Towards Top EFT combination: challenges and lessons learned so far

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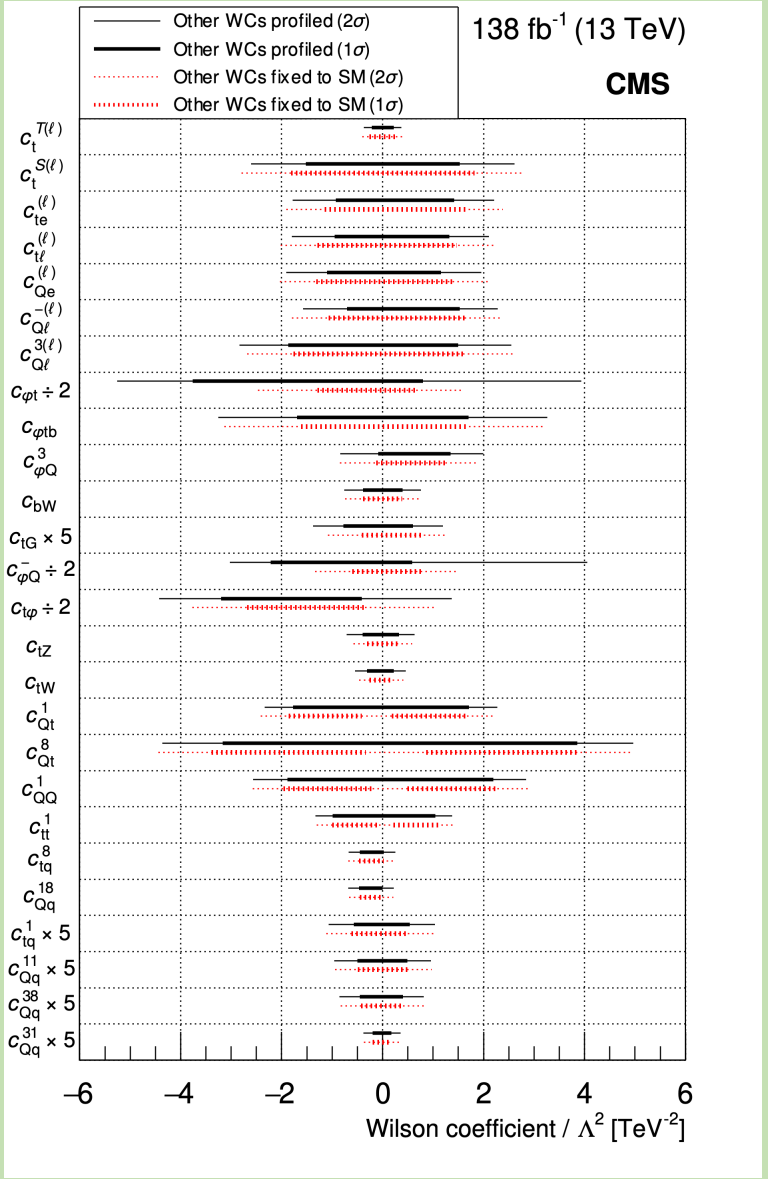
Top-22-006 Overview

- Search for new physics impacting associated top production in multilepton final states in context of Effective Field Theory (EFT) using full R2 data.
- Signal processes: $t\bar{t}H, tl\bar{l}q, t\bar{t}lv, t\bar{t}l\bar{l}, tHq, t\bar{t}t\bar{t}$
- Core idea is the parametrization of predicted yields in terms of 26 dim6top EFT operators.
- Fitting differential distributions to extract Confidence Intervals (CIs) on 26 dim-6 WCs strongly impacting the top processes.
- 43 total event categories further binned by differential distributions leading to 178 total analysis bins.
- More details in Brent's talk.

