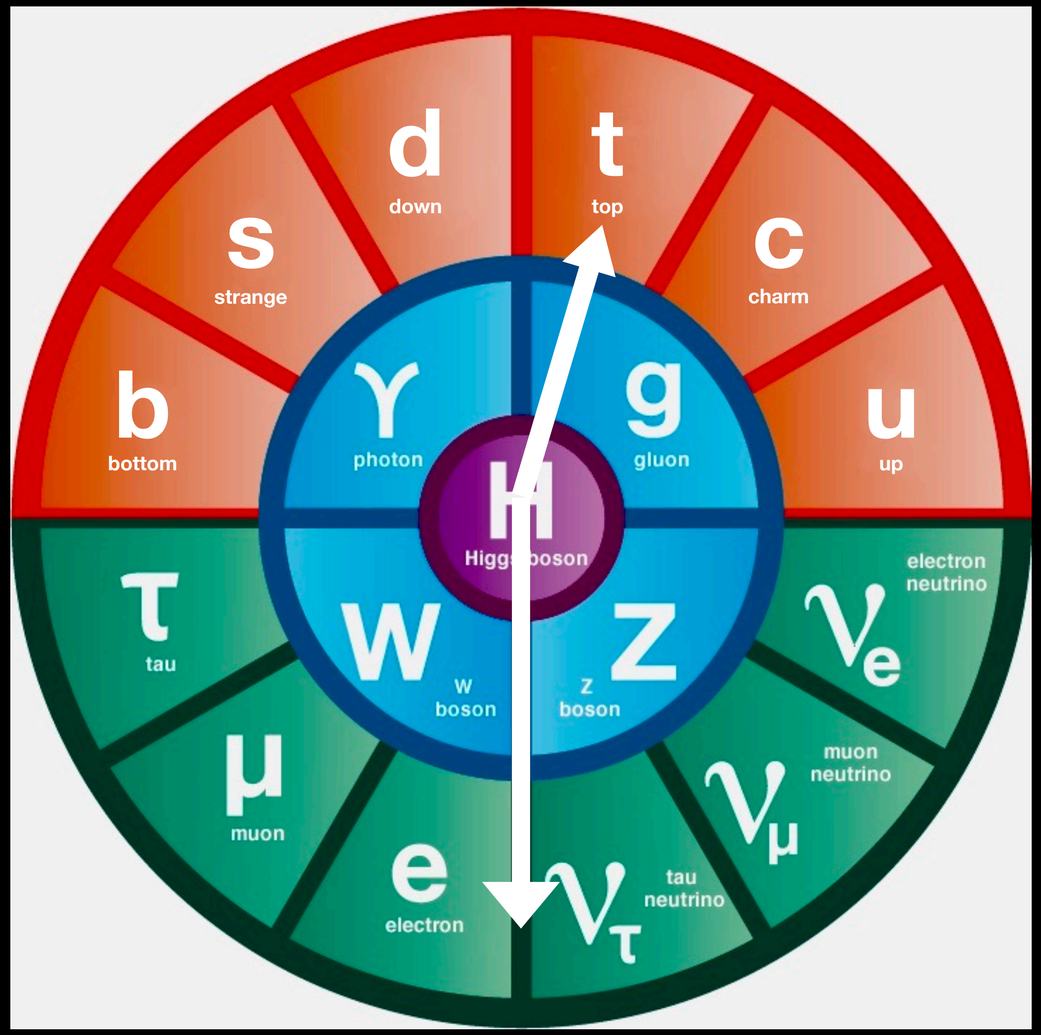
LHCP2020

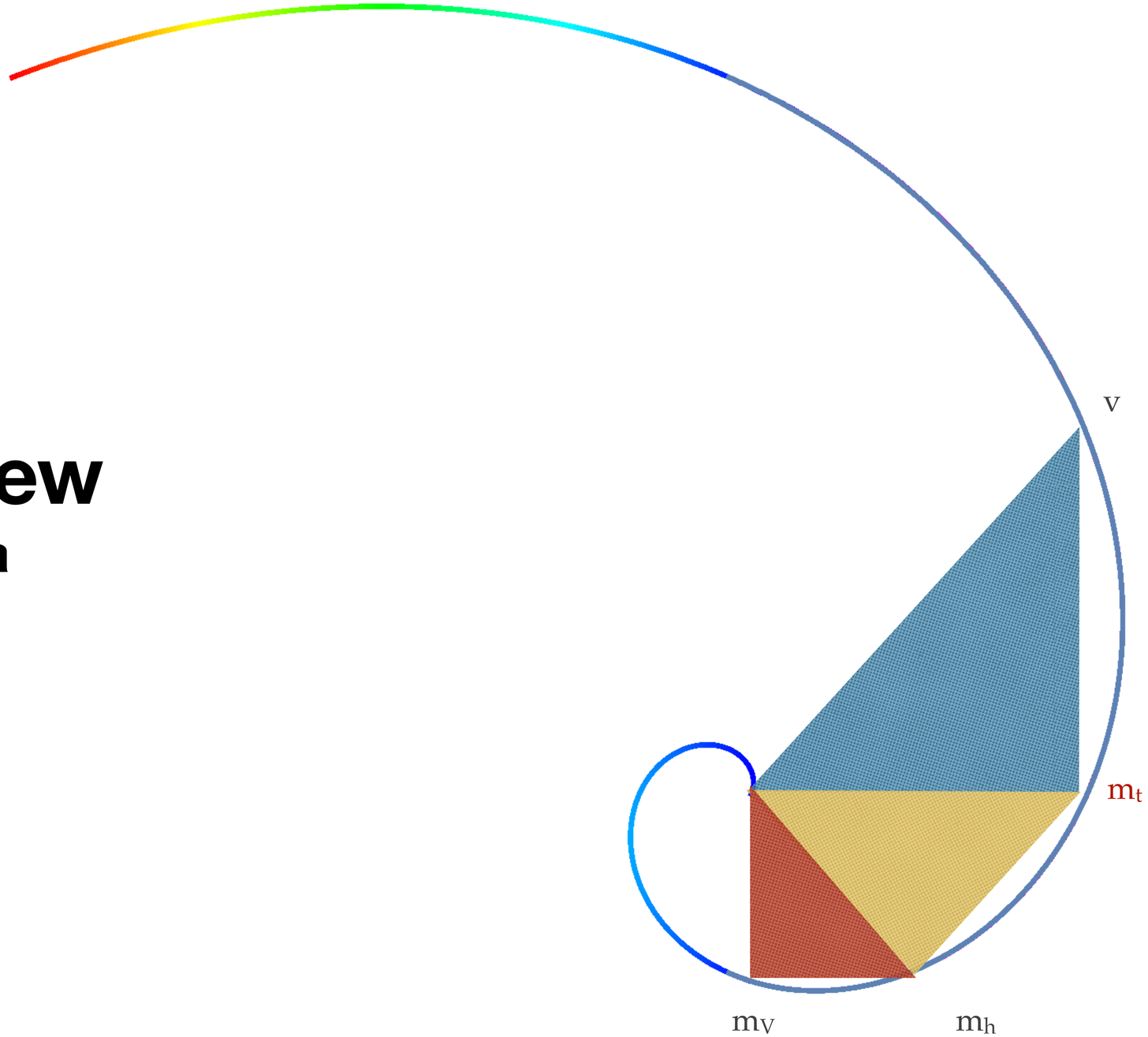


Tue 26 May at 12:30 : It’s top time!

Top-quark theory review

The inception of the precision era

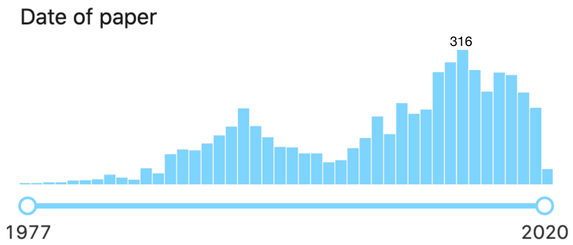
Fabio Maltoni
Università di Bologna
Université catholique de Louvain



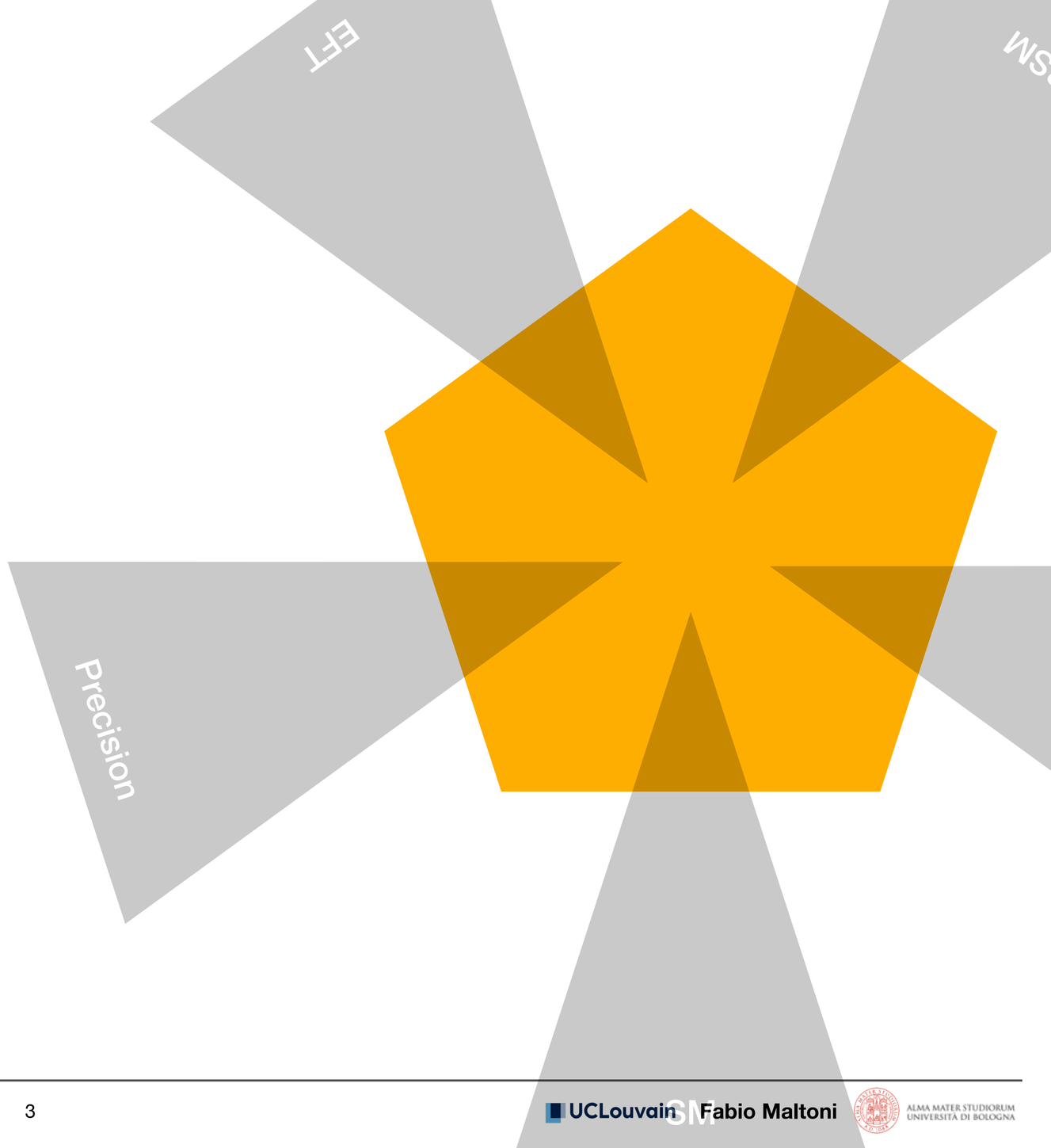
Top-quark physics

Introduction

- The top quark is one of the main influencers in the HEP community and has many followers.



- Its appeal resides on the many different ways it can be studied:
    - Precision SM properties
    - Coupling to new states
    - Explore new interactions



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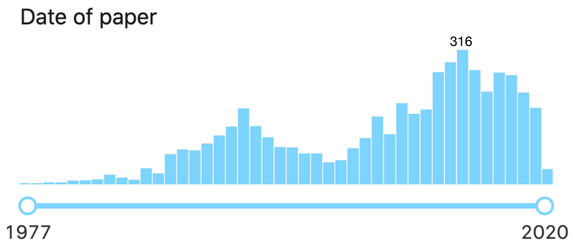

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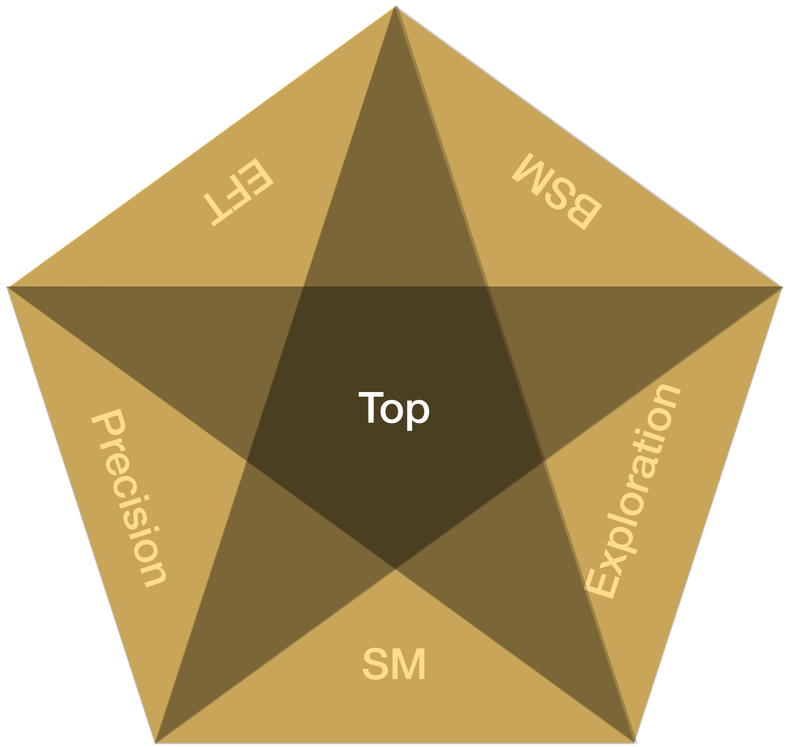


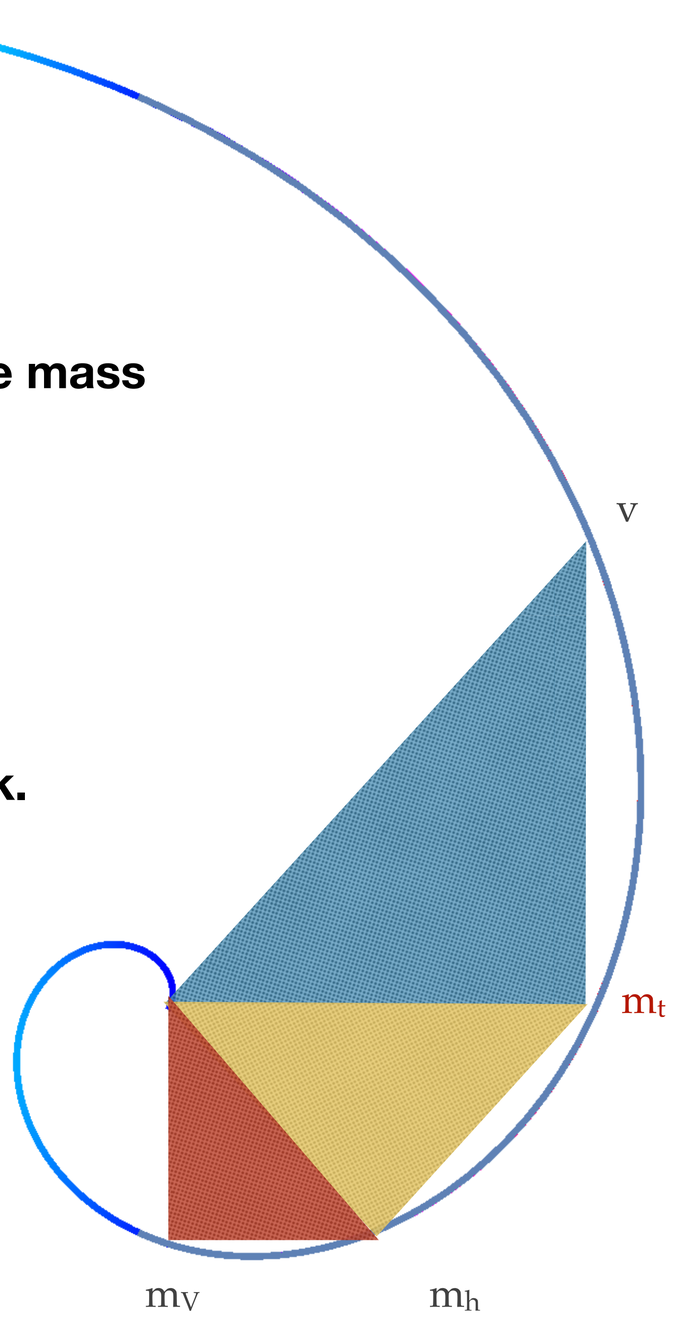
Top-quark physics essentials I

Properties

All of the unique phenomenology of the top quark ultimately originates from its **large mass** (with respect to the b and the other quarks)

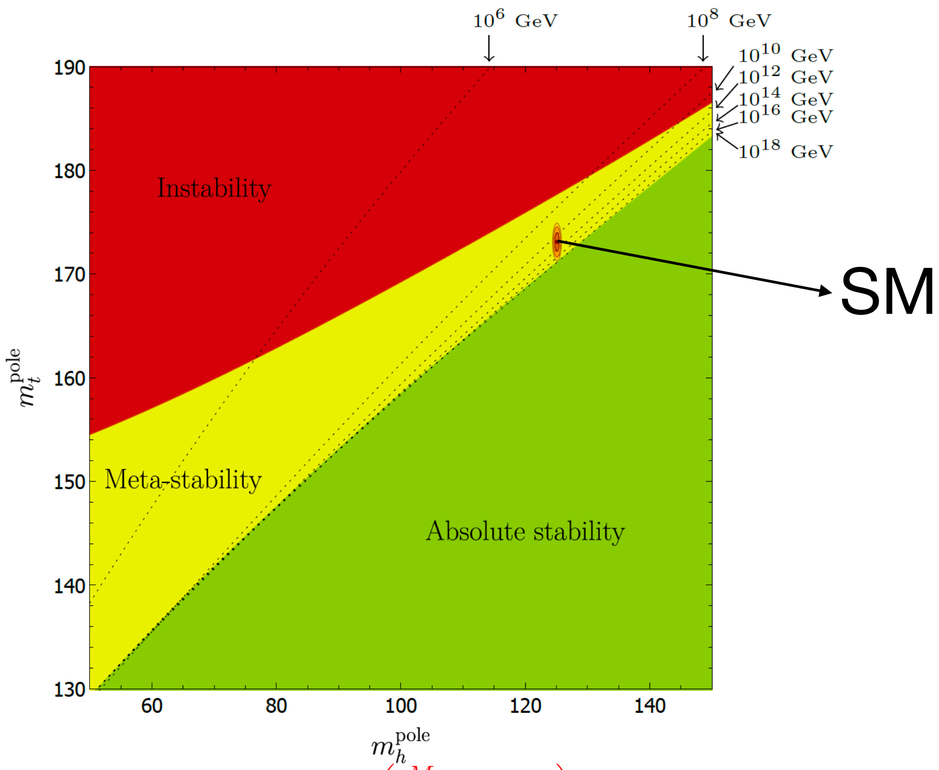
$$m_t = \frac{y_t}{\sqrt{2}} v = 172.9 \pm 0.4\,\mathrm{GeV} \Rightarrow y_t = 0.994 \pm 0.002$$

- The dominant part of the top mass comes from EWSB⇒ **The only natural quark.**
- It gives large corrections to EW observables and drives FCNC contributions.
- It points to a mass generation mechanism at low scales.
- It drives Higgs phenomenology and the Higgs potential at high scales.



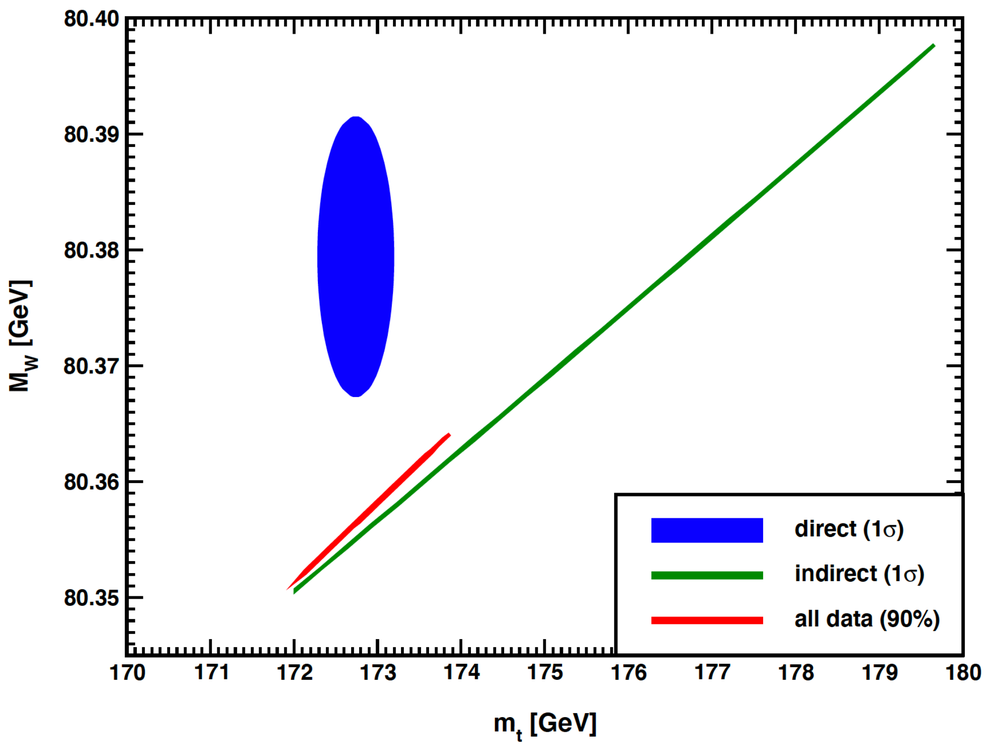
Top-quark mass

[Hoang, 2004.12915][Ravasio, 1810.10931][Beneke et al. 1605.03609]



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

[Andreassen et al. 1707.08124]

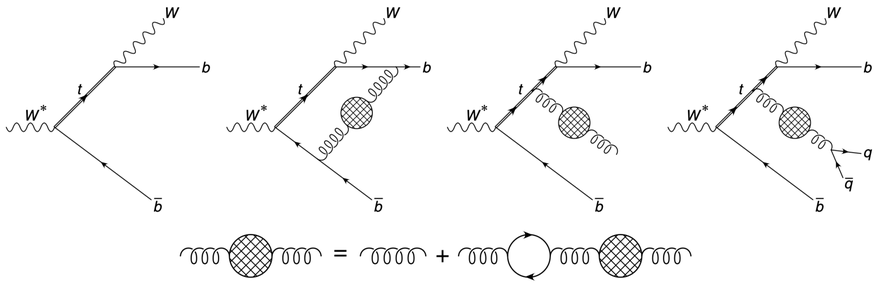


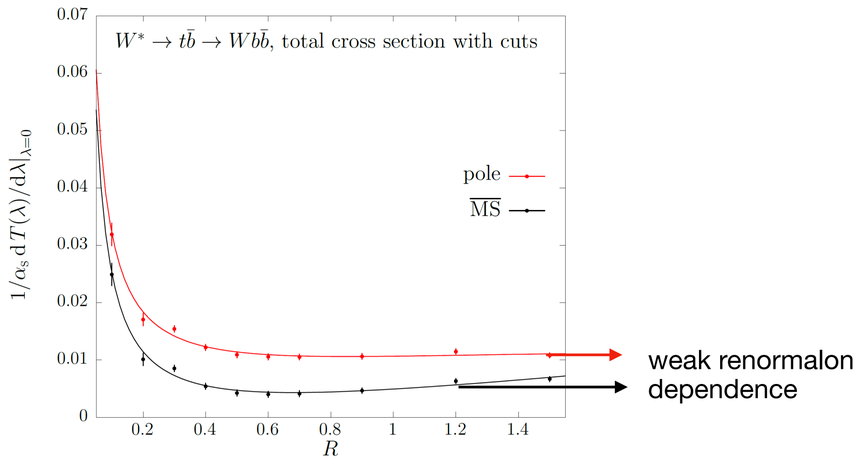
[PDG 2019]

Top-quark mass

[Hoang, 2004.12915][Ravasio, 1810.10931][Beneke et al. 1605.03609]

- m_t^{pole} is the goal of the direct measurement. Being colored the pole mass is an ambiguous quantity. Non-perturbative effects estimated via renormalon computations. The renormalon ambiguity associated to the pole mass is relatively small, order 100 MeV. However the ambiguity depends on the observable used (e.g. broad jets, smaller effects).





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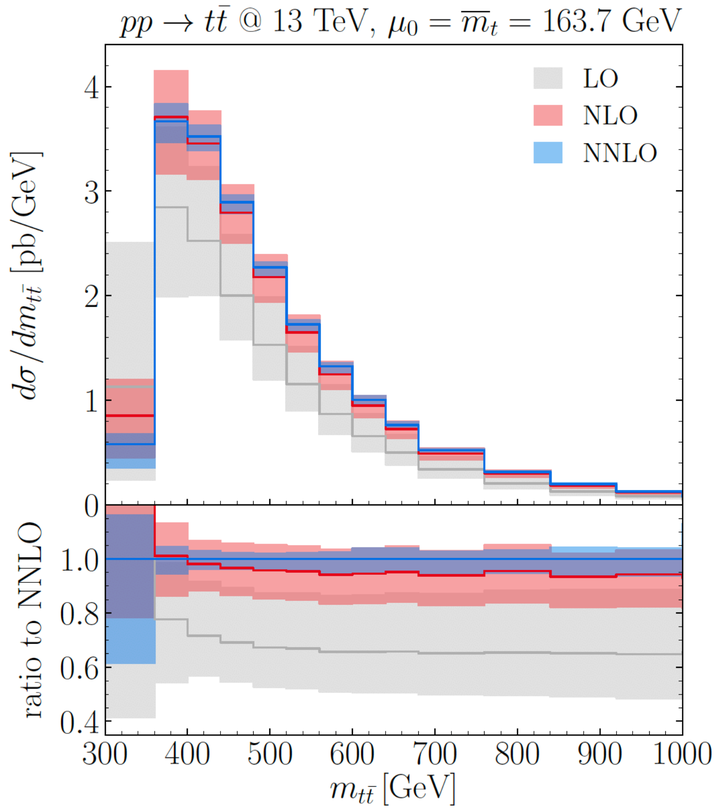
- $m_t^{\overline{\text{MS}}}$ short distance parameter that can be extracted from other top-related measurements. Other short distances versions exist that are tailored to specific observables.



