Top-quark Physics - Theory

- A unique laboratory to probe the SM and beyond -

Bramsche
August 29-30, 2024

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Outline

From prediction to discovery to precision, an incredible journey

Why top-quark physics is unique

- The multiple implications of the large top-quark mass.
- Short life-time and the access to an *unbound* quark state.

Theory predictions for top-quark physics at the LHC

- An incredibly rich program.
- Progress of theoretical predictions, meeting (HL-)LHC precision.

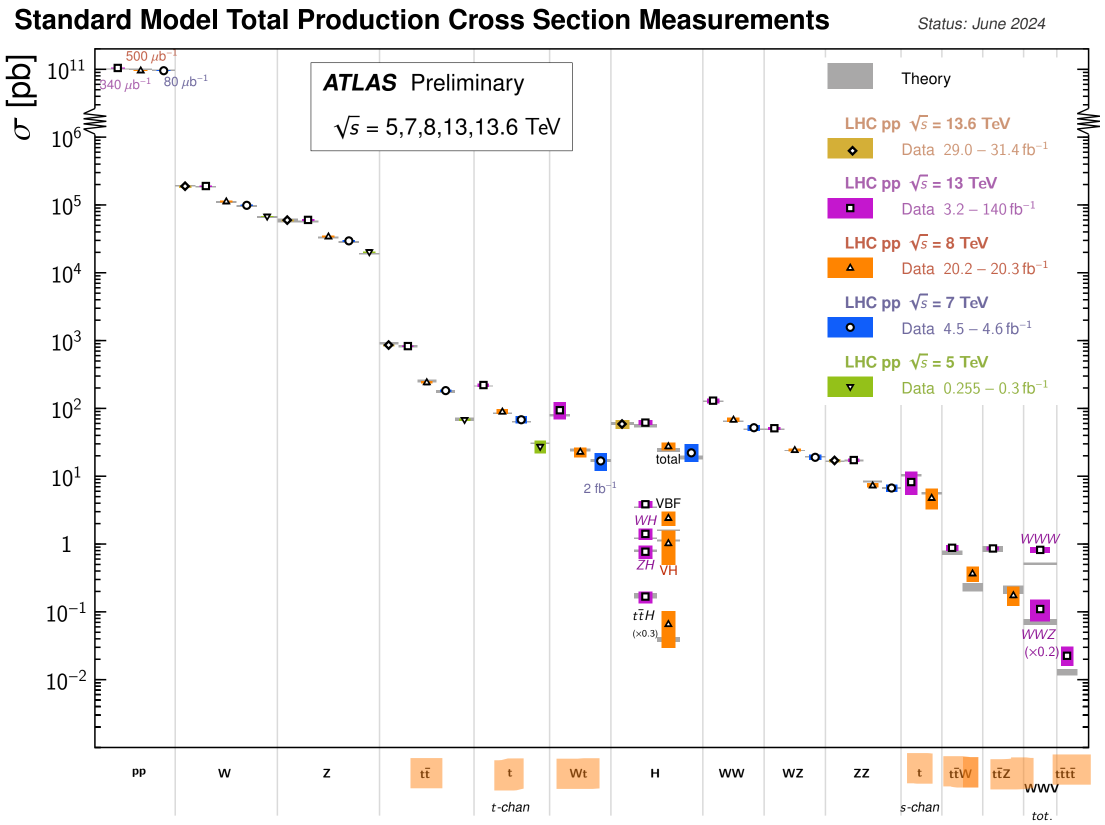
Constraining new physics via top-quark measurements

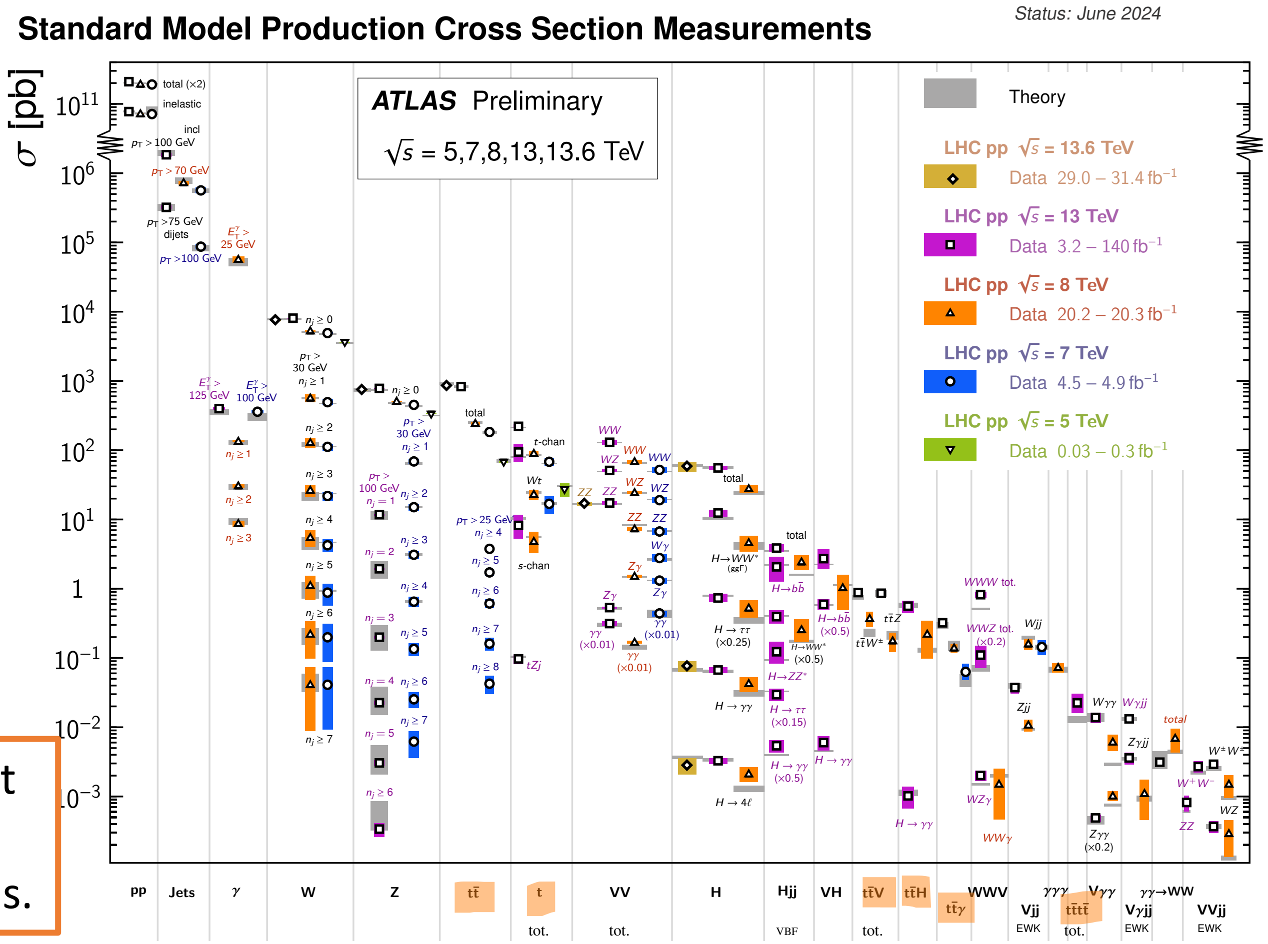
- Top-quark plays a special role in many models of new physics.
- Interesting to explore this connection in terms of effective interactions (EFT).

Theory predictions for top-quark physics at the LHC

- Top-quark physics is central and unique to the physics program of the (HL-)LHC. A growing spectrum of top-physics observables is being measured with higher precision and theoretical predictions are being improved to match the experimental accuracy.

The breadth of LHC measurements

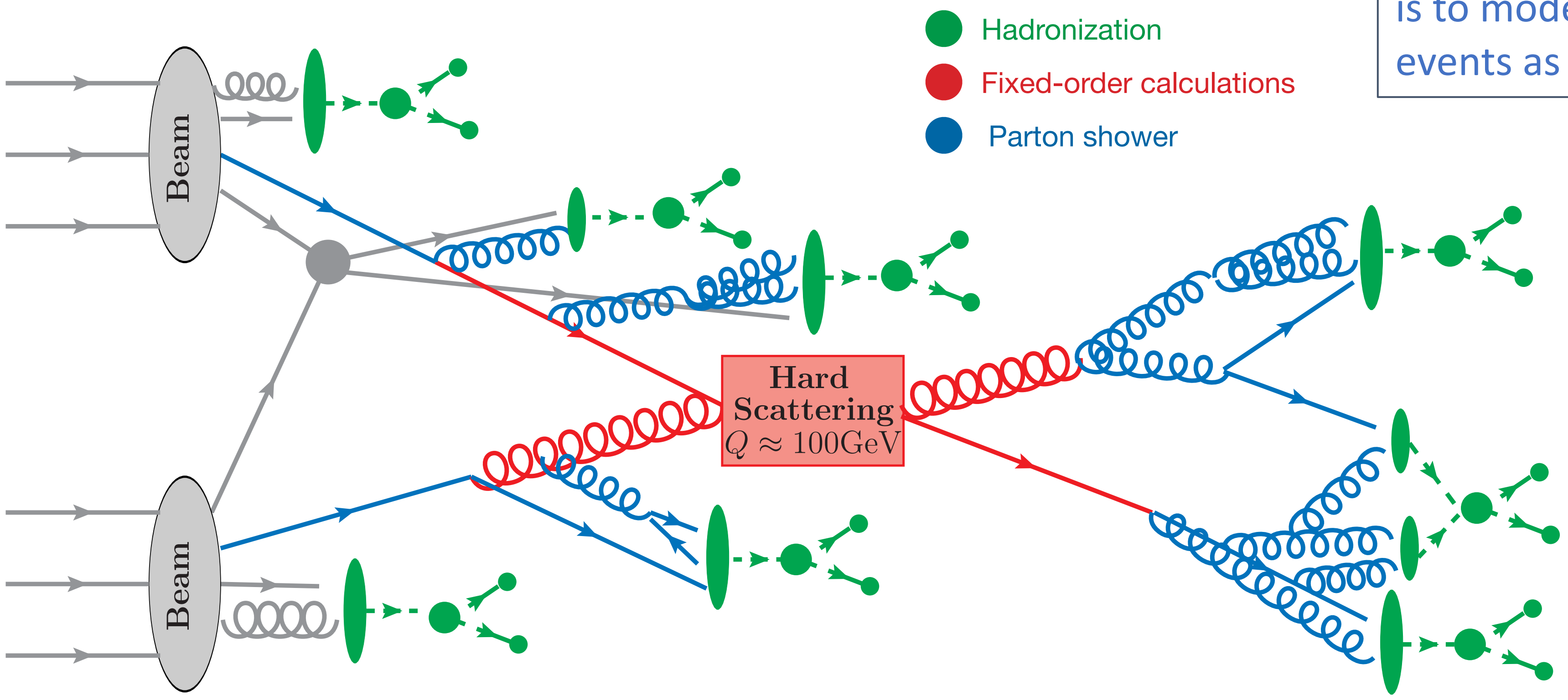




Top-quark properties are extracted from the measurement of processes that involve direct top-quark production or receive indirect top-quark dependent quantum corrections.

Dissecting the challenge

The goal of theoretical predictions is to model the complexity of LHC events as closely as possible



Huge progress in the last two decades for all components of hadronic event modeling

From S. Ferrario Ravasio, RADCOR 2023

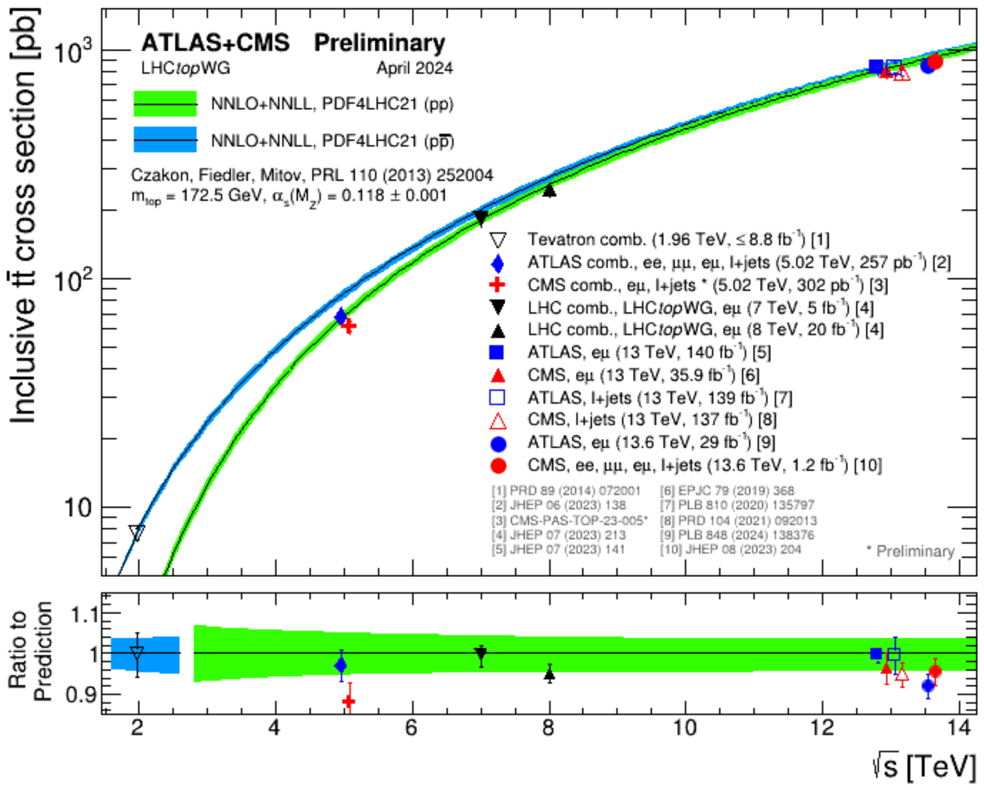
$$d\sigma = \sum_{ij} \int dx_1\, dx_2\, f_{p,i}(x_1) f_{p,j}(x_2) \widehat{d\sigma}(x_1 x_2 s) + O((\Lambda_{QCD}/Q)^p)$$

