, \mathcal{O}_{W}, \mathcal{O}_{HW}, \mathcal{O}_{HB}$,

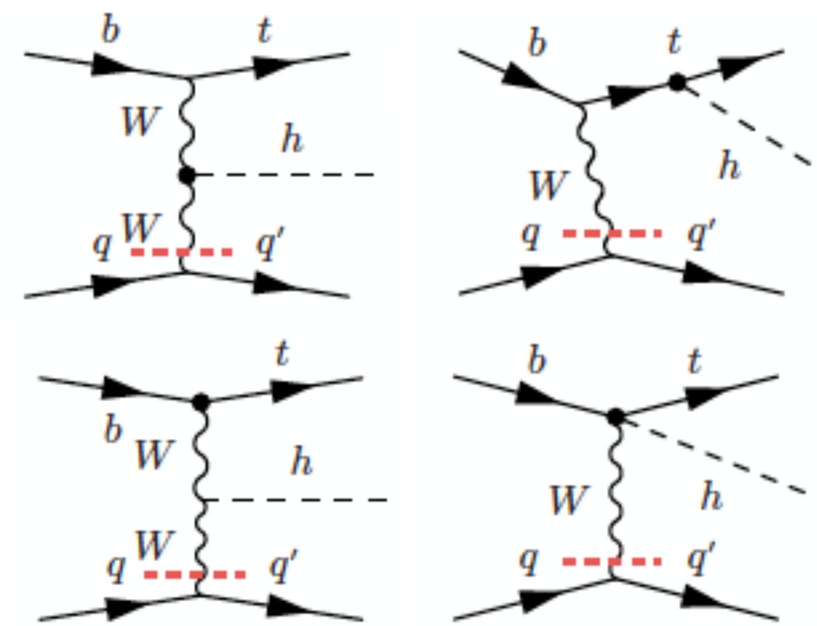
Two-fermion top-quark operators (8): $\mathcal{O}^{(3)}_{\varphi Q}, \mathcal{O}^{(1)}_{\varphi Q}, \mathcal{O}_{\varphi t}, \mathcal{O}_{tW}, \mathcal{O}_{tB}, \mathcal{O}_{tG}, \mathcal{O}_{\varphi tb}, \mathcal{O}_{t\varphi}$

Four-fermion top-quark operators (2): $\mathcal{O}^{(3,1)}_{Qq}, \mathcal{O}^{(3,8)}_{Qq}$.

Helicity amplitudes

bW → tH

$\lambda_b, \lambda_W, \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{HW}$
$-,0,-$	s^0	s^0	$\sqrt{s(s+t)}$	s^0	s^0	$\sqrt{s(s+t)}$
$-,0,+$	$\frac{1}{\sqrt{s}}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$\frac{1}{\sqrt{s}}$	$\frac{m_W s}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$
$-,-,-$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$	$m_W\sqrt{-t}$	$\frac{m_W s}{\sqrt{-t}}$	$m_t\sqrt{-t}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
$-,-,+$	$\frac{1}{s}$	s^0	s^0	$-$	$\sqrt{s(s+t)}$	$\frac{1}{s}$
$-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
$-,+,+$	s^0	$-$	s^0	s^0	s^0	$\frac{1}{s}$



