Measurements of $t\bar{t}$ and single top production cross sections in CMS

ICHEP 2022

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on behalf of the CMS Collaboration

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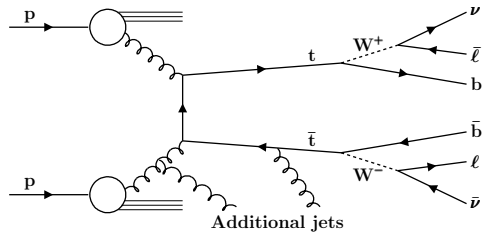
Differential dileptonic $t\bar{t}$ + additional jets cross section

CMS-PAS-TOP-20-006

- Cross sections measured as functions of **one, two or three** kinematic variables for top (anti-)quark and $t\bar{t}$ systems, as well as leptons, b jets, number of additional jets
- Distributions at parton level (full phase space) and particle level (fiducial phase space)
- First comparisons to **predictions beyond NLO accuracy**



Differential dileptonic $t\bar{t}$ + additional jets cross section

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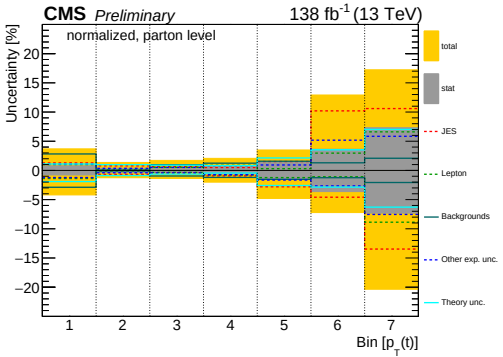
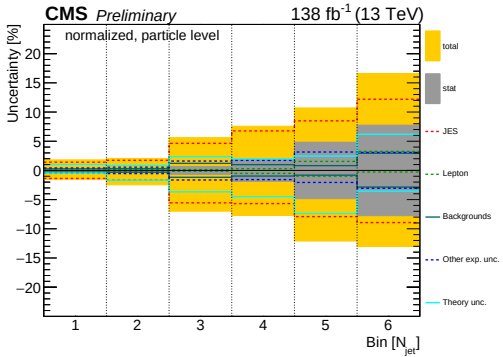
Systematic uncertainties:

- Dominant sources: jet energy scale, ME level and final-state radiation scales





Differential dileptonic $t\bar{t}$ + additional jets cross section

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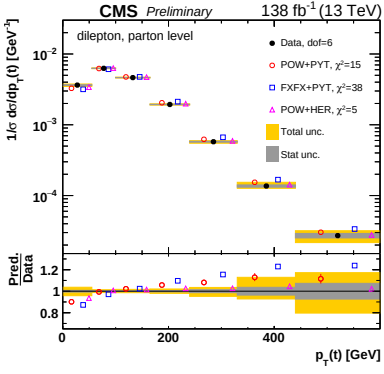
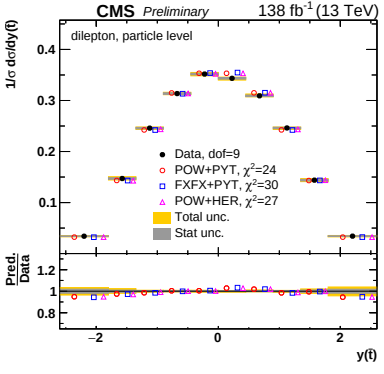
Single-differential:

- Models predict harder p_T spectra for individual quarks and slightly more central rapidity distributions than seen in data





Differential dileptonic $t\bar{t}$ + additional jets cross section

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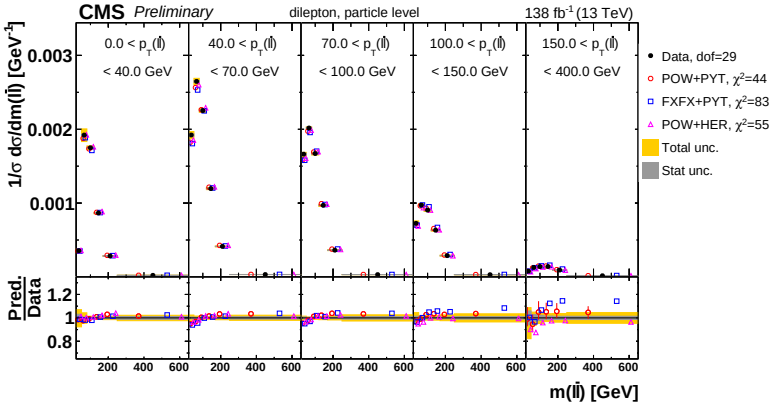
Double-differential:

- Increased deviations of models compared to single-differential distributions
- Indicates deficiency for predicting multi-dimensional process dynamics



Differential dileptonic $t\bar{t}$ + additional jets cross section

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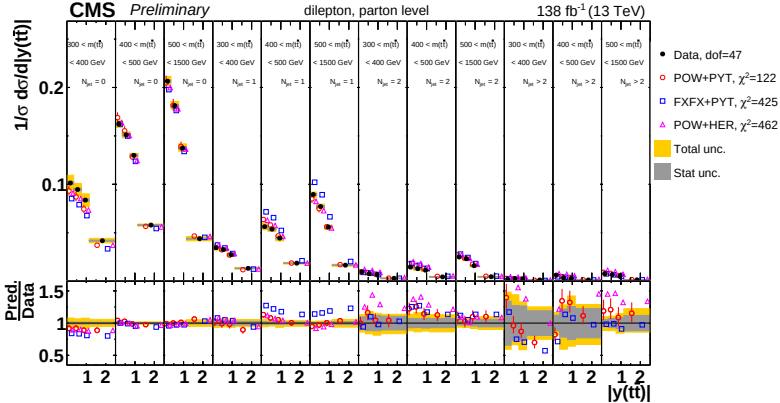
Triple-differential:

- Can be used for simultaneous extraction of top pole mass, α_S, and PDFs
- POWHEG+HERWIG7 overshoots data for ≥ 2 additional jets



Differential dileptonic $t\bar{t}$ + additional jets cross section

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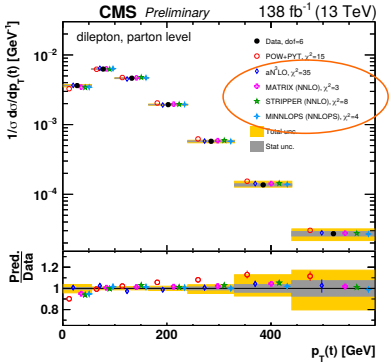
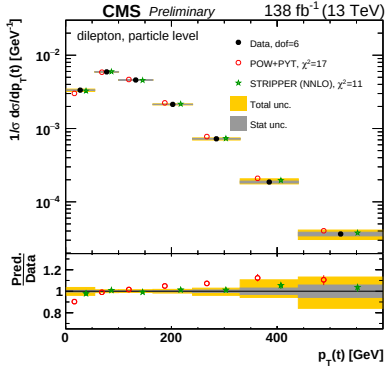
Comparison to beyond-NLO predictions:

- Comparison to MATRIX, STRIPPER, MiNNLOPS, and aN^{3}LO
- Provide similar or improved description, e.g., p_T of top quark: trend towards harder distribution decreased compared to NLO

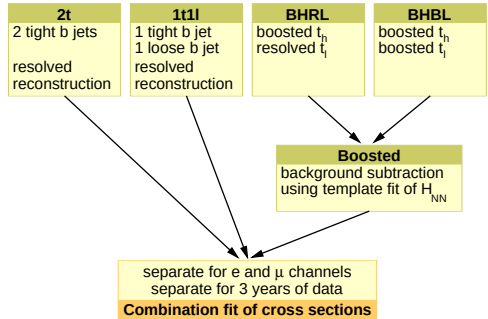




Differential $t\bar{t}$ cross section (ℓ + jets) in full kinematic range

PHYS. REV. D 104, 092013

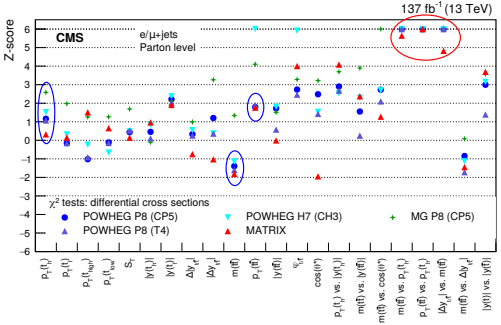
- First differential measurement combining low top quark p_T **(resolved)** with high top quark p_T region **(boosted)**
  - Provides constraints on systematic unc. which improve precision
- Differential cross section extracted via combined χ^2 fit to several event categories
  - Defined by top quark reconstruction method, lepton flavors, three years of data-taking
  - Boosted tops: reconstruction with NNs
  - Results at **parton and particle level**: unc. due to theoretical extrapolations reduced by the latter



