CMS Top Physics Highlights

Mykola Savitskyi (DESY)

on behalf of the CMS Collaboration

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Top quark is unique

- **Heaviest** known elementary particle
  - $\frac{1}{2}$ spin, $+\frac{2}{3} e$, color charge
  - large coupling to Higgs boson
  - may play special role in electroweak symmetry breaking: $y_t = \sqrt{2}m_t / \nu \approx 1$

- Decays before forming hadrons
  - unique opportunity to study properties of bare quark

- Deviations of top quark properties from SM predictions may reveal new physics

5 orders of magnitude among quark masses
Top quark production and decay

Top quark pair ($t\bar{t}$) production
- dominant production mode
- via strong interaction

Single top quark production
- via weak interaction
- at LO, production in 3 channels

Decay and channels
- in most cases to W boson and b quark
  → via weak interaction
- final state topology governed by decay mode of W boson
  → $t\bar{t}$ decay channels:
  all-hadronic, lepton+jets, dilepton
Top quark production and decay

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Decay and channels
- in most cases to W boson and $b$ quark
  → via weak interaction
- final state topology governed by decay mode of W boson
  → $tt'$ decay channels:
    all-hadronic, lepton+jets, dilepton
    - low BR
    - low background

Top Pair Branching Ratios
- "all-hadronic" 46%
- "dilepton" 15%
- "lepton+jets" 15%
- $\tau+\text{jets}$ 15%
- $\mu+\text{jets}$ 15%
- $e+\text{jets}$ 15%

Mykola Savitskyi (DESY)

This talk:

- selection of recent CMS results from Run2
- all presented results based on ~36 fb⁻¹ of 13 TeV data, unless the opposite stated
Top quark pair production

Rate and dynamics of $t\bar{t}$ production are key to studies in top quark sector

- precision tests of SM predictions
- new physics may couple to $t\bar{t}$, e.g. SUSY, $Z'$, dark matter
- background for Higgs boson processes, rare processes, and beyond-SM searches
Inclusive $\bar{t}t$ cross section at CMS: overview

Measurements at different energies and in all $\bar{t}t$ decay channels

- Good agreement with NNLO+NNLL calculations
- Most precise results in dilepton and lepton+jets channel (about 4%)
Inclusive $t\bar{t}$ cross section

- Measurement of $\sigma_{t\bar{t}}$ from a likelihood fit with a high precision
- Dilepton events in $e\mu$, $ee$, $\mu\mu$ categories classified according to number of jets and b-tags
- Standalone measurement of $\sigma_{t\bar{t}}$ for $m_{t}^{\text{MC}} = 172.5$ GeV
  - $\sigma_{t\bar{t}} = 803 \pm 2$ (stat) $\pm 25$ (syst) $\pm 20$ (lumi) pb ($4\%$)
  - good agreement with predictions
- Also did simultaneous measurement of $\sigma_{t\bar{t}}$ and $m_{t}^{\text{MC}}$
  - resulting $\sigma_{t\bar{t}}$ used, together with a theoretical prediction at NNLO accuracy, to determine the $m_{t}(m_{t})$, $m_{t}^{\text{pole}}$ and to extract a value of $\alpha_{S}$ with different sets of PDFs (more info on top mass later)

NNLO + NNLL prediction (JHEP 2013 (2013) 80): $\sigma_{t\bar{t}} = 832^{+20}_{-29}$ (scale) $\pm 35$ (PDF+$\alpha_{S}$) pb

![Diagram showing $t\bar{t}$ cross section and distribution of events](image-url)
Inclusive $\bar{t}t$ cross section

