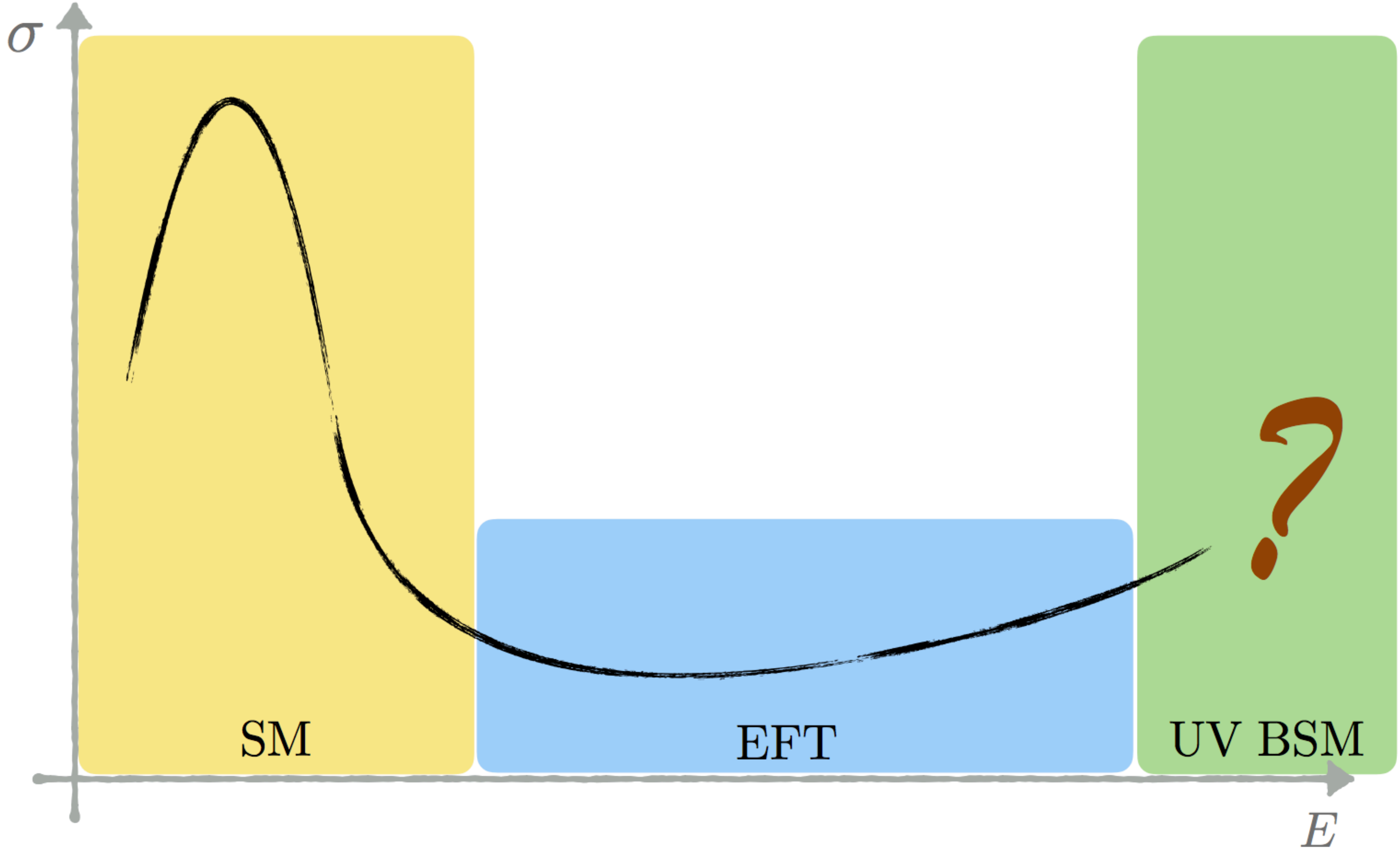
SMEFT for Top Physics at LHC

Cen Zhang

Institute of High Energy Physics
Chinese Academy of Sciences

Chongqing
May 19 2019

SMEFT



SMEFT

Parametrizing our ignorance

Wilson Coefficient

$$L_{\mathrm{EFT}} = L_{\mathrm{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4} O_i^{(8)} + \cdots$$

Scale of new physics, $\Lambda \gg E_{\mathrm{LHC}}$

-> leading effects come from $O_i^{(6)}$

With no assumption on UV:

- A complete set of independent “basis operators”
- Compare to experiments and measure the coefficients

SMEFT for tops

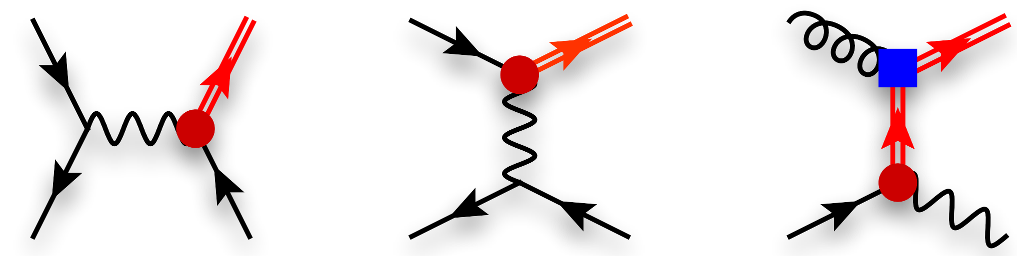
Charged current

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

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

$$O_{\varphi\varphi} = iy_t^2\left(\varphi^\dagger D_\mu \tilde{\varphi}\right)(\bar{b}\gamma^\mu t)$$

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



SMEFT for tops

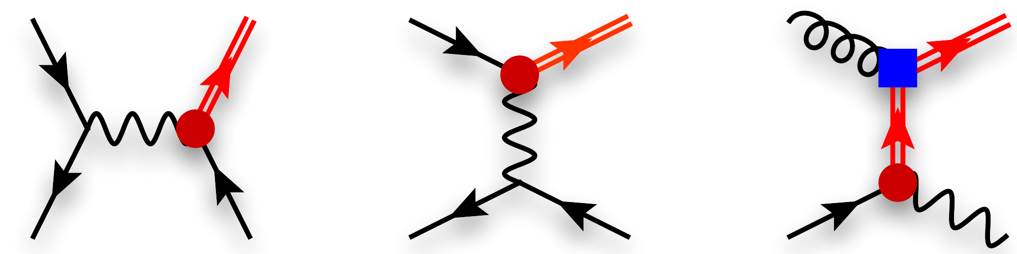
Charged current

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

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

$$O_{\varphi\varphi} = i y_t^2 \left(\varphi^\dagger D_\mu \tilde{\varphi}\right)\left(\bar{b}\gamma^\mu t\right)$$

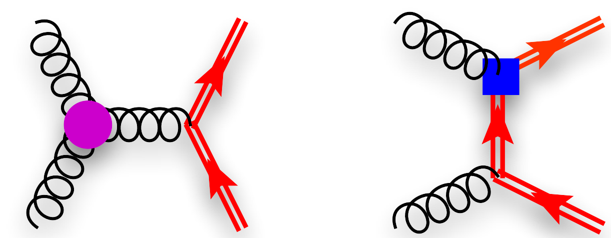
$$O_{bW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$



Strong

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

$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$



SMEFT for tops

Charged current

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

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

$$O_{\varphi\varphi} = i y_t^2\left(\varphi^\dagger D_\mu \tilde{\varphi}\right)(\bar{b}\gamma^\mu t)$$

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

Strong

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

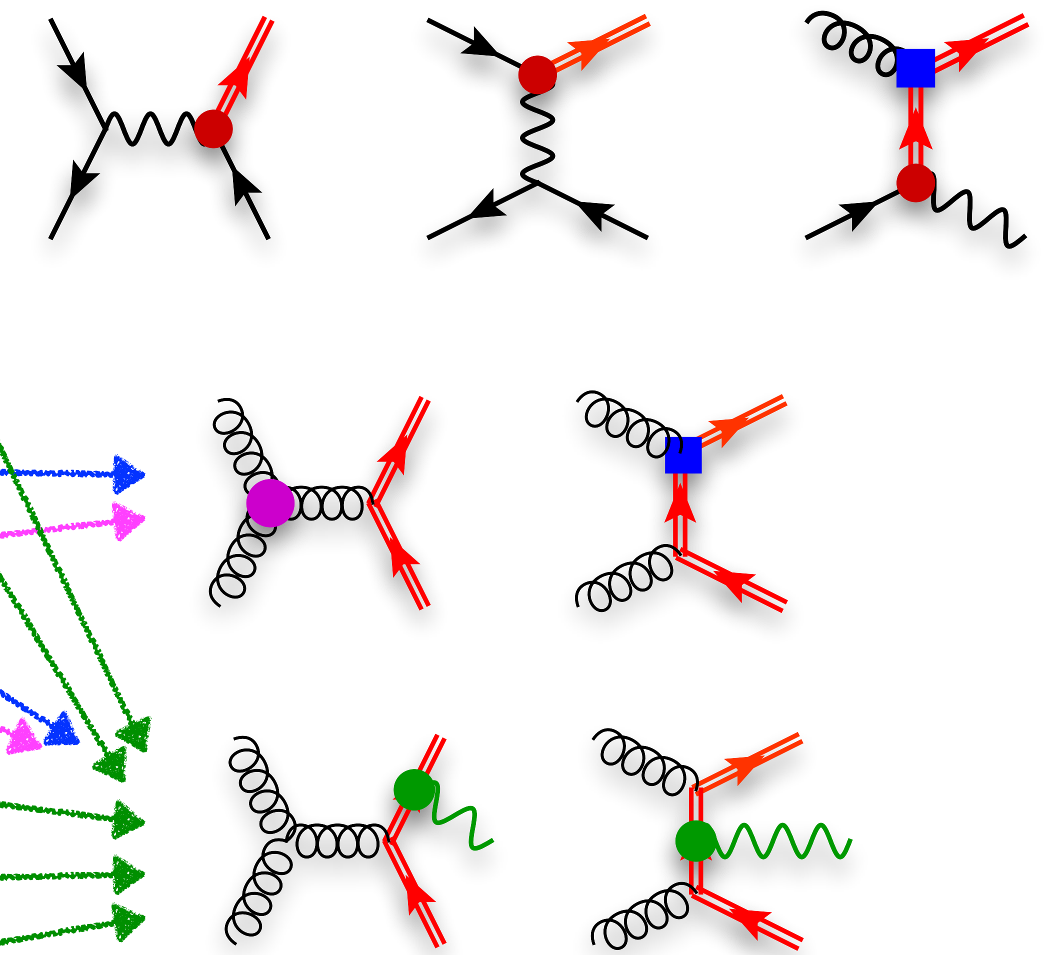
$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$

Neutral current

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

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

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



SMEFT for tops

Charged current

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

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

$$O_{\varphi\varphi} = i y_t^2 \left(\varphi^\dagger D_\mu \tilde{\varphi}\right)(\bar{b}\gamma^\mu t)$$

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

Strong

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

$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$

Neutral current

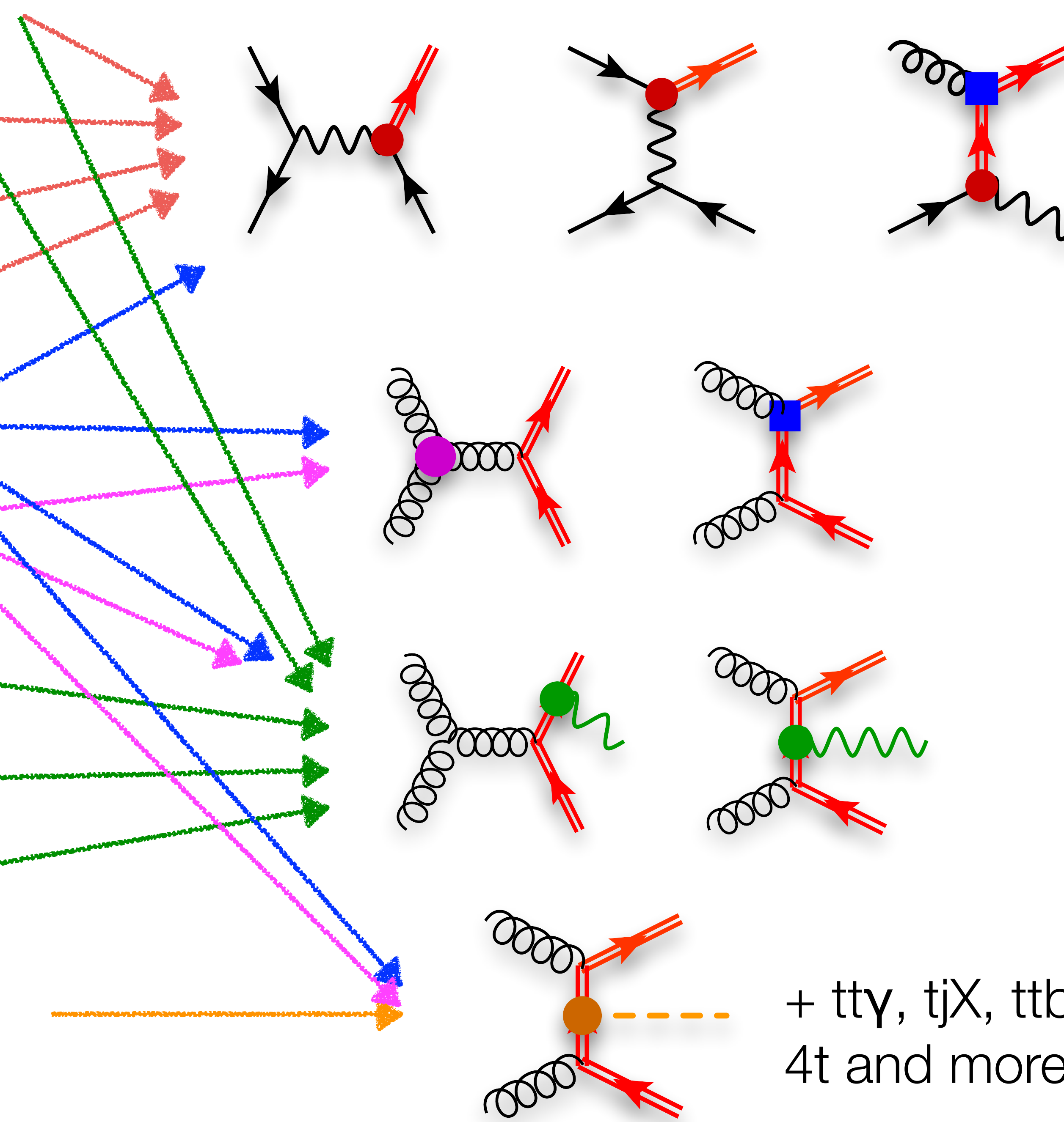
$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

