UCLouvain
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SMEFT at NLO

Celine Degrande

Plan

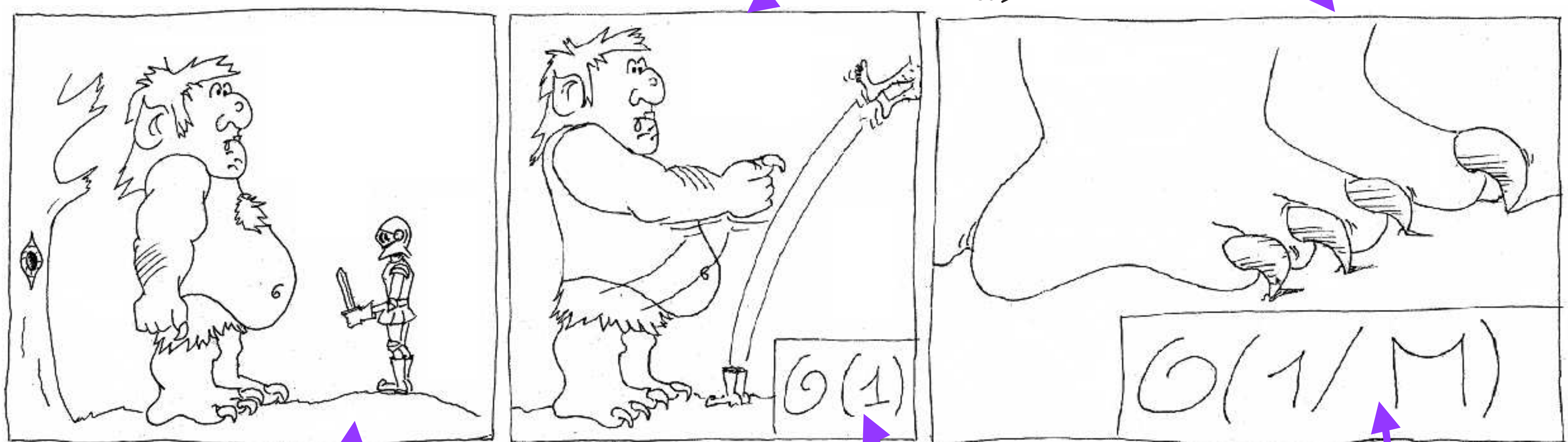
- Introduction
- Challenges
- Status
- Outlook

In collaboration with G. Durieux, F. Maltoni, K. Mimasu, A. Vasquez, E. Vryonidou, C. Zhang

Introduction

EFT and NLO

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_i \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$



