EF03: Heavy flavor and top quark physics

Manfred Kraus
on behalf of the EF03 topical group

Snowmass Day
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EF03: Heavy flavor and top quark physics

- Connection to EW physics (EFT fits)
- Precision Measurements (higher-orders: QCD,EW)
- HF physics at future colliders (HL-LHC, FCC, ILC, μ)

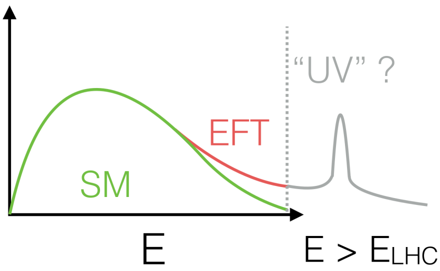
Why top physics?

- The top quark is special

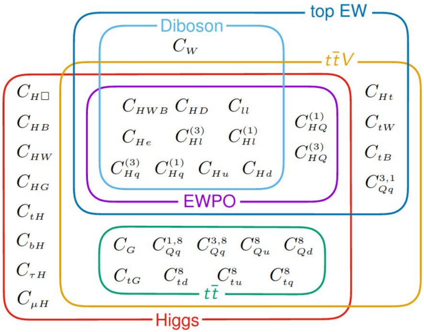
$$y_t = \frac{\sqrt{2} m_t}{v} \sim 1\,, \qquad \delta m_h, \lambda(\mu^2) \propto m_t^2$$

- Top-quark may be window to BSM physics

Effective Field Theory



[K. Mimasu TOP2021]



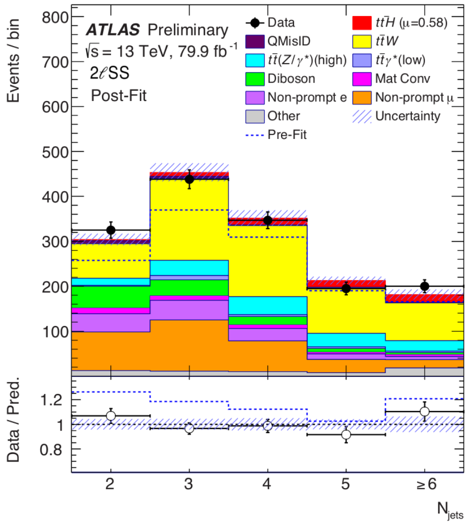
[N. Castro EF Workshop]

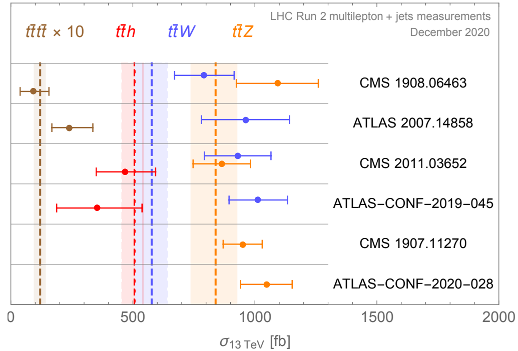
- SM effective field theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_n \frac{c_n}{\Lambda^2} O_n$$

- new processes accessible at HL-LHC: $tWZ, tW\gamma, tWH$
- new observables, multi-differential distributions?
- Needs precise predictions for the SM: new physics vs QCD

Experimental status





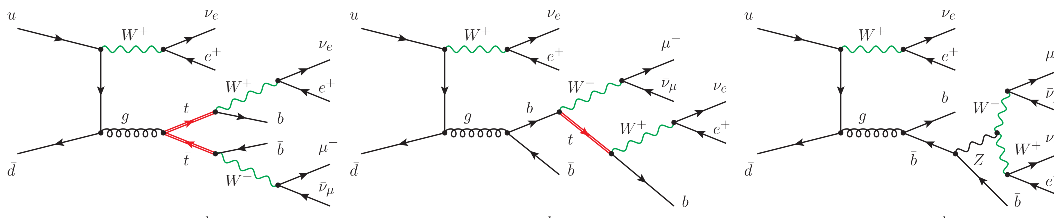
[Banelli et al, JHEP 02 (2021) 043]

ATLAS-CONF-2019-045

- Largest discrepancies for $t\bar{t}W$ in multi-lepton signatures
- Disrepancies: New Physics or QCD?
- How well is the modeling of these signatures?