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

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

Yukawa

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi - v^2/2\right)\left(\bar{Q}t\right)\tilde{\phi}$$



+ ttγ, tjX, ttbb, 4t and more

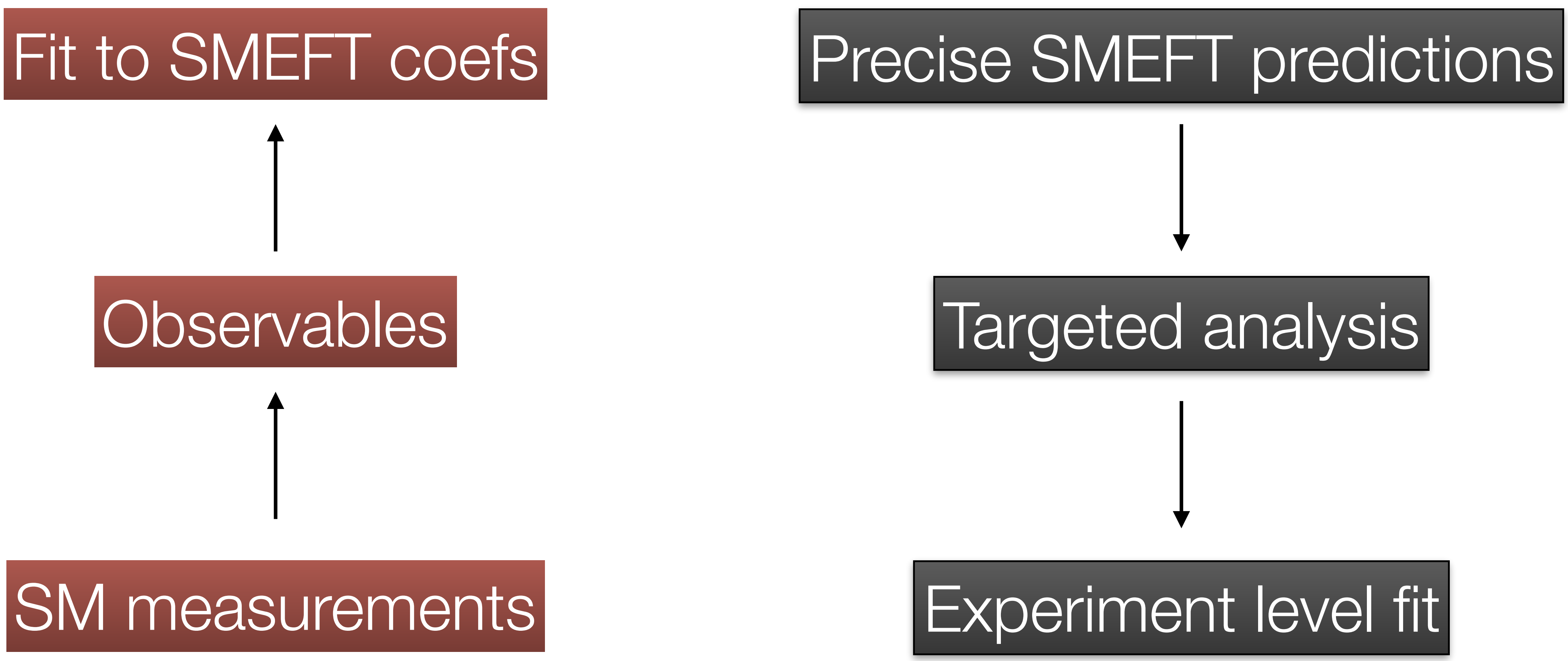
+ four-fermion Ops

Non-negligible effects from O_{tG} to ttH: [Maltoni, Vryonidou, CZ, 16]

see also constraining O_G from multi-jets: [Krauss, Kuttimalai, Plehn, 16]

Global fit

Theorists | Experimentalists



TH dependence cannot be removed: background, signal shape, acceptance, MVA, …

Desirable but more complicated…

- Theory status
  TH predictions and tools
- Application: global fits, projections
- Experiments

Recent SMEFT calculations at NLO

NLO corrections to EFT can be useful:

$$1+\mathcal{O}(\alpha_s)+\mathcal{O}\left(\frac{1}{\Lambda^2}\right)+\mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right)+\cdots$$

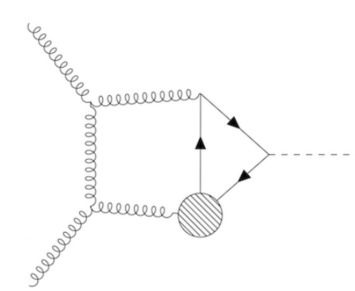
SM NLO EFT EFT @ NLO

- For QCD corrections at LHC
- For better understanding TH uncertainty
- NLO may be the first order for nontrivial effects (e.g. probing h^3 from single higgs)

[G. Degrassi et al., ’16] [Gorbahn, Haisch, ’16]

Some recent progresses (past two years):

- Higgs decay: γγ **[A. Dedes et al. ’18]**, γZ **[Dedes, Suxho, Trifyllis ’19]**, ZZ **[Dawson, Giardino ’18]**, WW **[Dawson, Giardino ’18]**, bb **[Cullen, Pecjak, Scott ’19]**
- HZ production (QCD): vh@nnlo **[R. Harlander et al. ’18]**
- WW production: **[Balio, Dawson, Lewis ’19]**
- gg to H, **two loop**: **[Deutschmann, Duhr, Maltoni, Vryonidou ’18]**



- Top production NLO+PS, automated: **[Degrande, Maltoni, Mimasu, Vryonidou, CZ ’18]**
- Single top, fNLO production+decay, off shell: **[Neumann, Sullivan, ’19]**
- Top loops in Higgs processes: **[Vryonidou, CZ ’18]**

SMEFT at NLO in QCD

Automation with **`MadGraph5_aMC@NLO`**, see **[CZ 1611.05091]** for a summary

Pros

User friendly interface

A wide range of processes

Including top/Higgs/EW operators

Fully automated

Cons

No optimization for specific channel

Production + decay is hard

MC@NLO -> negative weights

Eg. ttZ

```
shell> ./bin/mg5
MG5_aMC> import model TopEFT
MG5_aMC> generate p p > t t~ Z EFT=1 [QCD]
MG5_aMC> output some_DIR
MG5_aMC> launch
```

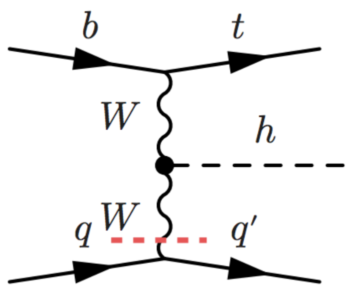
	ttg	ttZ/γ, tbW					ttH	qqtt	ggH
Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

See e.g. [Shao et al., 11] [Rontsch, Schulze, 15] … for previous work on similar calculations

tZj: a case study with both top and EW operators

[Degrande, Maltoni, Mimasu, Vryonidou, CZ ’18]

tHj (tZj = h→Z)

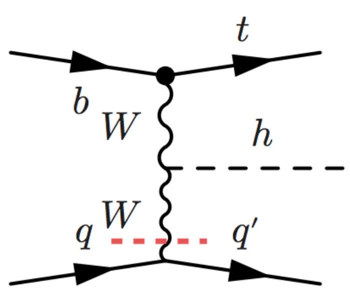


$\mathcal{O}_{\varphi W} : \varphi^\dagger \varphi W_i^{\mu\nu} W^i_{\mu\nu}$

HWW

TGC

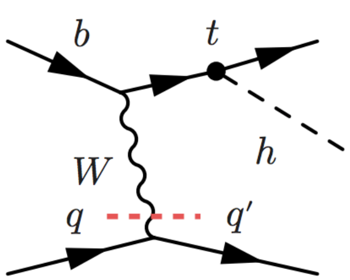
$\mathcal{O}_W : \epsilon^{ijk} W_{i,\mu\nu} W_j^{\nu\rho} W^\mu_{k,\rho}$



$\mathcal{O}^{(3)}_{\varphi Q} : i(\varphi^\dagger \overleftrightarrow{D}^i_\mu \varphi)(\bar{Q}\gamma^\mu \sigma_i Q)$

Wtb vertex

$\mathcal{O}_{\varphi tb} : i(\tilde{\varphi}\, D_\mu \varphi)(\bar{b}\gamma^\mu t)$

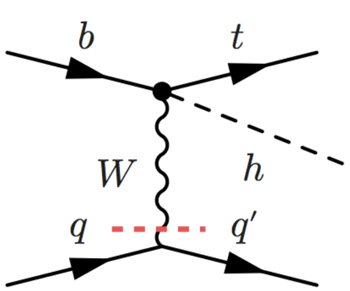


$\mathcal{O}_{t\varphi} : (\varphi^\dagger\varphi)\,(\bar{Q}\,t)\,\tilde{\varphi}$

top Yukawa

ttZ coupling

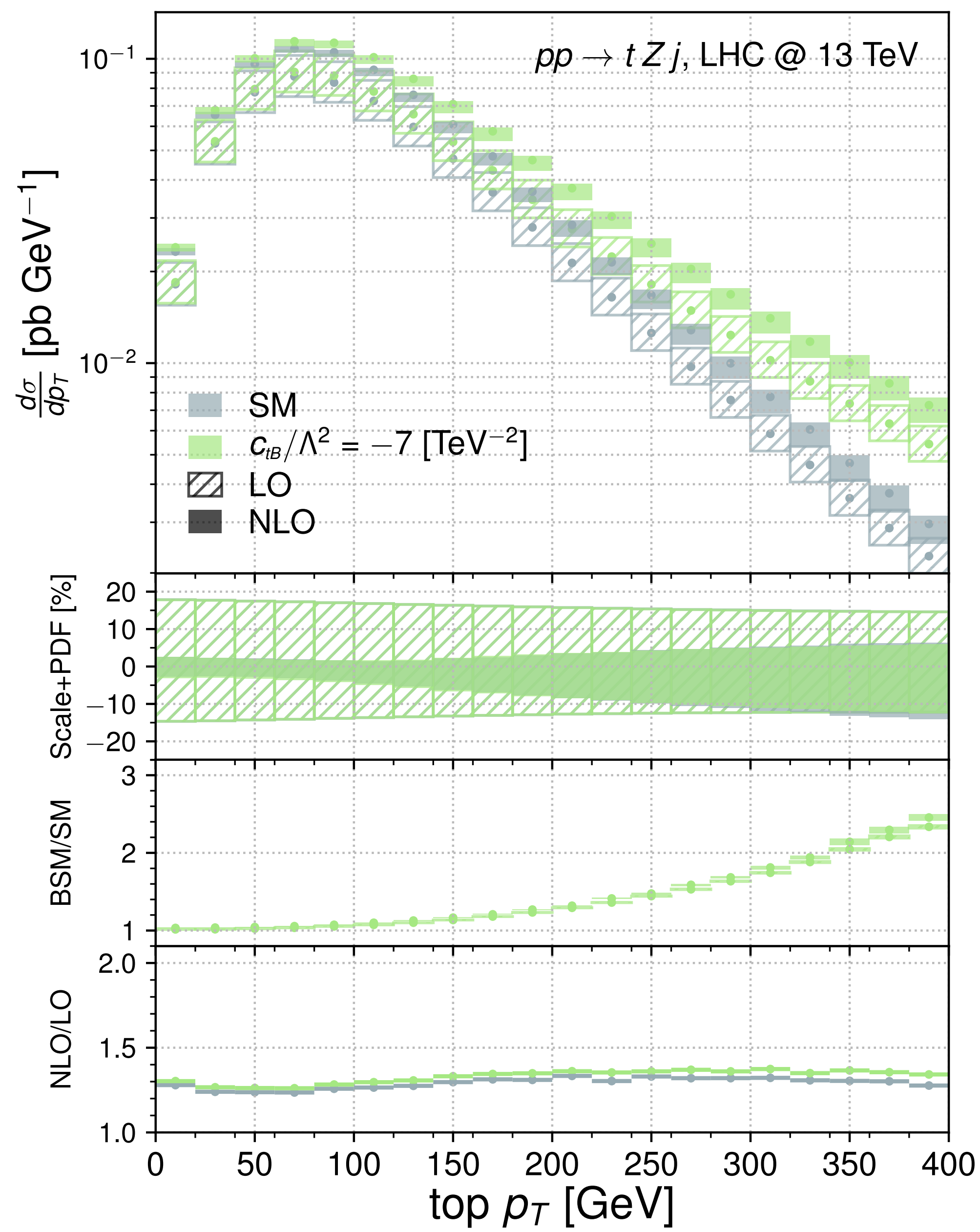
$\mathcal{O}_{\varphi t} : i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$