[Catani et al. 2005.00557]

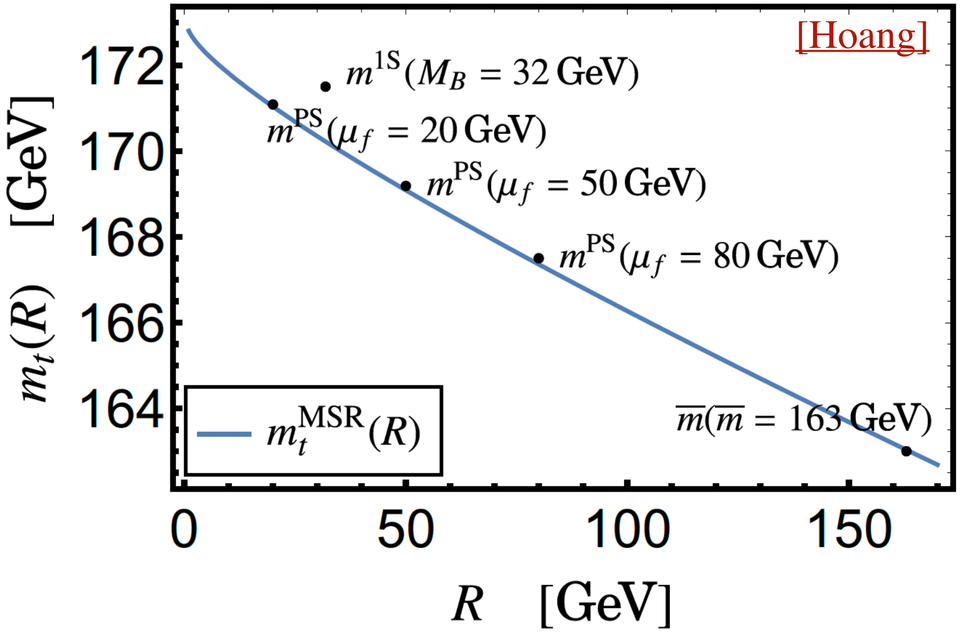
Top-quark mass

[Hoang, 2004.12915][Ravasio, 1810.10931][Beneke et al. 1605.03609]

- $m_t^{\rm pole}$ is the goal of the direct measurement. Being color the pole mass is an ambiguous quantity. Non-perturbat effects estimated via renormalon computations. T renormalon ambiguity associated to the pole mass relatively small, order 100 MeV. However the ambigu depends on the observable used (e.g. broad jets, smal effects).

$$m_t^{\rm MSR}(R) = m_t^0 \left\{ 1 + \left(\frac{\alpha_s(R)}{\pi}\right) \left[\frac{1}{\epsilon} + \ln(4\pi e^{-\gamma_E}) + A^{\rm fin}(m_t^0/R) \right] \right\} - R\left(\frac{\alpha_s(R)}{\pi}\right) A^{\rm fin}(1)$$

- $m_t^{\overline{\rm MS}}$ short distance parameter that can be extracted fr other top-related measurements. Other short distanc versions exist that are tailored to specific observables.

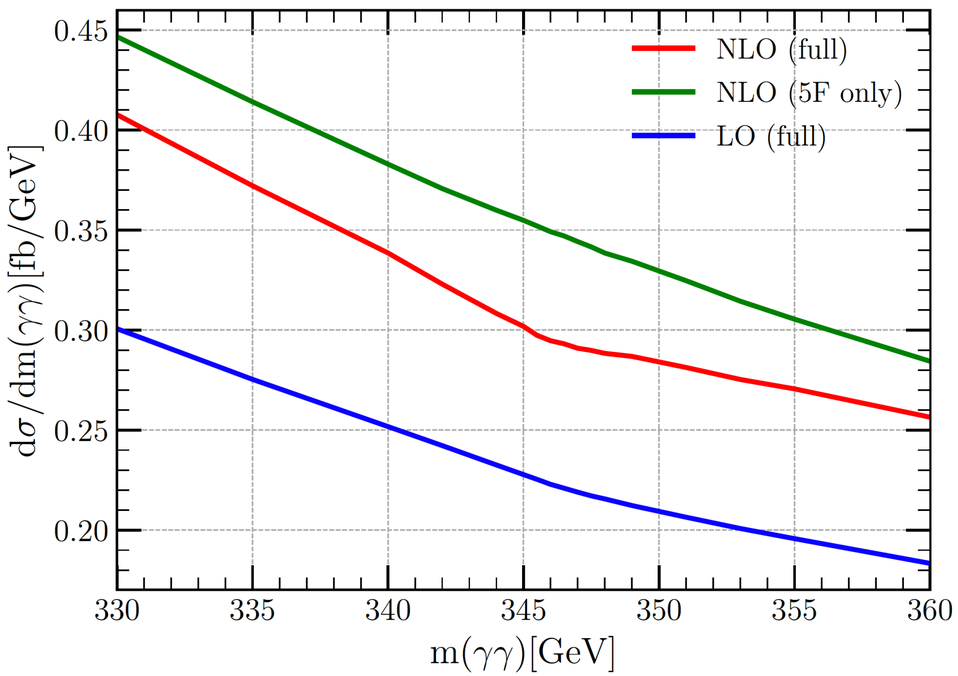


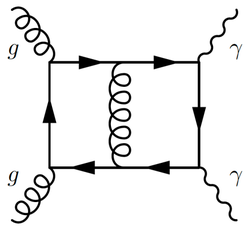
$$\frac{\rm d}{{\rm d}\ln R}\, m_t^{\rm MSR}(R) = -\frac{4}{3}\, R\left(\frac{\alpha_s(R)}{\pi}\right) + \ldots$$

Top-quark mass

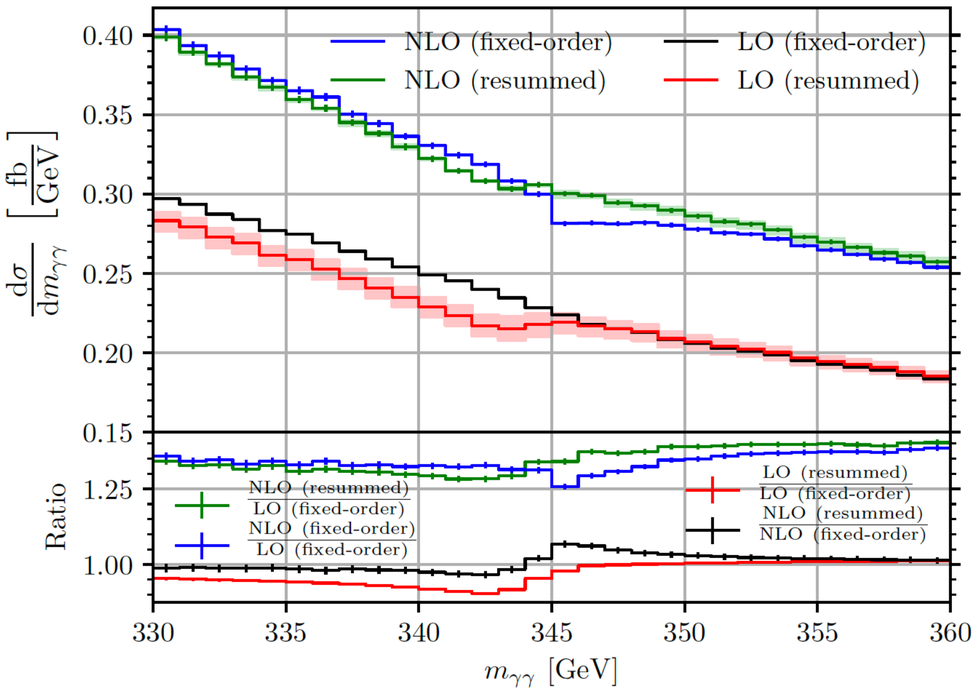
The possibility of accessing a short distance mass (~potential mass) from $gg \to \gamma\gamma$ at the LHC has been put forward by [Kawabata & Yokoya, 1607.00990]. NLO (two-loop) computations have followed.

[FM, Mandal, Zhao, 1812.08703]





[Chen et al., 1911.09314]



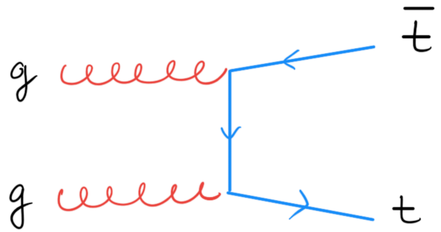
$$\mathrm{M}_t^{\mathrm{match}} \equiv \mathrm{M}_t + \mathcal{B}_t\, G(\vec{0};\mathcal{E}) - \mathrm{M}_{\mathrm{OC}}$$

Top-quark physics essentials II

Production at the LHC

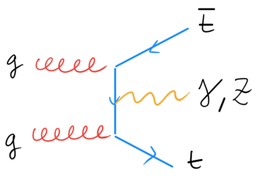
- It has a multifaceted social life: it goes to parties mostly in pair, very often alone, rarely accompanied by movie-stars and friends. At the LHC, the top is produced via:

10^3

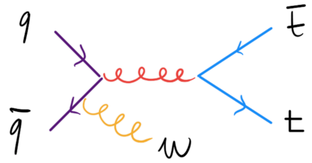


830 pb

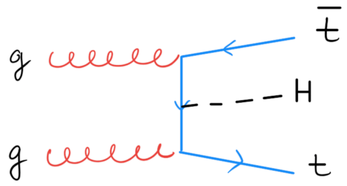
1



810 fb (ttZ)

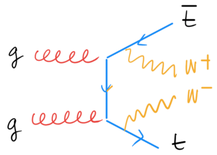


580 fb

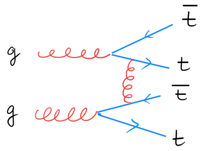


500 fb

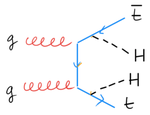
$10^{-2(3)}$



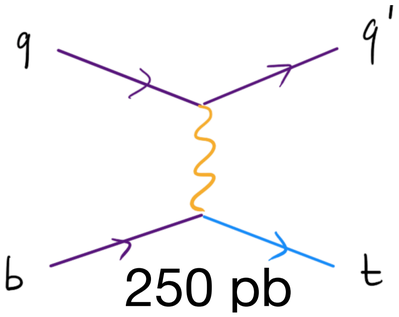
12 fb



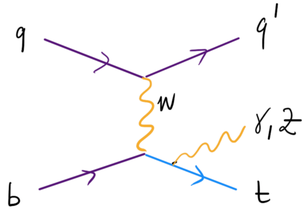
12 fb



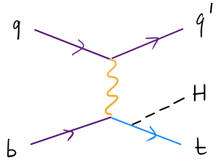
0.8 fb



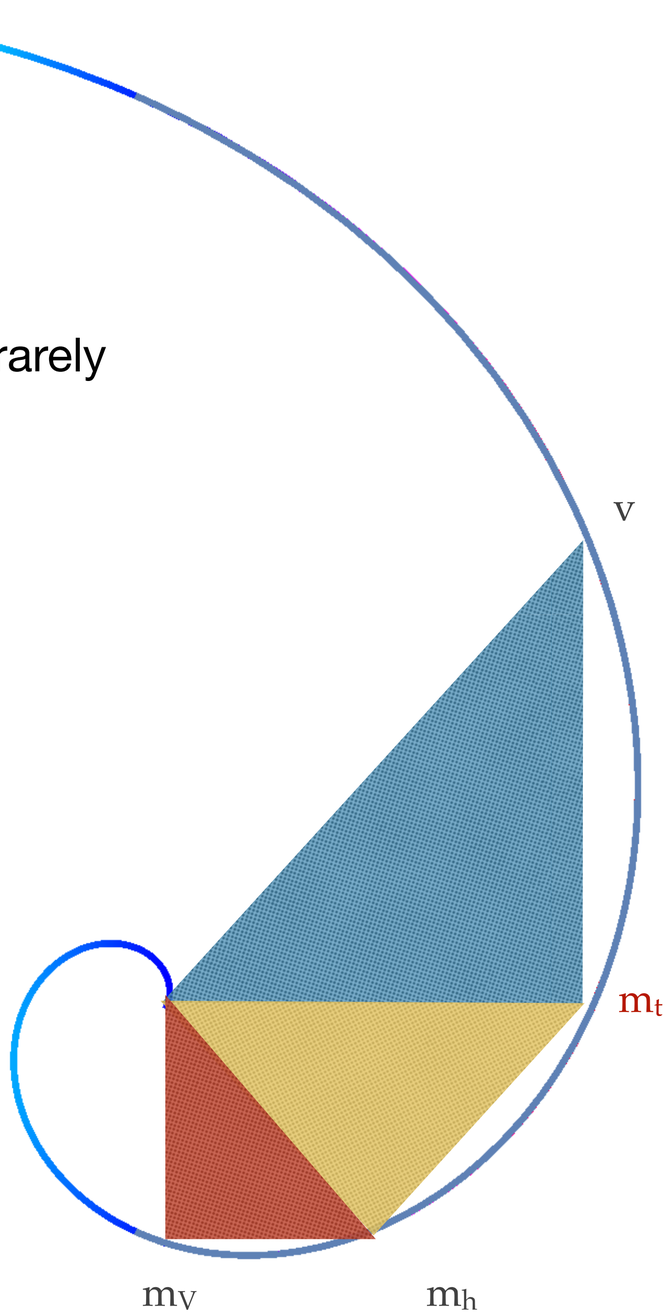
250 pb



840 fb (tZj)



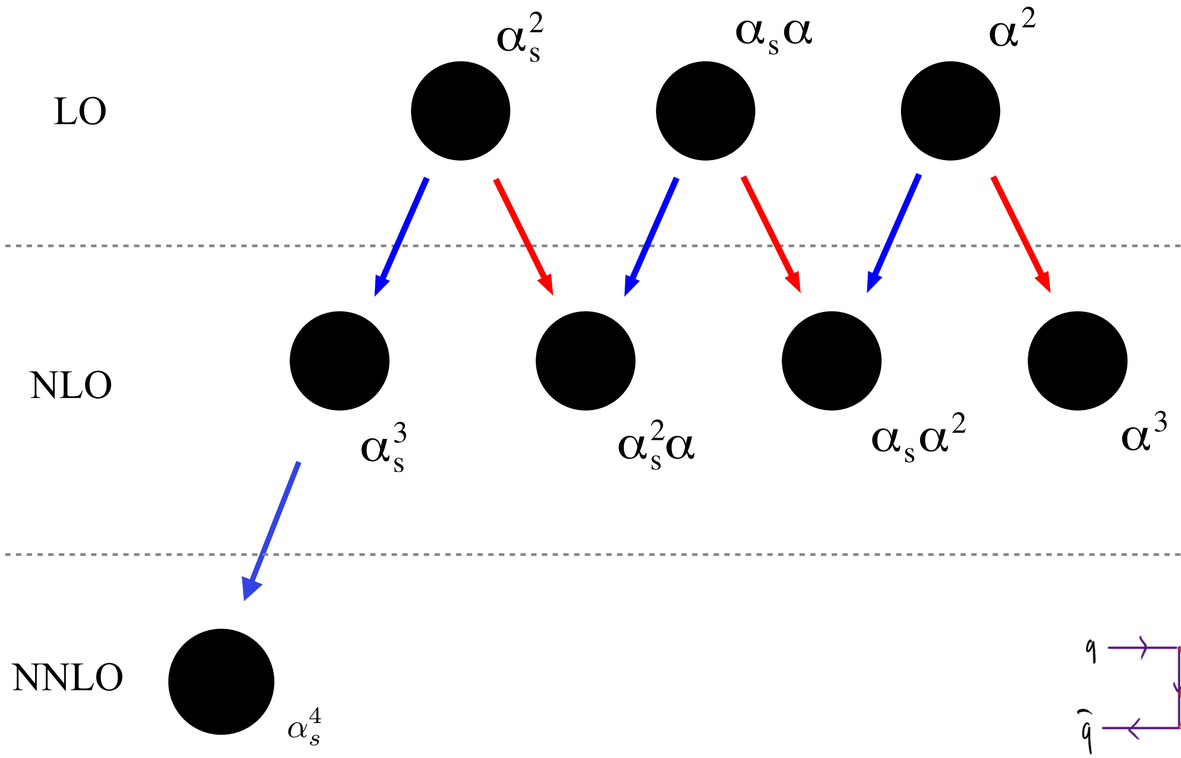
76 fb



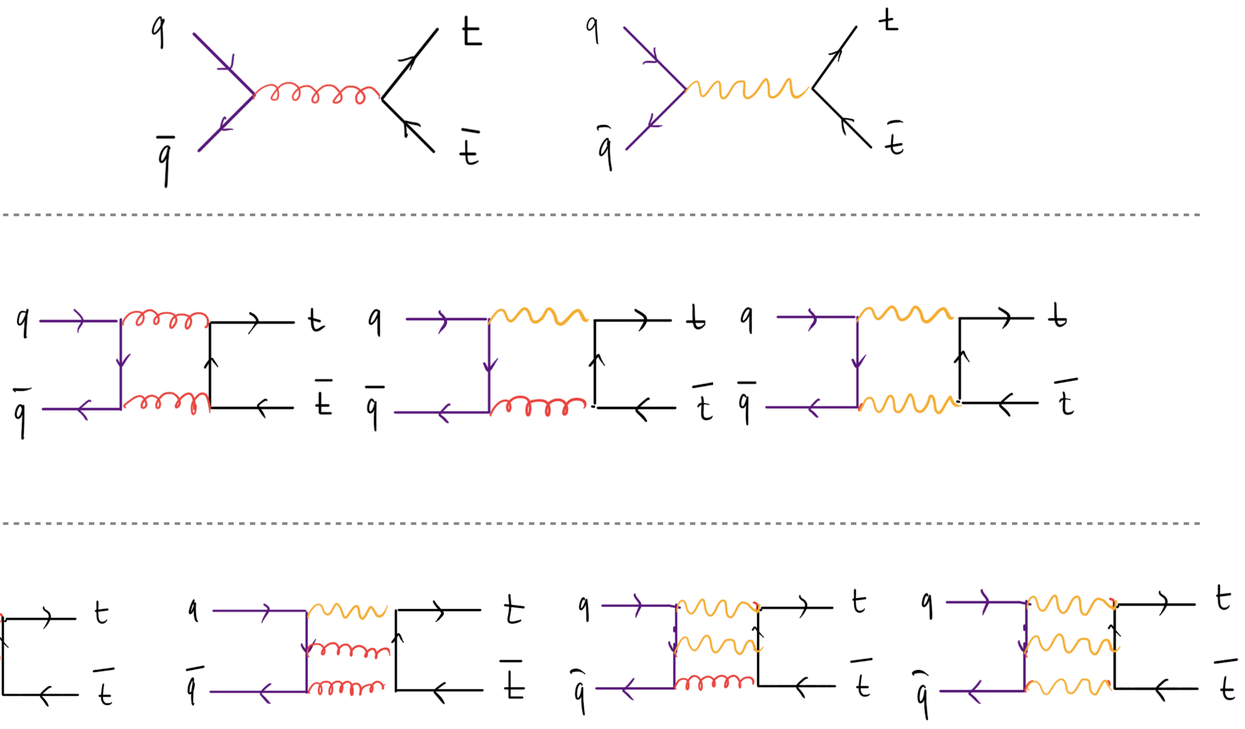
Precision SM Top Physics

Fixed-order computations

Cross section level



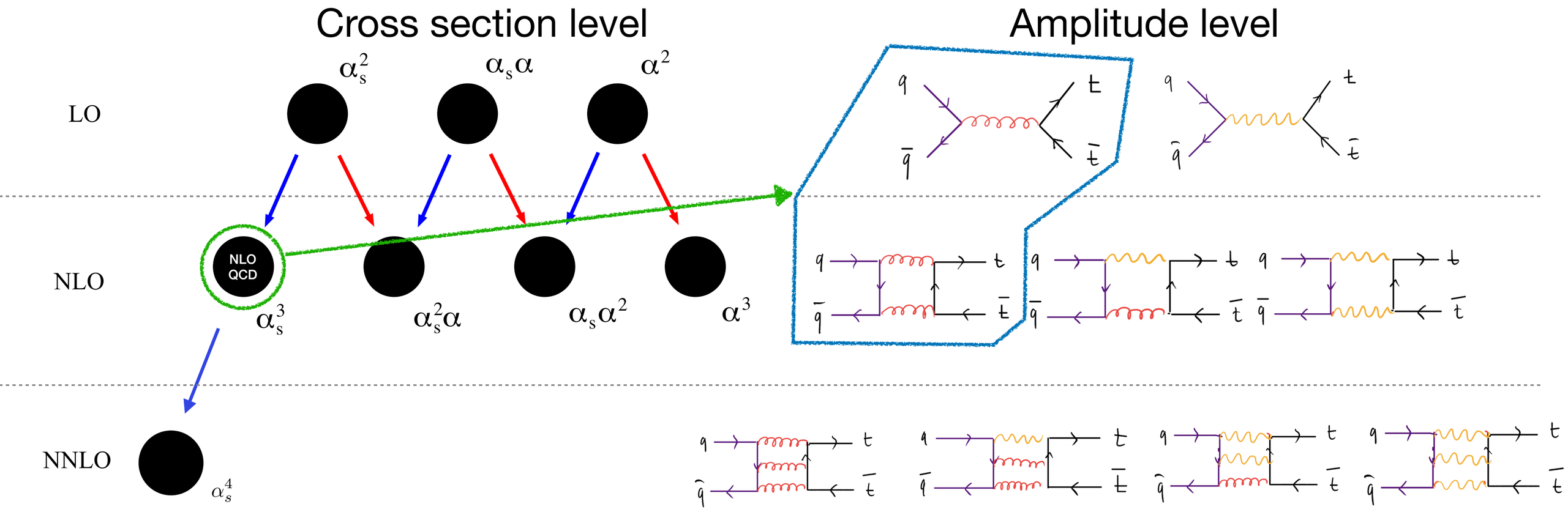
Amplitude level



$$\alpha_W/\alpha_S = 0.1$$

Precision SM Top Physics

Fixed-order computations



Precision SM Top Physics

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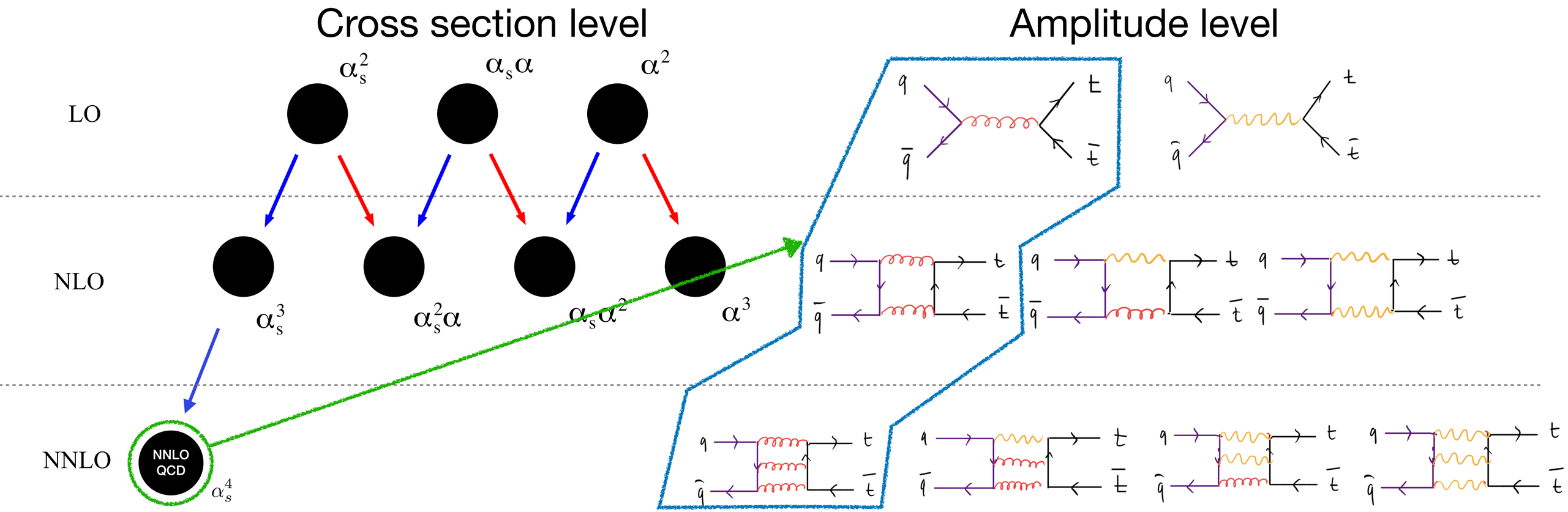

Precision SM Top Physics

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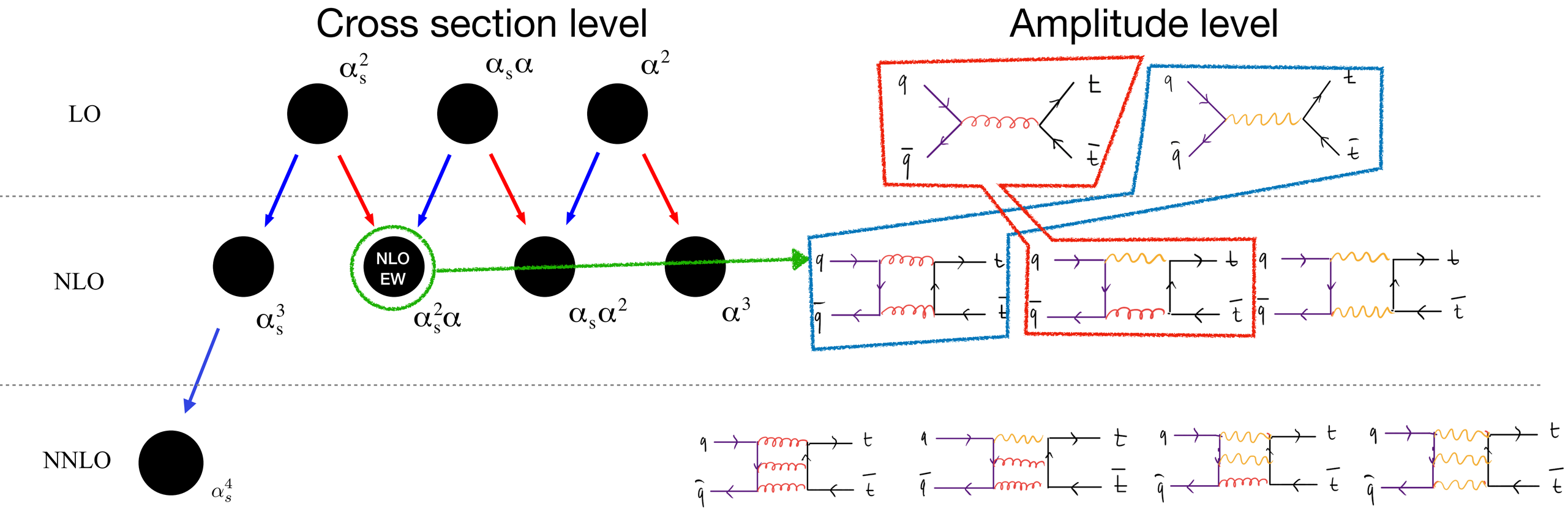
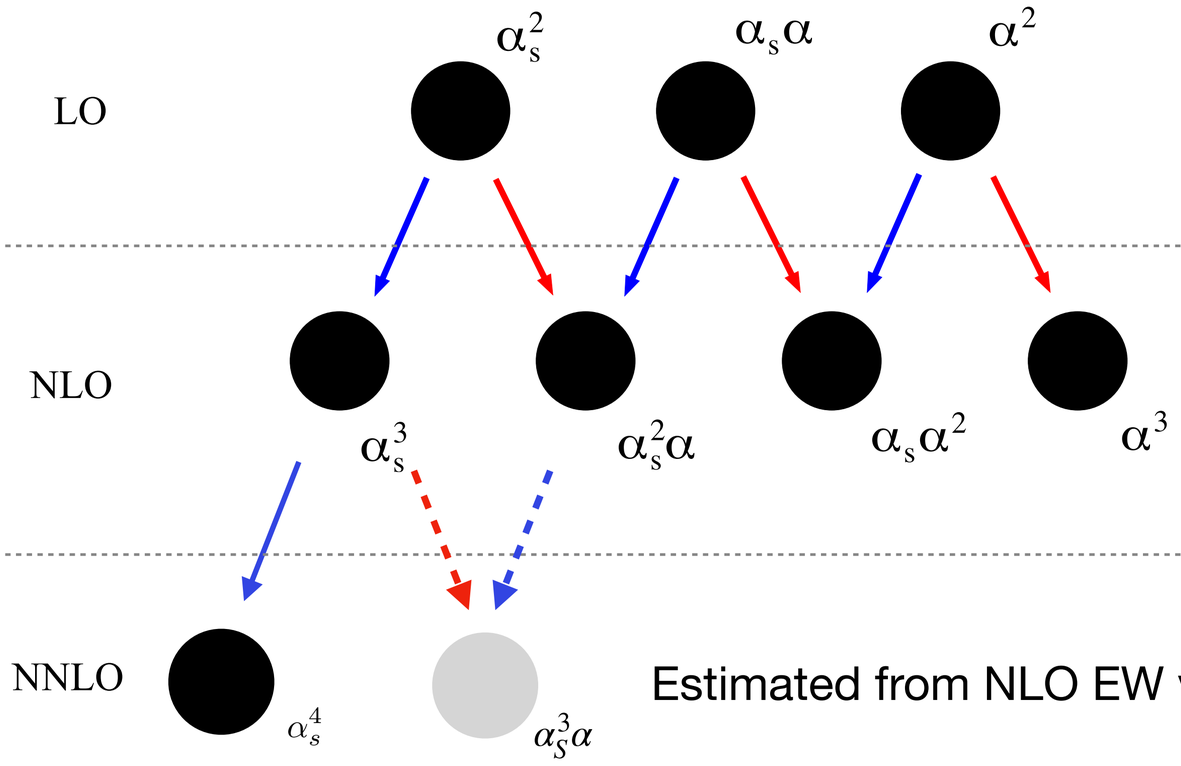