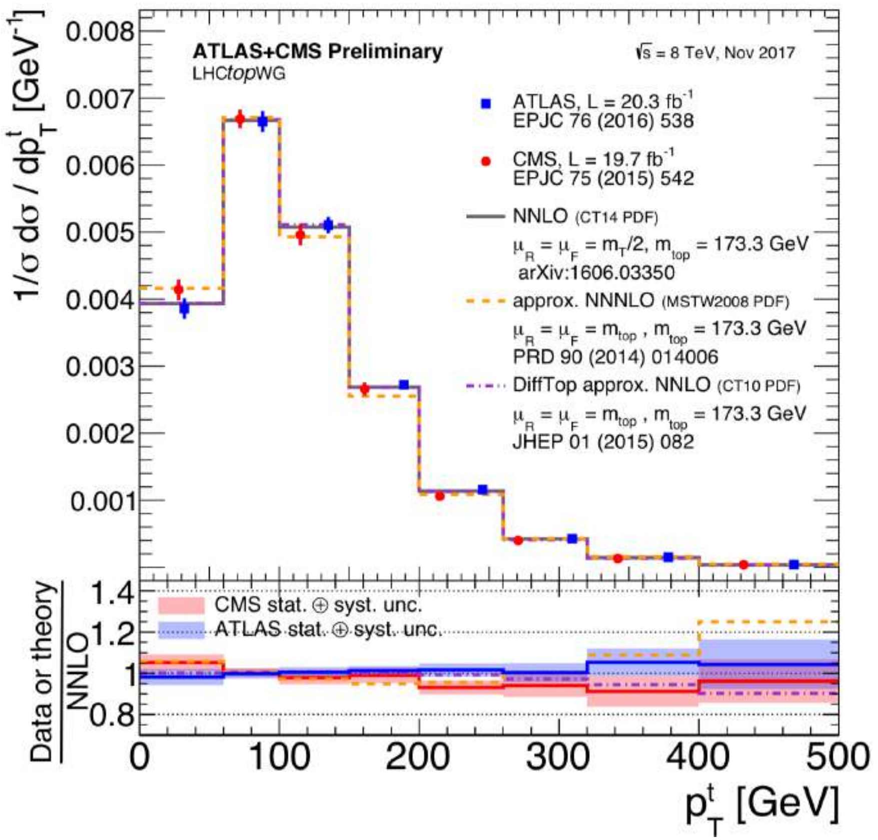
Parton Distribution Functions (PDF)

hard-scattering partonic xsection (pQCD+EW)

Hadronization, non-p QCD

$t\bar{t}$ production





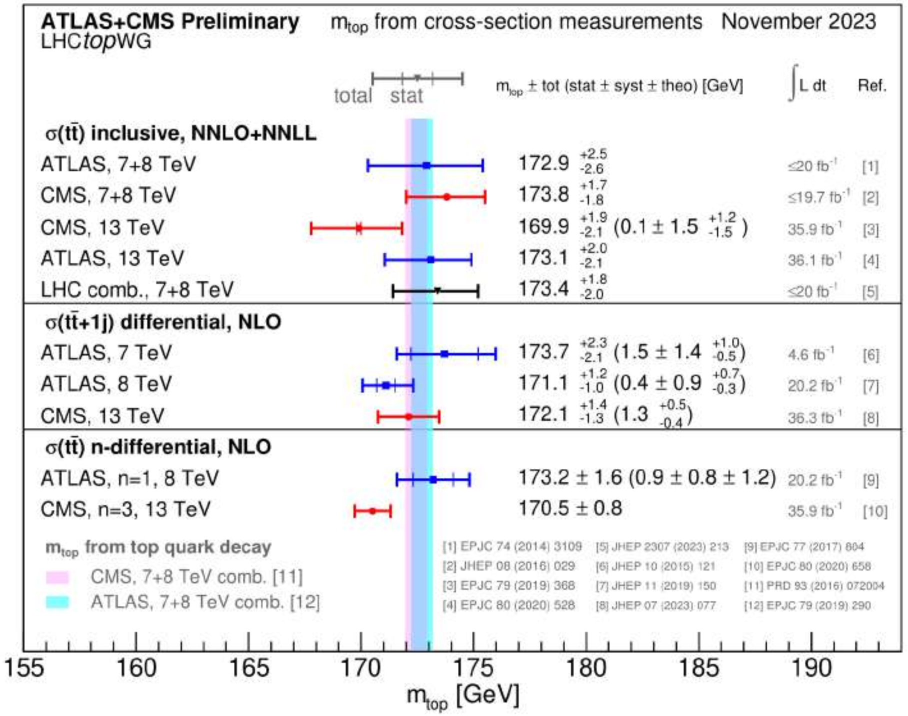
Two partonic channels at tree level:
- $q\bar{q} \to t\bar{t}$ (dominant at the Tevatron)
- $gg \to t\bar{t}$ (dominant at the LHC

- NNLO refers to the fixed QCD order of the calculation
  - State-of-the-art of $2 \to 2$ calculations
  - Available also at differential level

- NNLL refers to the order of resummation of soft or threshold logs ($\log(1 - 4m_t^2/\hat{s})$).
  - Relevant if the threshold region is important

Comparing m_t determinations

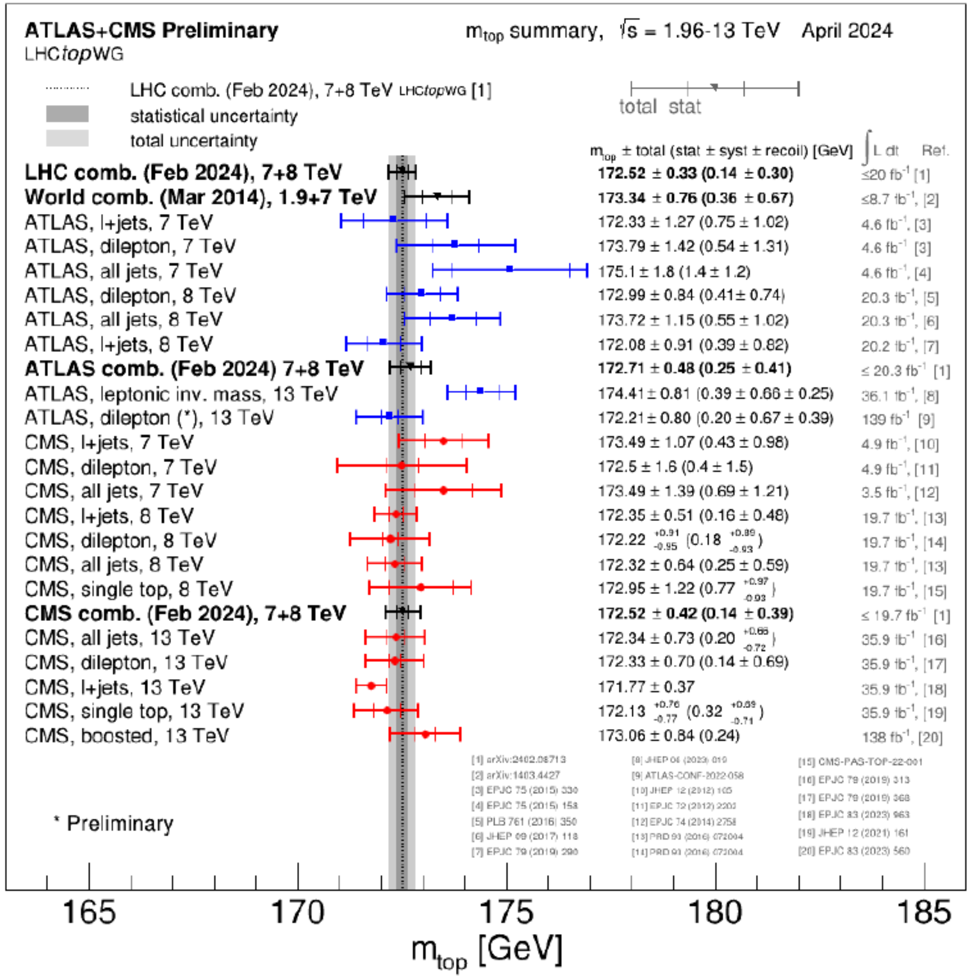
m_t from cross section



Where the debate is

What precision can we reach and what does it take?

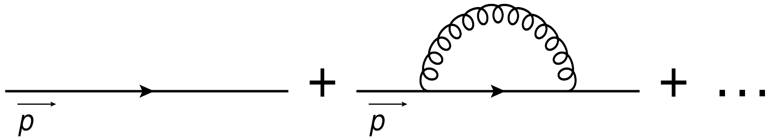
m_t from direct reconstruction



The top quark mass

Pole mass, Monte Carlo mass, … what is measured?

The top mass parameter in a theoretical calculation must be defined within a given renormalization scheme since (divergent) corrections appear at each order in perturbation theory



$$\sim \frac{i}{\not p - m_t^0 - \Sigma(p, m_t^0, \mu)}$$

- ➢ Pole mass scheme (subtract divergent corrections in such a way that the pole in the propagator remains fixed)
- ➢ $\overline{MS}$ scheme (only the $1/\epsilon$ poles are subtracted)

The two definitions lead to perturbatively equivalent theories, i.e. the relation between the two definition can be calculated order by order, e.g. (for $m_{\overline{MS}} = 163.643$ GeV, and $\alpha_s^{(6)} = 0.1088$)

$$m_p = m_{\overline{MS}} + 7.557 + 1.617 + 0.501 + 0.195 \pm 0.005 \text{ GeV}$$

NLO NNLO N^{3}LO N^{4}LO

[From P. Nason. arXiv:1712.0796]

and the difference between predictions in the two theories is to the next perturbative order.

So far, no ambiguity!

The top quark mass (cont'd)

The discussion arises because of the quoted precision of the determinations via direct reconstruction:

- Since the top is a colored object, no final-state hadronic system can be unambiguously associated to it.
- The mass distribution can be computed, and the top-mass enters as a parameter.
- Since this is performed via a parton-shower event generator people started calling it the *Monte Carlo mass*.
- Perturbative argument: since MC are LO, this mass does not correspond to any specific theory scheme.
- Non-perturbative argument: MC reconstruction is affected by non-perturbative effects (jets reconstruction, hadronization, etc.)
- Hence the quoted error is largely underestimated.

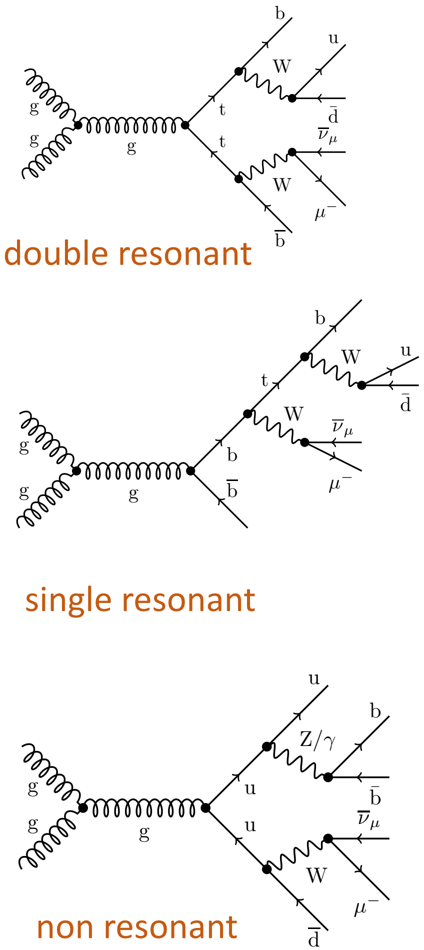
This argument can be argued because:

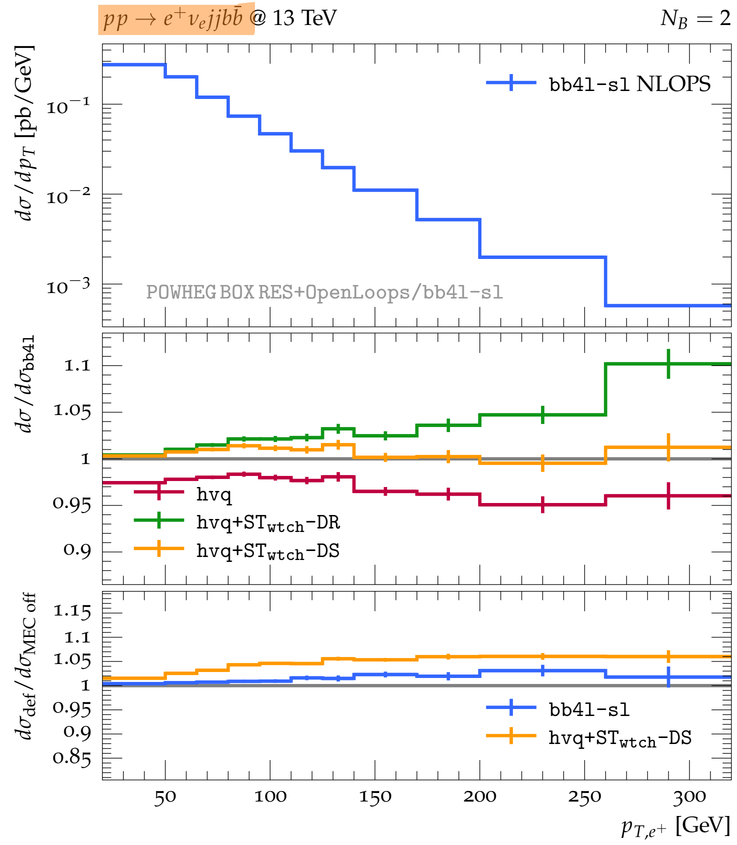
- The fact that MC are LO or include higher effects depend on the observable and on the MC.
- MC preserve the resonance structure, and the corresponding mass corresponds to a pole mass modulus non-factorizable effects and non-perturbative effects.
- MC effects affect the indirect determination (from cross-sections measurements) as well.

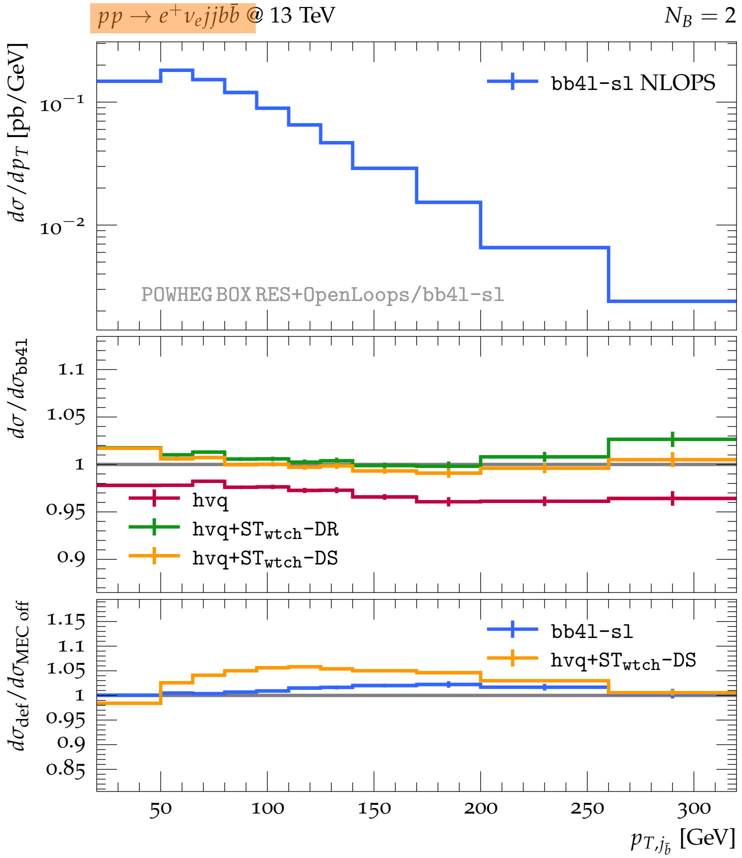
It would be more correct (and constructive!) to say that direct reconstruction analyses measure the pole mass, and one should determine how the approximations present in the MC used propagate to such measurements.