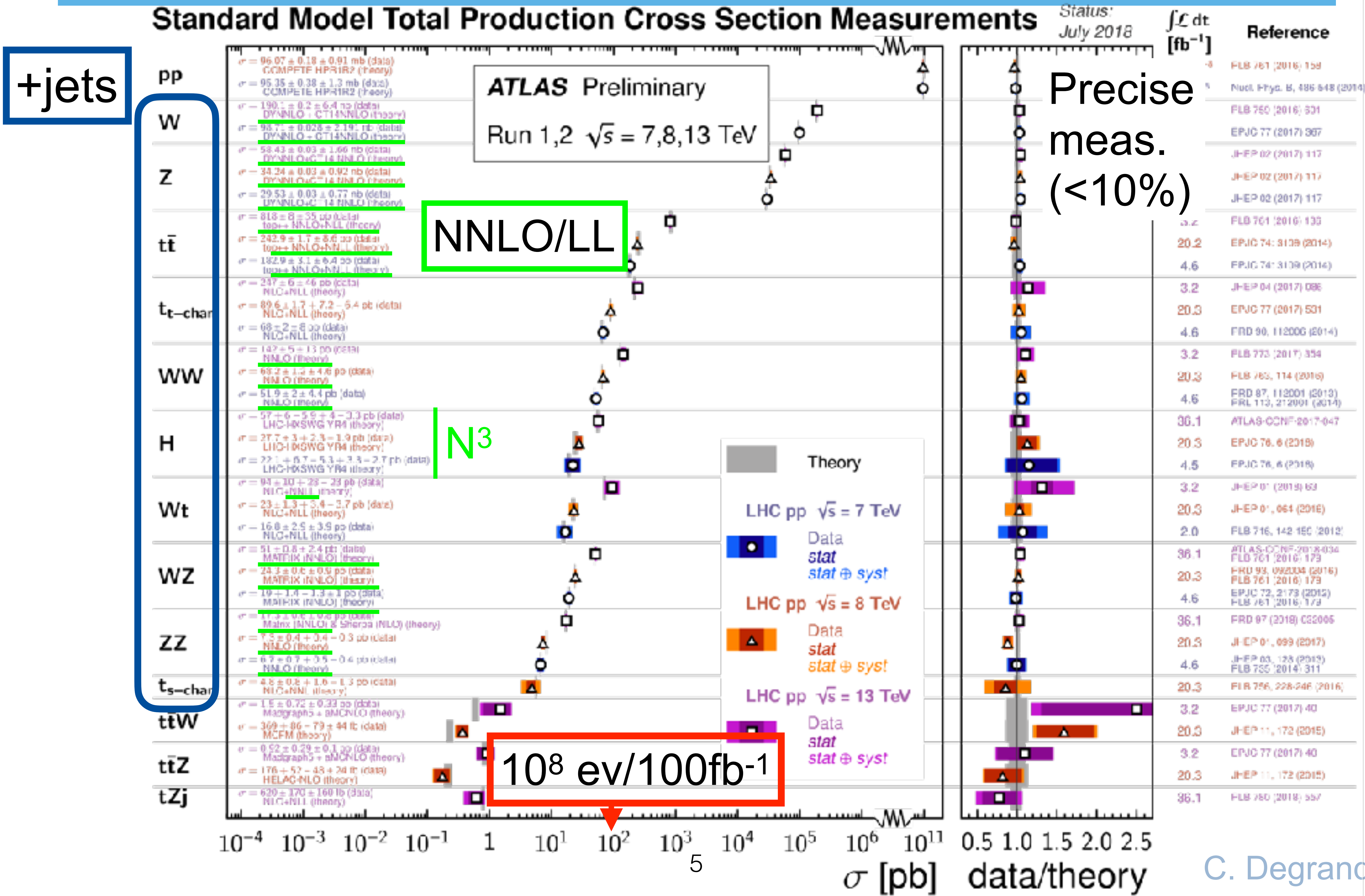
$$\frac{d\sigma}{dX} = \alpha_s^2 \frac{d\sigma^{LO}}{dX} + \alpha_s^3 \frac{d\sigma^{NLO}}{dX} + \alpha_s^4 \frac{d\sigma^{NNLO}}{dX} + \dots$$

$$\frac{d\sigma}{dX} = \alpha_s^2\, 0 + \alpha_s^3 \frac{d\sigma^{LO}}{dX} + \alpha_s^4 \frac{d\sigma^{NLO}}{dX} + \dots$$