Differential $t\bar{t}$ cross section (ℓ + jets) in full kinematic range

PHYS. REV. D 104, 092013

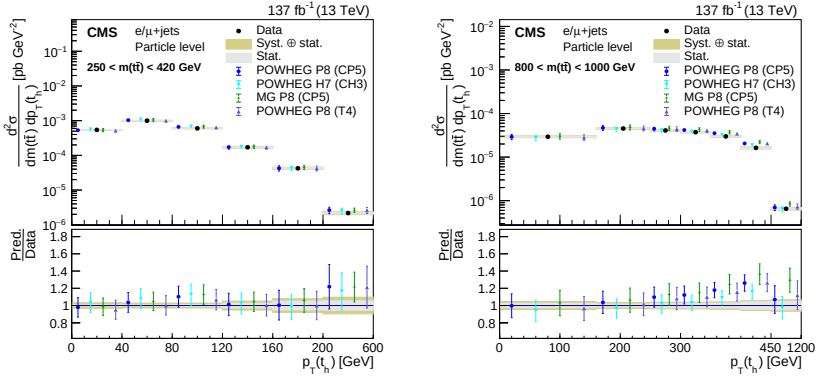
- Single and double differential cross section measured for various kinematic distributions defined in the top quark and $t\bar{t}$ system
- Dominant systematic uncertainties: jet energy scale and int. luminosity
- χ^2 tests: most differential distributions in agreement with SM, deviations observed for $m(t\bar{t})$ vs. $p_T(t_h)$, $p_T(t\bar{t})$ vs. $p_T(t_h)$, $|\Delta y_{t/\bar{t}}|$ vs. $m(t\bar{t})$
  - One-dimensional distributions $p_T(t_h)$, $m(t\bar{t})$, $p_T(t\bar{t})$ consistent with predictions at 2 std. dev. ⇒ kinematic relations to be further understood



Differential $t\bar{t}$ cross section (ℓ + jets) in full kinematic range

PHYS. REV. D 104, 092013

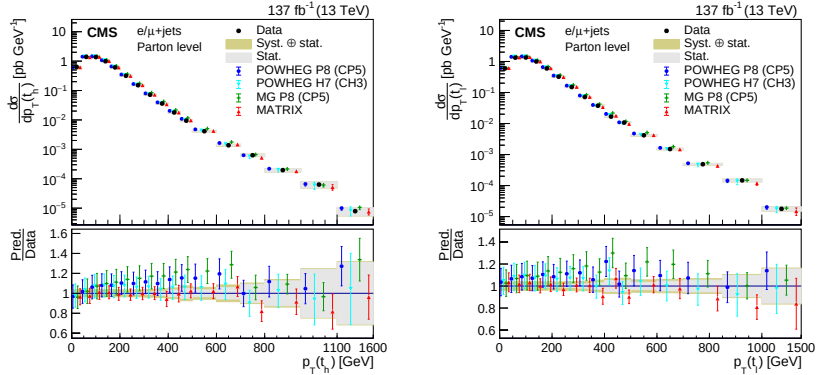
- Tension for double-differential $m(t\bar{t})$ vs. $p_T(t_h)$ distribution:
  - Measured p_T spectra in agreement/softer than predicted at low $m(t\bar{t})$
  - Measured p_T spectra harder than predicted at high $m(t\bar{t})$



Differential $t\bar{t}$ cross section (ℓ + jets) in full kinematic range

PHYS. REV. D 104, 092013

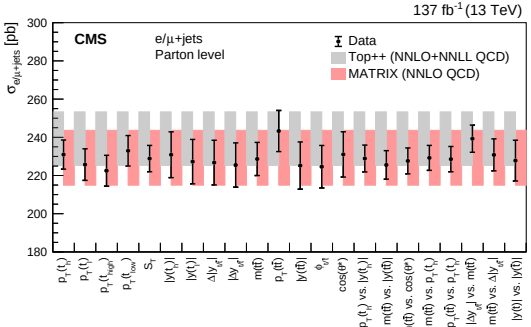
- Parton-level cross sections compared to MATRIX (NNLO)
  - MATRIX describes data better than POWHEG+PY8 and MADGRAPH5_AMC@NLO+PY8 and has reduced uncertainties
- Top quark p_T spectrum in data softer than predicted by NLO models at low p_T



