TOP QUARK COUPLING MEASUREMENTS: THE ROAD AHEAD

Fabio Maltoni
Center for Cosmology, Particle Physics and Phenomenology (CP3), UCLouvain Belgium

TOP-QUARK PHYSICS IN THE  ERA

- Are the theoretical motivations for thinking the top-quark might play a special role in EWSB and as a portal to New Physics still there ?

- What do the current Higgs measurements tell us ?

- How does the Higgs discovery impact on the current "SM" top-quark campaign of measurements ?

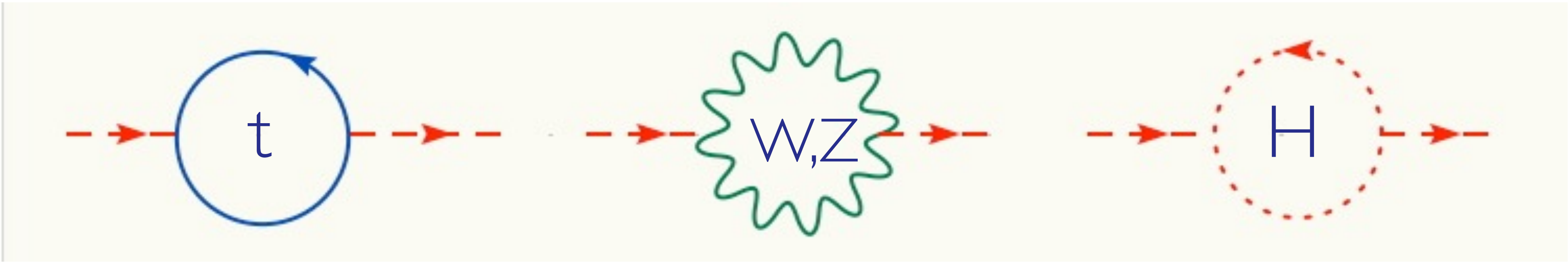
- And on the top-quark related BSM searches ?

- Do we have to retune our NP search strategies for the LHC Run II ?

- Are we well-equipped to face the coming challenges?

THE TOP-HIGGS NATURAL CONNECTION

Quantum corrections affect the stability of the Higgs mass. Consider the SM as an effective field theory valid up to scale Λ:



$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

Putting numbers, one gets:

$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right] \left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

THE TOP-HIGGS NATURAL CONNECTION

mH^2 ~ (125 GeV)^2

$$(125\,\mathrm{GeV})^2 = m^2_{H0} + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right]\left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

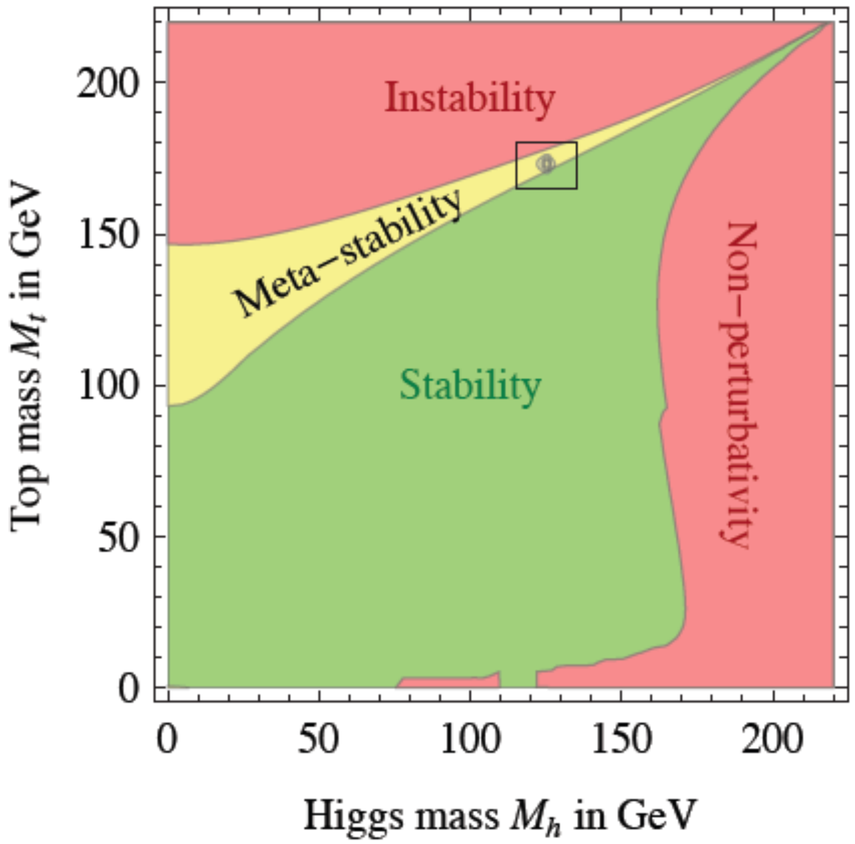
Definition of naturalness: less than 90% cancellation:

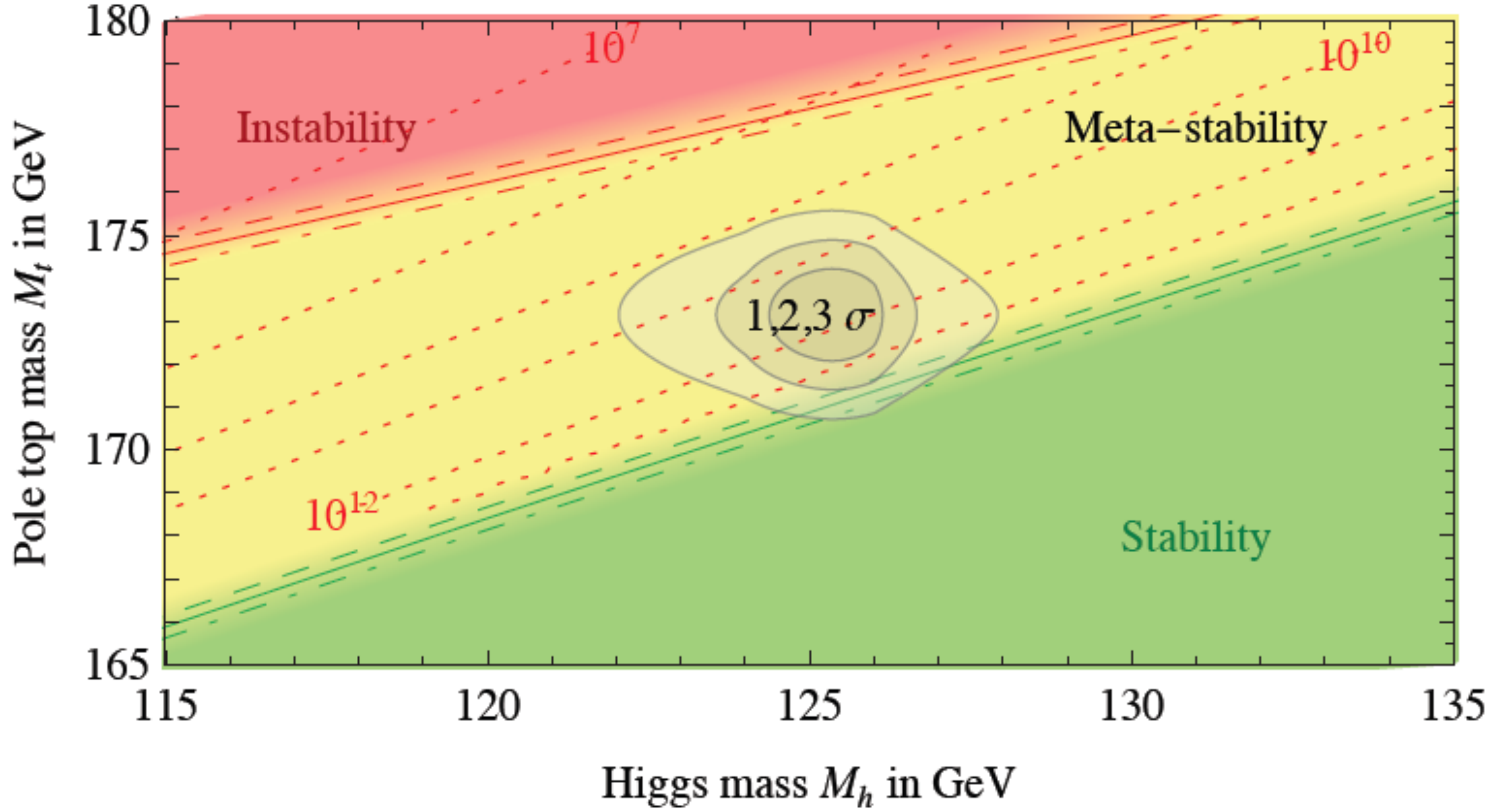
$\Lambda_t < 3\,\mathrm{TeV}$ $\Rightarrow$ NEW TOP/HIGGS RELATED PHYSICS MUST BE "LIGHT"

TOP CORRECTIONS TO THE HIGGS POTENTIAL

NO SIGN OF NEW PHYSICS....EVERYTHING LOOKS CONSISTENT UP TO VERY HIGH SCALE...EVEN THE FATE OF THE UNIVERSE.

[Degrassi, et al. 2012]





$$y_t(M_t) = 0.93587 + 0.00557\left(\frac{M_t}{\mathrm{GeV}} - 173.15\right) \ldots \pm 0.00200_{\mathrm{th}}$$

THE TOP QUARK IS SPECIAL

IN THE SM, IT IS THE ONLY QUARK:

1. WITH A "NATURAL MASS"

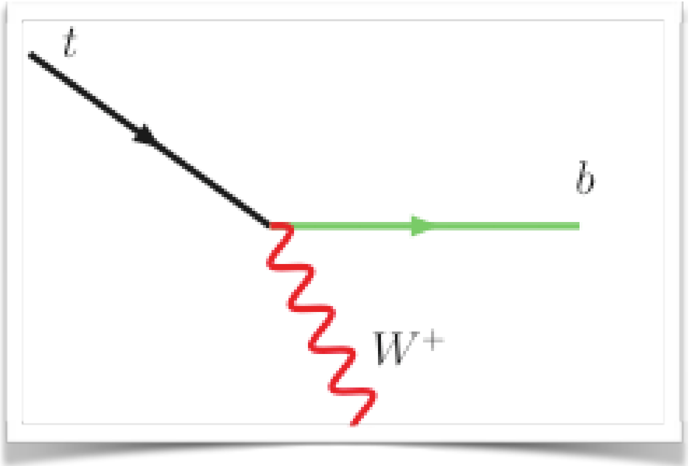
$$m_{top} = y_t v/\sqrt{2} \approx 174 \text{ GeV} \Rightarrow y_t \approx 1$$

IT "STRONGLY" INTERACTS WITH THE HIGGS SECTOR.

2. THAT DECAYS SEMI-WEAKLY, BEFORE HADRONIZING AND WAY BEFORE SPIN-FLIPPING

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

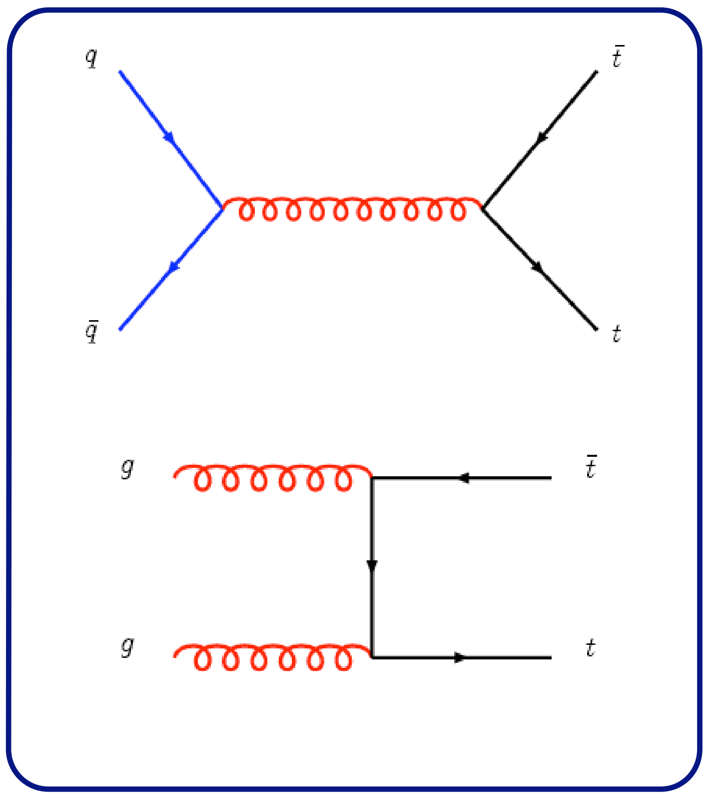
Compare with $\tau_b \approx (G_F^2 m_b^5 |V_{bc}|^2 k)^{-1} \approx 10^{-12}$ s



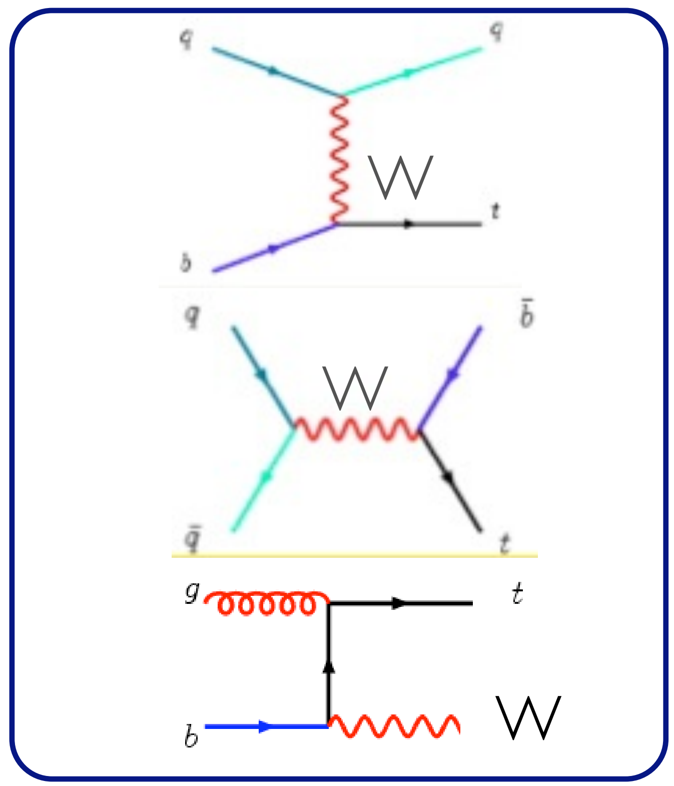
THE TOP QUARK IS SPECIAL

3. WITH AN UNMISTAKABLE EXPERIMENTAL SIGNATURE, ABUNDANTLY PRODUCED IN PAIRS, SINGLY, AND IN ASSOCIATION WITH OTHER STATES:

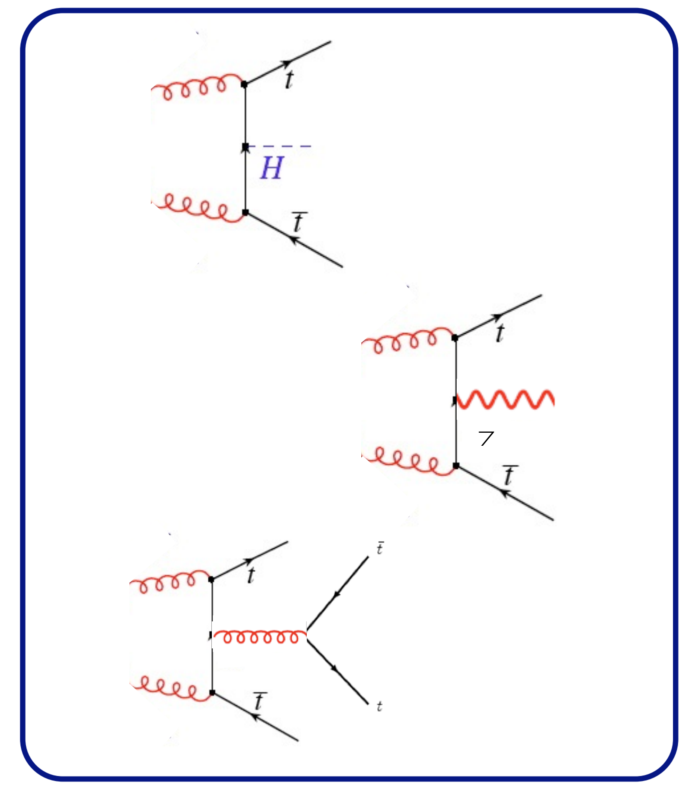
Strong



Weak



Associated



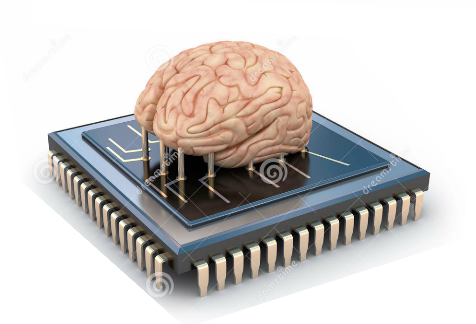
number of events @13TeV 1 fb^{-1}

10^6 $\qquad$ $250 \cdot 10^3$ $\qquad$ $< (2-3) \cdot 10^3$

THE TOP-QUARK GATEWAY TO NP

Strategies:

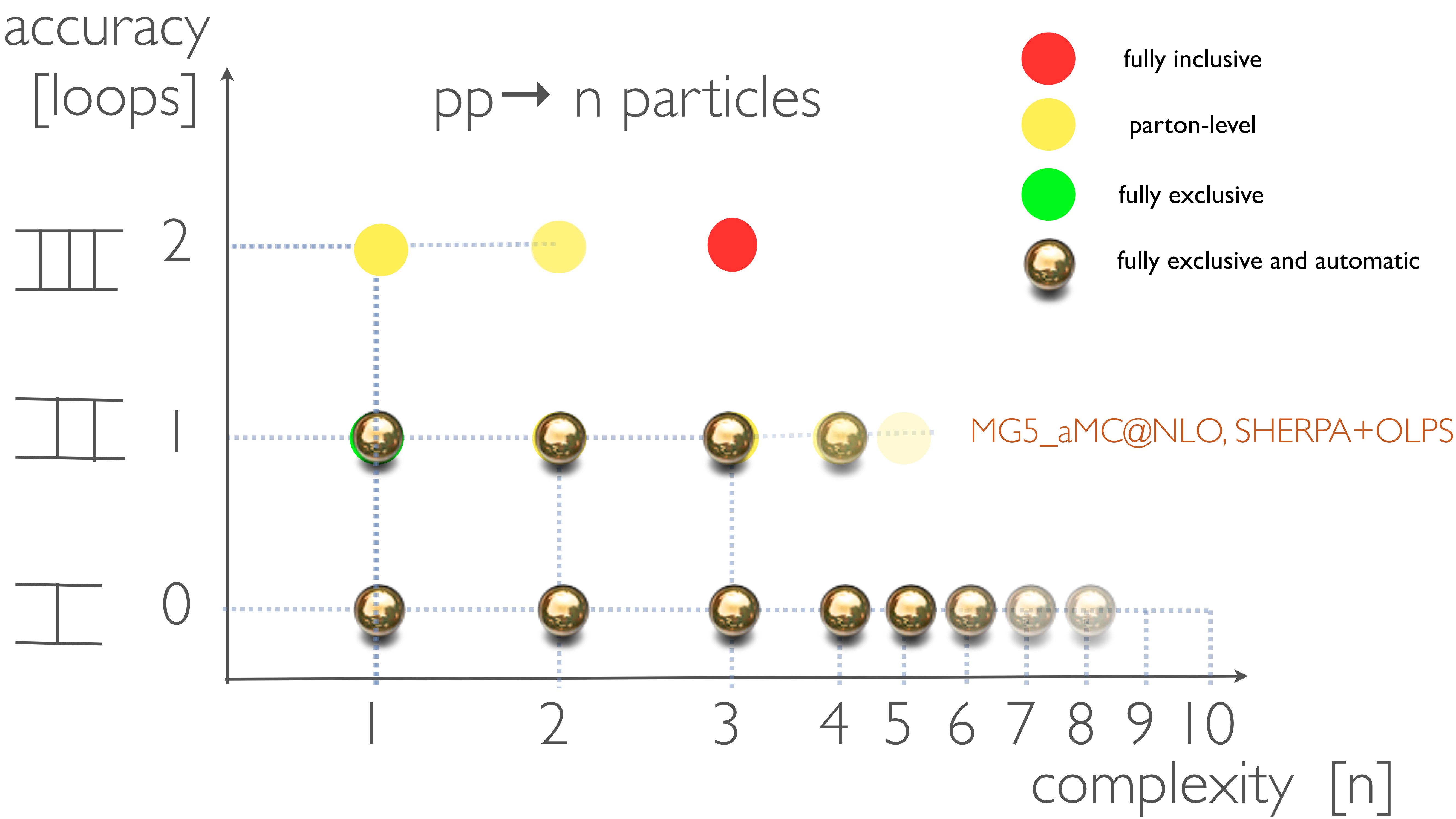
- Precision SM top-quark properties measurements
- Searches of top-quark partners and new states
- Search for new top-quark interactions



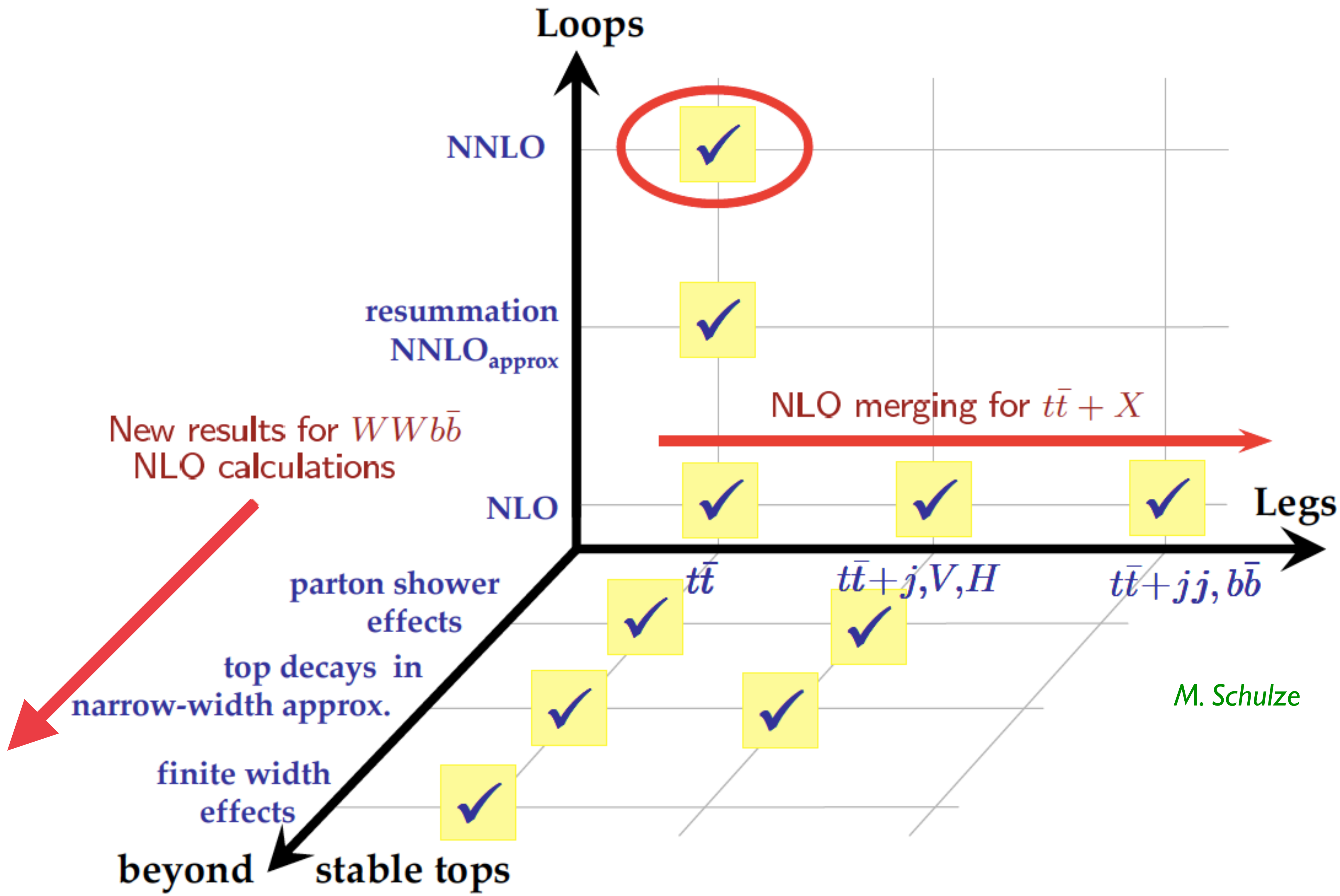
Needs:

- High precision predictions (NNLO in QCD and NLO) for key SM obs
- NLO for any SM (BSM) process in the form of (automatic) MC tools
- A consistent and complete model-independent framework, the EFT at NLO

LHC Prediction/MC's in 2015



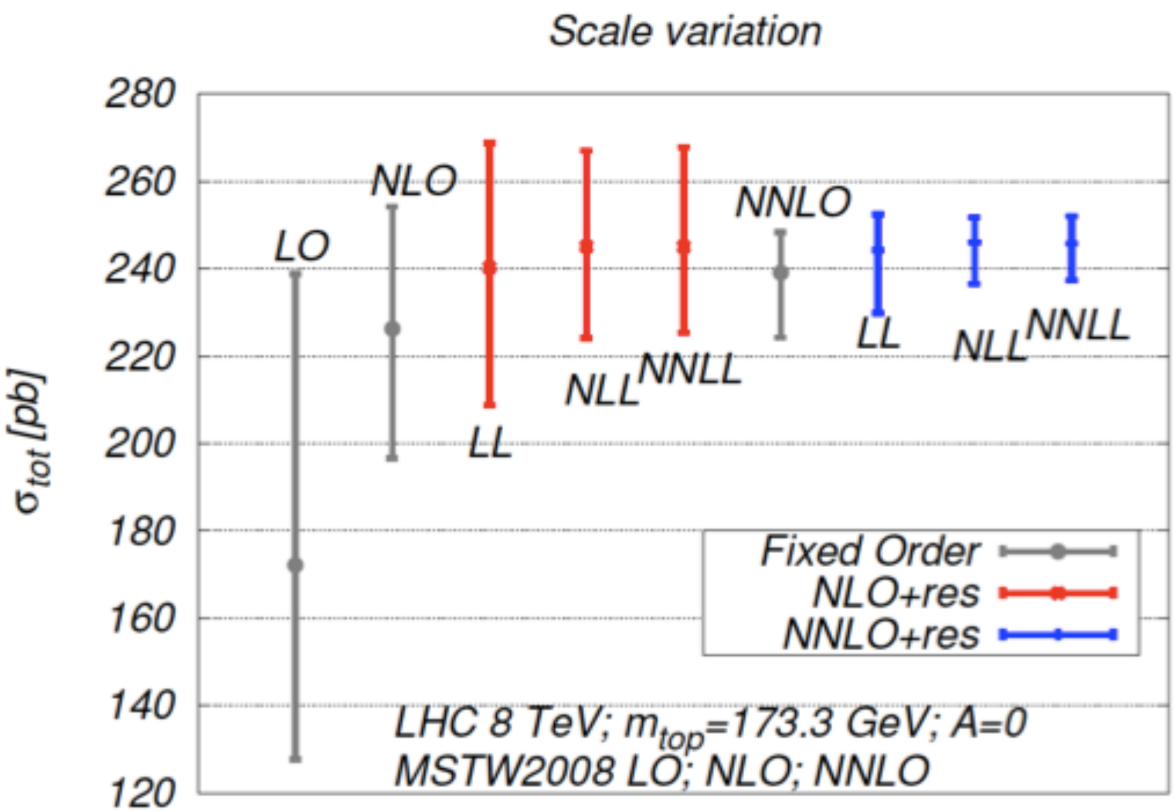
TOP PREDICTIONS IN 2015

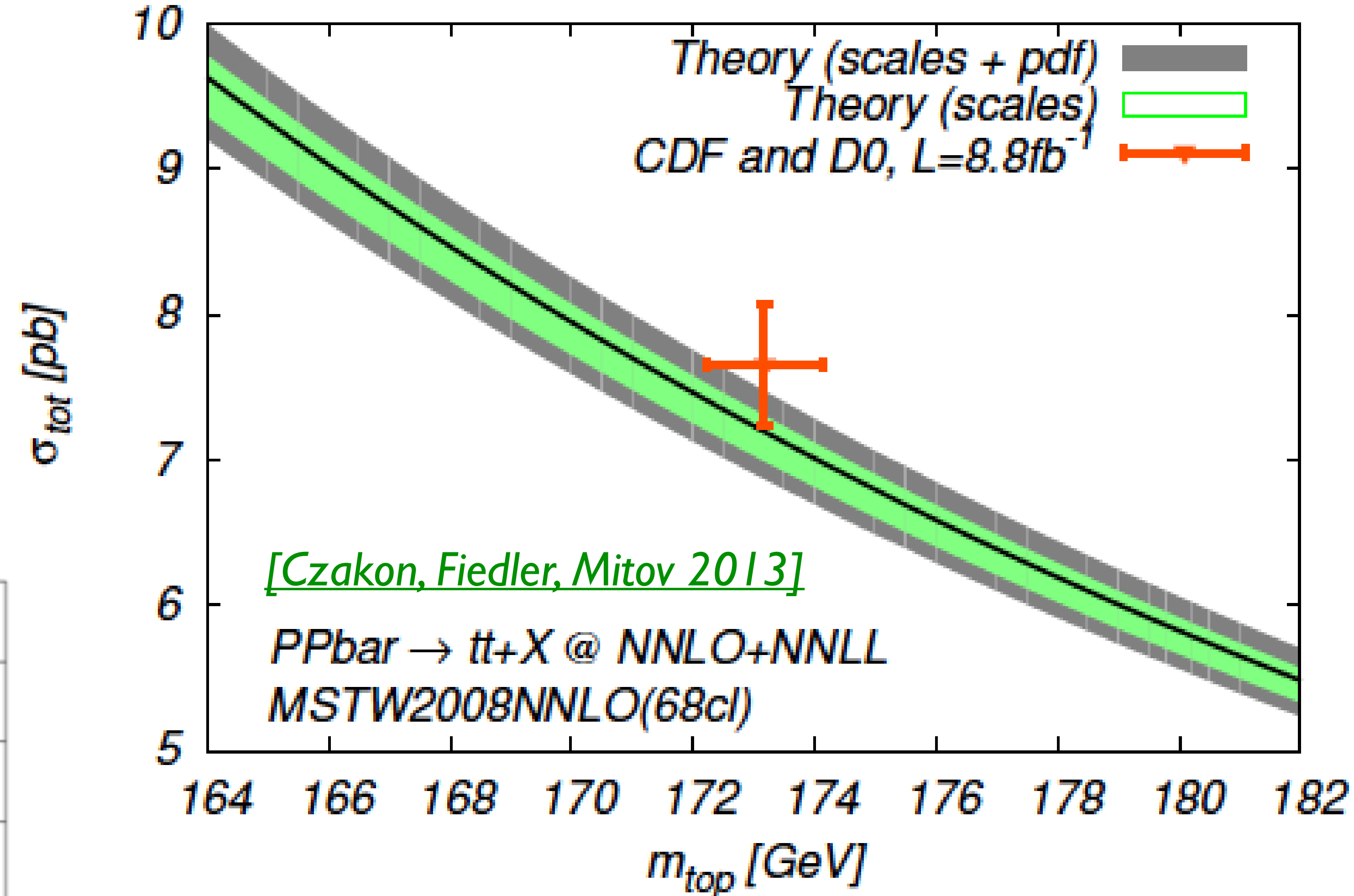


TTBAR CROSS SECTION AT NNLO

MONUMENTAL MILESTONE IN PERTURBATIVE QCD:

[Bärnreuther, Czakon, Mitov 2012]
[Czakon, Mitov 2012]
[Czakon, Mitov 2012]
[Czakon, Fiedler, Mitov 2013]





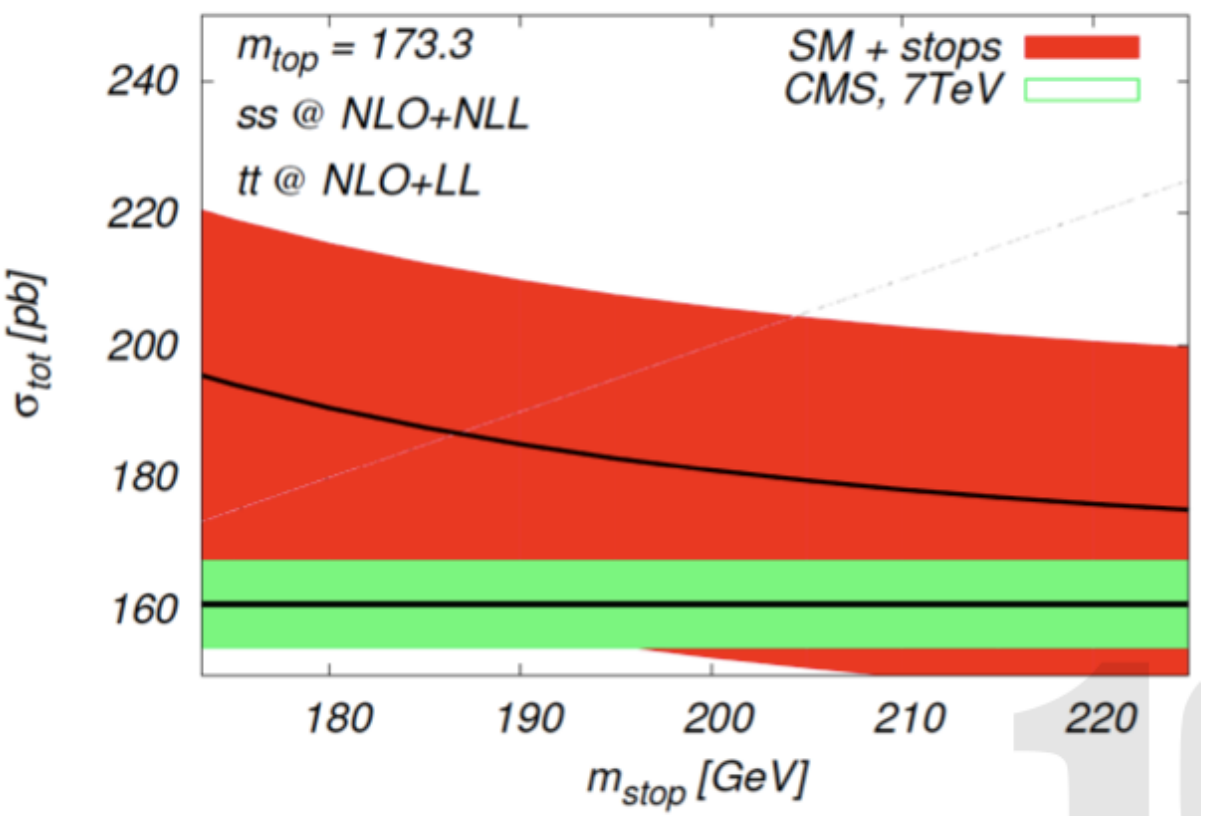
- TWO LOOP HARD MATCHING COEFFICIENT EXTRACTED AND INCLUDED
- VERY WEAK DEPENDENCE ON UNKNOWN PARAMETERS (SUB 1%): GG NNLO, A, ETC.
- ~ 50% SCALES REDUCTION COMPARED TO THE NLO +NNLL ANALYSIS

TTBAR CROSS SECTION AT NNLO

Having a NNLO prediction opens the door to new possibilities.

Consider the light stop window in a compressed spectrum, that mimicks the normal ttbar production:

[Czakon, Mitov, Papucci, Ruderman, Weiler, 2014]



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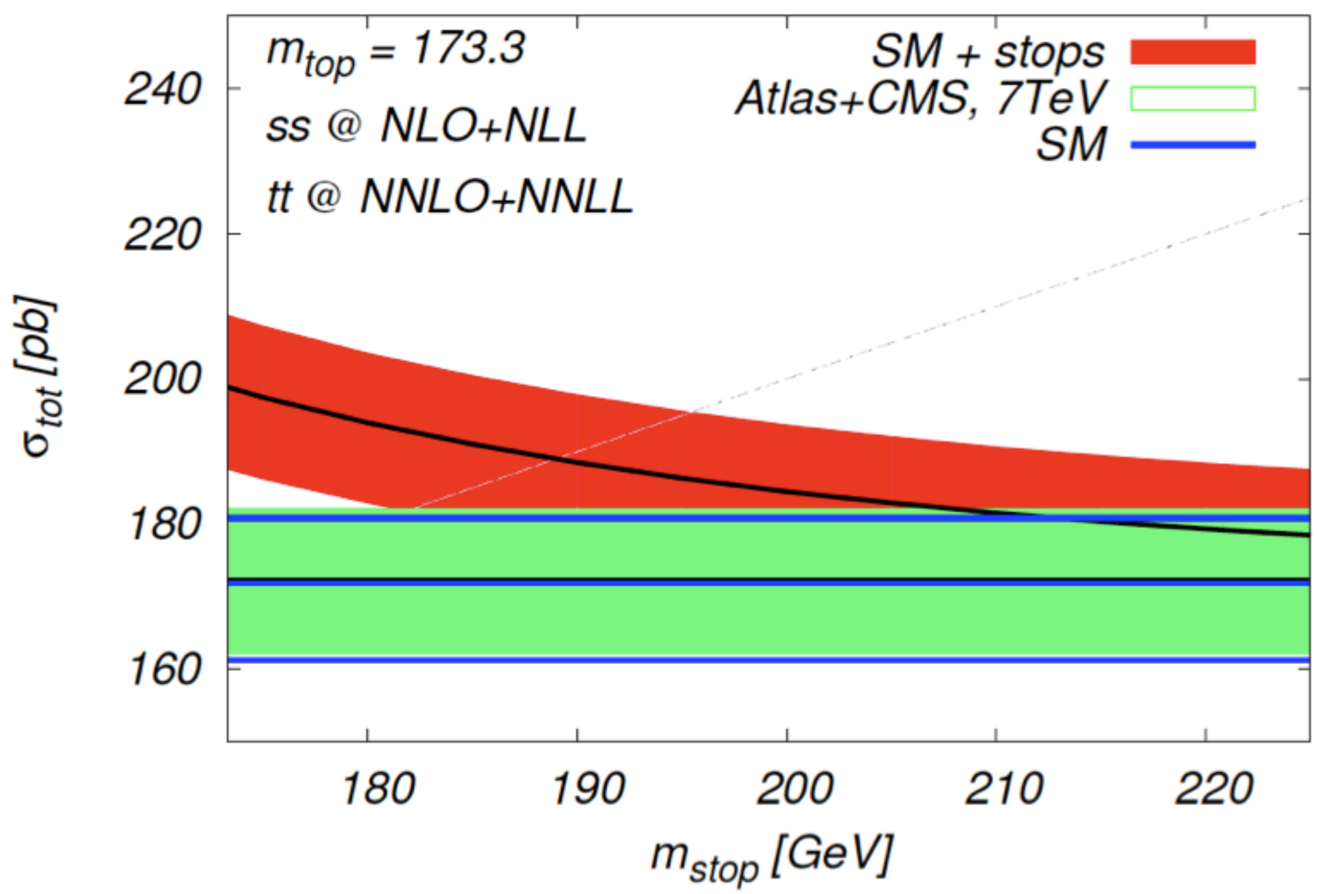

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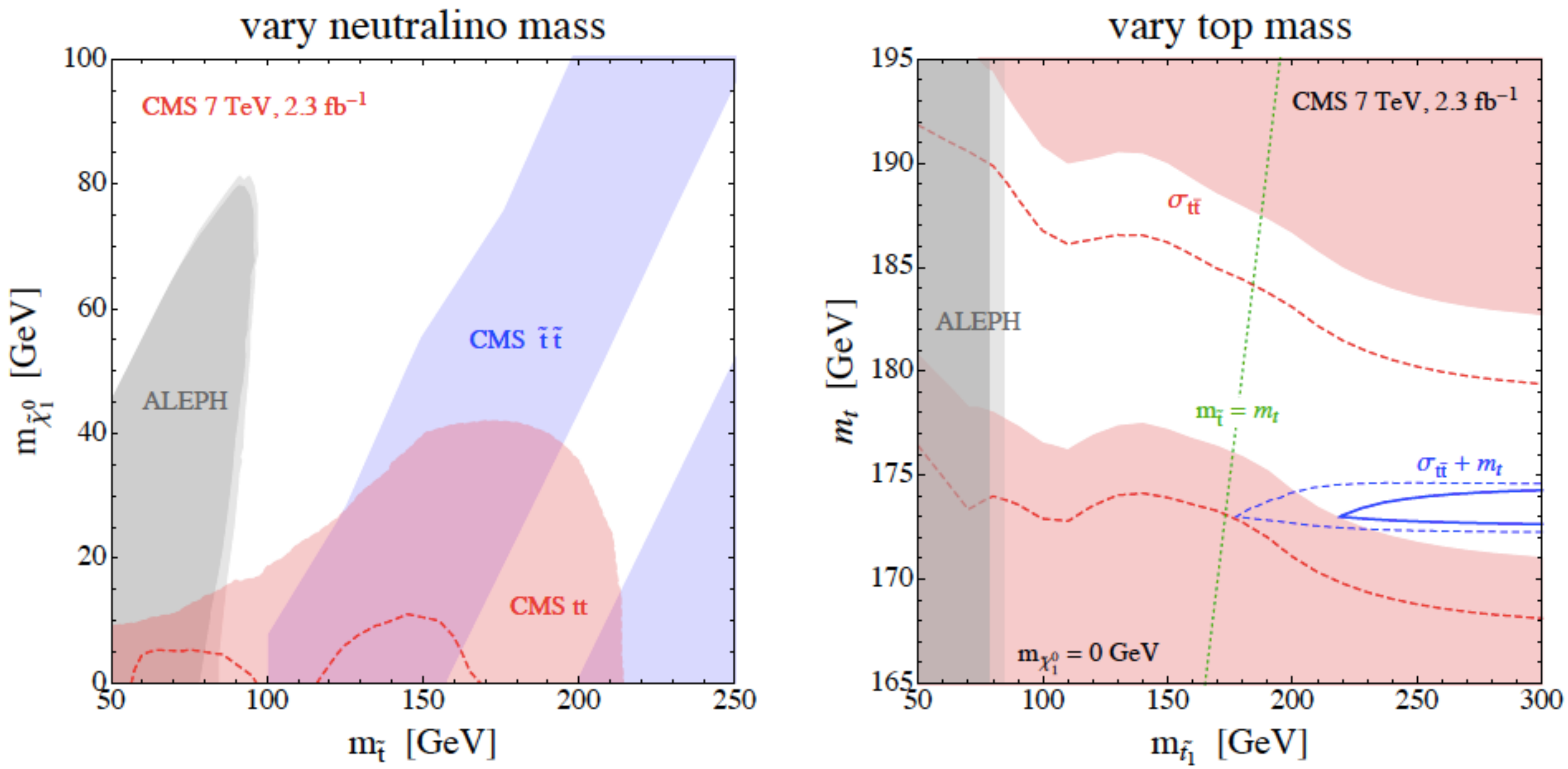
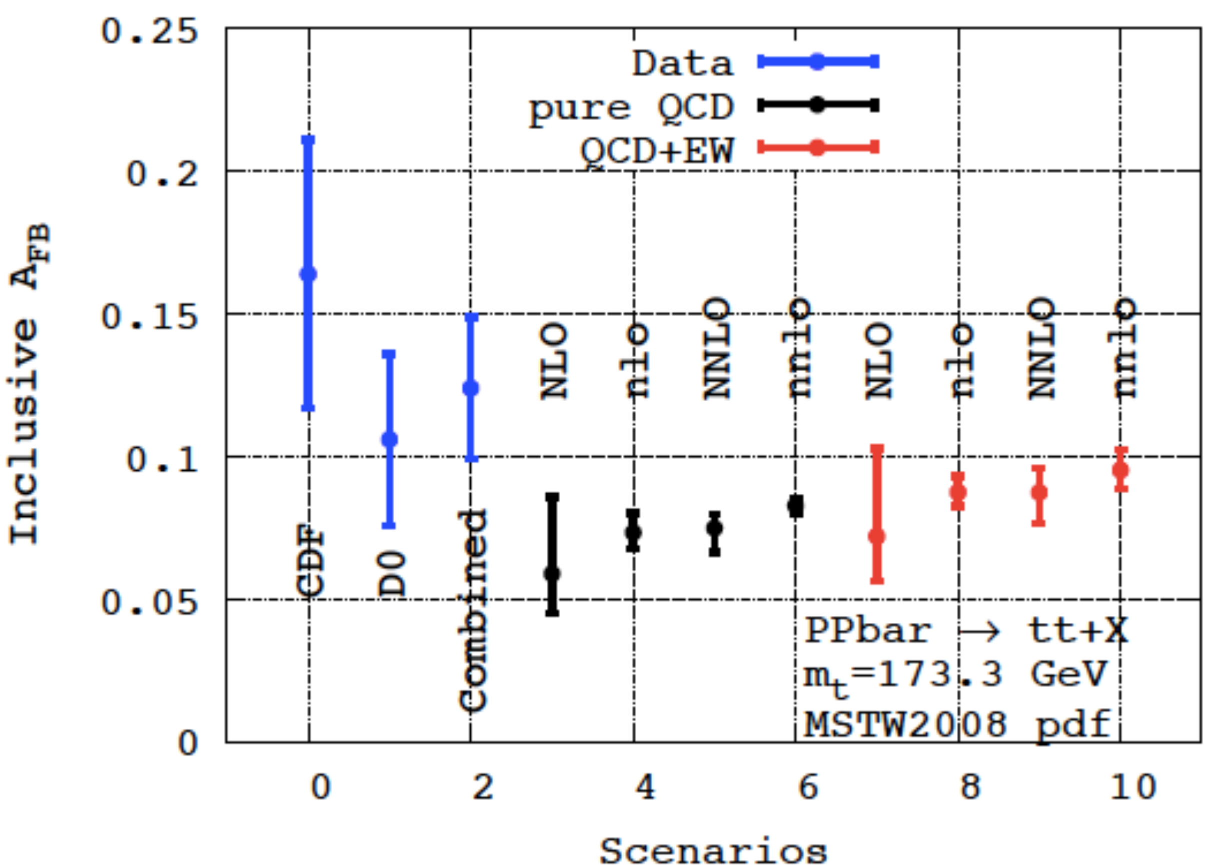
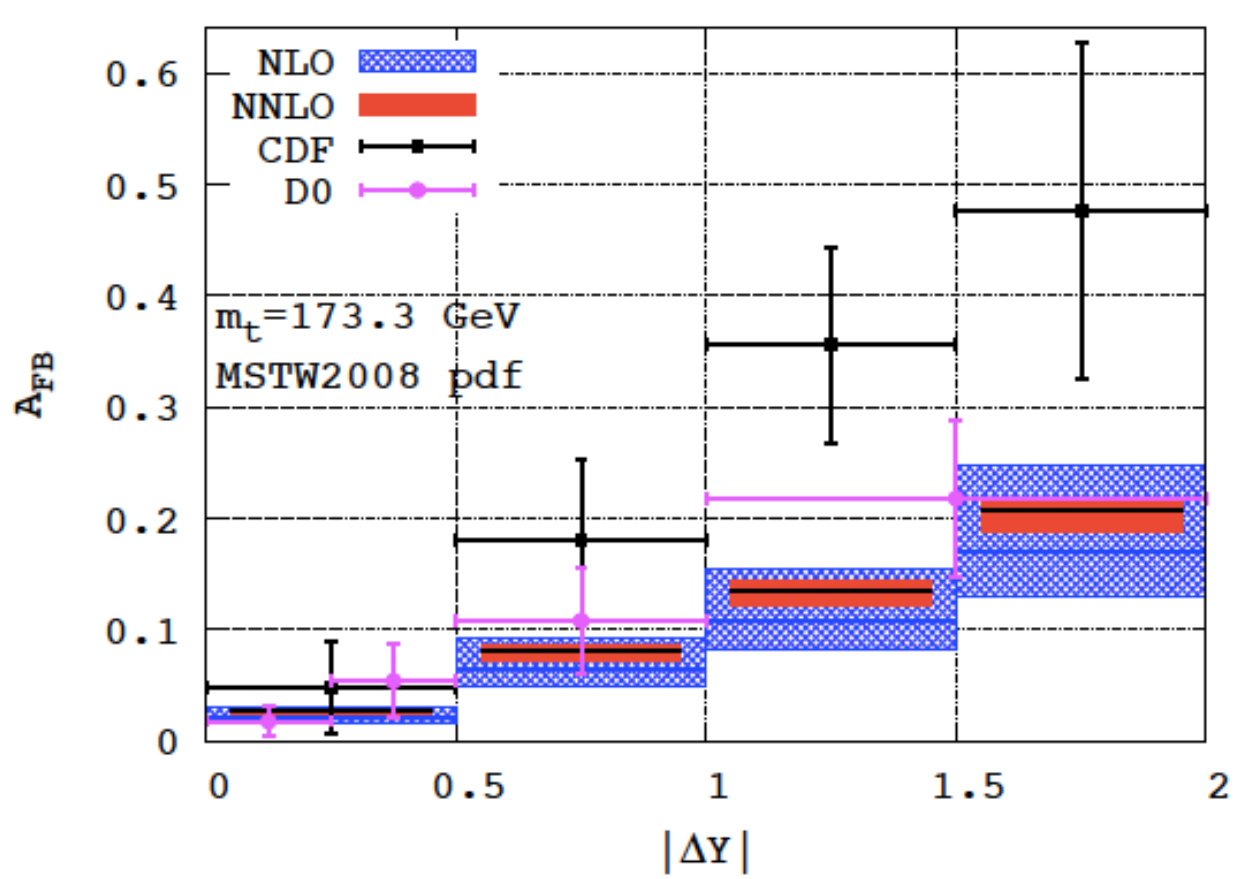