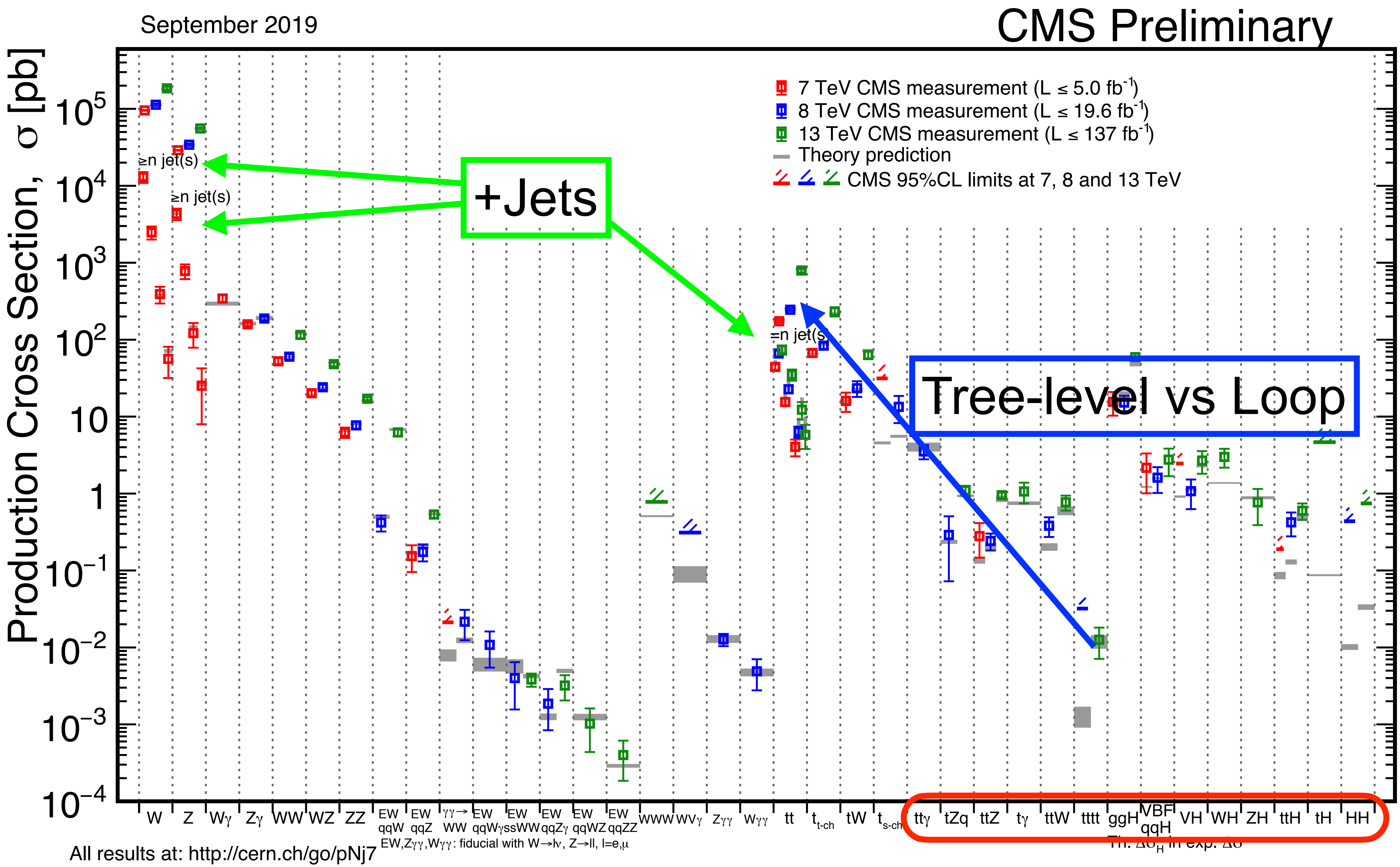
Tree-level | One-loop | Two-loop

Automation of one-loop for SMEFT

Precision era at the LHC



Precision era at the LHC



C. Degrande

Challenges

EFT at NLO (QCD)

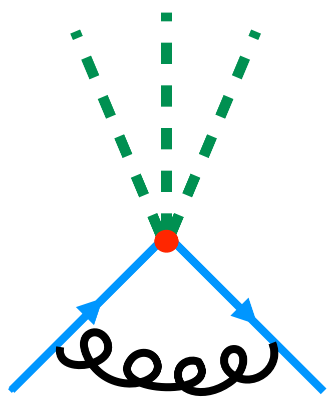
B. Grzadkowski et al, JHEP 1010 (2010) 085