bW → tZ

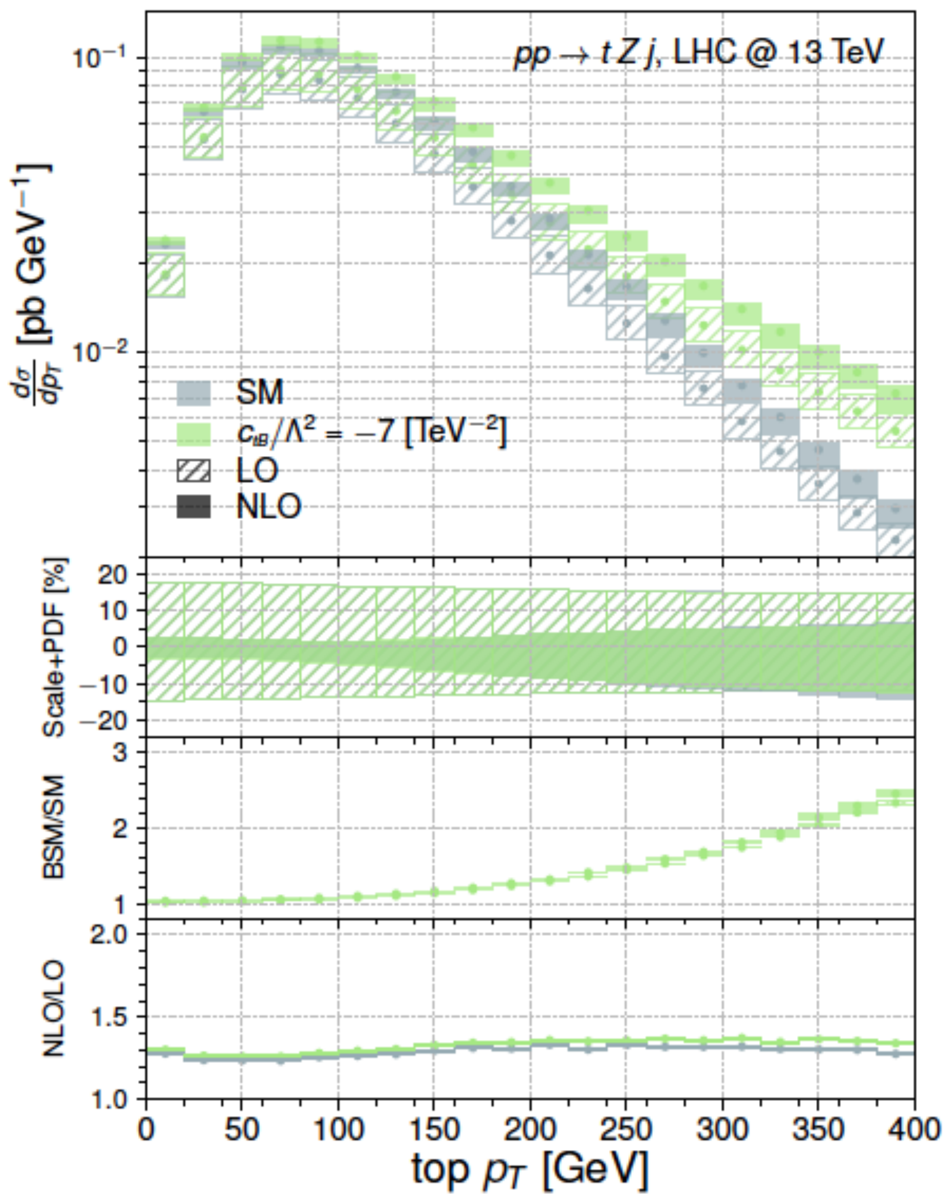
$\lambda_b, \lambda_W, \lambda_t, \lambda_Z$	SM	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{W}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$
$-,0,-,0$	s^0	$\sqrt{s(s+t)}$	$-$	$-$	$-$	s^0	s^0	$\sqrt{s(s+t)}$	s^0
$-,0,+,0$	$\frac{1}{\sqrt{s}}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_Z\sqrt{-t}$	$\frac{m_W(2s+3t)}{\sqrt{-t}}$	$-$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,-,-,0$	$\frac{1}{\sqrt{s}}$	$m_W\sqrt{-t}$	$-$	$-$	$-$	$-$	$\frac{m_W(s+2t)}{\sqrt{-t}}$	$m_W\sqrt{-t}$	$\frac{1}{\sqrt{s}}$
$-,-,+,0$	$\frac{1}{s}$	s^0	s^0	s^0	s^0	$\sqrt{s(s+t)}$	s^0	s^0	$\frac{1}{\sqrt{s}}$
$-,0,-,-$	$\frac{1}{\sqrt{s}}$	$m_W\sqrt{-t}$	$-$	$-$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$\frac{m_W(s+2t)}{\sqrt{-t}}$	$\frac{m_W(ss_W^2+2t)}{\sqrt{-t}}$	$\frac{m_W s}{\sqrt{-t}}$
$-,0,-,+$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
$-,0,+,-$	s^0	s^0	s^0	$-$	$-$	s^0	s^0	s^0	s^0
$-,0,+,+$	$\frac{1}{s}$	s^0	s^0	s^0	$\sqrt{s(s+t)}$	$\sqrt{s(s+t)}$	$-$	s^0	s^0
$-,+,-,0$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$
$-,+,+,0$	s^0	s^0	$-$	$-$	$-$	s^0	$-$	s^0	$\frac{1}{s}$
$-,-,-,-$	s^0	s^0	s^0	$-$	s^0	s^0	s^0	s^0	s^0
$-,-,-,+$	$\frac{1}{s}$	$-$	$-$	$-$	$-$	$-$	$\sqrt{s(s+t)}$	s^0	s^0
$-,-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$\frac{m_Z\left(s_W^2 t-3c_W^2(2s+t)\right)}{\sqrt{-t}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$
$-,-,+,+$	$-$	$-$	$-$	$-$	$m_W\sqrt{-t}$	$m_Z\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,+,-,-$	$\frac{1}{s}$	$-$	$-$	$-$	$-$	$-$	$\sqrt{s(s+t)}$	s^0	s^0
$-,+,-,+$	s^0	s^0	s^0	$-$	$-$	$-$	$-$	s^0	s^0
$-,+,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,+,+,+$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$