Precision SM Top Physics

Fixed-order computations

Cross section level



Complete NLO (C-NLO) ≡ all blobs at NLO level

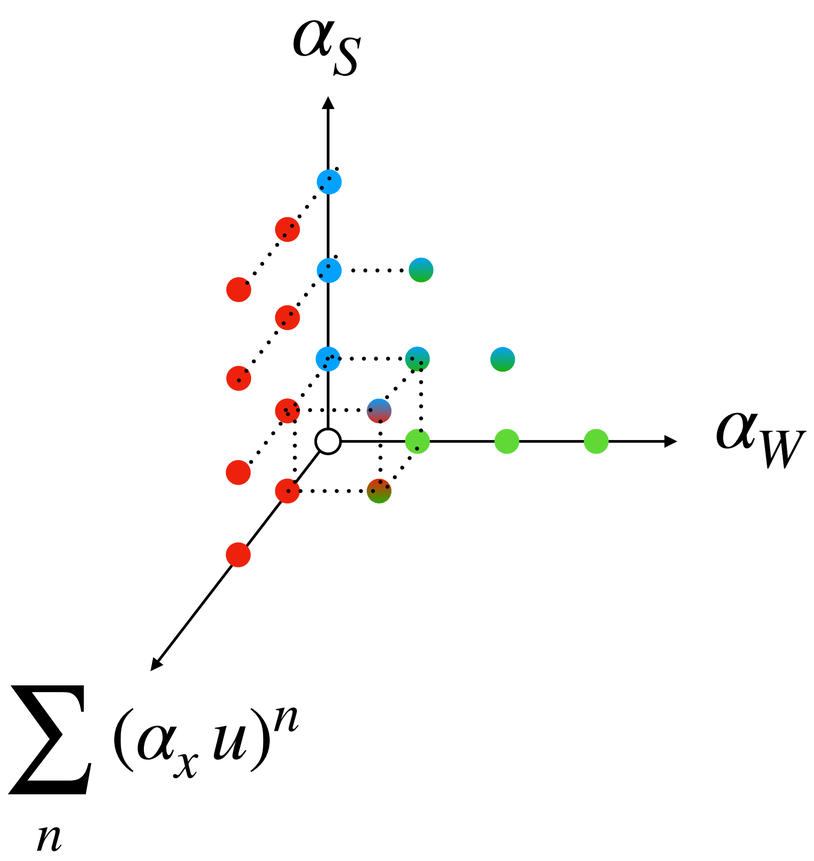
Estimated from NLO EW via multiplicative scheme

Precision SM Top Physics

The path

"Rules of thumb at the LHC":

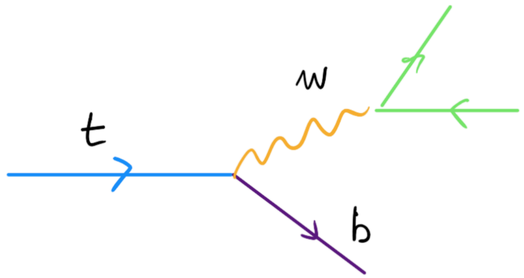
- Predictions must be calculated at least to **NLO QCD** to control the central value.
- NNLO QCD provides control on the uncertainties stabilizing the perturbative expansion.
- **NNLO QCD** is expected to be of the **same order** as **NLO EW** $\alpha_S^2 \sim \alpha_W$**, yet EW** corrections grow large and negative at high energies (Sudakov logs).
- Universal, all-order terms that are potentially large for some observables (logs or 1PI loops for propagators) need to be resummed. These typically lead to improvements in precision and accuracy.



Top-quark physics essentials III

Width

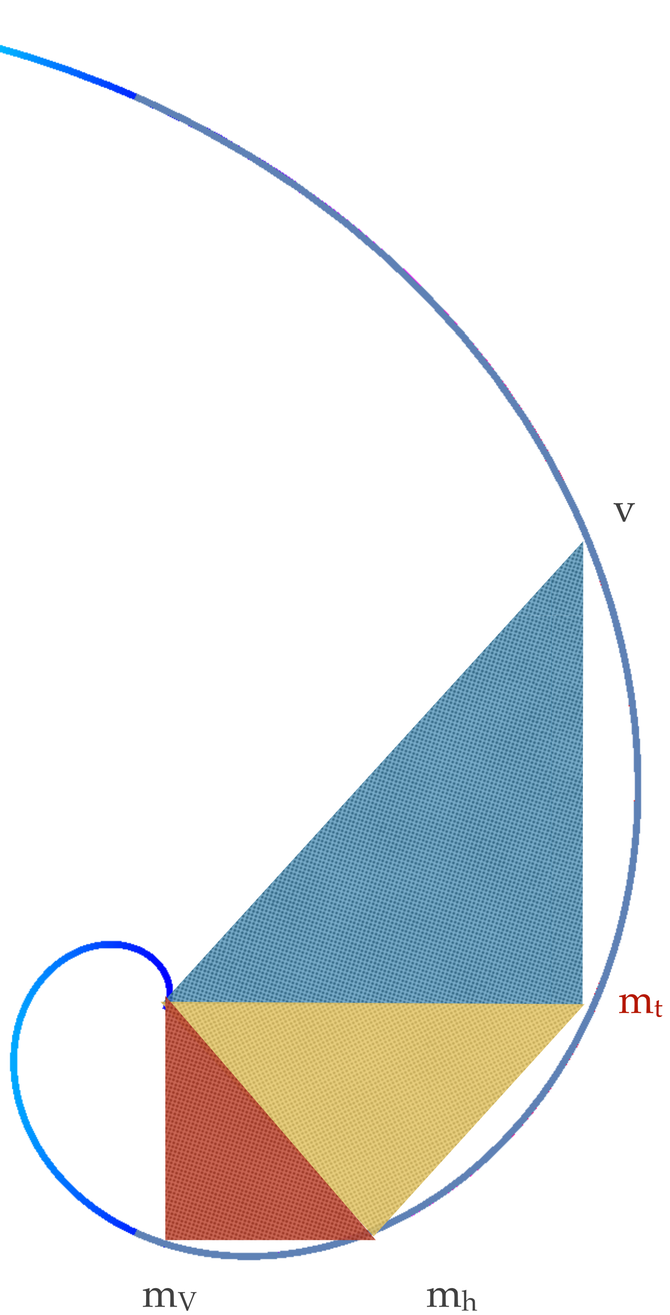
- It decays semi-weakly in $5 \cdot 10^{-25} s$, $\Gamma_t \simeq 1.5$ GeV $\Rightarrow$ it does not spin flip nor hadronises.



- Thanks to L-handed nature of the weak interactions the direction of lepton is 100% correlated to the spin direction $\Rightarrow$ we can measure its spin $\Rightarrow$ EPR type measurements in $t\bar{t}$ production.

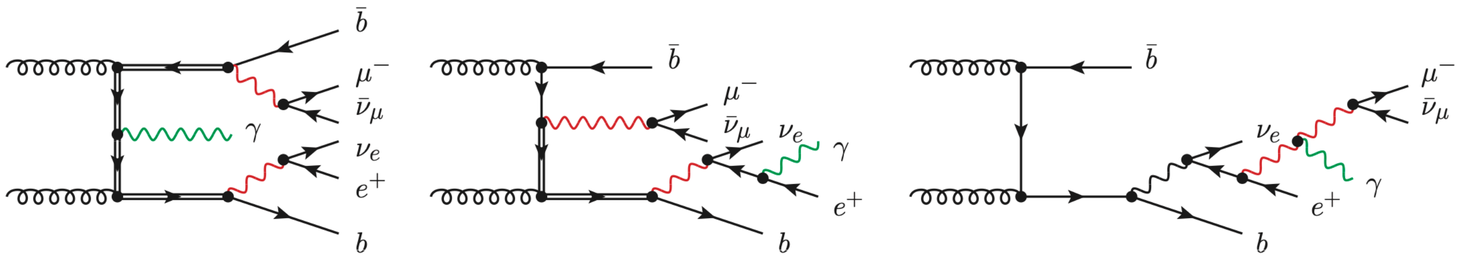
- 3-body decay + spin of the top gives enough independent momenta to build CP-odd observables $\Rightarrow$ look for extra CP violation.

- $V_{tb} = 0.99911 \pm 0.00003$ (3 generations)
  $V_{tb} = 0.988 \pm 0.024$ (direct) [CMS 2004.12181]



Off-shell effects

$t\bar{t} + X$



- tj [Frederix et al. 1907.12586] QCD/EW and QCD+PS
- $t\bar{t}Z$ [Bevilacqua et al.1907.09359] QCD
- $t\bar{t}W$ [Bevilacqua et al. 2005.09427] QCD
- $t\bar{t}\gamma$ [Bevilacqua et al. 1912.09999][Bevilacqua et al., 1809.08562][Bevilacqua et al., 1803.09916] QCD
- $t\bar{t}j$ [Bevilacqua et al. 1710.07515][Bevilacqua, 1609.01659][Bevilacqua, 1509.09242] QCD
- $t\bar{t}H$ [Denner et al. 1612.07138] EW/QCD (dileptonic)
  [Denner and Pellen, 1711.10359] QCD (semileptonic)
- $t\bar{t}$ [Denner et al. 1607.05571] EW (dileptonic)
  [Jezo et al. 1607.04538] QCD+PS (dileptonic)
  [Denner, 1207.5018] QCD (dileptonic)

- Inclusion of off-shell effects is a very challenging technical task: many diagrams, needs consistent treatment of the width, difficult phase space integration, higher-point integrals,…
- These can be important for very precisely measured final states where selection cuts force one or both tops off-shell.
- A famous case is the overlapping between $t\bar{t}$ and tWb.
- Another problem is the interface with the parton shower.

Precision SM Top Physics

Status of the SM predictions

SM	QCD	EW	Complete	Res	Off-Shell	NLO+PS	+jets	+ jets merging LO	+jets merging NLO
$t\bar{t}$	NNLO	NLO	NLO	NNLL	NLO (QCD and EW)	YES (also OS)	up to 3 NLO QCD	✓	✓
$t\bar{t}W$	NLO	NLO	NLO	NNLL	NLO QCD	✓	(+1 NLO ALL)	✓	(✓)
$t\bar{t}Z$	NLO	NLO	NLO	NNLL	NLO QCD	✓	(+1 NLO ALL)	✓	(✓)
$t\bar{t}\gamma$	NLO	(NLO)	NLO	X	NLO QCD	✓	(+1 NLO ALL)	✓	(✓)
$t\bar{t}H$	NLO	NLO	NLO	NNLL	NLO (QCD and EW)	✓	(+1 NLO ALL)	✓	(✓)
$t\bar{t}VV$	NLO	(NLO)	(NLO)	(NNLL)	X	✓	(+1 NLO ALL)	✓	(✓)
$t\bar{t}t\bar{t}$	NLO	NLO	NLO	NLL	X	✓	LO	✓	X
tj	NNLO	NLO	NLO	NNLL	NLO (QCD and EW)	✓	1 jet NLO QCD	✓	1+jet
tjZ	NLO	(NLO)	(NLO)	X	X	✓	(1 jet NLO QCD)	✓	(✓)
tjH	NLO	(NLO)	(NLO)	X	X	✓	(1 jet NLO QCD)	✓	(✓)

5F scheme assumed. When in ( ) is being/can be done.

Precision SM Top Physics

Status of the SM predictions

SM	QCD	EW	Complete	Res	Off-Shell	NLO+PS	+jets	+ jets merging LO	+jets merging NLO
$t\bar{t}$	NNLO	NLO	NLO	NNLL	NLO (QCD and EW)	YES (also OS)	up to 5 NLO QCD	✓	✓
$t\bar{t}W$	NLO	NLO	NLO	NNLL	NLO QCD	✓	(+1 NLO ALL)	✓	(✓)
$t\bar{t}Z$	NLO	NLO	NLO	NNLL	NLO QCD	✓	(+1 NLO ALL)	✓	(✓)
$t\bar{t}\gamma$	NLO	(NLO)	NLO	X	NLO QCD	✓	(+1 NLO ALL)	✓	(✓)
$t\bar{t}H$	NLO	NLO	NLO	NNLL	NLO (QCD and EW)	✓	(+1 NLO ALL)	✓	(✓)
$t\bar{t}VV$	NLO	(NLO)	(NLO)	(NNLL)	X	✓	(+1 NLO ALL)	✓	(✓)
$t\bar{t}t\bar{t}$	NLO	NLO	NLO	NLL	X	✓	LO	✓	X
tj	NNLO	NLO	NLO	NNLL	NLO (QCD and EW)	✓	1 jet NLO QCD	✓	1+jet
tjZ	NLO	(NLO)	(NLO)	X	X	✓	(1 jet NLO QCD)	✓	(✓)
tjH	NLO	(NLO)	(NLO)	X	X	✓	(1 jet NLO QCD)	✓	(✓)

tj at complete NLO and off-shell in the talk by Davide Pagani Study of ttW at complete NLO the talk by Ioannis Tsinikos

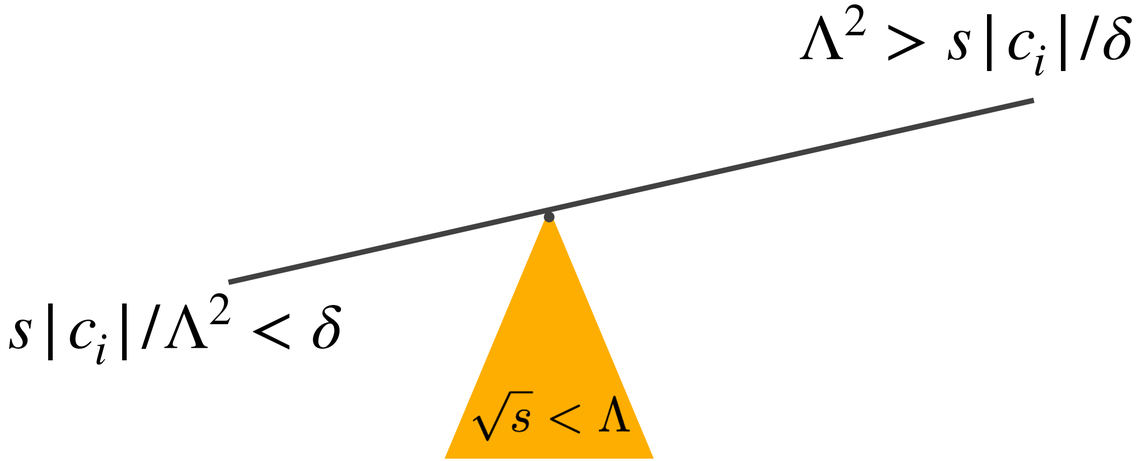
Study of ttZ/gamma at NLO QCD off-shell the talk by Giuseppe Bevilacqua

Precision…what for?

Searching for new interactions with an EFT

The matter content of SM has been experimentally verified and there is no evidence for light states. SM measurements can be interpreted as searches for deviations from the dim=4 SM Lagrangian predictions.

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



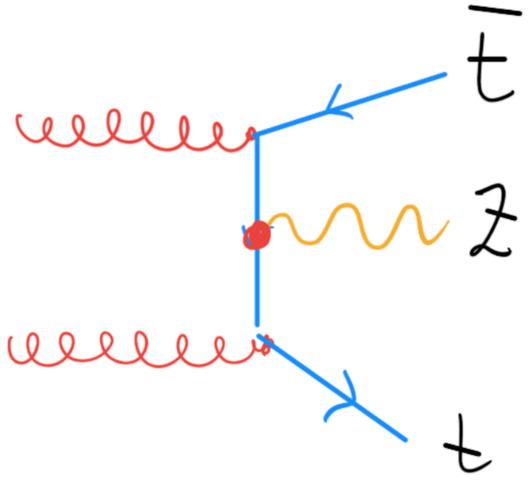
BSM goal of the precision LHC programme: determination of the couplings of the SMEFT lagrangian.

Precision…what for?

Searching for new interactions with the SMEFT

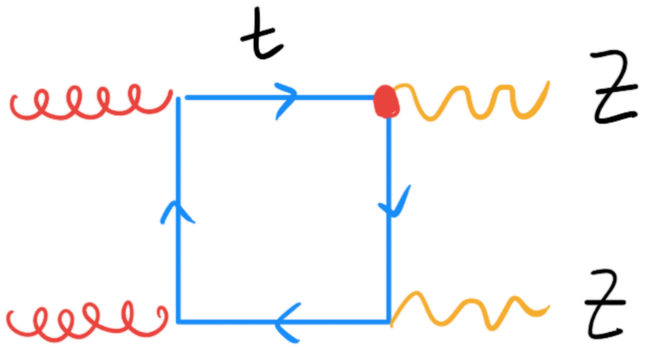
Tree level sensitivity

Top-X final states



Loop sensitivity

Top-X couplings without the top or the X*



*Paraphrasing [Henning et al., 1812.09299]

Top-quark physics essentials IV

The SMEFT

- New interactions among SM particles can be systematically parametrized in the context of the SMEFT. Directly related to the top fields, at dim=6

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots \quad \Rightarrow \quad \mathrm{Obs}_i = \mathrm{Obs}_i^{\mathrm{SM}} + M_{ij}\cdot\frac{s}{\Lambda^2}\,c_j$$

[Aguilar-Saavedra et al. 1802.07237]

2QBs

$$^{\ddagger}O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi),$$
$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_i\gamma^\mu\tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j),$$
$$^{\ddagger}O_{\varphi ud}^{(ij)} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{u}_i\gamma^\mu d_j),$$
$$^{\ddagger}O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}W^I_{\mu\nu},$$
$$^{\ddagger}O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi W^I_{\mu\nu},$$
$$^{\ddagger}O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}u_j)\quad\tilde{\varphi}B_{\mu\nu},$$
$$^{\ddagger}O_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{\varphi}G^A_{\mu\nu},$$

2Q2L

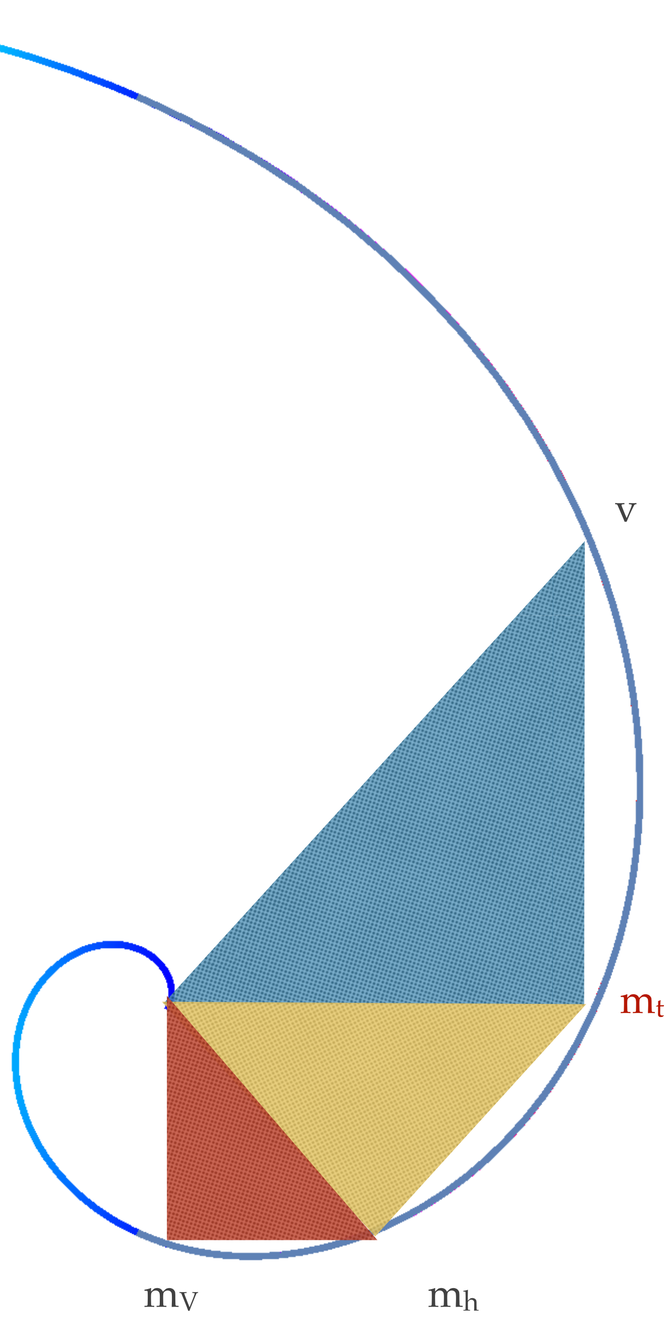
$$O_{lq}^{1(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{lq}^{3(ijkl)} = (\bar{l}_i\gamma^\mu\tau^I l_j)(\bar{q}_k\gamma^\mu\tau^I q_l),$$
$$O_{lu}^{(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{eq}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{eu}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l),$$
$$^{\ddagger}O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\,\varepsilon\,(\bar{q}_k u_l),$$
$$^{\ddagger}O_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu}e_j)\,\varepsilon\,(\bar{q}_k\sigma_{\mu\nu}u_l),$$
$$^{\ddagger}O_{ledq}^{(ijkl)} = (\bar{l}_i e_j)(\bar{d}_k q_l),$$

2Q2q-4Q

$$O_{qq}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l),$$
$$O_{qq}^{3(ijkl)} = (\bar{q}_i\gamma^\mu\tau^I q_j)(\bar{q}_k\gamma_\mu\tau^I q_l),$$
$$O_{qu}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{qu}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l),$$
$$O_{qd}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{qd}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$O_{uu}^{(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{ud}^{1(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{ud}^{8(ijkl)} = (\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$^{\ddagger}O_{quqd}^{1(ijkl)} = (\bar{q}_i u_j)\,\varepsilon\,(\bar{q}_k d_l),$$
$$^{\ddagger}O_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j)\,\varepsilon\,(\bar{q}_k T^A d_l),$$

which, assuming $U(2)_q$ x $U(2)_u$ x $U(2)_d$,corresponds to

42 degrees of freedom (11x4Q, 14x2Q2q, 9x2QBs, 8x2Q2L)



SMEFT

Processes and (some) operators

NLO	Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$	O_{4f}	O_G	$O_{\varphi G}$
✓	$t \to bW \to bl^+\nu$	N		L	L				L^2	L^2	$1L^2$		
✓	$pp \to tj$	N		L	L				L^2	L^2	1L		
✓	$pp \to tW$	L		L	L				L^2	L^2	1N	N	
✓	$pp \to t\bar{t}$	L									2L-4N	L	
✓	$pp \to t\bar{t}j$	L									2L-4N	L	
✓	$pp \to t\bar{t}\gamma$	L	L	L							2L-4N	L	
✓	$pp \to t\bar{t}Z$	L	L	L	L	L	L				2L-4N	L	
✓	$pp \to t\bar{t}W$	L								L	1L-2L		
✓	$pp \to t\gamma j$	N	L	L	L				L^2	L^2	1L		
✓	$pp \to tZj$	N	L	L	L	L	L		L^2	L^2	1L		
✓	$pp \to t\bar{t}t\bar{t}$	L									2L-4L	L	
✓	$pp \to t\bar{t}H$	L						L			2L-4L	L	L
✓	$pp \to tHj$	N		L	L			L	L^2	L^2	1L		N
○ ✓	$gg \to H$	L						L				N	L
○ ✗	$gg \to Hj$	L						L				L	L
○ ✗	$gg \to HH$	L						L				N	L
○ ✗	$gg \to HZ$	L			L	L	L	L				N	L

More on SMEFT with top and Higgs in the talk by Peter Galler

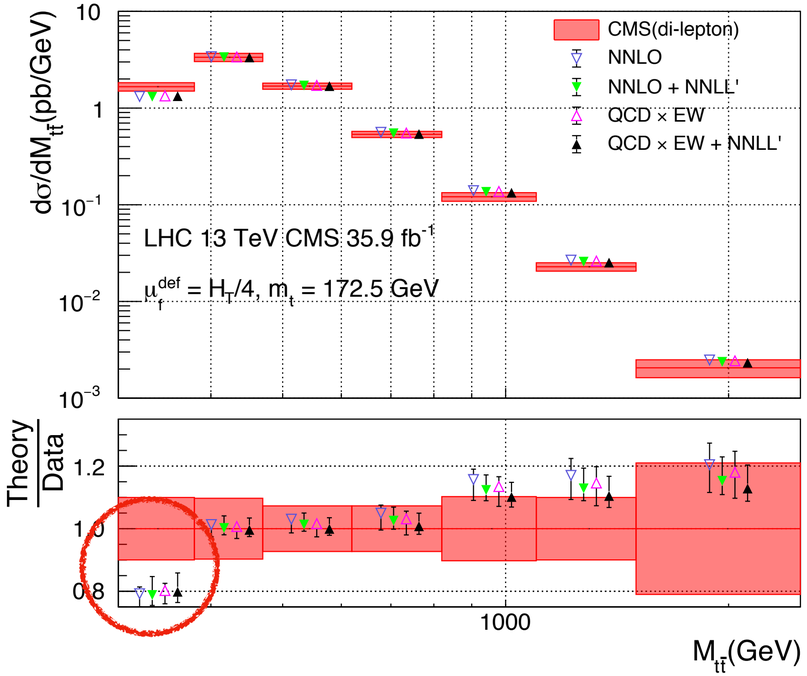
SMEFT

A few recent examples

1. $t\bar{t}$ at threshold at NNLO with Coulomb resummation
2. $t\bar{t}Z$ C-NLO+NNLL vs loops
3. tZj C-NLO
4. $t\bar{t}t\bar{t}$ C-NLO see additional material ➡