Differential $t\bar{t}$ cross section (ℓ + jets) in full kinematic range

PHYS. REV. D 104, 092013

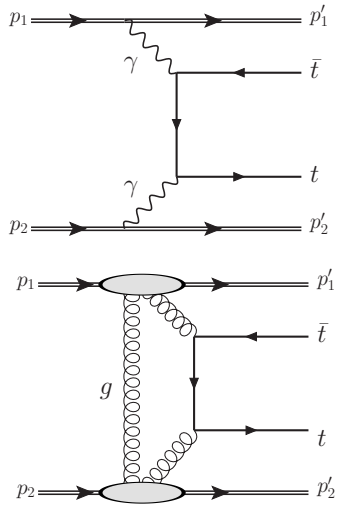
- Calculate **inclusive cross section** at parton level by summing up all bins
- Individual results correspond to $t\bar{t}$ cross section in e/μ + jets channel
- Measured cross section of $\sigma_{t\bar{t}} = 791 \pm 1\,(\text{stat}) \pm 21\,(\text{syst}) \pm 14\,(\text{lumi})$ pb
  - Total uncertainty of 3.2% $\Rightarrow$ **most precise result** in ℓ + jets channel to-date
  - Agrees well with prediction by MATRIX: 797^{+39}_{-51} (scale) $\pm$ 39 (PDF) pb



Search for central exclusive $t\bar{t}$ production with tagged protons

CMS-PAS-TOP-21-007

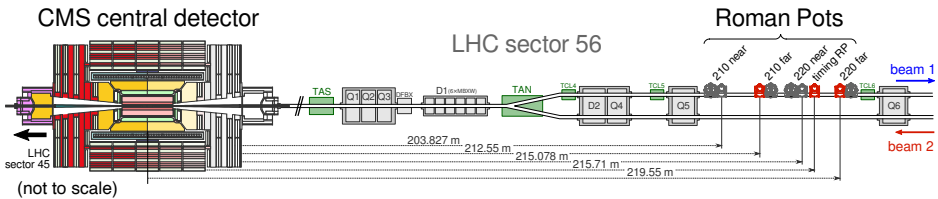
- Alternative production mode of top quark pairs at the LHC (≈0.3 fb): **exchange of colorless particles**, e.g., photons or pomerons
- One or both protons remain intact after interaction, energy fraction transferred to $t\bar{t}$ pair
- **Exclusive central production** via $pp \rightarrow pt\bar{t}p$
- Observation expected to be possible only at HL-LHC, but BSM physics could enhance cross section ⇒ potentially measurable at Run 2



Search for central exclusive $t\bar{t}$ production with tagged protons

CMS-PAS-TOP-21-007

- Detect two intact forward protons with CMS-TOTEM Precision Proton Spectrometer (CT-PPS), one on each side of interaction region
  - Array of movable near-beam devices called Roman Pots (RP): timing and tracker detectors (only the latter used in analysis)
  - Analysis of 2017 data set, corresponding to 29.4 fb^{-1} int. lumi



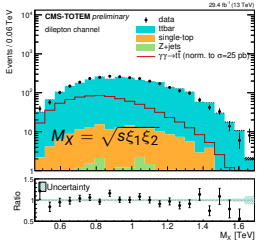
- Reconstruct top quark pair and their decay products in CMS central detector (separately for dilepton and ℓ + jets, combined for final result)

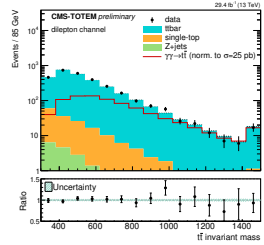
Search for central exclusive $t\bar{t}$ production with tagged protons

CMS-PAS-TOP-21-007

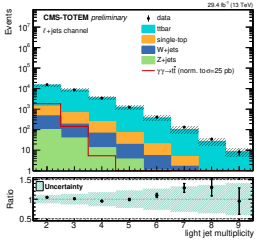
BDT for dilepton (ℓ + jets) with 15 (10) input variables to enhance signal content of selected samples

