The XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021)

Top Quark Physics

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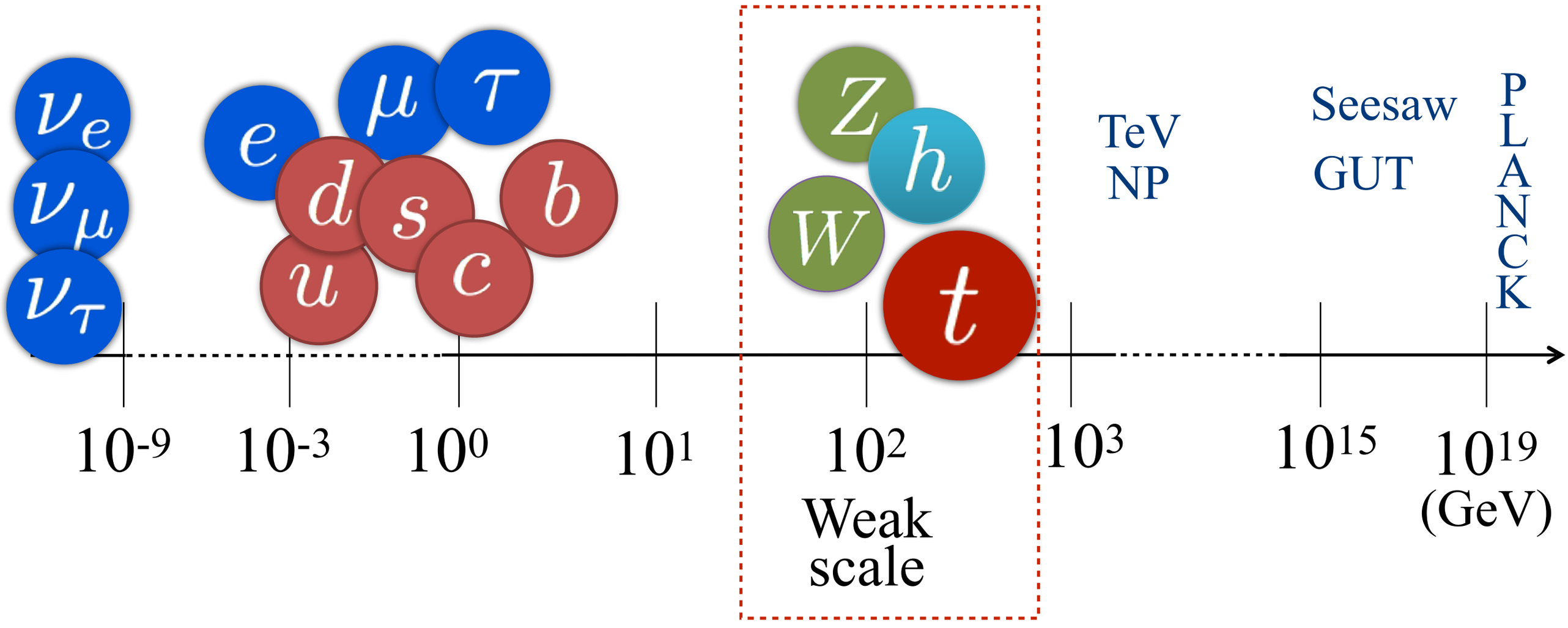
Peking University

Aug 24, 2021

Two outstanding puzzles in SM

Origins of EWSB and Flavor breaking

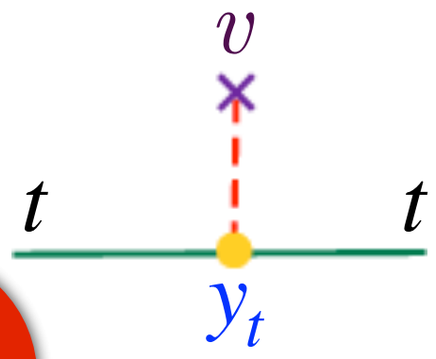


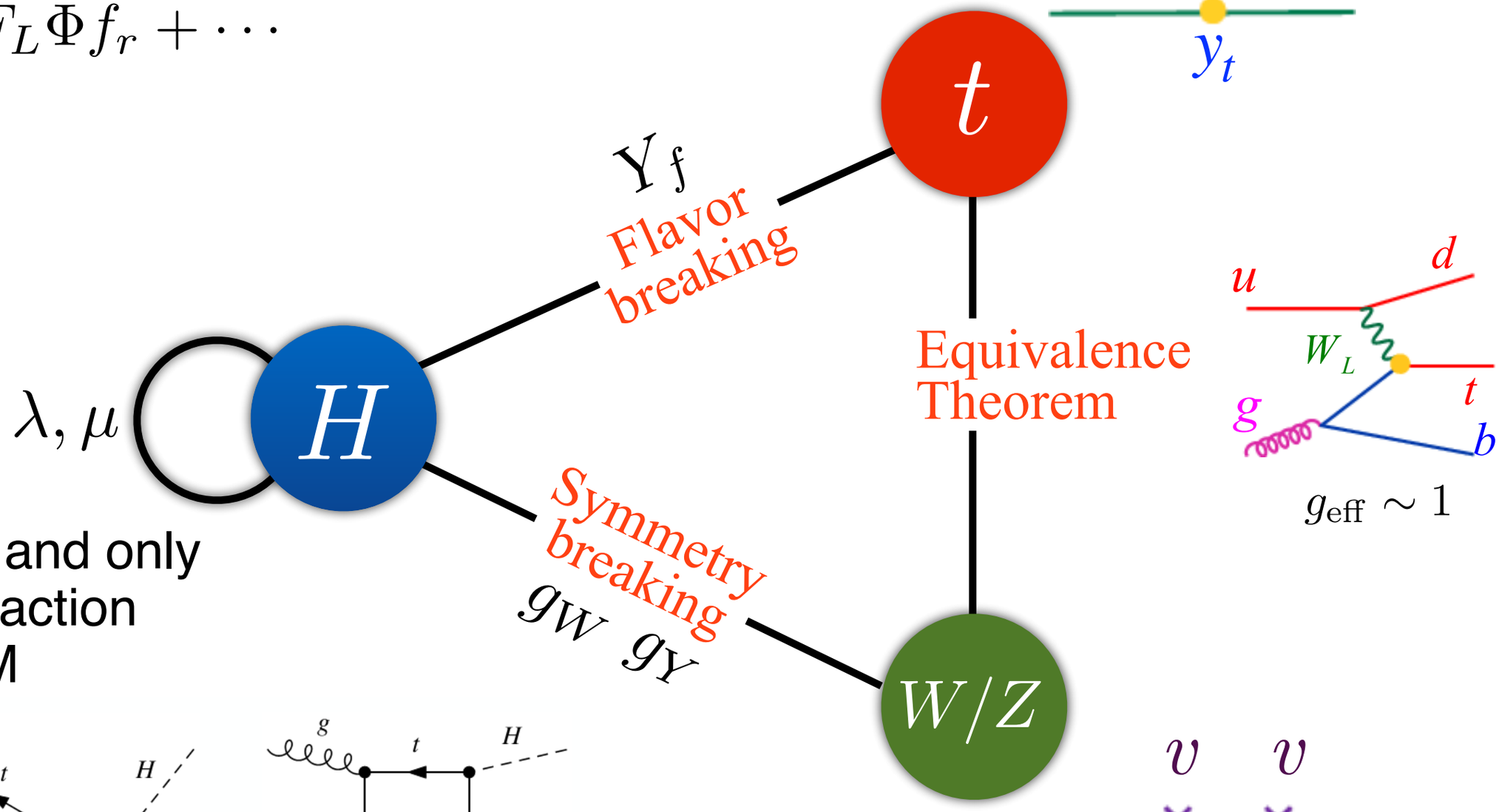
Top quark is not heavy! It is naturally around weak scale.

Why are the other quarks and leptons so light?

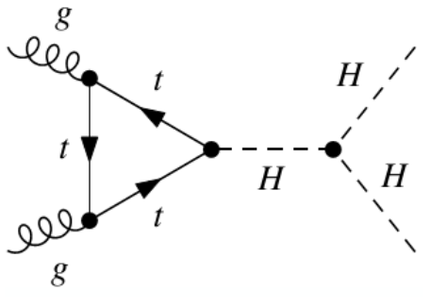
Testing the SM at weak scale

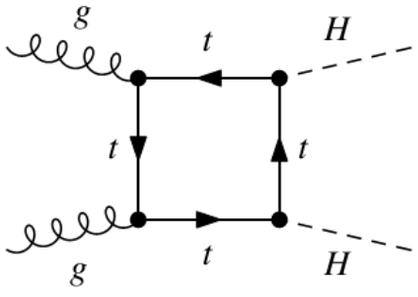
$$\mathcal{L} = \left(D_\mu \Phi\right)^\dagger \left(D^\mu \Phi\right) - \mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2$$
$$+ y_f \bar{F}_L \Phi f_r + \cdots$$

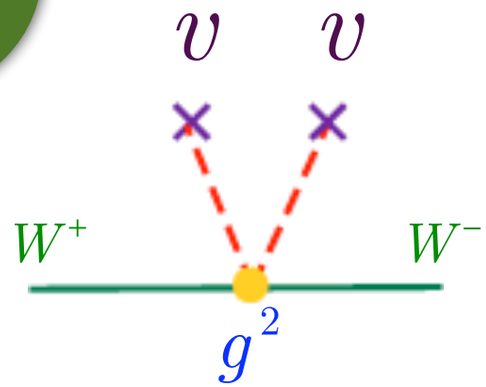




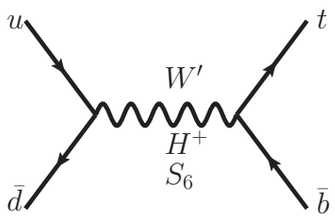
The one and only self-interaction in the SM

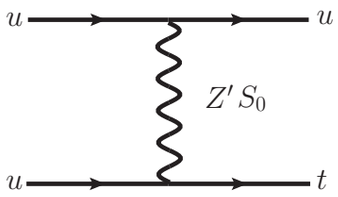


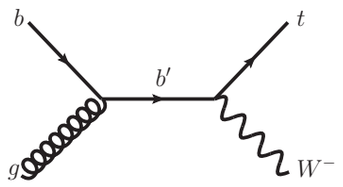


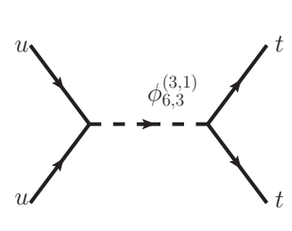


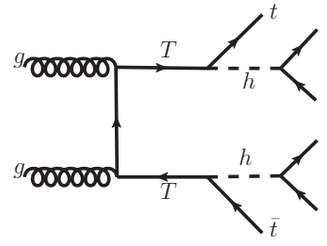
Top quark often appears in NP resonance decays

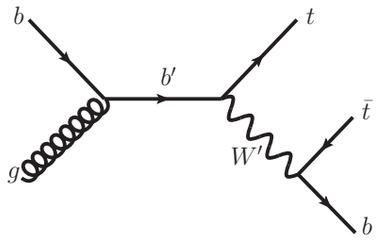












Single top quark

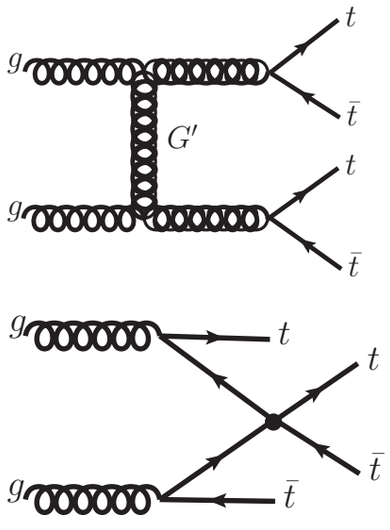
Tait, Yuan, 0007298
QHC, Wudka, Yuan, 0704.2809
Andrea, Fuks, Maltoni 1106.6199
Wang, Li, Shao,Zhang, 1109.5963
Nutter, Schwienhorst, Walker, Yu, 1207.5179
Li, Liu, Shu 1306.5841
Drueke, Nutter, Schwienhorst,Vignaroli, Walker 1409.7607
Neumann, Sullivan, 1903.11023
Kraus, Martini, Peitzsch, Uwer 1908.09100
QHC, Jiang, Zeng 2105.04464
…