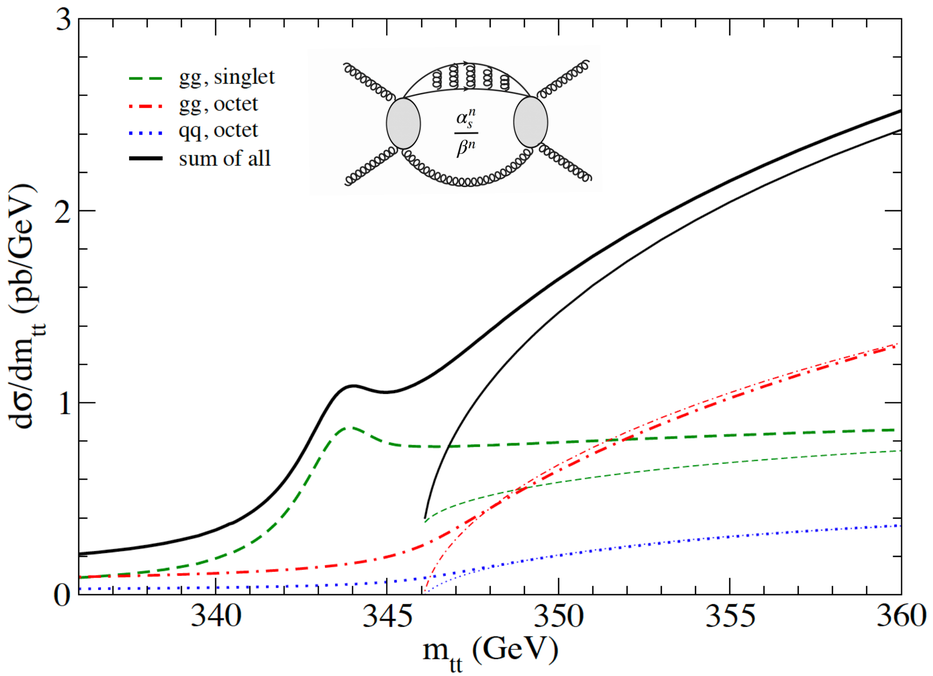
SMEFT

$t\bar{t}$ threshold production



[Czakon et al. 1901.08281]

A significant undershooting of our best theory with respect to data in the first $m(t\bar{t})$ bin



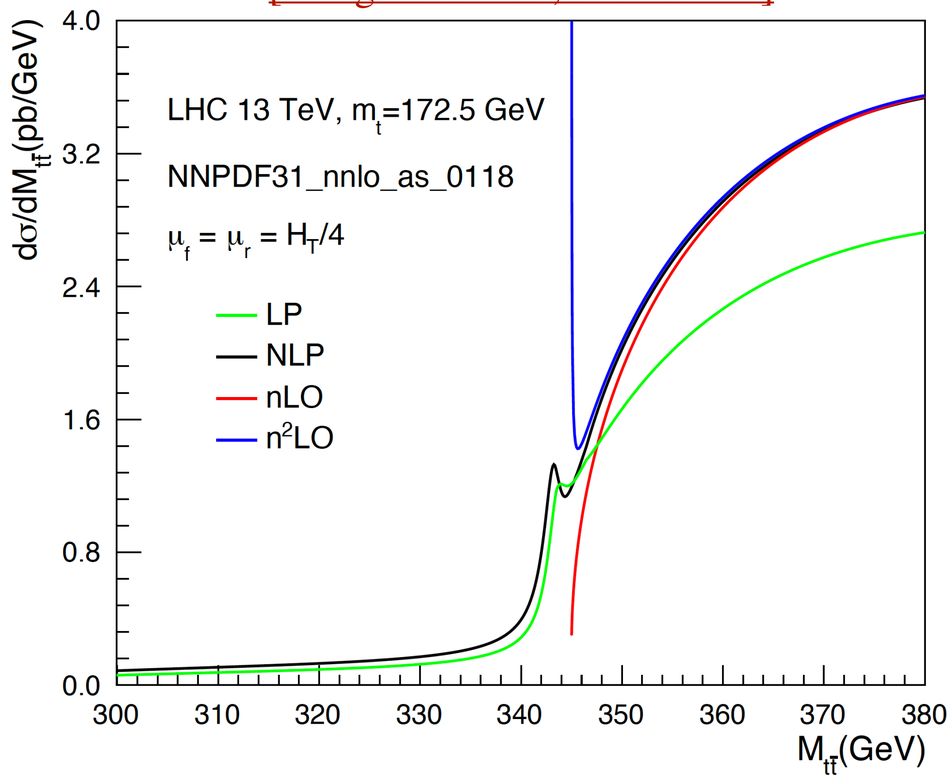
[Hagiwara et al., 0804.1014]

When produced almost at rest and in a color singlet the t and $\bar{t}$ tend to form a (pseudo) bound state ⇒ enhancement of the x-sec

SMEFT

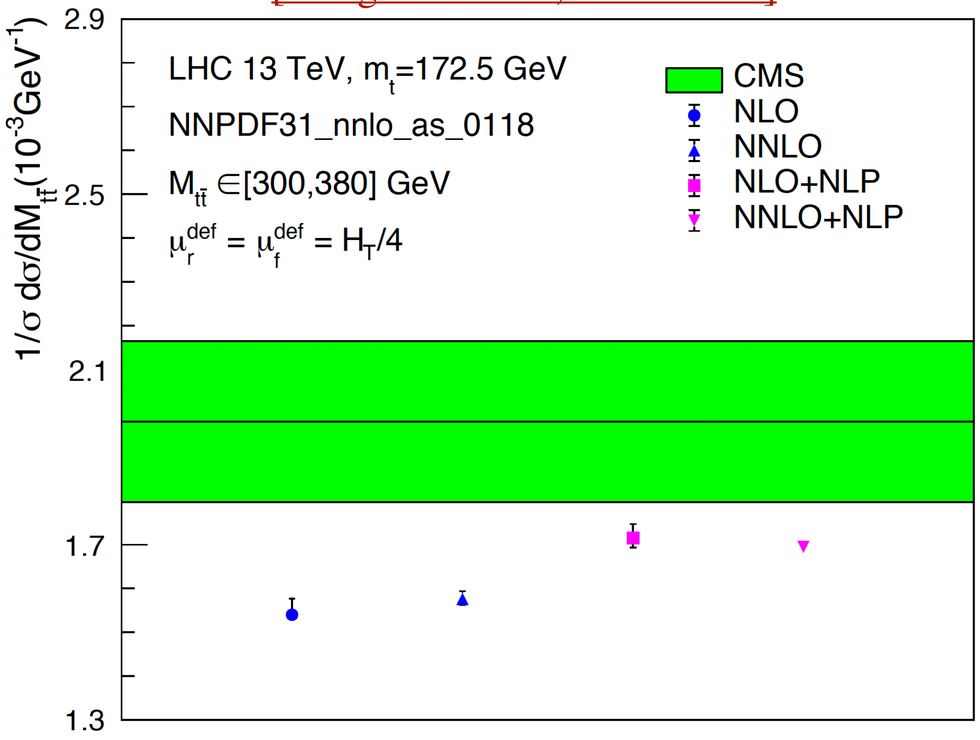
$t\bar{t}$ threshold production

[Wang Li-Ji et al., 2004.03088]



A very much refined analysis confirms the expectations of Hagiwara et al.

[Wang Li-Ji et al., 2004.03088]

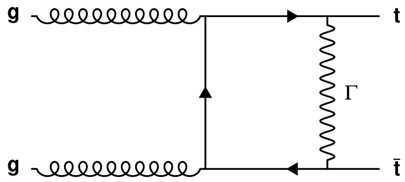


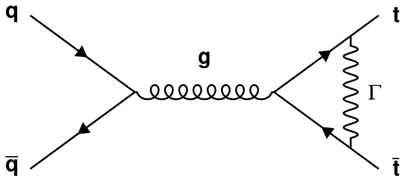
Coloumb resumption leads to a visible shift in the right direction that is stable under radiative corrections.

SMEFT

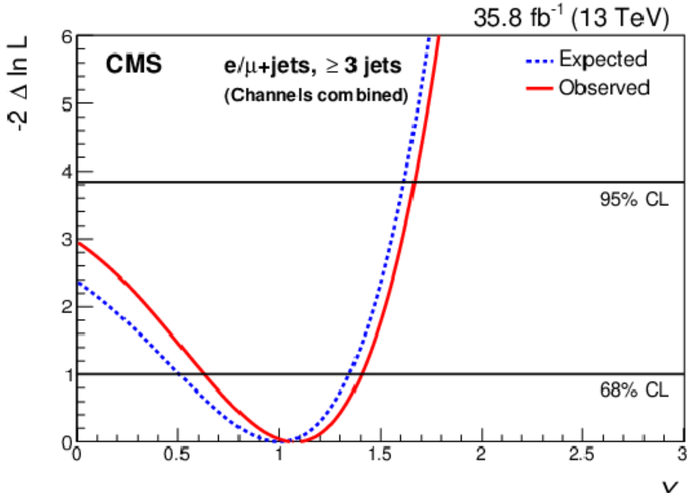
Top Yukawa coupling from $t\bar{t}$

The behavior at threshold could be affected by the exchange of a Higgs or a Z-boson. [Kuhn et al.,1305.5773]



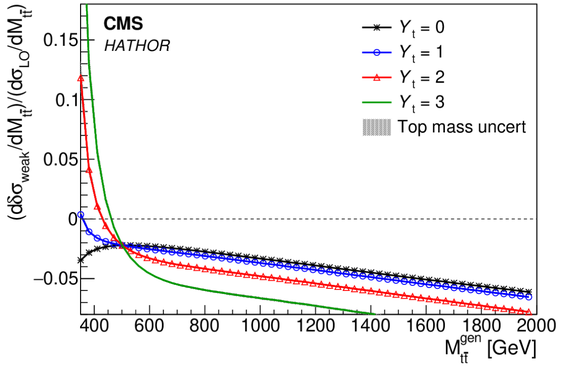


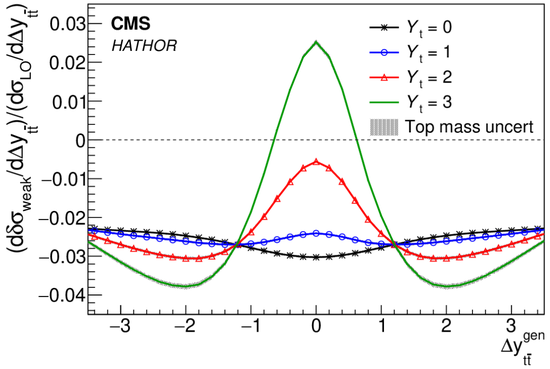
[CMS 1907.01590]



This can give a bound on the value of the Yukawa coupling. A first analysis performed by CMS finds y_t/y_t^{SM} value to be 1.07 +0.34 −0.43 with an upper limit of 1.67 at the 95% confidence level.

Q: How are these results affected by the new calculations?

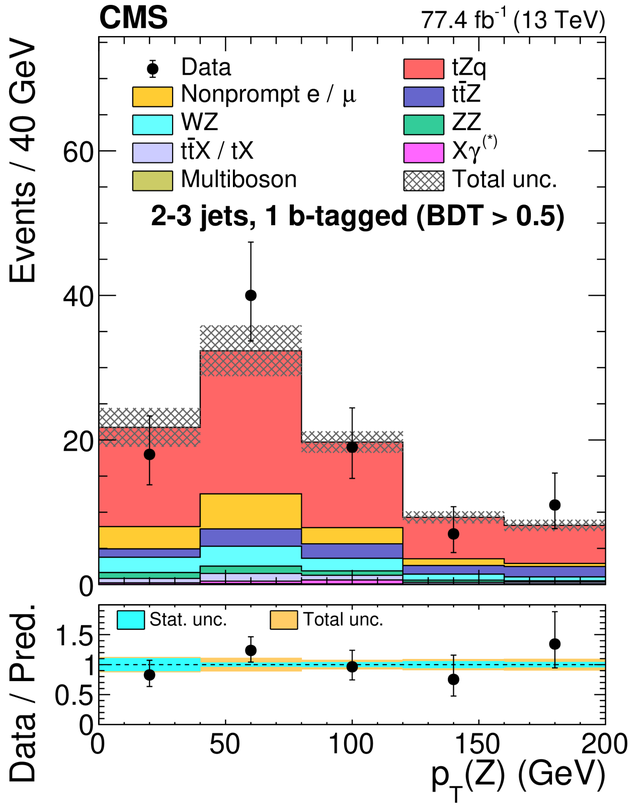




skip

SMEFT

tZj: Experimental status



$\sigma(pp \to tZq \to t\ell^+\ell^-q) = 111 \pm 13\ (\text{stat})\ ^{+11}_{-9}\ (\text{syst})$ fb,

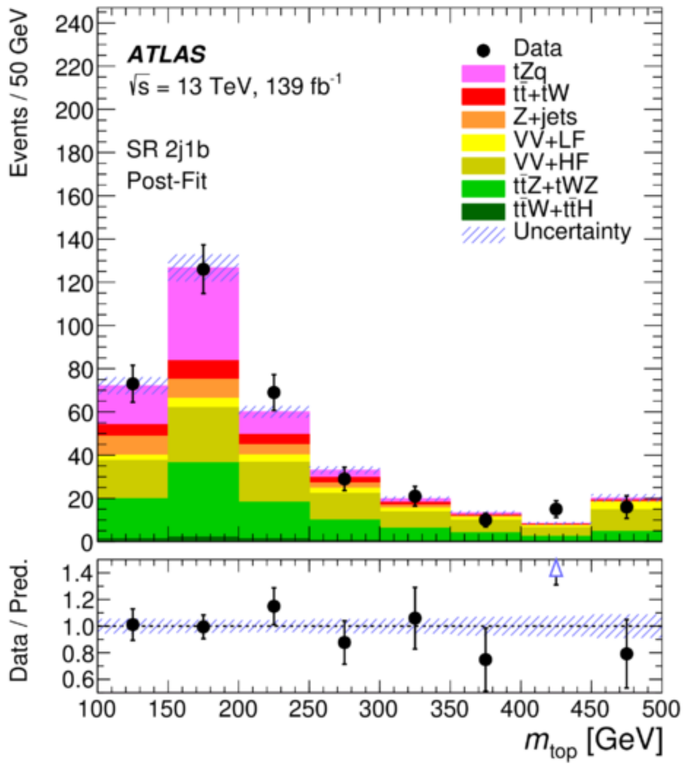
[CMS 1812.05900]

TH (NLO):

$$\sigma(tZq)^{\text{NLO}} = 75.87(4)^{+2.2\%}_{-6.4\%} \pm 1.2\%\ \text{fb}$$

[Degrande et al. 1804.07773]

([Campbell et al, 1302.3856])

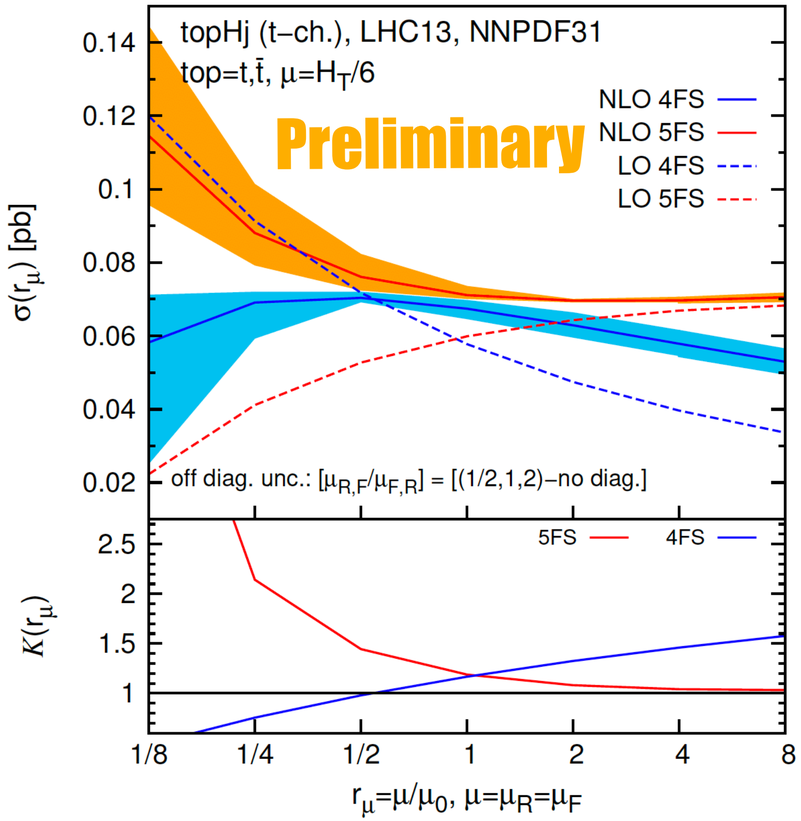


$\sigma(tZq) = 97 \pm 13\ (\text{stat.}) \pm 7\ (\text{syst.})$ fb

[ATLAS, 2002.07546]

SMEFT

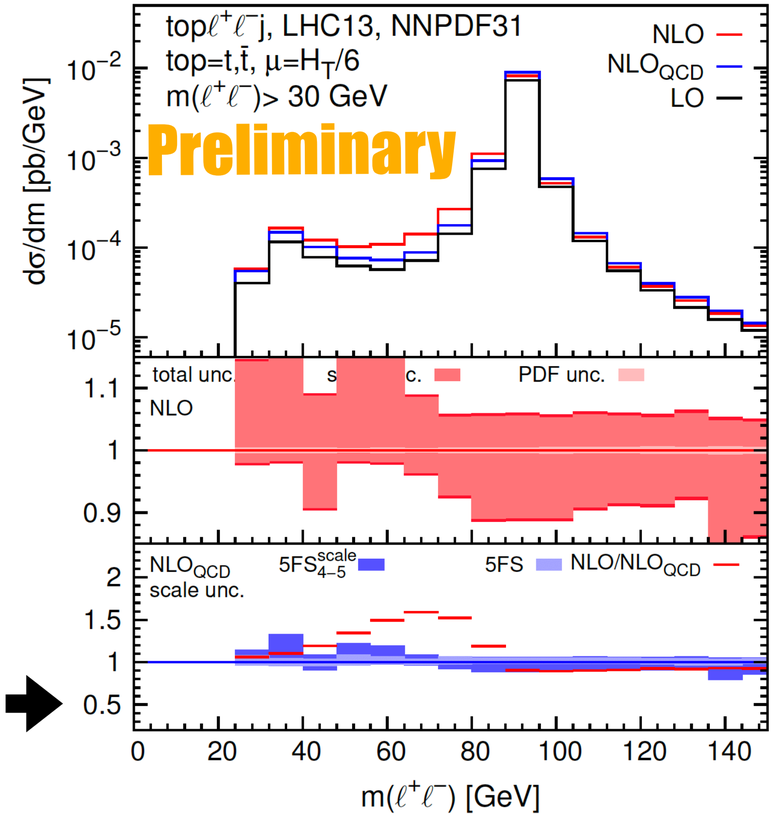
tZj and tHj : NLO complete corrections and 4F vs 5F



New calculation being performed including the C-NLO corrections to tZj and tHj and a comparison between 4F and 5F schemes.

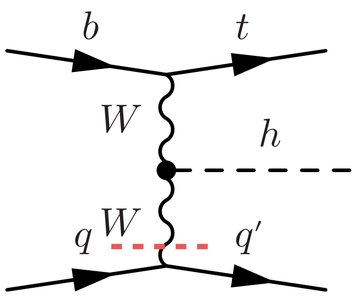
[Pagani, Tsinikos, Vryonidou to appear]

The upshot is an extremely good control/ understanding of rates of distributions.



SMEFT

tZj (tHj) : the interplay of operators/processes

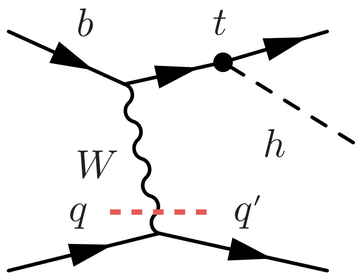


$\mathcal{O}_{\varphi W} : \varphi^\dagger \varphi\, W_i^{\mu\nu} W^i_{\mu\nu}$

HWW

TGC

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

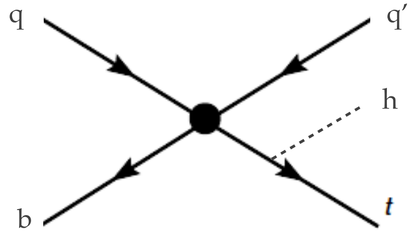


$\mathcal{O}_{t\varphi} \; : \; (\varphi^\dagger \varphi)\,(\bar{Q}\, t)\,\tilde{\varphi}$

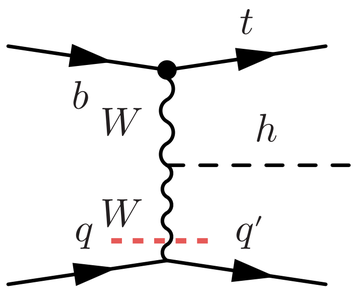
top Yukawa

ttZ coupling

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



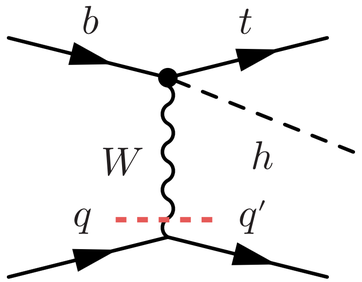
Four fermion



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

Wtb vertex

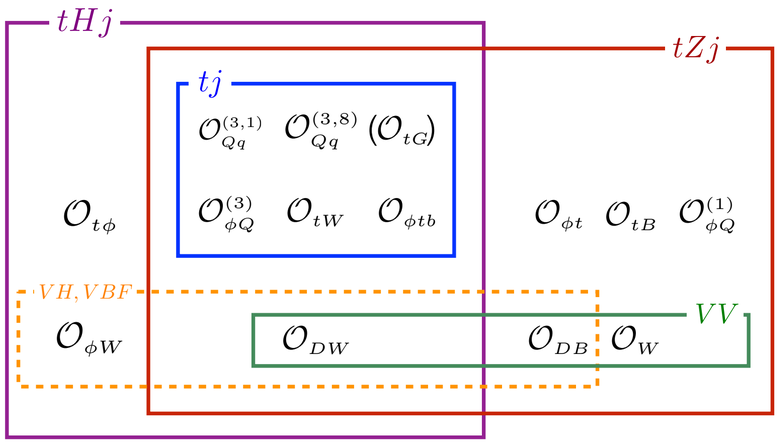
$\mathcal{O}_{\varphi tb} : i(\tilde{\varphi}\, D_\mu \varphi)(\bar{b}\gamma^\mu t)$



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

Contact terms

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

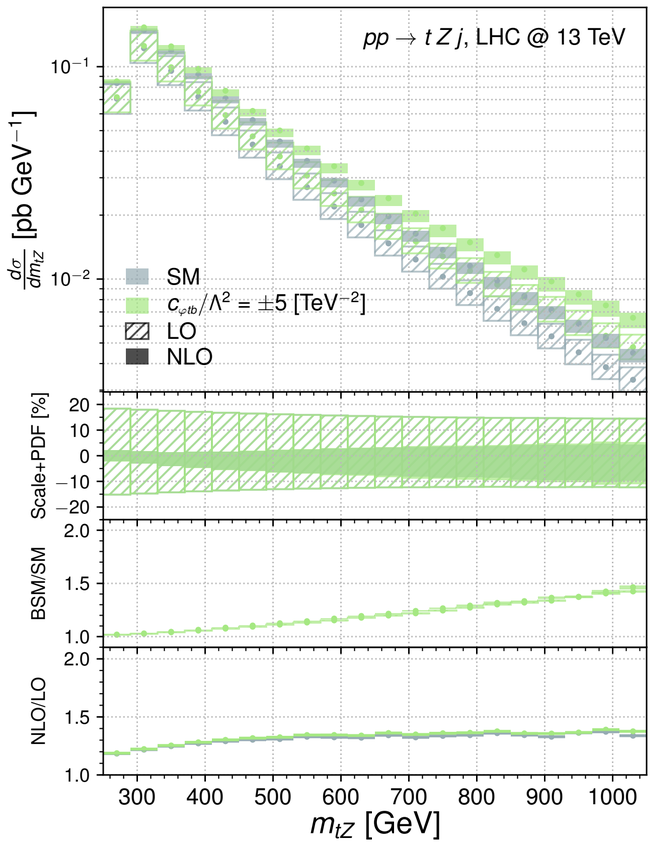


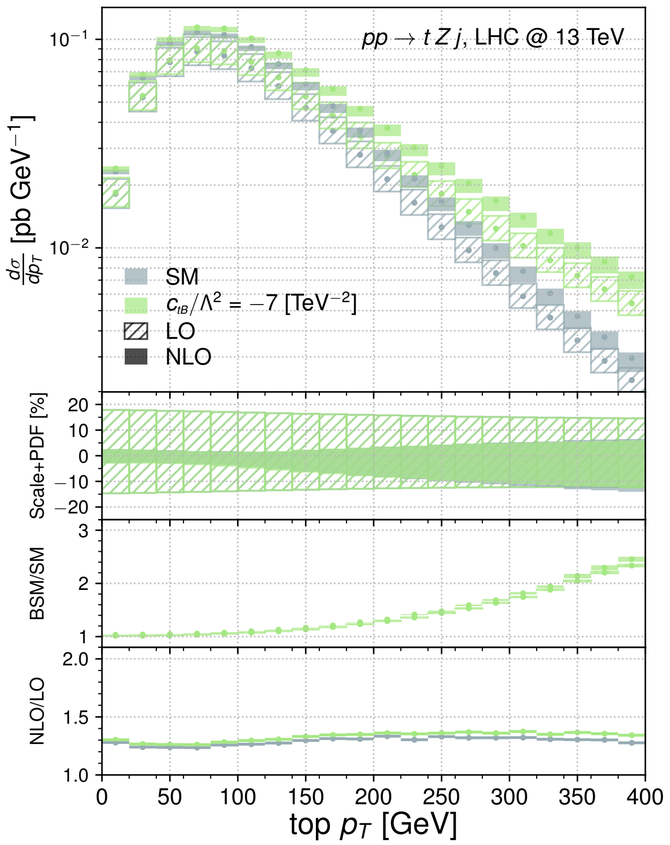
Accessing the bW→tH & bW→tZ sub-amplitudes

- Rich interplay between EFT operators from different sectors
- Different energy growth and interference with the SM
- Four fermion interactions also present

