Probing Top-Higgs interactions at NLO in QCD

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Outline

- Top EFT @ NLO
- ttH
- Summary

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Top quark is unique in many ways:

- Heaviest, of course… but also:
- It's a bare quark, decaying before hadronization.

  $\tau_{had} \approx h/\Lambda_{QCD} \approx 2 \cdot 10^{-24}$ s

  $\tau_{flip} \approx h\, m_t / \Lambda_{QCD}{}^2 >> \tau_{had}$

  $\tau_{top} \approx h/\Gamma_{top} = 1/(G_F\, m_t^3\, |V_{tb}|^2/8\pi\sqrt{2}) \approx 5 \cdot 10^{-25}$ s
- Top Yukawa is the largest SM coupling.

  $m_{top} = y_t\, v/\sqrt{2} \approx 174\ \text{GeV} \Rightarrow y_t \approx 1$

  and hence largest Higgs mass correction.
- They are many: 6 million from Run-I, ~2 orders of magnitude to go.

Top couplings

- The **old** way: Anomalous couplings (AC), vertex functions…

$$\Gamma^{ttV}_{\mu}(k^2,\, q,\, \bar{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}^V_{1V}(k^2)+\gamma_5\widetilde{F}^V_{1A}(k^2)\right)+\frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}^V_{2V}(k^2)+\gamma_5\widetilde{F}^V_{2A}(k^2)\right)\right\}.$$

- The **modern** way: SM EFT

$$\Delta\mathcal{L}=\sum_i\frac{C_i}{\Lambda^2}O_i+h.c.$$

with

$$O_{tW}=y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O_{tB}=y_t g_Y(\bar{Q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu}$$
$$O_{tG}=y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

and more

[arXiv: 0704.2809 Cao, Wudka, Yuan]
[arXiv: 0811.3842 Aguilar-Saavedra]
[arXiv:1008.3869 CZ and Willenbrock]

	Gauge invariance	Higher-order corrections	Complete description	Non-redundancy	Applies to off-shell top	…
AC	×	×	×	×	×	×
EFT	✓	✓	✓	✓	✓	✓

Top couplings

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AC	×	×	×	×	×	×
EFT	✓	✓	✓	✓	✓	✓

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

SM NLO EFT EFT @ NLO

We provide a framework based on MadGraph5_aMC@NLO, that

- provides automatic predictions at NLO in QCD + PS;
- is based on effective field theory of the top quark. (i.e. with dim-6 operators.)

New in this talk:
tt+H at NLO as well as loop-induced gg>H,Hj,HZ,…
are becoming available

SMEFT @ NLO

- SMEFT at NLO is an active field, for both HEFT and top-EFT.

  [1507.03568 C. Hartmann and M. Trott] [1512.02508 R. Gauld et al.]
  [1601.06163, CZ] [1601.08193 Bylund, Maltoni, Tsinikos, Vryonidou, CZ]
  …

- A common belief in HEFT is that NLO log terms should dominate over the finite correction, so NLO RG corrections/improvements are enough.

  $\mathbf{\Lambda \sim 1\,TeV \Rightarrow \ln(\Lambda^2/m_H^2) \sim 4}$ [1312.2014 R. Alonso et al.]

- While this may be true for HEFT in several cases, it is certainly not the case for top-EFT.

- Top operators involve colored fields, so it's important to study QCD NLO. <u>QCD corrections giving O(1) effects</u> are common at the LHC.

  - **Operator fit using differential information can be very sensitive to QCD correction.** [1601.06163, CZ]

- Always keep in mind that top measurements are becoming precision measurements.

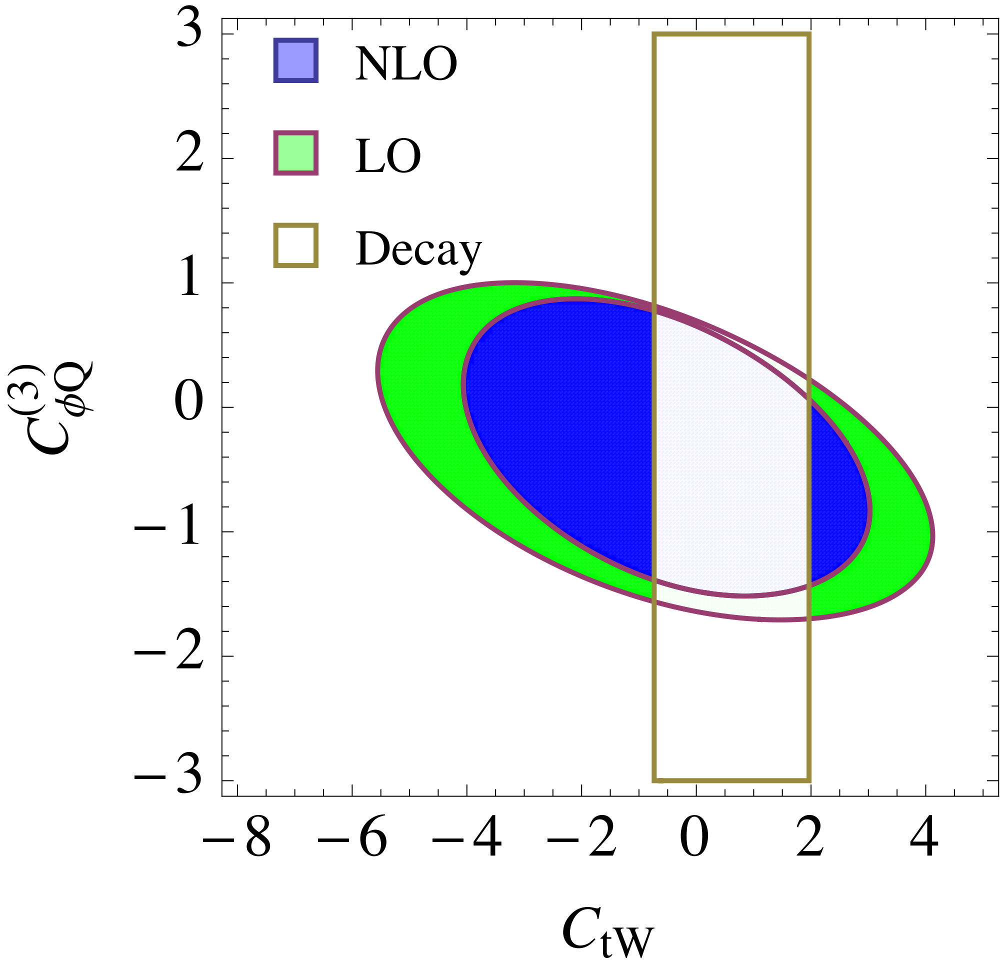
NLO effects: total xsec

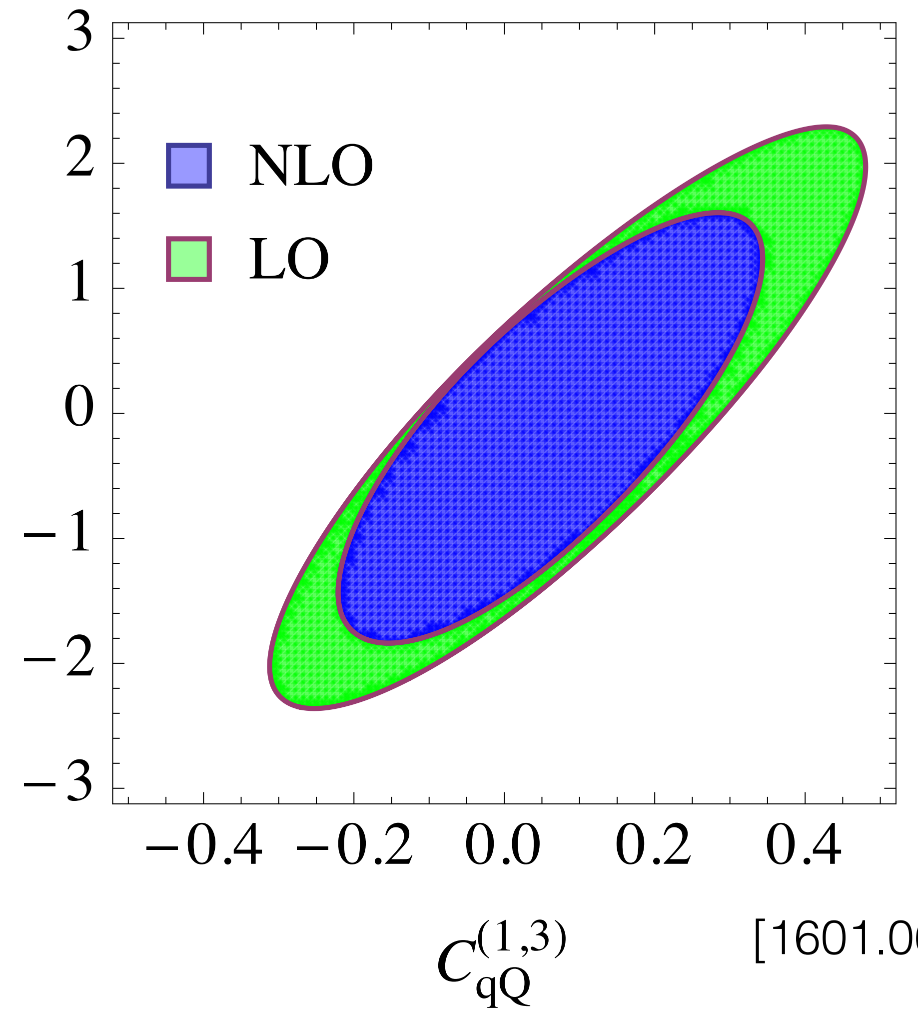
- Constraining coefficients with NLO xsecs: improved limits

Current limit on O_{tG} from top-pair cross section measurements:
[-1.10, 0.41] (LO) -> [-0.50, 0.25] (NLO)

[1503.08841 D.B. Franzosi, **CZ**]

Single top:

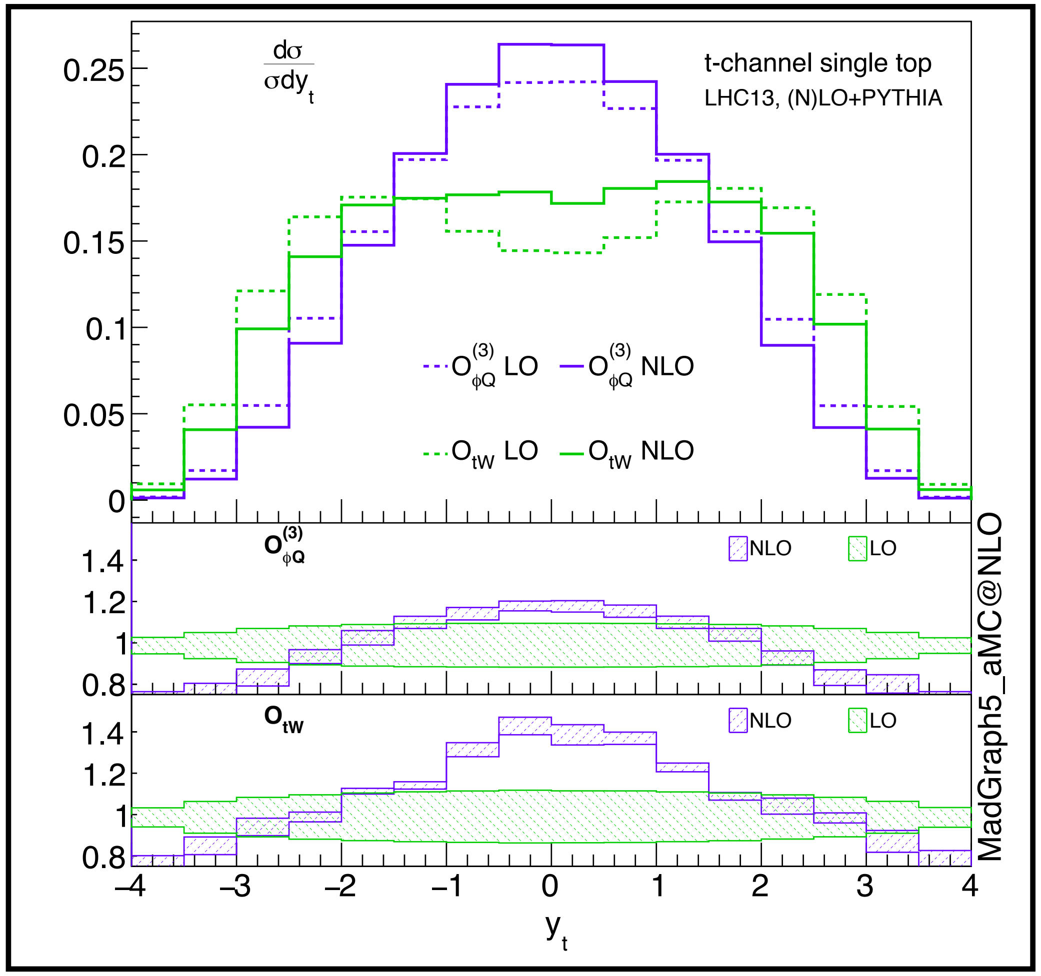


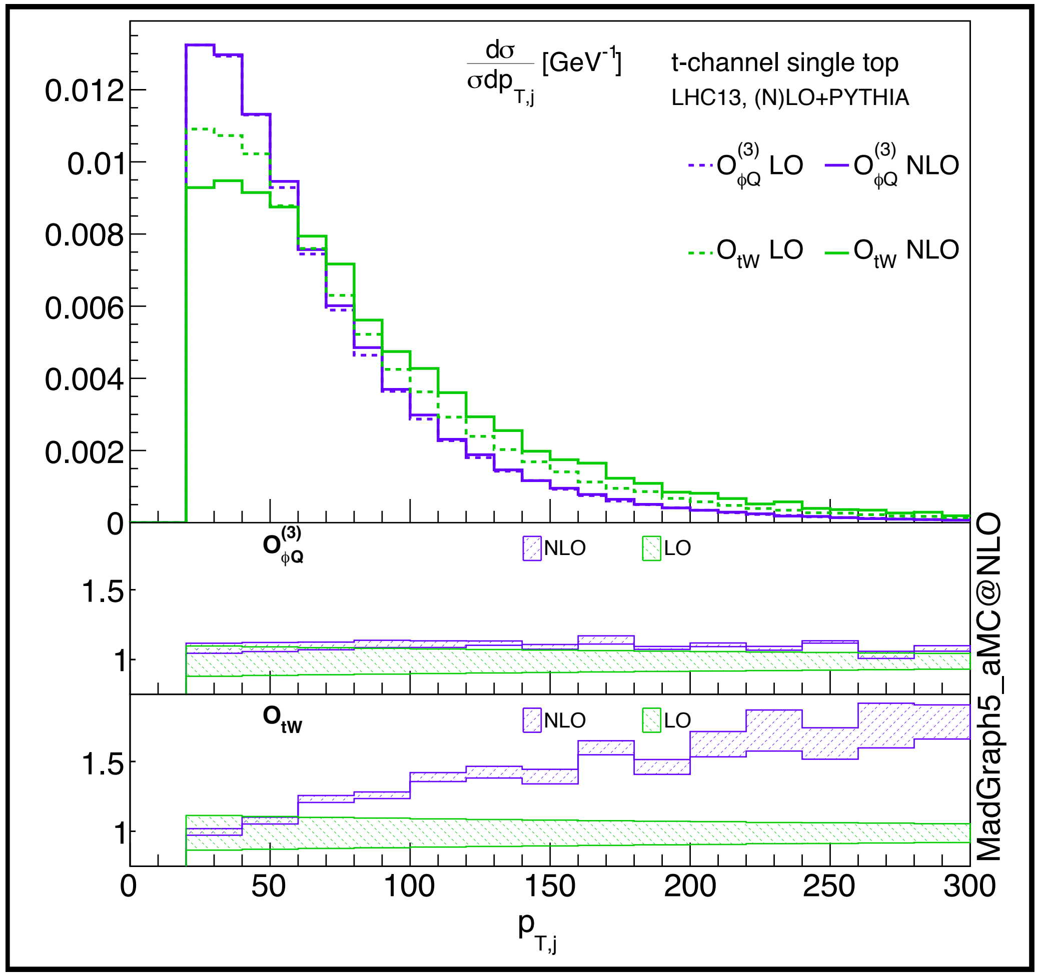


[1601.06163, **CZ**]

NLO effects: shapes

- Operator fit will be affected by QCD
  - If “discriminant” observables are used in global fits
  - Shapes of O_1 and O_2 differs
  - QCD corrections <u>shift both curves in one direction</u>
  - Leads to bias in a fit that uses shape info





t-ch. single top [1601.06163, CZ]

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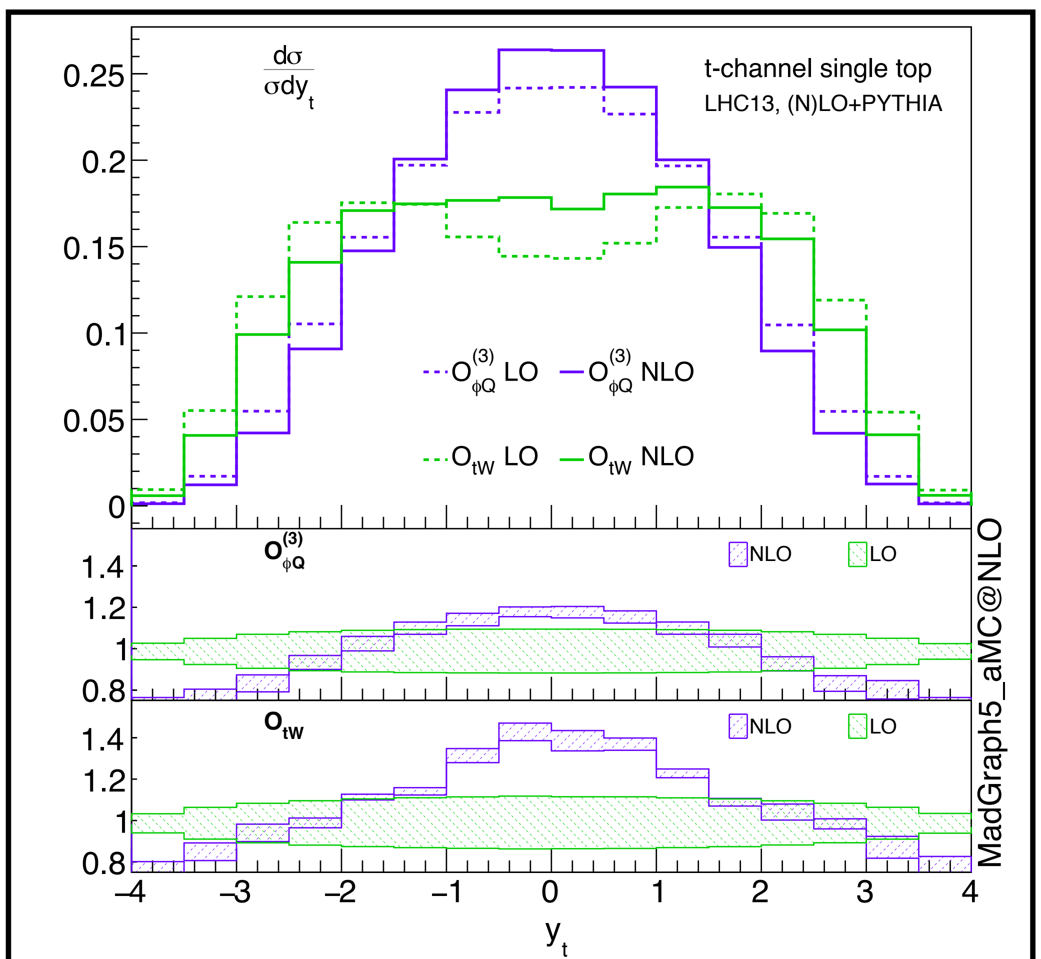

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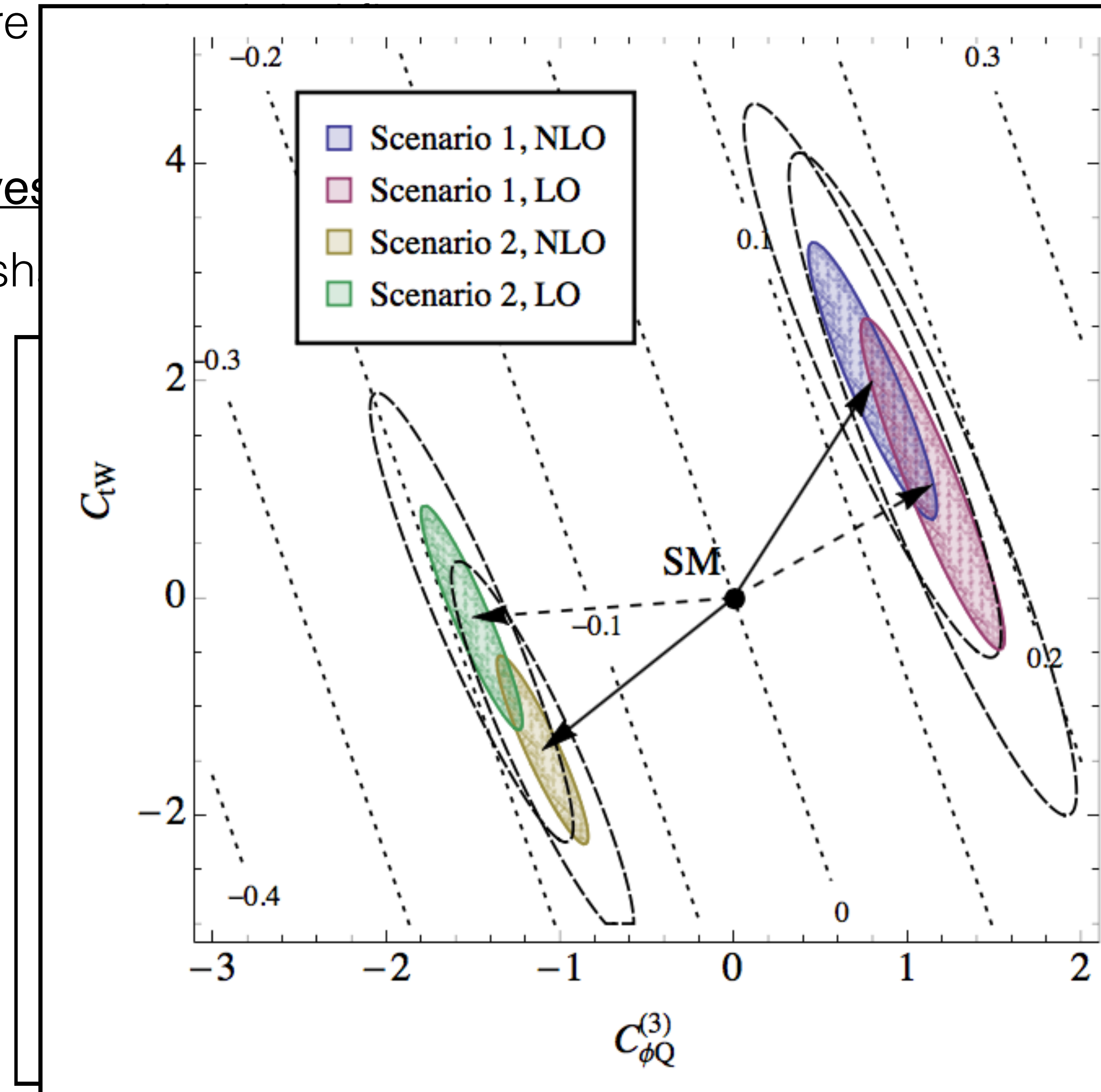

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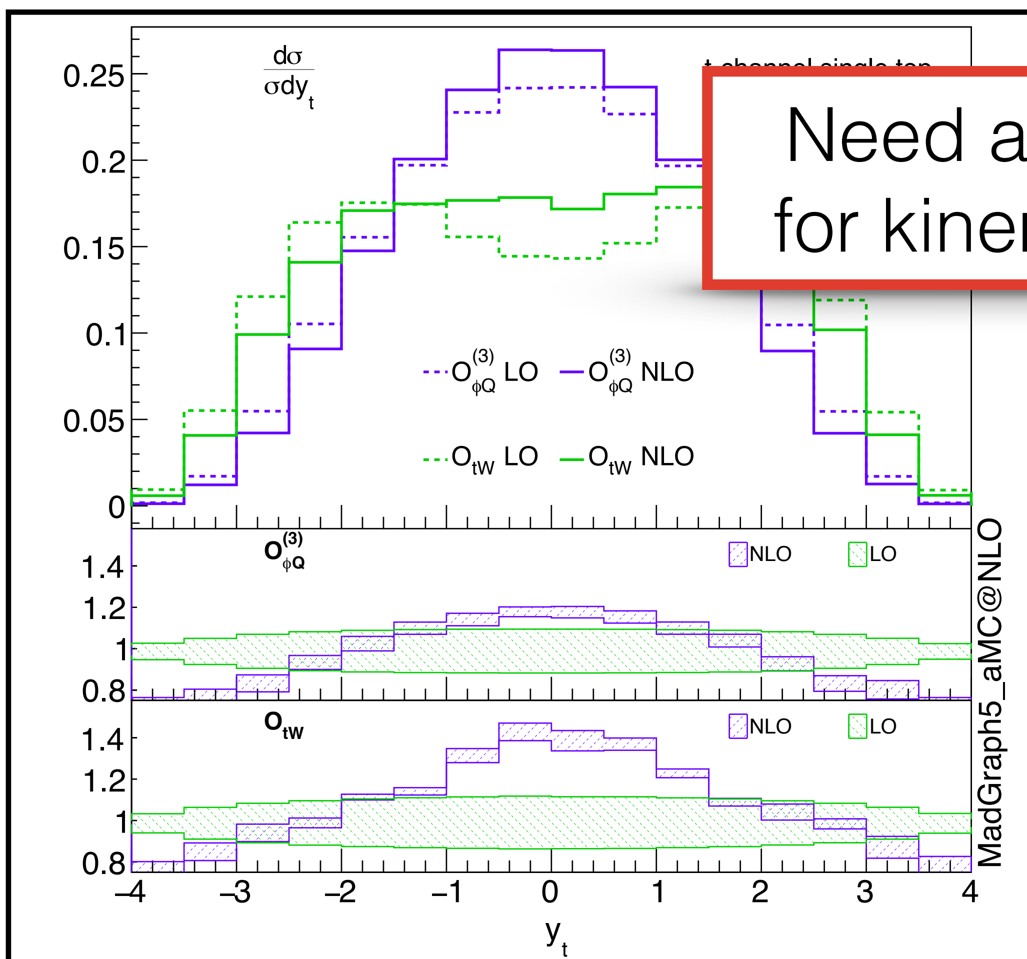