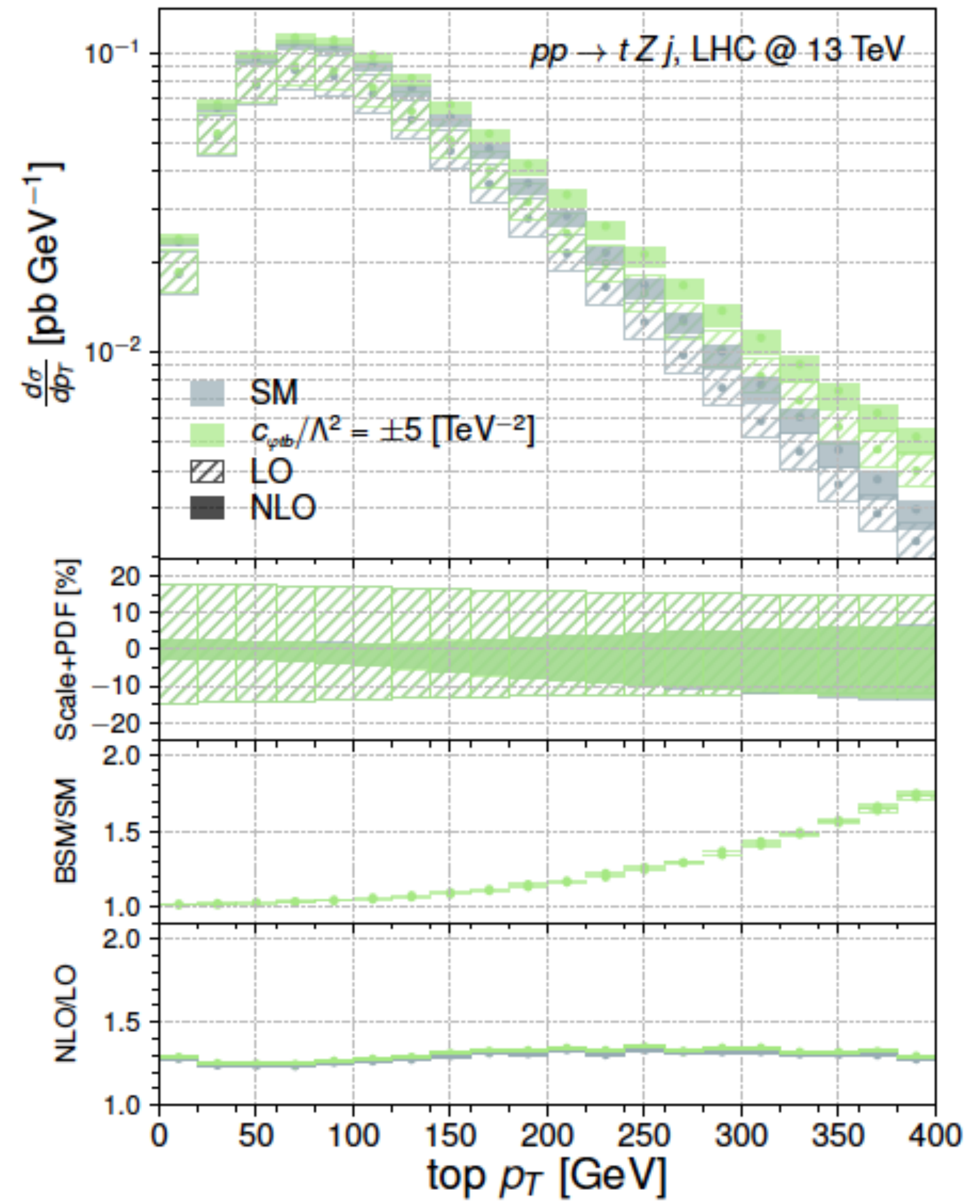
Amplitudes growing with energy as SM cancellations get spoiled ➡