Assigning a ballpark “1 GeV” uncertainty is not particularly meaningful.

Beyond fixed-order on-shell production







[arXiv:2307.15653, Ježo, Lindert, Pozzorini]

$t\bar{t} + X$ ($X = W, Z, X, \gamma$) production

- Crucial for a complete measurement of top-quark EW couplings
  (together with single-top processes, …)
- Top-quark couplings @ (HL-)LHC as indirect probe of BSM physics
  - Top-quark, unique probe
  - Unrivaled access to top-quark physics till future TeV-energy lepton collider
- Background to $t\bar{t}H$
  - Need accurate modeling of both $t\bar{t}Z$ and $t\bar{t}W$ to measure $t\bar{t}H$
- Background to many searches of BSM physics
  - signatures with multi-leptons, b jets, and missing energy

Received focused experimental and theoretical attention

Challenge: NNLO for 2→3 multi-scale processes

Most recently first NNLO results for multi-scale processes: $b\bar{b}W, t\bar{t}W, t\bar{t}H$

Major impact on LHC phenomenology

1 massive final-state particle (b massless)

Hartanto, Poncelet, Popescu, Zoia 2205.01687

3 massive final-state particles

Buonocore, Devoto, Grazzini, Kallweit, Mazzitelli, Rotoli, Savoini , 2306.16311

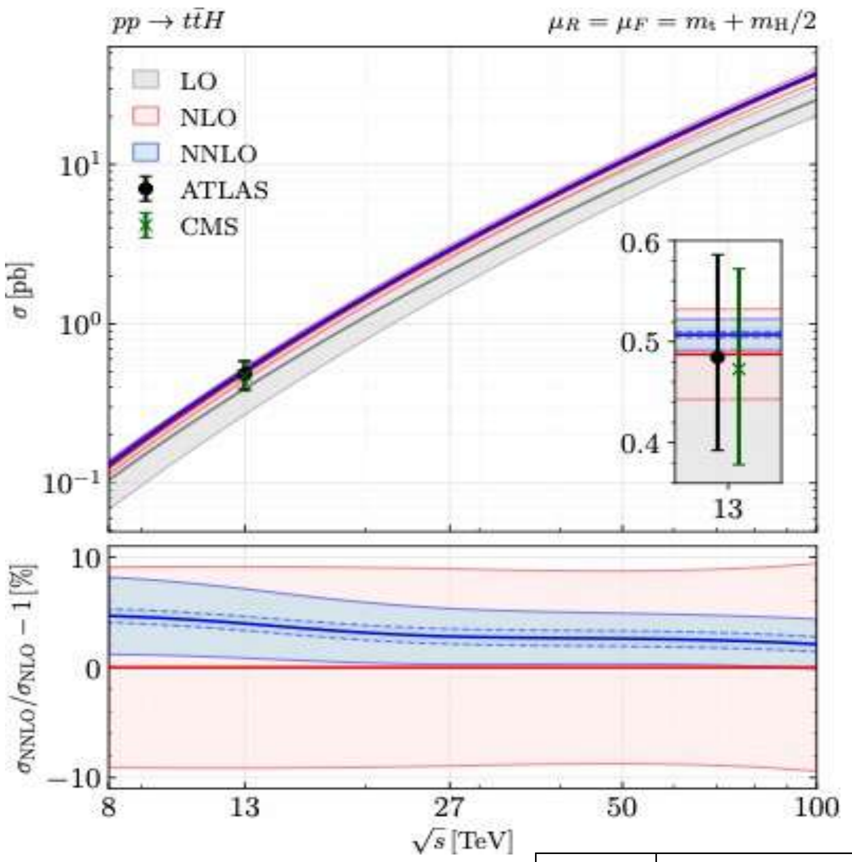
Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini , 2210.07846

Major bottle neck: 2-loop 5-point amplitudes
Evaluated in $t\bar{t}W, t\bar{t}H$ calculation by soft-W/H approximation

Very recently first results for 2-loop amplitudes

Febres Cordero, Figueiredo, Krauss, Page, Reina, 2312.08131
Buccioni, Kreer, Liu, Tancredi, 2312.10015
Agarwal, Heinrich, Jones, Kerner, Klein, 2402.03301

$t\bar{t}W$ and $t\bar{t}H$ at aNNLO

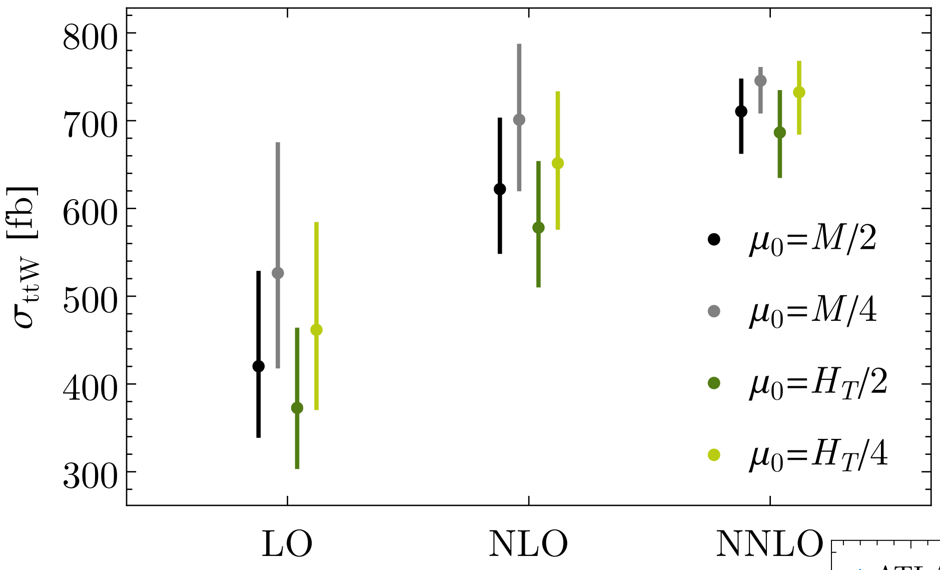


Catani et al., 2210.07846

Theoretical uncertainty reduced to 3% level

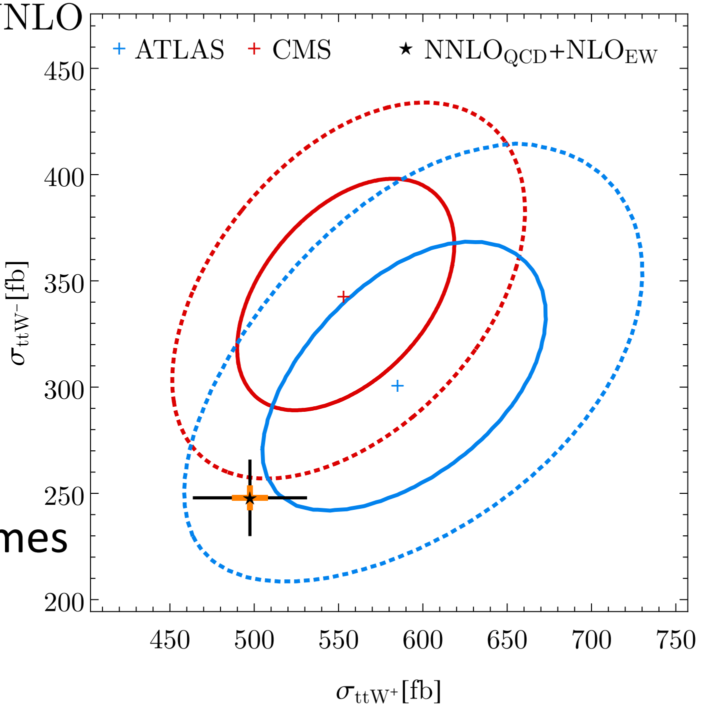
σ [pb]	$\sqrt{s} = 13$ TeV	$\sqrt{s} = 100$ TeV
σ_{LO}	$0.3910^{+31.3\%}_{-22.2\%}$	$25.38^{+21.1\%}_{-16.0\%}$
σ_{NLO}	$0.4875^{+5.6\%}_{-9.1\%}$	$36.43^{+9.4\%}_{-8.7\%}$
σ_{NNLO}	$0.5070\,(31)^{+0.9\%}_{-3.0\%}$	$37.20(25)^{+0.1\%}_{-2.2\%}$

Buonocore et al., 2306.16311



NNO QCD+NLO EW within at most 2σ of exp. measurement.

Ratio $\sigma_{t\bar{t}W^+}/\sigma_{t\bar{t}W^-}$ in very good agreement with ATLAS measurement



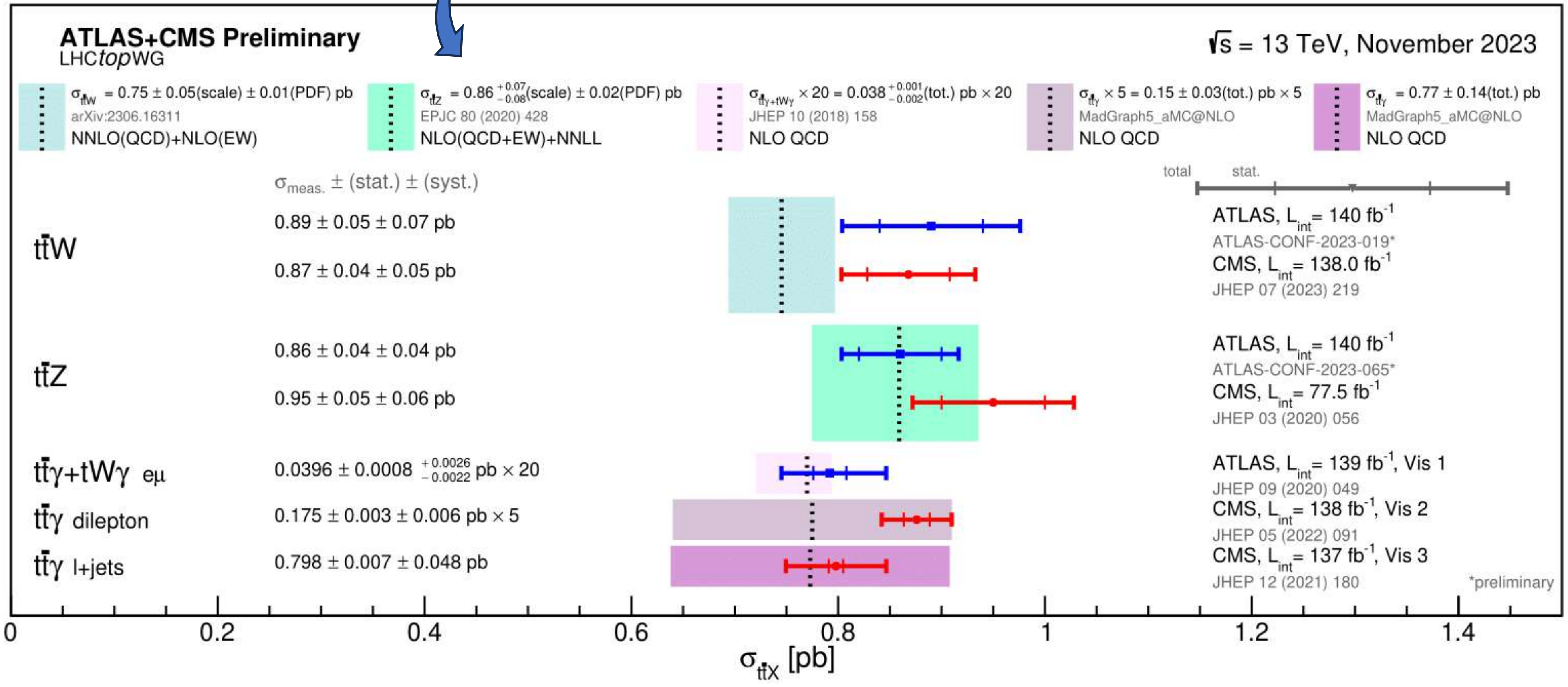
Comparison in fiducial volumes may give further insight

Comparison of most recent results

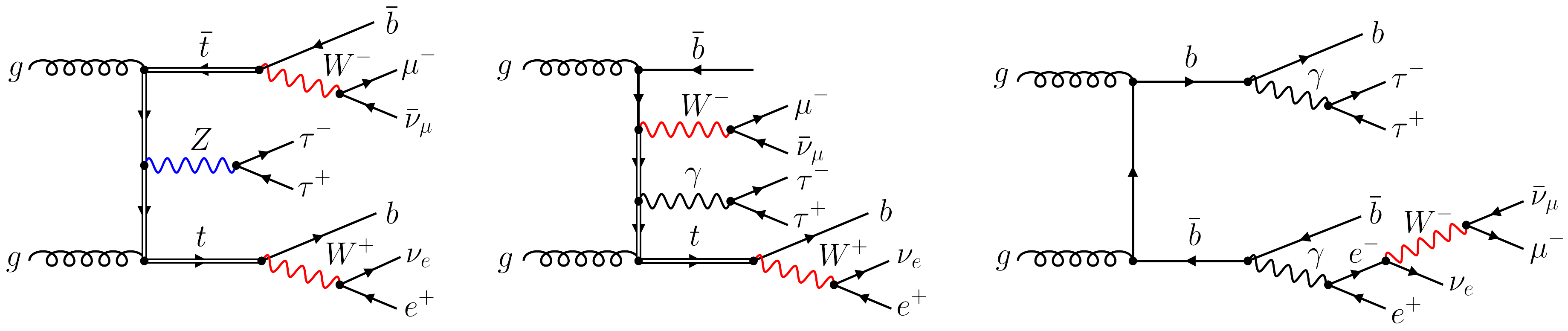
Buonocore, Devoto, Grazzini, Kallweit, Mazzitelli, Rottoli, Savoini