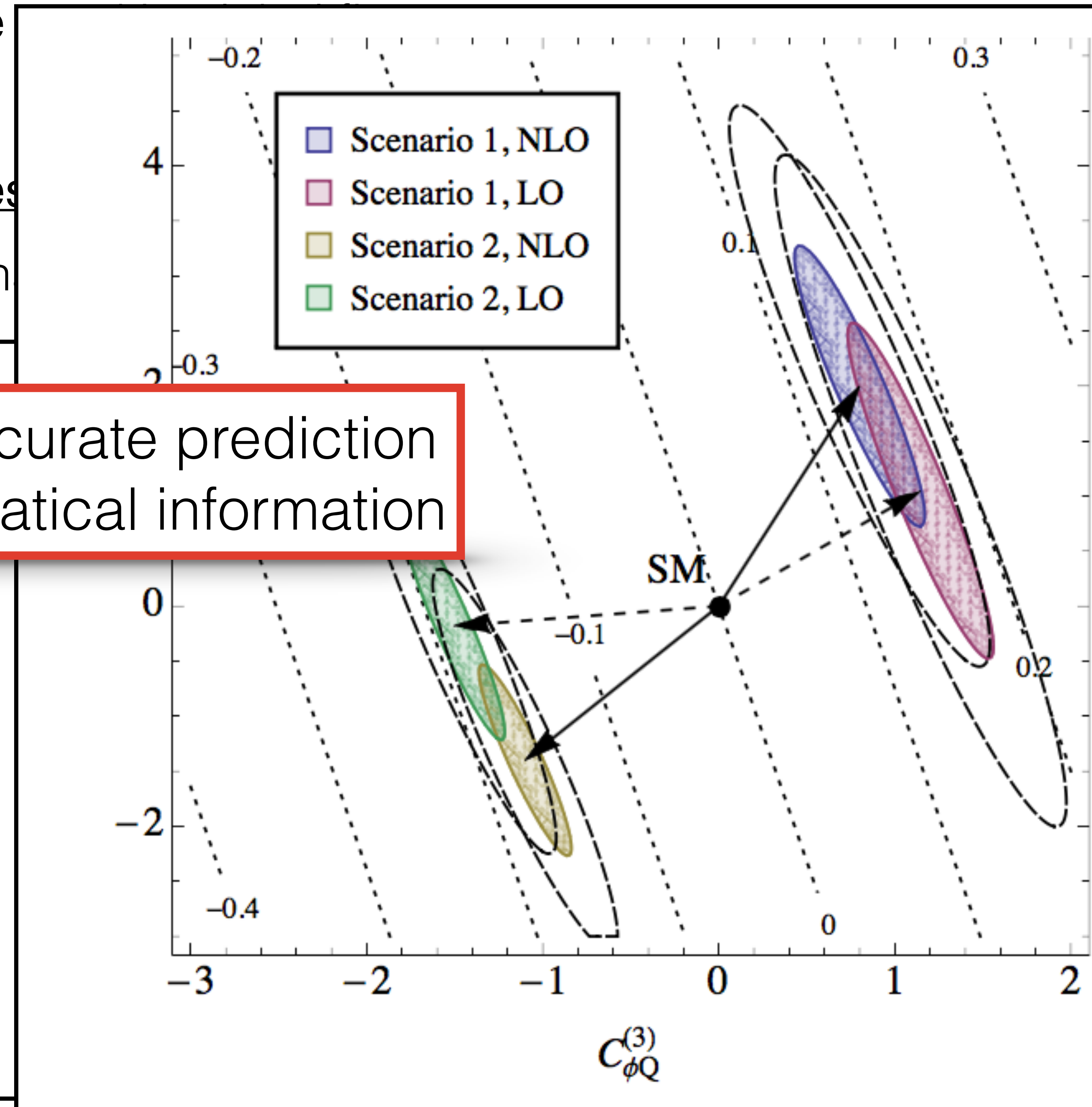

Need accurate prediction for kinematical information

t-ch. single top [1601.06163, CZ]

NLO effects: loop-induced

- At LO gg>H constrain $O_{\phi G}$
- At NLO becomes sensitive to top-quark operators. More interesting pheno.
  - Operator mixing: need NLO to understand the structure of the theory.
  - H+j, with boosted jet, will help to resolve the loop.

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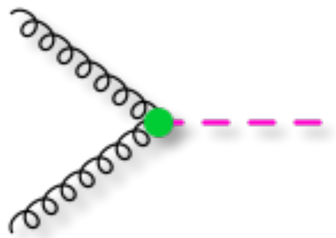
gluon-Higgs $O_{\phi G} = y_t^2(\phi^\dagger \phi) G^A_{\mu\nu} G^{A\mu\nu}$



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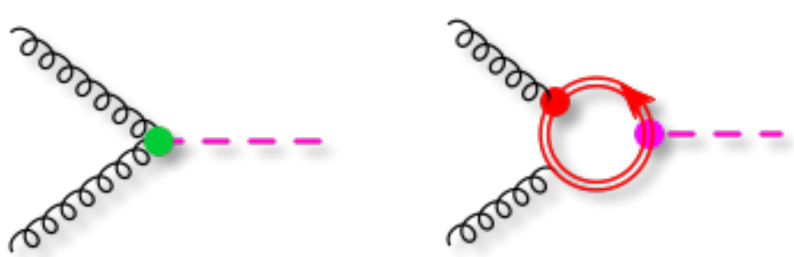
Yukawa $O_{t\phi} = y_t^3(\phi^\dagger\phi)\bar{Q}t\tilde{\phi}$



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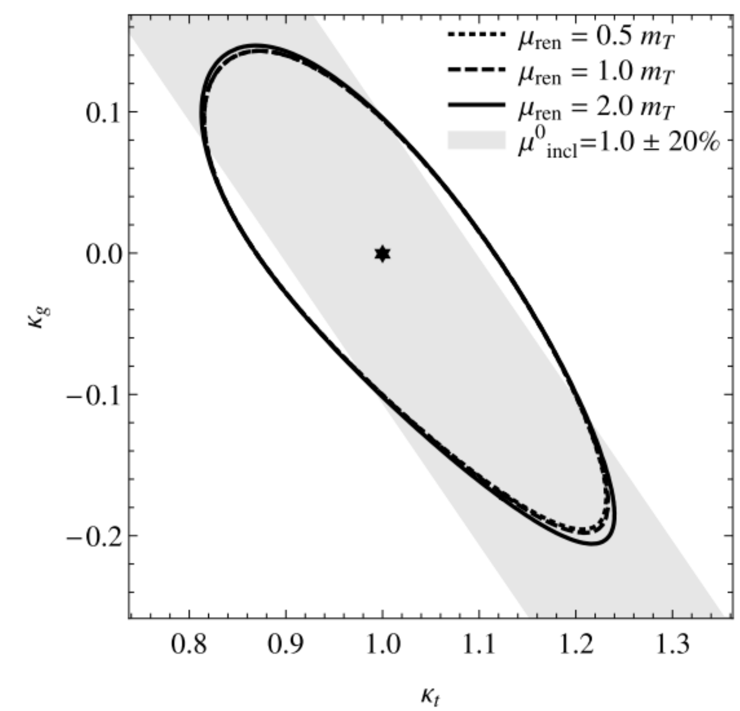
[1312.3317 C. Grojean et al.]



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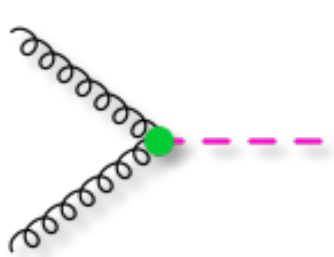
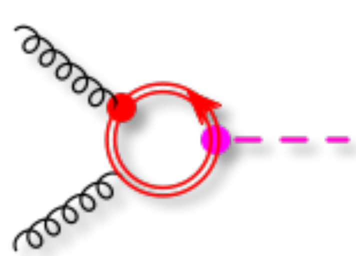
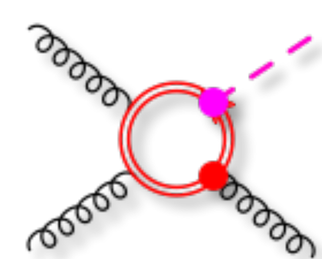
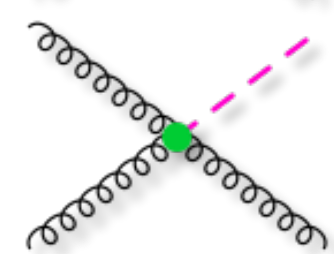

Outline

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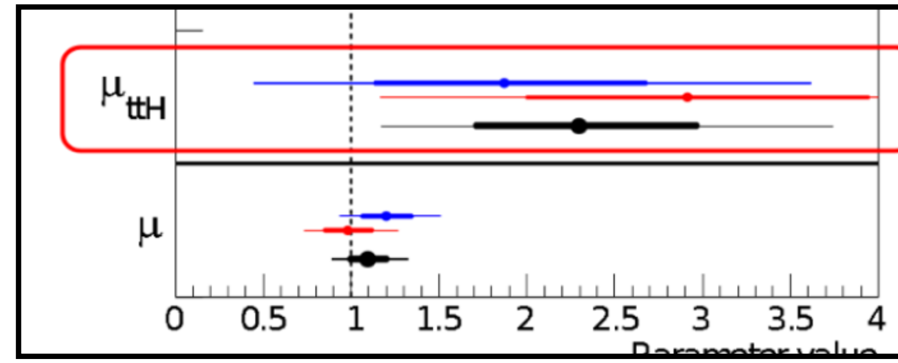
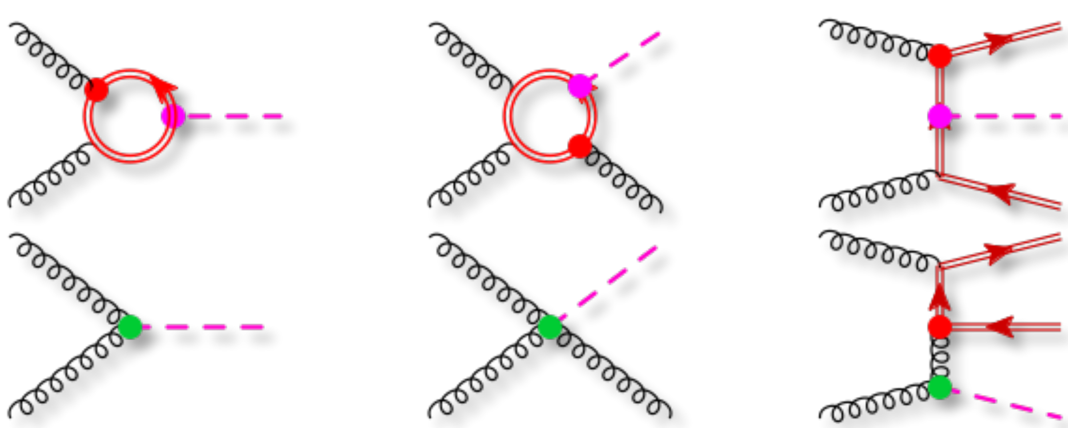
ttH motivation

- Direct probe of top Yukawa

Run 1 combination
$\mu=2.3^{+0.7}_{-0.6}$



- A global fit with three operators



$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G_{\mu\nu}$$
$$O_{t\phi} = y_t^3(\phi^\dagger\phi)\bar{Q}t\tilde{\phi}$$
$$O_{\phi G} = y_t^2(\phi^\dagger\phi)G^A_{\mu\nu}G^{A\mu\nu}$$

$$\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 \\ 4 & -1 & 4 \\ \frac{1}{4} & 0 & -\frac{7}{4} \end{pmatrix}$$

  - Loop-tree degeneracy might occur also for pp>ttH (which at LO is not captured)

- Finally, to complete SMEFT at NLO.

NLO status

	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}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

Coupling measurements

	tqZ/γ					tqg	tqH	lltq
Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to ql^+l^-$	✓	✓	✓	✓	✓	✓		✓
$t \to q\gamma$				✓	✓	✓		
$t \to qH$						✓	✓	
$pp \to t$						✓		
$pp \to tl^+l^-$	✓	✓	✓	✓	✓	✓		(✓)
$pp \to t\gamma$				✓	✓	✓		
$pp \to tH$						✓	✓	

FCNC searches

- Decays and FCNC direct t production is available analytically.
  [1404.1264 CZ], [1305.7386 F. Maltoni, CZ], [1004.0898 J. J. Zhang et al.]
- FCNC associated productions have been implemented.
  [1412.5594 Degrande, Maltoni, Wang, CZ] http://feynrules.irmp.ucl.ac.be/wiki/TopFCNC

	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}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

Coupling measurements

cf
[1501.05939 & 1404.1005, R. Rontsch and M. Schulze]

	tqZ/γ					tqg	tqH	lltq
Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to ql^+l^-$	✓	✓	✓	✓	✓	✓		✓
$t \to q\gamma$				✓	✓	✓		
$t \to qH$						✓	✓	
$pp \to t$						✓		
$pp \to tl^+l^-$	✓	✓	✓	✓	✓	✓		(✓)
$pp \to t\gamma$				✓	✓	✓		
$pp \to tH$						✓	✓	

FCNC searches

- ttbar with chromo [1503.08841 D.B. Franzosi, CZ]
- Complete top-EW operators, single t and ttV [1601.06163, CZ]
  [1601.08193 Bylund, Maltoni, Tsinikos, Vryonidou, CZ]
- ttH and tHj: ongoing [Maltoni, Vryonidou, CZ]
- Four fermion operators are planned [Degrande, Deuriex]

Do not trust anything beyond this slide!

```
MG5_aMC>import model TEFT_H
MG5_aMC>generate p p > t t~ h EFT=1 [QCD]
MG5_aMC>output
MG5_aMC>launch
```