Large deviations
Differential distributions

Differential results

tZj



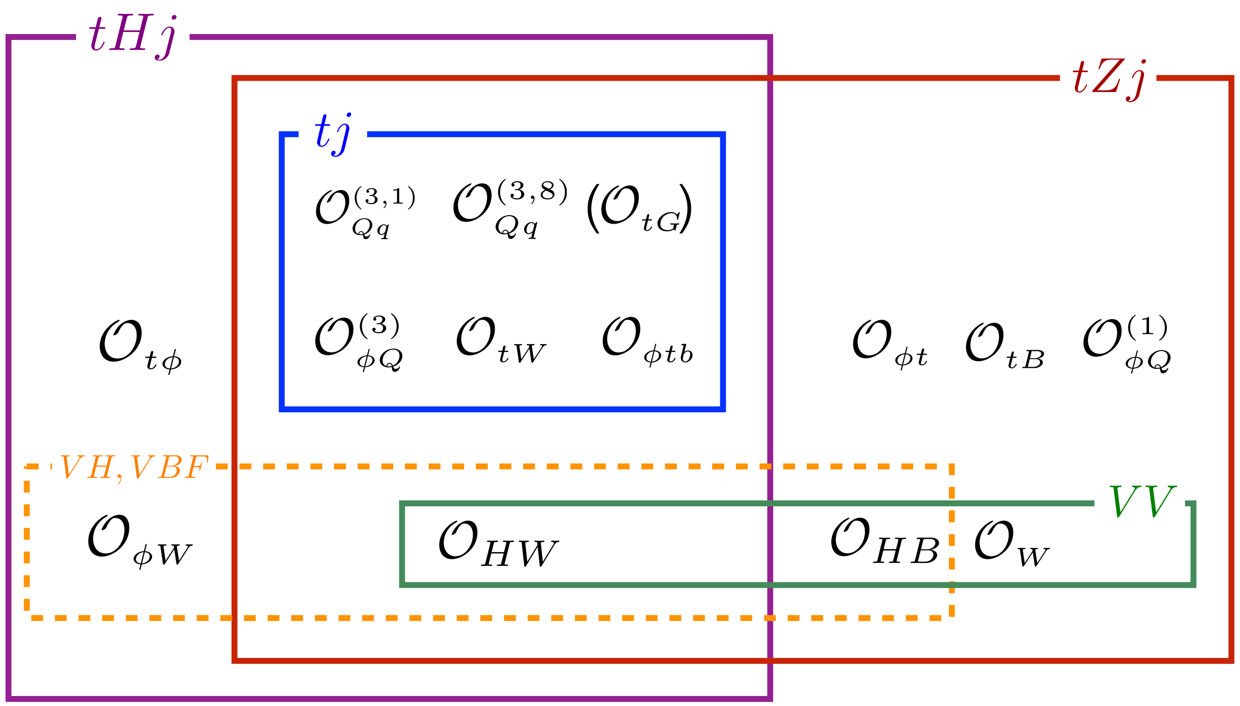


Degrande, Maltoni, Mimasu, EV, Zhang arXiv:1804.07773

Large deviations in the tails, as expected from helicity amplitudes

Comparison with single top

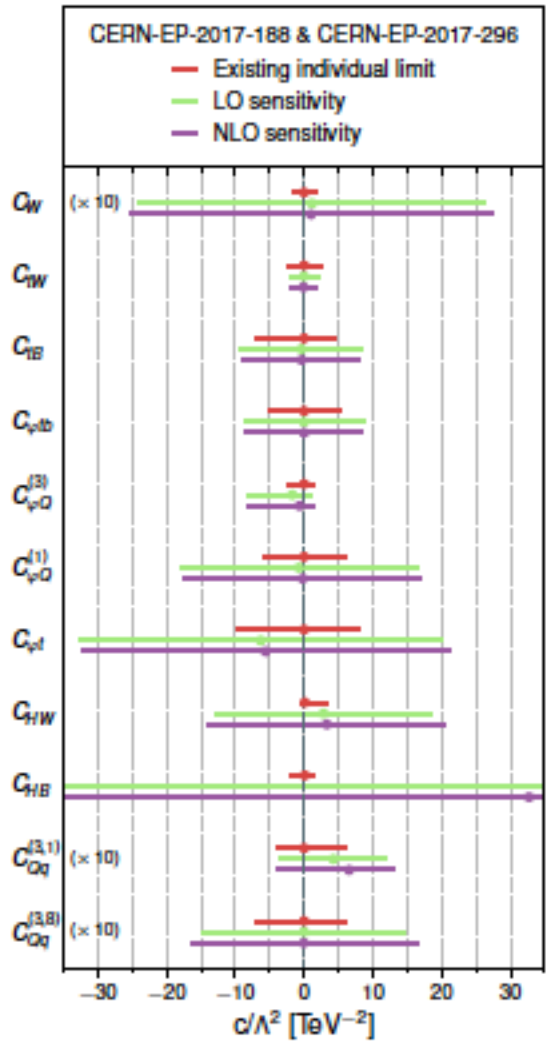
	tj	tj ($p_T^t > 350$ GeV)	tZj	tZj ($p_T^t > 250$ GeV)
σ_{SM}	224 pb	880 fb	839 fb	69 fb
r_{tW}	0.0275	0.024	0.016	0.010
$r_{tW,tW}$	0.0162	0.35	0.095	0.67
$r_{\varphi Q^{(3)}}$	0.121	0.121	0.192	0.172
$r_{\varphi Q^{(3)},\varphi Q^{(3)}}$	0.0037	0.0037	0.029	0.114
$r_{\varphi tb,\varphi tb}$	0.00090	0.0008	0.0050	0.027
$r_{Qq^{(3,1)}}$	-0.353	-4.4	-0.59	-2.22
$r_{Qq^{(3,1)},Qq^{(3,1)}}$	0.126	11.5	0.65	5.1
$r_{Qq^{(3,8)},Qq^{(3,8)}}$	0.0308	2.73	0.133	1.01