[NNLO QCD (no finite 2-loop)]

Kulesza, Motyka, Schwartländer, Stebel, Theeuwes



$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$ $(t\bar{t}Z)$, full off-shell description



+ NLO QCD

- EW G_μ input scheme (G_μ,m_Z,m_W). Other inputs: m_t, Γ_W, Γ_Z, Γ_t (LO, NLO, unstable-W and NWA)
- Unstable particles in complex mass scheme.
- Studied (μ_R,μ_F) scale dependence wrt to both a fixed and dynamical central scale (7-point variation)
- Studies PDF uncertainty.

$$\mu_0 = \frac{2m_t + m_Z}{2} \qquad \mu_0 = \frac{H_T}{3} \text{ for } H_T = \sum_i p_{T,i}$$

- Specific signature studied: $e^+\nu_e\mu^+\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$
  - $p_T^l > 20$ GeV, $|y^l| < 2.5$, $\Delta R_{ij} > 0.4$
  - $p_T^b > 25$ GeV, $|y^b| < 2.5$, $\Delta R_{bb} > 0.4$
  - $p_T^{miss} > 40$ GeV

[Bevilacqua et al., arXiv:1110.1499]

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$: theoretical systematics

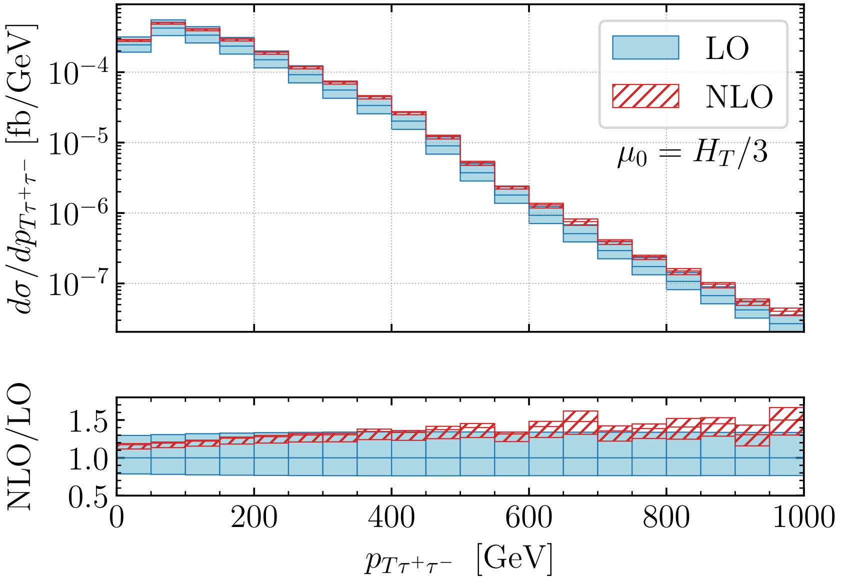
Very small residual systematic uncertainty at NLO QCD

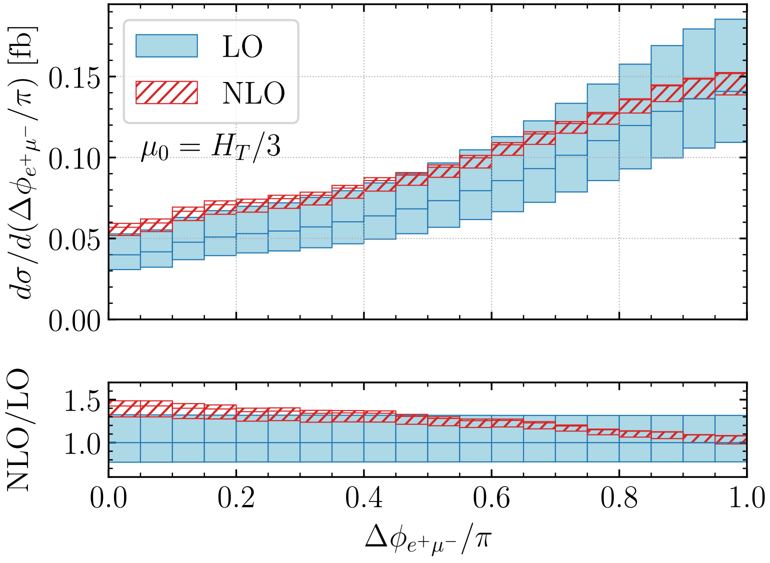
$$\sigma^{\rm LO}_{\rm full\ off\text{-}shell} = 80.32^{+25.51(32\%)}_{-18.02(22\%)} \left(76.98^{+24.30(32\%)}_{-17.17(22\%)}\right) \text{ ab}$$

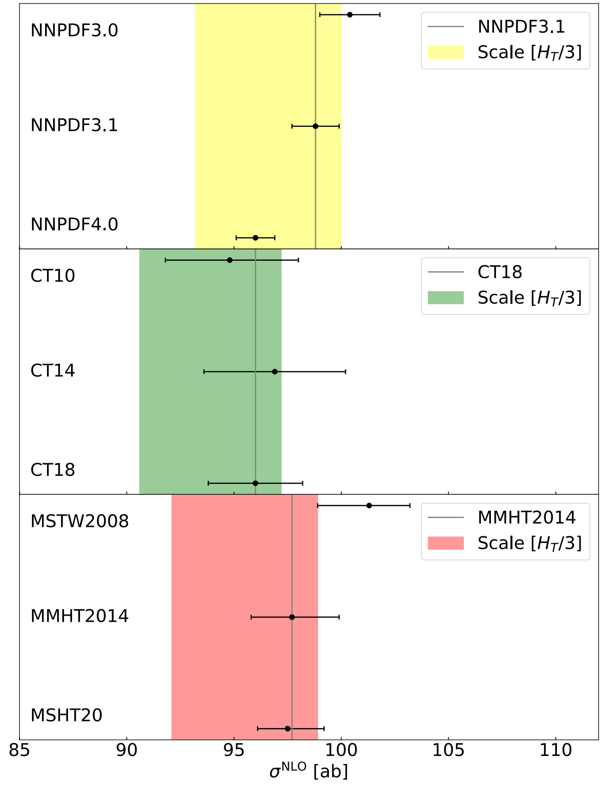
$$\sigma^{\rm NLO}_{\rm full\ off\text{-}shell} = 98.88^{+1.22(1\%)}_{-5.68(6\%)} \left(97.86^{+1.08(1\%)}_{-6.16(6\%)}\right) \text{ ab}$$

Dynamic scale preferred over full range of distributions.

Not a uniform rescaling.



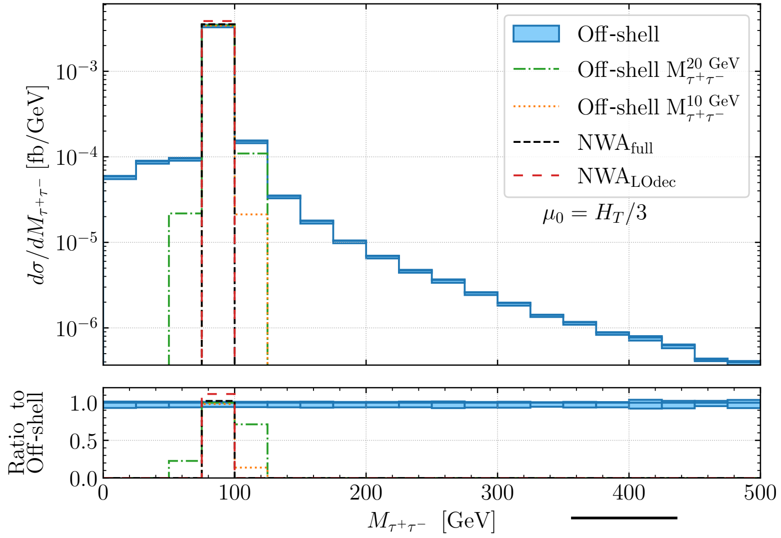




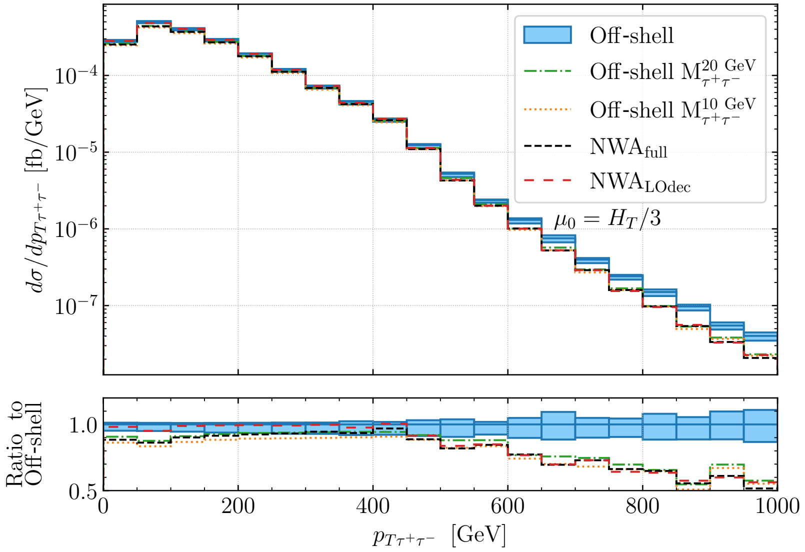
Small dependence on PDF

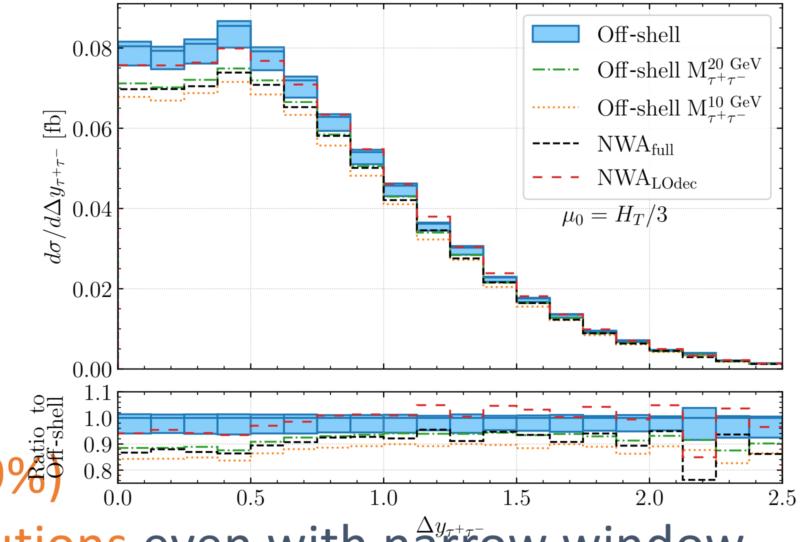
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$ $(t\bar{t}Z)$: fully off-shell vs NWA

Very thorough study of modelling effects



MODELLING	σ_i^{NLO} [ab]	$\sigma_i^{NLO}/\sigma_{NWA_{full}}^{NLO} - 1$
Off-shell	98.88	+11.4 %
Off-shell $M^{25\,GeV}_{\tau^+\tau^-}$	91.00	+2.5 %
Off-shell $M^{20\,GeV}_{\tau^+\tau^-}$	89.96	+1.4 %
Off-shell $M^{15\,GeV}_{\tau^+\tau^-}$	88.44	−0.3 %
Off-shell $M^{10\,GeV}_{\tau^+\tau^-}$	85.74	−3.4 %
NWA_{full}	88.75	–
NWA_{LOdec}	96.74	+9.0 %

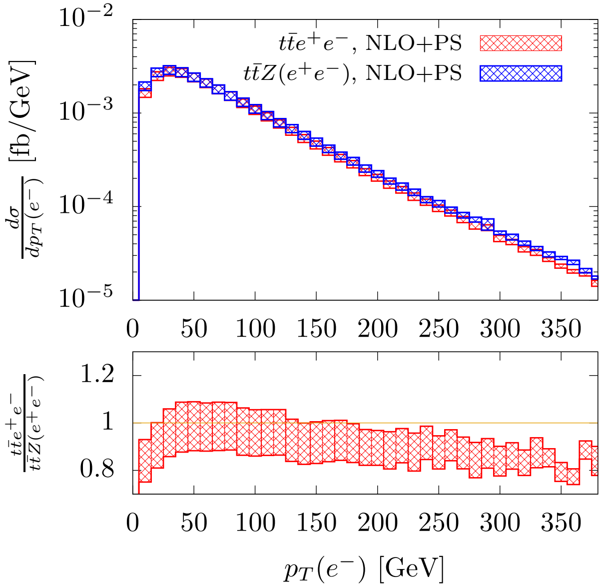


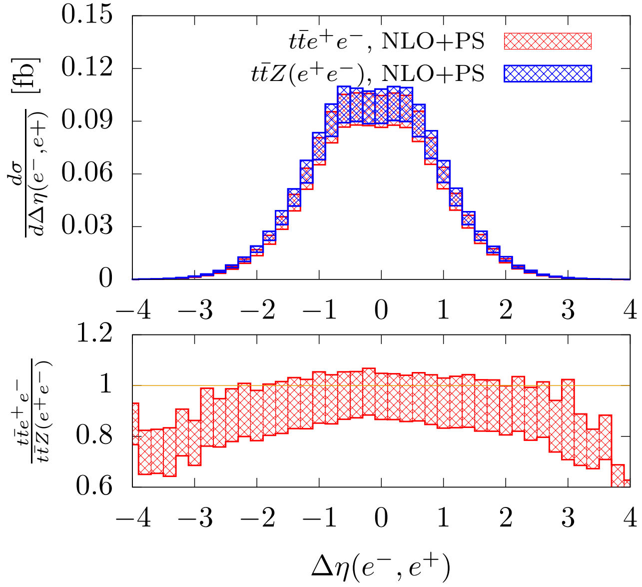


- Large off-shell effects on total cross section (11%) originating from $t\bar{t}\gamma^*$ contribution (including Z/γ^* interference): studied imposing narrower $|M_{\tau\tau}-m_Z| < X$ (X=25,20,15,10 GeV) cut.
  Less evident in $t\bar{t}l^+l^-$ study because it used X=10 GeV.
- Large effect from including NLO QCD corrections to top-quark decay (9%)
- Sizable off-shell effects in specific fiducial regions of differential distributions even with narrow window cut around the Z peak.