- **Testing lepton universality using $\bar{t}t$ decays to lepton+tau final states**
  - Measurement of $\sigma_{\bar{t}t}$ for the process: $\bar{t}t \rightarrow (\ell\nu_\ell)(\tau_h\nu_\tau)b\bar{b}$, $\ell = e,\mu$
    - a likelihood fit of the transverse mass $M_T(\ell,p_T^{miss})$ in signal-like and background-like categories
    $$\sigma_{\bar{t}t}(\ell\tau_h) = 781 \pm 7 \text{ (stat)} \pm 62 \text{ (syst)} \pm 20 \text{ (lumi)} \text{ pb} \ (8\%)$$
  - Ratio to the dilepton cross section (see previous slide) consistent with lepton universality
    $$R(\ell\tau_h/\ell\ell) = 0.973 \pm 0.009 \text{ (stat)} \pm 0.066 \text{ (syst)}$$
  - Ratio of the partial to the total width: $\Gamma(t \rightarrow \tau \nu \tau b) / \Gamma_{\text{total}} = 0.1050 \pm 0.0009 \text{ (stat)} \pm 0.0071 \text{ (syst)}$
Differential $t \bar{t}$ cross sections

- Study of $\sigma_{t \bar{t}}$ as a function of many observables in different $t \bar{t}$ decay channels
  - deeper probe of $t \bar{t}$ process in various corners of phase space
  - sensitivity to subtle hints of new physics
- Dedicated event selection and reconstruction of top quark candidates in each channel
- Unfolding back to parton and particle levels to correct for detector effects and acceptance
- Good agreement with SM, but none MC predictions describe all distributions
  - parton-level spectra better described by fixed-order calculations of NNLO accuracy

Consistent results among channels
Similar trends at parton and particle levels

Only small glimpse of results
- e.g. JHEP 02 (2019) 149 presents about 100 differential spectra

Spectra for top quark $p_T$

Left: dilepton (parton)  
Right: e/\mu+jets (particle)
Multi-differential $\bar{t}t$ cross sections in dilepton channel

- Measurement of $\bar{t}t$ 2D and 3D differential cross as a function of top quark and $\bar{t}t$ kinematics, and number of extra jets
  → unfolding in several dimensions allows detailed study of various corners of phase space
- $\bar{t}t$ triple-differential cross sections provide novel sensitivity to the gluon PDF
- Cross sections as a function of $|y(tt)|$ - vs- $M(tt)$ - vs- $N_{\text{jets}}$ used to perform world's first simultaneous fit of the gluon PDF, strong coupling $\alpha_s$ and top quark pole mass $m_{t\text{pole}}$ (will be discussed later)
Single top quark production

Deep insight into EWK processes
- direct measurement of $|V_{tb}|$
- sensitivity to proton structure
- search for anomalous top quark couplings (e.g. in FCNC interactions)

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Inclusive single top cross sections: overview

- Comprehensive study of dominant modes for single top quark production
  - Good agreement between experiments and with SM predictions at all energies
Differential single top t-channel cross sections

- Measurement of cross sections as a function of kinematic observables of top quarks, charged leptons and W boson from top quark decay

- Events with 1 isolated e or μ, and 2 or 3 jets:
  → top quarks reconstructed from decay products

- Strategy:
  → discrimination of signal and background via BDT
  → uncertainties profiled in a likelihood fit
  → unfolding of extracted yields to parton and particle levels

- Differential charge ratios computed as $\frac{\sigma_{t\text{-}ch,t}}{\sigma_{t\text{-}ch,t} + \bar{t}}$

- Overall reasonable agreement with SM
  - Charge ratios agree with all PDF sets

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ICNFP 2019
Rare modes of $t\bar{t}+X$ and $t+X$ production
**tt+X and t+X production at CMS: overview**

- Rare processes with production cross sections typically smaller than 1 pb
- Analyses require various machine learning techniques to gain signal sensitivity
- New possibilities for studies of rare processes owing to full Run2 dataset (~140 fb\(^{-1}\))

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**CMS Preliminary**

- 7 TeV CMS measurement (L ≤ 5.0 fb\(^{-1}\))
- 8 TeV CMS measurement (L ≤ 19.6 fb\(^{-1}\))
- 13 TeV CMS measurement (L ≤ 137 fb\(^{-1}\))
- Theory prediction
- CMS 95%CL limits at 7, 8 and 13 TeV
tt+V production

- Enhancements in BSM models → great potential for EFT studies
- ttZ/ttW processes serve as important backgrounds for many analyses, e.g. ttH, tttt, tt+DM