Top quark pair

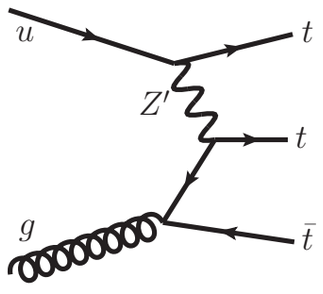
Mohapatra, Okada, Yu, 0709.1486
Bar-Shalom, Rajaraman, Whiteson, Yu, 0803.3795
Berger, QHC, Chen, Shaughnessy, Zhang, 1005.2622
Zhang, Berger, QHC, Chen, Shaughnessy, 1009.5379
Aguilar-Saavedra, Perez-Victoria, 1104.1385
Berger, QHC, Chen, Li, Zhang, 1101.5625
Atwood, Gupta, Soni, 1301.2250
Goldouzian, Yu, 1408.0493
Hou, Kohda, Modak, 1808.00333
Ozsimsek, Ari, Cakir, 2105.03982
…

Four top quarks

Darmé, Fuks, Goodsell, 1805.10835
Zhou, Whiteson, Tait, 1203.5862
Zhang, 1708.05928
Hou, Kohda, Modak, 1906.09703
Alvarez, Juste, Seoane, 1910.09581
Darmé, Fuks,Maltoni, 2104.09512
QHC, Fu, Liu, Wang,Zhang, 2105.03372
Carpenter, Murphy, Smylie, 2107.13565
…



Triple top quarks

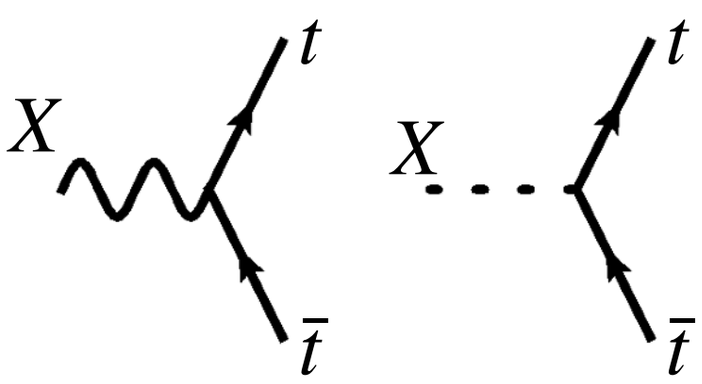


Barger,Keung, Yencho,1001.0221
Han, Liu, Wu, Yang 1203.2321
Chen, PLB736 (2014)
Kohda, Modak,Hou,1710.07260
QHC, Chen, Liu,Wang,1901.04643
Hou, Kohda, Modak 1906.09703
H. Khanpour 1909.03998
Khatibi, Khanpour 2011.15060
Boos, Dudko,2107.07629
..

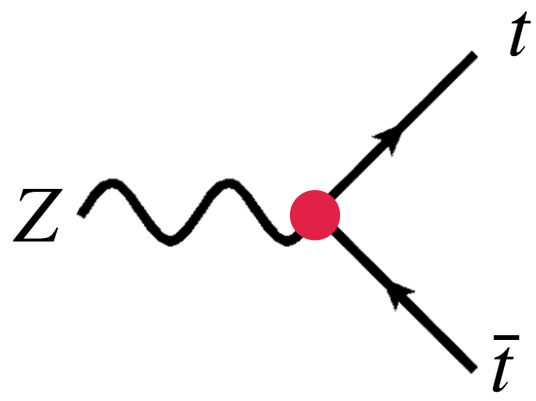
My apologies if I missed your works here

Top quark as a good probe of NP

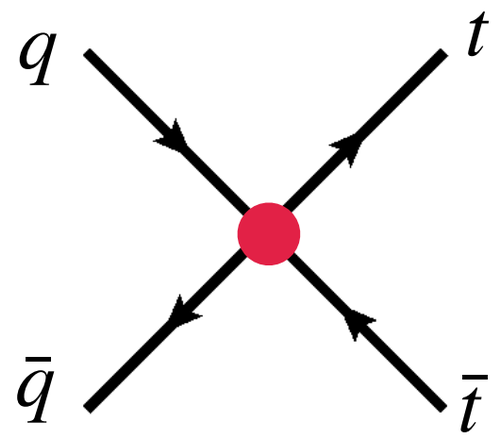
It often appears in the decay of NP resonances and involved in the symmetry breaking mechanism.



NP Resonance decays



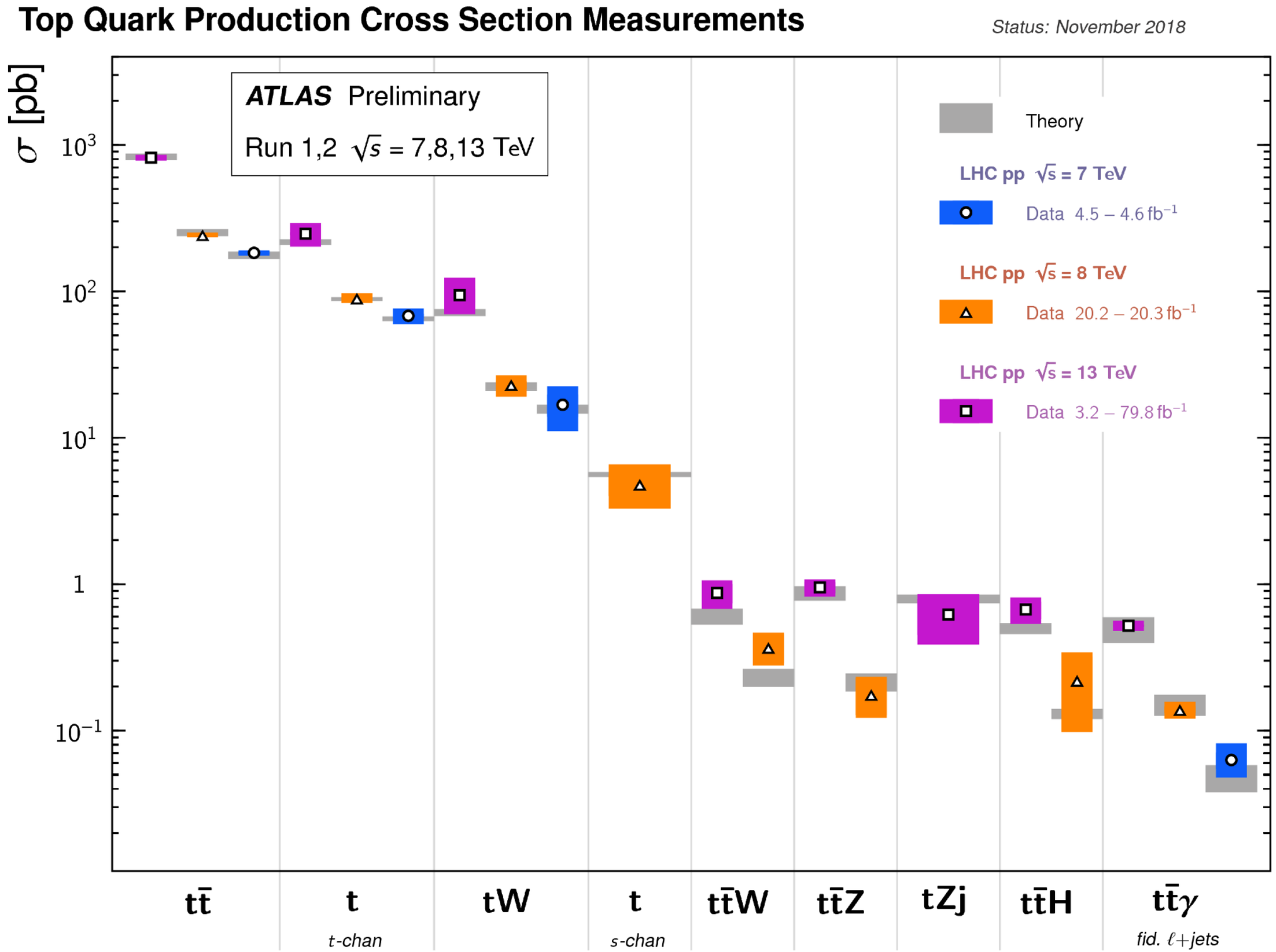
Effective couplings



Effective operators

We are in an era of **top quark precisions** at the LHC.

1. Top quark precisions in the SM

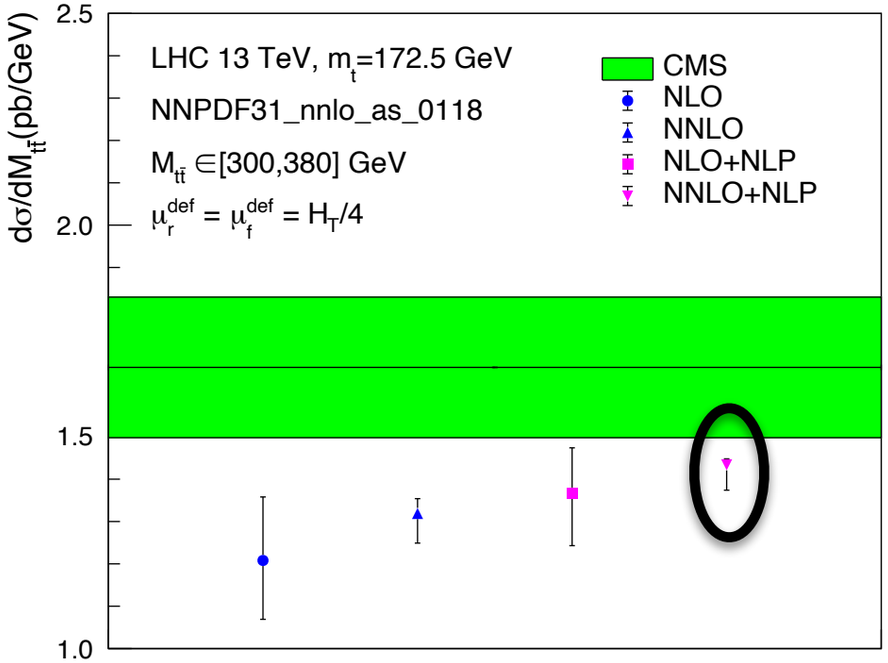


Top pair production at Next-to-Leading Power

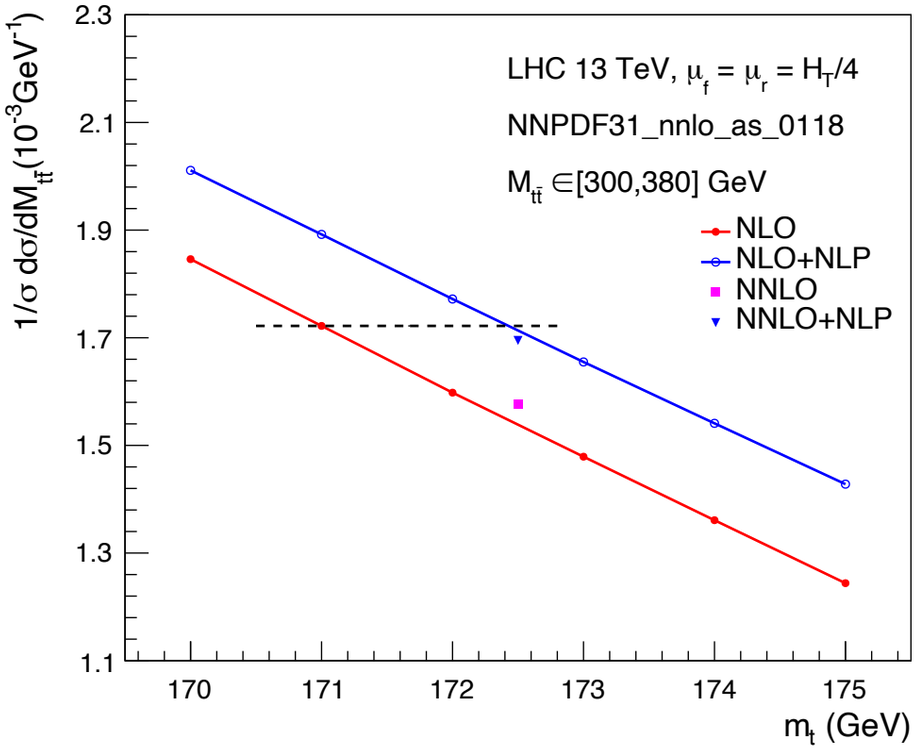
Being abundantly produced at LHC via strong interactions, top-quark pair is the key process for searches of new physics, test of SM;
QCD Coulomb corrections at threshold calculated to next-to-leading power

Ju, Wang, Wang, Xu, Xu, Yang, 1908.02179

predictions at top pair threshold vs. CMS



top quark mass dependence



QCD Coulomb corrections have been resummed to all-orders at NLP accuracy leading to better description of cross section close to threshold