TOP FORWARD-BACKWARD ASYMMETRY

[Czakon, Fiedler, Mitov,2014]

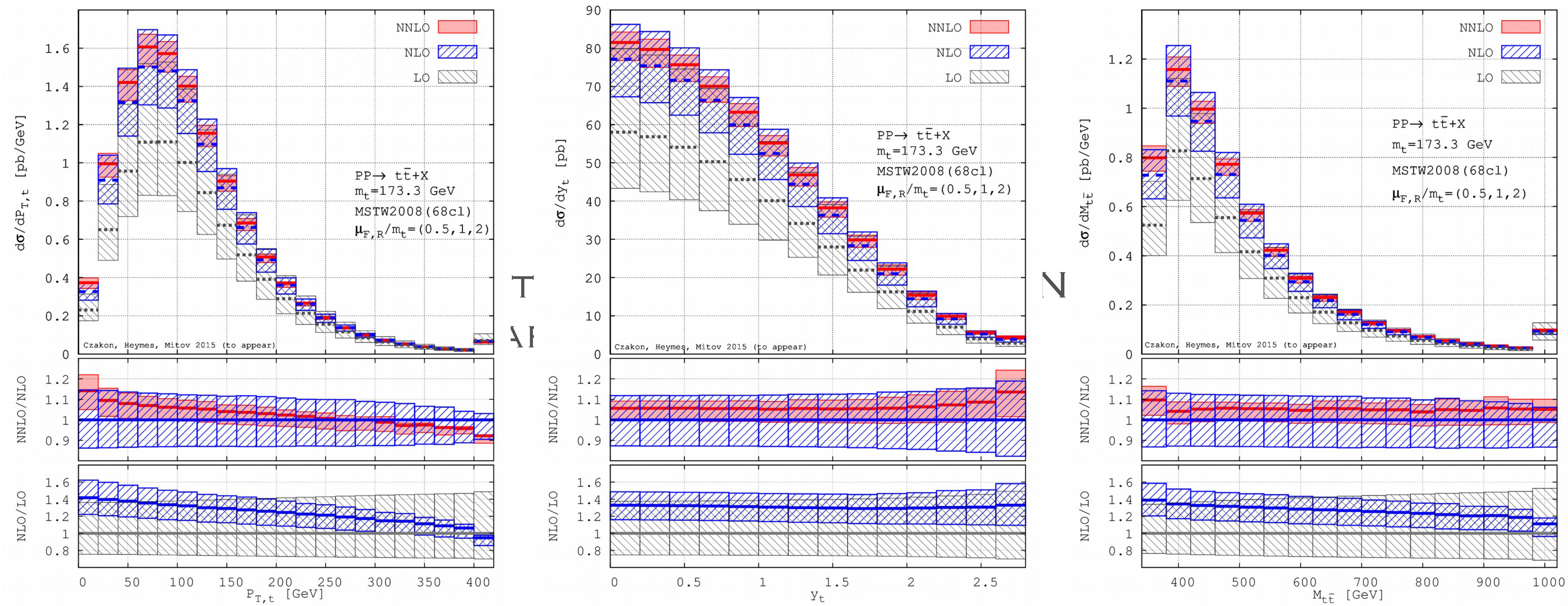




THE ASYMMETRY AT NLO ACCURACY (FROM THE NNLO TOTAL CROSS SECTION CALCULATION) IS SIZEABLY LARGER AND MUCH MORE PRECISE THAN THE LO RESULT.

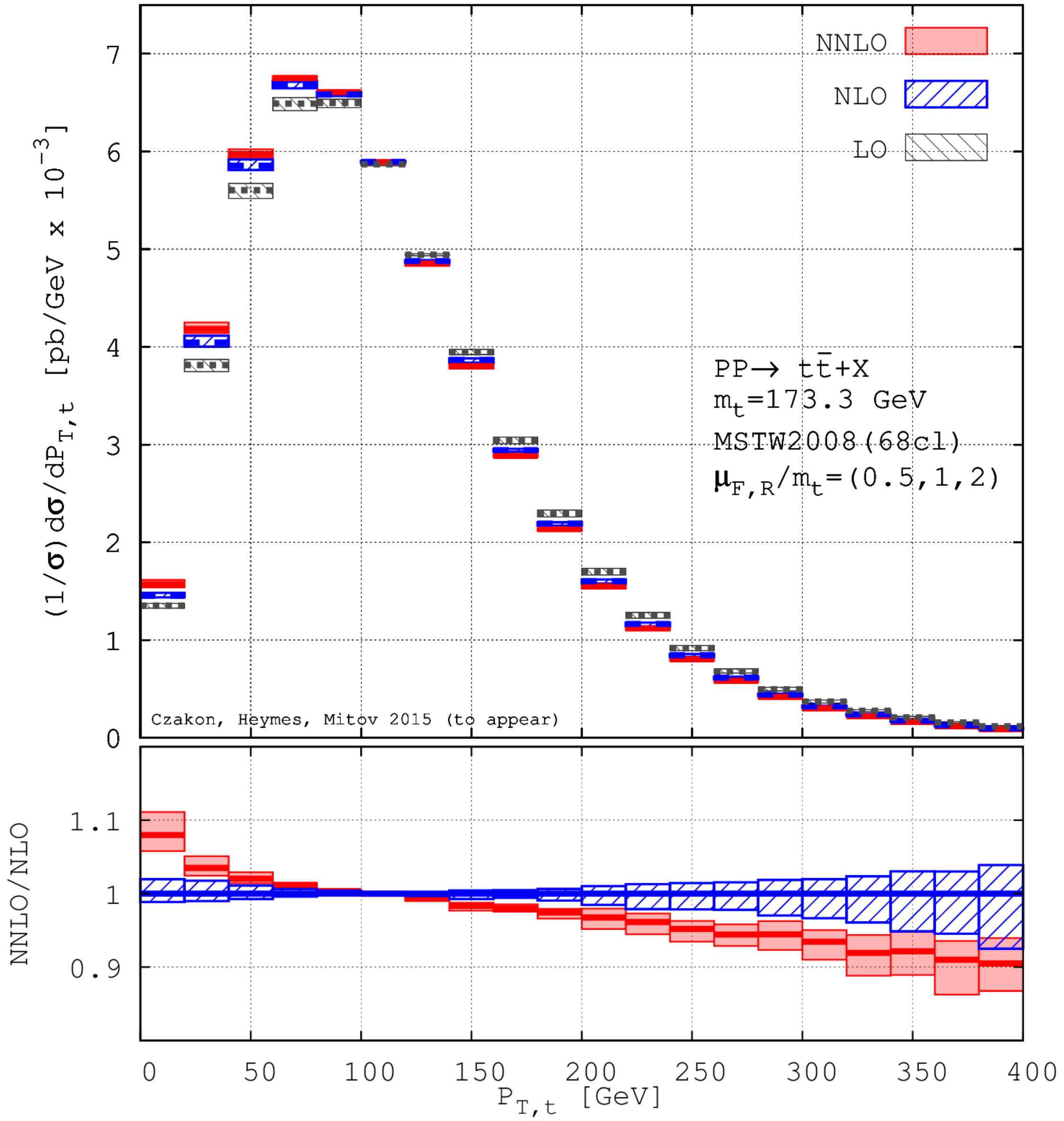
TT AT NNLO : DIFF. DISTRIBUTIONS

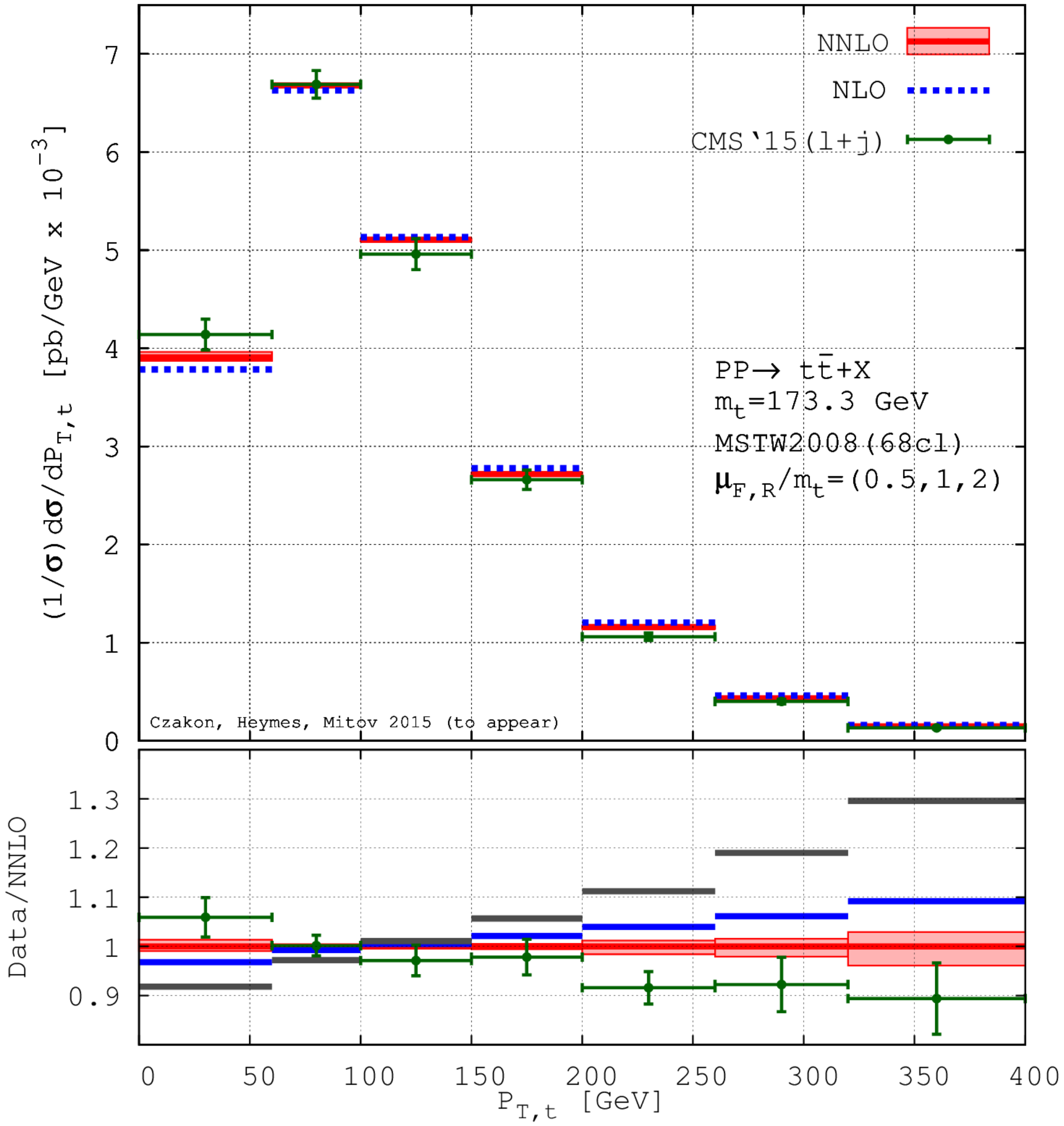
[Czakon, Fiedler, Heymes, Mitov.; in preperation]



Good perturbative convergence. Improved precision.

TT AT NNLO : DIFF. DISTRIBUTIONS

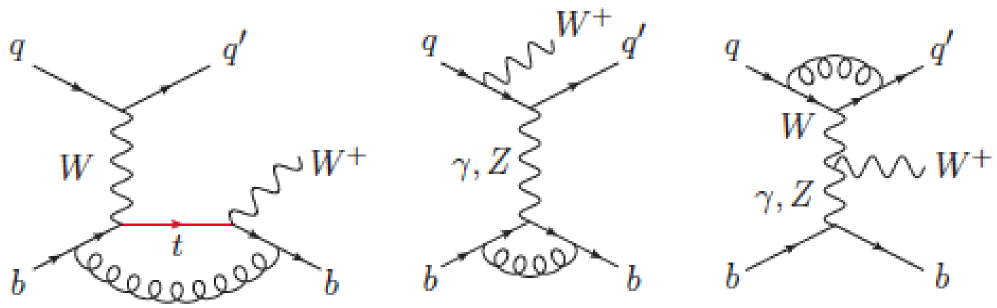


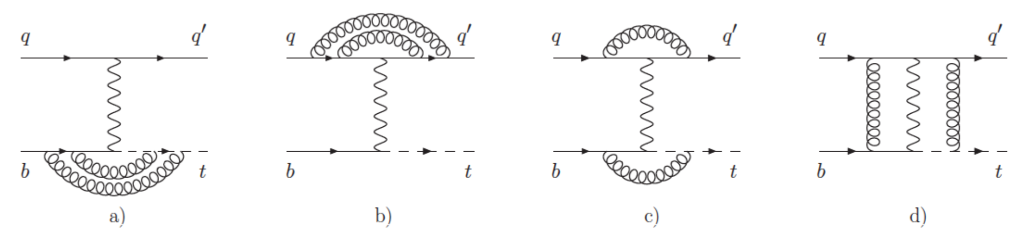


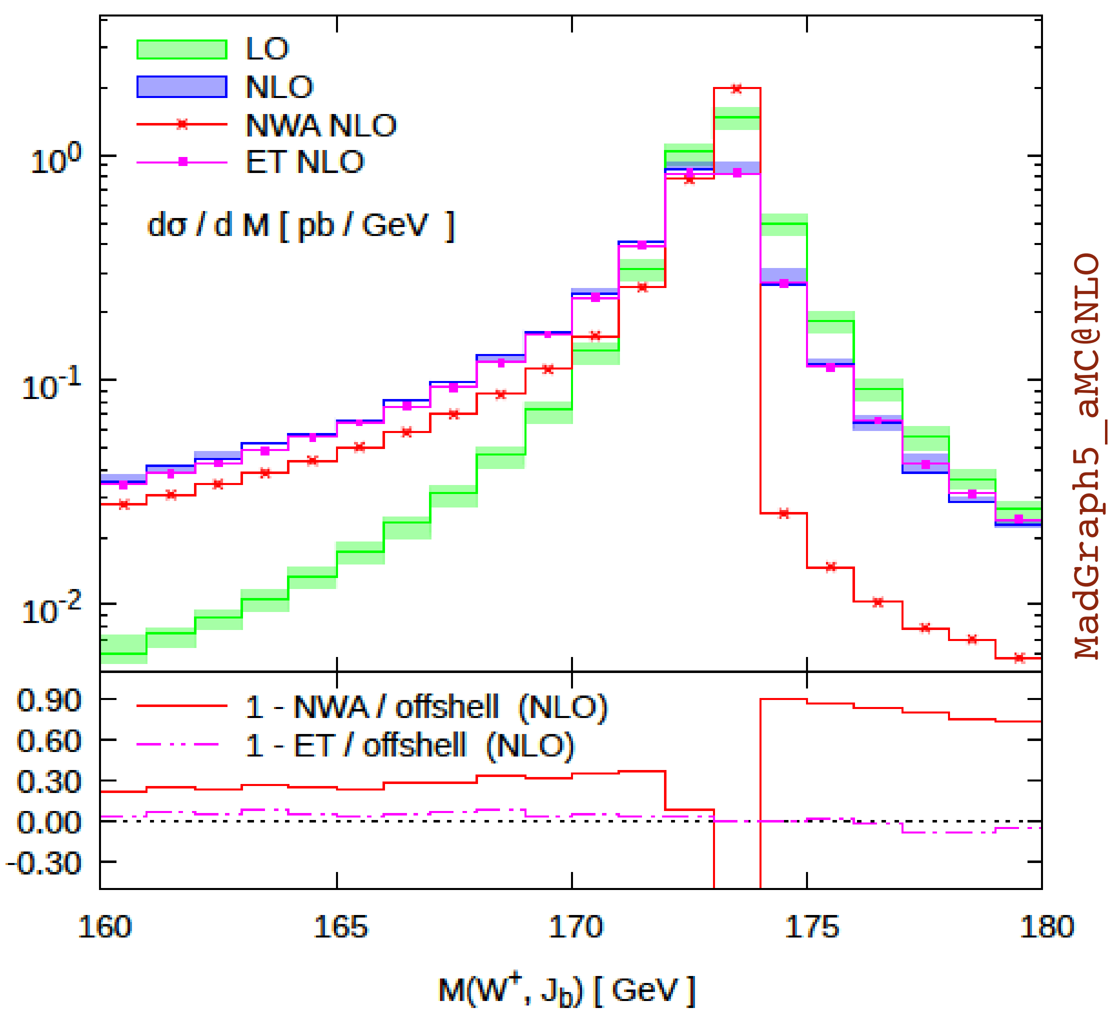
FOR THE FIRST TIME THE ISSUE OF "A SOFTER THAN NLO" P_T (TOP) HAS BEEN SEEN IN DATA CAN BE STUDIED. NNLO PREDICTIONS SEEM TO GO IN THE DIRECTION OF DATA.

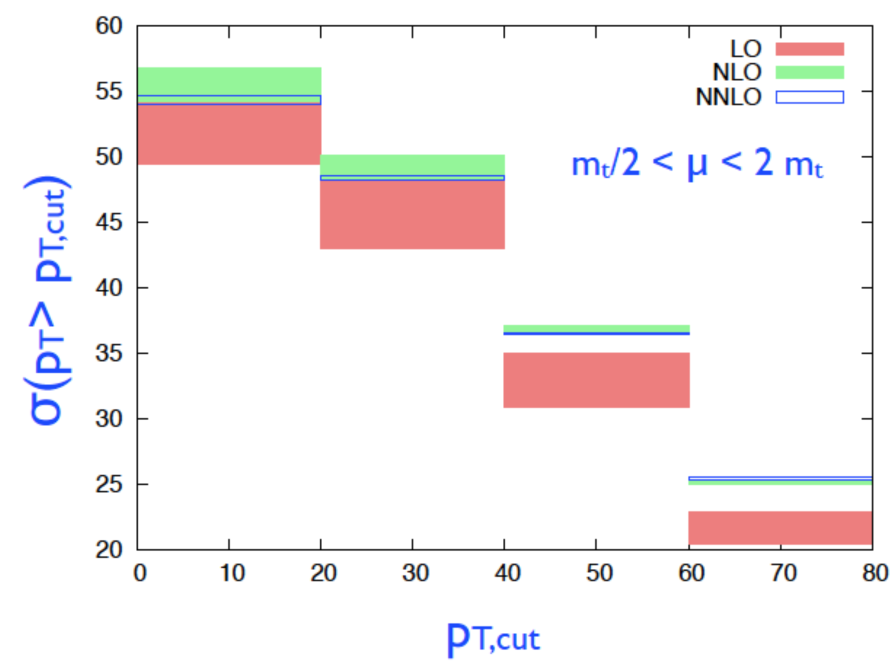
[Czakon, Fiedler, Heymes, Mitov.; in preperation]

IMPROVING SINGLE TOP









$\sigma_{\rm LO} = 53.8^{+3.0}_{-4.3}$ pb $\quad \sigma_{\rm NLO} = 55.1^{+1.6}_{-0.9}$ pb

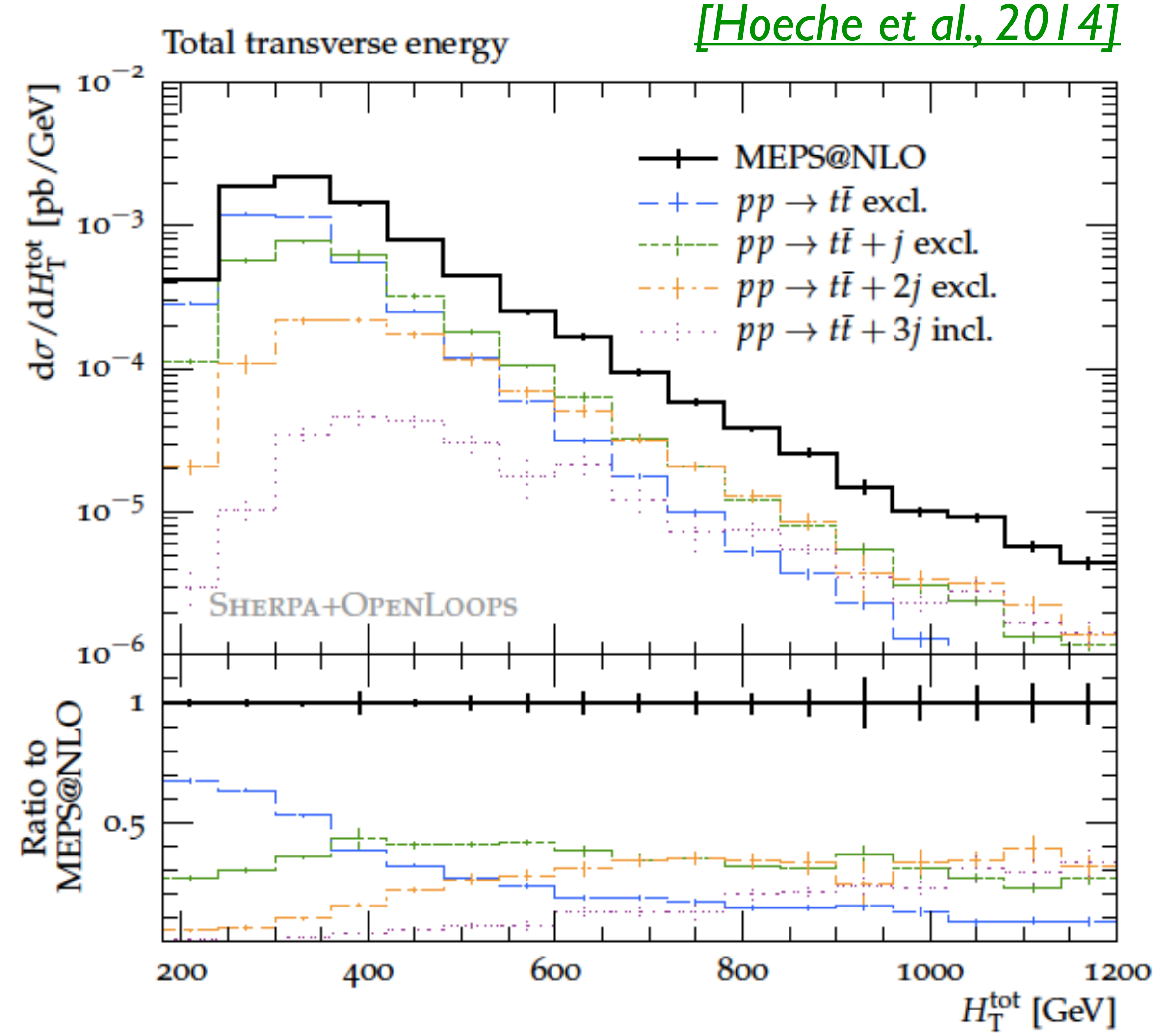
$$\sigma_{\rm NNLO} = 54.2^{+0.5}_{-0.2} \text{ pb}$$