SMEFT

tZj: LHC sensitivity



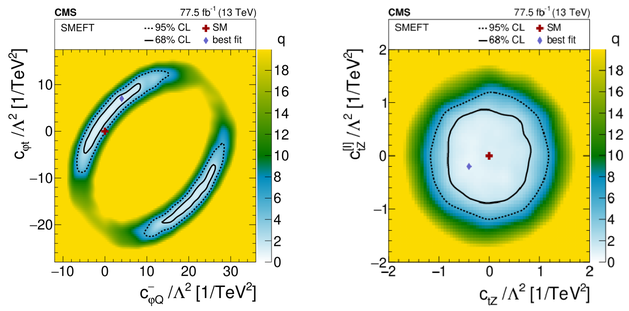


Effects of operators with coefficientes set at the boundaries of current exclusions

skip

SMEFT

$t\bar{t}Z$ experimental results

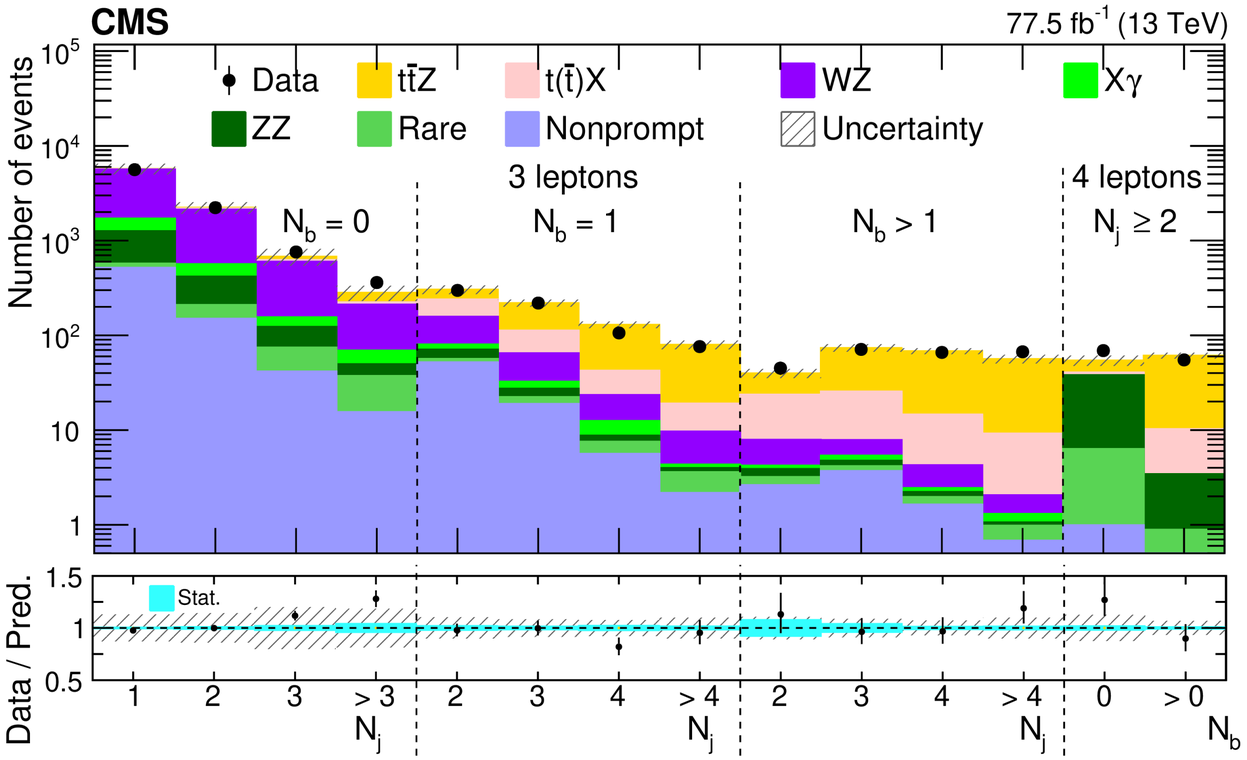


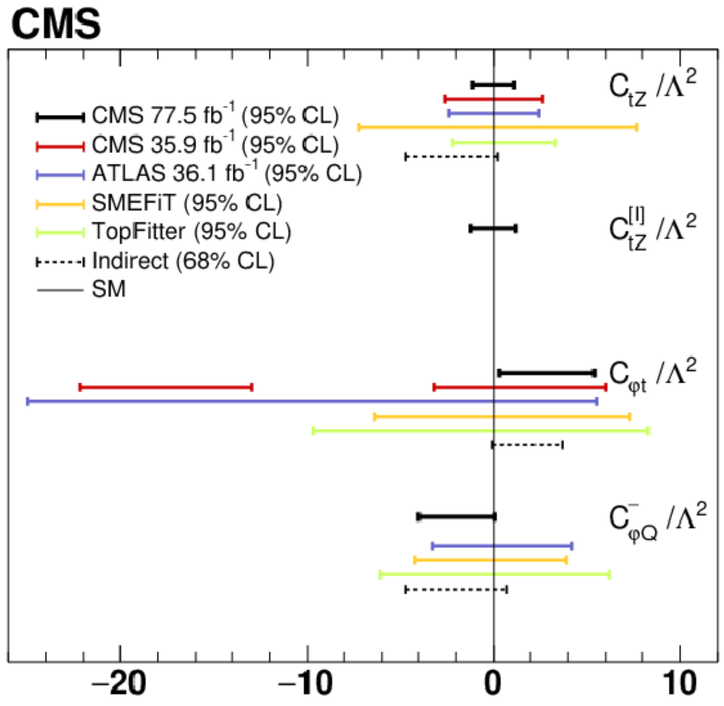
[Broggio et al., 1907.04343]

TH (C-NLO+NNLL): $\sigma_{t\bar{t}Z} = 810.9(2)^{+89.2(+11.0\%)+19.1(+2.4\%)}_{-77.8(-9.6\%)-19.1(-2.4\%)}$

[CMS 1907.11270]

$\sigma(t\bar{t}Z) = 0.95 \pm 0.05\ (\text{stat}) \pm 0.06\ (\text{syst})$ pb





SMEFT

$t\bar{t}Z$ production: SM predictions

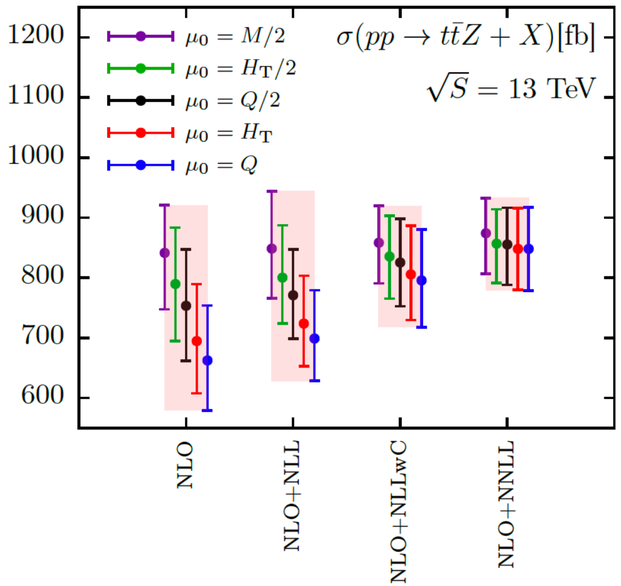
Two independent approaches available one using SCET and the other res in Mellin space. Give compatible results. For $t\bar{t}Z$ extremely good control of QCD uncertainties in total rates and main distributions, at better than 10% percent.

[Broggio et al., 1907.04343]

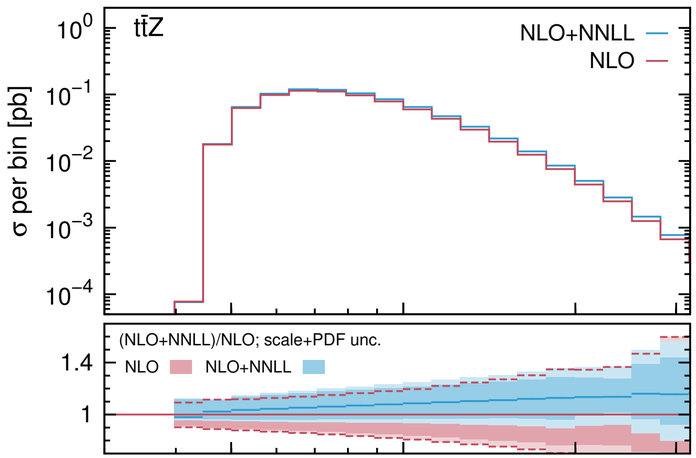
Combined scales

Order	σ [fb]			A_C[%]		
$\mathrm{LO_{QCD}}$	484.26(4)	$^{+171.26(+35.4\%)}_{-117.32(-24.2\%)}$	$^{+11.05(+2.3\%)}_{-11.05(-2.3\%)}$		0	
$\mathrm{NLO_{QCD}}$	751.2(1)	$^{+111.1(+14.8\%)}_{-108.5(-14.4\%)}$	$^{+17.7(+2.4\%)}_{-17.7(-2.4\%)}$	0.79(2)	$^{+0.23(+29.0\%)}_{-0.15(-19.1\%)}$	$^{+0.05(+6.3\%)}_{-0.05(-6.3\%)}$
NLO	759.5(1)	$^{+110.1(+14.5\%)}_{-107.8(-14.2\%)}$	$^{+17.9(+2.4\%)}_{-17.9(-2.4\%)}$	0.87(2)	$^{+0.22(+25.0\%)}_{-0.14(-16.2\%)}$	$^{+0.05(+5.3\%)}_{-0.05(-5.3\%)}$
$\mathrm{nNLO_{QCD}}$	817.1(1)	$^{+42.3(+5.2\%)}_{-29.9(-3.7\%)}$	$^{+19.3(+2.4\%)}_{-19.3(-2.4\%)}$	0.96(4)	$^{+0.02(+1.7\%)}_{-0.07(-7.5\%)}$	$^{+0.06(+5.8\%)}_{-0.06(-5.8\%)}$
nNLO	825.4(1)	$^{+41.3(+5.0\%)}_{-29.3(-3.5\%)}$	$^{+19.5(+2.4\%)}_{-19.5(-2.4\%)}$	1.03(4)	$^{+0.01(+1.4\%)}_{-0.07(-6.3\%)}$	$^{+0.05(+5.2\%)}_{-0.05(-5.2\%)}$
$\mathrm{NLO_{QCD}}$+NNLL	802.6(2)	$^{+89.4(+11.1\%)}_{-78.1(-9.7\%)}$	$^{+19.0(+2.4\%)}_{-19.0(-2.4\%)}$		–	
NLO+NNLL	810.9(2)	$^{+89.2(+11.0\%)}_{-77.8(-9.6\%)}$	$^{+19.1(+2.4\%)}_{-19.1(-2.4\%)}$		–	

[Kulesza et al., 2001.03031]



[Broggio et al., 1907.04343]



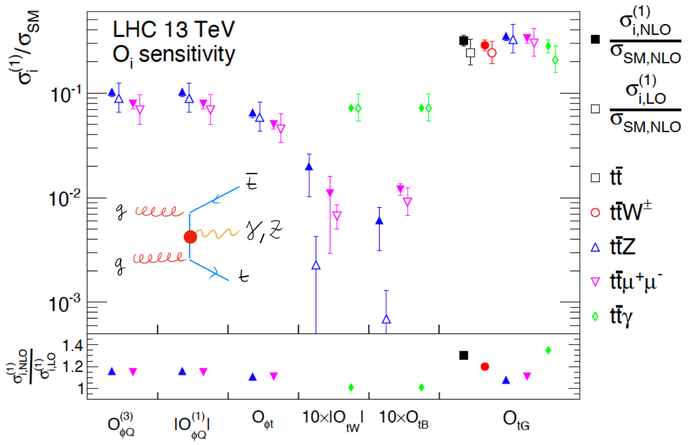
SMEFT

$t\bar{t}Z$ operators: trees and loops $gg \to HZ, gg \to ZZ, t\bar{t}$

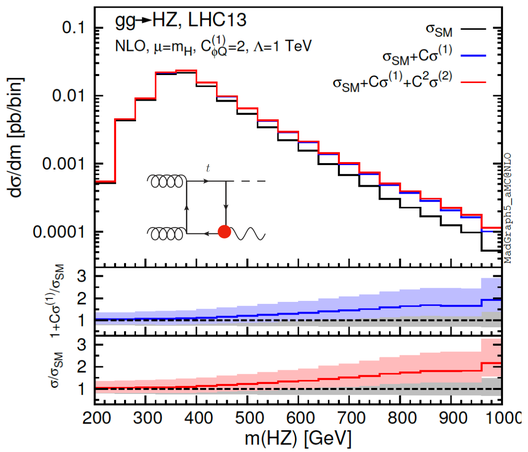
SMEFT computations at NLO in QCD are available for $t\bar{t}Z$ too. A natural way to test the couplings of the Z-boson to the top. However, comparable sensitivity can be obtained from high p_T tails in loop induced processes such as $gg \to HZ$, where only the top loop contributes, $gg \to ZZ$ and also $t\bar{t}$ close to threshold, as recently suggested.

$$O^1_{\phi Q} = (\phi^\dagger\, i \overleftrightarrow{D}_\mu\, \phi)(\bar{Q}\gamma^\mu Q)$$
$$O^3_{\phi Q} = (\phi^\dagger\, i \overleftrightarrow{D}^I_\mu\, \phi)(\bar{Q}\gamma^\mu \tau^I Q)$$
$$O_{\phi t} = (\phi^\dagger\, i \overleftrightarrow{D}_\mu\, \phi)(\bar{t}\gamma^\mu t)$$

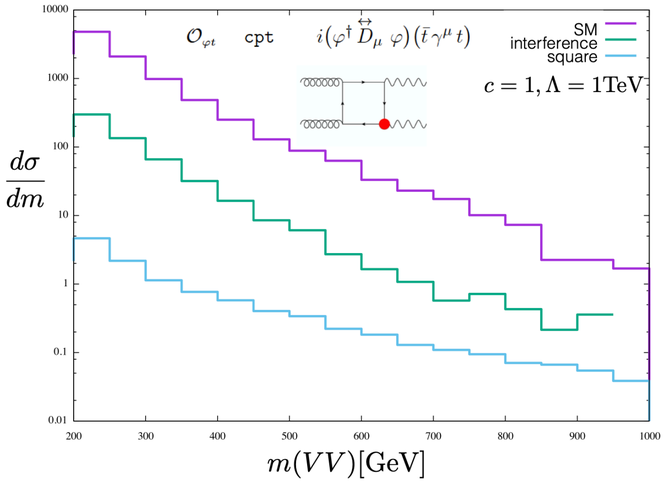
[Bylund et al., 1601.08193]



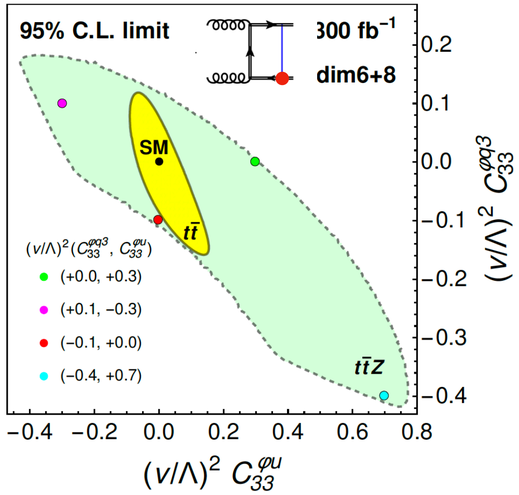
[Bylund et al., 1601.08193]



[Vryonidou at HEFT2020]



[Martini and Schultze, 1911.11244]



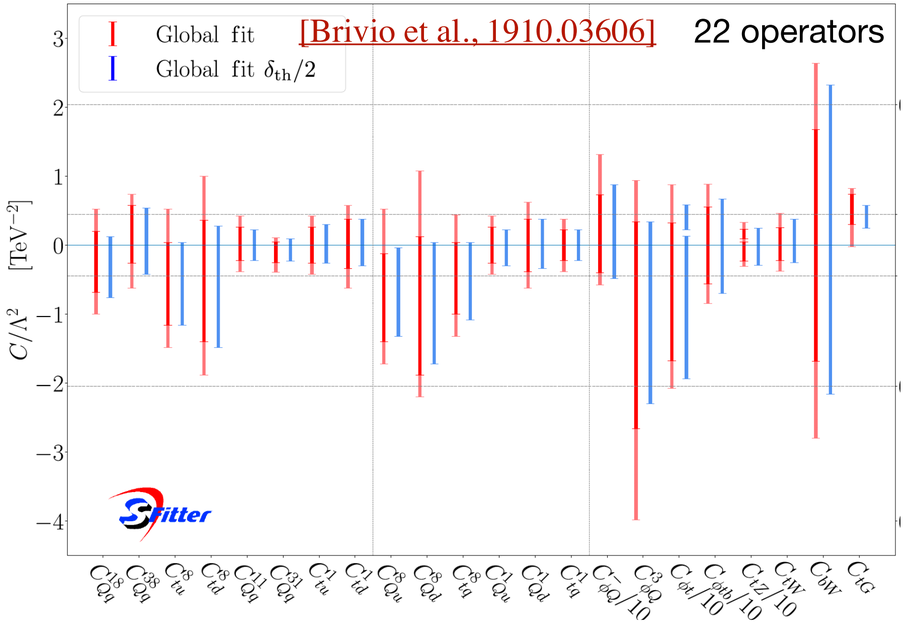
See also [Englert et al. 1410.5440] [Englert et al., 1603.05304] [Azatov et al., 1608.00977]

More details and insights in the talk by Till Martini

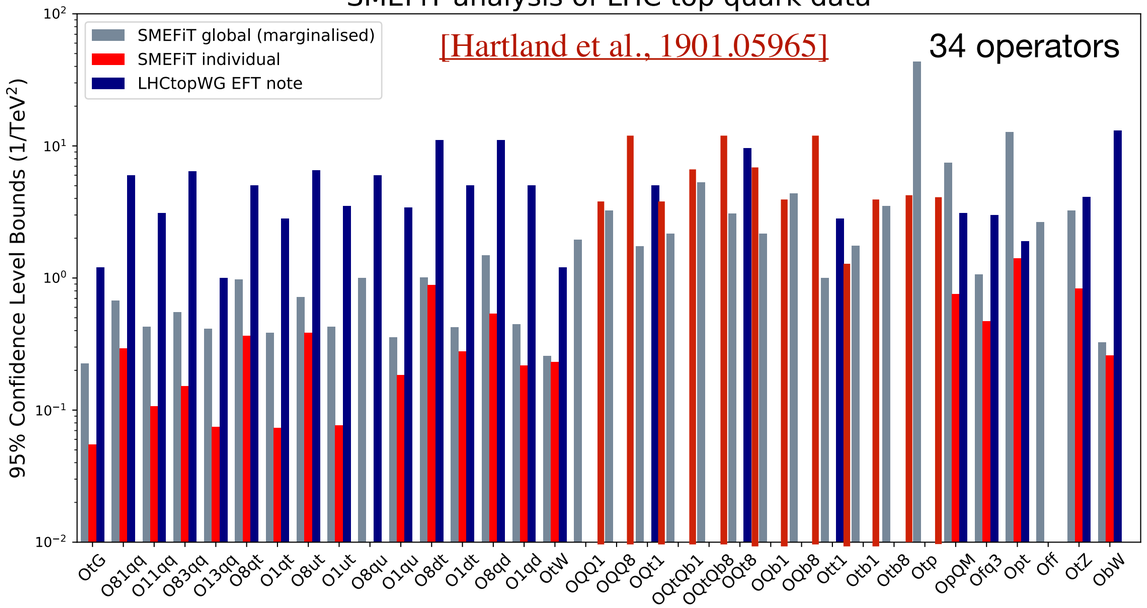
SMEFT

Global fits in the top sector

- Already now and without a dedicated experimental effort there is considerable information that can be used to set limits. Fits dedicated to the top sector:
  - TopFitter (Global, LHC+Tevatron, LO) [Buckley et al. 1506.08845]
  - SMEFiT (Global, LHC,NLO) [Hartland et al., 1901.05965]
  - EFTfitter (Partial, LHC+Flavor, LO) [Bissmann et al., 1909.13632]
  - SFitter (Global, LHC,NLO) [Brivio et al., 1910.03606]
- Several flat directions can be lifted with specific observables, also exploiting NLO effects.
- Combination with EW and Higgs data is needed to constrain all operators entering the all processes.



SMEFiT analysis of LHC top quark data

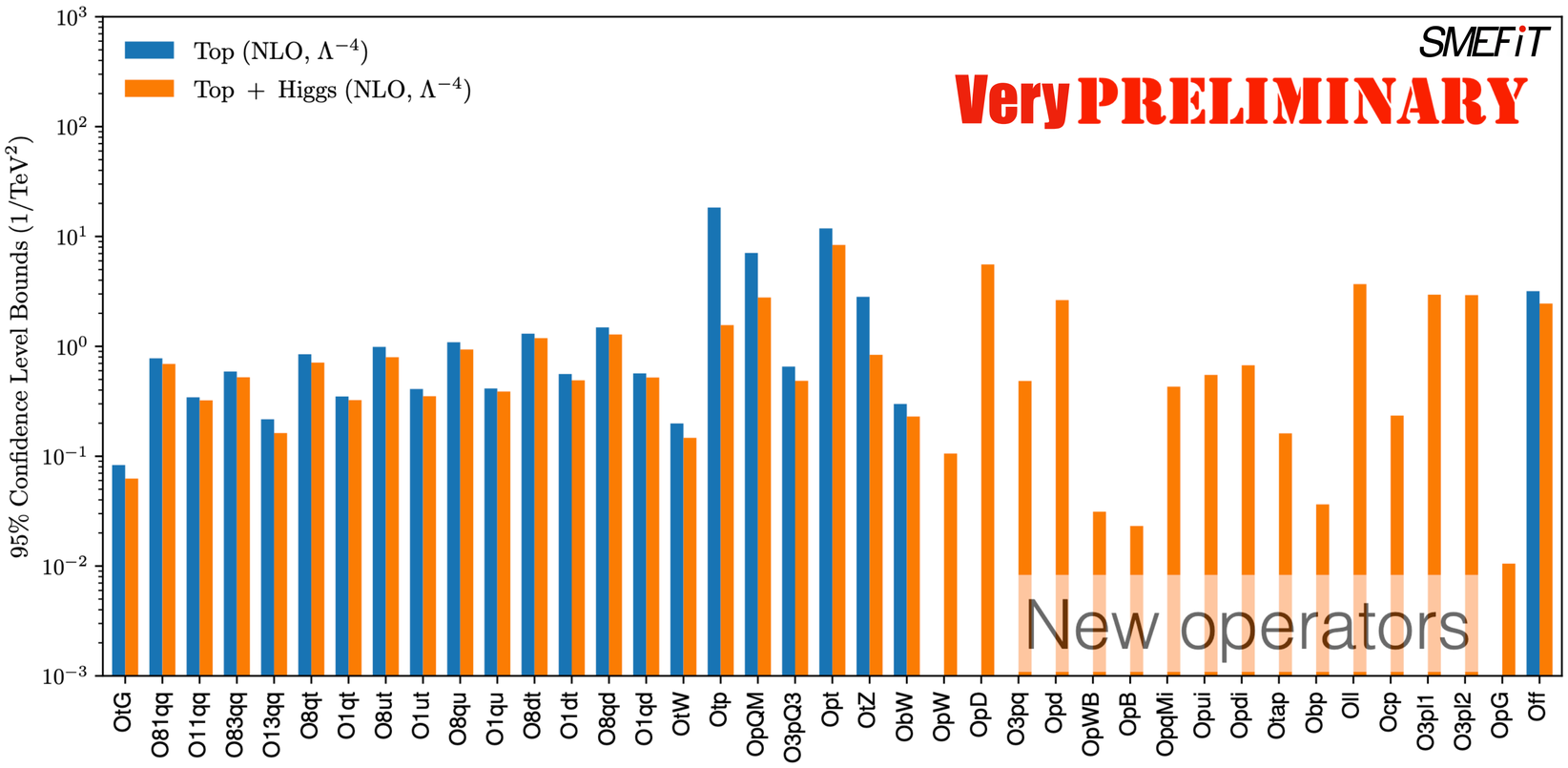


SMEFT

Global fit in the top + Higgs @ NLO

The top sector is connected to both the EW and Higgs sectors and therefore a really global approach is needed. A total of 24 additional operators are needed in addition to the 42 giving 66 operators.

Robustness and convergence of the fitting procedure is being explored right now (starting with a smaller number of operators).

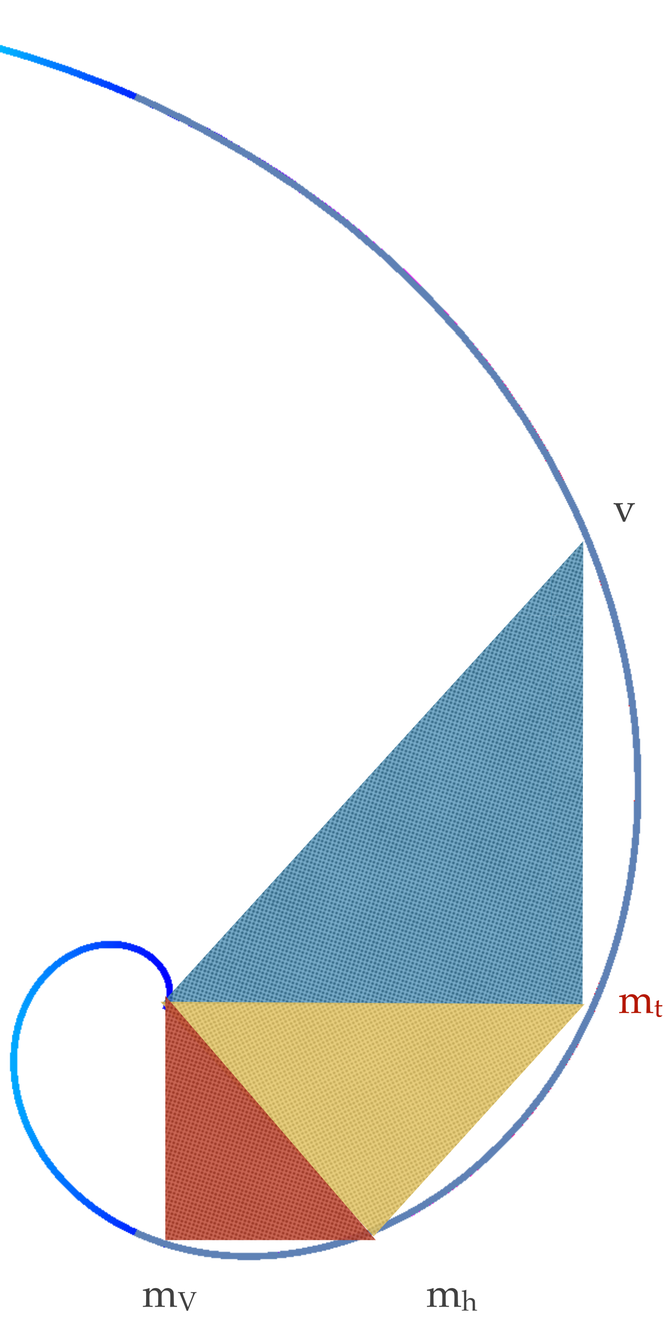


[Courtesy of Eleni Vryonidou, from Ethier et al., work in progress]

Conclusions & Outlook

The inception of the precision era

- The top quark is special, i.e. is the only standard quark in the standard model. It plays an important role and its electroweak behaviour could be a gateway to new physics.
- Tremendous improvements in the accuracy/precision of SM predictions have been achieved, opening a new realm of opportunities.
- The top-quark campaign of precision measurements at the LHC is entering a new phase measuring at unprecedented precision the main production channels and accessing for the first time rare final states.
- A far reaching approach to interpreting SM measurements is to constrain the top interactions by employing an EFT.
- Predictions are now available at NLO accuracy in QCD and constraints start to be obtained in a global way.
- Busy future ahead with even more room for TH/EXP collaborations.



Acknowledgements

Thanks to:

- Davide Pagani, Eleni Vryonidou, Ioannis Tsinikos for discussions and precious material.
- Rikkert Frederix and Carlo Oleari for useful discussions.