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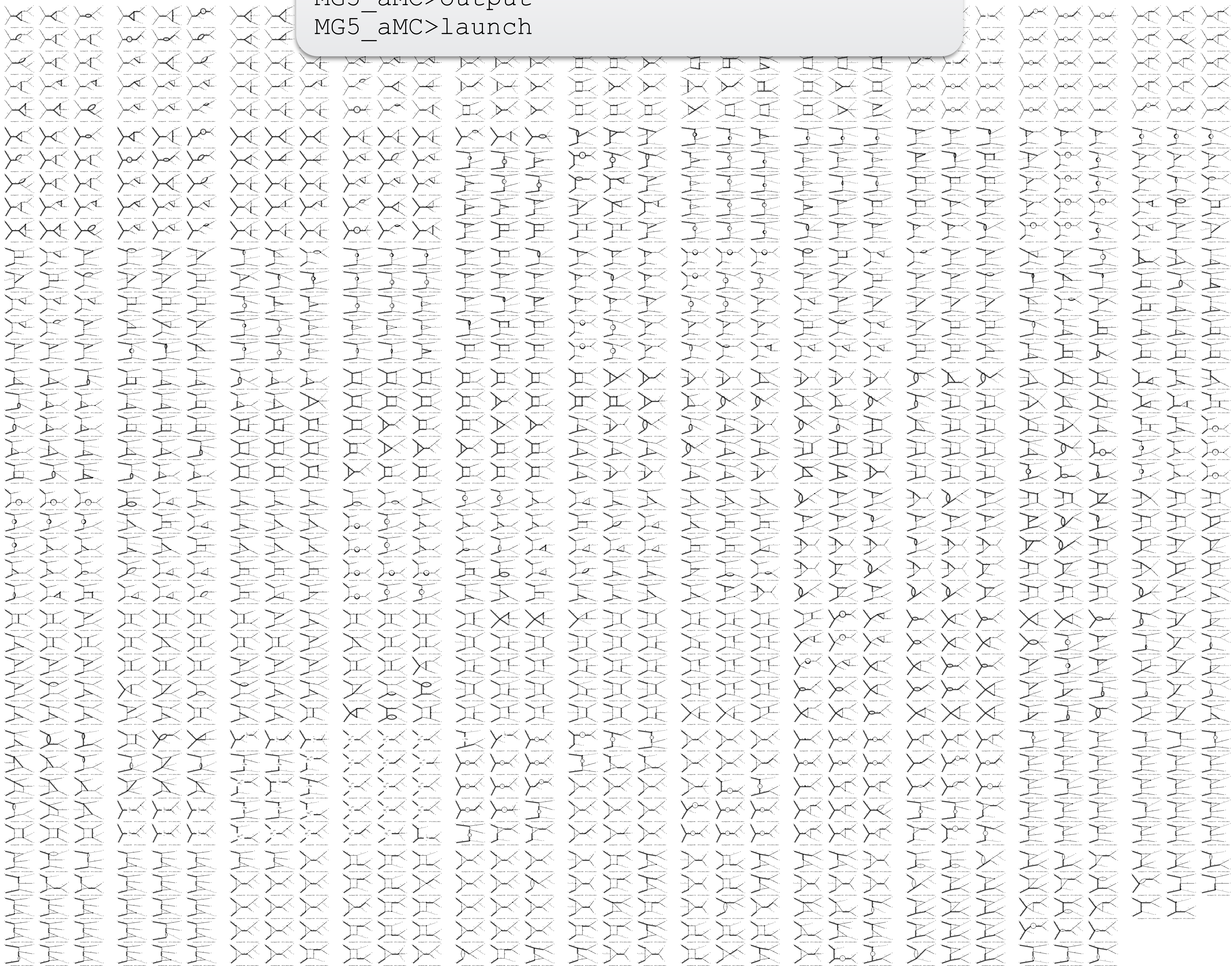

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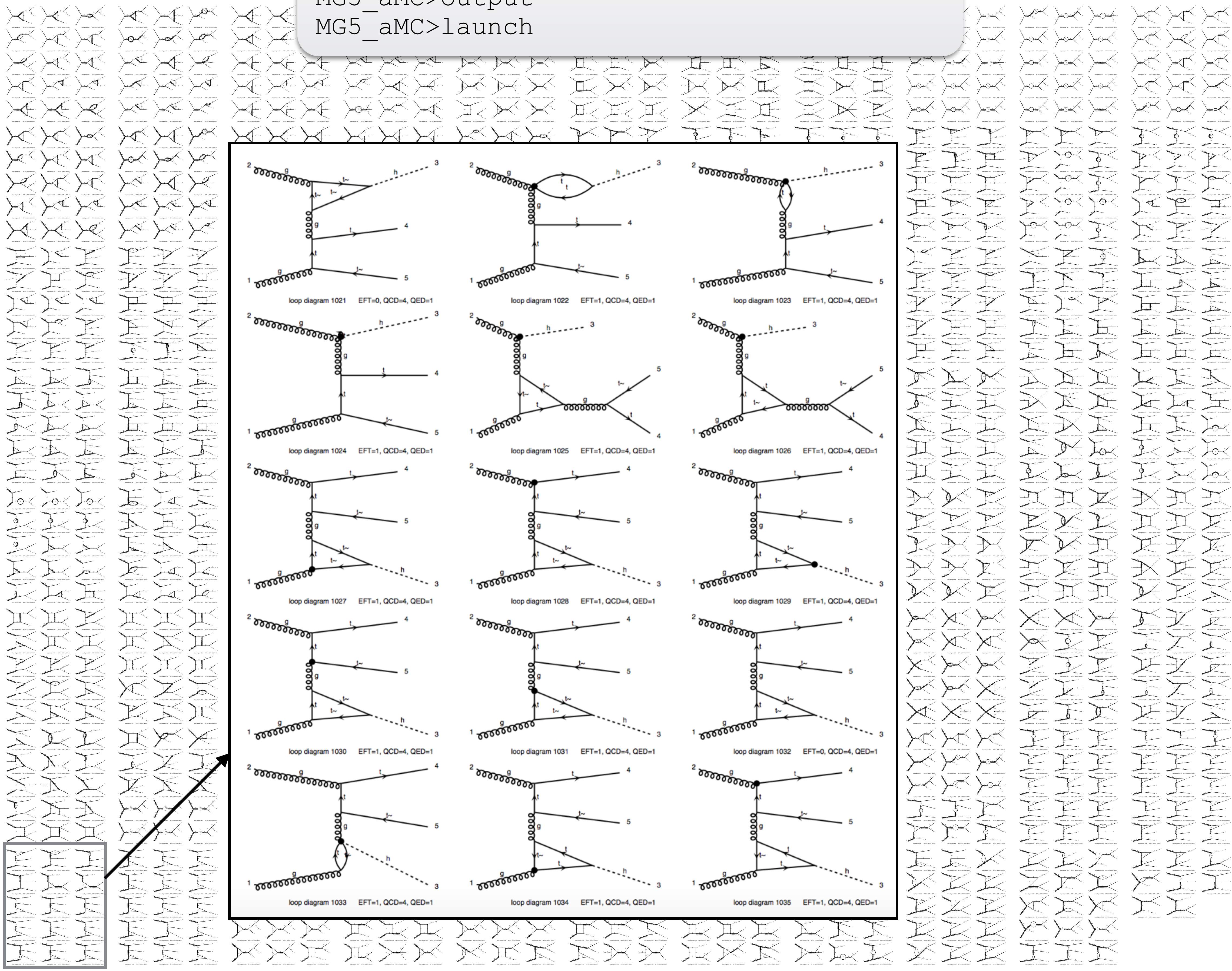


$$\sigma = \sigma_{SM} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \leq j} \frac{1\mathrm{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}$$

	LO	LO/SM	NLO	NLO/SM	K
σ_{SM}	$0.464^{+0.161+0.000+0.005}_{-0.111-0.000-0.004}$	$1.000^{+0.000+0.000+0.000}_{-0.000-0.000-0.000}$	$0.507^{+0.030+0.000+0.007}_{-0.048-0.000-0.008}$	$1.000^{+0.000+0.000+0.000}_{-0.000-0.000-0.000}$	1.09
$\sigma_{t\phi}$	$-0.055^{+0.013+0.002+0.000}_{-0.019-0.003-0.001}$	$-0.119^{+0.000+0.005+0.000}_{-0.000-0.006-0.000}$	$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	$-0.123^{+0.001+0.001+0.000}_{-0.001-0.002-0.000}$	1.13
$\sigma_{\phi G}$	$0.627^{+0.225+0.081+0.007}_{-0.153-0.067-0.005}$	$1.351^{+0.011+0.175+0.002}_{-0.011-0.145-0.001}$	$0.872^{+0.131+0.037+0.013}_{-0.123-0.035-0.016}$	$1.722^{+0.146+0.073+0.004}_{-0.089-0.068-0.005}$	1.39
σ_{tG}	$0.470^{+0.167+0.000+0.005}_{-0.114-0.002-0.004}$	$1.014^{+0.006+0.000+0.001}_{-0.006-0.004-0.001}$	$0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$	$0.991^{+0.004+0.003+0.000}_{-0.010-0.006-0.001}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0016^{+0.0005+0.0002+0.0000}_{-0.0004-0.0001-0.0000}$	$0.0035^{+0.0000+0.0004+0.0000}_{-0.0000-0.0003-0.0000}$	$0.0019^{+0.0001+0.0001+0.0000}_{-0.0002-0.0000-0.0000}$	$0.0037^{+0.0001+0.0002+0.0000}_{-0.0000-0.0001-0.0000}$	1.17
$\sigma_{\phi G,\phi G}$	$0.646^{+0.274+0.141+0.018}_{-0.178-0.107-0.010}$	$1.392^{+0.079+0.304+0.025}_{-0.066-0.231-0.014}$	$1.021^{+0.204+0.096+0.024}_{-0.178-0.085-0.029}$	$2.016^{+0.267+0.190+0.021}_{-0.178-0.167-0.027}$	1.58
$\sigma_{tG,tG}$	$0.645^{+0.276+0.011+0.020}_{-0.178-0.015-0.010}$	$1.390^{+0.082+0.023+0.028}_{-0.069-0.031-0.016}$	$0.674^{+0.036+0.004+0.016}_{-0.067-0.007-0.019}$	$1.328^{+0.011+0.008+0.014}_{-0.038-0.014-0.018}$	1.04
$\sigma_{t\phi,\phi G}$	$-0.037^{+0.009+0.006+0.000}_{-0.013-0.007-0.000}$	$-0.081^{+0.001+0.012+0.000}_{-0.001-0.015-0.000}$	$-0.053^{+0.008+0.003+0.001}_{-0.008-0.004-0.001}$	$-0.105^{+0.006+0.006+0.000}_{-0.009-0.007-0.000}$	1.42
$\sigma_{t\phi,tG}$	$-0.028^{+0.007+0.001+0.000}_{-0.010-0.001-0.000}$	$-0.060^{+0.000+0.002+0.000}_{-0.000-0.003-0.000}$	$-0.031^{+0.003+0.000+0.000}_{-0.002-0.000-0.000}$	$-0.061^{+0.000+0.000+0.000}_{-0.000-0.001-0.000}$	1.10
$\sigma_{\phi G,tG}$	$0.627^{+0.252+0.053+0.014}_{-0.166-0.047-0.008}$	$1.349^{+0.054+0.114+0.016}_{-0.046-0.100-0.009}$	$0.859^{+0.127+0.021+0.017}_{-0.126-0.020-0.022}$	$1.691^{+0.137+0.042+0.013}_{-0.097-0.039-0.017}$	1.37

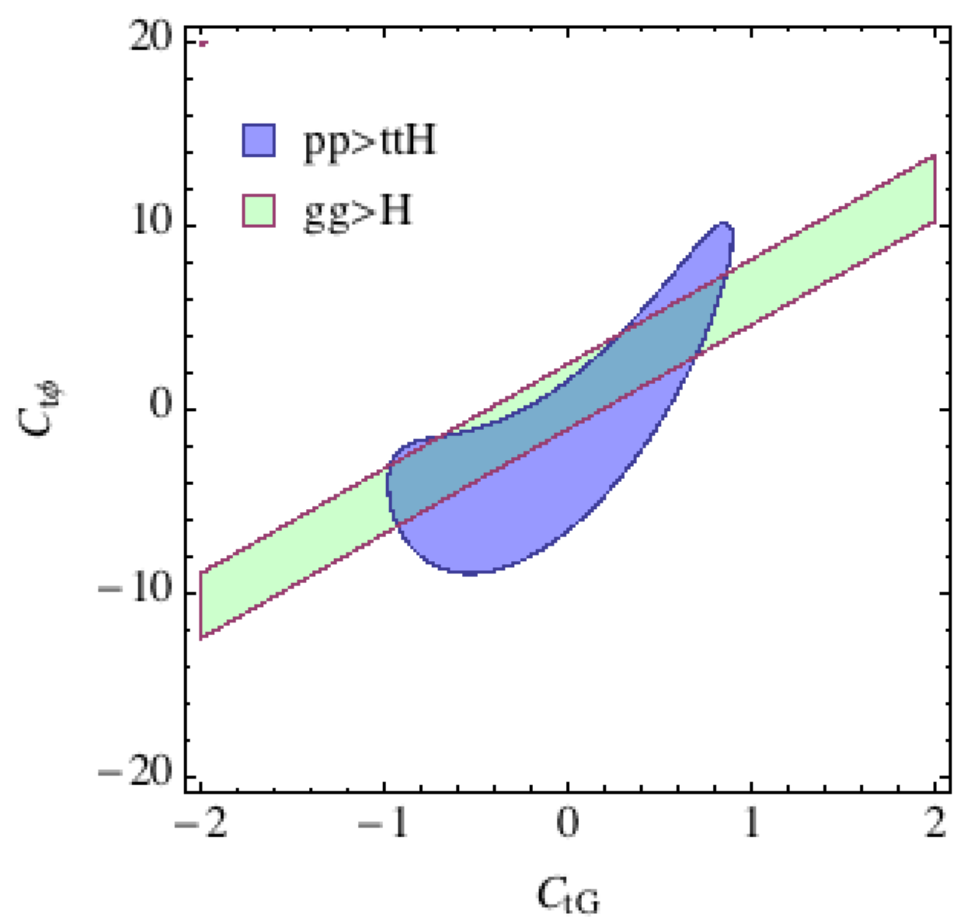
"EFT scale uncertainty"

- K factors: vary between 1~1.6
- Uncertainties: μ_R and μ_F, μ_{EFT}, PDF
  - The EFT scale uncertainties come from varying the defining scale of the theory by a factor of 1/2~2. It represents an estimation of missing higher order correction to the operators, including mixing.
  - Can be brought down by full NLO
  - typically less than μ_R and μ_F uncertainty, but once take ratios, it's the dominant piece. e.g. in σ(ttH)/σ(ttZ) [1507.08169 M.L. Mangano et al.]