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

No QCD particle

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

EFT at NLO



In the loop:
same as SM
+axial anomaly

$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$

$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$

$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$

$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$

More momenta: higher rank of the integral numerator

Additional gamma and colour algebra

$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$

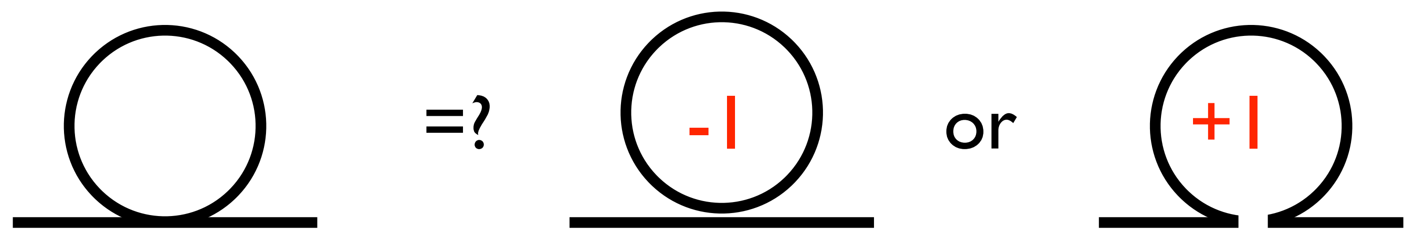
EFT at NLO

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

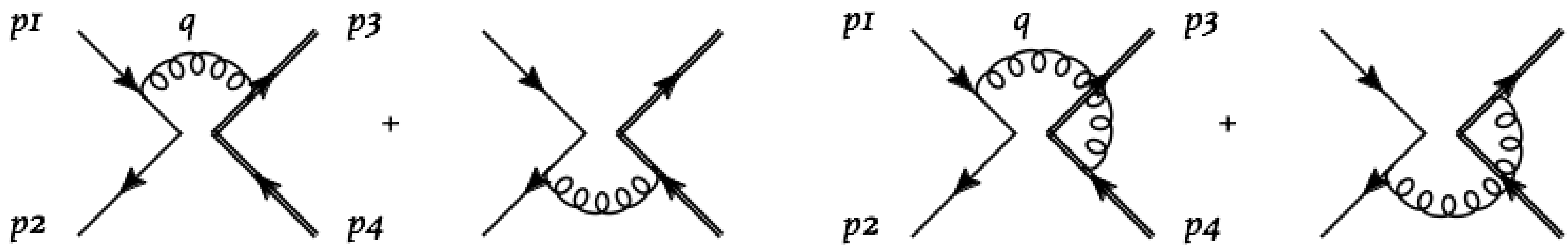
Same as SM but axial anomaly!

$(\bar{L}R)(\bar{R}L)$ 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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

EFT at NLO



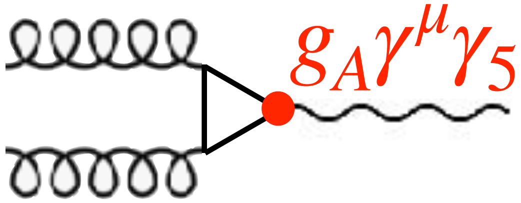
Evanescent operators: $O_{ut}^{(8)} = \left(\bar{u}\gamma^{\mu}T^{A}u\right)\left(\bar{t}\gamma_{\mu}T^{A}t\right)$



$$\gamma^{\mu}\gamma^{\nu}\gamma^{\rho}P_R\otimes\gamma_{\mu}\gamma_{\nu}\gamma_{\rho}P_R = E + (16-4a\varepsilon)\gamma^{\mu}P_R\otimes\gamma_{\mu}P_R$$
$$\gamma^{\mu}\gamma^{\nu}\gamma^{\rho}P_R\otimes\gamma_{\rho}\gamma_{\nu}\gamma_{\mu}P_R = -E + [4-(12-4a)\varepsilon]\gamma^{\mu}P_R\otimes\gamma_{\mu}P_R$$

Extra R2 (gauge invariant)
Change the UV matching

Axial anomaly



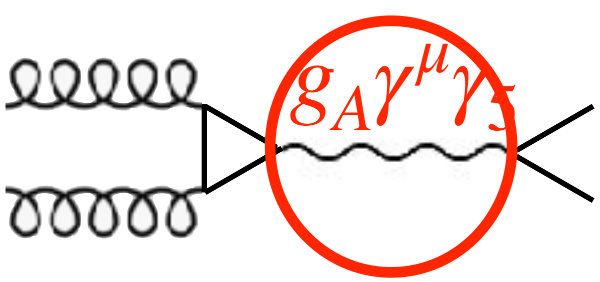
SM:

$$g_A^u = g_A^c = g_A^t = -g_A^d = -g_A^s = -g_A^b$$

SMEFT:

$$g_A^u \neq g_A^c \neq g_A^t \neq -g_A^d \neq -g_A^s \neq -g_A^b$$

+ modification of quarks-gluon vertex (chromo)