Additional material

TH calculations

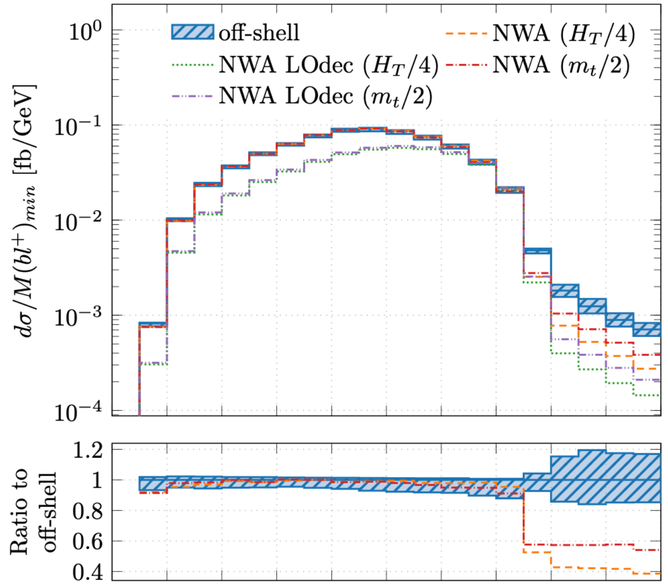
Rare processes

$t\bar{t}\gamma$ in ATLAS

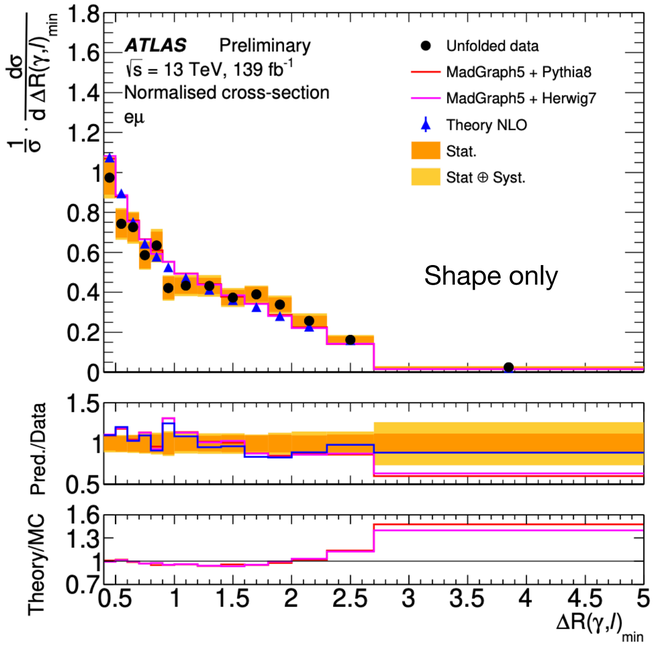
TH (NLO): $\sigma = 39.50\,^{+0.56}_{-2.18}\,(\text{scale})\,^{+1.04}_{-1.18}\,(\text{PDF})\,\text{fb}$

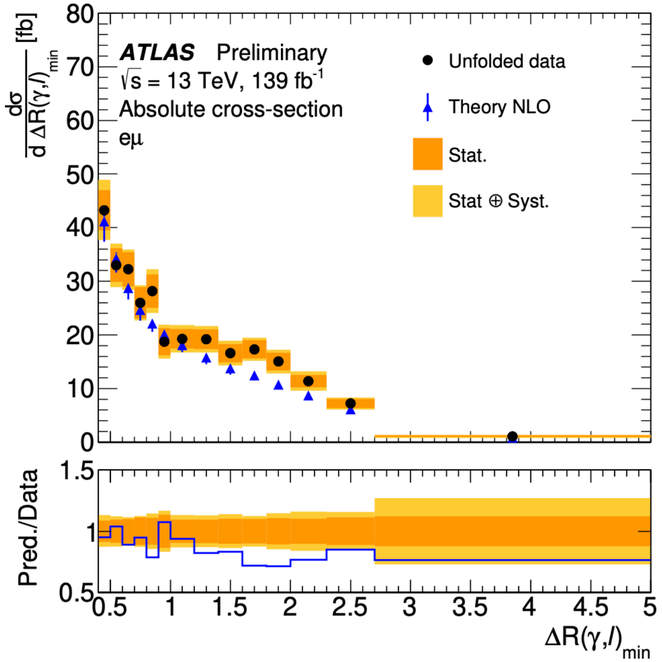
EXP: $\sigma = 44.2 \pm 2.6\,\text{fb}$

[Bevilacqua et al., 1803.09916]



[ATLAS, 2019]

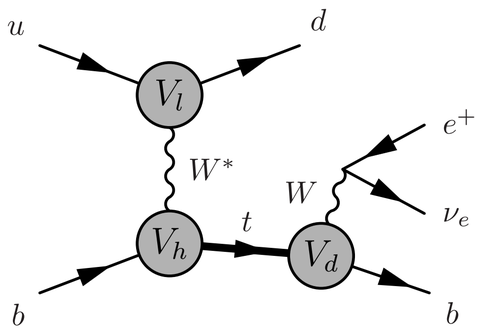


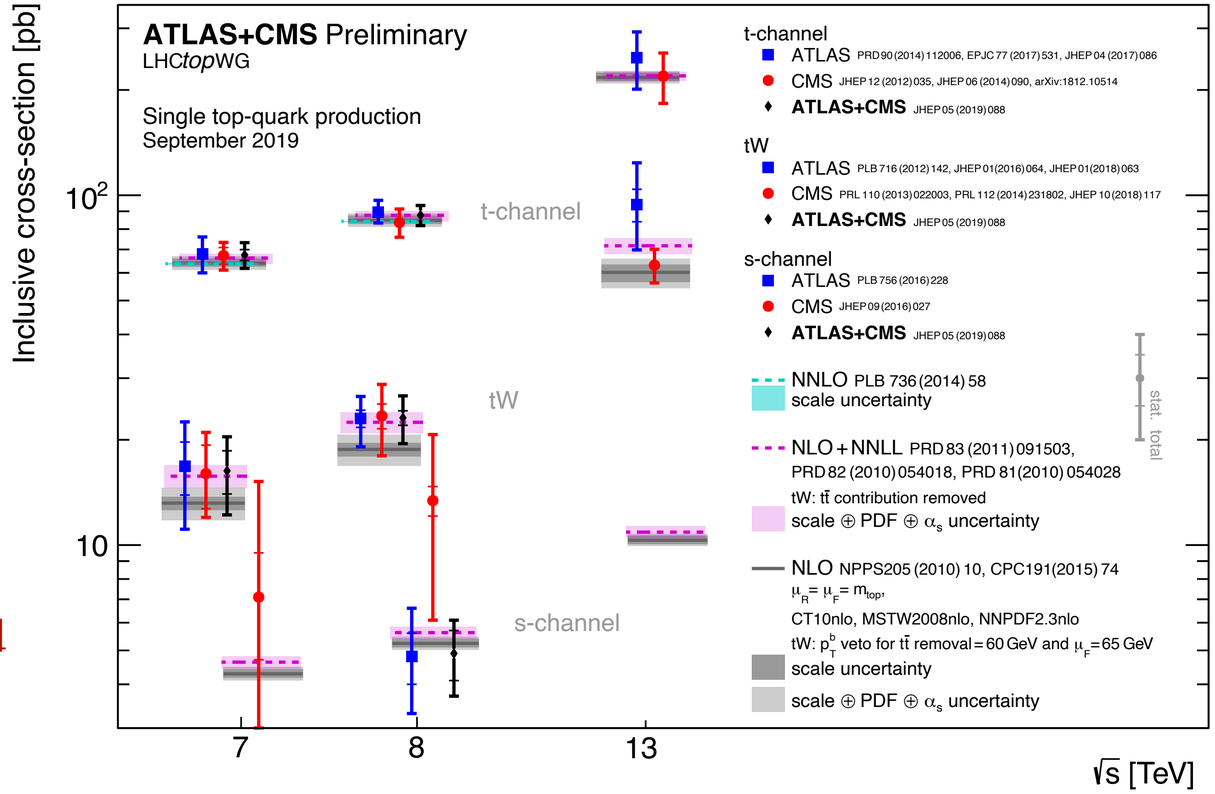


More details and insights in the talk by Giuseppe Bevilacqua.

Single-top t-channel

Status





NNLO QCD [Brucherseifer et al. 1404.7116] [Berger et al. 1606.08463] [Berger et al., 1708.09405]

NLO QCD+PS [MadGraph5_aMC@NLO] [POWHEG]

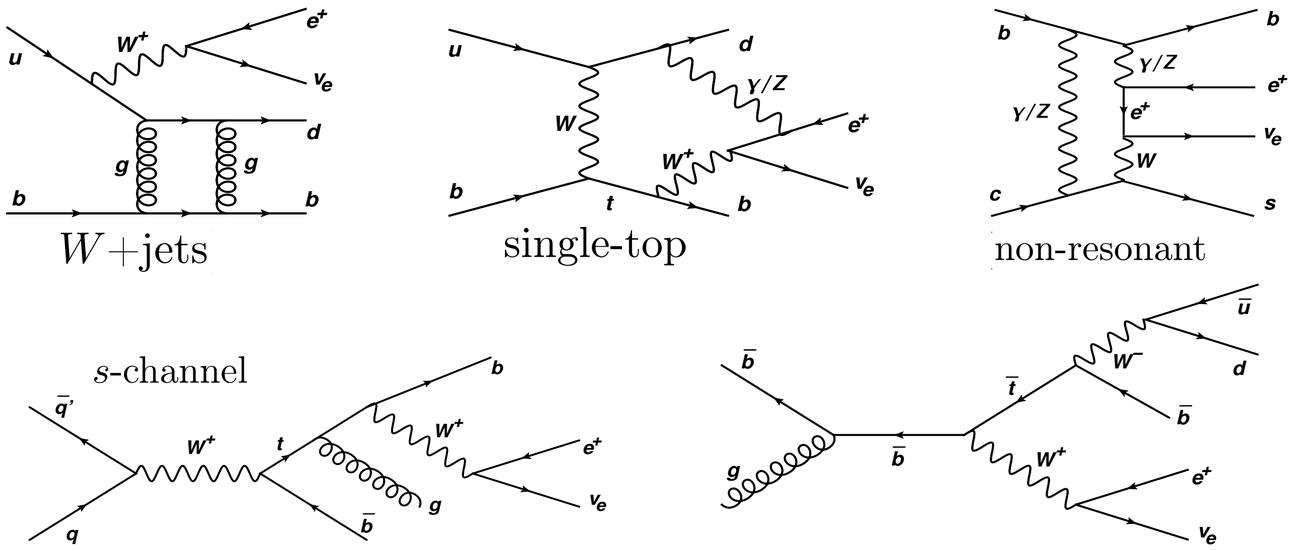
1+jet NLO QCD+PS [POWHEG]

NLO+QCD+OS+ PS+EW [Frederix et al. 1907.12586]

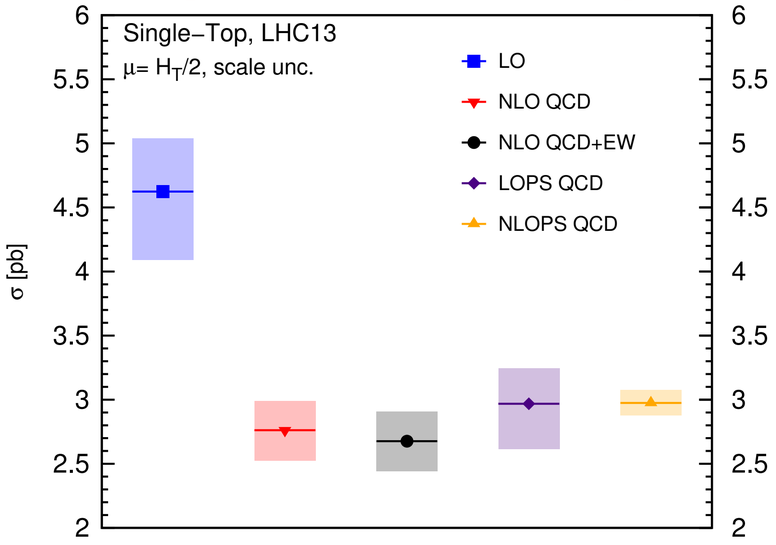
Single-top t-channel

Complete NLO+OS calculation

Complete NLO corrections to the $pp \to \nu_e J J J$ contribution to the t-channel signature, in the five-flavor-scheme, where J is a fully democratic (EW) jet.



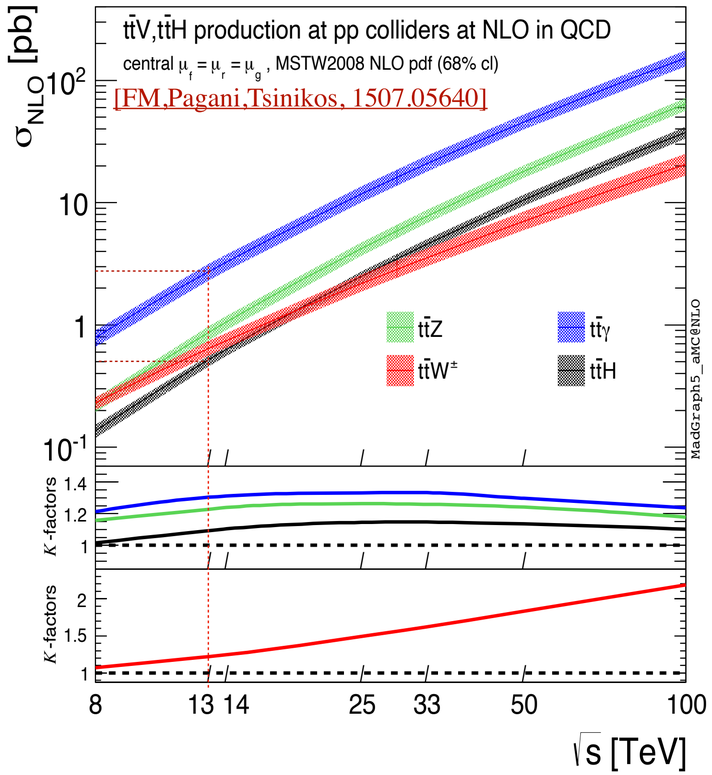
[Frederix et al. 1907.12586]



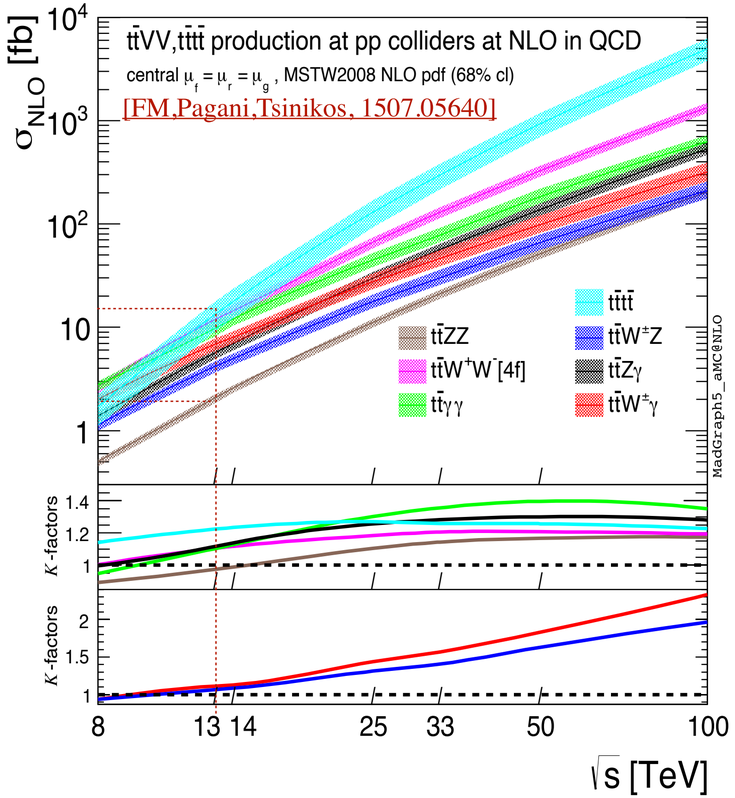
More details and insights in the talk by Davide Pagani.

Associated top production

$t\bar{t}H, t\bar{t}V, t\bar{t}VV, t\bar{t}t\bar{t}$



$\sim 0.5 - 3$ pb



$\sim 2 - 10$ fb

NLO (QCD+EW) + NLL

$t\bar{t}W^+$

Combined scales

Order	σ [fb]			A_C[%]		
$\mathrm{LO_{QCD}}$	233.297(8)	$^{+64.88(+27.8\%)}_{-47.26(-20.3\%)}$	$^{+6.16(+2.6\%)}_{-6.16(-2.6\%)}$	0		
$\mathrm{NLO_{QCD}}$	365.66(3)	$^{+57.95(+15.85\%)}_{-49.27(-13.5\%)}$	$^{+8.35(+2.3\%)}_{-8.35(-2.3\%)}$	2.68(1)	$^{+0.66(+24.6\%)}_{-0.47(-17.4\%)}$	$^{+0.08(+2.9\%)}_{-0.08(-2.9\%)}$
NLO	387.24(4)	$^{+62.05(+16.0\%)}_{-52.39(-13.5\%)}$	$^{+8.25(+2.1\%)}_{-8.25(-2.1\%)}$	2.85(1)	$^{+0.60(+21.1\%)}_{-0.42(-14.7\%)}$	$^{+0.09(+3.2\%)}_{-0.09(-3.2\%)}$
$\mathrm{nNLO_{QCD}}$	371.72(3)	$^{+51.11(+13.8\%)}_{-35.88(-9.7\%)}$	$^{+8.50(+2.3\%)}_{-8.50(-2.3\%)}$	3.30(2)	$^{+0.19(+5.8\%)}_{-0.08(-2.5\%)}$	$^{+0.09(+2.6\%)}_{-0.09(-2.6\%)}$
nNLO	393.29(4)	$^{+55.21(+14.0\%)}_{-39.00(-9.9\%)}$	$^{+8.40(+2.1\%)}_{-8.40(-2.1\%)}$	3.43(2)	$^{+0.21(+6.2\%)}_{-0.11(-3.3\%)}$	$^{+0.10(+2.9\%)}_{-0.10(-2.9\%)}$
$\mathrm{NLO_{QCD}}$+NNLL	362.59(8)	$^{+47.94(+13.2\%)}_{-29.95(-8.3\%)}$	$^{+8.26(+2.3\%)}_{-8.26(-2.3\%)}$	–		
NLO+NNLL	384.17(9)	$^{+51.52(+13.4\%)}_{-32.36(-8.4\%)}$	$^{+8.16(+2.1\%)}_{-8.16(-2.1\%)}$	–		

[Broggio et al., 1907.04343]

NLO (QCD+EW) + NLL

$t\bar{t}H$

Combined scales

Order	σ [fb]			A_C[%]		
$\mathrm{LO_{QCD}}$	336.25(3)	$^{+109.98(+32.7\%)}_{-77.07(-22.9\%)}$	$^{+7.42(+2.2\%)}_{-7.42(-2.2\%)}$	0		
$\mathrm{NLO_{QCD}}$	467.96(5)	$^{+45.57(+9.7\%)}_{-53.98(-11.5\%)}$	$^{+11.31(+2.4\%)}_{-11.31(-2.4\%)}$	0.88(1)	$^{+0.25(+28.9\%)}_{-0.17(-19.2\%)}$	$^{+0.04(+4.2\%)}_{-0.04(-4.2\%)}$
NLO	479.99(5)	$^{+47.46(+9.9\%)}_{-55.42(-11.5\%)}$	$^{+11.45(+2.4\%)}_{-11.45(-2.4\%)}$	1.05(1)	$^{+0.27(+25.5\%)}_{-0.18(-16.8\%)}$	$^{+0.04(+4.0\%)}_{-0.04(-4.0\%)}$
$\mathrm{nNLO_{QCD}}$	490.27(6)	$^{+18.56(+3.8\%)}_{-9.50(-1.9\%)}$	$^{+11.93(+2.4\%)}_{-11.93(-2.4\%)}$	0.87(4)	$^{+0.23(+26.4\%)}_{-0.01(-1.5\%)}$	$^{+0.04(+5.1\%)}_{-0.04(-5.1\%)}$
nNLO	502.31(6)	$^{+20.32(+4.0\%)}_{-10.95(-2.2\%)}$	$^{+12.06(+2.4\%)}_{-12.06(-2.4\%)}$	1.03(4)	$^{+0.20(+19.5\%)}_{-0.03(-2.6\%)}$	$^{+0.05(+4.7\%)}_{-0.05(-4.7\%)}$
$\mathrm{NLO_{QCD}}$+NNLL	484.33(7)	$^{+39.60(+8.2\%)}_{-29.43(-6.1\%)}$	$^{+11.78(+2.4\%)}_{-11.78(-2.4\%)}$	–		
NLO+NNLL	496.36(7)	$^{+38.64(+7.8\%)}_{-29.35(-5.9\%)}$	$^{+11.92(+2.4\%)}_{-11.92(-2.4\%)}$	–		

[Broggio et al., 1907.04343]

NLO (QCD+EW) + NLL

$t\bar{t}Z$

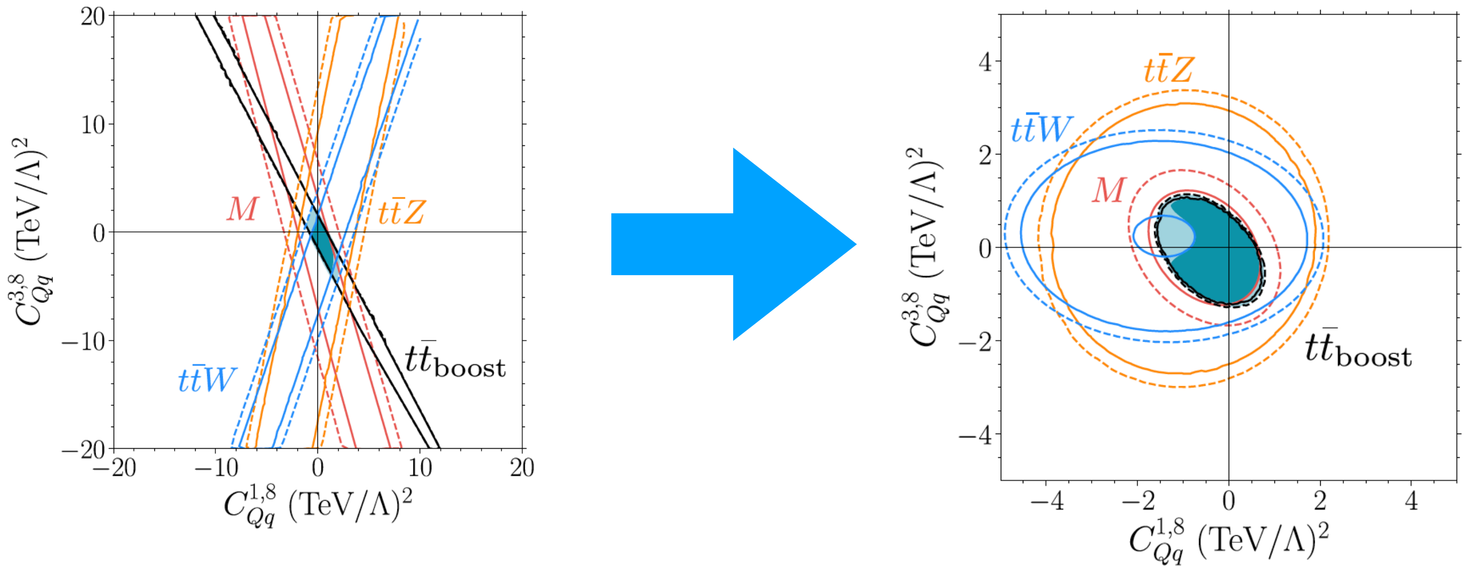
Combined scales						
Order	σ [fb]			A_C[%]		
$\mathrm{LO_{QCD}}$	484.26(4)	$^{+171.26(+35.4\%)}_{-117.32(-24.2\%)}$	$^{+11.05(+2.3\%)}_{-11.05(-2.3\%)}$	0		
$\mathrm{NLO_{QCD}}$	751.2(1)	$^{+111.1(+14.8\%)}_{-108.5(-14.4\%)}$	$^{+17.7(+2.4\%)}_{-17.7(-2.4\%)}$	0.79(2)	$^{+0.23(+29.0\%)}_{-0.15(-19.1\%)}$	$^{+0.05(+6.3\%)}_{-0.05(-6.3\%)}$
NLO	759.5(1)	$^{+110.1(+14.5\%)}_{-107.8(-14.2\%)}$	$^{+17.9(+2.4\%)}_{-17.9(-2.4\%)}$	0.87(2)	$^{+0.22(+25.0\%)}_{-0.14(-16.2\%)}$	$^{+0.05(+5.3\%)}_{-0.05(-5.3\%)}$
$\mathrm{nNLO_{QCD}}$	817.1(1)	$^{+42.3(+5.2\%)}_{-29.9(-3.7\%)}$	$^{+19.3(+2.4\%)}_{-19.3(-2.4\%)}$	0.96(4)	$^{+0.02(+1.7\%)}_{-0.07(-7.5\%)}$	$^{+0.06(+5.8\%)}_{-0.06(-5.8\%)}$
nNLO	825.4(1)	$^{+41.3(+5.0\%)}_{-29.3(-3.5\%)}$	$^{+19.5(+2.4\%)}_{-19.5(-2.4\%)}$	1.03(4)	$^{+0.01(+1.4\%)}_{-0.07(-6.3\%)}$	$^{+0.05(+5.2\%)}_{-0.05(-5.2\%)}$
$\mathrm{NLO_{QCD}}$+NNLL	802.6(2)	$^{+89.4(+11.1\%)}_{-78.1(-9.7\%)}$	$^{+19.0(+2.4\%)}_{-19.0(-2.4\%)}$	–		
NLO+NNLL	810.9(2)	$^{+89.2(+11.0\%)}_{-77.8(-9.6\%)}$	$^{+19.1(+2.4\%)}_{-19.1(-2.4\%)}$	–		

[Broggio et al., 1907.04343]

SMEFT

Linear vs quadratic

At the fitting level the squared can have an important effect, as there are no flat directions in the fit with the squares:



[Brivio et al., 1910.03606]

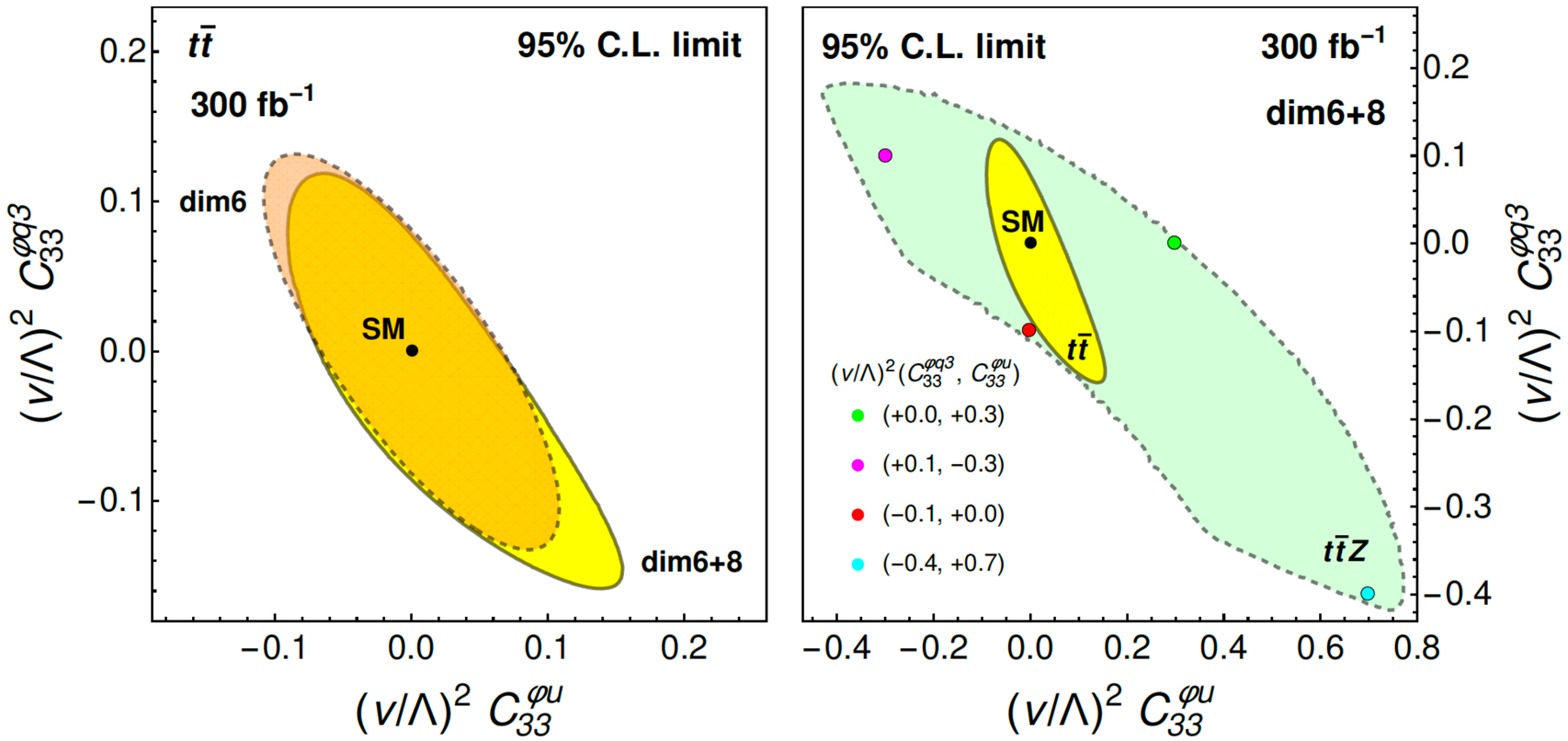
In general without knowing the effect of the squares one is left in the dark about the meaning/reliabilty of the fit.

