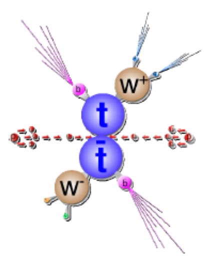
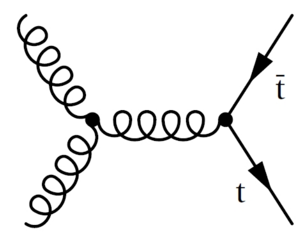
TOP2020

THEORY SUMMARY



S. Dawson, BNL

September 18, 2020



Why is the top so interesting?

- Heaviest fundamental particle

$$M_t(pole) = 173.1^{+2.0}_{-2.1}\ GeV$$

- Short lifetime: Decays before forming bound states
  - Directly measure top properties from decays
  - Top quark predominantly produced through QCD interactions
  - Dominant decays through weak interactions

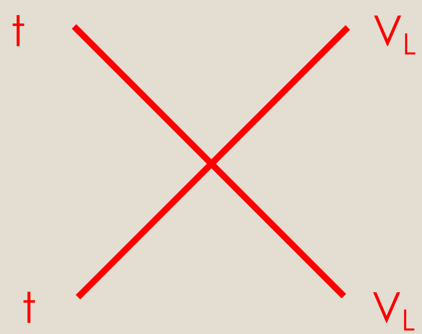
- Large coupling to Higgs $Y_t = \frac{\sqrt{2} M_t}{v} \sim 1$

The top is a window into EWSB

- Longitudinal W's ↔ Goldstones

$$\Phi = \begin{pmatrix} -iG^+ \\ v + H + iG^0 \end{pmatrix} \qquad \begin{array}{c} \partial^\mu G^+ \leftrightarrow W_L^{\mu +} \\ \partial^\mu G^0 \leftrightarrow Z_L^\mu \end{array}$$

- Longitudinal gauge interactions with top are enhanced $t\bar{t}Z_L,\ t\bar{b}W_L \sim \frac{M_t}{v}$
- Higher dimension interactions can give effects growing with energy
  - Tails of top distributions are sensitive to new physics effects

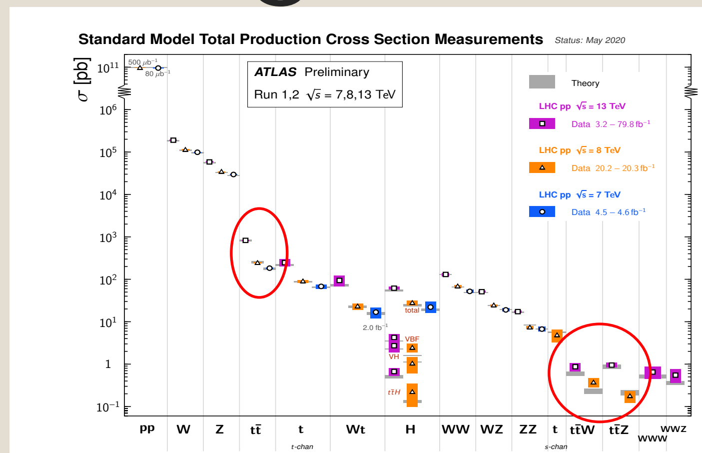


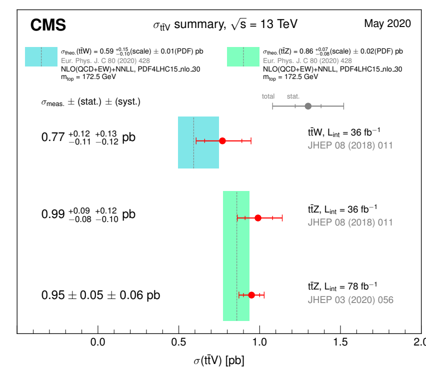
$$\sim \frac{(Energy)^2}{\Lambda^2}$$

Deep connection between Higgs and top

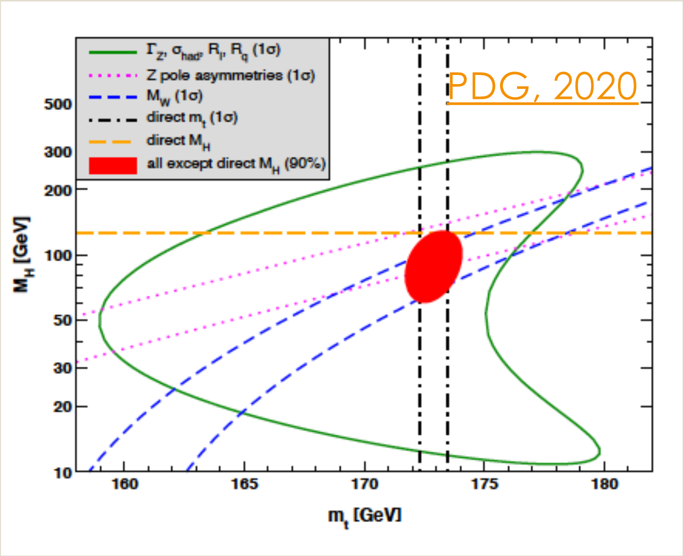
Why is the top so interesting?

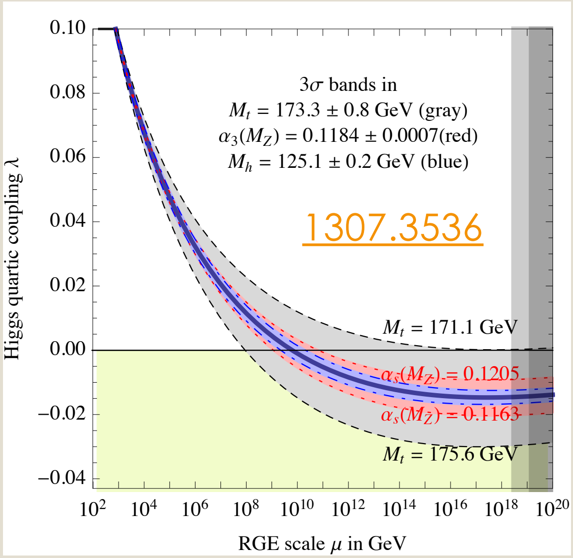
- Huge statistics
  - Many precision measurements and calculations:
  - $t\bar{t}, t, t\bar{t}\gamma$ production
  - $t\bar{t}H,\ tH$ measure Y_t
  - $t\bar{t}W,\ t\bar{t}Z,\ t\bar{t}t\bar{t}$ test EWSB
- Precision QCD/EW calculations tested and SM parameters extracted
  - α_s, M_t, Γ_t, gluon PDFs, V_{tb}….
- Large background to SM measurements (in particular Higgs production)
- Tool for new physics studies and to precisely verify consistency of SM





The top mass determines the fate of the universe and constrains new physics

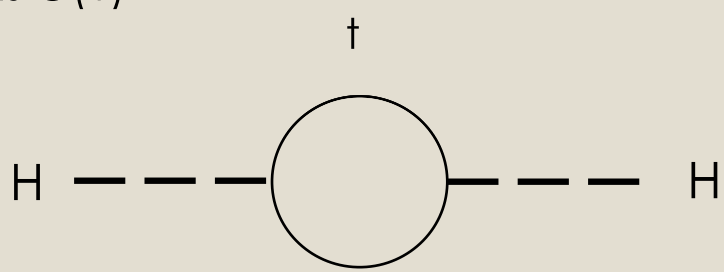




NNLO top calculations sensitive to $\Delta M_t \sim 1$ GeV

The top is heavy

- Top coupling to Higgs is O(1)