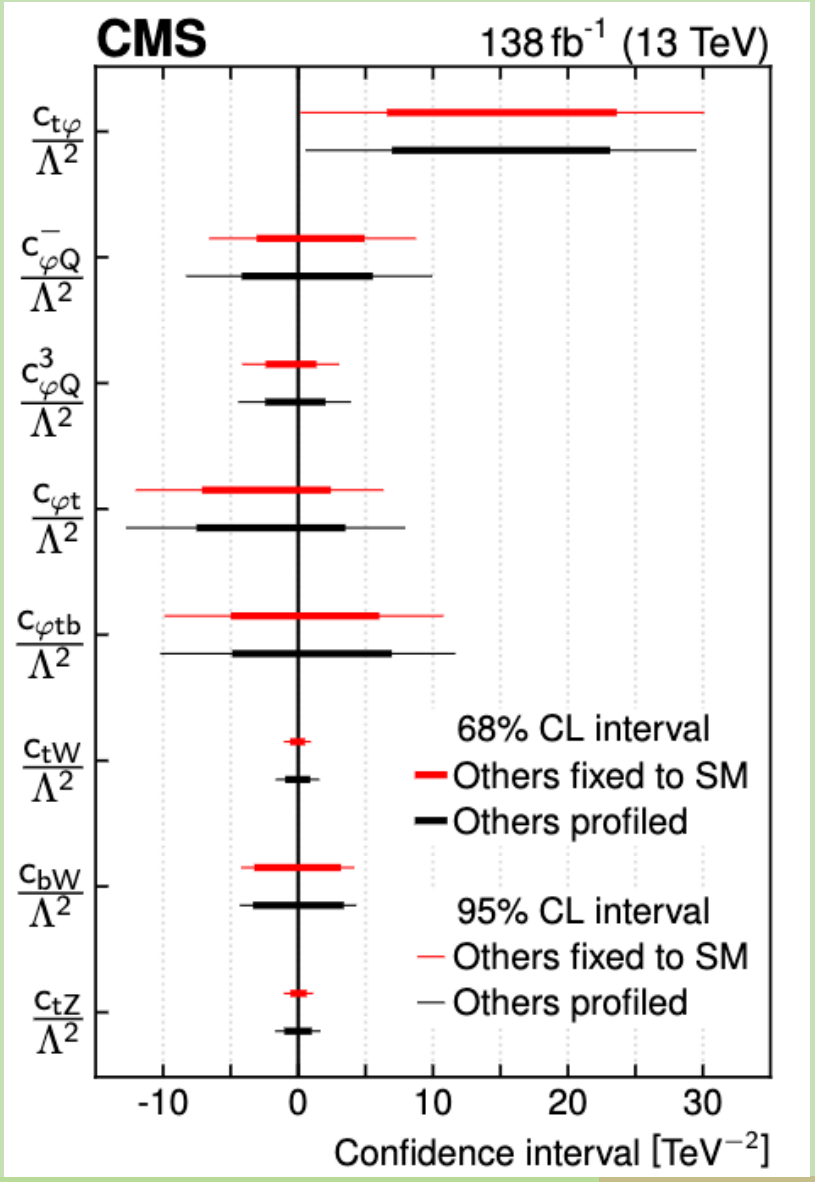


arXiv: 2307.15761

multilepton analysis

Top-21-003 Overview

- Search for new physics using data sample consisting of top quark pair production associated with boosted Z or Higgs boson in context of EFT using full R2 data.
- Signal processes: boosted $t\bar{t}Z/H$ with only single lepton from a top quark decay and Z/H decaying to $b\bar{b}$.
- measures $t\bar{t}Z/H$ cross-section as a function of Z/H p_T.
- constrains 8 dim-6 WCs by simultaneous fit to data.
- Data categorized based on the p_T and m_{SD} of the reconstructed Z/H boson candidate and DNN score resulting into 198 analysis bins.



arXiv: Phys. Rev. D 108 (2023) 032008

boosted analysis

Towards combination

Feasibility studies for combination

- Are the two analyses probing orthogonal phase spaces?

Technical aspects of performing fits using bins with EFT parametrization

- How to handle the custom physics model used for fitting?

Implementation of systematics

- How do the two analyses handle the systematics?

Run fits to extract the results

- Asimov/fit to data?

Feasibility studies for combination

- Performed dedicated studies to make sure the two analyses were orthogonal to each other.
- Some relevant statistics:
  - Total number of events passing event selection cuts for boosted analysis: 15925
  - Total number of events passing event selection cuts for multilepton analysis: 3927
  - Total number of overlapping events: 6
- Further investigated the kinematic bin occupancy of these 6 overlapping events for each analysis.
  - In boosted analysis, these 6 events fall in its lowest or second-lowest NN bins (out of 6 total bins).
  - In multilepton analysis, these 6 events fall in separate kinematic bins.
    - Only 3 of these 6 events fall in high-pT bins with relatively low occupancy.
    - All 6 bins have fairly low sensitivity to the WCs that are considered for the combination.

The overlapping events fall in low sensitivity NN bins in boosted analysis and in bins that have mostly low sensitivity towards the WCs considered for the combination.

No issue in combining the two analyses!

Towards combination – Wilson Coefficients (WCs)

- The boosted analysis considers 8 WCs from "two heavy + boson" category.
  - Omits c_{tG} since it is better constrained by dedicated $t\bar{t} + jets$ measurements with better sensitivity to the WC.
  - c_{tG} also has a relatively large normalization effect on $t\bar{t} + jets$ (which is a background to this analysis).
- The multilepton analysis considers 26 WCs, with c_{tG} included.
- For the combination, we decided to omit c_{tG} and included the 8 WCs that are common to both analyses.
- This is a challenge for future analyses that needs to be addressed. Emphasizes the need for a proper machinery which can help us handle WCs that are omitted by at least one analysis in the combination.
  - Our combination did not explore this avenue.