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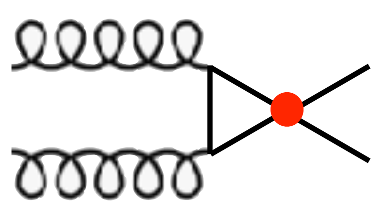
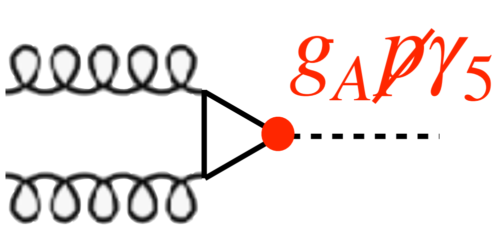
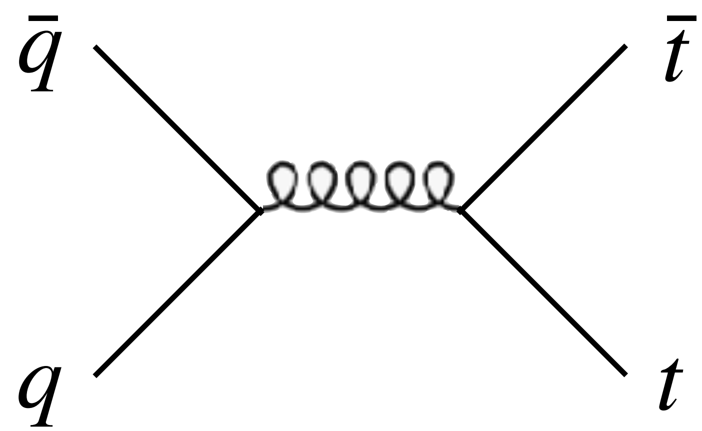