CMS (35.9 fb⁻¹ @ 13 TeV)
- ttZ / ttW inclusive cross sections
- EFT constraints

CMS (19.7 fb⁻¹ @ 8 TeV)
- ttγ inclusive cross section in lepton+jets

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Recent $ttZ$ cross sections (77.5 fb$^{-1}$)

- Studying events with 3 or 4 leptons
  - further categorisation w.r.t. $N_{jets}$ and $N_{b-tags}$
- $Z$ boson detected via its decay to lepton pair
- Most precise $\sigma(ttZ)$ to date

\[ \sigma(pp\rightarrow ttZ) = 0.95 \pm 0.05 \text{ (stat)} \pm 0.06 \text{ (syst)} \text{ pb} \]

- First differential measurements as function of $p_T(Z)$ and angular distribution of $\ell(-)$ from $Z$

\[ \sigma(pp\rightarrow ttZ) = 0.95 \pm 0.05 \text{ (stat)} \pm 0.06 \text{ (syst)} \text{ pb} \]

SM NLO prediction: 0.84 ± 0.10 pb
Observation of tZq production (77.4 fb⁻¹)

- Studying events with 3 leptons (e or μ) and at least 2 jets
  - 3 signal regions w.r.t. $N_{\text{jets}}$ and $N_{\text{b-tags}}$
  - dedicated BDT in each region
- tZq signal strength measured from a fit to BDT outputs, and event yields in control regions
- Observation of tZq with > 5σ significance

$\sigma(pp\rightarrow tZq\rightarrow t\ell^+\ell^-q) = 111 \pm 13 \, (\text{stat}) \, ^{+11}_{-9} \, (\text{syst}) \, \text{fb}$

Agrees with SM NLO prediction: 94.2 ± 3.1 fb

- Direct sensitivity to tZ and WWZ couplings
- Enhancement in BSM models
First evidence of $t\gamma q$ process

- Studying events with a muon, a photon, MET, and at least 2 jets (with exactly 1 b-tag)
  → BDT based on topological and kinematic event properties in signal region
- Simultaneous fit of BDT output in signal region and the $tt\gamma$ control region
- Evidence of $t\gamma q$: $4.4\sigma$ observed ($3.0\sigma$ expected)

$\sigma(pp\to t\gamma q) \times BR(t\to \mu vb) = 115 \pm 17 \text{ (stat)} \pm 30 \text{ (syst)} \text{ fb}$

Agreement with SM NLO prediction: $81 \pm 4 \text{ fb}$

- Sensitivity to top quark charge and its electric and magnetic dipole moments
Search for production of 4 top quarks (137 fb^{-1})

- Results based on full Run2 data
  - Studying same-sign dileptonic (e or \( \mu \)) and trileptonic events with several jets
  - BDT analysis: signal regions w.r.t S/B separation
  - Measurement of \( \sigma(pp \to t\bar{t}t\bar{t}) \) fitting event yields in all BDT categories

\[ \sigma(pp \to t\bar{t}t\bar{t}) = 12.6^{+5.8}_{-5.2} \text{ (total) fb} \]

- NLO+EW prediction: 12.0^{+2.2}_{-2.5} fb

- Significance: 2.6\( \sigma \) observed (2.7\( \sigma \) expected)

- Constraints on top quark Yukawa coupling

\[ |y_t/y_t^{\text{SM}}| < 1.7 \text{ (95\% CL)} \]

- extremely rare process that can receive significant enhancement in BSM models
- direct probe of top-Higgs Yukawa coupling

CMS-PAS-TOP-18-003
**tt+bb̅ production**

- Scrutinizing \(tt+bb\) production in dileptonic, lepton+jets and all-hadronic channels
  - major background for \(tt+H(bb)\) and \(tttt\)
  - complex final state governed by very different scales, i.e. \(m_t\) and \(p_T^{\text{jet}}\) → challenging modelling
- Measurements of \(\sigma(ttbb)\), \(\sigma(tjj)\) and their ratio
  - comparisons to NLO MC predictions
  - overall good agreement, but \(\sigma(ttbb)\) slightly higher in data

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Some top quark properties are predicted by the SM, some are not (e.g. mass, $V_{tq}$)