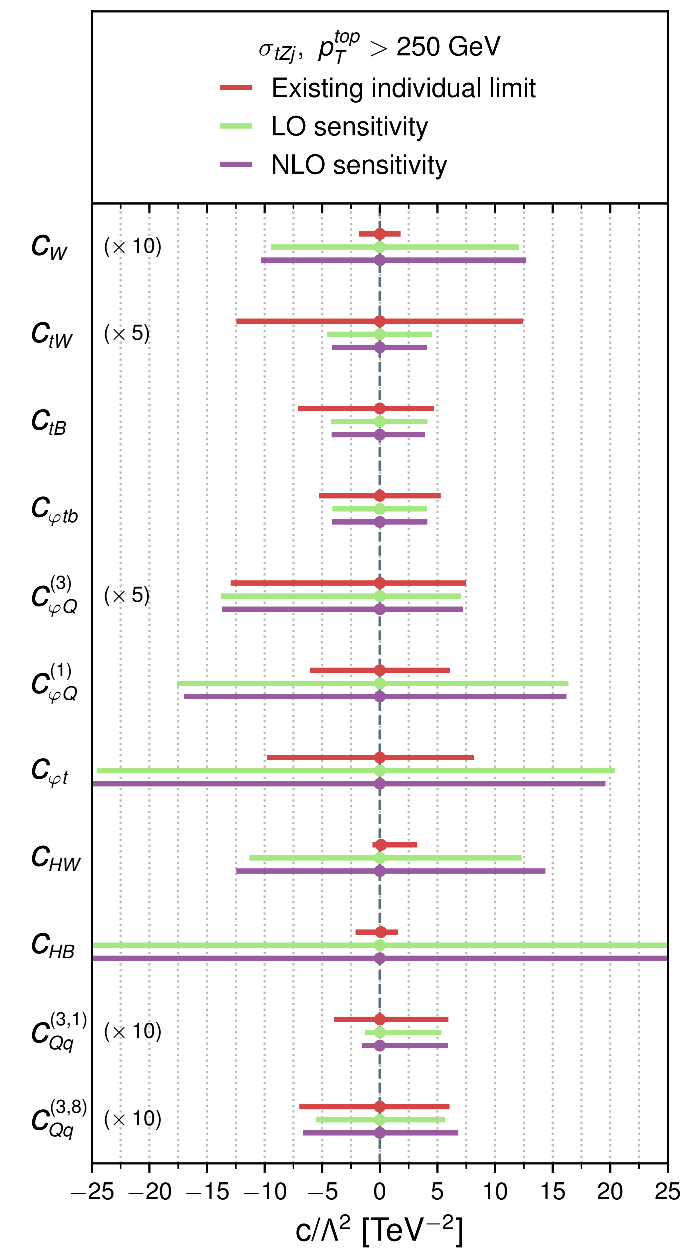


$\mathcal{O}^{(3)}_{\varphi Q} : i(\varphi^\dagger \overleftrightarrow{D}^i_\mu \varphi)(\bar{Q}\gamma^\mu \sigma_i Q)$

Contact terms

$\mathcal{O}_{tB} : (\bar{Q}\,\sigma_{\mu\nu}\,t)\,\tilde{\varphi}\,B^{\mu\nu}$

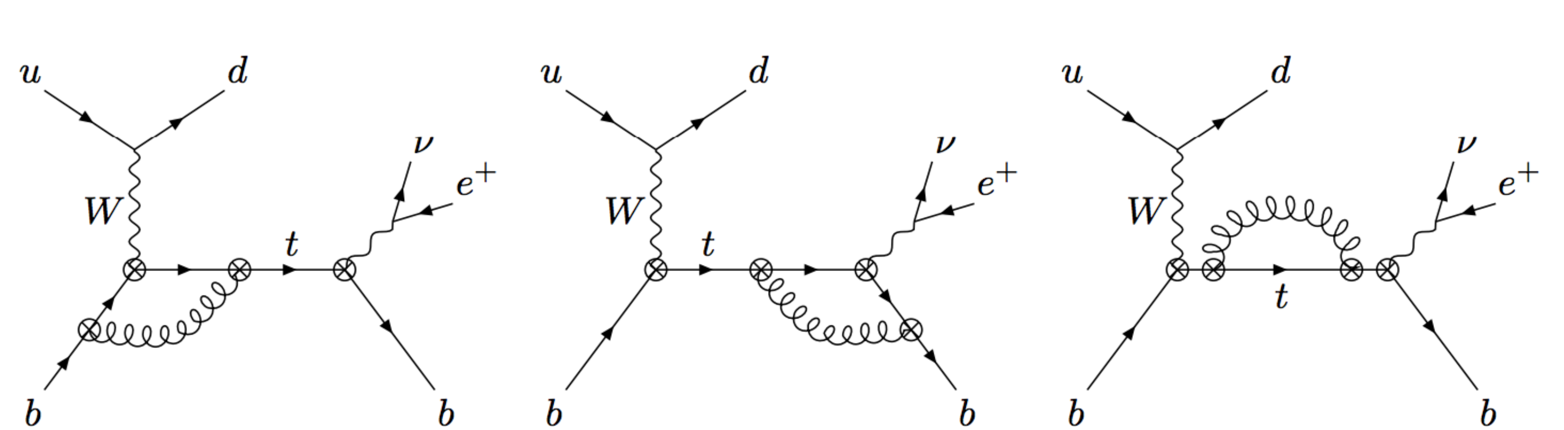




SMEFT at NLO in QCD: single top production + decay

[Neumann, Sullivan, '19]

$$\mathcal{Q}_{\varphi q}^{(3,33)} = \frac{1}{2} y_t^2 (\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{Q}_L \gamma^\mu \tau^I Q_L)\,,$$
$$\mathcal{Q}_{uW}^{33} = y_t g_W (\bar{Q}_L \sigma^{\mu\nu} \tau^I t) \tilde{\varphi} W_{\mu\nu}^I\,,$$
$$\mathcal{Q}_{uG}^{33} = y_t g_s (\bar{Q}_L \sigma^{\mu\nu} T^A t) \tilde{\varphi} G_{\mu\nu}^A\,,$$
$$\mathcal{Q}_{4L} = \mathcal{Q}_{qq}^{(3,1133)} = (\bar{q}_L \gamma_\mu \tau^I q_L)(\bar{Q}_L \gamma^\mu \tau^I Q_L)\,,$$
$$\mathcal{Q}_{\varphi ud}^{33} = y_t^2 (\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{t}\gamma^\mu b)\,,$$
$$\mathcal{Q}_{dW}^{33} = y_t g_W (\bar{Q}_L \sigma^{\mu\nu} \tau^I b) \Phi W_{\mu\nu}^I\,,$$
$$\mathcal{Q}_{dG}^{33} = y_T g_s (\bar{Q}_L \sigma^{\mu\nu} T^A b) \Phi G_\mu^A \nu\,,$$
$$\mathcal{Q}_{4R} = \mathcal{Q}_{ud}^{(1,1331)} + \mathcal{Q}_{ud}^{(1,3113)} = (\bar{d}\gamma_\mu u)(\bar{t}\gamma^\mu b) + (\bar{u}\gamma_\mu d)(\bar{b}\gamma^\mu t)\,,$$



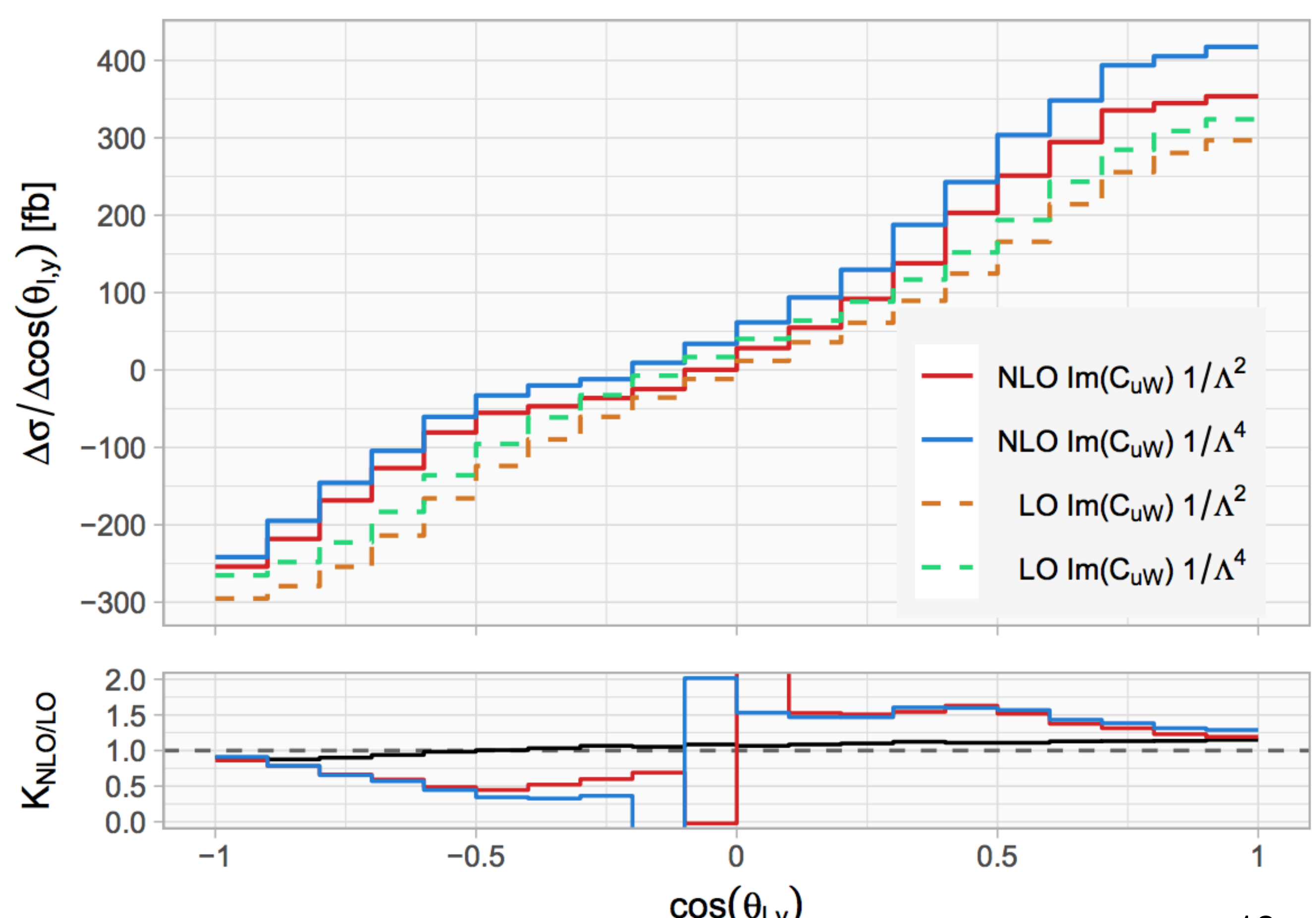
(a) production (b) decay (c) self-energy