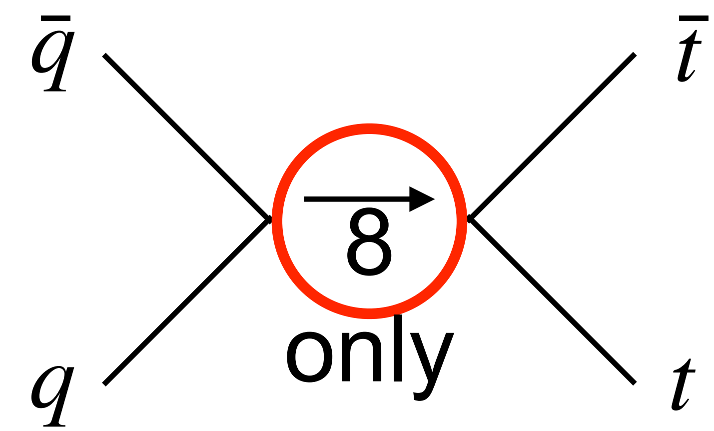


$$\propto \epsilon^{p_1 p_2 \mu_1 \mu_2}$$

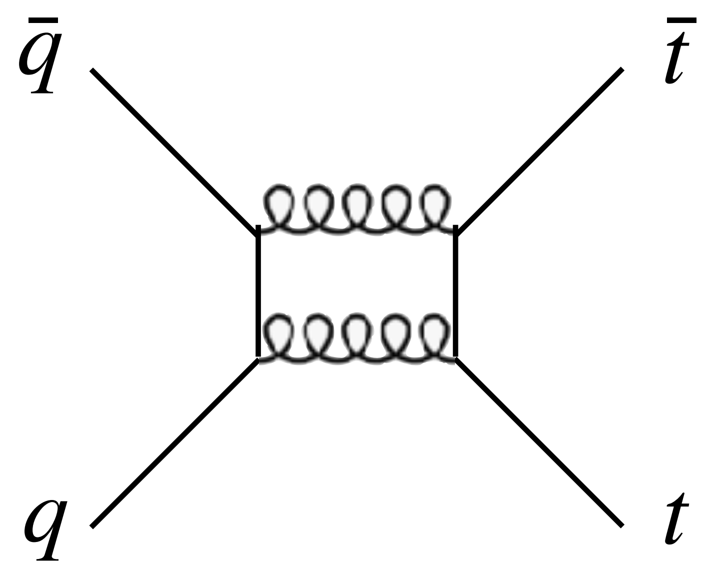
More operators/process

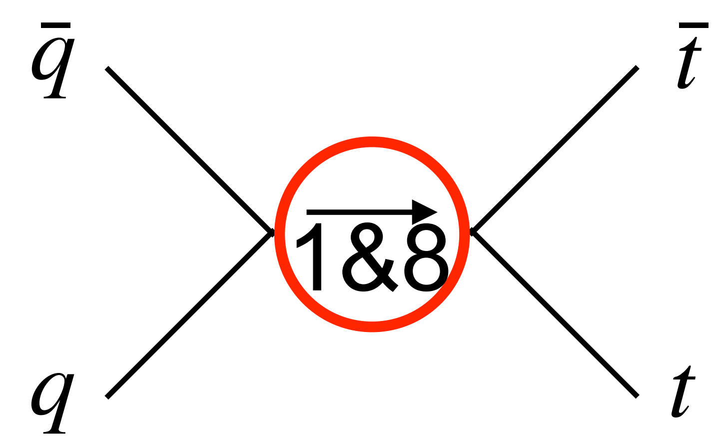
LO:





NLO:



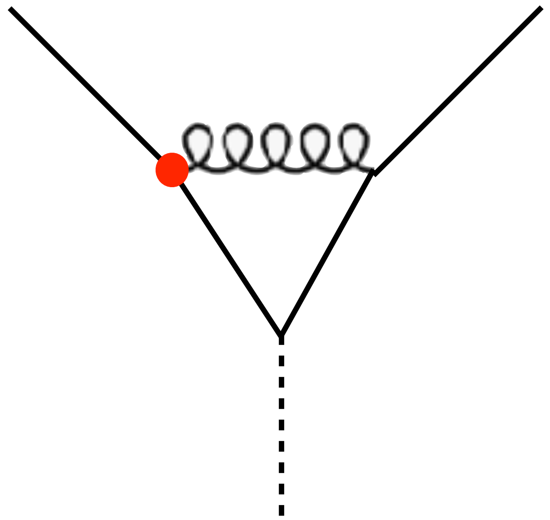


- 4-tops to top pair prod.,…
- Fit & correlations

Running and mixing

$C_{uG}^{(13)}, C_{uW}^{(13)}, C_{uB}^{(13)}$ and $C_{u\varphi}^{(13)}$

$$\gamma = \frac{\alpha_S}{\pi} \begin{pmatrix} \frac{1}{3} & 0 & 0 & 0 \\ \frac{2}{3} & \frac{2}{3} & 0 & 0 \\ \frac{10}{9} & 0 & \frac{2}{3} & 0 \\ 4y_t^2 & 0 & 0 & -2 \end{pmatrix}$$