- important input to theory
- precision measurements can reveal signs of new physics
- wide variety of properties can be studied

In this talk:

top quark mass

spin correlation & polarisation
Top quark mass

- Fundamental parameter in the SM → not an observable
- Renormalisation scheme dependent → i.e. $m_t^{MC}$ vs $m_t^{pole}$, $m_t(m_t)$
- Input to precision tests of SM → $m_t$, $m_W$, $m_H$ interplay at loop level → need to measure $m_t$ with highest possible precision
- Directly measured from reconstructed top quark decay products → most precise way to determine $m_t$

- Higher precision through combination of many measurements in many channels → uncertainties below 500 GeV (< 0.3%)

- However, probing mass as defined in MC → $m_{t}^{MC}$ can’t be exactly interpreted in terms of on-shell mass in perturbation theory, i.e. $m_{t}^{pole}$

**m(top) at CMS: direct measurements**

![Graph showing CMS measurements of $m_{t}$ from various channels and combinations.](image-url)
Extraction from a fit to a sensitive observable
→ e.g. $\sigma(t\bar{t})$, exploiting dependence of theoretical predictions on $m_t$

Overall smaller precision w.r.t. direct measurements
→ measurements with sub-GeV uncertainties started to appear only recently

Probing theoretically well-defined parameter, e.g. $m_t^{\text{pole}}$, $m_t(m_t)$
→ e.g. difference between $m_t^{\text{pole}}$ and $m_t^{\text{MC}}$ estimated to be < 1 GeV
m(top) at CMS: indirect measurements

- Novel extraction of gluon PDF, $\alpha_s$ and $m_t^{\text{pole}}$
  from triple-differential $\sigma(\ell\ell)$ and NLO predictions
  (analysis details in slide 12)

CMS

$[N_{\text{jet}}^{0,1+}, M(\ell\ell), y(\ell\ell)]$
- $m_t^{\text{pole}}$ with total unc.
- data unc.
- PDF unc.
- $\mu$ unc.
- $\alpha_s \pm 0.001$ unc.

ABMP16
HERAPDF20
CT14

World average [PDG2018]

Precision of 0.5%

CMS Preliminary

June 2019

$\tilde{t}\tilde{t}$-j shape, 8 TeV
TOP-13-006 (2016), 19.7 fb$^{-1}$
NLO
$\sigma(\ell\ell)$, 7+8 TeV
JHEP 08 (2016) 029; 5.0 + 19.7 fb$^{-1}$
NNLO+NNLL, NNPDF3.0
$\sigma(\ell\ell)$, 13 TeV
EPJC 79 (2019) 368, 35.9 fb$^{-1}$
NNLO+NNLL, NNPDF3.1

triple-differential $\sigma(\ell\ell)$, 13 TeV
arXiv:1904.05237 (2019), 35.9 fb$^{-1}$
NLO, HERAPDF2.0

triple-differential $\sigma(\ell\ell)$, 13 TeV
arXiv:1904.05237 (2019), 35.9 fb$^{-1}$
NLO, 3D fit ($m_t^{\text{pole}}, \alpha_s, \text{PDF}$)

CMS Run 1 legacy
PRD 93 (2016) 072004
$m_t$ from standard measurements

165
170
175
$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

$160 \pm 0.52 - 3.66 \text{ GeV}$
$173.90 \pm 1.70 - 1.80 \text{ GeV}$
$173.20 \pm 2.10 - 2.30 \text{ GeV}$
$170.83 \pm 0.72 - 0.72 \text{ GeV}$
$170.50 \pm 0.80 - 0.80 \text{ GeV}$
$172.44 \pm 0.49 - 0.49 \text{ GeV}$

Mykola Savitskyi (DESY)

arXiv:1904.05237 - submitted to EPJC -
Top quark mass in boosted topologies

- First measurement of the top quark mass in the highly boosted regime to better understand ambiguities between $m_t^{\text{pole}}$ and $m_t^{\text{MC}}$
  
- Differential $\sigma(t\bar{t})$ measured as a function of jet mass $m_{\text{jet}}$ via unfolding in lepton+jets events
  