$(\mu_R = \mu_F = \{m_t/2, m_t, 2\,m_t\})$

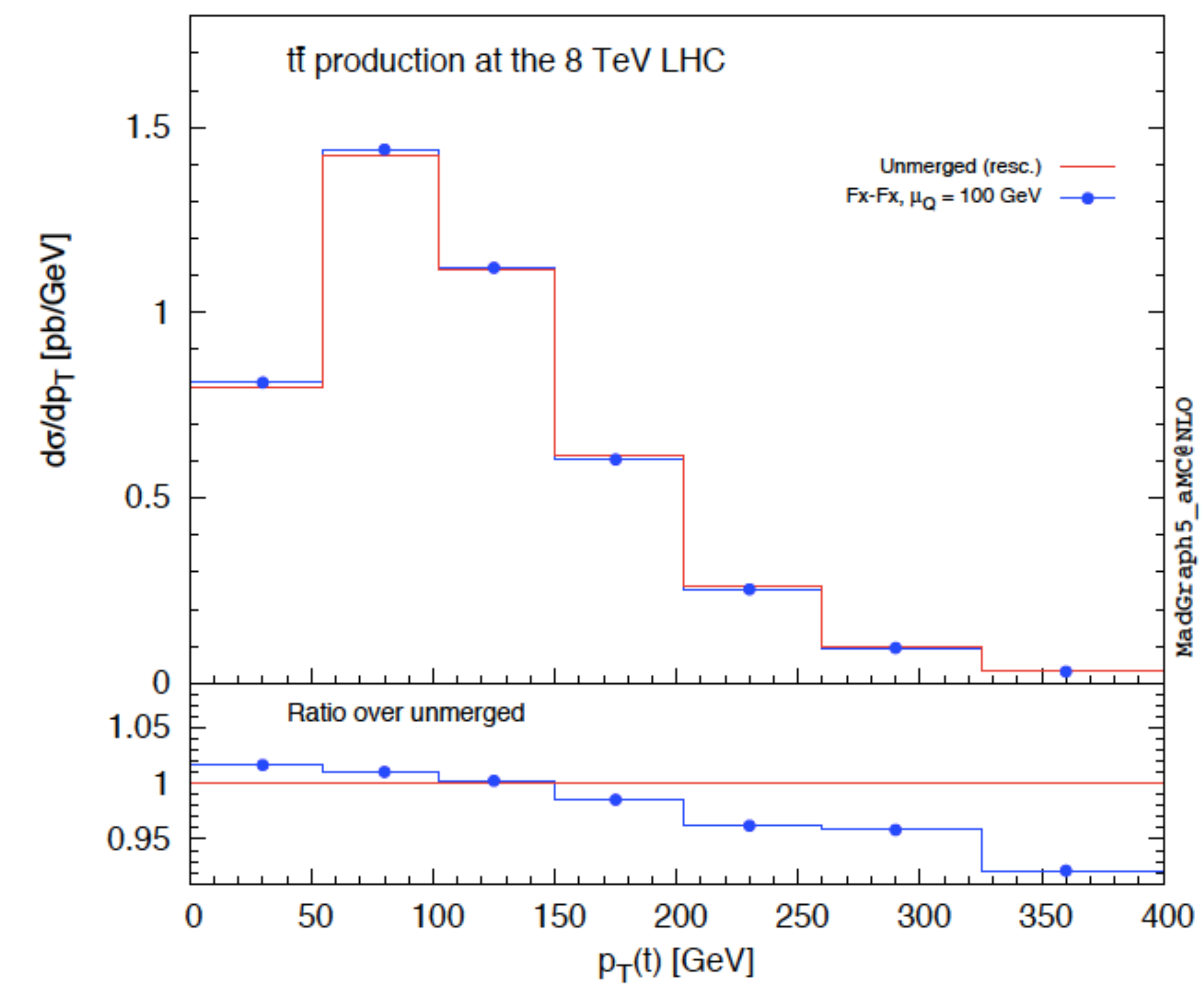
[Papanastasiou et al., 2013] [Caola et al., 2014]

REALISTIC AND ACCURATE PREDICTIONS

[Hoeche et al., 2014]



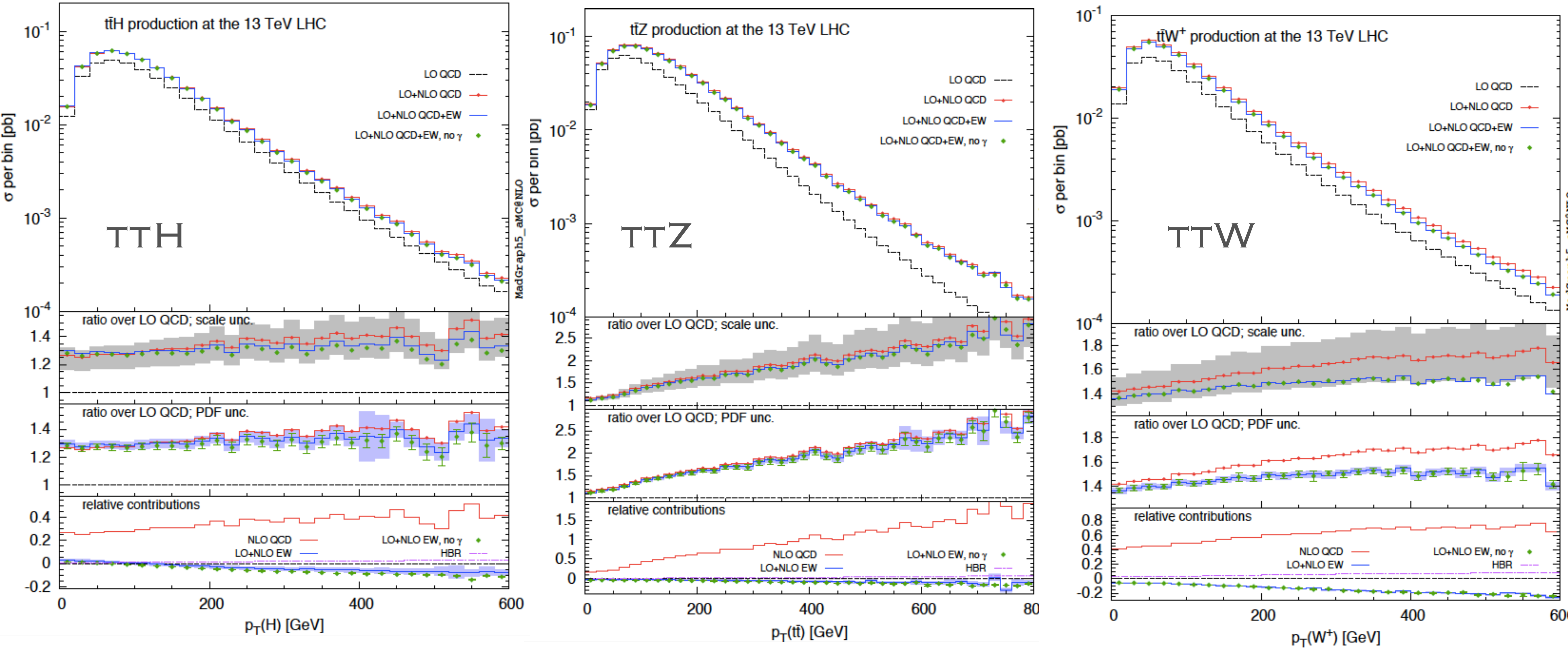
[Frixione et al, 2014]



Three methods available to merge at NLO different jet multiplicities (MEPS@NLO, FxFx, UNLOPS) in SHERPA and MG5_AMC@NLO+PYTHIA8. State-of-the-art MC's for TTBAR.

REALISTIC AND ACCURATE PREDICTIONS

[Frixione et al, 2015]

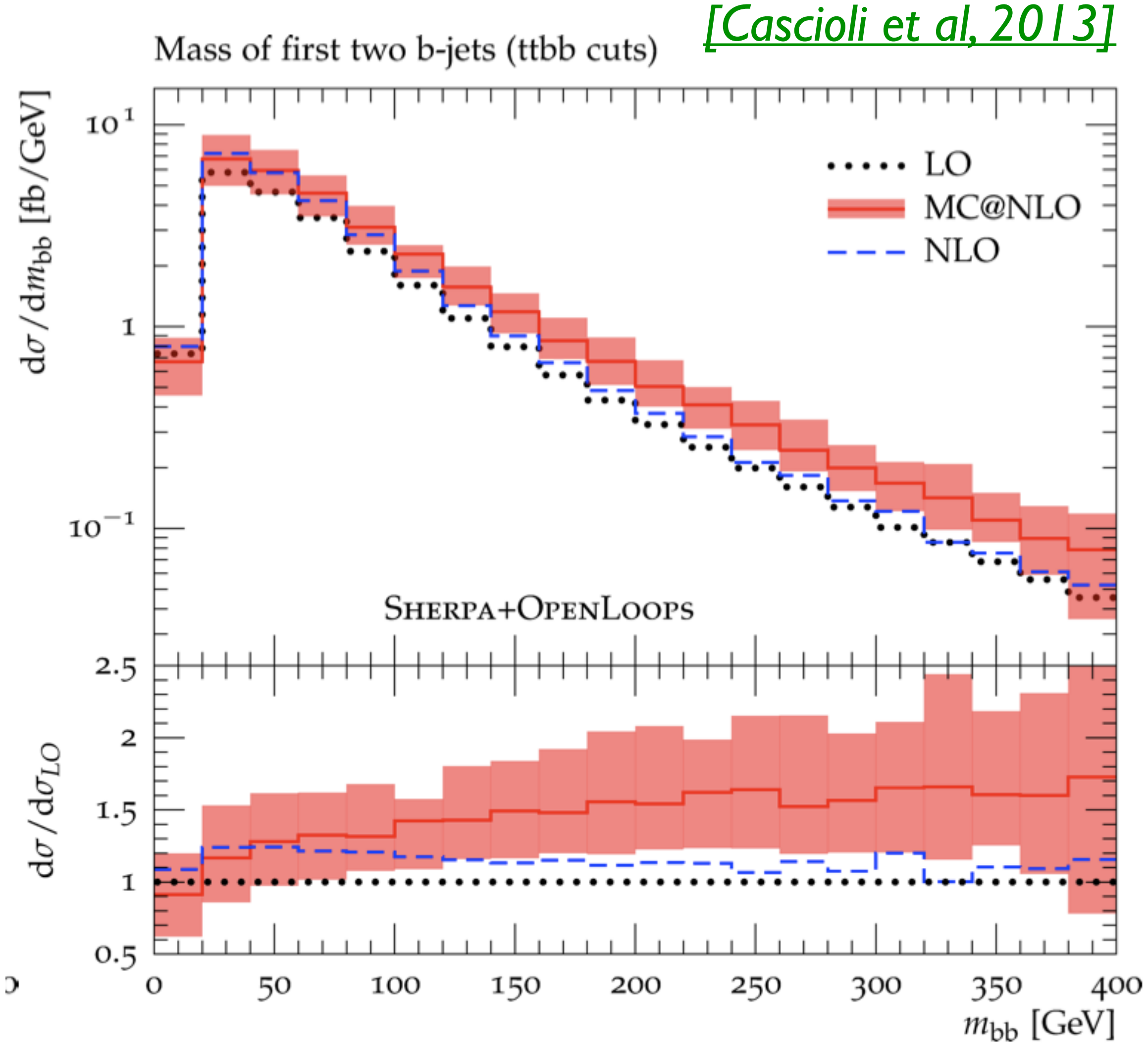


NLO FOR QCD & EW CORRECTIONS INCLUDED. QCD CORRECTIONS AVAILABLE ALSO FOR TTVV FINAL STATES. QCD EFFECTS NEED TO BE TAKEN INTO ACCOUNT FOR PRECISION AND ACCURACY. EW ONES FOR ACCURACY.

REALISTIC AND ACCURATE PREDICTIONS

$pp \to t\bar{t}b\bar{b}$

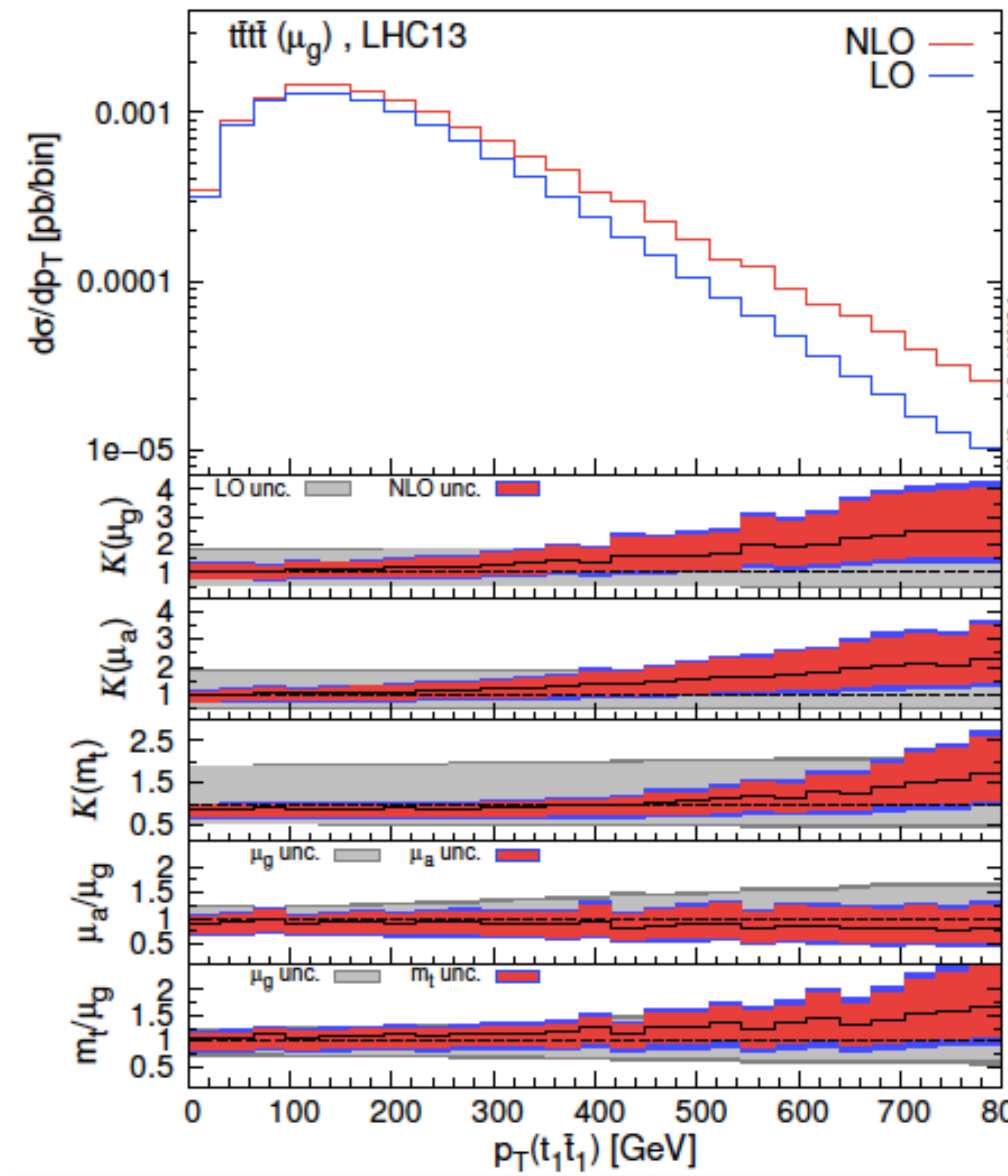
[Cascioli et al, 2013]



See also [Kardos and Trocsanyi, 2013]

$pp \to t\bar{t}t\bar{t}$

[Pagani et al, 2015]



See also [Bevilacqua and Worek, 2012]

Summary

- NNLO calculation for key top (even differential) observables available
- NLO+PS available for ANY process with on-shell tops (keeping spin correlations in the decays)
- NLO MERGING available for key processes with state of the art showers (Sherpa, HW++, Pythia8)
- NLO for resonant/non-resonant bW final states available

THE TOP-QUARK GATEWAY TO NP

Strategies:

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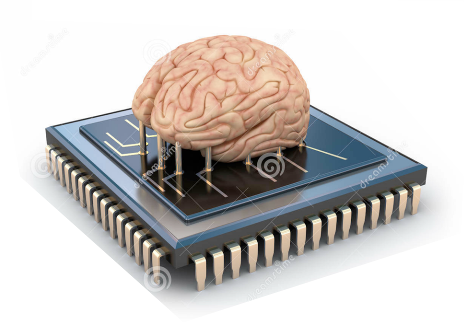
- Searches of top-quark partners and other states
- **Search for new top-quark interactions**



Needs:

- High precision predictions (NNLO in QCD and NLO) for key SM obs
- NLO for any SM (BSM) process in the form of (automatic) MC tools
- A consistent and complete model-independent framework, the EFT at NLO

THE EFT APPROACH

THE MATTER CONTENT OF SM HAS BEEN EXPERIMENTALLY VERIFIED AND EVIDENCE FOR LIGHT STATES IS NOT PRESENT.

SM MEASUREMENTS CAN ALWAYS BE SEEN AS SEARCHES FOR DEVIATIONS FROM THE DIM=4 SM LAGRANGIAN PREDICTIONS. MORE IN GENERAL ONE CAN INTERPRET MEASUREMENTS IN TERMS OF AN EFT:

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

THE BSM AMBITIONS OF THE LHC HIGGS/TOP/SM PHYSICS PROGRAMMES CAN BE RECAST IN A SIMPLE AND POWERFUL WAY IN TERMS OF ONE STATEMENT:

“BSM GOAL” OF THE SM LHC PROGRAMME:

DETERMINATION OF THE COUPLINGS OF THE SM $\mathcal{L}$ UP TO DIM=6

THE EFT APPROACH : DIM=6 SM LAGRANGIAN

[Grzadkowski et al, 10]

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

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
[illegible]	[illegible]	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
		Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
		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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

- Based on all the symmetries of the SM
- New physics is heavier than the resonance itself : $\Lambda > M_X$
- QCD and EW renormalizable (order by order in $1/\Lambda$)
- Number of extra couplings reduced by symmetries and dimensional analysis
- Extends the reach of searches for NP beyond the collider energy.
- Valid only up to the scale Λ

THE EFT APPROACH

- Very powerful approach.
- Note, however, that it only makes sense if a **global constraining strategy** is used to extract information from the data:
  - assume all couplings might not be zero at the EW scale.
  - Identify the operators entering each observable.
  - find enough observables (cross sections, BR's, distributions,...) to constrain all operators.
  - solve the (linear) system.
  - Hierarchical approach on the couplings.

TOP EFT INTERACTIONS

IN PRINCIPLE A LARGE NUMBER OF OPERATORS ARE PRESENT. YET VERY FEW OPERATORS OF DIM-6 ENTER IN TOP AND TOP-HIGGS PHYSICS:

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011, Degrande et al. 2011]

operator	process
$O_{\phi q}^{(3)} = i(\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$	top decay, single top
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$ (with real coefficient)	top decay, single top
$O_{qq}^{(1,3)} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{q}\gamma^\mu \tau^I q)$	single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu}$ (with real coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_G = f_{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$gg \to t\bar{t}$
$O_{\phi G} = \frac{1}{2}(\phi^+\phi) G^A_{\mu\nu} G^{A\mu\nu}$	$gg \to t\bar{t}$
7 four-quark operators	$q\bar{q} \to t\bar{t}$

CP-even

operator	process
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$ (with imaginary coefficient)	top decay, single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu}$ (with imaginary coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_{\tilde{G}} = f_{ABC} \tilde{G}^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$gg \to t\bar{t}$
$O_{\phi\tilde{G}} = \frac{1}{2}(\phi^+\phi) \tilde{G}^A_{\mu\nu} G^{A\mu\nu}$	$gg \to t\bar{t}$

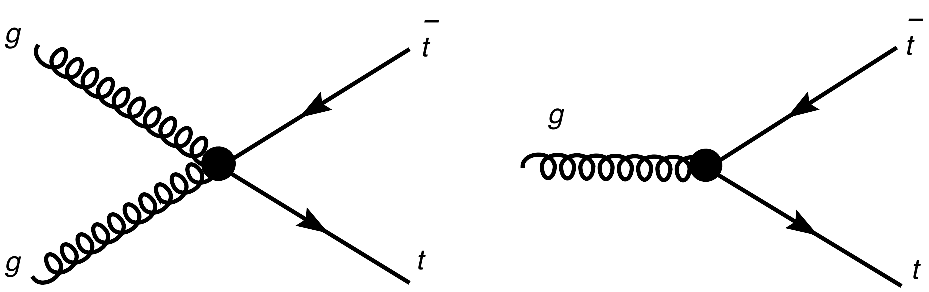
CP-odd

top EFT interactions

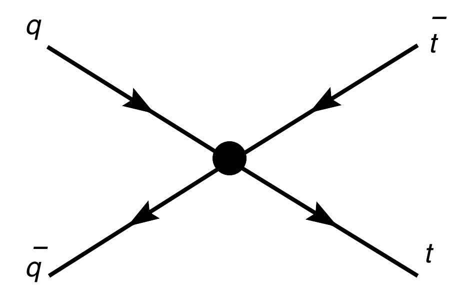
First constrain operators through top-anti-top production. There are only five operators entering:

$$\mathcal{L}_{t\bar{t}} = \mathcal{L}_{t\bar{t}}^{SM} + \frac{1}{\Lambda^2}\left[g_h \mathcal{O}_{hg} + c_R \mathcal{O}_{Rg} + a_R \mathcal{O}_{Ra}^{8} + (R \leftrightarrow L)\right]$$

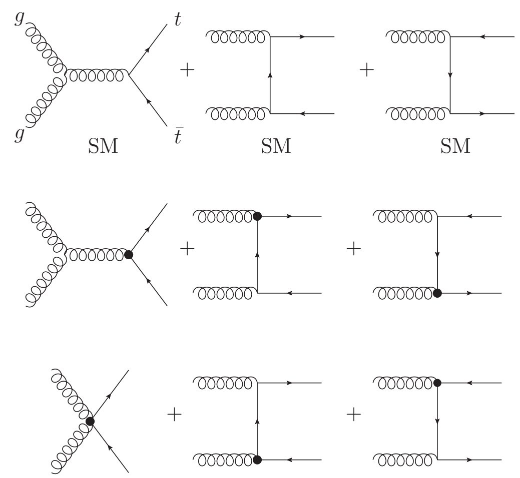
and in case one is interested only in total rates (and spin independent / FB symmetries) only three parameters are left : gh , cV=cR+cL and aA = aR - aR



Chromomagnetic operator $\mathcal{O}_{hg} = (H\bar{Q})\sigma^{\mu\nu}T^A t\, G^A_{\mu\nu}$

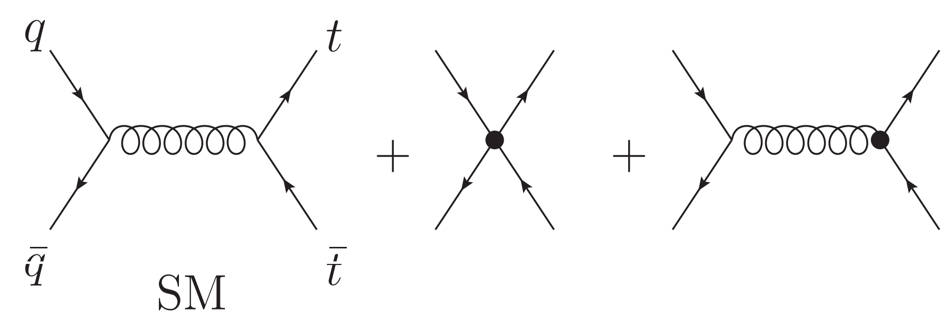


Four-fermion operators



gluon fusion
corrections from c_{hg} only

qq annihilation:
both c_{hg} and 4-fermion operators



TOP EFT INTERACTIONS

NON-RESONANT TOP PHILIC NEW PHYSICS CAN BE PROBED USING MEASUREMENTS IN TOP PAIR PRODUCTION AT HADRON COLLIDERS

THIS MODEL-INDEPENDENT ANALYSIS CAN BE PERFORMED IN TERMS OF 8 OPERATORS.