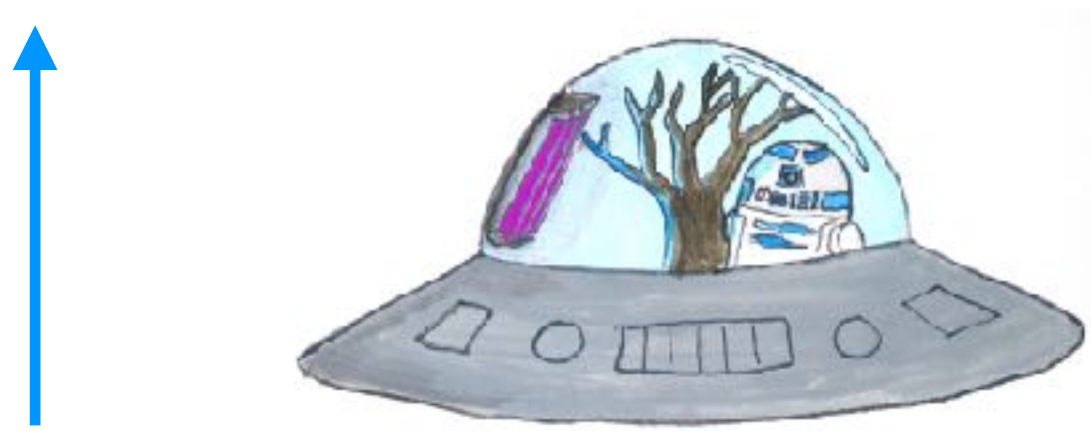


R. Alonso, E. Jenkins, A. Manohar, M. Trott, *JHEP* 10 (2013) 087, *JHEP* 01 (2014) 035, *JHEP* 04 (2014) 159

Status

Automated BSM at one-loop

- NLO for tree-level processes/LO for loop-induced
- dimension-4 BSM at first
- MadGraph5_aMC@NLO: one-loop computation + PS



- FeynRules: Model tree-level vertices and UV/R2 counterterms
    - UV+basis reduction, check R. Alonso, E. E. Jenkins, A. V. Manohar, M. Trott, JHEP 1404 (2014) 159

0F

- SM counterterms for EW
- Anomalous gluon interaction:
  - V. Hirschi, F. Maltoni, I. Tsinikos, E. Vryonidou, *JHEP* 07 (2018) 093
- Higgs gluon interaction: like SM heavy top limit for H prod but for HH (A. Buchalla et al, *JHEP* 09 (2018) 057), …

2F

CD et al. (*Phys.Rev.D* 91 (2015) 034024) (FCNC)

- Non-trivial: Chromomagnetic
- $\psi^2\varphi^3$ like SM
- $\psi^2\varphi^2 D$ like SM but
  - axial anomaly : gg > Z > tt, gg>gz,uu>gz,… few fb/TeV^4 but larger when not properly taken into account