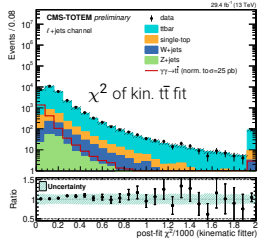
In all distributions:
signal scaled to $\approx 10^5 \times$ SM prediction





dilepton





ℓ + jets

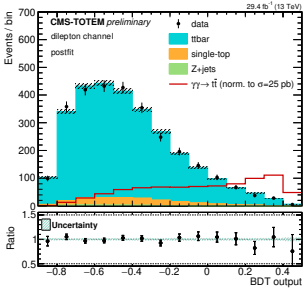
Search for central exclusive $t\bar{t}$ production with tagged protons

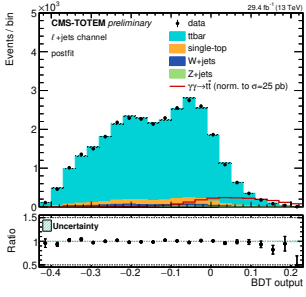
CMS-PAS-TOP-21-007

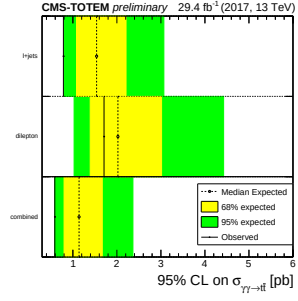
Poster by Beatriz Ribeiro Lopes tomorrow!

Further CT-PPS results by Andrea Bellora today!

Upper limits at 95% CL extracted via binned fits to BDT output distributions







Observed (expected) limits:

- Dilepton (ee, $\mu\mu$, eμ): 1.70 pb (2.02 pb)
- ℓ + jets (ℓ = e/μ): 0.78 pb (1.54 pb)
- **Combined: 0.59 pb (1.14 pb)**

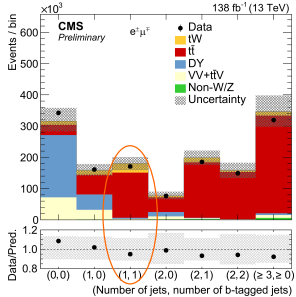
Systematic uncertainties:

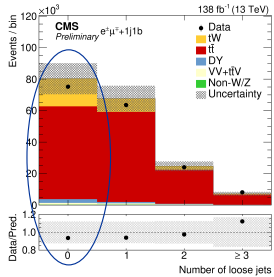
- Effect of about 10%
- Dominant: bkg. normalization, FSR modeling, jet energy corrections, proton reconstruction

Measurement of inclusive and differential single top tW production

CMS-PAS-TOP-21-010

- First full Run 2 (2016–2018) measurement of inclusive and differential tW cross section
- Overlap at NLO with $t\bar{t}$ background considered via diagram removal scheme
- Analysis in **dilepton eμ** final state
  - Event categories: number selected jets and b-tagged jets "*mj*n*b*" ($p_T > 30$ GeV and $|\eta| < 2.4$)
  - 1j1b: signal category, 2j1b: sensitive to tW, 2j2b: constrain $t\bar{t}$
  - 1j1b: "loose jets" with 20 GeV $< p_T <$ 30 GeV $\Rightarrow$ use 1j1b category with zero loose jets for differential measurement



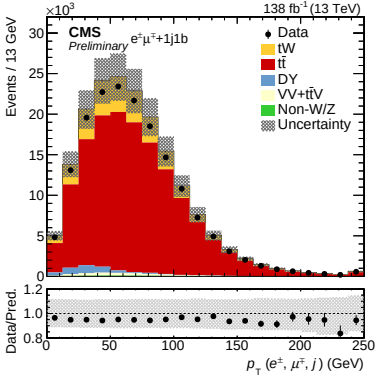


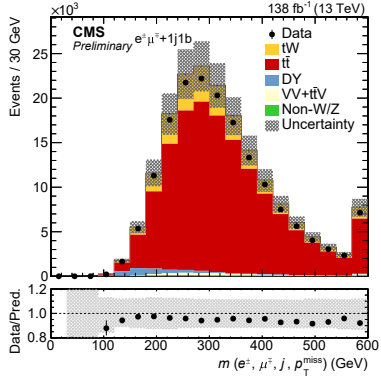
Measurement of inclusive and differential single top tW production

CMS-PAS-TOP-21-010

Inclusive cross section measurement:

- Two BDTs, one for 1j1b and one for 2j1b category:
  - 1j1b: 6 input variables, most discriminating: $p_T(e^{\pm}, \mu^{\pm}, j)$ and $m(e^{\pm}, \mu^{\pm}, j, p_T^{miss})$
  - 2j1b: 3 input variables $\Delta R(\ell_1, j_1)$, $\Delta R(\ell_{12}, j_{12})$, subleading jet p_T



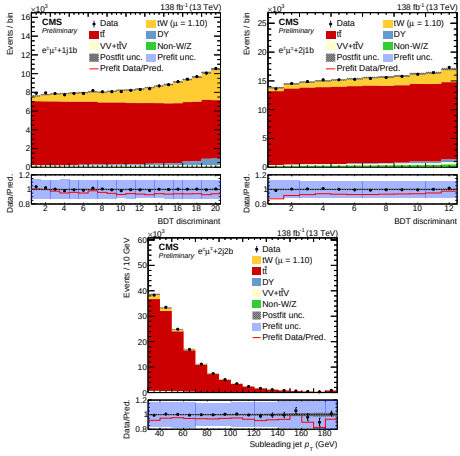


Measurement of inclusive and differential single top tW production

CMS-PAS-TOP-21-010

Inclusive cross section measurement:

- Maximum likelihood fit performed to 1j1b and 2j1b BDT output distributions and 2j2b distribution of subleading jet p_T
- Measured cross section:
  $\sigma_{tW} = 79.2 \pm 0.8\,(\text{stat})\,^{+7.0}_{-7.2}\,(\text{syst}) \pm 1.1\,(\text{lumi})$ pb
  $\Rightarrow$ uncertainty of 9.3%, consistent with predicted cross section of
  $71.7 \pm 1.8\,(\text{scale}) \pm 3.4\,(\text{PDF})$ pb (NNLO)
- Dominant syst. unc.: jet energy scale corrections, ME scales for tW process



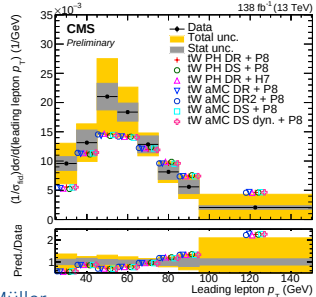
Measurement of inclusive and differential single top tW production

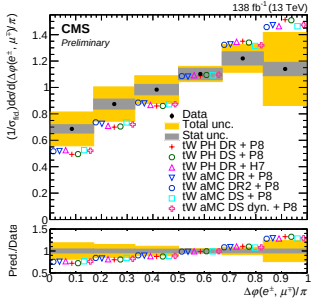
CMS-PAS-TOP-21-010

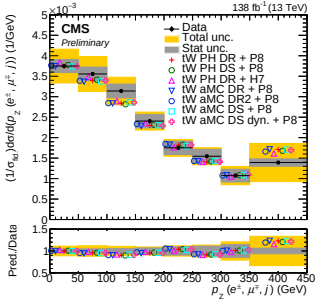
Poster by Alejandro Soto Rodriguez tomorrow!

Differential cross section measurement:

- Differential cross section measured in 6 different kinematic distributions, e.g.:
  - Leading lepton $p_T \Rightarrow$ additional probe of top quark p_T
  - $\Delta\phi(e^{\pm}, \mu^{\pm}) \Rightarrow$ correlations between top and W, spin-related properties
  - $p_z(e^{\pm}, \mu^{\pm}, j) \Rightarrow$ boost of tW system
- Small diff. in produced tW types $\Rightarrow$ small effect due to tW/$t\bar{t}$ interference







Summary

Run 1 ATLAS + CMS $t\bar{t}$ cross section combination: talk by Richard Hawkings!

- LHC @ Run 2:
  - Top quark pair factory ⇒ multi-differential measurements
  - Sufficient amount of single top events for inclusive and differential measurements
- First search for central exclusive $t\bar{t}$ production
- Results in good agreement with SM predictions
  - Deviations of NLO predictions from data in double- and triple $t\bar{t}$ differential distributions, and single-differential $t\bar{t}$ and tW cross sections related to top p_T
  - First comparisons with beyond-NLO predictions for single-differential $t\bar{t}$ distributions
- More data at Run 3 expected: further increase precision of $t\bar{t}$ and single top results, better access to more exotic/rare production modes!