OBSERVABLES DEPEND ON DIFFERENT COMBINATIONS OF ONLY 4 PARAMETERS:

$$\sigma(gg \to t\bar{t}), d\sigma(gg \to t\bar{t})/dt \quad \leftrightarrow \quad c_{hg}$$

$$\sigma(q\bar{q} \to t\bar{t}) \quad \leftrightarrow \quad c_{hg}, c_{Vv}$$

$$d\sigma(q\bar{q} \to t\bar{t})/dm_{tt} \quad \leftrightarrow \quad c_{hg}, c_{Vv}$$

$$A_{FB} \quad \leftrightarrow \quad c_{Aa}$$

$$\text{spin correlations} \quad \leftrightarrow \quad c_{hg}, c_{Vv}, c_{Av}$$

TOP-HIGGS INTERACTIONS

Consider, for example, the following top-Higgs interactions:

$$\mathcal{O}_{hg} = \left(\bar{Q}_L H\right) \sigma^{\mu\nu} T^a t_R G^a_{\mu\nu},$$

CHROMOMAGNETIC OPERATOR

$$\mathcal{O}_{Hy} = H^\dagger H \left(H \bar{Q}_L\right) t_R$$

YUKAWA OPERATOR

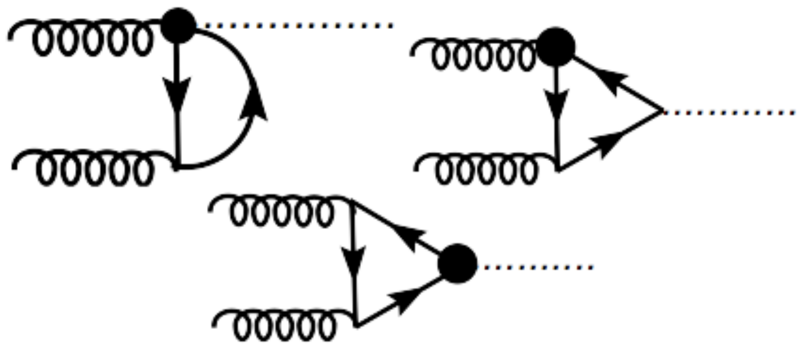
$$\mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$

HIGGS-GLUON OPERATOR

At NLO in QCD the first two operators mix:

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

In addition, the third operator receives contributions from the first two at one loop:



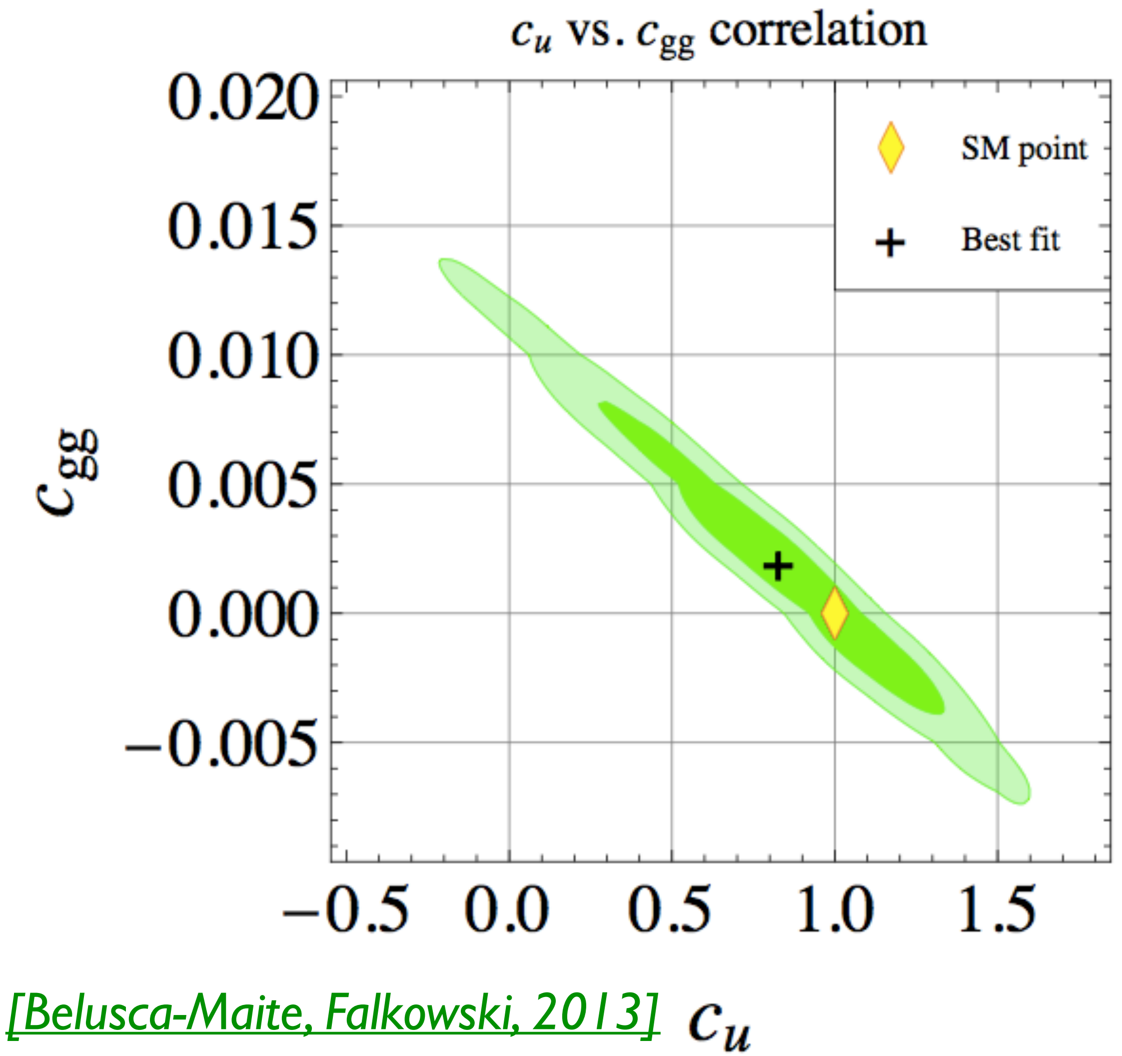
A meaningful analysis can only be made by considering them all!

TOP-HIGGS INTERACTIONS: CONSTRAINTS

FROM A GLOBAL FIT THE COUPLING OF THE HIGGS TO THE TOP IS POORLY DETERMINED.

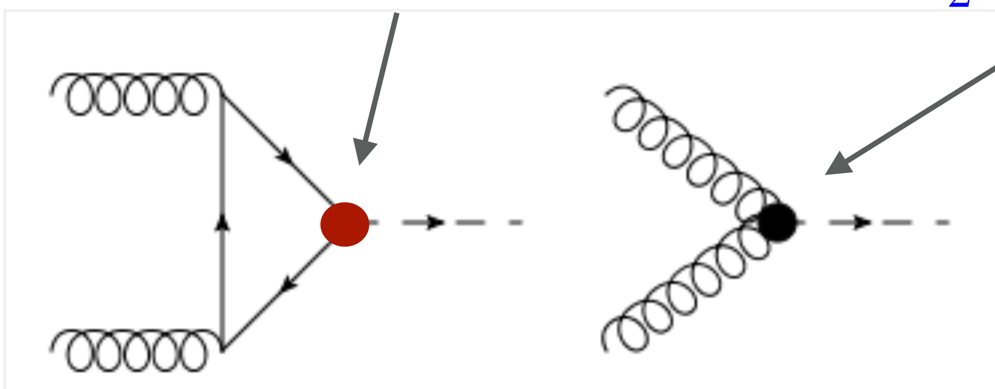
$$c_V = 1.04 \pm 0.03, \quad c_t = 1.1^{+0.9}_{-3.0} \quad c_b = 1.06^{+0.30}_{-0.23}, \quad c_\tau = 1.04 \pm 0.22$$

$$c_{gg} = -0.002 \pm 0.036, \quad c_{\gamma\gamma} = 0.0011^{+0.0019}_{-0.0028}, \quad c_{Z\gamma} = 0.000^{+0.019}_{-0.035} \;.$$



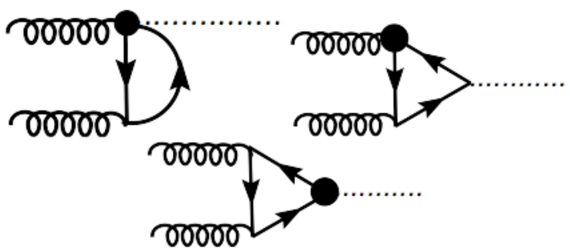
[Belusca-Maite, Falkowski, 2013]

$$\mathcal{O}_{Hy} = H^\dagger H \left(H\bar{Q}_L\right) t_R \qquad \mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$



THE LOOP COULD STILL BE DOMINATED BY NP.

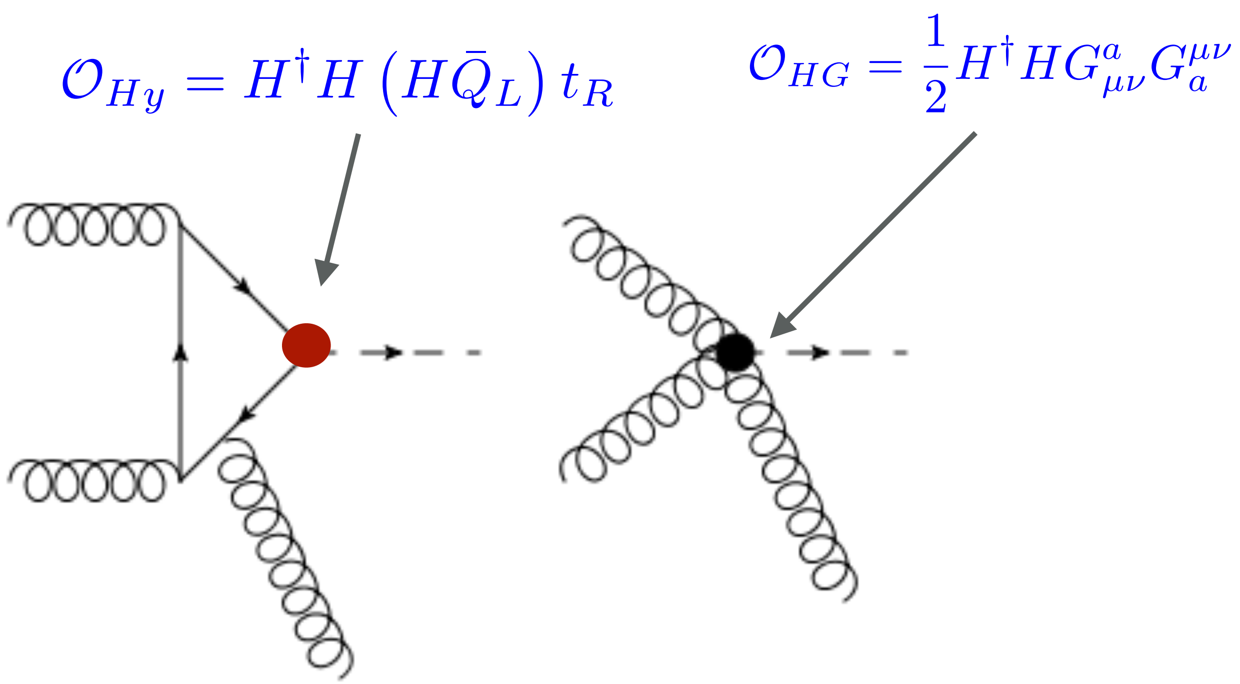
THE EFFECT OF THE CM OPERATOR NOT INCLUDED

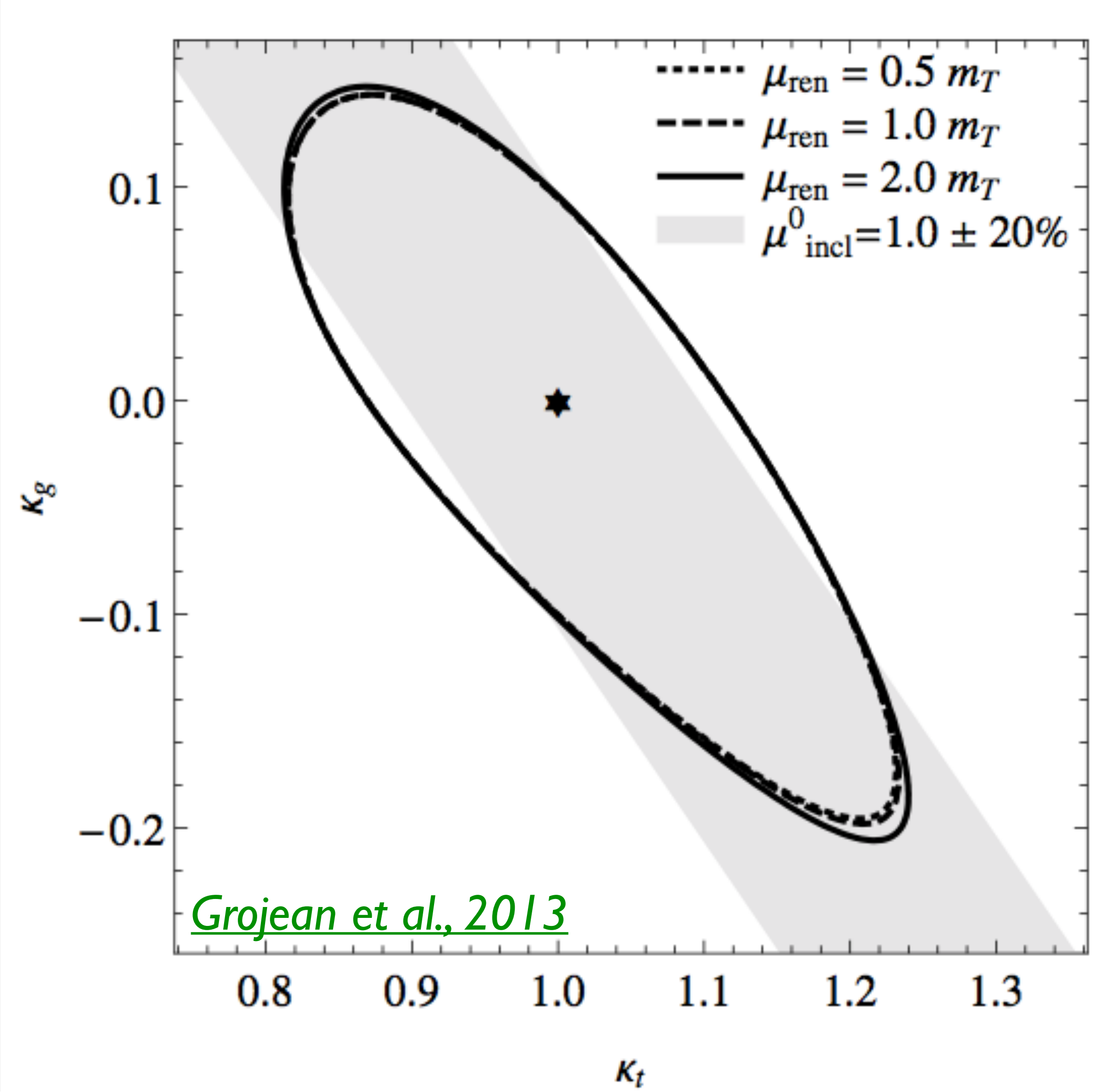


TOP-HIGGS INTERACTIONS: HIGH-PT

FROM A GLOBAL FIT THE COUPLING OF THE HIGGS TO THE TOP IS POORLY DETERMINED: THE LOOP COULD STILL BE DOMINATED BY NP.

[Grojean et al., 2013] [Banfi et al. 2014] [Buschmann, et al. 2014]



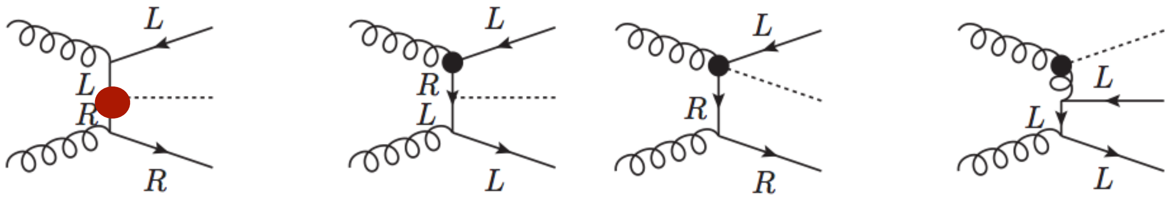


EFT AT NLO PREDICTIONS AVAILABLE, YET SM NLO PREDICTIONS ARE NEEDED CONTROL ACCURACY AND PRECISION.

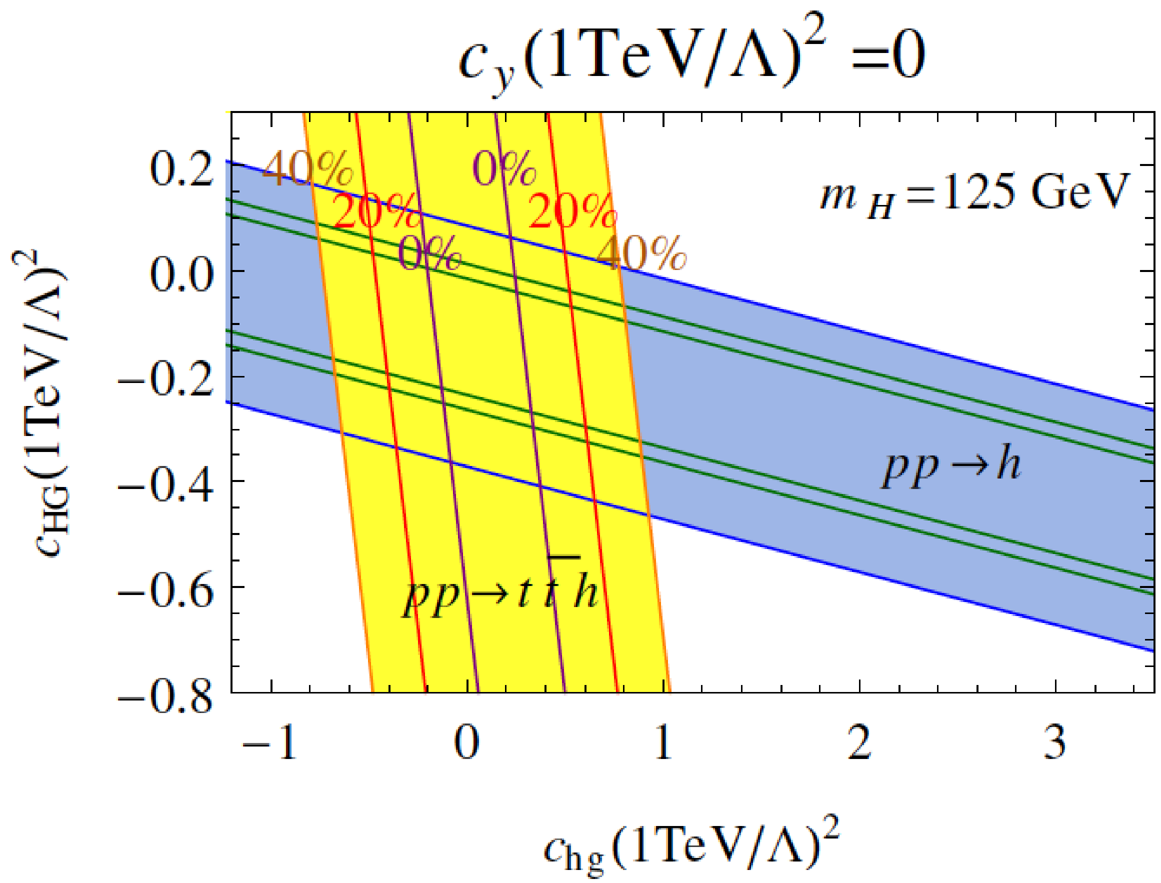
TOP-HIGGS INTERACTIONS: TTH

$$pp \to t\bar{t}h$$

[Degrande et al. 2012]



$$\frac{\sigma\left(pp \to t\bar{t}h\right)}{\text{fb}} = 611^{+92}_{-110} + \left[457^{+127}_{-91}\Re c_{hg} - 49^{+15}_{-10}c_G + 147^{+55}_{-32}c_{HG} - 67^{+23}_{-16}c_y\right]\left(\frac{\text{TeV}}{\Lambda}\right)^2 + \left[543^{+143}_{-123}(\Re c_{hg})^2 + 1132^{+323}_{-232}c_G^2 + 85.5^{+73}_{-21}c_{HG}^2 + 2^{+0.7}_{-0.5}c_y^2 + 233^{+81}_{-144}\Re c_{hg}c_{HG} - 50^{+16}_{-14}\Re c_{hg}c_y - 3.2^{+8}_{-8}\Re c_{Hy}c_{HG} - 1.2^{+8}_{-8}c_H c_{HG}\right]\left(\frac{\text{TeV}}{\Lambda}\right)^4$$

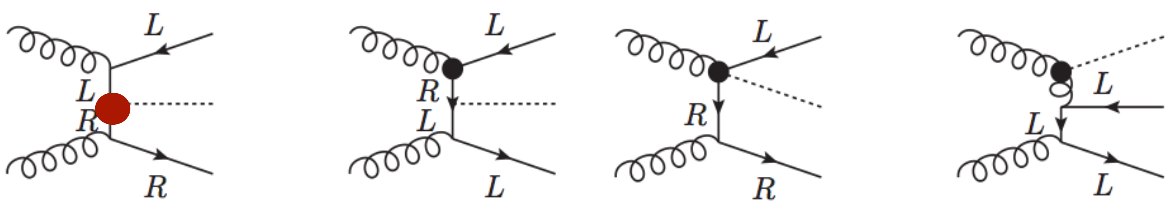


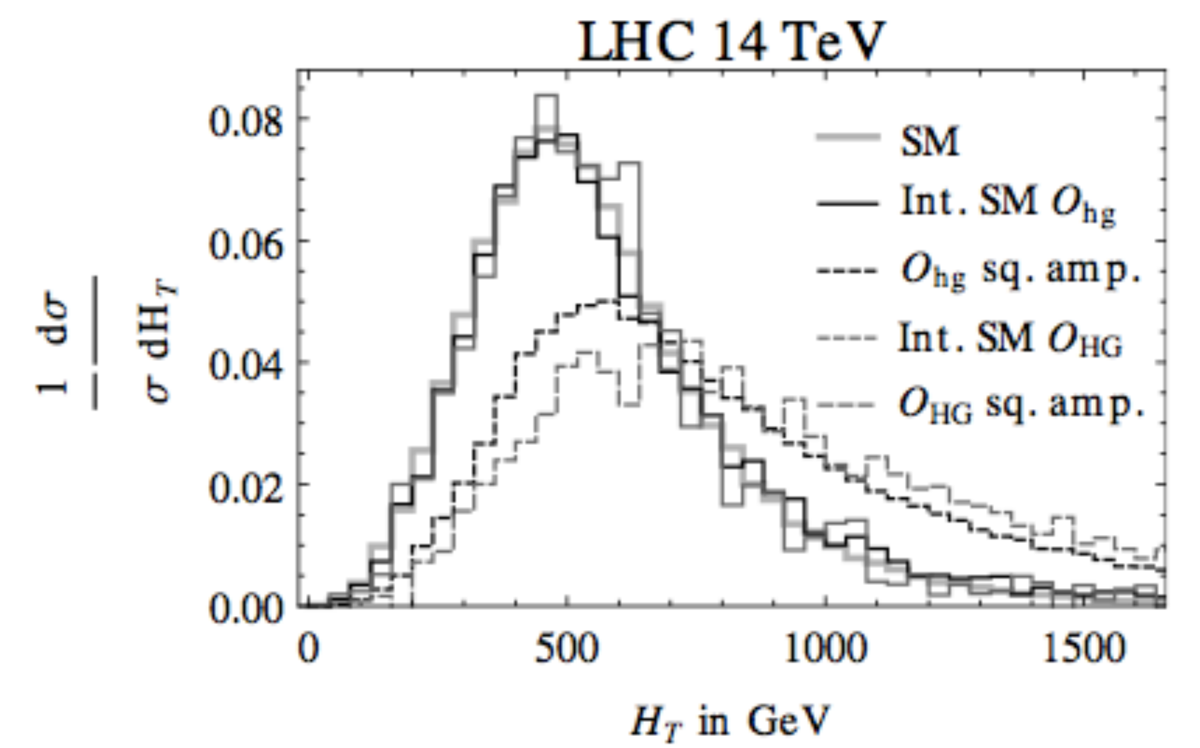
Analysis done at **LO! NLO** is now within reach

Top-Higgs interactions: ttH

[Degrande et al. 2012]

$$pp \to t\bar{t}h$$





Different operators interfere in a given process. This together with the fact that the Wilson coefficients run and operators mix, implies that the it makes no sense to constrain operators one at the time. Global strategy is needed:

obs1(s,t,u) = c1 F11(s,t,u) + c3 F31(s,t,u) + ...

obs2(s,t,u) = c1 F12(s,t,u) + c2 F22(s,t,u) + ...

obs3(s,t,u) = c1 F13(s,t,u) + c4 F43(s,t,u) + ...