All operators up to dim-6 squared

Complex mass scheme

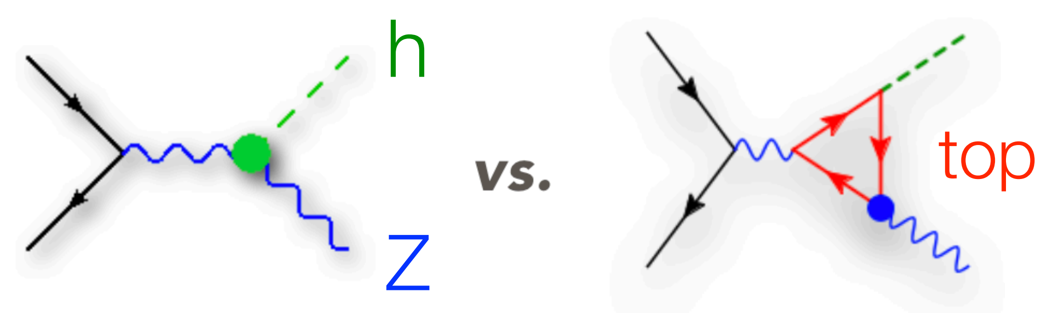
Spin info accurate at NLO

Implemented in `MCFM`

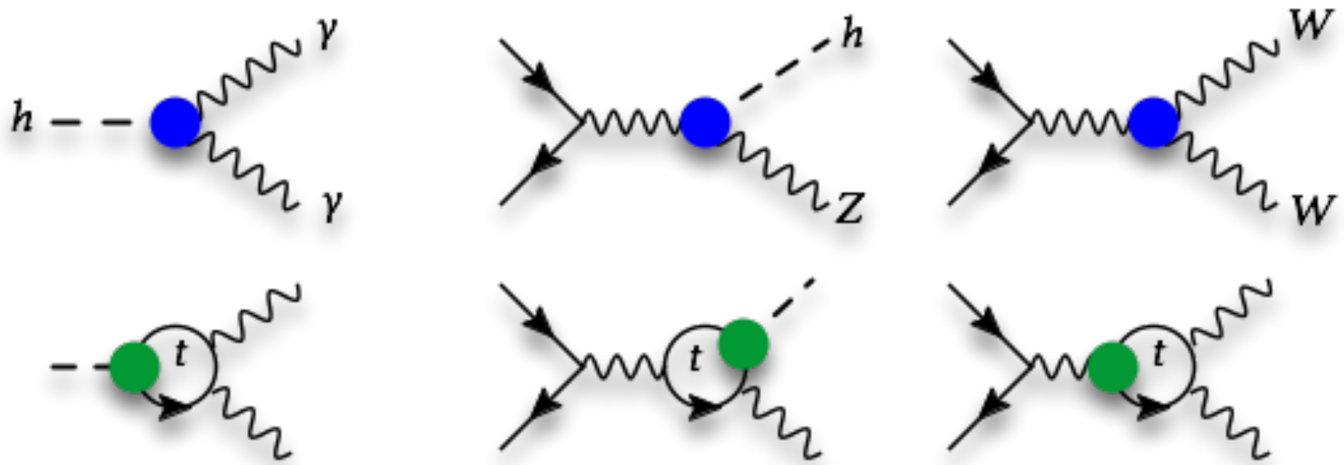


Towards automated SMEFT at NLO in EW

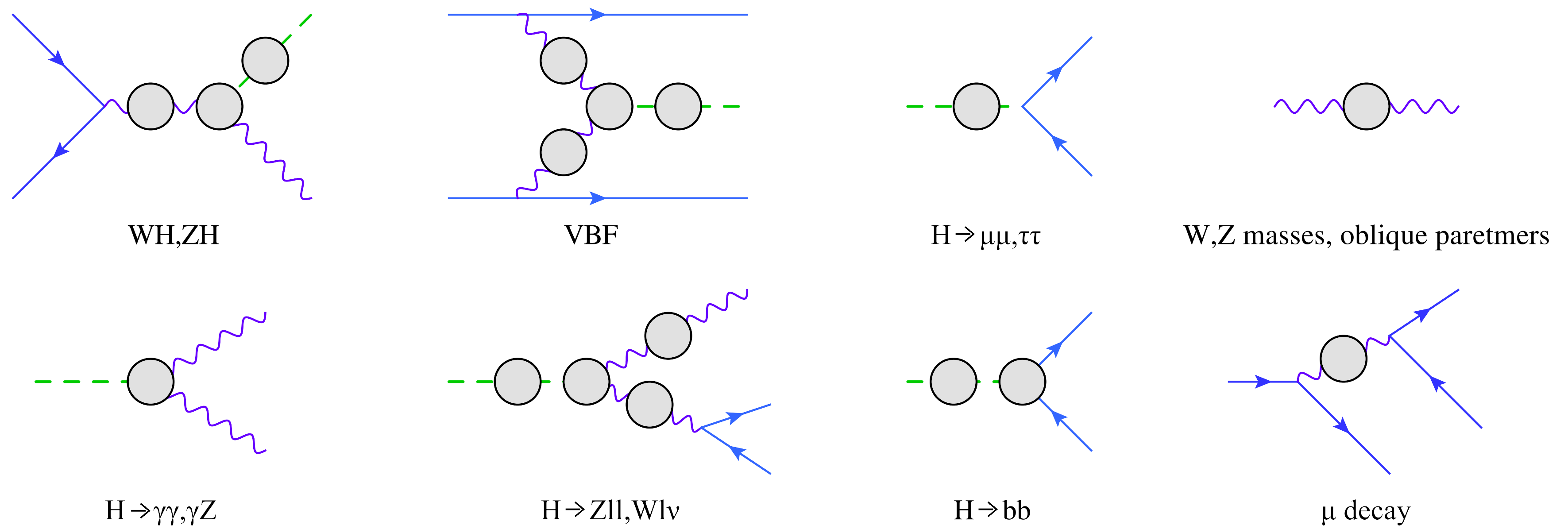
Suppose we see 5% deviation in HZ production (at HL-LHC, CEPC/ILC/FCC), how do we decide:



In fact, in a global fit, it is consistent only if all loops in the 2nd row are considered **[Durieux, Grojean, Gu, Wang '17]**

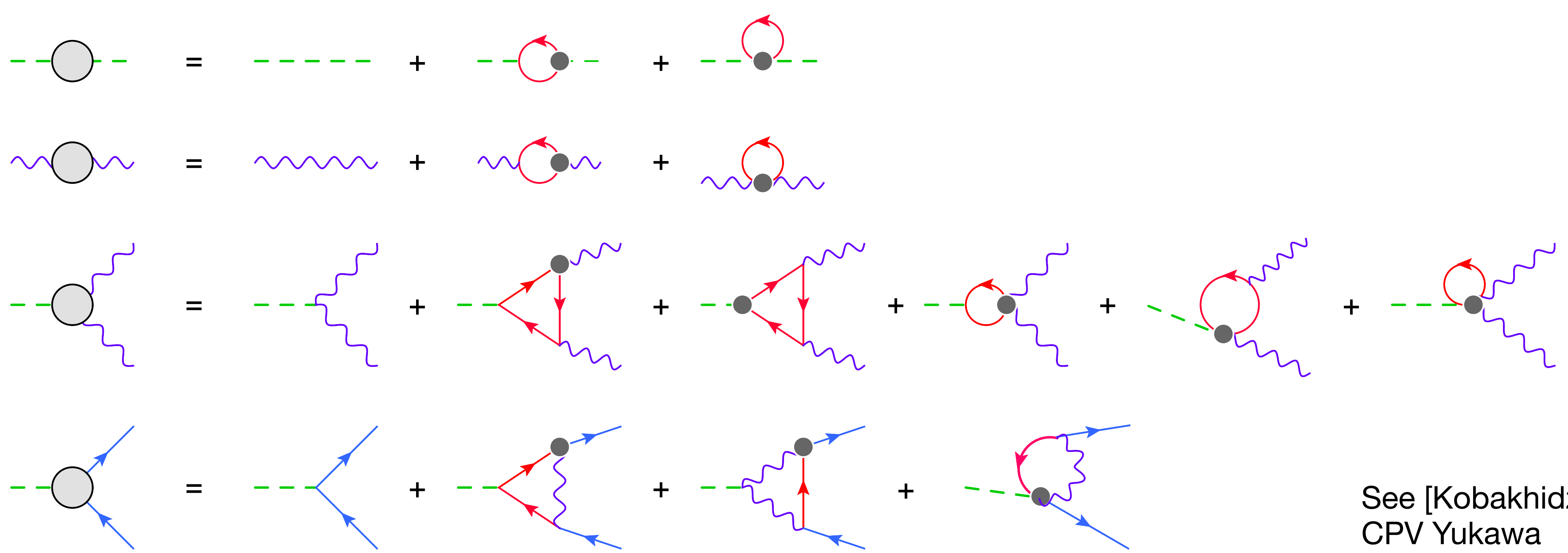


Towards automated SMEFT at NLO in EW



Automated with MG5_aMC@NLO

[Vryonidou, CZ '18]

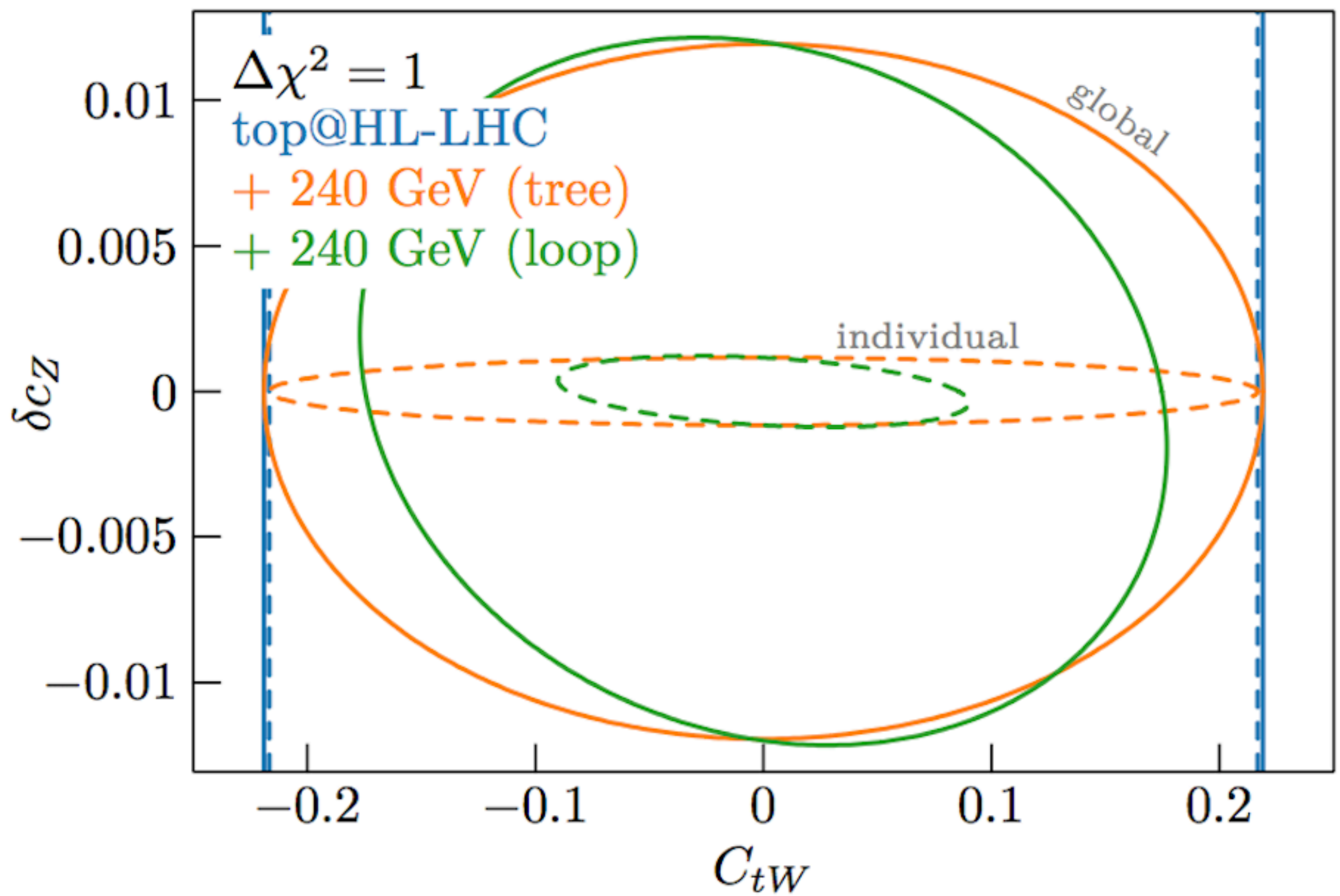


See [Kobakhidze, Liu, Wu, Yue '16] for CPV Yukawa

Towards automated SMEFT at NLO in EW

[Durieux, Gu, Vryonidou, CZ ’17]

On a linear scale, in the $(C_{tW}, \delta c_Z)$ plane:



- extra parameter space covered thanks to loop sensitivity

Why global fits

Combine LHC top measurements, set constraints on coefficients…

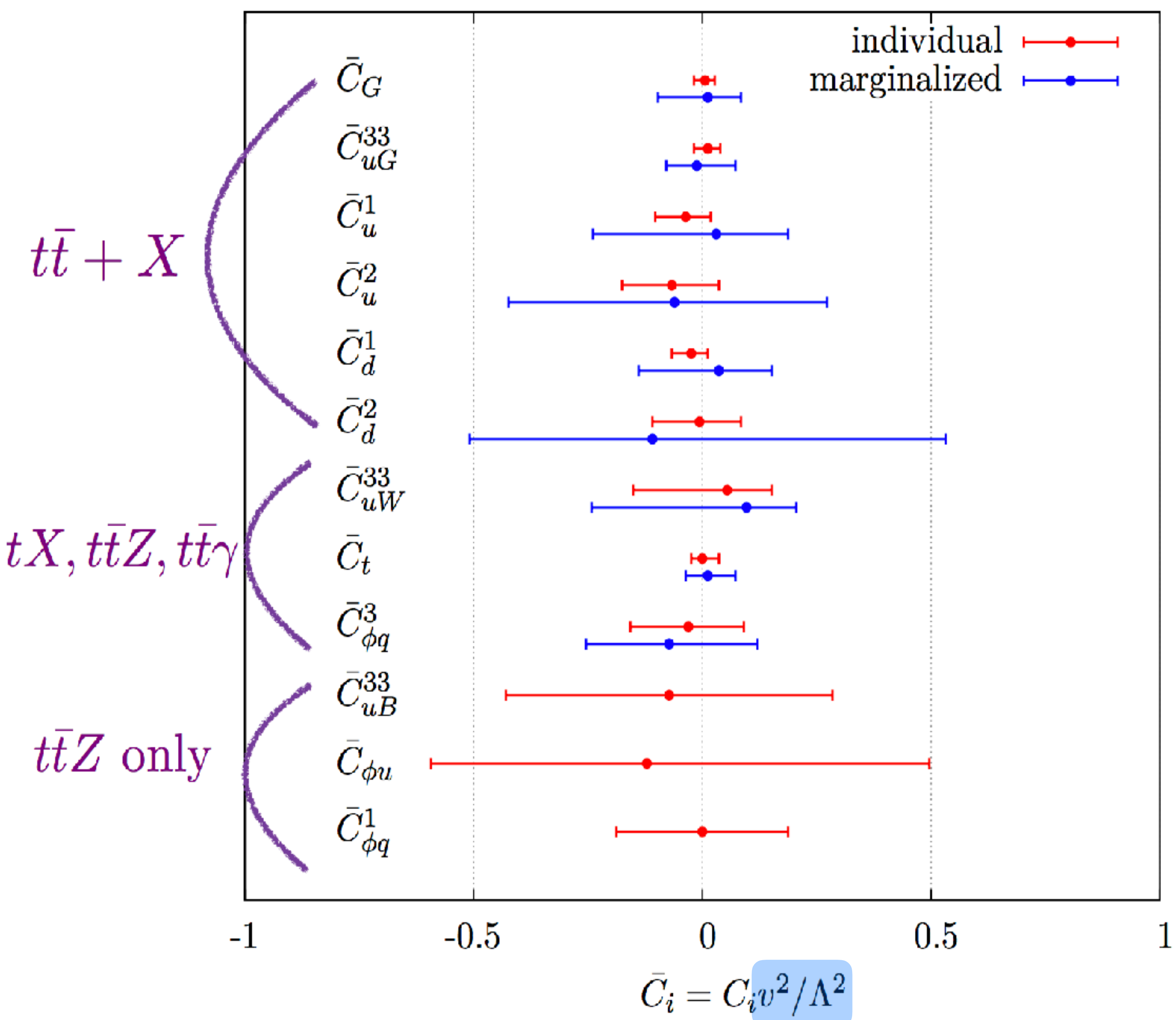
- As the **LHC legacy**, like the S/T/U parameters from LEP
- **Discovery by combination is possible**