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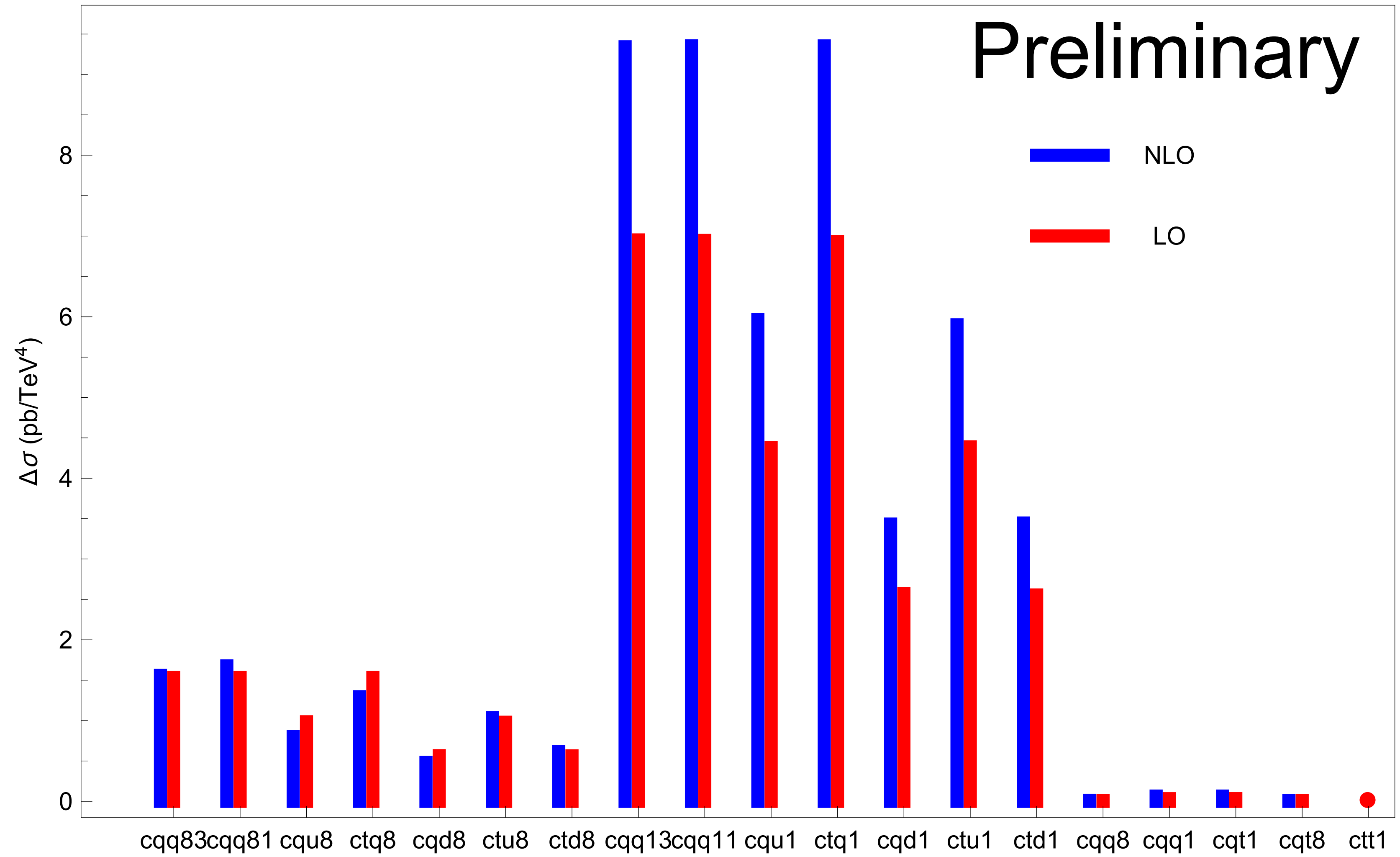
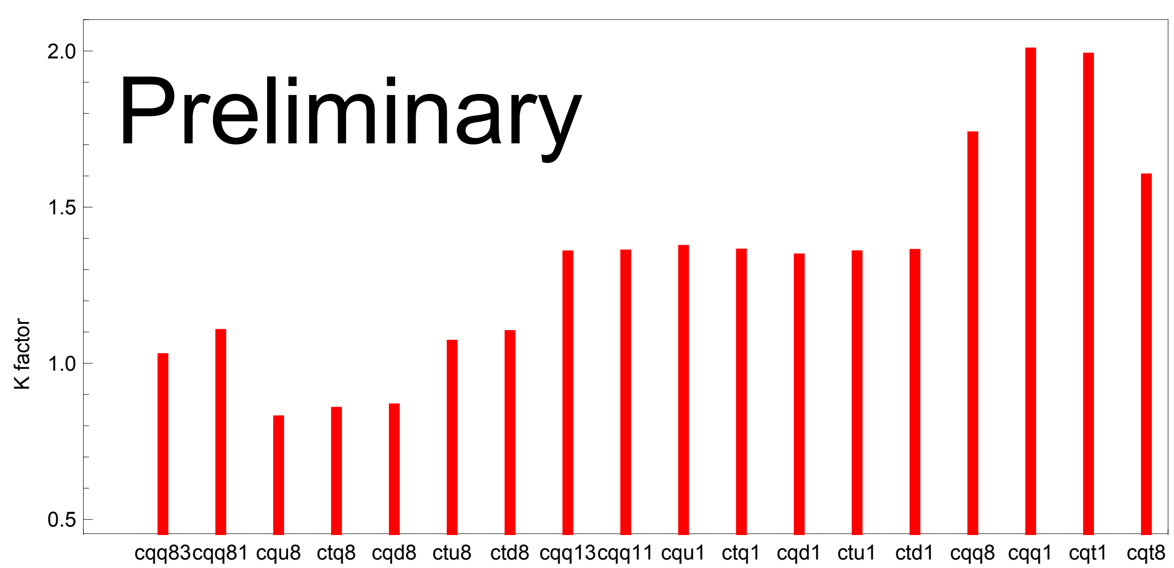
Full UFO for top SMEFT being tested

dim6²





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Outlook

Outlook

- LHC is entering the precision era
- EFT is multi-channel/observable (even more at one-loop)
- Global fit with a large number of parameters/multiple data
- Interplay between PDF and EFT
- Interplay between EFT and SM parameters

Outlook