Not yet done at the LHC! Room for improvements and new ideas...

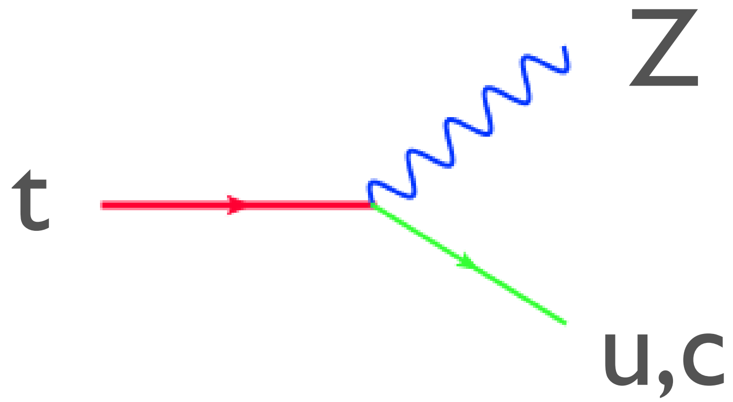
THE NEED TO GO NLO

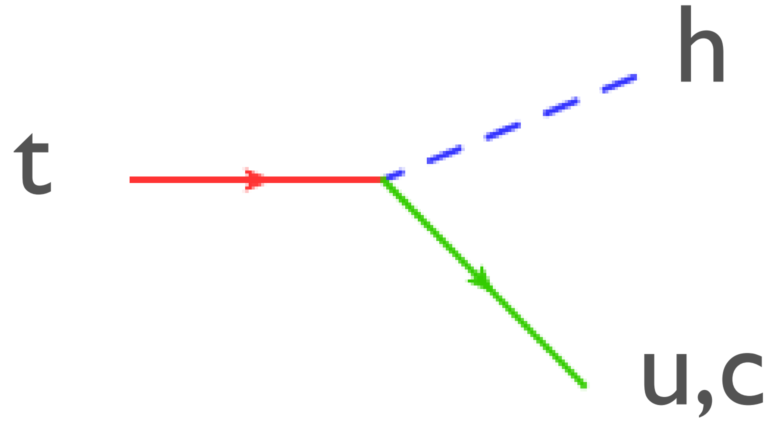
- A global approach with constraints on top couplings coming from a wide set of observables is the (only) way to go.
- a precision physics effort needs accurate predictions not only for the SM but also for the EFT.
- This is because the top is coloured and the LHC is hadron collider.
- In fact, the structure of the EFT for the top becomes non trivial at NLO in QCD, with operator mixings.
- Let's see a first self-contained example

Top FCNC at NLO

The study of FCNC couplings can bring new information:

[Drobnak, 2012 based on CMS and ATLAS results] [Kao et al. 2011 , Kai-Feng et al 2013] [Zhang FM, 2013]





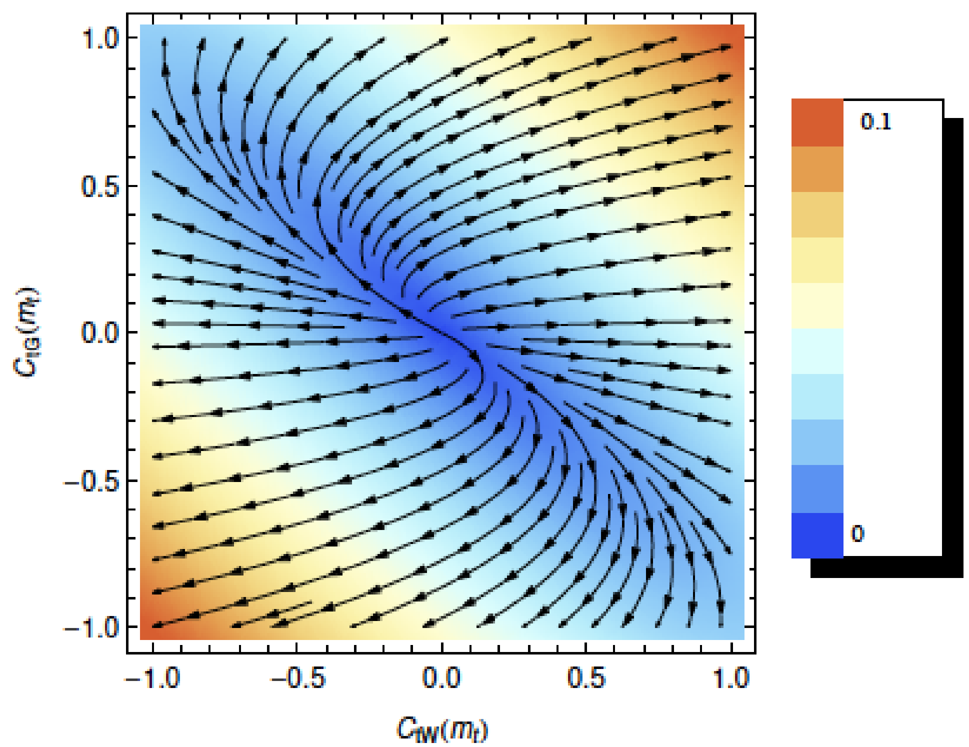
While the exp searches are completely different, one has to remember that the decay rates will depend on several operators that are linked by gauge symmetry. For example:

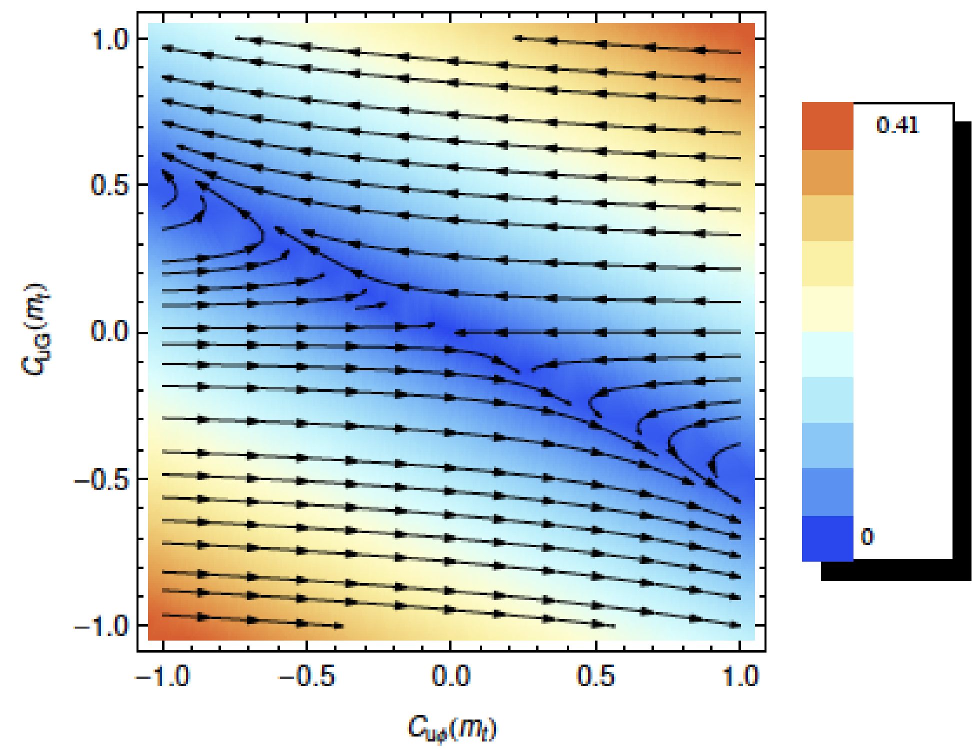
$$O_{uB}^{(13)} = y_t g_Y (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$
$$O_{uW}^{(13)} = y_t g_W (\bar{q}\sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$
$$O_{uG}^{(13)} = y_t g_s (\bar{q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$
$$O_{u\varphi}^{(13)} = -y_t^3 (\varphi^\dagger \varphi)(\bar{q} t)\tilde{\varphi}$$

$$\gamma = \frac{2\alpha_s}{\pi} \begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -2 & 0 & 0 & -1 \end{pmatrix}$$

Top FCNC at NLO

[Durieux, FM, Zhang 2014]





$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}$$
$$O_{tW} = y_t g_W (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$
$$O_{t\varphi} = -y_t^3 (\varphi^\dagger\varphi)(\bar{Q}t)\tilde{\varphi}\ .$$

$$\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -4 & 0 & 0 & -1 \end{pmatrix}$$

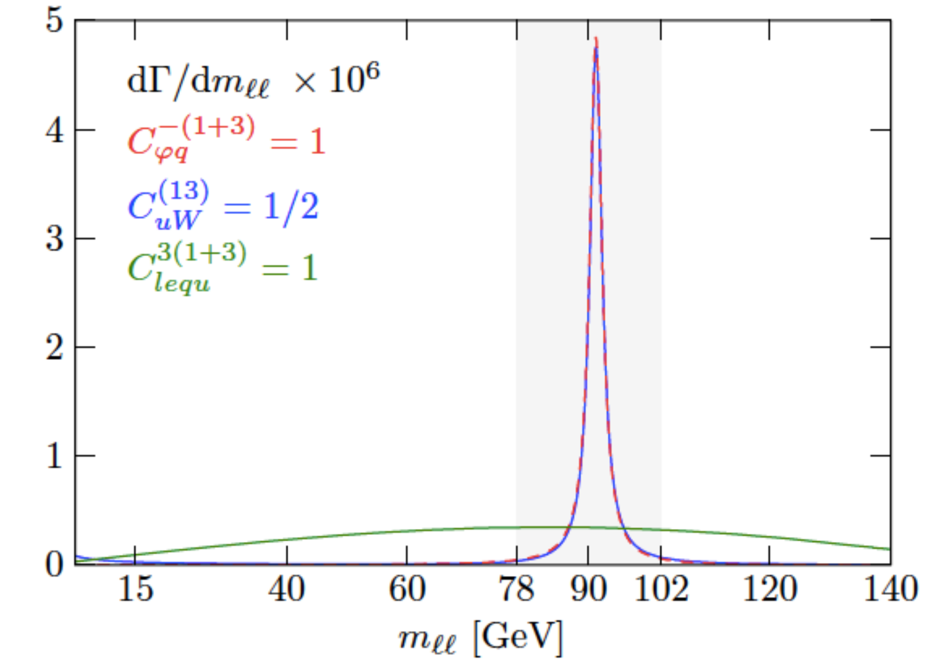
$$O^{(13)}_{uG} = y_t g_s (\bar{q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}$$
$$O^{(13)}_{uW} = y_t g_W (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O^{(13)}_{uB} = y_t g_Y (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$
$$O^{(13)}_{u\varphi} = -y_t^3 (\varphi^\dagger\varphi)(\bar{q}t)\tilde{\varphi}\ .$$

$$\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -2 & 0 & 0 & -1 \end{pmatrix}$$

$$\begin{cases} C^{(13)}_{uG}(1\ \text{TeV}) = 1, \\ C^{(13)}_{u\varphi}(1\ \text{TeV}) = 0, \end{cases} \longrightarrow \begin{cases} C^{(13)}_{uG}(m_t) = 0.98, \\ C^{(13)}_{u\varphi}(m_t) = 0.23. \end{cases}$$

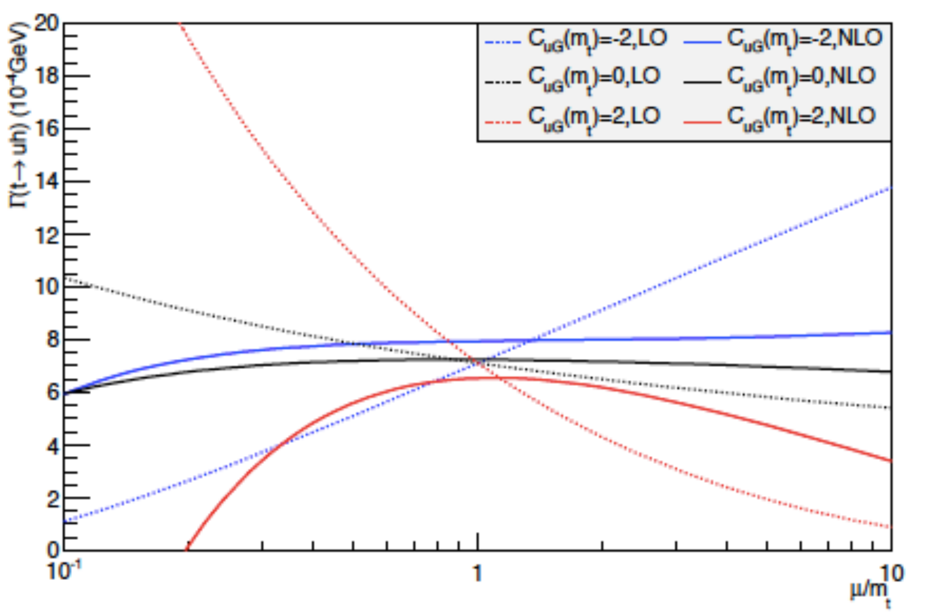
Top FCNC at NLO : decays

[Durieux, FM, Zhang 2014]



$$\Gamma^{\text{on-peak}}_{t\to u\, e^+e^-}\ /10^{-5}\ \text{GeV}\ \times (\Lambda/1\ \text{TeV})^4$$
$$= 1.7\,|C_{\varphi q}^{-(1+3)}|^2 + 6.6\,|C_{uW}^{(13)}|^2 + 0.81\,|C_{lequ}^{3(13)}|^2$$

$$\Gamma^{\text{off-peak}}_{t\to u\, e^+e^-}\ /10^{-5}\ \text{GeV}\ \times (\Lambda/1\ \text{TeV})^4$$
$$= 0.2\,|C_{\varphi q}^{-(1+3)}|^2 + 1.0\,|C_{uW}^{(13)}|^2 + 2.7\,|C_{lequ}^{3(13)}|^2$$



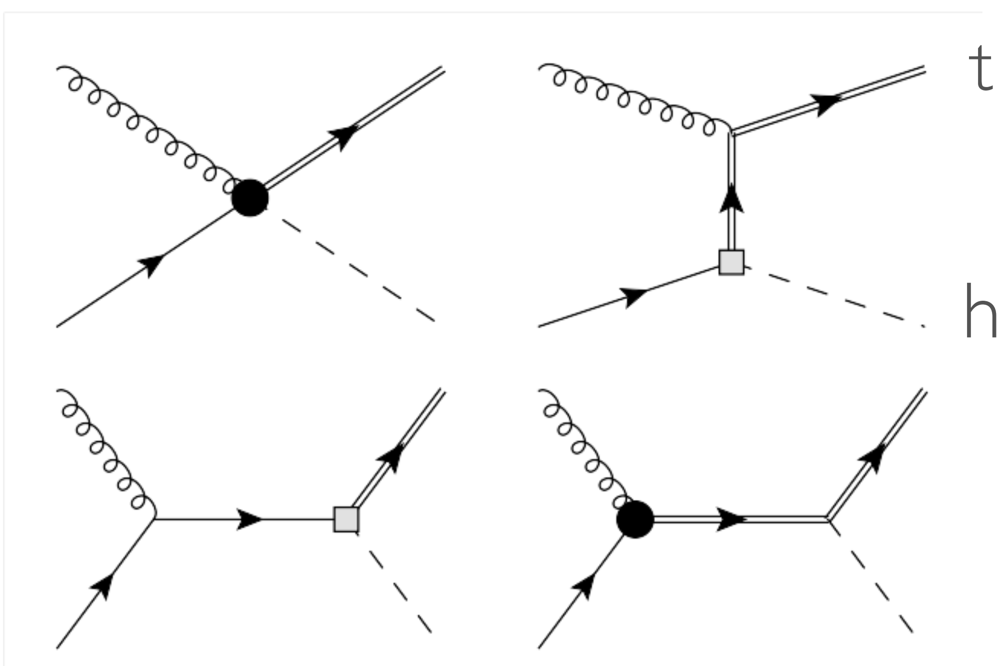
$$\Gamma(t\to u_i h) = \Gamma^{(0)} + \alpha_s \Gamma^{(1)}$$

$$\Gamma^{(0)} = 7.11|C_{u\varphi}(\mu)|^2\ \times 10^{-4}\,\text{GeV}\,,$$
$$\Gamma^{(1)} = \Bigg\{ \left[1.19 - 9.05\log\left(\frac{m_t}{\mu}\right)\right]|C_{u\varphi}(\mu)|^2 - \left[3.26 + 18.1\log\left(\frac{m_t}{\mu}\right)\right]\text{Re}C_{uG}(\mu)C^*_{u\varphi} + 9.33\times 10^{-5}|C_{uG}(\mu)|^2 \Bigg\} \times 10^{-4}\,\text{GeV}\,. \quad (48)$$

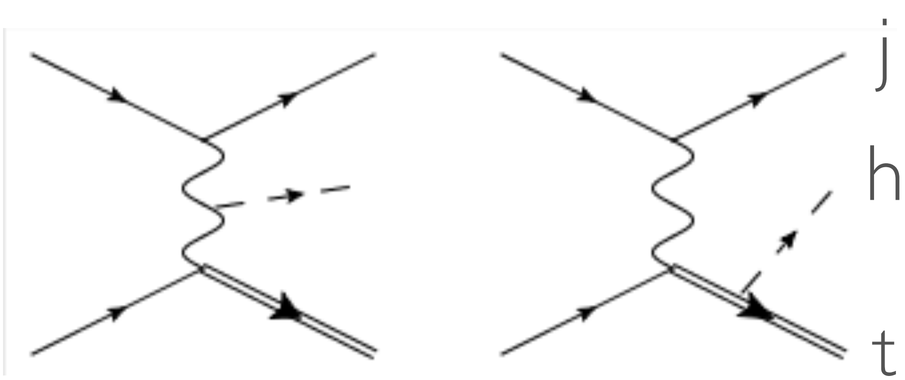
Top FCNC at NLO : production

[Degrande, FM, Wang, Zhang, 2014]

pp →th



pp →thj (SM)



Contributions appear at LO from $O_{t\phi}$ and one from O_{tG}..

At NLO in QCD O_{tG} mixes with all the other operators so it has always to be included.

It also means that if a specific (arbitrary) choice of coefficient operators is made at high scales (where one can imagine a full theory to live) many operators become active when evolved to lower scales.

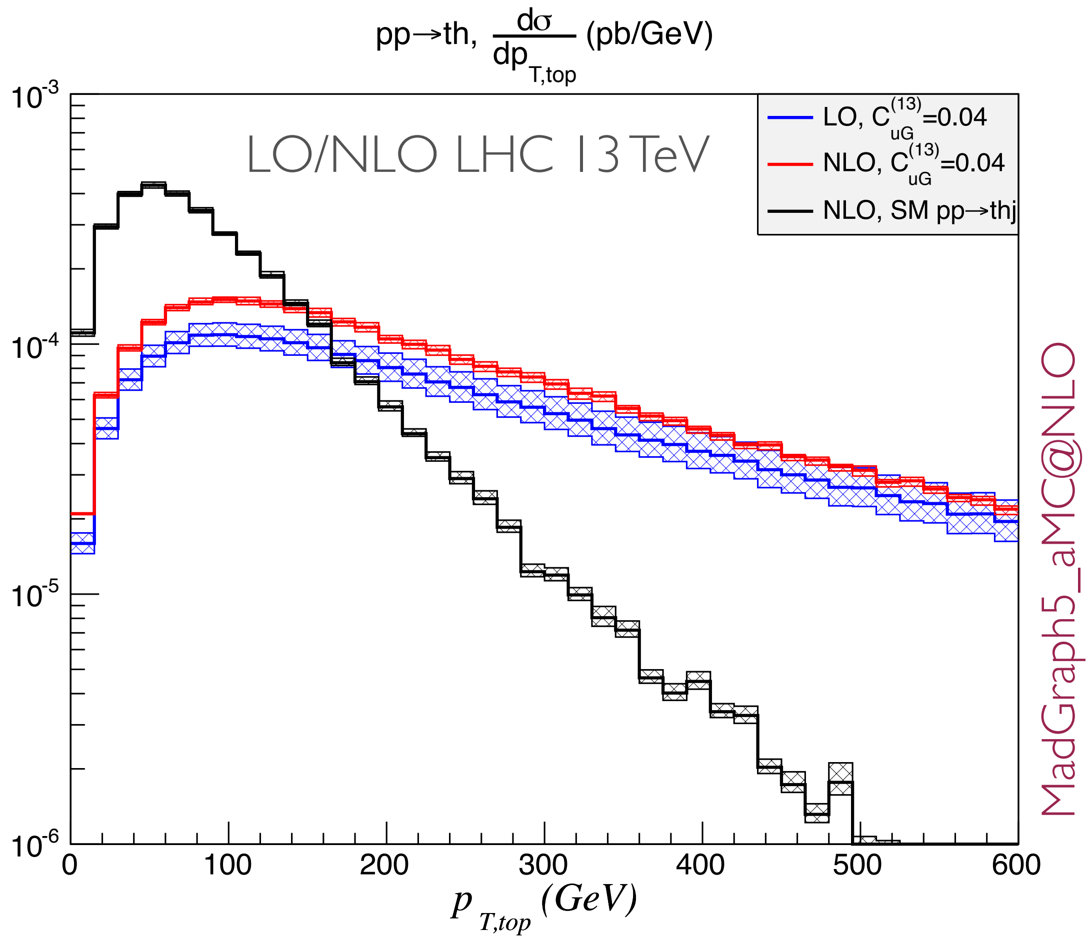
Only a global/fit approach on constraining such operators at the same time can be useful strategy and it has to be at least NLO in QCD.