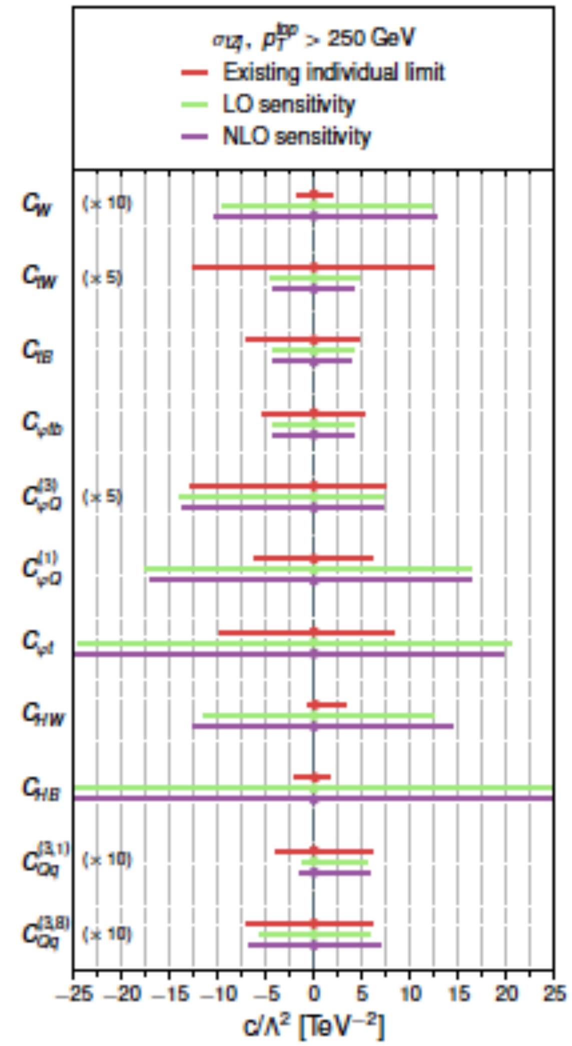
- Increased sensitivity for dipoles and right-handed current (as expected from helicity analysis)
- 4-fermion operators sensitivity due to higher thresholds can be outperformed by high-pT single top measurements

Current and future sensitivity

Current:



Future:



Degrande, Maltoni, Mimasu, EV, Zhang arXiv:1804.07773

tZj measurements:
CMS; PLB 779 (2018) 358-384: 0.75 ± 0.27
ATLAS; CERN-EP-2017-188: 1.31 ± 0.47

Promising for weak dipoles, RHCC and SU(2) current in particular for HL-LHC where high pT data can be used

Rare processes can play a role in a global fit

Global fit Setup

Theory

(N)NLO QCD for SM
NLO QCD for SMEFT

Data

Top pair production and single top (differential)
Associated production with W,Z
W helicity fractions
Parton-level

Global SMEFT fit of the top-quark sector

Methodology

Sfitter framework
Theoretical and experimental uncertainties/Correlations

Output

Fit results can be used to bound specific UV complete models
New data can be straightforwardly added

See also: Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965 (SMEFiT analysis)

Observables and theory predictions

Data

- Top-pair production
- W-helicities
- Single top: t-channel, s-channel
- tW, tZ
- ttW, ttZ