[Bevilacqua et al., arXiv:1110.1499]

$pp \to t\bar{t}e^+e^-$: partial off-shell and spin-correlation effects + PS





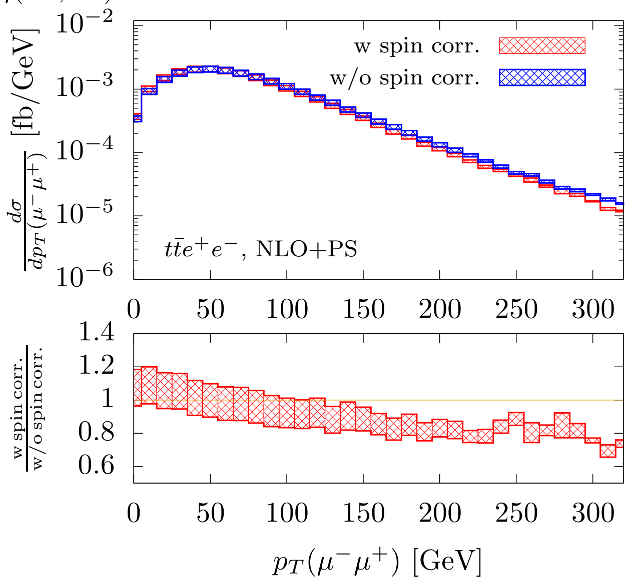
Compare $t\bar{t}Z$ and $t\bar{t}e^+e^-$ keeping stable top quarks:

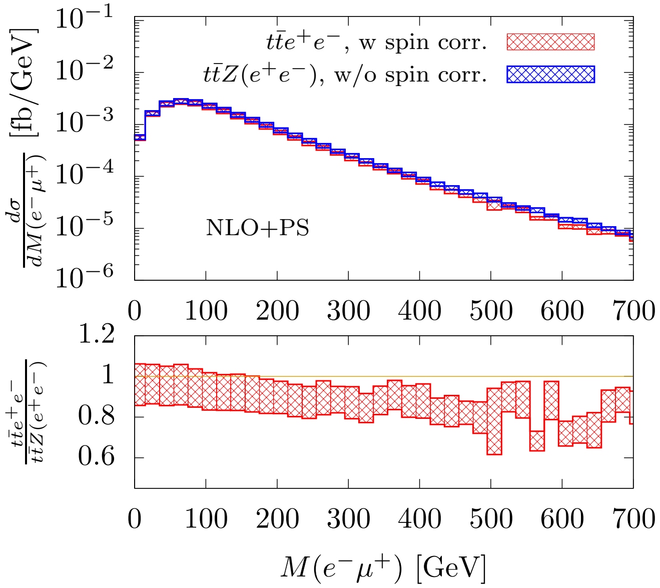
- ➢ Effects of off-shell Z
- ➢ Effects of e^+e^- spin correlations

10-20% effect in high p_T region and in the large pseudo-rapidity difference region

Compare $t\bar{t}e^+e^-$ with and without modeling of top decays (NWA with LO spin correlations).

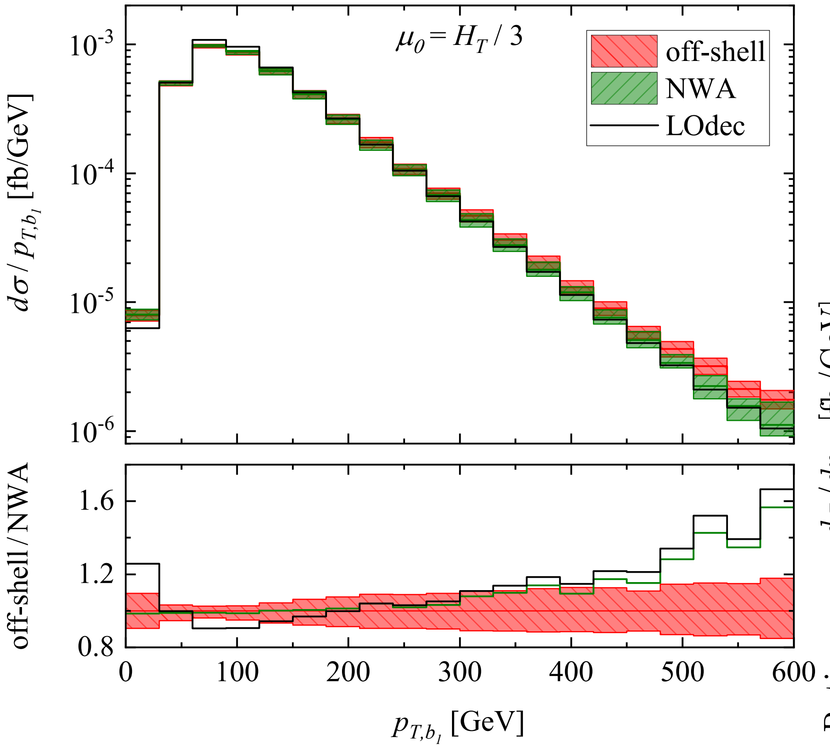
10-20% visible effects in the tails of distributions



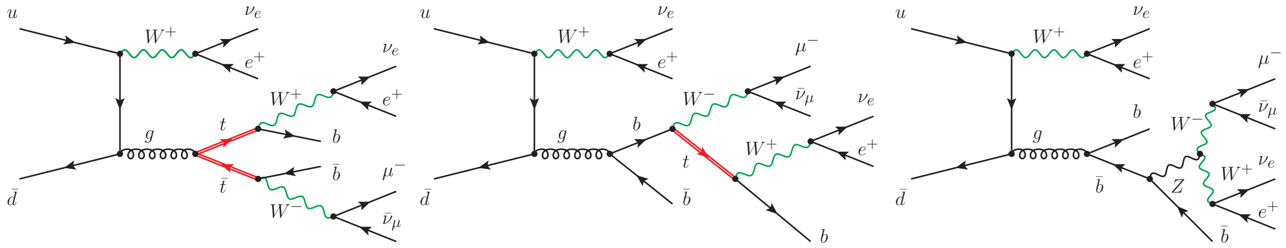


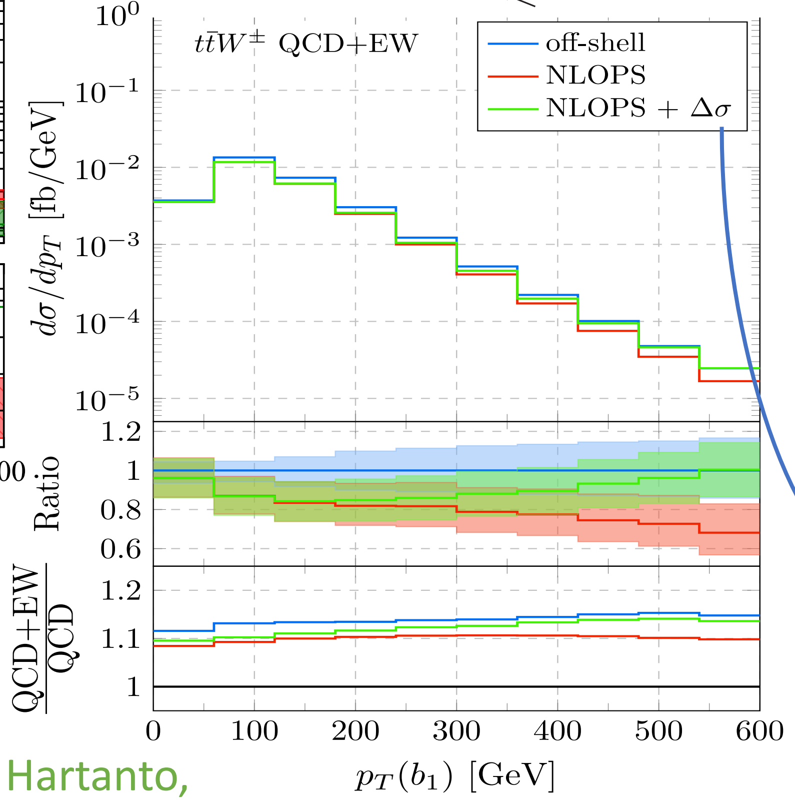
NLO $t\bar{t}W$: push the multiplicity challenge

Beyond on-shell production to match fiducial measurements



Bevilacqua, Bi, Hartanto, Kraus, Worek, 2005.09427





Bevilacqua, Bi, Febres Cordero, Hartanto, Kraus, Nasufi, LR, Worek, 2109.15181

Modelling full process crucial to match experimental fiducial cuts and estimate theoretical systematic

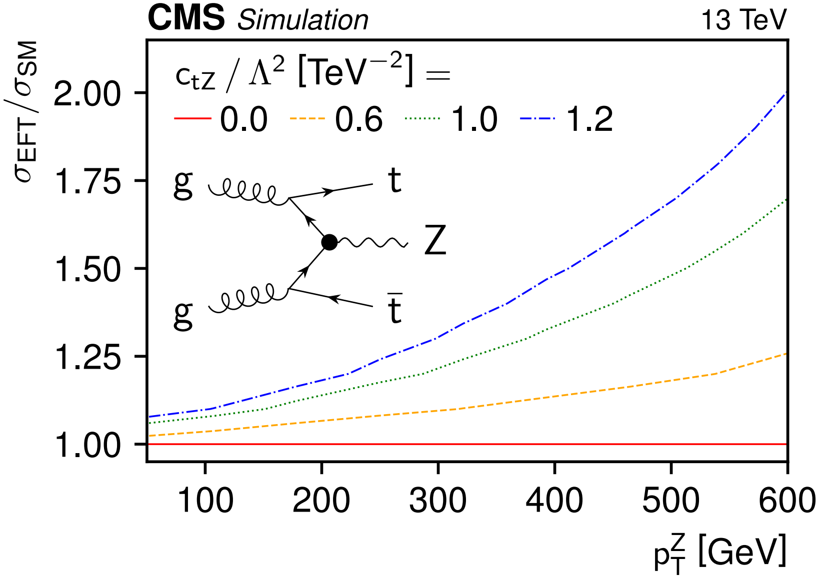
Off-shell effects most relevant in tails and end-points of distributions, where new physics effects can be hidden

$$\frac{d\sigma^{th}}{dX} = \frac{d\sigma^{NLO+PS}}{dX} + \frac{d\Delta_{off-shell}}{dX}$$

$$\frac{d\Delta_{off-shell}}{dX} = \frac{d\sigma^{NLO}_{off-shell}}{dX} - \frac{d\sigma^{NLO}_{NWA}}{dX}$$

… exploring boosted kinematics and off-shell signatures

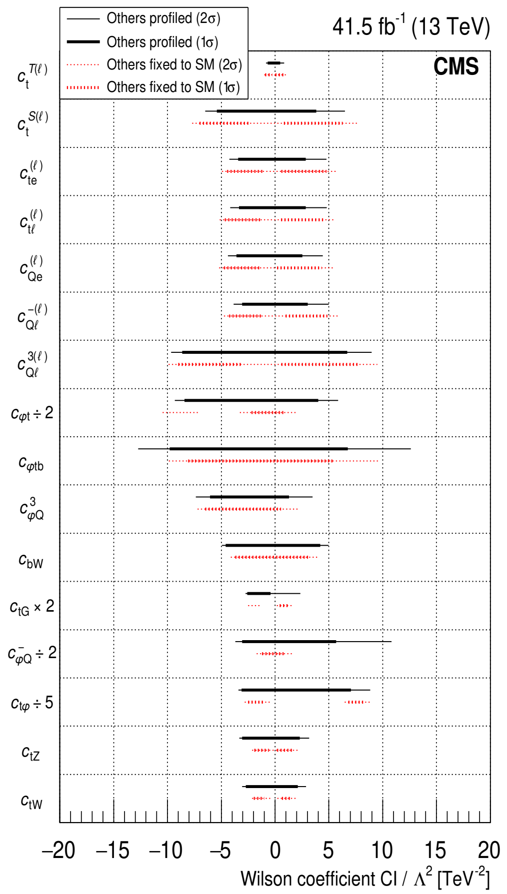
Top pair + boosted Z/H



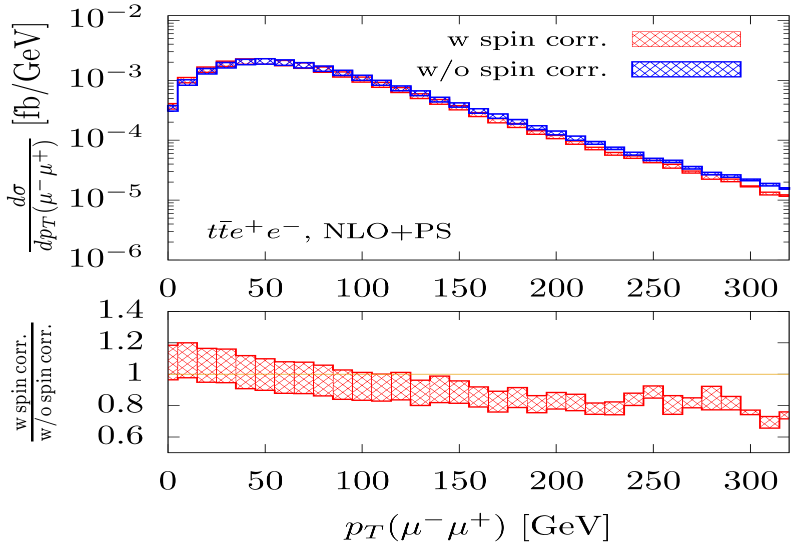
$$\delta\eta_{SM} \sim g^2_{BSM}\frac{E^2}{M^2}$$

Effects in tails of distributions but also anomalous shapes

Top+additional leptons

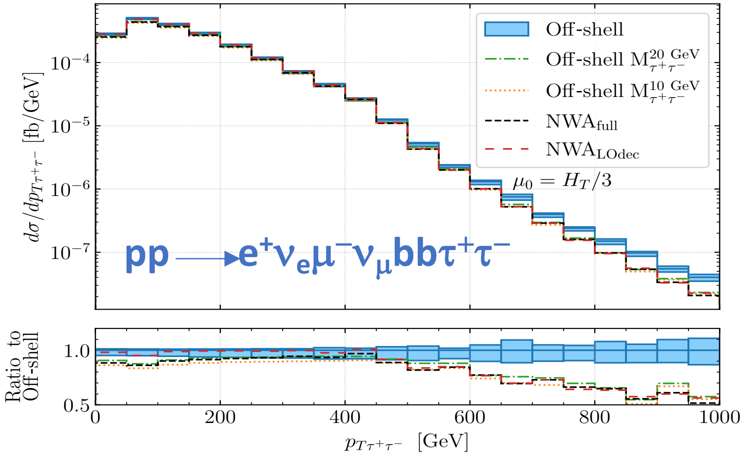


[CMS: arXiv:2012.04120]