TopFitters

[Buckley, Englert, Ferrando, Miller, Moore, Russell, White 16]

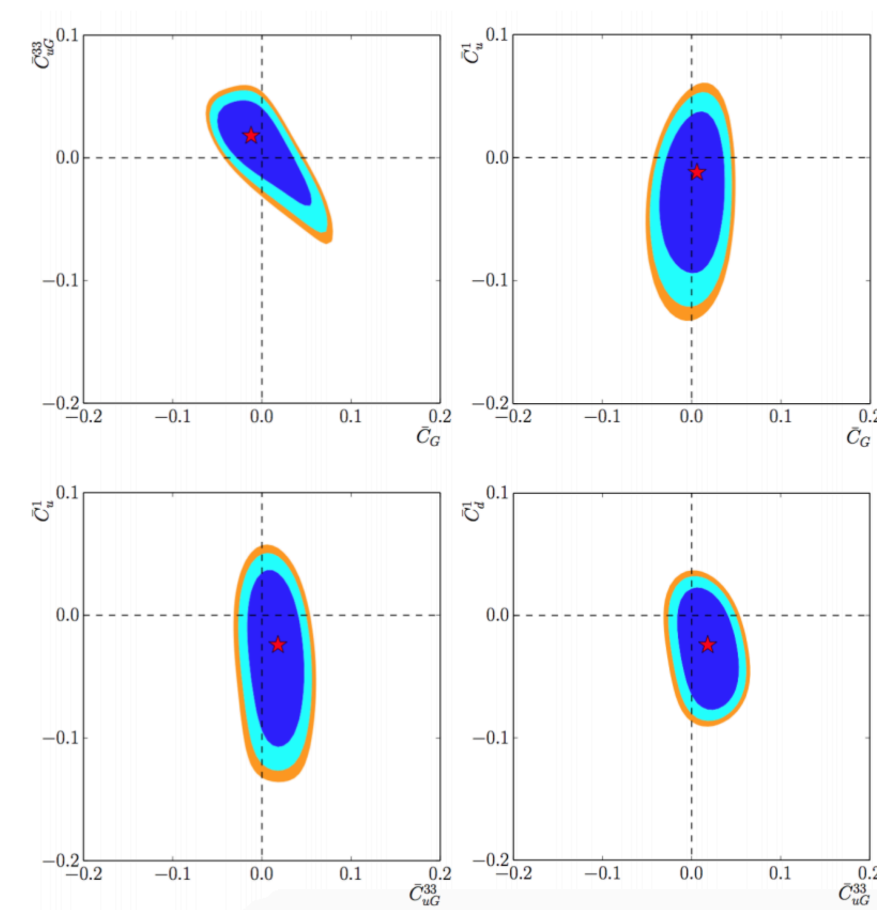
$$\chi^2(\mathbf{C}) = \sum_{\mathcal{O}} \sum_{i,j} \frac{(f_i(\mathbf{C}) - E_i)\rho_{i,j}(f_j(\mathbf{C}) - E_j)}{\sigma_i \sigma_j}$$

$$\frac{C_i}{\Lambda^2} = \frac{g_*^2}{M_*^2}$$



Tevatron + LHC Run I summary:

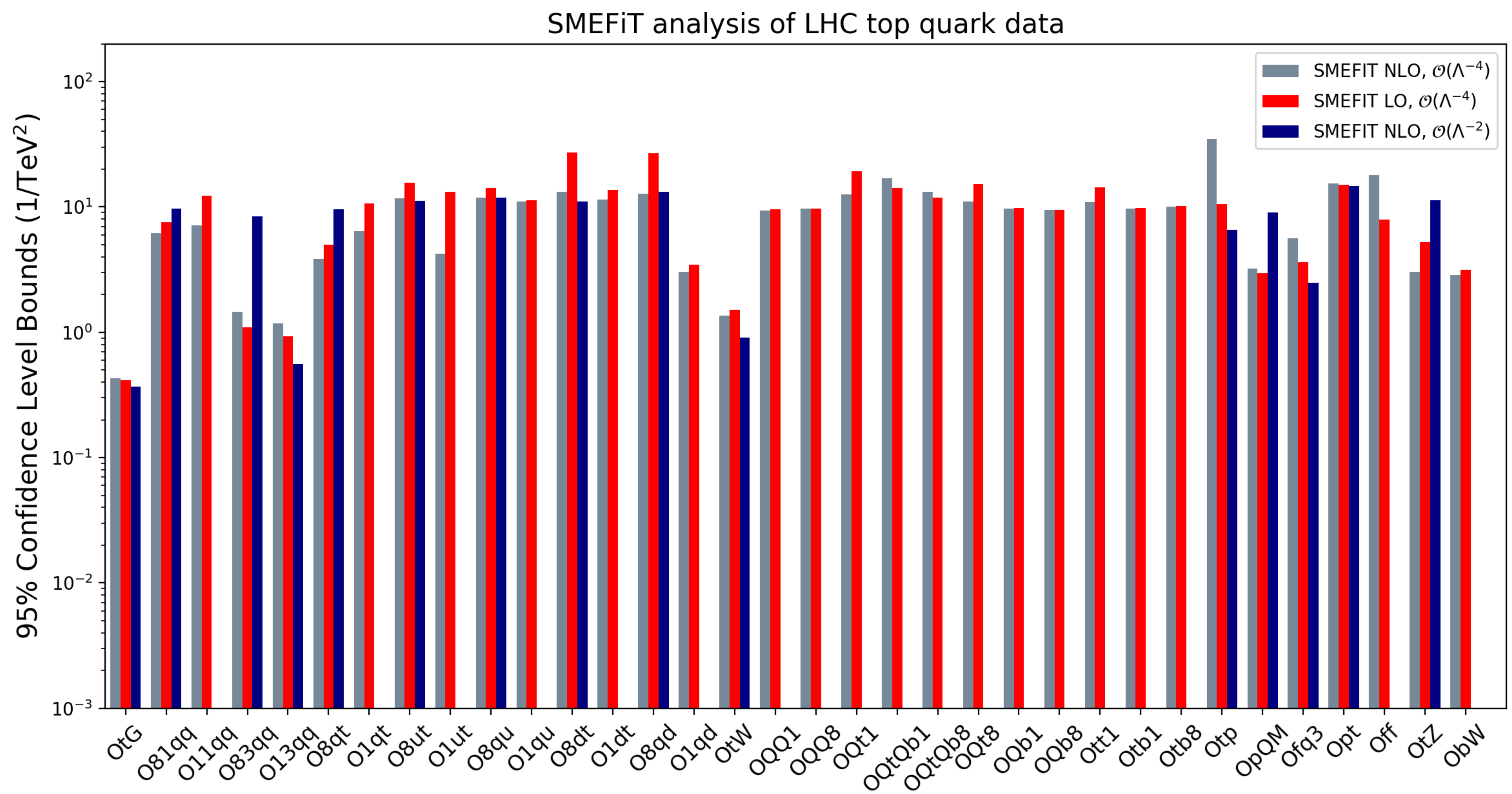
- No significant deviation
- Still early stage in LHC program
- Many measurements dominated by statistics
- Improvements expected for HL



SMEFiT

[Hartland, Maltoni, Nocera, Rojo, Slade, Vryonidou, CZ 19]

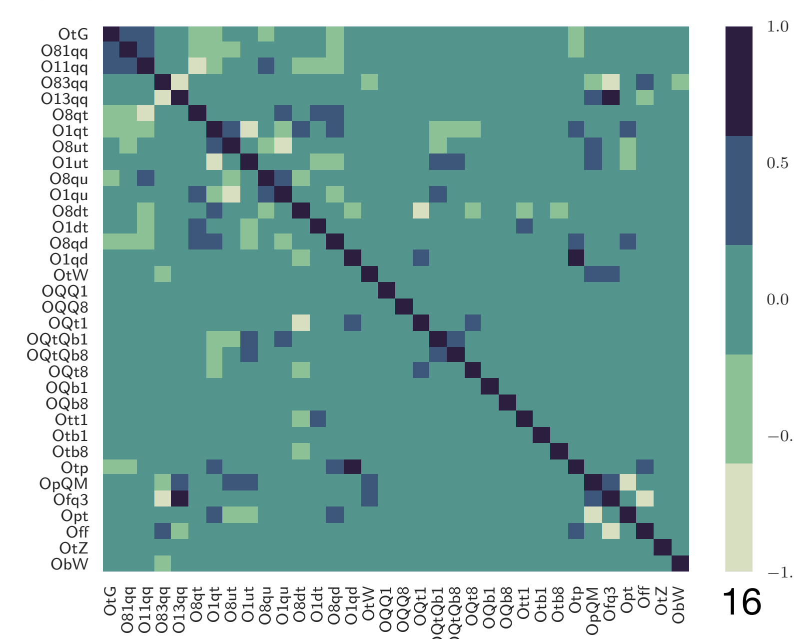
- Fitting approach based on NNPDF: MC replicas + cross validation and closure test
- Theory predictions from MG5_aMC@NLO, i.e. operator contributions are at NLO in QCD
- Parametrization & operator basis etc. are consistent with TOP working group EFT recommendation



Gray NLO

Red LO

Blue w/o dim6 squared

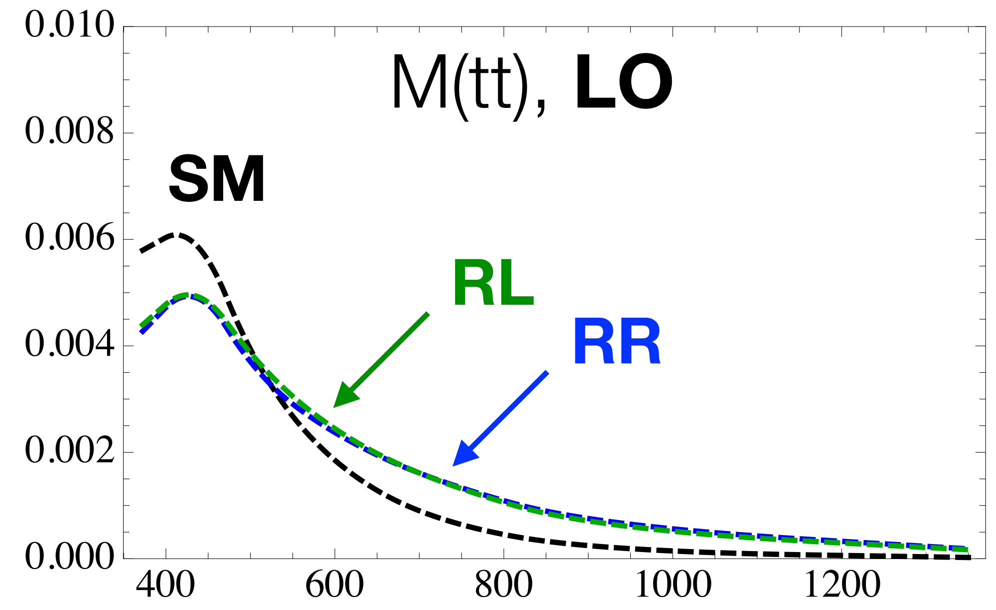


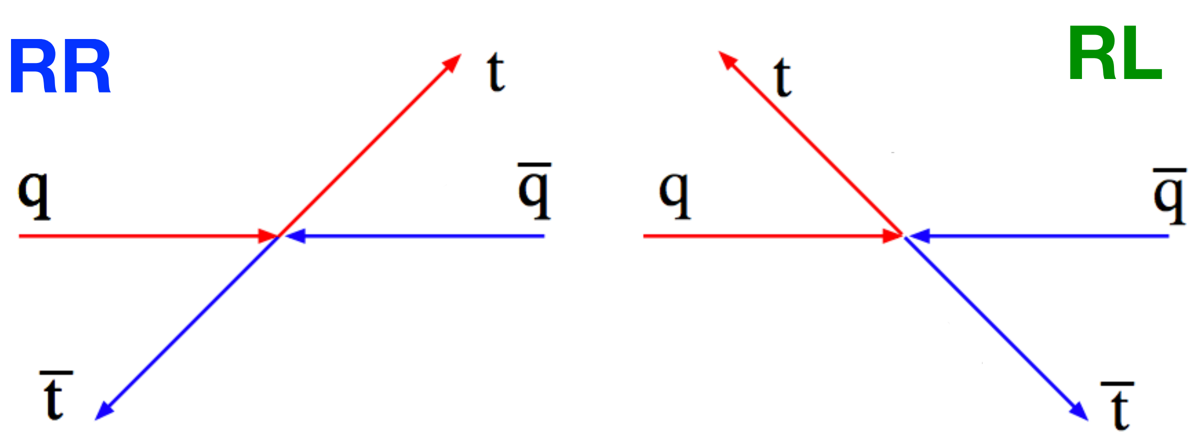
How can NLO corrections play a role?