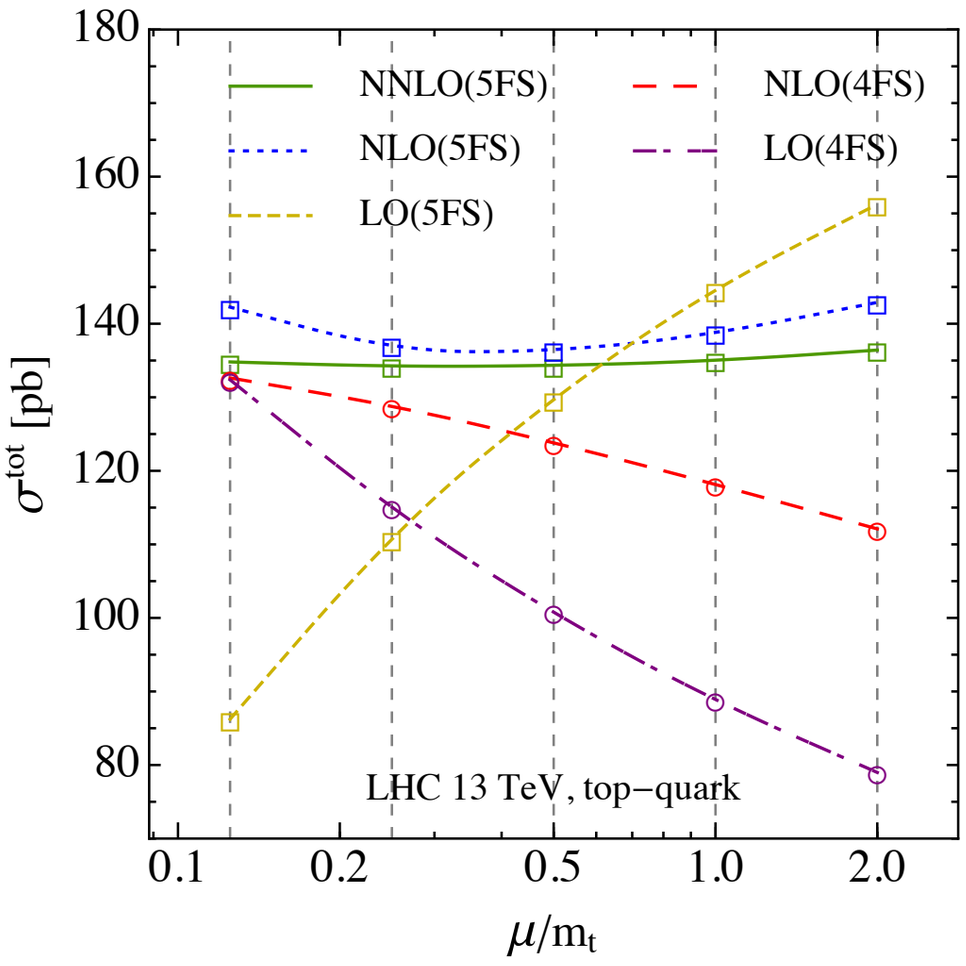
New predictions resolve the tensions between different top-quark mass measurements

Single top production at NNLO

Single top-quark production probes directly charged-current coupling of top quark, setting constraints on various new physics extensions; production with subsequent top decays calculated to full NNLO

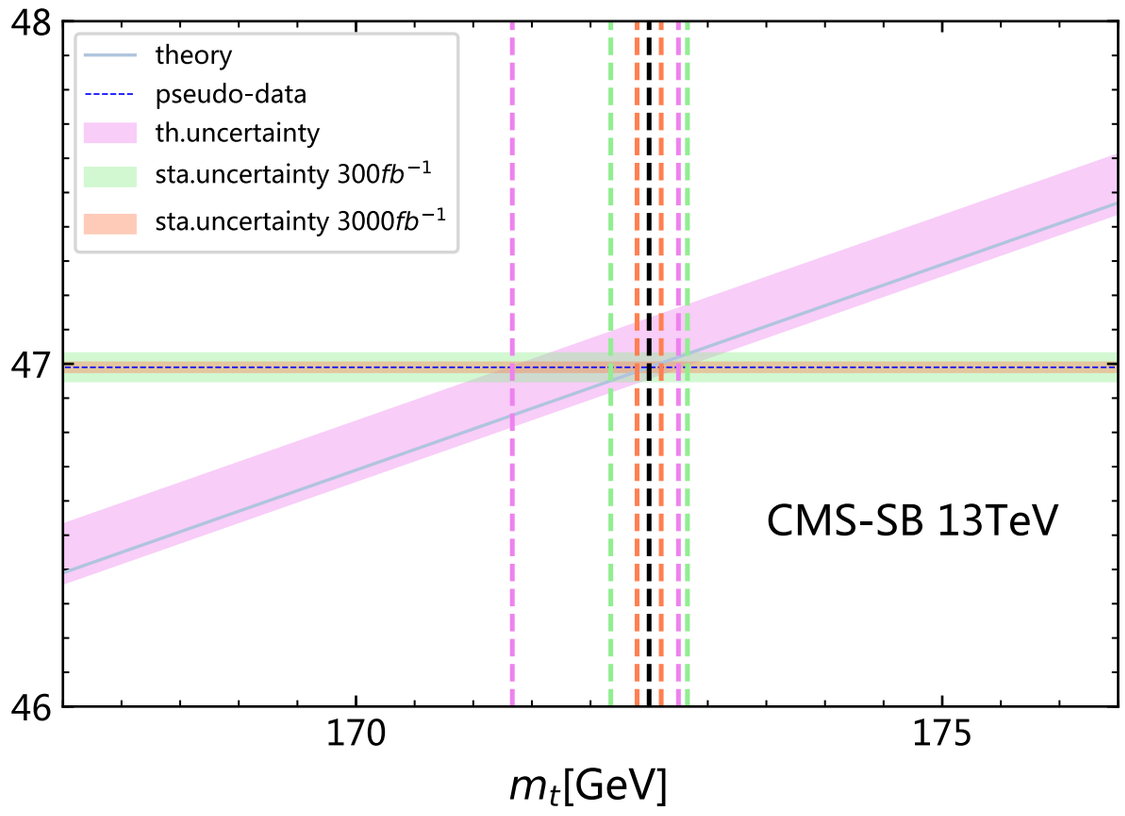
Gao, Berger, 2005.12936; Berger, Gao, Zhu, 1708.09405; Berger, Gao, Yuan, Zhu, 1606.08463

cross sections vs. QCD scale



scale variations reduced to ~1%; demonstrate the better stability of 5FS comparing to 4FS

averaged lepton pT vs. top mass



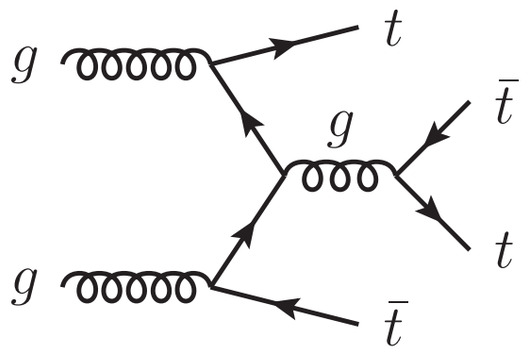
Single top production can provide independent and complementary determination on top quark mass.

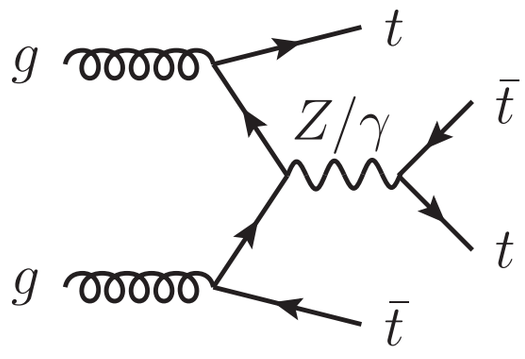
NNLO calculation gives precise modeling on decayed leptonic kinematics, thus a top mass precision of ~1GeV.

2. Top effective couplings at tree level

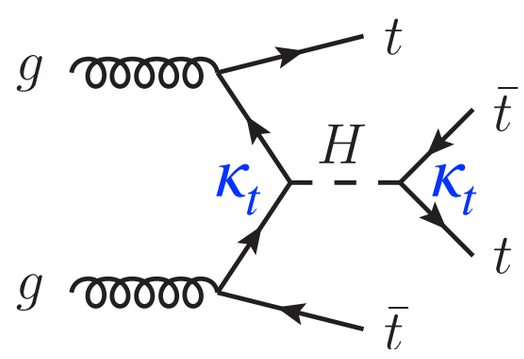
Four top quark production and the Higgs-top interaction

Barger, Stange, Phillips, 1991





QHC, Chen, Liu, 1602.01934



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

LO

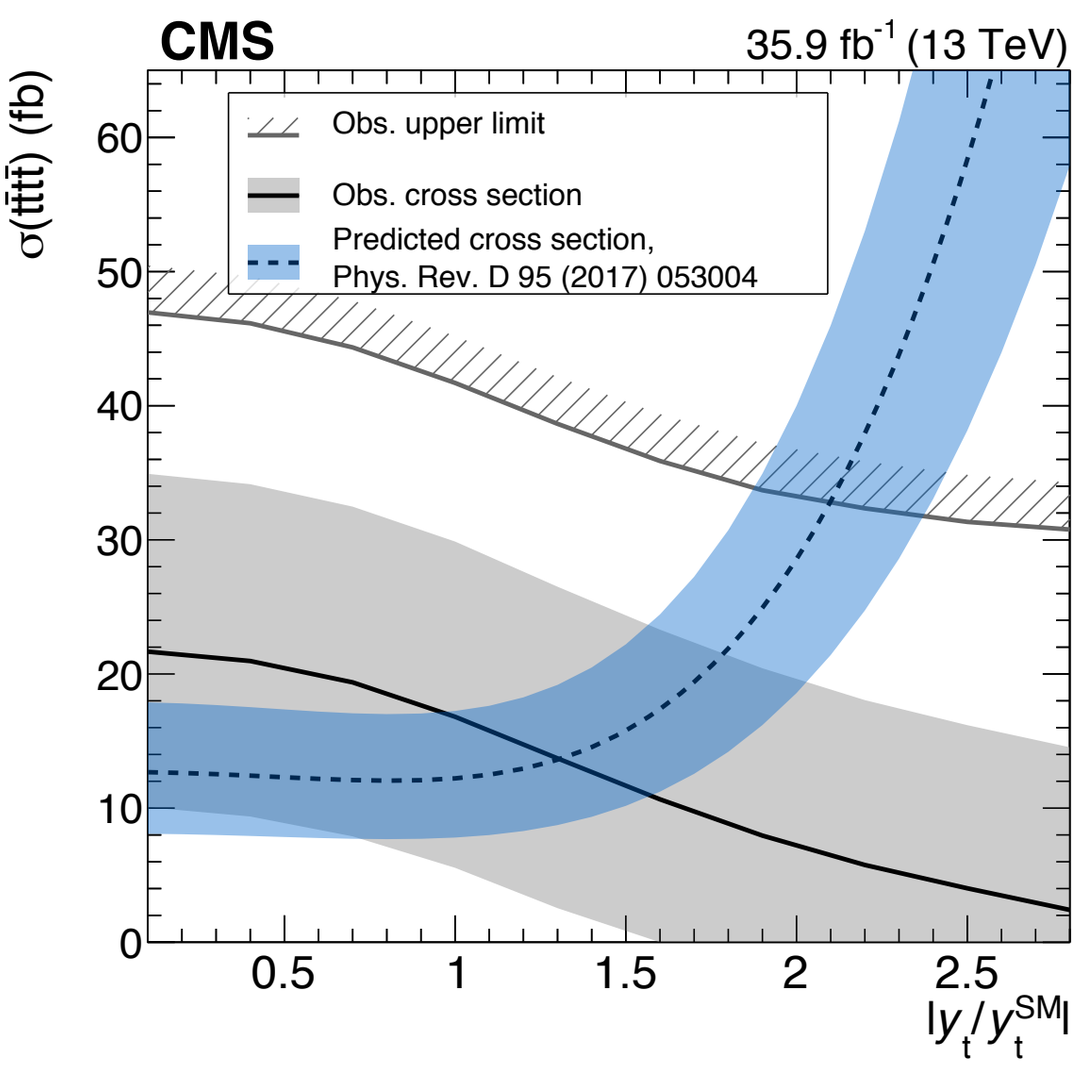
8 TeV	1.344	-0.224	0.171
13 TeV	9.997	-1.547	1.108
14 TeV	13.14	-2.007	1.515
27 TeV	115.1	-15.57	11.73
100 TeV	3276	-356.9	273.1