  → boosted top quarks ($p_T > 400$ GeV): a single jet includes all $t \to bW \to bq'q'$ decay products, i.e. fat jet
  
  → improved resolution of $m_{\text{jet}}$ owing to novel X Cone algorithm [JHEP 11 (2015) 072] used to reconstruct fat jets

- Location of the $m_{\text{jet}}$ peak can be calculated analytically and is sensitive to $m_t$

- Top quark mass extracted from $d\sigma(t\bar{t})/dm_{\text{jet}}$

  \[ m_t^{\text{pole}} = 172.56 \pm 2.47 \text{ GeV} \ (1.4\%) \]
Running of top quark mass

- First measurement of the running, i.e. scale dependence, of the top quark mass defined in the $\overline{\text{MS}}$ scheme, i.e. $m_t(m_t)$

- Differential $d\sigma(t\bar{t})/dm(t\bar{t})$ measured using events with oppositely charged electron and muon
  - maximum-likelihood fit to multidifferential distributions of final state observables at parton level
  - constraining systematic uncertainties in-situ and accounting for dependence on $m_t^{MC}$

- $m_t(m_t)$ extracted in bins of $m(t\bar{t})$ via a fit to NLO predictions to determine the running of $m_t(\mu)$

- Observed running found to be compatible with scale dependence predicted by renormalization group equations

![Graph showing running of top quark mass](image)
Spin correlations and polarization

- In SM, top quarks from pair production are almost unpolarized, but have correlated spins.
- Top quark lifetime (~$10^{-25}$ s) is much shorter than the spin decorrelation time scale (~$10^{-21}$ s).
  - Angular distributions of top quark decay products provide access to spin of top quark.
- Best sensitivity in the **dilepton** channel: spin analyzing power of the lepton ~1.
Spin correlations & polarization in dileptons

- Probing spin-dependent parts of the $t\bar{t}$ production density matrix
- Measurement of $t\bar{t}$ differential cross sections as a function of observables sensitive to top quark polarization and $t\bar{t}$ spin correlations (strategy follows JHEP 02 (2019) 149 presented previously)
  - e.g. $\Delta\phi(\ell^+\ell^-)$: difference in azimuthal angles between two leptons in the laboratory frame
- Extraction of spin coefficients and asymmetries
- Results used to improve current constraints on the anomalous top quark CMDM in EFT
- All results in agreement with SM expectations

\[
A_{|\Delta\phi_{\ell\ell}|} = \frac{N(|\Delta\phi_{\ell\ell}| > \pi/2) - N(|\Delta\phi_{\ell\ell}| < \pi/2)}{N(|\Delta\phi_{\ell\ell}| > \pi/2) + N(|\Delta\phi_{\ell\ell}| < \pi/2)}
\]
Summary

- Probing nature with many measurements in top quark sector with CMS
  - top quark cross sections and properties at high precision
  - rare top quark production modes may be accessed better than ever
  - wide variety of results offer great potential for BSM searches (e.g. many interpretations in EFT not covered today)
    - constantly providing valuable input for improvement of theoretical predictions
- All results are in agreement with SM and no evidence of new physics
- Next generation of new exciting results to come with study of full Run2 data from LHC

See more:
Summary

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THANK YOU FOR YOUR ATTENTION

See more:

Differential $t\bar{t}$ cross sections

- Study of $\sigma_{t\bar{t}}$ as a function of many observables in various $t\bar{t}$ decay channels
  - deeper probe of $t\bar{t}$ process in various corners of phase space
  - sensitivity to subtle hints of new physics

- Dedicated event selection and reconstruction of top quark candidates in each channel

- Unfolding to correct measured spectrum for detector effects and acceptance, i.e. back to:
  - **parton level**: results can be compared to predictions from perturbative calculations
  - **particle level**: reduced dependence on theoretical assumptions used in the simulation
Differential $\tt$ cross sections

<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>CMS</strong> 35.9 fb$^{-1}$ (13 TeV)</td>
<td><strong>CMS</strong> 35.8 fb$^{-1}$ (13 TeV)</td>
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- **Left:** dilepton
- **Right:** $e/\mu$+jets