If NLO only show up as K-factors, NO

But if it changes differential distribution…

$$O_{RR} = (\bar{u}_R \gamma^\mu T^A u_R)(\bar{t}_R \gamma_\mu T^A t_R)$$
$$O_{RL} = (\bar{u}_R \gamma^\mu T^A u_R)(\bar{t}_L \gamma_\mu T^A t_L)$$



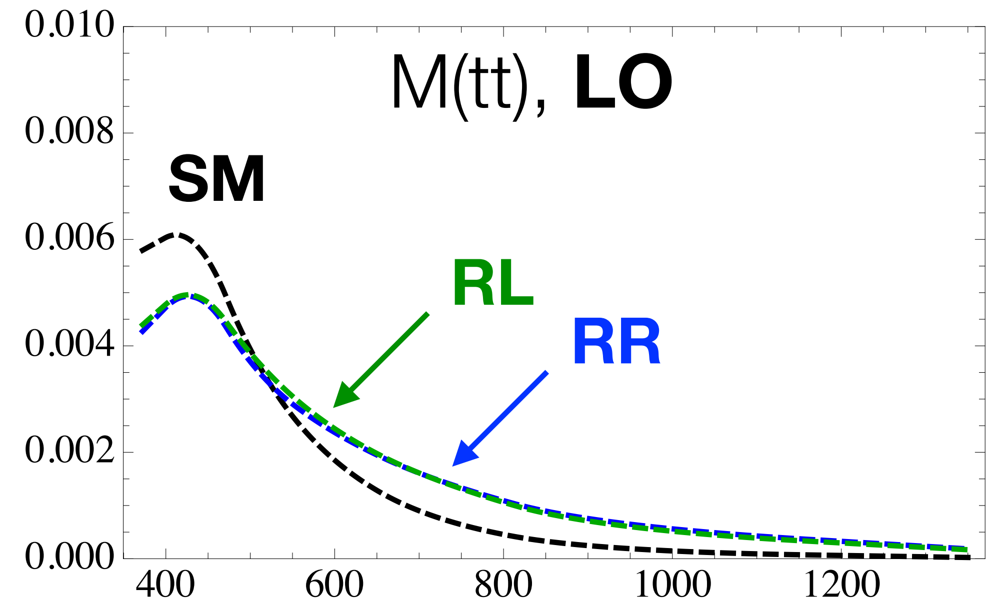


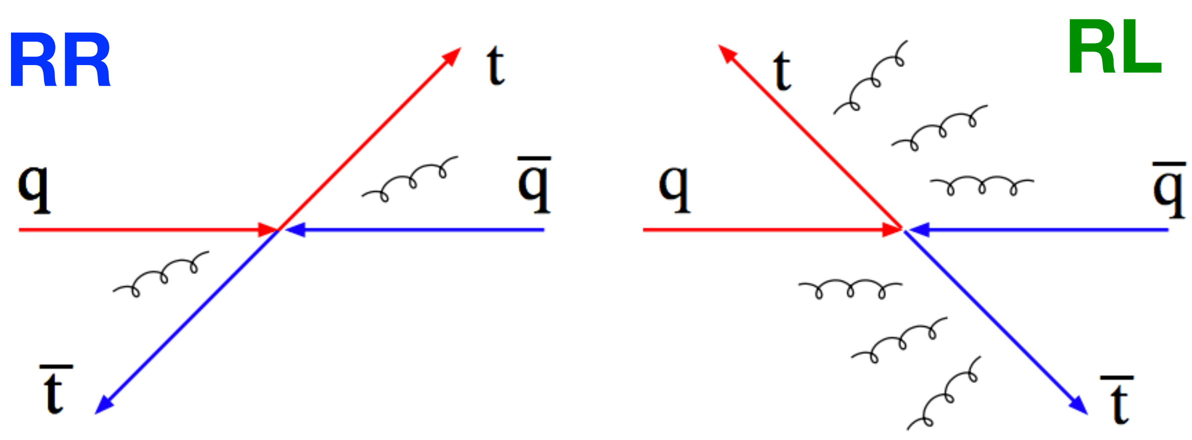
How can NLO corrections play a role?

If NLO only show up as K-factors, NO

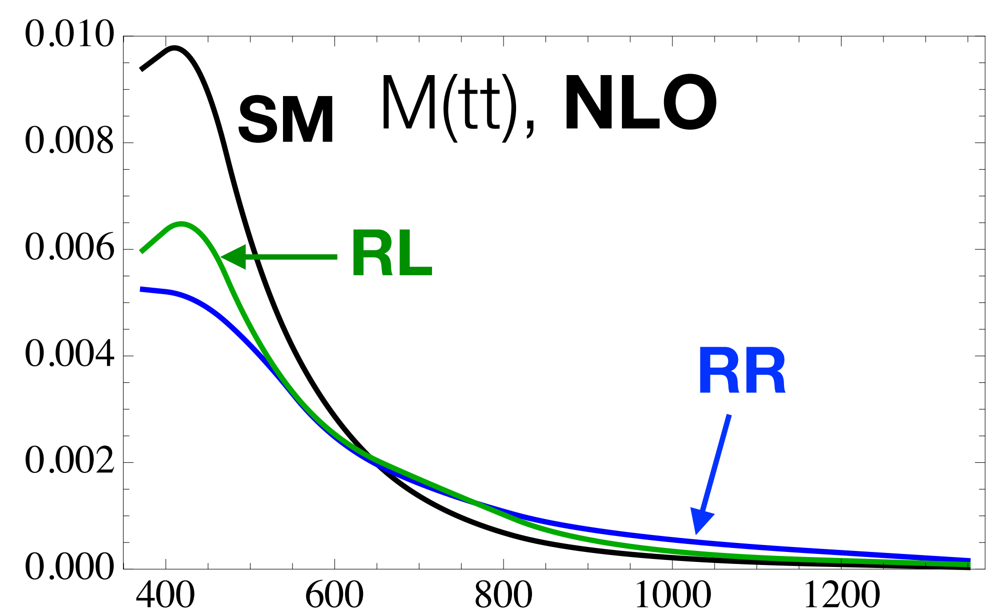
But if it changes differential distribution…

$$O_{RR} = (\bar{u}_R \gamma^\mu T^A u_R)(\bar{t}_R \gamma_\mu T^A t_R)$$
$$O_{RL} = (\bar{u}_R \gamma^\mu T^A u_R)(\bar{t}_L \gamma_\mu T^A t_L)$$



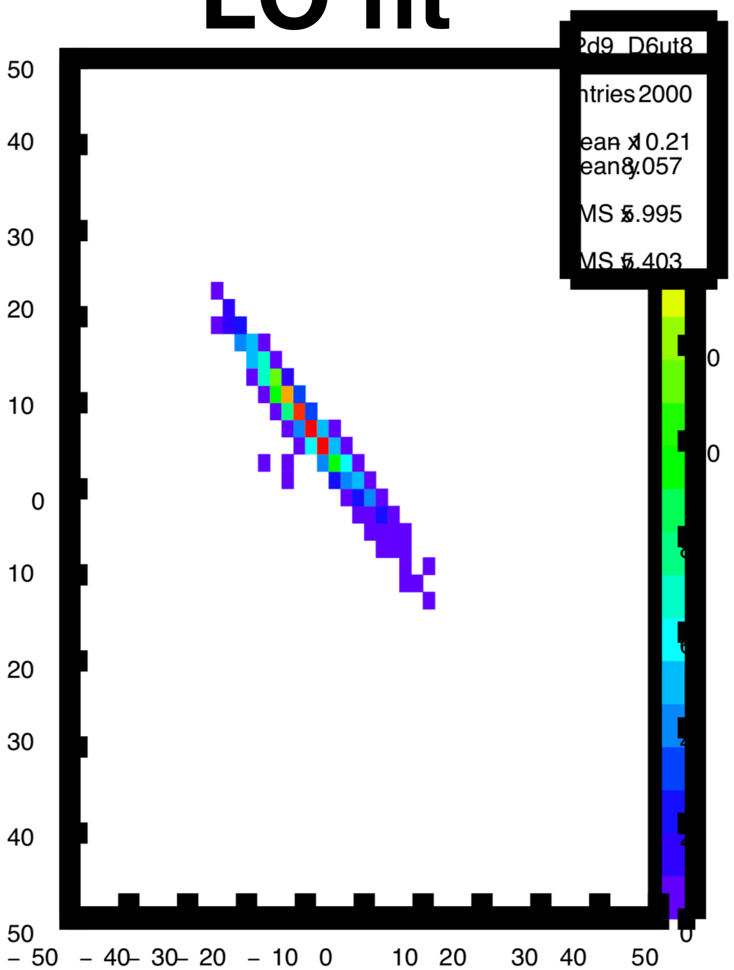


[Skands, Webber, Winter '12]

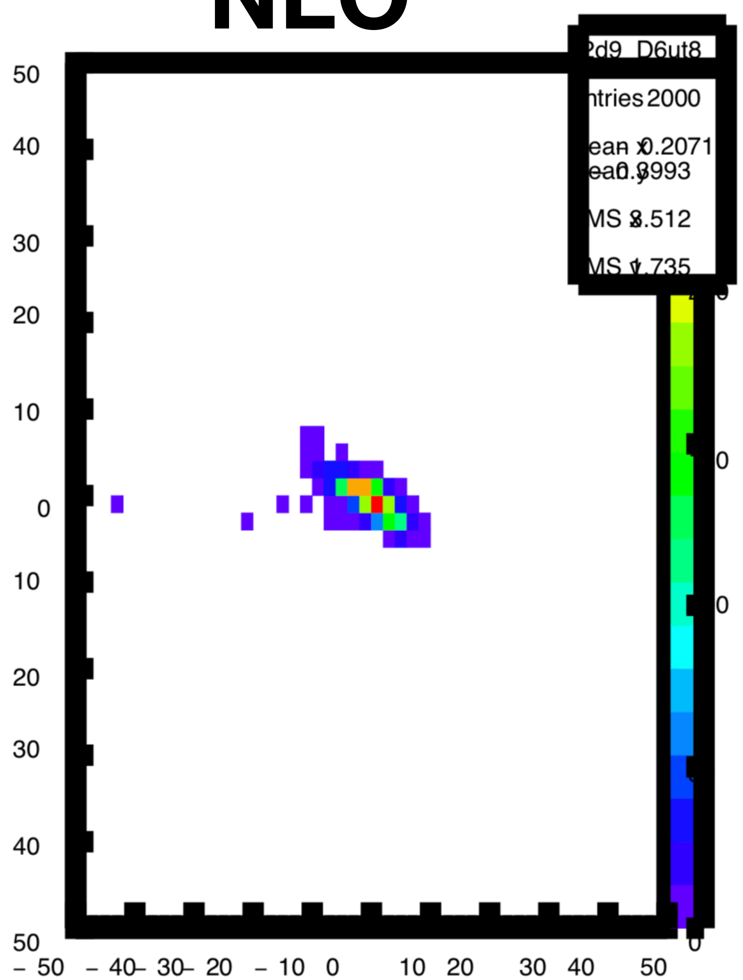


How can NLO corrections play a role?