Beyond stable tops

- off-shell contributions to $t\bar{t}W^+$



Double resonant　　Single resonant　　Non-resonant

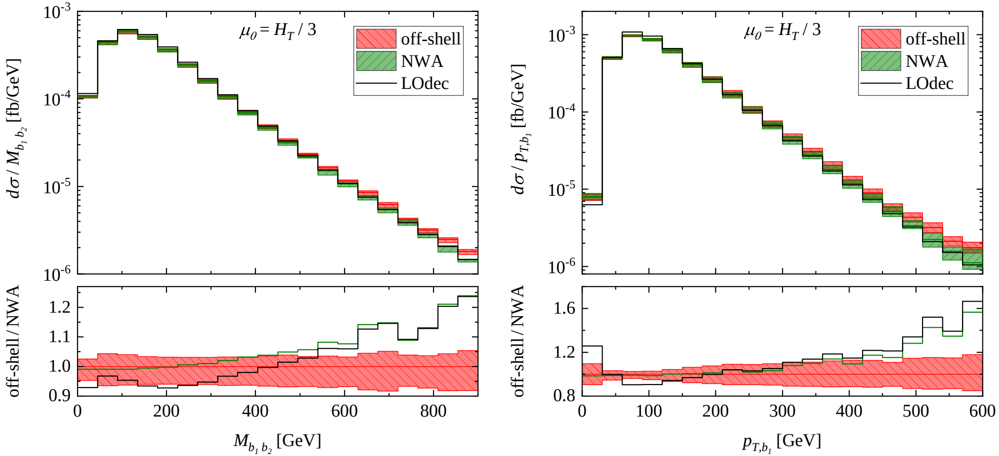
- Narrow-width approximation (NWA)

$$\frac{1}{(p^2 - m_t^2)^2 + m_t^2\Gamma_t^2} \to \frac{\pi}{m_t\Gamma_t}\delta(p^2 - m_t^2) + \mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)$$

Keeps only double resonant contributions

- How large are these effects at the differential level?
- What is the impact of QCD corrections on the top decay?

Impact of radiative top decays in $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu e^+\nu_e b\bar{b}$ @ $\sqrt{s} = 13$ TeV

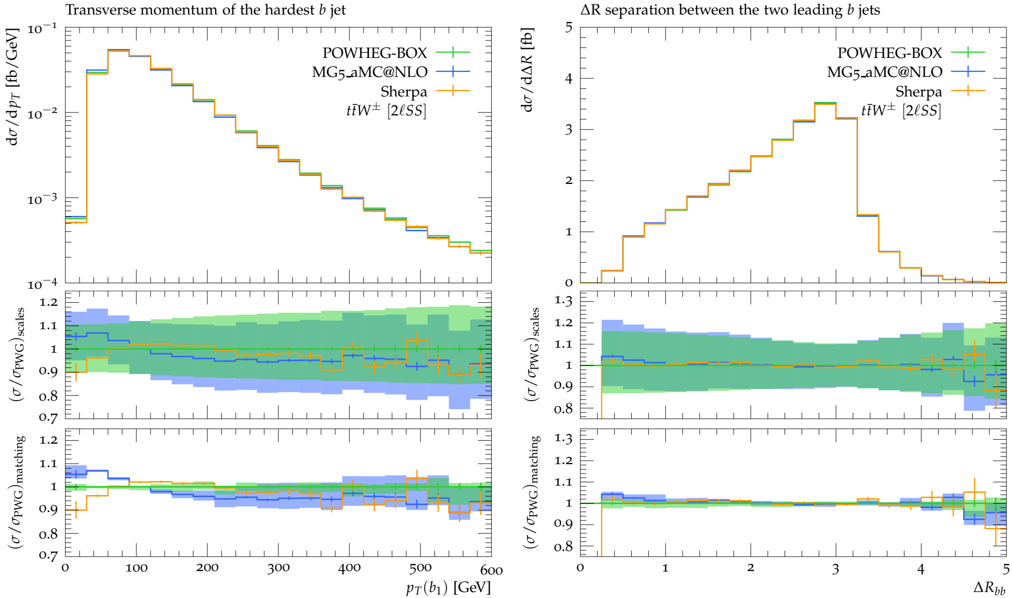


- Large off-shell effects in the tails of the distributions
- Differences between NWA and $\text{NWA}_{\text{LOdec}}$ are $\mathcal{O}(10\%)$ in the bulk