Towards combination – the physics model

- Most CMS analyses use `Combine`, which provides an interface between user and statistical tools provided by `RooFit/RooStats`.
- `Combine`, by itself, doesn't handle EFT. Depending on the nature of the analyses, different groups create custom physics models to perform EFT fitting using `Combine`.
- The two analyses in this combination also used different custom physics models.
  - Boosted analysis used `EFTModel` whereas the multilepton analysis used `AnaliticAnomalousCouplingEFTNegative` model. Common base model (`PhysicsModel`), but different technical implementations.

The two physics models need to be made compatible with each other to do the combination!

Towards combination – the physics model

- The combination needed a new physics model that would systematically handle different physics options and yield scales.
- No clear roadmap in the beginning since not many combinations of this kind exist.
- Created a new physics model based off `PhysicsModel` that fully incorporates the individual models.
- The combined model has been fully validated.
- The combined physics model is highly specific to meet our purpose and cannot be generalized for future combination efforts at this moment.
- Used the combined physics model to create a workspace without any systematics involved (faster turnaround time for the fits plus some other caveats with implementing systematics).

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The combination would have been easier if both the analyses had used the same custom physics model.

Towards combination - Systematics

- The two analyses varied in terms of the number of systematics and the way they were implemented.
- Categorized all the systematics into three groups:
  - Type1 systematics: Unique to each analyses (straightforward to implement)
    - Ex. charge flips in multilepton analysis, AK8 JER in boosted analysis, etc.
  - Type2 systematics: Implemented in both analyses but have different names (correlated them)
    - Ex. AK4 JER
  - Type3 systematics: Implemented in both analyses but in different manner i.e. correlated among years/processes in one analysis but not in the other (dealt individually)
    - Ex. Luminosity, Pileup, Prefiring, Final State Radiation (FSR), Initial State Radiation (ISR), etc.
- To correlate Type2 systematics, we followed the prescriptions from the Nuisance Parameter manipulation guide of Combine.
- Once Type1 and Type2 systematics were implemented, we ran Asimov fits to extract Confidence Intervals (CIs). Type3 systematics were frozen during this exercise.

Towards combination - Systematics

- Proper implementation of Type3 systematics was not as straightforward.
- Important to understand why each analyses decided to implement the systematics in a certain way and how they should be correlated for the combination.
- The Type3 systematics were of 9 major types:

btagging scale factor, ISR/FSR, lepton scale factor, factorization/renormalization Scales, Jet Energy Scale (JES), QCD Scale, pdf scale, Pileup, PreFiring

- After deciding on the strategy to implement them for the combination, we also explored the effect of these categories on the CIs.
- To that end, we ran the Asimov fits several times by unfreezing the Type3 systematics category one-by-one. We did not see a significant change in the CIs.
- The combination is moving forward; we don't have public results yet. We will seek to "unblind" very soon!

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- After deciding how the combination would implement them, we wanted to understand how the 2 sigma limits are affected by each of these categories.
- To that end, we ran the Asimov fits several times by unfreezing the above Type3 systematics one-by-one. We did not see a significant change in the 2 sigma limits.
- The combination is moving forward; we don't have public results yet. We will seek to "unblind" very soon!

Future combinations could largely benefit if we could minimize the differences in the ways systematics are implemented.