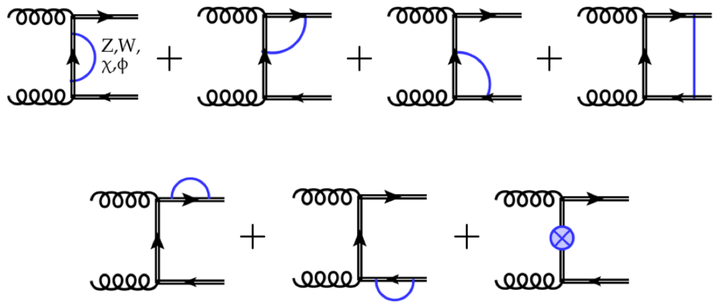
Always provide constraints using i) linear and ii) linear+squared terms

SMEFT

$t\bar{t}Z$ couplings from loops in $t\bar{t}$

[Martini 1911.11244]





$$Q_{33}^{\varphi q1} = \left(\varphi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu \varphi\right)\ (\bar{t}'_{\mathrm{L}}\gamma^\mu t'_{\mathrm{L}}),$$

$$Q_{33}^{\varphi q3} = \left(\varphi^\dagger \mathrm{i}\tau^I \overleftrightarrow{D}_\mu \varphi\right)\ (\bar{t}'_{\mathrm{L}}\tau^I\gamma^\mu t'_{\mathrm{L}}),$$

$$Q_{33}^{\varphi u} = \left(\varphi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu \varphi\right)\ (\bar{t}'_{\mathrm{R}}\gamma^\mu t'_{\mathrm{R}}),$$

SMEFT

Top-philic scenario

- Same flavour symmetries as baseline scenario
- Assumes new physics couples more strongly to 3rd-generation LH doublet and RH up-type singlet (+ bosons)

$$c_{t\varphi}^{[I]}, \quad c_{\varphi Q}^{-}, \quad c_{\varphi Q}^{3}, \quad c_{\varphi t}, \quad c_{tW}^{[I]}, \quad c_{tZ}^{[I]}, \quad c_{tG}^{[I]},$$

$$c_{\varphi tb}^{[I]} \text{ and } c_{bW}^{[I]} \quad \text{appear proportional to } y_b$$

$$c_{QQ}^{1}, \quad c_{QQ}^{8}, \quad c_{Qt}^{1}, \quad c_{Qt}^{8}, \quad c_{tt}^{1},$$

$$c_{QDW} = c_{Qq}^{3,1} = c_{Ql}^{3(\ell)},$$

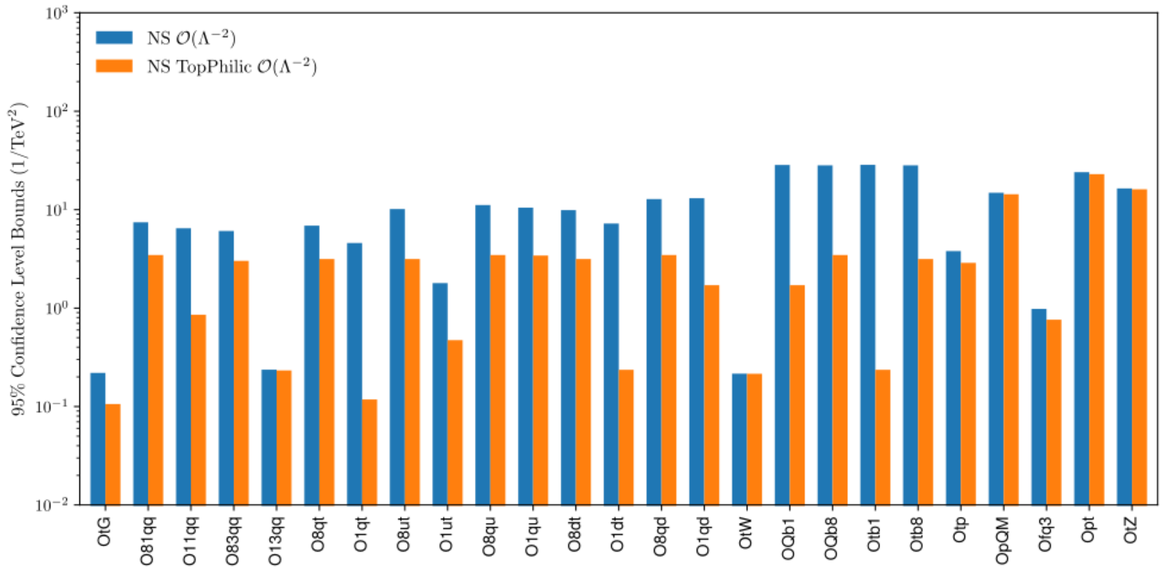
$$c_{QDB} = 6c_{Qq}^{1,1} = \frac{3}{2}c_{Qu}^{1} = -3c_{Qd}^{1} = -3c_{Qb}^{1} = -2c_{Ql}^{1(\ell)} = -c_{Qe}^{(\ell)},$$

$$c_{tDB} = 6c_{tq}^{1} = \frac{3}{2}c_{tu}^{1} = -3c_{td}^{1} = -3c_{tb}^{1} = -2c_{tl}^{(\ell)} = -c_{te}^{(\ell)},$$

$$c_{QDG} = c_{Qq}^{1,8} = c_{Qu}^{8} = c_{Qd}^{8} = c_{Qb}^{8},$$

$$c_{tDG} = c_{tq}^{8} = c_{tu}^{8} = c_{td}^{8} = c_{tb}^{8}.$$

- 34 parameter basis reduced to 19 free parameters

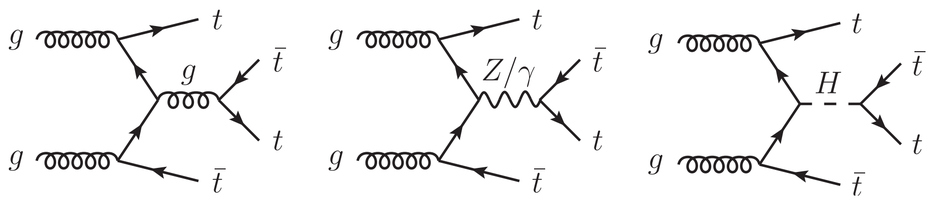


Reducing the number of dofs leads to an improvement of the bounds as could be expected. The pattern, however is not always trivial.

SMEFT

$t\bar{t}t\bar{t}$: the power of 4

The cross section depends on y_t to the fourth power.
It does not depend on Γ_H, since the Higgs is off-shell.



$$\kappa_t \equiv y_{Htt}/y_{Htt}^{\rm SM}$$

$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \boxed{\kappa_t^2}\sigma^{\rm SM}_{\rm int} + \boxed{\kappa_t^4}\sigma^{\rm SM}(t\bar{t}t\bar{t})_H$$

$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} \propto |\mathcal{M}_g + \mathcal{M}_{Z/\gamma}|^2 ,$$
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_H \propto |\mathcal{M}_H|^2 ,$$
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int} \propto \mathcal{M}_{g+Z/\gamma}\mathcal{M}_H^\dagger + \mathcal{M}_{g+Z/\gamma}^\dagger\mathcal{M}_H$$

In combination with the measurement of $t\bar{t}H$ both y_t and Γ_H can be determined.

[Cao et al., 1602.01934]

$$\sigma(pp \to t\bar{t}H \to t\bar{t}xx)$$

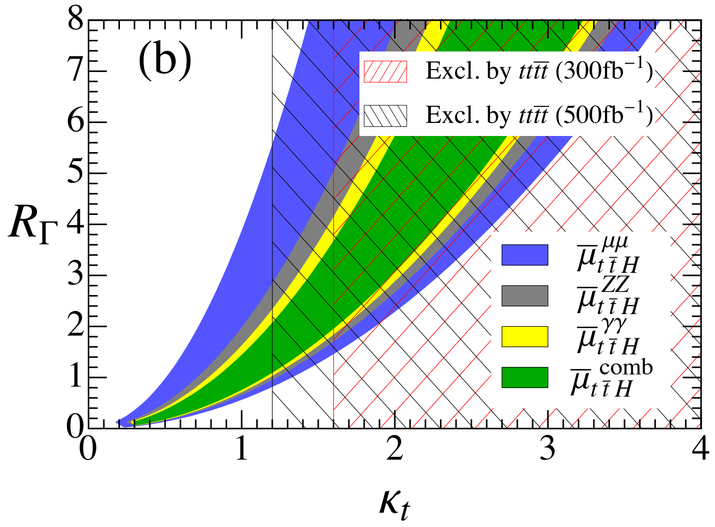
$$\mu_{t\bar{t}H}^{xx} \equiv \frac{\sigma}{\sigma^{\rm SM}} = \frac{\kappa_t^2\kappa_x^2}{R_\Gamma}$$
$$R_\Gamma \equiv \frac{\Gamma_H}{\Gamma_H^{\rm SM}}$$

100 TeV

$$0.962 \le \kappa_t \le 1.031$$

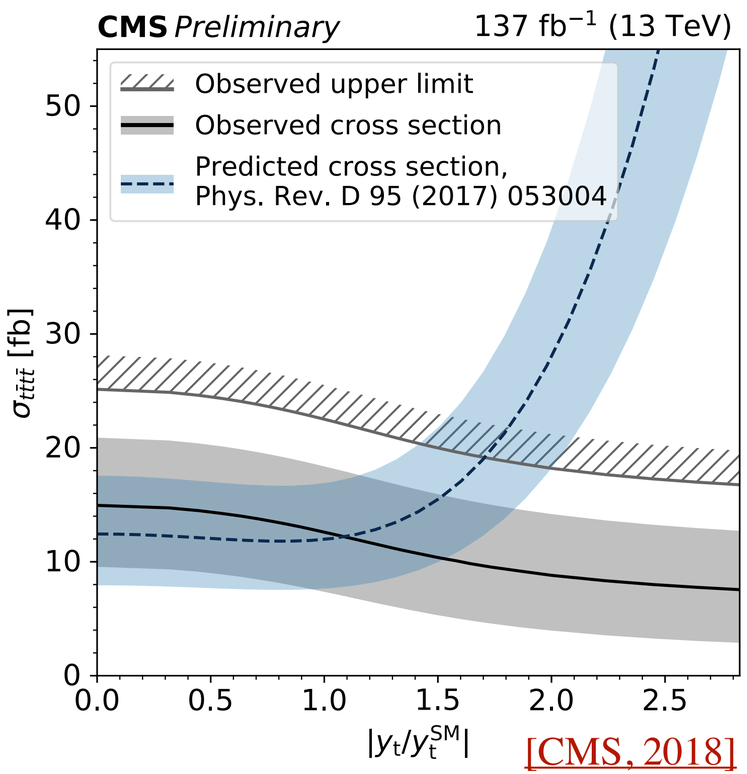
$$0.91\ \Gamma_{\rm H}^{\rm SM} \le \Gamma_{\rm H} \le 1.08\ \Gamma_{\rm H}^{\rm SM}$$

for $\mathcal{L} = 30$ ab^{-1}



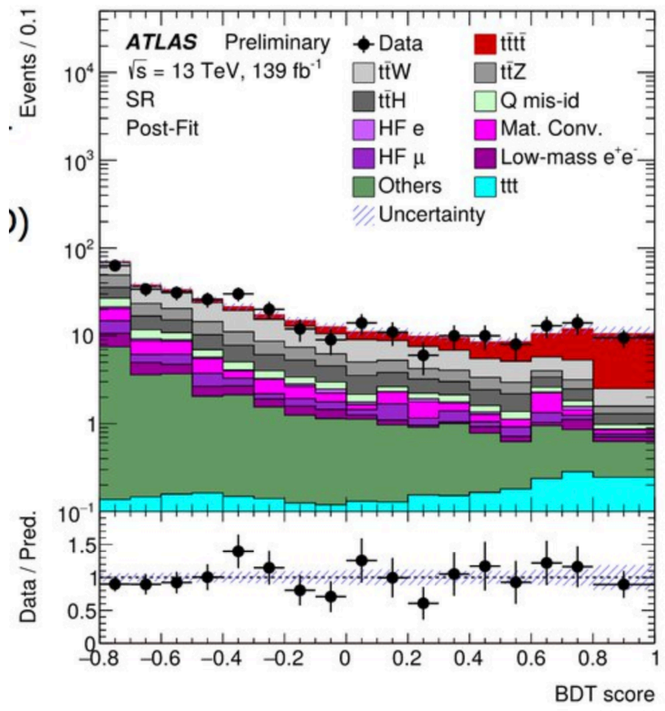
SMEFT

$t\bar{t}t\bar{t}$: the power of 4



[CMS, 2018]

$$\sigma(4t) = 24 + 7 - 6\,\text{fb}$$



[ATLAS, 2020]

Blue band: **LO** calculation **rescaled** to the **SM C-NLO** predictions.

95% confidence level limit of $|y_t/y_t^{SM}| < 1.7$

SMEFT

$t\bar{t}t\bar{t}$: the power of 4

$$\mathcal{O}_T = \frac{c_T}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)^2 \qquad \mathcal{O}_{2W} = -\frac{c_{2W}}{4M^2}(D_\rho W^a_{\mu\nu})^2$$

$$\mathcal{O}_{WB} = \frac{gg' c_{WB}}{M^2} H^\dagger \sigma^a H B^{\mu\nu} W^a_{\mu\nu} \qquad \mathcal{O}_{2B} = -\frac{c_{2B}}{4M^2}(\partial_\rho B_{\mu\nu})^2$$

$$\mathcal{O}_\Box = \frac{c_\Box}{M^2}|\Box H|^2 \qquad \mathcal{O}_{2G} = -\frac{c_{2G}}{4M^2}(D_\rho G^a_{\mu\nu})^2$$

$$\mathcal{O}_B = \frac{ig' c_B}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$$

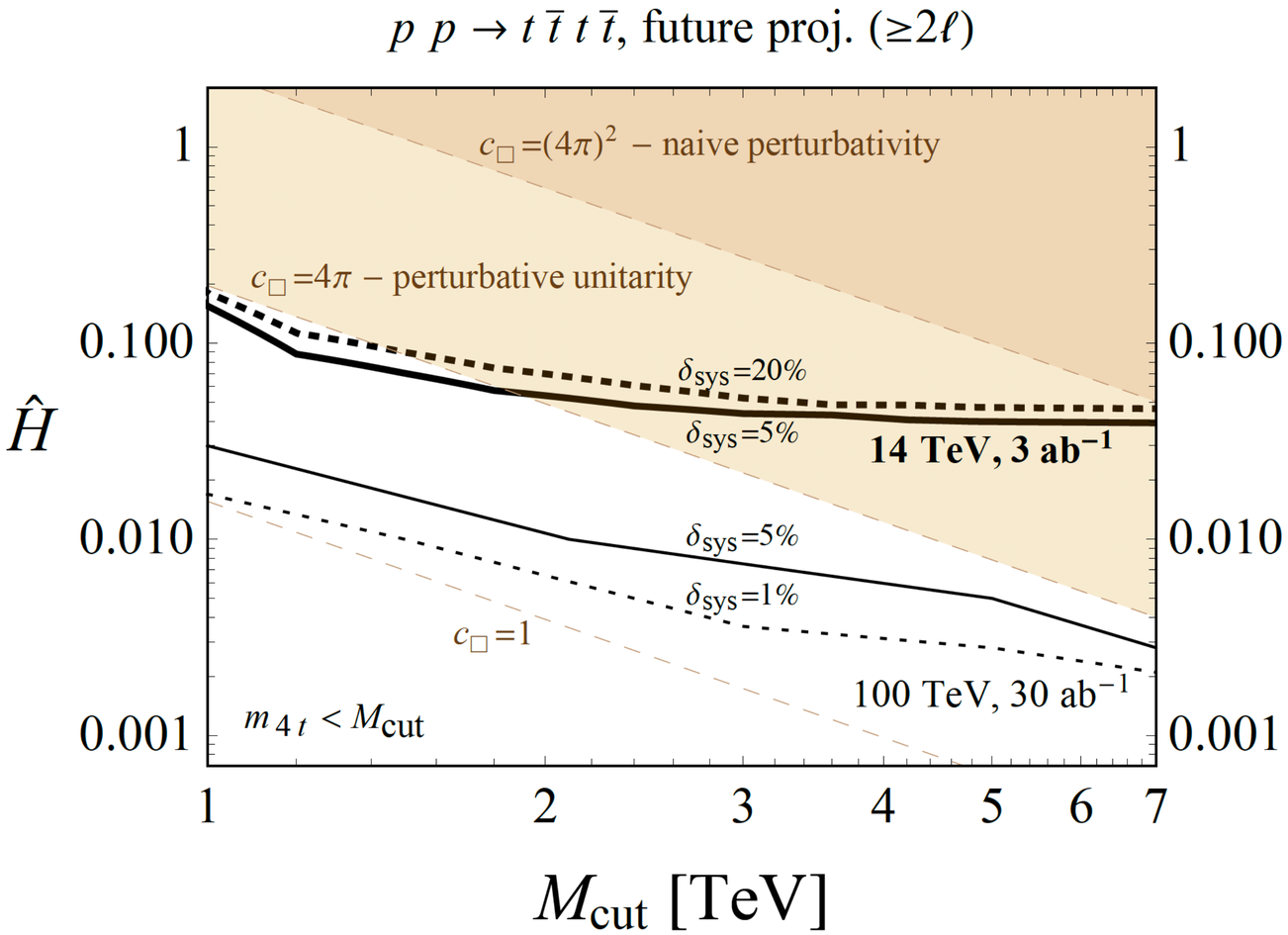
$$\mathcal{O}_W = \frac{ig c_W}{2M^2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}$$

$$\hat{S} = 4\left(c_{WB} + \frac{c_W + c_B}{4}\right)\frac{m_W^2}{M^2} \qquad \hat{T} = c_T \frac{v^2}{M^2}$$

$$\hat{W} = c_{2W}\frac{m_W^2}{M^2} \qquad \hat{Y} = c_{2B}\frac{m_W^2}{M^2}$$

$$\hat{Z} = c_{2G}\frac{m_W^2}{M^2} \qquad \hat{H} = c_\Box \frac{m_h^2}{M^2}$$

[Englert et al., 1903.07725]



SMEFT

$t\bar{t}t\bar{t}$: C-NLO

[Frederix et al., 1711.02116]

13 TeV

$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
LO_2	-26.0	-28.3	-30.5
LO_3	32.6	39.0	45.9
LO_4	0.2	0.3	0.4
LO_5	0.02	0.03	0.05
NLO_1	14.0	62.7	103.5
NLO_2	8.6	-3.3	-15.1
NLO_3	-10.3	1.8	16.1
NLO_4	2.3	2.8	3.6
NLO_5	0.12	0.16	0.19
NLO_6	< 0.01	< 0.01	< 0.01
$NLO_2 + NLO_3$	-1.7	-1.6	0.9

Naive estimate

10
1
0.1
10
1
0.1
0.01
0.001
0.0001

100 TeV

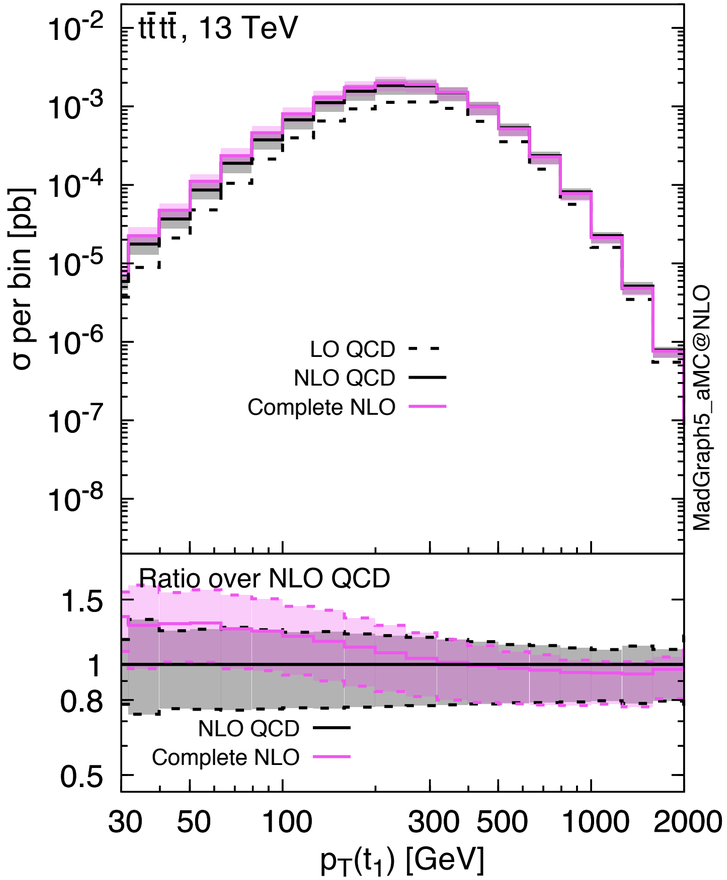
$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
LO_2	-18.7	-20.7	-22.8
LO_3	26.3	31.8	37.8
LO_4	0.05	0.07	0.09
LO_5	0.03	0.05	0.08
NLO_1	33.9	68.2	98.0
NLO_2	-0.3	-5.7	-11.6
NLO_3	-3.9	1.7	8.9
NLO_4	0.7	0.9	1.2
NLO_5	0.12	0.14	0.16
NLO_6	< 0.01	< 0.01	< 0.01
$NLO_2 + NLO_3$	-4.2	-4.0	2.7

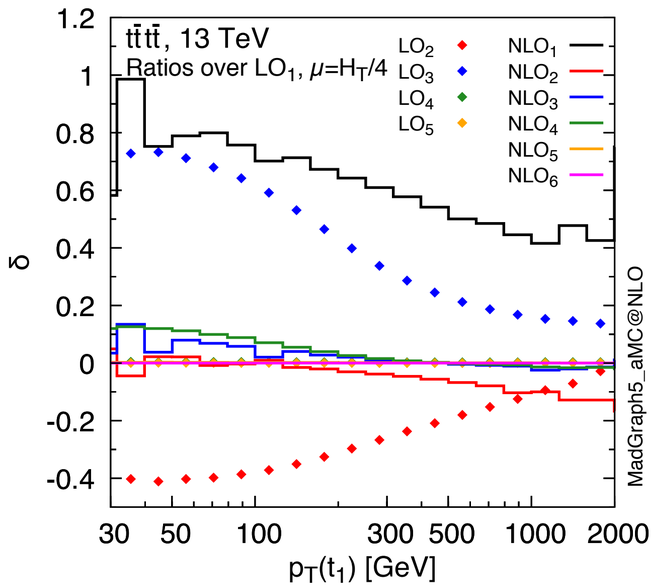
LO_2 and LO_3 are large and have also large cancellations. NLO_2 and NLO_3 are mainly given by 'QCD corrections' on top of them, so they are large and strongly depend on the scale choice, at variance with standard EW corrections. Accidentally, relatively to LO_1 , NLO_2+NLO_3 scale dependence almost disappear.