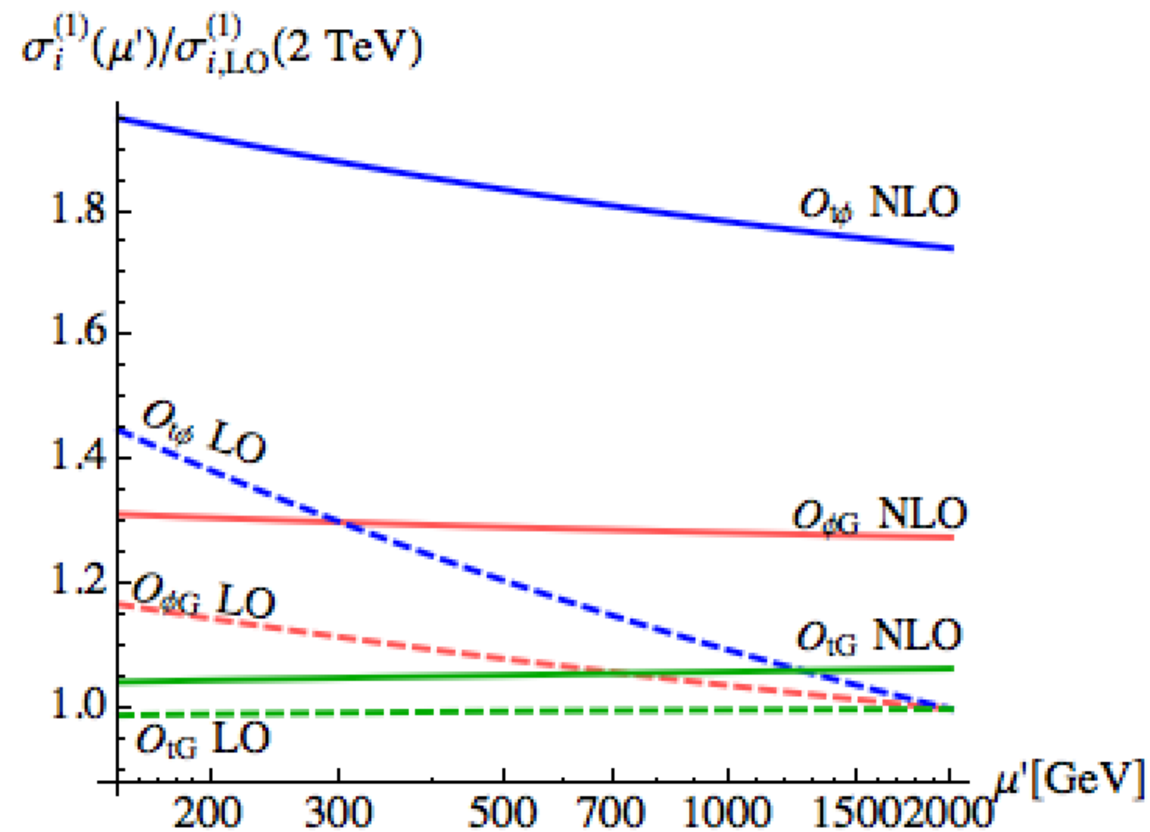
Limits

	Fixed	Marginalized
$C_{t\phi}$	[-7.2,0.57]	[-13,47]
$C_{\phi G}$	[-0.07,-0.00015]	[-0.08,0.08]
C_{tG}	[-0.55,0.57]	[-1.6,1.6]

Comparable to the limit obtained from ttbar production



RG vs Full NLO



pp>ttH

Limits

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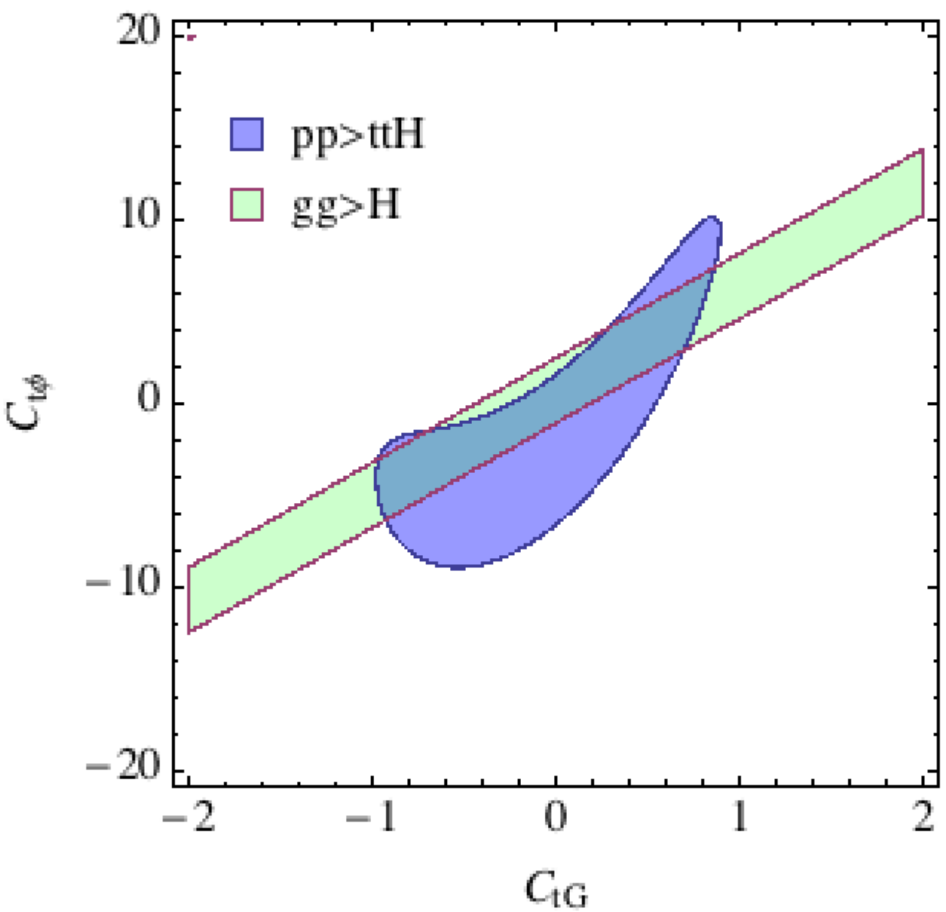
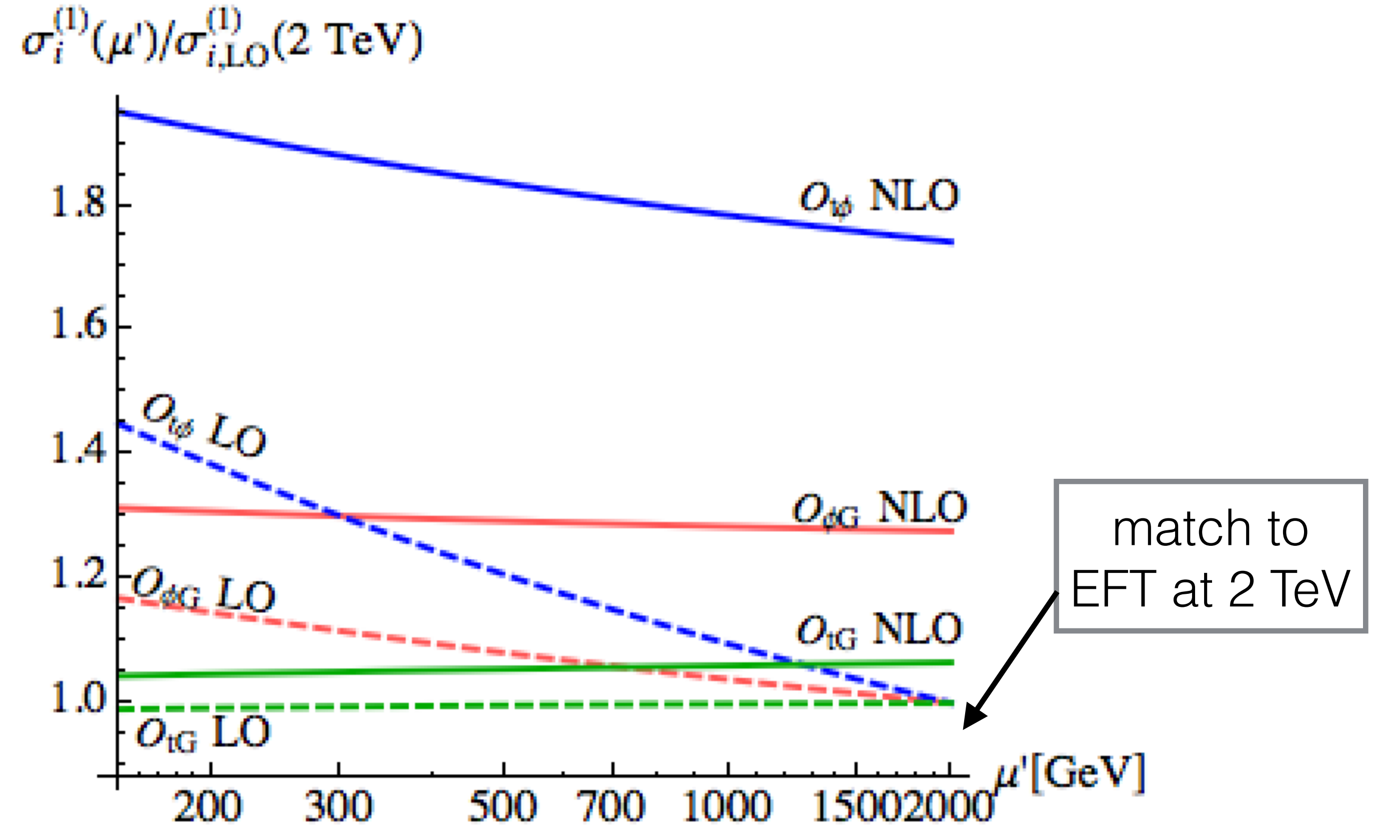


RG vs Full NLO



pp>ttH

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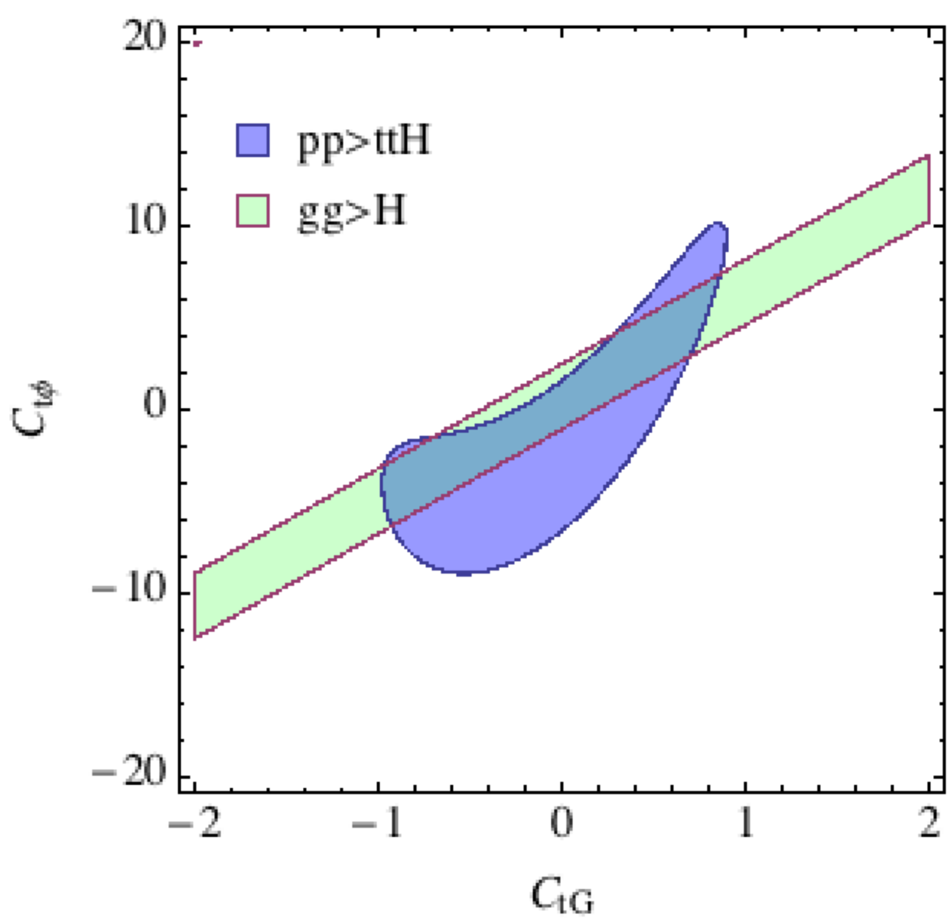
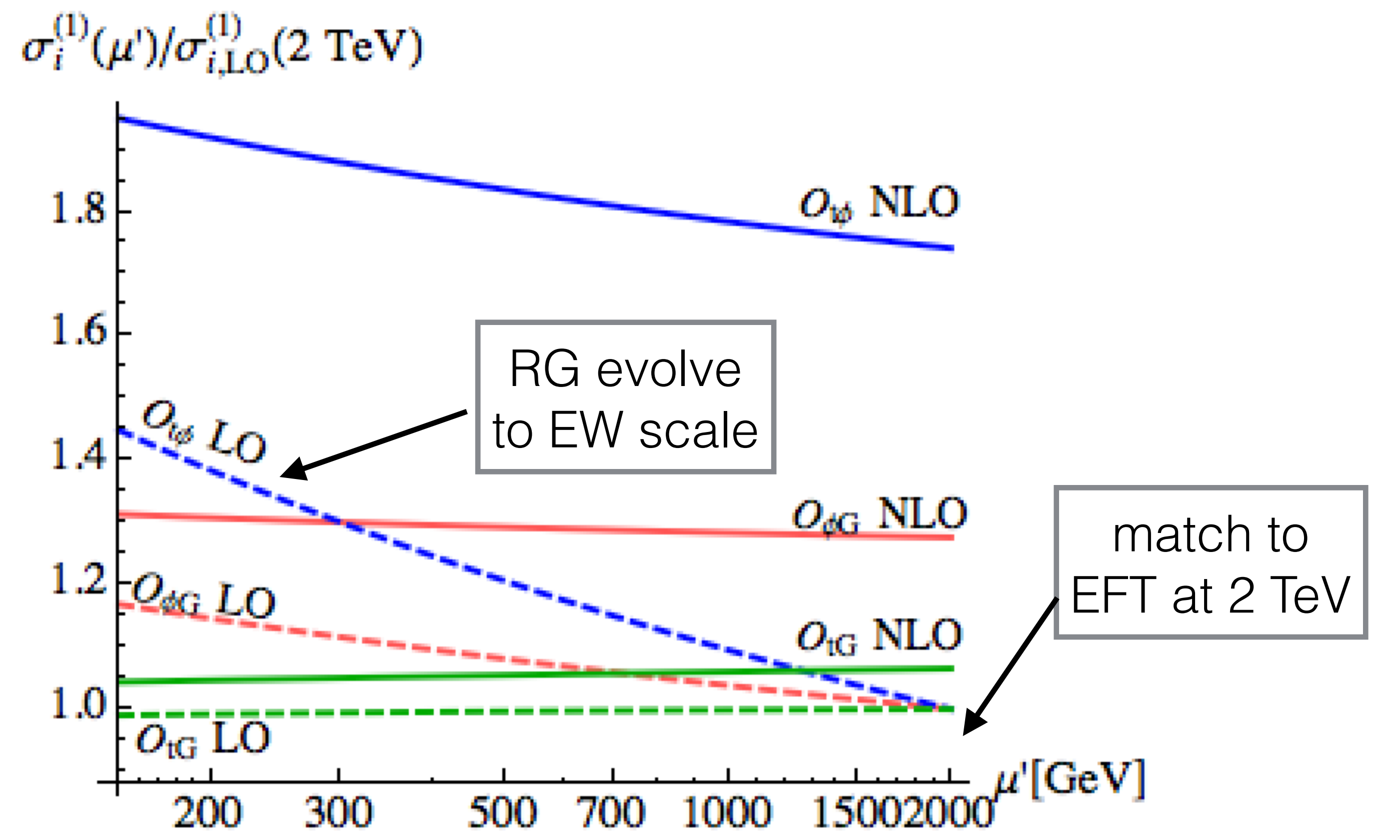
Comparable to the limit obtained from ttbar production