Overall Status and Future Plans

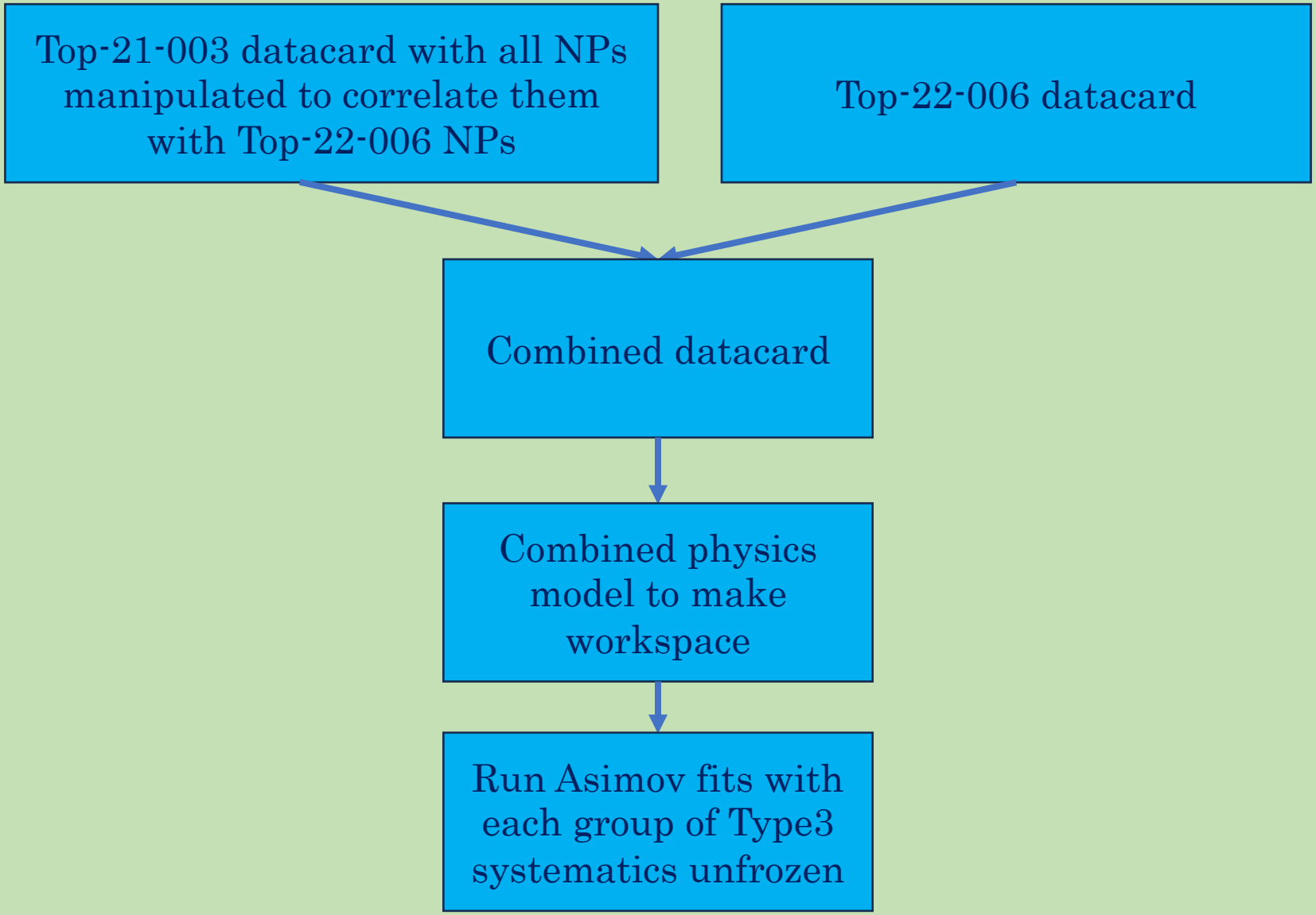
- At this point, we have implemented all the systematics between the analyses and performed Asimov fits to extract CIs for the 8 WCs that are common to both.
- Also considering the possibility of including all the WCs (except ctG) from the multilepton EFT analysis.
  - Might be interesting because the WCs that are omitted now could have correlations with the 8 WCs, and this could impact the limits.
  - Doesn't need any change in the physics model.
  - Turnaround time to make the workspace and run the Asimov fits will be longer (as expected).

Summary and Conclusion

- A combination between multilepton and boosted EFT analyses is in progress.
- Given the technical differences in the physics model used by the individual analyses, we needed to create a new custom physics model.
  - Although not technically difficult, it needed dedicated studies for validation.
  - The model is strictly specific to the combination and cannot be generalized right now.
- Systematics implementation needed special care since they had to be handled on a case-by-case basis.
- Important to stress that future combinations can avoid the challenges we have faced so far through some planning before the individual analyses are carried out.
  - Ensure that the analyses being combined have no overlap in the phase space being probed right from the onset.
  - Could easily avoid the need for a new physics model.
  - Only a few systematics would need special handling.

BACKUP

Systematics Implementation Workflow



Nuisance Parameter Manipulation

Example manipulation

- To correlate the AK4 JER systematics, we added the following line to boosted analysis datacard:

```
nuisance edit rename * * ak4jer_{YEAR} JER_{YEAR} ifexists
```

Special case

Luminosity systematics

- Multilepton analysis has a single lumi rate systematics across all bins/processes.
- Boosted analysis has lumi split by year and also a correlated lumi across all Run II data-taking years.
- Dropped all the luminosity systematics from boosted analysis.
- Added a new correlated luminosity systematics with same normalization rate as that of the multilepton luminosity by adding following lines on boosted analysis datacard:

```
nuisance edit drop * * lumi_13TeV_1718 ifexists
nuisance edit drop * * lumi_13TeV_2016 ifexists
nuisance edit drop * * lumi_13TeV_2017 ifexists
nuisance edit drop * * lumi_13TeV_2018 ifexists
nuisance edit drop * * lumi_13TeV_correlated ifexists
nuisance edit add * * lumi lnN 1.016 ifnotexists
```