in unit of fb

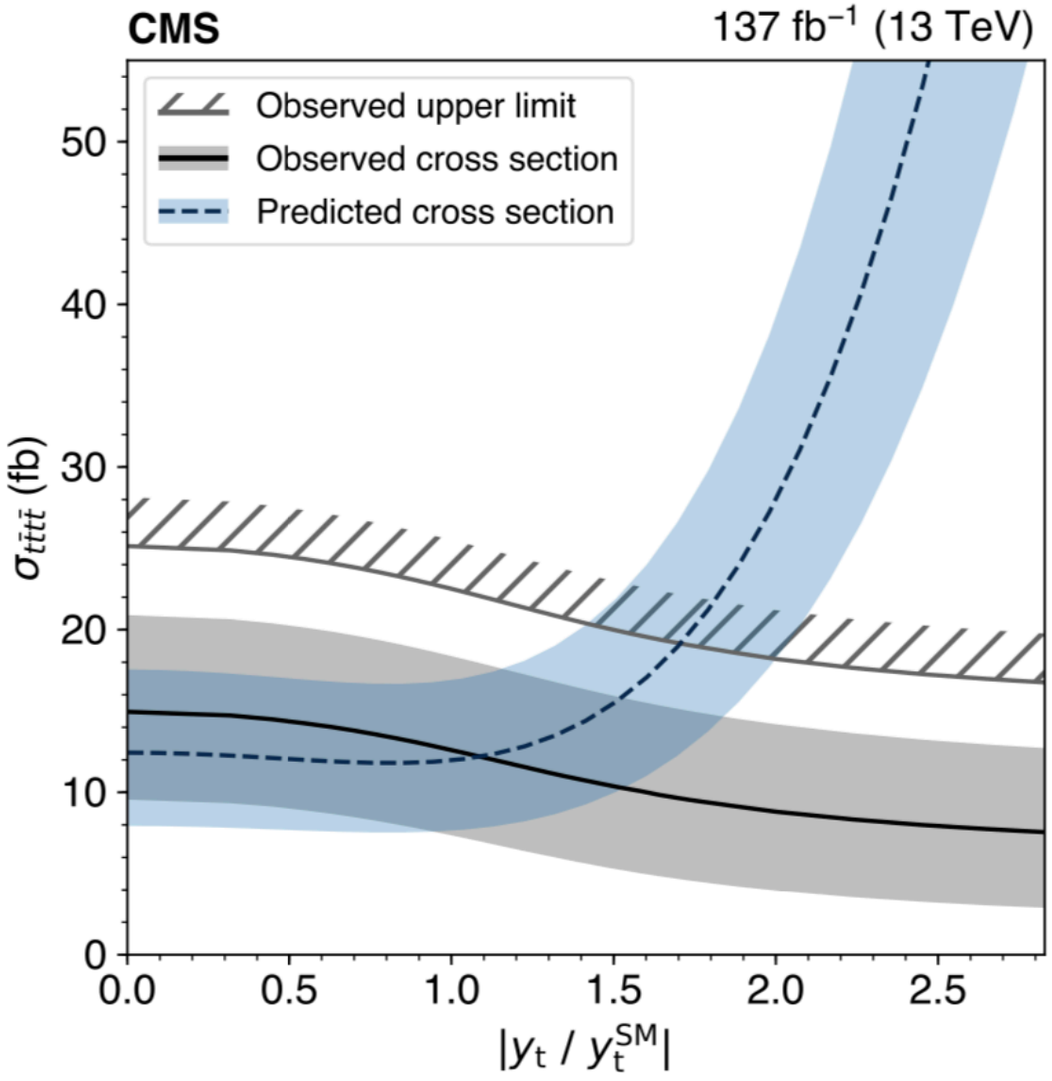
NLO corrections: Bevilacqua, Worek (2012); Alwall et al (2014); Frederix, Pagani, Zaro (2017)

Four top quark productions

CP-even $\sigma(t\bar{t}t\bar{t}) = 9.997 - 1.547 \times y_t^2 + 1.108 \times y_t^4$ (fb)



$y_t \leq 2.1 \times y_t^{\mathrm{SM}}$ 1710.10614



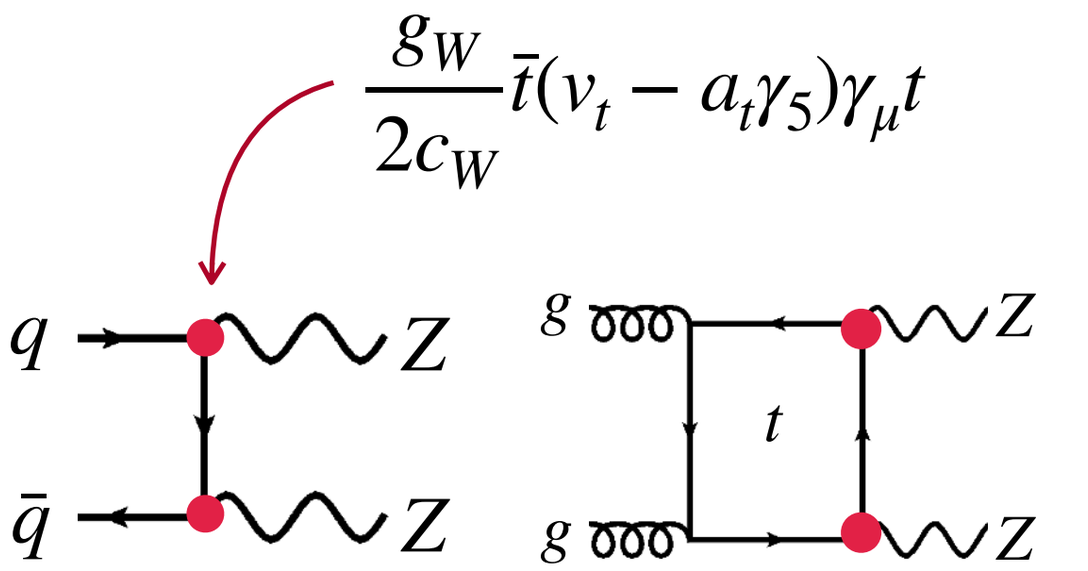
$y_t \leq 1.7 \times y_t^{\mathrm{SM}}$ 1908.06463 1909.05306

The channel is also sensitive to the CP property of top-Higgs interaction.

QHC, Chen, Liu, Zhang, Zhang, 1901.04567

3. Top effective couplings in loops

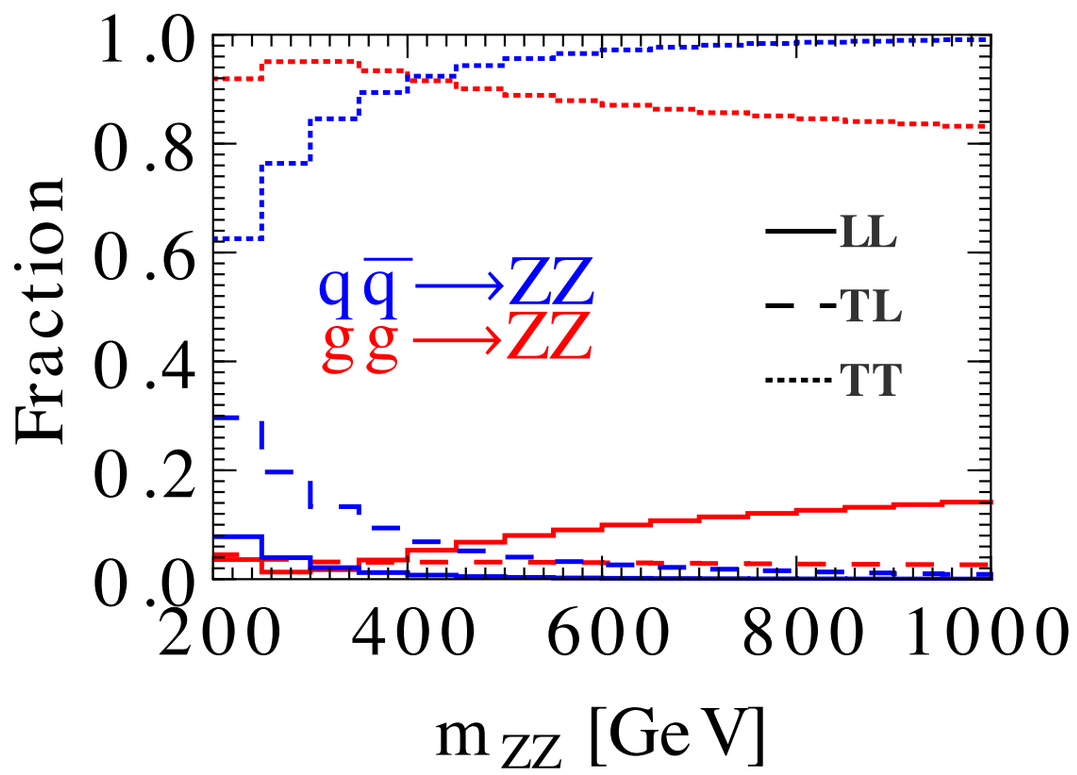
The polarizations of Z-bosons in the ZZ pair are sensitive to anomalous Ztt couplings.



Goldstone boson equivalence theorem

Unitarity cancelation between triangle and box

QHC, Yan, Yuan, Zhang, 2004.02031



Transversely polarized Z-bosons dominate in the SM production

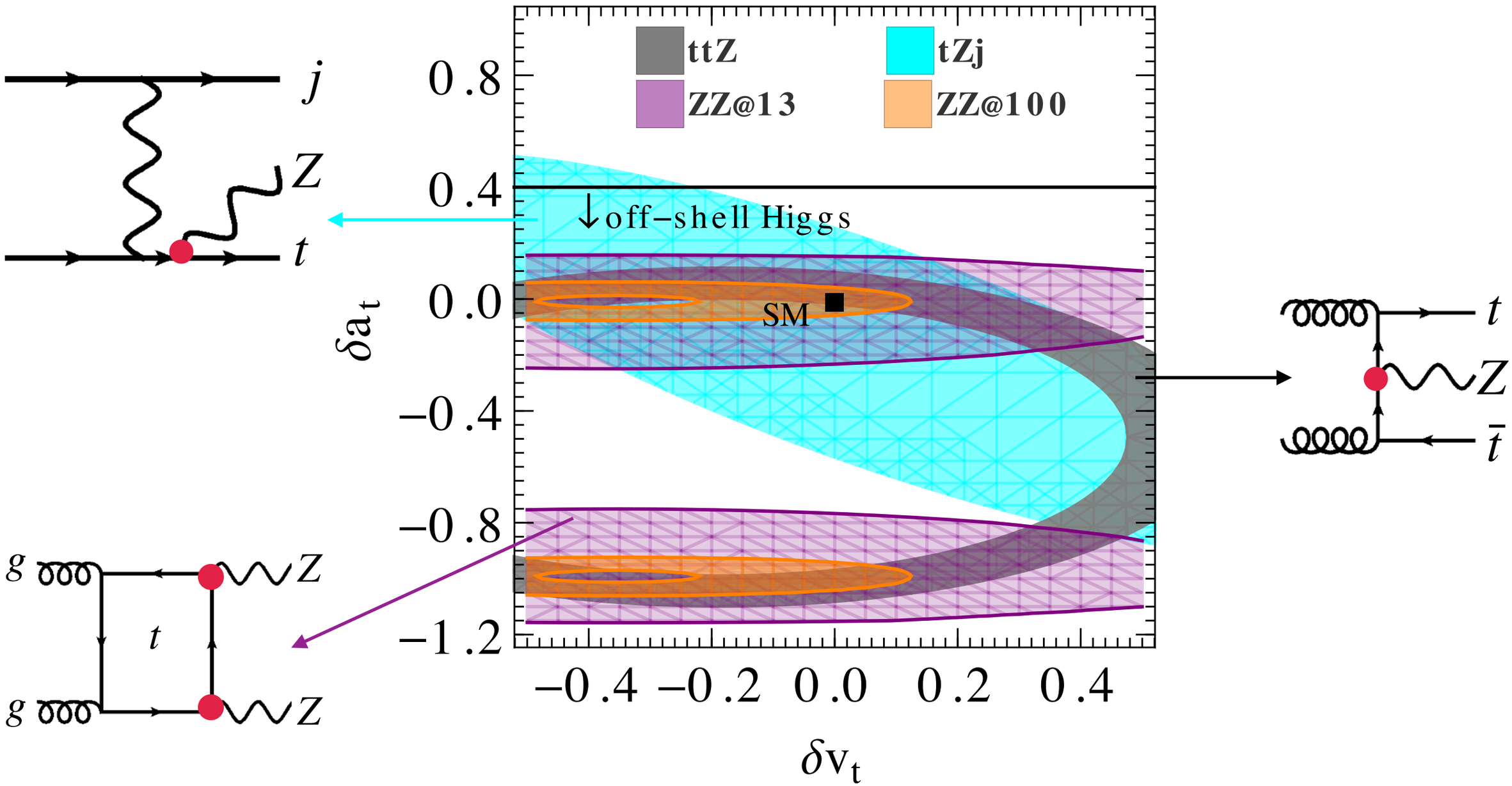
$$M_{\pm,\pm,0,0} \sim \frac{m_t^2}{m_Z^2}\left(a_t^2 - \frac{1}{4}\right)\left[\log^2\left(\frac{\hat{s}}{m_t^2}\right) - 2i\pi\log\left(\frac{\hat{s}}{m_t^2}\right)\right]$$

Deviation of a_t in NP models spoils the cancellation and enhances the longitudinal polarization of the Z-bosons.