RG vs Full NLO



pp>ttH

Limits

	Fixed	Marginalized
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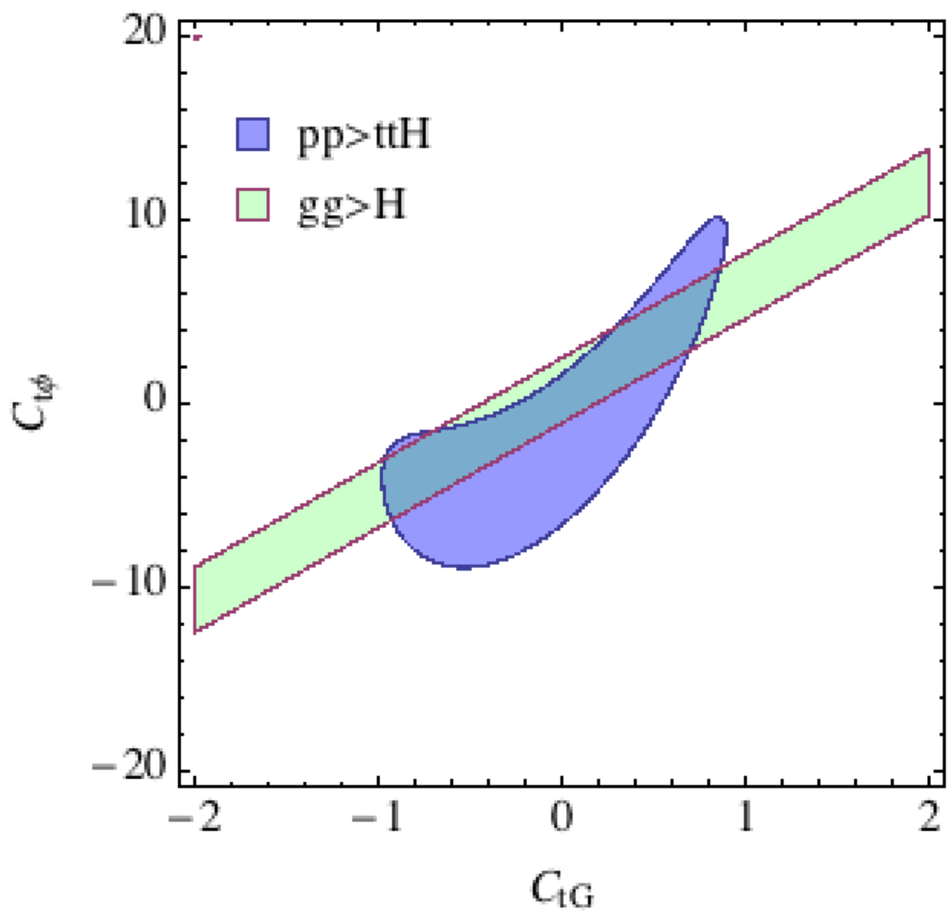
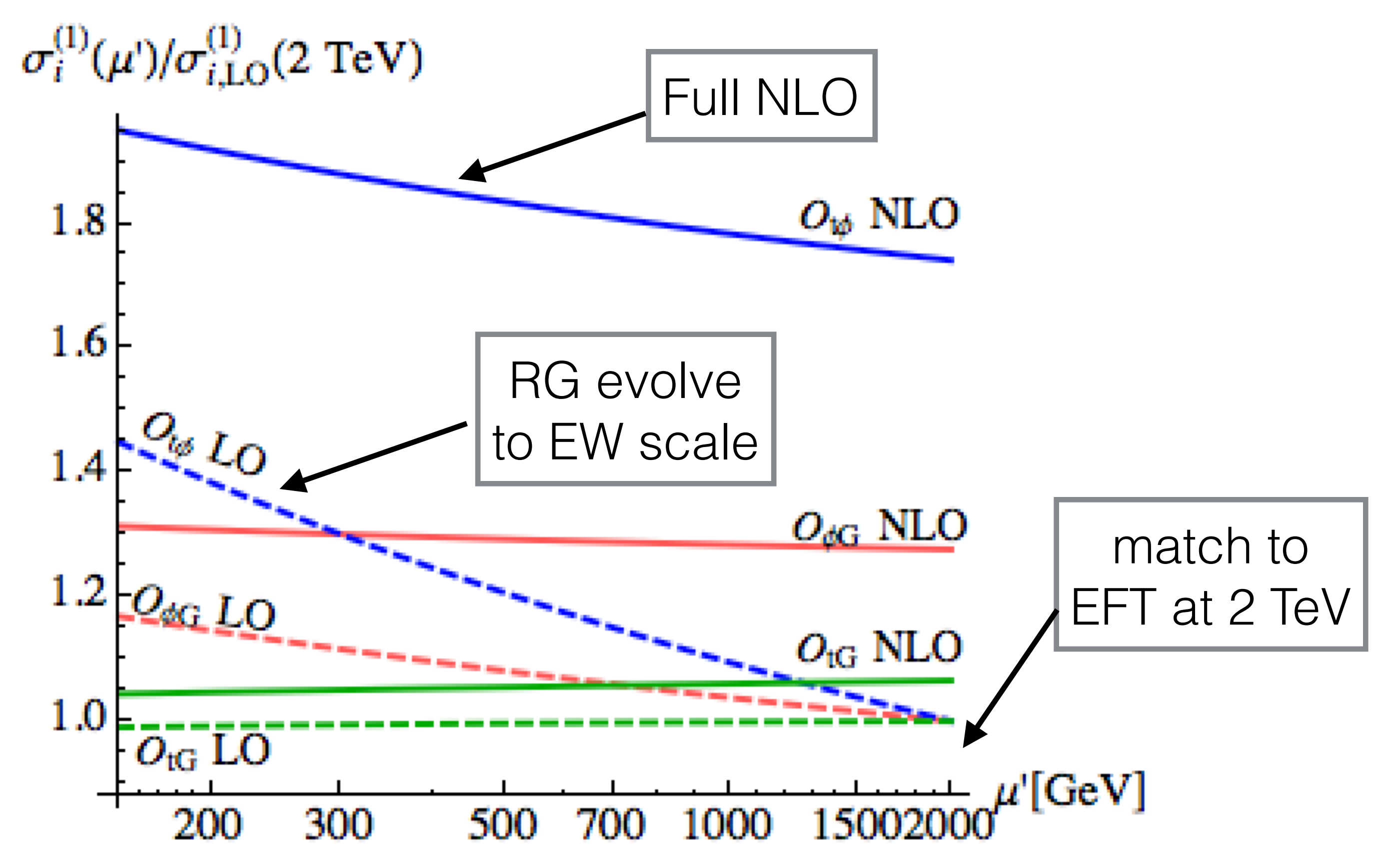
Comparable to the limit obtained from ttbar production



RG vs Full NLO



pp>ttH

Limits

	Fixed	Marginalized
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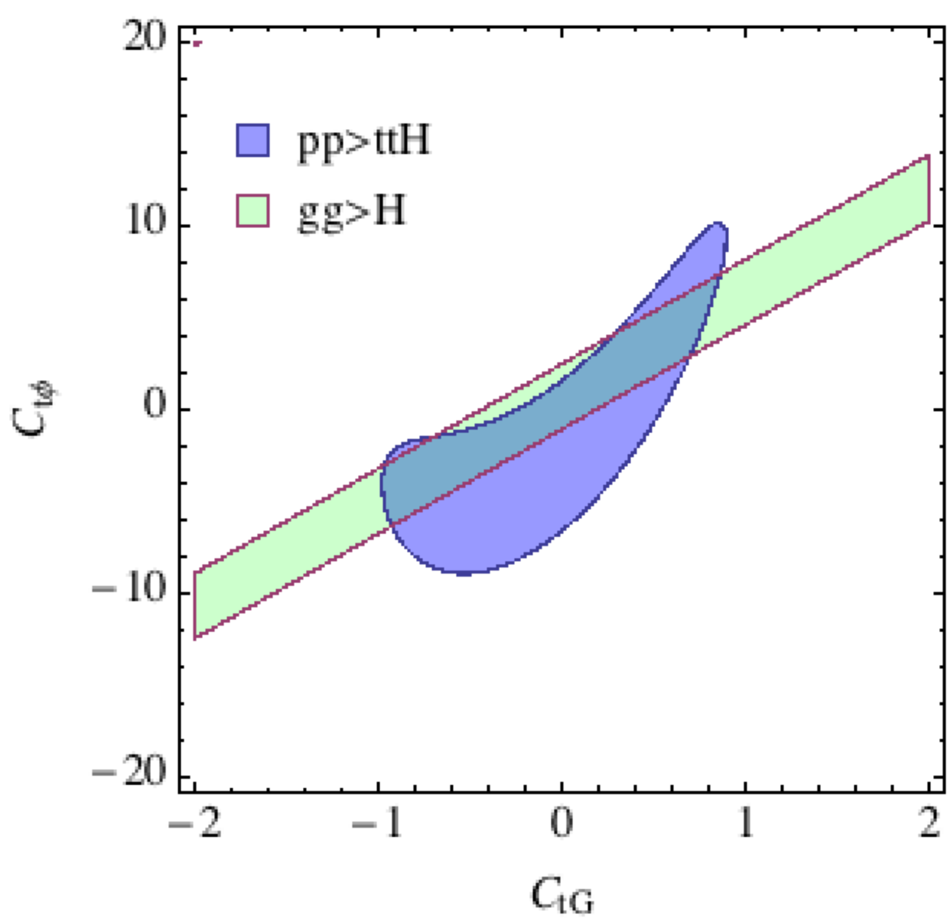
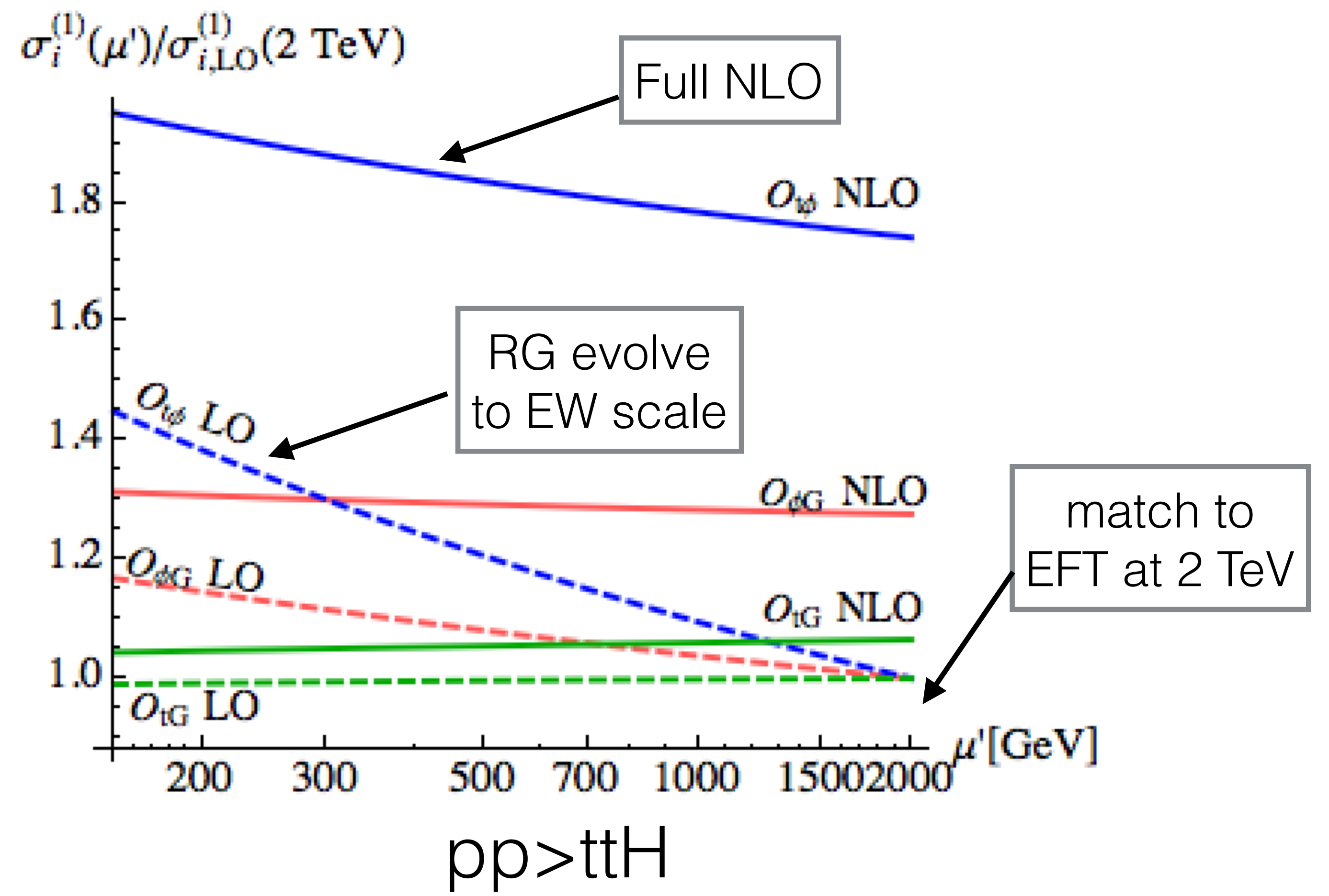
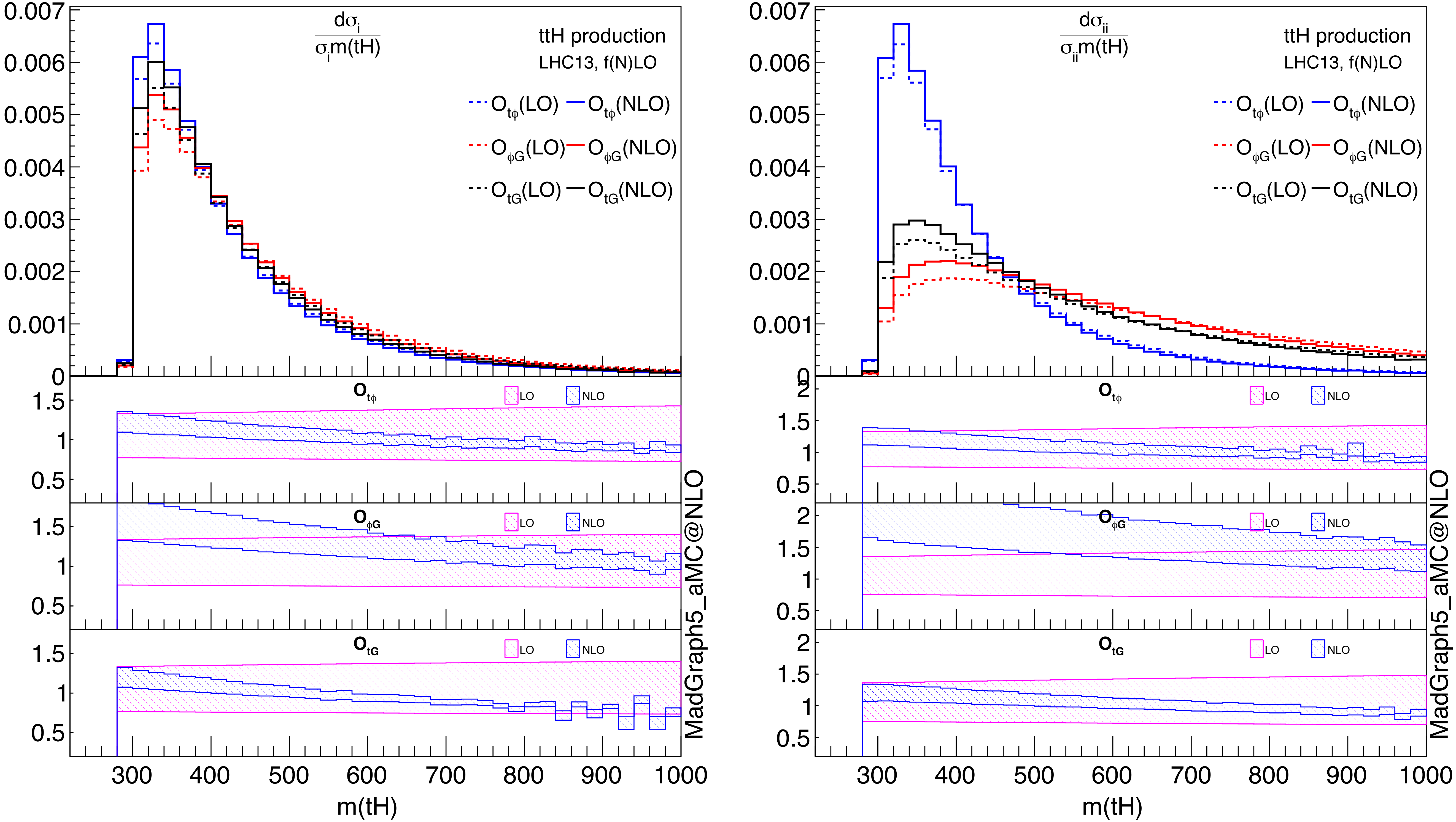
Comparable to the limit obtained from ttbar production