$$\delta M_H^2 \sim \frac{3Y_t^2}{4\pi^2}\Lambda^2$$

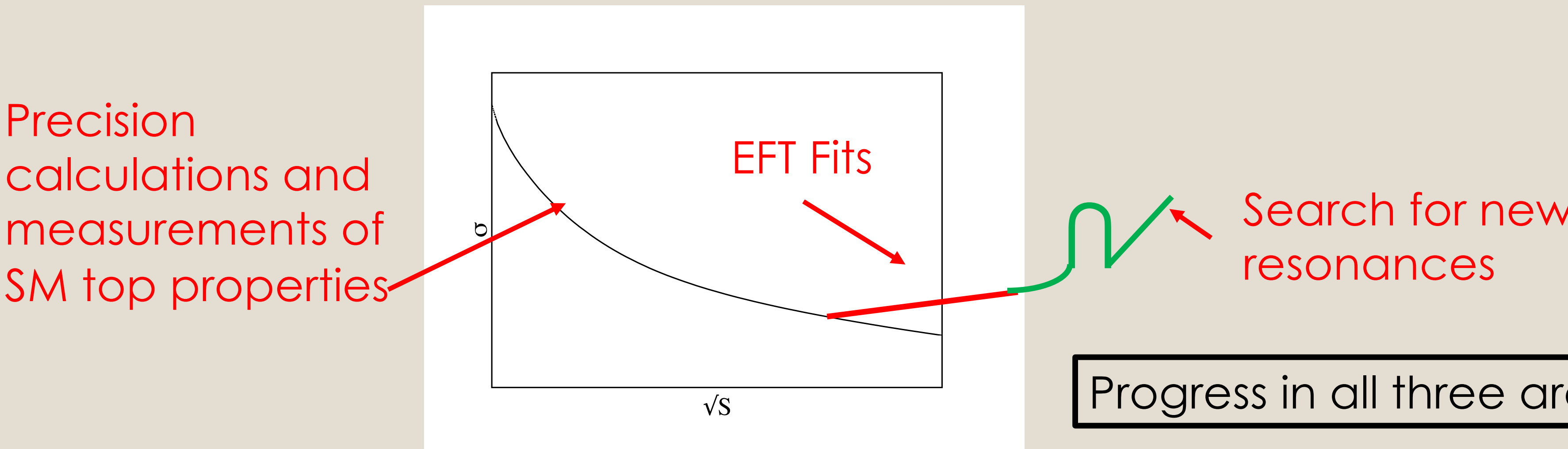
- Motivates connection between Higgs mass and top quark interactions at the TeV scale
- Many possibilities for top partners that would cancel SM top contributions to Higgs mass

$$\delta M_H^2 \sim \frac{M_H^2}{\Delta} \quad \rightarrow \quad \Lambda \sim \frac{450\ GeV}{\Delta}$$

[McCullough]

New physics from top

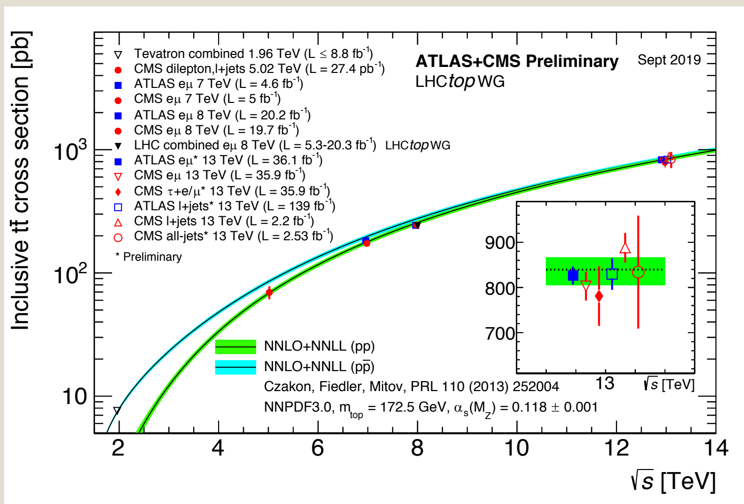
- Directly: Probe on-shell new physics with direct searches
- Indirectly: Probing the effect of new physics on SM observables through precision physics



Progress in all three areas

Top and precision measurements

- Top quark pair production
- NNLO : STRIPPER [Czakon, Heymes, Mitov,'15], q_T subtraction [Catani, Devoto, Grazzini, Kallweit, Mazzitelli, '19]



- *Tour de force!*
- *New tools and new insights into QFT needed*

Top quark spin correlation at NNLO

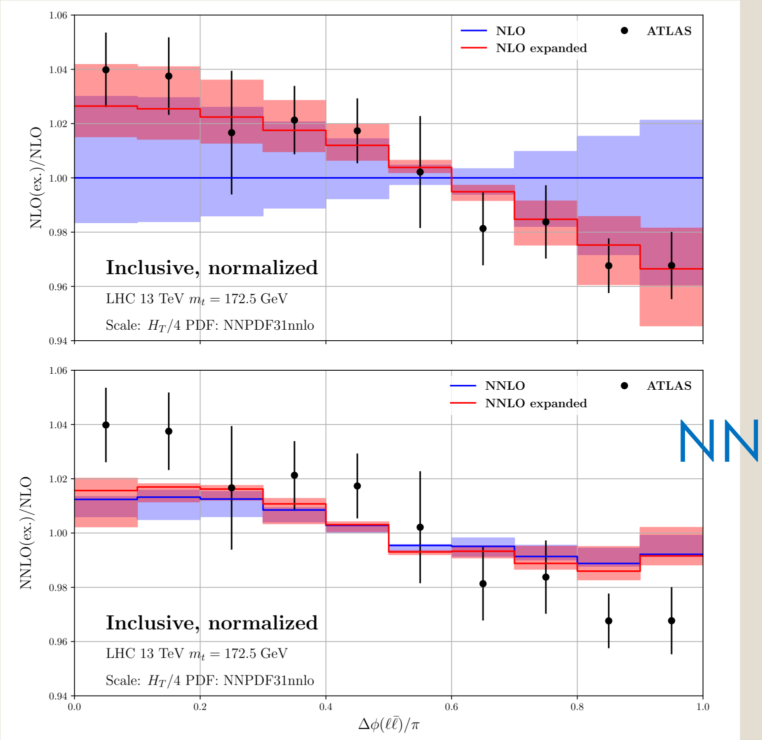
- Spin information of tops carried by leptons

$$pp \to t\bar{t} \to b\bar{b}l^+l^-\nu\bar{\nu}X$$

- Fiducial results in good agreement with experiment
- At NNLO consistent theory results
  - Can expand consistently in α_s (red curves)
  - Blue curves are full result
  - Tension in comparison of data with inclusive measurements

[Czakon, Mitov, Poncelet, '20]