LO fit

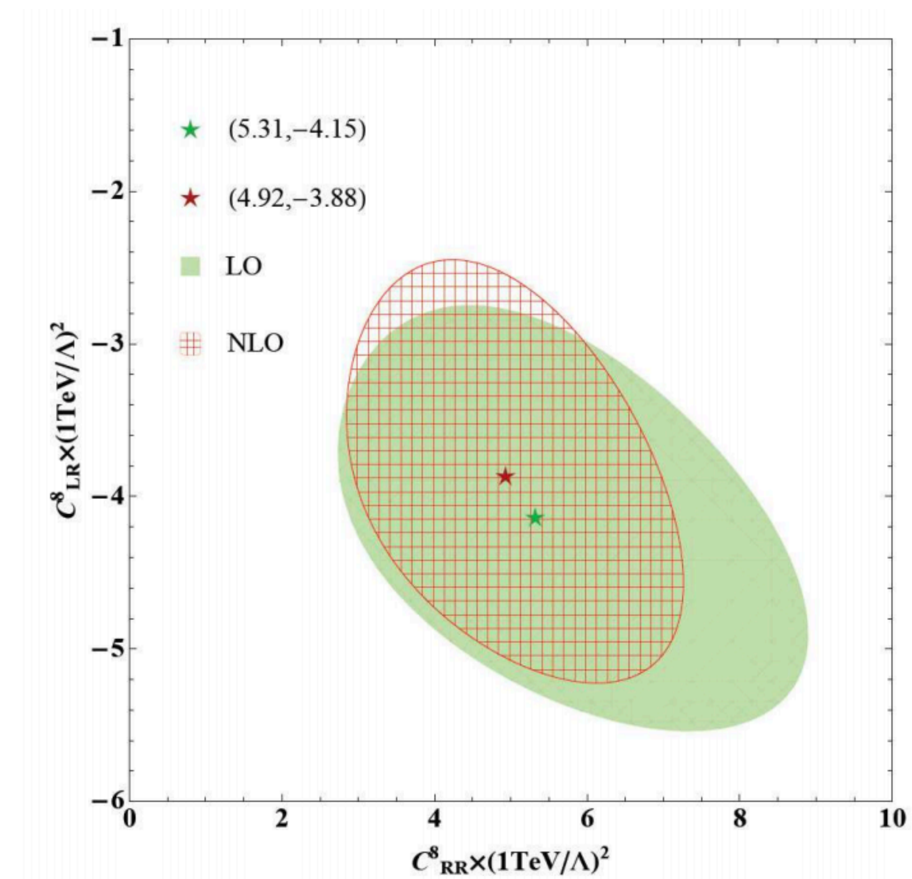


NLO



(preliminary) Toy fit by S. Bruggisser

Tevatron



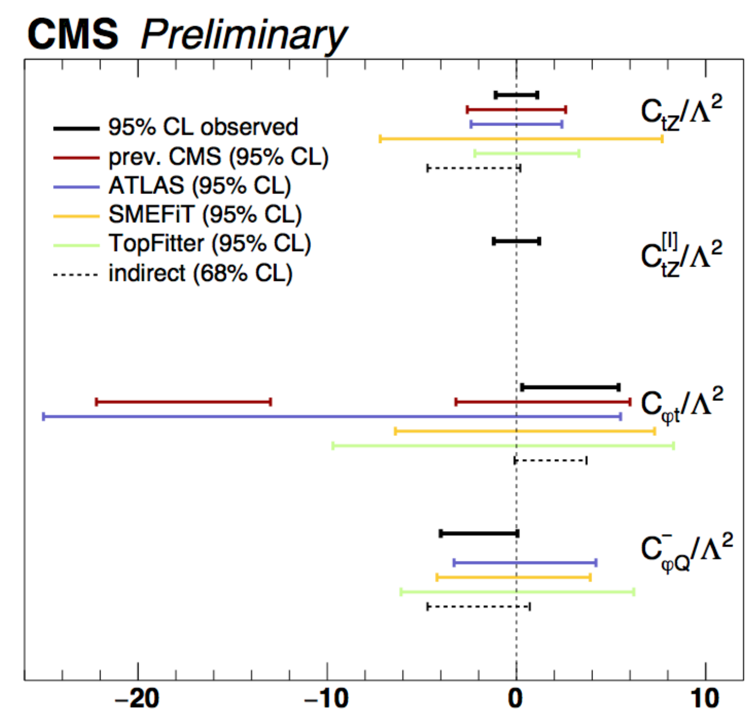
[Shao et al., 1107.4012]

LHC current and future: tt+Z

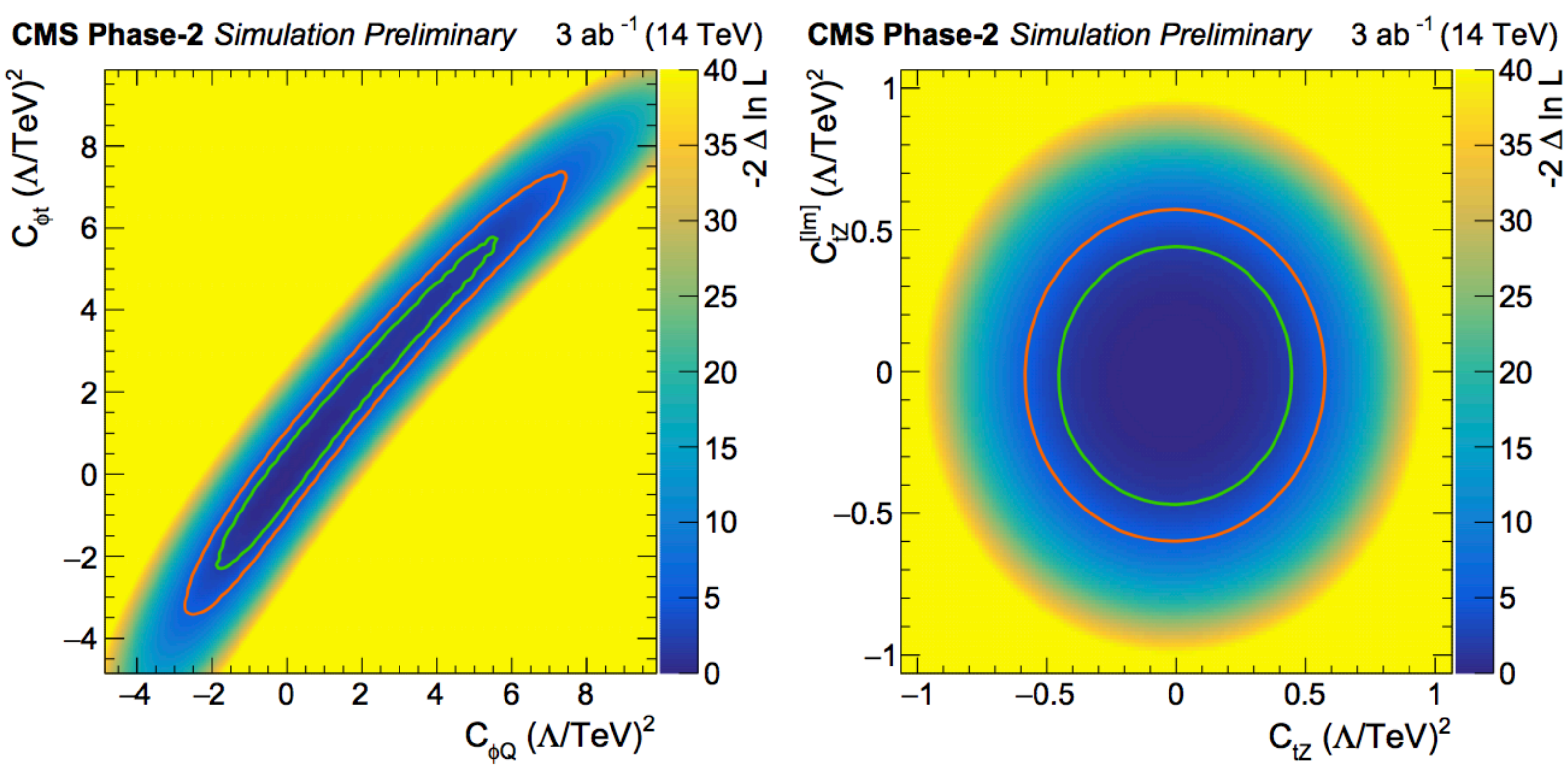
What theorist cannot do in a fit:

- Correlation between different channels
- When EFT affects both S/B (tjZ/ttZ, ttZ/ttH)
- EFT modifies signal efficiency, unfolding, etc.
- MVA

CMS PAS TOP-18-009



HL-HE-YR

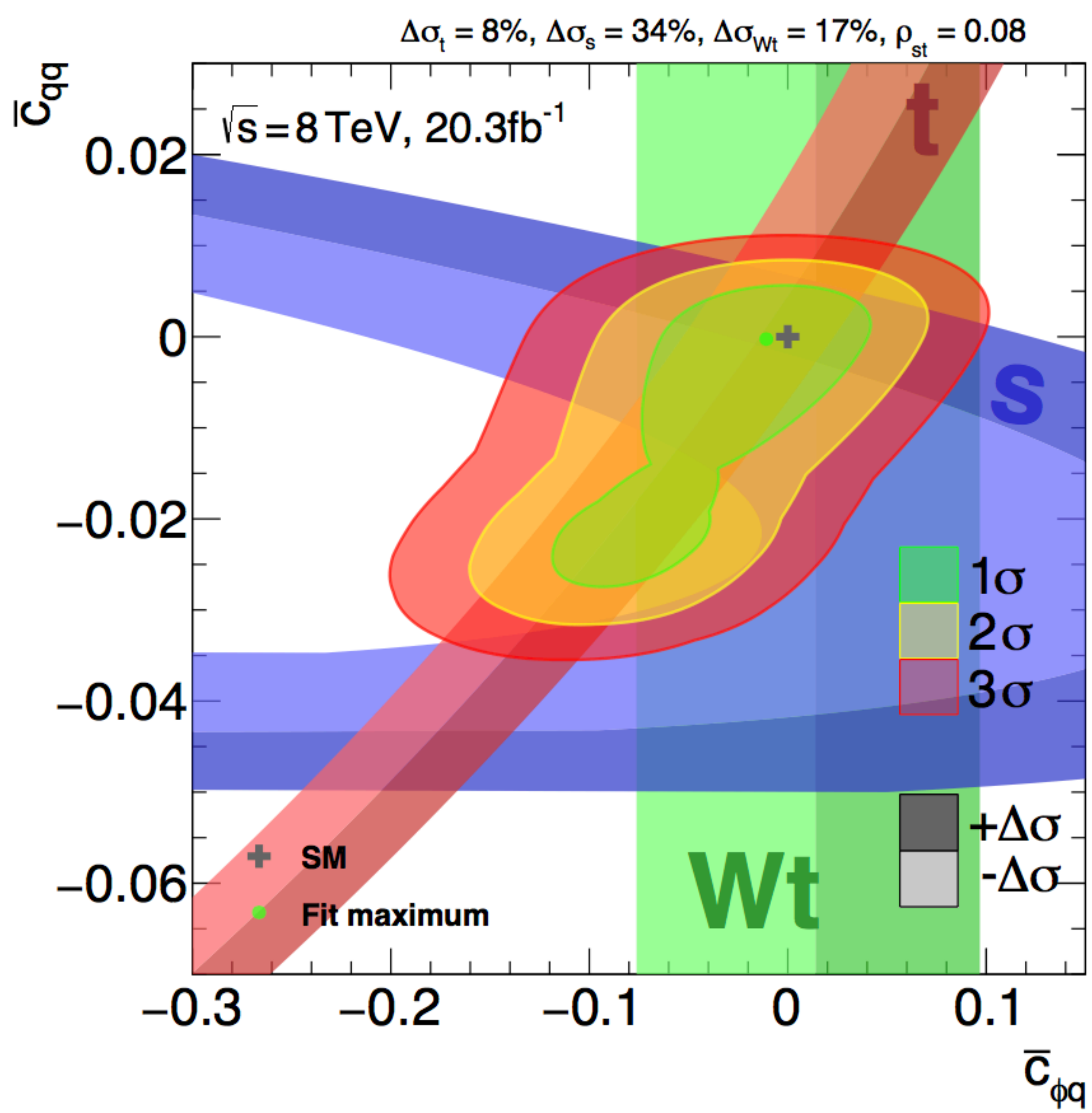


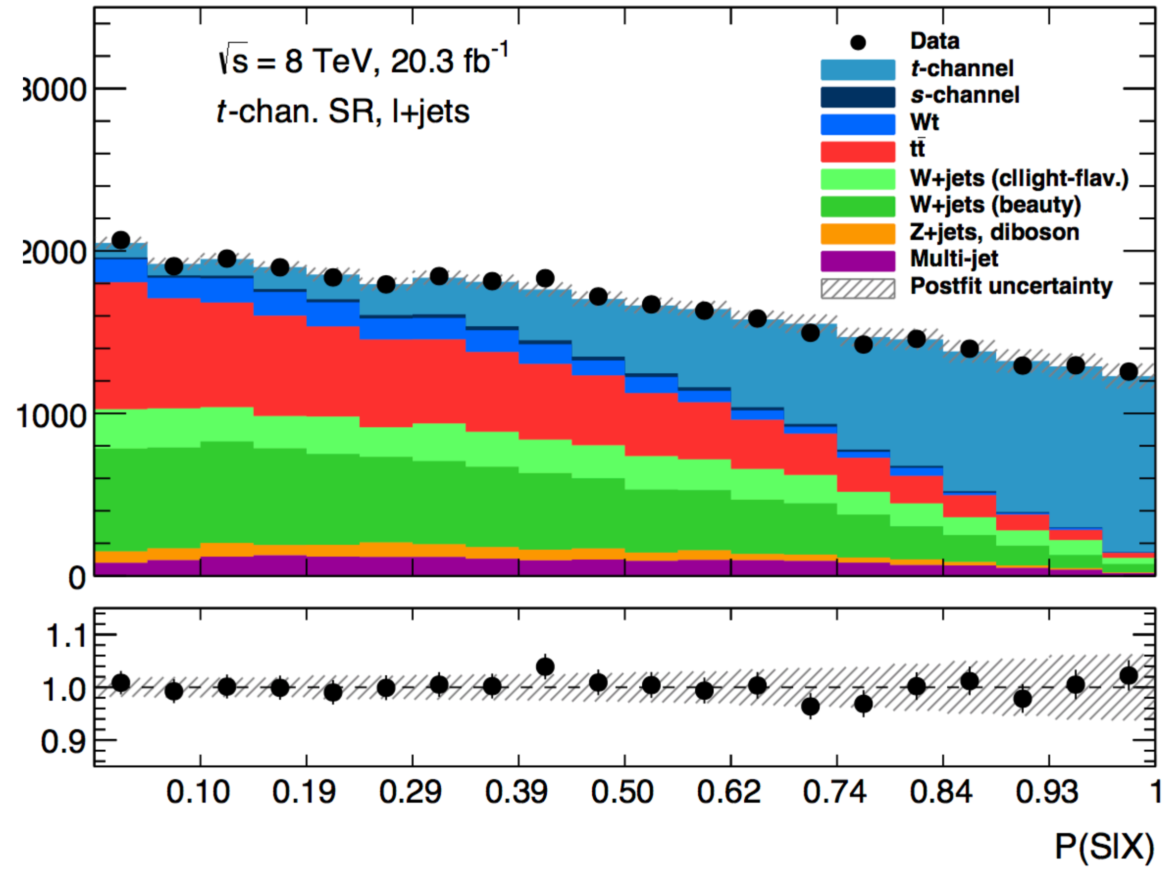
[ATLAS 1901.03584]