M. Ghezzi et al. [2112.08892]

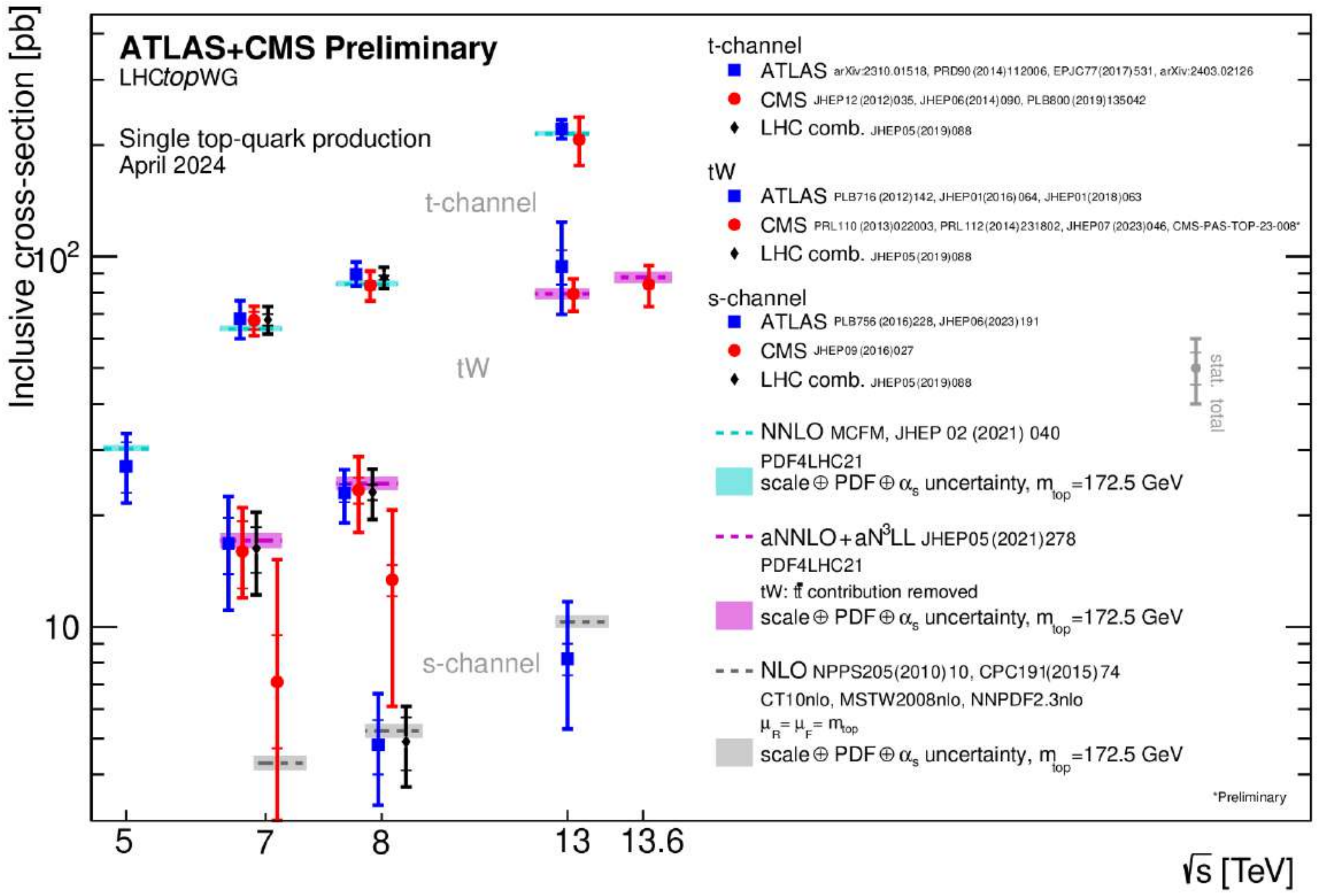
Off-shell studies



G. Bevilacqua et al. [2203.15688]

Pointing to the need for precision in modelling signatures from $t\bar{t} + X$ processes in regions where on-shell calculations may not be accurate enough

Single-top production

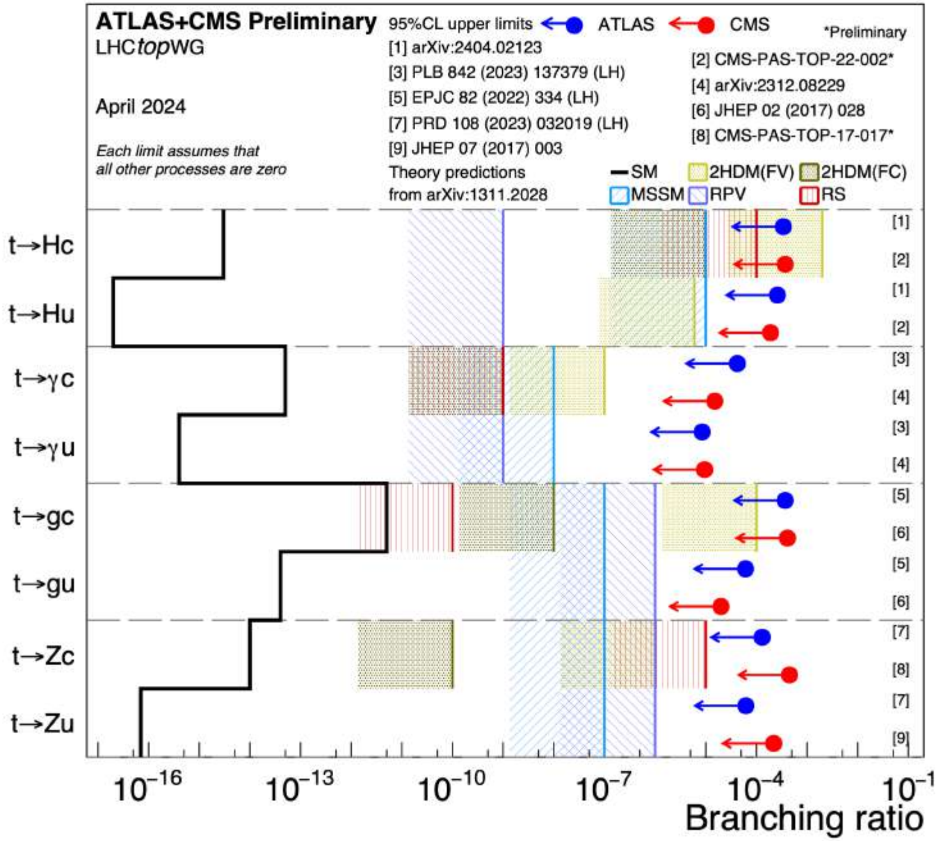


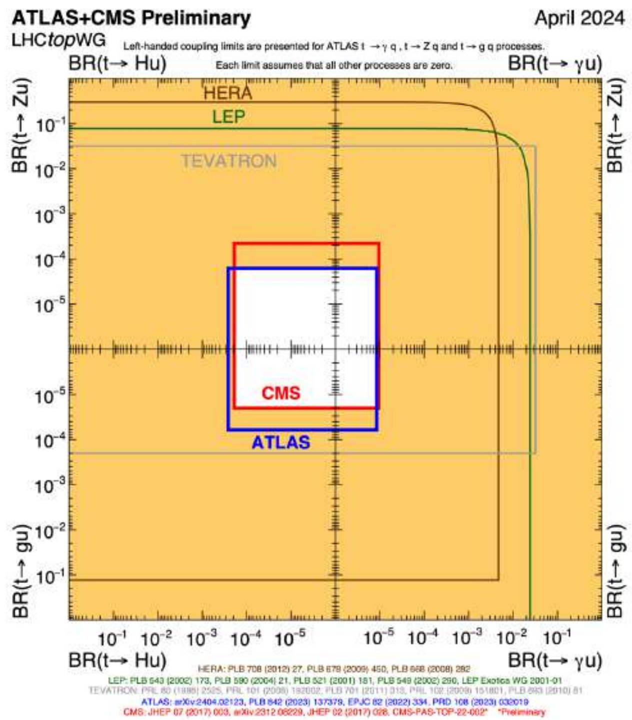
See Robert Schöfbeck's lecture on Thursday

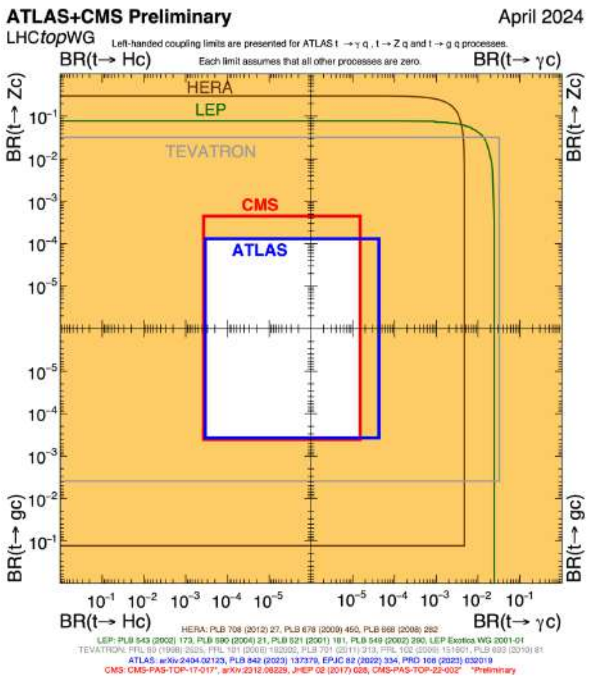
Constraining new physics via top-quark measurements

- Examples of direct bounds on new physics models from top-quark physics measurement and their interpretation within the SM Effective Field Theory framework.

Constraining flavor-changing top-quark couplings







Notice the constraining power of LHC measurements!

Are these decays allowed at tree-level in the SM? In a 2HDM?

The SMEFT framework

Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{C_i}{\Lambda^2} Q_i + \dots$$

"Warsaw" basis

$$\mathcal{L}_{SM}^{(4)} = -\frac{1}{4} G_{\mu\nu}^A G^{A,\mu\nu} - \frac{1}{4} W_{\mu\nu}^I W^{I,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$
$$+ (D_\mu \varphi)^\dagger (D^\mu \varphi) + m^2 \varphi^\dagger \varphi - \frac{1}{2} \lambda (\varphi^\dagger \varphi)^2$$
$$+ i \left(\bar{l}'_L \not{D} l'_L + \bar{e}'_R \not{D} e'_R + \bar{q}'_L \not{D} q'_L + \bar{d}'_R \not{D} d'_R \right)$$
$$- \left(\bar{l}'_L \Gamma_e e'_R \varphi + \bar{q}'_L \Gamma_u u'_R \tilde{\varphi} + \bar{q}'_L \Gamma_d d'_R \varphi \right) + h.c.$$

with covariant derivative:

$$D_\mu = \partial_\mu + i g_s G_\mu^A T^A + i g_W W_\mu^I T^I + i g_1 B_\mu Y$$

Higgs field and Mh

Yukawa couplings

Vff, HFF

gauge fields and masses, HVV, VVV

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
$\mathcal{O}_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_\varphi$	$(\varphi^\dagger\varphi)^3$	$\mathcal{O}_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p \varphi e_r)$
$\mathcal{O}_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p \tilde{\varphi} u_r)$
		$\mathcal{O}_{\varphi D}$	$\left(\varphi^\dagger D^\mu \varphi\right)^\star \left(\varphi^\dagger D_\mu \varphi\right)$	$\mathcal{O}_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p \varphi d_r)$

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$\mathcal{O}_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$\mathcal{O}_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$\mathcal{O}_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$\mathcal{O}_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\tilde{\varphi}\, G_{\mu\nu}^A$	$\mathcal{O}_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$\mathcal{O}_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \tilde{\varphi}\, W_{\mu\nu}^I$	$\mathcal{O}_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
		$\mathcal{O}_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tilde{\varphi}\, B_{\mu\nu}$	$\mathcal{O}_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
		$\mathcal{O}_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$\mathcal{O}_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
		$\mathcal{O}_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$\mathcal{O}_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
		$\mathcal{O}_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$\mathcal{O}_{\varphi ud}$	$(\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

4-fermion interactions: tt, ttH, DY

- Dim-6 operators only, including linear and quadratic effects
- Obeying SM symmetries, CP even
- Assuming $U(2)^5$ flavor symmetry (3rd generation singled out)
- One Higgs doublet of $SU(2)_L$, SSB linearly realized.

Where EFT effects matter most

Extend SM Lagrangian by effective interactions (ex. SM EFT)

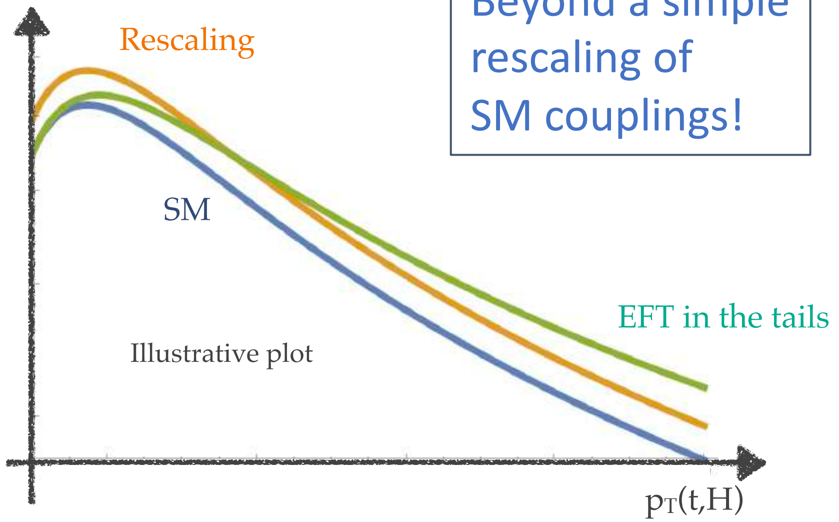
$$\mathcal{L}_{\rm SM}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}, \quad \left[\mathcal{O}_i^{(d)}\right] = d$$