Top effective couplings in the loop

The polarizations of Z-bosons in the ZZ pair are sensitive to anomalous Ztt couplings and can be measured from the angular distribution of the charged lepton from the Z-decay.

QHC, Yan, Yuan, Zhang, 2004.02031

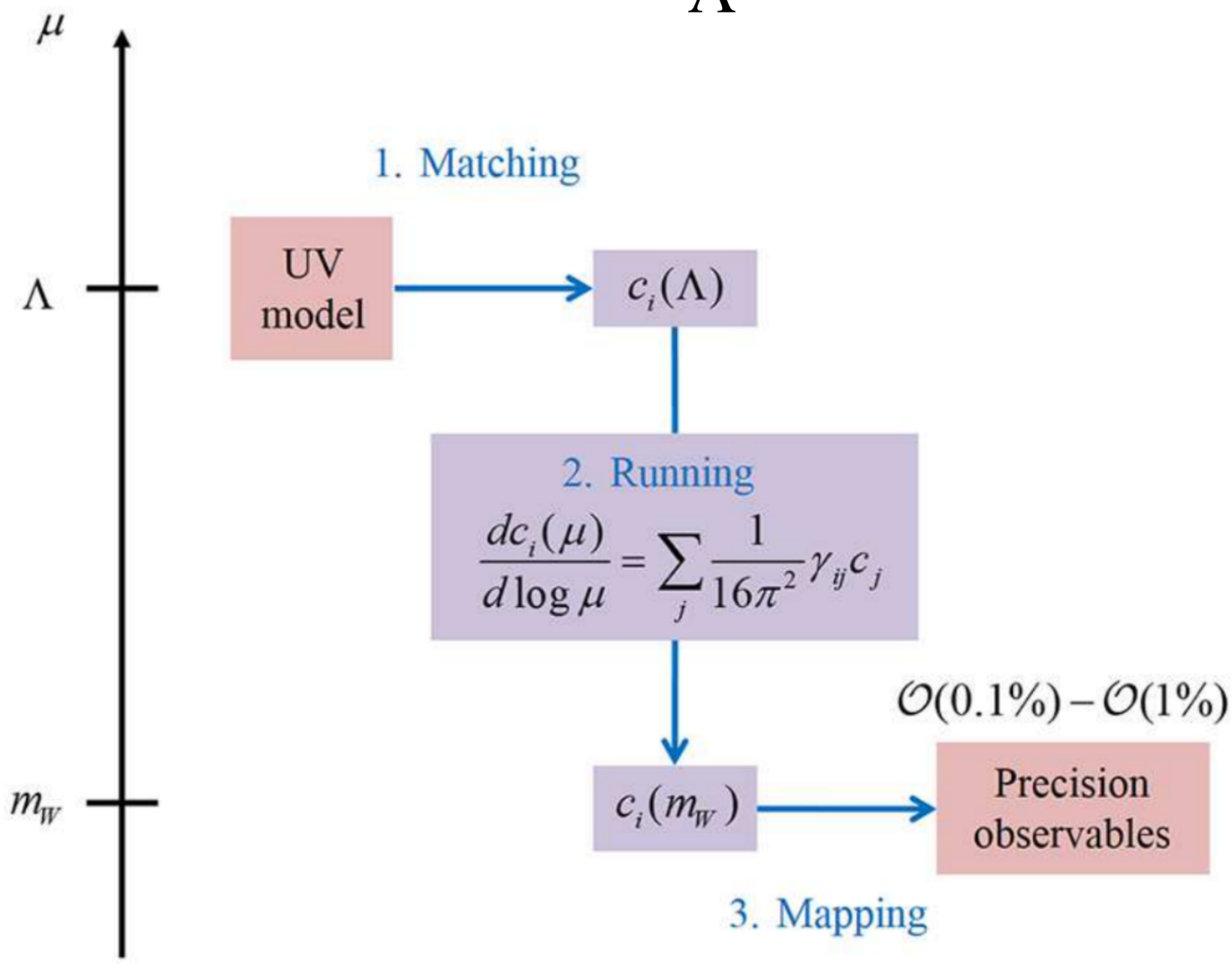


The $gg \to ZZ$ channel is complementary to the $Zt\bar{t}$ and tZj channels.

4. Top quark physics in SMEFT

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

Only consider dim-6 operators



Henning, Lu, Murayama, 1412.1837

4. Top quark physics in SMEFT

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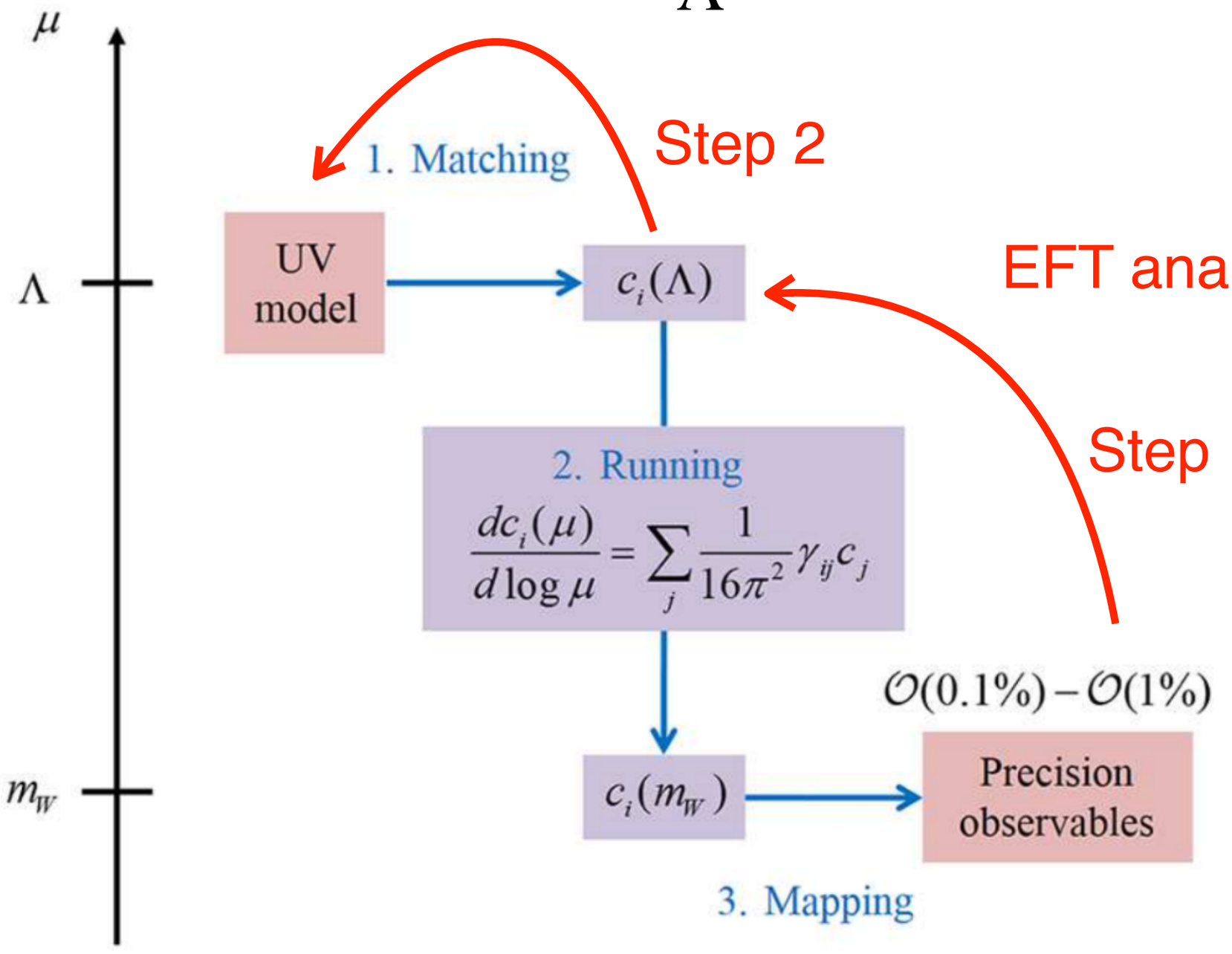


Henning, Lu, Murayama, 1412.1837

SMEFT analysis

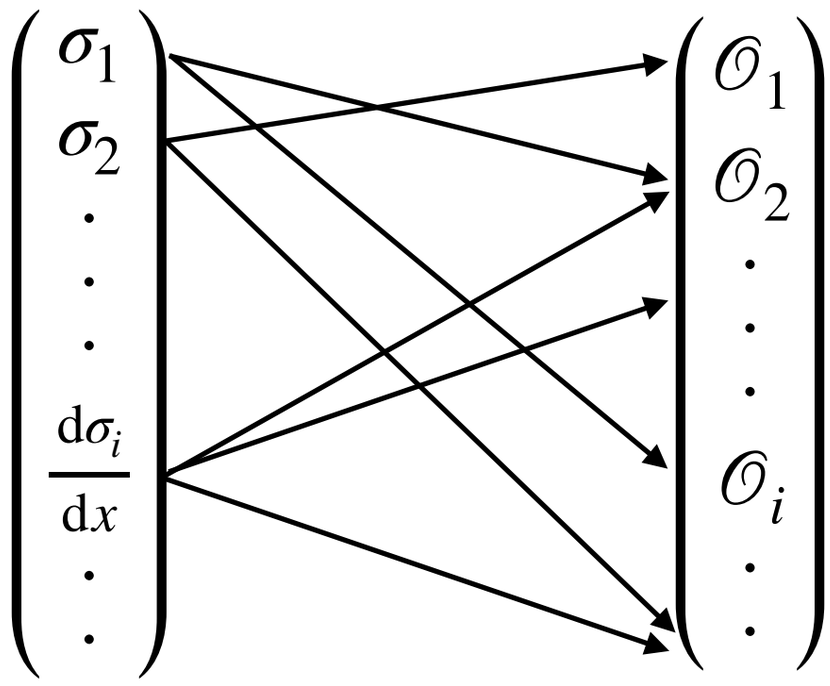
SMEFT

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)} O_i^{(6)}}{\Lambda^2}$$

Measurements

$$o_n^{\rm EXP} - o_n^{\rm SM} = \sum_i \frac{a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu)}{\Lambda^2}$$

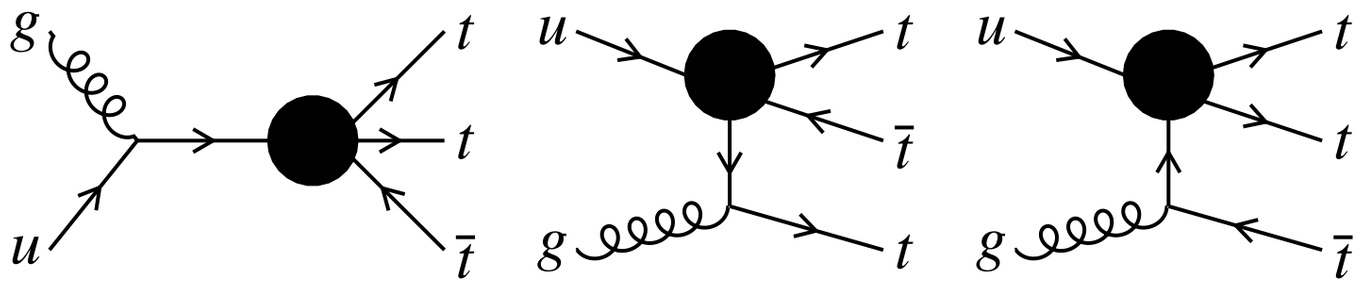
59 independent operators at dim-6



1) Linear (interference) or Quadratic (operator squared)?
2) RG running effects?
3) Basis? Field and mass redefinitions?
4) QCD corrections? Operator mixing?