- Normalized differential spectra for top quark $p_T$
- Consistent results among channels
- Similar trends at parton and particle levels
- Good agreement with SM, but none MC predictions describe all distributions
- Parton-level spectra better described by fixed-order calculations of NNLO accuracy

Only small glimpse of results
e.g. JHEP 02 (2019) 149 presents about 100 differential spectra
Double-differential $\bar{t}t$ cross sections in $\ell+jets$ channel

- Results unfolded in two dimensions as a function of:
  - top quark and $\bar{t}t$ kinematics
  - jet multiplicity
- Provide more sensitivity in various corners of phase space
- Plots: 2D unfolding in $p_T(t_h)$ and number of additional jets
  - slope in $p_T(t_h)$ diminishes at higher jet multiplicities
  - Herwig++ shows different trends w.r.t. other generators

Only small glimpse of results

PRD 97 (2018) 112003 presents about 175 differential spectra
Inclusive single top cross sections at CMS: overview

Single top-quark production

Inclusive cross sections

April 2019

Graph showing single top-quark production with cross sections plotted against center-of-mass energy (\(\sqrt{s}\)). The graph includes data points and curves for different production mechanisms:
- **t-channel**
  - CDF & D0, PRL 115, 152003 (2015)
  - CMS, JHEP 12, 035 (2012)
  - CMS, JHEP 06, 090 (2014)
- **W-associated**
  - CMS, PRL 110, 022003 (2013)
  - CMS, PRL 112, 231802 (2014)
  - CMS, JHEP 10, 117 (2018)
- **Z-associated**
  - CMS, JHEP 07, 003 (2017)
  - CMS, PRL 122, 132003 (2019)

Additional details and references are provided in the text accompanying the graph.
Inclusive single top t-channel cross section

- Measuring the t-channel production of single top quarks and antiquarks
  - different production rates for \( t \) and \( \bar{t} \) owing to proton PDF
  - direct sensitivity to \( V_{tb} \)

- Events with one e or \( \mu \), and multiple jets:
  - different categories of jet and b jet multiplicity and multivariate discriminators are applied to separate signal from background

- Cross sections measured from a likelihood fit to BDT output in all categories
  \[
  \sigma_{t-ch,t} = 136 \pm 1 \text{ (stat)} \pm 22 \text{ (syst)} \text{ pb} \\
  \sigma_{t-ch,\bar{t}} = 82 \pm 1 \text{ (stat)} \pm 14 \text{ (syst)} \text{ pb}
  \]

- Ratio \( R_{t-ch} = \frac{\sigma_{t-ch,t}}{\sigma_{t-ch,\bar{t}}} \) measured for different PDF sets

- Resulting \( V_{tb} \)
  \[
  |f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{t-ch,t+\bar{t}}}{\sigma_{t-ch,t+\bar{t}}^{\text{theo}}}} = 1.00 \pm 0.08 \text{ (exp)} \pm 0.02 \text{ (theo)}
  \]


\[
\sigma_{t-ch,t} = 136.0^{+14}_{-2.9} \text{ (scale)} \pm 3.5 \text{ (PDF+\( \alpha_s \)) pb} \\
\sigma_{t-ch,\bar{t}} = 81.0^{+2.5}_{-1.7} \text{ (scale)} \pm 3.2 \text{ (PDF+\( \alpha_s \)) pb}
\]
Inclusive $tW$ production cross section

- Probing associated $tW$ production
- Events with oppositely charged $e$ and $\mu$, and at least 1 $b$ quark jet
- Measurement of $\sigma_{tW}$ using a likelihood fit
  - events classified into categories w.r.t. number of jets and $b$ quark jets
  - fitting BDT output (in 1j1b and 2j1b categories) and subleading jet $p_T$ (in 2j2b category)

$$\sigma_{tW} = 63.1 \pm 1.8 \text{ (stat)} \pm 6.4 \text{ (syst)} \pm 2.1 \text{ (lumi)} \text{ pb (11%)}$$

**aNNLO prediction:** $\sigma_{tW} = 71.7 \pm 1.8 \text{ (scale)} \pm 3.4 \text{ (PDF)} \text{ pb}$

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**Diagrams:**

- CMS $e^+\mu^- + 1j1b$ postfit
- CMS $e^+\mu^- + 2j2b$ postfit
Charge asymmetry

- Non-zero charge asymmetry in $t\bar{t}$ production through $q\bar{q}$ interaction beyond LO
  