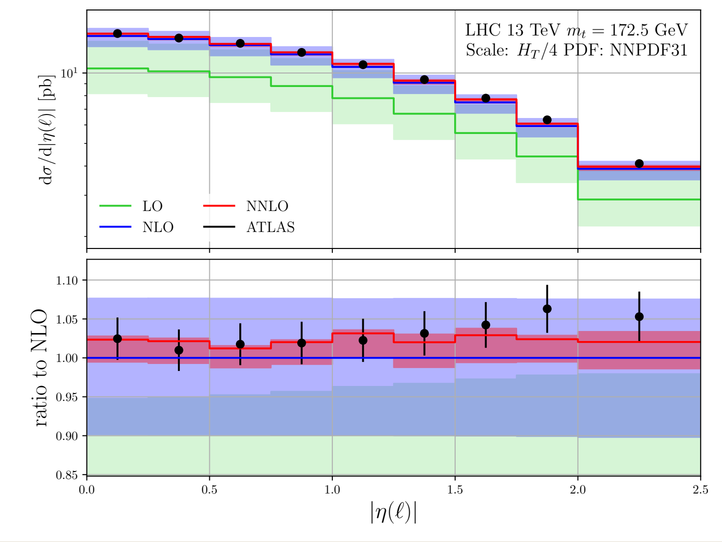
NLO

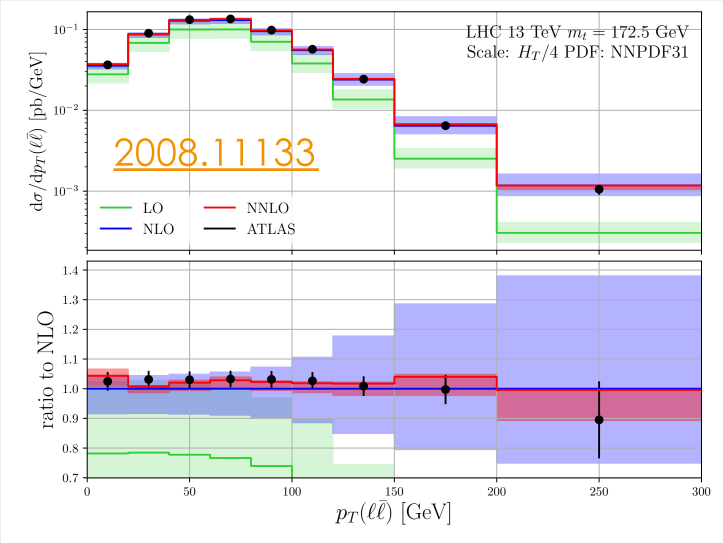


NNLO

Top quark lepton observables at NNLO

- Impressive agreement with data; significantly reduced scale dependence at NNLO

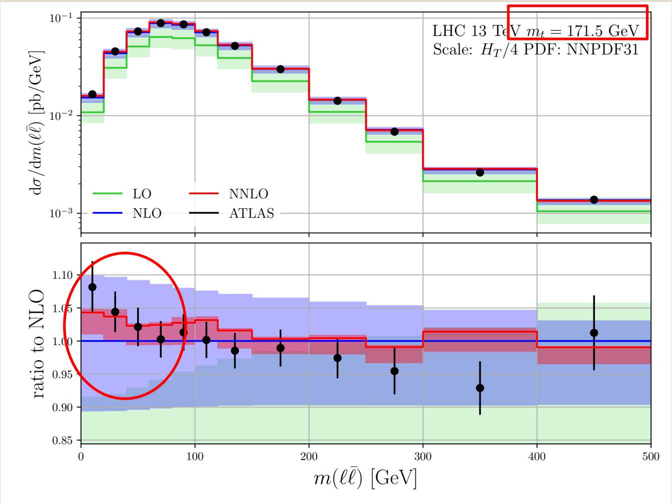


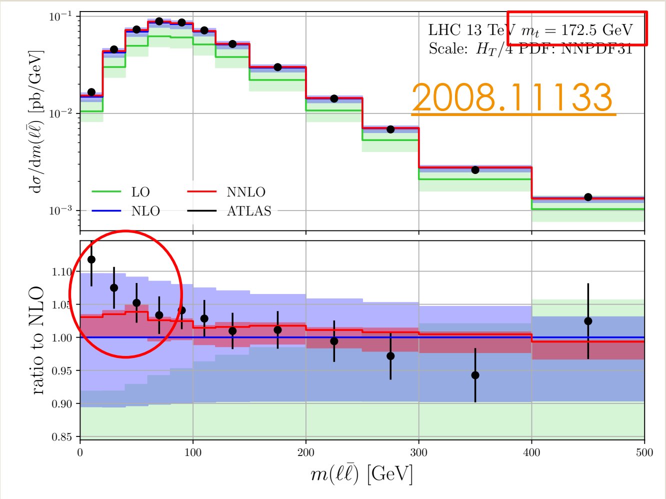


[Poncelet]

Top mass sensitivity @NNLO

- Sensitive to ΔM_t~ 1 GeV

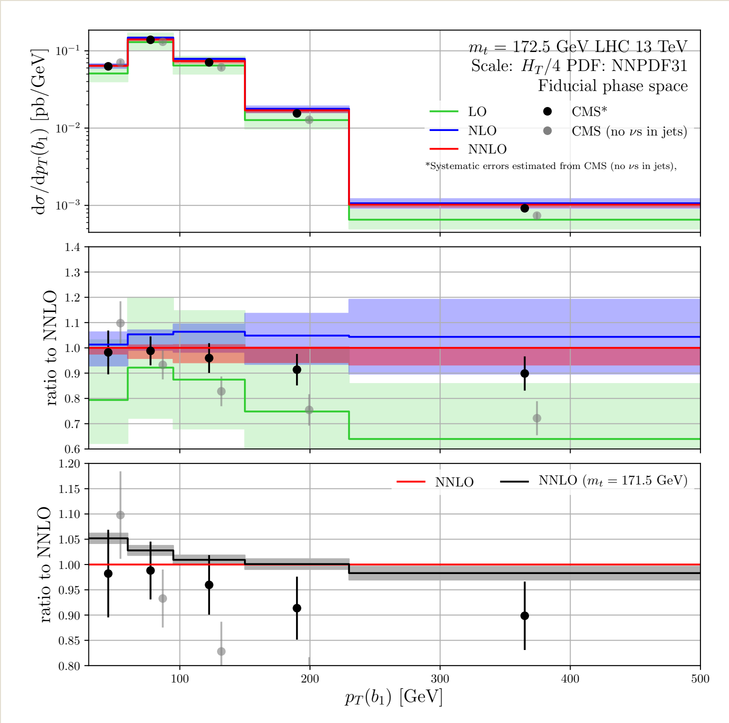




[Poncelet]

Top quark lepton observables at NNLO

- Reanalysis of CMS fiducial analysis with ν momentum included in jets
- Excellent agreement
- Black is reanalyzed data
- Grey is original analysis



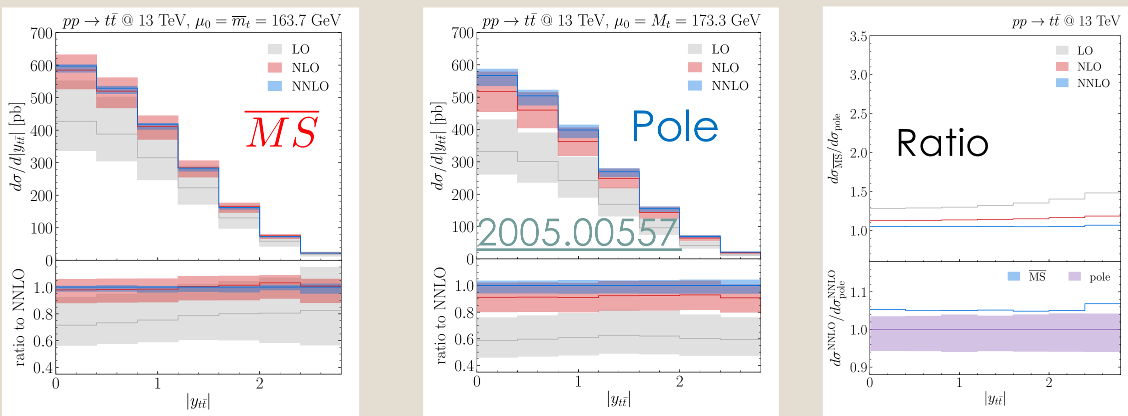
Note sensitivity to ΔM_t shift of 1 GeV

[Poncelet]

Differential distributions at NNLO

- Continuing question: Are we measuring pole mass or $\overline{MS}$ mass?

$$M_t = m_t(\mu_m)\left[1 + \Sigma_k \left(\frac{\alpha_s(\mu_m)}{\pi}\right)^k d^k(\mu_m)\right]$$