Under the assumption that new physics leaves at scales $\Lambda > \sqrt{s}$

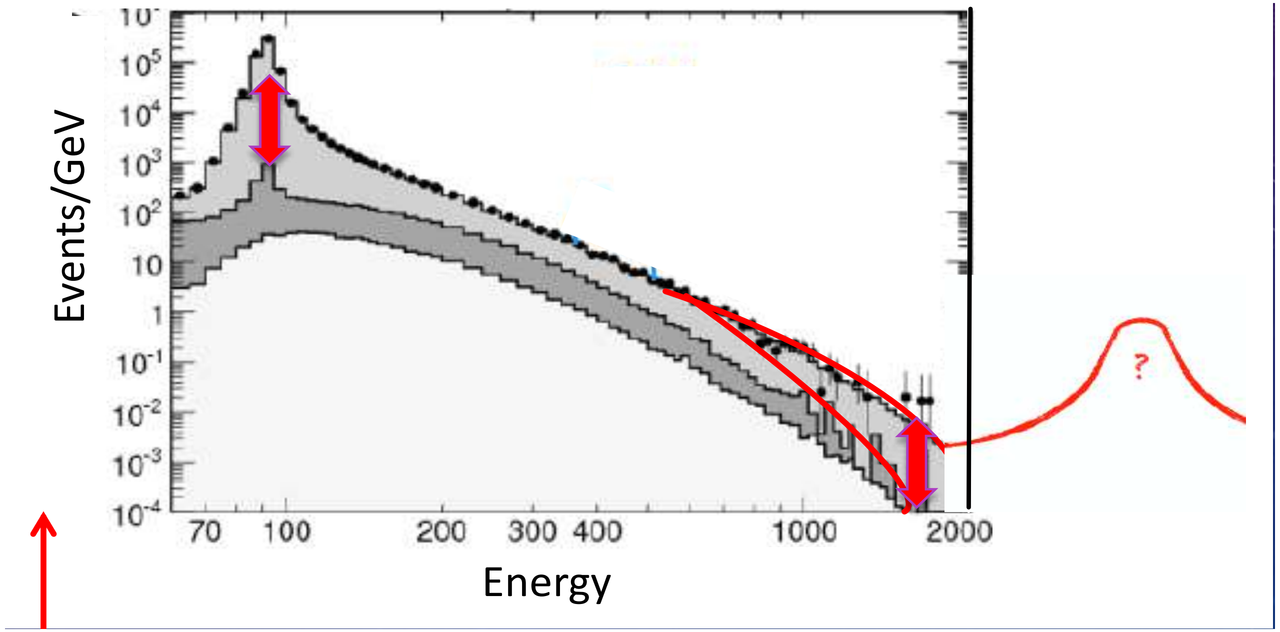
Expansion in $(v, E)/\Lambda$: **affects all SM observables** at both low and high energy

- **SM masses and couplings** → **rescaling**
- **Shapes of distributions** → more visible in **tails of distributions**



Beyond a simple rescaling of SM couplings!

How to see SMEFT effects



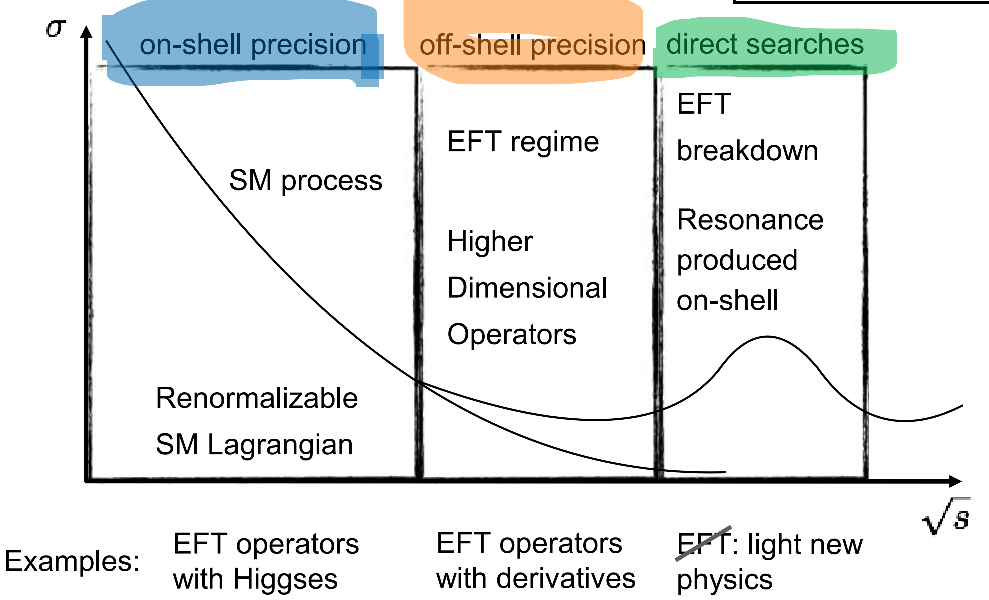
Need SM precision calculations at differential level both at **lower energy,** where rates are large and at **higher energy** where rates are small but effects of new physics may be more visible.

Extending the SM via effective interactions above the EW scale ⟶ **SMEFT**

dim=6

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \left(\frac{1}{\Lambda^2} \sum_i C_i O_i + \text{h.c.} \right) + O(\Lambda^{-4})$$

dim=8 and above

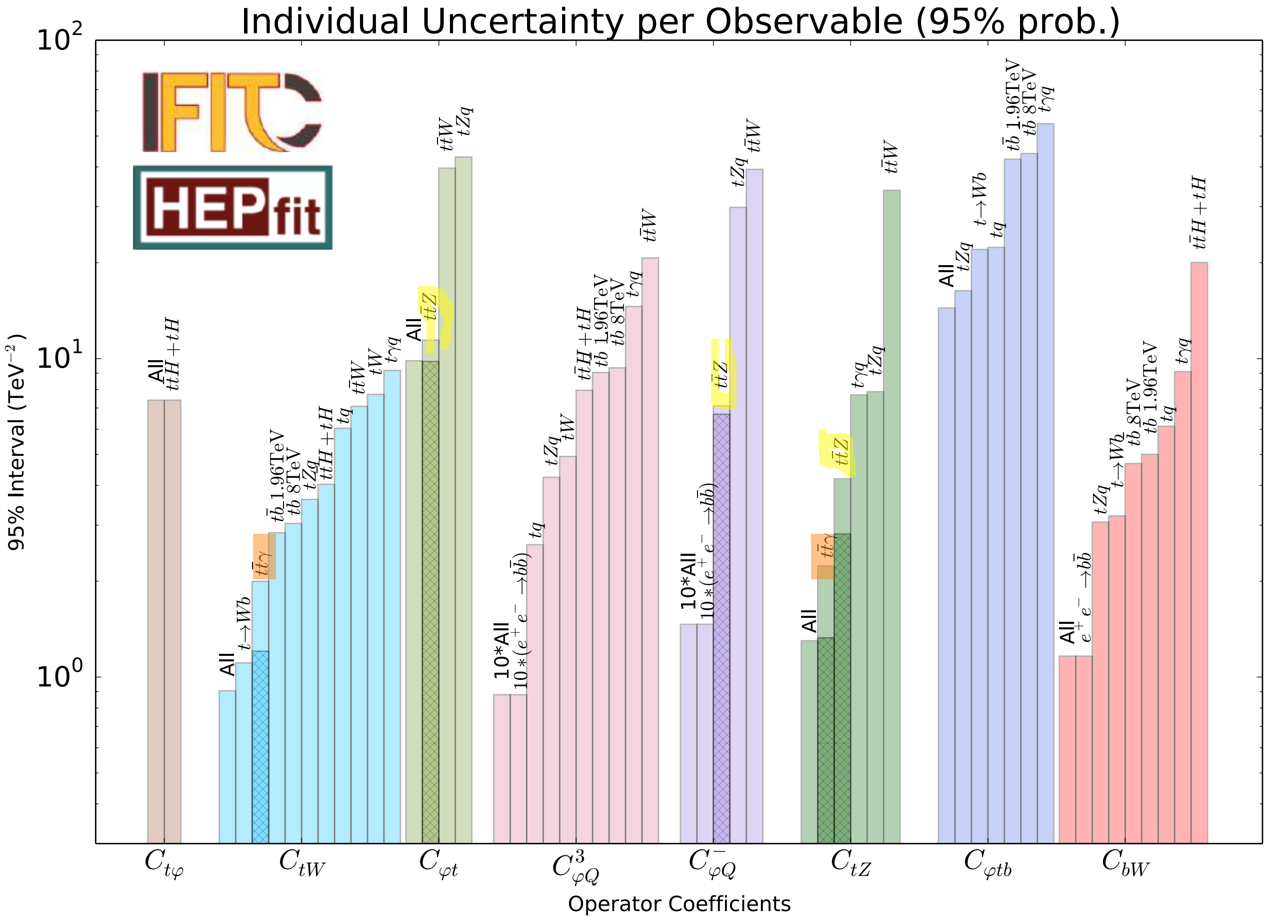


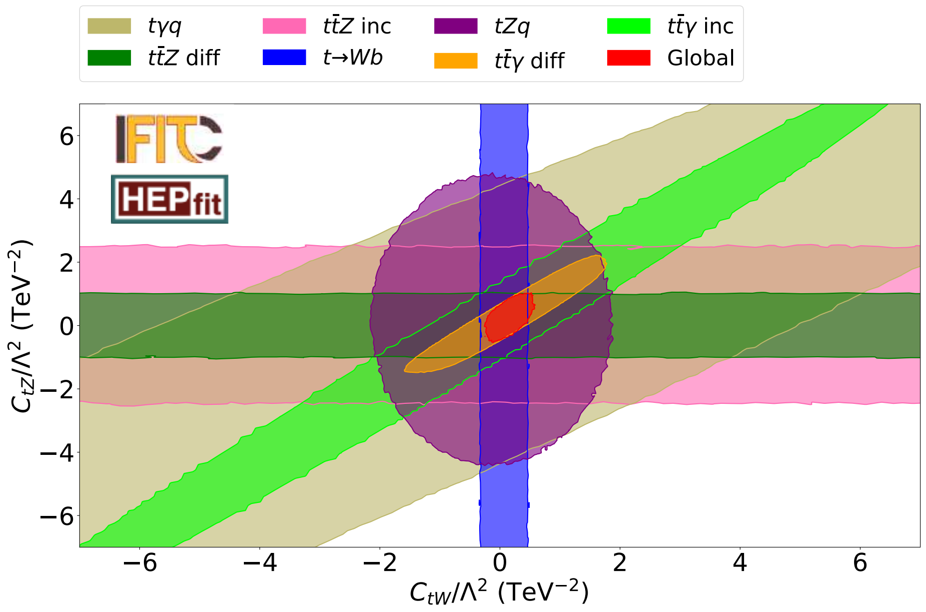
Crucial to control EFT sensitive regions

… through multiple probes

Global fits of top observables

V Miralles, M. Miralles López, M. Moreno Llacer, A. Peñuelas, M. Perelló, M. Vos [arXiv:2107.13917]





Kinematic distributions add substantial constraining power

Accurate modelling of $t\bar{t}Z$ differential cross sections and signatures is crucial

Beyond EW fits: adding Higgs, top, DY, di-boson, flavor

Constraining new physics through the spectrum of LHC measurements and beyond

- Higgs boson observables
  - Signal strengths.
  - Simplified Template Cross Sections (STXS)

$$\mu_{ij} = \frac{\sigma_i \times Br_j}{(\sigma_i \times Br_j)_{SM}}$$

- Top quark observables
  - $pp \to t\bar{t}, t\bar{t}Z, t\bar{t}W, t\bar{t}\gamma, tZq, t\gamma q, tW, \ldots$

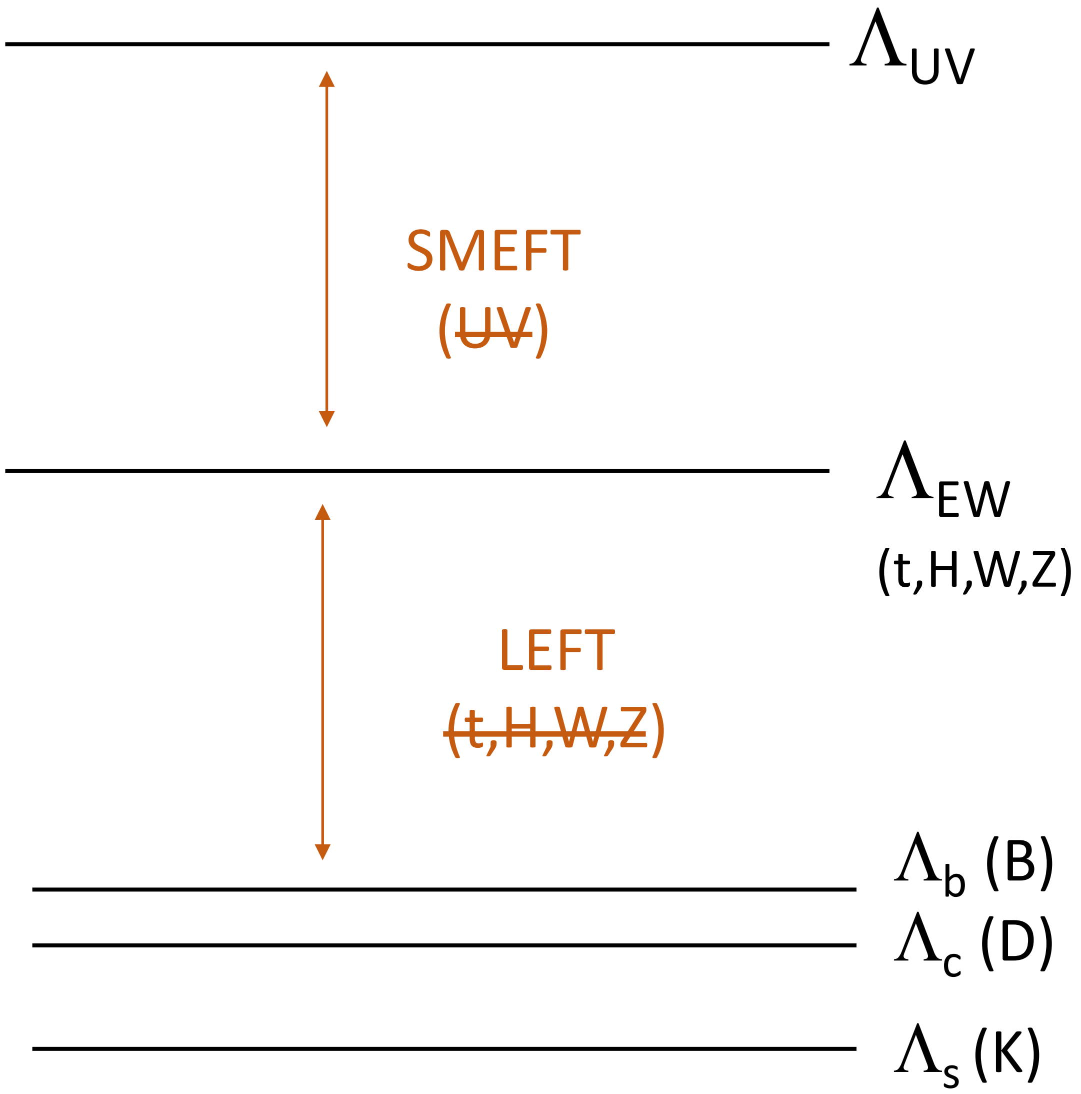
Preliminary results in this talk

- Drell-Yan, Di-boson measurements
  - $pp \to W, Z \to f_i \bar{f}_j$
  - $pp \to WZ, WW, ZZ, Z\gamma$
- Flavor observables
  - ΔF=2: $\Delta MB_{d,s}$, $D^0 - \bar{D}^0$, ε_K
  - Leptonic decays: $B_{d,s} \to \mu^+\mu^-$, $B \to \tau\nu$, $D \to \tau\nu$, $K \to \mu\nu$, $\pi \to \mu\nu$
  - Semi-leptonic decays: $B \to D^{(*)} l\nu$, $K \to \pi\nu\bar{\nu}$, $B \to K\nu\bar{\nu}$, $B, K \to \pi l\nu$
  - Radiative B decays ($B \to X_{s,d}\gamma$)