experiment	$\sqrt{S}$ (TeV)	$\mathcal{L}$ (fb^{-1})	channel	observable & K-f
$pp \to t\bar{t}$				
CMS [52]	8	19.7	$e\mu$	$\sigma_{t\bar{t}}$
ATLAS [54]	8	20.02	lj	$\sigma_{t\bar{t}}$
CMS [55]	13	2.3	lj	$\sigma_{t\bar{t}}$
CMS [56]	13	3.2	ll	$\sigma_{t\bar{t}}$
ATLAS [57]	13	3.2	$e\mu$	$\sigma_{t\bar{t}}$
ATLAS [58]	8	20.3	lj	$\sigma^{-1}(d\sigma/dm_{t\bar{t}})$
CMS [62]	8	19.7	lj	$\sigma^{-1}(d\sigma/dp_{T,t})$
			ll	$\sigma^{-1}(d\sigma/dp_{T,1})$
CMS [63]	8	19.7	$e\mu$	$\sigma^{-1}(d^2\sigma/dm_{t\bar{t}}dy_{t\bar{t}}$
CMS [65]	8	19.7	lj high p_T	$d\sigma/dp_{T,t}$
CMS [66]	13	2.3	lj	$\sigma^{-1}(d\sigma/dm_{t\bar{t}})$
CMS [67]	13	35.8	lj	$\sigma^{-1}(d\sigma/dp_T(t_h))$
CMS [68]	13	2.1	ll	$\sigma^{-1}(d\sigma/dp_{T,t})$
CMS [69]	13	35.9	ll	$\sigma^{-1}(d\sigma/d\Delta y_{t\bar{t}})$
ATLAS [70]	13	36.1	aj high p_T	$\sigma^{-1}(d\sigma/dm_{t\bar{t}})$
CMS [71]	8	19.7	lj	A_C
CMS [73]	8	19.7	ll	A_C
ATLAS [74]	8	20.3	lj	A_C
ATLAS [75]	8	20.3	ll	A_C
ATLAS [76]	13	139	lj	A_C
$pp \to t\bar{t}Z$				
CMS [77]	13	77.5	multi lept.	$\sigma_{t\bar{t}Z}$
ATLAS [79]	13	3.2	multi lept.	$\sigma_{t\bar{t}Z}$
$pp \to t\bar{t}W$				
CMS [80]	13	35.9	multi lept.	$\sigma_{t\bar{t}W}$
ATLAS [79]	13	3.2	multi lept.	$\sigma_{t\bar{t}W}$