RG vs Full NLO



RG is not a good approximation to full NLO. Rather it should be used as an estimation of missing higher orders.



Given large RG mixing effects, using dynamic scales for μ_{EFT} may give nontrivial corrections

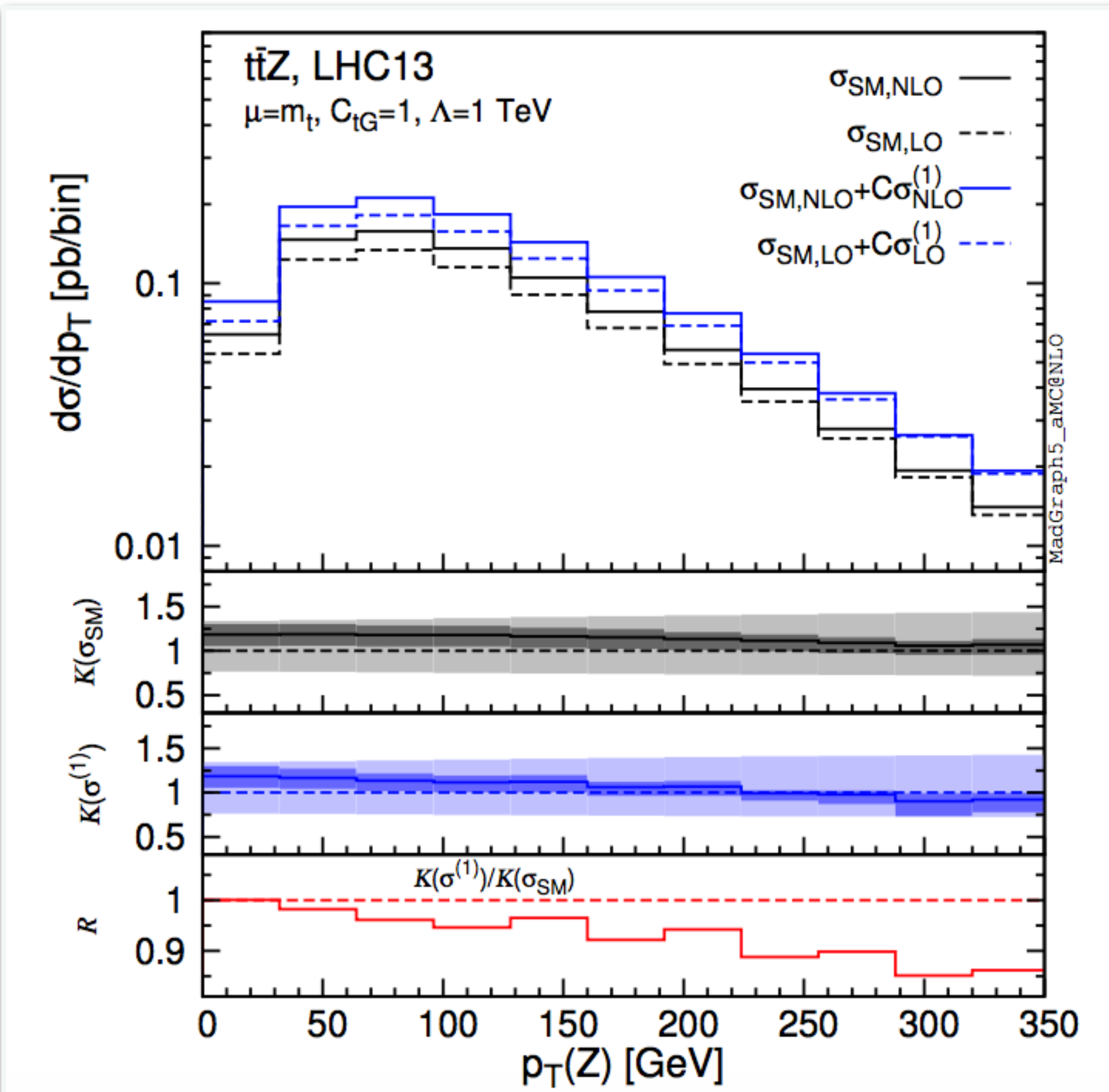
Outline

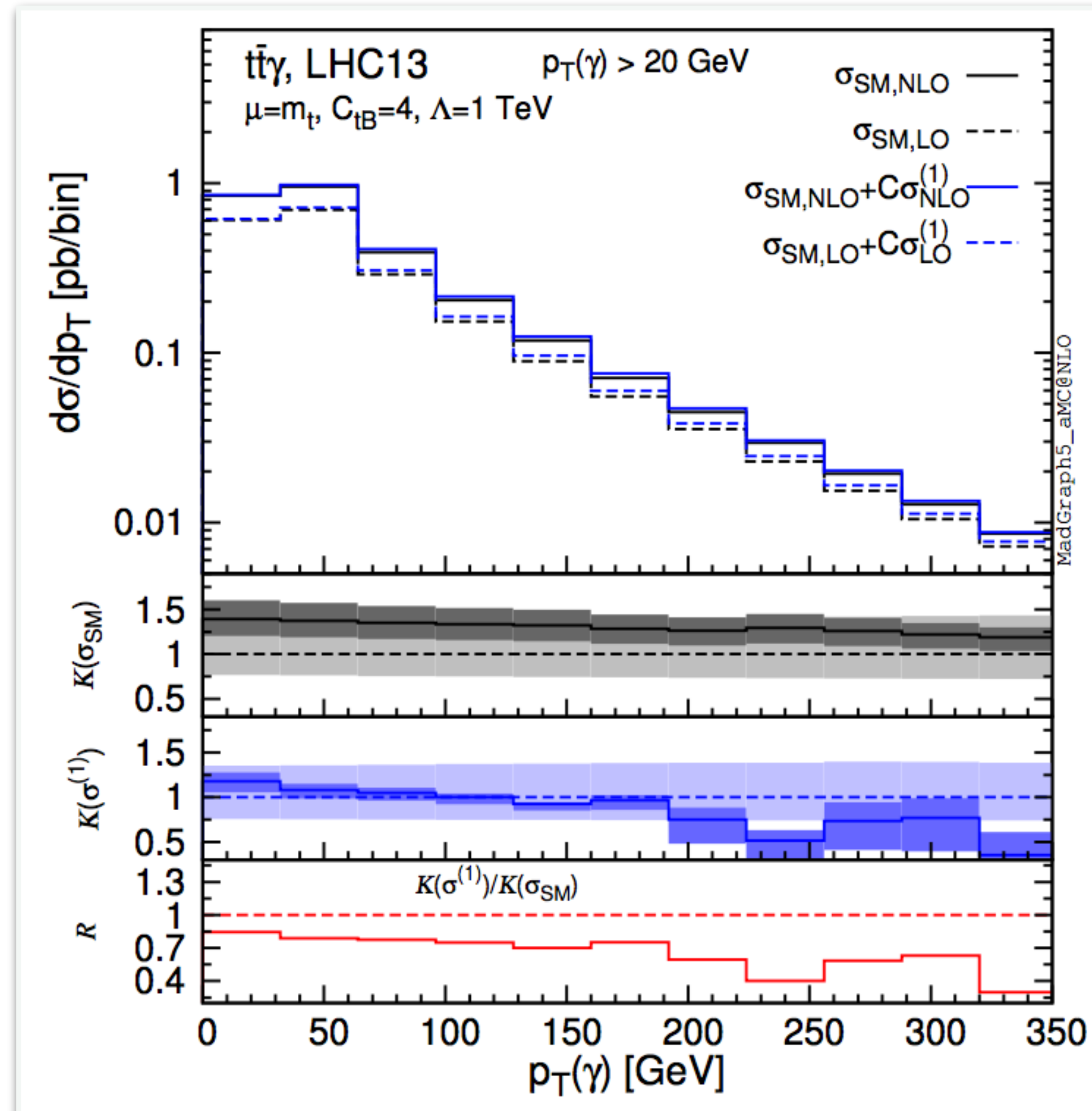
- Top EFT @ NLO
- ttH
- Summary

Summary

- NLO predictions of Dim-6 Yukawa/dipole/ggH operators are available for ttH (and many loop-induced processes), with parton shower.
- Dim-6 EFT in the top sector at is being completed at NLO
- Outlook
    - CP-violating
    - Including producing & decay
    - RG-effects in terms of phenomenology
    - NLO global fit
    - …