[Bevilacqua, Bi, Hartanto, MK, Worek, JHEP 08 (2020) 043]

on-shell $t\bar{t}W$ + parton showers

two same-sign leptons [Febres Cordero, MK, Reina, PRD 103, 094014]



Small shape differences at the beginning of the p_T spectrum

Modeling of multi-lepton signatures

How to model leptonic final states?

$$pp \longrightarrow b\bar{b}\ell^{\pm}\nu_{\ell}\ell^{\pm}\nu_{\ell}\ell^{\pm}\nu_{\ell}$$

fixed-order

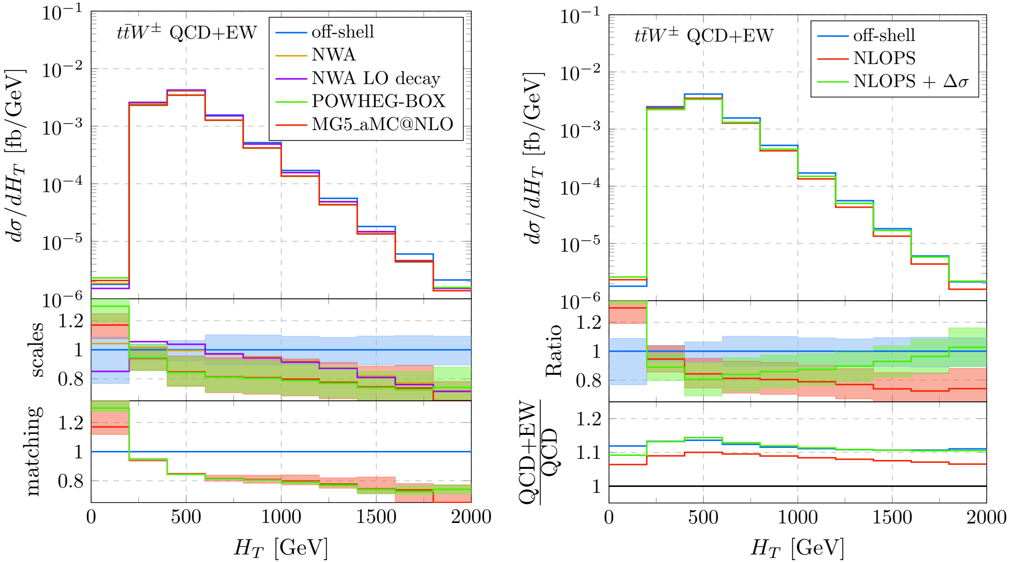
- top decay at NLO
- spin correlations
- double, single and non-resonant contributions or NWA
- only one extra parton

parton showers

- Additional radiation
- Hadronization
- More flexiable
- NLO only for production
- LO spin correlations

How compatible are the different descriptions?

Modeling of multi-lepton signatures



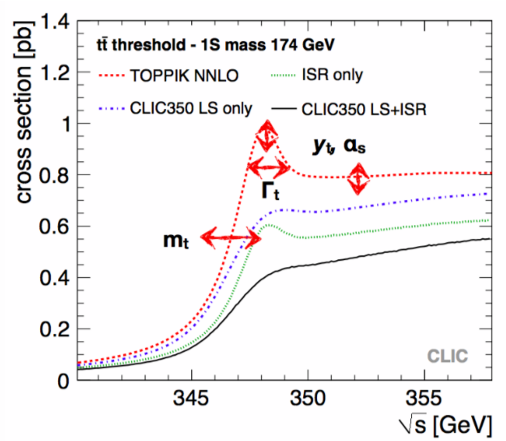
$$\frac{d\sigma^{\text{th}}}{dX} = \frac{d\sigma^{\text{NLO+PS}}}{dX} + \frac{d\Delta\sigma_{\text{off-shell}}}{dX}\,, \quad \text{with} \quad \frac{d\Delta\sigma_{\text{off-shell}}}{dX} = \frac{d\sigma_{\text{off-shell}}}{dX} - \frac{d\sigma_{\text{NWA}}}{dX}$$

[Bevilacqua, Bi, Hartanto, Febres Cordero, MK, Nasufi, Reina, Worek (to appear)]