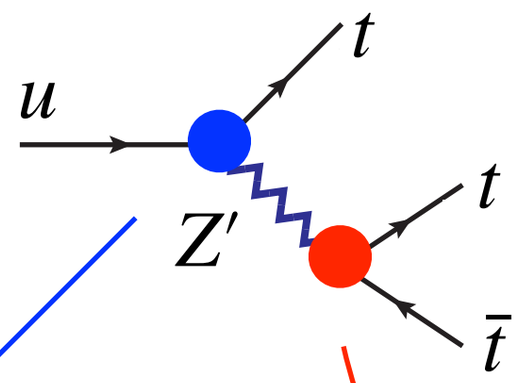
Two, Triple and Four top quark productions

Resonance-guided EFT analysis

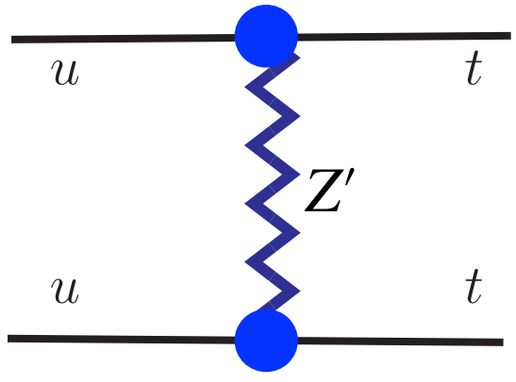


QHC, Chen, Liu, Wang
1901.04643

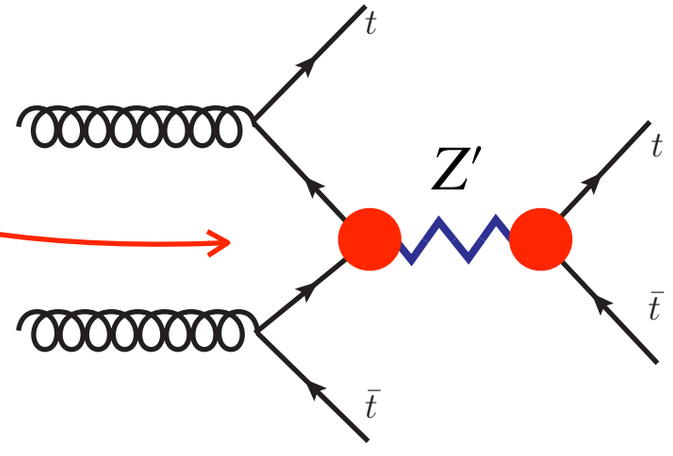
Triple top production requires both flavor changing and flavor conservation neutral interactions



$$\mathcal{O}^{\mathcal{V}}_{uttt} = \frac{f^{\mathcal{V}}_{\rm FVNI} f^{\mathcal{V}}_{\rm FCNI}}{\Lambda^2}(\bar{t}\gamma^\mu P_R t)(\bar{t}\gamma_\mu P_R u)$$



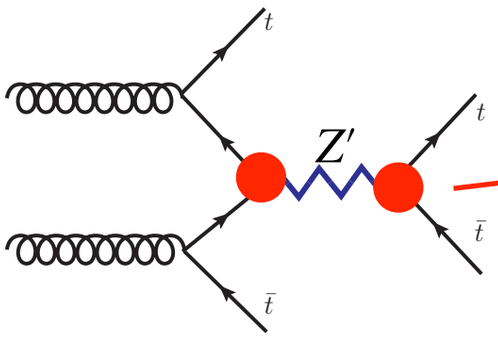
$$\mathcal{O}^{\mathcal{V}}_{uutt} = \frac{1}{2}\frac{(f^{\mathcal{V}}_{\rm FVNI})^2}{\Lambda^2}(\bar{t}\gamma^\mu P_R u)(\bar{t}\gamma_\mu P_R u)$$



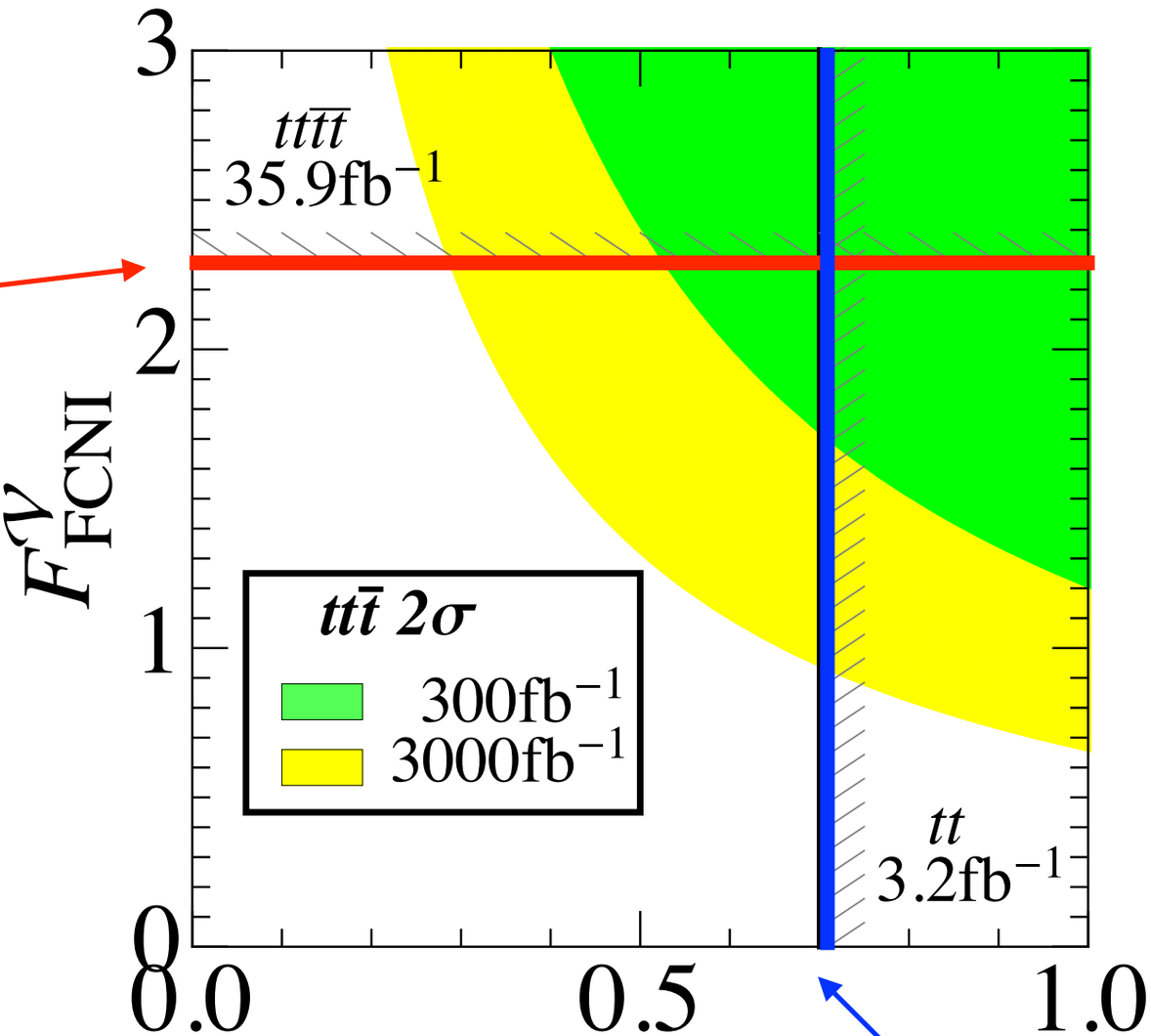
$$\mathcal{O}^{\mathcal{V}}_{tttt} = \frac{1}{2}\frac{(f^{\mathcal{V}}_{\rm FCNI})^2}{\Lambda^2}(\bar{t}\gamma^\mu P_R t)(\bar{t}\gamma_\mu P_R t)$$

Two, Triple and Four top quark productions

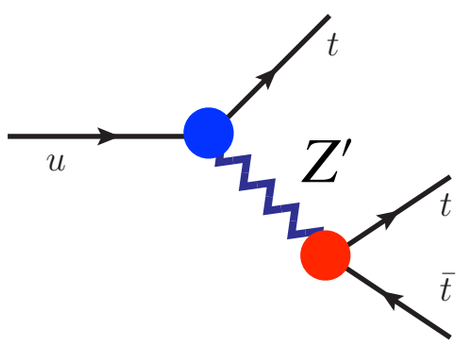
$$\mathcal{O}^{S}_{tttt} = \frac{1}{2}\frac{(f^{S}_{\mathrm{FCNI}})^2}{\Lambda^2}(\bar{t}t)(\bar{t}t)$$



$\Lambda = 1$ TeV

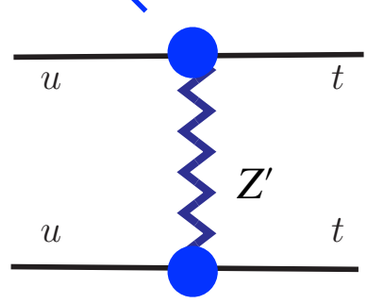


$$\mathcal{O}^{V}_{uttt} = \frac{f^{V}_{\mathrm{FVNI}} f^{V}_{\mathrm{FCNI}}}{\Lambda^2}(\bar{t}\gamma^{\mu}P_R t)(\bar{t}\gamma_{\mu}P_R u)$$



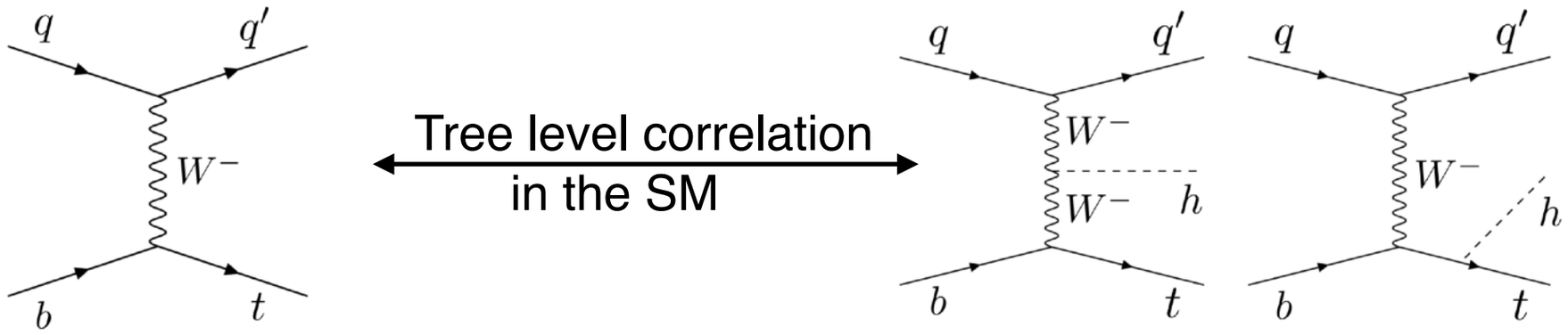
Green/Yellow bands

$$\mathcal{O}^{V}_{uutt} = \frac{1}{2}\frac{(f^{V}_{\mathrm{FVNI}})^2}{\Lambda^2}(\bar{t}\gamma^{\mu}P_R u)(\bar{t}\gamma_{\mu}P_R u)$$

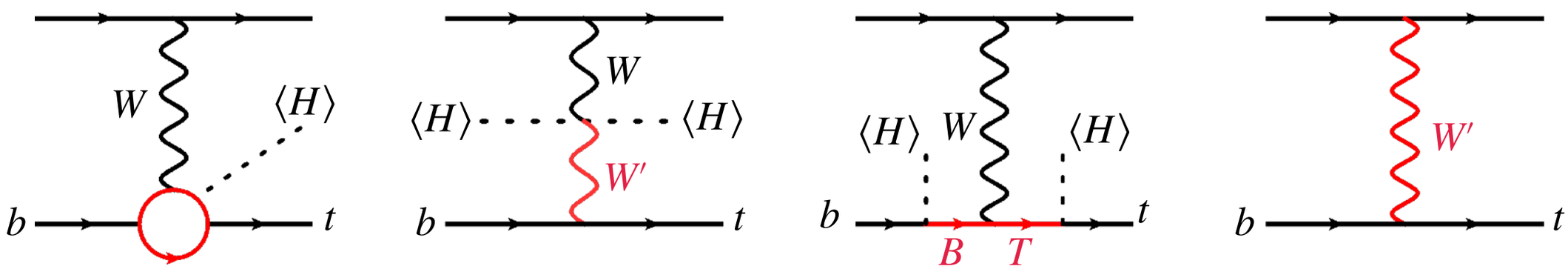


Single top production w/ and w/o a Higgs boson

QHC, Jiang, Zeng, 2105.04464 (SMEFT analysis w/o QCD corrections)



correlation in the linear analysis in SMEFT



$$O_{uw} = (\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \tilde{\phi} W^I_{\mu\nu} + h.c., \qquad \text{WMD}$$