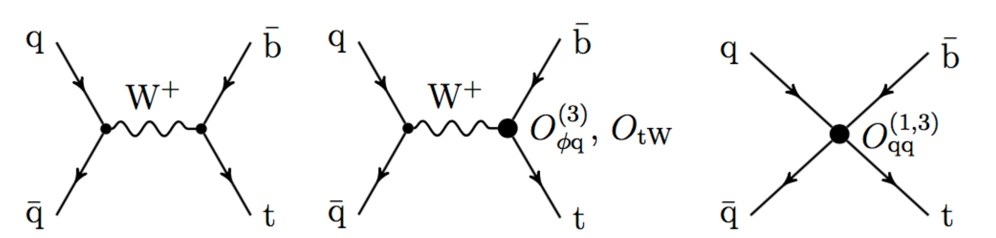
Coefficients	$C_{\phi Q}^{(3)}/\Lambda^2$	$C_{\phi t}/\Lambda^2$
Expected limit at 68% CL	[−2.1, 1.9]	[−3.8, 2.7]
Expected limit at 95% CL	[−4.5, 3.6]	[−23, 4.9]
Observed limit at 68% CL	[−1.0, 2.7]	[−2.0, 3.5]
Observed limit at 95% CL	[−3.3, 4.2]	[−25, 5.5]

SMEFT+MEM: single top

$$\mathcal{P}(S|X) = \frac{\sum_i P(S_i)\mathcal{P}(X|S_i)}{\sum_i P(S_i)\mathcal{P}(X|S_i) + \sum_j P(B_j)\mathcal{P}(X|B_j)}.$$



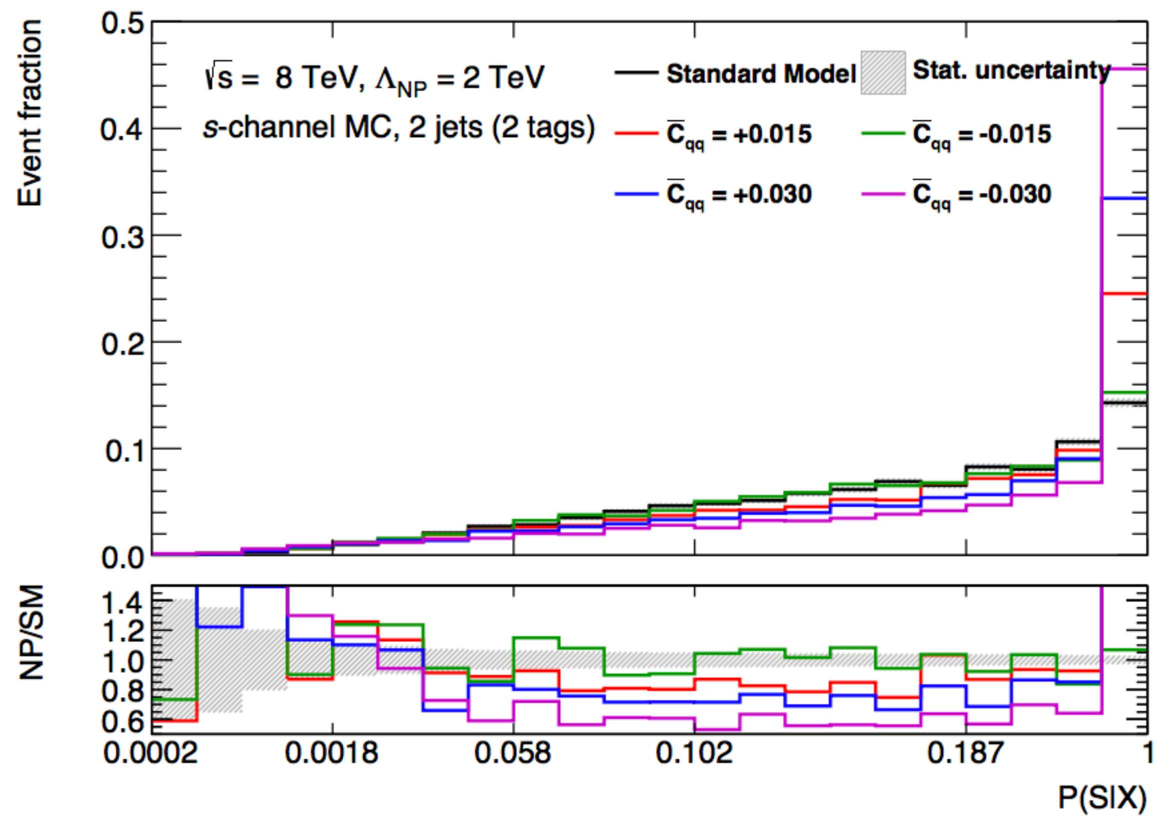


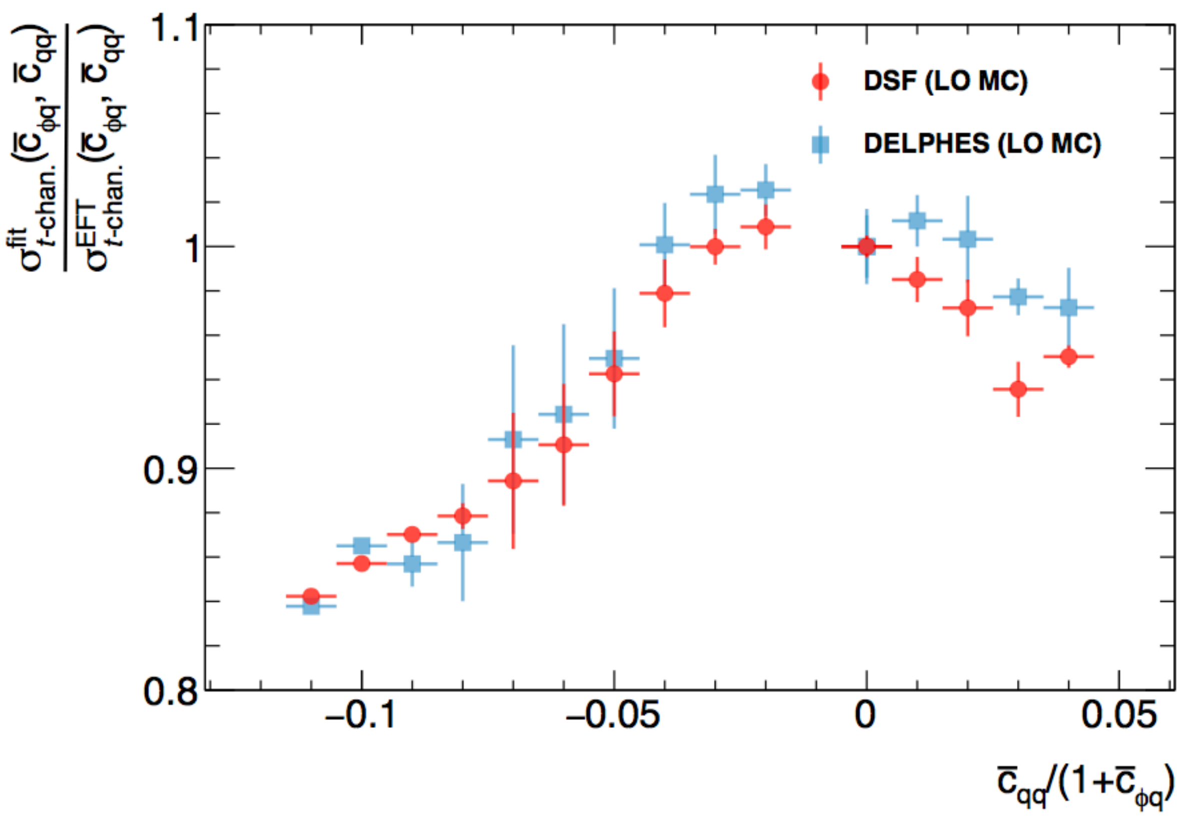


(a) s-channel, SM (b) s-channel, $O_{\phi q}^{(3)}$, O_{tW} (c) s-channel, $O_{qq}^{(1,3)}$

SMEFT+MEM: single top

ME discriminant variables modified by EFT (sensitive to operators)





Acceptance correction due to EFT

For discussion…

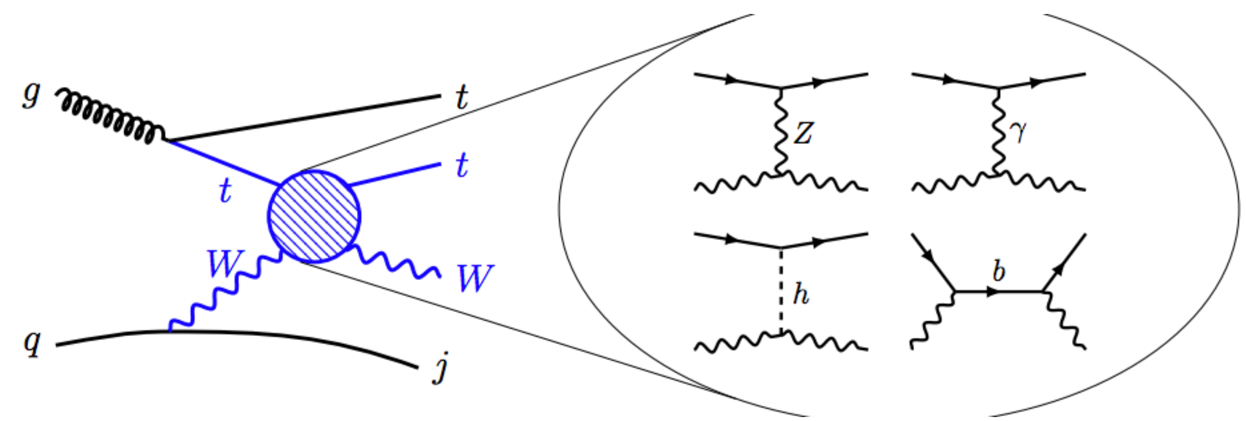
Theory

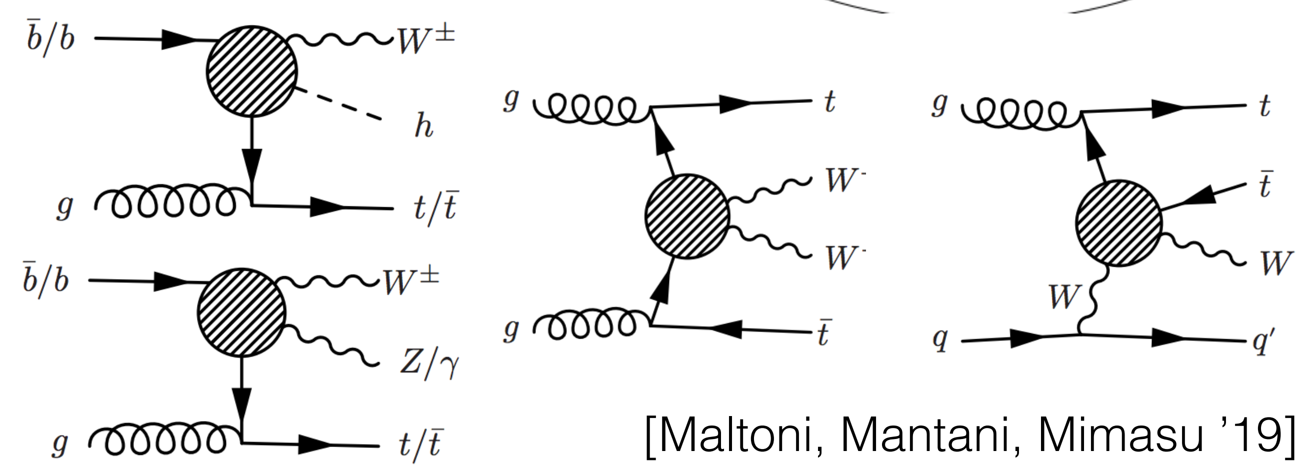
- TH predictions: what else to calculate
  NLO and higher, CPV observables, Off shell tops, spin correlation, EW corrections, loop-induced…
- What if PDF “absorbs” new physics?
- Global fit
  connection with Higgs, Precision EW, flavor… How to proceed?

Experiment

- What else to measure?
  - Top width ([0.6,2.5] from M_{lb})
  - Rare processes (3t/4t/5t/6t?)
  - Unitarity cancellation
  - STXS for tops
  - Best ways to present results…

[J. Dror et al. ’15]





[Maltoni, Mantani, Mimasu ’19]

Thank you