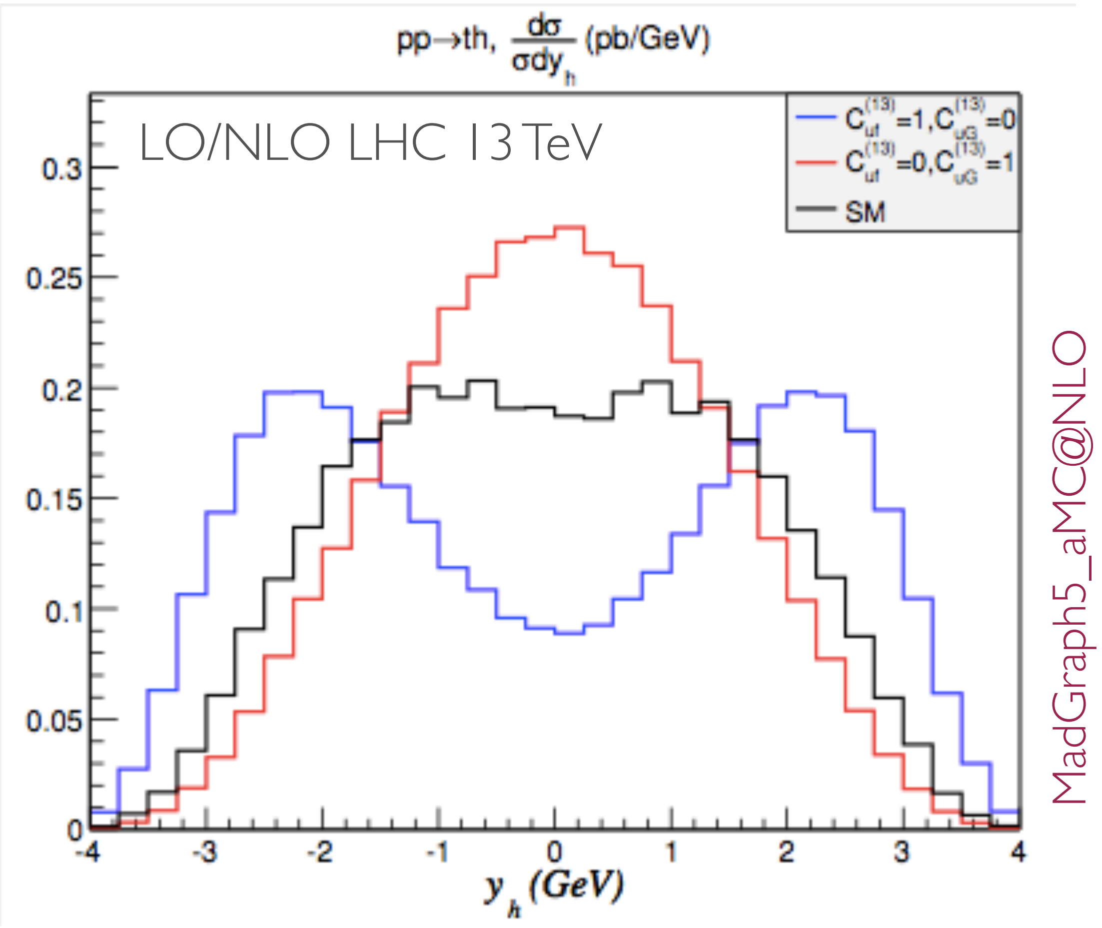
TOP FCNC AT NLO : PRODUCTION

[Degrande, FM, Wang, Zhang, 2014]

The operators have been implemented in FeynRules, the model was upgraded to NLO automatically and then passed to MG5_aMC.

Results shown here at NLO. the pp →thj interesting process by itself...





Complete implementation of all operators of dim=6 at NLO (including four fermion operators) in QCD is on going.

TOP FCNC AT NLO : GLOBAL FIT

[Durieux, FM, Zhang 2014]

$$\mathrm{Br}(t \to j\, e^+e^-) + \mathrm{Br}(t \to j\, \mu^+\mu^-) \lesssim 0.0017\%$$ CMS

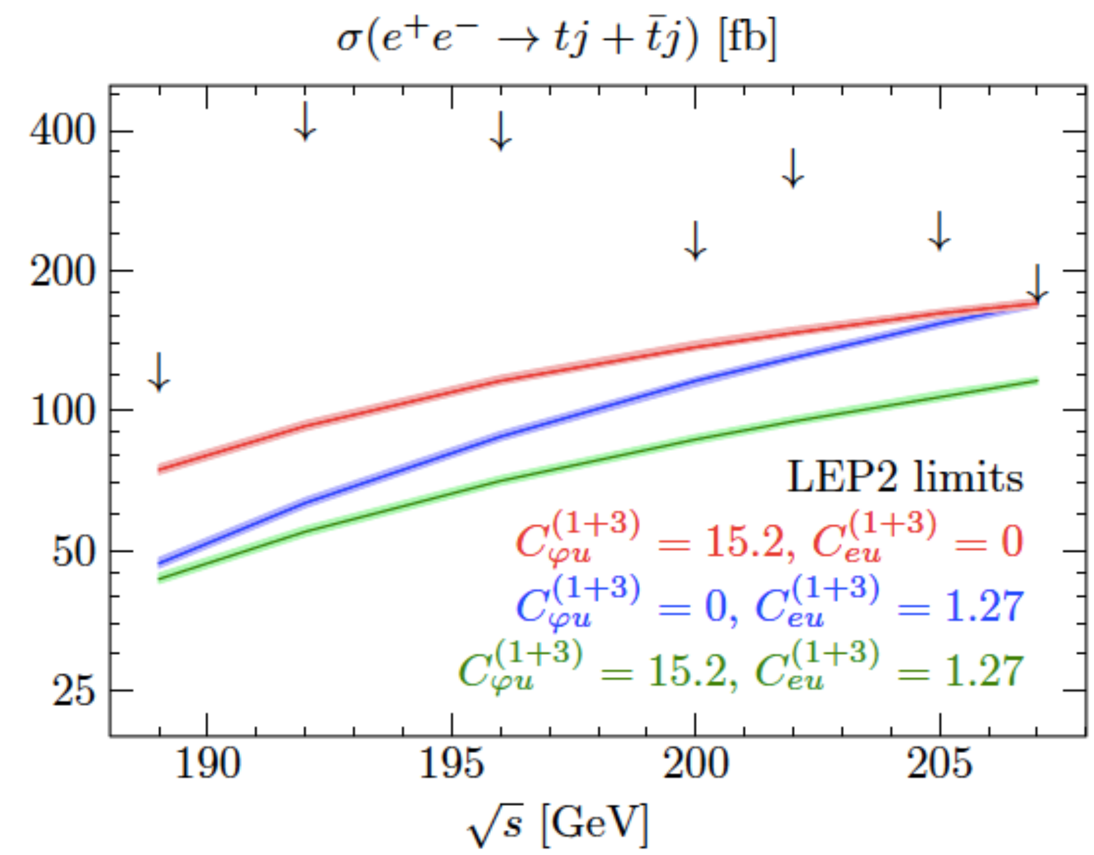
$$\mathrm{Br}(t \to j\gamma) < 3.2\%$$ CDF

$$\mathrm{Br}(t \to j\, \gamma\gamma) < 0.0016\%$$ CMS

$$\sigma(pp \to t) + \sigma(pp \to \bar{t}) < 2.5 \text{ pb} \quad \text{at } \sqrt{s} = 8 \text{ TeV}$$ ATLAS

$$\sigma(ug \to t\gamma) + \sigma(ug \to \bar{t}\gamma) + 0.778\, [\sigma(cg \to t\gamma) + \sigma(cg \to \bar{t}\gamma)] < 0.0670 \text{ pb} \quad \text{at } \sqrt{s_{pp}} = 8 \text{ TeV}$$ CMS

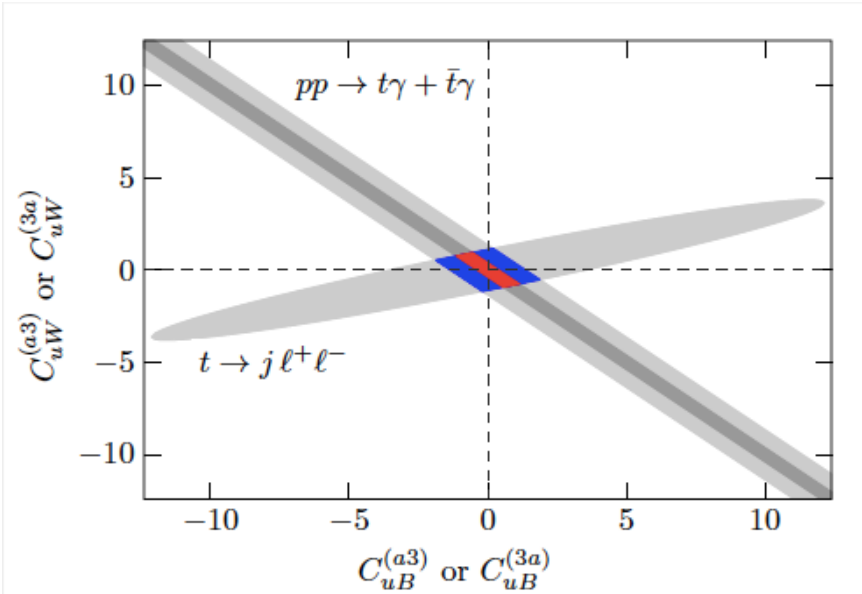
$$\sigma(e^+e^- \to tj + \bar{t}j) < 176 \text{ fb} \quad \text{at } \sqrt{s} = 207 \text{ GeV}$$ LEPII

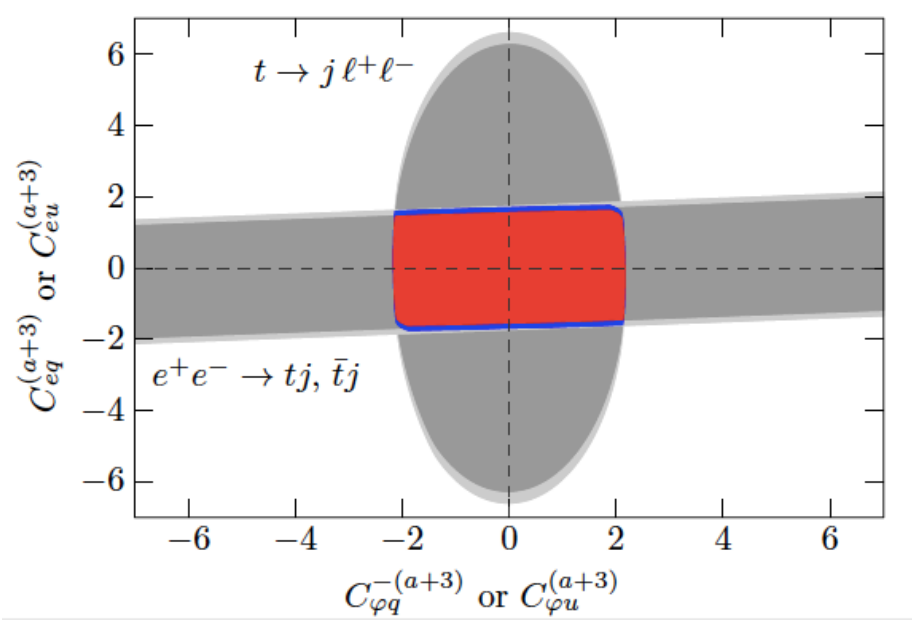


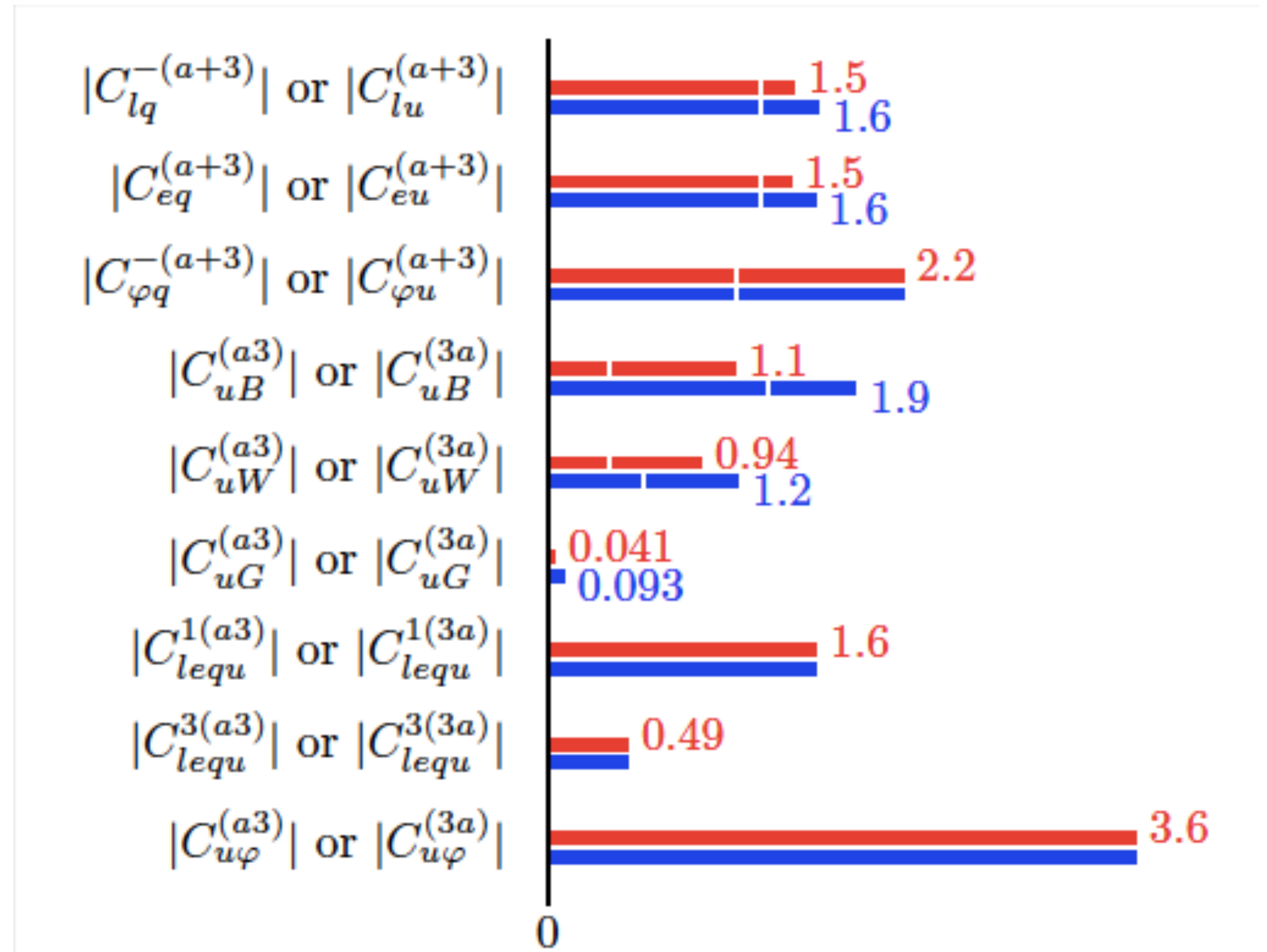
For the sake of illustration and simplicity, we only consider the most constraining observables. This suffices to set significant bounds on all two-quark operators as well as on a subset of the two-quark–two-lepton ones.

TOP FCNC AT NLO : GLOBAL FIT

[Durieux, FM, Zhang 2014]







First proof of principle that a complete global fitting strategy in a self-contained sector of the top EFT is possible with the available measurements. The red (blue) are for 1st (2nd) generation. Ticks = one on at the time.

GOING NLO: THE CHROMO MAGNETIC OP

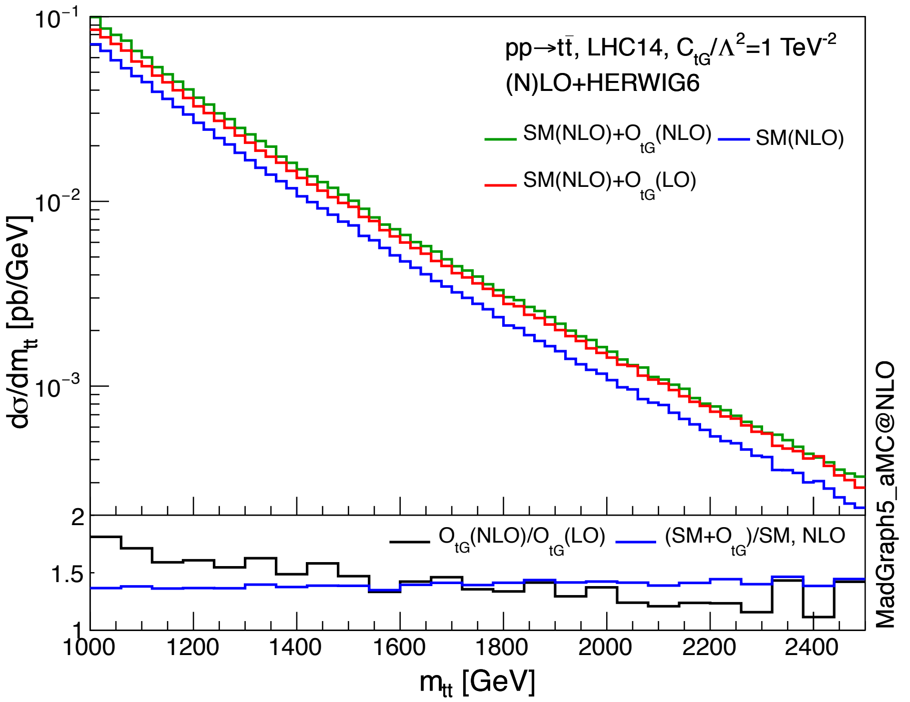
[Franzosi and Zhang, 2015]

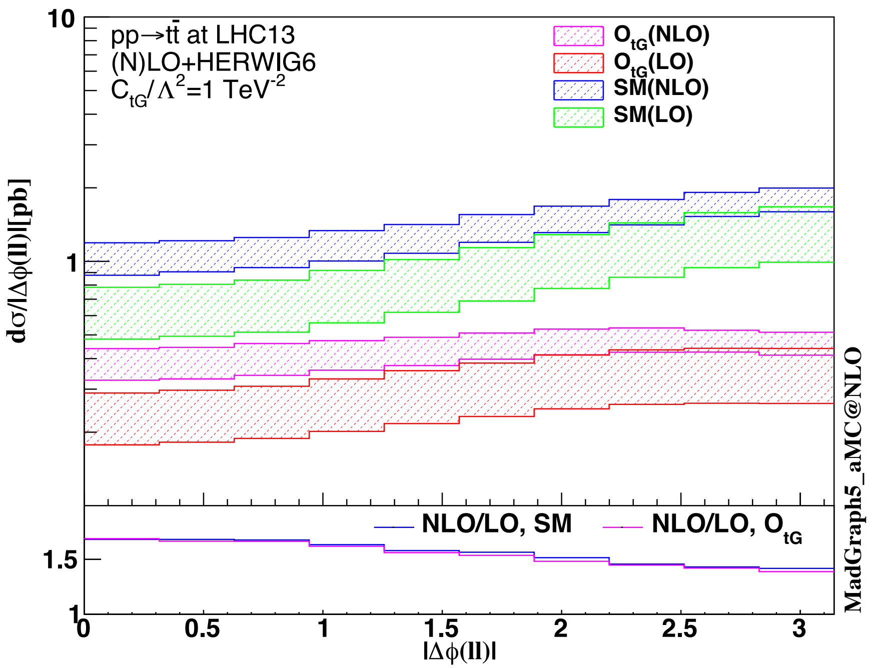
Recent analysis at NLO in QCD

$$\sigma = \sigma_{\rm SM} + \frac{C_{tG}}{\Lambda^2}\beta_1 + \left(\frac{C_{tG}}{\Lambda^2}\right)^2 \beta_2$$

β_1	LO [pb TeV^2]	NLO [pb TeV^2]	K factor
Tevatron	$1.61^{+0.66}_{-0.43}$ $(+41\%)$ (-27%)	$1.810^{+0.073}_{-0.197}$ $(+4.05\%)$ (-10.88%)	1.12
LHC8	$50.7^{+17.3}_{-12.4}$ $(+34\%)$ (-25%)	$72.62^{+9.26}_{-10.53}$ $(+12.7\%)$ (-14.5%)	1.43
LHC13	$161.6^{+48.0}_{-36.2}$ $(+29.7\%)$ (-22.4%)	$239.5^{+29.0}_{-31.8}$ $(+12.1\%)$ (-13.3%)	1.48
LHC14	$191.3^{+55.6}_{-42.2}$ $(+29.0\%)$ (-22.0%)	$283.0^{+33.6}_{-36.9}$ $(+11.9\%)$ (-13.1%)	1.48

β_2	LO [pb TeV^4]	NLO [pb TeV^4]
Tevatron	0.156	0.158
LHC8	8.94	11.8
LHC13	30.0	43.2
LHC14	35.7	51.6





Limits on ctG from LHC8

	LO [TeV^{-2}]	NLO [TeV^{-2}]
Tevatron	[-0.33, 0.75]	[-0.32, 0.73]
LHC8	[-0.56, 0.41]	[-0.42, 0.30]
LHC14	[-0.56, 0.61]	[-0.39, 0.43]

GOING NLO : TTZ AND TTY AT NLO

[Rontsch and Shulze, 2014, 2015]

$$\mathcal{L}_{t\bar{t}Z} = \mathrm{i}e\bar{u}(p_t)\left[\gamma^\mu(C_{1,V}+\gamma_5 C_{1,A}) + \frac{\mathrm{i}\sigma_{\mu\nu}q_\nu}{M_Z}(C_{2,V}+\mathrm{i}\gamma_5 C_{2,A})\right]v(p_{\bar{t}})Z_\mu$$

$$\mathcal{L}_{\gamma tt} = -eQ_t\bar{t}\,\gamma^\mu t\;A_\mu - e\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\,(d_V^\gamma + id_A^\gamma\gamma_5)\,t\;A_\mu$$

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

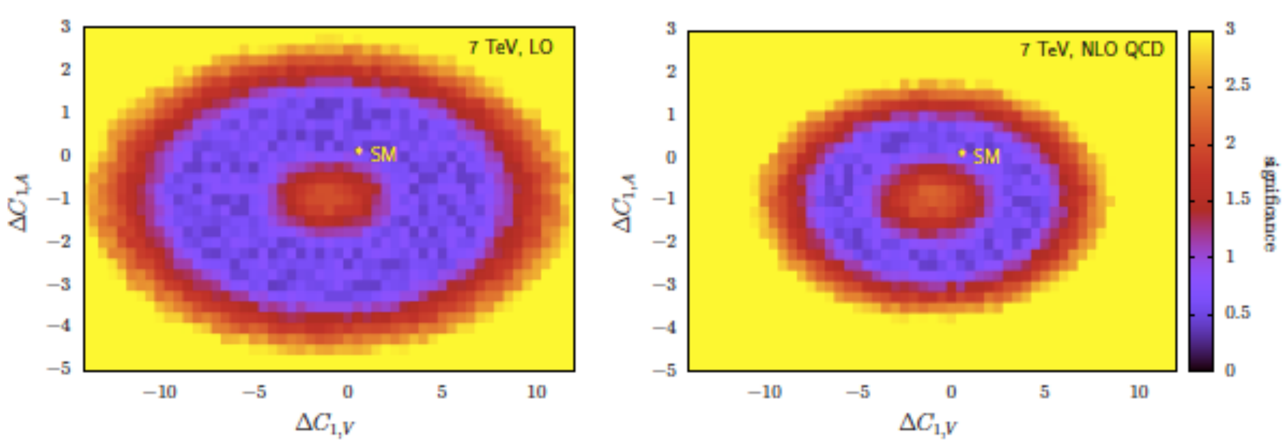
$$O_{\varphi Q}^{(1)} = iy_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu\varphi\right)(\bar{Q}\gamma^\mu Q)$$

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

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

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

- Top couplings not constrained by LEPI Z decays.
- the photon dipole coefficients depend on OtW and tB
- Photon and Z are related above the EWSB.
- Photon couplings enter in the off-shell TT$\ell\ell$