  
  
  FSR & ISR  
  
  Box diagram & tree-level  
  
  
  
  Enhanced by BSM scenarios, e.g. axigluons, $Z'$ bosons
  
  At LHC, different width of rapidity for top quarks and anti-quarks
  
  Measure $t\bar{t}$ charge asymmetries $A_C$ from $\Delta|y|(t,\bar{t}) = |y_t| - |y_{\bar{t}}|

\[
A_C^{t\bar{t}} = \frac{\sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) > 0) - \sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) < 0)}{\sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) > 0) + \sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) < 0)}
\]
- **tt** charge asymmetry

- **Using results from tt differential cross sections in dileptons** (analysis details in slides 10-11)
  - extracted at parton and particle levels
  - in addition, extraction of **leptonic** asymmetry

- Resultant charge asymmetries consistent with SM

\[
A_c^{\ell\ell} = \frac{\sigma_{tt}(\Delta \eta(\ell, \bar{\ell}) > 0) - \sigma_{tt}(\Delta \eta(\ell, \bar{\ell}) < 0)}{\sigma_{tt}(\Delta \eta(\ell, \bar{\ell}) > 0) + \sigma_{tt}(\Delta \eta(\ell, \bar{\ell}) < 0)}
\]
Event selection

Lepton+jets:
- Exactly 1 high-p_T isolated lepton (e or $\mu$)
  - $p_T >$ around 30 GeV (analysis dependent), $|\eta| < 2.1$
- $\geq 4$ jets: $p_T >$ 30 GeV, $|\eta| < 2.4$
- $\geq 2$ b-tagged jets

Dileptons:
- $\geq 2$ OS, high-p_T isolated leptons (ee, $\mu\mu$, $\mu e$)
  - $p_T >$ 20 GeV, $|\eta| < 2.4$
- QCD veto: $m_{ll} >$ 20 GeV
- $\geq 2$ jets: $p_T >$ 30 GeV, $|\eta| < 2.4$
- $\geq 1$ b-tagged jets
- ee, $\mu\mu$ channels: $E_T^{miss} >$ 40 GeV
  - Z veto: $|m_Z - m_{ll}| >$ 15 GeV

In addition: kinematic reconstruction of $t\bar{t}$ system
Definition of differential cross sections

- Differential results corrected (unfolded) back to true level, i.e. parton or particle level

- **Parton level** top quark
  - after QCD radiation and before decay
  - results can be compared to predictions from perturbative calculations
  - *study of various parameters, e.g.:* $\alpha_s$, $m_t$, PDFs

- **Particle level** top quark
  - reconstructed from stable particles after hadronization
  - minimized dependence on theoretical assumptions used in the simulation
  - *useful for testing of new physics models, MC validation and tuning*
Constraining top quark CMDM in EFT

- **Effective field theory (EFT):** modelling of new physics effects at high-energy scale $\Lambda_{NP}$

- **EFT approach:** extension of SM Lagrangian by higher-dimensional operators $O_i$

\[ \mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda_{NP}^2} O_i + h.c. \]

→ size of new physics effects parametrized by ratio $C_i/\Lambda_{NP}^2$ ($C_i$ – dimensionless coefficient)

- Dimension-6 operator $O_{tG}$ models **top quark chromomagnetic dipole moment** (CMDM)

→ modification of $g_t\bar{t}$ vertex and introduction of new $g^*g_t\bar{t}$ vertex

→ changes in chirality of top quarks alter $\bar{t}t$ spin correlation

- $\Delta\phi(l,\bar{l})$ sensitive to changes in $\bar{t}t$ production rate and event dynamics induced by $O_{tG}$

Mykola Savitskyi (DESY)
CMS: Compact Muon Solenoid

CMS – general purpose particle detector:
- cylindrical geometry, installed around LHC beampipe
- length: 21.6 m, diameter: 14.6 m, weight: 12 500 tons
- multiple subdetectors