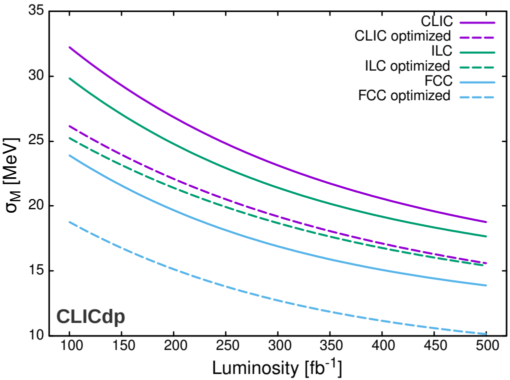
Beyond the LHC

Top-quark threshold scans at future lepton colliders

Nowak,Zarnecki arXiv:2103.00522



Precision on m_t measurements



- Correlated effects: $m_t, \Gamma_t, y_t, \alpha_s$
- Needs precise α_s determination

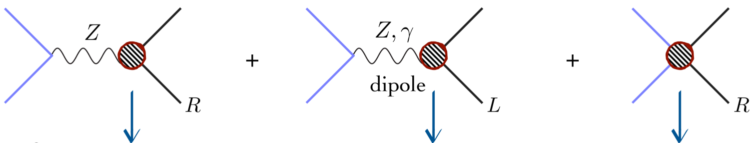
Top-quark physics at muon colliders

Banelli et al, JHEP 02 (2021) 043

Top compositeness at future lepton colliders

- Multiple operators enter top pair production

$$\mathcal{M}_{\ell^+\ell^-\to t\bar{t}} \sim$$



$$\frac{g_*^2}{m_*^2}(H^\dagger D_\mu H)(\bar{t}_R\gamma^\mu t_R) \qquad \frac{y_t g}{m_*^2}\bar{q}_L H\sigma_{\mu\nu}W^{\mu\nu}t_R \qquad \frac{c_{te}}{m_*^2}(\bar{e}_R\gamma_\mu e_R)(\bar{t}_R\gamma^\mu t_R)$$

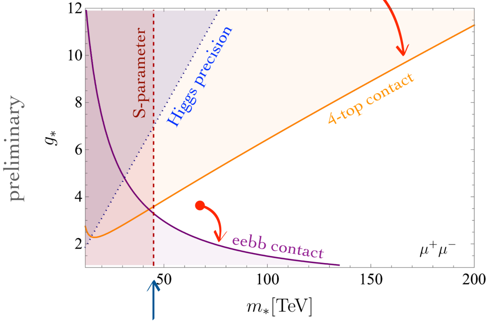
$$\sim \frac{g_*^2}{m_*^2}m_W^2 \qquad \sim \frac{g^2}{m_*^2}m_t\sqrt{s} \qquad \sim \frac{g_*^2}{m_*^2}s$$

[Taken from T. Thiel]

Top compositeness at μ-Collider

Same conclusion at a high-energy muon collider, with larger reach!

$\sqrt{s_{\mu^+\mu^-}} = 10\,\text{TeV} \quad L_{\mu^+\mu^-} = 10\,/\text{ab}$ $\times\sqrt{\frac{s_{\text{CLIC}}}{s_{\mu^+\mu^-}}}\sqrt{\frac{L_{\text{CLIC}}}{L_{\mu^+\mu^-}}}$ (statistically dominated errors)



$\frac{m_*}{g_*} \gtrsim 18\,\text{TeV}$

$\frac{m_*}{g_*} \gtrsim 6.4\,\text{TeV}$

[Han et al. 2008.12204]

[Buttazzo et al. 2012.02769]

$$\left(\frac{m_*}{g_*}\right)_{\text{LHC}} > 730\,\text{GeV}, \quad \left(\frac{m_*}{g_*}\right)_{\text{CLIC}} > 7.7\,\text{TeV} \quad \left(\frac{m_*}{g_*}\right)_{\mu\mu,10\text{TeV}} > 18\,\text{TeV}$$

[Taken from T. Thiel]

Summary

- Very broad range of topics studied
- The top-quark is everywhere ... as a signal and as background
- Many more studies that I could not cover!
  - Precise predictions for top-quark flavor-changing neutral interactions at future lepton colliders
  - Study on the discovery potential of all-hadronic searches for ttbar resonances at future colliders
  - Soft gluons in top processes (tt and tW) at high energies
  - Spin-correlations as a probe for BSM physics
  - Heavy Flavor PDFs and systematic uncertainties
  - and more ...