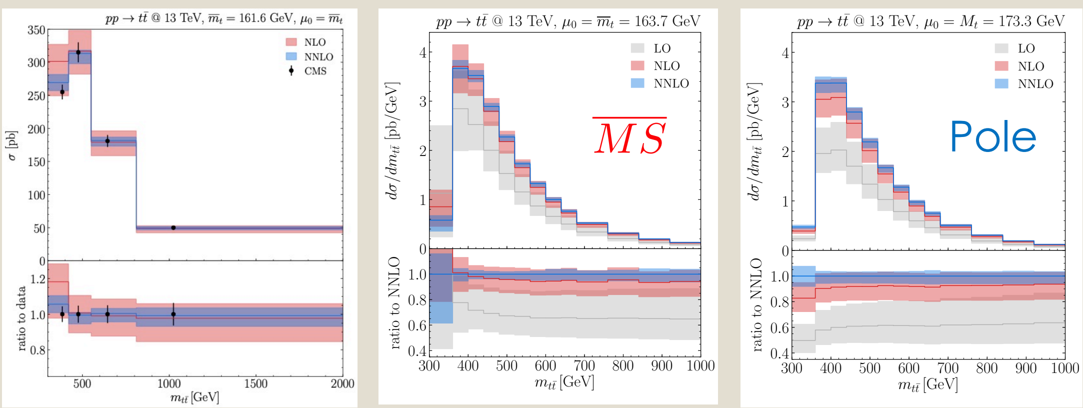


- Scheme dependence reduced at NNLO

[Catani]

Differential distributions at NNLO

- Difference between using pole mass or $\overline{MS}$ mass reduced at NNLO

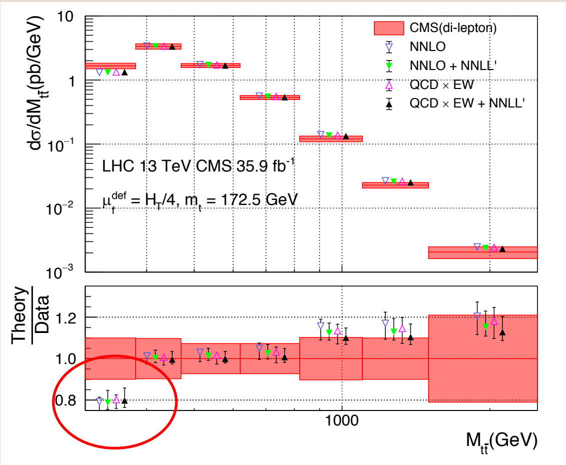


- Good agreement with data
- Threshold uncertainties

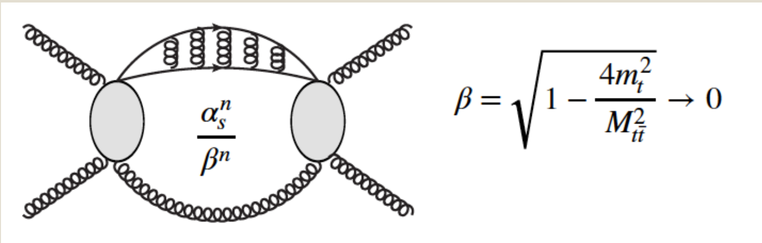
[Catani]

Top mass extraction beyond NNLO

- Even including NNLO, NNLL' (soft gluon resummation), QCD x EW, there is theory/experimental discrepancy at low M_{tt} (which is region most sensitive to M_t)



Improve by including Coulomb corrections → resum to all orders in α_s using effective field theory techniques

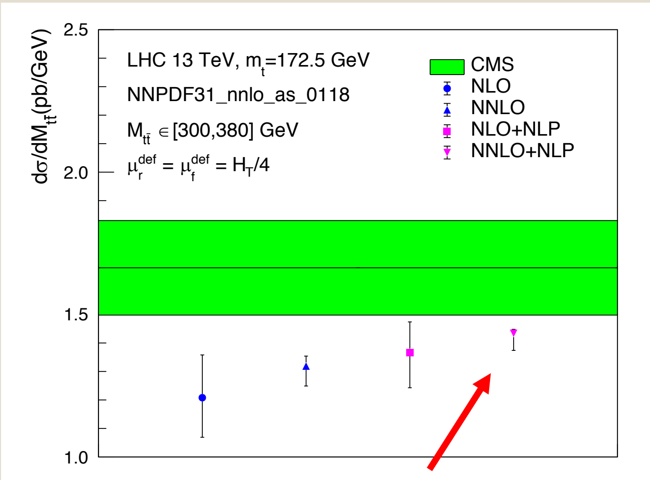


[Yang]

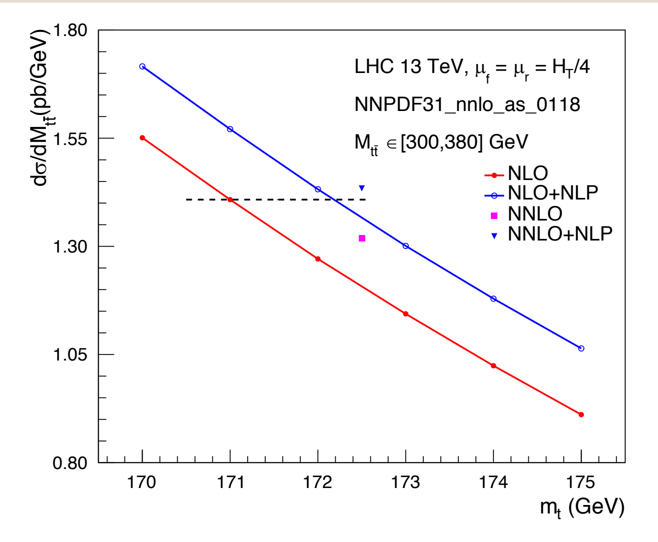
Top mass extraction

- Include next-to-leading power resummation of Coulomb corrections and combine with NNLO calculations

Resummation moves the extracted mass up by more than a GeV: Closer to world average



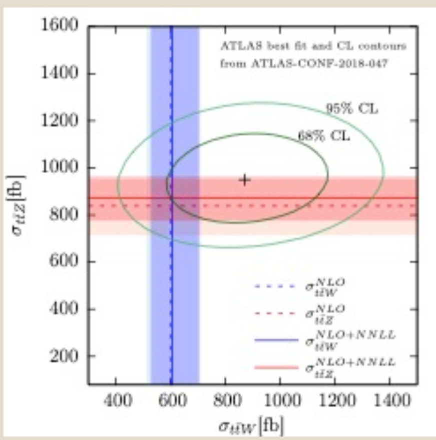
Improved agreement

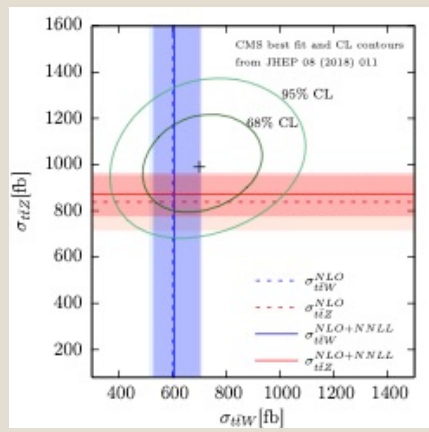


[Yang]

$t\bar{t}W$ production

- $t\bar{t}W$ is window for new physics, anomalous top couplings, important background for multi-lepton signatures, background to $t\bar{t}H$
- ATLAS and CMS see excess over SM NLO+NNLL theory





1812.08622

Theory improvements highly motivated!