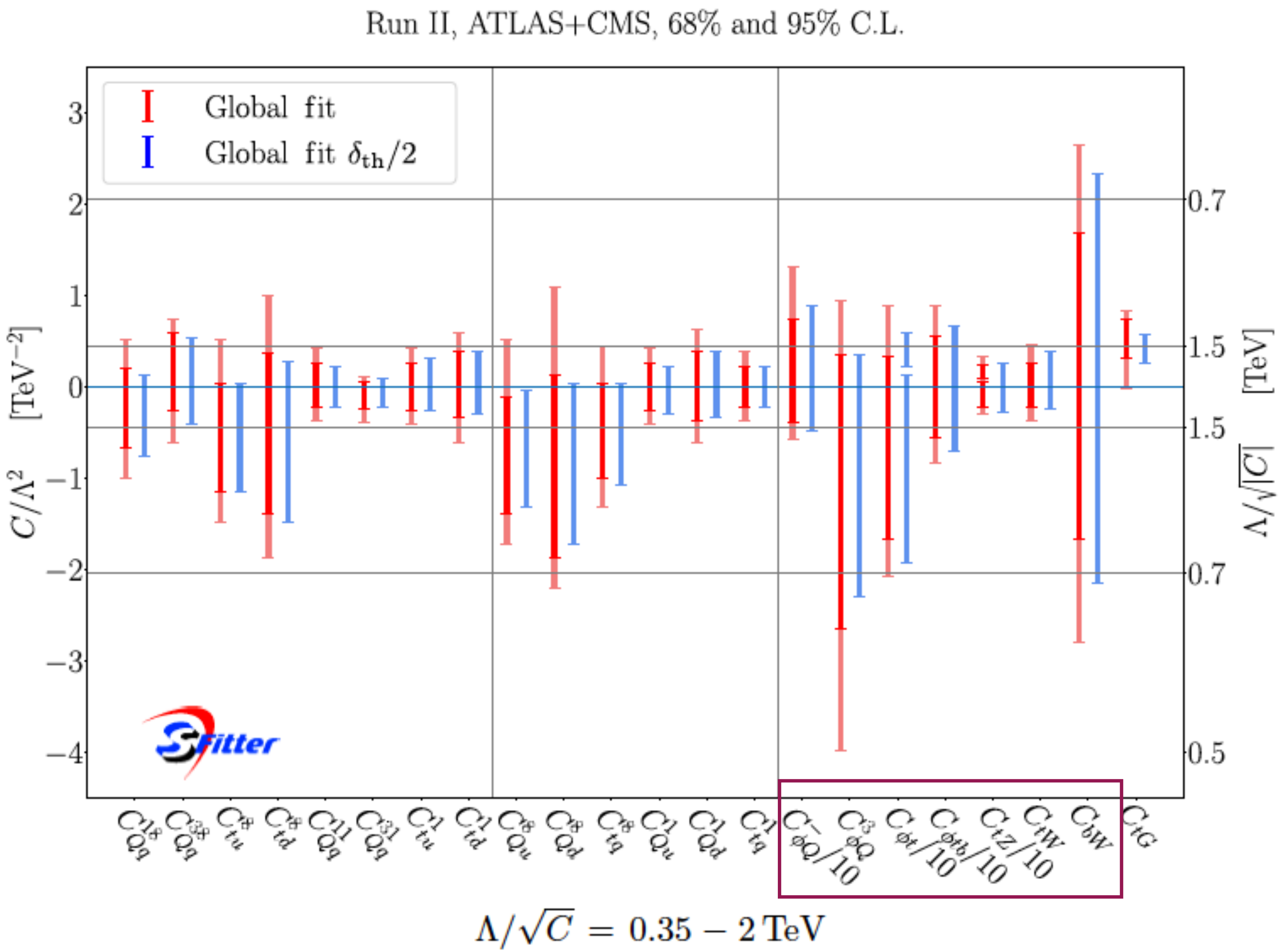
experiment	$\sqrt{S}$ (TeV)	$\mathcal{L}$ (fb^{-1})	channel	observable
$t-$channel				
CMS [81]	7	1.17 (μ), 1.56 (e)	$e+\mu$	$\sigma_{tq+\bar{t}q}$
ATLAS [82]	7	4.59	$e+\mu$	$\sigma_{tq+\bar{t}q}$
ATLAS [83]	8	20.2	$e+\mu$	$\sigma_{tq}, \sigma_{\bar{t}q}$
CMS [84]	8	19.7	$e+\mu$	$\sigma_{tq}, \sigma_{\bar{t}q}$
ATLAS [85]	13	3.2	$e+\mu$	$\sigma_{tq}, \sigma_{\bar{t}q}$
CMS [87]	13	2.3	μ	$\sigma_{tq}, \sigma_{\bar{t}q}$
$s-$channel				
CMS [88]	7	5.1	μ	$\sigma_{t\bar{b}+\bar{t}b}$
	8	19.7	$e+\mu$	$\sigma_{t\bar{b}+\bar{t}b}$
ATLAS [89]	8	20.3	$e+\mu$	$\sigma_{t\bar{b}+\bar{t}b}$
tW channel				
ATLAS [90]	7	2.05	$2lj$	$\sigma_{tW+\bar{t}W}$
CMS [91]	7	4.9	$2lj$	$\sigma_{tW+\bar{t}W}$
ATLAS [92]	8	20.3	$2lj$	$\sigma_{tW+\bar{t}W}$
CMS [93]	8	12.2	$2lj$	$\sigma_{tW+\bar{t}W}$
ATLAS [94]	13	3.2	$2lj$	$\sigma_{tW+\bar{t}W}$
CMS [95]	13	35.9	$e\mu j$	$\sigma_{tW+\bar{t}W}$
tZ channel				
ATLAS [96]	13	36.1	$3l2j$	σ_{tZq}
W helicities in top decays				
ATLAS [97]	7	1.04		F_0, F_L
CMS [98]	13	5.0		F_0, F_L
ATLAS [99]	8	20.2		F_0, F_L
CMS [100]	8	19.8		F_0, F_L

Theoretical predictions

- Best available SM predictions
- NLO EFT predictions
- $O(1/\Lambda^4)$ terms

See also: Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

Global fit results



Brivio, Bruggisser, Maltoni, Moutafis, Plehn, EV, Westhoff, Zhang arXiv:1910.03606

Summary

- Differential SM tZ predictions available at NLO in both the 5F and 4F scheme
- Off-shell and interference effects needed to ensure a good description beyond the Z-mass peak
- EFT tools also available for NLO prediction in the SMEFT
- Differential information from the measurements will play a special role in determining the top-Z interaction

thanks for your attention