NLO effects: shapes

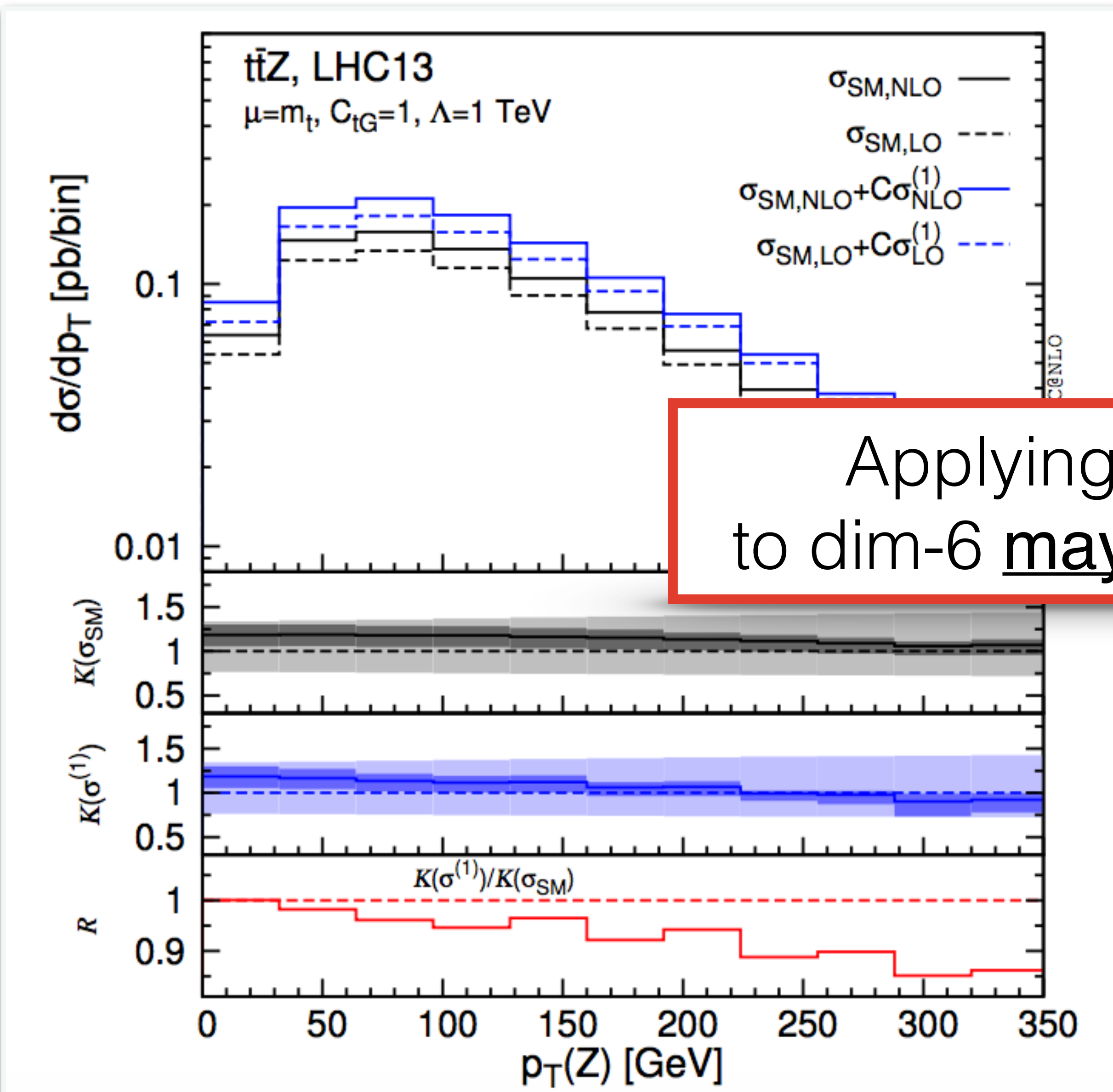


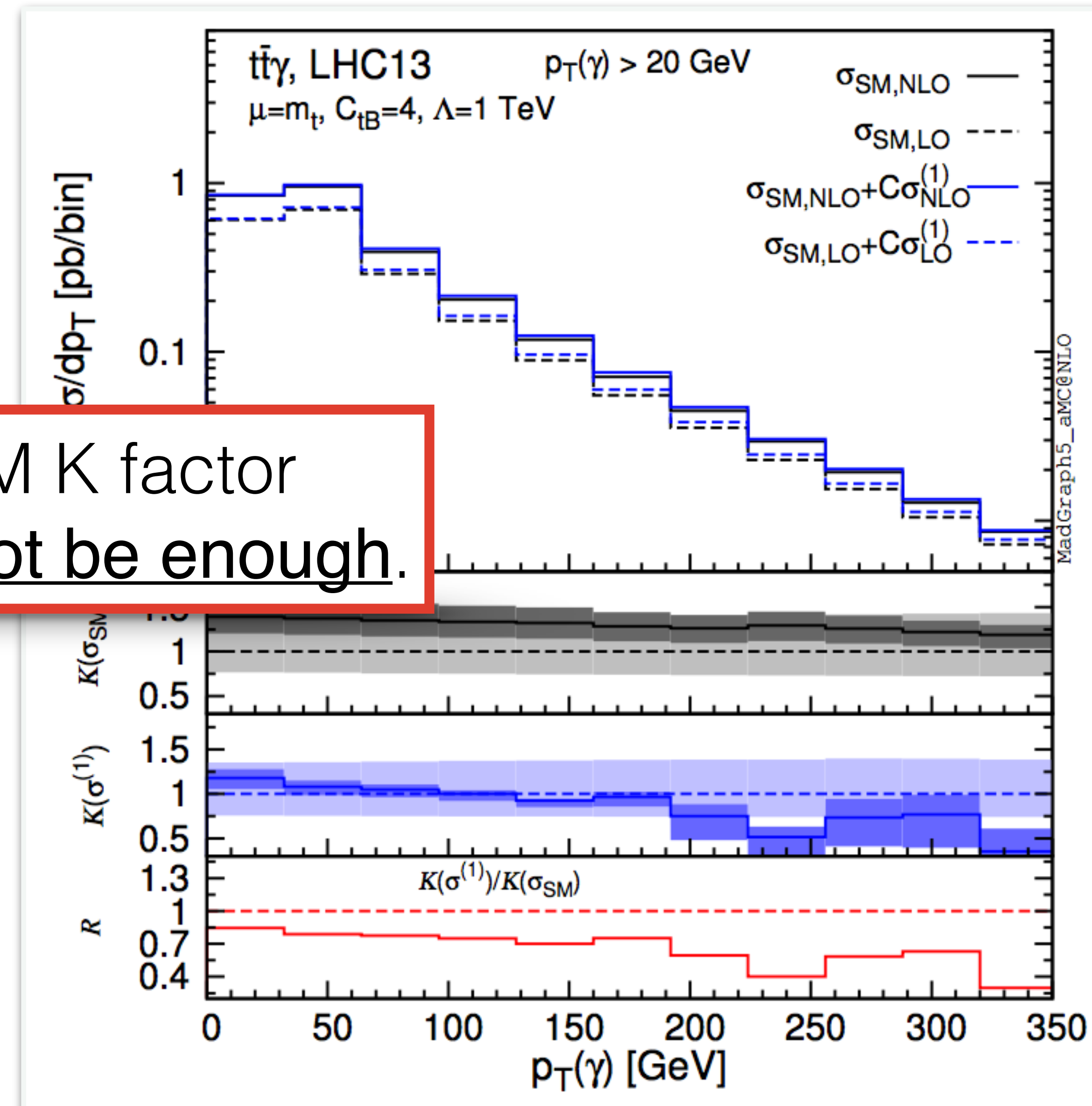


pp>ttZ,tt**γ**

[1601.08193 Bylund, Maltoni, Tsinikos, Vryonidou, CZ]

NLO effects: shapes





Applying SM K factor
to dim-6 <u>may not be enough</u>.

pp>ttZ,tt**γ**

[1601.08193 Bylund, Maltoni, Tsinikos, Vryonidou, CZ]

Top-down search based on EFT

- In addition, there are non-trivial effects on the “discriminant” observables
  - Important for top-down search strategy: designing optimized search based on all information we know from an EFT

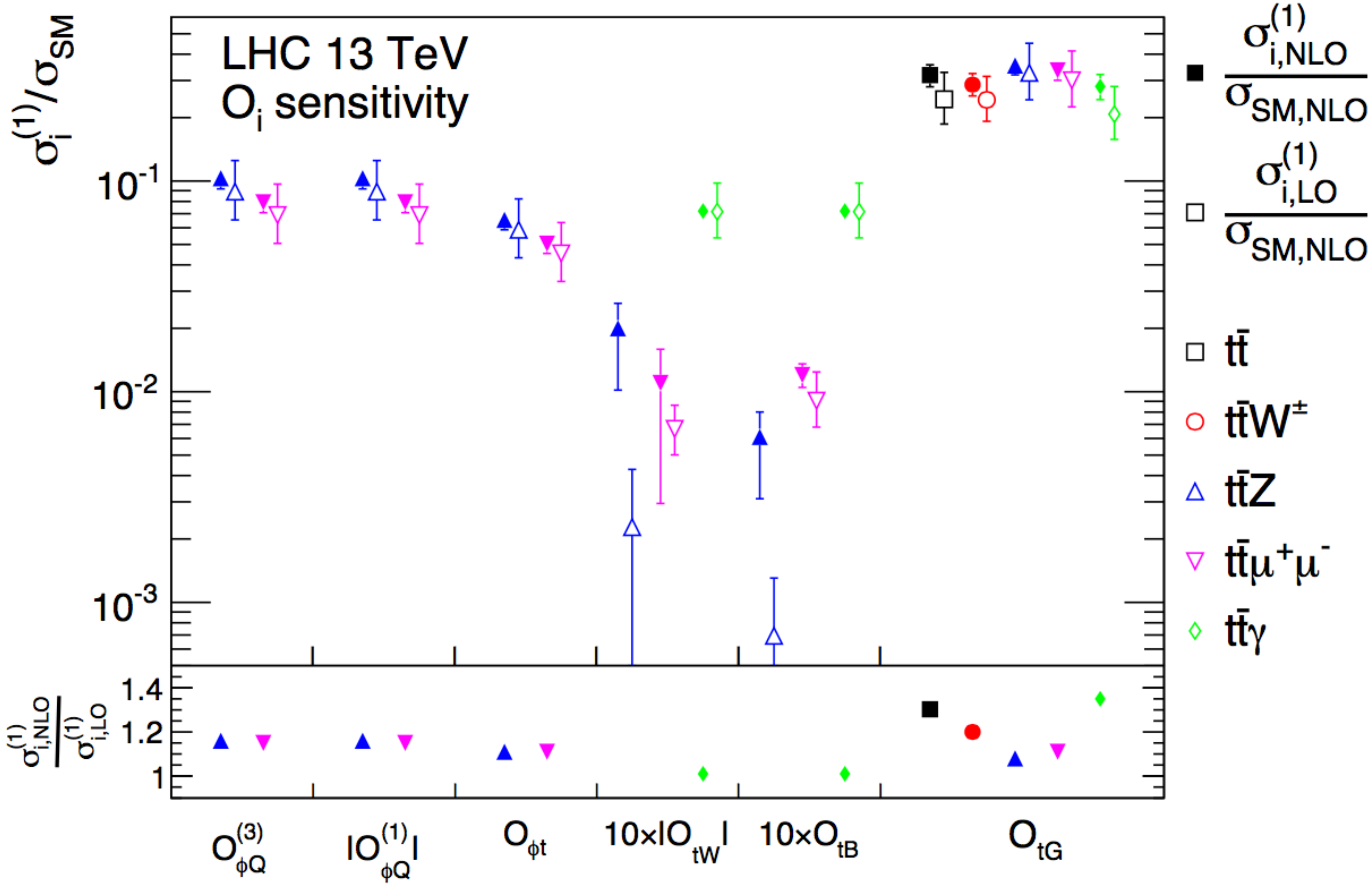
preliminary

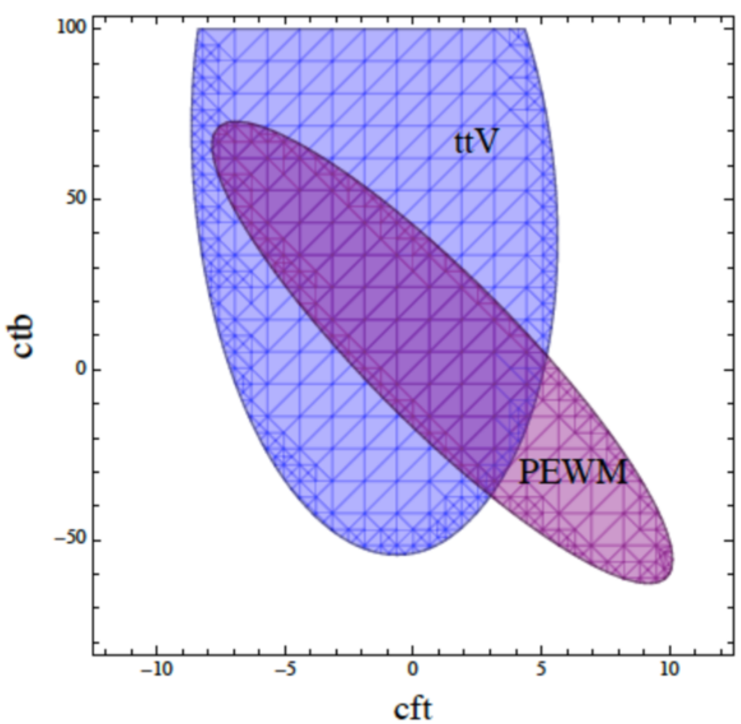
SM $t\bar{t}$ fixed, float one operator at a time:

Operator	Uncertainty on $c_i\Lambda^{-2}$ (TeV^{-2})		
	Yields only	$\Delta\phi(l^+, l^-)$	Variable D_i
$\mathcal{O}_{tG}$	0.0057	0.0057	0.0057
$\mathcal{O}_{G}$	0.072	0.071	0.049
$\mathcal{O}_{\phi G}$	0.19	0.18	0.17
$\mathcal{O}_{qq}^{(8,1)}$	0.32	0.31	0.24
$\mathcal{O}_{qq}^{(8,3)}$	2.23	2.06	1.29
$\mathcal{O}_{ut}^{(8)}$	0.55	0.46	0.36
$\mathcal{O}_{dt}^{(8)}$	0.73	0.63	0.50

Already substantial improvements using MEM-based discriminants

[V. Lemaitre, S. Brochet, S. Wertz]





More to look with the model:

- Single t+V+j
- Resonant top with complex mass scheme, i.e. WbWb, Wbj, etc.