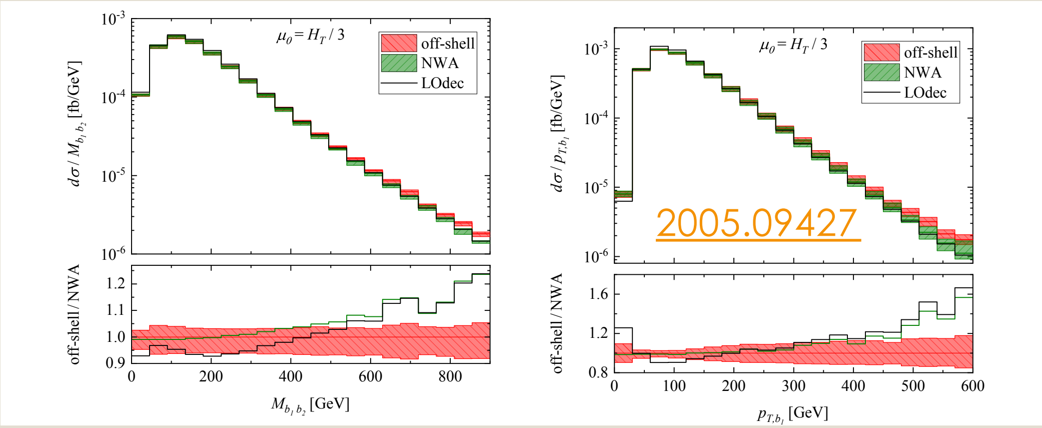
[Bevilacqua]

Theory progress in $t\bar{t}W$

- NLO QCD complete off-shell (resonant and non-resonant diagrams, interferences, finite width) for 3 lepton channel

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

  - 2 independent calculations at 13 TeV



Off-shell effects increase up to 30-50% in tails, well above scale uncertainties

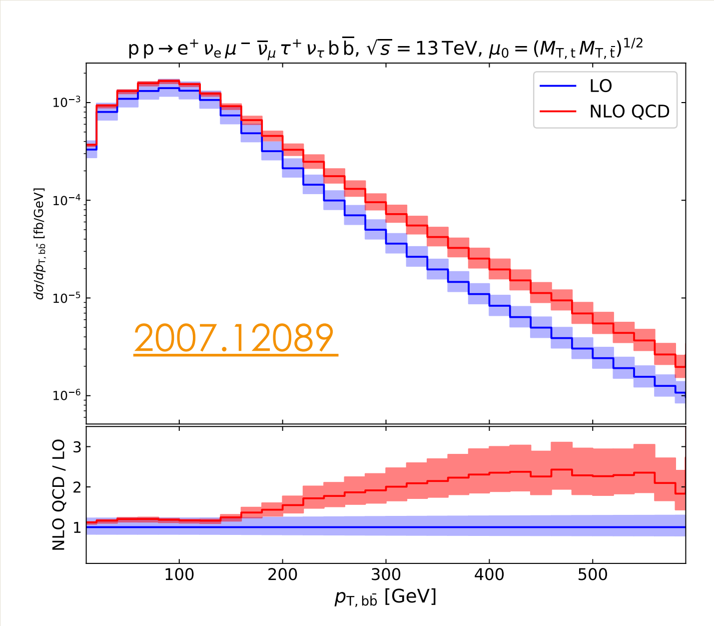
[Bevilacqua]

Theory progress in $t\bar{t}W$

- NLO corrections to off-shell $t\bar{t}W$

$$pp \to e^+\nu_e\mu^-\overline{\nu}_\mu\tau^+\nu_\tau b\bar{b}$$

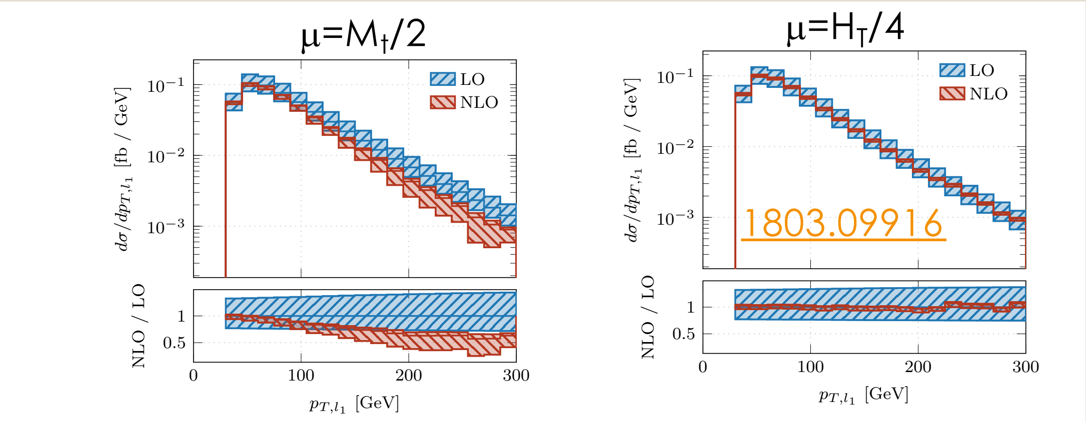
- Large K factors when tt recoils against W + light jet at NLO
- Both calculations find that integrated cross section shows excellent agreement with double pole approximation



[Pelliccioli]

Theory progress in $t\bar{t}\gamma$ production

- $t\bar{t}\gamma$ at NLO including off-shell effects, resonant and non-resonant interactions, interferences $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$



Theory uncertainties reduced significantly by use of dynamical scale

- NLO correction up to -43%
- Theory uncertainties up to ± 56%

- NLO correction up to +8%
- Theory uncertainties up to ± 7%

[Worek]

Improving precision with $t\bar{t}\gamma$

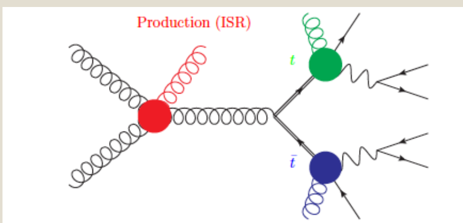
- Can improve precision by taking NLO ratios
  - Fiducial integrated $\sigma_{tt\gamma}$ with dynamical scale theory error of ± 6%
  - Fiducial differential $d\sigma_{tt\gamma}/dX$ theory error ± 10-30%
- $\sigma_{tt\gamma}/\sigma_{tt}$ ±(1-3)% theory uncertainty
- Differential cross section ratios give theory uncertainties of ±(1-6)%

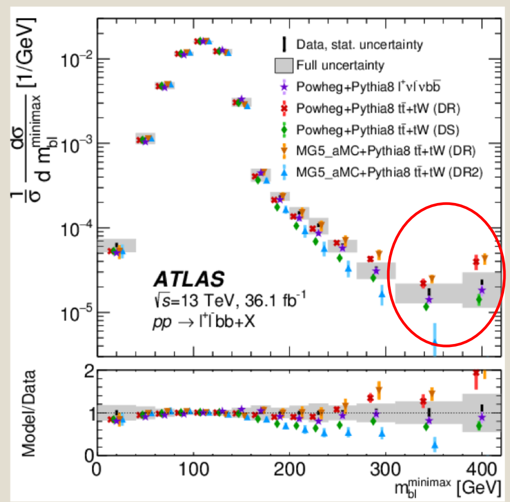
$$\left[\frac{d\sigma_{tt\gamma}/dX}{d\sigma_{tt}/dX}\right]_{NLO}$$

[Worek]

Connecting theory and experiment

- Progress in including NLO effects in generators
  - *bb4l* generator in POWHEG box describes top pair production and decay including full offshell and non-resonant contributions exactly at NLO (Wt and $t\bar{t}$ combined straightforwardly)





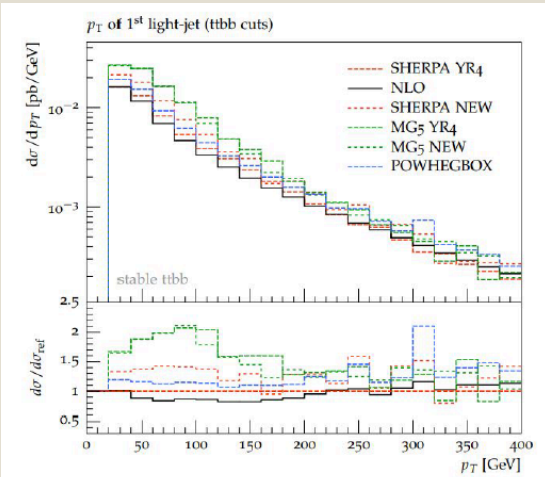
Kinematic edges well described

New generators include QCD corrections also in decays with resonance aware subtractions that preserve virtuality of resonances