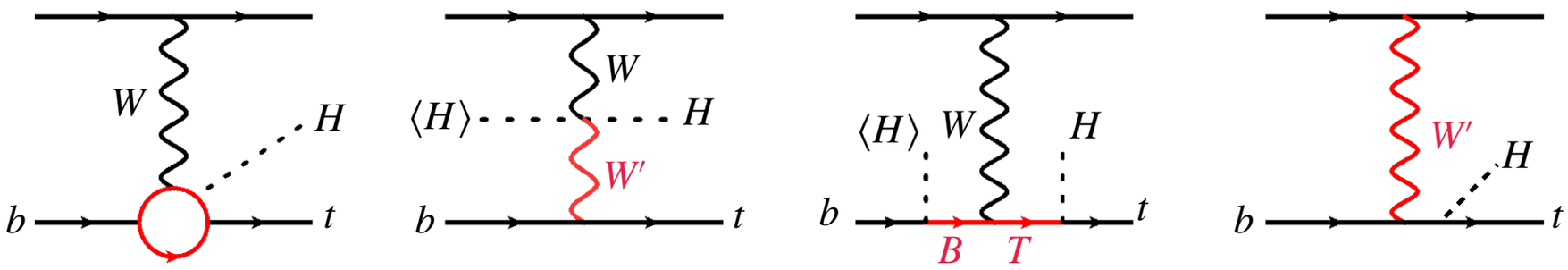
$$O^{(3)}_{\phi q} = (\phi^\dagger i \overleftrightarrow{D^I_\mu} \phi)(\bar{q}_p \tau^I \gamma^\mu q_r) + h.c., \qquad \text{W-prime or Extra quarks}$$

$$\left.\begin{aligned} O^{(1)}_{qq} &= (\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t) + h.c., \\ O^{(3)}_{qq} &= (\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_p \gamma^\mu \tau^I q_r) + h.c.. \end{aligned}\right\} \longrightarrow \begin{aligned} O^{(1)}_{3113} &= (\bar{q}_3 \gamma_\mu q_1)(\bar{q}_1 \gamma^\mu q_3) + h.c., \\ O^{(3)}_{3311} &= (\bar{q}_3 \gamma_\mu \tau^I q_3)(\bar{q}_1 \gamma^\mu \tau^I q_1) + h.c.. \end{aligned} \xrightarrow{\text{same interference}} O^{(3)}_{qq}$$

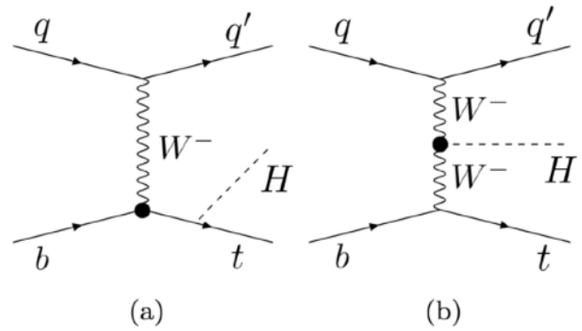
$$\sigma_t(\Lambda = 1\text{TeV}) = \left[214^{+2}_{-1} - 13^{+2}_{-1} C^{(3)}_{qq} + 16^{+2}_{-3} C_{uW} + 13^{+1}_{-2} C^{(3)}_{\phi q}\right] \text{pb}$$

Single top production w/ and w/o a Higgs boson

Direct correlation induced by the three operators



For comprehensive EFT analysis of the tHq channel, see 1804.07773 (Degrande,Maltoni,Mimasu, Vryonidou,Zhang)



More operators involved in tHq channel but bounded

Operators

$$O_{\phi D} = \left(\phi^\dagger D^\mu \phi\right)^* \left(\phi^\dagger D_\mu \phi\right)$$

$$O_{\phi\Box} = \left(\phi^\dagger \phi\right) \Box \left(\phi^\dagger \phi\right)$$

$$O_{u\phi} = \left(\phi^\dagger \phi\right) \left(\bar{q}_p u_r \tilde{\phi}\right) + h.c$$

$$O_{\phi W} = \phi^\dagger \phi W^I_{\mu\nu} W^{I\mu\nu}$$

Measurements

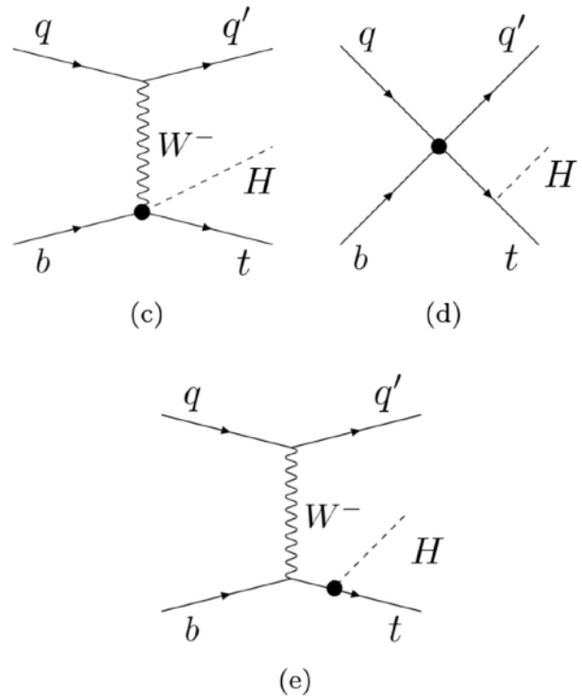
EWPT at LEP

$gg \to H$

$H \to b\bar{b}$

$gg \to H, \quad gg \to t\bar{t}H$

$H \to ZZ^*/Z\gamma/\gamma\gamma$



The same three operators contributing predominantly in the tHq channel

$$\sigma_{tHq}(\Lambda = 1\text{TeV}) = \left[70.0 - 11.3^{+0.6}_{-0.3} C^{(3)}_{qq} + 22^{+1}_{-2} C_{uW} - 2.6^{+0.2}_{-0.2} C^{(3)}_{\phi q}\right] \text{fb}$$

Single top production w/ and w/o a Higgs boson

Three operators require at least three independent measurements; fortunately, single-top production provides richer info than expected.

$$\sigma_t = \sigma(tq) + \sigma(\bar{t}q) \longrightarrow O_{qq}^{(3)}, O_{uW'}, O_{\varphi q}^{(3)}$$

$$R_t \equiv \frac{\sigma(tq)}{\sigma(\bar{t}q)} \longrightarrow O_{qq}^{(3)}, O_{uW}$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \longrightarrow O_{uW}$$

$$\sigma_{tHq} = \left[-95.1 - 44.0 \times \frac{\sigma_{t+\bar{t}}}{\sigma_{t+\bar{t}}^{\mathrm{SM}}} - 266.0 \times \frac{A_{\mathrm{FB}}}{A_{\mathrm{FB}}^{\mathrm{SM}}} + 479.4 \times \frac{R_t}{R_t^{\mathrm{SM}}} \right] \text{ fb}$$

Current

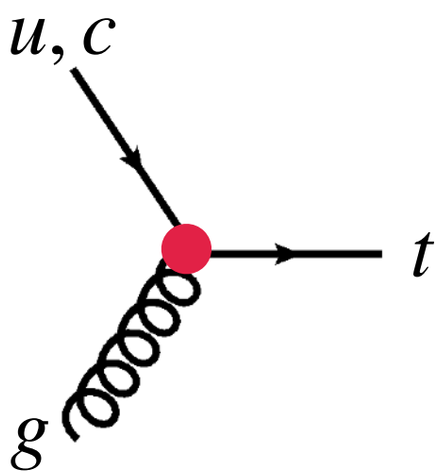
$$\sigma_{tHq} = \left[106.8 \pm 64.8 \right] \text{ fb}$$

HL-LHC

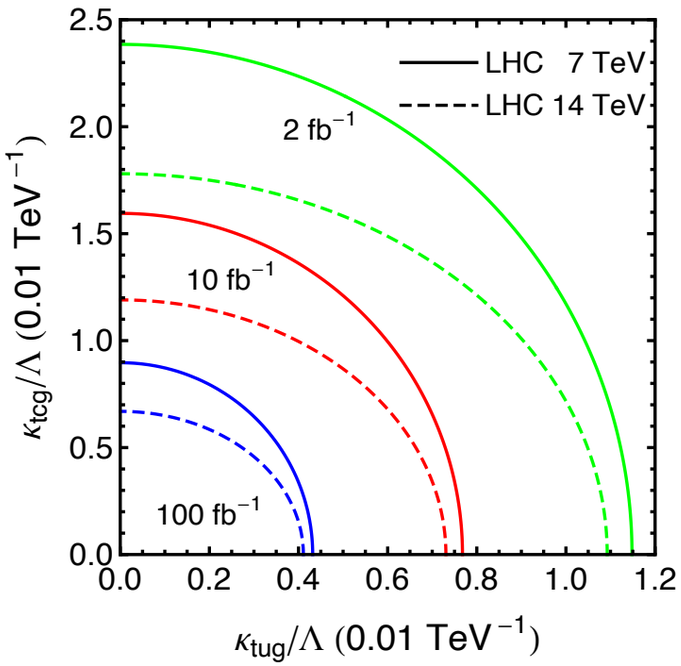
$$\sigma_{tHq} = \left[74.3 \pm 45.4 \right] \text{ fb}$$

QCD improved SMEFT

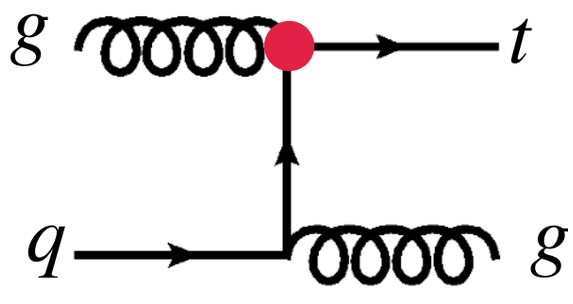
Interpretation of searches of NP with SMEFT can be improved with higher-order QCD corrections; e.g. the QCD corrections to direct-top production and top rare decay



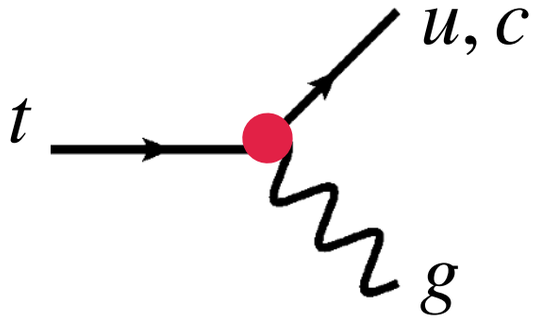
Liu, Li, Yang, Jin, 0508016 (NLO)
Yang, Li, Gao, Liu, 0601180 (Threshold resum)
Yang, Li, Gao, Wang, 1409.6959 (NNLL resum)



Gao, Li, Yang, Zhang, 1104.4945 (Collider Pheno)



Gao, Li, Zhang, Zhu, 0910.4349 (NLO)



Zhang, Li, Gao, Zhang, Li, Yuan, Yuan, 0810.3889, 1004.0898 (NLO)

QCD improved SMEFT

Dedicated tools have been developed (MG5 SMEFT@NLO)

Cen Zhang
1984-2021

Automated one-loop computations in the SMEFT

Céline Degrande,[1,*] Gauthier Durieux,[2,†] Fabio Maltoni,[1,3,‡]
Ken Mimasu,[1,§] Eleni Vryonidou,[4,¶] and Cen Zhang[5,6,**]

SMEFT

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)} O_i^{(6)}}{\Lambda^2}$$

Measurements

$$o_n^{\rm EXP} - o_n^{\rm SM} = \sum_i \frac{a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu)}{\Lambda^2}$$