Still being tested

Beyond EW fits – Higgs, top, flavor observables

Connecting far apart scales naturally lends itself to the EFT framework



Heavy physics decouples and leaves effective contact interactions of dim > 4

RGE

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{i,d} \frac{C_{i,d}^{\rm SMEFT}}{\Lambda^2} \mathcal{O}_{i,d}^{\rm SMEFT}$$

RGE

$$\mathcal{L}_{\rm LEFT} = \mathcal{L}_{\rm QCD+QED} + \sum_{i,d} \frac{C_{i,d}^{\rm LEFT}}{v^2} \mathcal{O}_{i,d}^{\rm LEFT}$$

Operators mix through RGE and what we really want to know is the SMEFT structure at the high scale

Beyond EW fits – Higgs, top, flavor observables

Connecting far apart scales naturally lends itself to the EFT framework

Matchmakereft, 2112.10787
MATCH2FIT, 2309.04523

Λ_{UV}

$C_{i,d}^{SMEFT}(\Lambda_{UV})$ (from matching to UV theory)

Will be constrained by the fit

SMEFT
(~~UV~~)

Evolved to $C_{i,d}^{SMEFT}(\Lambda_{EW})$
using **RGEsolver++**

Di Noi and Silvestrini, 2210.06838

Based on 1-loop SMEFT anomalous dimension

Jenkins, Manohar, and Trott, 1308.2627, 1310.4838,1312.2014

Λ_{EW}
(t,H,W,Z)

All fit observables are calculated in terms of $C_{i,d}^{SMEFT}(\Lambda_{EW})$

LEFT
(~~t,H,W,Z~~)

Match to LEFT operators to calculate flavor observables

Jenkins, Manohar, Stoffer, 1709.04486, 1711.05270

Λ_b (B)

Λ_c (D)

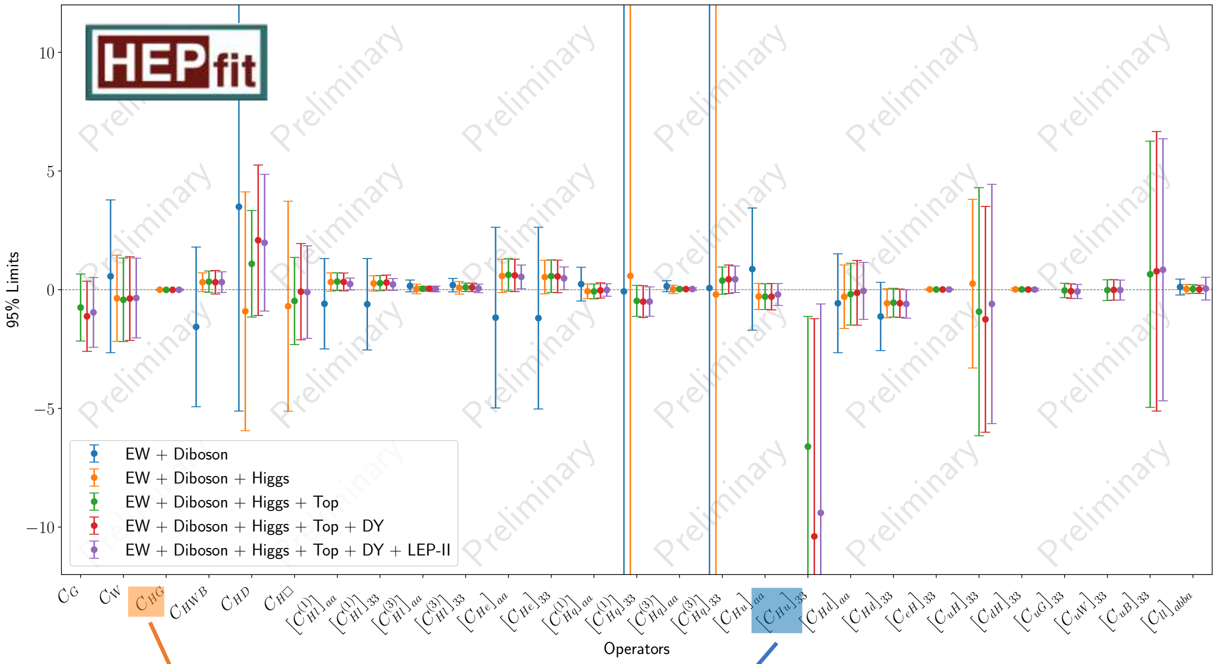
Λ_s (K)

Notice that the NLO evolution requires tree level initial conditions at Λ_{UV} and matrix elements at Λ_{EW}

Preliminary results

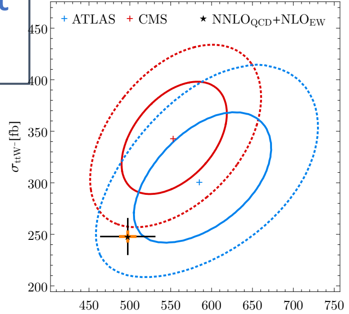
Fits with $U(2)^5$ flavour symmetry: 2-Fermion

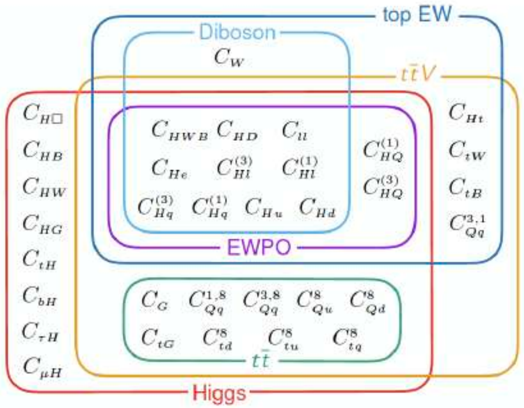
Limits for WC at the scale $\Lambda_{UV} = 1$ TeV



Highly constrained from ggH RGE effects visible

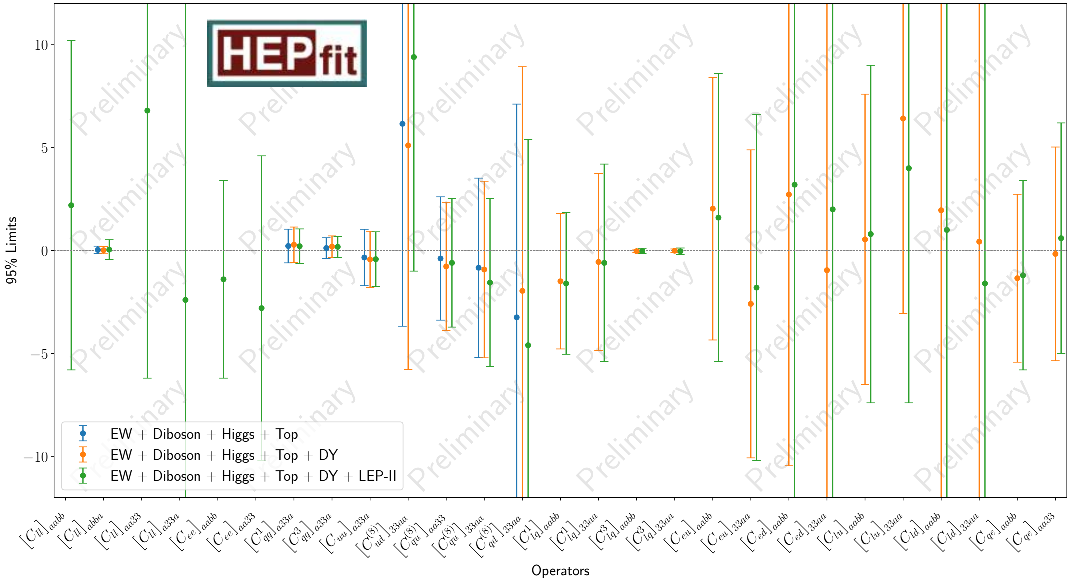
Effect of Vtt (V=Z,W,γ)





Mainly constrained by top observables

Fits with $U(2)^5$ flavour symmetry: 4-Fermion

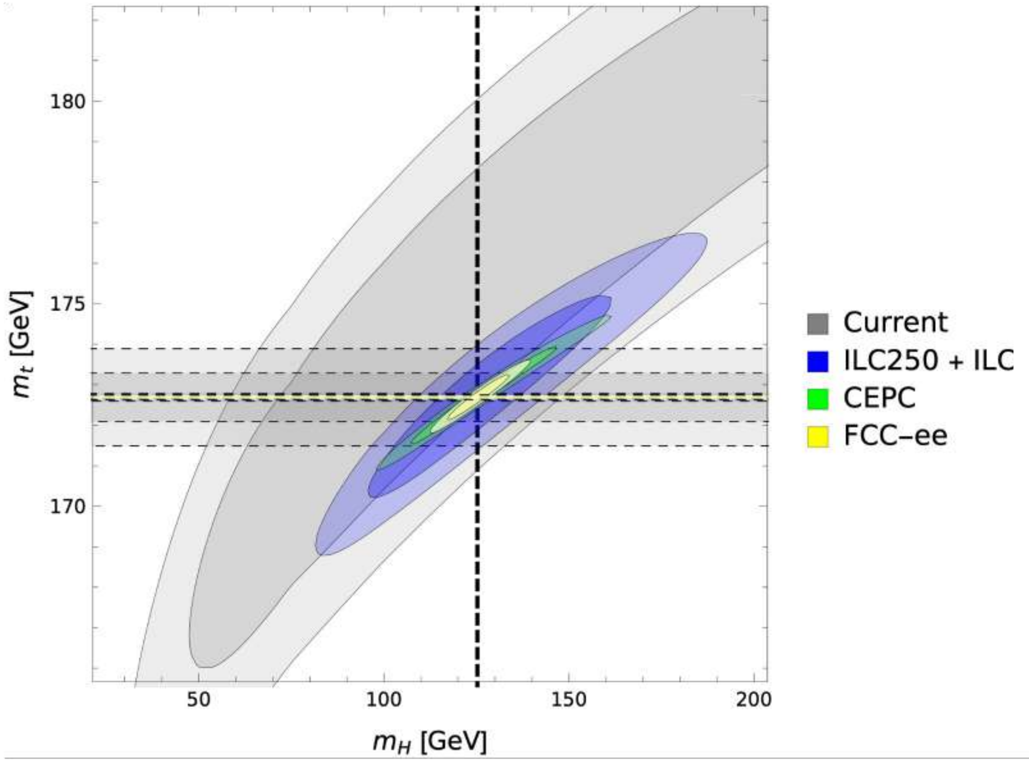


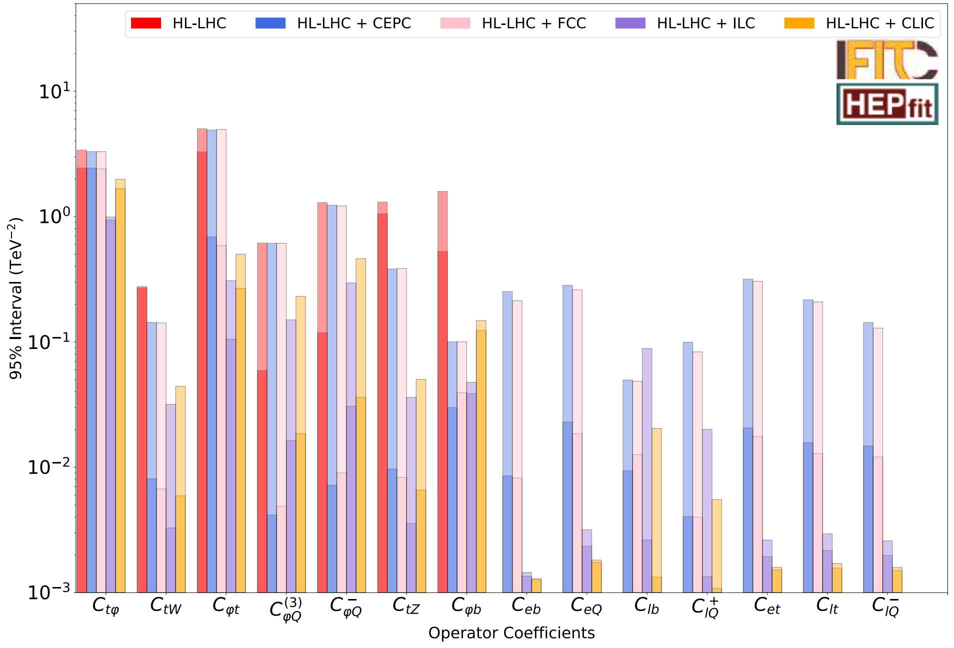
A glance to the future

Reach of future colliders for top mass/couplings

Stress testing the SM and exploring anomalous couplings

Parameter	HL-LHC	ILC 500	FCC-ee	FCC-hh
$\sqrt{s}$ [TeV]	14	0.5	0.36	100
Yukawa coupling y_t (%)	3.4	2.8	3.1	1.0
Top mass m_t (%)	0.10	0.031	0.025	–
Left-handed top-W coupling $C^3_{\phi Q}$ (TeV^{-2})	0.08	0.02	0.006	–
Right-handed top-W coupling C_{tW} (TeV^{-2})	0.3	0.003	0.007	–
Right-handed top-Z coupling C_{tZ} (TeV^{-2})	1	0.004	0.008	–
Top-Higgs coupling $C_{\phi t}$ (TeV^{-2})	3	0.1	0.6	
Four-top coupling c_{tt} (TeV^{-2})	0.6	0.06	–	0.024





From Snowmass 2021 EF HF and EW TG's Reports arXiv:2209.11267, arXiv:2209.08078