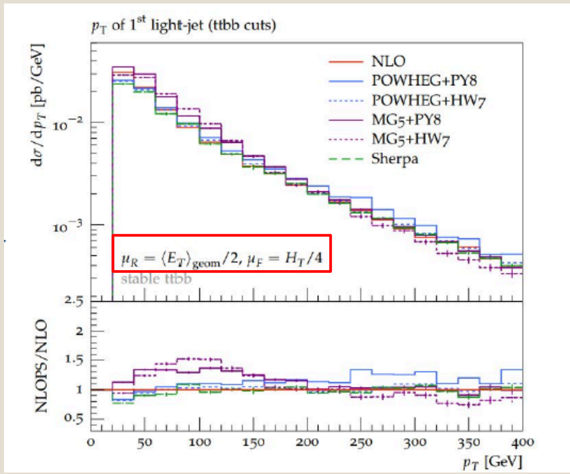
[Ferrario-Ravasio]

Generator progress at NLO

- Discrepancy between the $t\bar{t}b\bar{b}$ generators ➜ can be reduced by proper scale choice (Buccioni et al]



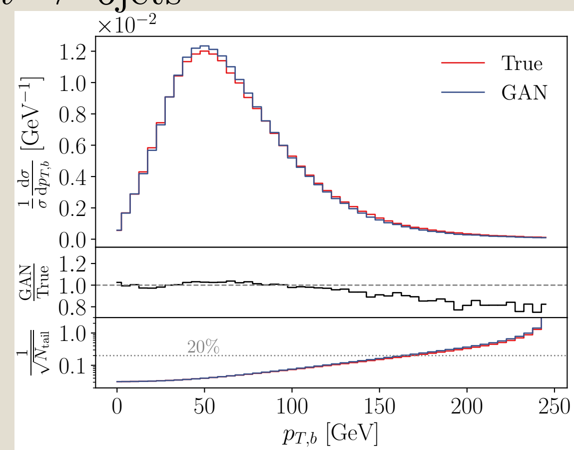
➜



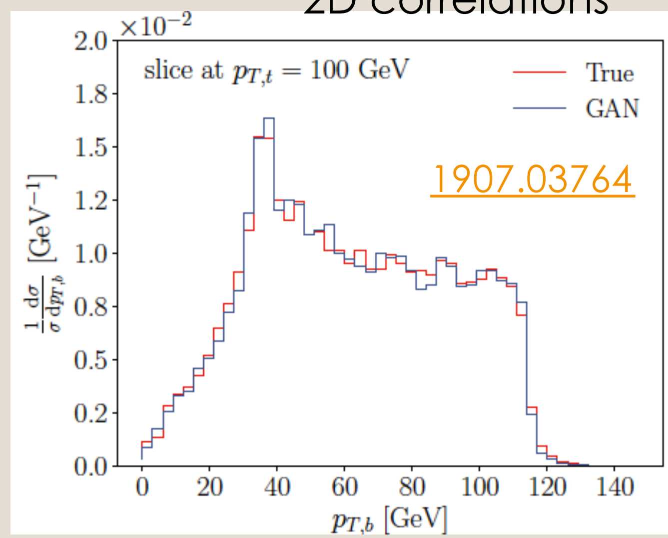
[Ferrario-Ravasio]

New techniques with ML

- Need for more efficient event generation at HL-LHC
  - Train generative adversarial networks directly on events to generate more statistics and replace fast detector simulations
  - Significant technical progress on GANs
  - Example: LHC $t\bar{t} \to$ 6jets



2D correlations

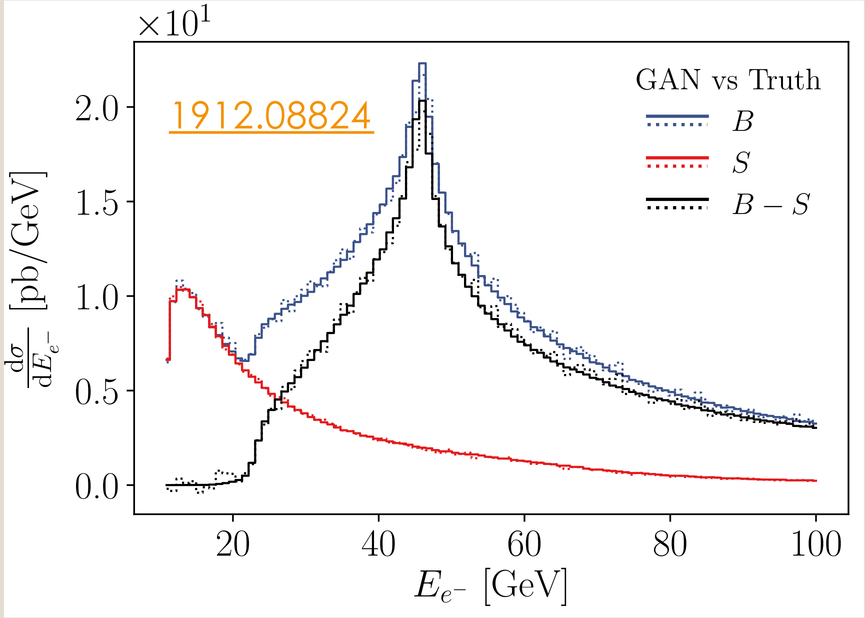


Systematic undershoot in tails

[Butter]

Technical progress with GANs

- Progress using GANs for event subtraction
- Example:
  - Background: $pp \to e^+e^-$
  - Signal: $pp \to \gamma \to e^+e^-$

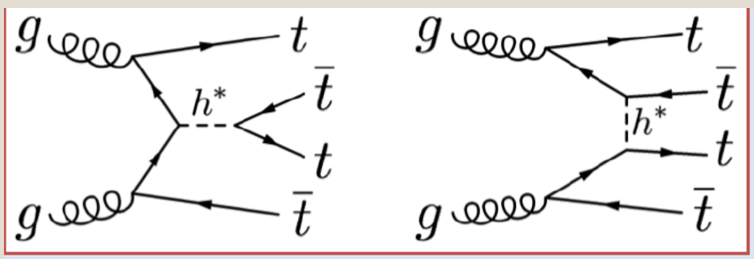


GANs may be useful for subtracting dipoles from real emission terms

[Butter]

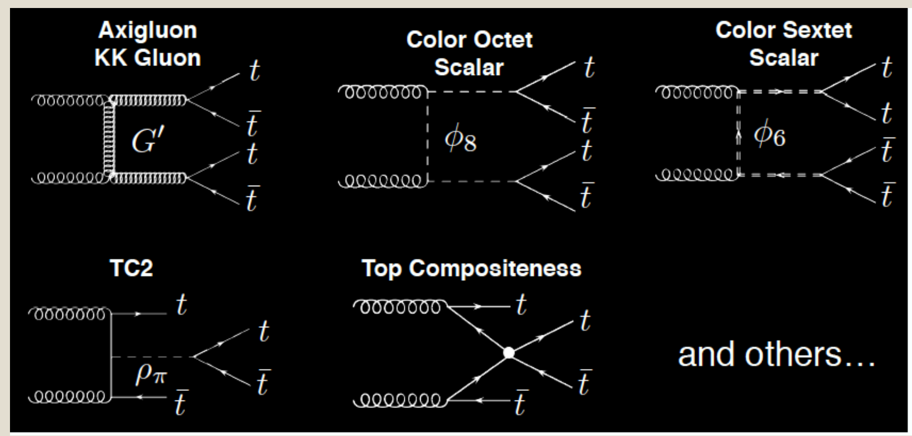
4 top production

- Large sensitivity to BSM effects
- Many possibilities:



CMS: $\left| \frac{Y_t}{Y_{t,SM}} \right| < 1.7$

@ 95% CL

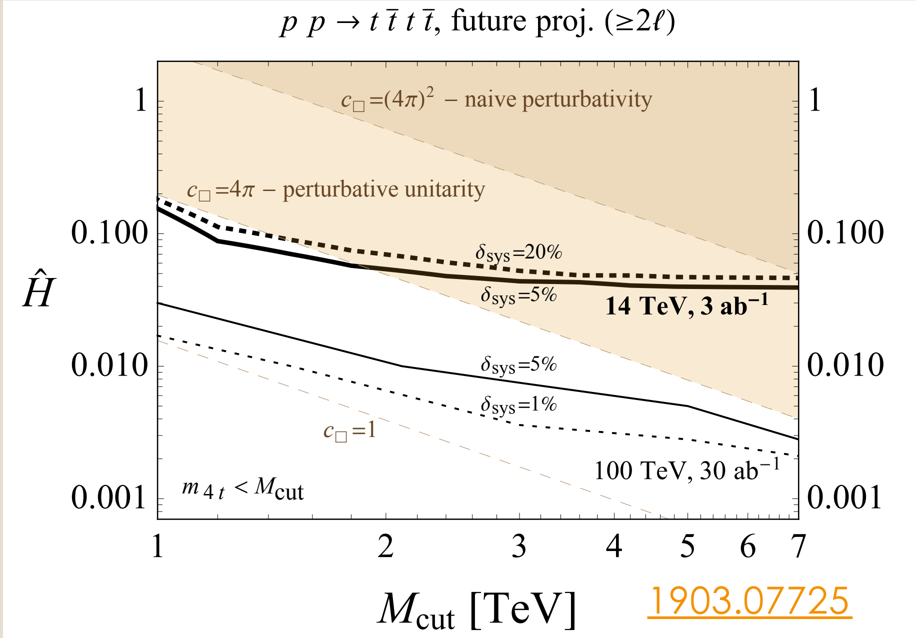


4 top production

- Sensitive to EFT effects that grow with energy
- Motivates high energy colliders

$$L_{EFT} \sim L_{SM} + \frac{C_\square}{\Lambda^2} \mid \square H \mid^2$$

$$\hat{H} = C_\square \frac{M_H^2}{\Lambda^2}$$



1903.07725

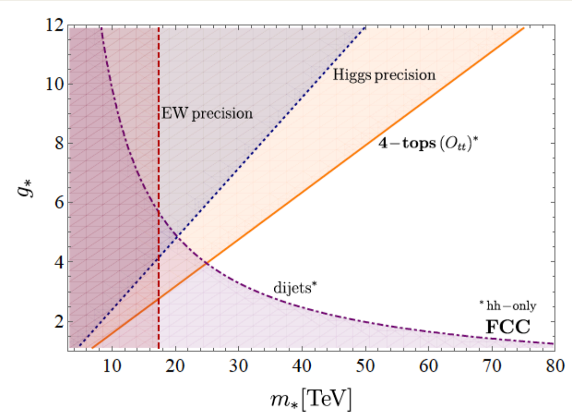
[McCullough]

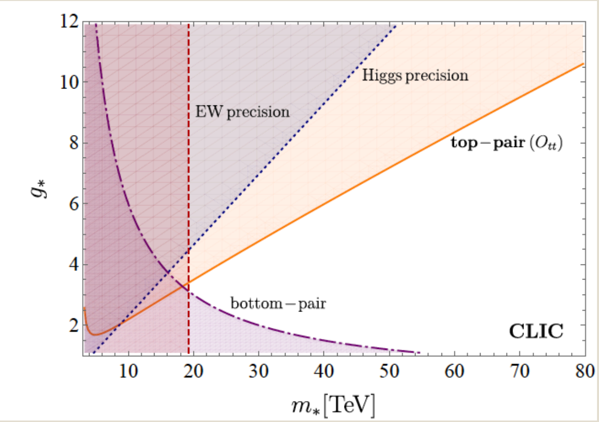
4 tops in the future

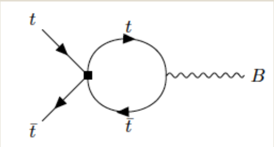
- Contact interactions probed at FCC-hh and high energy e⁺e⁻

$$L \sim \frac{g_*^2}{m_*^2}(\bar{t}_R\gamma_\mu t_R)(\bar{t}_R\gamma^\mu t_R)$$

- Contribution to $t\bar{t}W$ from 4-fermion top operator?



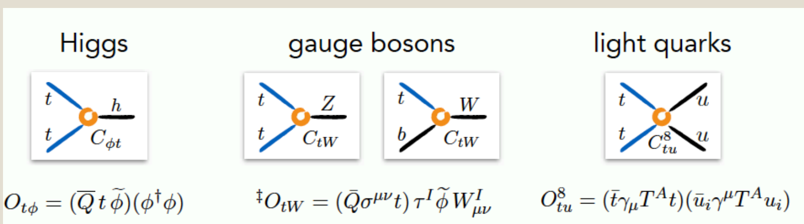




[Theil]

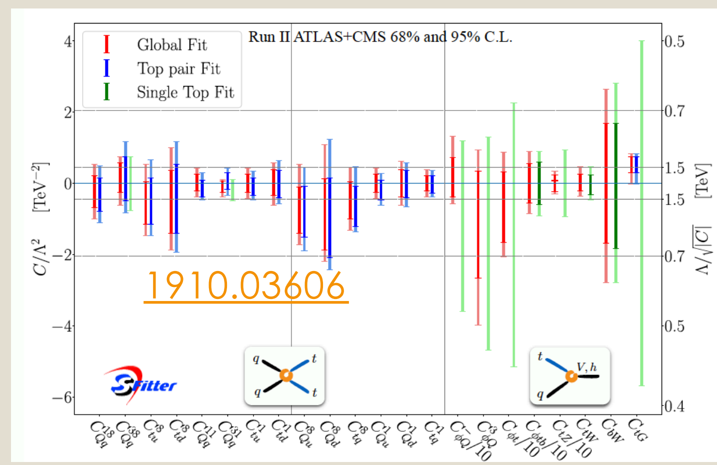
Top as a window to new physics

- Effective field theory connects contributions from different types of measurements



[Westhoff]

- Consider 22 operators involving top quarks and fit to $t\bar{t},\ t,\ tW,\ tZ,\ t\bar{t}W,\ t\bar{t}Z,\ t$ decay including NLO QCD



Top as a window to new physics

- How to untangle effects of different operators?
- 4-quark vs gluon operators using boosted tops
- Sensitivity to 4-quark operators grows with energy

$$\sigma_{t\bar{t}}(s) \sim \sigma_{\rm SM}\left(1 + \frac{m_t v}{\Lambda^2} C_{tG} + \frac{s}{\Lambda^2} C_{tu}^8 + \mathcal{O}\left(\frac{s^2}{\Lambda^4}\right) C_i C_j\right)$$

$$O_{tG} = (\bar{Q}\sigma^{\mu\nu} T^A t)\,\widetilde{\phi}\, G^A_{\mu\nu}$$
$$O_{tu}^8 = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i \gamma^\mu T^A u_i)$$

- Similarly, charge asymmetries sensitive to chiral structure of operators

charge asymmetry:

$$A_{|y|} = \frac{\sigma^A_{\rm SM} + \sigma_{AA}(C^{1,8}_{Qq} - C^8_{tq})}{\sigma_{t\bar{t}}}$$

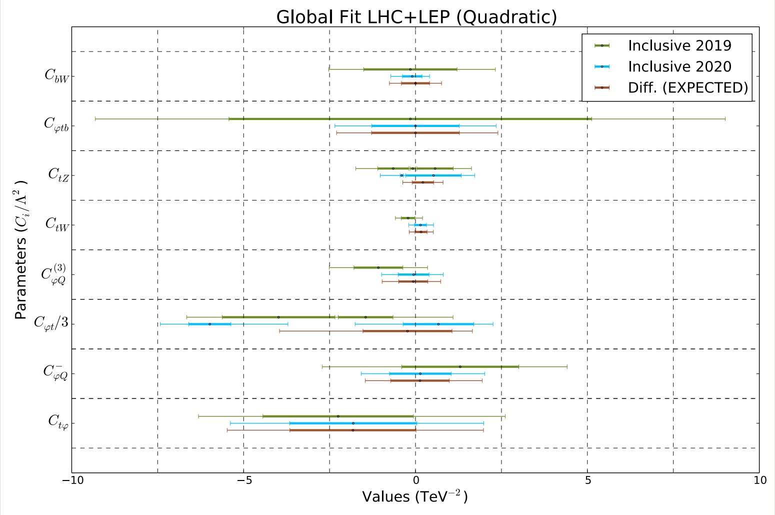
$$O_{tq}^8 = (\bar{t}_R \gamma_\mu T^A t_R)(\bar{q}_L \gamma^\mu T^A q_L) \quad \sim RL$$
$$O_{Qq}^{1,8} = (\bar{Q}_L \gamma_\mu T^A Q_L)(\bar{q}_L \gamma^\mu T^A q_L) \sim LL$$