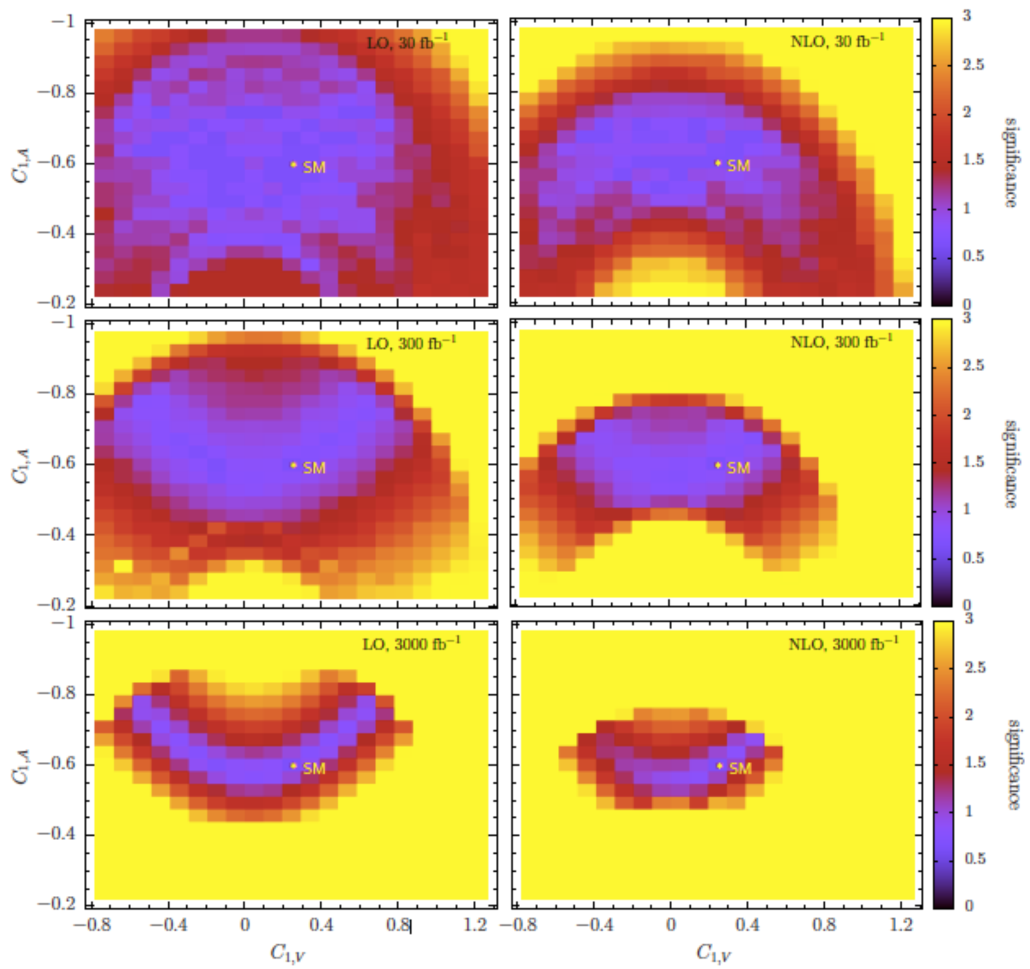


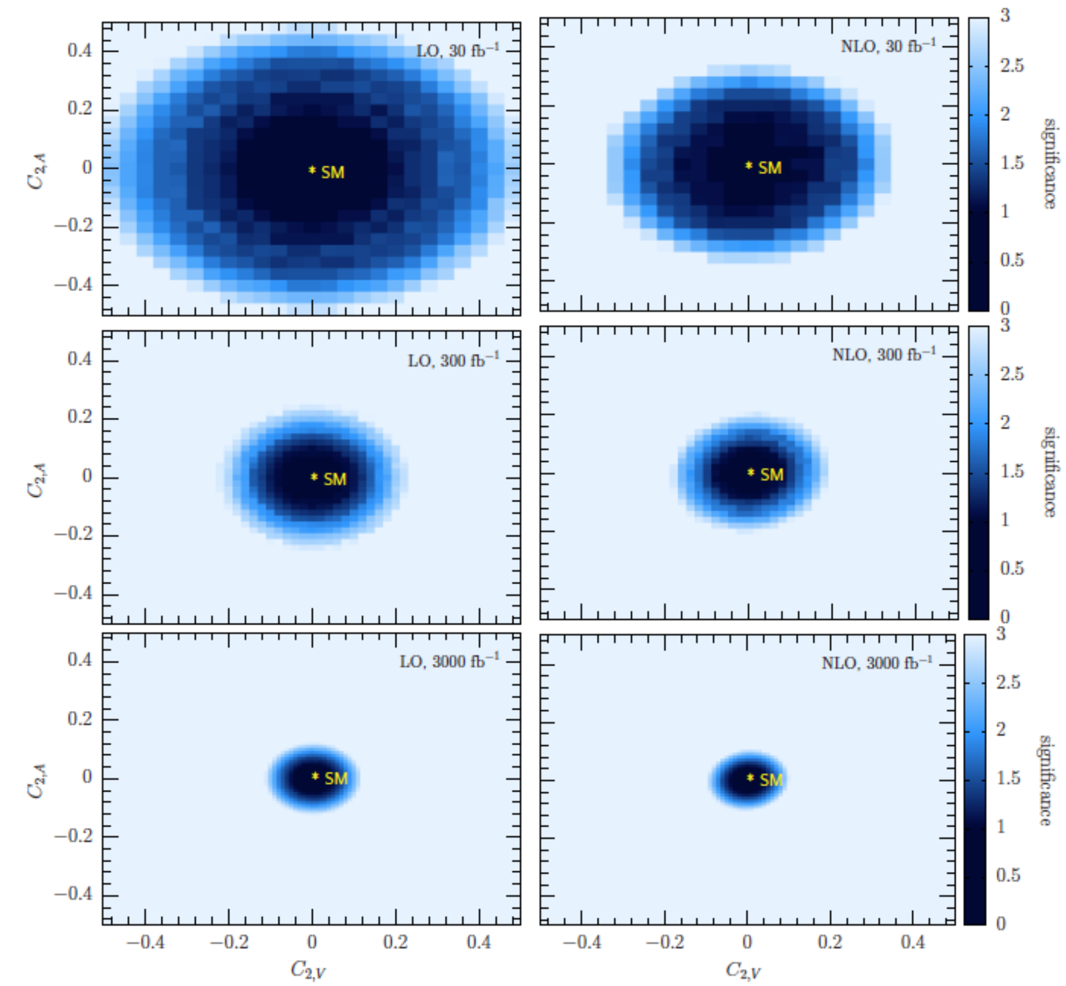
- Constraints from the 7 TeV Run

$$-8 \lesssim \Delta C_{1,\mathrm{V}} \lesssim 7 \text{ and } -3 \lesssim \Delta C_{1,\mathrm{A}} \lesssim 1$$

GOING NLO : TTZ AND TTY AT NLO

[Rontsch and Shulze, 2014, 2015]





HOWEVER MORE WORK NEEDED:

- IN ESSENCE STILL AN ANOMALOUS COUPLING APPROACH.
- GLOBAL ANALYSIS CONSIDERING TTZ AND TTY NEEDED.
- CONSTRAINS FROM LEP EW OBSERVABLES [Mebane et al, 2013]
- ALSO THE CHROMOMAGNETIC OPERATOR CONTRIBUTES TO TTZ AND TTY. GIVEN THE PRESENT CONSTRAINTS IT IS QUITE IMPORTANT.
- FOUR-FERMION OPERATORS ENTER IN THE OFF-SHELL TT$\ell\ell$

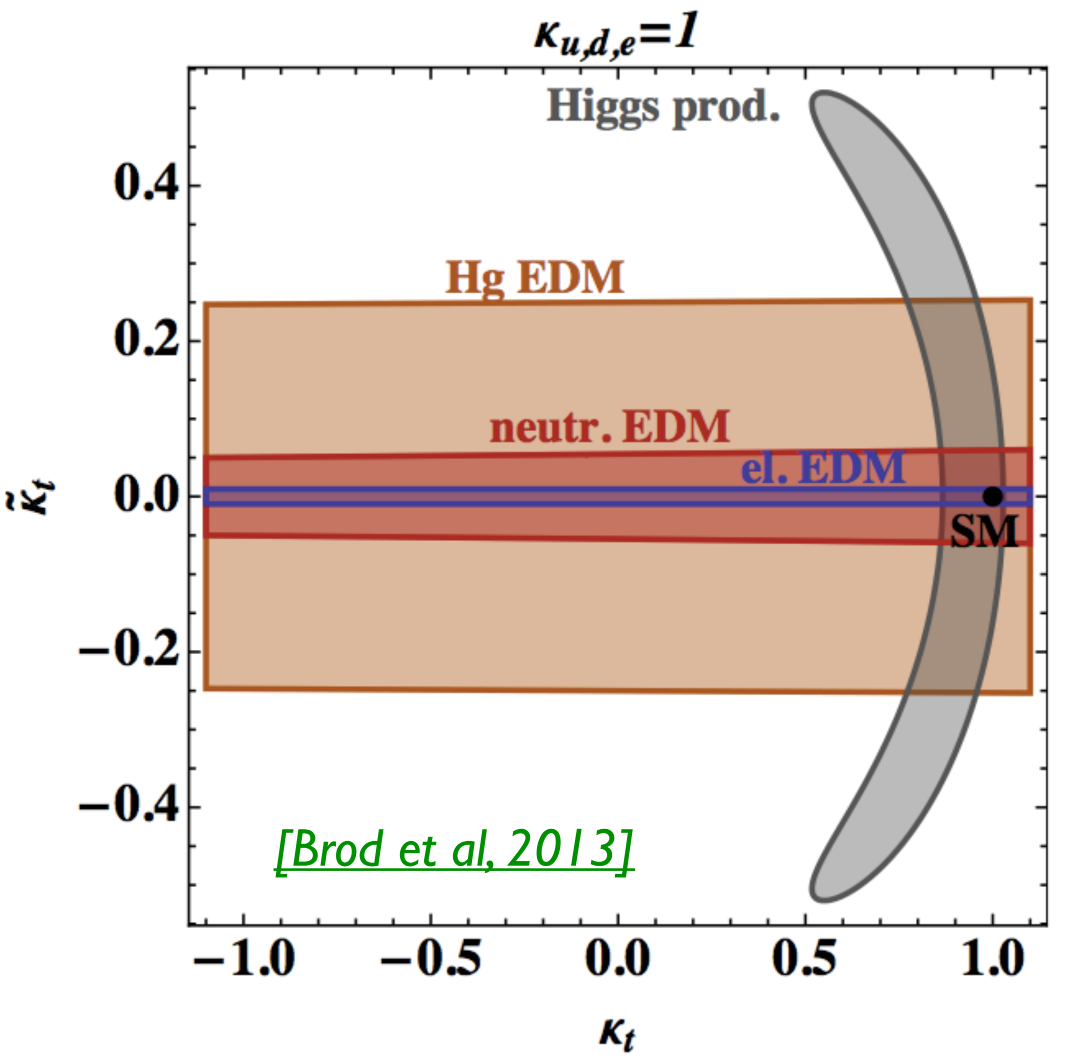
GOING NLO : CP-VIOLATION IN TTH COUPLING

$$\mathcal{L} = y_t(H\bar{Q}_L)t_R + c_{Hy}H^\dagger H(H\bar{Q}_L)t_R$$
$$= m_t\bar{\psi}_t\psi_t + \bar{\psi}_t(\mathrm{Re}\,c_{Hy} + i\mathrm{Im}\,c_{Hy}\gamma_5)\psi_t h$$

CP violation implies Re AND Im non-zero. Inclusive gg production only constrains [$\mathrm{Re}(c_{HY})^2 + 9/4\ \mathrm{Im}(c_{HY})^2$].

Indirect constraints from e-EDM very strong, yet rely on assuming

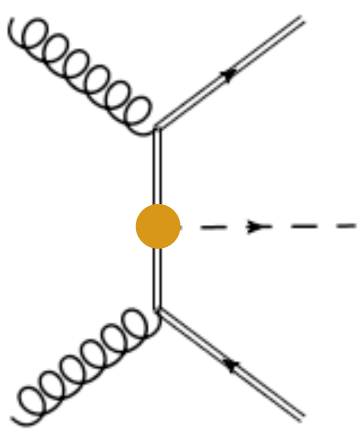
- SM couplings for the light fermions.
- no other states present in the spectrum



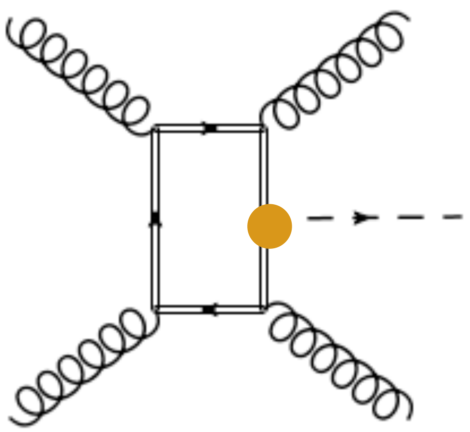
GOING NLO : CP-VIOLATION IN TTH COUPLING

$$\mathcal{L} = y_t(H\bar{Q}_L)t_R + c_{Hy}H^\dagger H(H\bar{Q}_L)t_R$$
$$= m_t\bar{\psi}_t\psi_t + \bar{\psi}_t(\mathrm{Re}\,c_{Hy} + i\mathrm{Im}\,c_{Hy}\gamma_5)\psi_t h$$

THERE ARE WAYS OF DIRECTLY ACCESSING PRESENCE OF CP-MIXING IN TOP-HIGGS INTERACTIONS AT THE LHC:



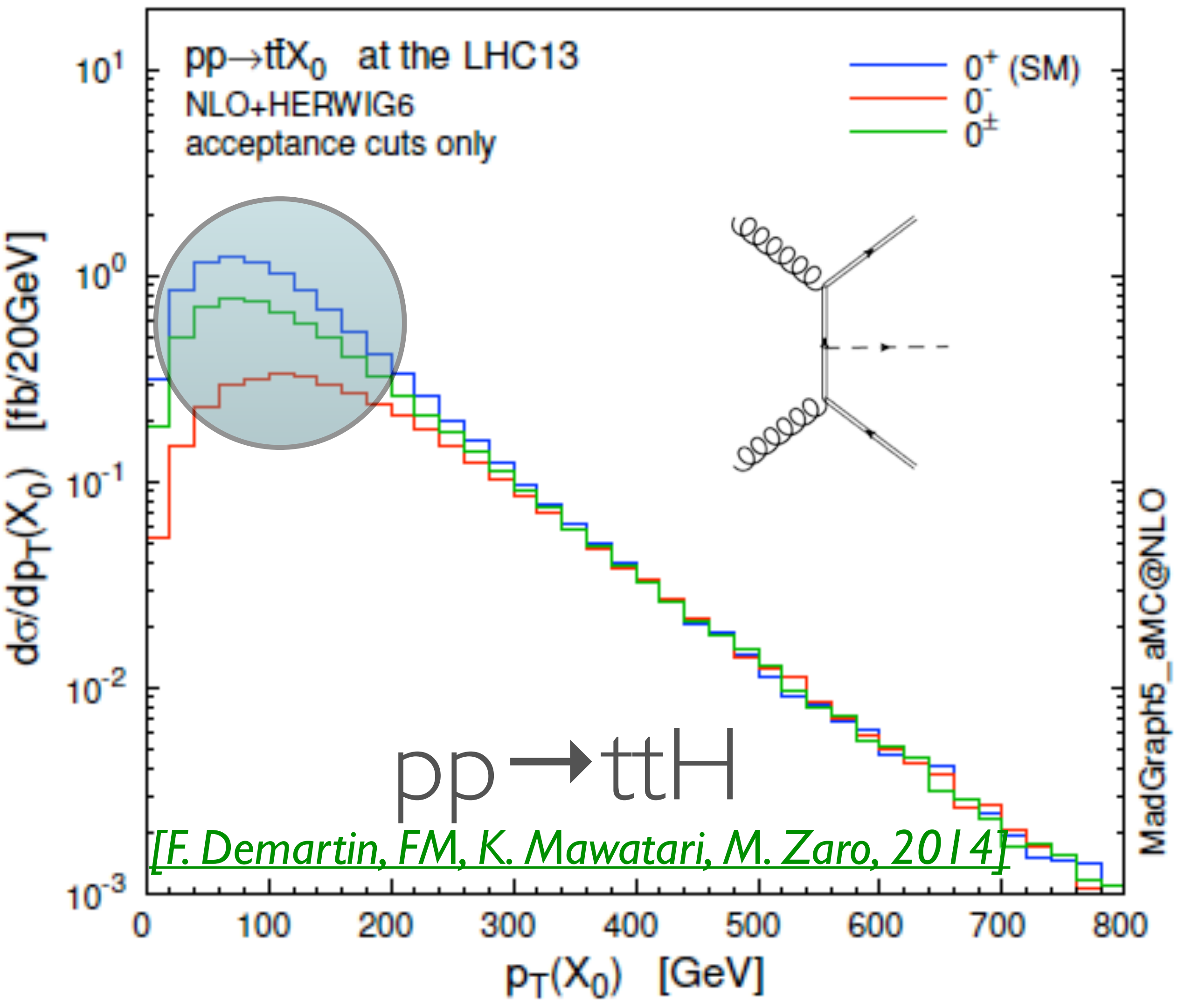
pp→ttH



pp→Hjj

GOING NLO : CP-VIOLATION IN TTH COUPLING

$$\mathcal{L} = y_t(H\bar{Q}_L)t_R + c_{Hy}H^\dagger H(H\bar{Q}_L)t_R$$
$$= m_t\bar{\psi}_t\psi_t + \bar{\psi}_t(\mathrm{Re}\,c_{Hy} + i\mathrm{Im}\,c_{Hy}\gamma_5)\psi_t h$$



At LO the two contributions add up incoherently. At NLO in QCD CP-even and CP-odd amplitudes interfere.

At threshold large differences appear.

At high Higgs pT shapes and normalization exactly equal (mt effects become subdominant)

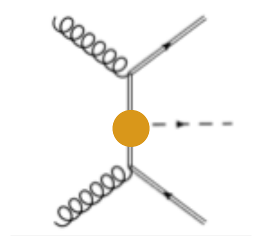
⇒ boosted analyses insensitive to CP?

Angular variables between the daughters of the top are sensitive to the CP-mixing.

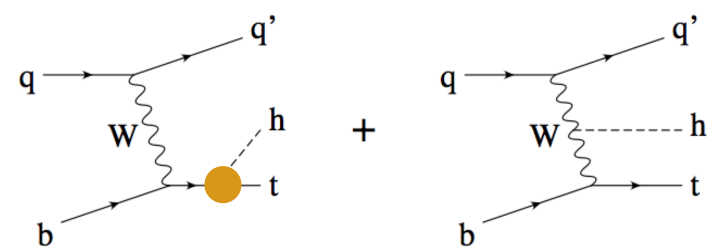
GOING NLO : CP-VIOLATION IN TTH COUPLING

It is interesting to compare how a phase in the top-Higgs coupling would change many of the processes relevant in Higgs phenomenology at the LHC:

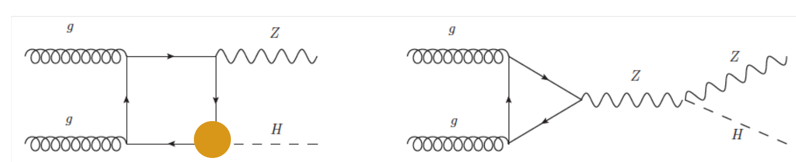
- pp → ttH



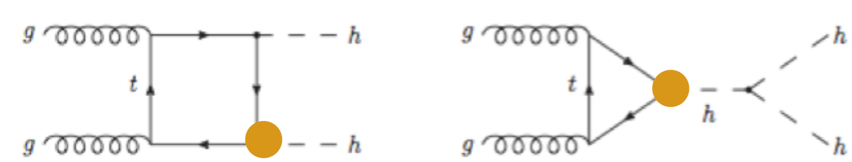
- pp → tHj



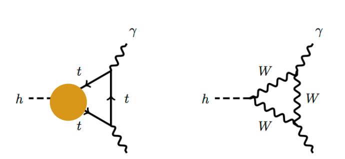
- gg → ZH

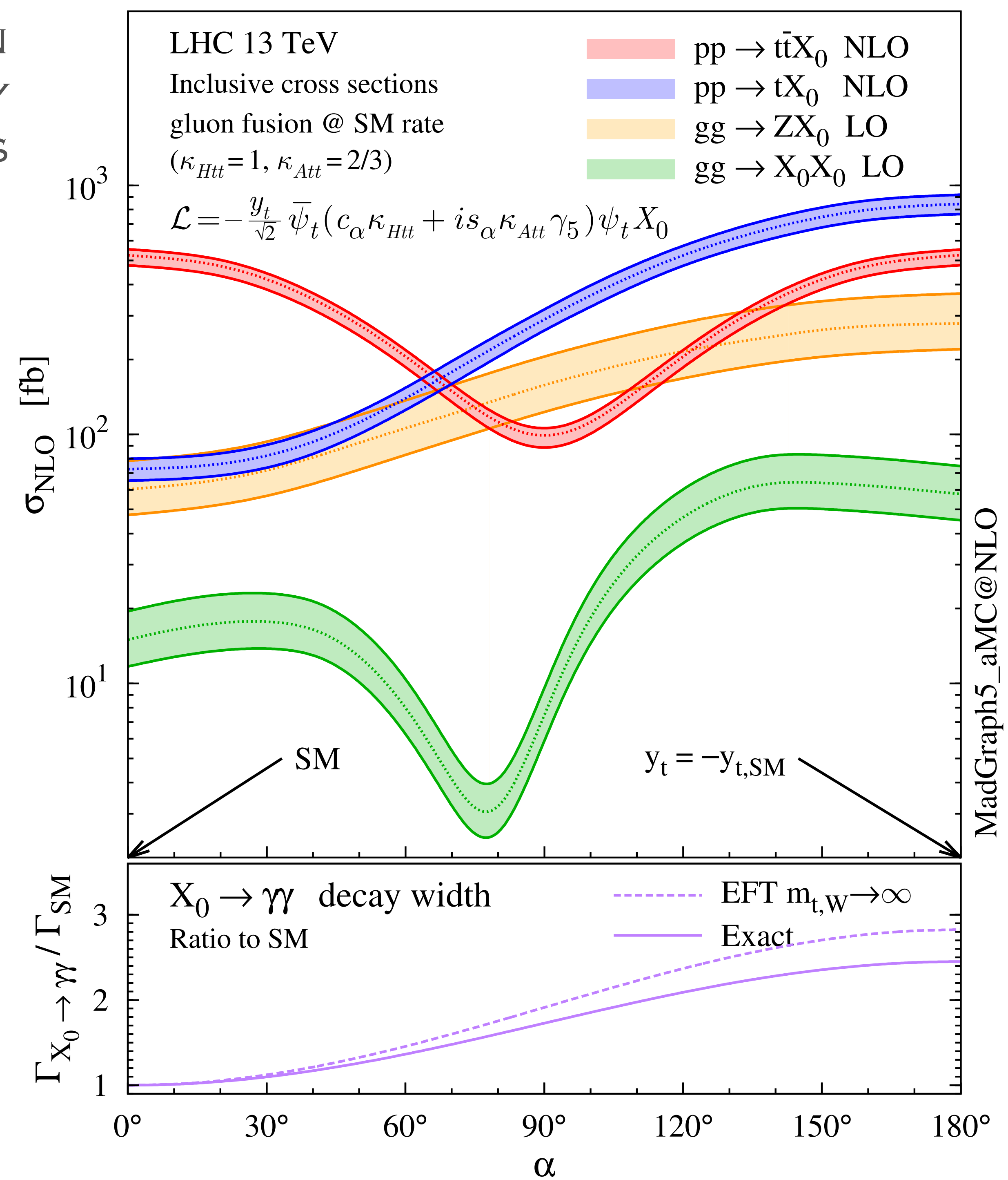


- gg → HH



- H → γγ





Towards a global fit at NLO

[Cen Zhang]

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	N		L	L				L		
$pp \to t\bar{q}$	N		L	L				L		
$pp \to tW$	L		L	L				N	N	N
$pp \to t\bar{t}$	L						N	L	L	L
$pp \to t\bar{t}\gamma$	L	L	L				N	L	L	L
$pp \to t\bar{t}Z$	L	L	L	L	L	L	N	L	L	L
$pp \to t\bar{t}h$	L						L	L	L	L
$gg \to H, H \to \gamma\gamma$	N						N			L

$O_G = g_s f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ and $O_{\varphi G} = g_s^2 \left(\varphi^\dagger \varphi\right) G_{\mu\nu}^A G^{A\mu\nu}$ are included because they mix with other top-quark operators and play a role in NLO calculations.

THE ROAD AHEAD

- The interpretation of most of the SM/Higgs/top measurements analyses can be recast in terms of an EFT. Yet the **implementation of a global approach/framework is needed**. (Dedicated) differential measurements will also provide valuable information.

- the precision of the theoretical predictions for the dim=4 SM will keep to be improved, by including NNLO in QCD and NLO in EW corrections in a fully exclusive way. Predictions for **EFT at NLO** have started to become **available.**

- Proof of principle available of a global approach at NLO in QCD for FCNC top quark.

- Considerable work still to be done and constraining strategies need to be fully worked out/optimised.

NEW JOINT TH/EXP EFFORT!

Conclusions

- The discovery of a scalar boson has opened a new realm of possibilities for searching new physics and in particular in connection with the top quark
- The most beaten path for searching new physics at the LHC involve top-down (or simplified models) approach to detecting new resonances.
- **A complementary and far reaching approach is that of searching for new interactions employing an EFT framework.**
- Precision dim=6 SM measurements, in particular for top quark, can extend the reach of new physics searches at the LHC.