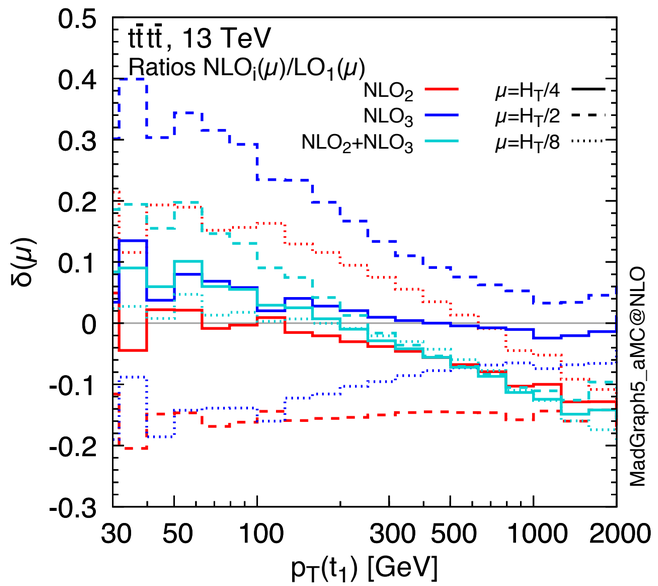
SMEFT

$t\bar{t}t\bar{t}$: C-NLO

[Frederix et al., 1711.02116]



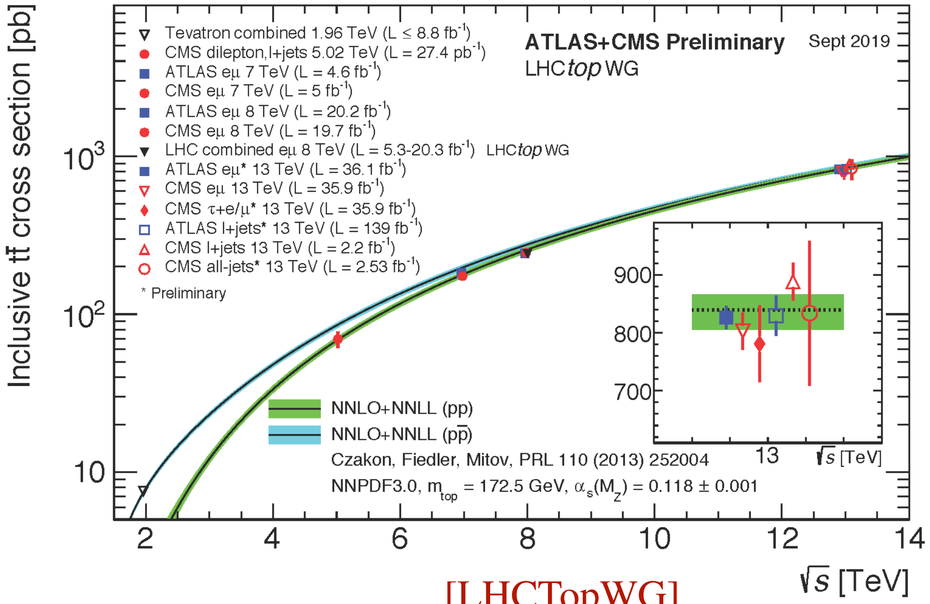




Additional material

Exp results

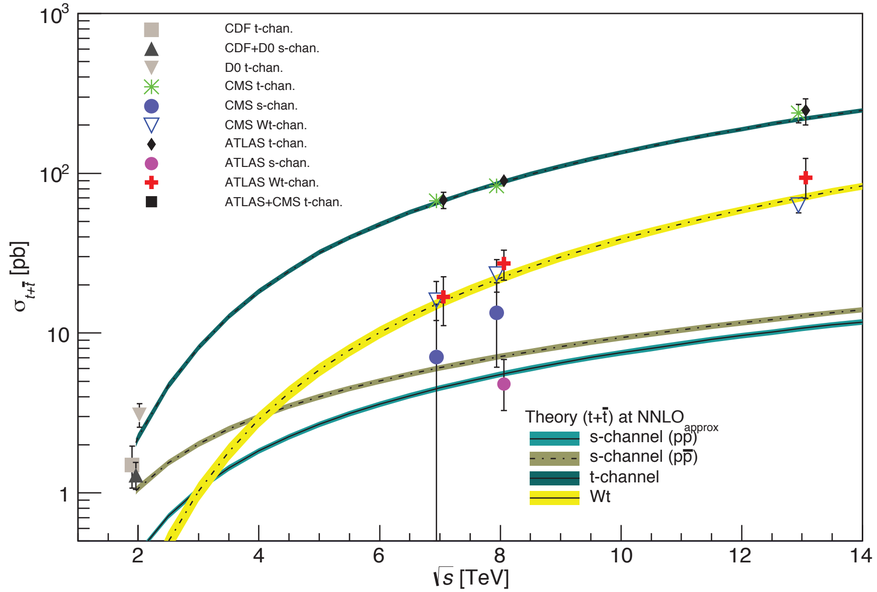
$\sigma(t\bar{t})$



[LHCTopWG]

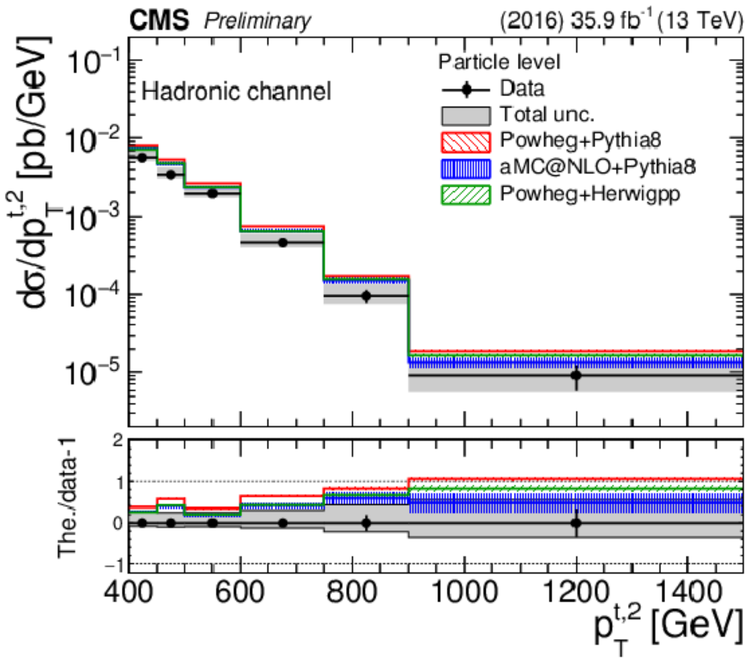
[PDG]

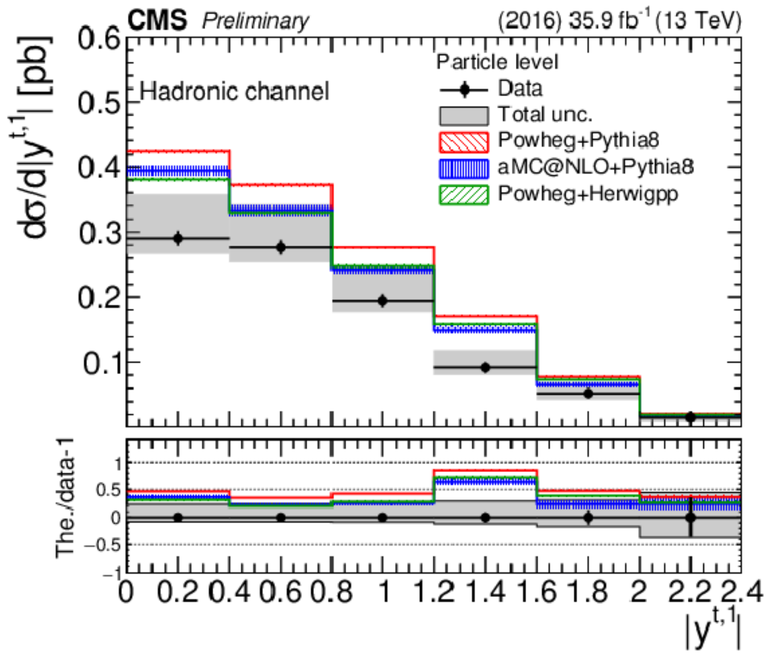
$\sigma(t)$



Precision top physics

High-p_T tops in $t\bar{t}$



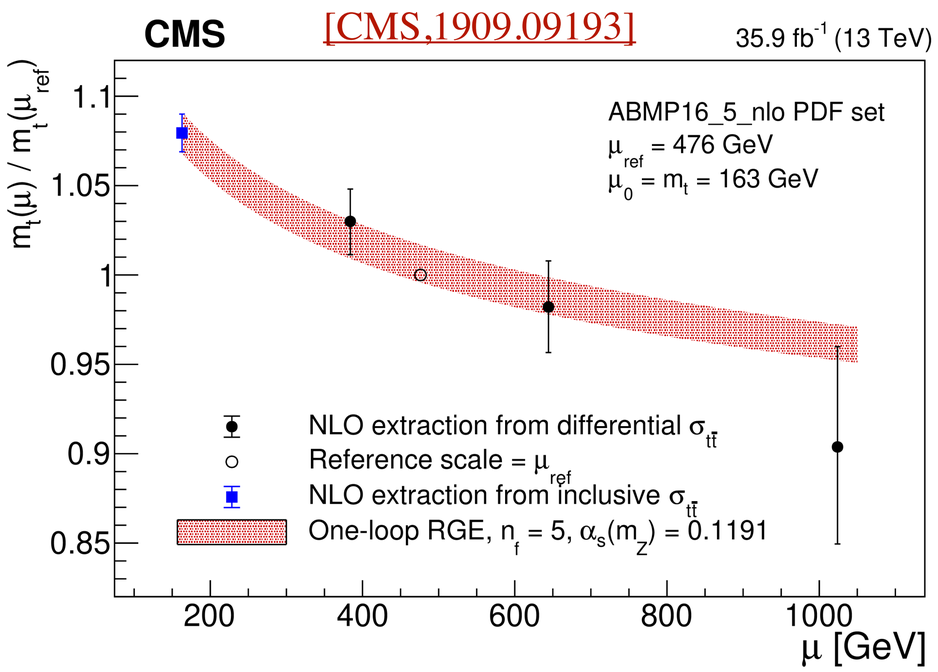


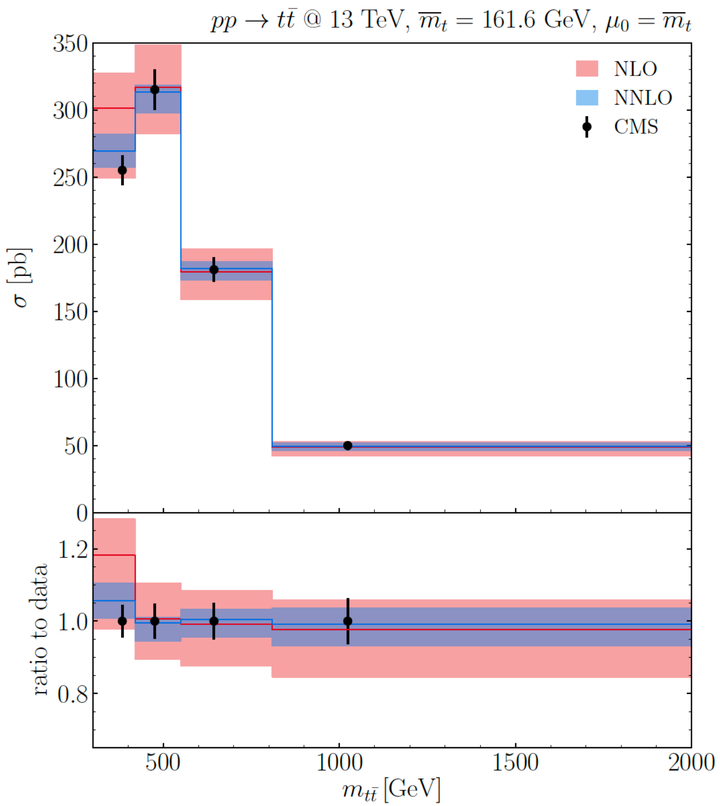
[CMS, 2020]

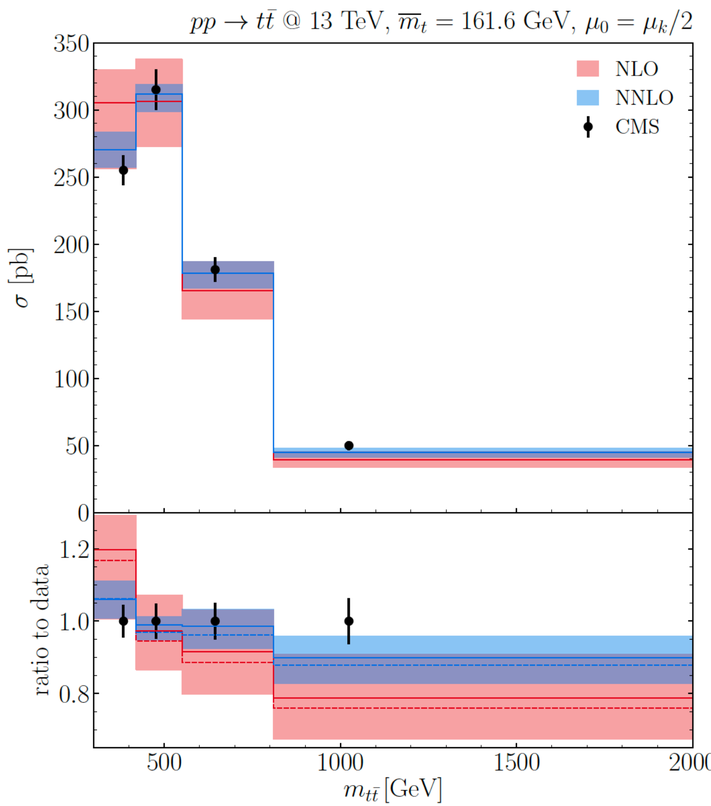
Shapes ok. Rates are significantly smaller than predicted.

Running top mass

CMS measurement





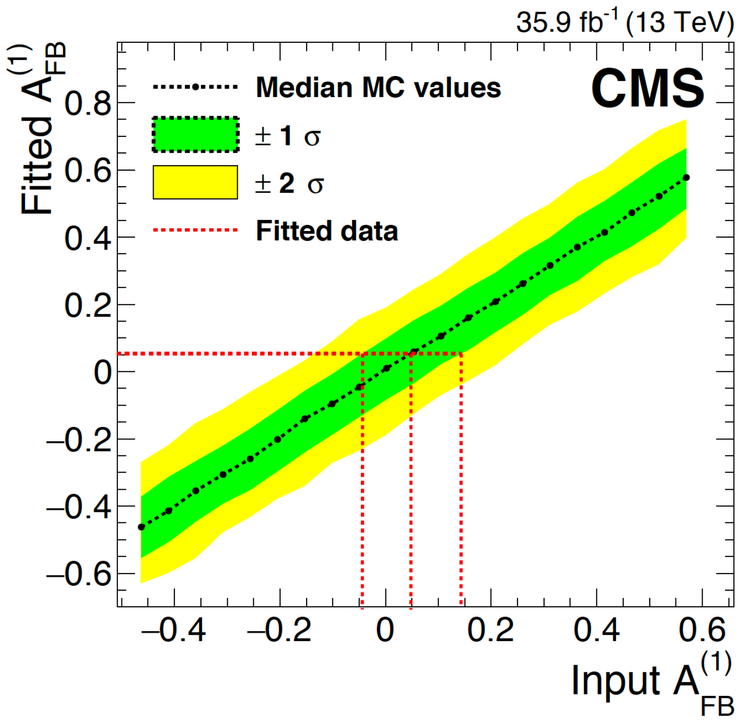


The interpretation of the CMS analysis has been put into question in [Catani et al. 2005.00557] where no evidence for the running is found.

Precision top physics

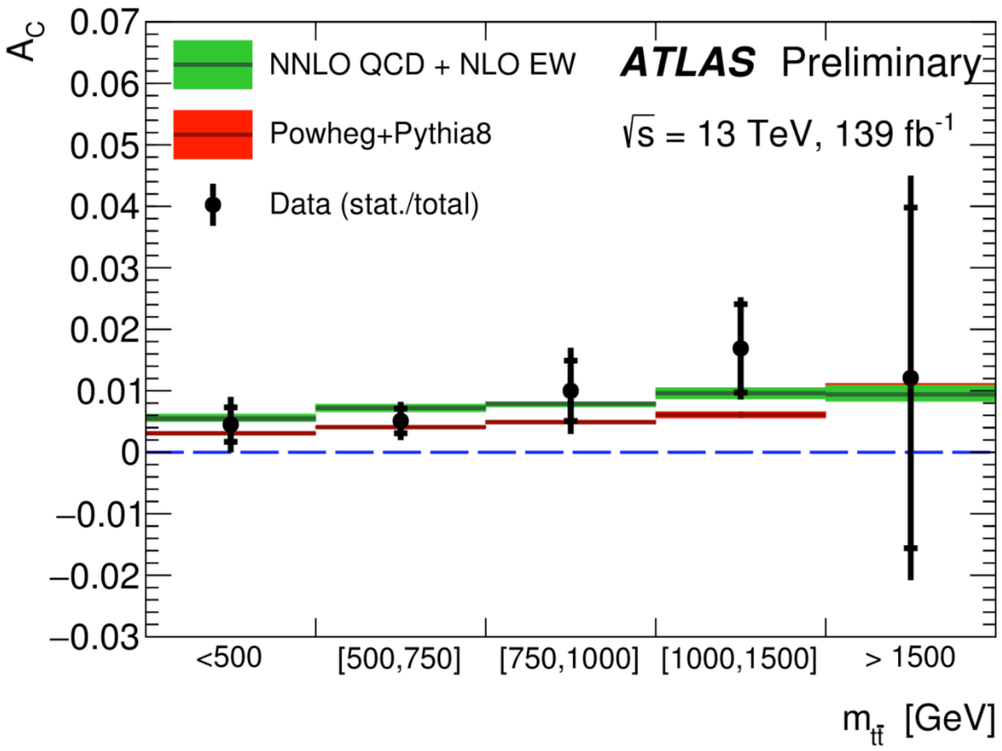
$t\bar{t}$ Asymmetries CMS and ATLAS

[CMS,1912.09540]



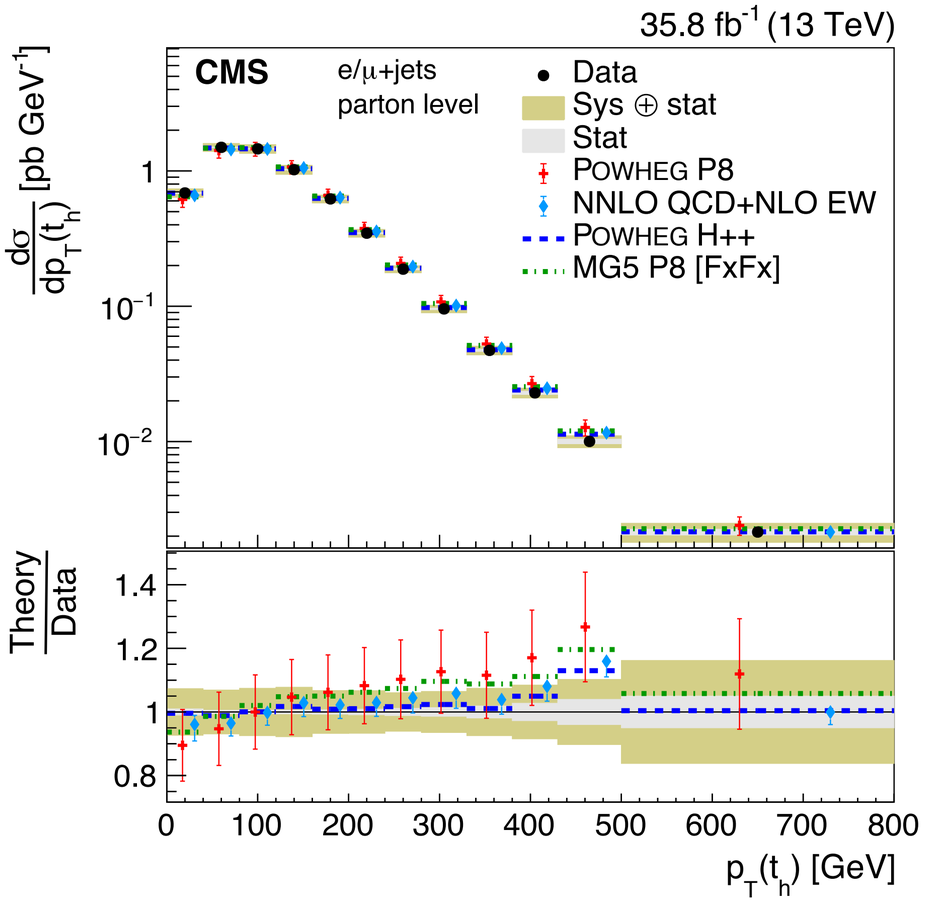
$$\frac{d\sigma}{dc^*}(q\bar{q}) = K\frac{\pi\alpha_S^2}{9m_{t\bar{t}}^2}\beta\left\{2-\beta^2+\beta^2c^{*2}+\alpha\left(1-\beta^2c^{*2}\right)+2\left[2-\frac{2}{3}\beta^2+\alpha\left(1-\frac{1}{3}\beta^2\right)\right]A_{FB}^{(1)}c^*\right\}$$

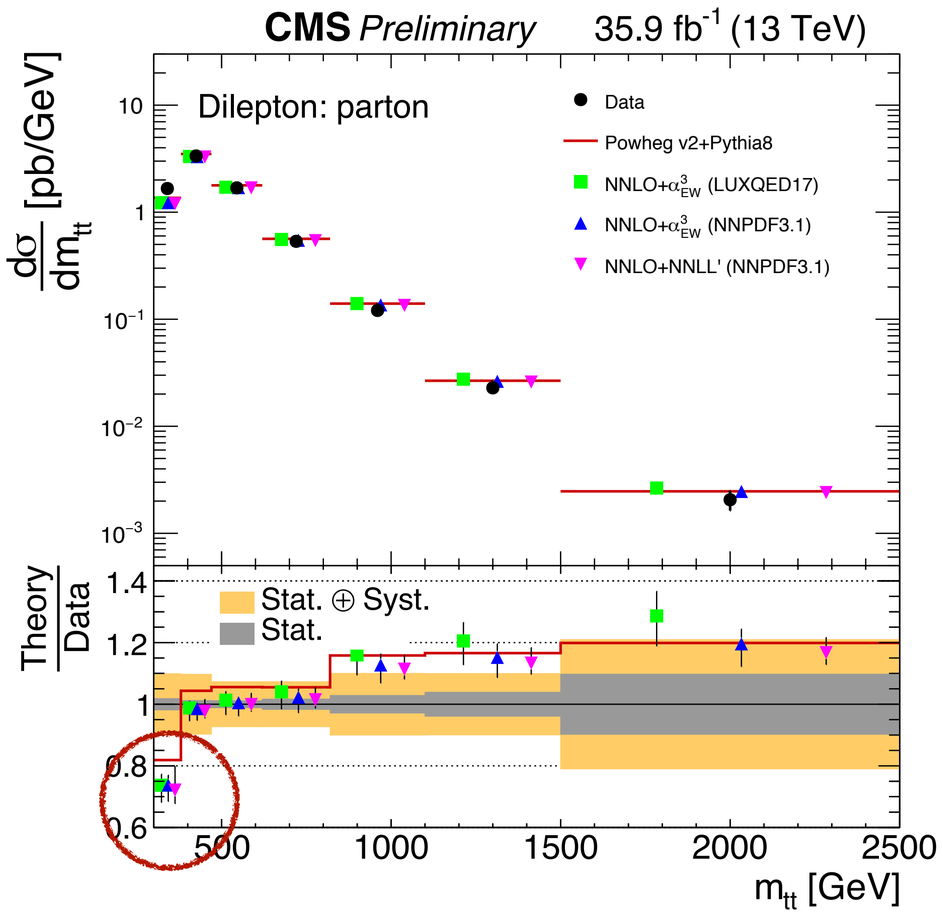
[Czakon et al. 1711.03945] [ATLAS, 2019]



Precision top physics

Differential $t\bar{t}$ distributions



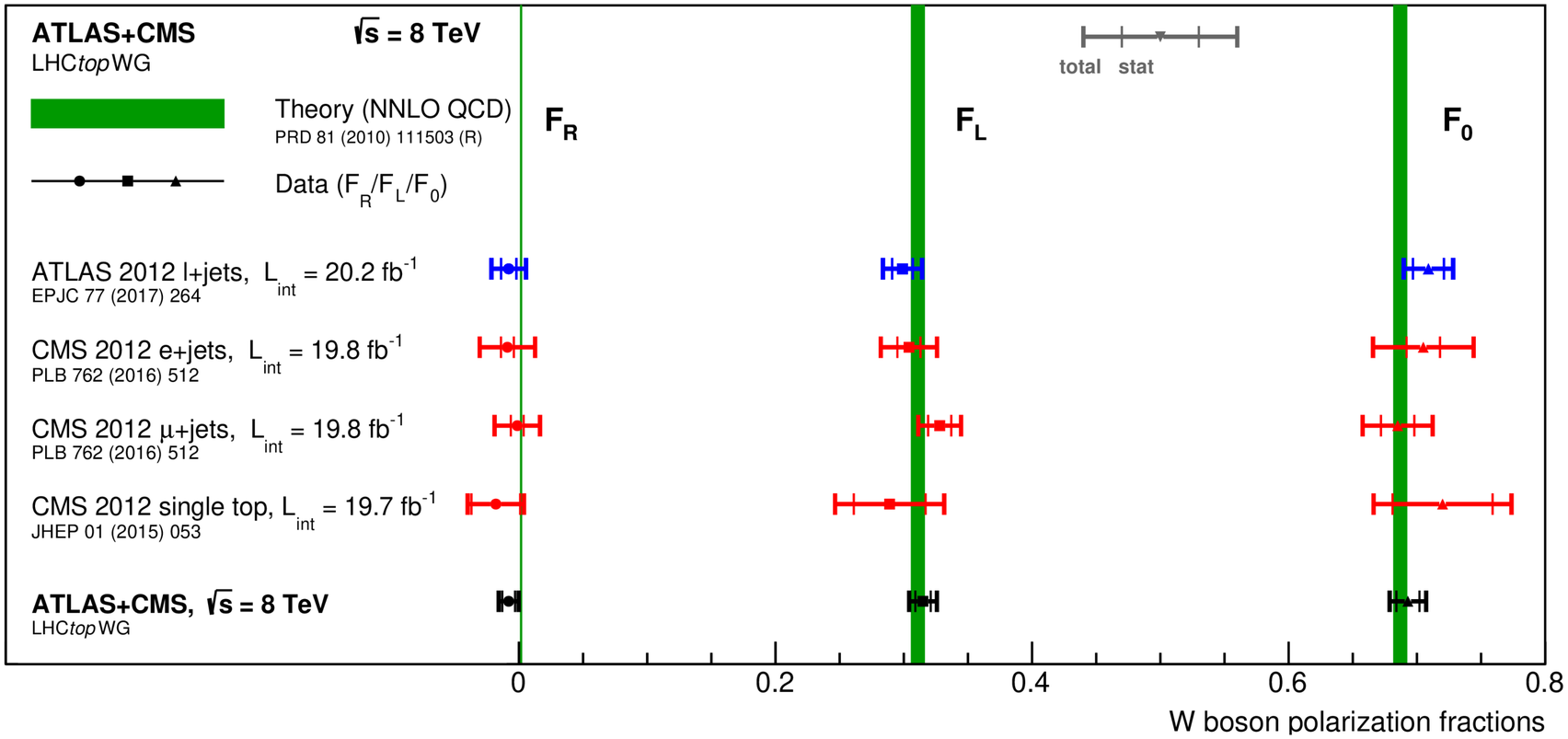


[CMS, 1803.08856]

Precision top physics

W-helicity fractions

[ATLAS+CMS, 2005.03799]

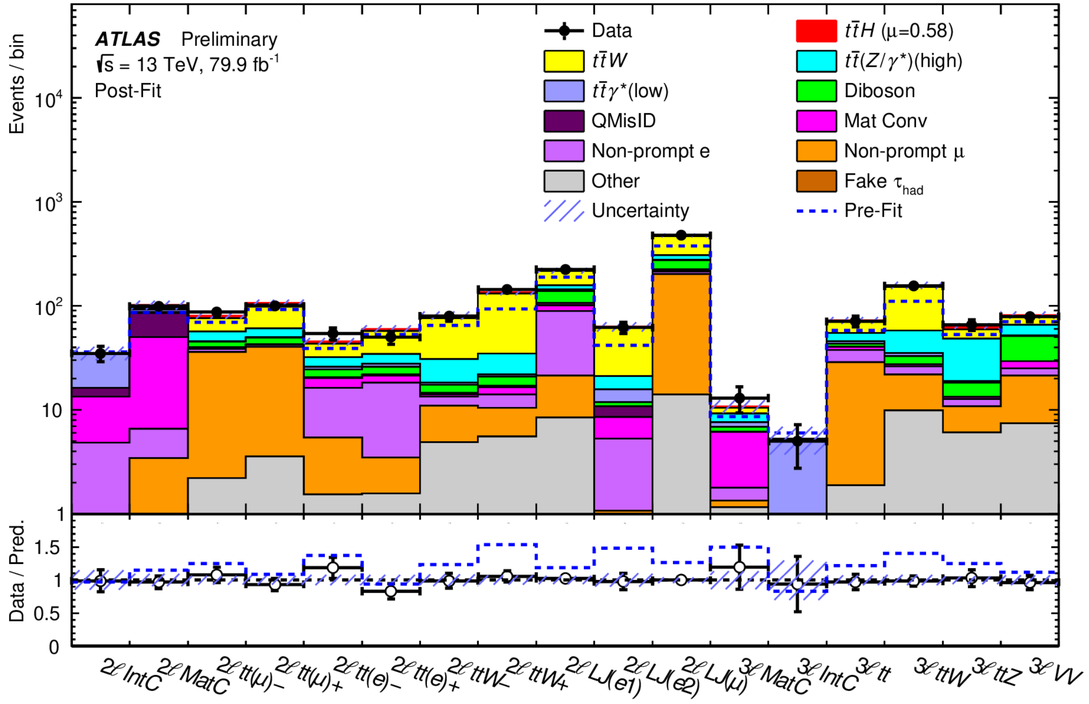


$$F_0 = 0.693 \pm 0.014$$
$$F_L = 0.315 \pm 0.011$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$

Rare processes

$t\bar{t}W$ background to $t\bar{t}H$ needs to be scaled up in ATLAS analysis



Normalisation factors for several important irreducible and reducible backgrounds are determined by the fit (see Section 6). Of particular interest are the three measured normalisation factors for the $t\bar{t}W$ background in the 2ℓSS and 3ℓ event categories: $\hat{\lambda}^{2\ell\mathrm{LJ}}_{t\bar{t}W} = 1.56^{+0.30}_{-0.28}$, $\hat{\lambda}^{2\ell\mathrm{HJ}}_{t\bar{t}W} = 1.26^{+0.19}_{-0.18}$, and $\hat{\lambda}^{3\ell}_{t\bar{t}W} = 1.68^{+0.30}_{-0.28}$. They are consistent with each other and systematically above unity, indicating a preference of the data for a higher value of the $t\bar{t}W$ cross section than the updated $t\bar{t}W$ theoretical cross section (see Section 3). Because the $t\bar{t}W$ modelling uncertainties are constructed to only affect the shapes of distributions while the total yield is fixed, the normalisation factors represent a scaling factor for $t\bar{t}W$ events selected in this analysis. Uncertainties to extrapolate the $t\bar{t}W$ scaling factor to the inclusive phase space are not included.

More details and insights in the talk by Ioannis Tsinikos

[ATLAS, 2019]