[Westhoff]

Precision QCD calculations crucial for subtracting SM background in tails

EFT and the top

- Fit to $t\bar{t}H,\ t\bar{t}W,\ t\bar{t}Z,\ t\bar{t}\gamma,\ tZq,\ t\gamma q, t\bar{b},\ tW,\ tq$ production at the LHC, along with $t \to Wb$, $e^+e^- \to b\bar{b}$
- NLO QCD effects included in fit
- Effects of inclusion of LEP data apparent in improved fit to $C_{HQ}{}^3$ (affects $Zb\bar{b}$ and $Zt\bar{t}$ vertices)



Note 2020 improvement

[Miralles]

New physics and the top

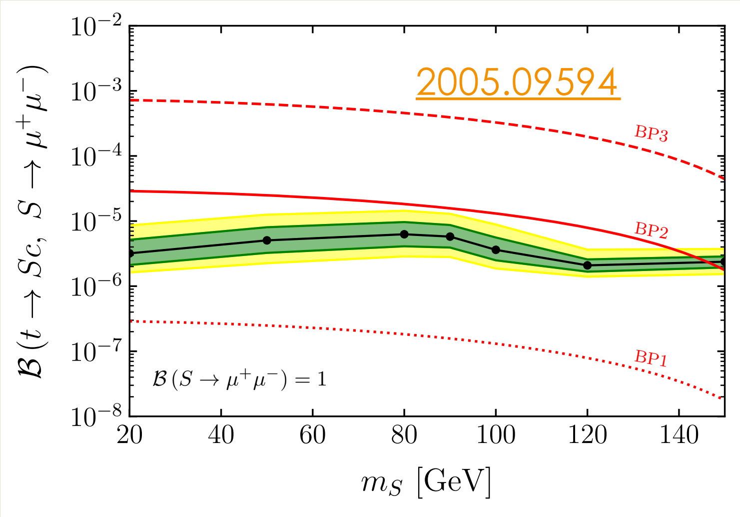
- Flavor changing neutral currents in top sector can arise in BSM scenarios
  - Add effective FC top interaction with leptophobic scalar

$$L \sim \frac{S}{\Lambda}\bar{t}_L Y_{tq} q_R$$

- Example of poorly constrained scenario:

$$pp \to tS, \;\; S \to l^+ l^-$$

- Can be probed at LHC with 150 fb^{-1}



* q is light quark

[Peixoto]

B meson production in top events

- b→ B at low energy described by non-perturbative fragmentation function
  - Many pieces to get fully NNLO description of B meson production from top

$$O_B\left(\frac{Q^2}{m^2},\alpha_s\right) = O_b\left(\frac{Q^2}{m^2},\alpha_s\right) \times D^{NP}_{b\to B}(z)$$

Non-perturbative, fit from data

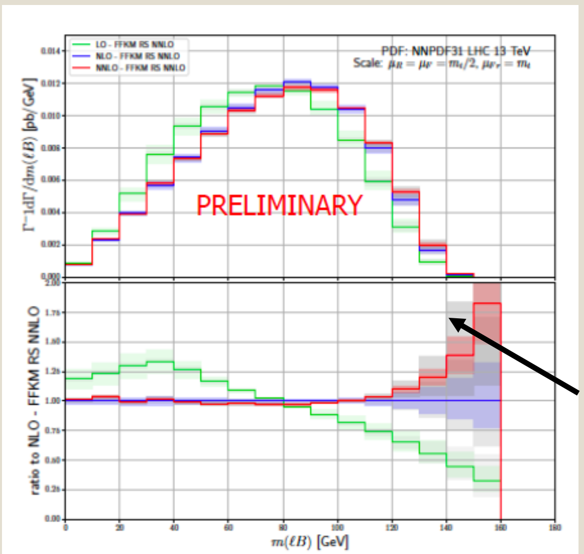
$$O_b\left(\frac{Q^2}{m^2},\alpha_s\right) = \Sigma_{i,j} C_i\left(\frac{Q^2}{\mu_F^2},\alpha_s\right) \times E_{i\to j}\left(\frac{\mu_F^2}{\mu_0^2},\alpha_s\right) \times D_{j\to b}\left(\frac{\mu_0^2}{m^2},\alpha_s\right)$$

  - Goal: fully differential MC calculation of one B-hadron + X at NNLO

[Mitov]

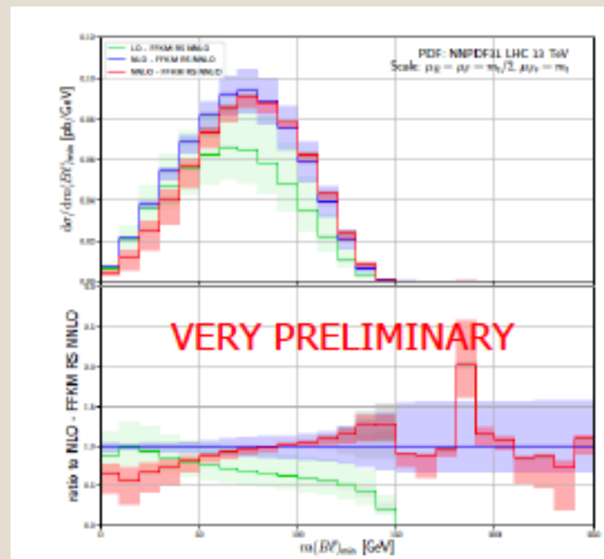
B meson production in top events

B production in decay of unpolarized top quark at NNLO



Grey band is variation of fragmentation function

B production in $t\bar{t}$ production and decay



[Mitov]

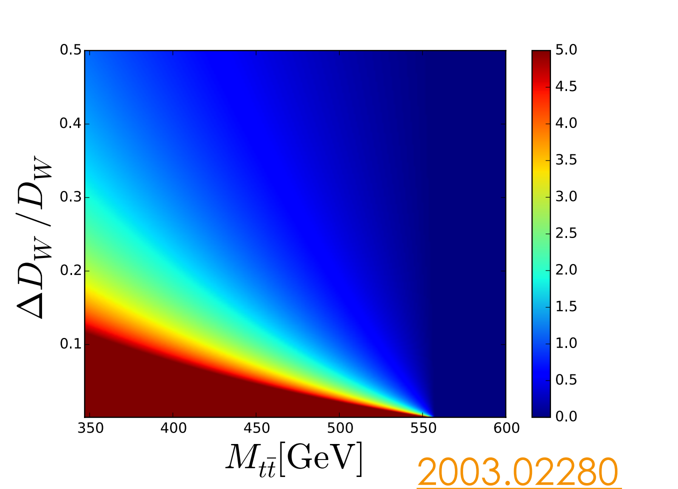
Beyond the usual paradigm

- Quantum information and entanglement with top quarks
- Idea is to detect entanglement at the LHC by characterizing spin correlations of $t\bar{t}$ pairs

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\phi}=\frac{1}{2}(1-D\cos\phi)$$

- φ is angle between the lepton directions in the t and $\bar{t}$ rest frames

Statistical deviation from null hypothesis



2003.02280

[Afik]

Thanks

- Thanks to organizers and speakers for such an interesting meeting!
- Apologies for my inadequate coverage of the immense number of interesting results presented here
- I predict many more exciting meetings about the top quark!