SMEFT operator in four top quark production

c_i	$\mathcal{O}(\Lambda^{-2})$ LO	NLO	K	$\mathcal{O}(\Lambda^{-4})$ LO	NLO	K
c_{QQ}^8	$0.081^{+55\%}_{-33\%}$ $[-0.358]$	$0.090^{+4\%}_{-11\%}$	1.1	$0.115^{+46\%}_{-29\%}$	$0.158^{+4\%}_{-11\%}$	1.37
c_{Qt}^8	$0.274^{+54\%}_{-33\%}$ $[-0.639]$	$0.311^{+5\%}_{-10\%}$	1.14	$0.342^{+46\%}_{-29\%}$	$0.378^{+4\%}_{-13\%}$	1.10
c_{QQ}^1	$0.242^{+55\%}_{-33\%}$ $[-1.07]$	$0.24(3)^{+3\%}_{-18\%}$	0.99	$1.039^{+47\%}_{-29\%}$	$1.41^{+4\%}_{-11\%}$	1.36
c_{Qt}^1	$-0.0098(10)^{+38\%}_{-33\%}$ $[0.862]$	$-0.019(9)^{+63\%}_{-27\%}$	1.9	$1.406^{+46\%}_{-30\%}$	$1.86^{+4\%}_{-10\%}$	1.32
c_{tt}^1	$0.483^{+55\%}_{-33\%}$ $[-1.86]$	$0.53(8)^{+3\%}_{-10\%}$	1.10	$4.154^{+47\%}_{-29\%}$	$5.61^{+4\%}_{-11\%}$	1.35

QCD corrections of EFT contributions can be important due to possible operator mixings and complicated interference with the SM

Fully automated with NLO QCD corrections matched with parton shower and hadronizations

A remarkable achievement in the SMEFT analysis with QCD at NLO

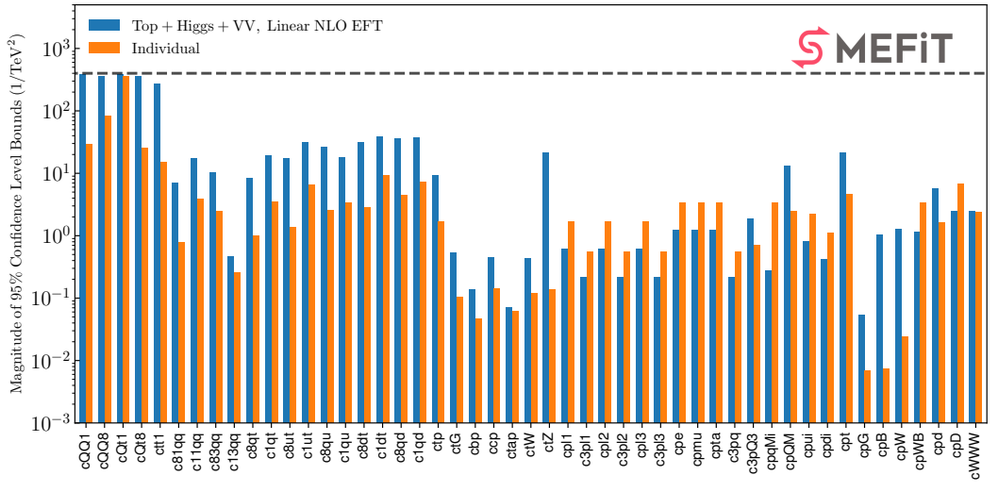
Combined SMEFT interpretation of Higgs, diboson, and top quark data from the LHC

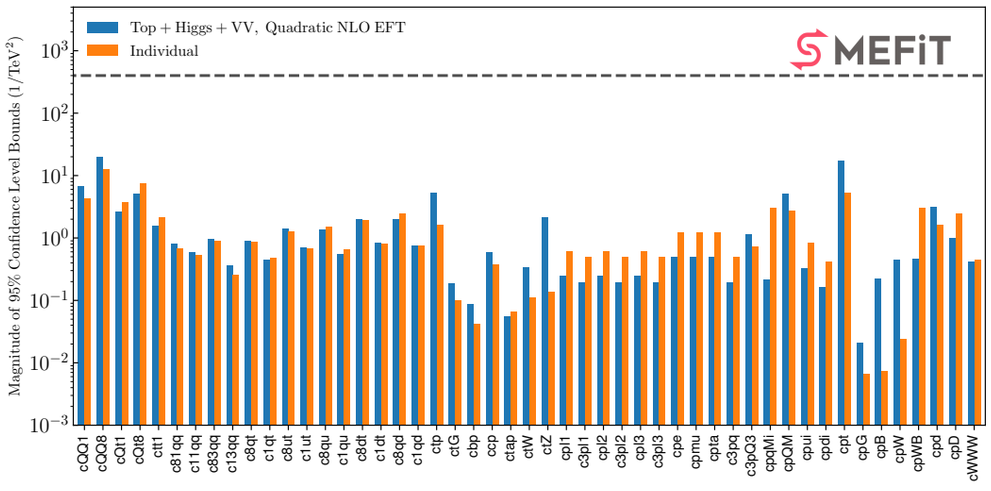
SMEFiT

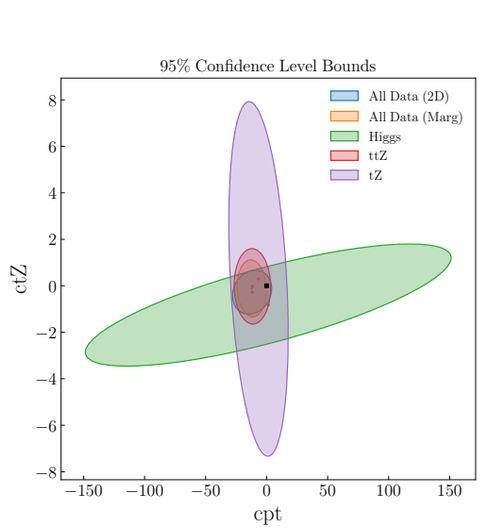
2105.00006

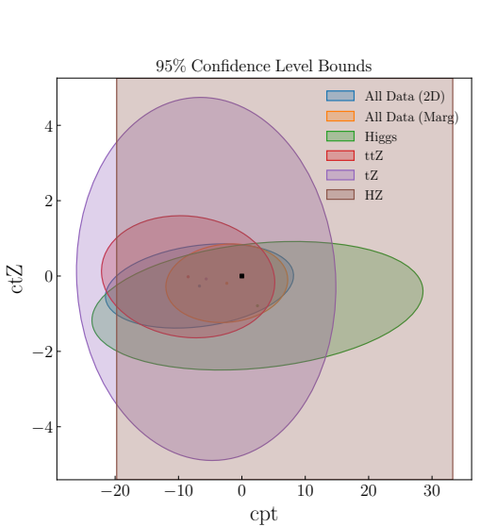
The SMEFiT Collaboration:

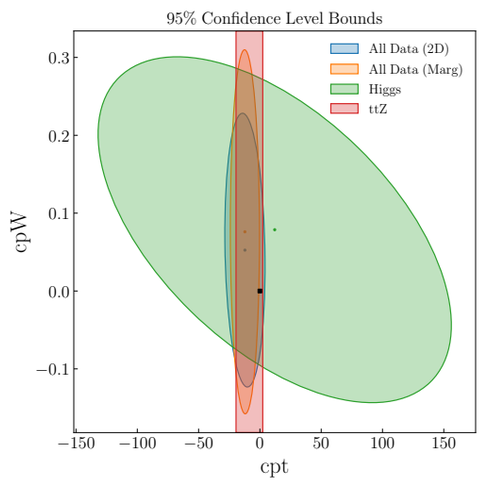
Jacob J. Ethier,[1,2] Giacomo Magni,[1,2] Fabio Maltoni,[3,4] Luca Mantani,[3]
Emanuele R. Nocera,[2,5] Juan Rojo,[1,2], Emma Slade,[6] Eleni Vryonidou,[7] and Cen Zhang[8,9]

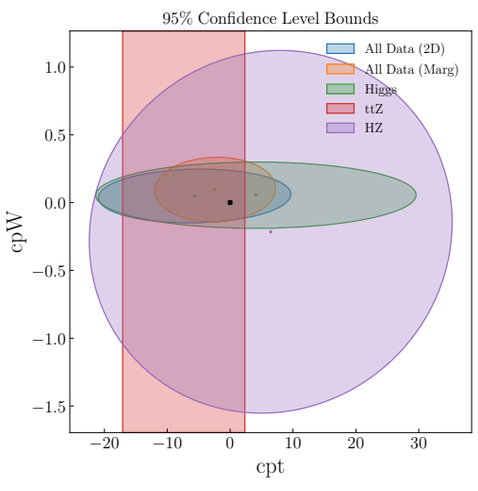






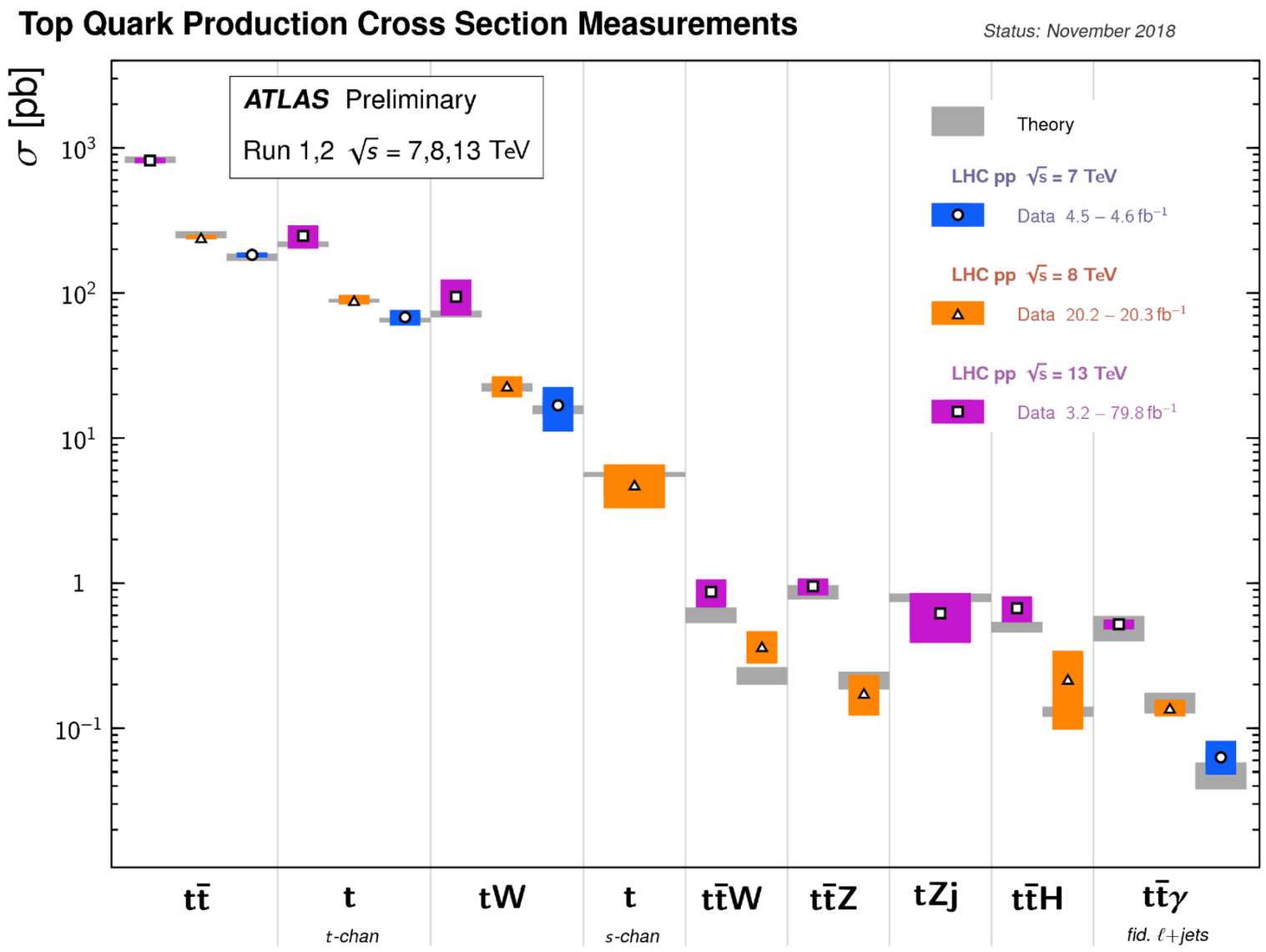






Summary

We are in an era of top-quark precision at the LHC.



It is time to see what we can learn from data.

Thank You!